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Compression Mechanisms in The Plasma Focus Pinch

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Abstract. The compression of the plasma focus pinch is a dynamic process, governed by the electrodynamics of pinch elongation and opposed by the negative rate of change of current dI/dt associated with the current dip. The compressibility of the plasma is influenced by the thermodynamics primarily the specific heat ratio; with greater compressibility as the specific heat ratio γ reduces with increasing degree of freedom f of the plasma ensemble due to ionization energy for the higher Z (atomic number) gases. The most drastic compression occurs when the emitted radiation of a high-Z plasma dominates the dynamics leading in extreme cases to radiative collapse which is terminated only when the compressed density is sufficiently high for the inevitable self-absorption of radiation to occur. We discuss the central pinch equation which contains the basic electrodynamic terms with built-in thermodynamic factors and a dQ/dt term; with Q made up of a Joule heat component and absorption-corrected radiative terms. Deuterium is considered as a thermodynamic reference (fully ionized perfect gas with f = 3) as well as a zero-radiation reference (bremsstrahlung only; with radiation power negligible compared with electrodynamic power). Higher Z gases are then considered and regimes of thermodynamic enhancement of compression are systematically identified as are regimes of radiation-enhancement. The code which incorporates all these effects is used to compute pinch radius ratios in various gases as a measure of compression. Systematic numerical experiments reveal increasing severity in radiation-enhancement of compressions as atomic number increases. The work progresses towards a scaling law for radiative collapse and a generalized specific heat ratio incorporating radiation.

INTRODUCTION

The Lee Code [1,2] envisages the compression of the plasma focus in its pinch phase as an elongating pinch driven by an open-ended cylindrical magnetic piston (see Figure 1, right section). The radial trajectories of the three radial phases: the inward radial shock phase, the reflected shock RS phase and the radiative slow compression (pinch) phase are shown in radius-time coordinates in Figure 2.

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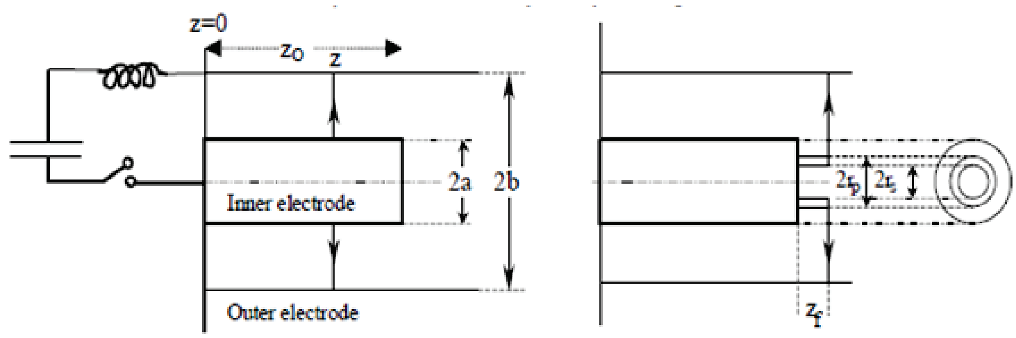

FIGURE 1. Schematic of the axial and radial phases. The left section depicts a snapshot of the axial phase, the right section a snapshot of the radial inward shock phase taken before the pinch phase. In the right section r_s is the position of the inward moving shock front driven by the piston at position r_p. Between r_s and r_p is the radially imploding slug, elongating with a length z_f. At later times the value of r_s decreases until the inward shock coalesces on-axis, at which time a reflected shock RS develops and moves outward. When the outward-moving RS hits the incoming r_p the pinch phase starts. The dynamics as a function of time is shown in Figure 2.

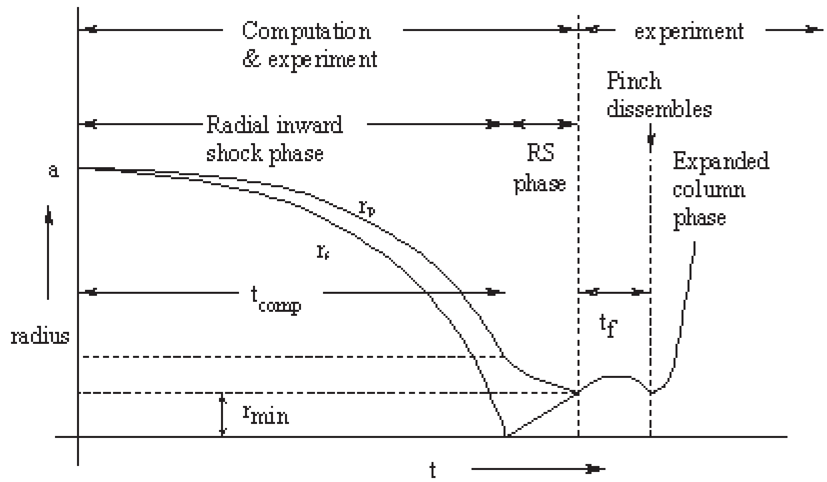

FIGURE 2. Schematic of radius vs time trajectories to illustrate the radial inward shock phase when r_s moves radially inwards, the reflected shock (RS) phase when the reflected shock moves radially outwards, until it hits the incoming piston r_p leading to the start of the pinch phase (t_f).

THE EQUATION OF MOTION

During the pinch phase, the equation describing the motion [1, 2] of the magnetic piston is:

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

The three terms affecting the value of compression speed dr_p/dt are:

dI/dt term: $-[(r_p/I)(1/(\gamma-1))][dI/dt]$
dz_f/dt term: $-[(r_p/z_f)(\gamma/(\gamma+1))(1/(\gamma-1))][dz_f/dt]$
dQ/dt term: $[(4\pi/\mu)(r_p/z_f)(1/(f_c^2 I^2))][dQ/dt]$

Electrodynamics

During the inward compression the value of compression speed dr_p/dt is negative. Note that positive values of dI/dt increases (inward) compression speed through the dI/dt term. Typically however during the inward compression phase the value of dI/dt term is negative due to energy being intensively extracted from the magnetic field to pump into the plasma. Hence during the compression phase, the negative value of dI/dt (current dip) makes the dI/dt term positive, thus opposing the compression.

