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School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

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Scaling Laws for Ion Beam number (and energy) fluence and flux

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8-12 October 2012, ICTP, Trieste, Italy

Scaling Laws for Ion Beam number (and energy) fluence and flux

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Summary

- Much work using variety of diagnostics reported on plasma focus ion beams, mainly experimental
- No benchmark or scaling patterns appears to have been reported.
- We adapt our beam-target neutron yield mechanism to carry out numerical experiments on deuteron beams from plasma focus
- Ion beam data are computed for a range of fitted machines 0.4-486 kJ
- Ion number fluence: 2.4-5.7 x 10^{20} ions m^{-2}; independent of E_0
- Energy fluence : 2.2-10.6 x10^{6} J m^{-2} ; independent of E_0
- Typical inductance PF's (33-55 nH) produce 1.2-2 x 10^{15} ions per kJ carrying 1.3-4 % E_0 at mean ion energy 50-200 keV; higher L_0 giving lower number per kJ.

Brief review of existing work

- Measurements of ion beams from PF's have produced a wide variety of results using different units;
- Less correlated than expected
- Not giving any discernable pattern or benchmarks.
- In summarizing experimental results, Bernard el al[1] in 1996, it was reported that **total yields** of ions reach 10^{10}-10^{14} **sr^{-1}** depending on energetics and experimental conditions.
- In a single discharge fast ions are emitted from point-like (sub-mm) sources mostly as narrow **micro-beams** with duration times of 2-8 ns forming intense bunches having **total powers** reaching 10^{11} to 10^{12} **W**.

Brief Review: Takao et al^2 2003

- 19.4 kJ (43 μF, 30 kV 500 kA peak current) PF published nitrogen ion **beam power brightness** of 0.23 GW **cm^{-2} sr** (maximum ion energy at 0.5 MeV) using a solid anode;
- and 1.6 GW cm^{-2} sr (maximum ion energy of 1 MeV) using a hollow anode.
- Peak **ion current densities** of 1100-1300 **A cm^{-2}** (50-60 ns) were recorded.

Brief Review- Bhuyan et al[3], 2011

- reported **beam ion densities** of 9.7-15.5x10^{19} **m^{-3}** (ion energy 15-50 keV) at the aperture of Faraday Cups for 0-25 degree angular positions 6 cm from the anode top in a 40 kV 2.2 kJ neon PF.
- **Track densities** (CR-39 film) had a maximum value of 10.9x10^{9} tracks **m^{-2}** at 30 degrees.

- In another experiment, Bhuyan[6] operating a 1.8 kJ methane PF quoted a **flux** of 2x10^{22}**$m^{-2}s^{-1}$** multiple-charged carbon ions (50-120 keV).

Brief Review- Kelly et al[4]

- UBA PF II (4.75 kJ 30 kV) in nitrogen; used Faraday Cup and Thomson spectra to measure nitrogen ions (50-1000 keV) recording 3.2×10^{13} **ions/sterad** with energy content of **0.74 J/sterad.**
- In another experiment[5] same machine in dueterium, Kelly surmised a **total number** of 10^{15}deuterons at 20-50 keV.

Brief Review- Szydlowski et al[7]

- foil-covered CR-39 track detectors states that the PF-1000 generates 10^5 **ions/mm^2** (energy above several dozen keV) with neutron yields of 10^{10}-10^{11} neutrons/shot.

Brief review- Bostick et al[8]

- 5.4 kJ PF using TOF and ion filters recorded fluence of 10^{14} **(MeV.sr)$^{-1}$** for the energy spectrum of deuterons (0.3-0.5 MeV) with FWHM of 40-60 ns and 10^{12} (MeV.sr)$^{-1}$ (at 1-9 MeV) with FWHM of 10-20 ns.

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?**

Gribkov et al[9] 2007

- A more integrated approach.
- Examination of plasma conditions and energetics within the PF at the time of formation of the plasma diode mechanism[9]; estimate for PF-1000 at 500 kJ:
- (a) **Energy of the electron and ion beam= 20 kJ or 2.5% of E_0**.

  They comment that these values are conservative when compared to the highest values of 10-20% reported at Kurchatov, Limeil Laboratory and Lebedev using different methods.
- (b) Assume cross-section of the ion bunch= pinch cross section (1 cm radius) and bunch length= 15 cm; thus bunch volume ~50 cm^3, they estimate

  average ion energy ~100 keV

  total number of beam ions ~ $6\text{x}10^{17}$ ions and

  concentration of ions within bunch volume~ 10^{16} cm^{-3}.

