The Abdus Salam
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for Theoretical Physics

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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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Designing Procedure and Issues in the Development of Low Energy Fast Miniature Plasma Focus Device as Neutron and SXR Source

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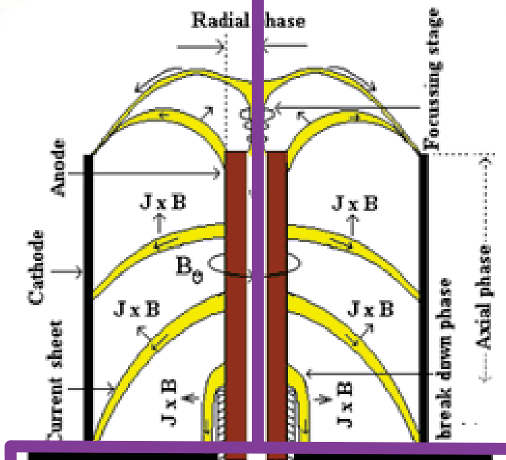
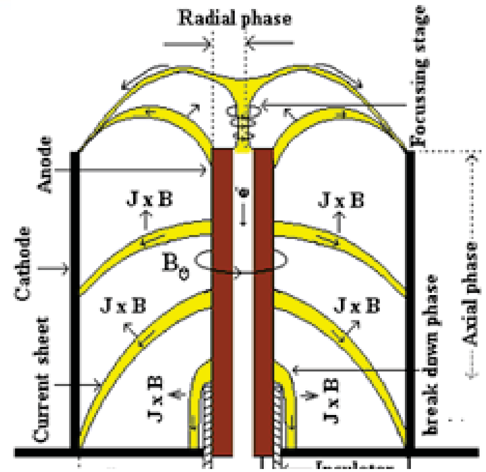
Multiple Radiation Source:

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

Plasma Focus Research – Before 2003

	Device – location	Energy (kJ)	Peak current (kA)	Neutron Yield (neutrons/shot)	Energy density parameter (J m^{-3})	Speed factor (kA cm^{-1} mbar$^{-1/2}$)
Mega-Joule (≥ MJ)	PF-1000 – Poland	1064	2300	2×10^{11}	1.6×10^{10}	73.4
	FRASCATI – Italy	1000	1850	5×10^{11}	5.46×10^{10}	69.10
Large (10 – 500kJ)	TAMU – USA	480	1400	2.6×10^{11}	10×10^{10}	76.77
	SPEED2 – Germany	187	4000	1×10^{11}	2.42×10^{10}	421.63
	PF-360 – Poland	130	1200	3.8×10^{10}	1.7×10^{10}	84.51
	DENA – Iran	90	2800	1.2×10^{9}	0.16×10^{9}	98.23
	DPF-40 – China	18	350	2.1×10^{8}	1.53×10^{10}	60.20
Medium (2 – 10kJ)	7 kJ PF – Japan	7	400	5.8×10^{8}	3.65×10^{10}	93.31
	GN1 – Argentina	4.7	350	3×10^{8}	1.91×10^{10}	92.10
	FN II – Mexico	4.6	350	3×10^{8}	0.82×10^{10}	72.78
	UNU/ICTP	2.9	170	1.2×10^{8}	9.5×10^{10}	61.37
	NX2	2.9	410	7×10^{8}	5.3×10^{10}	79.72
	BARC – India	2.2	180	14.4×10^{7}	5.32×10^{10}	68.84
	PACO – Argentina	2	250	5×10^{8}	0.35×10^{10}	81.64
Sub-kilojoule	PF-400-Chile	0.4	127	1.05×10^{6}	5.2×10^{10}	70

2003

Sub-kJ Miniature Plasma Focus Research

Device	PF-400J	PF-50J	NF
Capacity (nF)	880	160	5
Charging voltage (kV) Maximum Typical operation	 35 30	 35 25-30	 15 5-10
Inductance (nH)	38	38	5
Time to peak current (ns)	300	150	16
Stored energy (J) Maximum Typical operation	 540 400	 100 50-70	 0.56 0.1
Peak current (kA) Maximum Typical operation	 168 127	 70 50-60	 15 5-10
Maximum repetition rate (Hz) Typical operation	1 single shot	1 single shot	50 1-20
Neutron yield per shot	1.1×10^6 at 400J and 9mbar in D_2	3.3×10^4 at 70J and 9mbar in D_2 1.1×10^4 at 50J and 6mbar in D_2	10^3 with low reproducibility

Chilean Nuclear Energy Commission, CCHEN.

P.Silva et al, RSI, 73, 2583, 2002.
P. Silva et al, APL, 83, 3269, 2003
J. Moreno et al, PSST, 12, 39, 2003

Fomenkov I V *et al* 2004
J. Phys. D: Appl. Phys. **37** 3266–76

S.M. Hassan, T. Zhang, A. Patran, R. S. Rawat, S. V. Springham, T. L. Tan, D. Wong, W. Wang, S. Lee, V.A. Gribkov, S.R. Mohanty and P. Lee, *Pinching evidences in a miniature plasma focus with fast pseudospark switch*, Plasma Sources Science and Technology 15 (4), 614-619 (2006).

Why Miniature DPF? - Reason 1

SolidState TECHNOLOGY WaferNEWS Microlithography WORLD FEB 2002

Dense plasma focus for production-level EUV lithography

B. Nikolaus, W.N. Partlo, I.V. Fomenkov, *Cymer Inc.*, San Diego, California

overview

Optical lithography will be replaced by a nonoptical technique at some point for device shrinks to 35nm. Extreme ultraviolet lithography is currently showing the most promise. However, issues such as power scaling and cost of consumables, necessary for a production-level source, are still works in progress. Cymer is proposing a concept for a 13.5nm source based on dense plasma focus to meet these challenges.

Pinch Plasma Temp ~ 1 keV
Soft x-ray

↓

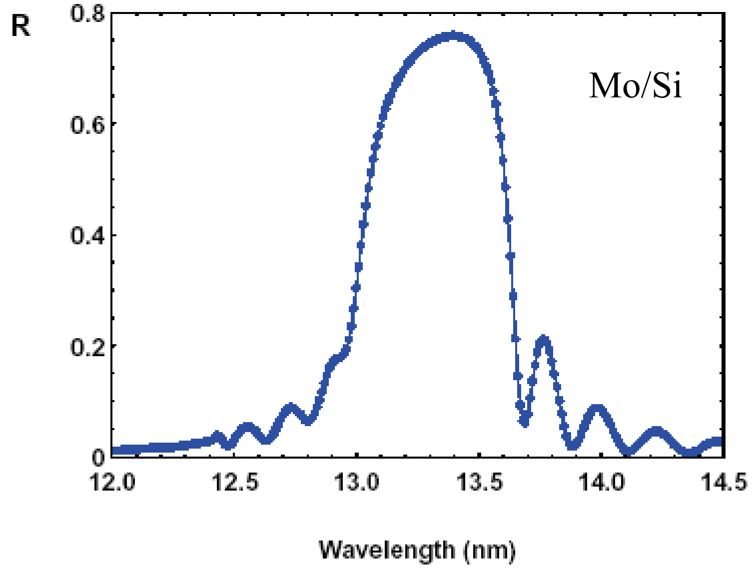
Temp ~ 100 eV
EUV

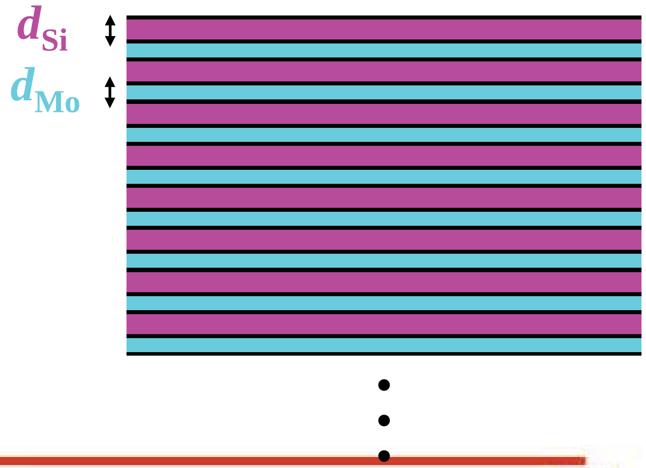
A Dense Plasma Focus device has been identified as a source for EUV lithography because

(i) possible tuning of plasma temperature for desired EUV emission at 13.5 nm
(ii) high source brightness,
(iii) possible high repetition rate operation, and
(iv) PF based sources are expected to offer lower cost of ownership in comparison to synchrotron radiation sources and laser produced plasma.

The Choice of 13.5 nm as the EUV Wavelength for Lithography

- Mo/Si multilayers have high reflectivity near 13.5 nm
- Peak reflectivity near 75%, though 69% is more typical including capping layers and diffusion barriers
- Optimal layer thickness ratio:
  - $d_{Mo} / (d_{Mo} + d_{Si}) = 0.4$
  - Each layer is 3 to 4 nm!