For low radiation plasmas dQ/dt is negligible and it is the net value of the first two terms (the dI/dt and the dz_f/dt terms) which determines the compression. Since the current dips during the radial pinch compression phase, causing the dI/dt term to oppose the compression, it remains for the elongation of the pinch to provide the negative value of dr_p/dt needed for the inward compression. The net value of these first two terms is:

$$-(1/(\gamma-1))\ [(\gamma/(\gamma+1))(r_p/z_f)\ (dz_f/dt) + (r_p/I)\ (dI/dt)] \qquad (2)$$

Thermodynamics – The effect of the specific heat ratio γ:

Note that this net value is strongly dependent on γ due to the factor (1/(γ-1)) and the fact that the value of the specific heat ratio γ has a narrow range of effectively 1.0 to 1.667 (although 2.0 is the absolute limit for the case of a strongly magnetized fully ionized plasma constraint to only two degrees of freedom f = 2. The value of γ may be written as γ = (f+2)/f; where f=2/(γ-1) is the degree of freedom of the plasma ensemble [3].

We consider the case of D which is fully ionized in a plasma focus pinch with f effectively close to 3 giving a value of γ around 5/3. This factor (1/(γ-1)) has a value of 1.5.

Compare this to the case of Ne which is ionizing in a plasma focus pinch and at some pressure may have a value of γ of 1.3. This factor (1/(γ-1)) has a value of 3.3.

Thus this thermodynamic effect (i.e. value of γ) causes the value of dr_p/dt to increase by a factor of > 2 for the case of ionizing Ne when compared to that of fully ionized D in a plasma focus pinch.

Consider γ as an index of compressibility

If an ensemble of particles at temperature T has one degree of freedom (f = 1) then (1/2) kT of energy has to be provided per particle to raise its temperature by 1 degree K.

Thus if a gaseous ensemble has infinite degrees of freedom (i.e. f = infinity) then the gas will not heat up however much energy is provided. Such a gas is perfectly compressible; since it will not heat up and does not provide any opposing pressure to any compression forces.

Thus γ = (f+2)/f can be considered to be an index of compressibility.

If γ = 1, i.e. f = infinity, gas is perfectly compressible.

If γ = 2, i.e. f = 2 (minimum value of f is 2; corresponding to the case of a highly ionized gas in a strong magnetic B field) gas is least compressible. The relationship between γ and f is shown in Figure 3 illustrating the case of a freely ionizing plasma (the term freely ionizing implies the ionization is not approaching a closed shell situation).

We take the case of the ideal gas γ = 5/3, i.e. f = 3, as the reference case for compressibility. This is the case of deuterium which in the PF pinch has attained such high temperatures that it is fully ionized and behaves thermodynamically as a perfect gas with f=3.

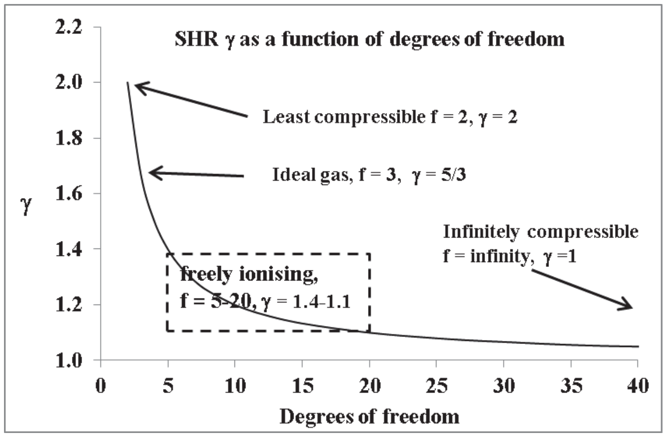

FIGURE 3. Regimes of compressibility showing the least compressible (f = 2, γ = 2), ideal reference compression (f = 3, γ = 3), freely ionizing regime, SHR due to thermodynamics (exclude radiation losses) (f = 4-20, γ = 1.4 – 1.1) and infinitely compressible (f = infinity, γ = 1)

In the case of a plasma undergoing ionization freely, energy has to be supplied to the ionization over and above that needed to be supplied to the translational degrees of freedom. The effective f is thus more than 3 and computations show that for the gases neon to xenon f ranges from around 5 to 20. We define a regime of freely ionizing plasma with SHR in the range of 1.4 to 1.1, where the SHR includes ionization energies. The conclusion is that in low-radiation situations where radiation is not affecting compressions, thermodynamic effects due to specific heat ratio can affect compressions significantly. In that context we may expect ionizing Ne to be compressed more than fully ionized D even when the neon plasma is not radiating significantly. We confirm this later in the paper with numerical experiments.

Radiation dynamics -High Radiation Plasmas

In respect of compressibility we may define a high-radiation plasma as one in which the net radiation dQ/dt affects the compression.

The effect of dQ/dt on compression may be assessed by comparing the value of
radiation power: $((4\pi/\gamma)/f_c^2)(r_p/z_f)(1/I^2)(dQ/dt)$
with dynamic power $-(1/(\gamma-1))\ [(\gamma/(\gamma+1))(r_p/z_f)\ (dz_f/dt) + (r_p/I)\ (dI/dt)]$
or equivalently compare energy depletion time with expected pinch lifetime [4].

Components of dQ/dt: These are calculated respectively as Joule heating, and from the bremsstrahlung and line radiation generated in a plasma column of radius r_p, length z_p at temperature T (SI units):

$$P_J = C_J T^{-3/2} \frac{z_p}{\pi r_\rho^2} Z_{eff} I^2 \quad (3)$$

$$P_{brem} = C_1 T^{1/2} n_i^2 Z_{eff}^3 \pi r_p^2 z_p \quad (4)$$

$$P_{line} = C_2 T^{-1} n_i^2 Z_n^4 Z_{eff} \pi r_p^2 z_p \quad (5)$$

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

We note that in the cases of D and He which are fully ionized at the temperature of typical plasma focus pinches, P_{line} is negligible and radiation power is predominantly P_{brem}. On the other hand for gases such as Ar, Kr and Xe, the plasmas are not fully ionized and radiation power is predominantly P_{line}. Moreover note that whereas P_{brem} depends on Z_{eff}^3, P_{line} depends on $Z_n^4 Z_{eff.}$ This difference alone gives Ne (with Z_{eff} = 9 typically in a plasma focus pinch) radiation power a factor of 9 x 10^4 when compared with the radiation power of D.

