

Report to

# Defense Sciences Office,

*Defense Advanced Research Projects Agency (DARPA)*

regarding

## **Feasibility Demonstration re Manufacturability of Metamatter (Crystallized Gasses, such as MetaStable Helium [MSH]) Via PRECURSOR Liquid Metallic Plasmoids (LMPs)**

submitted by

**Innoventek Inc.** (a Maryland Corporation)

CAGE Code: **472P8**  
DUNS # 609829010

### CONTENTS

### PAGE

1	Task 1A.1 Deliverable <b>Report:</b>	2
2	Task 1A.2 Deliverable <b>Report</b>	3
3.	Task 1A.3 Deliverable <b>Report</b>	24
4.	Task 1A.4 Deliverable <b>Report</b>	37
5.	Task 1A.5 Deliverable <b>Report</b>	40
6.	Task 1A.6 Deliverable <b>Report</b>	49
7.	Task 1A.7 Deliverable <b>Report</b>	50
	Appendix: Graphs & Summarizing Plots	53

## Task 1A.1

The relationship between the various theories of Liquid Metallic Plasmoids (LMPs) has been summarized in the original proposal.

The most complete theory is that of Brush, Sahlin & Teller, but this work did not produce an analytical theory of the desired Equation of State, but rather presented various numerical tabulations equivalent to an Equation of State, based upon computer-intensive Monte Carlo (MC) simulations using a cubic lattice, defined by a finite number  $N$  of particles. (where  $N$  ranges from 32 to 500), with periodic boundary conditions.

Let  $Z$  denote the atomic number: for Protium & Deuterium,  $Z = 1$ , and for Helium  $Z = 2$ .

Let  $n$  denote the electron density in particles/cm<sup>3</sup>, and assume complete ionization (or gross electrical neutrality) so that if  $n_i$  denotes the ion density then  $n = Zn_i$ . Also let  $T$  denote the plasma temperature in degrees Kelvin, and let  $k$  denote the Boltzmann constant. Then define the dimensionless parameter  $\Gamma$  by

$$\Gamma \equiv [(Ze)^2/kT](4\pi n/3)^{1/3},$$

where  $e$  denotes the electronic charge. The MC simulations were performed for  $0.05 \leq \Gamma \leq 100.0$  and it was found that Debye-Hückel (D-H) theory was accurate for  $0.05 \leq \Gamma \leq 0.1$  but starts to deteriorate as  $\Gamma \rightarrow 1.0$ . This confirms the need to use the Berlin-Montroll (B-H) theory as  $n$  increases relative to  $(kT)^3$ .

Accordingly it is concluded that Pozwolski's equation of state, namely, the Equation of State for "pressure"  $p$  or, more precisely, energy density

$$(D-H): \quad p = n_i kT(1 + Z) \left\{ 1 - [1/3]\pi^{1/2} Z^{3/2} (1 + Z)^{1/2} [(n_i)^{1/3} e^2 / (kT)]^{3/2} \right\},$$

should be used only for lower-density cases, while Wilhelm's alternative

$$(B-M): \quad p = n_i kT(1 + Z) \left\{ (7/6) - [1/2]\pi^{1/3} Z(1 + Z)^{1/3} [(n_i)^{1/3} e^2 / (kT)] \right\},$$

should be used in higher-density cases. But in either case the critical density is found from the requirement that the second term in the curly brackets must be larger than the first term.

Upon setting  $Z = 1$ , for the hydrogenic plasma cases, one recovers the expressions already discussed in the original proposal, wherein it was shown that in either case the critical density is within a factor of 1.41 of the alternative.

Accordingly it remains only to implement the B-M theory from the formulae presented by Wilhelm in order to find a range of temperatures and densities at which the LMP state can be maintained.

## Task 1A.2

### Internally-Documented MATLAB Source Codes

- [1] EnergyDensityBerlinMontroll
- [2] nCritFromWilhelm
- [3] Plot\_pBM
- [4] grphexs1
- [5] grphexs2
- [6] grphexs3
- [7] grphexs4
- [8] grphexs5
- [9] grphexs6
- [10] grphexs7
- [11] grphexs8
- [12] checkWilhelm011407A

```

function [pBM] = EnergyDensityBerlinMontroll(epstr,Z,T,ni);
%*****
%
% inputs:
%       epstr = relative permittivity of gas with Z-charged ions
%       Z = charge number of ions
%       T = plasma temperature, kelvins [degrees K]
%       ni = ion density, particles per cm^3
%
% output:
%       p = energy density, J/cm^3
%
% Copyright 9/17/07 by Robert W. Bass
%*****
eps0 = 8.854187817e-14; % permittivity of free space [ F/cm ], where
%                   actual permittivity is espstr*eps)
elchg = 1.60217733e-19; % charge on an electron [ C ]
kB = 1.380658e-23; % Boltzmann's constant [ J/K ]
eps = epstr*eps0;
fctr1 = kB*(1 + Z);
fctr2 = (pi^(1/3))/2;
fctr3 = (elchg^2)/(4*pi*eps);
fctr4 = (Z*(1 + Z)^(1/3))/kB;
fctrBM = (7/6) - (fctr2*fctr3*fctr4)*(1./T).*(ni).^(1/3);
pFL = fctr1*ni.*T; % energy density [fluid pressure], neglecting
%                   cohesive electrostatic Coulomb energy
pBM = pFL.*fctrBM; % inclusion of sign-changing Coulomb-energy factor
% end of EnergyDensityBerlinMontroll.m

```

```

function [niCRIT] = nCritFromWilhelm(epstr,Z,T);
%*****
%
% inputs:
%     epstr = relative permittivity of gas with Z-charged ions
%     Z = charge number of ions
%     T = plasma temperature, kelvins [degrees K]
%
% output:
%     niCRIT = critical ion density, particles per cm^3
%
% Copyright 9/17/07 by Robert W. Bass
%*****
eps0 = 8.854187817e-14; % permittivity of free space [ F/cm ], where
%                               actual permittivity is espstr*eps)
elchg = 1.60217733e-19; % charge on an electron [ C ]
kB = 1.380658e-23; % Boltzmann's constant [ J/K ]
fctr = (1/pi)*((7/3)*(4*pi*eps0*kB)/(elchg)^2)^3; % from Wilhelm
niCRIT = fctr*((epstr*T/Z).^3)/(1+Z);
% end of nCritFromWilhelm.m

```

```

function [X,Y,ZZ] = Plot_pBM(epstr,Z,N);
%*****
%
% inputs:
%       epstr = relative permittivity [where actual eps = epstr.eps0]
%       Z = charge number of ions (Hydrogen: Z=1 ; Helium: Z=2 )
%       N = number of lines on each grid; mesh is N-by-N
%
% outputs:      X =      T = plasma Temperature in degrees K
%              Y = ni = ion-Density/10^17 in particles/cm^3
%              ZZ = pMB = energy density (Berlin-Montroll Thy.) in J/cm^3
%
% Copyright 9/17/2007 by Robert W. Bass
%*****
Tmin=400;Tmax = 6000;          % plasma Temperature min/max in degrees K
nimin=0.0005;nimax=500;      % plasma ion-Density/10^17 min/max in #/cm^3
dT = (Tmax - Tmin)/(N-1);    % increment on x-axis
dni = (nimax - nimin)/(N-1); % increment on y-axis
T = [Tmin:dT:Tmax];
ni = [nimin:dni:nimax];
[X,Y] = meshgrid(T,ni);      % horizontal base mesh-grid
% now compute surface pBM = pressure [energy density] over horizontal grid:
for j = 1:N
    for k = 1:N
        ZZ(j,k)= EnergyDensityBerlinMontroll(epstr,Z,X(j,k),(10^17)*Y(j,k));
    end
end
meshz(X,Y,ZZ),xlabel('Temperature [deg K]'),...
ylabel('Ion Density divided by 10^1^7 [per cm^3]'),...
zlabel('Energy Density [J/cm^3]'),...
if Z == 1
title('Hydrogen Plasma Energy Density via Berlin-Montroll Theory')
else
title('Helium Plasma Energy Density via Berlin-Montroll Theory')
end
% end of Plot_pBM.m

```

```

function [indx,p,p0,pc,ps] = grphexs1(n0,nf,T,N);
kB = 1.38065812*10^(-16);           % erg/K
eV = 1.6021773349*10^(-20);        % emu
c = 2.99792458*10^10;              % cm/sec
es = c*eV;                          % esu
atm = 1.01*10^6;                    % dyn/cm^2
f0 = 2.0*kB*T;
f1 = ((2*pi)^(1/3))*es*es;
f2 = kB*T/3.0;
p = zeros(N,1);
p0 = p;
pc = p;
sgnp = p;
ps = p;
indx = p;
indx0 = log10(n0);
indxf = log10(nf);
for k = 1:N
    indx(k) = indx0 + (indxf - indx0)*(k - 1)/(N - 1);
    ni(k) = 10^indx(k);
    p0(k) = f0*ni(k);
    pc(k) = f1*(ni(k)^(4/3)) - f2*ni(k);
    p(k) = p0(k) - pc(k);
end
p0 = p0/atm;
pc = pc/atm;
p = p/atm;
for k = 1:N
    pk = p(k);
    sgnpk = sign(pk);
    abspk = abs(pk);
    abslogpk = abs(log10(abspk));
    ps(k) = sgnpk*abslogpk;
end
% end of grphexs1.m

```

```
function grphexs2(n0,nf,T1,T2,T3,N);
[indx,p,p0,pc,ps1] = grphexs1(n0,nf,T1,N);
[indx,p,p0,pc,ps2] = grphexs1(n0,nf,T2,N);
[indx,p,p0,pc,ps3] = grphexs1(n0,nf,T3,N);
plot(indx,ps1,'-',indx,ps2,':',indx,ps3,'--');
xlabel('Log of particle Density [per cubic cm]');
ylabel('Log of Pressure [in atmospheres]');
title('Plasma Temperatures of T1, T2, & T3 Thousand Kelvins');
legend('T1','T2','T3');
grid;
% end grphexs2.m
```

```

function [indx,p,p0,pc,ps] = grphexs3(n0,nf,T,N);
kB = 1.38065812*10^(-16);           % erg/K
eV = 1.6021773349*10^(-20);        % emu
c = 2.99792458*10^10;              % cm/sec
es = c*eV;                          % esu
atm = 1.01*10^6;                    % dyn/cm^2
f0 = 2.0*kB*T;
f1 = ((8*pi)^(1/2))*((es*es*es)/3);
f2 = (kB*T)^1/2;
f3 = f1/f2;
p = zeros(N,1);
p0 = p;
pc = p;
ps = p;
indx = p;
indx0 = log10(n0);
indxf = log10(nf);
for k = 1:N
    indx(k) = indx0 + (indxf - indx0)*(k - 1)/(N - 1);
    ni(k) = 10^indx(k);
    p0(k) = f0*ni(k);
    pc(k) = f3*(ni(k)^(3/2));
    p(k) = p0(k) - pc(k);
end
p0 = p0/atm;
pc = pc/atm;
p = p/atm;
ps = sign(p).*log10(abs(p));
% end of grphexs3.m

```

```
function grphexs4(n0,nf,T1,T2,T3,N);
[indx,p,p0,pc,ps1] = grphexs3(n0,nf,T1,N);
[indx,p,p0,pc,ps2] = grphexs3(n0,nf,T2,N);
[indx,p,p0,pc,ps3] = grphexs3(n0,nf,T3,N);
plot(indx,ps1,'-',indx,ps2,':',indx,ps3,'--');
xlabel('Log of particle Density [per cubic cm]');
ylabel('Log of Pressure [in atmospheres]');
title('Plasma Temperatures of T1, T2, & T3 Thousand Kelvins');
legend('T1','T2','T3');
grid;
% end grphexs4.m
```

```

function [indx,T,Tlog,ncrit] = grphexs5(T0,Tf,N);
kB = 1.38065812*10^(-16);           % erg/K
eV = 1.6021773349*10^(-20);        % emu
c = 2.99792458*10^10;              % cm/sec
es = c*eV;                          % esu
atm = 1.01*10^6;                    % dyn/cm^2
f1 = (7/3)^3;
f2 = 2*pi*es^6;
f3 = f1/f2;
indx = zeros(N,1);
ncrit = indx;
T = indx;
indx0 = log10(T0);
indxf = log10(Tf);
for k = 1:N
    indx(k) = indx0 + (indxf - indx0)*(k - 1)/(N - 1);
    Tk = 10^indx(k);
    T(k) = Tk;
    ncrit(k) = f3*(kB*Tk)^3;
end
ncritlog = log10(ncrit);
Tlog = log10(T);
plot(T,ncrit);
title('Critical Density for Plasma Self-Cohesion');
xlabel('Temperature [degrees Kelvin]');
ylabel('particle Density [per cubic cm]');
grid;
pause;
plot(Tlog,ncritlog);
title('Critical Density for Plasma Self-Cohesion');
xlabel('Log of Temperature [degrees Kelvin]');
ylabel('Log of particle Density [per cubic cm]');
grid;
% end of grphexs5.m

```

```

function [indx,T,Tlog,p,plog] = grphexs6(T0,Tf,N);
kB = 1.38065812*10^(-16);           % erg/K
eV = 1.6021773349*10^(-20);        % emu
c = 2.99792458*10^10;              % cm/sec
es = c*eV;                          % esu
atm = 1.01*10^6;                    % dyn/cm^2
f1 = (7/3)^3;
f2 = 2*pi*es^6;
f3 = f1/f2;
indx = zeros(N,1);
p = indx;
T = p;
indx0 = log10(T0);
indxf = log10(Tf);
for k = 1:N
    indx(k) = indx0 + (indxf - indx0)*(k - 1)/(N - 1);
    Tk = 10^indx(k);
    kBTk = kB*Tk;
    T(k) = Tk;
    ncritk = f3*(kBTk)^3;
    p(k) = 2*ncritk*kBTk;
end
p = p/atm;
Tlog = log10(T);
plog = log10(p);
plot(T,p);
title('Energy Density at Critical Particle Density for Plasma Self-Cohesion');
xlabel('Temperature [degrees Kelvin]');
ylabel('Energy Density [atmospheres "pressure"]');
grid;
pause;
plot(Tlog,plog);
title('Energy Density at Critical Particle Density for Plasma Self-Cohesion');
xlabel('Log of Temperature [degrees Kelvin]');
ylabel('Log of Energy Density [atmospheres "pressure"]');
grid;
% end of grphexs6.m

```

```

function [indx,T,Tlog,p,plog] = grphexs7(n0,nf,N);
kB = 1.38065812*10^(-16);           % erg/K
eV = 1.6021773349*10^(-20);        % emu
c = 2.99792458*10^10;              % cm/sec
es = c*eV;                          % esu
atm = 1.01*10^6;                    % dyn/cm^2
f1 = (7/3)*kB;
f2 = ((2*pi)^(1/3))*es*es;
f3 = f2/f1;
indx = zeros(N,1);
p = indx;
T = p;
indx0 = log10(n0);
indxf = log10(nf);
for k = 1:N
    indx(k) = indx0 + (indxf - indx0)*(k - 1)/(N - 1);
    nk = 10^indx(k);
    Tk = f3*nk^(1/3);
    kBTk = kB*Tk;
    pk = 2*nk*kB Tk;
    T(k) = Tk;
    p(k) = pk;
end
p = p/atm;
Tlog = log10(T);
plog = log10(p);
plot(plog,T);
title('Berlin-Montroll State Equation (at critical density)');
ylabel('Degrees Kelvin');
xlabel('Log of Energy Density [atmospheres "pressure"]');
legend('Temperature');
grid;
% end of grphexs7.m

```

```
function grphexs8(n0,nf,N);
T1 = 6400;
T2 = 6700;
T3 = 7000;
[indx,p,p0,pc,ps1] = grphexs1(n0,nf,T1,N);
[indx,p,p0,pc,ps2] = grphexs1(n0,nf,T2,N);
[indx,p,p0,pc,ps3] = grphexs1(n0,nf,T3,N);
plot(indx,ps1,'-',indx,ps2,':',indx,ps3,'--');
xlabel('Log of particle Density [per cubic cm]');
ylabel('Log of Pressure [in atmospheres]');
title('Plasma Temperatures T1 = 6400, T2 = 6700, & T3 = 7000 Kelvins');
legend('T1','T2','T3');
grid;
% end grphexs8.m
```

```
function [fctr] = CheckWilhelm011407A(dum);  
eps0 = 8.854187817e-14; % permittivity of free space [ F/cm ]  
elchg = 1.60217733e-19; % charge on an electron [ C ]  
kB = 1.380658e-23;      % Boltzmann's constant [ J/K ]  
fctr = (1/pi)*((7/3)*(4*pi*eps0*kB)/(elchg)^2)^3;
```

T/10 <sup>4</sup>	niCRIT/10 <sup>20</sup>	niCRIT_He/10 <sup>19</sup>
0.050000000000000	0.00054166544311	0.00045138786926
0.05317725752508	0.00065162678043	0.00054302231703
0.05635451505017	0.00077554547315	0.00064628789429
0.05953177257525	0.00091425545129	0.00076187954275
0.06270903010033	0.00106859064491	0.00089049220409
0.06588628762542	0.00123938498403	0.00103282082002
0.06906354515050	0.00142747239869	0.00118956033224
0.07224080267559	0.00163368681894	0.00136140568245
0.07541806020067	0.00185886217481	0.00154905181234
0.07859531772575	0.00210383239635	0.00175319366362
0.08177257525084	0.00236943141358	0.00197452617799
0.08494983277592	0.00265649315656	0.00221374429714
0.08812709030100	0.00296585155532	0.00247154296277
0.09130434782609	0.00329834053990	0.00274861711658
0.09448160535117	0.00365479404033	0.00304566170027
0.09765886287625	0.00403604598666	0.00336337165555
0.10083612040134	0.00444293030893	0.00370244192410
0.10401337792642	0.00487628093717	0.00406356744764
0.10719063545151	0.00533693180142	0.00444744316785
0.11036789297659	0.00582571683173	0.00485476402644
0.11354515050167	0.00634346995813	0.00528622496510
0.11672240802676	0.00689102511065	0.00574252092555
0.11989966555184	0.00746921621935	0.00622434684946
0.12307692307692	0.00807887721426	0.00673239767855
0.12625418060201	0.00872084202542	0.00726736835451
0.12943143812709	0.00939594458286	0.00782995381905
0.13260869565217	0.01010501881662	0.00842084901385
0.13578595317726	0.01084889865676	0.00904074888063
0.13896321070234	0.01162841803329	0.00969034836108
0.14214046822742	0.01244441087627	0.01037034239689
0.14531772575251	0.01329771111573	0.01108142592978
0.14849498327759	0.01418915268171	0.01182429390143
0.15167224080268	0.01511956950425	0.01259964125354
0.15484949832776	0.01608979551339	0.01340816292783
0.15802675585284	0.01710066463917	0.01425055386597
0.16120401337793	0.01815301081162	0.01512750900968
0.16438127090301	0.01924766796079	0.01603972330066
0.16755852842809	0.02038547001671	0.01698789168059
0.17073578595318	0.02156725090943	0.01797270909119
0.17391304347826	0.02279384456898	0.01899487047415
0.17709030100334	0.02406608492540	0.02005507077117
0.18026755852843	0.02538480590874	0.02115400492395
0.18344481605351	0.02675084144902	0.02229236787418
0.18662207357860	0.02816502547629	0.02347085456357
0.18979933110368	0.02962819192059	0.02469015993382
0.19297658862876	0.03114117471195	0.02595097892663
0.19615384615385	0.03270480778042	0.02725400648369
0.19933110367893	0.03431992505604	0.02859993754670
0.20250836120401	0.03598736046884	0.02998946705737
0.20568561872910	0.03770794794886	0.03142328995738
0.20886287625418	0.03948252142614	0.03290210118845
0.21204013377926	0.04131191483073	0.03442659569227
0.21521739130435	0.04319696209265	0.03599746841054
0.21839464882943	0.04513849714196	0.03761541428496
0.22157190635452	0.04713735390868	0.03928112825723
0.22474916387960	0.04919436632285	0.04099530526904
0.22792642140468	0.05131036831453	0.04275864026211
0.23110367892977	0.05348619381373	0.04457182817811
0.23428093645485	0.05572267675052	0.04643556395876

0.23745819397993	0.05802065105491	0.04835054254576
0.24063545150502	0.06038095065696	0.05031745888080
0.24381270903010	0.06280440948669	0.05233700790558
0.24698996655518	0.06529186147416	0.05440988456180
0.25016722408027	0.06784414054939	0.05653678379116
0.253344448160535	0.07046208064244	0.05871840053536
0.25652173913043	0.07314651568333	0.06095542973610
0.25969899665552	0.07589827960210	0.06324856633508
0.26287625418060	0.07871820632880	0.06559850527400
0.26605351170569	0.08160712979346	0.06800594149455
0.26923076923077	0.08456588392613	0.07047156993844
0.27240802675585	0.08759530265684	0.07299608554737
0.27558528428094	0.09069621991563	0.07558018326302
0.27876254180602	0.09386946963254	0.07822455802711
0.28193979933110	0.09711588573760	0.08092990478134
0.28511705685619	0.10043630216087	0.08369691846739
0.28829431438127	0.10383155283237	0.08652629402698
0.29147157190635	0.10730247168215	0.08941872640179
0.29464882943144	0.11084989264024	0.09237491053353
0.29782608695652	0.11447464963669	0.09539554136391
0.30100334448161	0.11817757660153	0.09848131383461
0.30418060200669	0.12195950746480	0.10163292288733
0.30735785953177	0.12582127615654	0.10485106346378
0.31053511705686	0.12976371660679	0.10813643050566
0.31371237458194	0.13378766274559	0.11148971895466
0.31688963210702	0.13789394850298	0.11491162375248
0.32006688963211	0.14208340780899	0.11840283984083
0.32324414715719	0.14635687459367	0.12196406216139
0.32642140468227	0.15071518278706	0.12559598565588
0.32959866220736	0.15515916631919	0.12929930526599
0.33277591973244	0.15968965912010	0.13307471593342
0.33595317725753	0.16430749511983	0.13692291259986
0.33913043478261	0.16901350824843	0.14084459020702
0.34230769230769	0.17380853243592	0.14484044369660
0.34548494983278	0.17869340161235	0.14891116801029
0.34866220735786	0.18366894970776	0.15305745808980
0.35183946488294	0.18873601065219	0.15728000887683
0.35501672240803	0.19389541837567	0.16157951531306
0.35819397993311	0.19914800680825	0.16595667234021
0.36137123745819	0.20449460987996	0.17041217489997
0.36454849498328	0.20993606152085	0.17494671793404
0.36772575250836	0.21547319566095	0.17956099638412
0.37090301003344	0.22110684623029	0.18425570519191
0.37408026755853	0.22683784715893	0.18903153929911
0.37725752508361	0.23266703237690	0.19388919364741
0.38043478260870	0.23859523581423	0.19882936317852
0.38361204013378	0.24462329140097	0.20385274283414
0.38678929765886	0.25075203306716	0.20896002755596
0.38996655518395	0.25698229474283	0.21415191228569
0.39314381270903	0.26331491035802	0.21942909196502
0.39632107023411	0.26975071384278	0.22479226153565
0.39949832775920	0.27629053912714	0.23024211593928
0.40267558528428	0.28293522014114	0.23577935011762
0.40585284280936	0.28968559081482	0.24140465901235
0.40903010033445	0.29654248507822	0.24711873756518
0.41220735785953	0.30350673686137	0.25292228071781
0.41538461538462	0.31057918009433	0.25881598341194
0.41856187290970	0.31776064870712	0.26480054058926
0.42173913043478	0.32505197662978	0.27087664719148
0.42491638795987	0.33245399779236	0.27704499816030
0.42809364548495	0.33996754612489	0.28330628843741

