Plasma focus: novel dense-hot plasma and radiation source for plasma nanotechnology and studying fusion relevant materials under extreme condition

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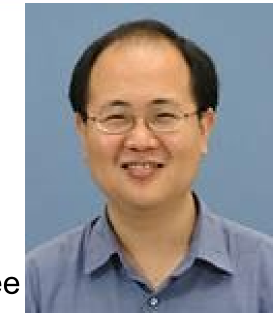
Prof Paul Lee


Prof Stuart Springham

- Over 350 researchers/students trained
- Over $15m Grant received
- Over 400 research publications
- Since 1991

Acknowledgement

PhD Students: Drs Tao Zhang, Lin Jiaji, Shumaila, Zhenying Pan, Wang Ying, Rishi Verma, Tan Kin Seng, Bo Ouyang, Z. Umar, A. Hussnain, I A Khan, S. Mahmood, Sun Ye, Mahmud Roshan, S M P Kalaiselvi

Collaborators: Profs Lee Sing, Riaz Ahmed, Fan Hongjin, R V Ramanuajn, M Jacob, Chen Zhong, S N Piramanayagam

Granting Agencies: MOE Tier 2, MOE Tier 1, NIE AcRF, NTUitive Gap, Industrial Grants, IAEA CRP

PlasmaActivities @ PEARL&PRSL@NIE/NTU

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- **High-temperature High Energy Density Plasmas**
  - Dense Plasma Focus (DPF) Devices
- **Low-temperature Plasmas**
  - Laser Produced Plasmas (PLD)
  - RF/Microwave Plasmas

Outline of Presentation

- Introduction to Dense Plasma Focus (DPF) Device
- Characteristics of Plasma Focus Device
- Applications of DPF as Multiple Radiation Source
- Plasma Focus Device for Plasma Nanotechnology
- Plasma Focus for studying materials under fusion relevant extreme conditions
- Summary

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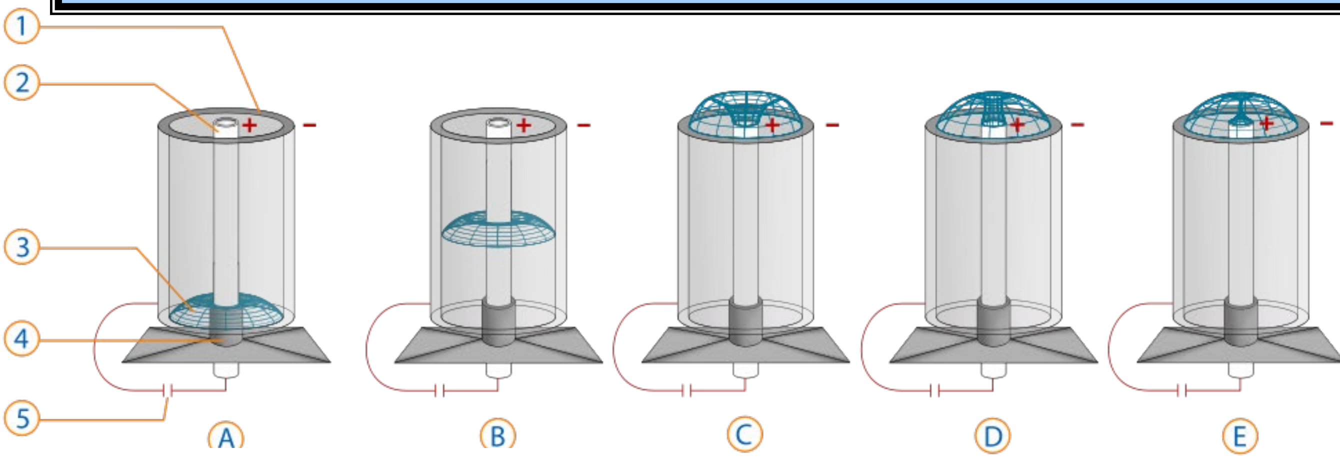
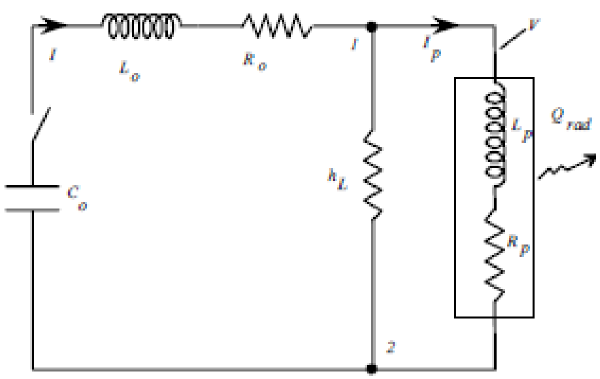
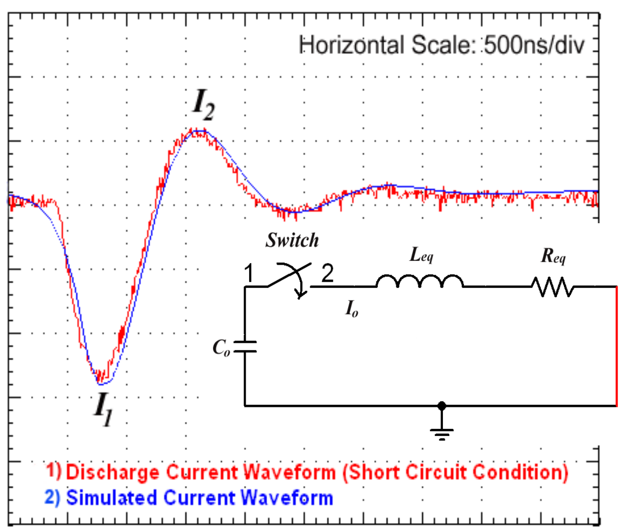
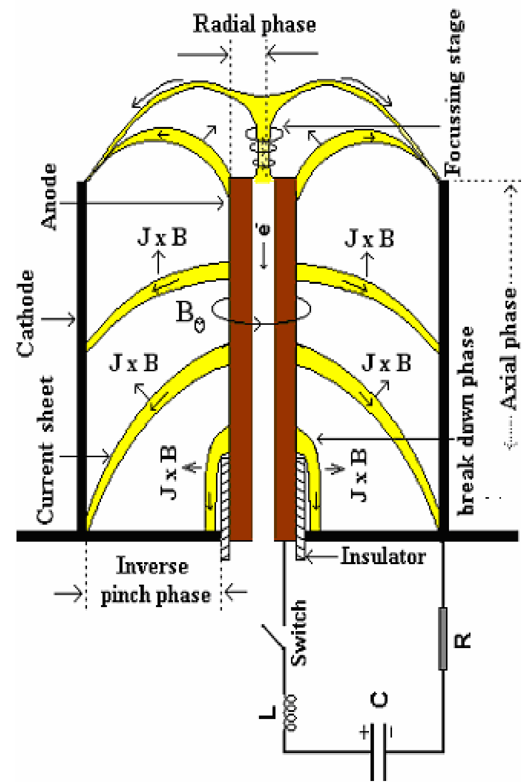
Dense Plasma Focus

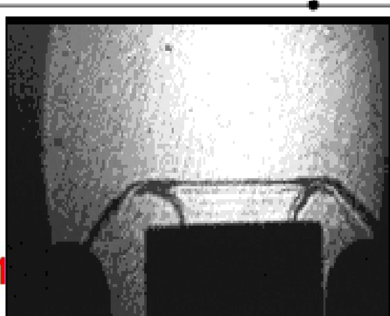
Dense plasma focus device is a coaxial plasma accelerator that produces ***high temperature***, ***high density, short lived plasma***







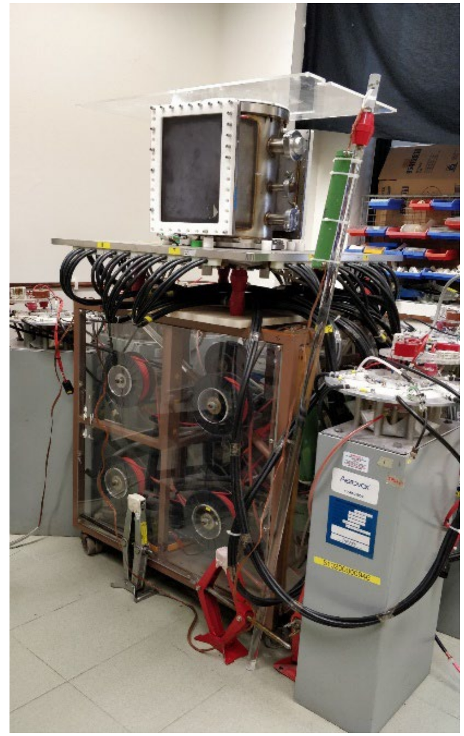




Single Shot DPF Facilities @ PEARL & PRSL

UNU-ICTP DPF
Maximum Operating Voltage: 15kV
Capacitor: 30 μF
Energy: 3 kJ

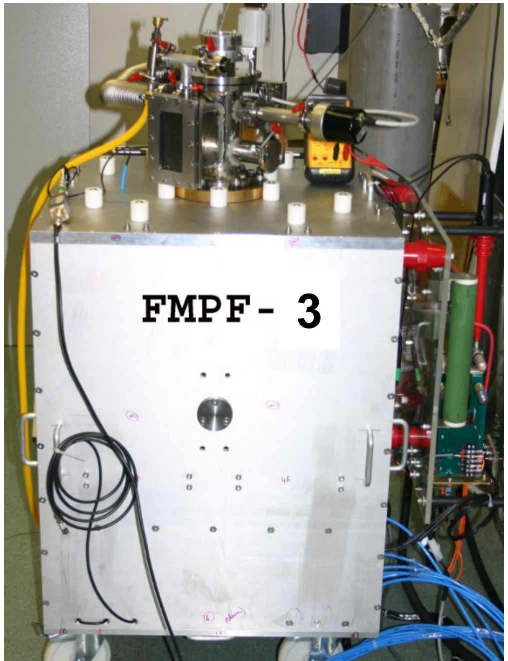
Carbon-ICTP DPF
Maximum Operating Voltage: 15kV
Capacitor: 30 μF
Energy: 3 kJ



NX-3 DPF
Maximum Operating Voltage: 20 kV
Capacitor: 100 μF
Energy: 20 kJ

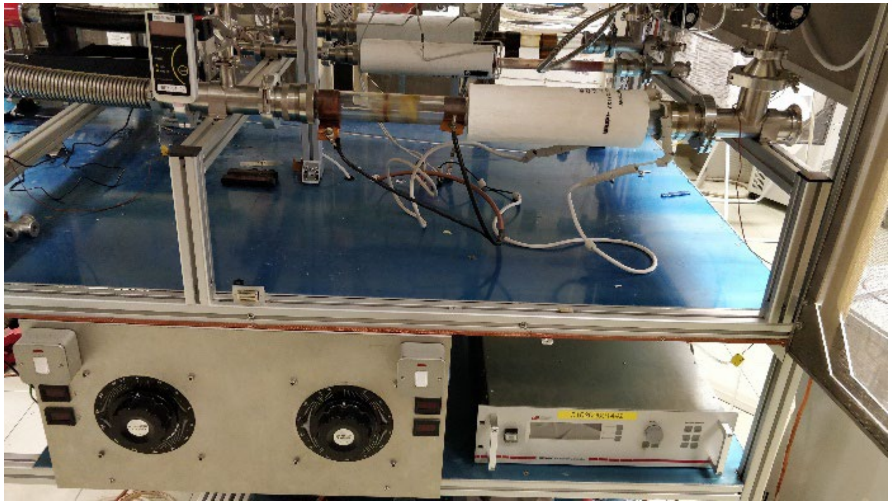
LVSFM DPF
Maximum Operating Voltage: 13 kV
Capacitor: 350 μF
Energy: 40 kJ

Repetitive DPF Facilities @ PEARL & PRSL

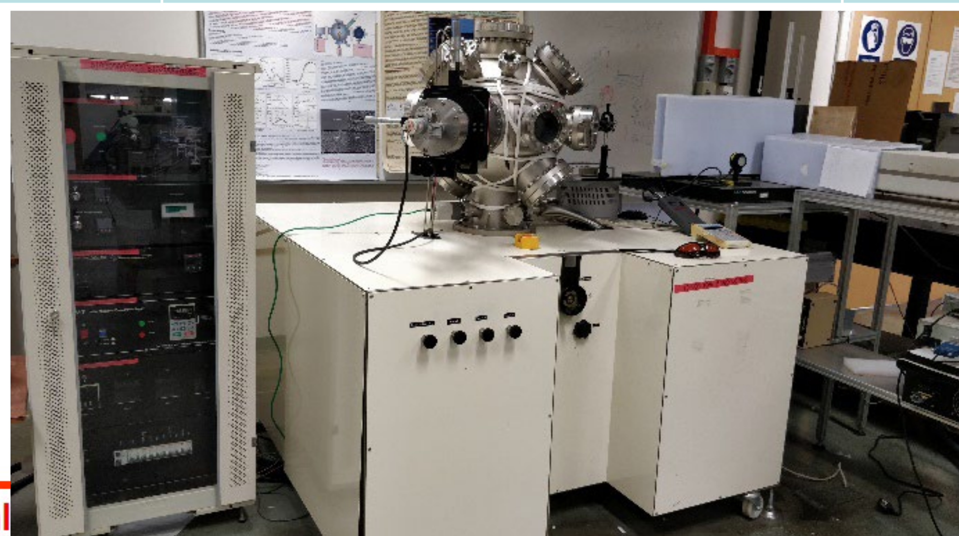


Specifications	FMPF-1	FMPF-2	FMPF-3	NX2
Total capacitance	2.4μF	2.4μF	2.4μF	28.8μF
Capacitance (C_o) × No. of Capacitors	0.6μF × 4	0.3μF × 8	0.3μF × 8	0.6μF × 48
Max. charging voltage (V_o)	30kV	30kV	30kV	20kV
ESL/ESR of capacitor(s)	~70nH/ ~250mΩ	~20nH/ ~80mΩ	~20nH/ ~80mΩ	~26nH/ ~10mΩ
No. of energy transfer switch(s)	1	1	4	4
Switch type/ Model	Trigatron/ Indigenous	Trigatron/ SG-101M-75C	Pseudospark/ TDI1-150k/25	Pseudospark/ TDI1-150k/25
Operating voltage range/ Maximum current handling limit	8 – 18kV/ 100kA	10 – 40kV/ 100kA	3 – 20kV/ 150kA	10-15kV/ 450kA
Max. discharge repetition rate (*PRR*)	1Hz	10Hz	10Hz	16Hz

Other Plasma Facilities @ PEARL & PRSL



PECVD **Max. Temp: 1100deg C** **Max RF Power: 2 kW**	**PLD** **Nd-Yag Laser**	**DC/RF Magnetron Sputtering(AJA)** **4-Gun System**



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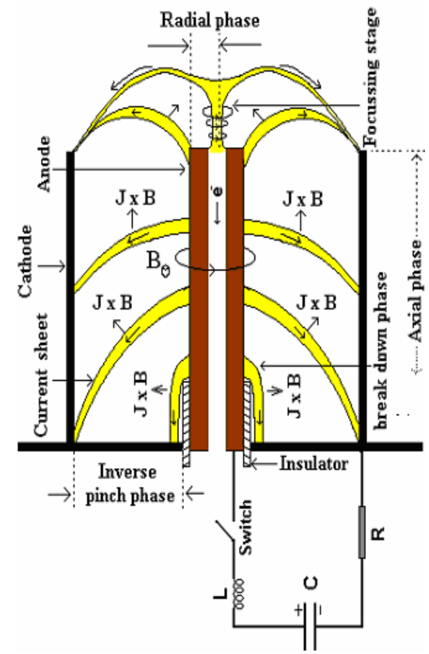
Typical Plasma, charge particle & current sheath parameters in HEDP Plasma Focus Device

- The current sheath speed in axial acceleration phase → **2 to 10 cm/μs** [A, B] which **shock-heats the plasmas to electron and ion temperatures of about 100 and 300 eV**, respectively [C].

- The current sheath speed in radial compression phase → about 2 to 2.5 times that of the axial speed [A] → as high as **25 cm/μs**.