Calculation shows that for high-Z gases such as Ne and higher, P_{line} dominates radiation power. Net radiation power (i.e. attenuated by plasma self-absorption) is given a sign of negative in computing dQ/dt since the power is a loss from the plasma, whereas Joule heating is given a sign of positive as it adds power into the plasma. The value of dQ/dt is calculated from summing the Joule power term and the radiation terms (attenuated by plasma self-absorption).

A negative value of dQ/dt contributes to increasing the compression speed dr_p/dt. When this contribution is significant the compression is considered as radiation-enhanced, leading to radiative collapse when the dQ/dt term is dominant [5-7].

The equation of motion for the plasma focus pinch incorporating the electrodynamics, thermodynamics and radiation dynamics has already been discussed. In the Lee code this equation is coupled to the capacitor discharge circuit. The self-absorption by the plasma of its own radiation is also included; thus realistically limiting radiative collapse [1,2].

NUMERICAL EXPERIMENTS

We run numerical experiments in NX2 as a reference machine in various gases. We analyse the results to show the regimes of compression. The following configuration of NX2 is used.

TABLE 1. Configuration of NX2 for these numerical experiment (showing 10 Torr D)

Lo	Co	b	a	Zo	ro mOhm
15	**28**	**4.1**	**1.9**	**5**	**2.5**
massf	**currf**	**massfr**	**currfr**	**Model Parameters**	
0.1	**0.7**	**0.14**	**0.7**		
Vo	**Po**	**MW**	**A**	**At-1 mol-2**	Operational
14	**10**	**4**	**1**	**2**	Parameters

Deuterium

Typical operation: Plasma focus pinch temperature: <1-10 x10^6 K or <100 eV to 1 keV. In the deuterium PF pinch the plasma is fully ionized (see ionization curves in Figure 4); SHR=1.6667 effectively f = 3; radiation is bremsstrahlung, negligible compared to dynamic power.

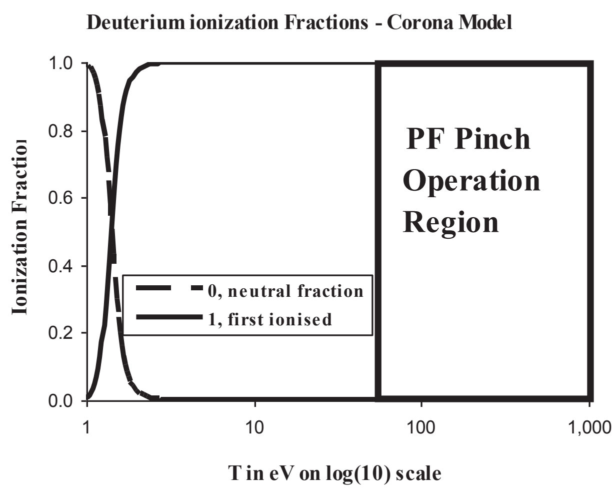

FIGURE 4. Deuterium ionization versus temperature showing typical PF pinch regime. Two traces from left to right represent 0, and 1st ionization fractions as temperature increases.

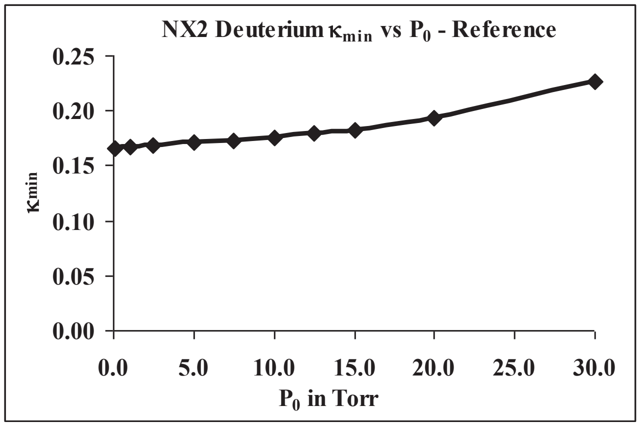

FIGURE 5. Deuterium minimum pinch radius ratio versus pressure - Reference compression, f = 3; negligible radiation

Compression of deuterium pinch is taken as reference with plasma f = 3, thermodynamically practically an ideal gas and with radiation (bremsstrahlung) power practically negligible compared to dynamic power. The minimum pinch radius ratio κ_{min} is just above 0.15 for NX2 (see Figure 5). We use the compression curve for deuterium for reference (no enhancement) when discussing thermodynamic- and radiative- enhancement in other gases.

Helium

The case of helium is similar to deuterium. In the PF temperature regime, helium is fully ionized; SHR= 1.6667 effectively f=3, radiation power not significant when compared to dynamic power.

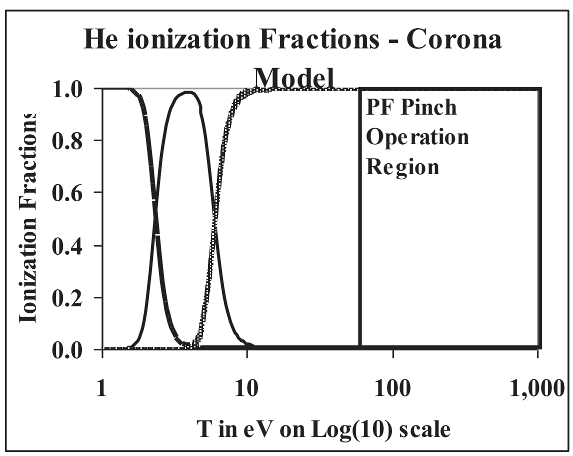

FIGURE 6. Helium ionization versus temperature- showing typical pinch regime. Three traces represent 0, 1^{st} and 2^{nd} ionization fractions from left to right as temperature increases

Neon

For PF, neon is operated typically at around 200-500 eV so that the neon plasma is mainly 8^{th} and 9^{th} ionized (see Figure 7); H-like and He-like for characteristic neon radiation. SHR ~ 1.5 (see Figure 8); f ~ 4; Z_{eff} ~ 9. Radiation is line-type; in the optimum pressure range, radiation power is significant when compared to dynamic power and Joule heating power

