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THE SLOW FOCUS MODE IN PLASMA FOCUS FOR FAST PLASMA STREAM NANO-MATERIALS FABRICATION: SELECTION OF ENERGY OF BOMBARDING PARTICLES BY PRESSURE CONTROL

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ABSTRACT

As a radiation source the plasma focus PF is operated in time-matched regime TMR. Maximum energy is pumped into the compression, resulting in large inductive voltages V_{max}, high temperatures and copious multi-radiations. In this Fast Focus Mode (FFM), targets in front of anode are subjected to strong bursts of fast ion beams (FIB), post-pinch fast plasma streams (FPS) followed by materials exploded off the anode by relativistic electron beams (REB). In INTI PF in hydrogen, as operational pressure P is increased beyond TMR, dynamics slows, minimum pinch radius ratio k_{min} increases, V_{max} decreases, FIB reduces in energy per ion U, in beam power P_{FIB} and damage factor D_{FIB}, as operation moves from FFM into Slow Focus Mode (SFM). This is the same pattern for other gases; but for Ar, Kr and Xe, radiative collapse becomes dominant, past the TMR. As P is increased further, there comes a point (slowest SFM or SSFM) where compression is so weak that outgoing reflected shock barely reaches the incoming piston. At SSFM k_{min} is maximum (typically > twice that at FFM), V_{max}, P_{FIB} and D_{FIB} are low and we expect great reduction of anode boil-offs. However FPS energy is near its highest. Operation near SSFM reduces FIB damage and anode sputters on-target; allowing largest area of interaction, primarily with the FPS. The above is surmised from RADPF FIB code. Recent experiments in INTI PF confirm experimental observations (Rawat, private communication 2013) that such high pressure operations produce bigger area of more uniform interaction. This should improve production of nano-materials e.e carbon nano-tubes on graphite substrate. Operational pressure may be used to select FPS particle energy enabling control of bombarding particle energy, in range tens to hundreds of eV; and thus contribute to make PF materials technology more of a science than the present state-of-the-art.

Keywords: Plasma Focus Modes, Plasma Focus Damage Studies, Plasma Focus Materials Studies, Particle Energy Control and Selection, Ion Beam Code, Fast Plasma Stream

INTRODUCTION

To capture time-resolved images of the focus pinch an exposure time of 1 ns is necessary to freeze the motion to less than 0.3 mm (since the highest speed of the current sheet is expected to be around 30 cm/μs (or 0.3 mm/ns). A collimated laser beam with an exposure time of 1 ns is shone through the plasma focus (side-on) and the shadow of the moving plasma is cast onto a recording CCD. The plasma self-light is filtered away. The time of the laser pulse is adjustable. A composite sequence of shots is obtained [1] as shown in Fig 1. The time of the image is recorded on top of the image with t=0 being the time when the plasma focus pinch is judged to be at its most compressed state.

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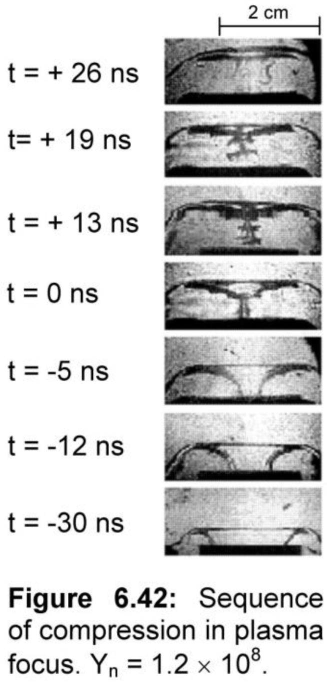

Figure 1. A composite sequence [1] of the radial implosion dynamics of the plasma focus (anode shown pointing upwards). Highest pre-pinch radial speed>25cm/us M250

From this sequence the average speed of implosion from a=8mm (t=-30 ns) to a~0.5 mm (t=0) is found to be 0.25 mm/ns or 25 cm//μs. The peak speed is more as the current sheet is accelerating as it speeds inwards. Taking the speed of 25 cm/μs, due to the equipartition of energy in a shock the on-axis temperature is immediately found to be $1.5\text{x}10^6$K; and on shock reflection, all the kinetic energy is stagnated causing the column to reach a temperature of $3\text{x}10^6$K. The instability break-up of the column is seen in the last 3 frames.

