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Scaling of Ion Beams from Plasma Focus in Various Gases

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Summary- Previous work

- Much work using variety of diagnostics reported on plasma focus ion beams, mainly experimental
- Confusing picture- even units are confusing un-correlated across devices and experiments
- No benchmark or scaling patterns appears to have been reported until:

- Our basic work: We adapted beam- gas target neutron yield mechanism for D beams from plasma focus
- Our basic results: (first plasma focus results on ion beam scaling- D)
- ➢ Ion number fluence: 2.4-5.7 x 10^{20} ions m^{-2}; independent of E_0
- ➢ Ion Number: 1.2-2 x 10^{15} ions per kJ; dependent on E_0

Summary- New work

Extending that work: First principle derivation of ion number flux and fluence equations applicable to all gases.

New results (1 machine NX2: many gases):

- ➢ Fluence, flux, ion number and ion current decrease from the lightest to the heaviest gas
- ➢ Energy fluence, energy flux and damage factors are constant from H_2 to Ne;

  but increase for the 3 high-Z gases Ar, Kr and Xe due to to radiative collapse.
- ➢ The FIB energy has a range of 4-9% E_0.

Brief Review- Summary

- Many different experiments
- Many different machines
- Different gases
- Many types of diagnostics
- Many sets of data
- Data- some total (FC), some sampling (track detectors) ie not all ions recorded
- Different perspectives,
- different units:

  number sr^{-1}; bunch power in W;

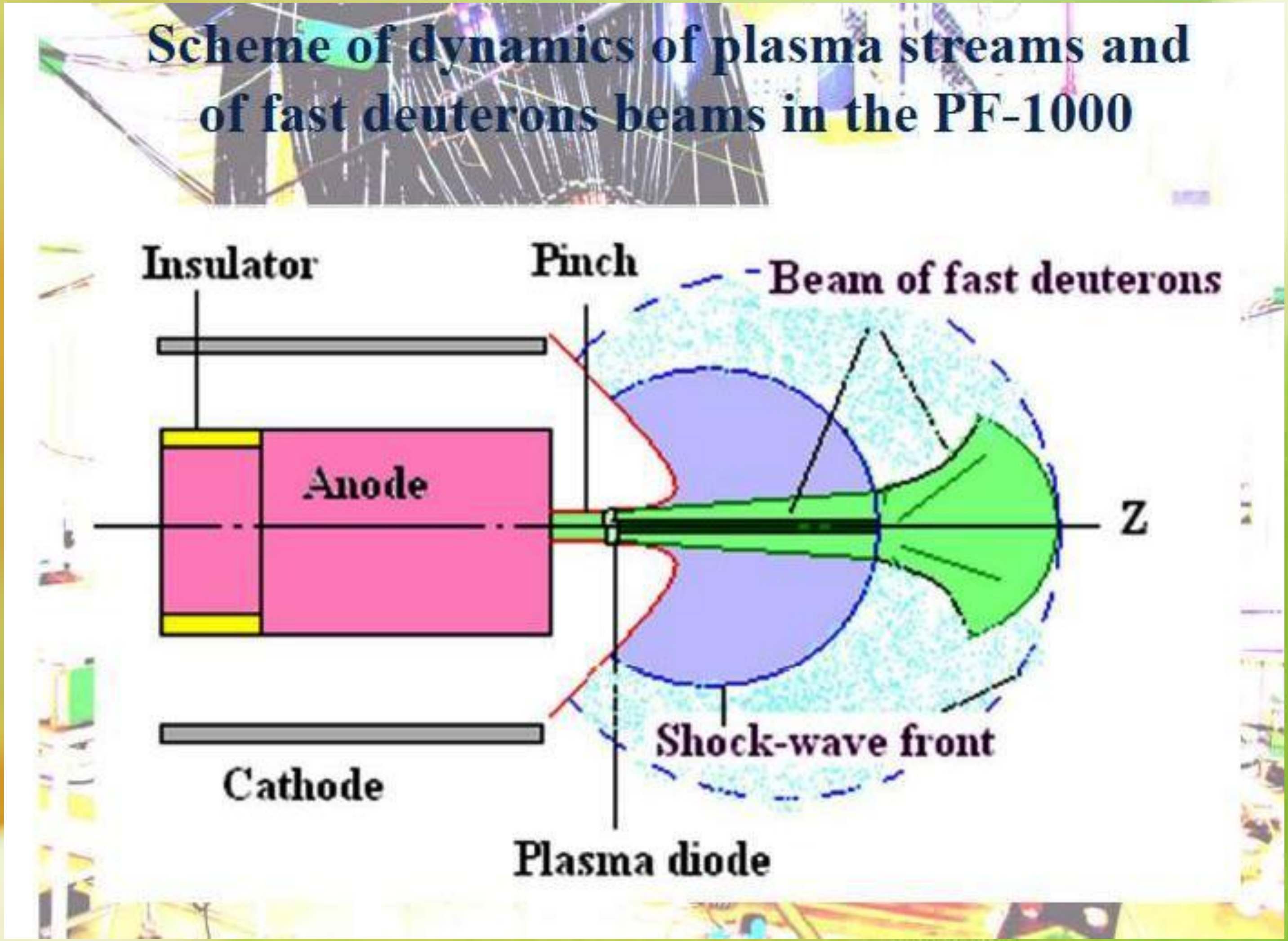
  beam power brightness in GW cm^{-2} sr ;