Gribkov et al[9] 2007

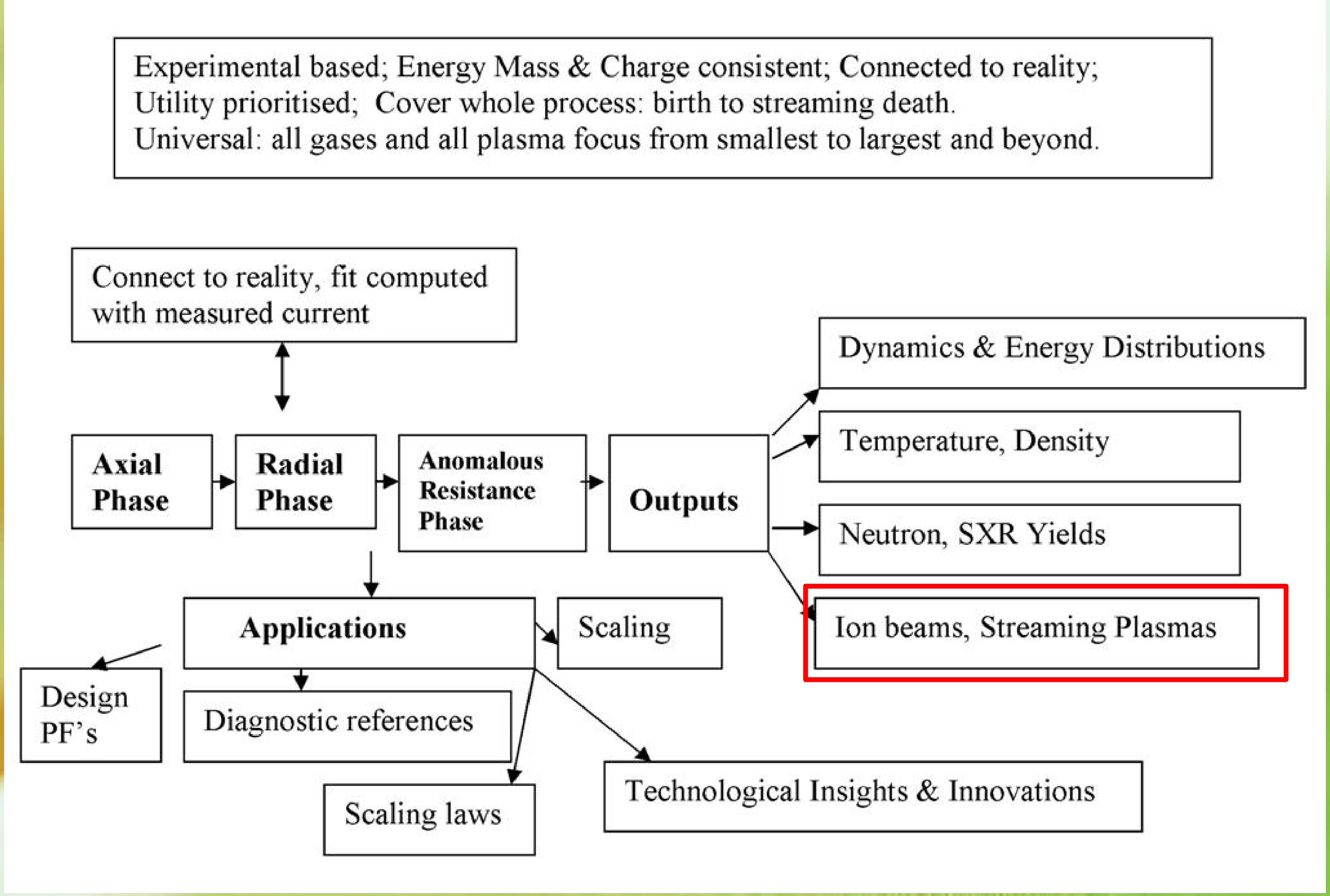
- Among published results, Gribkov et al stand out in their presentation
- Correlates the energetics of the ion beams to the energetics of the system
- Gives a sense of proportion of how the ion beams fit into the overall scheme of things within the PF discharge

Our numerical experiments on Ion Beams

- The ion beam numerical experiments adds on as a branch to the integrated view which our numerical experiments strive to present of the plasma focus

Philosophy, modelling, results & applications of our Model code

Philosophy



Experimental based; Energy Mass & Charge consistent; Connected to reality;
Utility prioritised; Cover whole process: birth to streaming death.
Universal: all gases and all plasma focus from smallest to largest and beyond.

Connect to reality, fit computed with measured current

Axial Phase

Radial Phase

Anomalous Resistance Phase

Outputs

Dynamics & Energy Distributions

Temperature, Density

Neutron, SXR Yields

Ion beams, Streaming Plasmas

Applications

Scaling

Design PF's

Diagnostic references

Scaling laws

Technological Insights & Innovations

Latest development

Latest

Modelling:

