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Radiative Cooling and Collapse in the Plasma Focus

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Abstract

- Radiative collapse in PF Pinch-potential of creating extreme HED (High Energy Density).
- Pease-Braginskii current : hydrogen pinch: bremsstrahlung balances Joule heating; - 1.4 MA
- For gases undergoing line-radiation, threshold current greatly lowered - because $P_{line} >> P_{brems}$
- For radiative collapse, additional condition: characteristic depletion time t_{dep} of pinch energy E_p by radiation should be of the order of the pinch time t_p.
- In a PF in D_2 & He, $t_{dep} >> t_p$. Hence no radiative collapse-even for multi-MA pinch.
- For INTI PF in Ne, a few % of E_p is radiated within t_p, hence only small effect.
- In Ar $t_{dep} \sim t$; in Kr and Xe, $t_{dep} << t_p$ - expect strong radiative collapse
- Numerical experiments are performed: our code incorporates radiation-coupled dynamics , PF pinch-elongation and plasma self-absorption. The latter limits the radiated power and eventually stops the radiative collapse.
- Current waveforms in various gases are measured in INTI PF. For each measured waveform the computed current waveform is fitted to the measured.
- Resultant dynamics are computed; confirm the expectations arising from t_{dep} discussed above.
- Example of Kr at 0.5 Torr is discussed in detail.
  - -shows radiative collapse to a minimum radius ratio of 0.0014.
  - -ion density reached 3.7×10^{26} m^{-3};
  - -immense burst of radiation is emitted with peak power of TW (10^{12} W), radiating 30 J in 50 ps, during time of peak radiative compression.

Pease-Braginskii Current

- For H_2 pinch, only bremsstrahlung is emitted
- Balance P_{brems} with P_J; I_{P-B}=1.4 MA

Reduced Pease-Braginskii Current

For gases not fully ionized. P_{line}>>P_{brem}; $I_{P\text{-}B}$ is reduced to $I_{P\text{-}Breduced}$

$$I_{\text{P-Breduced}}{}^{2} = I_{\text{P-B}}{}^{2} \times \frac{1}{K} \times Z'$$

where Z' = (¼) $\frac{(1+Z_{eff})^2}{Z_{eff}^2}$ and $K = \left[\frac{(dQ_{line}/dt)+(dQ_{Brem}/dt)}{(dQ_{Brem}/dt)}\right]$

- For He the factor Z'=0.56. This factor reduces the P-B current to 1.2 MA; we assume that He is completely ionised with insignificant line radiation so that K=1.

- It is obvious that for INTI PF we are not able to attain the $I_{P\text{-}B}$ for D_2 or the $I_{P\text{-}Breduced}$ for He.

- When line radiation becomes dominant the calculation of K is complicated by the dependence of P_{line} on density and temperature; so that there is no one value for $I_{P\text{-}Breduced}$.
- So I is to certain extent dependant on the PF and the operation point of that PF.

High-Z gases in INTI PF

For INTI PF, we take possible points of operation for Ne, Ar, Kr and Xe. Estimate typical values of $I_{P\text{-}Breduced}$ for these gases in Table I.

- For example: Ne - Typical point of operation for intense line radiation: - $Z_{eff} \sim 8.5$ so that $Z' \sim 0.31$.
  - P_{line} is 136 P_{brem}; so $I_{P\text{-}Breduced} \sim 76$ kA.

- It is emphasised that when higher-Z gases are considered with line radiation in factor K, then there is no one value for the $I_{P\text{-}Breduced}$.

- Table I gives indicative values of $I_{P\text{-}Breduced}$: trend: as Z-number increases, a lower value of $I_{P\text{-}Breduced}$ is expected.

$I_{P\text{-Breduced}}$ in INTI PF

Table I Reduced Pease-Braginskii current for various gases; typical INTI PF operating conditions.

Gases	P_0 (Torr)	$I_{P\text{-Breduced}}$ (kA)	T (10^6 K)
D2	NA	NA	NA
He	NA	NA	NA
Ne	**1.2**	**76**	**3.5**
Ar	**0.17**	**47**	**5.8**
Kr	**0.025**	**23**	**5.6**
Xe	**0.007**	**15.4**	**7.5**

NA=Not Applicable

Note: Indicative only

- We note that in deriving Table I the radiation powers are considered at source. The derived $I_{\text{P-Breduced}}$ is indicative of the situation when the plasma is assumed to be completely transparent to the radiation. Inclusion of plasma opacity will reduce the effect of the emission.