0.43127090301003	0.34759345555741	0.28966121296451
0.43444816053512	0.35533256001997	0.29611046668331
0.43762541806020	0.36318569344259	0.30265474453549
0.44080267558528	0.37115368975532	0.30929474146277
0.44397993311037	0.37923738288820	0.31603115240684
0.44715719063545	0.38743760677127	0.32286467230939
0.45033444816054	0.39575519533456	0.32979599611214
0.45351170568562	0.40419098250812	0.33682581875677
0.45668896321070	0.41274580222198	0.34395483518499
0.45986622073579	0.42142048840619	0.35118374033849
0.46304347826087	0.43021587499077	0.35851322915898
0.46622073578595	0.43913279590578	0.36594399658815
0.46939799331104	0.44817208508125	0.37347673756771
0.47257525083612	0.45733457644721	0.38111214703934
0.47575250836120	0.46662110393372	0.38885091994476
0.47892976588629	0.47603250147080	0.39669375122566
0.48210702341137	0.48556960298849	0.40464133582374
0.48528428093645	0.49523324241684	0.41269436868070
0.48846153846154	0.50502425368589	0.42085354473824
0.49163879598662	0.51494347072567	0.42911955893806
0.49481605351171	0.52499172746622	0.43749310622185
0.49799331103679	0.53516985783758	0.44597488153132
0.50117056856187	0.54547869576979	0.45456557980816
0.50434782608696	0.55591907519289	0.46326589599407
0.50752508361204	0.56649183003692	0.47207652503076
0.51070234113712	0.57719779423191	0.48099816185993
0.51387959866221	0.58803780170791	0.49003150142326
0.51705685618729	0.59901268639496	0.49917723866246
0.52023411371237	0.61012328222309	0.50843606851924
0.52341137123746	0.62137042312234	0.51780868593528
0.52658862876254	0.63275494302275	0.52729578585229
0.52976588628763	0.64427767585437	0.53689806321197
0.53294314381271	0.65593945554722	0.54661621295602
0.53612040133779	0.66774111603135	0.55645093002613
0.53929765886288	0.67968349123681	0.56640290936400
0.54247491638796	0.69176741509361	0.57647284591134
0.54565217391304	0.70399372153182	0.58666143460985
0.54882943143813	0.71636324448146	0.59696937040121
0.55200668896321	0.72887681787257	0.60739734822714
0.55518394648829	0.74153527563520	0.61794606302933
0.55836120401338	0.75433945169937	0.62861620974948
0.56153846153846	0.76729017999514	0.63940848332929
0.56471571906355	0.78038829445254	0.65032357871045
0.56789297658863	0.79363462900161	0.66136219083467
0.57107023411371	0.80703001757238	0.67252501464365
0.57424749163880	0.82057529409491	0.68381274507909
0.57742474916388	0.83427129249922	0.69522607708268
0.58060200668896	0.84811884671535	0.70676570559612
0.58377926421405	0.86211879067335	0.71843232556112
0.58695652173913	0.87627195830325	0.73022663191937
0.59013377926421	0.89057918353509	0.74214931961257
0.59331103678930	0.90504130029891	0.75420108358243
0.59648829431438	0.91965914252476	0.76638261877063
0.59966555183946	0.93443354414266	0.77869462011888
0.60284280936455	0.94936533908266	0.79113778256888
0.60602006688963	0.96445536127479	0.80371280106233
0.60919732441472	0.97970444464911	0.81642037054092
0.61237458193980	0.99511342313563	0.82926118594636
0.61555183946488	1.01068313066442	0.84223594222035
0.61872909698997	1.02641440116549	0.85534533430458
0.62190635451505	1.04230806856890	0.86859005714075

0.62508361204013	1.05836496680468	0.88197080567056
0.62826086956522	1.07458592980286	0.89548827483572
0.63143812709030	1.09097179149350	0.90914315957792
0.63461538461538	1.10752338580662	0.92293615483885
0.63779264214047	1.12424154667228	0.93686795556023
0.64096989966555	1.14112710802049	0.95093925668374
0.64414715719064	1.15818090378131	0.96515075315110
0.64732441471572	1.17540376788478	0.97950313990398
0.65050167224080	1.19279653426093	0.99399711188411
0.65367892976589	1.21036003683980	1.00863336403317
0.65685618729097	1.22809510955143	1.02341259129286
0.66003344481605	1.24600258632587	1.03833548860489
0.66321070234114	1.26408330109314	1.05340275091095
0.66638795986622	1.28233808778329	1.06861507315274
0.66956521739130	1.30076778032635	1.08397315027196
0.67274247491639	1.31937321265237	1.09947767721031
0.67591973244147	1.33815521869139	1.11512934890949
0.67909698996656	1.35711463237344	1.13092886031120
0.68227424749164	1.37625228762857	1.14687690635714
0.68545150501672	1.39556901838680	1.16297418198900
0.68862876254181	1.41506565857819	1.17922138214849
0.69180602006689	1.43474304213277	1.19561920177731
0.69498327759197	1.45460200298057	1.21216833581714
0.69816053511706	1.47464337505165	1.22886947920971
0.70133779264214	1.49486799227603	1.24572332689669
0.70451505016722	1.51527668858376	1.26273057381980
0.70769230769231	1.53587029790487	1.27989191492072
0.71086956521739	1.55664965416940	1.29720804514117
0.71404682274247	1.57761559130740	1.31467965942284
0.71722408026756	1.59876894324890	1.33230745270742
0.72040133779264	1.62011054392395	1.35009211993662
0.72357859531773	1.64164122726257	1.36803435605214
0.72675585284281	1.66336182719481	1.38613485599567
0.72993311036789	1.68527317765071	1.40439431470892
0.73311036789298	1.70737611256031	1.42281342713359
0.73628762541806	1.72967146585364	1.44139288821136
0.73946488294314	1.75216007146074	1.46013339288395
0.74264214046823	1.77484276331167	1.47903563609305
0.74581939799331	1.79772037533644	1.49810031278037
0.74899665551839	1.82079374146511	1.51732811788759
0.75217391304348	1.84406369562770	1.53671974635642
0.75535117056856	1.86753107175427	1.55627589312856
0.75852842809365	1.89119670377485	1.57599725314571
0.76170568561873	1.91506142561947	1.59588452134956
0.76488294314381	1.93912607121818	1.61593839268182
0.76806020066890	1.96339147450102	1.63615956208419
0.77123745819398	1.98785846939802	1.65654872449835
0.77441471571906	2.01252788983923	1.67710657486603
0.77759197324415	2.03740056975468	1.69783380812890
0.78076923076923	2.06247734307441	1.71873111922868
0.78394648829431	2.08775904372847	1.73979920310705
0.78712374581940	2.11324650564688	1.76103875470573
0.79030100334448	2.13894056275969	1.78245046896641
0.79347826086957	2.16484204899694	1.80403504083078
0.79665551839465	2.19095179828867	1.82579316524056
0.79983277591973	2.21727064456491	1.84772553713743
0.80301003344482	2.24379942175571	1.86983285146309
0.80618729096990	2.27053896379110	1.89211580315925
0.80936454849498	2.29749010460113	1.91457508716761
0.81254180602007	2.32465367811582	1.93721139842985
0.81571906354515	2.35203051826523	1.96002543188769

0.81889632107023	2.37962145897939	1.98301788248283
0.82207357859532	2.40742733418834	2.00618944515695
0.82525083612040	2.43544897782211	2.02954081485176
0.82842809364548	2.46368722381076	2.05307268650896
0.83160535117057	2.49214290608431	2.07678575507026
0.83478260869565	2.52081685857280	2.10068071547733
0.83795986622074	2.54970991520628	2.12475826267190
0.84113712374582	2.57882290991478	2.14901909159565
0.84431438127090	2.60815667662834	2.17346389719028
0.84749163879599	2.63771204927701	2.19809337439751
0.85066889632107	2.66748986179081	2.22290821815901
0.85384615384615	2.69749094809979	2.24790912341650
0.85702341137124	2.72771614213400	2.27309678511166
0.86020066889632	2.75816627782345	2.29847189818621
0.86337792642140	2.78884218909821	2.32403515758184
0.86655518394649	2.81974470988830	2.34978725824025
0.86973244147157	2.85087467412376	2.37572889510314
0.87290969899666	2.88223291573464	2.40186076311220
0.87608695652174	2.91382026865097	2.42818355720914
0.87926421404682	2.94563756680279	2.45469797233566
0.88244147157191	2.97768564412014	2.48140470343345
0.88561872909699	3.00996533453306	2.50830444544422
0.88879598662207	3.04247747197159	2.53539789330966
0.89197324414716	3.07522289036576	2.56268574197147
0.89515050167224	3.10820242364562	2.59016868637135
0.89832775919732	3.14141690574121	2.61784742145101
0.90150501672241	3.17486717058256	2.64572264215213
0.90468227424749	3.20855405209971	2.67379504341643
0.90785953177258	3.24247838422271	2.70206532018559
0.91103678929766	3.27664100088158	2.73053416740132
0.91421404682274	3.31104273600638	2.75920228000532
0.91739130434783	3.34568442352714	2.78807035293928
0.92056856187291	3.38056689737389	2.81713908114491
0.92374581939799	3.41569099147668	2.84640915956390
0.92692307692308	3.45105753976555	2.87588128313796
0.93010033444816	3.48666737617053	2.90555614680878
0.93327759197324	3.52252133462167	2.93543444551806
0.93645484949833	3.55862024904900	2.96551687420750
0.93963210702341	3.59496495338256	2.99580412781880
0.94280936454850	3.63155628155239	3.02629690129366
0.94598662207358	3.66839506748854	3.05699588957378
0.94916387959866	3.70548214512103	3.08790178760086
0.95234113712375	3.74281834837991	3.11901529031659
0.95551839464883	3.78040451119521	3.15033709266268
0.95869565217391	3.81824146749699	3.18186788958082
0.96187290969900	3.85633005121527	3.21360837601272
0.96505016722408	3.89467109628009	3.24555924690008
0.96822742474916	3.93326543662150	3.27772119718458
0.97140468227425	3.97211390616953	3.31009492180794
0.97458193979933	4.01121733885422	3.34268111571185
0.97775919732441	4.05057656860560	3.37548047383800
0.98093645484950	4.09019242935373	3.40849369112811
0.98411371237458	4.13006575502864	3.44172146252387
0.98729096989967	4.17019737956036	3.47516448296697
0.99046822742475	4.21058813687895	3.50882344739912
0.99364548494983	4.25123886091442	3.54269905076202
0.99682274247492	4.29215038559683	3.57679198799736
1.00000000000000	4.33332354485621	3.61110295404684

T/10 <sup>3</sup>	niCRIT/10 <sup>20</sup>	niCRIT_He/10 <sup>19</sup>
6.000000000000000	0.93599788568894	0.77999823807412
6.14634146341463	1.00616954708902	0.83847462257418
6.29268292682927	1.07976355388736	0.89980296157280
6.43902439024390	1.15686139049821	0.96405115874850
6.58536585365854	1.23754454133580	1.03128711777984
6.73170731707317	1.32189449081439	1.10157874234533
6.87804878048780	1.40999272334823	1.17499393612352
7.02439024390244	1.50192072335154	1.25160060279295
7.17073170731707	1.59775997523858	1.33146664603215
7.31707317073171	1.69759196342360	1.41465996951966
7.46341463414634	1.80149817232083	1.50124847693402
7.60975609756098	1.90956008634452	1.59130007195377
7.75609756097561	2.02185918990892	1.68488265825743
7.90243902439024	2.13847696742827	1.78206413952356
8.04878048780488	2.25949490331681	1.88291241943067
8.19512195121951	2.38499448198879	1.98749540165732
8.34146341463415	2.51505718785845	2.09588098988204
8.48780487804878	2.64976450534004	2.20813708778337
8.63414634146342	2.78919791884780	2.32433159903983
8.78048780487805	2.93343891279598	2.44453242732998
8.92682926829268	3.08256897159881	2.56880747633234
9.07317073170732	3.23666957967055	2.69722464972546
9.21951219512195	3.39582222142544	2.82985185118787
9.36585365853658	3.56010838127772	2.96675698439810
9.51219512195122	3.72960954364164	3.10800795303470
9.65853658536585	3.90440719293144	3.25367266077620
9.80487804878049	4.08458281356137	3.40381901130114
9.95121951219512	4.27021788994567	3.55851490828806
10.09756097560976	4.46139390649858	3.71782825541548
10.24390243902439	4.65819234763435	3.88182695636196
10.39024390243903	4.86069469776722	4.05057891480602
10.53658536585366	5.06898244131145	4.22415203442621
10.68292682926829	5.28313706268126	4.40261421890105
10.82926829268293	5.50324004629091	4.58603337190909
10.97560975609756	5.72937287655464	4.77447739712887
11.12195121951219	5.96161703788670	4.96801419823891
11.26829268292683	6.20005401470132	5.16671167891777
11.41463414634146	6.44476529141276	5.37063774284397
11.56097560975610	6.69583235243525	5.57986029369605
11.70731707317073	6.95333668218306	5.79444723515255
11.85365853658537	7.21735976507040	6.01446647089200
12.00000000000000	7.48798308551154	6.23998590459295

T/10 <sup>3</sup>	niCRIT/10 <sup>19</sup>	niCRIT_He/10 <sup>19</sup>
0.400000000000000	0.00277332706871	0.00023111058906
0.53658536585366	0.00669479971353	0.00055789997613
0.67317073170732	0.01321894490814	0.00110157874235
0.80975609756098	0.02300826111977	0.00191735509331
0.94634146341463	0.03672524681561	0.00306043723463
1.08292682926829	0.05503240046291	0.00458603337191
1.21951219512195	0.07859222052887	0.00654935171074
1.35609756097561	0.10806720548072	0.00900560045673
1.49268292682927	0.14411985378567	0.01200998781547
1.62926829268293	0.18741266391094	0.01561772199258
1.76585365853659	0.23860813432375	0.01988401119365
1.90243902439024	0.29836876349133	0.02486406362428
2.03902439024390	0.36735704988089	0.03061308749007
2.17560975609756	0.44623549195965	0.03718629099664
2.31219512195122	0.53566658819482	0.04463888234957
2.44878048780488	0.63631283705363	0.05302606975447
2.58536585365854	0.74883673700330	0.06240306141694
2.72195121951220	0.87390078651105	0.07282506554259
2.85853658536585	1.01216748404409	0.08434729033701
2.99512195121951	1.16429932806965	0.09702494400580
3.13170731707317	1.33095881705493	0.11091323475458
3.26829268292683	1.51280844946717	0.12606737078893
3.40487804878049	1.71051072377359	0.14254256031447
3.54146341463415	1.92472813844139	0.16039401153678
3.67804878048781	2.15612319193780	0.17967693266148
3.81463414634146	2.40535838273004	0.20044653189417
3.95121951219512	2.67309620928533	0.22275801744044
4.08780487804878	2.95999917007089	0.24666659750591
4.22439024390244	3.26672976355393	0.27222748029616
4.36097560975610	3.59395048820168	0.29949587401681
4.49756097560976	3.94232384248135	0.32852698687345
4.63414634146341	4.31251232486017	0.35937602707168
4.77073170731707	4.70517843380535	0.39209820281711
4.90731707317073	5.12098466778411	0.42674872231534
5.04390243902439	5.56059352526367	0.46338279377197
5.18048780487805	6.02466750471125	0.50205562539260
5.31707317073171	6.51386910459407	0.54282242538284
5.45365853658537	7.02886082337935	0.58573840194828
5.59024390243902	7.57030515953430	0.63085876329452
5.72682926829268	8.13886461152615	0.67823871762718
5.86341463414634	8.73520167782212	0.72793347315184
6.00000000000000	9.35997885688942	0.77999823807412

T/10 <sup>3</sup>	niCRIT/10 <sup>18</sup>	niCRIT_He/10 <sup>18</sup> ]
0.400000000000000	0.02773327068708	0.00231110589059
0.51428571428571	0.05894330708712	0.00491194225726
0.62857142857143	0.10761802706852	0.00896816892238
0.74285714285714	0.17763847142716	0.01480320595226
0.85714285714286	0.27288568095888	0.02274047341324
0.97142857142857	0.39724069645954	0.03310339137163
1.08571428571429	0.55458455872501	0.04621537989375
1.200000000000000	0.74879830855115	0.06239985904593
1.31428571428571	0.98376298673382	0.08198024889448
1.42857142857143	1.26335963406887	0.10527996950574
1.54285714285714	1.59146929135216	0.13262244094601
1.65714285714286	1.97197299937956	0.16433108328163
1.77142857142857	2.40875179894692	0.20072931657891
1.88571428571429	2.90568673085010	0.24214056090418
2.000000000000000	3.46665883588497	0.28888823632375
2.11428571428571	4.09554915484738	0.34129576290395
2.22857142857143	4.79623872853319	0.39968656071110
2.34285714285714	5.57260859773826	0.46438404981152
2.45714285714286	6.42853980325846	0.53571165027154
2.57142857142857	7.36791338588963	0.61399278215747
2.68571428571429	8.39461038642765	0.69955086553564
2.800000000000000	9.51251184566836	0.79270932047236
2.91428571428571	10.72549880440763	0.89379156703397
3.02857142857143	12.03745230344133	1.00312102528678
3.14285714285714	13.45225338356530	1.12102111529711
3.25714285714286	14.97378308557540	1.24781525713128
3.37142857142857	16.60592245026750	1.38382687085562
3.48571428571429	18.35255251843747	1.52937937653646
3.600000000000000	20.21755433088115	1.68479619424010
3.71428571428571	22.20480892839440	1.85040074403287
3.82857142857143	24.31819735177309	2.02651644598109
3.94285714285714	26.56160064181307	2.21346672015109
4.05714285714286	28.93889983931021	2.41157498660918
4.17142857142857	31.45397598506038	2.62116466542170
4.28571428571429	34.11071011985939	2.84255917665495
4.400000000000000	36.91298328450316	3.07608194037526
4.51428571428571	39.86467651978750	3.32205637664896
4.62857142857143	42.96967086650832	3.58080590554236
4.74285714285714	46.23184736546145	3.85265394712179
4.85714285714286	49.65508705744273	4.13792392145356
4.97142857142857	53.24327098324806	4.43693924860400
5.08571428571429	57.00028018367325	4.75002334863944
5.200000000000000	60.92999569951424	5.07749964162619
5.31428571428571	65.03629857156679	5.41969154763057
5.42857142857143	69.32306984062684	5.77692248671890
5.54285714285714	73.79419054749025	6.14951587895752
5.65714285714286	78.45354173295279	6.53779514441273
5.77142857142857	83.30500443781040	6.94208370315087
5.88571428571429	88.35245970285889	7.36270497523824
6.000000000000000	93.59978856889420	7.79998238074118

**Task 1A.3****Analysis & Optimization of Spark-Laser-Produced Fireballs**

by

Robert W. Bass

[donquixote@innoventek.com](mailto:donquixote@innoventek.com)**Abstract/Summary**

While hundreds of laser-spark experiments have been reported (Bekefi [1], Hughes [2], Raizer [3], Ready [4]) there has not been reported any theoretical attempt to optimize the relationship between the ambient cold gas pressure, the pulsed energy, the pulsed laser wavelength, the spark focal spot radius, the supply laser wavelength & power, the plasma transparency, the bremsstrahlung loss, and any subsequent pressure increase ratio (or wavelength increase ratio) for further heating beyond mere steady-state maintenance.

We shall reduce this problem to finding the unique positive root of a transcendental perturbation of an eighth-degree polynomial in the ratio of the spark focal spot radius to the supply laser wavelength.

The basic theory shows how to choose the parameters of a short-lived laser-spark but then attempt to maintain it in steady state by means of a supply laser (or microwave beam) which compensates for the inevitable energy loss from bremsstrahlung, assuming the validity of Bass's correction [8]-[9] to Kapitza's Free Floating Plasma Filament explanation (presented in his 1977 Nobel Prize Acceptance Speech), and the 1977 BGK-wave soliton theory of Bass *et al* [6], [7] which explains why a hot plasma in contact with a cold gas will spontaneously produce an insulating electrostatic-inertial Double Layer (of precisely the type that was later confirmed experimentally by Ludmirsky & Eliezer [10]).

The analysis presented below was first disclosed by me in my US Patent 4,448,743 issued May 15, 1984 [7], which ran for the statutory 17 years and expired in 2002, untried and ignored. Because of current potential applicability to scenarios other than those initially proposed, it is deemed desirable to publish the following [slightly revised, amended & corrected] version of the Bass self-insulated Plasmasphere concept because of the utility of the following design-optimization algorithms both to the originally-proposed innovative technology and for further novel applications to my more recent proposals regarding creation of a pressure-ionized rather than thermally ionized self-confined plasmoid, which can be designed to have the physical state of a liquid metal rather than that of an expansive gas.

## INTRODUCTION

The following analysis involves an extremely complicated sequence of algebraic calculations, whose motivation may tax the reader's patience unless the entire physical scenario under investigation is kept in mind. Thus it should aid the reader's comprehension if the two principal possible scenarios are explained first in terms of a pair of proposed experimental protocols whose sequential steps are easier to follow than the lengthy sequence of equations required to analyze these experiments in terms of accepted physical and engineering principles. Accordingly I shall append Figures 1-13 of my expired Plasmasphere Patent [7] and ask the reader to consult these figures systematically in terms of the following **procedural protocols** before proceeding on to the analytical theory.

### DEMONSTRATION PROTOCOL DESIGN DERIVATION

The demonstration designed herein is based on an empirical fact (if one accepts the presently proposed interpretation of prior relevant experiments in migmas by Farnsworth and in plasmas by Kapitza), or, alternatively upon a single, physically viable proposition (which can be demonstrated rigorously [8]-[9] to be compatible with exact solutions of the Poisson-Boltzmann equations of the BGK-wave type), namely that a hot plasma fireball (at least 10 Debye lengths in diameter) in pressure equilibrium with a cold plasma envelope will spontaneously develop a self-confining and near-perfectly self-insulating boundary layer capable of maintaining a near-discontinuity in temperature (by means of a localized trapped-particle charge-separation phenomenon).