Ion beam fluence

Post focus axial shock waves

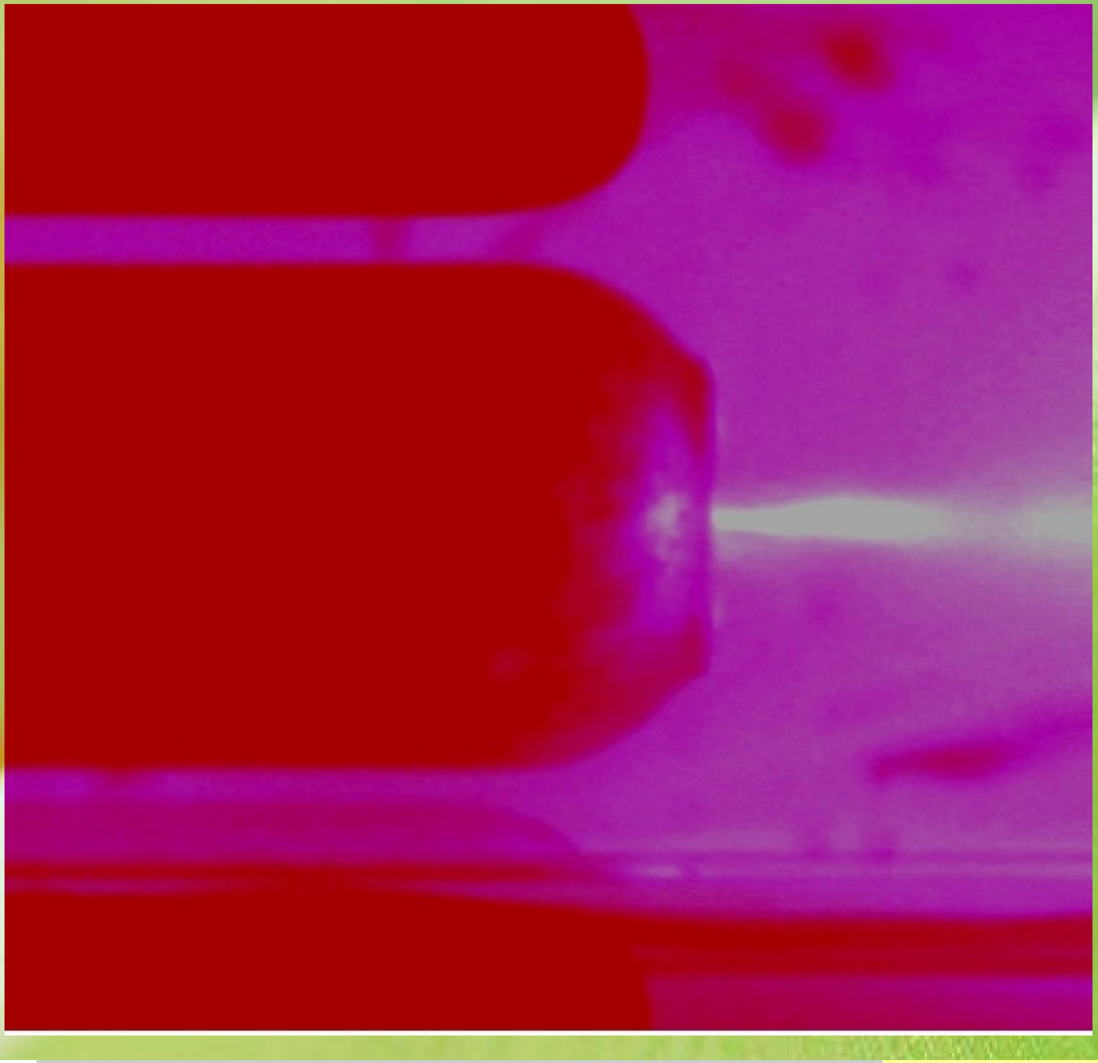
Plasma streams

Anode sputtered material

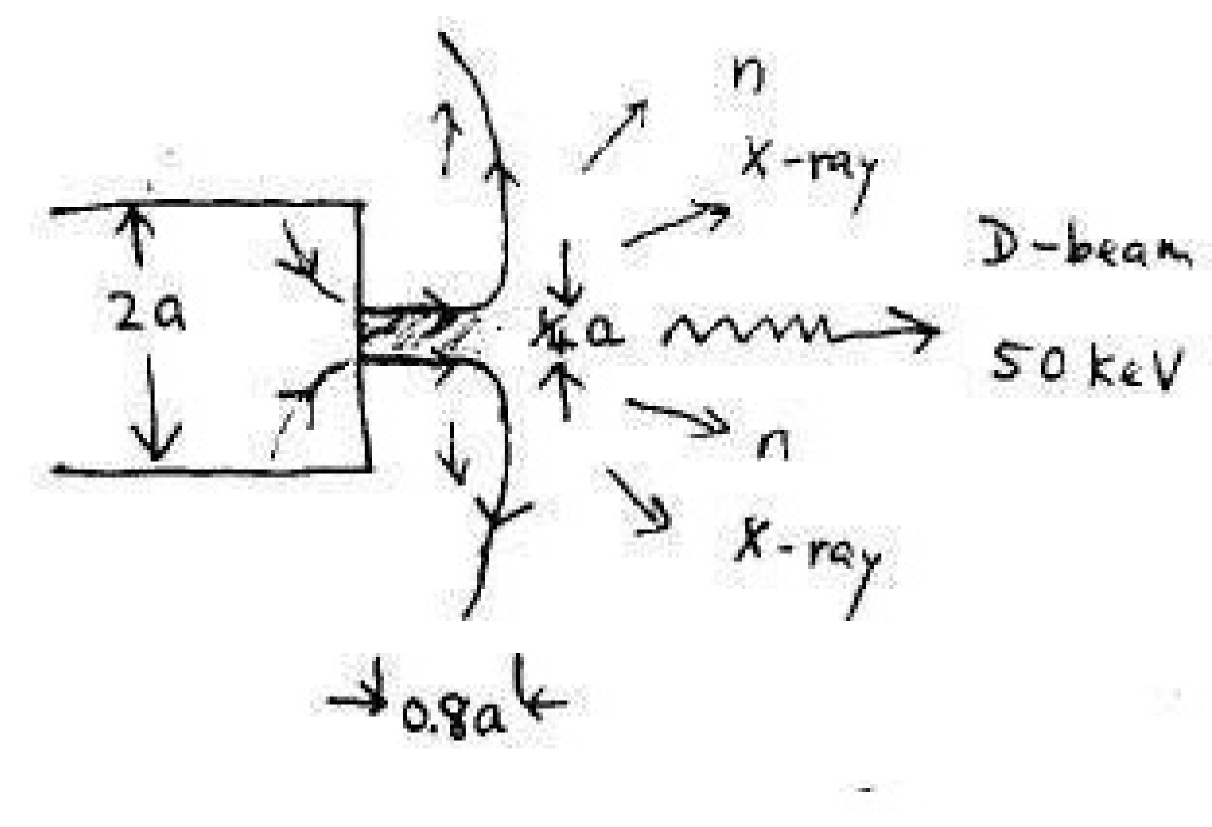
Summarise basic physical picture

Plasma Focus Pinch with plasma stream

(Paul Lee- INTI PF)



Emissions from the PF Pinch region



Mach500 Plasma stream

Mach20 anode material jet

Sequence of shadowgraphs of PF Pinch-

(M Shahid Rafique PhD Thesis NTU/NIE Singapore 2000)

