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ORIGINAL RESEARCH

Measurement of Radiative Collapse in 2.2 kJ PF: Achieving High Energy Density (HED) Conditions in a Small Plasma Focus

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Abstract Radiative collapse in the plasma focus (PF) pinch creates extreme high energy density (HED) in the laboratory. The Pease–Braginskii current is that current flowing in a hydrogen pinch which is just large enough for bremsstrahlung to balance Joule heating; this threshold value being 1.4 MA. For high-Z gases undergoing strong line-radiation the radiation-cooled threshold current is considerably lowered. Recent work applied to a MJ PF has revealed that even if a threshold current is exceeded there is a condition that the characteristic depletion time of the pinch energy by radiation should be of the order of the pinch time in order for strong radiative collapse to be observed, thus explaining why no radiative collapse may be expected in deuterium; and also in helium; even in multi-MA PF devices. This paper extends the computation of depletion times to a kJ PF, the INTI PF showing that in the INTI PF only a small reduction in radius ratio may be anticipated in Ne whilst in Ar, Kr and Xe strong radiative collapse is expected. Two useful Tables are obtained applicable to kJ PF devices, one of reduced Pease–Braginskii currents in various high-Z gases and the other of corresponding characteristic depletion times. Two earlier papers using the Lee code had already demonstrated that radiative collapse occurs in plasma focus operated in high-Z gases. However in those papers computation could only be carried out up to a cut-off radius set at 0.01 of anode radius. Thus as shown in this paper most of the radiative compression was not computed or measured. This paper reports the measurement of the pinch trajectory in Kr by the fitting of a measured current waveform using the code with the cut-off radius successfully removed, so that the fitting fully follows the compression to its minimum radius and beyond to the rebound of the trajectory. The measured current waveform shows radiative collapse to a minimum radius ratio of 0.0014 or 0.0013 cm. Ion density reached $3.7 \times 10^{26}\ \mathrm{m^{-3}}$; and an immense burst of radiation is emitted with peak power of 10^{12} W, radiating 30 J in 50 ps, during the time of peak radiative compression. The energy density at peak compression is $4 \times 10^{13}\ \mathrm{J\ m^{-3}}$ or $40\ \mathrm{kJ\ mm^{-3}}$. This is the first time such a measurement has been made; and indicates that even in a kJ plasma focus, such a HED state is achieved.

Keywords Plasma focus numerical experiments · Radiation cooling · Radiation collapse · Plasma focus radiation enhancement · Plasma focus HED

Introduction

In a Z-pinch compressed by large electric currents to high densities and temperatures [1–5] equilibrium state may be envisaged when the plasma kinetic pressure rises to balance the compressing magnetic pressure, resulting in the pinch achieving an equilibrium pinch radius. This is the pressure balance basis of the Bennett equation [2]. When Joule heating and radiation emission are considered, these will modify pinch dynamics and pinch configuration. Joule heating will increase internal energy requiring a bigger equilibrium pinch radius whilst radiation emission will

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oppose this trend. The power of emitted radiation may exceed that liberated by Joule heating. In such a situation the magnetic pressure associated with the electric current continues to exert a radially inward squeezing (pinching) force; but the kinetic (resisting) pressure drops due to the excess radiation power (emitted radiation power minus the Joule power gain). This radiation cooling effect, if sufficient, will lead to a sharp enhancement of compression to very small radius, which could be far smaller than envisaged in the case of the electromagnetic pinch.

In the case of a hydrogen pinch, the plasma is typically far above fully-ionized temperature and the dominant radiation is free–free bremsstrahlung. The bremsstrahlung power P_{brem} is proportional to $T^{1/2}$ whilst plasma resistive heating P_{joule} is proportional to $T^{-3/2}$. Thus as pinch current is increased and pinch temperature rises, there comes a point when P_{brem} exceeds P_{joule}. Pease [6] and Braginskii [7] separately showed that in hydrogen this point may be defined by a critical pinch current referred to as $I_{P\text{–}B}$ of 1.4 MA. In such a pinch at equilibrium when pinch current is raised above 1.4 MA, radiation collapse may occur.