For the reader's convenience in checking our arithmetic, we have carried three- and four-place numerical accuracy, but do not imply that an actual experiment would agree to more than within a few percent. [The arithmetic below was originally based on use of a methanol laser at a wavelength of 1.217 mm which in theory can produce 5 mW; however, we have since learned of commercially available methyl fluoride lasers of wavelength 1.222 mm which are guaranteed to produce 2 mW; therefore we have rounded-off the far infra-red laser wavelength to 1.22 mm which may produce third-place discrepancies in the numerical results to be presented.]

#### Case 1: ISOCHORIC HEATING EXAMPLE PROTOCOL

##### 1. Required:

1.1 Hydrogen gas pressure vessel capable of having its contained pressure increased slowly (without turbulence) from 1.84 atmospheres pressure to 21.8 atmospheres pressure, and fitted with windows transparent to infra-red and far-infra-red radiation, and also fitted with a down-draft vertical hydrogen-gas jet designed by Stokes' Law to prevent a lighter-than-ambient fluid "bubble" from floating upward.

1.2 One Q-switched or chopper-pulsed ND-YAG “spark laser” of wavelength  $\lambda_p = 1.06$  mm capable of delivering a pulse of energy  $E_p = 3.43$  mJ, in a ten-nanosecond or shorter interval, onto a focal spot of radius  $r_o = 12.4$   $\mu\text{m}$ .

1.3 Four tetrahedrally-spaced cw FIR (Far Infra- Red) "supply lasers" of wavelength  $\lambda_{\text{FIR}} = 1.2$  mm capable of delivering 1.70 mW power each and of being focused to a minimum beam radius of one wavelength ( $r_1 = 1.2$  mm).

1.4 One carcinotron (O-type backward wave oscillator) "supply microwave" capable of delivering 1.81 W power at a wavelength of 1.2 mm and of being focused to a minimum beam radius of 2.93 mm.

**2.** Fill vessel with  $\text{H}_2$  gas at temperature  $T_o = 288.2$  °K and an initial pressure of  $p_o = 1.84$  atmospheres. Turn on supply lasers to a total power level of 6.80 mW and focus them on a central gas volume of radius  $r_1 = 1.2$  mm. **(FIG. 4).**

**3.** Focus spark laser at center of said volume and pulse  $E_p = 3.43$  mJ of laser light onto its center, creating a fully ionized plasma cylinder of radius  $r_o = 12.4$   $\mu\text{m}$  and length about 124  $\mu\text{m}$  and containing originally  $N = 2.80 \times 10^{12}$  hydrogen molecules now ionized to  $N_e = 5.60 \times 10^{12}$  electrons and an equal number of ions (after having absorbed 98.8% of the light and transmitted the remaining 0.04 mJ). **(FIG. 5)**

**4.** The plasma cylinder immediately expands to an equilibrium plasma fireball of radius  $r_1 = 1.2$  mm, Debye length 7.3  $\mu\text{m}$ , and a temperature of  $T_1 = 8.73 \times 10^6$  °K (= 752 eV); the electron density is now  $n_{el} = 7.74 \times 10^{14}$   $\text{cm}^{-3}$  and so the critical (resonant absorption) plasma frequency is now  $\nu_{el} = c/\lambda_{\text{FIR}} = 249.83$  GHz which (by design) corresponds perfectly to the supply laser wavelength; bremsstrahlung losses are now 2.0 mW. **(FIG. 6)**

**5. Isochoric Heating.** Increase ambient gas pressure to its final value of  $p_2 = 21.8$  atmospheres. This will increase the plasma temperature to  $T_2 = 1.03 \times 10^8$  °K (= 8.88 keV) and increase the bremsstrahlung loss to a steady-state 6.8 mW, which is (by design) compensated for perfectly by the supply lasers. (Debye length is now 25.6  $\mu\text{m}$ .) **(FIG. 7)**

**6.** Turn on the supply microwave generator to a power level of 1.81 W focused on a volume of radius  $r_3 = 2.93$  mm centered on the 1.2 mm radius fireball. The fireball continues to absorb energy, while heating and expanding, but less and less efficiently as its density decreases; it eventually becomes 99.9% transparent to the microwave beam after having expanded to a final radius of  $r_3 = 2.93$  mm and after having been heated to a final temperature of  $T_3 = 1.51 \times 10^9$  °K (= 130 keV); the steady state bremsstrahlung loss is finally 1.81 W which (by design) is perfectly compensated for by the supply microwave beam; the final electron density is  $5.14 \times 10^{13}$   $\text{cm}^{-3}$  and the final Debye length is 0.37 mm (or less than 1/16 the fireball’s diameter). **(FIG. 8)**

**7.** The result is a 6 mm diameter steady-state plasma fireball contained in 22 atmospheres pressure at 130 keV.

## Case 2: ISOBARIC HEATING EXAMPLE PROTOCOL

### 1. Required:

- 1.1. As in Case 1.
  - 1.2. As in Case 1, except that now  $E_p = 0.42$  mJ and  $r_o = 5.52$   $\mu\text{m}$ .
  - 1.3. Replace by a tunable cw FIR laser, e.g. a free electron laser, capable of being tuned from a wavelength of 0.12 mm to 1.2 mm and of delivering 1.78 W power and of being throttled in power by a factor of 26.1, and of being focused to a minimum beam radius of one wavelength.
  - 1.4. Omit
2. Fill vessel with  $\text{H}_2$  gas at room temperature ( $T_0 = 288.2$  °K) and a pressure of  $p_0 = 21.1$  atmospheres. Turn on the supply laser at a power level of 68.0 mW and a wavelength of  $\lambda_{\text{FIR}} = 0.122$  mm and focus it on a central gas volume of radius  $r_1 = 0.262$  mm. (FIG. 9)
  3. Focus spark laser at the center of the gas volume and pulse  $E_p = 0.418$  mJ of laser light onto a focal spot of radius  $r_o = 5.52$   $\mu\text{m}$  at the center of said volume, creating a fully ionized plasma cylinder of radius  $r_o = 5.52$   $\mu\text{m}$  and length about 55.2  $\mu\text{m}$  and containing originally  $2.84 \times 10^{12}$  hydrogen molecules now ionized to  $5.68 \times 10^{12}$  electrons and an equal number of ions (after having absorbed virtually 100% of the 0.42 mJ of energy delivered.) (FIG. 10)
  4. The plasma cylinder immediately expands to an equilibrium plasma fireball of radius  $r_1 = 0.262$  mm, a Debye length of 0.26  $\mu\text{m}$ , and a temperature  $T_1 = 1.03 \times 10^6$  °K (= 88.8 eV); the electron density is now  $n_{el} = 7.53 \times 10^{16}$   $\text{cm}^{-3}$  and so critical (resonant absorption) plasma frequency is  $\nu_{el} = 2,498.3$  GHz which (by design) corresponds perfectly to the initial supply laser wavelength; the bremsstrahlung loss is now 68.0 mW, which (by design) is compensated for perfectly by the supply laser. (FIG. 11)
  5. **Isobaric Heating.** Tune the supply laser from 2,498 GHz to 249 GHz, *i.e.* increase its wavelength from  $\lambda_{\text{FIR}} = 0.12$  mm to  $\lambda_{\text{FIR}} = 1.2$  mm; this increases the plasma fireball's temperature to  $T_2 = 1.03 \times 10^9$  °K (= 8.88 keV) while increasing its radius to  $r_1 = 1.22$  mm (and decreasing the bremsstrahlung loss to 6.80 mW). (FIG. 12)
  6. Keeping the supply laser wavelength at  $\lambda_{\text{FIR}} = 1.22$  mm, increase its power level to 1.81 W. The remainder of this step is identical to Step 6 of Case 1. (FIG. 13)
  7. The result is identical to Step 7 of Case 1.

### A Preliminary Thermodynamic Lemma

The following theory has been developed under the assumption of a diatomic hydrogenic gas (e.g. hydrogen or deuterium), but via obvious changes [such as the replacement of the factor 2 by unity in equations (3c) & (5)] could be adapted to monoatomic gasses like helium.

Let

$$\gamma_0 = 7/5 = \text{ratio of specific heats of a diatomic gas,} \quad (1a)$$

$$\gamma_1 = 5/3 = \text{ratio of specific heats of a fully ionized plasma,} \quad (1b)$$

$$N = \text{number of molecules in} \quad (1c)$$

$$V_0 = \text{initial volume, at} \quad (1d)$$

$$T_0 = \text{initial temperature} = 288.2 \text{ }^\circ\text{K} \text{ [same as at STP],} \quad (1e)$$

$$p = \text{pressure, in Pascals [initially unspecified \& TBD],} \quad (1f)$$

$$k = \text{Boltzmann's constant} = 1.3807 \times 10^{-23} \text{ J/}^\circ\text{K,} \quad (1g)$$

$$e/k = 1.1604 \times 10^4 \text{ }^\circ\text{K/eV,} \quad (1h)$$

$$E_p = \text{energy of initial laser light pulse from Spark Laser,} \quad (1i)$$

$$\eta = \text{efficiency of absorption of } E_p, \quad (1j)$$

$$Z = \text{atomic number of atoms in the molecules,} \quad (1k)$$

$$n = \text{molecular number density} = N/V_0. \quad (1l)$$

By the ideal gas law, or equation of state, the initial pressure  $p_0$  is

$$p_0 = n \cdot k \cdot T_0 = (N/V_0) \cdot k \cdot T_0. \quad (2)$$

Let  $E_p$  be sufficient to dissociate all  $N$  molecules to atoms of atomic number  $Z$  and to fully ionize these  $2N$  atoms and to expand the resultant initial plasma volume  $V_0$  to a pressure-equilibrium plasma volume  $V_1$  at a temperature  $T_1$ . Then

$$V_1 = \text{final plasma volume, at} \quad (3a)$$

$$T_1 = \text{final plasma temperature,} \quad (3b)$$

whence, as is well-known,

$$p_1 = \{2(1+Z) \cdot (N/V_1)\} \cdot k \cdot T_1, \quad (3c)$$

where, by deliberate design, the energy-density or pressure of the fireball is

$$p_1 = p_0. \quad (3d)$$

Let

$$U = \text{internal energy} = p \cdot V / (\gamma - 1), \quad (4a)$$

$$E_i = \text{energy of both molecular dissociation \& ionization of resultant 2 atoms}, \quad (4b)$$

$$\Delta V = V_1 - V_0 = \text{change in volume}, \quad (4c)$$

$$\Delta U = p_1 \cdot V_1 / (\gamma_1 - 1) - p_0 \cdot V_0 / (\gamma_0 - 1) = \text{change in internal energy}, \quad (4d)$$

whence, by (2), (3c), (3d), (4d), and conservation of energy

$$\eta \cdot E_p = \Delta U + p_0 \cdot \Delta V + N \cdot E_i, \quad (4e)$$

where

$$\Delta U = \{2(1+Z) \cdot N \cdot k \cdot T_1 / (\gamma_1 - 1)\} - \{N \cdot k \cdot T_0 / (\gamma_0 - 1)\}, \quad (5)$$

and

$$p_0 \cdot \Delta V = p_0 \cdot (V_1 - V_0) = p_1 \cdot V_1 - p_0 \cdot V_0 = 2(1+Z) \cdot N \cdot k \cdot T_1 - N \cdot k \cdot T_0, \quad (6)$$

whence, noting that, by (1b) & (1a),

$$\beta := \{[1/(\gamma_1 - 1)] + 1\} = 5/2, \quad (7a)$$

$$\gamma := \{[1/(\gamma_0 - 1)] + 1\} = 7/2, \quad (7b)$$

we find finally that

$$\eta \cdot E_p = 2(1+Z) \cdot \beta \cdot N \cdot k \cdot T_1 - \gamma \cdot N \cdot k \cdot T_0 + N \cdot E_i. \quad (7c)$$

Now, defining dimensionless parameters

$$\kappa_i = E_i / (k \cdot T_0), \quad (7d)$$

$$\theta = T_1 / T_0, \quad (7e)$$

$$\alpha_p = E_p / (N \cdot k \cdot T_0), \quad (7f)$$

we find from (7c) the desired final result:

$$\eta \cdot \alpha_p = [2(1+Z) \cdot \beta] \cdot \theta + (\kappa_i - \gamma). \quad (8)$$

### Configuration Design Optimization

Using MKS units, let

$$\lambda_p = \text{spark laser wavelength [m]}, \quad (9a)$$

$$t_p = \text{spark laser pulse duration [sec]}, \quad (9b)$$

$$p_0 = \text{ambient gas pressure [Pascals (Newton/m}^2\text{)]} \quad (9c)$$

$$I_0 = \text{hydrogen gas ionization breakdown threshold intensity [W/m}^2\text{]}. \quad (9d)$$

Then, if  $t_p < 10$  nanosec or less, it is well-known ([1]-[4]) that

$$I_0 = k_3/[(\lambda_p)^2 \cdot p_0 \cdot t_p], \quad (9e)$$

$$k_3 = 1.49 \text{ [J}^2/\text{m}^3], \quad (9f)$$

where the constant  $k_3$  has been reported on, both theoretically and experimentally, in the references cited. It is equally well-known that the plasma resonant absorption frequency

$$\nu = c/\lambda_{\text{FIR}} = k_2 \cdot (N_{\text{ec}})^{1/2}, \quad (10a)$$

$$k_2 = 8.98 \text{ [sec}^{-1} \text{ m}^{3/2}], \quad (10b)$$

where

$$c = 2.9979 \times 10^8 \text{ [m/sec]} = \text{speed of light in } \textit{vacuo}, \quad (10c)$$

and where  $N_{\text{ec}}$  denotes the critical electron density

$$N_{\text{ec}} = 2Z \cdot N/V_1, \quad (11)$$

and  $V_1$  is the final plasma volume formed by complete ionization of the  $N$  original diatomic molecules of atomic number  $Z$ .

Recall the plasma equation of state, as in (3c), namely

$$p = (1 + Z^1) \cdot N_e \cdot k \cdot T, \quad (12a)$$

where

$$N_e = 2Z \cdot N/V = \text{electron density [m}^{-3}], \quad (12b)$$

$$T = \text{plasma temperature [}^\circ\text{K]}. \quad (12c)$$

According to Guenther [5], if

$$l = \text{length of optical path [m]}, \quad (13a)$$

$$\nu = \text{frequency of light [sec}^{-1}], \quad (13b)$$

then

$$\eta = \text{transmissivity} = 1 - \exp(-K_v \cdot l), \text{ where} \quad (13c)$$

$$K_v = k_4 \cdot (N_e)^2 / [\nu^3 \cdot T^{1/2}], \quad (14a)$$

$$k_4 = 3.68 \times 10^{-2} \text{ [m}^5 \text{ k}^{1/2} / \text{sec}^6], \quad (14b)$$

where  $N_e = N_{ec}$  the first time that we apply (13c), to the supply-laser-design, using  $\lambda_{FIR}$ , but  $N_e$  is appropriate to the electron density in the initial laser-spark plasma, using  $\lambda_p$ , the second time that we apply (13c). By (1h), the ionization potential of an H-atom is

$$T_i = 13.6 \text{ eV} = 1.578 \times 10^5 \text{ [}^\circ\text{K]}. \quad (15)$$

For two atoms we have 27.2 eV and, using additionally the dissociation-potential of 3.6 eV, we have for  $H_2$  molecules

$$E_i = 30.8 \text{ eV}. \quad (16)$$

Thus, by (1e) and (16), and converting  $k \cdot T_0$  to eV [by dividing it by (1h), i.e. by using  $k \cdot T_0 = 2.48 \times 10^{-2} \text{ eV}$ ], we find that

$$\kappa_i = E_i / (k \cdot T_0) = 1.241935 \times 10^3. \quad (17)$$

Next, by (1a) and (7b), and (17)

$$\gamma = 3.5, \quad (18)$$

$$\kappa_i - \gamma = 1.2384 \times 10^3, \quad (19)$$

and also, by (7a),

$$\beta = 2.5. \quad (20)$$

Recalling (3b), (7e), (1i), (1j), (9b), and using

$$T_1 = \text{temperature of fireball after pulse}, \quad (21a)$$

$$\theta = T_1 / T_0, \quad (21b)$$

$$E_p = \text{total pulse energy}, \quad (21c)$$

$$\eta_p = \text{absorption efficiency}, \quad (21d)$$

$$t_p = \text{pulse duration}, \quad (21e)$$

and assuming a uniform pulse shape, and that the initially-ionized volume is a cylinder of radius

$$r_0 = \text{initial focal spot radius, and} \quad (21f)$$

$$l = \text{length} = \zeta \cdot r_0 \quad (\zeta > 1), \quad (21g)$$

$$V_0 = \text{volume} = l \cdot \pi \cdot (r_0)^2 = \zeta \cdot \pi \cdot (r_0)^3, \quad (21h)$$

then

$$I_0 = \text{pulse intensity} = E_p/\pi \cdot (r_0)^2 \cdot t_p, \quad (21i)$$

And, by (8),

$$\theta = \{\eta_p \cdot \alpha_p - (\kappa_i - \gamma)\} / [2(1+Z) \cdot \beta]. \quad (22)$$

Now, by design, choose the final pressure-equilibrium plasma radius to be

$$r_1 = \lambda_{\text{FIR}}, \quad (23)$$

where  $\lambda_{\text{FIR}}$  is the wavelength of a Far Infrared supply laser. Next, defining

$$x = r_0/r_1 < 1, \quad (24a)$$

we have, by (23) & (24a),

$$r_0 = x \cdot \lambda_{\text{FIR}}, \quad (24b)$$

in terms of the *UNKNOWN* ratio  $x$ , where now by (21h), (23), & (24b),

$$V_0 = \pi \cdot \zeta \cdot (\lambda_{\text{FIR}})^3 \cdot x^3, \quad (25)$$

$$V_1 = (4/3) \cdot \pi \cdot (\lambda_{\text{FIR}})^3. \quad (26)$$

Next, by (2), (3c), (3d), (25) we have

$$p_0 = (N/V_0) \cdot k \cdot T_0 = N \cdot k \cdot T_0 / [\pi \cdot \zeta \cdot (\lambda_{\text{FIR}})^3 \cdot x^3], \quad (27)$$

and so, by (2), (26), & (10a), the critical resonant absorption density for  $\lambda_{\text{FIR}}$  is

$$N_{\text{ec}} = 2Z \cdot N/V_1 = 3Z \cdot N / [2\pi \cdot (\lambda_{\text{FIR}})^3] = (c/[k_2 \cdot \lambda_{\text{FIR}}])^2, \quad (28)$$

whence, combining (2), (3), (28), (27) we find that

$$N = [2\pi \cdot \lambda_{\text{FIR}} / (3Z)] \cdot (c/k_2)^2 = \quad (29a)$$

$$= [\pi \cdot \zeta \cdot (\lambda_{\text{FIR}})^3 \cdot p_0 / (k \cdot T_0)] \cdot x^3, \quad (29b)$$

which gives  $N$  in terms of  $\lambda_{\text{FIR}}$  alone, as well as in terms of  $\lambda_{\text{FIR}}$  &  $p_0 \cdot x^3$ , and also gives

$$p_0 \cdot x^3 = \{2k \cdot T_0 / [3Z \cdot \zeta \cdot (\lambda_{\text{FIR}})^2]\} \cdot (c/k_2)^2. \quad (30)$$

For later convenience, (29b) & (30) yield

$$N \cdot k \cdot T_0 = \pi \cdot \zeta \cdot (\lambda_{\text{FIR}})^3 \cdot p_0 \cdot x^3 = \{2\pi \cdot [(\lambda_{\text{FIR}})^3 / (\lambda_p)^2] \cdot k \cdot T_0 / (3Z)\} \cdot (c/k_2)^2. \quad (31)$$

Now from (7f), (21i), (24b), (9e), (31)

$$\alpha_p = E_p / (N \cdot k \cdot T_0) = I_0 \cdot \pi \cdot (r_0)^2 \cdot t_p / [N \cdot k \cdot T_0] = k_3 \cdot \pi \cdot (r_0)^2 \cdot t_p / [(\lambda_p)^2 \cdot p_0 \cdot t_p \cdot N \cdot k \cdot T_0] = \quad (32a)$$

$$= \{k_3 \cdot \pi \cdot (\lambda_{\text{FIR}})^2 \cdot x^5\} / [(\lambda_p)^2 \cdot (p_0 \cdot x^3) \cdot N \cdot k \cdot T_0] = \varepsilon_p \cdot x^5, \quad (32b)$$

where, by (29a) & (30),

$$\varepsilon_p = \{((3/2) \cdot Z)^2 \cdot \zeta \cdot k_3 \cdot (\lambda_{\text{FIR}})^3 \cdot (k_2/c)^4\} / [\lambda_p \cdot (k \cdot T_0)]^2. \quad (33)$$

Next, write (2)-(3) as

$$p_0 = N \cdot k \cdot T_0 / V_0 = 2(1+Z) \cdot N \cdot k \cdot T_1 / V_1, \quad (34)$$

whence, by (25)-(26)

$$\theta = T_1 / T_0 = V_1 / [2(1+Z) \cdot V_0] = 2 / [3\zeta \cdot (1+Z) \cdot x^3], \quad (35)$$

so that, by (22) & (32) we have, finally

$$\eta_p \cdot \varepsilon_p \cdot x^8 - (\kappa_i - \gamma) \cdot x^3 - (4\beta / [3\zeta]) = 0. \quad (36)$$

It remains only to express  $\eta_p$  in terms of  $x$  before concluding by solving (36). From (13), (14), (15), (11), & (26)

$$K_v = \{k_4 / [(c/\lambda_p)^3 \cdot (T_i)^{1/2}]\} \cdot \{2Z \cdot N / [\pi \cdot \zeta \cdot (\lambda_{\text{FIR}})^3 \cdot x^3]\}^2, \quad (37)$$

whence by (21g), (24b)

$$K_v \cdot l = K_v \cdot \zeta \cdot r_0 = k_5 / x^5, \quad (38)$$

where

$$k_5 = \{k_4 / [\zeta \cdot (T_i)^{1/2} \cdot (\lambda_{\text{FIR}})^5]\} \cdot \{2Z \cdot N / \pi\}^2 \cdot (\lambda_p / c)^3 \quad (39)$$

Thus the initial laser pulse absorption efficiency is

$$\eta_p = 1 - \exp(-k_5 / x^5). \quad (40)$$

Therefore the unknown  $x$  is determined by

$$(1 - \exp[-k_5 / x^5]) \cdot \varepsilon_p \cdot x^8 - (\kappa_i - \gamma) \cdot x^3 - (4\beta / [3\zeta]) = 0. \quad (41)$$