  ion current densities in A cm^{-2} ; beam ion densities in m^{-3} ;

  tracks m^{-2} ; ions/sterad ; J/sterad ;

  total ion numbers; flux in m^{-2}s^{-1} ; ion fluence in (MeV.sr)$^{-1}$
- **Correlation among experiments? Benchmarking? Scaling? Obvious errors of orders of magnitude!!**

Extracted from V A Gribkov presentation: IAEA Dec 2012- V N Pimenov 2008 Nukleonika 53: 111-121



Scheme of dynamics of plasma streams and of fast deuterons beams in the PF-1000

Comparing large and small PF's- Dimensions and lifetimes- putting shadowgraphs side-by-side, same scale

Comparing UNU ICTP PFF (170 kA) and PF1000 (at 2 MA)- Deuterium 3 Torr

Anode radius 1 cm	11.6 cm
Pinch Radius: 1mm	12mm
Pinch length: 8mm	90mm

Lifetime ~10ns order of ~100 ns

Flux out of Plasma Focus

- Charged particle beams
- Neutron emission when operating with D
- Radiation including Bremsstrahlung, line radiation, SXR and HXR
- Plasma stream
- Anode sputtered material

Basic Definition of Ion Beam characteristics

- Beam **number fluence F_{ib}** (ions m^{-2})
- Beam **energy fluence** (J m^{-2})

Flux =fluence / pulse duration

- Beam **number flux F_{ib}/τ** (ions $m^{-2}s^{-1}$)
- Beam **energy flux** (W m^{-2})

Ion beam flux and fluence equations

Ion beam flux $\mathbf{J_b = n_b v_b}$ where

n_b= number of beam ions N_b divided by volume of plasma traversed

v_b = effective speed of the beam ions.

All quantities in SI units, except where otherwise stated.

Note that $n_b v_b$ has units of ions per m^{-2} s^{-1}.

We derive **n_b from pinch inductive energy considerations.**

Total number of beam ions N_b (each ion mass Mm_p, speed v_b) has

KE= $(1/2)\ N_b\ Mm_p v_b^2$

where $m_p = 1.673\text{x}10^{-27}$ kg is proton mass; M=mass number of ion e.g. neon ion has mass number M=20.

Assume this KE is imparted by a fraction f_e of the inductive pinch energy $(1/2)\ L_p\ I_{pinch}^2$ where $L_p = (\mu/2p)\ (\ln[b/r_p])z_p$; where $\mu = 4p\ \text{x}10^{-7}$ Hm-1, b=outer electrode of PF carrying the return current,

rp= pinch radius and zp= length of the pinch.

The pinch current Ipinch is the value taken at start of pinch.

Thus:

$(1/2)\ N_b\ Mm_p\ v_b^2 = (1/2)\ f_e\ (m/2p)\ (\ln[b/r_p])\ z_p\ I_{pinch}^2$; $n_b = N_b/(pr_p^2 z_p)$

$$\mathbf{n_b = (m/[2p^2\ m_p])\ (f_e/M)\ \{(\ln[b/r_p])/(r_p^2)\}\ (I_{pinch}^2 / v_b^2)\ \ – (1)}$$

We **derive v_b from the accelerating voltage taken as the diode voltage U**

Each ion mass Mm_p, speed v_b, effective charge Z_{eff} is given KE (1/2) $Mm_p v_b^2$ by diode voltage U. Therefore:

(1/2) $Mm_p v_b^2 = Z_{eff}\, eU$ where e is the electronic (or unit) charge $1.6\mathrm{x}10^{-19}$ C; Hence

$$v_b = (2e/m_p)^{1/2} (Z_{eff}/M)^{1/2} U^{1/2} \qquad – (2)$$

From (1) multiplying both sides of equation by v_b, we have

Algebraic manipulations:

$n_b\, v_b = (m/[2p^2\, m_p])\ (f_e\, /M)\ \{(\ln[b/r_p])/(r_p{}^2)\}\ (I_{pinch}{}^2\, /\ v_b)$

Eliminate v_b on RHS of this equation by using Eqn (2) gives

$J_b = n_b\, v_b = (m/[2p^2\, m_p])(f_e\, /M)\{(\ln[b/r_p])/(r_p{}^2)\}(I_{pinch}{}^2)(m_p/2e)^{1/2}(M/Z_{eff})^{1/2}/U^{1/2}$

$\quad = \ (m/[2.83p^2\, (em_p)^{1/2}])(f_e/[M\, Z_{eff}]^{1/2})\{(\ln[b/r_p])/(r_p{}^2)\}(I_{pinch}{}^2)/U^{1/2}$

Noting that: $(m/[2.83p^2\, (em_p)^{1/2}]) = 2.74\text{x}10^{15}$. We have:

Result: Flux

$$\mathbf{J_b = 2.75x10^{15}\ (f_e/[M\, Z_{eff}]^{1/2})\{(\ln[b/r_p])/(r_p{}^2)\}(I_{pinch}{}^2)/U^{1/2}\ \ ions\ m^{-2}s^{-1}} \quad (3)$$

The fluence is the flux multiplied by pulse duration t; Thus:

Fluence:

$$J_b\tau = 2.75\mathrm{x}10^{15}\, t\, (f_e/[M\, Z_{eff}]^{1/2})\{(\ln[b/r_p])/(r_p{}^2)\}(I_{pinch}{}^2)/U^{1/2} \text{ ions m}^{-2} \qquad (4)$$

Assumptions:

1. Ion beam flux $\mathbf{J_b}$ is $n_b v_b$ with units of ions m^{-2} s^{-1}.
2. Ion beam is produced by diode mechanism (ref).
3. The beam is produced uniformly across the whole cross-section of the pinch
4. The beam speed is characterized by an average value v_b.
5. The beam energy is a fraction f_e of the pinch inductive energy, taken as 0.14 in the first instance; to be adjusted as numerical experiments indicate.
6. The beam ion energy is derived from the diode voltage U
7. The diode voltage U is proportional to the maximum induced voltage V_{max}; with $U=3V_{max}$ (ref) taken from data fitting in extensive earlier numerical experiments.

Procedure

The value of the ion flux is deduced in each situation (specific machine using specific gas)

by computing the values of Z_{eff}, $r_{p,}$ I_{pinch} and U by configuring the Lee Model code with the parameters of the specific machine and specific gas.

Example: Numerical Experiment for NX2 based on following fitted parameters:

L_0=20 nH, C_0=28 uF, r_0=2.3 mΩ
b=4.1cm, a= 1.9 cm, z_0=5 cm
f_m=0.08, f_c=0.7, f_{mr}=0.2, f_{cr}=0.7
V_0=14 kV, P_0= within appropriate P range for each gas

Range of Pressures

PF axial run-down time covers a range which encompasses at least from 0.5 to to 1.3 of the short-circuit rise time $1.57*(L_0/C_0)^{0.5}$.

The matched condition with the strongest energy transfer into the plasma focus pinch is well covered within the range;

also the range covers conditions of high enough pressures that the focus pinch is almost not ocurring as defined by the condition that the reflected shock is barely able to reach the rapidly decelerating magnetic piston.

Collection of data

For each shot the dynamics is computed and displayed by the code; which also calculates and displays the ion beam properties.

For H_2, D_2, He, N_2 and Ne the procedure is relatively simple even though Ne already exhibits enhanced compression due to radiative cooling.

RESULTS

Fig 2(a) shows a typical PF discharge current computed for NX2 and fitted to the measured discharge current in order to obtain the model parameters f_m, f_c, f_{mr} and f_{cr}[32,33,41]. Fig 2(b) shows the computed radial trajectories of the radially inward shock wave, the reflected radially outward shock wave, the piston trajectory and the pinch length elongation trajectory.

Range of pressures: widest for lightest gas H_2 (1 Torr -70 Torr). For D_2 and He 1- 40 Torr; for Ne we successfully ran numerical experiments 0.1-10 Torr; N_2 from 0.1 -6Torr; Xe 0.05- to 1.8 Torr.