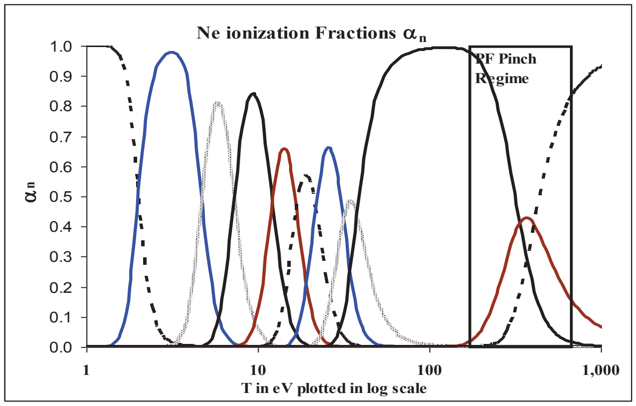

FIGURE 7. Neon ionization versus temperature- showing typical pinch regime. Eleven traces represent 0, 1st, …… 10th ionization fractions from left to right as temperature increases.

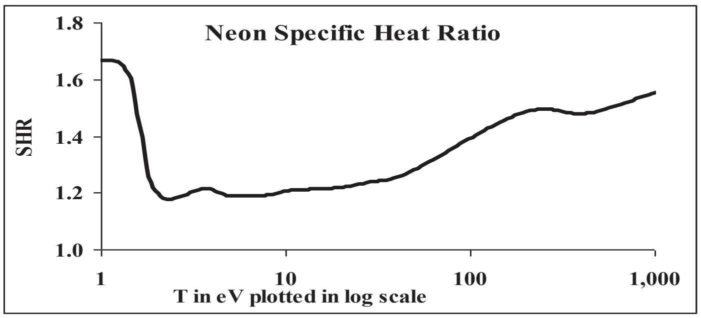

FIGURE 8. Neon: SHR (including ionization energy) vs temperature

TABLE 2. NX2: Computations of pinch properties in neon as a function of pressure, P_0

Ne																		
P_0 Torr	I_{peak} kA	I_{pinch} kA	T_p min 10^6	T_p max 10^6	v_a cm/μs	v_s cm/μs	v_p cm/μs	r_{min} cm	z_{max} cm	τ dur ns	V_{max} kV	n_i $10^{23}m^{-3}$	Yline	Q_{dot}min W	γ_{rmin}	k_{min}	EINP J	t_{dep}/τ
0.20	306	**167**	21.92	24.53	16.9	61.5	41.8	0.27	2.8	10.1	53.5	0.2	0.00	1.9E+06	1.602	0.143	259.7	-13275
0.50	363	**195**	11.89	13.61	12.9	45.6	32.2	0.26	2.8	13.5	49.2	0.5	0.05	4.3E+06	1.532	0.135	367.2	-6250
0.75	388	**206**	8.79	10.68	11.4	39.7	28.3	0.25	2.8	15.5	46.2	0.7	0.17	3.1E+06	1.506	0.134	415.5	-8661
1.00	404	**212**	6.98	8.75	10.4	35.8	25.7	0.25	2.8	16.8	43.5	0.9	0.43	-6.6E+06	1.491	0.133	445.7	4041
1.25	416	**216**	6.01	7.43	9.6	33.4	23.7	0.25	2.8	18.1	41.1	1.2	0.81	-2.5E+07	1.483	0.133	464.0	1010
1.50	424	**218**	5.24	6.41	9.0	31.5	22.4	0.25	2.8	19.1	39.3	1.4	1.38	-5.4E+07	1.476	0.132	476.6	459
2.00	435	**218**	4.11	4.96	8.1	28.4	19.5	0.25	2.8	21.1	35.5	1.9	3.32	-1.5E+08	1.485	0.131	488.4	152
2.50	444	**216**	3.30	3.95	7.5	26.4	17.6	0.24	2.8	22.4	32.5	2.6	6.87	-3.3E+08	1.485	0.127	487.3	65
3.00	451	**211**	2.67	3.19	7.0	25.1	16.7	0.22	2.8	23.0	30.5	3.6	13.07	-6.7E+08	1.485	0.118	480.6	31
3.50	457	**205**	2.12	2.58	6.5	24.4	15.9	0.19	2.8	23.8	29.0	5.6	25.27	-1.4E+09	1.444	0.102	477.2	15
4.00	461	**197**	1.61	2.08	6.2	21.9	15.0	0.16	2.9	28.9	27.7	9.5	42.44	-1.4E+09	1.383	0.084	481.4	12
4.50	465	**188**	1.34	1.69	5.8	19.8	14.2	0.18	2.8	31.4	25.8	8.7	29.96	-1.2E+09	1.35	0.092	442.1	12
5.00	469	**179**	1.11	1.38	5.6	18.0	13.3	0.20	2.8	34.5	23.5	7.5	16.28	-3.8E+08	1.332	0.105	396.4	30
6.00	475	**159**	0.73	0.90	5.1	15.1	11.7	0.20	2.7	42.2	18.5	8.6	4.22	3.5E+08	1.33	0.107	312.9	-21
8.0	483	**102**	0.26	0.41	4.3	10.0	8.1	0.26	2.7	90.7	7.6	7.0	0.33	5.2E+07	1.33	0.137	161.3	-34

From the series of computations (NX2 in neon) starting at low pressures and then with increasing pressures, the results are summarized in Figure 9 showing the pinch radius ratio as a function of operating pressure.

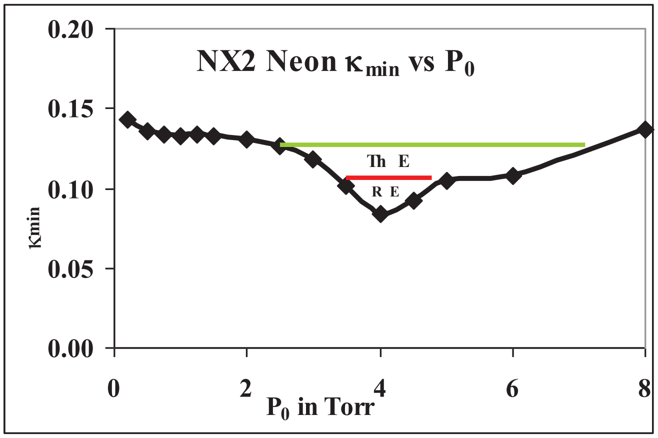

FIGURE 9. NX2 in neon: Radius ratio vs P_0, showing thermodynamically enhanced (Th E) regime and radiation-enhanced (RE) regime.