As the compressed density increases and temperature drops due to emitted radiation, plasma self-absorption [8, 9] sets in limiting the emission of radiation. Radiation collapse will stop. This mechanism will place a lower limit on the radius of the pinch.

For the case of high-Z gases such as Ne, Ar, Kr and Xe, at the typical temperatures encountered in Z-pinches the dominant radiation emitted is line radiation, with radiating powers typically several orders of magnitude of P_{brem}. Analysis [10–12] shows that it is thus easier to achieve radiative collapse in high-Z gases when compared to the case of H.

However the critical current is only one condition for the occurrence of radiative collapse. Another condition would be the magnitude of the excess radiative power dQ/dt (which we call Qdot, where Q = total energy radiated out of the pinch plasma less Joule heat released in the pinch plasma) acting to reduce the energy in the pinch E_{pinch}. A characteristic radiative time (characteristic time of depletion of pinch energy by radiation) has been defined [13] as $t_{rad} \sim E_{pinch}/\text{Qdot}$ which is the time required for all the pinch energy to be radiated away at the rate Qdot. Robson [8] considered this situation for the case of the hydrogen and helium Z-pinch including the effects of opacity.

In this paper we consider radiative cooling and collapse in a kJ plasma focus (PF) for a range of gases [11, 12] using the Lee code [14, 15]. The code couples the actual electrical circuit with PF dynamics, thermodynamics and radiation. It is energy-, charge- and mass-consistent. It was first used in the design and interpretation of experiments [15–17]. An improved 5-phase code [15] incorporating finite small disturbance speed [18], radiation and radiation-coupled dynamics was used [19–21]. Plasma self-absorption was included [14, 15] in 2007. It has been used extensively as a complementary facility in several machines, for example: UNU/ICTP PFF [17, 20–22], NX2 [21, 23], NX1 [21], DENA [24]. It has been used for design and interpretation including sub-kJ PF machines [25], FNII [26], the UBA hard X-ray source [27], KSU PF [28] and a sequential plasma focus [29]. Information computed includes axial and radial dynamics [16, 19–22, 28–30], SXR emission characteristics and yield [20–23, 31–36] for various applications including as a source for microelectronics lithography [21], optimization of machines [15, 19–23, 31] and adaptation in the form of ML (Modified Lee) to Filippov-type PF devices [24]. Speed-enhanced PF [19] was demonstrated. Plasma focus neutron yield calculations [37, 38], current and neutron yield limitations [39, 40], deterioration of neutron scaling (neutron saturation) [41, 42], radiative collapse [11–13], current-stepped PF [43], extraction of diagnostic data [36, 44–48] and anomalous resistance data [49–51] from current signals have been studied using the code [14, 15] or variants. Radiation and particle yields scaling laws [33, 35, 37, 41, 42, 52–57] have been deduced including those of ion beams [52, 53].

Incorporated into the code since 2007, the radiation-coupled equation of motion of the current sheath provides the mechanism of radiative collapse whilst plasma self-absorption is computed giving the code the mechanism for limiting the collapse. Using this code the case of radiation collapse had been demonstrated in Kr [11] and extended to Ar and Xe [12]. However in those two papers, the computation was terminated when the pinch radius reached 0.01 of the anode radius; thus missing out on 90 % of the radiative collapse as was realized when the cut-off limit was successfully removed in this paper. We are thus able to measure the full extent of the radiative compression in the final part of this paper.