- The electron/ion densities in pinch plasmas have been estimated to be in the range of 5×10^{24} –10^{26} m^{-3} [D, E].



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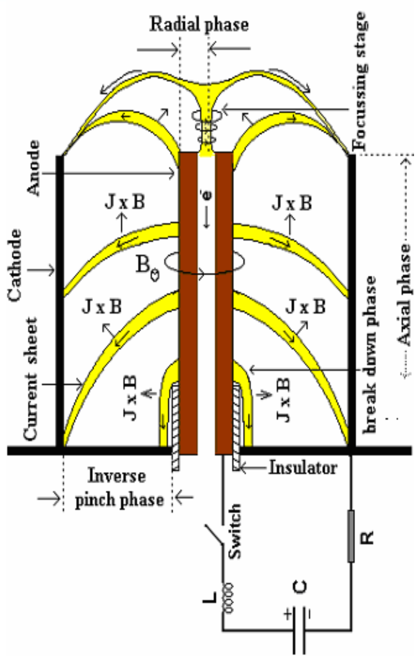
B - H. Krompholz, F. Ruhl, W. Schneider, K. Schönbach and G. Herziger, Physics Letters A 82, 2 (1981).
C - A. J. Toepfer, D. R. Smith and E. H. Beckner, Physics of Fluids 14, 52 (1971).
D - V. A. Gribkov, A. Banaszak, B. Bienkowska, A. V. Dubrovsky, I. Ivanova-Stanik, L. Jakubowski, L. Karpinski, R. A. Miklaszewski, M. Paduch, M. J. Sadowski, M. Scholz, A. Szydlowski, and K. Tomaszewski, Journal of Physics D-Applied Physics 40(12), 3592-3607 (2007).
E - N. Qi, S.F. Fulghum, R.R. Prasad, and M. Krishnan, IEEE Transactions on Plasma Science 26(4), 1127 (1998).

Typical Plasma, charge particle & current sheath parameters in HEDP Plasma Focus Device

- Electron & ion temperatures of pinched plasmas → 200 eV–2 keV [F, G] and 300 eV – 1.5 keV [H], respectively.
- The energies of instability accelerated electrons → tens to few hundreds of keV [I, J].
- The energies of instability accelerated ions → tens of keV to few MeV [K, L]. **The ions are mostly forward directed with most of the ions being emitted in narrow angel of 20° with respect to the anode axis** [M].
- The energy spectrum and yield soft X-rays, emitted by hot dense plasma through bound-bound, free-bound and free-free transitions, is highly dependent on the gas type. Typical wall plug efficiency with neon has been found to be 1-5 %.



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G - N. J. Peacock, M. G. Hobby and P. D. Morgan, in 5th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-28/D-3, Tokyo, (1972).
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J - P. Choi, C. Deeney, H. Herold, C.S. Wong, Laser and Particle Beams 8, 469 (1990).
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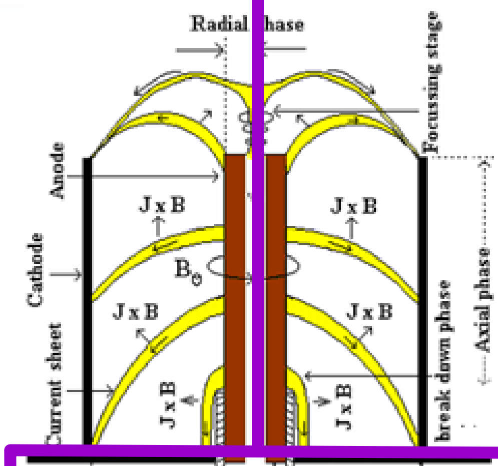
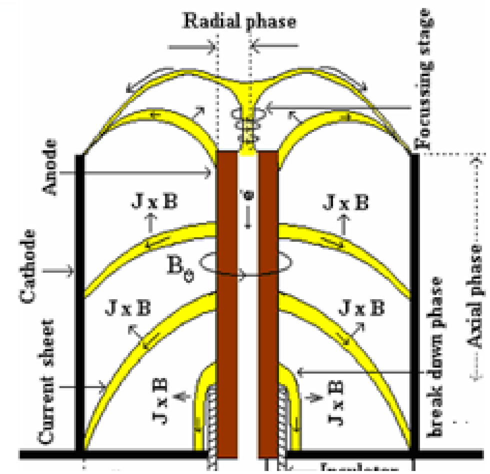
M - R. L. Gullickson, J. S. Luce and H. L. Shalin, Journal of Applied Physics **48,** 3718 (1977).

Multiple Radiation Source:
Avenues for Physics and Applications



Plasma Focus

- High Energy Ions
- Relativistic Electrons
- Soft and Hard x-rays
- EUV Emissions
- Neutron Emission



- Plasmas Dynamics
- Plasma Turbulence
- Plasma Instabilities
- Shock Waves

Diagnostic Facilities @ PRSL

- Fast voltage (resistive-divider), current (Rogowski coil) and magnetic probes
- CCD-based Laser shadowgraphy system (time-resolved plasma dynamics, plasma instabilities)
- Laser-interferometry for plasma density measurement.
- CCD based Magnetic electron energy analyzer (Electron beam energy)
- High speed Optical Streak Camera with CCD imaging (single shot fast plasma dynamics, shock waves physics and instability imaging)
- Diode X-ray Spectrometer and Photo-conducting Diamond detector (X-ray yield and time-resolved electron temperature)
- CCD based pin-hole soft X-ray imaging (time-integrated spatially-resolved)
- Soft X-ray microscopy
- Hard X-ray radiography setup
- Transmission grating spectrometer for soft X-ray

- VUV Vacuum Monochromator (up to 150 nm)
- EUV detectors
- Fast-gated (ns) imaging
- Photomultiplier-scintillator based hard X-ray/neutron measurement system
- Indium Foil activation detector (Neutron count from plasma focus),
- Neutron bubble detectors
- An axial magnetic spectrometer for ions with automated measuring system for etched ion tracks in CR39,
- Be Activation detector for upto 3 Hz neutron diagnostics
- He3 proportional counters for high rep-rate neutron diagnostics
- Faraday cup (biased-ion collector) detector for ion energies and flux measurements,
- Coded aperture imaging of fusion neutron source
- Spatial Langmuir probe system

Universality of DPF Devices

All DPF devices either big or small (in terms of storage energy, discharge current and physical dimensions)

have typically similar

- current sheath speed in axial and radial compression phase,
- plasma temperature and density of the pinch plasma,
- energies of the instability accelerated ions and electrons,
- EUV/SXR/HXR radiation spectra, and
- post collapse dynamics: shocks and ionization wave

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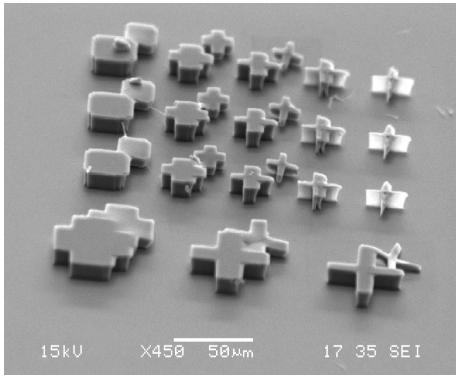
DPF as Multiple Radiation Source

Soft X-ray source for microlithography and imaging



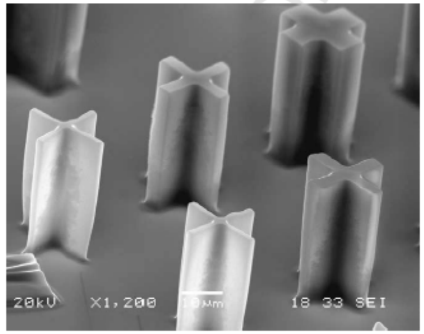


Fig. 9. SEM micrograph showing a close-up view of test structures with an aspect ratio of up to 20:1 on 25-µm-thick SU-8 resist.

1800/300 shot exposure using Ne NX2

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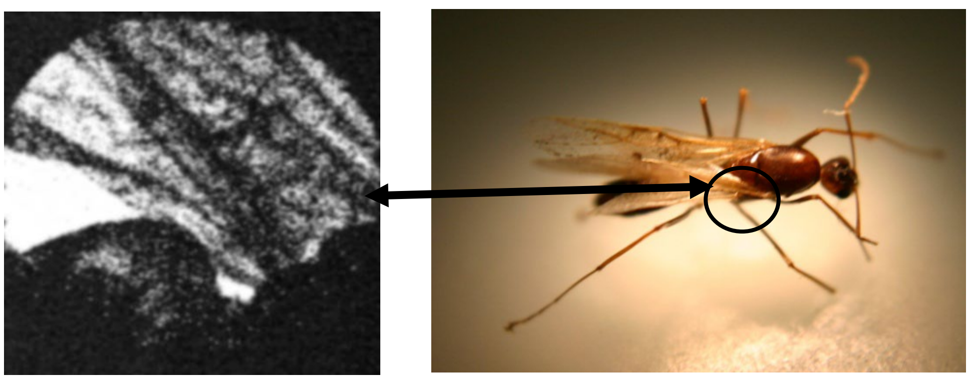

R.S. Rawat*, T. Zhang, G. J. Lim, W.H. Tan, S. J. Ng, A. Patran, S.M. Hassan, S. V. Springham, T. L. Tan, M. Zakaullah, S. Lee and P. Lee, *Soft X-ray Imaging using a Neon filled Plasma Focus X-ray Source*, Journal of Fusion Energy **23** (1), 49-53 (2004).

X-ray Applications

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2. S.M.P. Kalaiselvi, T.L. Tan, A. Talebitaher, P. Lee and R.S. Rawat*, *Influence of Kr doping on Neon Soft X-rays Emission in Fast Miniature Plasma Focus Device*, Physics Letters A, 378(10), 804-809, (2014).
3. S.H. Saw*, R.S. Rawat, P. Lee, A. Talebitaher, A.E. Abdou, P.L Chong, F. Roy Jr, J. Ali and S. Lee, *SXR measurements in INTI PF operated in neon to identify typical (normal N) profile for shots with good yield*, IEEE Transactions on Plasma Science, 41(11), 3166-3172 (2013).
4. S.M.P. Kalaiselvi, T.L. Tan, A. Talebitaher, P. Lee and R.S. Rawat*, Optimization of neon soft X-rays emission from 200 J fast miniature dense plasma focus device: A potential source for soft X-ray lithography, Physics Letters A 377(18), 1290-1296 (2013).

Applications: HXR radiography source

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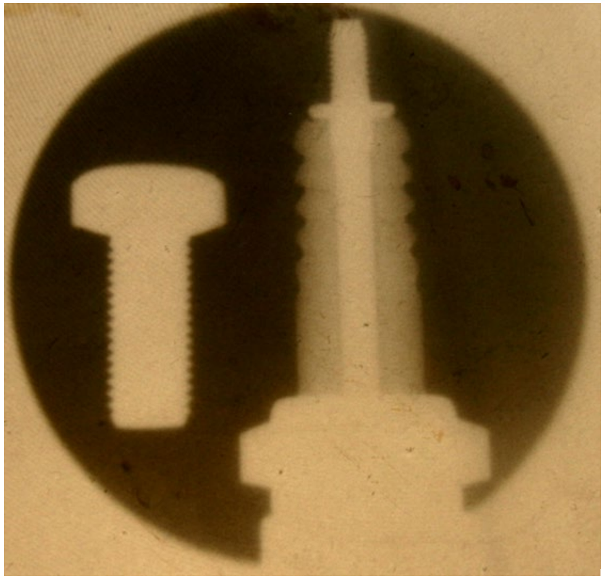

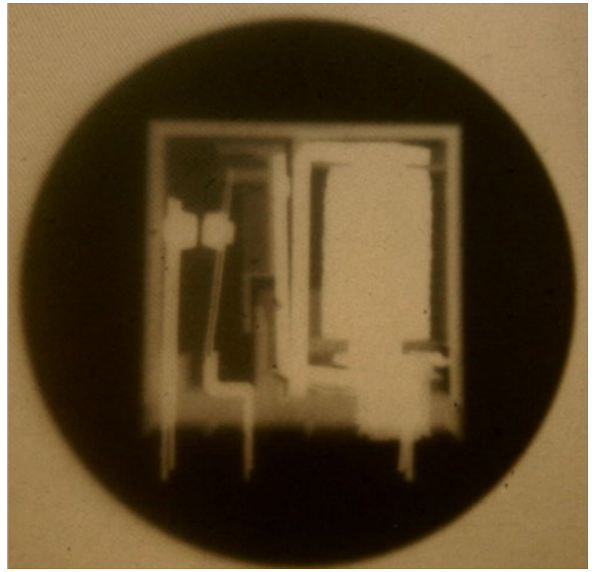

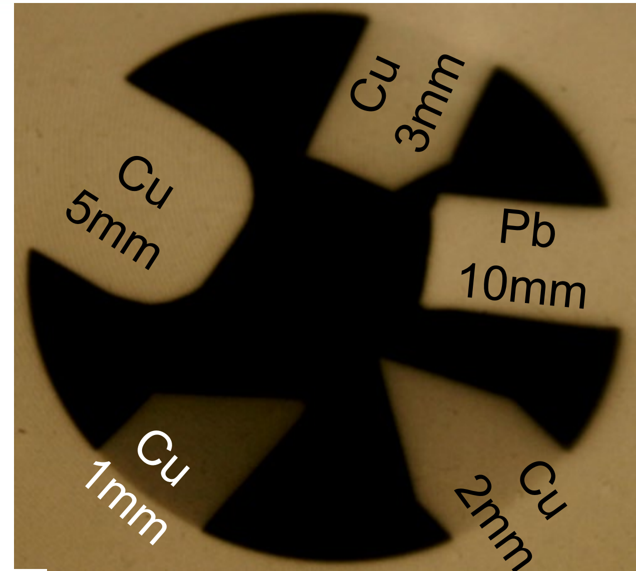

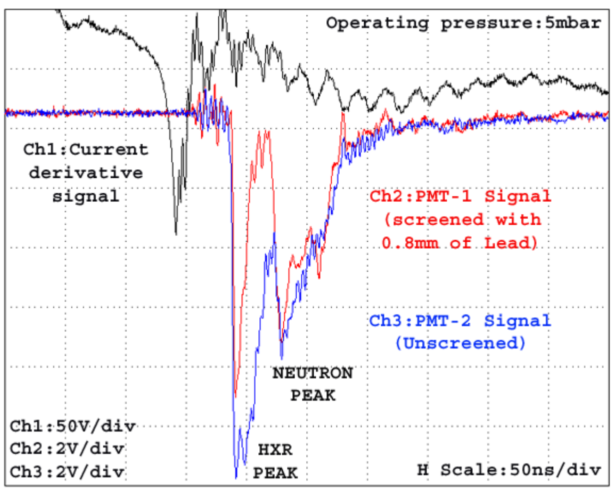

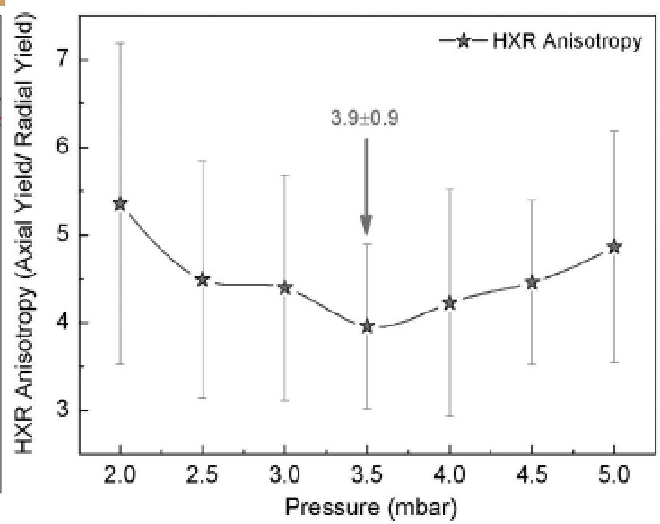

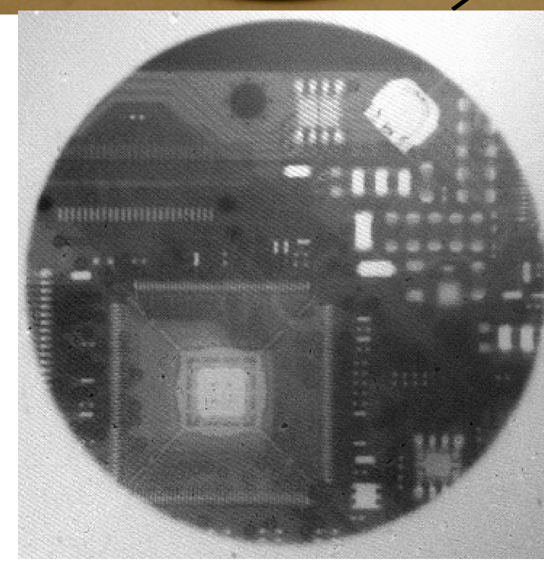

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Pulsed portable neutron source