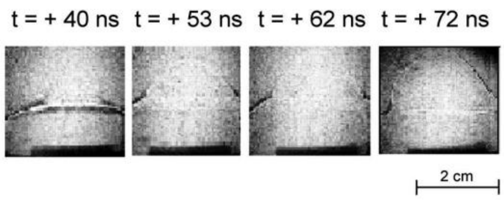

Figure 2. A sequence showing post focus axial shock waves blown out from the pinch [6] (anode shown pointing up) **Highest post-pinch axial shock waves speed ~50cm/us M500**

In Fig 2 the anode is shown pointing. This sequence [1] follows that of the inward implosion and instability break-up of the pinch. This post-focus sequence shows that 14 ns after the

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break-up (shown in the sequence of Fig 1) a fast shock wave is shot out from the focus region traversing 9 mm in 22 ns or 40 cm/μs.

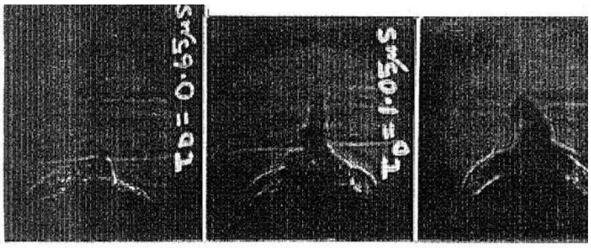

Figure 3. Composite sequence [2] showing anode-sputtered copper plasma jet occurring at a later time (anode shown pointing up)

Figure 3 shows a sequence of shadowgraphs taken at a much later time from 0.65 μs (t=+650 ns) to 1.75 μs. Measurements [2] show that this copper jet comes from material sputtered from the anode by the electron beam. This copper jet travels much more slowly at 2 cm/μs containing ¼ mg of copper carrying 50 J of kinetic energy

FFM mode

The above shadowgraphic sequences give an idea of the speed of the plasma focus radial phases and post pinch axial dynamics. The radiations from the plasma focus are produced for the 3 kJ PF from -5ns to +26 ns (Fig 1). First the soft x-rays which is characteristic of the gas (particularly in gases from nitrogen upwards in atomic number) start to be emitted just before t=0; the ion beams emitted in a downstream direction and the electron beam in the opposite direction towards the anode; and the neutrons (from deuterium pinches) are emitted just after t=0; as are the hard x-rays (see schematic of Fig 4). The high speed axial shock waves (Figure 2) carrying considerable energy and the associated post-pinch plasma streaming and then the slower jet from anode sputtered materials (see Fig 3) constitute the final products of the plasma focus phenomenon. The use and control of these 'streaming death' products are proving of importance for plasma focus materials modification, fabrication and deposition as thin films. The speed of the dynamics of the radial compression of the plasma focus pinch is adjustable using the operational pressure. For efficiency in coupling capacitor energy into the radial plasma pinch the pressure is adjusted until the pinch occurs at about the time of peak current or a little after. This is termed time-matching. When the PF is time-matched the dynamics is fast and the plasma compression is characterized by efficient energy coupling. This mode is described by the term FFM (Fast Focus Mode) with current waveform and radial trajectories computed from the Lee Model code [4-6] as shown in Fig 5.

The operational pressure may be increased above that of the pressure at FFM. As the pressure is increased, the compression becomes weaker as the dynamics slows. We say that the PF is moving from the FFM to the slow focus mode SFM. When the pressure in increased too much, the pinch may not form at all.