In the 2013 paper [11] Lee et al. had already demonstrated that the radiation-coupled piston equation of the code produced the correct Pease–Braginskii current of 1.6 MA for deuterium PF pinch. They also showed that in higher-Z gases, there is a reduction in the Pease–Braginskii current due to two mechanisms, one related to the charge number (the charge factor) and the other due to the predominant line radiation in high-Z gases, which are not fully-ionized in the PF pinch. According to these calculations for He the reduced P–B current ($I_{P\text{-}Breduced}$) is 1.2 MA considering only the charge factor; though there may be a further reduction due to line radiation. However running the code for PF1000 [58] at a hypothetical 100 kV when the pinch current exceeds 2 MA, there is no sign of a sharp drop in pinch radius ratio which is the most indicative sign of radiative collapse [13]. To explain this, an expression was developed for the characteristic time required to radiate away all the pinch energy through bremsstrahlung and through line radiation [13]. The numerical experiments show that for a MJ PF the pinch duration has to be of the order (typically at least 0.1) of the characteristic time of radiation (t_{rad}) in order for that radiation to cause significant radiative cooling resulting in radiative collapse. In this paper we apply the calculations to the 2.2 kJ INTI PF, to demonstrate that in a kJ PF the concept of characteristic time of radiation also shows strong radiative contraction in the case of the gases with $Z_n > 10$.

The Radiation-Coupled Dynamics for the Magnetic Piston

The code uses the following equation for the piston position r_p [11–13] derived from the first law of thermodynamics:

$$\frac{dr_p}{dt} = \frac{\frac{-r_p dI}{\gamma I dt} - \frac{1 r_p dz_f}{(\gamma+1) z_f dt} + \frac{4\pi(\gamma-1)}{\mu\gamma z_f}\frac{r_p dQ}{f_c^2 I^2 dt}}{\frac{\gamma-1}{\gamma}} \tag{1}$$

where I is the total discharge current in the circuit, f_c is the fraction of current flowing into the pinch, z_f is the time-varying length of the PF pinch and γ is the specific heat ratio (SHR) of the plasma. When dQ/dt is negative, energy is lost from the plasma adding a negative component to dr_p/dt which tends to reduce the radius r_p.

The Reduced Pease–Braginskii Current

Following Lee et al. [11] we write the reduced P–B current $I_{\text{P-Breduced}}$ as:

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

$$\text{where } Z' = (1/4)\frac{(1+Z_{\text{eff}})^2}{Z^2_{\text{eff}}} \text{ and } K = \left[\frac{(dQ_{line}/dt) + (dQ_{Brem}/dt)}{(dQ_{Brem}/dt)}\right] \tag{3}$$

We consider the following powers (all quantities in SI units unless otherwise stated): respectively Joule heating, bremsstrahlung and line radiation generated in a plasma column of radius r_p, length z_p at temperature T:

$$P_J = C_J T^{-3/2}\frac{z_p}{\pi r_p^2} Z_{eff} I^2, \tag{4}$$

$$P_{brem} = C_1 T^{1/2} n_i^2 Z_{eff}^3 \pi r_p^2 z_p, \tag{5}$$

$$P_{line} = C_2 T^{-1} n_i^2 Z_n^4 Z_{eff} \pi r_p^2 z_p, \tag{6}$$

where $C_J \cong 1300$, $C_1 = 1.6 \times 10^{-40}$ and $C_2 = 4.6 \times 10^{-31}$.

For He the factor $Z' = 0.56$. This factor alone reduces the P–B current to 1.2 MA, even if 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 $I_{\text{P–B}}$ for D or the $I_{\text{P-Breduced}}$ for He.

We take some possible points of operation for the gases Ne, Ar, Kr and Xe and estimate typical values of $I_{\text{P-Breduced}}$ for these gases in Table 1. It is emphasised that unlike the value for H or D which is derived by balancing P_J and P_{brem} resulting in a value dependant only on the pinch current, when higher-Z gases are considered with line radiation that needs to be included in the factor K, then there is no one value for the $I_{\text{P-Breduced}}$. Table 1 thus gives only indicative values of $I_{\text{P-Breduced}}$ with the trend that as the Z-number increases, a lower value of $I_{\text{P-Breduced}}$ may be expected.