To solve (41), rearrange and solve iteratively (assuming an adequate initial “guesstimate”  $x_i$ ) by taking  $x$  to be the limit of the following sequence:

$$x = \lim \{x_m\}, \quad (m = 1, 2, 3, \dots), \quad (42)$$

$$x_{m+1} = \{[k_6 + k_7 \cdot (x_m)^3]/[1 - \exp(-k_5/(x_m)^5)]\}^{1/8}, \quad (43)$$

$$k_6 = (4\beta/[3\zeta])/ \varepsilon_p, \quad (44a)$$

$$k_7 = (\kappa_i - \gamma)/ \varepsilon_p. \quad (44b)$$

Then the remaining unknowns are determined by

$$r_0 = x \cdot \lambda_{\text{FIR}}, \quad (45)$$

$$\theta = 2/[3\zeta \cdot (1 + Z) \cdot x^3], \quad (46)$$

$$T_1 = \theta \cdot T_0, \quad (47)$$

$$p_0 = \{2k \cdot T_0/[3Z \cdot \zeta \cdot (\lambda_p)^2]\} \cdot [(c/k_2)^2/x^3], \quad (48)$$

$$E_p = k_3 \cdot \pi \cdot (r_0)^2/[(\lambda_p)^2 \cdot p_0]. \quad (49)$$

For comparison with  $r_0$  &  $r_1$ , the Debye length  $\lambda_D$  is given by

$$\lambda_D = k_8 \cdot (T/N_e)^{1/2}, \quad (50a)$$

$$k_8 = 69.0 \text{ m}^{-1} \text{K}^{-1}, \quad (50b)$$

or, using (12) with  $Z = 1$ ,

$$\lambda_D = k_9 \cdot T/p^{1/2}, \quad (51a)$$

$$k_9 = 3.63 \times 10^{-10} \text{ Newton/}^\circ\text{K}. \quad (51b)$$

Now let  $T_3$  be prespecified, and let  $\xi$  be unknown, where

$$0 < \xi < 1, \quad (52)$$

and where, by definition,

$$r_3 = r_1/\xi = \lambda_{\text{FIR}}/\xi, \quad (53)$$

whence

$$V_3 = V_1/\xi^3, \quad (54a)$$

$$N_{e3} = \xi^3 \cdot N_{e1}. \quad (54b)$$

Also, clearly,

$$p_2 = (1 + Z^1) \cdot N_{e1} \cdot k \cdot T_2 = p_3 = (1 + Z^1) \cdot N_{e3} \cdot k \cdot T_3, \quad (55)$$

whence

$$\xi^3 \cdot N_{e1} \cdot T_3 = N_{e3} \cdot T_3 = N_{e1} \cdot T_2, \quad (56)$$

and so

$$T_2 = \xi^3 \cdot T_3. \quad (57)$$

Now take

$$\nu = \nu_{\text{FIR}} = \nu_{\text{mic}} \quad (58a)$$

to be the frequency of the microwave and find from (14) & (54b) that, at  $T = T_3$ ,

$$K_\nu = k_{10} \cdot \xi^6, \quad (58b)$$

where

$$k_{10} = k_4 \cdot (N_{e1})^2 / [(c/\lambda_{\text{FIR}})^3 \cdot (T_3)^{1/2}]. \quad (59)$$

Hence the final transparency to the microwave is defined by the absorption efficiency factor

$$\eta_{\text{mic}} = 1 - \exp(-2K_\nu \cdot r_3) = 1 - \exp(-2k_{10} \cdot \lambda_{\text{FIR}} \cdot \xi^5), \quad (60)$$

and so

$$\xi = \{[\log(1 - \eta_{\text{mic}})^{-1}] / [2k_{10} \cdot \lambda_{\text{FIR}}]\}^{1/5}. \quad (61)$$

Next,

$$p_2/p_0 = p_2/p_1 = [2(1 + Z) \cdot N \cdot k \cdot T_2] / [2(1 + Z) \cdot N \cdot k \cdot T_1] = T_2/T_1 = \xi^3 \cdot T_3/T_1, \quad (62)$$

whence, finally

$$p_2 = \xi^3 \cdot (T_3/T_1) \cdot p_0. \quad (63)$$

It is easy to see that the bremsstrahlung loss decreases during the final expansion. It is well known that this power  $P_{\text{brem}}$  in Watts is given by

$$P_{\text{brem},1} = C \cdot (N_{e1})^2 \cdot (T_2)^{1/2} \cdot V_1, \quad (64a)$$

where, if  $T_2$  is expressed in keV,

$$C = 5.354 \times 10^{-37} \text{ W m}^3 / \text{k}^{1/2}. \quad (64b)$$

Now

$$P_{\text{brem},2} = C \cdot (N_{e3})^2 \cdot (T_3)^{1/2} \cdot V_3 = C \cdot (N_{e1} \cdot \xi^3)^2 \cdot (T_2/\xi^3)^{1/2} \cdot (V_1/\xi^3) = \xi^{3/2} \cdot P_{\text{brem},1} < P_{\text{brem},1}, \quad (65)$$

by (52).

To find  $\xi$ , assume final transparency to the microwave defined by the absorption efficiency factor

$$\eta_{\text{mic}} = 10^{-3} = 0.001, \quad (66)$$

and use (61). To find  $x$ , assume that

$$\zeta = 10, \quad (67)$$

which agrees well with numerous measured experiments and is satisfactorily accurate for preliminary design by virtue of the fact that the solution of (41) is not very sensitive to variations of  $\zeta$  around the nominal value (67).

The microwave power  $P_{\text{mic}}$  can be found from  $\eta_{\text{mic}} \cdot P_{\text{mic}} = P_{\text{brem},2}$ , i.e. by (65),

$$P_{\text{mic}} = P_{\text{brem},1} \cdot (\xi^{3/2} / \eta_{\text{mic}}). \quad (68)$$

## REFERENCES

- [1]. G. Bekefi (ed.), *Principles of Laser Plasmas*, Wiley-Interscience (1976).
- [2]. T. P. Hughes, *Plasmas and Laser Light*, Adam Hilger (1975), p. 190.
- [3]. Yu. P. Raizer, *Laser-Induced Discharge Phenomena*, Consultants Bureau (1977); Russian original Nauka Press (1974).
- [4]. J. F. Ready, *Effects Of High-Power Laser Radiation*, Academic Press (1971).
- [5]. A. H. Guenther and W. K. Pendleton, "Laser-Produced Deuterium Plasmas," *Laser Interaction*, vol. 2, Plenum Press (1972), pp. 97-145.
- [6]. Golka, R.K. & Bass, R.W. "Tesla's Ball Lightning Theory, a BGK-Wave Soliton-Pair Langmuir-Debye Sheath Surface-Tension Hypothesis, the Farnsworth Effect, and the 'Hydroton' Electrostatic-Inertial Self-Confined Plasmoid Concept," *Proc. Annual Controlled Fusion Theory Conference*, May 4-6, 1977, San Diego, Paper J3.
- [7]. Bass, R. W., "Generation, Insulated Confinement, and Heating of Ultra-High Temperature Plasmas," [The Plasmasphere™], U.S. Patent 4,448,743, May 15, 1984.
- [8]. R.W. Bass, I. Oh & W. Schrader, "Proof of Implausibility of Kapitza's Single-Well Potential Hypothesis in a Plasma Confinement," *Transactions*, American Nuclear Society, (1984), p. 140.
- [9]. R.W. Bass, I. Oh & W. Schrader, "Computer Simulation on Double Layers for Inertial-Electrostatic Confinement of Plasmas," *Fusion Technology*, vol. 6 (1984), pp. 35-43.
- [10]. Ludmirsky, A. & Eliezer, S. *et al*, "Experimental Evidence of Charge Separation (double Layer) in Laser-Produced Plasmas," *IEEE Trans. Plasma Science*, Vol. PS-13, 1985.

## Task 1A.4

```

function [r0,T1,p0,p0atm,x,Ep,etp,N,n0,nel, lamdD,xi,numic,p2,p2atm,T2,r3,V3,Pmic] =
LaserSpark(Z,lamdP,lamdFIR,zet,T3);
%*****
%
% usage:
%
% [r0,T1,p0,p0atm,x,Ep,etp,N,n0,nel,lamdD,xi,numic,p2,p2atm,T2,r3,V3,Pmic] =
%                               LaserSpark(Z,lamdP,lamdFIR,zet,T3);
%
% inputs:
%       Z = atomic number of diatomic gas molecules in ambient gas
%       lamdp = wavelength of pulsed laser [m]
%       lamdFIR = wavelength of supply laser or microwave beam [m]
%       zet = length of initial spark laser cylinder relative to radius
%       T3 = desired final temperature, after further heating by either
%           pressure increase (isochoric) or by supply lasers (isobaric)
%
% outputs:
%       r0 = initial focal spot radius [m], smaller than
%           r1 = lamdFIR = steady-state fireball radius (before heating)
%       T1 = final steady-state plasma temperature (before heating)
%       p0 = initial ambient gas pressure [Pascals or Newton/m^2]
%       p0atm = p0 [atm]
%       x = r0/r1 [ratio between focal-spot & initial plasma radii]
%       Ep = initial amount of energy projected by pulse laser [J]
%       etp = efficiency of absorption of Ep
%       N = Number of molecules ionized
%       n0 = number density of ambient gas
%       nel = number density of electrons in final plasma fireball
%       lamD = Debye radius [m]
%       xi = ratio of r1 = lamdFIR to final (increased) radius r3
%       numic = frequency of sustaining microwave beam, Hz
%       p2 = final ambient gas pressure after increase from p1 = p0
%       T2 = plasma temperature after gas pressure increase
%       T3 = plasma temperature after its expansion to near transparency
%       r3 = plasma radius after it is nearly transparent to microwave
%       V3 = final plasma volume, in steady-state after heating
%       Pmic = microwave beam power used to sustain steady-state fireball
%             after heating to desired final temperature T3
%
% typical input data: Z=1; lamdp = 1.06/10^6; lamdFIR = 0.0012; zet = 10;
%                   T3 = 1.5085*10^9; [T3 = 130 keV]
% Copyright February 3, 2008 by Robert W. Bass
%*****
atm_perPa = 101325; % atmosphere in Pascals [or Newtons/m^2]
gam0 = 7/5; % from (1a)
gam1 = 5/3; % from (1b)
T0 = 288.2; % Kelvins [room temperatue at STP] from (1e)
k = 1.3807/10^23; % J/deg K [Boltzmann's constant] from (1g)
c = 2.9979*10^8; % m/sec [lightspeed in vacuo] from (10b)
eok = 1.1604*10^4; % e/k in deg K/eV from (1h)
bet = 5/2; % from (7a)
gam = 7/2; % from (7b)
k2 = 8.98; % [m^(3/2)]/sec from (10a)
k3 = 1.49; % J^2/m^3 from (9c)
k4 = 3.68/100; % m^3.k^0.5/sec^6 from (14b)
kapiminusgam = 1238.4; % from (19)
Ti = 157800; % = 13.6 eV from (15)
N = (2*pi*(lamdFIR/(3*Z))*((c/k2)^2)); % from (29a)

```

```

k5num = k4*((2*Z*N/pi)^2)*(lamdp/c)^3; % from (39)
k5den = zet*sqrt(Ti)*lamdFIR^5; % from (39)
k5 = k5num/k5den; % from (39)
epspnum = 9*(Z^2)*zet*k3*(lamdFIR^3)*(k2/c)^4; % from (33)
epspden = 4*(lamdp*k*T0)^2; % from (33)
epsp = epspnum/epspden; % from (33)
eps1 = 1/10^6; % relative convergence tolerance
k6 = ((4*bet)/(3*zet))/epsp; % from (44a)
k7 = kapiminusgam/epsp; % from (44b)
k8 = 69.0; % (1/m).(1/k) from (50b)
k9 = 3.63/10^10; % Newton/deg K from (51b)
xnew = 0.001; % initial "guesstimate"
kount = 0; % set up iteration counter
for knt = 1:100; % start loop
    kount = kount + 1; % increment counter
    if kount == 100
        disp('convergence failed after 100 iterations')
        break % terminate loop
    end
    xold = xnew; % update estimate
    NUM = k6 + k7*xold^3; % from (43)
    DEN = 1 - exp(-k5/xold^5); % from (43)
    xnew = (NUM/DEN)^(1/8); % improve estimate from (43)
    if abs(xnew - xold)/abs(xold) < eps1
        strkount = num2str(kount);
        disp(['converged after ' strkount ' iterations'])
        break % termnate loop
    end
end % end of loop
x = xnew; % solution from (43)
r0 = x*lamdFIR; % focal spot radius from (45)
thetden = 3*zet*(1 + Z)*x^3; % from (46)
thet = 2/thetden; % from (46)
T1 = thet*T0; % from (47)
etp = 1 - exp(-k5/x^5); % pulse efficiency from (40)
p0num = (2*k*T0)*((c/k2)^2); % from (48)
p0den = 3*Z*zet*(lamdFIR^2)*(x^3); % from (48)
p0 = p0num/p0den; % initial pressure, Pa from (48)
p0atm = p0/atm_perPa; % " " , atm from (48)
Epnun = k3*pi*r0^2; % from (49)
Epden = (lamdp^2)*p0; % from (49)
Ep = Epnun/Epden; % from (49)
alfp = epsp*x^5; % from (32b)
Epalt = alfp*N*k*T0; % from (32a)
% checkEp = abs(Ep - Epalt) was < 1/10^18, so (32a) & 32(b) agree
V0 = pi*zet*r0^3; % from (24b) & (25)
V1 = (4/3)*pi*lamdFIR^3; % fireball volume from (26)
p1 = 2*(1+Z)*N*k*T1/V1; % from (3c)
% checkp0 = abs(p0 - p1) was exactly 0, as designed
n0 = p0/(k*T0); % density, per m^3 from (2)
Ne = 2*Z*N; % from (12b)
ne1 = Ne/V1; % density, per m^3 from (12b)+(28)
lamdD = k9*T1/sqrt(p0); % Debye length, Z = 1 from (50a)
etmic = 0.001; % final transparency from (61)
k10num = k4*ne1^2; % from (59)
k10den = ((c/lamdFIR)^3)*sqrt(T3); % from (59)
k10 = k10num/k10den; % from (59)
xinun = log(1/(1 - etmic)); % from (61)
xiden = 2*k10*lamdFIR; % from (61)
xi = (xinun/xiden)^(1/5); % from (61)
p2 = (xi^3)*(T3/T1)*p0; % final pressure, Pa from (63)

```

```

p2atm = p2/atm_perPa;           % " " , atm from (63)
r3 = lamdFIR/xi;                % from (53)
T2 = T3*(xi^3);                 % from (57)
T2keV = (T2/eok)/1000;          % convert to keV from (1h)
numic = c/lamdFIR;              % from (58a)
C = 5.354/10^37;                % W m^3/sqrt(k) from (64b)
V3 = V1/xi^3;                   % per m^3 from (54a)
Pbrem1 = C*(ne1^2)*sqrt(T2keV)*V1; % W from (64a)
Pmic = Pbrem1*(xi^(3/2))/etmic; % W from (68)
% end of LaserSpark.m

```

```

function [TABLE] = TabulateSparkLaserRanges(M,Z,zet,lamdP,lamdFIRmin,lamdFIRmax,T3);
TABLE = zeros(M,10);
n = M;
ndx = ((1:n)' - 1)/(n - 1);
lamdFIRvec = lamdFIRmin + ndx*(lamdFIRmax - lamdFIRmin);
for k = 1:M
lamdFIR = lamdFIRvec(k);
[r0,T1,p0,p0atm,x,Ep,etp,N,n0,nel,lamdD,xi,numic,p2,p2atm,T2,r3,V3,Pmic] =
LaserSpark(Z,lamdP,lamdFIR,zet,T3);
v = [r0,lamdFIR,Ep,T1,p0atm,n0,p2atm,r3,lamdD,Pmic];
TABLE(k,:) = v;
end
r0vec = TABLE(:,1);
lamdFIRvec = TABLE(:,2);
Epvec = TABLE(:,3);
T1vec = TABLE(:,4);
p0atmvec = TABLE(:,5);
n0vec = TABLE(:,6);
p2atmvec = TABLE(:,7);
r3vec = TABLE(:,8);
lamdDvec = TABLE(:,9);
Pmicvec = TABLE(:,10);
plot(lamdFIRvec,1000*lamdDvec);xlabel('lamdFIR'),ylabel('Debye length [micron]');grid on
title('Laser Spark Properties'), legend('Nd-Yag laser, lamdp = 1.06 micron')
pause
subplot(2,2,1)
plot(lamdFIRvec,r0vec);xlabel('lamdFIR'),ylabel('focal spot radius [m]');hold on; grid on
subplot(2,2,2)
plot(lamdFIRvec,Epvec);xlabel('lamdFIR'),ylabel('pulse energy [J]');grid on
subplot(2,2,3)
plot(lamdFIRvec,r3vec);xlabel('lamdFIR'),ylabel('final radius [m]');grid on
subplot(2,2,4)
plot(lamdFIRvec,n0vec/(10^6));xlabel('lamdFIR'),ylabel('particle density [per cm^3]');grid
on
pause
subplot(2,2,1)
plot(lamdFIRvec,p0atmvec);xlabel('lamdFIR'),ylabel('pressure [atm]');hold on; grid on
subplot(2,2,2)
plot(lamdFIRvec,p2atmvec);xlabel('lamdFIR'),ylabel('final pressure [atm]');grid on
subplot(2,2,3)
plot(lamdFIRvec,T1vec);xlabel('lamdFIR'),ylabel('initial Temperature [K]');grid on
subplot(2,2,4)
plot(lamdFIRvec,Pmicvec);xlabel('lamdFIR'),ylabel('Pmic [W]');grid on
% end of TabulateSparkLaserRanges.m

```

**Task 1A.5**

MATLAB Diary 02/03/08D

&gt;&gt; help LaserSpark

\*\*\*\*\*

usage:

```
[r0,T1,p0,p0atm,x,Ep,etp,N,n0,ne1,lamdD,xi,numic,p2,p2atm,T2,r3,V3,Pmic] =
    LaserSpark(Z,lamdP,lamdFIR,zet,T3);
```

inputs:

```
Z = atomic number of diatomic gas molecules in ambient gas
lamdP = wavelength of pulsed laser [m]
lamdFIR = wavelength of supply laser or microwave beam [m]
zet = length of initial spark laser cylinder relative to radius
T3 = desired final temperature, after further heating by either
    pressure increase (isochoric) or by supply lasers (isobaric)
```

outputs:

```
r0 = initial focal spot radius [m], smaller than
    r1 = lamdFIR = steady-state fireball radius (before heating)
T1 = final steady-state plasma temperature (before heating)
p0 = initial ambient gas pressure [Pascals or Newton/m^2]
p0atm = p0 [atm]
x = r0/r1 [ratio between focal-spot & initial plasma radii]
Ep = initial amount of energy projected by pulse laser [J]
etp = efficiency of absorption of Ep
N = Number of molecules ionized
n0 = number density of ambient gas
ne1 = number density of electrons in final plasma fireball
lamdD = Debye radius [m]
xi = ratio of r1 = lamdFIR to final (increased) radius r3
numic = frequency of sustaining microwave beam, Hz
p2 = final ambient gas pressure after increase from p1 = p0
T2 = plasma temperature after gas pressure increase
T3 = plasma temperature after its expansion to near transparency
r3 = plasma radius after it is nearly transparent to microwave
V3 = final plasma volume, in steady-state after heating
Pmic = microwave beam power used to sustain steady-state fireball
    after heating to desired final temperature T3
```

```
typical input data: Z=1; lamdP = 1.06/10^6; lamdFIR = 0.0012; zet = 10;
    T3 = 1.5085*10^9; [T3 = 130 keV]
```

Copyright February 3, 2008 by Robert W. Bass

\*\*\*\*\*

```
>> Z=1; lamdP = 1.06/10^6; lamdFIR = 0.0012; zet = 10; T3 = 1.5085*10^9;
>> [r0,T1,p0,p0atm,x,Ep,etp,N,n0,ne1,lamdD,xi,numic,p2,p2atm,T2,r3,V3,Pmic] =
```

LaserSpark(Z,lamdP,lamdFIR,zet,T3)

converged after 5 iterations

```
r0 = 1.239011744779276e-005
T1 = 8.727506691897200e+006
p0 = 1.865256790974301e+005
p0atm = 1.84086532541258
x = 0.01032509787316
Ep = 0.00342875636660
etp = 0.98843190063175
N = 2.801053930218253e+012
n0 = 4.687543689241654e+025
ne1 = 7.739610744118334e+020
lamdD = 7.335462489025662e-006
xi = 0.40905344731350
numic = 2.498250000000000e+011
p2 = 2.206652390393598e+006
p2atm = 21.77796585633948
T2 = 1.032489124127060e+008
```

```
r3 = 0.00293360197275  
V3 = 1.057528733832021e-007  
Pmic = 1.81158168061617  
>>
```

TABLE A

lamdFIR = wavelength of supply laser & plasma radius before expansion [m]  
 r0 = radius of focal spot of pulse laser [m]  
 r3 = radius after expansion to target temperature T3 = 1712 Kelvins [m]  
 lamdD = Debye length in final plasma

lamdFIR	r0	r3	lamdD
0.00003000000000	0.00000127194901	0.00028830047179	0.00000002203871
0.00003979797979	0.00000150518314	0.00038245921173	0.00000003470213
0.00004959595960	0.00000171866796	0.00047661795168	0.00000004930776
0.00005939393939	0.00000191741784	0.00057077669162	0.00000006567010
0.00006919191919	0.00000210458571	0.00066493543157	0.00000008365194
0.00007898989899	0.00000228231418	0.00075909417151	0.00000010314621
0.00008878787879	0.00000245214184	0.00085325291146	0.00000012406616
0.00009858585859	0.00000261521980	0.00094741165140	0.00000014633957
0.00010838383838	0.00000277243710	0.00104157039135	0.00000016990505
0.00011818181818	0.00000292449818	0.00113572913129	0.00000019470951
0.00012797979798	0.00000307197296	0.00122988787124	0.00000022070643
0.00013777777778	0.00000321533065	0.00132404661118	0.00000024785461
0.00014757575758	0.00000335496328	0.00141820535113	0.00000027611717
0.00015737373737	0.00000349120261	0.00151236409107	0.00000030546087
0.00016717171717	0.00000362433239	0.00160652283102	0.00000033585553
0.00017696969697	0.00000375459790	0.00170068157096	0.00000036727354
0.00018676767677	0.00000388221268	0.00179484031091	0.00000039968958
0.00019656565657	0.00000400736423	0.00188899905085	0.00000043308027
0.00020636363636	0.00000413021828	0.00198315779080	0.00000046742393
0.00021616161616	0.00000425092219	0.00207731653074	0.00000050270040
0.00022595959596	0.00000436960771	0.00217147527069	0.0000005389086
0.00023575757576	0.00000448639328	0.00226563401063	0.00000057597768
0.00024555555556	0.00000460138580	0.00235979275058	0.00000061394428
0.00025535353535	0.00000471468220	0.00245395149052	0.00000065277509
0.00026515151515	0.00000482637071	0.00254811023046	0.00000069245537
0.00027494949495	0.00000493653190	0.00264226897041	0.00000073297121
0.00028474747475	0.00000504523964	0.00273642771035	0.00000077430939
0.00029454545455	0.00000515256182	0.00283058645030	0.00000081645737
0.00030434343434	0.00000525856105	0.00292474519024	0.00000085940323
0.00031414141414	0.00000536329520	0.00301890393019	0.00000090313558
0.00032393939394	0.00000546681791	0.00311306267013	0.00000094764357
0.00033373737374	0.00000556917899	0.00320722141008	0.00000099291682
0.00034353535354	0.00000567042484	0.00330138015002	0.00000103894538
0.00035333333333	0.00000577059873	0.00339553888997	0.00000108571974
0.00036313131313	0.00000586974114	0.00348969762991	0.00000113323074
0.00037292929293	0.00000596788995	0.00358385636986	0.00000118146961
0.00038272727273	0.00000606508072	0.00367801510980	0.00000123042790
0.00039252525253	0.00000616134686	0.00377217384975	0.00000128009746
0.00040232323232	0.00000625671983	0.00386633258969	0.00000133047046
0.00041212121212	0.00000635122928	0.00396049132964	0.00000138153934
0.00042191919192	0.00000644490320	0.00405465006958	0.00000143329677
0.00043171717172	0.00000653776808	0.00414880880953	0.00000148573571
0.00044151515152	0.00000662984895	0.00424296754947	0.00000153884933
0.00045131313131	0.00000672116959	0.00433712628942	0.00000159263100
0.00046111111111	0.00000681175254	0.00443128502936	0.00000164707432
0.00047090909091	0.00000690161922	0.00452544376931	0.00000170217307
0.00048070707071	0.00000699079001	0.00461960250925	0.00000175792123
0.00049050505051	0.00000707928433	0.00471376124920	0.00000181431293
0.00050030303030	0.00000716712069	0.00480791998914	0.00000187134248
0.00051010101010	0.00000725431674	0.00490207872908	0.00000192900435
0.00051989898990	0.00000734088938	0.00499623746903	0.00000198729315
0.00052969696970	0.00000742685473	0.00509039620897	0.00000204620361