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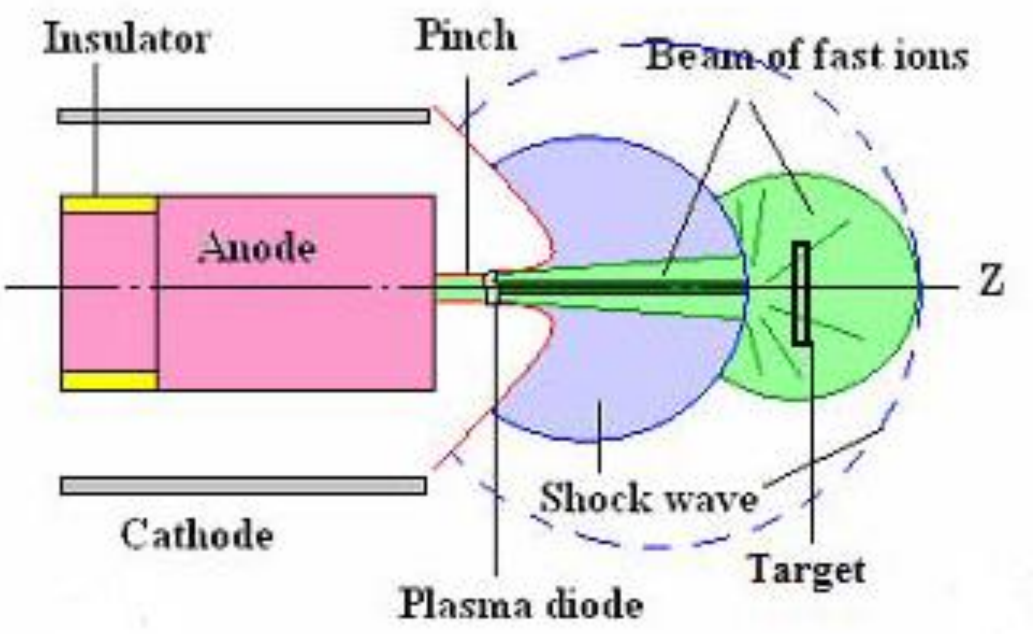

Figure 4. PF is typically operated in FFM, with a schematic of FIB abd FPS.[3]

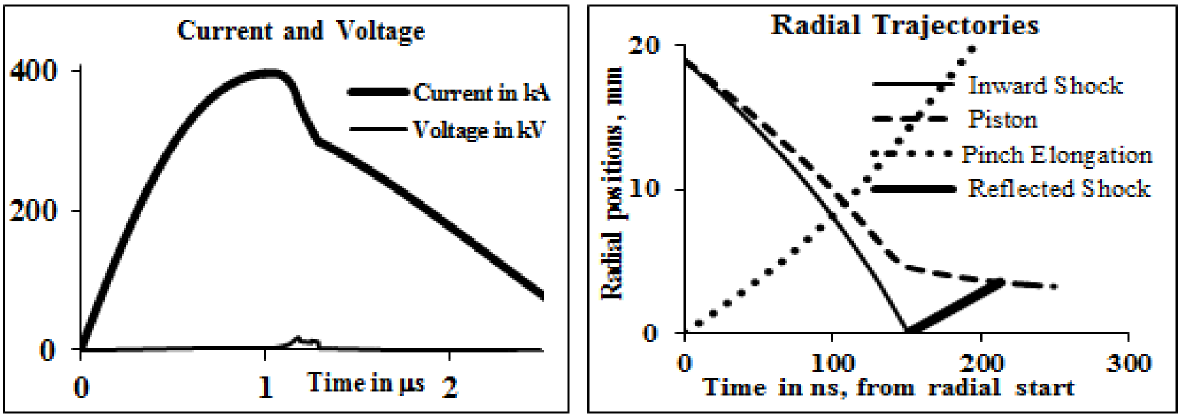

Figure 5. Current waveform and radial trajectories of PF in FFM.