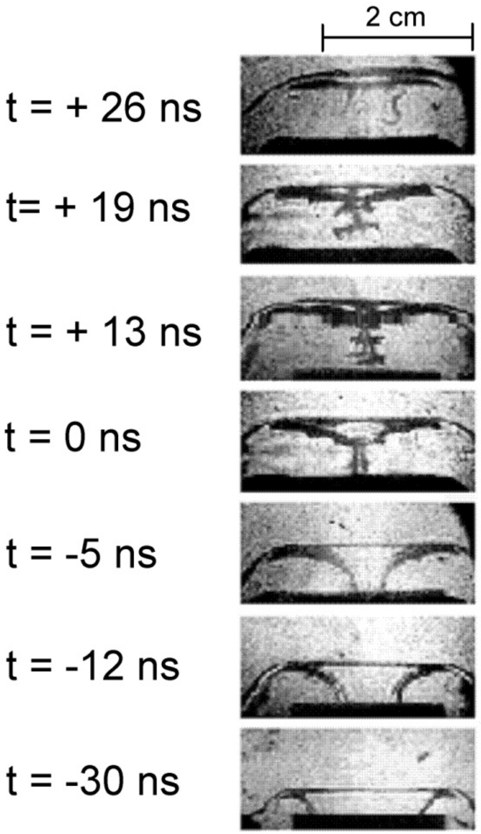


Figure 6.42: Sequence of compression in plasma focus. $Y_n = 1.2 \times 10^8$.

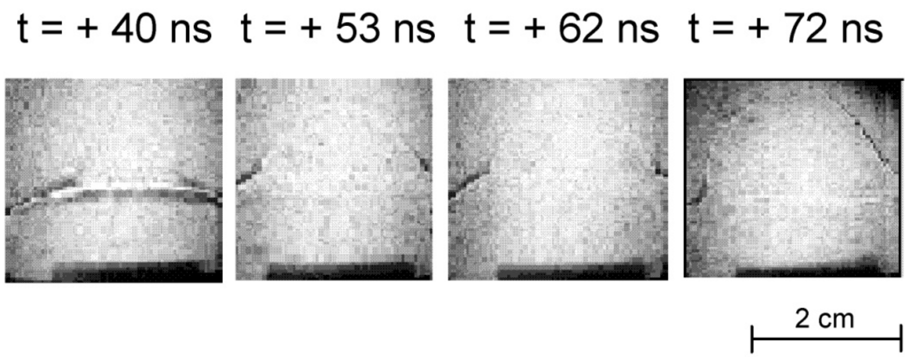
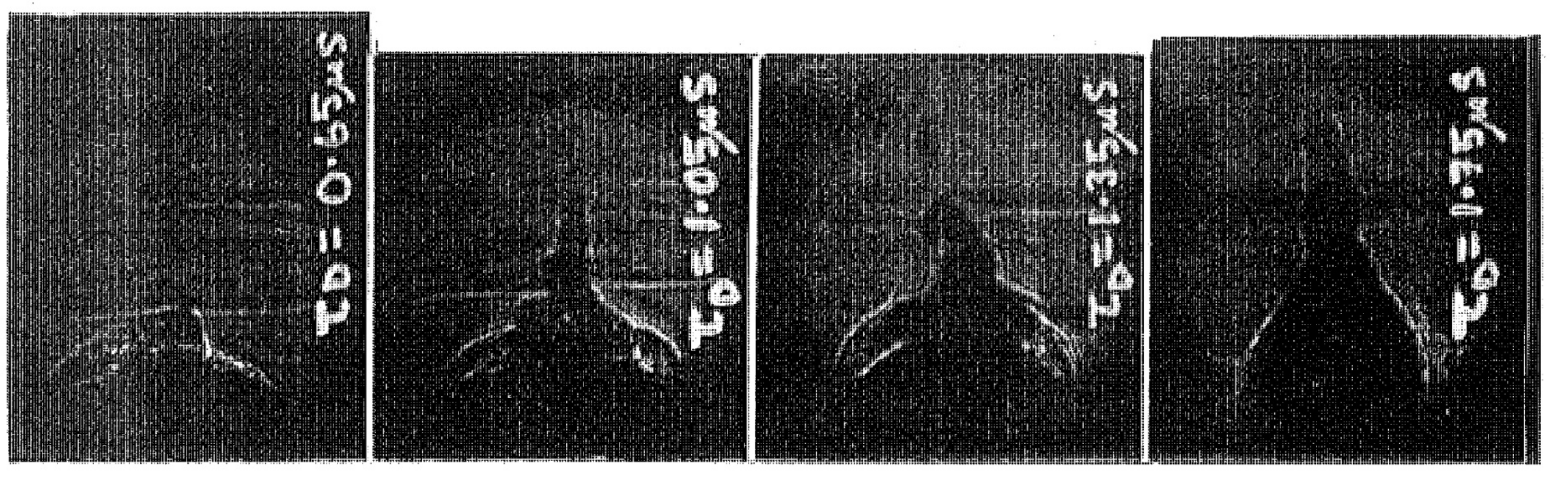


Figure 6.40: Shadowgraphs during the post focus phase forming bubble-like structures. Average $Y_n = 1.6 \times 10^8$.

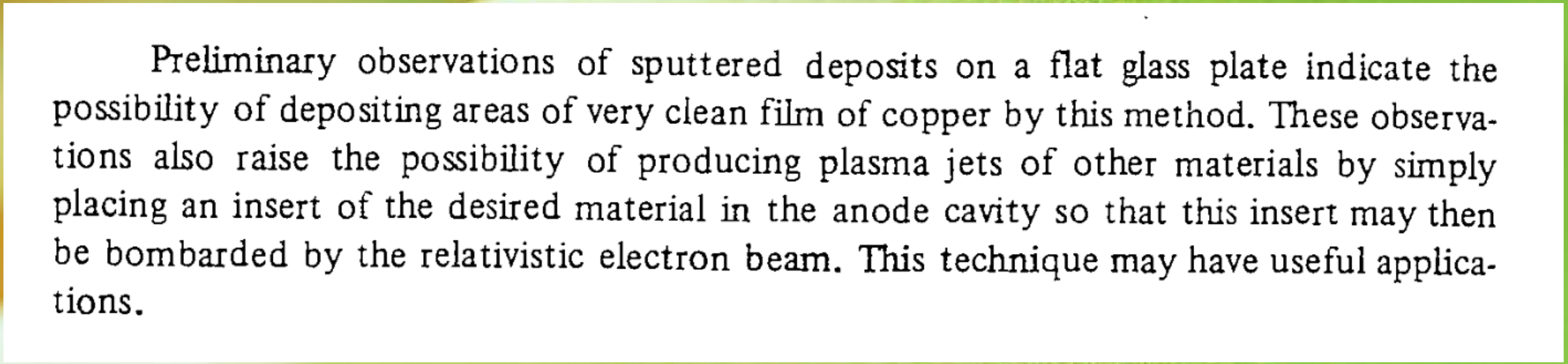
Highest post-pinch axial shock waves speed ~50cm/us M500