Additional Condition for Radiative Collapse

- Fulfilling the P-B current is not enough for radiative collapse to occur
- Radiation power must be sufficient so that in the pinch time t_p, enough energy is radiated away to affect the dynamics [ref: Conditions for Radiative Cooling and Collapse in the Plasma Focus Illustrated with Numerical Experiments on the PF1000-S Lee, S H Saw, M Akel, J Ali, H-J Kunze, P Kubes, M Paduch- submitted to IEEE TPS (2015)]

Characteristic Depletion Time of Pinch Energy by Radiation

- We define a characteristic time to deplete the pinch energy by radiation as follows:

$$t_{rad} = E_{pinch} / P_{radiation}$$

Condition for Radiative Collapse

- If $t_{rad} >> t_p$: no radiative effects on dynamics
- If $t_{rad} << t_p$: radiation greatly affects dynamics
  - radiative collapse
- If $t_{rad} \sim t_p$: radiation affects dynamics

Pinch Energy

- $E_{pinch} = [kT/(\gamma-1)]\, n_i(1+Z_{eff})\, p r_p^2 z_p$

where γ is the specific heat ratio

which may be written in terms of the degree of freedom f as $\gamma = (2+f)/f$; so that $1/(\gamma-1) = f/2$.

Characteristic Depletion Time by Bremsstrahlung

Dividing E_p by P_{brem} gives:

$$t_{brem} = (kb^{1/2}/C_1)\,[I/(n_0^{3/2} f_n^{3/2} r_p)]\,(1+Z_{eff})^{1/2}/[Z_{eff}^3\,(\gamma-1)]$$

where $b = 1.15\times10^{15}$.

PF in D_2 cannot fulfil Depletion Time even with multi-MA Pinch Current

- Estimate t_{brem} at pinch current higher than $I_{P\text{-}B}$ for D_2

  $I = 2.1\times10^6$ at 3 Torr; $n_0 = 10^{23}$, $a = 0.2$, $r_p = 3\times10^{-2}$, $f_m = 0.2$, $f_g = 1/3$, so that $f_n \sim 3$; $\gamma = 5/3$ and $Z_{eff} = 1$.

- Then $t_{brem} \sim 1\times10^{-3}$ s. It would take 10^{-3} s to radiate away all the pinch thermal energy. Even to radiate away 10% would take 100 μs. The lifetime of such a PF pinch (anode radius of 20 cm) may typically be estimated as 0.2 μs

- Thus in the lifetime of such a plasma focus it is unlikely that the radiation would affect the dynamics.

- Careful examination of a large range of numerical experiments extending to even 10 MA shows no sign of radiative cooling in D_2.

Characteristic Depletion Time by Line Radiation

- $t_{line} = (kb^2/C_2)\ I^4/[(n_0{}^3 f_n{}^3 r_p{}^4)\ (1+Z_{eff})\ Z_{eff}\ Z_n{}^4\ (\gamma-1)]$

- Line radiation power >> bremsstrahlung power
- So the radiation is controlled by line radiation and the relevant characteristic depletion time is t_{line} .

Table II Depletion times in D_2, He, Ne, Ar, Kr and Xe for various conditions (Ab=absorption correction factor at peak emission, Ab=1. no absorption) NA= not applicable, the depletion times are infinity)

Gas	a (cm)	Vo (kV)	Po (Torr)	I_{pinch} (kA)	Ab	Z_{eff}	SHR	t_Q (ns)	$t_Q{}^*$ (t_{pinch})
D	0.95	12	4	100	1	1	1.67	NA	NA
He	0.95	12	4	100	1	2	1.64	NA	NA
Ne	0.95	12	2.5	79	0.72	8	1.35	700	70
Ar	0.95	12	1.1	84	0.30	16	1.33	30	3
Kr	0.95	12	0.47	87	0.13	23	1.4	0.7	.07
Xe	0.95	12	0.25	92	0.16	30	1.43	0.15	0.015

Depletion Times in INTI PF

- In Table II we calculated depletion times t_Q and t_Q^* expressed in units of a characteristic pinch time t_{pinch}.
- The pinch time as proportional to anode radius with a figure of 10 ns per cm (rounding τ_{pinch} to 10 ns).
- From Table II it may be surmised that in Ne with less than 2% of pinch energy radiated away within one τ_{pinch}, radiative cooling should be hardly apparent leading to at most a small reduction in minimum radius ratio.
- In Ar, Kr and Xe one would expect strong radiative collapse.