NX2

1.4 x 1.6m x 1.6m

V ~ $3.6m^3$

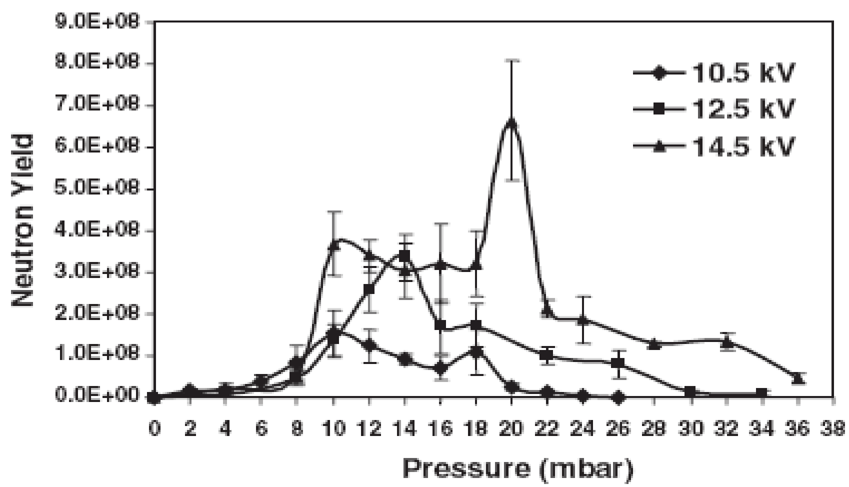
FMPF-1

2.9kJ ↑ ↓ 0.2kJ

10^7 - 10^8 n/s ↑ ↓ 10^6 n/s

0.2m x 0.2m x 0.5m
V ~ $0.02m^3$

↑ 10^6 x 10Hz ~10^7n/s



J.M. Koh, R.S. Rawat, A. Patran, T. Zhang, D. Wong, S.V. Springham, T.L. Tan, S. Lee and P. Lee, *Optimization of High Pressure Operation Regime for Enhanced Neutron Yield in a Plasma Focus Device*, Plasma Sources Science and Technology 14 (1), 12-18 (2005).

Record Time Averaged Neutron Yield from FMPF-3

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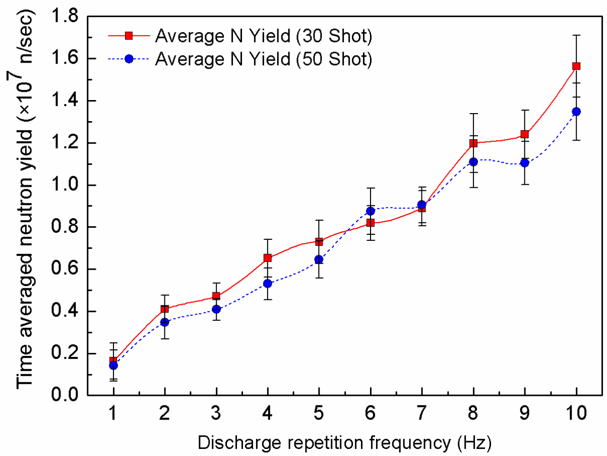

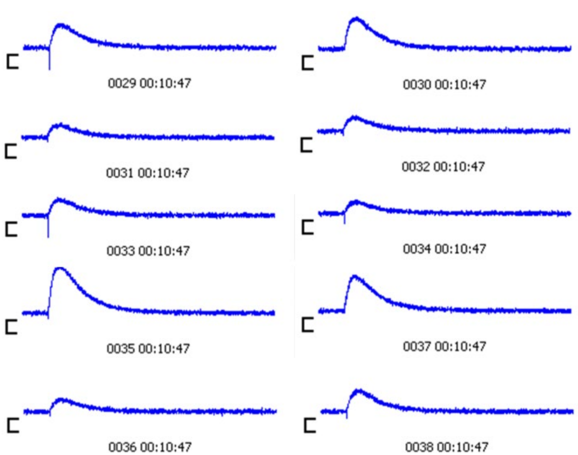

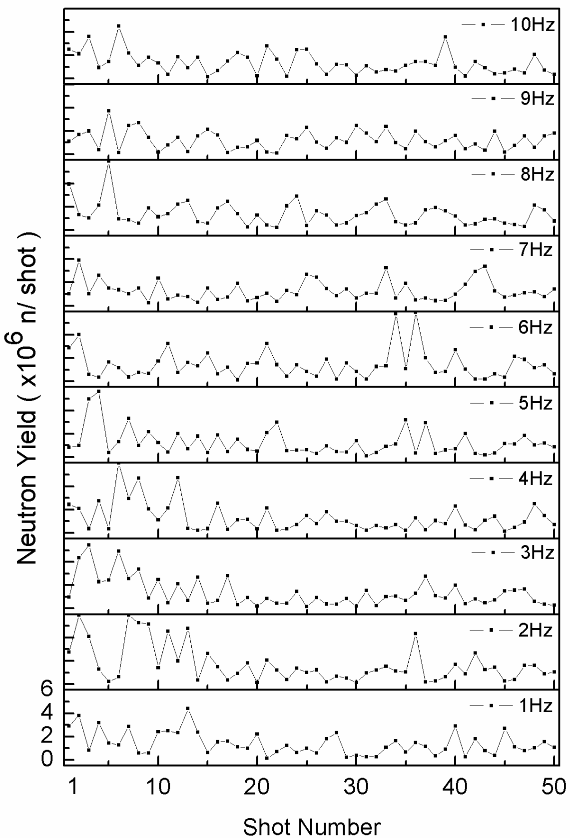

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2. A. Talebitaher, S. V. Springham*, R. S. Rawat and P. Lee, *Plasma focus neutron anisotropy measurements and influence of a deuteron beam obstacle*, Nuclear Instruments and Methods in Physics Research A 848, 60–65 (2017).
3. S. H. Saw, V. Damideh*, Jalil Ali, R. S. Rawat, P. Lee, and S. Lee, *Damage Study of Irradiated Tungsten using Fast Focus Mode of a 2.2 kJ Plasma Focus*, Vacuum 144, 14-20 (2017).
4. A. Talebitaher, Sing Lee, S. M. P. Kalaiselvi, Rishi Verma, Paul Lee, Stuart Victor Springham, T. L. Tan, R.S. Rawat, *Influence of Krypton Seeding on DD Fusion Neutron Production: Evaluation Methodology for Plasma Focus Optimization*, Journal of Fusion Energy, 35(2), 370-377 (2016).
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Plasmas of Interest for Materials Research

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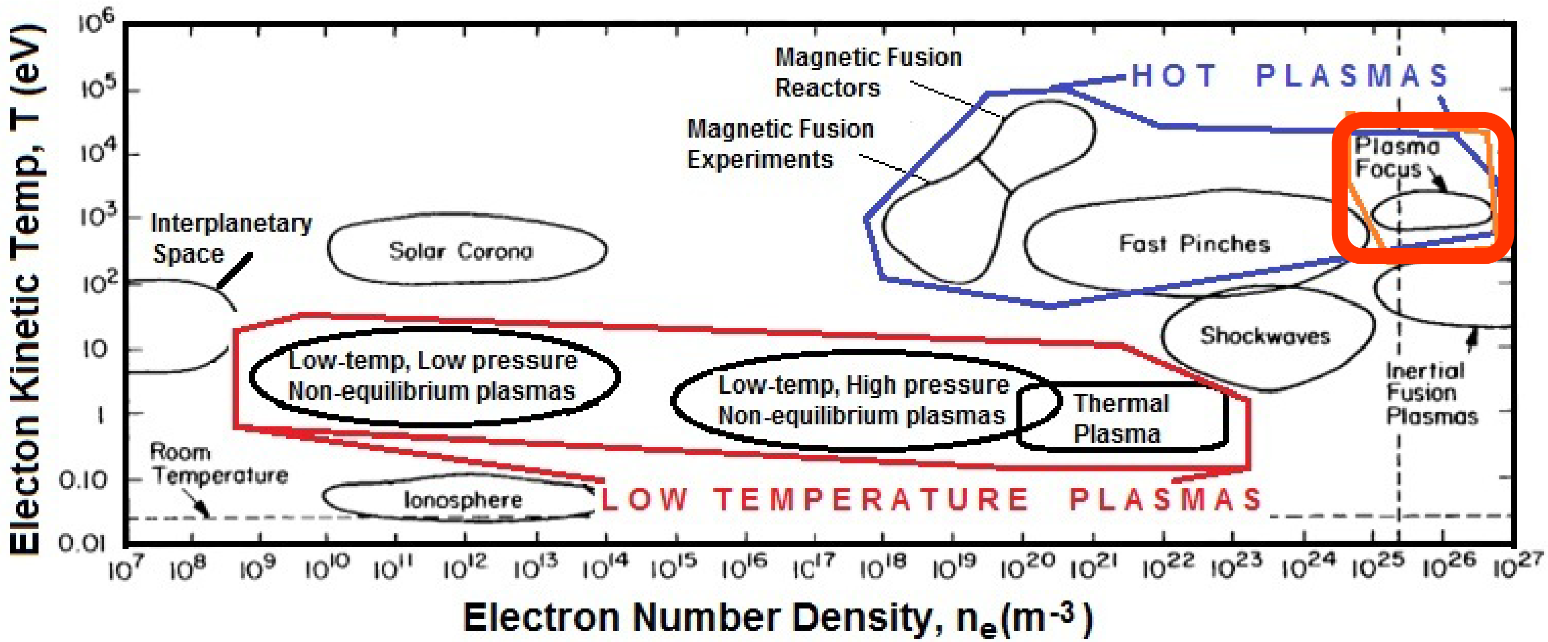
Plasma Type	Low –temp, Non-equilib., Low-pressure	Thermal Plasma	Low-temp, Non-equilib., High Pressure	High-pressure Microplasma	Plasmas in Liquids	High Energy Density Pinch Plasma
T_e	Few to tens of eV	0.1 – 5 eV	2 – 5 eV	> 10 eV	1 – 2 eV	200 – 2000 eV
N_e	$10^9 – 10^{14}$ m^{-3}	$10^{19} – 10^{23}$ m^{-3}	10^{16} -10^{20} m^{-3}	10^{18} m^{-3}	10^{21} - 10^{23} m^{-3}	10^{25} - 10^{26} m^{-3}
	Non-equilibrium	Equilibrium	Non-equilibrium	Non-equilibrium	Non-equilibrium	Non-equilibrium
K. Ostrikov et al . JPD:AP 44 (2011) 17400						Ion-beam Electron-beam Shock wave



HEDPP for PROCESSING of Bulk / Thin Films

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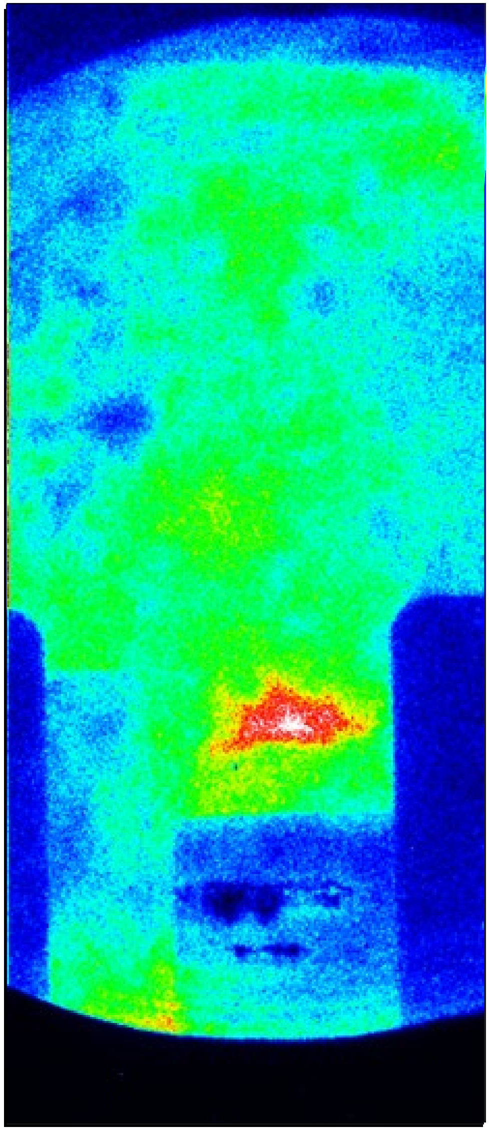
Top-down Approach

Processing

- Phase Transition
- Surface Reconstruction
- Ion Implantation
- Nano-structurization
- 1-Dim Nano-structures



HEDPP for Deposition of Nanostructured Materials

Bottom-Up Approach

Deposition

- Metal – N/C/O
- Superior/Enhanced properties
- Nano Particles
- Nano Plates/Flakes
- Nano Tubes

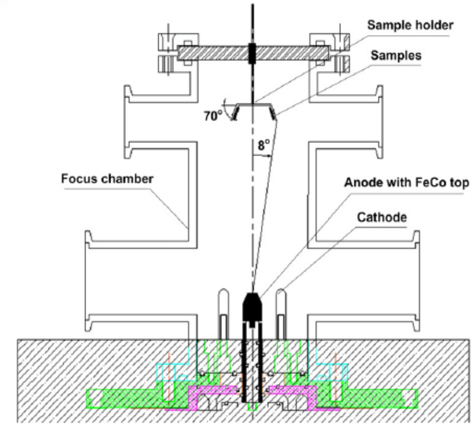
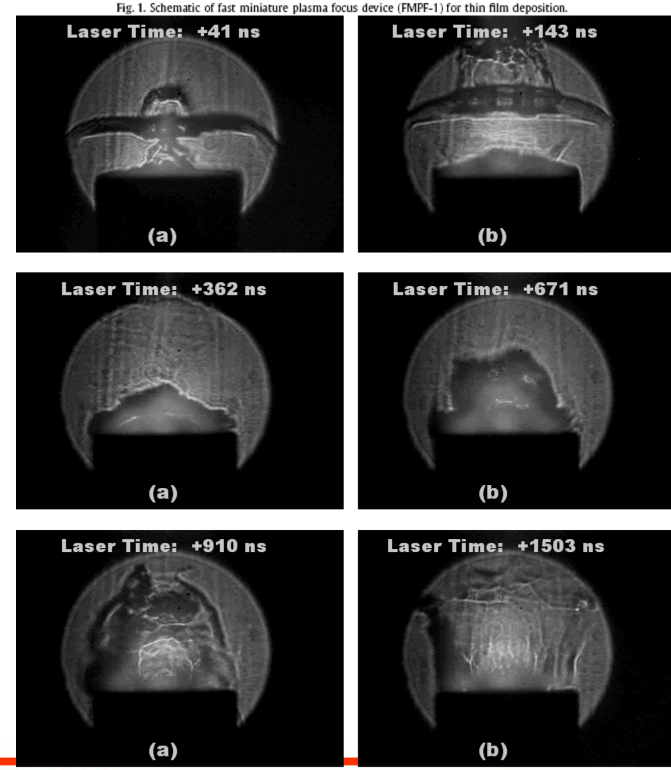


Fig. 1. Schematic of fast miniature plasma focus device (FMPF-1) for thin film deposition.