Why Miniature DPF ??? – Reason 2
A Spin-off in applications of 'Neutron Source'

Active Neutron Interrogation
- Explosives
- Special nuclear materials
- Narcotic drug

Nuclear Medicine
- P.E.T. Isotope Production
- Boron capture neutron therapy
- Neutron beam therapy

Nuclear Geophysics
- Gas and oil well-logging
- Ore (uranium) well-logging
- Mine mineral mapping

Industrial Processing
- Cement process control
- Coal quality analysis
- Wall thickness analysis

Neutron Radiography
- Thermal neutron radiography
- Fast neutron radiography

Global Market Potential of <u>Portable</u> <u>Neutron Generators</u>

2001: ~US $60M

2006: >US $750M

By 2010: >US $1.4 billion

Neutrons for Active Interrogation

Neutrons and γ - rays have very penetration capability

(Penetration Depth: Suitcases to sea-land containers)

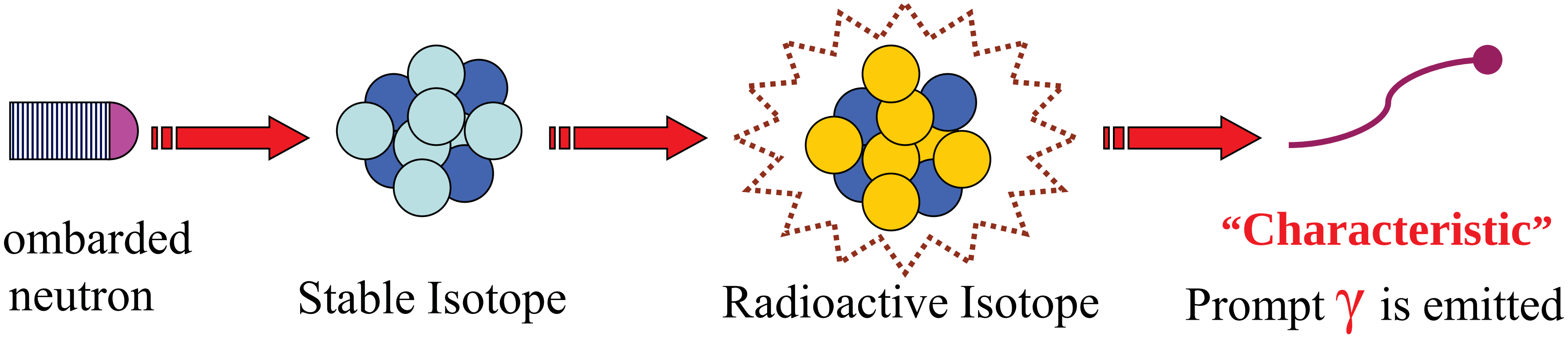
Non-intrusive Interrogation - Possible!

Elements	*H*	*C*	*N*	*O*	*Cl*	*C/O*	*C/N*	*Cl/O*
Explosives	Low	Medium	High	Very High	Medium	Low <1	Low <1	Very Low
Narcotics	High	High	Low	Low	Medium	High >3	High >1	Very High

Material	**Expected Ratio**	
	C/O	**N/O**
RDX	0.53	1
TNT	1.2	0.5
C-4	0.71	1

'fingerprints' of elements with neutrons ?

Neutrons for Active Interrogation



Possible Interactions…..

Thermal Neutron (H, N, Cl, S…)

Neutron Capture

$$n + {}^{A}X \rightarrow {}^{A+1}X + \gamma$$

Fast Neutron (C, O…..)

Elastic Scattering

$$n + X \rightarrow n' + X'$$

$$E_n + E_X = E_{n'} + E_{X'}$$

Inelastic Scattering

$$n + X = n' + X^* \rightarrow \gamma$$

$$E_n + E_X > E_{n'} + E_{X^*}$$

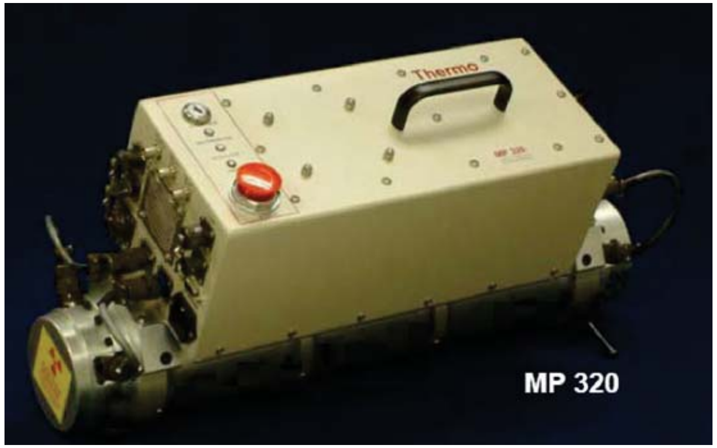
‘Portable Neutron Source’

Passive Radioactive Neutron Source (Continuous)

^{252}Cf	**2.1 MeV**	**2.6 years**
$^{241}Am(Be)$	**4.5 MeV**	**458 years**

- Handling and Storage is problem
- Energy of neutrons is constraint
- Energy spectrum is broad
- Heavy shielding requirement

Sealed Tube Neutron Source (Pulsed)



Accelerated hydrogen isotopes impinge on deuterated/ tritium (2-10 Ci) targets

- Cost of sealed tubes is very high
- Target limits hours of operation
- Accelerator tubes cannot be re-used

Novelty of Low Energy Miniature PF devices

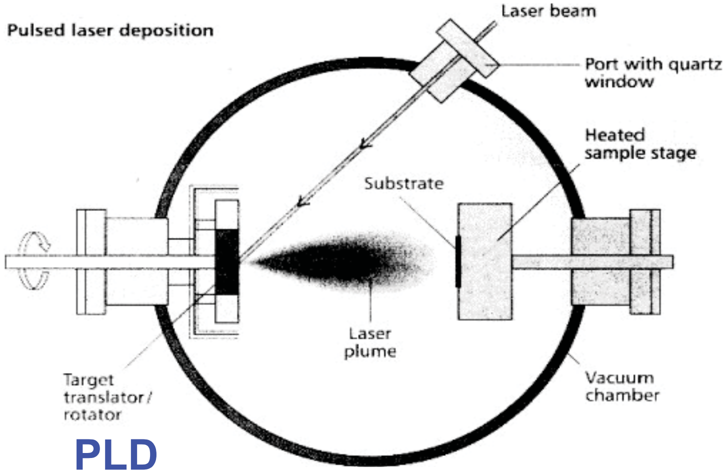
The neutron yield per shot, which scales as $Y_n \sim E^2$ or $Y_n \sim I^4$, is low in low energy PF devices as the stored energy, E, and the discharge current, I, are low in low energy PF device.

Due to low capacitance used the low energy PF devices are inherently fast (few hundreds of ns) resulting in **significantly short neutron pulse-width**.

The short neutron pulse is desirable for time of flight measurements **to detect the location of explosives** in complex environment.

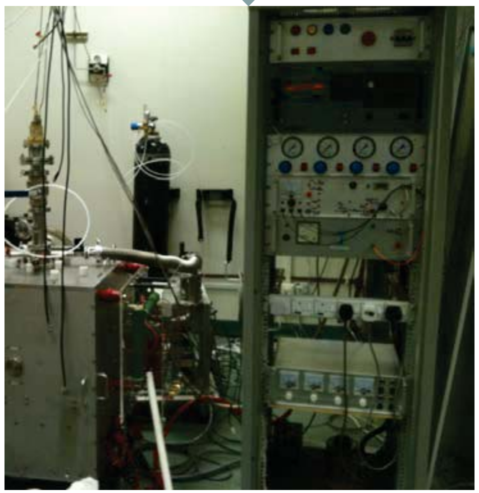
Why Miniature DPF ??? – Reason 3

Towards High Rep Rate HEDP Deposition Facility

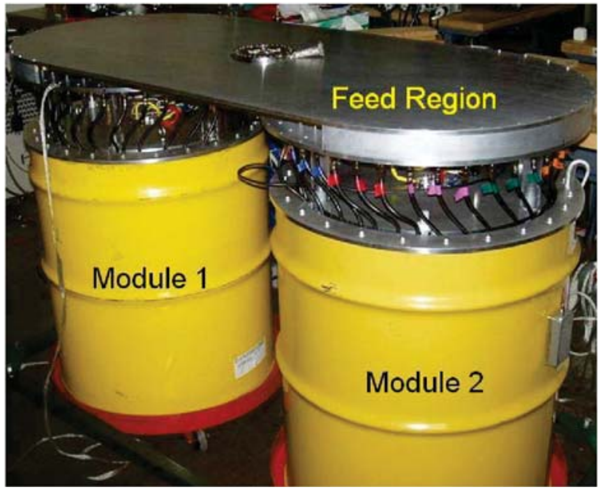


PLD
Nd:YAG – 10 Hz
Excimer – 100 Hz

NX2 – 3kJ
16 Hz – 48 kW
Water Cooled Anode



FMPF3 – 0.2kJ
10 Hz – 2 kW
No-water cooling required



DPF 2,
60 kA,
100Hz

AASC, USA High Rep Rate PF

Our Motivation

Pulsed portable neutron source

NX2

1.4 x 1.6m x 1.6m

V ~ $3.6m^3$

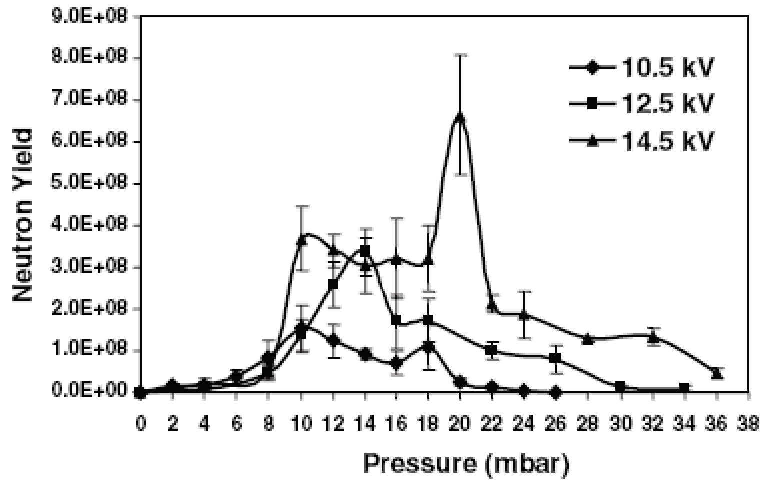
FMPF-1

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).