At low pressures, the pinch radius ratio approaches the deuterium pinch radius ratio of 0.15 due to the full ionization of neon (see Figure 8 and Table 2) at temperatures above 20 million K, resulting in the SHR approaching the value of 5/3. Then as pressure increases, the shock speed drops resulting in the temperature decreasing away from full ionization. The value of SHR drops towards 1.2, compressibility increases with pinch radius ratio dropping to 0.1. We define this region as thermodynamically enhanced compression. At pressures between 3.5–5 Torr, the NX2 neon pinch radiates enough to exhibit a radiatively enhanced regime with radius ratio dropping to 0.7 before rising (see Figure 9) due to the too high pressure slowing the speeds thus reducing the temperatures to below the temperature window needed for the He-like H-like radiation.

Argon

In plasma focus operation, in the pinch the argon plasma is mainly in freely ionizing region (see Figure 10). Typically SHR~1.4, f~5, Z_{ef} ~10-16 . Radiation is line-type. In the optimum pressure range for radiation (see Figure 12), radiation power is dominant compared to dynamic and Joule heating power.

Similar to the case of neon we define a region of themodynamically-enhanced compression and in the range of pressure 1-3 Torr for NX2, strong radiation-enhanced compression is computed with peak compression with pinch radius ratio of 0.02 at 1.5 Torr (see Figure 12).

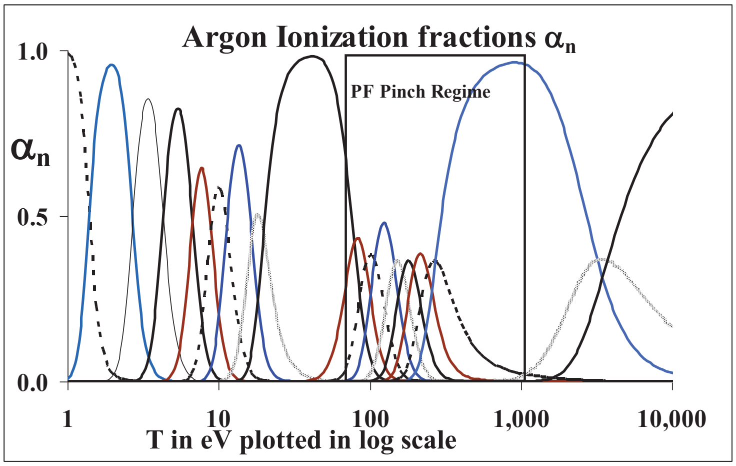

FIGURE.10. Argon: ionization versus temperature- showing typical pinch regime. Nineteen traces representing 0, 1st, 2nd …… 18th ionization fractions from left to right as temperature increases.

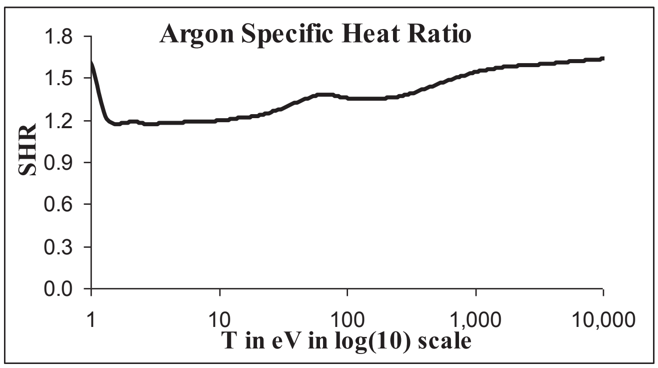

Figure 11. Argon: SHR (including ionization energy) with temperature

TABLE 3. NX2 in argon operation. Pinch plasma properties as a function of pressure, P_0

P_0 Torr	I_{peak} kA	I_{pinch} kA	T_p min 10^6	T_p max 10^6	v_a cm/μs	v_s cm/μs	v_p cm/μs	r_{min} cm	z_{max} cm	τ dur ns	V_{max} kV	n_i $10^{23}m^{-3}$	Yline	Q_{dot}min W	γ_{rmin}	k_{min}	EINP J	t_{dep}/τ
0.1	305	**166**	27.71	31.36	16.9	61.5	42.9	0.27	2.8	9.9	55	0.1	0.01	1.5E+06	1.55	0.142	260	-17325
0.5	404	**209**	8.74	9.96	10.4	40.4	28.0	0.22	2.8	15	53	0.6	1.62	-1.2E+08	1.49	0.116	457	253
1.0	435	**215**	4.36	5.64	8.1	29.4	21.8	0.17	2.8	20	45	2.1	25	-2.0E+09	1.37	0.089	536	13.2
1.2	443	**214**	3.25	4.98	7.6	27.0	20.2	0.12	2.9	21.9	59	5.2	69	-8.3E+09	1.35	0.062	579	3.18
1.5	451	**209**	2.12	4.13	7.0	23.9	18.0	0.03	3.5	25	170	79	291	-3.0E+10	1.32	0.018	742	1.01
2.0	461	**197**	1.59	3.12	6.2	19.4	15.0	0.05	3.8	31	123	51	285	-2.0E+10	1.30	0.026	654	1.04
2.5	469	**180**	1.24	2.28	5.6	16.2	12.5	0.07	3.5	39	84	28	198	-1.3E+10	1.30	0.038	511	1.02
3.0	475	**159**	0.94	1.61	5.1	13.4	10.7	0.12	3.1	49	76	13	111	-8.0E+09	1.30	0.061	375	0.96
3.5	479	**133**	0.64	1.01	4.7	11.3	8.8	0.21	2.9	62.9	24	4.9	46	-2.0E+09	1.31	0.109	257	2.00
4.0	483	**98**	0.28	0.51	4.3	9.6	7.0	0.35	2.9	97	4.8	2.0	9.4	-2.2E+06	1.33	0.182	163	755