A. Discharge current and general dynamics

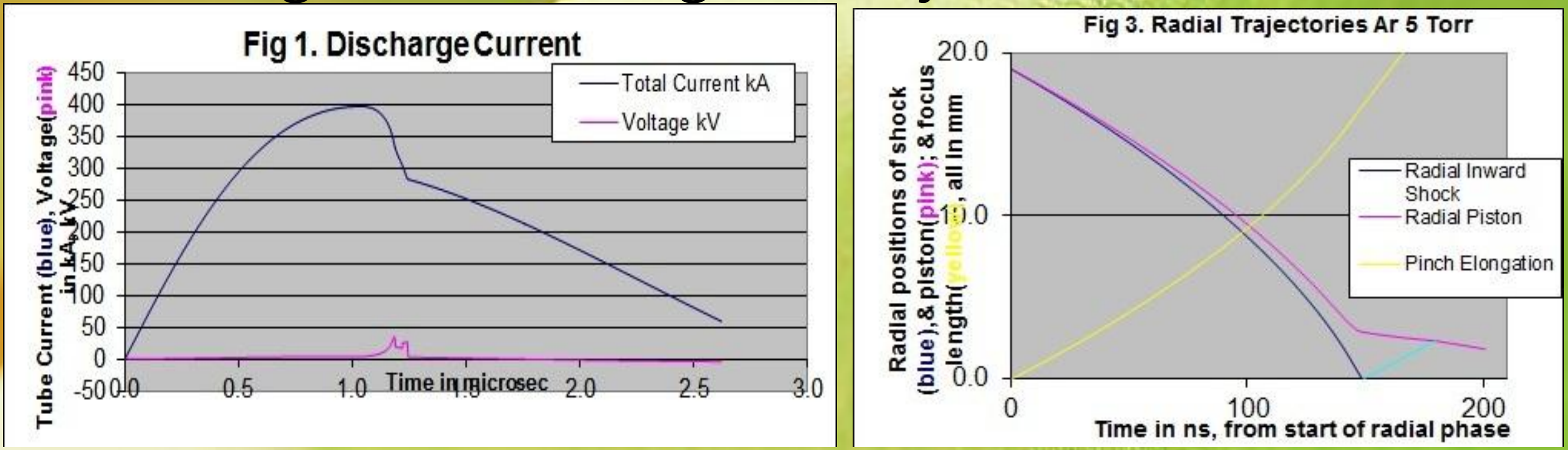


Fig 2. NX2 Ne 3 Torr (a) Typical discharge current (b) Radial trajectories

Fig 3 illustrates the different compression of the PF pinch.

In H_2, D_2 & He radius ratio ~0.15 up to 10 Torr then rises towards 0.2.

For N_2 the radius ratio drops from 0.15 to about 0.13 over range of operation.

Ne shows signs of enhanced compressions 3- 5 Torr; smaller radius ratio to 0.08 at 4 Torr.

Ar shows strong radiative collapse with radius ratio of 0.04 (cut-off value) around 2.0 Torr.

Kr strong radiative collapse from 0.5-2 Torr;

Xe from 0.3 to 1.5 Torr.