Note: These numbers are only a rough guide since the pinch system is non-static and the various properties are interacting continuously.

Example: INTI PF in Kr 0.5 Torr

Lo nH	Co uF	b cm	a cm	zo cm	Ro mΩ
124	30	3.2	0.95	16	13

massf	currf	massfr	currfr
0.0434	0.7	0.11	0.7

Vo kV	Po Torr	MW	A	At-1 mol-2
12	0.5	84	36	1

Current fitting for 0.5 Torr Kr

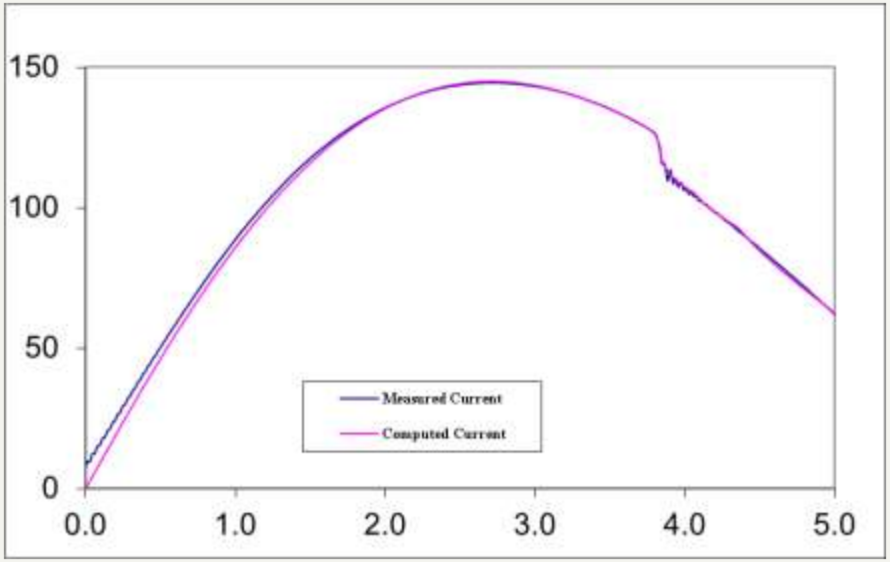


Fig 1. Fitting the computed current trace to the measured current trace of INTI PF at 12 kV 0.5 Torr Kr (shot 631).

Computed Radial Trajectory showing Radiative Collapse

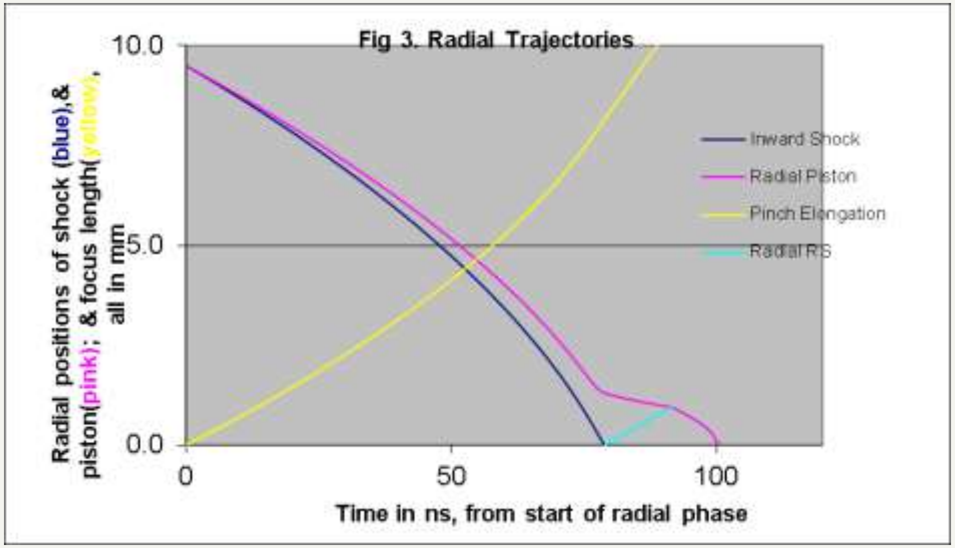
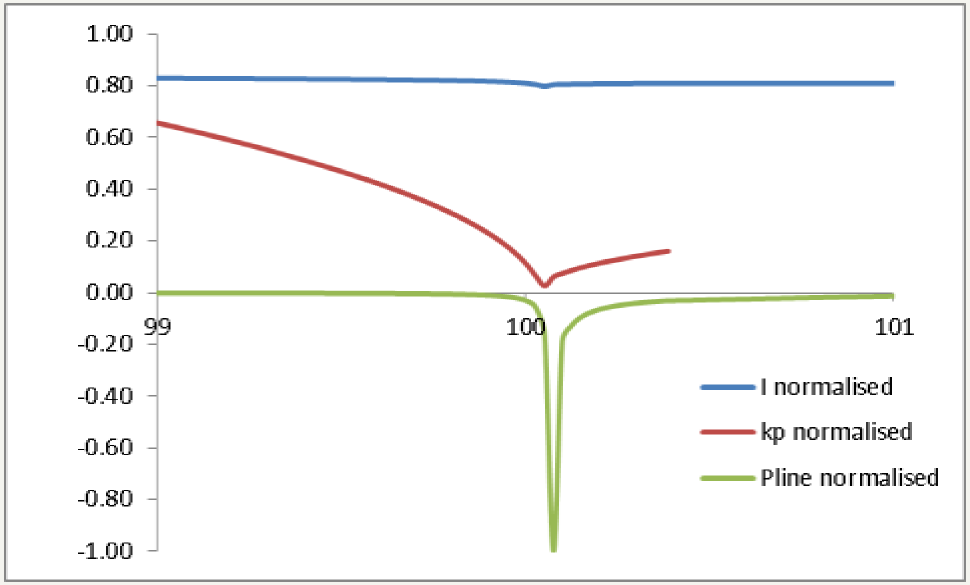