Objectives

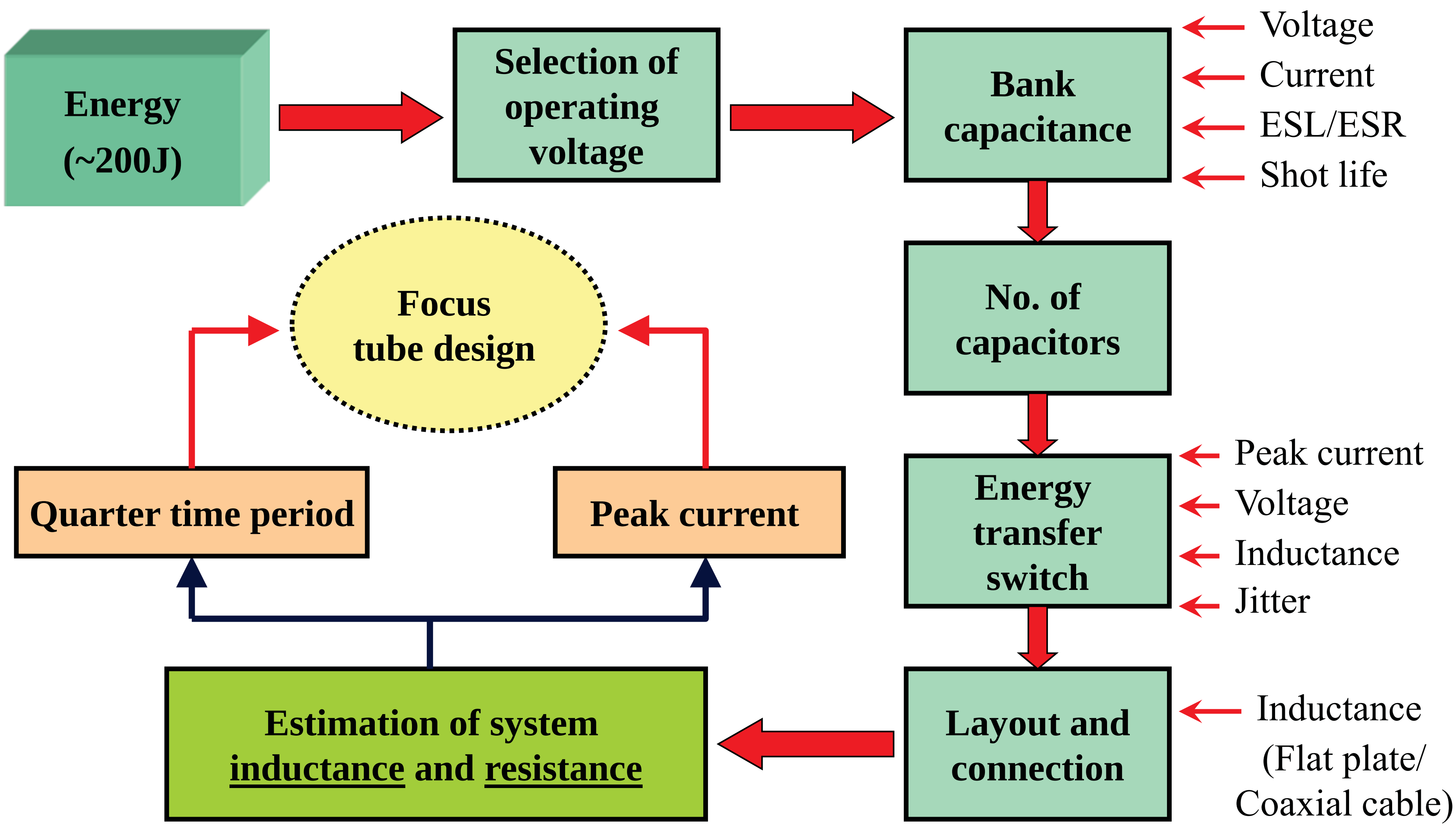
Demonstrate the feasibility of low energy miniature plasma focus device and optimize its performance as an efficient pulsed neutron source.

Resolve the technical intricacies confronted in repetitive mode of operation.

Explore the concept of "yield enhancement by repetition".

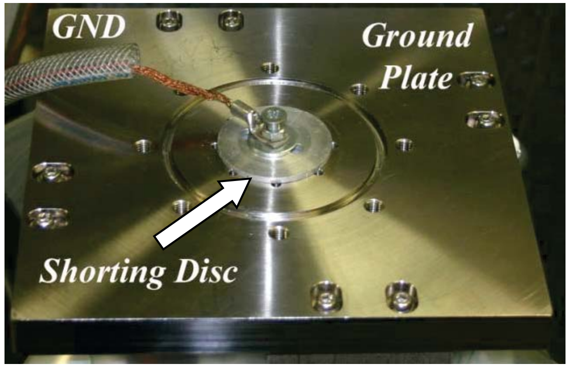
- **Significant soft and hard x-ray yields for possible applications in lithography and radiography**
- **Intense energetic ions and electrons emissions which can be used for nanostructured material synthesis**

Conceptualization of Basic Pulsed Power system



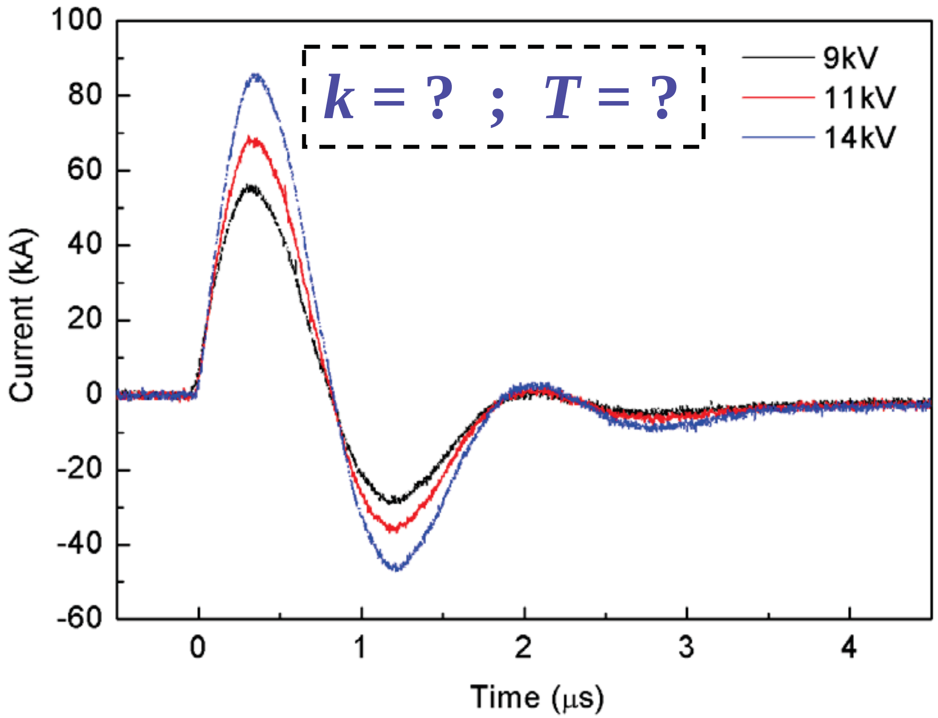
Electrical Characteristics Measurements: short circuit test

$L_{eq} = ?\ ;\ R_{eq} = ?\ ;\ I_0 = ?$

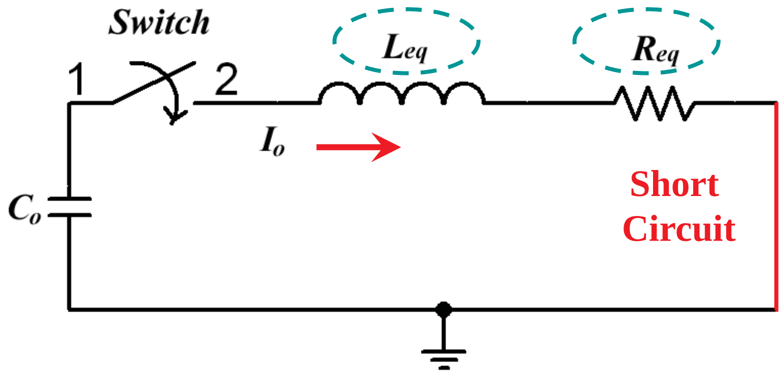


Main objectives were to determine:

- Peak discharge current delivering capacity (I_0)
- Series equivalent circuit parameters (L_{eq}, R_{eq})



Sample short circuit current traces in FMPF-1



$$L\frac{dI}{dt} + IR + \frac{1}{C}\int I dt = V_o$$

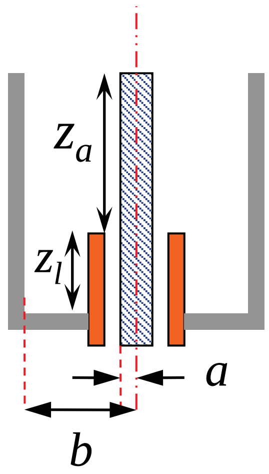
$$I_o = \frac{\pi C_o V_o (1+k)}{T}$$

$$L_{eq} = \frac{T^2}{4\pi^2 C_o}$$

$$R_{eq} = -\frac{2}{\pi}\sqrt{\frac{L_o}{C_o}}\ln k$$

Designing of Plasma Focus Tube Assembly

INPUTS
- I_o - Peak discharge current amplitude
- $T/4$ - Quarter time period of the discharge current signal
- L_{eq} – System inductance



Focus tube parameters

- a – Anode radius
- z_a – Anode length
- b – Cathode radius
- Z_l – Insulator length

1. Anode radius (a)

Speed factor

(90 kA/cm/torr$^{1/2}$)

$$\frac{I_0}{a\sqrt{p}}$$

2. Anode length (z_a)

Typical velocities in axial and radial phases

v_a : 10 cm/µs, v_r : 25cm/µs

$$z_a = v_a\left[\frac{T}{4} - \frac{a}{v_r}\right]$$

3. Cathode radius (b) $\quad L_{pf} \approx L_{eq}$; $L_{pf} = \dfrac{\mu_0}{2\pi}\ln\left(\dfrac{b}{a}\right) \times z_a$

4. Insulator length (z_l) $\quad z_l < (b\text{-}a)$, *paschen minima*

Optimization using Lee Code

Short Circuit Oscillogram → $k,\ T$ → Rogowski Coil Calibration Factor

$k,\ T$ ↓

$L_o,\ R_o$

$a,\ b,\ z_o,\ p,\ C_o,\ V_o$

↓

Simulated Trace → Fitting by adjusting mass And current shading factors

Rogowski Coil Calibration Factor ↓ Calibrated Current Trace from Experiment ↓ Fitting by adjusting mass And current shading factors

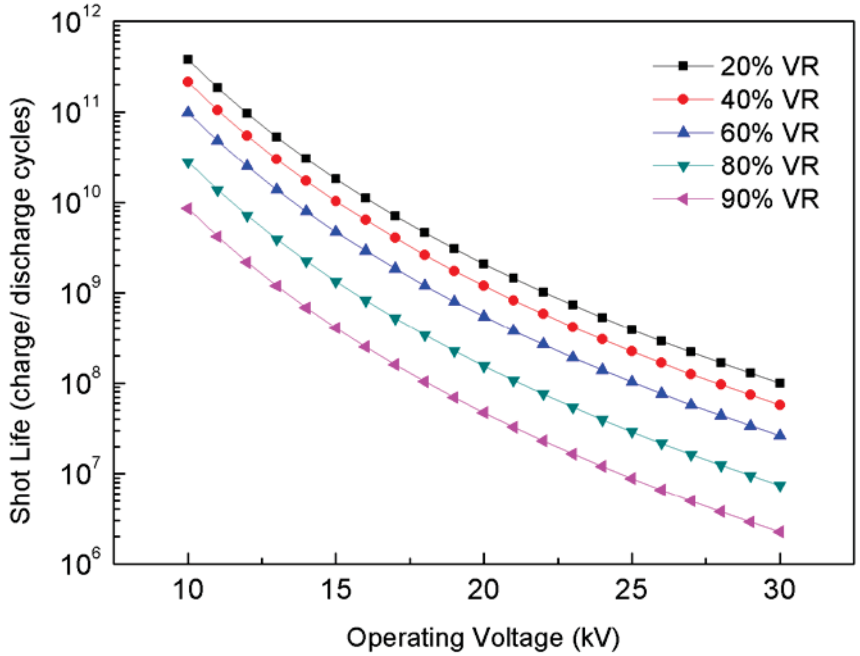
$$k = reversal\ \ ratio$$

$$T = time\ period$$

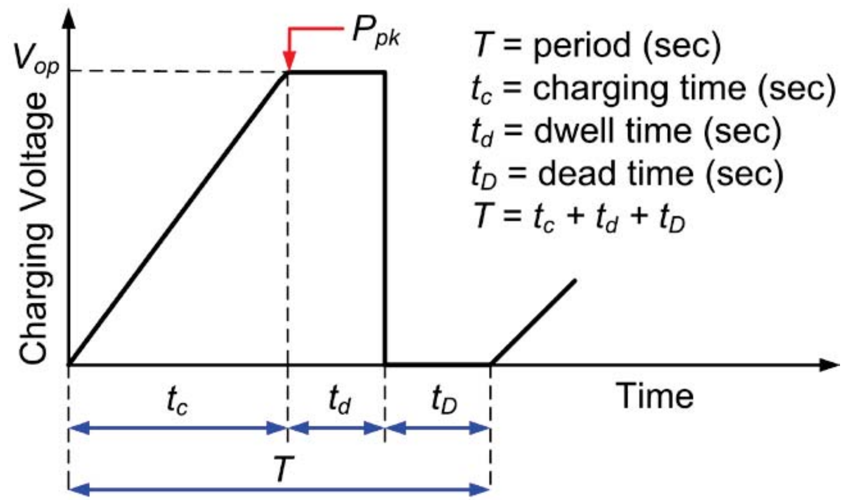
Intricacies in Repetitive Pulsed Power System

1. Selection of efficient and robust devices at the component level.

- ✓ **Capacitors: high energy density and shot life**
- ✓ **Switches: large coulomb transfer capacity, fast recovery and low jitter**
- ✓ **Chargers: high wattage constant power chargers for fast charging.**



(Capacitor #37323, GA, USA), (0.3μF/ 30kV/ 10% VR)

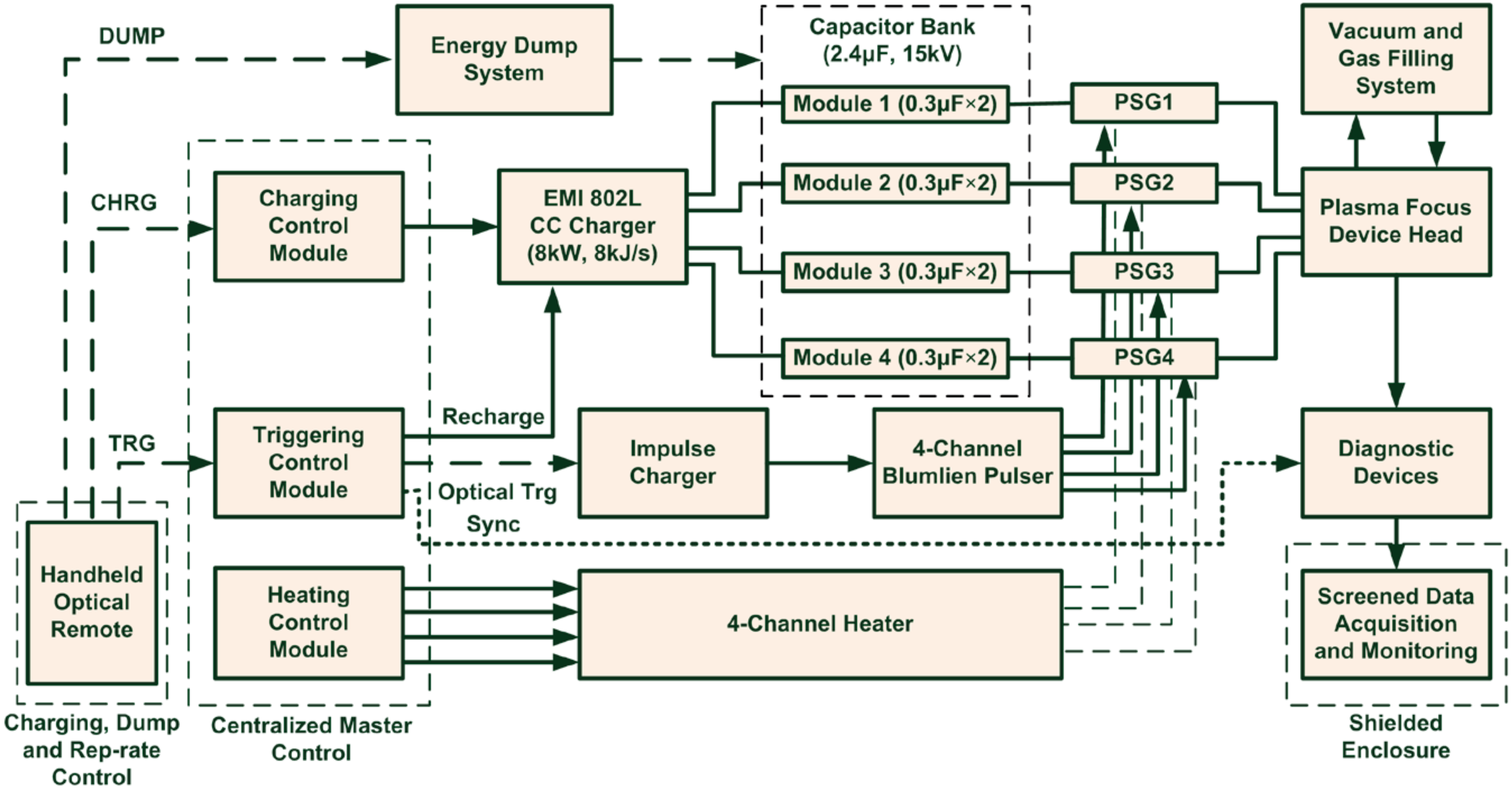


Charging time $$t_c(\text{sec}) = \frac{0.5 \times C_0 \times V_0 \times V_{rated}}{P_{pk}}$$