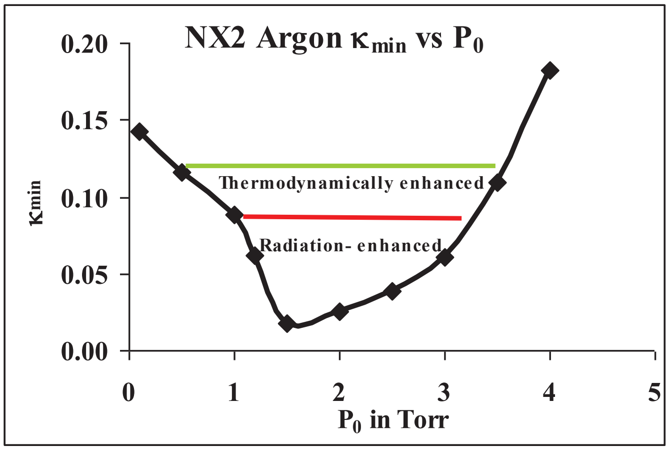

FIGURE 12. Pinch radius ratio of NX2 as a function of P_0, showing thermodynamically-enhanced and radiation-enhanced regimes.

Krypton

Operating the NX2 in krypton, the pinch conditions fall in freely ionizing region; SHR~ 1.3 – 1.4, f~5–7; Z_{eff} averages 20. Radiation is line-type. Over a good range of operational pressure, radiation power is overwhelming compared to dynamic and Joule heating power.

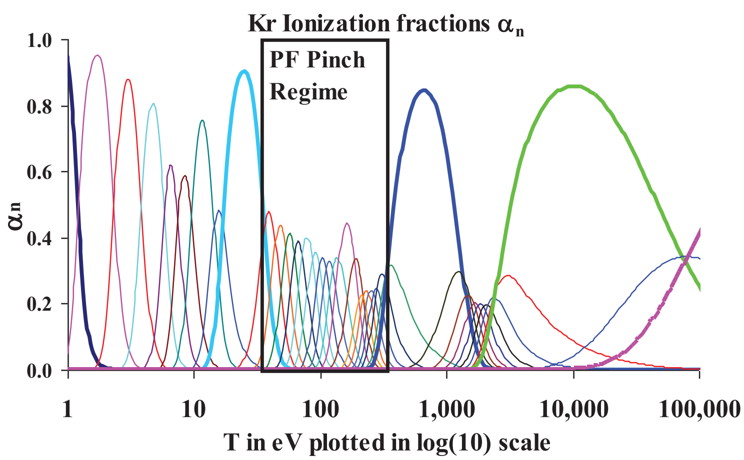

Figure 13. Kr ionization versus temperature- showing pinch regime. Thirty-seven traces represent 0, 1st and 2nd … 36th ionization fractions from left to right as temperature increases.

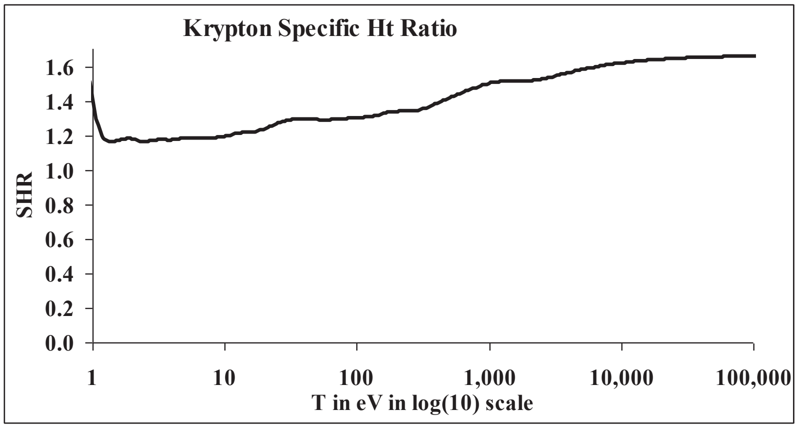

FIGURE 14. SHR (including ionization energy) with temperature

TABLE 4. NX2 krypton pinch properties as a function of operational pressure, P_0

Kr

P_0 Torr	I_{peak} kA	I_{pinch} kA	T_p min 10^6	T_p max 10^6	v_a cm/μs	v_s cm/μs	v_p cm/μs	r_{min} cm	z_{max} cm	τ dur ns	V_{max} kV	n_i $10^{23}m^{-3}$	Yline	Q_{dot}min W	γ_{rmin}	k_{min}	EINF J	t_{dep}/τ
0.05	309	**168**	30.30	33.42	16.6	61.2	42.1	0.271	2.7	9.6	55.5	0.04	0.06	-4.8E+06	1.57	0.1424	262	5640
0.10	352	**190**	19.93	22.07	13.6	50.0	34.8	0.257	2.7	11.5	53.4	0.09	0.50	-5.2E+07	1.53	0.1352	342	566
0.25	407	**213**	10.65	12.03	10.2	36.7	26.1	0.227	2.8	15.4	46.7	0.29	8.60	-8.0E+08	1.47	0.1195	456	37
0.40	428	**218**	6.93	8.42	8.7	30.4	21.9	0.159	2.8	18.3	51.1	0.9	52	-5.9E+09	1.44	0.0836	536	4.9
0.45	433	**218**	5.69	7.64	8.3	28.9	20.9	0.09	2.9	19.2	144	3.0	115	-2.5E+10	1.42	0.0499	601	1.3
0.50	437	**218**	1.96	6.97	8.0	27.5	19.9	0.006	4.2	20.2	4394	709	834	-8.6E+11	1.39	0.0034	903	0.05
0.60	444	**216**	1.15	5.90	7.5	25.2	18.3	0.008	4.7	21.9	3826	596	1035	-7.3E+11	1.38	0.0041	864	0.05
0.75	453	**210**	0.91	4.71	6.8	22.3	16.3	0.010	4.6	24.8	3039	427	1005	-5.6E+11	1.38	0.0054	788	0.06
1.00	463	**195**	0.79	3.35	6.0	18.6	13.7	0.02	4.3	29.9	2032	228	817	-3.5E+11	1.36	0.0085	656	0.06
1.50	476	**152**	0.59	1.70	4.9	13.0	9.8	0.04	3.5	46.4	815	52	378	-1.2E+11	1.33	0.0218	383	0.07
1.75	481	**121**	0.46	1.12	4.5	10.6	8.0	0.08	3.2	64.8	503	15.9	178	-5.1E+10	1.31	0.0427	256	0.08
1.90	483	**96**	0.30	0.79	4.3	9.2	7.1	0.14	3.1	93.0	192	5.8	89	-1.5E+10	1.28	0.0732	188	0.13