We note that in deriving Table 1 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. Table 1 gives a useful indication of required currents but these values need to be tested by a code which includes plasma self-absorption.

Characteristic Times of Radiation

Following Lee et al. [13] the thermal energy in the pinch is the total number of particles in the pinch multiplied by the thermal energy per particle:

$$E_{\text{pinch}} = [kT/(\gamma - 1)] n_i (1 + Z_{\text{eff}}) \pi r_p^2 z_p, \tag{7}$$

where γ is the specific heat ratio.

The pinch energy divided by the radiation power gives us a measure of the characteristic time it would take the pinch to have its energy radiated away by that radiation power taken as constant over the whole duration. This is termed [13] the characteristic depletion time of radiation.

Table 1 Reduced Pease–Braginskii current for various gases; typical INTI PF operating conditions

Gases	P_0 (Torr)	$I_{\text{P-Breduced}}$ (kA)	T (10^6 K)
D	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; unable to achieve P–B condition

Characteristic Depletion Time for Bremsstrahlung

The characteristic depletion time of pinch energy by bremsstrahlung is [13]:

$$t_{brem} = \left(kb^{1/2}/C_1\right)\left[I/\left(n_0^{3/2}f_n^{3/2}r_p\right)\right](1+Z_{eff})^{1/2} \\ /\left[Z_{eff}^3(\gamma-1)\right]. \tag{8}$$

For INTI PF, since we are unable to reach the P–B condition for D and He, the depletion time is effectively infinity and INTI PF pinch will not satisfy the depletion condition. For gases with Z higher than He, line radiation typically dominates.

Characteristic Depletion Time for Line Radiation

Following Lee et al. [13]:

$$t_{line} = (kb^2/C_2)I^4/\left[\left(n_0^3f_n^3r_p^4\right)(1+Z_{eff})Z_{eff}Z_n^4(\gamma-1)\right]. \tag{9}$$

However whilst radiation depletes, Joule heating will replenish the plasma thermal energy. So we need to factor in both radiation and Joule heating to obtain the net depletion time.

Characteristic Depletion Time t_Q

The net depletion time t_Q may be computed where t_Q is the ratio E_{pinch}/Qdot where Qdot or $dQ/dt = P_{line} + P_{brem} - P_J$. In Table 2 we show sample computations of depletion times in Ne, Ar, Kr and Xe for some conditions shown to be practicable operation for the INTI PF.

In Table 2 we show also t_Q* which is t_Q expressed in units of a characteristic pinch time τ_{pinch}. We took the pinch time as proportional to anode radius [59] with a figure of 10 ns per cm (rounding τ_{pinch} to 10 ns). From Table 2 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. Whilst Table 2 gives a useful guide to the radiative collapse propensity of the kJ PF in various gases, these numbers act only as a rough guide since the pinch system is non-static and the various properties are interacting continuously. A code which incorporates the necessary interactive mechanisms and follows the collapse process will produce a more accurate picture to test the numbers depicted in Table 2.

In the next part of this paper a test is provided for the case of Kr with a measurement of radiative contraction in INTI PF from a measured current trace. Earlier work with the code demonstrated radiative collapse but was limited by a cut-off of 0.01 anode radius [11, 12]. The measurement shown below uses the code with no cut-off, hence for the first time computes the full extent of the collapse. From this measurement we also deduce the high energy density HED conditions that can be achieved even in a kJ device like the INTI PF.

Numerical Experiments on INTIPF: Results and Discussion

Fitting for Model Parameters

We have a recent measured current waveform for the INTI PF operated at 12 kV 0.5 Torr Kr (Shot 631). We fitted the current waveform using Lee 6-phase radiative code (Figs. 1, 2):

Bank parameters: $L_0 = 124$ nH (fitted), $C_0 = 30\mu F$, $r_0 = 13$ mΩ (fitted),
Tube parameters: $b = 3.4$ cm, $a = 0.95$ cm, $z_0 = 16$ cm,
Operating parameters: $V_0 = 12$ kV, $P_0 = 0.5$ Torr and gas parameters (for Kr) are 84 (molecular weight), 36 (atomic number), and 1 (for atomic gas).
Fitted model parameters: $f_m = 0.0434$, $f_{mr} = 0.11$ and $f_c = f_{cr} = 0.7$