Much later…Sequence of shadowgraphics of post-pinch copper jet

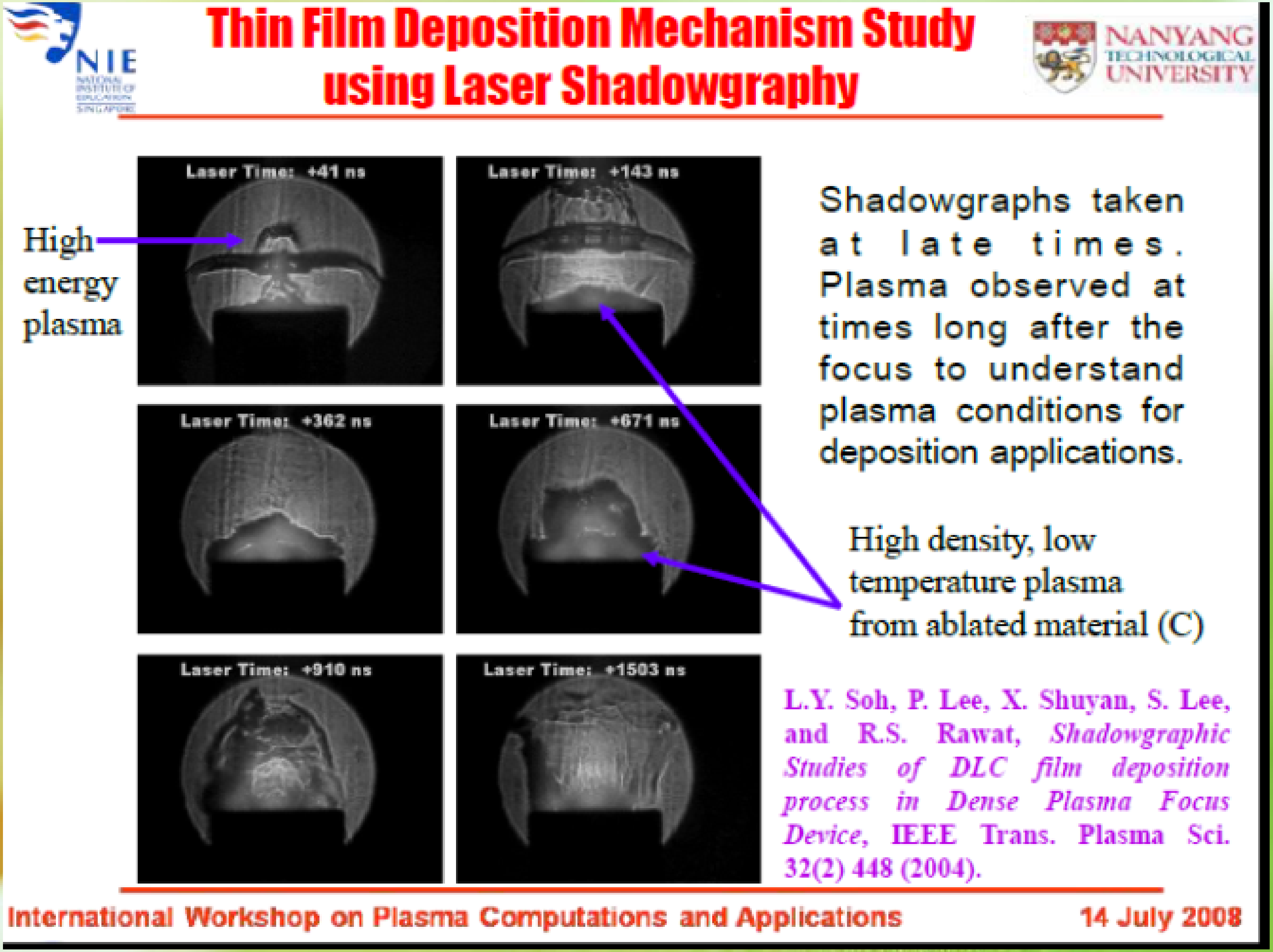
[S Lee et al J Fiz Mal 6, 33 (1985)] -10 kJ PF



Slow Copper plasma jet 2cm/μs M20, 0.2 mg copper carrying 50J KE (300 eV copper ions)



Preliminary observations of sputtered deposits on a flat glass plate indicate the possibility of depositing areas of very clean film of copper by this method. These observations also raise the possibility of producing plasma jets of other materials by simply placing an insert of the desired material in the anode cavity so that this insert may then be bombarded by the relativistic electron beam. This technique may have useful applications.