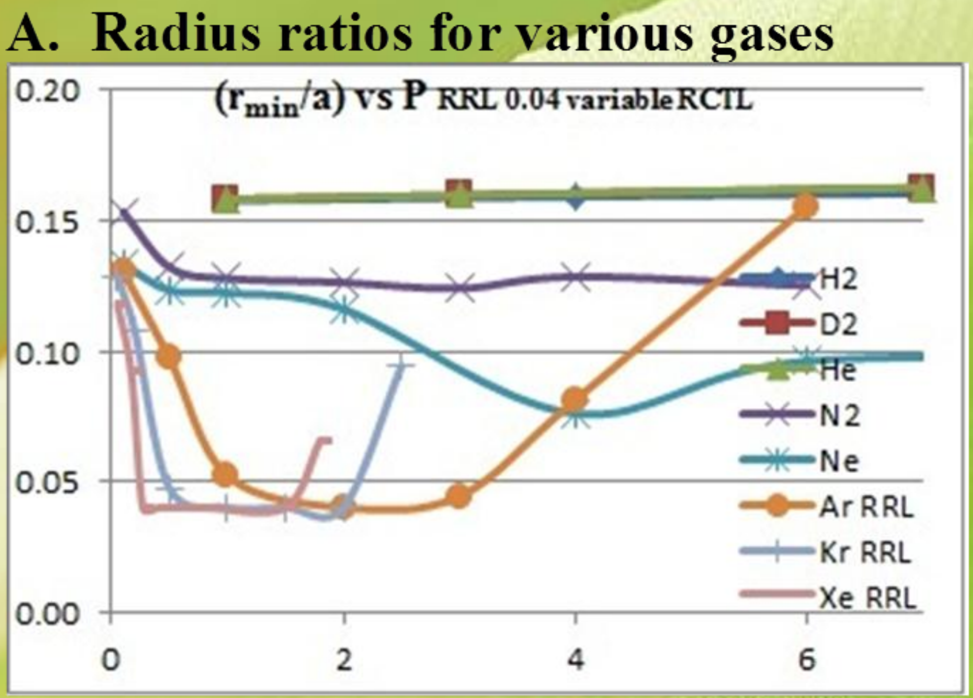


Fig 3. Radius ratio vs P for different gases

A. Ion Beam Flux for various gases

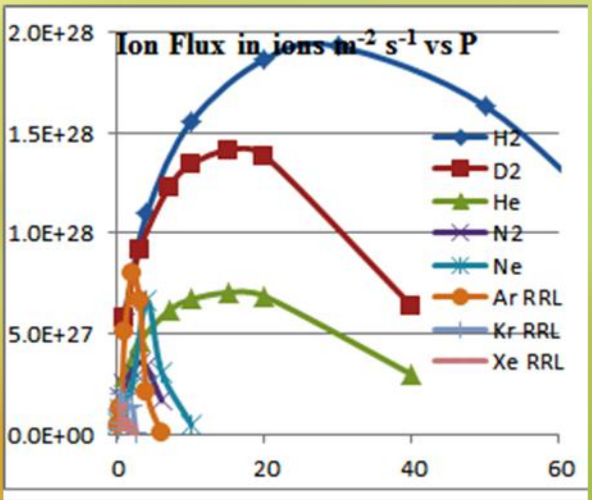


Fig 4a Flux vs Pressure, various gases

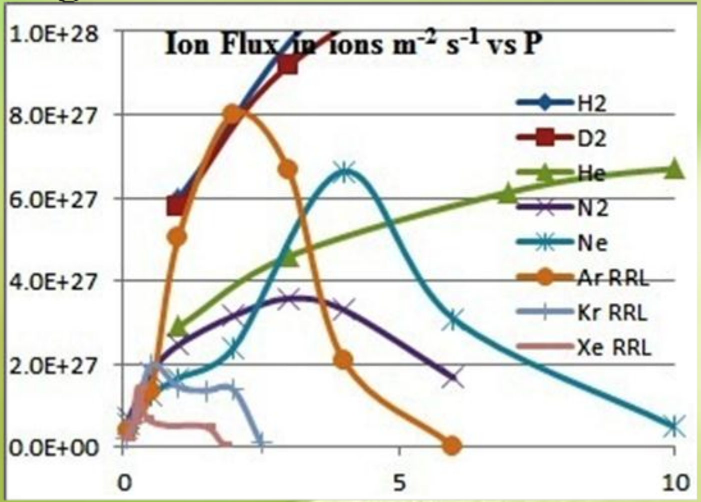


Fig 4b Flux, expanded scale

Fig. 4a shows the flux in ions m^{-2} s^{-1}.

H_2 : 6x10^{27} at 1 Torr , rises to a peak 1.9x10^{28} at 25 Torr; pressure of best energy transfer for NX2 in H_2.

The D_2 and He curve show same trend but lower peak flux values at 15 Torr.

N_2 shows same trend peaking at 3.6x10^{27} at 3 Torr.

Ne shows an accentuated peak of 6.6x10^{27}at 4 Torr due to radiative enhanced compression.

Ar flux is even more accentuated with 8x10^{27} at 2 Torr.

For Kr although the radiative collapse is more severe than Ar, flux is flat at 1.4x10^{27} at 1 Torr.; this is due to the much greater energy per ion. Xe shows the same flat flux curve as Kr with a flat central value around 6x10^{26}.

Conclusion: Beam ion flux drops as the mass number increases, with accentuating factors provided by radiatively enhanced compression.