ALE LAMBDA HVPS 802L (8kW)

Intricacies in Repetitive Pulsed Power System....Contd

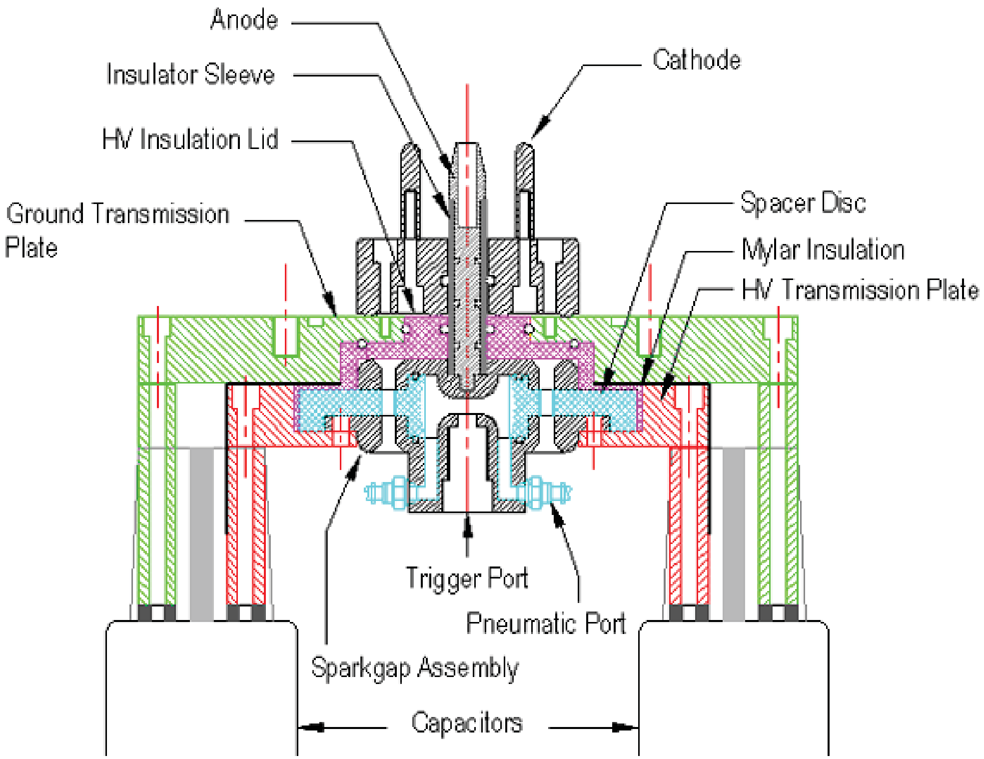
2. Deciding the integration and control scheme at the system level.

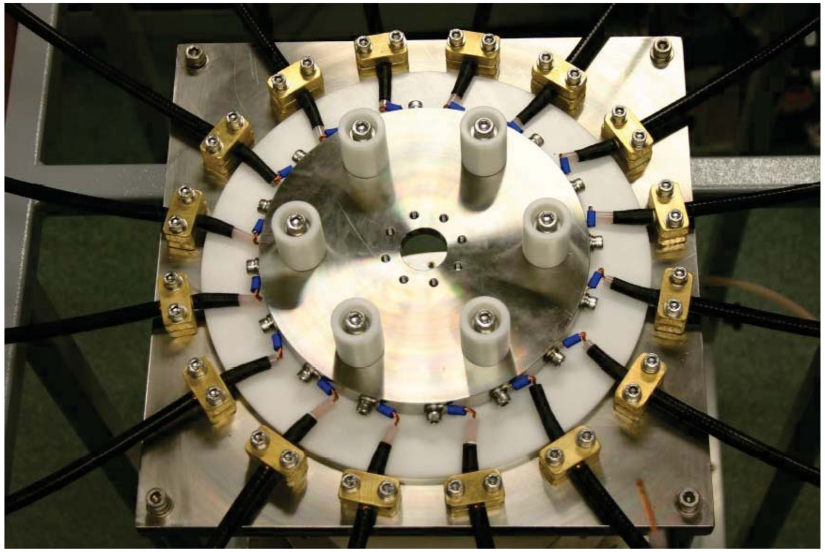


(Operation and control scheme implemented in FMPF-3 device)

3. Effective interface to deliver fast pulses at application level.

Capacitors ------------- Switch -------------- Load



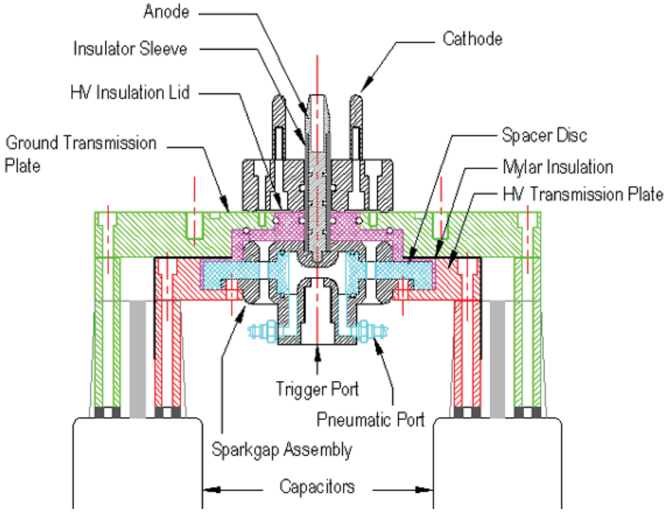


Flat plate transmission lines

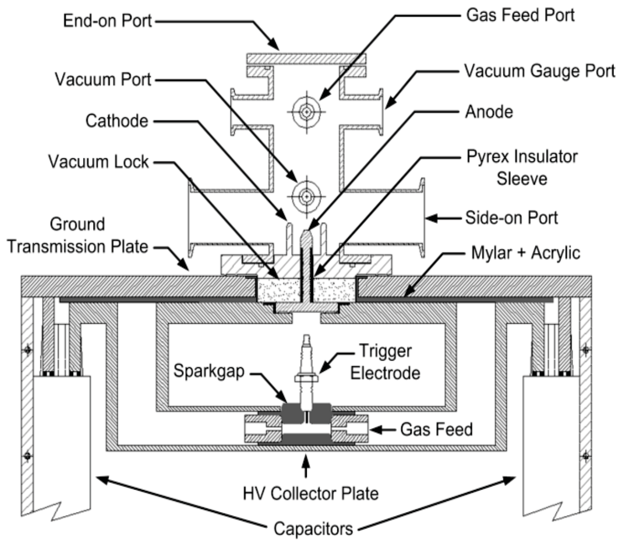
Coaxial Cables

Roles of Three Different Versions of FMPF

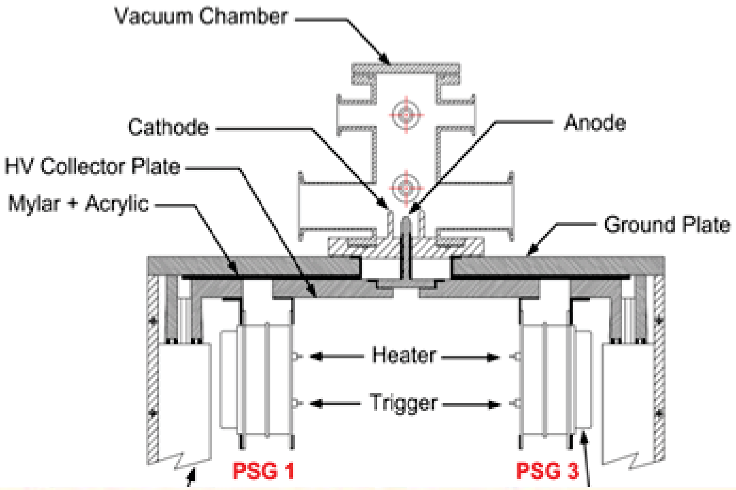
FMPF-1: benchmark device for all optimization experiments.