And fitted anomalous resistance parameters as follows:

	Ran 1	Ran 2	Ran 3
R_0 (Ω)	0.20	0.10	0.08
τ_2 (ns)	80.0	100.0	280.0
τ_1 (ns)	5.0	8.0	10.0
End time	2.80	0.10	3.50

Table 2 Depletion times in Ne, Ar, Kr and Xe for various conditions (Ab = absorption correction factor at peak emission)

Gas	a (cm)	Vo (kV)	Po (Torr)	I_{pinch} (kA)	Ab	Z_{eff}	SHR	t_Q (ns)	t_Q* (τ_{pinch})
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	1.40	0.7	0.07
Xe	0.95	12	0.25	92	0.16	30	1.43	0.15	0.015

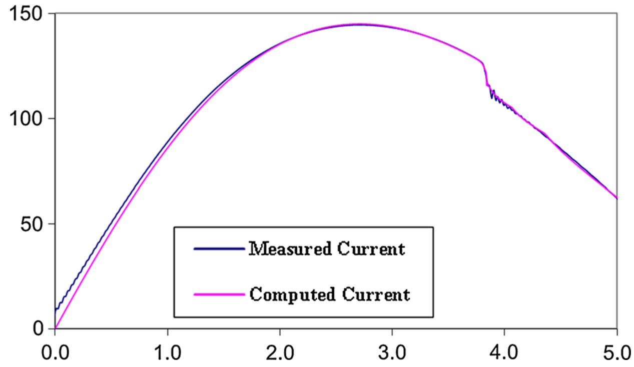

Fig. 1 Fitting the computed current trace to the measured current trace of INTI PF at 12 kV 0.5 Torr Kr (shot 631) (Note the two curves have a close fit except after the bottom of the current dip. Fitting is done only up to the bottom of the dip, so any agreement or divergence of the computed and measured traces after the bottom of the dip has no significance.)

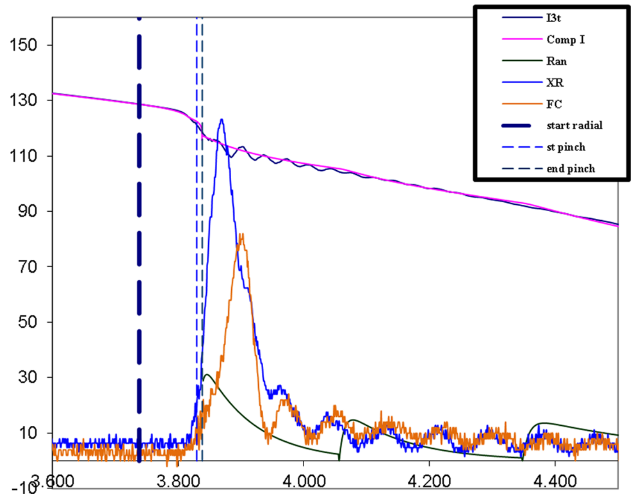

Fig. 2 Expanded view of the fitting with additional vertical lines indicating start of radial phase and start and end of pinch phase

Having fitted the computed current trace to the measured current trace, the resulting radial trajectory indicates strong radiative collapse, as shown in the following Fig. 3.

Figure 3 shows the radial trajectory corresponding to the fitting of the current waveform of Fig. 1 for INTI PF 12 kV, 0.5 Torr Kr.