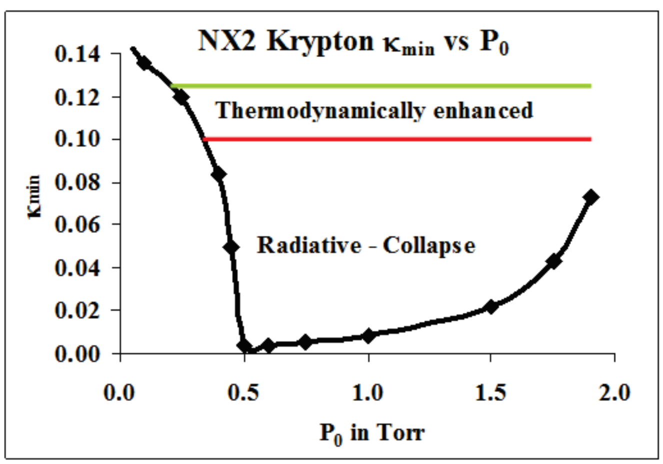

FIGURE 15. Computed pinch radius ratio in NX2 operating in krypton, showing thermodynamically enhanced regime and radiative-collapse regime.

Computed properties of the plasma pinch are summarized in Table 4 resulting in the compressibility situation summed up in κ_{min} versus P_0 curve (Figure 15). The compression is dominated by radiative compression from 0.4 Torr all the way to 1.9 Torr, with peak compression represented by a tiny pinch radius ratio of 0.003 at 0.55 Torr. Above 1.9 Torr, the pinch does not form due to the lateness of the pinch and the current dropping to too low a value at pinch time.

Xenon

Operating NX2 in xenon, the pinch is in freely ionizing region with SHR in the value region of 1.3–1.4, f ~ 5–7. Radiation is line-type. Over much of operating pressure range, radiation power is overwhelming compared to dynamic and Joule heating power.

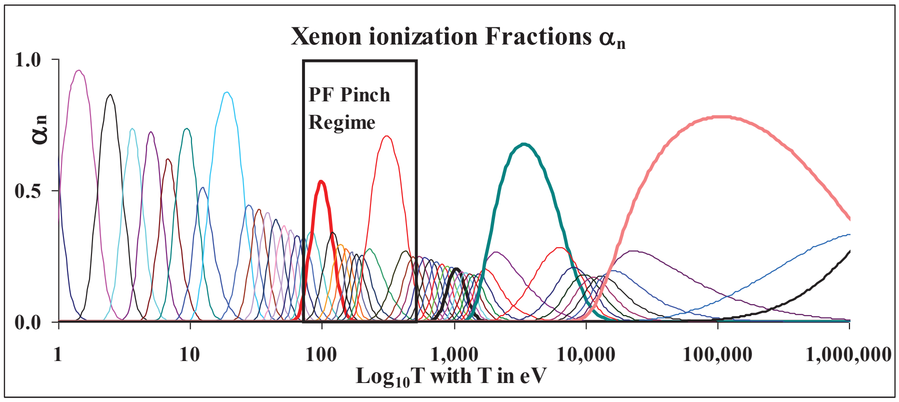

Figure 16. Xe: ionization versus temperature- showing pinch regime. Fifty-five traces represent 0, 1st and 2nd … 54th ionization fractions from left to right as temperature increases.

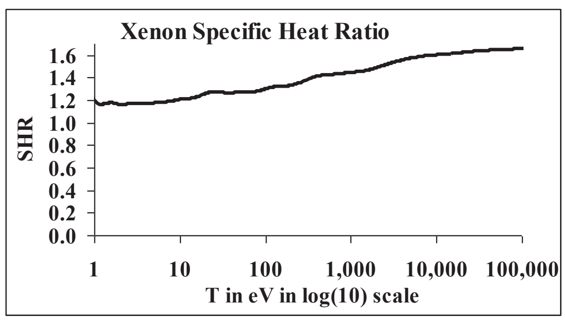

FIGURE 17. Xenon: SHR (including ionization energy) with temperature

TABLE 5. Pinch properties of NX2 operated in xenon at various operational pressure, P_0

Xe

P_0 Torr	I_{peak} kA	I_{pinch} kA	T_p min 10^6	T_p max 10^6	v_a cm/μs	v_s cm/μs	v_p cm/μs	r_{min} cm	z_{max} cm	τ dur ns	V_{max} kV	n_i $10^{23}m^{-3}$	Yline	Q_{dot}min W	γ_{rmin}	k_{min}	EINP J	t_{dep}/τ
0.030	305	**165**	34.0	39.6	16.9	62.3	43.9	0.253	2.7	8.9	58.7	0.0	0.15	-1.9E+07	1.515	0.1332	259	1535
0.050	337	**182**	25.9	29.0	14.6	53.3	37.9	0.248	2.7	10.2	56.1	0.0	0.65	-8.4E+07	1.492	0.1306	316	366
0.075	363	**194**	20.2	22.5	12.9	47.0	33.4	0.242	2.7	11.5	53.3	0.1	2.2	-2.6E+08	1.474	0.1274	364	123
0.100	380	**202**	17.1	19.2	11.8	42.7	30.5	0.235	2.7	12.6	51.0	0.1	5.0	-5.5E+08	1.467	0.1235	401	58
0.200	418	**216**	10.3	12.5	9.4	33.4	23.9	0.164	2.8	15.9	55.9	0.4	50	-6.3E+09	1.446	0.0861	515	5.2
0.220	422	**217**	9.3	11.7	9.1	32.1	23.0	0.126	2.8	16.5	92.8	0.8	83	-1.4E+10	1.442	0.0664	554	2.4
0.240	426	**218**	6.9	11.0	8.9	31.0	22.2	0.030	2.9	17.0	1908	16.1	229	-3.7E+11	1.429	0.0156	697	0.112
0.241	426	**218**	6.5	11.0	8.9	31.0	22.2	0.021	2.9	16.9	3846	32	260	-7.6E+11	1.427	0.0110	725	0.057
0.45	451	**212**	0.41	6.43	7.0	23.4	16.9	0.003	4.1	24.5	19496	2700	1214	-3.6E+12	1.382	0.0017	820	0.009
0.50	455	**208**	0.39	5.80	6.7	22.0	16.0	0.004	4.0	25.9	17137	1930	1155	-3.1E+12	1.375	0.0021	771	0.010
0.60	461	**199**	0.39	4.62	6.2	19.7	14.4	0.006	3.8	28.1	13064	866	1026	-2.3E+12	1.357	0.0034	678	0.010
0.80	471	**175**	0.36	2.95	5.4	15.8	11.8	0.012	3.5	36.2	7550	322	756	-1.2E+12	1.329	0.0064	513	0.012
1.00	478	**144**	0.31	1.85	4.8	12.5	9.5	0.023	3.3	49.6	3952	112	473	-5.4E+11	1.298	0.0122	354	0.013
1.20	483	**99**	0.18	0.95	4.4	9.2	7.3	0.066	3.2	95.7	1817	16.3	176	-1.5E+11	1.27	0.0348	206	0.014
1.22	484	**89**	0.13	0.83	4.3	8.9	7.0	0.08	3.2	115.8	1442	10.6	136	-1.1E+11	1.27	0.0437	189	0.015