From FFM to SFM- High Pressure Operation in SFM

We carry out numerical experiments on the INTI PF at 15 kV to determine the optimum pressure for energy coupling from capacitor back to plasma pinch in time-matched FFM. The results are shown in Fig 5. We notice that at FFM the reflected shock coming off the axis meets the incoming magnetic piston which then continues to compress the column since the magnetic piston is still strongly driven by the large current (see Fig 5). We define the moment the reflected shock meets the incoming piston as the start of the pinch. As the operational pressure is increased the radial compression slows, the reflected shock reaches the magnetic piston which is weakening since it is driven by reduced current which has dropped considerably from peak value. At 22 Torr the piston is pushed out by the reflected shock,

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abruptly ending the compression. The code shows that **24.3 Torr (Fig 6c) is the SSFM slowest SFM**; since a further increase in pressure to 24.4 Torr produces no pinch at all, the piston already moving outwards before the reflected shock meets it; accelerating away from the axis so rapidly that the reflected is not able to meet it at all. However note that we are using fixed fm, fc, fmr, fcr determined for typical FFM operation. In the laboratory we may likely find this SSFM region nearer to 10 Torr than 24 Torr.

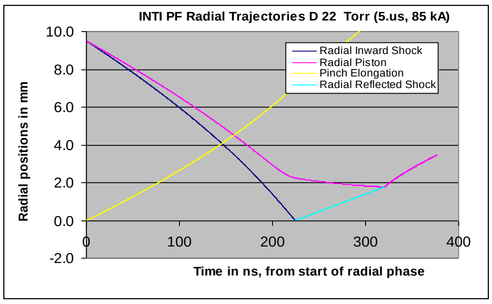

Figure 6a

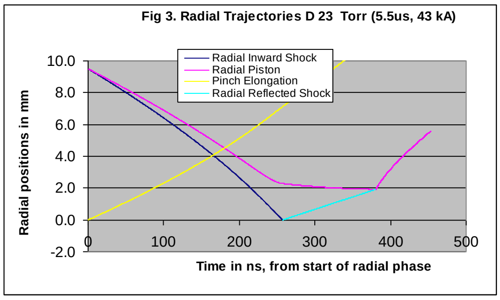

Figure 6b

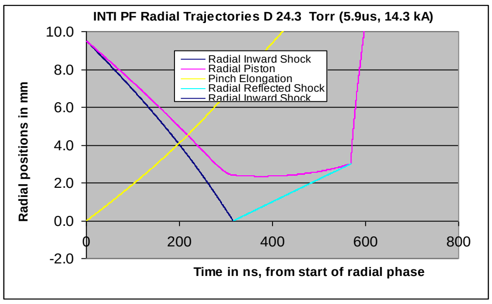

Figure 6c

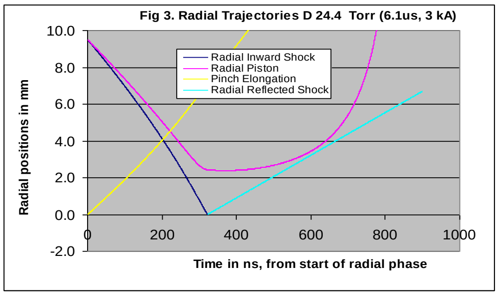

Figure 6d.

Figure 6. Interaction of magnetic piston with reflected shock as pressure increases towards SSFM.

Beam ion energy-Ion Beam Properties

We use our latest code version RADPF.FIB (8,9] which besides giving us all the properties of the dynamics and pinch plasma also yields information on the fast ion beams FIB and fdast plasma stream FPS. The results show that as the pressure is increased from FFM towards SFM, pinch radius ratio k_{min} increases with P; with k_{min}=0.15 (Fig 7). As the compression speed decreases, the induced voltages decrease and energy per FIB ion drops becoming 20 keV at 15 Torr (Fig 8). We note that operation at presssures higher than 15 Torr gives bigger source (ie bigger k_{min}) and lower FIB ion energy. Moreover, at P>15 Torr, Ion beam power flow (Fig 9) and Damage factor (Fig 10) < ¼ peak values and drop rapidly beyond 15 Torr.