A. Ion Beam Fluence for various gases

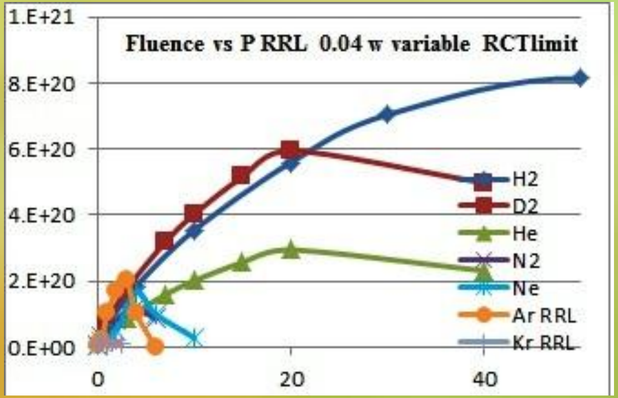


Fig 5a Fluence vs Pressure, various gases

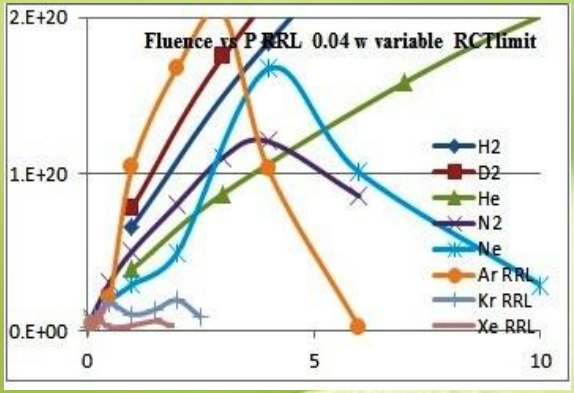


Fig 5b Fluence, expanded scale

Fig 5a shows the fluence in ions m^{-2}.

The shape of the curves and the trend with gases are very similar to the flux

The peak values of the fluence (ions m^{-2}) range from $8x10^{20}$ for H2 decreasing to $6x10^{18}$ for Xe; with clearly radiation enhanced values of $2x10^{20}$ and $1.7x10^{20}$ for Ar and Ne respectively..

A. Beam ion number per kJ

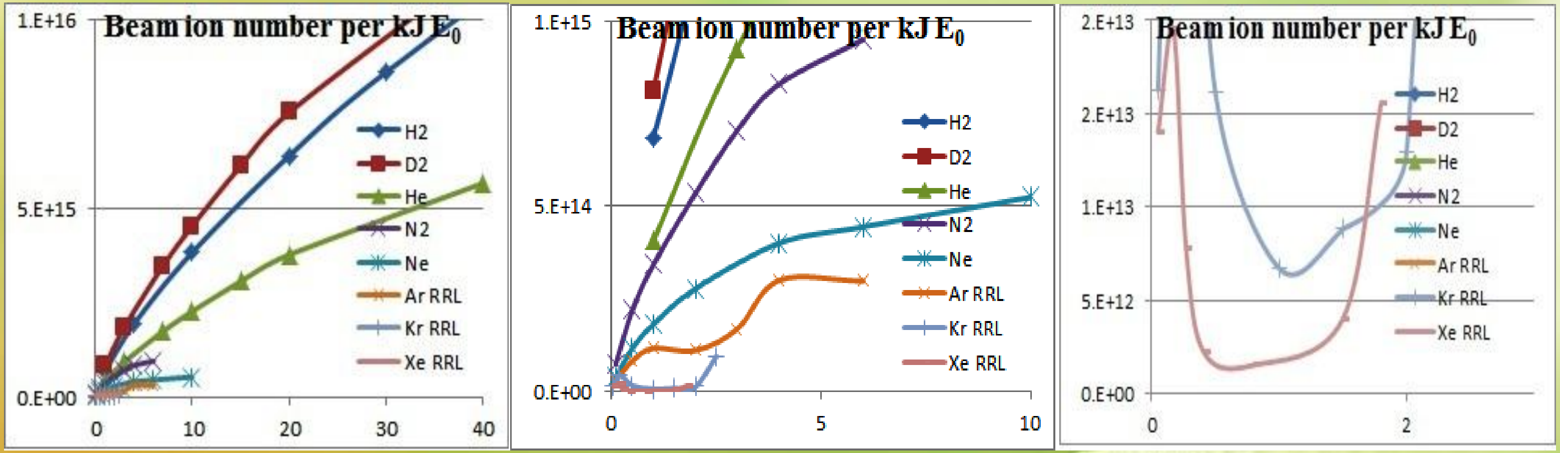


Fig 6 Beam ion number per kJ versus pressure (a) range up to 40 Torr (b) expanded showing up to 10 Torr (c) up to 3 Torr to show Kr and Xe graphs

Figure 6 a-c show that the beam ion number per kJ range from 10^{16} for the lightest gases decreasing to $1.5x10^{12}$ for Xe in the radiative enhanced regime.