FMPF-2: first version of high repetition rate FMPF device.



FMPF-3: high performance, high repetition rate FMPF device.

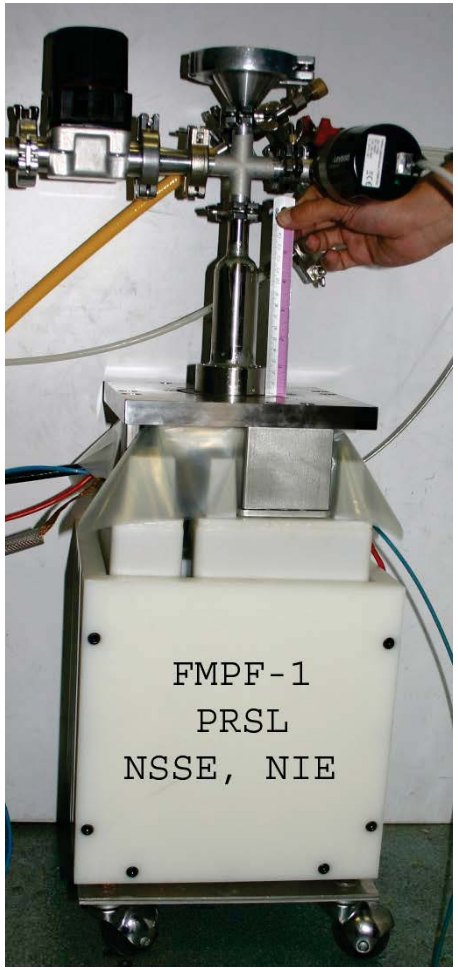


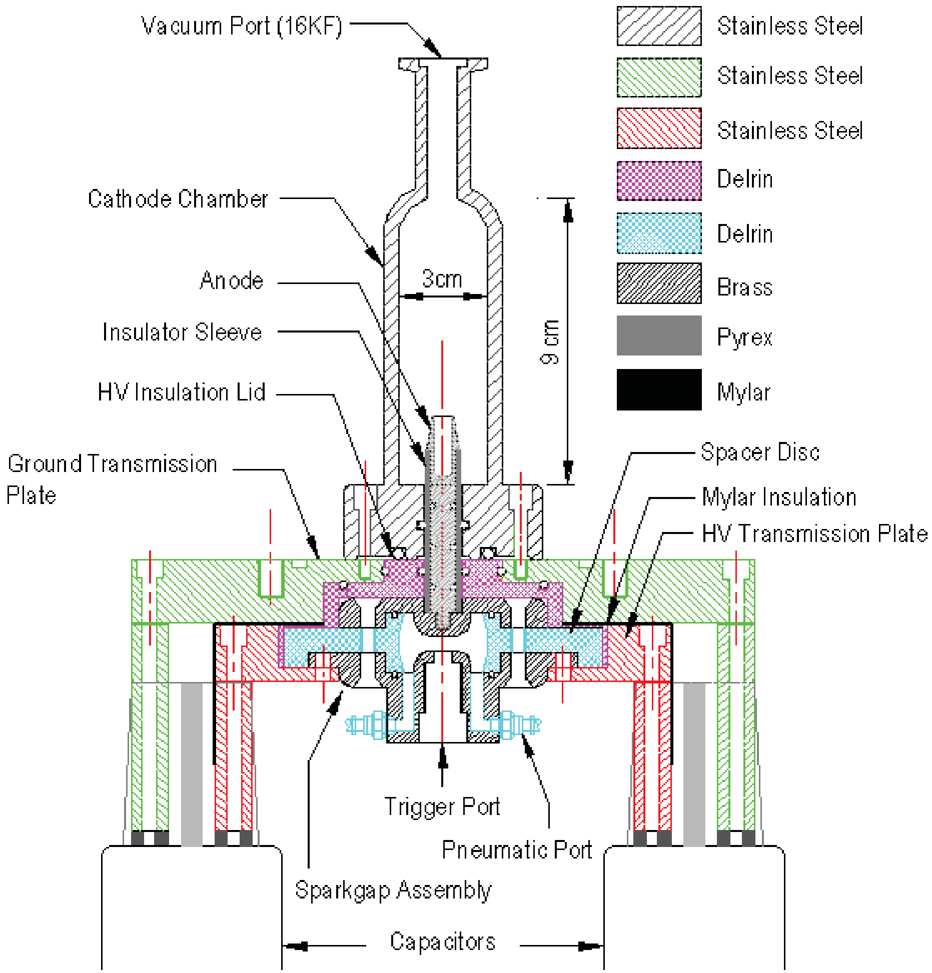
The FMPF-1 device

0.2m × 0.2m × 0.5m

(Total Weight: ~25kgs)

(0.6μF×4≈ 2.4μF)

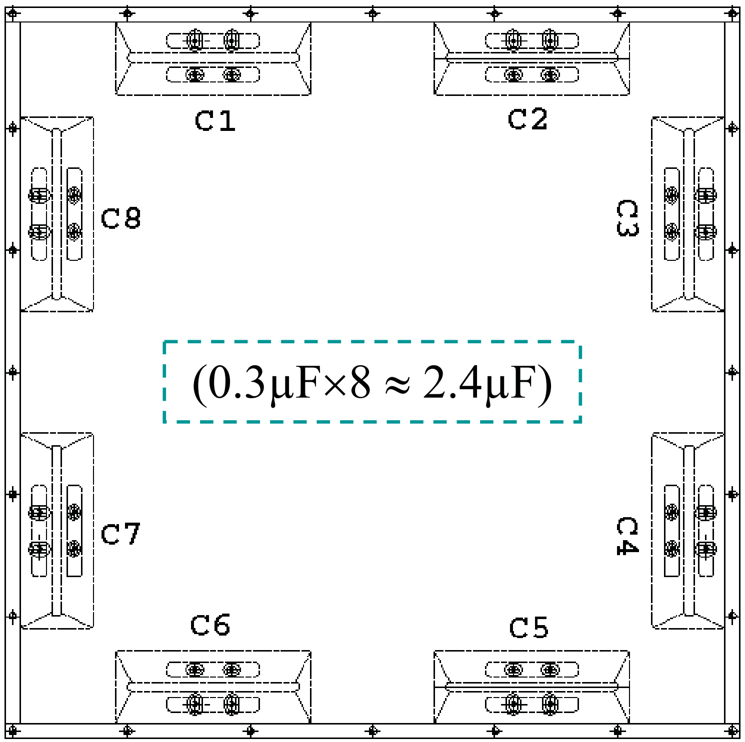




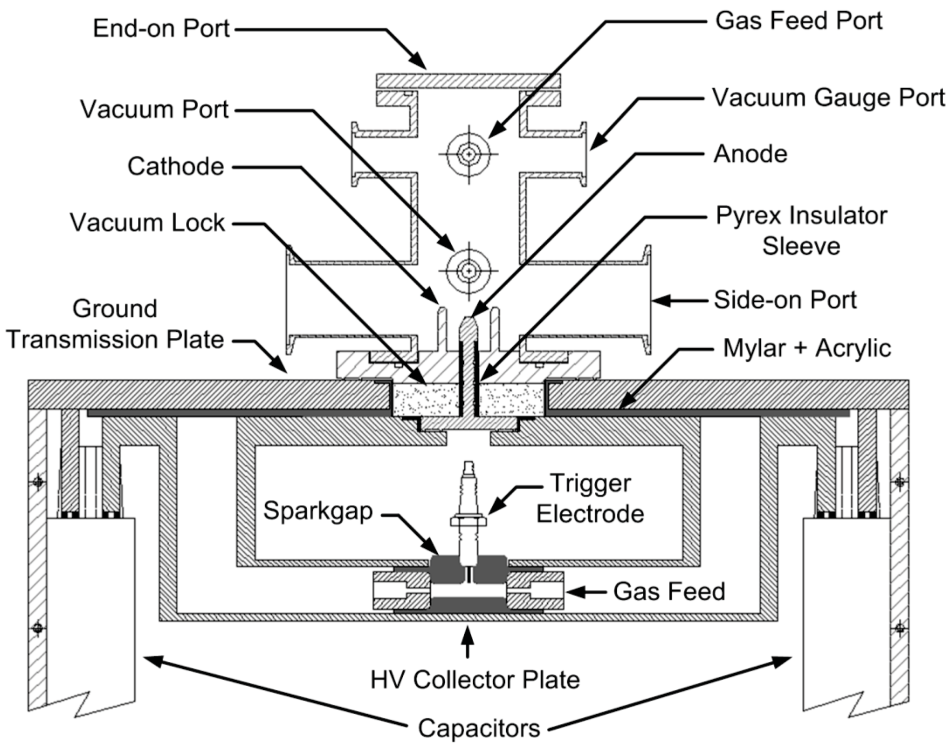
Capacitor bank **Integrated System** **Schematic View**

Rishi Verma, M. V. Roshan, F. Malik, P. Lee, S. Lee, S. V. Springham, T. L. Tan, M. Krishnan and R. S. Rawat, *Compact sub-kilojoule range fast miniature plasma focus as portable neutron source*, **Plasma Sources Science and Technology**, 17(4), 045020 (2008).