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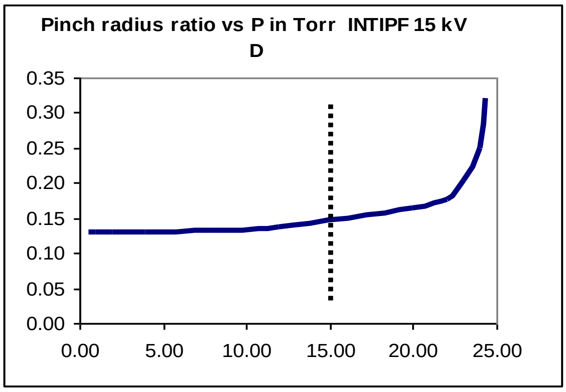

Figure 7 Radius ratios vs P

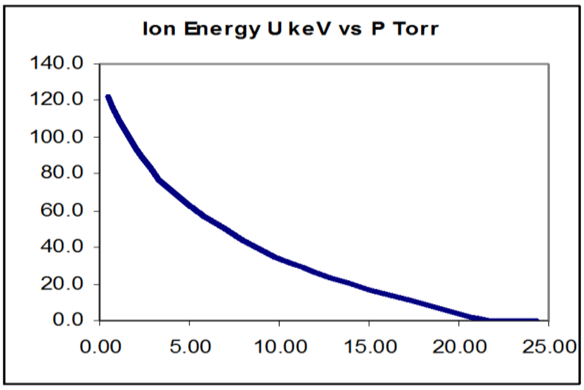

Figure 8. FIB Ion energy vs P

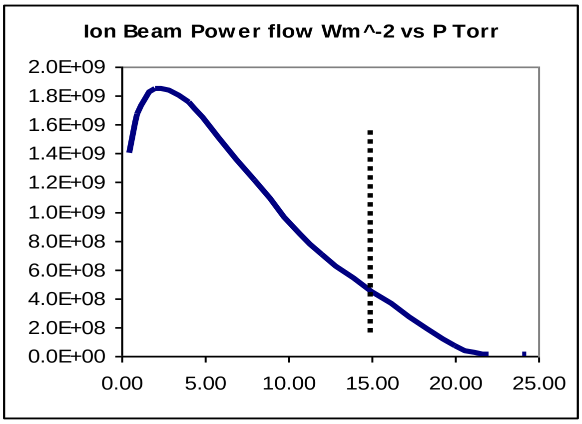

Figure 9. Ion beam power vs P

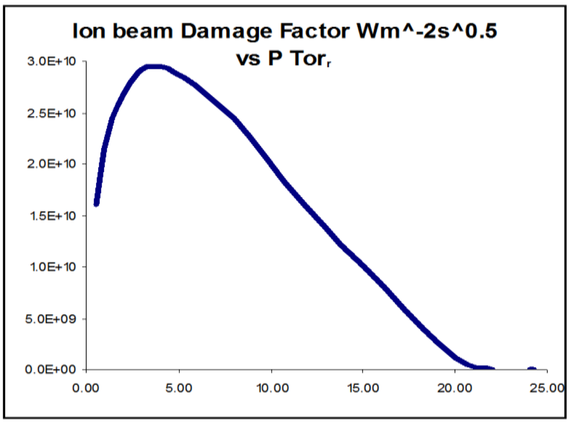

Figure 10. Ion Beam Damage Factor vs P

Contrary to the dramatic decrease in the effects of the FIB at higher pressures the fast plasma stream FPS energy is not reduced at higher P remaining near peak value throughout the whole range of pressure (Fig 11). Moreover the energy per FPS ion is between 800 eV and 30 eV from 10 Torr to 20 Torr (Fig 12). This may be a good range of ion energy to work on graphite surface for production of nano-materials.