A. Beam energy in the various gases

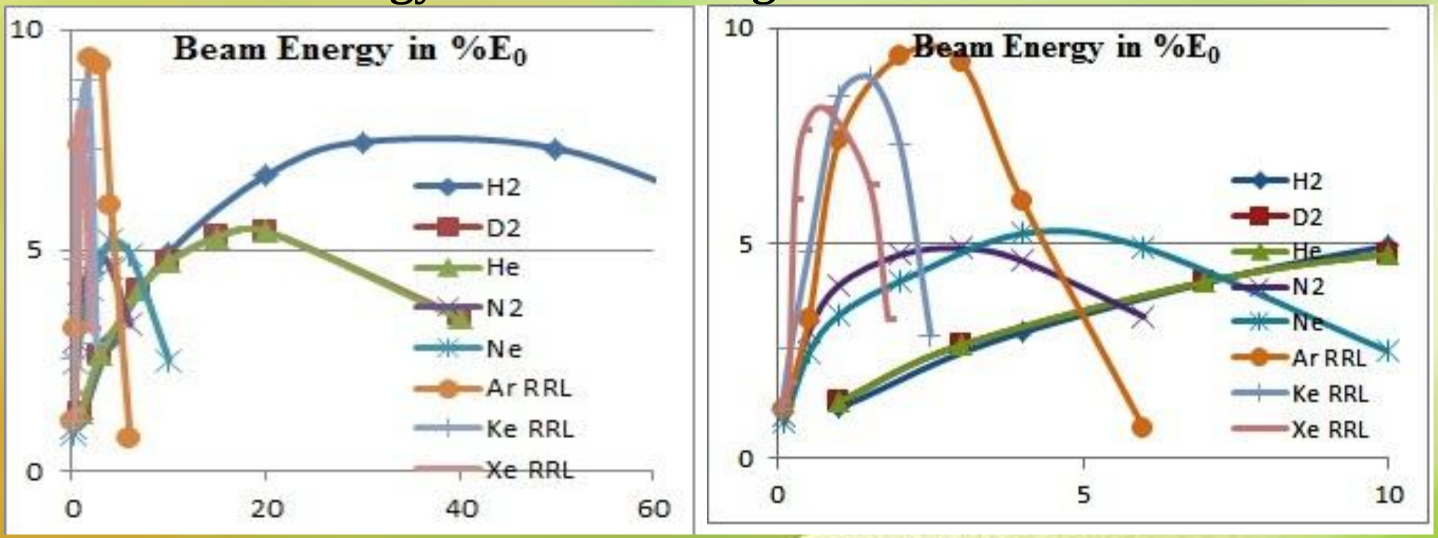


Fig 7. Beam energy as % E_0 in the various gases

Although the beam ion number is the lowest (see Fig 6) for the heaviest gases Ar Kr and Xe, yet these beams also carry the largest amounts of energy at 8-9% E_0 compared to around 5-8% for the other gases.

This is because the energy per ion more than compensate for the low numbers.