The peak compression region is magnified and shown in the Fig. 4. In this figure the circuit current is replaced by the pinch current, normalized by 101.5 kA, the P_{line} is normalized by 3.7×10^{12} W and the radius ratio $k_p = r_p/a$ is multiplied by 20. The normalization of the various quantities is to enable the 3 curves to be presented well on the same chart. The pinch compresses to a radius of 0.0013 cm corresponding to a radius ratio (pinch radius normalized to anode radius) of 0.0014. The radiative collapse is ended when plasma self-absorption [9, 14, 15] attenuates the

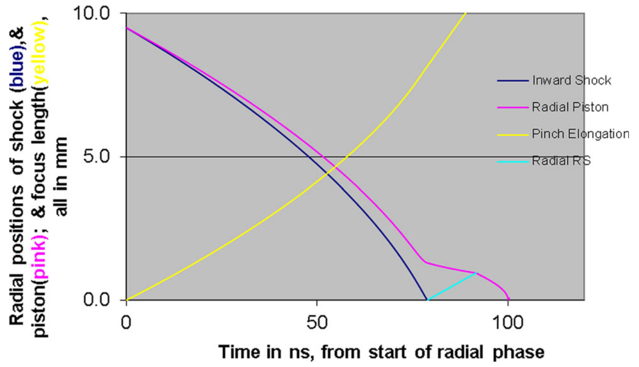

Fig. 3 Computed radial dynamics on INTI PF at 12 kV, 0.5 Torr Kr

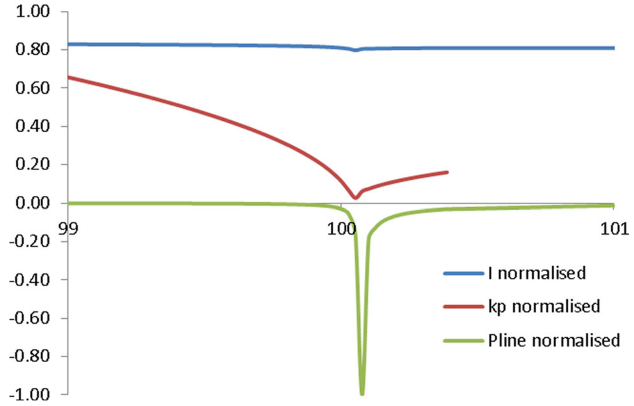

Fig. 4 Normalised pinch current, piston radius ratio and P_{line} at peak compression region

intense line radiation. The rebound of the pinch radius is also evident in Fig. 4. The line radiation power leaving the plasma is also plotted (in normalized unit) to show its correlation to the trajectory in order to show the effect of the radiation on the compression. This intense compression, despite the low mass swept in factor of $f_{mr} = 0.11$, reaches 3.7×10^{26} ions m^{-3}, which is 15 times atmospheric density (starting from less than 1/1000 of an atmospheric pressure). Moreover the energy pumped into the pinch is 11 % of stored capacitor energy being 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 with a peak radiation power of 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

In this paper we have derived a Table of indicative values of the reduced P–B currents for various gases from Ne to Xe for typical operations in a kJ PF such as the INTI PF.

We have also derived radiation levels from PF operations in these gases and from these we have obtained another Table with estimated characteristic depletion times of pinch energy due to radiation minus Joule heating. These depletion times indicate that Ne will show small radiation cooling effects; and that Ar, Kr and Xe will have severe radiative collapse in the INTI PF. These two Tables give valuable indicative values applicable to kJ PF's.

Finally a measurement of the current waveform in Kr at 0.5 Torr, 12 kV is presented. The computed current waveform is fitted to the measured current waveform and the resulting radial trajectory shows radiative collapse to 0.0013 cm for a minimum radius ratio of 0.0014. Ion density reached 3.7×10^{26} m^{-3}; and an immense burst of radiation is emitted with peak power of 10^{12} W, radiating away 30 J in 50 ps, during the time of peak radiative compression. Earlier use of the code had a cut-off radius imposed of 0.01 anode radius. Although compressing to 0.01 anode radius was sufficient to demonstrate radiative collapse the earlier demonstration missed most of the radiatively collapsed trajectory. Thus this paper gives the first measurement using a plasma focus current waveform of such a high HED state.

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