0.00053949494949	0.00000751222826	0.00518455494892	0.00000210573064
0.00054929292929	0.00000759702476	0.00527871368886	0.00000216586922
0.00055909090909	0.00000768125844	0.00537287242881	0.00000222661449
0.000568888888889	0.00000776494293	0.00546703116875	0.00000228796168
0.0005786868686869	0.00000784809132	0.00556118990870	0.00000234990615
0.0005884848484848	0.00000793071620	0.00565534864864	0.00000241244333
0.0005982828282828	0.00000801282970	0.00574950738859	0.00000247556878
0.0006080808080808	0.00000809444348	0.00584366612853	0.00000253927812
0.0006178787878788	0.00000817556879	0.00593782486848	0.00000260356707
0.0006276767676768	0.00000825621648	0.00603198360842	0.00000266843144
0.0006374747474747	0.00000833639702	0.00612614234837	0.00000273386711
0.0006472727272727	0.00000841612053	0.00622030108831	0.00000279987003
0.0006570707070707	0.00000849539679	0.00631445982826	0.00000286643623
0.0006668686868687	0.00000857423526	0.00640861856820	0.00000293356179
0.0006766666666667	0.00000865264508	0.00650277730815	0.00000300124288
0.0006864646464646	0.00000873063513	0.00659693604809	0.00000306947571
0.0006962626262626	0.00000880821399	0.00669109478804	0.00000313825655
0.0007060606060606	0.00000888539000	0.00678525352798	0.00000320758173
0.0007158585858586	0.00000896217124	0.00687941226793	0.00000327744762
0.0007256565656566	0.00000903856554	0.00697357100787	0.00000334785065
0.0007354545454545	0.00000911458052	0.00706772974782	0.00000341878730
0.0007452525252525	0.00000919022359	0.00716188848776	0.00000349025409
0.0007550505050505	0.00000926550194	0.00725604722770	0.00000356224757
0.0007648484848485	0.00000934042256	0.00735020596765	0.00000363476436
0.0007746464646465	0.00000941499226	0.00744436470759	0.00000370780109
0.0007844444444444	0.00000948921766	0.00753852344754	0.00000378135443
0.0007942424242424	0.00000956310522	0.00763268218748	0.00000385542112
0.0008040404040404	0.00000963666121	0.00772684092743	0.00000392999788
0.0008138383838384	0.00000970989176	0.00782099966737	0.00000400508151
0.0008236363636364	0.00000978280285	0.00791515840732	0.00000408066882
0.0008334343434343	0.00000985540027	0.00800931714726	0.00000415675665
0.0008432323232323	0.00000992768972	0.00810347588721	0.00000423334187
0.0008530303030303	0.00000999967673	0.00819763462715	0.00000431042138
0.0008628282828283	0.00001007136671	0.00829179336710	0.00000438799210
0.0008726262626263	0.00001014276493	0.00838595210704	0.00000446605100
0.0008824242424242	0.00001021387655	0.00848011084699	0.00000454459505
0.0008922222222222	0.00001028470659	0.00857426958693	0.00000462362124
0.0009020202020202	0.00001035525999	0.00866842832688	0.00000470312661
0.0009118181818182	0.00001042554153	0.00876258706682	0.00000478310821
0.0009216161616162	0.00001049555593	0.00885674580677	0.00000486356310
0.0009314141414141	0.00001056530777	0.00895090454671	0.00000494448837
0.0009412121212121	0.00001063480154	0.00904506328666	0.00000502588115
0.0009510101010101	0.00001070404164	0.00913922202660	0.00000510773856
0.0009608080808081	0.00001077303237	0.00923338076655	0.00000519005776
0.0009706060606061	0.00001084177792	0.00932753950649	0.00000527283591
0.0009804040404040	0.00001091028242	0.00942169824643	0.00000535607022
0.0009902020202020	0.00001097854989	0.00951585698638	0.00000543975789
0.0010000000000000	0.00001104658427	0.00961001572632	0.00000552389615

&gt;&gt;

TABLE B

lamdFIR = initial plasma radius before expansion (& wavelength of supply laser)  
 p0 = initial gas pressure [atm]  
 p2 = final gas pressure after expansion  
 Pmic = power level in supply laser or microwave beam [W]

lamdFIR	p0	p2	Pmic
0.00003000000000	42.53820827700950	0.00065100342706	0.00127082183530
0.00003979797980	34.05336530437775	0.00036991652257	0.00095795453067
0.00004959595960	28.50607328740883	0.00023819530074	0.00076870485760
0.00005939393939	24.58435845822653	0.00016608924897	0.00064189470252
0.00006919191919	21.65821014413678	0.00012238129106	0.00055099866435
0.00007898989899	19.38707610262583	0.00009390369192	0.00048265228271
0.00008878787879	17.57049337954218	0.00007432217718	0.00042939031295
0.00009858585859	16.08263030810953	0.00006028323336	0.00038671525111
0.00010838383838	14.84042929030078	0.00004987658723	0.00035175590408
0.00011818181818	13.78680532301885	0.00004194927409	0.00032259323511
0.00012797979798	12.88119919584508	0.00003577197707	0.00029789588404
0.00013777777778	12.09398139774877	0.00003086508184	0.00027671120607
0.00014757575758	11.40299008503488	0.00002690269212	0.00025833955173
0.00015737373737	10.79130927887478	0.00002365708699	0.00024225551032
0.00016717171717	10.24579784227043	0.00002096525636	0.00022805684899
0.00017696969697	9.75608664392173	0.00001870802621	0.00021543041386
0.00018676767677	9.31388316334832	0.00001679663756	0.00020412876424
0.00019656565657	8.91247302796177	0.00001516388568	0.00019395379501
0.00020636363636	8.54636031260820	0.00001375813100	0.00018474502451
0.00021616161616	8.21100192604591	0.00001253916528	0.00017637106780
0.00022595959596	7.90260876661602	0.00001147530415	0.00016872332815
0.00023575757576	7.61799481746321	0.00001054130720	0.00016171126182
0.00024555555556	7.35446119304325	0.00000971686694	0.00015525877626
0.00025535353535	7.10970602563876	0.00000898549557	0.00014930145771
0.00026515151515	6.88175370125593	0.00000833369416	0.00014378441336
0.00027494949495	6.66889875554010	0.00000775032531	0.00013866057498
0.00028474747475	6.46966099753439	0.00000722613418	0.00013388935264
0.00029454545455	6.28274931902342	0.00000675337917	0.00012943555730
0.00030434343434	6.10703228541038	0.00000632554442	0.00012526853139
0.00031414141414	5.94151406733028	0.00000593711410	0.00012136144215
0.00032393939394	5.78531461226119	0.00000558339372	0.00011769070318
0.00033373737374	5.63765320764778	0.00000526036762	0.00011423549791
0.00034353535354	5.49783477600686	0.00000496458453	0.00011097738462
0.00035333333333	5.36523838532886	0.00000469306493	0.00010789996715
0.00036313131313	5.23930756700556	0.00000444322580	0.00010498861894
0.00037292929293	5.11954211723454	0.00000421281889	0.00010223025056
0.00038272727273	5.00549112269617	0.00000399988001	0.00009961311298
0.00039252525253	4.89674700188447	0.00000380268701	0.00009712663023
0.00040232323232	4.79294039320549	0.00000361972486	0.00009476125661
0.00041212121212	4.69373575236347	0.00000344965646	0.00009250835419
0.00042191919192	4.59882754653324	0.00000329129813	0.00009036008740
0.00043171717172	4.50793695279752	0.00000314359897	0.00008830933203
0.00044151515152	4.42080898439736	0.00000300562338	0.00008634959622
0.00045131313131	4.33720998133710	0.00000287653620	0.00008447495190
0.00046111111111	4.25692541244185	0.00000275559006	0.00008267997483
0.00047090909091	4.17975794458449	0.00000264211450	0.00008095969221
0.00048070707071	4.10552574186704	0.00000253550671	0.00007930953668
0.00049050505051	4.03406096336335	0.00000243522345	0.00007772530582
0.00050030303030	3.96520843284479	0.00000234077418	0.00007620312640
0.00051010101010	3.89882445790892	0.00000225171498	0.00007473942279
0.00051989898990	3.83477577926410	0.00000216764340	0.00007333088888
0.00052969696970	3.77293863371086	0.00000208819383	0.00007197446321

0.00053949494949	3.71319791670181	0.00000201303357	0.00007066730670
0.00054929292929	3.65544643233405	0.00000194185933	0.00006940678284
0.00055909090909	3.59958422029438	0.00000187439416	0.00006819043994
0.000568888888889	3.54551795069112	0.00000181038474	0.00006701599522
0.0005786868686869	3.49316037890789	0.00000174959903	0.00006588132049
0.0005884848484848	3.44242985363984	0.00000169182412	0.00006478442930
0.0005982828282828	3.39324987214988	0.00000163686442	0.00006372346532
0.0006080808080808	3.34554867753428	0.00000158453994	0.00006269669187
0.0006178787878788	3.29925889343418	0.00000153468487	0.00006170248244
0.0006276767676768	3.25431719218708	0.00000148714623	0.00006073931205
0.0006374747474747	3.21066399289474	0.00000144178271	0.00005980574950
0.0006472727272727	3.16824318630148	0.00000139846360	0.00005890045023
0.0006570707070707	3.12700188373987	0.00000135706788	0.00005802214990
0.0006668686868687	3.08689018771649	0.00000131748334	0.00005716965845
0.0006766666666667	3.04786098198615	0.00000127960585	0.00005634185477
0.0006864646464646	3.00986973920350	0.00000124333865	0.00005553768174
0.0006962626262626	2.97287434445230	0.00000120859173	0.00005475614175
0.0007060606060606	2.93683493313750	0.00000117528129	0.00005399629257
0.0007158585858586	2.90171374188823	0.00000114332923	0.00005325724356
0.0007256565656566	2.86747497126319	0.00000111266269	0.00005253815216
0.0007354545454545	2.83408465917659	0.00000108321362	0.00005183822072
0.0007452525252525	2.80151056407444	0.00000105491841	0.00005115669356
0.0007550505050505	2.76972205699053	0.00000102771757	0.00005049285419
0.0007648484848485	2.73869002169880	0.00000100155537	0.00004984602286
0.0007746464646465	2.70838676225710	0.00000097637960	0.00004921555419
0.0007844444444444	2.67878591730688	0.00000095214129	0.00004860083506
0.0007942424242424	2.64986238055499	0.00000092879447	0.00004800128260
0.0008040404040404	2.62159222691896	0.00000090629595	0.00004741634235
0.0008138383838384	2.59395264386671	0.00000088460511	0.00004684548654
0.0008236363636364	2.56692186752527	0.00000086368377	0.00004628821254
0.0008334343434343	2.54047912317307	0.00000084349595	0.00004574404134
0.0008432323232323	2.51460456976542	0.00000082400774	0.00004521251618
0.0008530303030303	2.48927924817481	0.00000080518721	0.00004469320131
0.0008628282828283	2.46448503285621	0.00000078700418	0.00004418568076
0.0008726262626263	2.44020458667317	0.00000076943019	0.00004368955725
0.0008824242424242	2.41642131864395	0.00000075243835	0.00004320445113
0.0008922222222222	2.39311934438762	0.00000073600322	0.00004272999944
0.0009020202020202	2.37028344906906	0.00000072010074	0.00004226585499
0.0009118181818182	2.34789905265887	0.00000070470814	0.00004181168551
0.0009216161616162	2.32595217733964	0.00000068980386	0.00004136717285
0.0009314141414141	2.30442941690416	0.00000067536746	0.00004093201226
0.0009412121212121	2.28331790800355	0.00000066137955	0.00004050591169
0.0009510101010101	2.26260530311525	0.00000064782175	0.00004008859109
0.0009608080808081	2.24227974511102	0.00000063467661	0.00003967978186
0.0009706060606061	2.22232984331461	0.00000062192754	0.00003927922625
0.0009804040404040	2.20274465094768	0.00000060955879	0.00003888667681
0.0009902020202020	2.18351364387026	0.00000059755539	0.00003850189586
0.0010000000000000	2.16462670052935	0.00000058590308	0.00003812465506

TABLE C

lamdFIR = wavelength of supply laser or microwave beam [m]  
 Ep = energy projected in initial laser pulse [J]  
 T1 = initial plasma temperature [millions of degrees Kelvin]  
 n0 = initial particle density [units of  $10^{20}$  per  $\text{cm}^3$ ]

lamdFIR	Ep	T1	n0
0.00003000000000	0.00000156375246	0.12604551113608	10.83184668687550
0.00003979797980	0.00000273543531	0.17757743259950	8.67128276177402
0.00004959595960	0.00000426043910	0.23085308008964	7.25873110318404
0.00005939393939	0.00000614868787	0.28552807906754	6.26011326054426
0.00006919191919	0.00000840849889	0.34138072627737	5.51500454052302
0.00007898989899	0.00001104705050	0.39825488631055	4.93668738191608
0.00008878787879	0.00001407067778	0.45603376428257	4.47411628765813
0.00009858585859	0.00001748505929	0.51462633430531	4.09524972666259
0.00010838383838	0.00002129534777	0.57395943539800	3.77893807358206
0.00011818181818	0.00002550626484	0.63397284838433	3.51064531416690
0.00012797979798	0.00003012217161	0.69461605602147	3.28004352989892
0.00013777777778	0.00003514712307	0.75584601668630	3.07958791967127
0.00014757575758	0.00004058491073	0.81762558024727	2.90363523467478
0.00015737373737	0.00004643909687	0.87992232799352	2.74787802293506
0.00016717171717	0.00005271303922	0.94270773528260	2.60897005086542
0.00017696969697	0.00005940992660	1.00595636773031	2.48427094302297
0.00018676767677	0.00006653277845	1.06964557722050	2.37166910810829
0.00019656565657	0.00007408447461	1.13375493949496	2.26945481133419
0.00020636363636	0.00008206776553	1.19826596410676	2.17622858100025
0.00021616161616	0.00009048528415	1.26316182625582	2.09083357318174
0.00022595959596	0.00009933955613	1.32842714658971	2.01230493839598
0.00023575757576	0.00010863300888	1.39404780862294	1.93983139550265
0.00024555555556	0.00011836797931	1.46001080601049	1.87272570553177
0.00025535353535	0.00012854672082	1.52630411376828	1.81040172536125
0.00026515151515	0.00013917140946	1.59291657888961	1.75235638848310
0.00027494949495	0.00015024414937	1.65983782681131	1.69815541876846
0.00028474747475	0.00016176697769	1.72705818093686	1.64742190326868
0.00029454545455	0.00017374186902	1.79456859299575	1.59982707669693
0.00030434343434	0.00018617073935	1.86236058245676	1.55508283274630
0.00031414141414	0.00019905544970	1.93042618355242	1.51293559536260
0.00032393939394	0.00021239780941	1.99875789873762	1.47316126968193
0.00033373737374	0.00022619957911	2.06734865761379	1.43556105657645
0.00034353535354	0.00024046247352	2.13619178051702	1.39995796286663
0.00035333333333	0.00025518816398	2.20528094610086	1.36619387563230
0.00036313131313	0.00027037828080	2.27461016235286	1.33412709678849
0.00037292929293	0.00028603441542	2.34417374057104	1.30363025541106
0.00038272727273	0.00030215812254	2.41396627189901	1.27458853180858
0.00039252525253	0.00031875092199	2.48398260607805	1.24689814021849
0.00040232323232	0.00033581430063	2.55421783212494	1.22046502712231
0.00041212121212	0.00035334971408	2.62466726068638	1.19520375017266
0.00042191919192	0.00037135858844	2.69532640785725	1.17103650908472
0.00043171717172	0.00038984232195	2.76619098028055	1.14789230493269
0.00044151515152	0.00040880228658	2.83725686137396	1.12570620838383
0.00045131313131	0.00042823982969	2.90852009855053	1.10441872071092
0.00046111111111	0.00044815627556	2.97997689132147	1.08397521411252
0.00047090909091	0.00046855292699	3.05162358018589	1.06432544006463
0.00048070707071	0.00048943106688	3.12345663622772	1.04542309622757
0.00049050505051	0.00051079195982	3.19547265135246	1.02722544391409
0.00050030303030	0.00053263685366	3.26766832910797	1.00969296935090
0.00051010101010	0.00055496698118	3.34004047604240	0.99278908298389
0.00051989898990	0.00057778356161	3.41258599356063	0.97647985192602
0.00052969696970	0.00060108780237	3.48530187024707	0.96073376135669
0.00053949494949	0.00062488090062	3.55818517462798	0.94552150127765

0.00054929292929	0.00064916404499	3.63123304835106	0.93081577553252
0.00055909090909	0.00067393841717	3.70444269976353	0.91659113042140
0.00056888888889	0.00069920519360	3.77781139787249	0.90282380060205
0.00057868686869	0.00072496554714	3.85133646667349	0.88949157027491
0.00058848484848	0.00075122064869	3.92501527983507	0.87657364791039
0.00059828282828	0.00077797166885	3.99884525572732	0.86405055300019
0.00060808080808	0.00080521977955	4.07282385278407	0.85190401350581
0.00061787878788	0.00083296615561	4.14694856518800	0.84011687284216
0.00062767676768	0.00086121197639	4.22121691886839	0.82867300537633
0.00063747474747	0.00088995842726	4.29562646780132	0.81755723954418
0.00064727272727	0.00091920670118	4.37017479060160	0.80675528779390
0.00065707070707	0.00094895800013	4.44485948739598	0.79625368265798
0.00066686868687	0.00097921353658	4.51967817696650	0.78603971833569
0.00067666666667	0.00100997453486	4.59462849415289	0.77610139723790
0.00068646464646	0.00104124223251	4.66970808750251	0.76642738100793
0.00069626262626	0.00107301788157	4.74491461715622	0.75700694558536
0.00070606060606	0.00110530274982	4.82024575295833	0.74782993992717
0.00071585858586	0.00113809812199	4.89569917277876	0.73888674804201
0.00072565656566	0.00117140530086	4.97127256103541	0.73016825402970
0.00073545454545	0.00120522560837	5.04696360740485	0.72166580985072
0.00074525252525	0.00123956038661	5.12277000570941	0.71337120557842
0.00075505050505	0.00127441099880	5.19868945296907	0.70527664191239
0.00076484848485	0.00130977883022	5.27471964860656	0.69737470475338
0.00077464646465	0.00134566528902	5.35085829379448	0.68965834166052
0.00078444444444	0.00138207180707	5.42710309093352	0.68212084002869
0.00079424242424	0.00141899984064	5.50345174325112	0.67475580684021
0.00080404040404	0.00145645087118	5.57990195451046	0.66755714985857
0.00081383838384	0.00149442640585	5.65645142881987	0.66051906014493
0.00082363636364	0.00153292797822	5.73309787053345	0.65363599578897
0.00083343434343	0.00157195714875	5.80983898423386	0.64690266675598
0.00084323232323	0.00161151550528	5.88667247478883	0.64031402076088
0.00085303030303	0.00165160466352	5.96359604747363	0.63386523008829
0.00086282828283	0.00169222626743	6.04060740815164	0.62755167928466
0.00087262626263	0.00173338198960	6.11770426350638	0.62136895365524
0.00088242424242	0.00177507353156	6.19488432131811	0.61531282850470
0.00089222222222	0.00181730262411	6.27214529077916	0.60937925906514
0.00090202020202	0.00186007102752	6.34948488284216	0.60356437106052
0.00091181818182	0.00190338053181	6.42690081059601	0.59786445186048
0.00092161616162	0.00194723295690	6.50439078966477	0.59227594218076
0.00093141414141	0.00199163015280	6.58195253862521	0.58679542829082
0.00094121212121	0.00203657399973	6.65958377943870	0.58141963469249
0.00095101010101	0.00208206640822	6.73728223789408	0.57614541723662
0.00096080808081	0.00212810931924	6.81504564405812	0.57096975664713
0.00097060606061	0.00217470470421	6.89287173273046	0.56588975242434
0.00098040404040	0.00222185456508	6.97075824390056	0.56090261710190
0.00099020202020	0.00226956093433	7.04870292320416	0.55600567083326
0.00100000000000	0.00231782587499	7.12670352237711	0.55119633628583

**Task 1A.6 Deliverable Report**

Using the algorithm developed in Task 1A.3 and implemented as a MATLAB function in Task 1A.4, and providing ranges of variables derived in Task 1A.5, as presented in the preceding Tables, it is reasonable to seek to find an initial pressure not excessively above atmospheric pressure, and a final pressure (after explosive expansion of the ambient gas into an effectively infinite surrounding vacuum chamber) smaller than one-millionth of an atmosphere, while seeking a final plasma temperature of 1,712 Kelvins (which is within the LMP region as demonstrated in Tasks 1A.1-2) and using the preceding "steady-state" theory but neglecting to attempt to maintain the fireball in steady state by neglecting to use the supply laser (or supply microwave beam) with perfect efficiency.