Thin Film Deposition Mechanism Study using Laser Shadowgraphy

High energy plasma

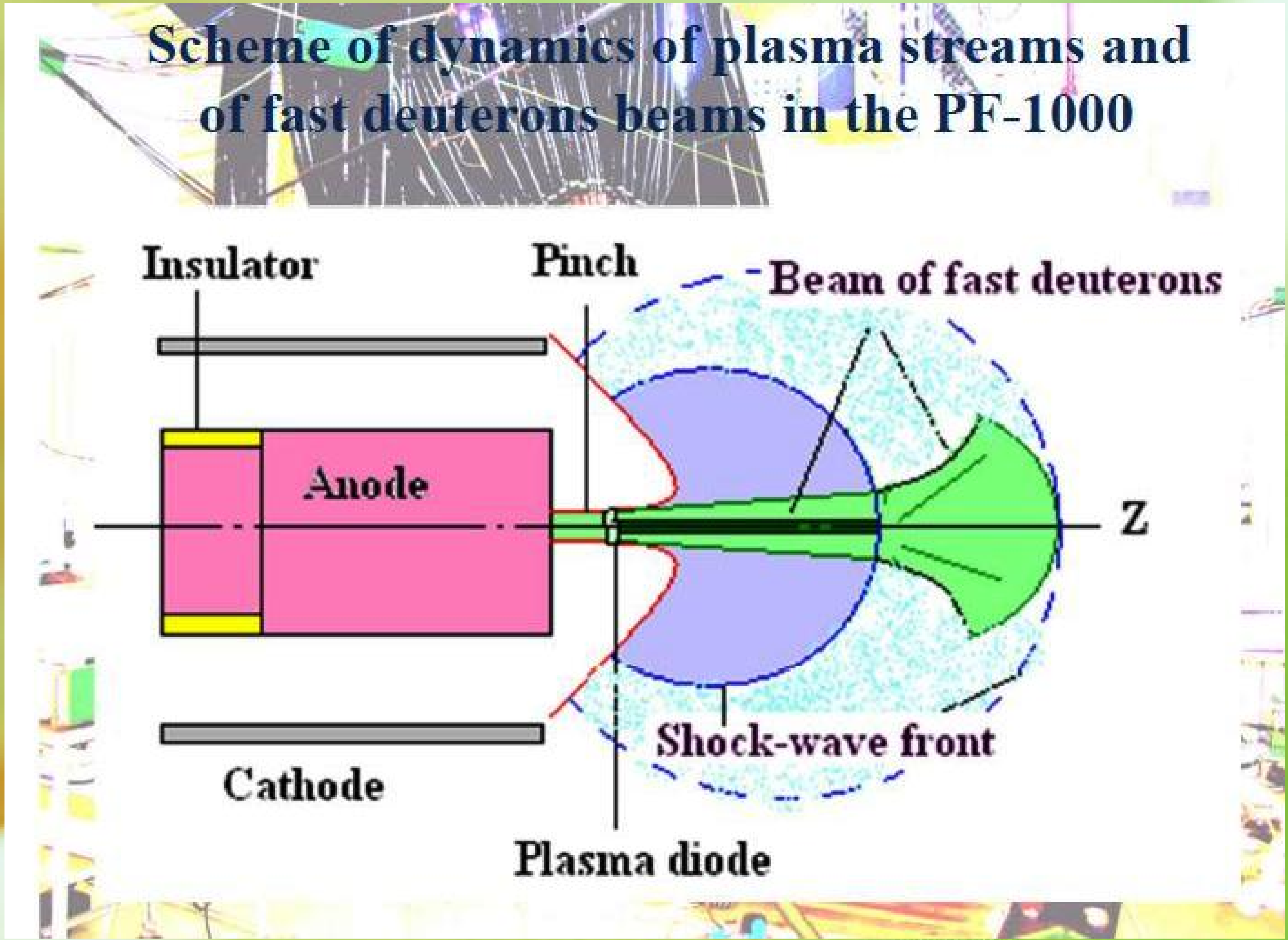
Shadowgraphs taken at late times. Plasma observed at times long after the focus to understand plasma conditions for deposition applications.

High density, low temperature plasma from ablated material (C)

L.Y. Soh, P. Lee, X. Shuyan, S. Lee, and R.S. Rawat, *Shadowgraphic Studies of DLC film deposition process in Dense Plasma Focus Device*, IEEE Trans. Plasma Sci. 32(2) 448 (2004).

International Workshop on Plasma Computations and Applications 14 July 2008

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

1997 ICDMP (International Centre for Dense Magnetised Plasmas) Warsaw-now operates one of biggest plasma focus in the world, the PF1000

PF1000 40kV 1332uF 9nH 1.1MJ Io= 15MA

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

Flux =fluence/pulse duration

- Beam **number flux $\mathbf{F_{ib}\tau}$** defines (ions $m^{-2}s^{-1}$)
- Beam **energy flux** defines (W m^{-2})

Our starting point: the mechanism described by V. A. Gribkov et al in J Phys. D 40, 3592 (2007)

- Beam of fast deuteron ions produced by diode action in thin layer close to the anode; plasma disruptions generating the high voltages. Beam interacts with the hot dense plasma of focus pinch column to produce the fusion neutrons.
- In our modeling of the neutron yields, each factor contributing to the yield is estimated as a proportional quantity. The yield is obtained as an expression with proportionality constant. The neutron yield is then calibrated against a known experimental point.(NESSIon-like)
- We start with the neutron yield (rather than the ion beam number) because our method requires a calibration point; and for neutron yields by placing published yields on a chart we can obtain a good fitted calibration point. **Had we started with the D ion beam number, we would not have been able to get a reliable calibration point**

The Beam-Target neutron Yield

- The beam-target yield is written as:

$$Y_{b\text{-}t} \sim n_b\, n_i\, (r_p{}^2 z_p)\, (\sigma\, v_b)\, \tau$$

n_b = number of beam ions/ plasma volume traversed,

n_i = pinch ion density,

r_p = radius of the plasma pinch with length z_p,

σ = cross-section of the D-D fusion reaction,

v_b = beam ion speed and

τ = beam-target interaction time assumed proportional to the confinement time of the plasma column

We first derive the equation for beam-target neutron yield which can be calibrated against a reliable neutron yield point

- Total beam energy~ $L_p I_{pinch}^2$, pinch inductance energy,

  L_p= focus pinch inductance.