Full range of Deposition/Processing Configurations

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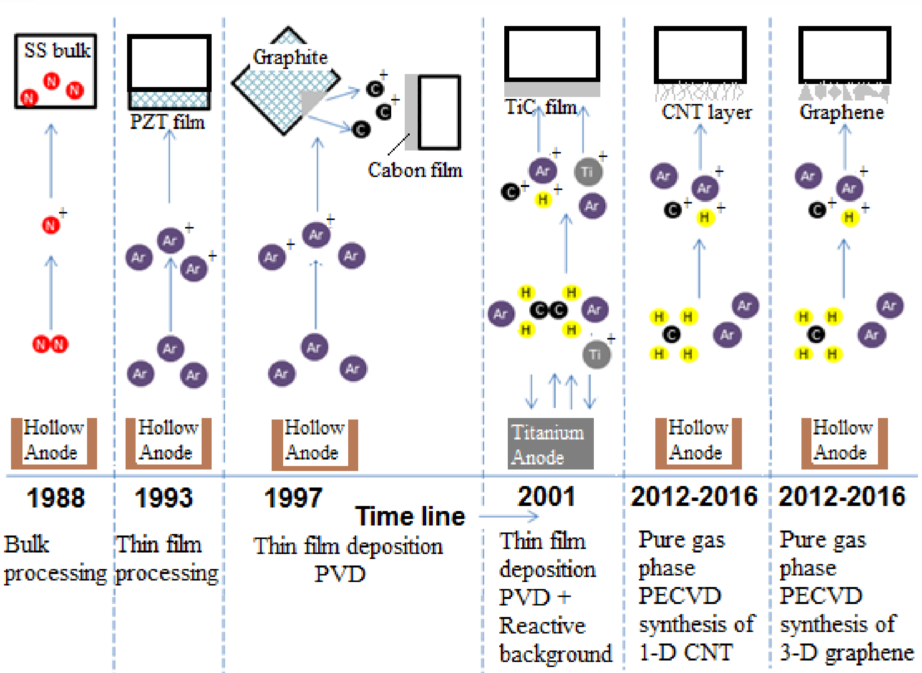
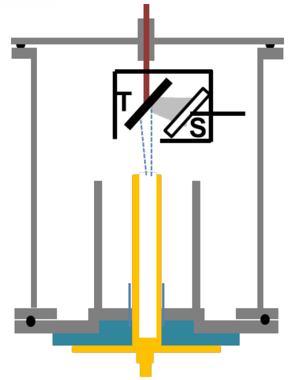
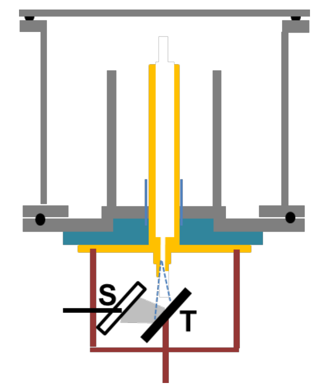
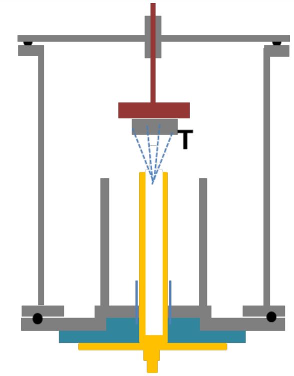




Kant, Chhaya R., Srivastava, M. P., & **Rawat, R. S.** (1998). Dense Plasma Focus energetic ions based fullerene films on Si(111) substrate. Physics Letters A, 239, 109



Zhang, T., Lin, J., Patran, A., Wong, D., Hassan, S. M., Mahmood, S., White, T., Tan, T. L.,Springham, S. V., Lee, S., Lee, P., & **Rawat, R. S.** (2007). Optimization of a Plasma Focus Device as an Electron Beam Source for Thin Film Deposition. Plasma Sources Science and Technology, 16(2), 250-256.



I.A. Khan*, M. Hassan, T. Hussain, R. Ahmad, M. Zakaullah and **R.S. Rawat**, *Synthesis of nano-crystalline zirconium aluminium oxynitride (ZrAlON) composite films by dense plasma focus device*, Applied Surface Science **255**(12) 6132-6140 (2009).

The evolutionary progress of material process and synthesis using DPF device.

1988– J N Feugeas et al. [79] – First application of DPF for processing of bulk material

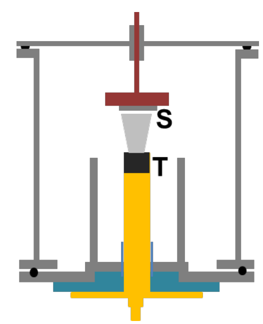
1993– R S Rawat, S Tandon, A Mansingh, M P Srivastava – First application of DPF for processing of thin films

1997– C R Kant, MP Srivastava, R S Rawat – First application of DPF for thin film deposition by target ablation using ion beams and hot and dense plasma – DPF in pure PVD mode

2001– R S Rawat, W M Chew, T White, P. Lee and S Lee – First application of DPF for thin film deposition with anode ablation along with usage of background reactive gas – DPF in PVD mode with reactive background gas plasma

2015– K S Tan and R S Rawat– First application of DPF for synthesis of one-dimensional carbon nanotube (CNT) using only pure gas based synthesis – DPF in pure PECVD mode

2015– K S Tan and M P Srivastava– First application of DPF for synthesis of three-dimensional graphene using only pure gas based synthesis – DPF in pure PECVD mode



R.S. Rawat, W.M. Chew, P. Lee, T. White and S. Lee, *Deposition of titanium nitride thin films on 304-stainless steel substrates at room temperature using a plasma focus device*, Surface and Coating Technology **173** (2-3), 276-284 (2003).

Advantages of DPF based Depositions

High material flux → High deposition rates

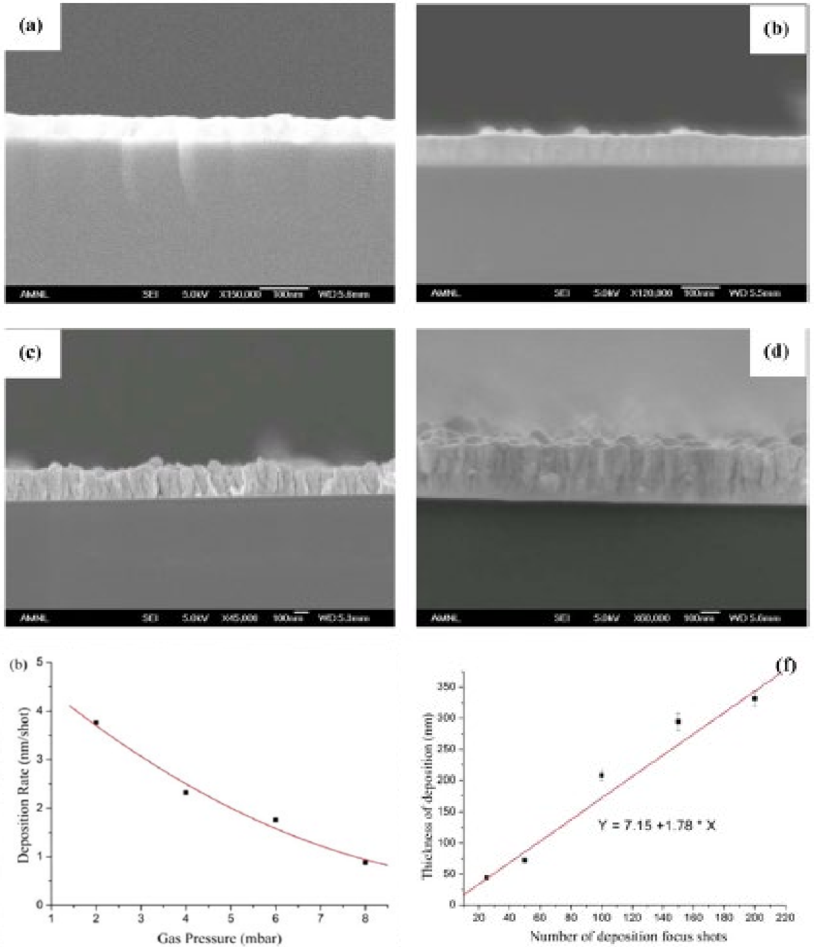
High energy flux → Dense films

Insitu processing of material → Phase transition

Insitu processing of material → Superior material properties

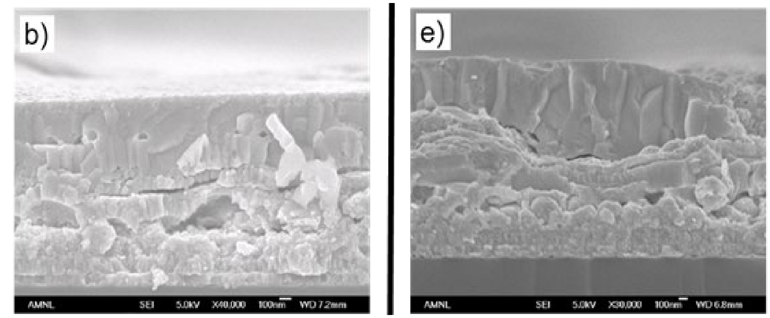
Insitu processing of material → Surface reconstruction

Advantages → High deposition rates



CoPt deposition rate in 6 mbar 880 J NX 2 PF

Z Y Pan, R S Rawat, M V Roshan, J J Lin, R Verma, P Lee, S V Springham and T L Tan, J. Phys. D: Appl. Phys. 42 (2009) 175001



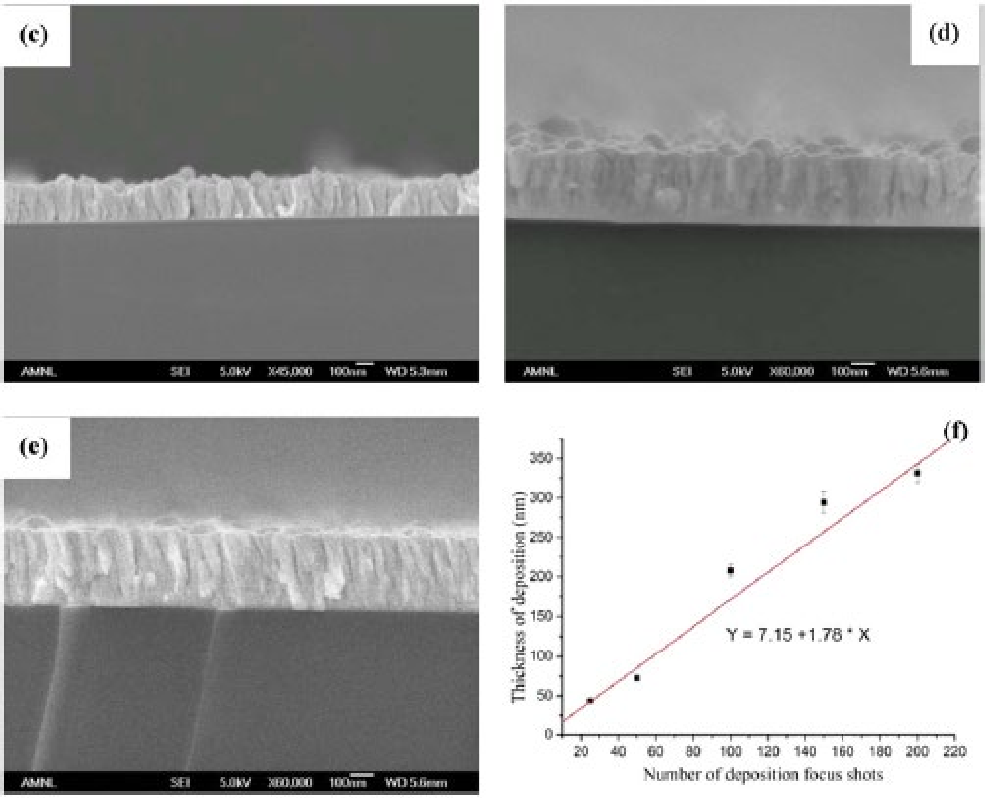
20 Shots, 15 cm　　20 Shots, 21 cm

FESEM cross sectional images of ZnO samples.

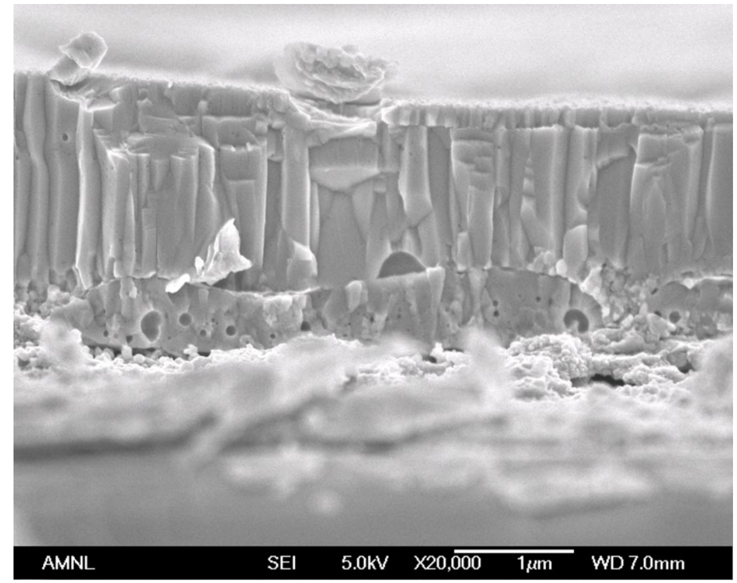
Plasma process	Growth rate	Growth Temperature, ° C
Conventional CVD	1.5 μm/min	950
RF sputtering	0.1 μm/min	RT
Plasma-assisted mist-CVD	0.1 μm/min	RT
RF magnetron sputtering	5 nm/min	250
DPF Device (10 Hz)	60 μm/min	RT

K.S. Tan, R.J. Mah and R.S. Rawat*, *Dense Plasma Focus Device Based High Growth Rate Room Temperature Synthesis of Nanostructured Zinc Oxide Thin Films*, Plasma Science, IEEE Transactions on Plasma Science 43(8), 2539-2546 (2015)

Advantages → Dense films



Z. Y. Pan, R. S. Rawat*, M.V. Roshan, J. J. Lin, R. Verma, P. Lee, S. V. Springham and T. L. Tan, *Nanostructured magnetic CoPt thin films synthesis using dense plasma focus device operating at sub-kilojoule range*, Journal of Physics D: Applied Physics **42**(17), 175001 (2009)



FESEM cross sectional image highlighting dense columnar growth for ZnO

K.S. Tan, R.J. Mah and R.S. Rawat*, *Dense Plasma Focus Device Based High Growth Rate Room Temperature Synthesis of Nanostructured Zinc Oxide Thin Films*, Plasma Science, IEEE Transactions on Plasma Science 43(8), 2539-2546 (2015)

Advantages → Phase transition

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Amorphous → Crystalline

[R.S.Rawat, M.P.Srivastava, S.Tandon and A.Mansingh, Phys. Rev B 47, 4858 (1993)

Crystalline →Amorphous

R. Sagar and M. P. Srivastava, "Amorphization of thin film of CdS due to ion irradiation by dense plasma focus," Physics Letters A **183, 209-213 (1993).**

M. Sadiq, M. Shafiq, A. Waheed, R. Ahmad, and M. Zakaullah, "Amorphization of silicon by ion irradiation in dense plasma focus," Physics Letters A **352 (1-2), 150-154 (2006).**

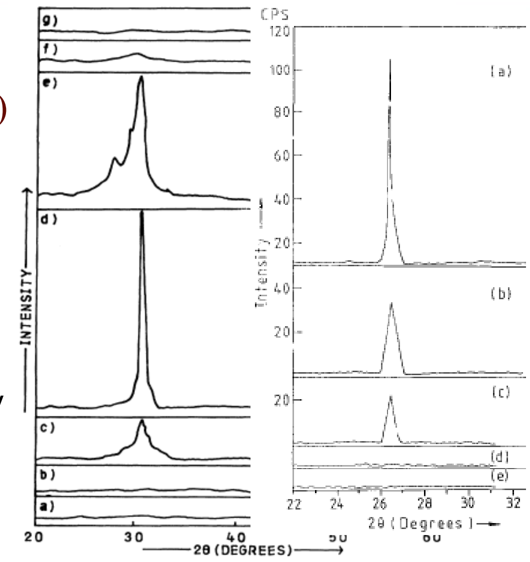


FIG. 3. XRD patterns of sample II: (a) unexposed to plasma shots, and (b)–(g) exposed by a single DPF shot at different distances Z from the anode. Pressure of argon = 80 Pa.