Fig 2 shows the radial trajectory corresponding to the fitting of the current waveform of Fig 1 for INTI PF 12 kV, 0.5 Torr Kr.

Correlating Radiative Collapse with Line Radiation Power Normalisation: I: 145 kA, kp: 0.05, P_{line}: 3.7 TW



Correlating RC Trajectory with P_{line}

- The peak compression region is magnified - Fig 3.
- The pinch compresses to a radius of 0.0013 cm; kp = 0.0014.
- The radiative collapse is ended when plasma self-absorption attenuates the intense line radiation.
- The rebound of the pinch radius is also evident in Fig 3.
- Shows the effect of the radiation on the compression.
- This intense compression, reaches 3.7×10^{26} ions m^{-3}, which is 15 times atmospheric density (starting from less than 1/1000 of an atmospheric pressure).
- Energy pumped into the pinch is 250 J whilst 41 J are radiated away in several ns,
- Most of the radiation occurring in a tremendous burst of 50 ps at peak compression
- Peak radiation power:- almost 4×10^{12} W.
- The energy density at peak compression is 4×10^{13} J m^{-3} or 40 kJ mm^{-3}.
- Thus even in this small plasma focus intense HED is achieved with immense radiation power.

Conclusion 1/2

- Presented indicative values of the reduced P-B currents for various gases from Ne to Xe for typical operations in INTI PF.

- Defined characteristic depletion of pinch energy by radiation as an additional condition for radiative collapse.

- Estimated depletion times in various gases.

- Indicated D_2 and He will not show radiative collapse even in multi-MA PF's.

- Indicated that in INTI PF, Ne will show small radiation cooling effects; Ar, Kr and Xe will have severe radiative collapse.

- Numerical experiments demonstrate substantial moderating effects of self-absorption and confirm the indications of these two Tables.

Conclusion 2/2

- **Presented example of Kr operation at 0.5 Torr, 12 kV is presented.**

- **Radial trajectory shows radiative collapse to 0.0013 cm for:**

  - Minimum radius ratio of 0.0014

  - Ion density reached 3.7 x10^{26} m^{-3};

  - An immense burst of radiation with peak power of 10^{12} W radiating 30 J in 50 ps, during time of peak radiative compression.

Concluding Note

Code assumes that the pinch is compressed as a column. Breakup of the column into a line of spots have been observed particularly, but not exclusively in the heavier gases.

- Such break-ups may lead to localized enhanced compression; easier for radiative collapse to occur; smaller final radius may be observed.
- Emission of ion and e- beams even partially within the pinch time could also lead to beam-enhanced radiative collapse, and smaller final radius.

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