  Thus number of beam ions $N_b \sim L_p I_{pinch}^2 / v_b^2$;

  n_b is N_b divided by the focus pinch volume; $L_p \sim \ln(b/r_p) z_p$, $r_p \sim z_p$, and $v_b \sim U^{1/2}$; U is the disruption-caused diode voltage; and

  U~ V_{max}, the maximum voltage induced by the current sheet collapsing radially towards the axis; 'b' is the cathode radius

- Hence : $\mathbf{Y_{b-t} = C_n\, n_i\, I_{pinch}^2 z_p^2 ((\ln b/r_p)) \sigma / U^{1/2}}$ **(1)**

  I_{pinch} = pinch current; r_p and z_p are pinch dimensions.

  C_n is a constant which in practice we calibrate with an experimental point.

The beam average ion energy

- The D-D cross-section is highly sensitive to the beam energy so it is necessary to use the appropriate range of beam energy to compute σ. The code computes V_{max} of the order of 20-50 kV. However it is known, from experiments that the ion energy responsible for the beam-target neutrons is in the range 50-150keV, and for smaller lower-voltage machines the relevant energy could be lower at 30-60keV.

- Thus to align with experimental observations the D-D cross section σ is reasonably obtained by using beam energy

  $U = n\ V_{max}$, where n is in the region of 2-4.

Calibrating C_n and fitting for average ion energy factor n

- A plot of experimentally measured neutron yield Y_n vs I_{pinch} was made combining all available experimental data.
- This gave a fit $Y_n=9\text{x}10^{10}I_{pinch}^{3.8}$ for I_{pinch} range 0.1-1MA. From this plot a calibration point was chosen at 0.5MA, $Y_n=7\text{x}10^9$ neutrons [NESSI-like point].
- The model code RADPFV5.13 was thus calibrated to compute $Y_{b\text{-}t}$ which in our model is the same as Y_n.

  with $C_n = 8.5\text{x}10^8$; All SI units
- During this calibration process, the numerical experiments were tested against the experimental data by using U=n V_{max} with n varied from 1 to 5. The best fit of computed yield against experimental yield was found when **n=3.**

Having calibrated the $Y_{b\text{-}t}$ equation we can now deal with the D beam fluence

- We note, as used in deriving the neutron yield Eqn (1) that for a beam passing through a plasma target, by definition,
- cross-section= reaction rate/(beam ion number flux x number of target particles). We re-write Equ (1) using this definition.

We obtain:

- $$Y_{b\text{-}t} = (n_b\, v_b)[\, n_i\, (\pi r_p{}^2 z_p)\tau]\sigma = (J_b\tau)\sigma\, n_i(\pi r_p{}^2 z_p) \qquad (2)$$

where $Y_{b\text{-}t}$ /t is the D-D fusion reaction rate,

$J_b=n_b v_b$ is the beam ion flux with units of (number of ions $m^{-2}s^{-1}$),

The number of plasma target particles= $n_i\ (\pi r_p{}^2 z_p)$,

n_i being the target plasma ion density; and

τ = beam-target interaction time assumed= confinement time of the plasma column.

Equation for the beam ion fluence

We denote:

$J_b\tau$ as the beam ion fluence with units of (number of ions m^{-2}).

This is the ion fluence that is generated by the inductive plasma diode action. **From equations (1) and (2)** we write the ion fluence as:

- $J_b\tau = C_n I_{pinch}^2 z_p (\ln b/r_p)/(\pi r_p^2 U^{1/2})$ **ions m^{-2}** **(3)**

Modelling the Fluence

Ion beam number fluence is derived from beam-plasma target considerations as:

$$F_{ib}\tau = C_n I_{pinch}^2 z_p[\ln(b/r_p)]/(\pi r_p^2 U^{1/2}) \quad \text{ions m}^{-2}$$

$C_n = 8.5\times10^8$; All SI units

I_{pinch}=pinch current

z_p=pinch length

b=outer electrode, cathode radius

r_p=pinch radius

U=beam energy in eV where in this model U=3 V_{max} (max dynamic induced voltage)

These focus properties are computed by our code so that for each shot we may determine the fluence

Example: Numerical Experiment for PF1000 based on following fitted parameters:

L_0=33 nH, C_0=1332 uF, r_0=6.3 mΩ
b=16 cm, a= 11.6 cm, z_0=60 cm
f_m=0.14, f_c=0.7, f_{mr}=0.35, f_{cr}=0.7 V_0=27 kV,

P_0= 3.5 Torr MW=4, A=1, At=2 for deuterium

Results are extracted from dataline after shot:

- $I_{pinch}=8.63\times10^5$ A,
- z_p=0.188 m, b/r_p=16 cm/2.23 cm, $\ln(b/r_p)$=1.97,
- U=3Vmax=$3\times4.21\times10^4=1.26\times10^5$ V

Example: Numerical Expt for INTI PF based on following fitted parameters:

L_0=110 nH, C_0=30 uF, b=3.2 cm, a= 0.95 cm, z_0=16 cm r_0=12 mΩ
f_m=0.073, f_c=0.7, f_{mr}=0.16, f_{cr}=0.7

V_0=15 kV, P_0= 3Torr MW=4, A=1, At=2 for deuterium

Results are extracted from dataline after shot:

$I_{pinch}=1.22\times10^5$ A,

z_p=0.014 m, b/r_p=3.2cm/0.12 cm, $\ln(b/r_p)$=3.28;

$U=3V\max=3\times2.52\times10^4=0.756\times10^5$ V

From the above; estimate ions/m^2 per shot

For PF1000 (at 500 kJ) we obtained

$J_b\tau$ =4.3x10^{20} ions/m^2 per shot

=**4.3x10^{16} ions/cm^2 per shot at 126 keV**

For INTI PF (at 3 kJ) we obtained

$J_b\tau$ =4.7x10^{20} ions/m^2 per shot

=**4.7x10^{16} ions/cm^2 per shot at 76 keV**

Fluence $J_b\tau$ is the same for small and big PF

Computing for various fitted plasma focus in energy range 0.4 – 500 kJ we obtain the following table:

Table 1: Parameters of a range of Plasma Focus and computed Ion Beam characteristics

Latest

Machine	PF1000	DPF78	NX3	INTIPF	NX2	PF-5M	PF400J
E_0 (kJ)	486	31.0	14.5	3.4	2.7	2.0	0.4
L_0 (nH)	33	55	50	110	20	33	40
V_0 (kV)	27	60	17	15	14	16	28
'a' (cm)	11.50	4.00	2.60	0.95	1.90	1.50	0.60
c=b/a	1.4	1.3	2	3.4	2.2	1.7	2.7
I_{peak} (kA)	1846	961	582	180	382	258	129
I_{pinch} (kA)	862	444	348	122	220	165	84
z_p (cm)	18.8	5.5	3.8	1.4	2.8	2.3	0.8
r_p (cm)	2.23	0.62	0.4	0.13	0.31	0.22	0.09
t (ns)	255	41.0	36.5	7.6	30.0	12.2	5.1
V_{max} (kV)	42	68.3	35	25	22	32.3	18

Latest

Machine	PF1000	DPF78	NX3	INTI	NX2	PF5M	PF400J
IB Ion Fluence (x10^{20}m^{-2})	3.9	3.2	5.7	3.6	3.4	2.4	2.6
IB Ion Flux (x10^{27}m^{-2}s^{-1})	1.5	7.8	15.6	46.7	11.5	19.6	50.4
Mean Ion Energy (keV)	126	205	105	75	66	97	54
IB Energy Fluence (x10^{6} J m^{-2})	7.8	10.6	9.6	4.3	3.6	3.7	2.2
IB Energy Flux (x10^{13} W m^{-2})	3.1	25.8	26.3	56.4	12.0	30.6	43.2
Ion Number (x10^{14})	6100	390	280	19	110	37	5.9
IB Energy (J)	12248	1284	479	23	111	58	5.1
(% E$_0$)	(2.5)	(4.1)	(3.3)	(0.7)	(4.1)	(2.8)	(1.3)
IB current (kA)	380.0	152.4	124.8	40.0	56.7	49.1	18.6
IB Damage Ftr (x10^{10} Wm^{-2}s$^{0.5}$)	1.6	5.2	5.0	4.9	2.1	3.4	3.1
Ion Speed (cm/ms)	347	443	317	269	250	305	226
Ion Number per kJ (x10^{14})	12.6	12.7	19.4	5.6	40.1	18.1	15.1
Plasma Stream Energy (J)	39120	394	1707	249	369	92	17
(% E$_0$)	(8.1)	(1.3)	(12.0)	(7.4)	(13.7)	(4.5)	(4.5)
Plasma Stream Speed (cm/μs)	18.2	23.1	24.2	47.4	20.1	48.6	35.7

Summary of range of ion beam properties and suggested scaling

Ion Beam Property	Units (multiplier)	Range	Suggested Scaling
Fluence	Ions m^{-2} ($x10^{20}$)	2.4 – 7.8	independent of E_0
Average ion energy	keV	55 - 300	independent of E_0
Energy Fluence	J m^{-2} ($x10^{6}$)	2 - 33	independent of E_0
Beam exit radius	fraction of radius 'a'	0.14 - 0.19	scales with 'a'
Beam Ion number	Ions per kJ ($x10^{14}$)	12 - 40*	scales with E_0
Beam energy	% of E_0	1.3 – 5.4^{+}	scales with E_0
Beam charge	mC per kJ	0.2 - $0.4^{\#}$	scales with E_0
Beam duration	ns per cm of ‘a’	8 – 20	scales with ‘a’
Flux	ions m^{-2} s^{-1} ($x10^{27}$)	1.5 – 50	independent of E_0
Energy flux	W m^{-2} ($x10^{13}$)	3 – 56	independent of E_0
Beam current	% of I_{peak}	14 – 23	scales with I_{peak}
Damage Factor	($x10^{10}$ $Wm^{-2}s^{0.5}$)	1.6 – 11	independent of E_0

*= 6 for INTI PF

$^{+}$= 0.7 for INTI PF

$^{\#}$= 0.1 for INTI PF

Ion Beam Benchmarks: Mather PF **Latest**

- ion number fluence: **2-6 x 10^{20} ions m^{-2}**
- The number of beam ions: **12-20 x 10^{14} beam ions per kJ** for PF's with typical static inductances L_0 of 33-55 nH.
- Total beam energy: **1.3-4 % E_0** for PF's with L_0 of 20-55 nH.
- Beam current: **14-22 % of I_{peak}**.
- Beam energy fluence: **2-11x10^{6} J m^{-2}**
- Beam Energy Flux: **3-57x10^{13} W m^{-2}**

The independence from E_0 of the ion beam fluence is likely related to the constancy of energy density (energy per unit mass) that is one of the key scaling parameters of the PF throughout its

E_0 range of sub kJ to MJ[14,28].

Conclusion

From numerical experiments integrated with experimental measurements of current traces we establish benchmarks and scaling laws for Iob Beam number and energy fluence and fluxes:

- Ion number fluence: 2.4-5.7 x 10^{20} ions m^{-2}; independent of E_0
- Energy fluence : 2.2-10.6 x10^6 J m^{-2} ; independent of E_0
- Plasma focus (33-55 nH) produce 1.2-2 x 10^{15} ions per kJ carrying 1.3-4 % E_0 at mean ion energy 50-200 keV; higher L_0 giving lower number per kJ.

Benchmarks are also set for beam ion currents, beam damage factor and plasma stream energies as % of storage energies.

Thank You

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