Other examples:

[M.P.Srivastava, S.R.Mohanty, S.Annapoorni and R.S.Rawat, Phys. Lett. A 215, 63 (1996)] – **N-type doping on PA for Diode formation**

[P.Aggarwala, S.Annapoorni, M.P.Srivastava, R.S.Rawat & P.Chauhan, Phys. Lett. A 231, 434 (1997)] – **Change of Magnetic Phase – Haemetite to Magnetite**

[R.S.Rawat, P.Arun, A.G.Videshwar, Y.L.Lam, P.Lee, M.H.Liu, S.Lee and A.C.H.Huan, Bull. Mat. Res. 35, 477 (2000)] – Sb2Te3 - **non-stoichiometric to fully stoichiometric**

[R.S.Rawat, P.Arun, A.G.Videshwar, P.Lee and S.Lee, Journal of Applied Physics 95 (12), 7725 (2004)] – **Band gap modification of CdI2 thin films**

[A. Lepone, H. Kelly, D. Lamas, and A. Marquez, Applied Surface Science 143 (1-4), 124 (1999).] – **austenitic to martensitic**

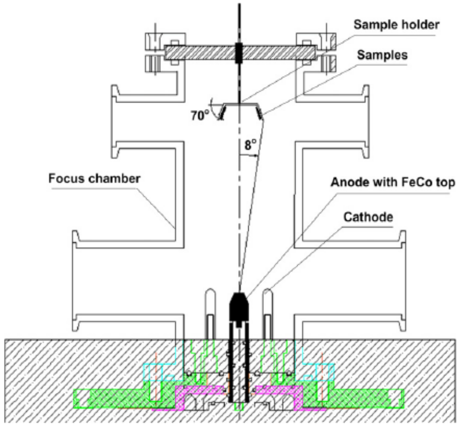
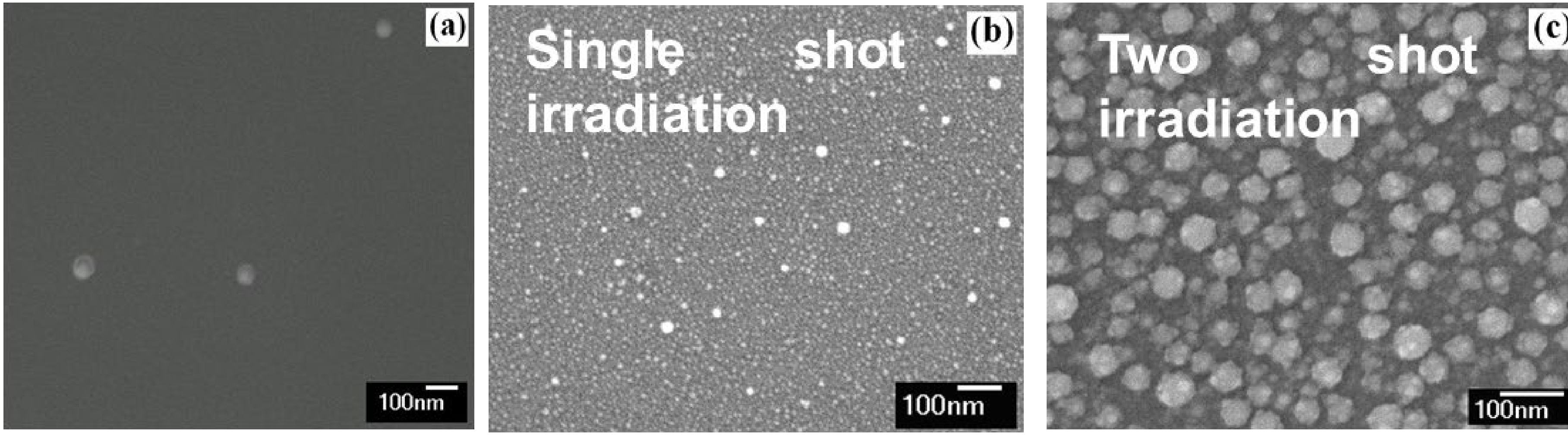
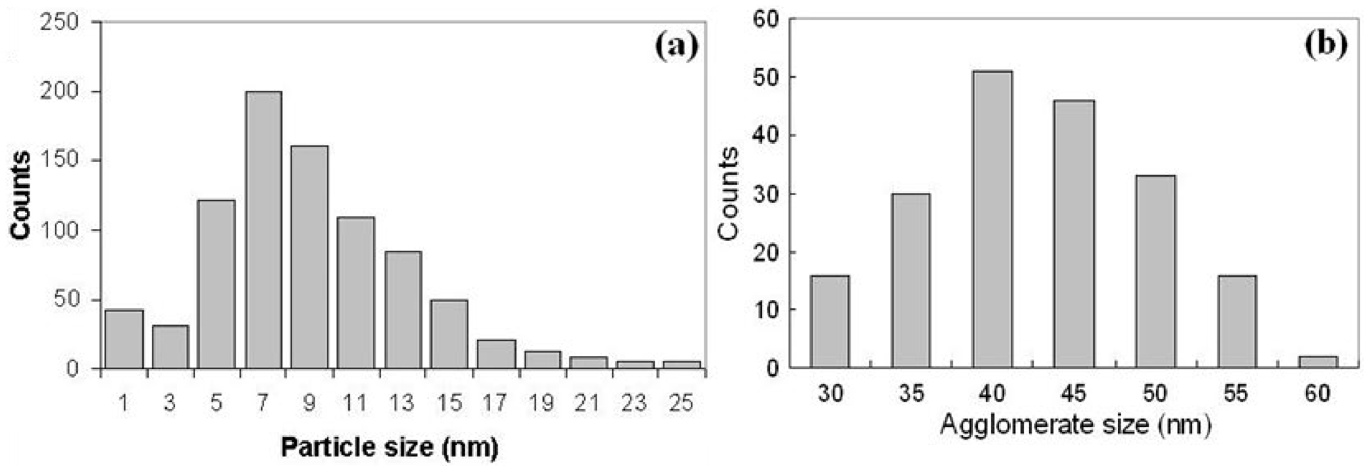


Fig. 1. Schematic of fast miniature plasma focus device (FMPF-1) for thin film deposition.

Advantages – Surface Reconstruction



H+ irradiation
14 kV, 2.94 kJ
Z=5.0 cm
Thickness=67 nm
35 keV to 1.5 MeV
Mean E – 124 keV



J.J. Lin, M.V. Roshan, Z.Y. Pan, R.Verma, P. Lee, S.V. Springham, T.L. Tan, R.S. Rawat, *FePt nanoparticle formation with lower phase transition temperature by single shot plasma focus ion irradiation*, Journal of Physics D: Applied Physics 41, 135213 (2008)

Advantage – Superior properties

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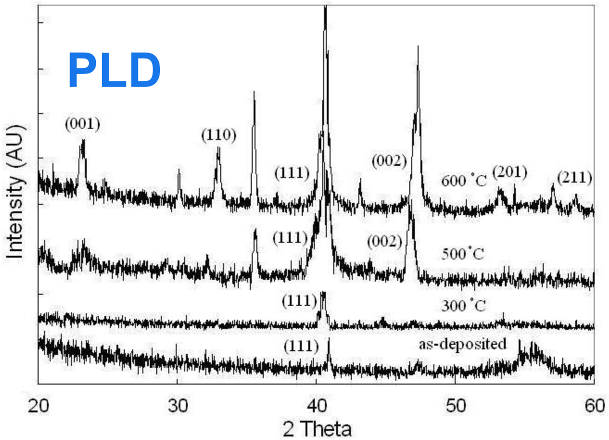


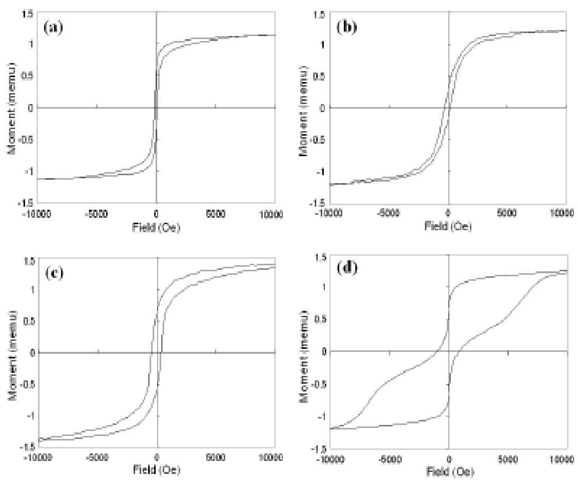
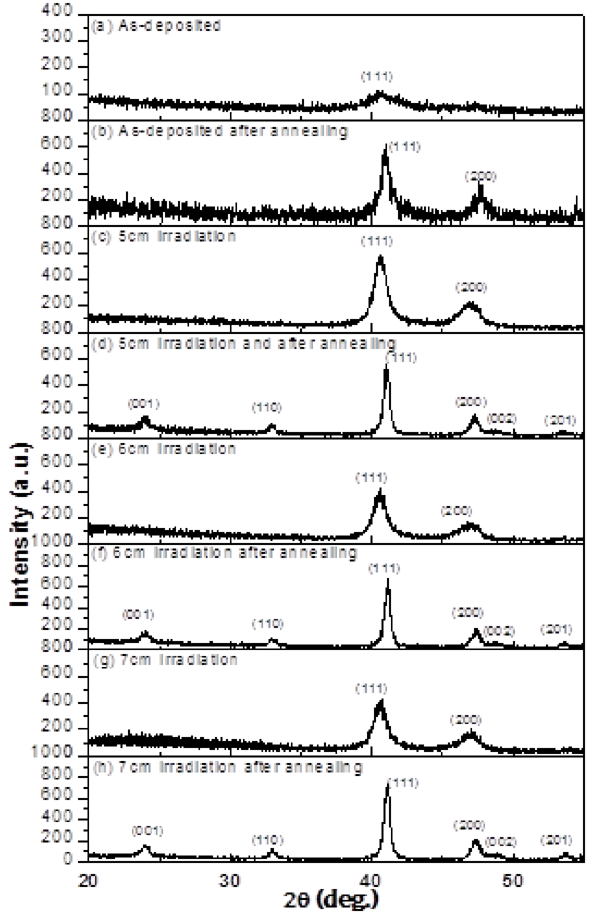


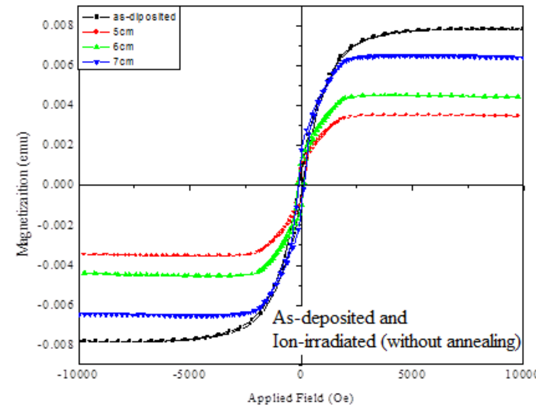
Figure 5. VSM hysteresis loops of samples deposited by conventional PLD at 0.5 mbar: (a) as-deposited and annealed at (b) 400 °C, (c) 500 °C and (d) 600 °C.

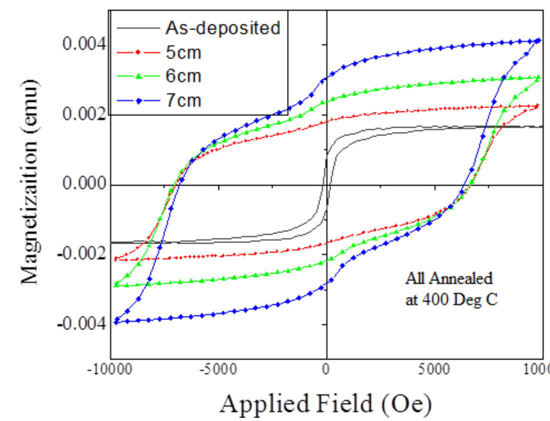
J.J. Lin, L.S. Loh, P. Lee, T.L. Tan, S.V. Springham and R.S. Rawat, ASS 255 (8), 4372-4377 (2009).

H+ irradiation; 4 kV, 2.94 kJ
Z=5, 6 and 7 cm; Thick=100 nm
Annealing – 400 Deg C

DPF







Z.Y. Pan, J. J. Lin, T. Zhang, S. Karamat, R.Verma, M.V. Roshan, S. Mahmood, P. Lee, S.V. Springham, T.L. Tan, R.S. Rawat, *Lower phase transition temperature and two order of coercivity enhancement*, Thin Solid Films, 517, 2753-2757 (2009),

Key Criticism of DPF based Synthesis

However, DPF devices have been used on very limited basis for material synthesis as it faces criticism of **lack of controlled deposition with desired features**.

The criticisms include

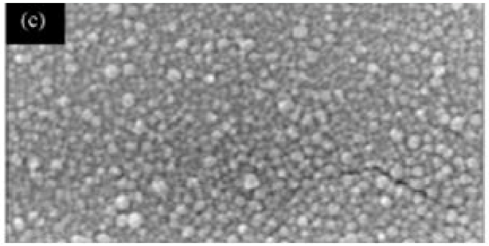
(i) limited type of deposition, e.g. mostly nanoparticle morphology,

(ii) Lack of uniformity in deposition – small area uniformity,

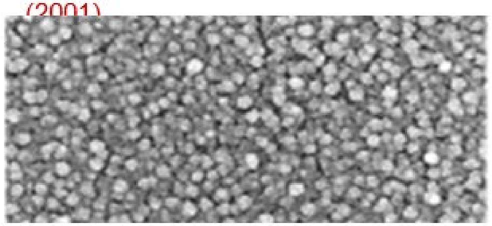
(iii) limited metal anode-based deposition only and

(iv) shot to shot variation in operation leading to uncertainty in deposition

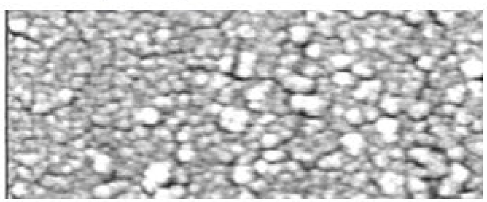
Criticism 1 – Limited 0-D NP Morphology



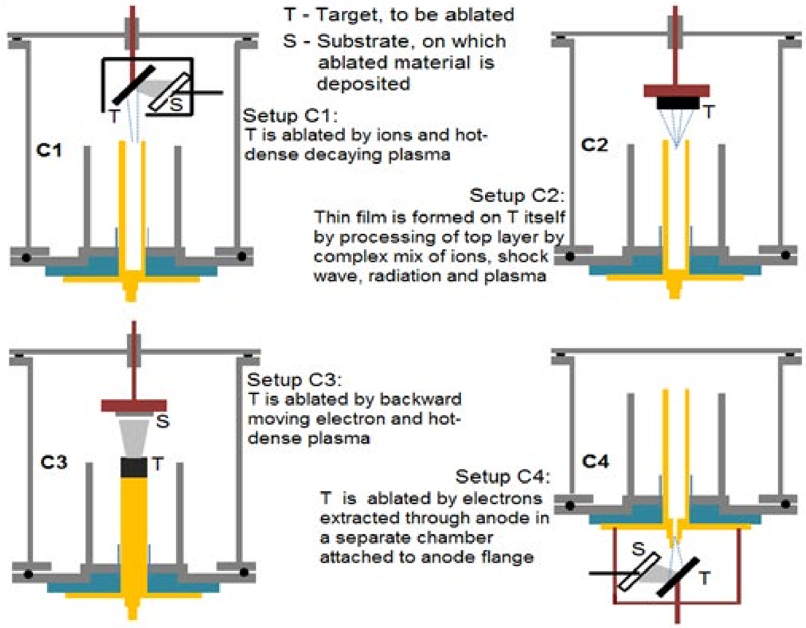
R.S. Rawat, P. Lee, T. White, Li Ying and S. Lee, *RT deposition of **TiC thin film***, SCT 138, 159, (2001)

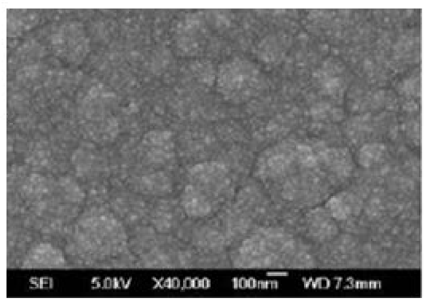


RS Rawat, T Zhang, KS Thomas Gan, P Lee, RV Ramanujan, *Nano Fe thin film deposition using PF*, Applied Surface Science 253, 1611 (2006).