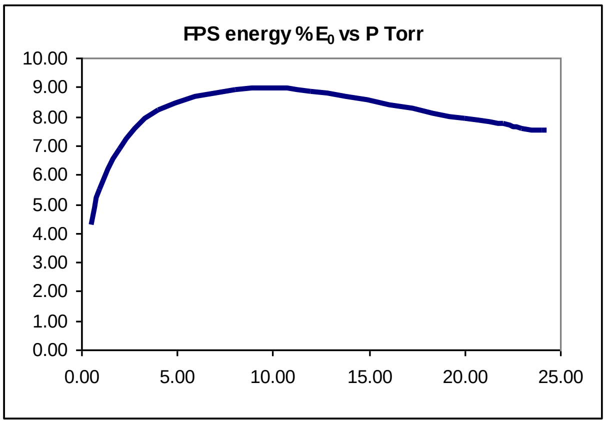

Figure 11. FPS energy vs P

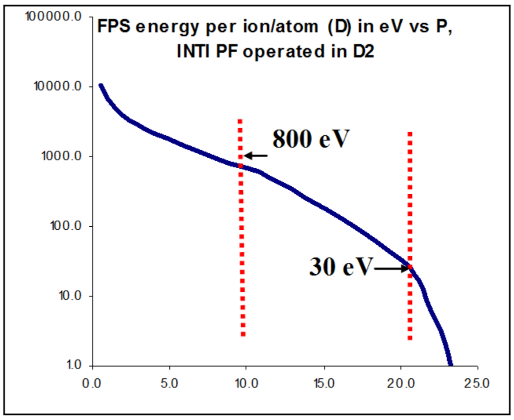

Figure 12 FPS energy per ion/atom vs P

CONCLUSION

FFM:

- target interaction dominated by high ion beam power and anode impurities
- each beam ion high energy; causes explosive impact on target surface;
- large FIB damage factor
- flow source (hence interaction area) relatively small

SFM:

- target interaction dominated by FPS,
- each beam ion lower energy; less explosive impact
- each FPS ion ~50 eV energy per
- interaction area increased several times

Moreover the selection of energetic particles may be effected simply by setting the operational pressure. These are results from numerical experiments and seem to agree with the experience of experiments carried out in plasma focus machines at NTU/NIE Plasma Radiation Laboratory. The above comparative features need to be more thoroughly tested.

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REFERENCES

[1] Muhammad Shahid Rafique. *Compression Dynamics and Radiation Emission from a Deuterium Plasma Focus.* PhD thesis Nanyang Technological University, Singapore (2000).

[2] Lee S, Ahmad H, Tou T Y, Kwek K H & Wong C S, Dynamics of REB-sputtered copper plasma jets. *J. Fiz. Mal., Malaysia* 6(1985) 23-28

[3] Pimenov V N, Dubrovsky A V, Demina E V, Gribkov V A, Latyshev S V, Maslyaev S A, Sasinovskaya I P, & Scholz M, "Innovative Powerful Pulsed Technique, Based on a Plasma Accelerator, for Simulation of Radiation Damage and Testing of Materials for Nuclear Systems." © IAEA; Published in http://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/papers/at_p5-04.pdf (2013)

[4] Lee S, Radiative Dense Plasma Focus Computation Package: RADPF. http://www.plasmafocus.net; http://www.intimal.edu.my/school/fas/UFLF/(archival websites) (2013)

[5] Lee S in *Radiation in Plasmas* Vol II, Ed B McNamara, Procs of Spring College in Plasma Physics (1983) ICTP, Trieste, p. 978-987, ISBN 9971-966-37-9, Published World Scientific Pub Co, Singapore (1984)

[6] Lee S , *J Fusion Energy* 33, 319-335 (2014) (10.1007/s10894-014-9683-8

[7] Saw S H, Damideh V, Lee P, Rawat R S & Lee S, "A 160 kJ Dual Plasma Focus (DuPF) for Fusion- Relevant Materials Testing and Nono-Materials Fabrication, *Accepted for publication by International J Mod Phys: Conference series* (2014)

[8] Lee S & Saw S H, *Phys. Plasmas* 19, 112703 (2012); http://dx.doi.org/10.1063/1.4766744

[9] Lee S, Saw S H *Phys. Plasmas* 20, 062702 (2013); doi: 10.1063/1.4811650.