Accordingly the hereby-selected lamdFIR = 400 microns is well within the known FIR wavelength range of 30 to 800 microns, and will be used a "nominal place-holder" in order to find a set of LMP parameters consistent with the all-important Thermodynamic Lemma of Task 1A.3. This results in:

-----  
 MATLAB Diary 02/03/08C

```
>> Z=1; lamdp = 1.06/10^6; lamdFIR = 400/10^6; zet = 10; T3 = 1712;
>> [r0,T1,p0,p0atm,x,Ep,etp,N,n0,nel,lamdD,xi,numic,p2,p2atm,T2,r3,V3,Pmic] =
    LaserSpark(Z,lamdp,lamdFIR,zet,T3)
```

converged after 4 iterations

```
r0 = 6.234184801397992e-006
T1 = 2.537544573710257e+006
p0 = 4.880953030510626e+005
p0atm = 4.81712610955897
x = 0.01558546200349
Ep = 3.317257053250115e-004
etp = 0.99999978757031
N = 9.336846434060845e+011
n0 = 1.226623630932018e+026
nel = 6.965649669706498e+021
lamdD = 1.318463132893634e-006
xi = 0.10405810234636
numic = 7.494750000000000e+011
p2 = 0.37104143763620
p2atm = 3.661894277189200e-006
T2 = 1.92899661359143
r3 = 0.00384400629053
V3 = 2.379254385022188e-007
Pmic = 9.531163764714609e-005
```

-----  
 which yields, for an Nd-YAG Spark Laser having a wavelength of 1.06 microns the following parameters for an LMP demonstration:

```
p0 = initial ambient gas pressure = 4.817 atm
r0 = initial focal spot radius = 6.23 microns
Ep = initial energy in spark-laser pulse = 0.3317 mJ
P2 = final ambient gas pressure = 0.000003661 atm [essentially a vacuum]
R3 = final fireball radius = 3.84 mm
nel = final electron density = 6.9656 X 10^15 per cm^3
Subsequent Energy Loss through bremsstrahlung radiation = 0.0953 mW
Expected lifetime of LMP = [(0.03317 mJ)/(0.0953 mW)] = 0.3480 sec
```

which is nearly 2,000 times longer than the lifetime of the accidentally-created LMP of which Nobel Laureate Melvin Cook published a sequence of photographs on the cover of the *Journal of Applied Physics* in October, 1958) and therefore would represent achievement of the present project's aim of verifying Cook's results, that were achieved in self-destructive conditions, under controlled laboratory conditions for further measurements and thorough experimental scientific investigation as to ultimate practical utility.

**Task 1A.7**

**Historical Background** [narrative format, from a recent email by Bass to known experts in the relevant fields]:

So I thought that you might be interested in the **story** of how I am in the position of posthumously trying to **vindicate the legacy of THREE of my deceased friends**, one of whom was a Nobel Laureate and the other two of whom were almost equally accomplished [namely Drs. Cook, Tuck, & Blauer].

I have NOT promised DARPA that I will do any original 21<sup>st</sup> Century R&D work, rather that I will attempt to replicate and put in publishable form work that I had COMPLETED several times in the past, many years ago, when first collaborating with the late Nobel Laureate Melvin Cook (a professor of metallurgy at the U of Utah when I was a professor of physics at the nearby BYU [1971-81]), and later (during 1982-86 and again during 1991-1995) with one of the world's top authorities on both Shock Tubes and High-Energy Chemical Lasers, the late Dr. Jay Blauer. Also when at BYU I had visited LANL for two weeks under their "visiting academicians" program and knew CTR Director Dr. Jim Tuck very well when he told me both his theory of "surface tension" in fireballs (that was used in my 1984-Patented Plasmasphere concept) and his related theory of "volumetric cohesion" in same, which is identical to the presently-considered LMP phenomenon.

Unfortunately much of this was lost and has only been recovered by me in fragmentary form (although some of the key equations are in my own Plasmasphere Patent [issued 1984, expired untried 2001]), but the fragments in hand are sufficient to confirm the validity of my current attempt to reconstruct and recover it all for the purpose of the DARPA Purchase Order under discussion.

In 1968 Melvin Cook received from the Swedish Royal Academy the Nitro-Nobel Gold Medal for the best work on the physical chemistry of high explosives "in the century since Alfred Nobel discovered dynamite." This award was made under the same rules as the other Nobel Prizes, except that it was funded by Nobel's company rather than from his Will, but that kind of technicality hasn't stopped the Swedish Royal Academy from referring to recipients of the Nobel Memorial Award in Economics [funded by the Bank of Sweden rather than Nobel's Will] as Nobel Laureates, so I have a definitive rebuttal to those who say that Cook wasn't really a "genuine" Nobel Laureate.

Ironically, Cook's discovery (which he patented and from which he earned Million\$\$ in royalties [though the U of UT sued and claimed they should have been part owners, he proved in court that he had offered it to the U of UT and had been rejected, so the courts awarded him sole ownership]) was motivated by his desire to discover a commercial blasting agent that could not be delivered in conventional shells & bombs and would have only 'peaceful' utility, as in mining operations, but his concept of site-mixed "slurry explosives" (as in the Oklahoma Federal Building bombing from a truckload of oil drums & fertilizer drums, or in the incident in which 230 Marines were killed in the Middle East when their barracks building was bombed by a suicide-truck driver) has turned out to be the weapon of choice of modern Terrorists!

Anyway, when doing an experiment with the high-explosive *dithekite* at the Naval Research Lab's facility at the China Lake Naval Weapons Center, Cook accidentally created a "fireball" which maintained its volume and shape for several milliseconds when, if it had been a conventionally THERMALLY ionized plasma, it would have been expanding at the local speed of sound instead of remaining at the same size. He therefore deduced that it was indeed a fully ionized plasma, yet one that had been PRESSURE ionized rather than thermally ionized, and that it was in the physical state of a liquid metal (like Mercury). This appeared in color photos on the cover of the *Journal of Applied Physics* in 1958, as shown in slides 6-9 of my slideshow about MetaStableHelium (MSH) crystals which is available online at my website [www.innoventek.com](http://www.innoventek.com).

Cook's explanation was to put forward the concept of a *cryscapade*, which I am calling a self-confined Liquid Metallic Plasmoid (LMP).

Independently, my late friend Dr. Jim Tuck (co-inventor of the Theta Pinch and head of Controlled Thermonuclear Research [CTR] at Los Alamos for many decades) discovered the same phenomenon experimentally, while trying to replicate anecdotal accounts of Ball Lightning inside of submerged submarines. He short-circuited a submarine battery, blowing the roof off of a bunker, and LANL required him to cease investigating his "miniature fireballs" any further, which he had been pursuing as a hobby after his

retirement. Slow-motion movies of Tuck's miniature fireballs were shown on the BBC in "The Wonderful World of Arthur C. Clarke" popular science TV series, and Tuck showed them to me personally also. Tuck told me (after Robert Golka has shown me Tuck's paper on the fireballs) that he attributed the phenomenon to "dynamic Madelung forces," where Madelung forces are what holds a crystal together. (In his published work, Cook also had derived a Madelung-force explanation of his cryscapades.)

Thus LMPs were discovered TWICE experimentally, and explained theoretically, independently, by the same physical considerations pertaining to Madelung forces.

Moreover, quite independently, writing in different languages in different journals published all around the world, from France to India to Germany to the USA, THREE other theoreticians discovered the almost-identical LMP theory while trying to explain the natural phenomenon of Ball Lightning.

In my previous two completed Tasks for DARPA I have unified these FIVE independent discoveries (of Cook, Tuck, Pozwolski, Wilhelm, Winterberg) into a "best" version, which contains all of the others as special cases, and shows (in the Figures following page 53 below) the physical conditions [namely RELATIVELY Low Temperature and RELATIVELY High Density] under which a hydrogenic or helium plasma will be in the state of an LMP.

BUT the experiments of Cook and Tuck were self-destructive.

So the remaining problem in converting LMPs to usefulness is to replicate the Cook/Tuck work under controlled conditions in a reusable apparatus.

My late friend Dr. Jay Blauer was such an internationally-respected authority on High Energy Chemical Lasers that the USAF lab in AZ which sponsors such R&D told him that if he would resign from Rockwell and join them, they would make him head of ALL Air Force sponsored R&D in lasers in the USA, but he declined their offer.

Blauer helped me to design the experimental demonstration shown on slides 17-22 of the slideshow mentioned above, which I was invited to present publicly at SFVEC in February, 2006 and which was the basis of the proposal to DARPA that resulted in the instant Purchase Order.

Blauer told me that he could perform the experimental demonstration of an LMP which did not grow in size, though in free-fall *in vacuo*, "in his spare time on nights & weekends, in 2 weeks, using equipment sitting around in his lab at Rockwell" if only I could get him \$10K for parts which he didn't have on hand.

Later, when I was Chief Scientist of Litton Industries' SDI-oriented Advanced Systems Group (LASG) I persuaded the Litton Vice President over LASG to agree to offer Rockwell \$25K to rent use of Jay's lab on nights & weekend for 15 days for \$15K plus leaving him the needed \$10K for the missing parts. But, suddenly, this Litton VP accepted a better offer from Systron Donner and resigned, and, before I could get to meet his successor, someone who personally disliked me "got to" the new Litton VP and he arbitrarily retracted the offer (that Rockwell had already accepted!).

Then, before I could find an alternative source of funding, Jay got leukemia (which he attributed to job-related radiation exposure) and suddenly passed away.

Accordingly, it is merely an ACCIDENT OF RANDOM HISTORICAL CONTINGENCIES that the replicability of LMPs under controlled conditions has not long-since been accomplished!

### Conclusions:

After disclosing the results of Tasks 1A.1-1A.6 above to Dr. Frank K. Lu of UTA, a well-known expert on both shock-tube experiments and high-energy laser experiments in his Aerospace Research Center (ARC) laboratory at UTA, it has become evident that there is a possible weakness, if not problematic aspect to original Bass-Blauer experiment discussed above.

This concerns the fact that in the original Bass-Blauer Protocol, it was expected that the LMP fireball would remain above the critical temperature for an LMP at the given density during the time that it would take for the ambient cold gas to flow out of the shock tube and into the vacuum chamber. But this flow was to be achieved by the pressure of the initially-ambient cold gas as it moved explosively out into the vacuum. However, without having attempted to model this difficult problem in gas-dynamics, it is likely from experience that such a motion will take many milliseconds rather than microseconds.

But a greater chance of success would be in prospect if the ambient gas were "rammed" out into the vacuum chamber by a column of gas being driven by a piston, as in the Figure on page 67 below.

The piston will be set in motion before the spark laser has been fired, and the entire demonstration will depend upon exquisitely-timed synchronization between the mechanical and optical portions of the experiment.

In other words, the Proof-of-Principle Protocol is more likely to succeed if one attempts it with "cutting edge 21<sup>st</sup> century state-of-the-art technology" than with the relatively crude technology that was available to Bass & Blauer in the 1980s.

Accordingly it is concluded that the greatest chance of success in Phase 1B will be ensured if that phase is under the co-direction and co-management of ARC, which Innoventek is hereby pleased to select as the Prime Contractor for the anticipated follow-on Purchase Order from DARPA for Phase 1B.

[54] **GENERATION, INSULATED CONFINEMENT, AND HEATING OF ULTRA-HIGH TEMPERATURE PLASMAS**

[75] Inventor: Robert W. Bass, Provo, Utah

[73] Assignee: Applied Fusion Research Corporation, Denver, Colo.

[21] Appl. No.: 84,837

[22] Filed: Oct. 15, 1979

[51] Int. Cl.<sup>3</sup> ..... G21B 1/00

[52] U.S. Cl. .... 376/103; 376/152

[58] Field of Search ..... 176/1, 3, 5, 9;  
376/103, 104, 151, 152

[56] **References Cited**

**U.S. PATENT DOCUMENTS**

3,346,458 10/1967 Schmidt ..... 176/1

**OTHER PUBLICATIONS**

Laser Plasmas and Nuclear Energy, Henrich Hora (1975) Plenum Press, pp. 31-33, 64-72.

Laser & Electro-Optik, vol. 6 (3/74), Hora, pp. 26-27.

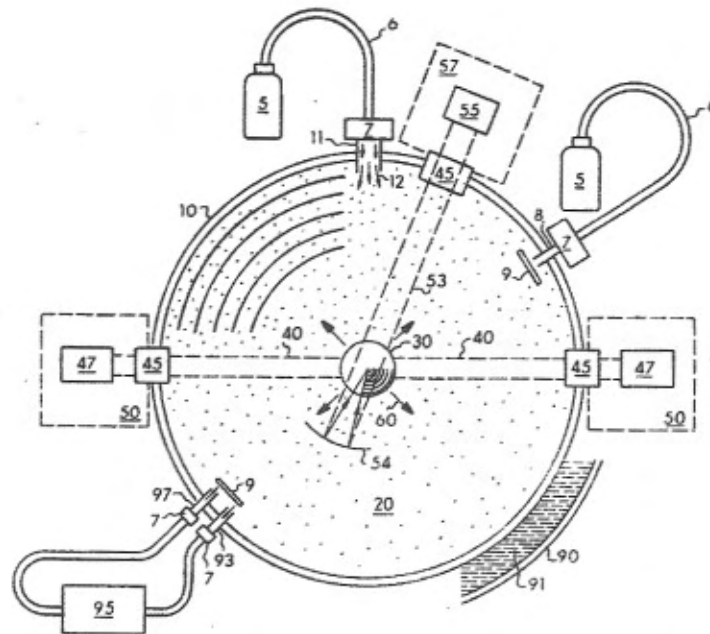
JETP Letter, vol. 21, No. 2. (1/20/75), pp. 68-70, Basov et al.

Primary Examiner—Sal Cangialosi

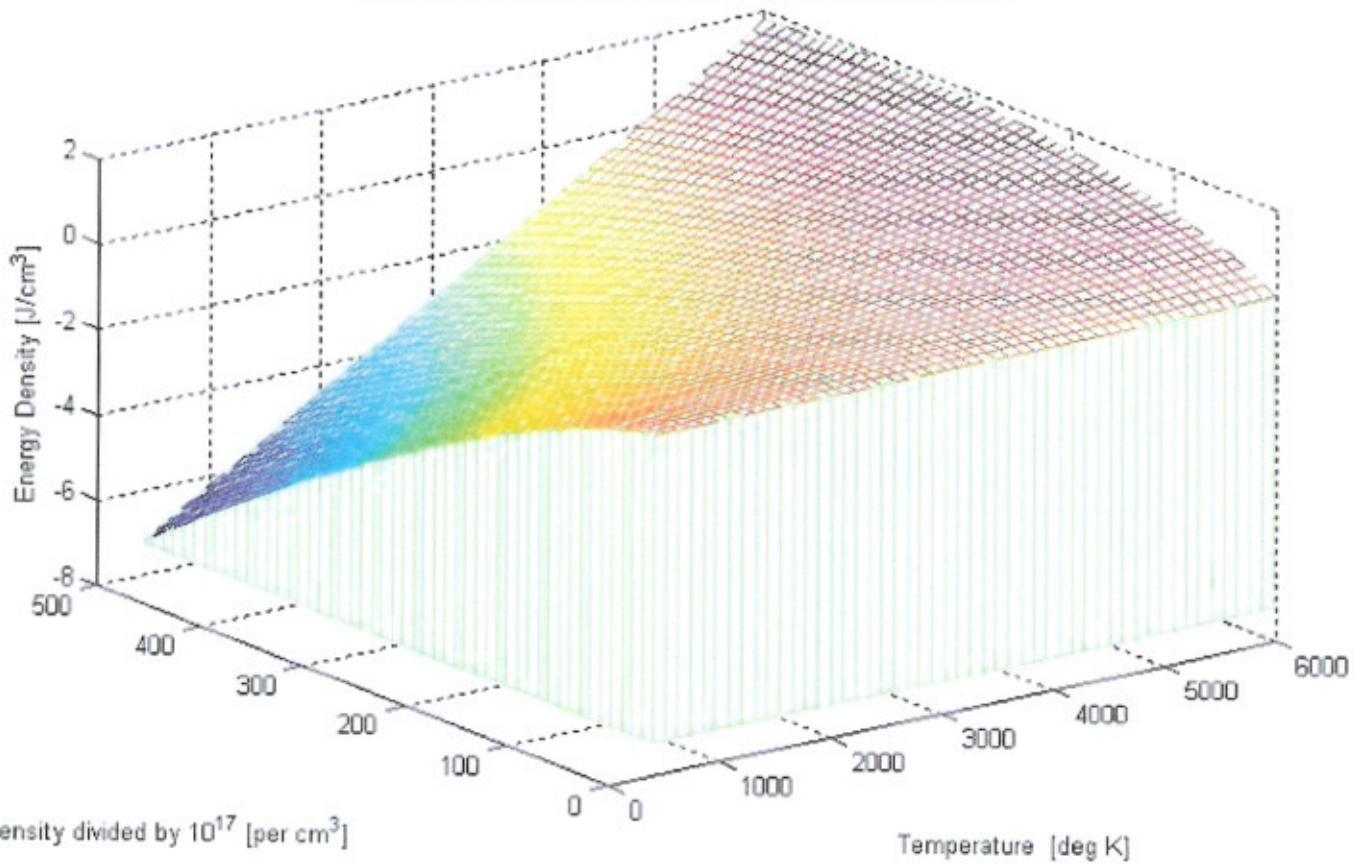
[57] **ABSTRACT**

Improved generation, insulated confinement and heating of ultra-high temperature steady-state plasmas in such devices as the optical plasmotron of Raizer and the freely floating plasma filament of Kapitza wherein the temperature of the plasma is increased by increasing the static pressure of the ambient medium (or decreasing the frequency of the radiant energy supply) while increasing the radiant energy supply's power and wherein the relationships between the ambient pressure, the amount of initially projected ionizing energy, the focal spot radius of this initial energy, the wavelength of the radiant energy supply, the transparency of the plasma, the rate of bremsstrahlung radiation energy losses, the power of the radiant energy supply and the ratio of the static pressure increase (or frequency decrease) are so optimized as to enable attainment of plasma temperatures more than an order of magnitude greater than hitherto attainable by any process of such a type.

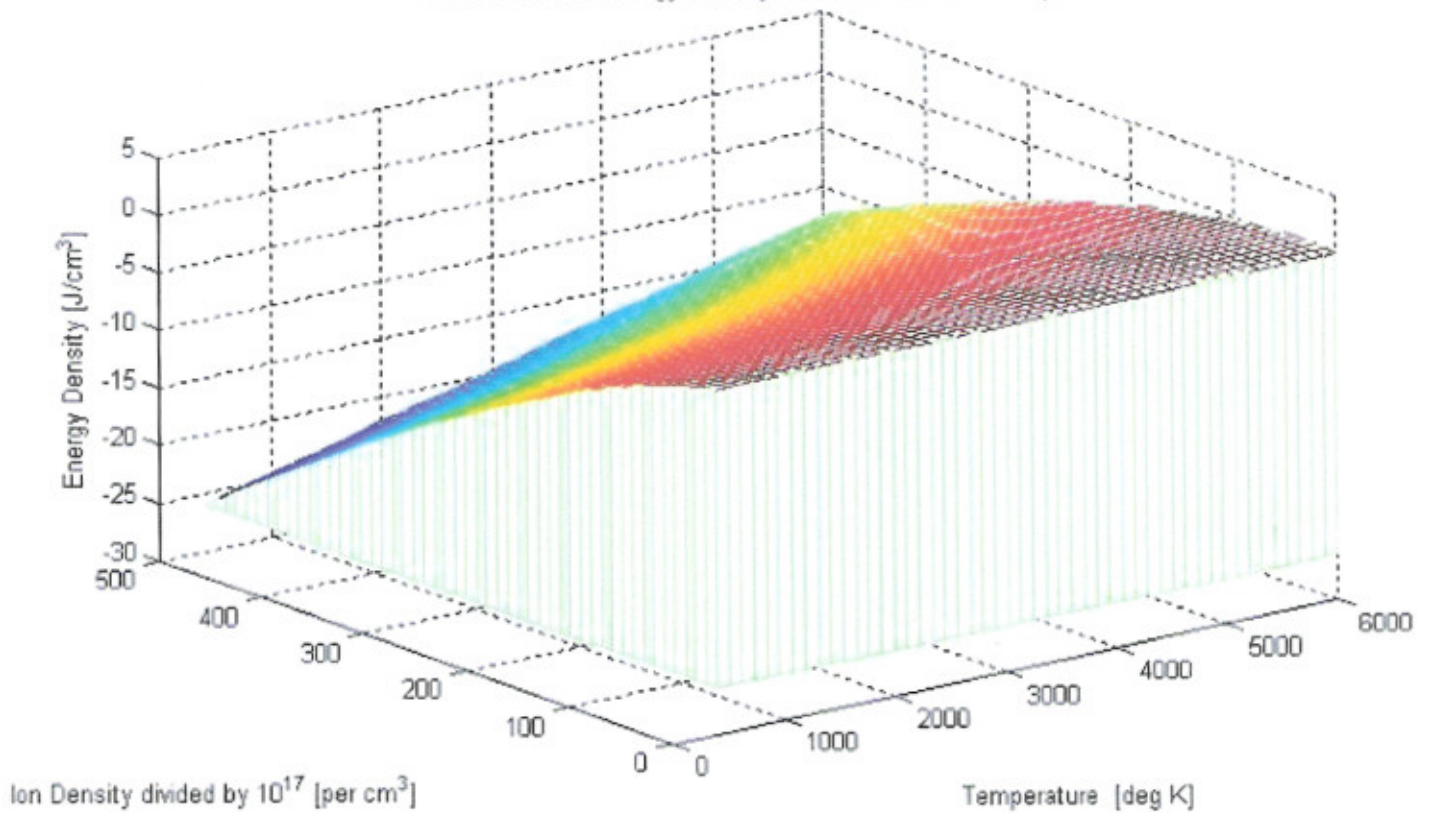
5 Claims, 13 Drawing Figures



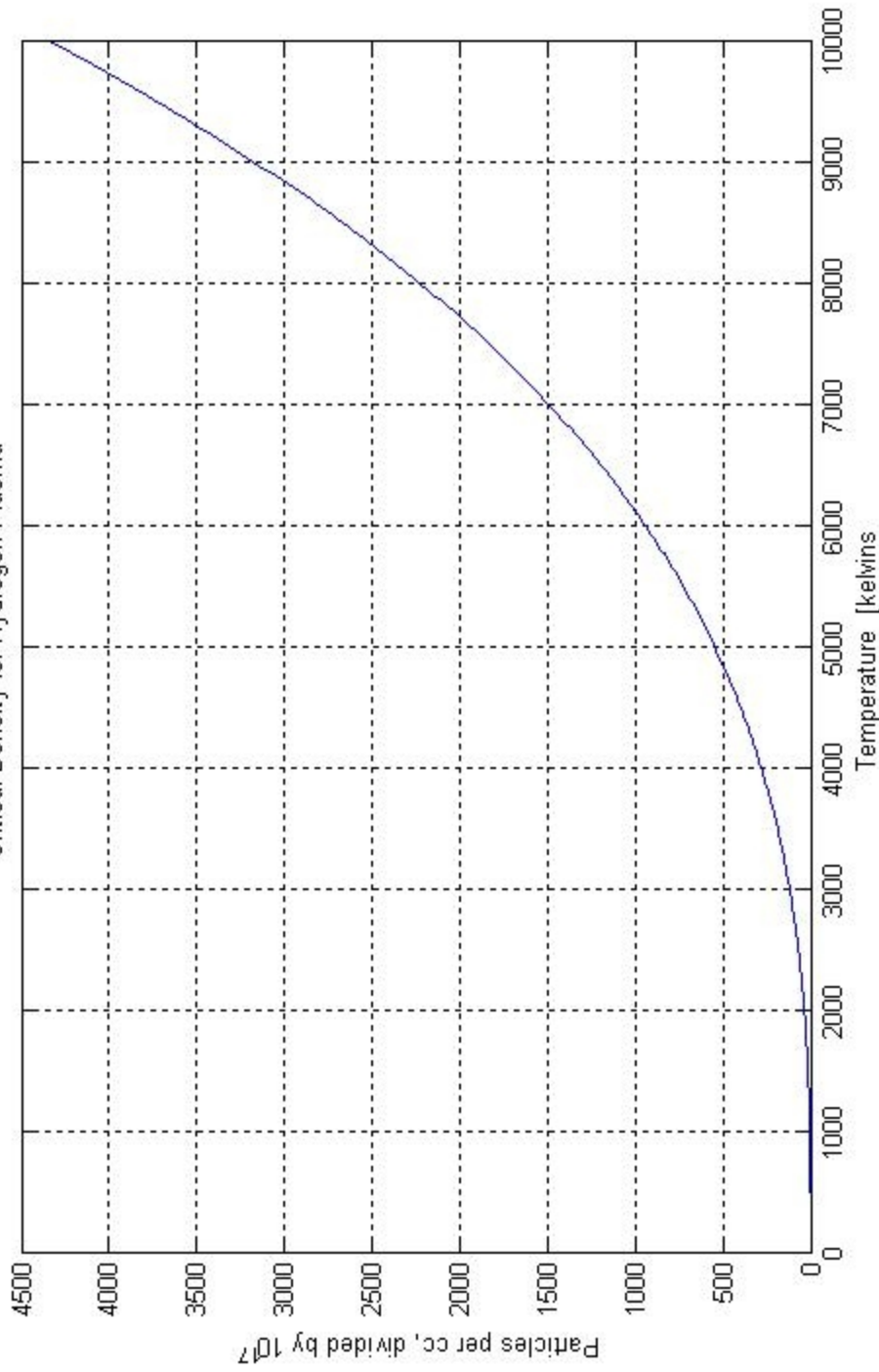
Hydrogen Plasma Energy Density via Berlin-Montroll Theory