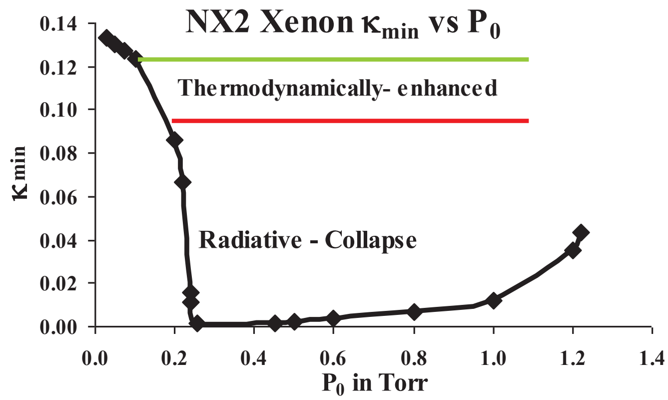

FIGURE 18. Computed pinch radius ratio in NX2 operating in krypton, showing thermodynamically enhanced regime and radiative - collapse regime.

The computed pinch properties are listed in Table 5 and the compressibility is represented by the pinch radius ratio versus operating pressure graph in Figure 18. At low pressures of 0.05 to 0.2 Torr can be identified a thermodynamically-enhanced pressure region before the number density becomes high enough for radiation to dominate. From 0.2 Torr onwards this dominance is seen with the radius ratio falling to 0.001 at pressure of 0.4 Torr, maintaining extreme radiation dominance until 1 Torr; with radiation domination of the compression all the way to the highest possible operation of the PF at around 1.2 Torr.

CONCLUSION

In this paper we have discussed the electrodynamics of the plasma focus pinch in terms of the effects of dI/dt and pinch column elongation on the inward speed of the magnetic piston. We establish the case of the deuterium plasma focus as a reference in which the pinch occurs in an ideal gas situation with f = 3 corresponding to specific heat ratio of 5/3 and with essentially negligible radiation effect on the dynamics. Then we look for the effects of thermodynamic enhancement of compression, delineating such a regime in neon which also shows significant effects of radiation-enhancement in a small region of radiation-optimized pressure. In argon, the compression is strongly radiation-enhanced over a 2- Torr range of operational pressure. In krypton and xenon, the plasma focus pinch is characterized by radiative collapse over most of the operational interval of pressures. From this systematic study we are proposing to develop a first scaling law of radiative compression.

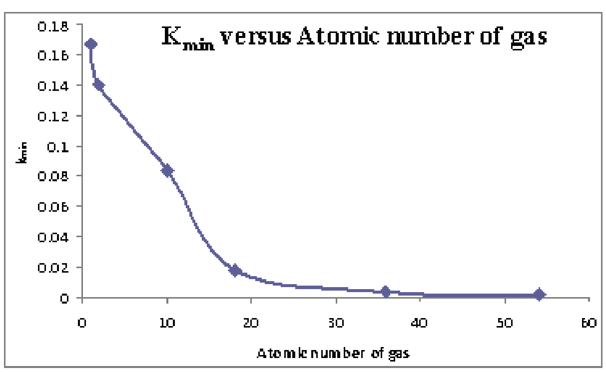

FIGURE 19. κ_{min} minimum pinch radius (in units of anode radius 'a') as a function of atomic number

It would also be useful to extend the Figures 8, 11, 14, 17 to include radiation emissions in the SHR; so that we obtain a generalized specific heat ratio for each gas.

The general procedure may be as follows:

Starting with an ideal atomic degree of freedom of 3 being the translational degrees of freedom, when ionization and excitation energies are included, the degrees of freedom becomes (for the case including ionization and excitation energies):

$$f = 3 + \frac{\frac{2}{m}\left(\sum \alpha_r U_r + \sum \alpha_r U_{er}\right)}{(R_o/M)TD} \tag{6}$$

And for the generalised case including also radiation:

$$f = 3 + \frac{\frac{2}{m}\left(\sum \alpha_r U_r + \sum \alpha_r U_{er}\right) + F(dQ/dt)}{(R_o/M)TD} \tag{7}$$

(in this expression a_r is the r^{th} ionisation fraction, U_r and U_{er} are the ionization and excitation energies per r^{th}-ionised ion of mass m; R_0 is the Universal gas constant SI units and M is the molecular weight; D is the departure coefficient being the number of particles per original atom)

where in the second term both numerator and denominator are in units of energy per unit mass, the denominator being the energy per degree of freedom per unit mass and the first term of the numerator is the ionisation and excitation energies per unit mass whilst the second is the nett radiation energy per unit mass; the value of F being:

$$F = 8(\pi(\gamma-1)/\mu\gamma)^2(r_p/z_f)^2(1/f_c^2 I^4)$$

It is anticipated that such a generalised treatment may be of use for standardising calculations; with a value of the generalised SHR reflecting both the thermodynamic as well as radiation energy content.

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