The FMPF-2 device



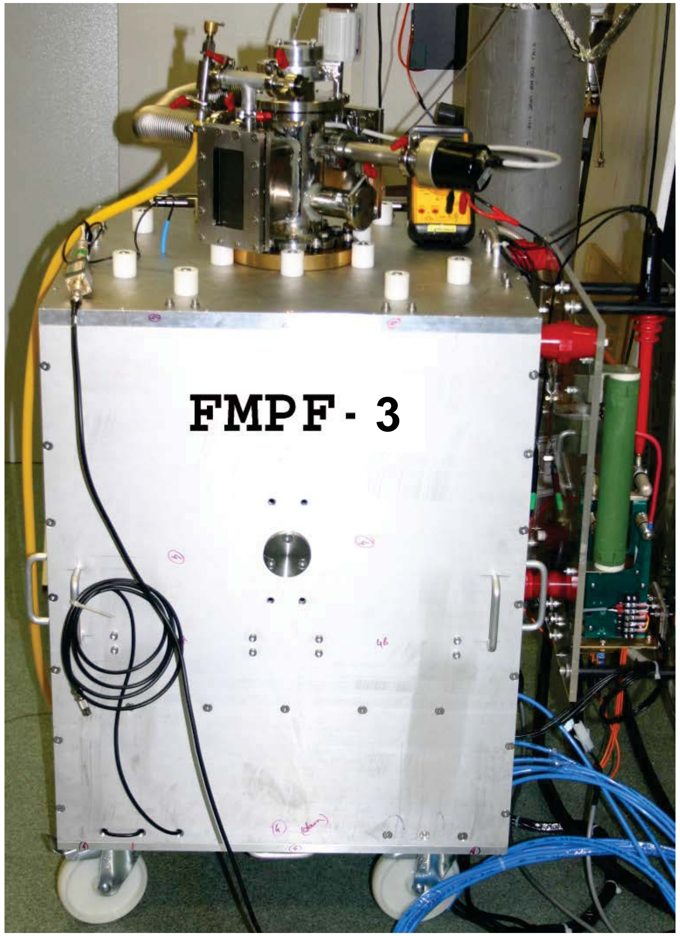
Layout of the capacitor bank



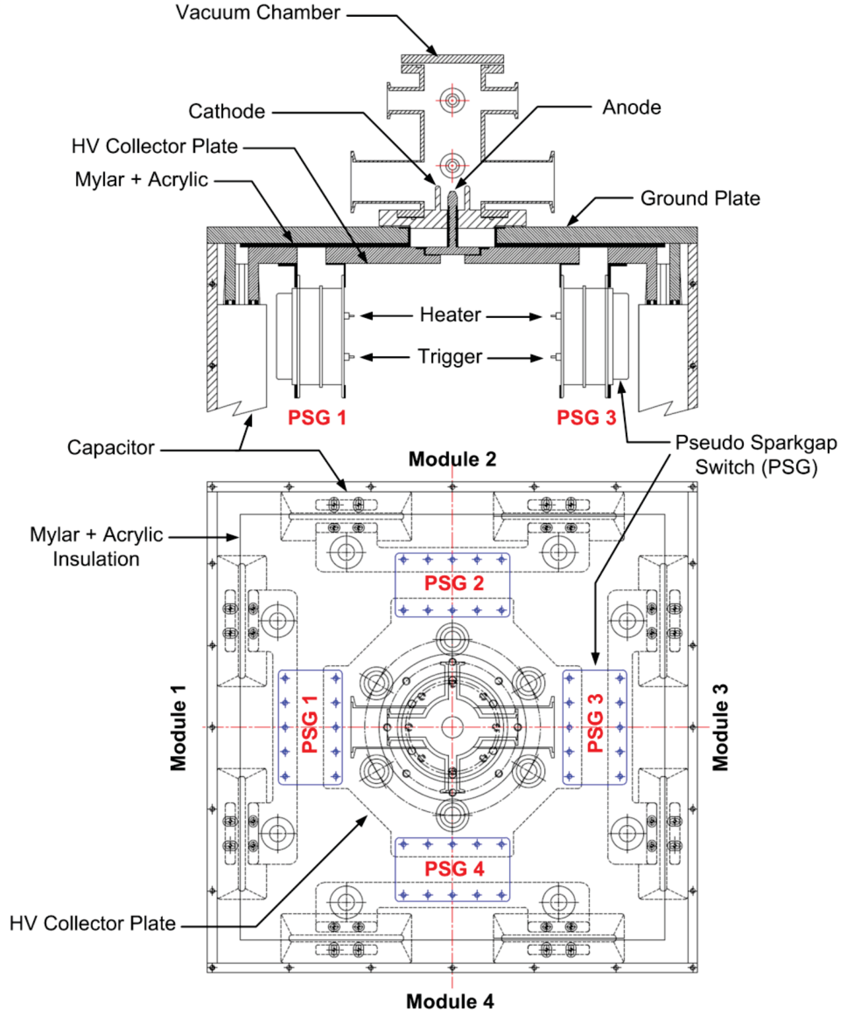
Constructional layout of FMPF-2 device

Rishi Verma, R. S. Rawat, P. Lee, M. Krishnan, S. V. Springham and T. L. Tan, *Realization of enhancement in time averaged neutron yield by using repetitive miniature plasma focus device as pulsed neutron source*, **J. Phys. D: Appl. Phys.**, 42, 235203, (2009).

The FMPF-3 device



Fully Integrated System



Schematic View

Rishi Verma, R. S. Rawat, P. Lee, S. V. Springham and T. L. Tan, *High performance high repetition rate miniature plasma focus device: Record time averaged neutron yield at 200 J with enhanced reproducibility*, Journal of Fusion Energy, In Press (2012).: DOI: 10.1007/s10894-012-9517-5.

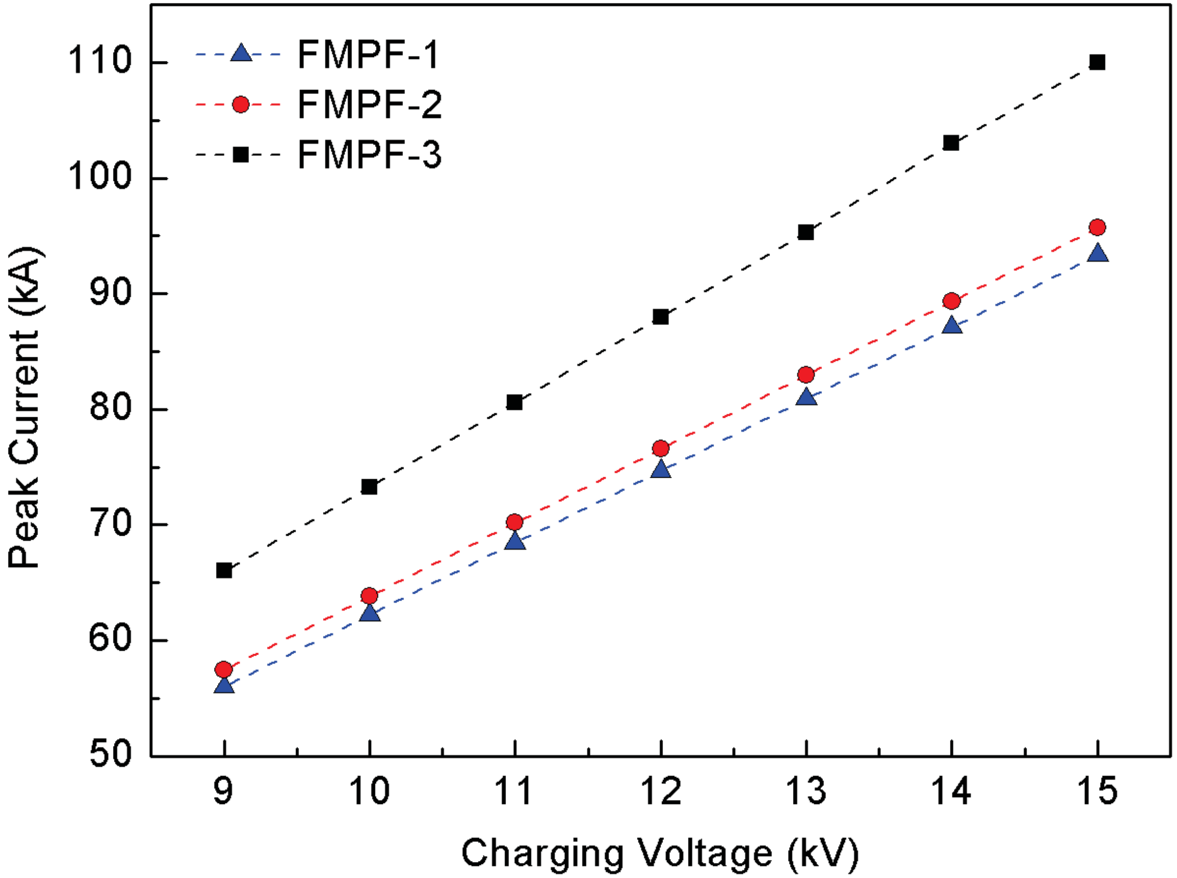
Hardware configuration summary of FMPF devices