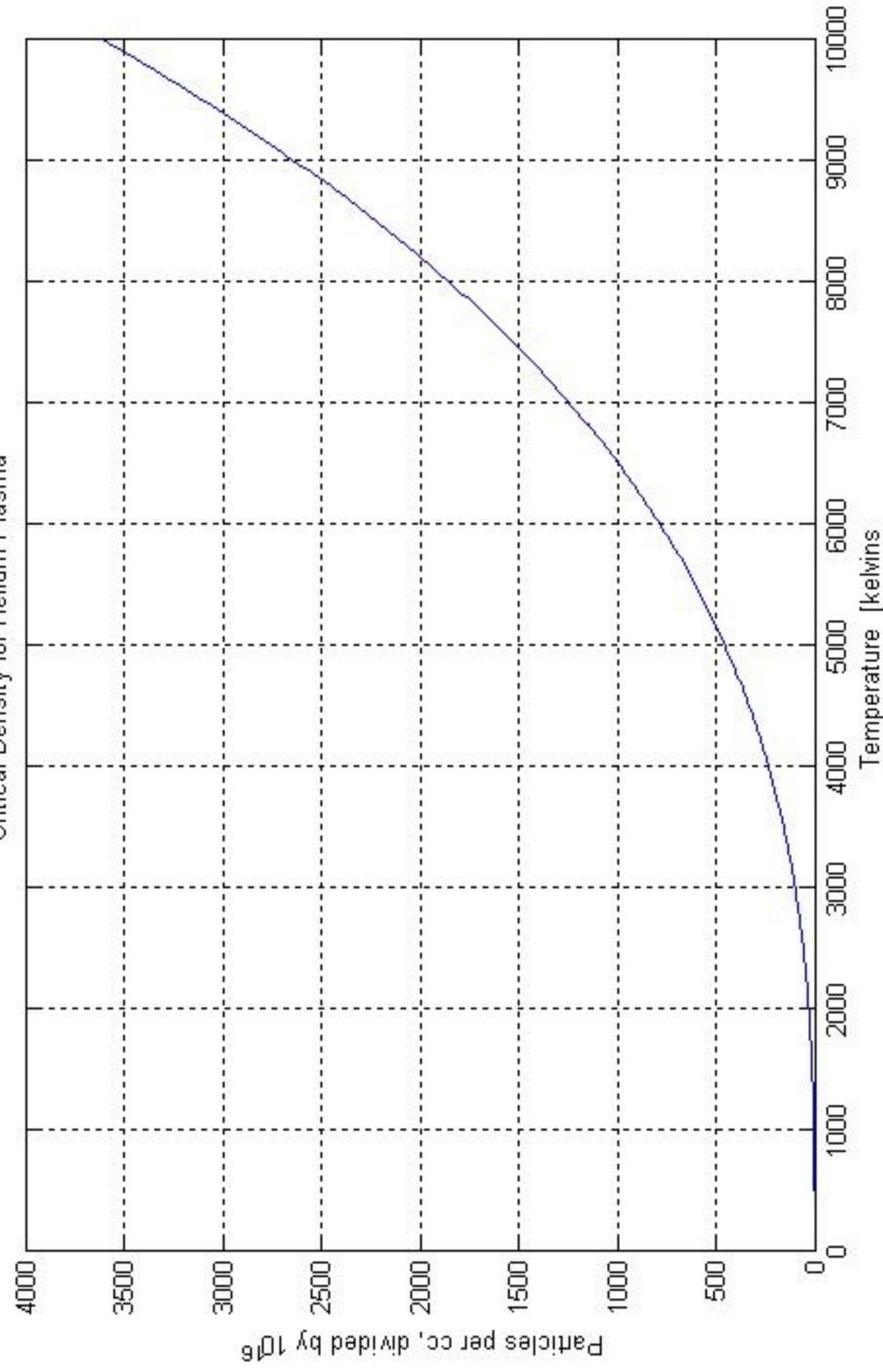
Helium Plasma Energy Density via Berlin-Montroll Theory

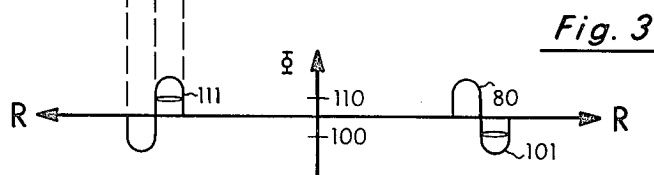
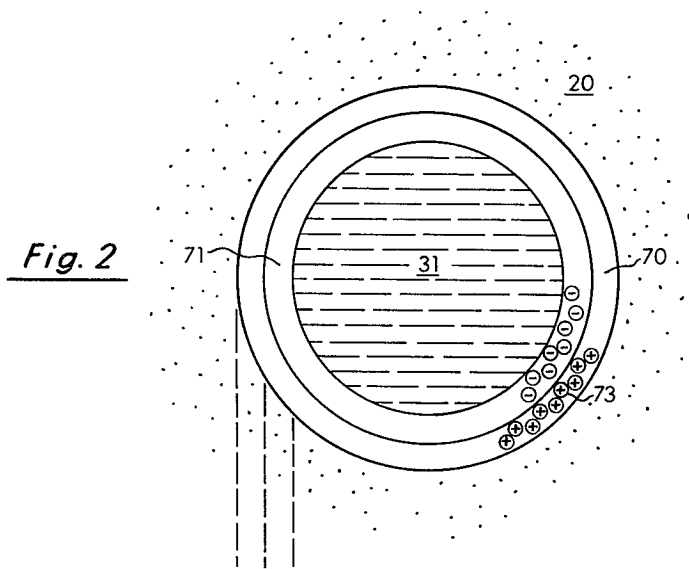
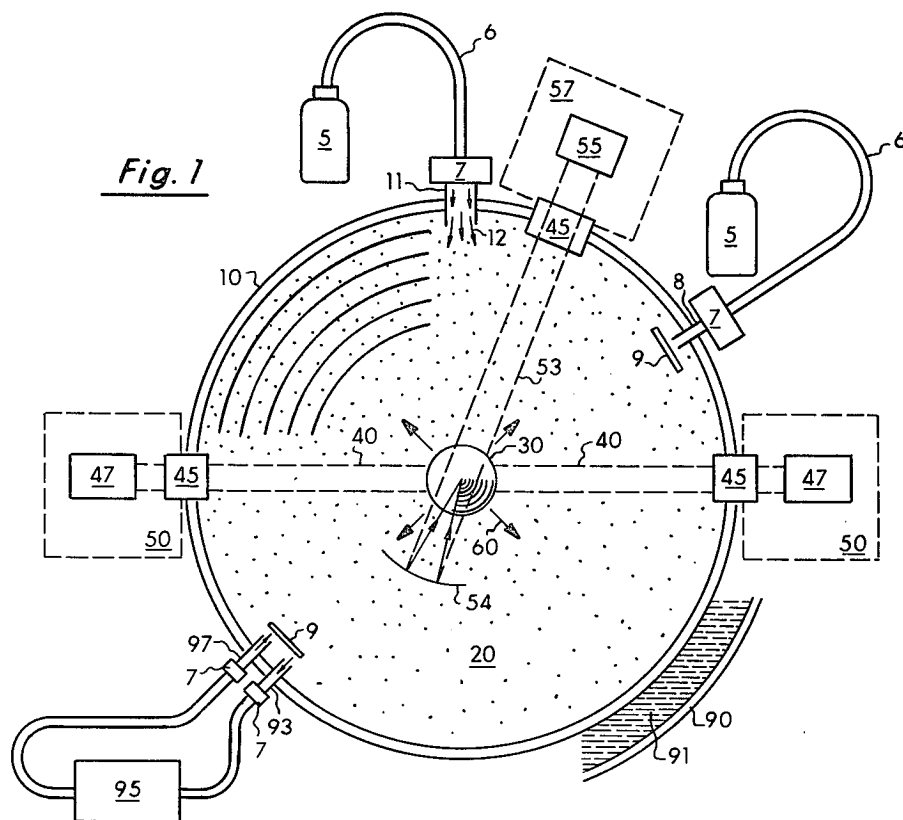


Critical Density for Hydrogen Plasma



Critical Density for Helium Plasma





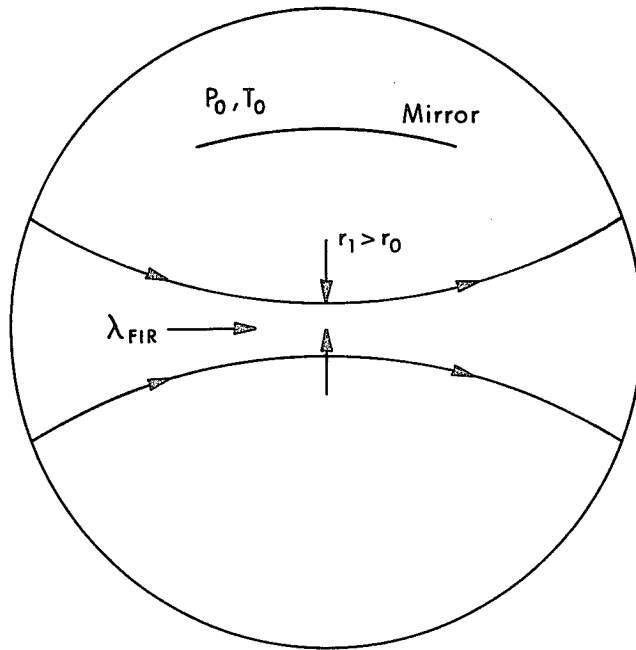


Fig. 4

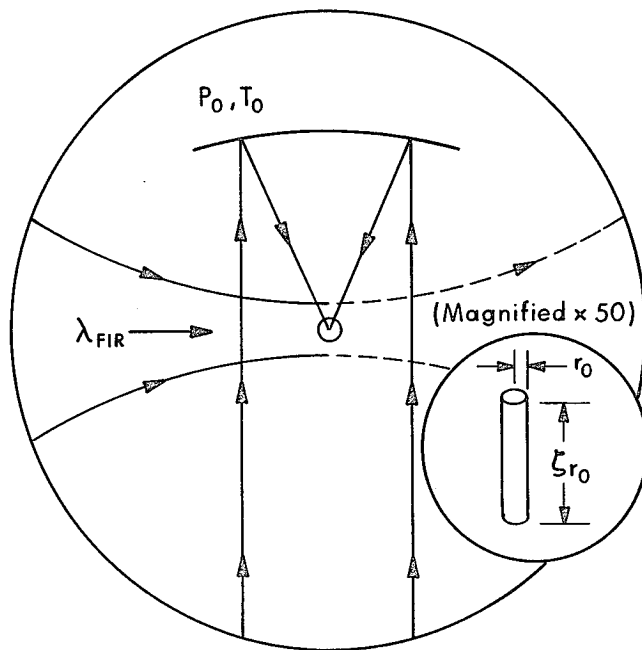


Fig. 5

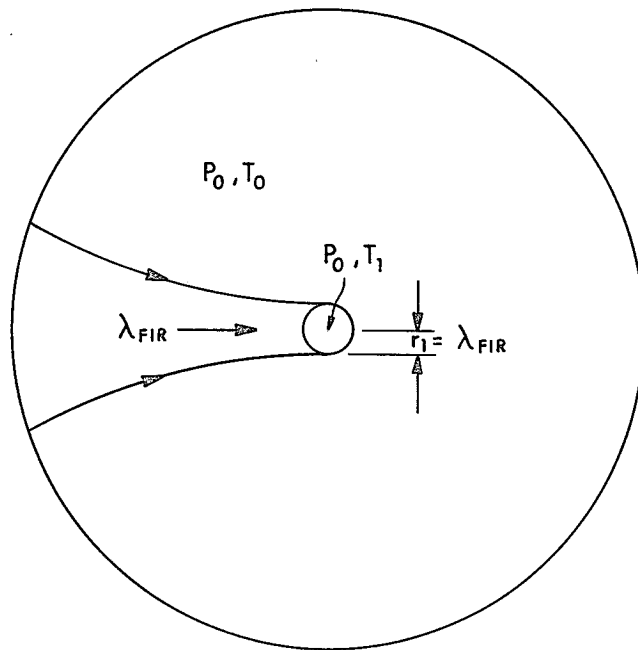
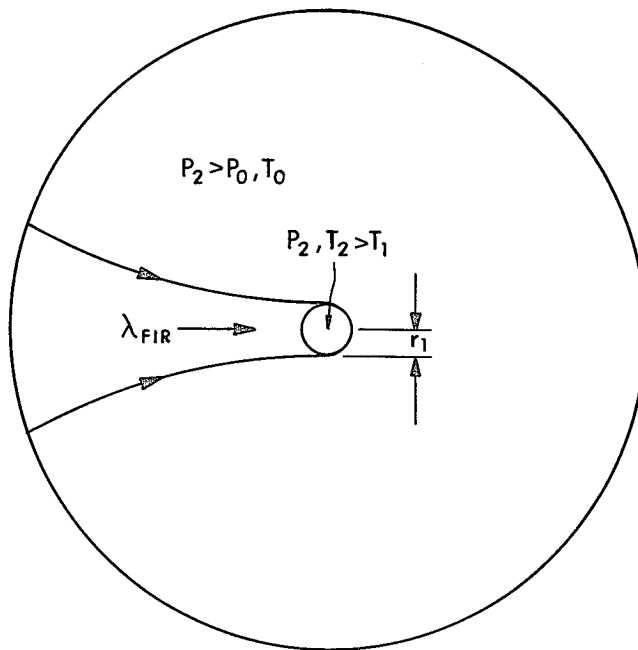


Fig. 6



$(P_0 \rightarrow P_2)$   
Fig. 7

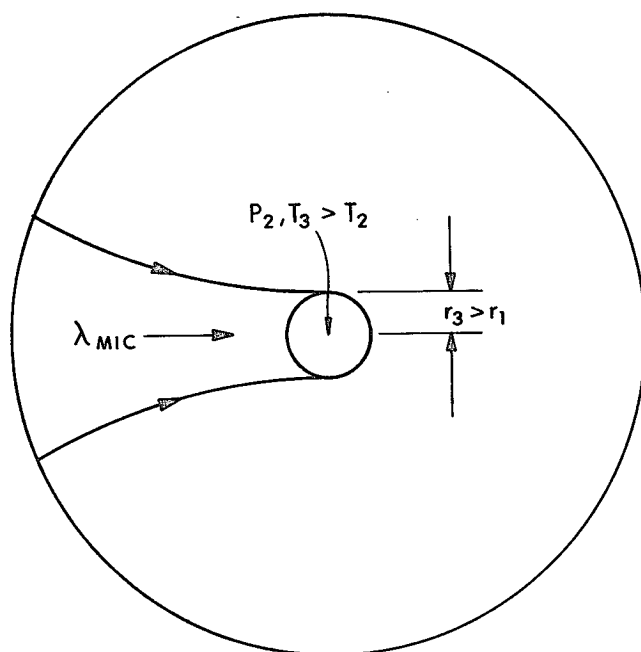


Fig. 8

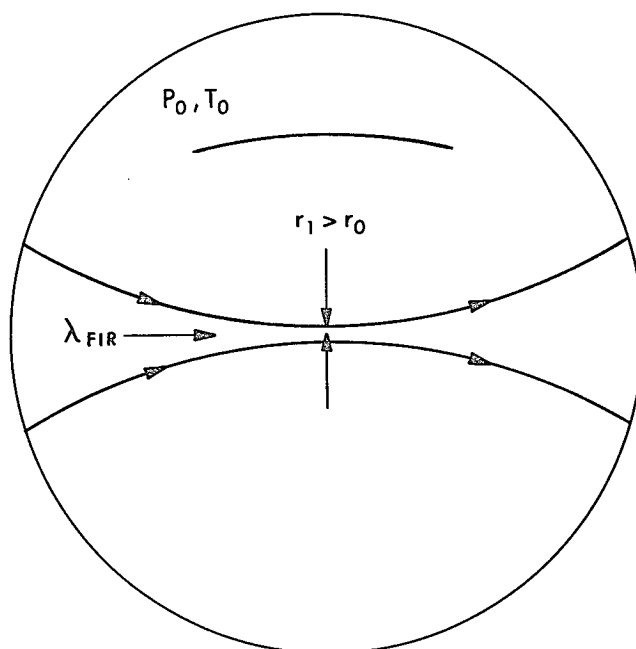


Fig. 9

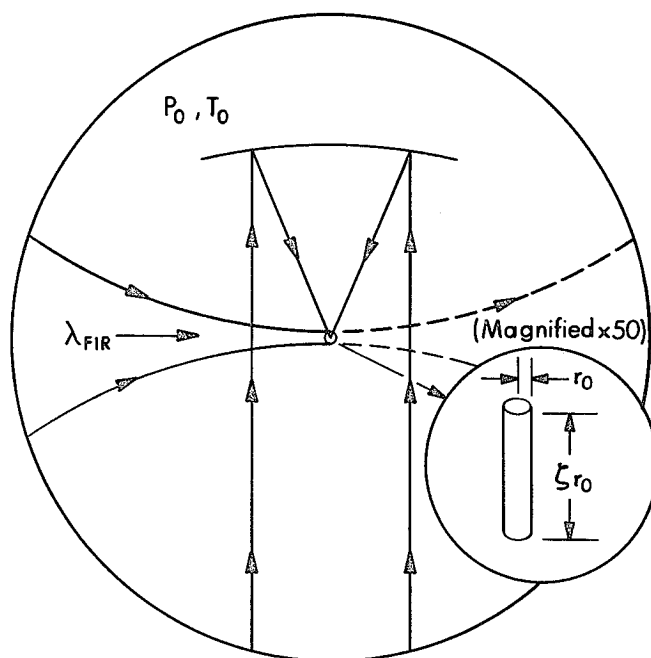


Fig. 10

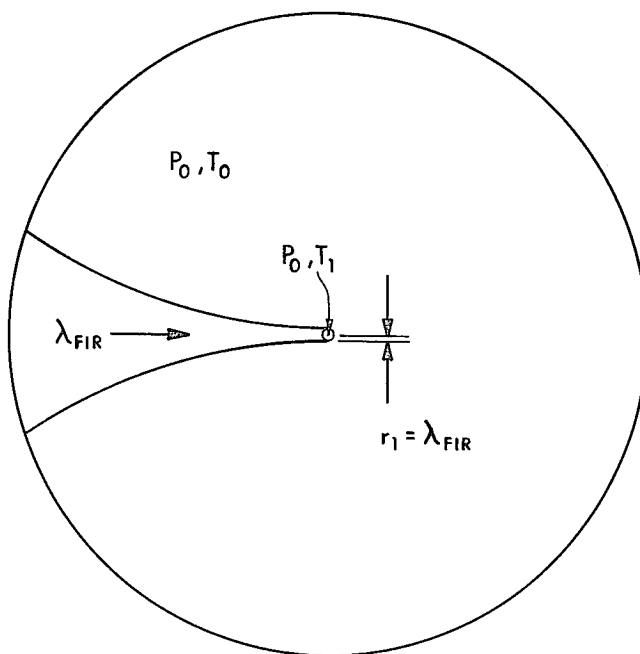
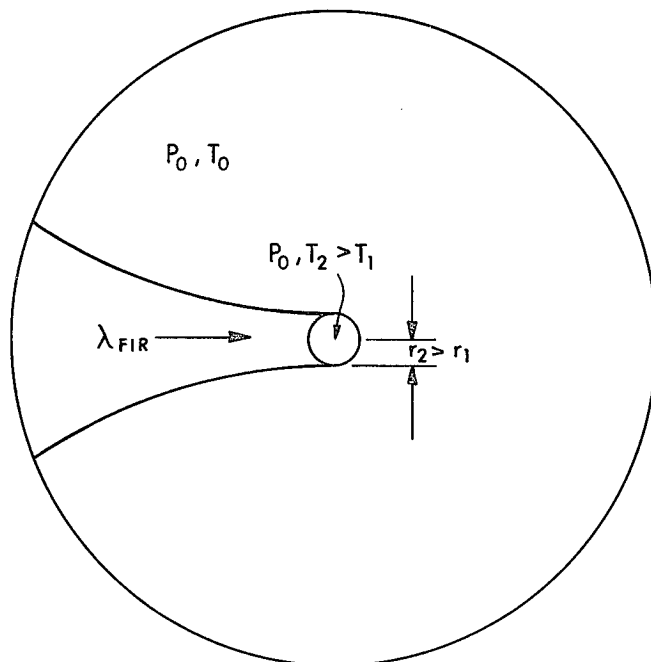