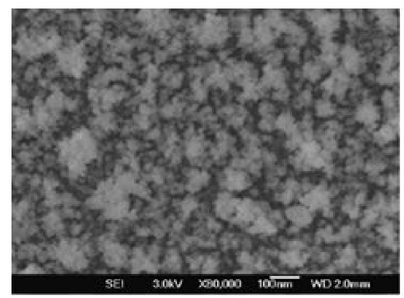


I.A. Khan, **R.S. Rawat**, R. Verma, G. Macharaga, R. Ahmad*, ***AlN films*** *using PF*, Journal of Crystal Growth **317(1)**, 98-103 (2011).

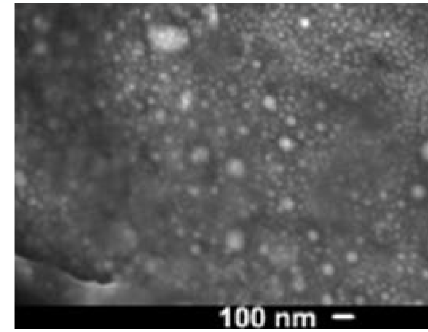




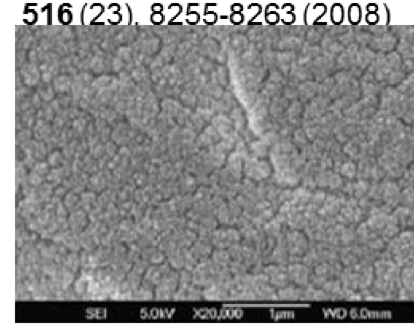
K.S. Tan, R.J. Mah and R.S. Rawat, *Nanostructured ZnO Thin Films*, IEEE TPS 43(8), 2539-2546 (2015)



T. Zhang, et al, ***PF as electron beam source for thin film deposition***, PSST 16 (2), 250-256 (2007)



I. A. Khan*, M. Hassan, R. Ahmad, A. Qayyum, G. Murtaza, M. Zakaullah and **R.S. Rawat**, *Nitridation of zirconium using ion beam delivered by plasma focus discharges*, Thin Solid Films **516** (23), 8255-8263 (2008)



I.A. Khan, S. Jabbar, T. Hussain, M. Hassan, R. Ahmad*, M. Zakaullah, **R.S. Rawat**, *ZrCN films using PF*, Nucl. Inst. Meth. Phys. Res. B **268**, 2228 (2010)

Not True: 1-D NW/NT Morphologies

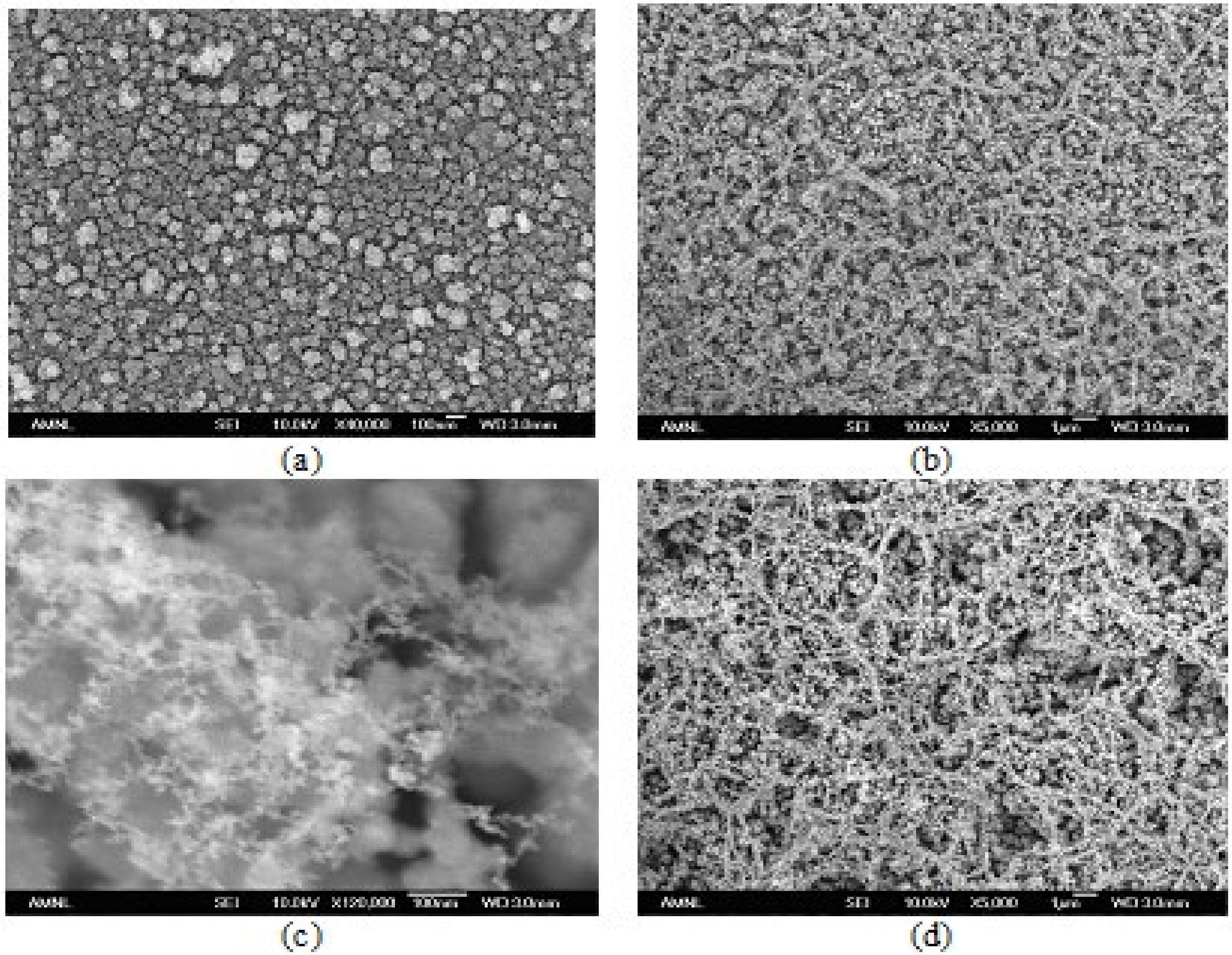
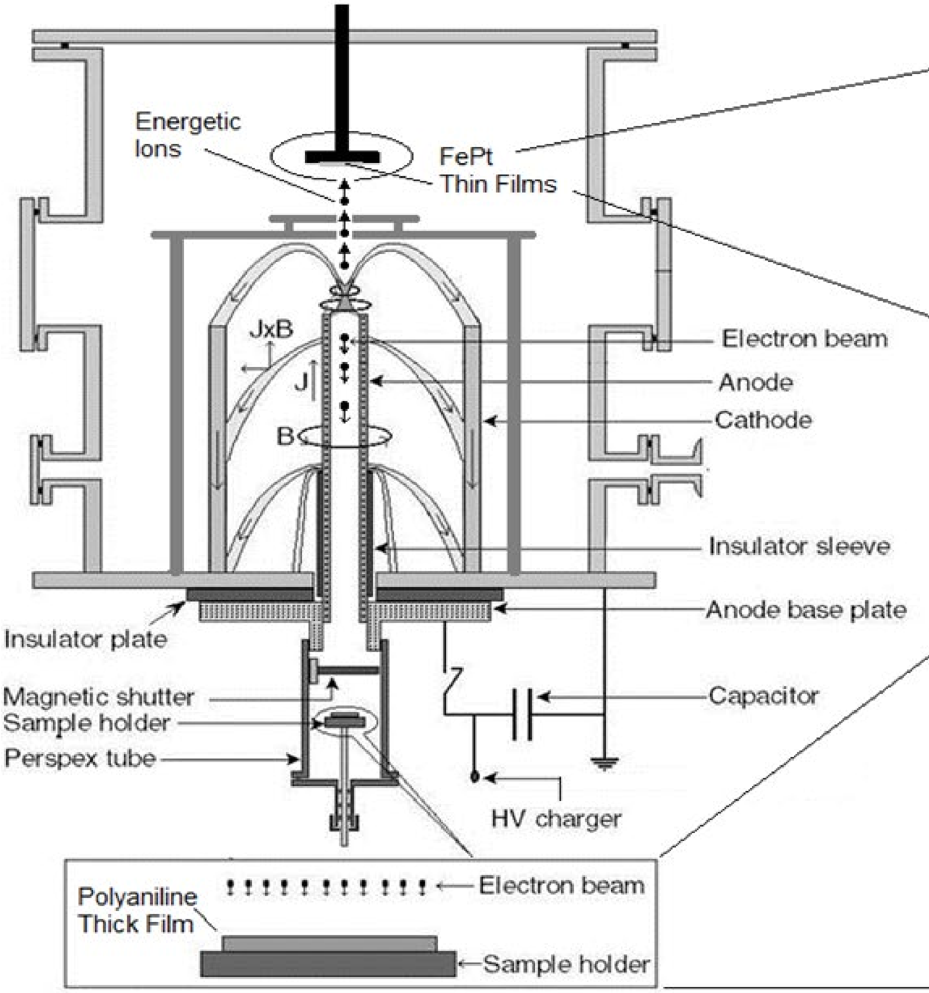
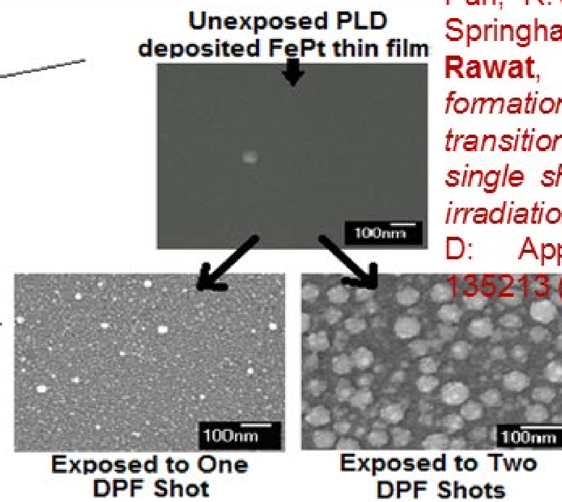


Figure 2 Topography of FeCo thin film deposited using (a) 25 focus shots, (b) 100 shots, (c) high magnification for 100 shots and (d) 250 shots.

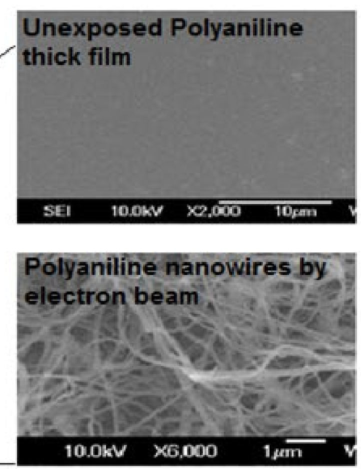
T Zhang, K S Thomas Gan, P Lee, R V Ramanujan, and R S Rawat, *Characteristics of FeCo nano-particles synthesized using plasma focus device*, Journal of Physics D: Applied Physics 39, 2212–2219, 2006.

Not True: 1-D NW/NT Morphologies



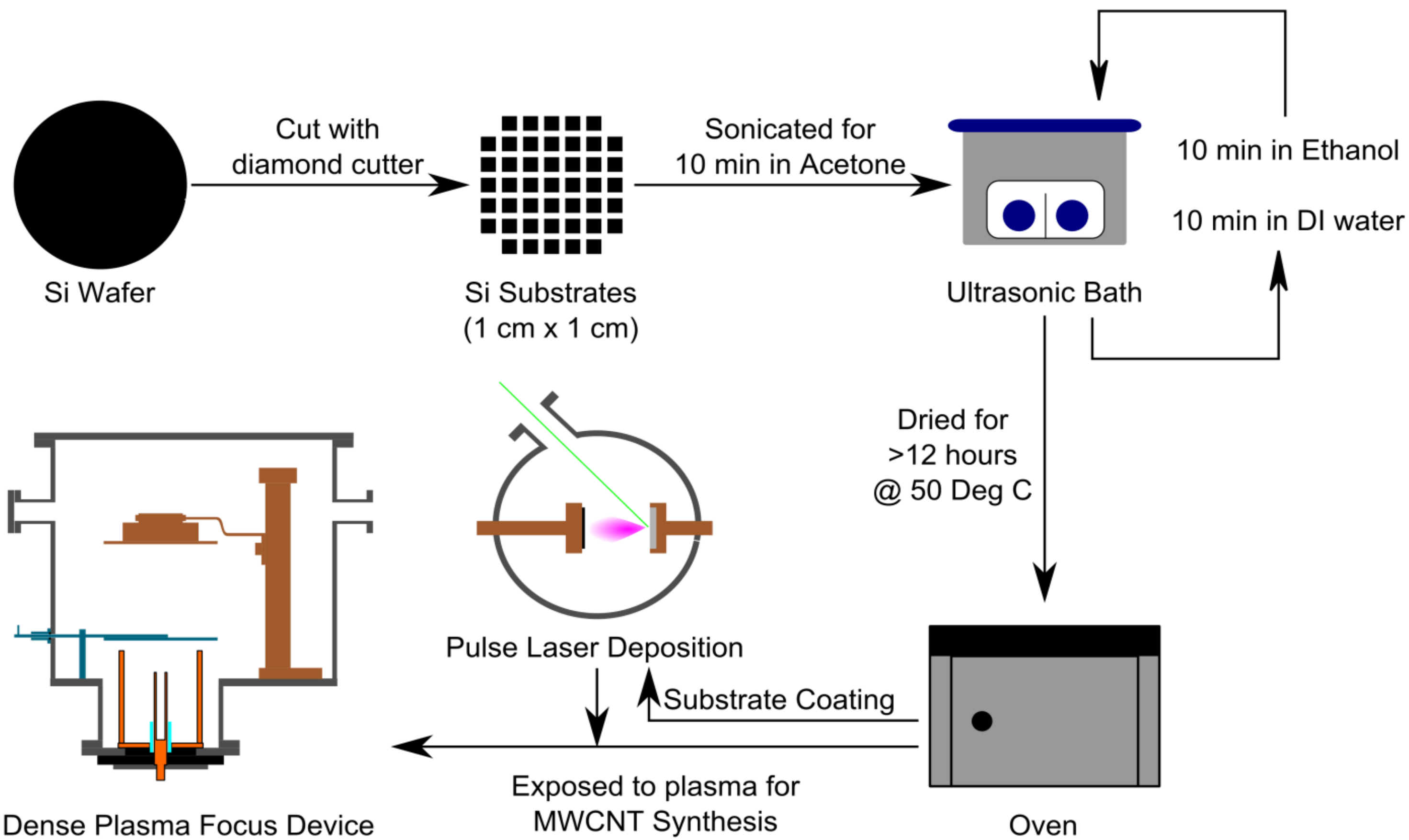


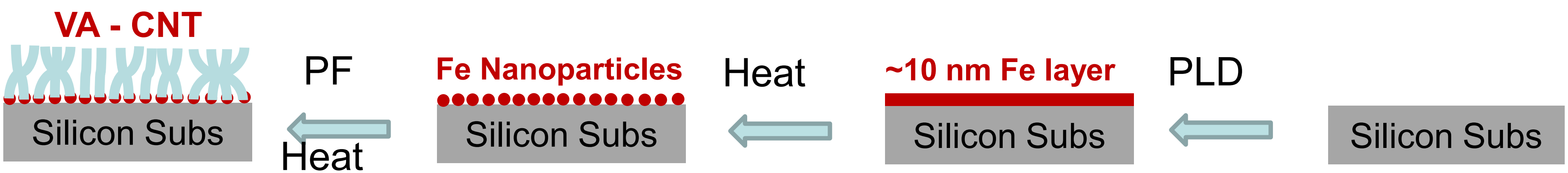
J.J. Lin, M.V. Roshan, Z.Y. Pan, R.Verma, P. Lee, S.V. Springham, T.L. Tan, **R.S. Rawat**, *FePt nanoparticle formation with lower phase transition temperature by single shot plasma focus ion irradiation*, Journal of Physics D: Applied Physics 41, 135213 (2008)