A. Damage factor

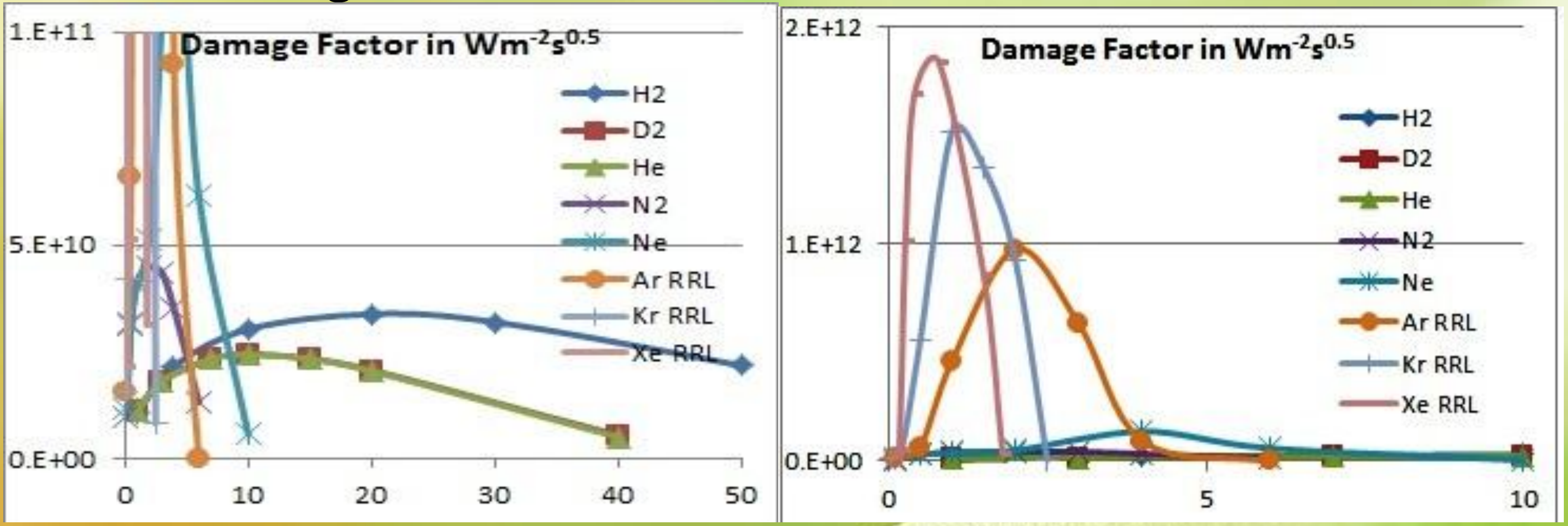


Fig 10. Damage Factor (a) showing the lighter gases (b) the heavier gases

The damage factor defined as power flow density multiplied by (pulse duration)$^{0.5}$. This quantity is considered to be important for assessing the utility of a beam for damage simulation of plasma-facing wall materials in fusion test reactors.

The results show that the heaviest ions produce the biggest damage factors.

Table 1: NX2 Ion beam characteristics in a number of gases

NX2	H_2	D_2	He	N_2	Ne	Ar	Kr	Xe
Pressure (Torr)	30	15	15	2	4	2	1	0.5
I_{peak} (kA)	397	397	397	395	406	406	408	400
I_{pinch} (kA)	222	222	222	215	208	209	210	213
z_p (cm)	2.8	2.8	2.8	2.8	2.8	3.4	2.5	2.4
r_p (cm)	0.33	0.32	0.32	0.24	0.14	0.08	0.08	0.08
τ (ns)	36.5	36.5	36.5	25.6	25.2	30	11.2	7.4
V_{max} (kV)/Vmax*	18.1	18.1	18.1	29	34	152*	1784*	4693*
Z_{eff}	1	1	2	6.4	8	11	13.5	13.6
Ion Fluence ($\times 10^{20}$ m^{-2})	7.0	5.2	2.6	0.8	1.7	4.3	0.29	0.1
Ion Flux ($\times 10^{27} m^{-2} s^{-1}$)	19	14	7	3.2	6.6	14	2.6	1.3

NX2	H_2	D_2	He	N_2	Ne	Ar	Kr	Xe
Mean ion energy (keV)	54	54	108	553	815	16740	24038	636294
En Fluence ($\times 10^6 Jm^{-2}$)	6.1	4.5	4.5	7.2	22	110	110	100
En Flux ($\times 10^{13} Wm^{-2}$)	17	12	12	28	87	380	1000	1300
Ion number/kJ ($\times 10^{14}$)	86	61	31	5.3	4	2.8	0.19	0.06
FIB Energy (J)	205	146	146	130	143	207	204	179
FIB Energy (%E_0)	7.5	5.3	5.3	4.7	5.2	7.5	7.4	6.5
IB Current (kA)	103	74	74	58	56	45	10	5
Beam power ($\times 10^9$ kW)	5.6	4	4	5.1	5.7	6.9	18	24
Damage Fr ($\times 10^{10} Wm^{-2}s^{0.5}$)	3.2	2.3	2.3	4.5	14	66	110	120
Ion speed (cm/μs)	321	227	227	275	279	283	739	960
FPS En (J)	221	341	341	394	406	215	94	114
FPS En (%E_0)	8	12.4	12.4	14.3	14.8	7.8	3.4	4.1
FPS speed (cm/μs)	15.8	16.1	16	21	26.5	38	22	14

Conclusion

- First principle derivation of ion number flux and fluence equations applicable to all gases.

New results (1 machine NX2: many gases):

- Fluence, flux, ion number and ion current generally decrease from the lightest to the heaviest gas; e.g. ion fluence range from $7\text{x}10^{20}$ H_2 decreasing through heavier gases until $0.8\text{x}10^{20}$ for N_2. For Ne and Ar the fluence increase to $4.3\text{x}10^{20}$ as radiative collapse constricts the pinch. For Kr and Xe radiative collapse is more severe but there is a decrease in fluence down to $0.1\text{x}10^{20}$. The very small fluence value of Xe is due to the very large energy of the Xe ion, with Z_{eff} of 13.6; accelerated by large electric fields induced in the radiative collapse. This complex behavior, deviates from simple dependence on $(MZ_{eff})^{-1/2}$ reflects effects of specific heat ratio; radiative cooling & collapse.

Conclusion (continued)

- Energy fluence, energy flux and damage factors are constant from H_2 to Ne; but increase for the 3 high-Z gases Ar, Kr and Xe due to to radiative collapse.
- The FIB energy has a range of 4-9% E_0.

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