Fig. 11



$(\lambda_{FIR} = r_1 \rightarrow \lambda_{FIR} = r_2 > r_1)$

Fig. 12

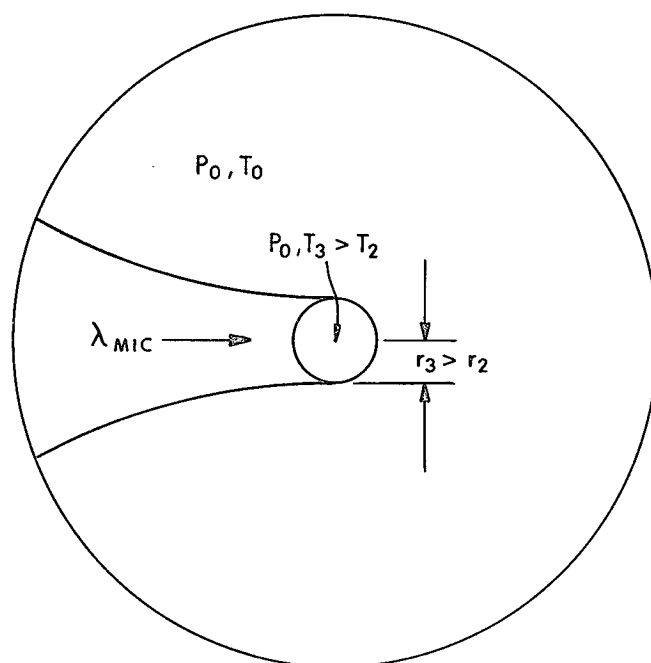
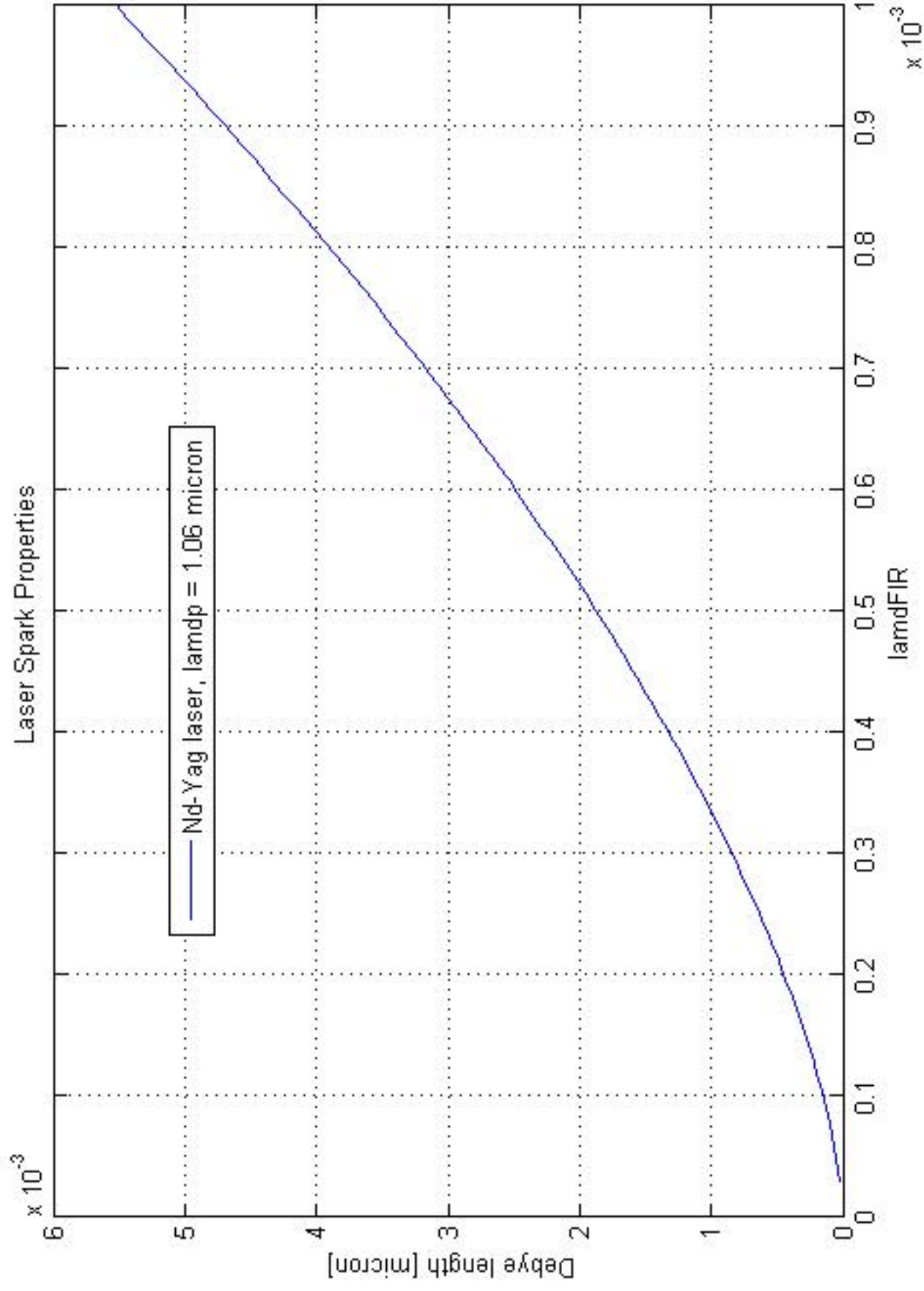
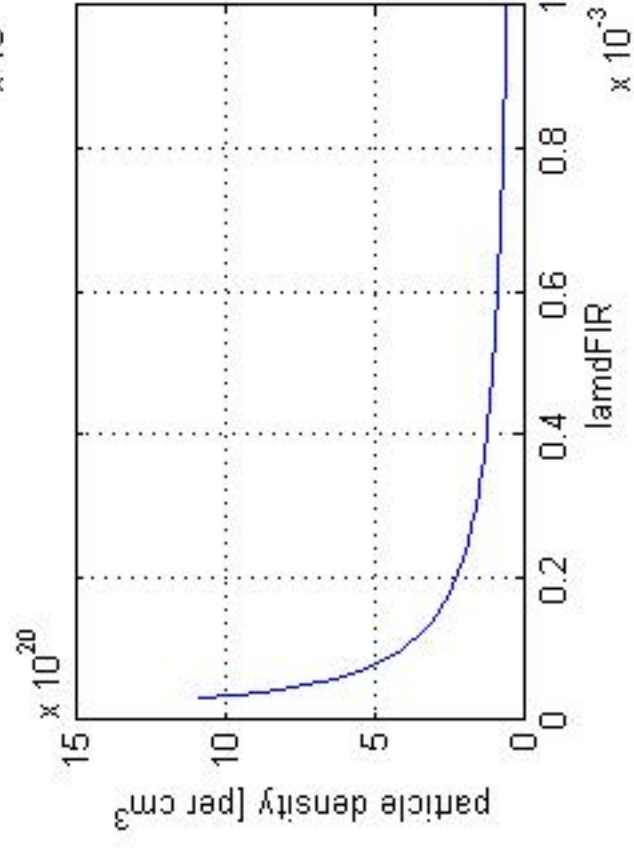
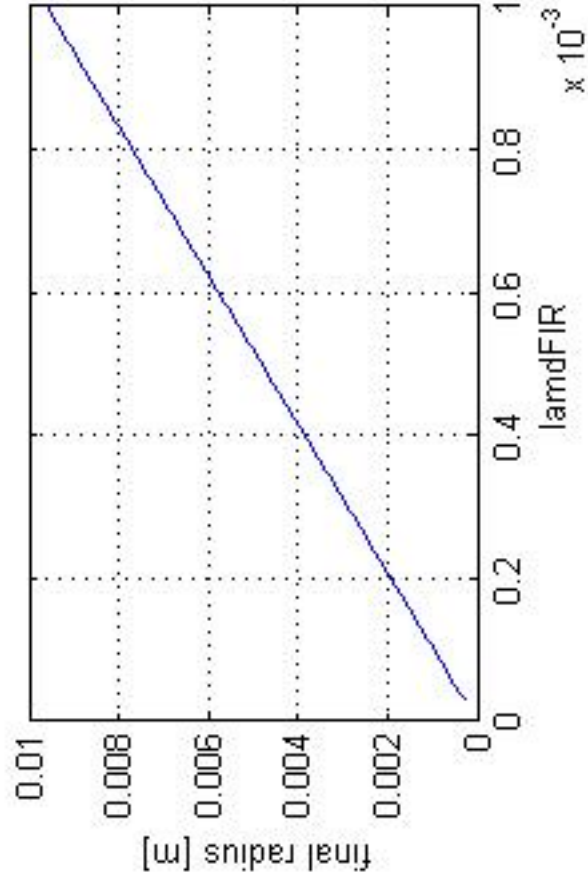
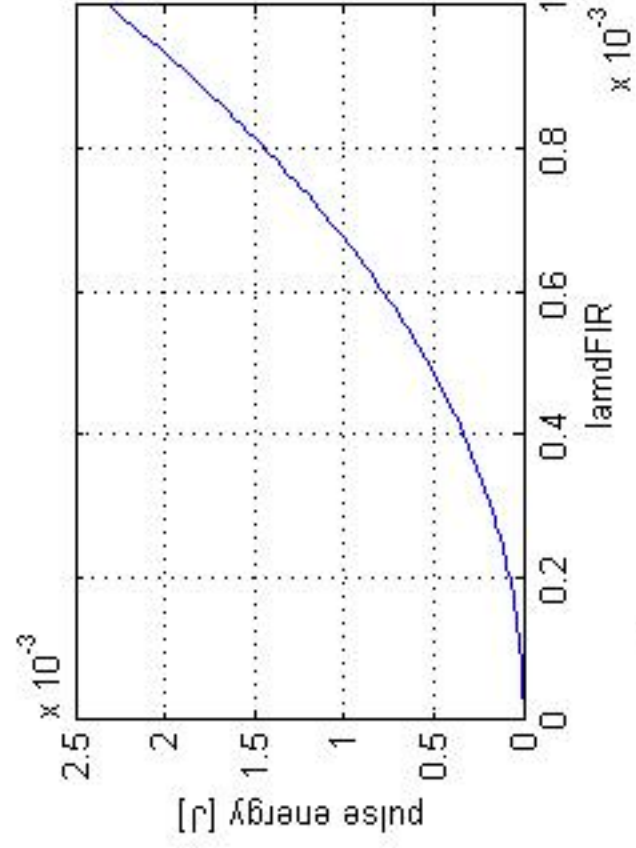
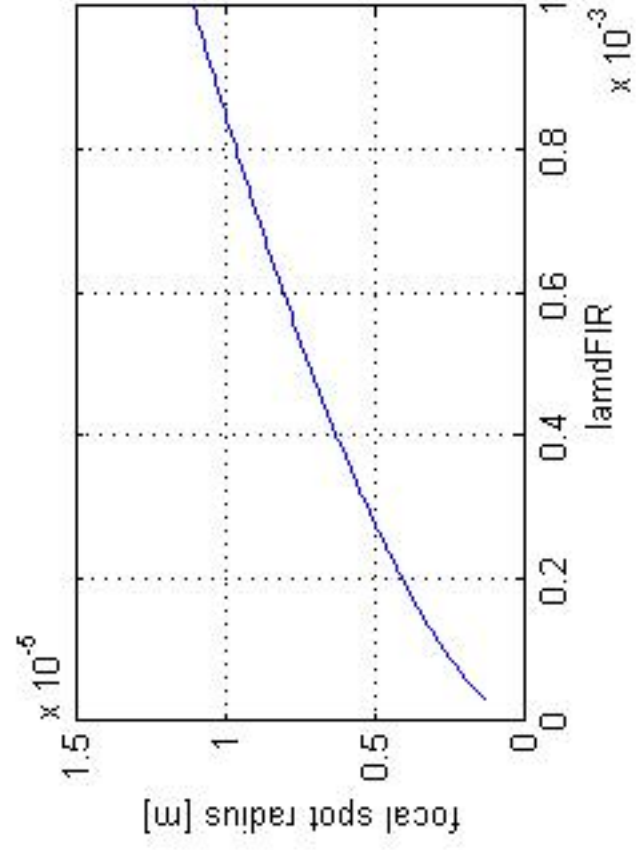
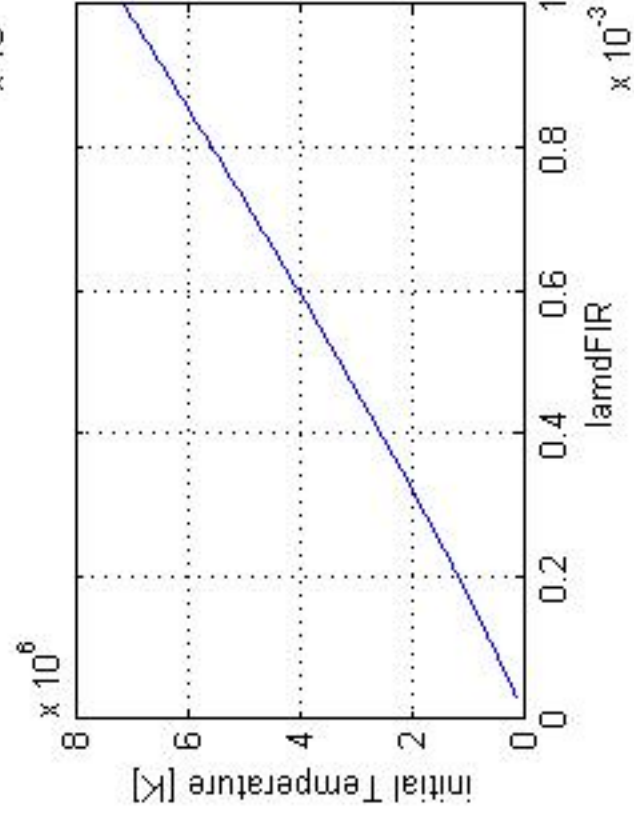
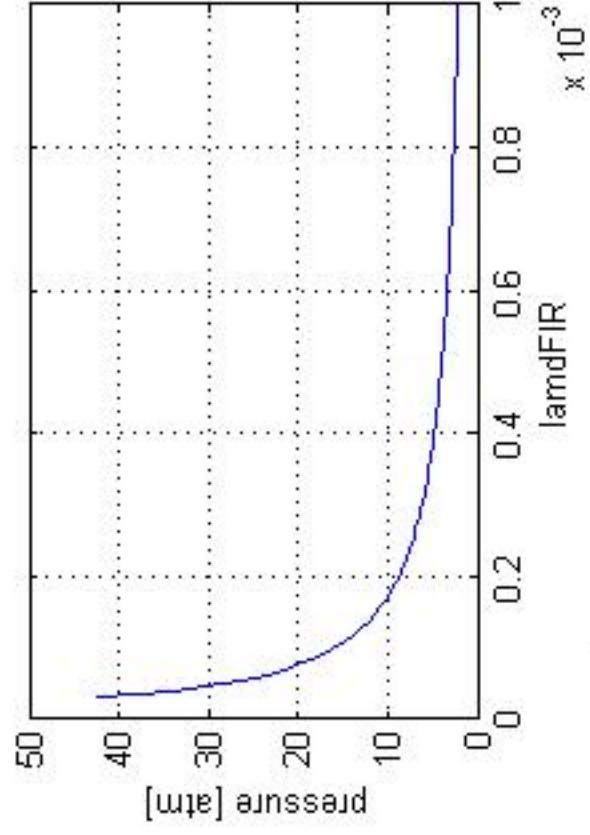
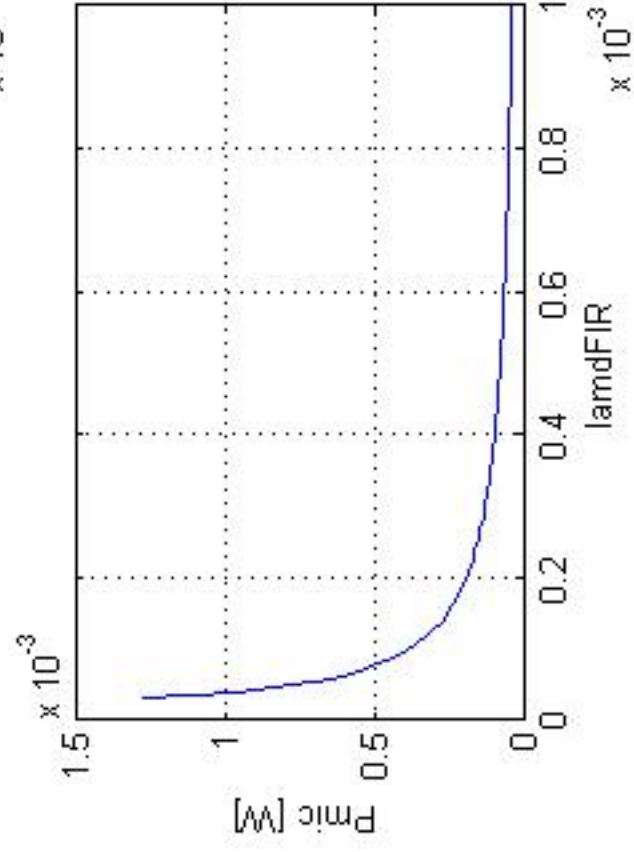
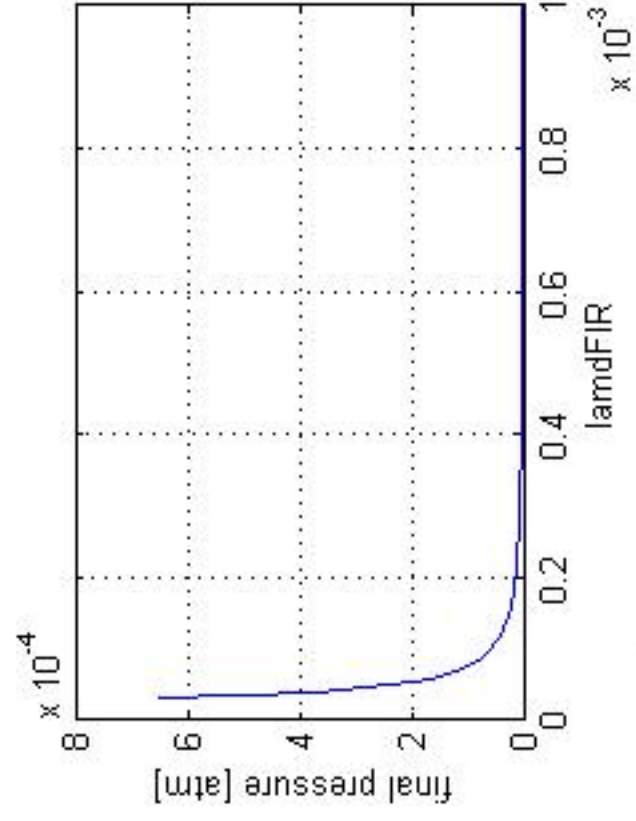


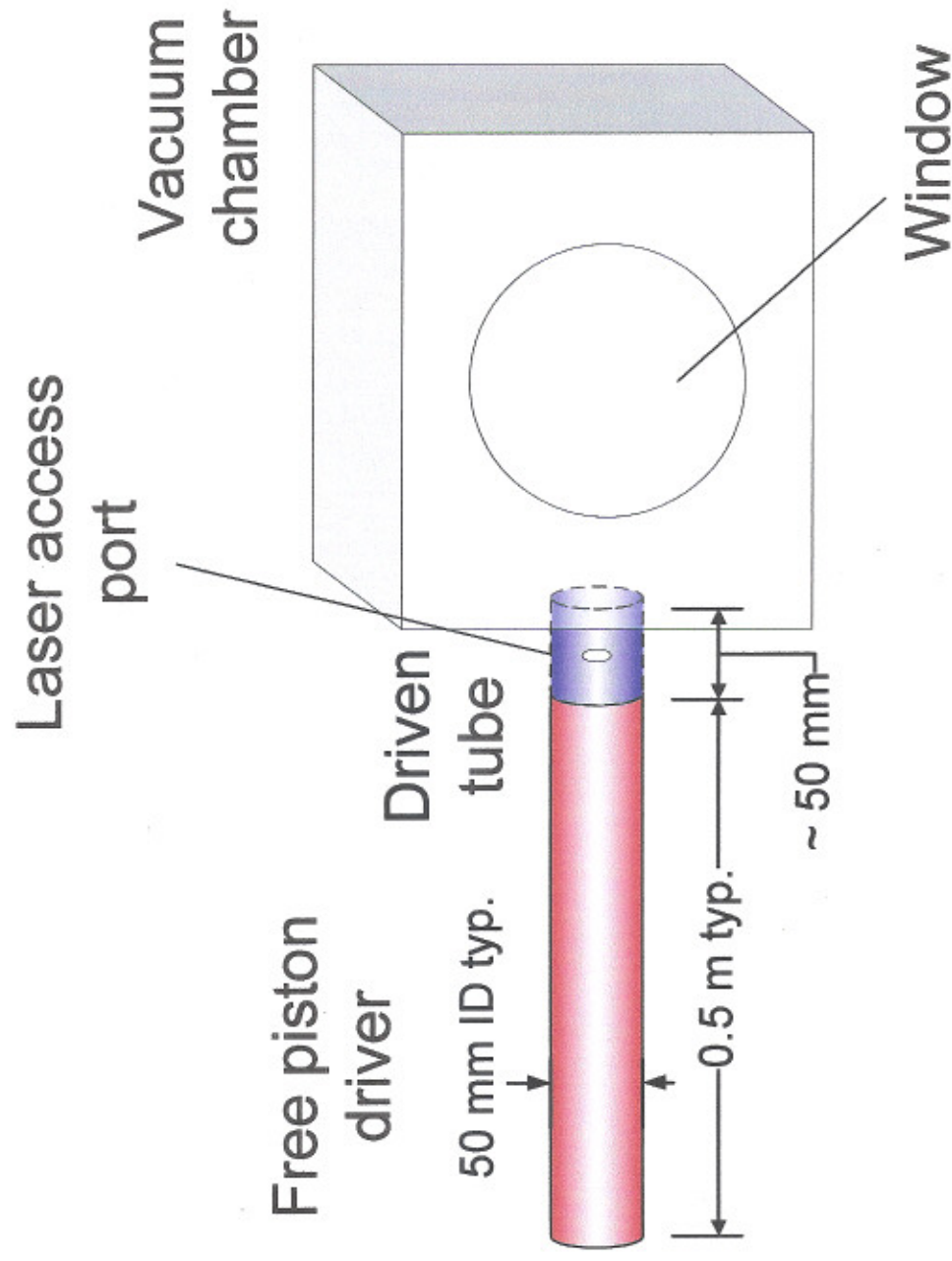
Fig. 13







# Facility Schematic



- Gas separated from vacuum by diaphragm (not indicated)
- Diaphragm is ruptured by high pressure from compression by free piston driver