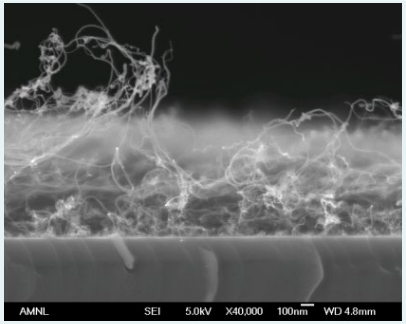
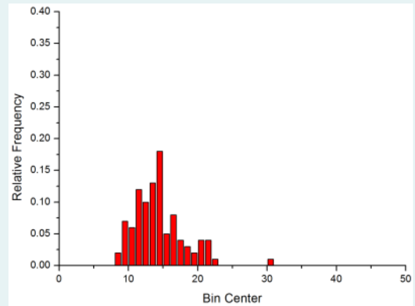
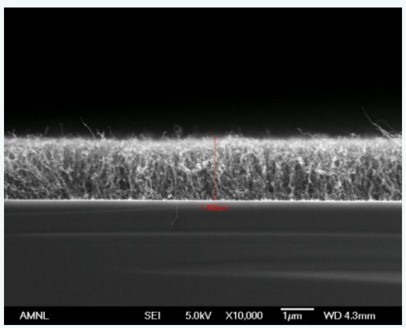
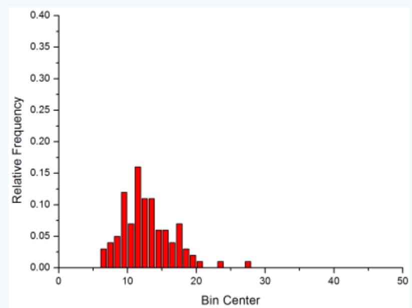
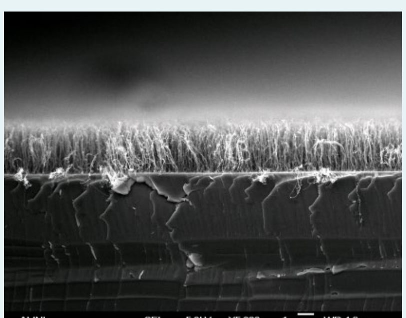
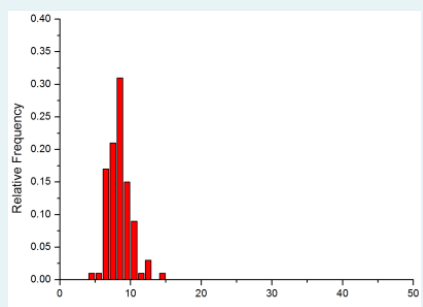
S.R. Mohanty*, N.K. Neog, **R.S. Rawat**, P. Lee, B.B. Nayak, and B.S. Acharya, *Room temperature fabrication of polyaniline nanowires in nanosecond timescale using electron beam of a plasma focus device*, Physics Letters A 373, 1962-1966 (2009)

CNT Synthesis Using HEDPP-PF Device

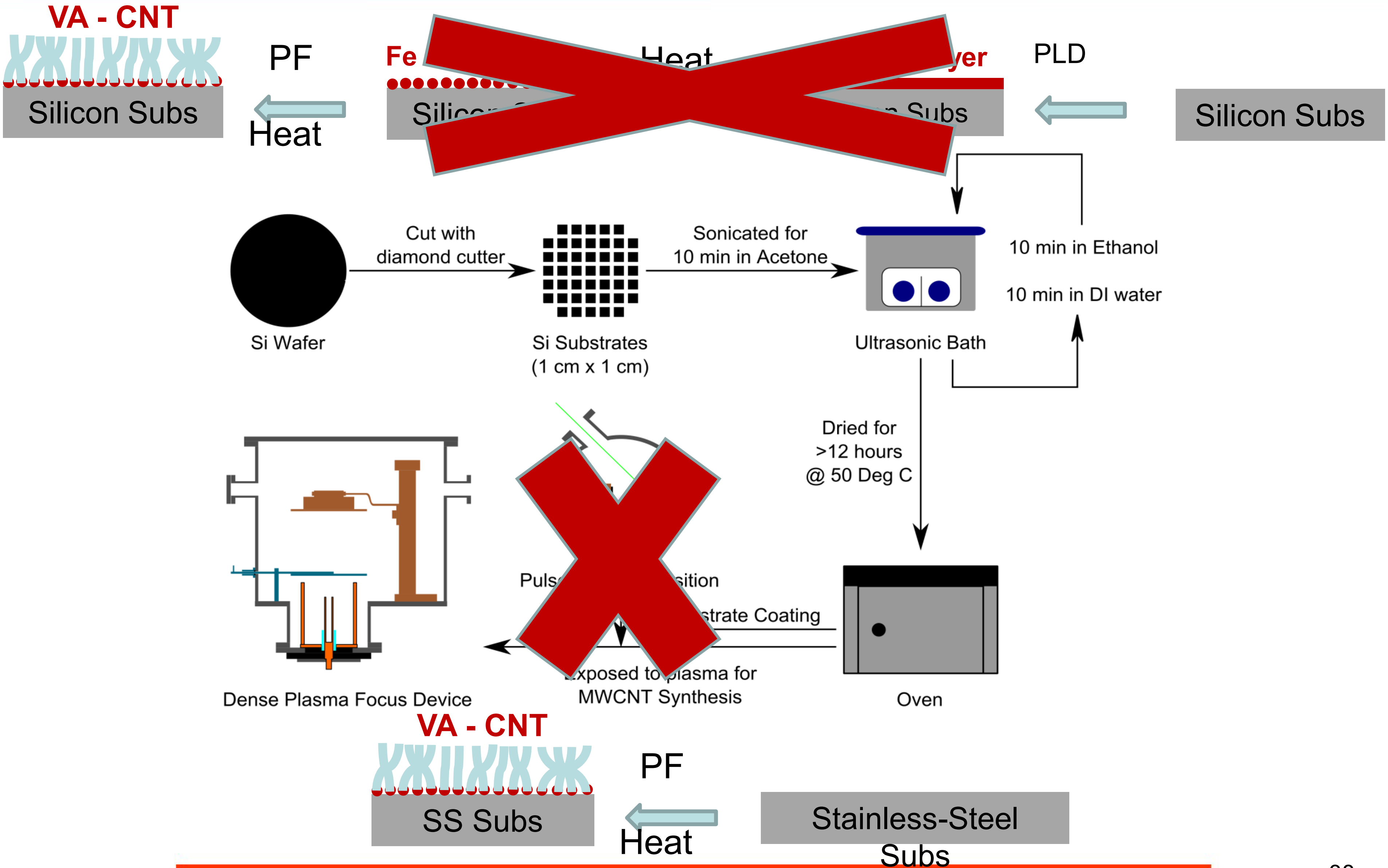




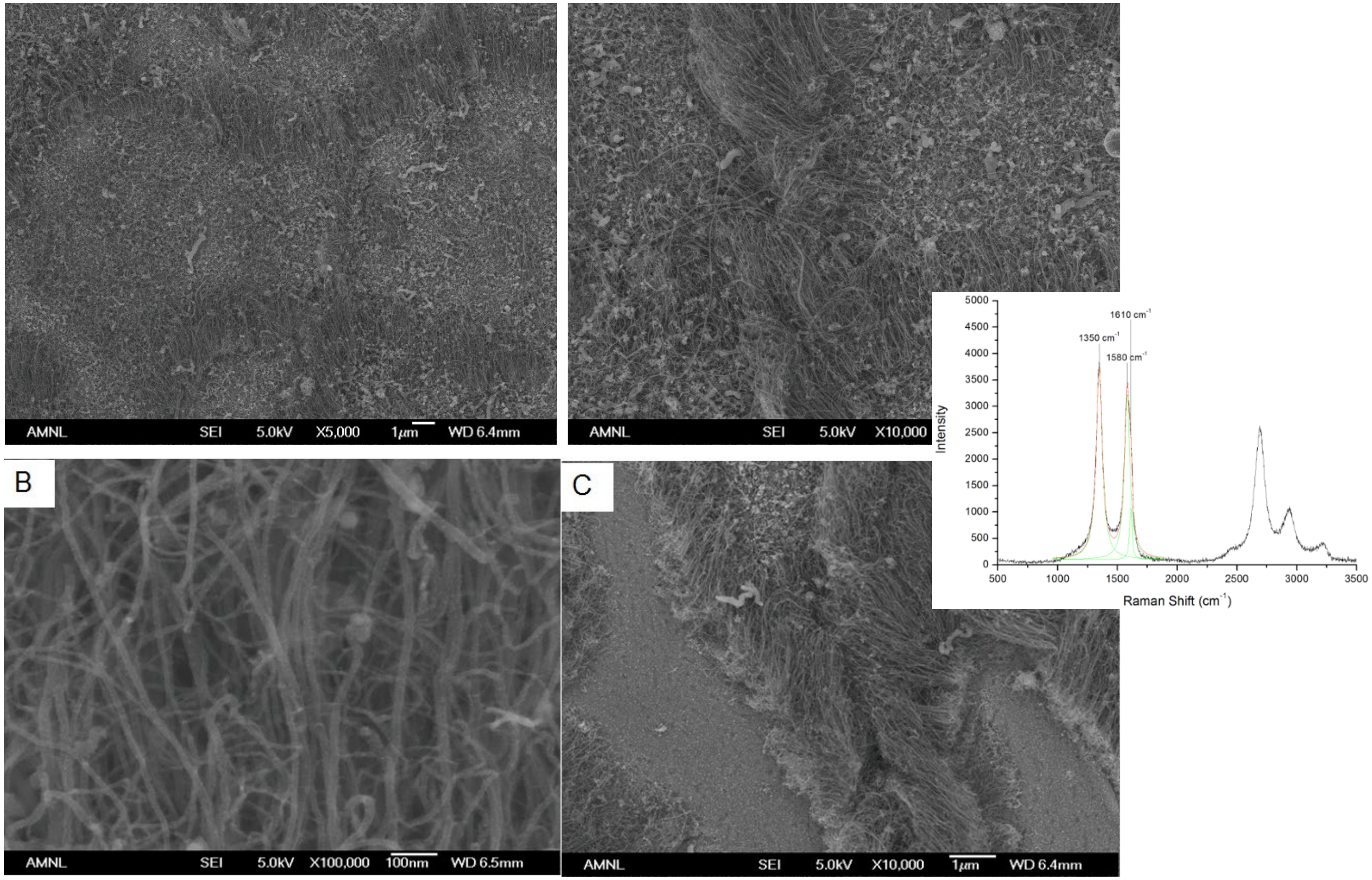
CNT Synthesis Using HEDPP-PF Device

Number of Shots	Cross Sectional FESEM	Average Tube Diameter, nm and Histogram		Material Characteristics
5			14.5 ± 3.7	Compressed and non-uniform surface. Anisotropy: 103.8
2			12.9 ± 3.7	Highly dense and uniform. Vertically aligned MWCNT. Anisotropy: 233.5
1			8.5 ± 1.5	Highly dense and uniform. Vertically aligned MWCNT. Anisotropy: 224.0

Direct Synthesis of CNT on Bulk Target



Gas Phase Synthesis of CNT Using PF Device



Ultrafast CNT Growth using HEDPP-PF Device

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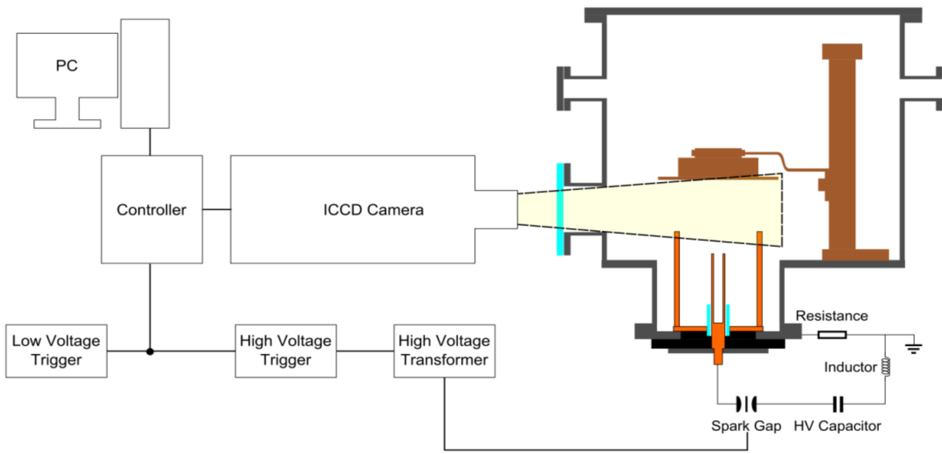
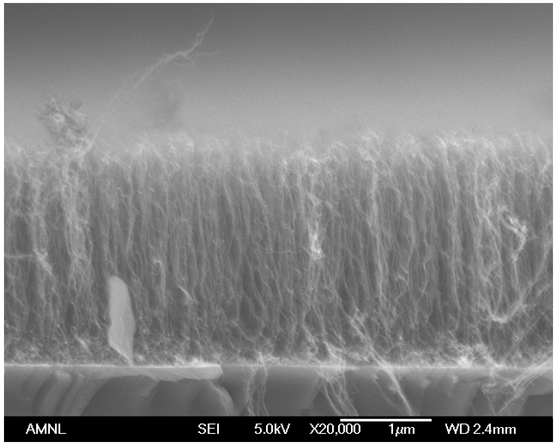
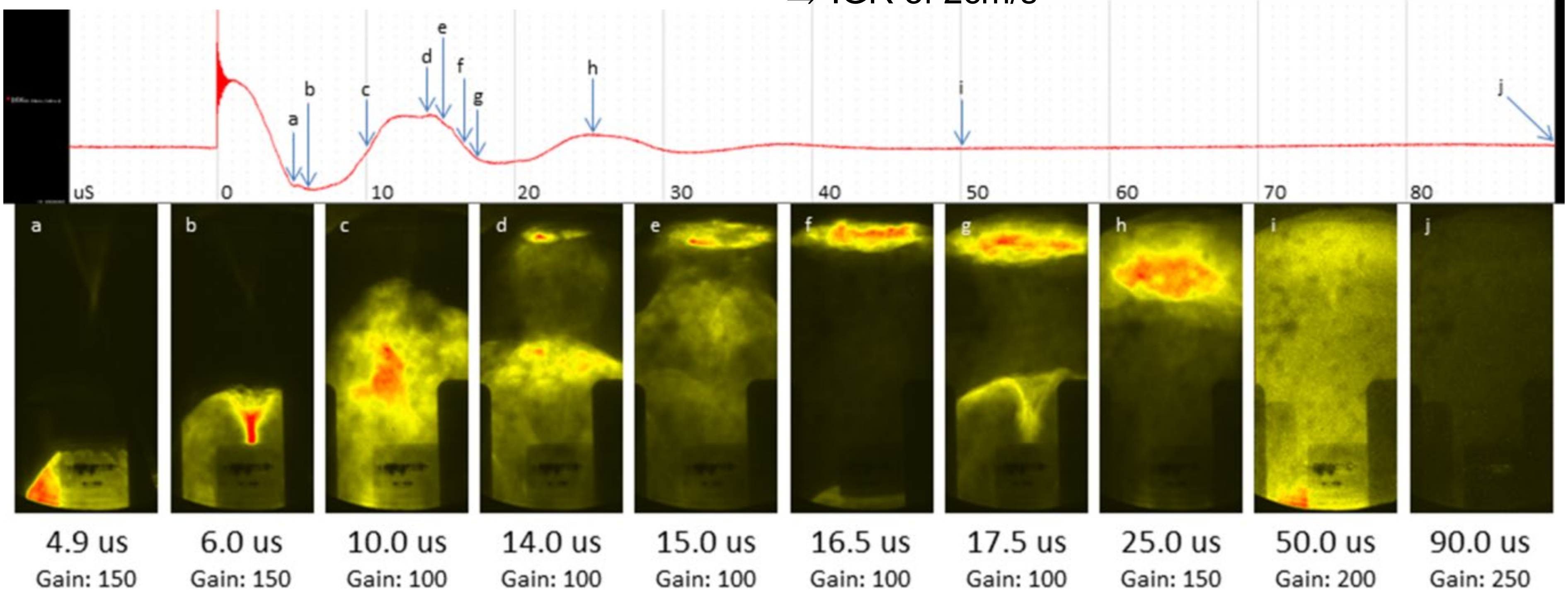


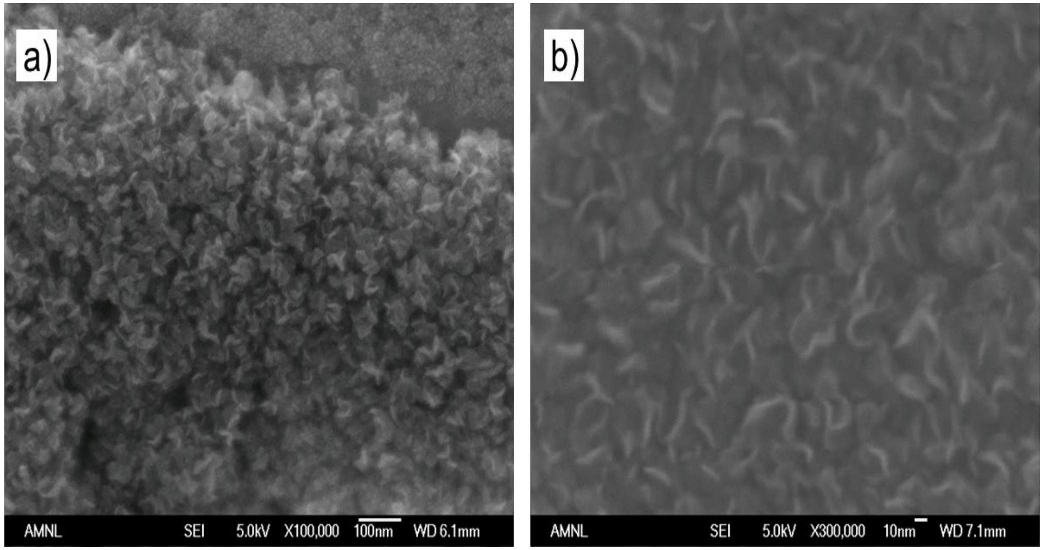
Probably the highest ever instantaneous growth rate of about 2μm/100μs ⇒ IGR of 2cm/s





3-D Graphene

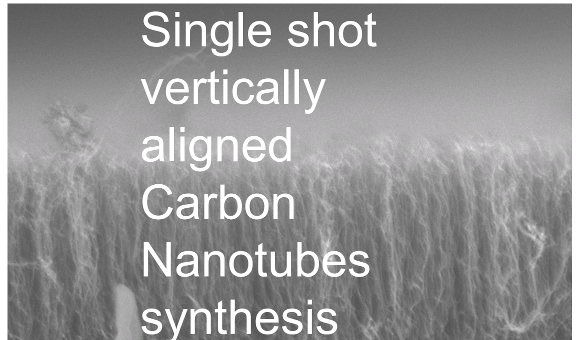
- Bulk Catalyst Synthesis of Graphene Nanoflakes Films using Dense Plasma Focus Device
  - Effect of substrate type.

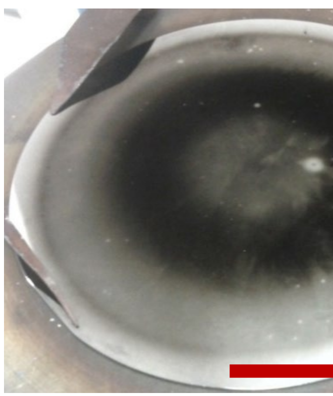


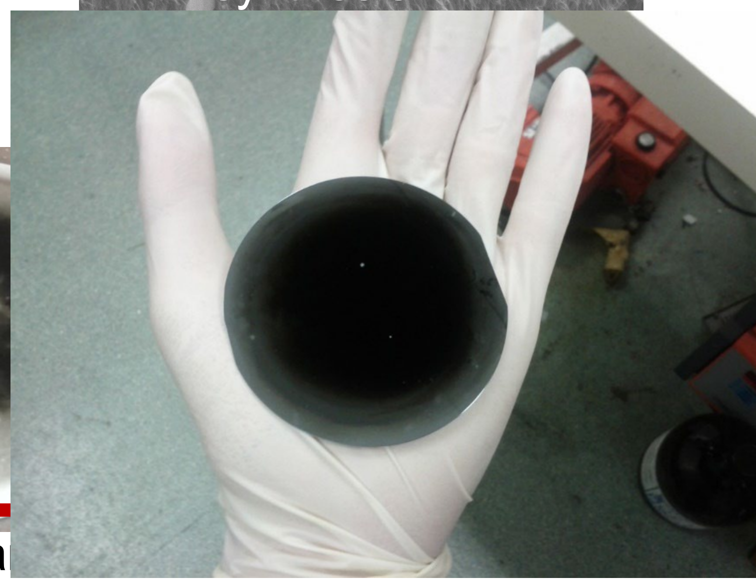
High magnification FESEM of GNF synthesize on a) SS and b) Si substrate.

Criticism 2 – small area uniformity

Large Area Synthesis is Possible





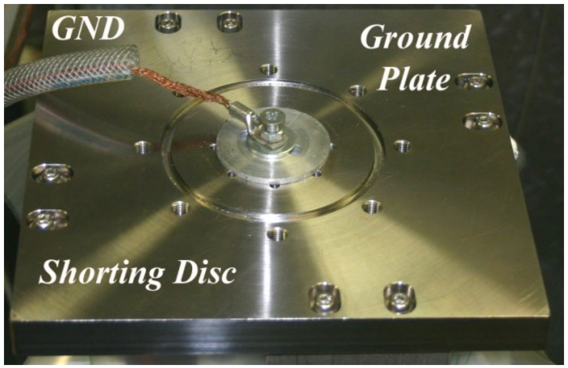


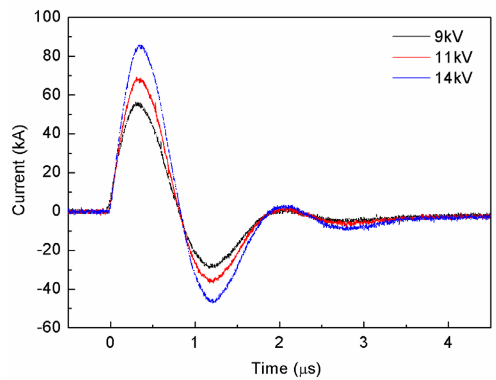
X1 mba

X3 mbar

Scalability of DPF Devices

Another issue is that typical current sheath speed in axial phase for maximum compression efficient **is in a limited range of about few cm/μs** .





Short circuit current → $T/4$ (μs)
→ z_0= 5 (cm/ μs) × $T/4$ (μs)

Speed factor (s) (90 kA/cm/torr$^{1/2}$) ⇒ $s = \frac{I_0}{a\sqrt{p}} = 90\ \text{kA/cm/torr}^{1/2}$ ⇒ **Anode radius** $a = \frac{I_0}{90\sqrt{p}}\ \text{cm}$

z_0 depends on $T/4$ which depends on C_0, as $T = 2\pi\sqrt{L_0 C_0}$

a depends on I_0 which also depends on C_0, as $I_0 = V_0/\sqrt{L_0/C_0}$

High energy plasma focus device use large C_0, which in turn increases both the quarter time period $T/4$ and the discharge current I_0. Hence, large energy plasma focus will have bigger anode length with bigger anode radius.

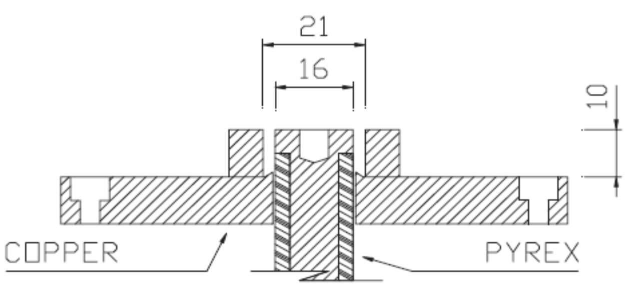
Scalability of DPF Devices

So electrode dimensions (z_0 and a) scales in accordance with the PF storage energy.

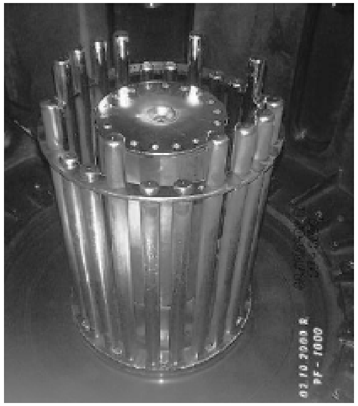
The C_0 varies from160 nF to 1320 μF for 50 J to 1 MJ [N, O] with quarter time period ranging from as short as 200 ns to as big as 12 μs.

The anode length is about 1 and 60 cm, respectively,

The anode radius is about 0.8 and 11.5 cm, respectively,



N. - J. Moreno, P. Silva, L. Soto, Plas. Sour. Sci. Tech., **12**(1) 39 (2003).



O - V. A. Gribkov, A. Banaszak, B. Bienkowska, A. V. Dubrovsky, I. Ivanova-Stanik, L. Jakubowski, L. Karpinski, R. A. Miklaszewski, M. Paduch, M. J. Sadowski, M. Scholz, A. Szydlowski, and K. Tomaszewski, Journal of Physics D-Applied Physics 40(12), 3592-3607 (2007).

According to experimental results

The final pinch radius ~0.1a

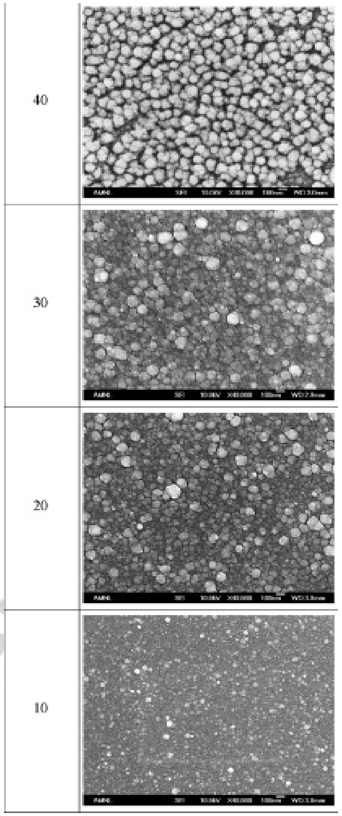
The maximum pinch length ~a

The final plasma volume V_p is of the order of $\pi(0.1a)^2\times(a) \approx 0.03a^3$.

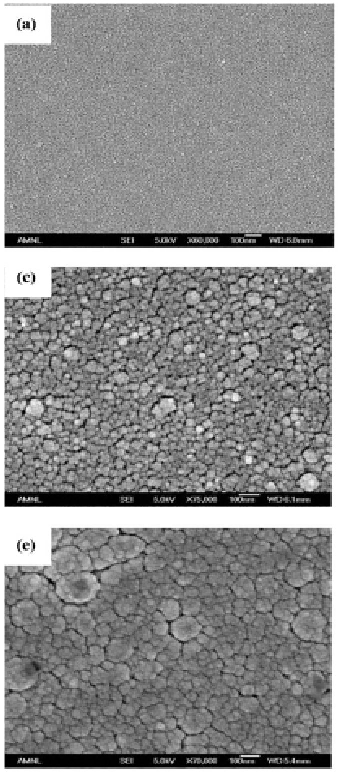
Scalability → Industrial Relevance

Criticism 3 – Shot to shot variation

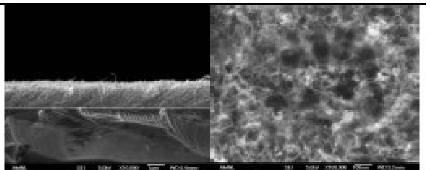
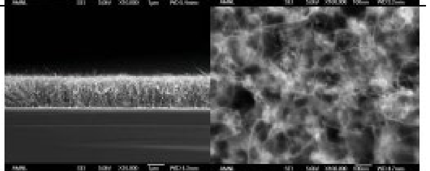
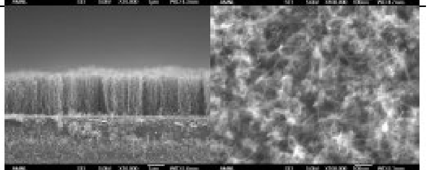
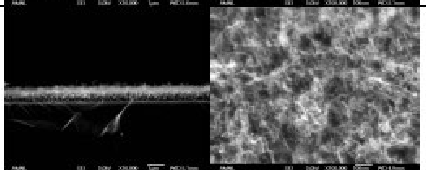
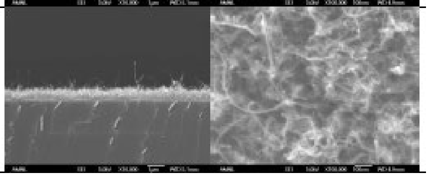
→Reproducibility Issue



R S Rawat, T Zhang, K S Thomas Gan, P Lee, RV Ramanujan, *Fe thin film,* Appl Surf Sci 253, 1611 (2006).



CoPt using 50, 100 and 200 PF Shots
Z Y Pan, R S Rawat1, M V Roshan, J J Lin, R Verma, P Lee, S V Springham and T L Tan, J. Phys. D: Appl. Phys. 42 (2009) 175001

Gas Density, g/m^3	FESEM
12.30	
15.38	
18.45	
23.07	
30.76	

Criticism 4 – Limited Metal/Graphite Anode Based depositions

Stage 1: until year 2000
Metal/Graphite Ablation → Physical Vapor Deposition (PVD)

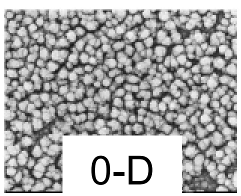
Stage 2: year 2000 onwards
Anode Metal Ablation + Background reactive gas → PVD + PECVD

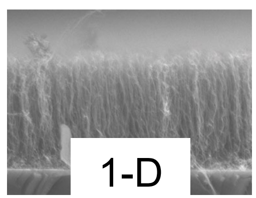
Stage 3: Year 2012 onwards
We have started doing purely gas phase based deposition – CNT and Graphene were using carbon containing gas precursor → PECVD or more appropriately → **HED-PECVD**

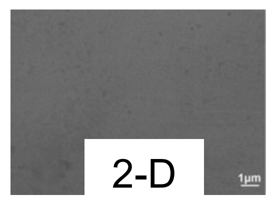
Conclusion

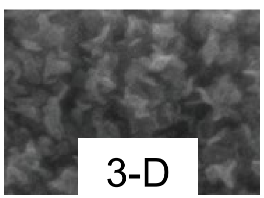
Plasma Focus is versatile device and is maturing for its remarkable usefulness as NOVEL Material Processing and Synthesis Facility

- **High deposition rates**
- **Phase transition**
- **Surface reconstruction**
- **Reproducibility**
- **Dense films**
- **Superior material properties**
- **Large Area Uniform Deposition**









Bi-metals	MX	Carbon
FePt, CoPt	M= Metal; X=N/C/O/ON/CN	DLC, CNT, G