Specifications	FMPF-1	FMPF-2	FMPF-3
Total capacitance	2.4μF	2.4μF	2.4μF
Capacitance (C_o) × No. of Capacitors	0.6μF × 4	0.3μF × 8	0.3μF × 8
Max. charging voltage (V_o)	30kV	30kV	30kV
ESL/ESR of capacitor(s)	~70nH/ ~250mΩ	~20nH/ ~80mΩ	~20nH/ ~80mΩ
No. of energy transfer switch(s)	1	1	4
Switch type/ Model	Trigatron/ Indigenous	Trigatron/ SG-101M-75C	Pseudospark/ TDI1-150k/25
Operating voltage range/ Maximum current handling limit	8 – 18kV/ 100kA	10 – 40kV/ 100kA	3 – 20kV/ 150kA
Max. discharge repetition rate (*PRR*)	0.5Hz	10Hz	10Hz

Major electrical characteristics of FMPF devices

Electrical Parameters	FMPF-1	FMPF-2	FMPF-3
Energy bank capacitance (C_o)	**2.4μF**	**2.4μF**	**2.4μF**
Max. charging voltage (V_o)	**14kV**	**14kV**	**14kV**
Max. stored energy (E_o)	**235J**	**235J**	**235J**
Peak short circuit current (I_{sc}) @ 14kV	**87kA**	**89kA**	**103kA**
Eq. circuit inductance (L_{eq})	**27±2nH**	**56±3nH**	**34±2nH**
Eq. circuit resistance (R_{eq})	**66±3mΩ**	**26±3mΩ**	**23±3mΩ**
Driver impedance (Z_o)	**~161mΩ**	**~157mΩ**	**~106mΩ**
Reversal factor (*k*)	**33%**	**77%**	**78%**
Quarter time period (*T/4*)	**~400ns**	**~575ns**	**~458ns**
Max. discharge repetition rate (*PRR*)	**0.5Hz**	**10Hz**	**10Hz**

Comparison of peak discharge currents in FMPF devices



while operating at similar energies/ charging voltages, the peak discharge current delivered by FMPF-3 device is ~18-20% higher in comparison to the two other versions of FMPF devices.

Complications in diagnostics customization of FMPF devices

1. Device operation is inherently fast

   ($t_{1/4} \sim 400$ns and $t_{pinch} \sim 10 - 15$ns)

Requires **high bandwidth response electrical diagnostics** for event observation

2. Measuring Neutron Yields $\leq 10^6$ n/s

Requires **customization of high sensitivity neutron detection setup**

3. Generation of intense electromagnetic noise

Effective shielding of implemented diagnostics is very important

Neutron Diagnostics at PRSL

Bubble Detectors

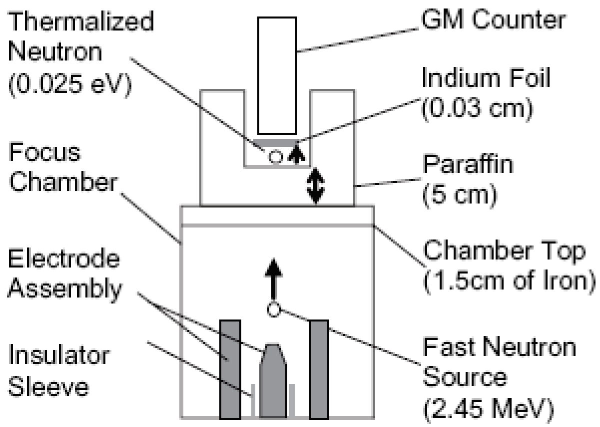


Figure 1. Schematic of the set-up for the total neutron yield measurement from the plasma focus device.

Indium Foil Activation Detector

(for single shot operations)

Beryllium Activation Detector

(for repetitive; up to 3 Hz)

S. Mahmood, S.V. Springham, T. Zhang, R.S. Rawat, T.L. Tan, M. Krishnan, F.N. Beg, S. Lee and P. Lee, *A novel fast neutron activation counter for high repetition rate measurements*, Review Scientific Instruments 77 (10), 100713 (2006).

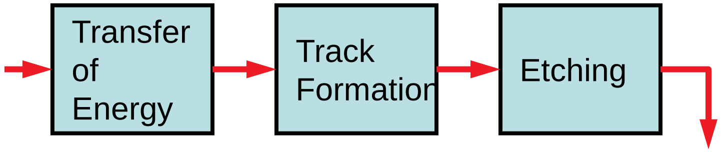
^{3}He Proportional Counter

$$n + {}^3He \rightarrow {}^3H\ (573keV) + {}^1H\ (192keV)$$

Time resolved neutron and HXR

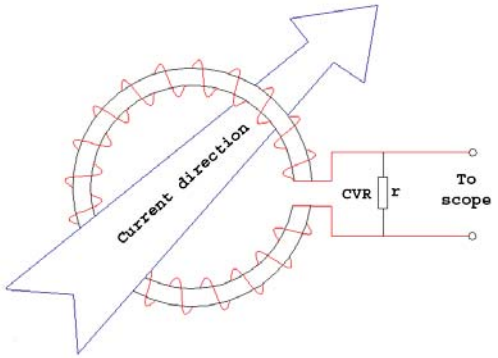
(NE102A Scintillator Photomultiplier)

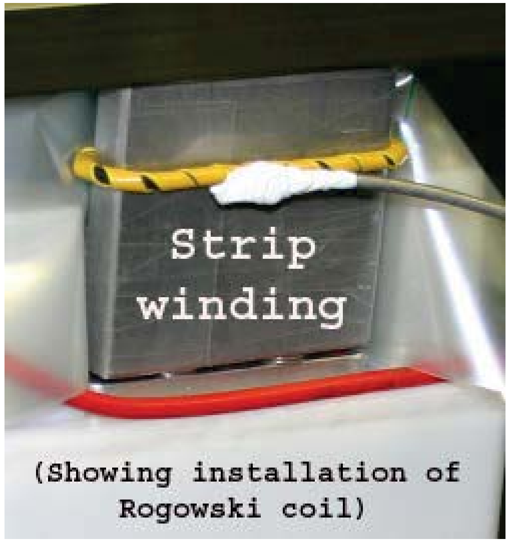
Solid State Nuclear Track Detector



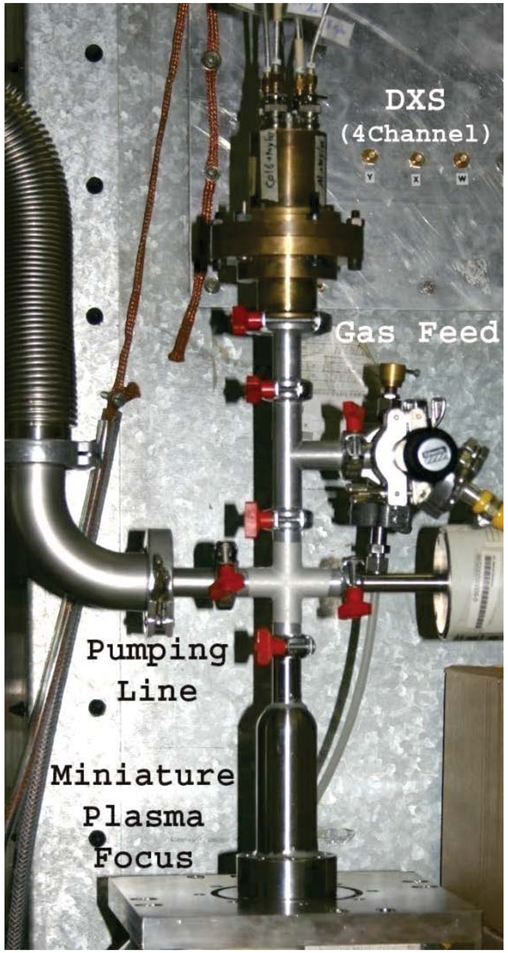
Diagnostics

Electrical

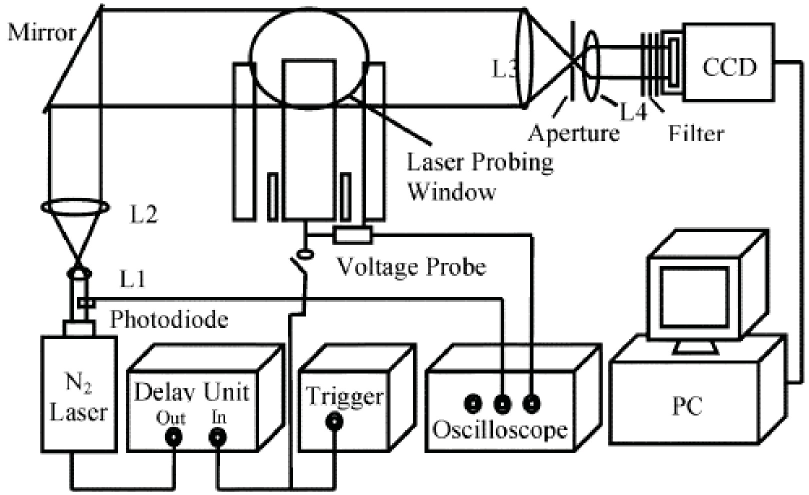




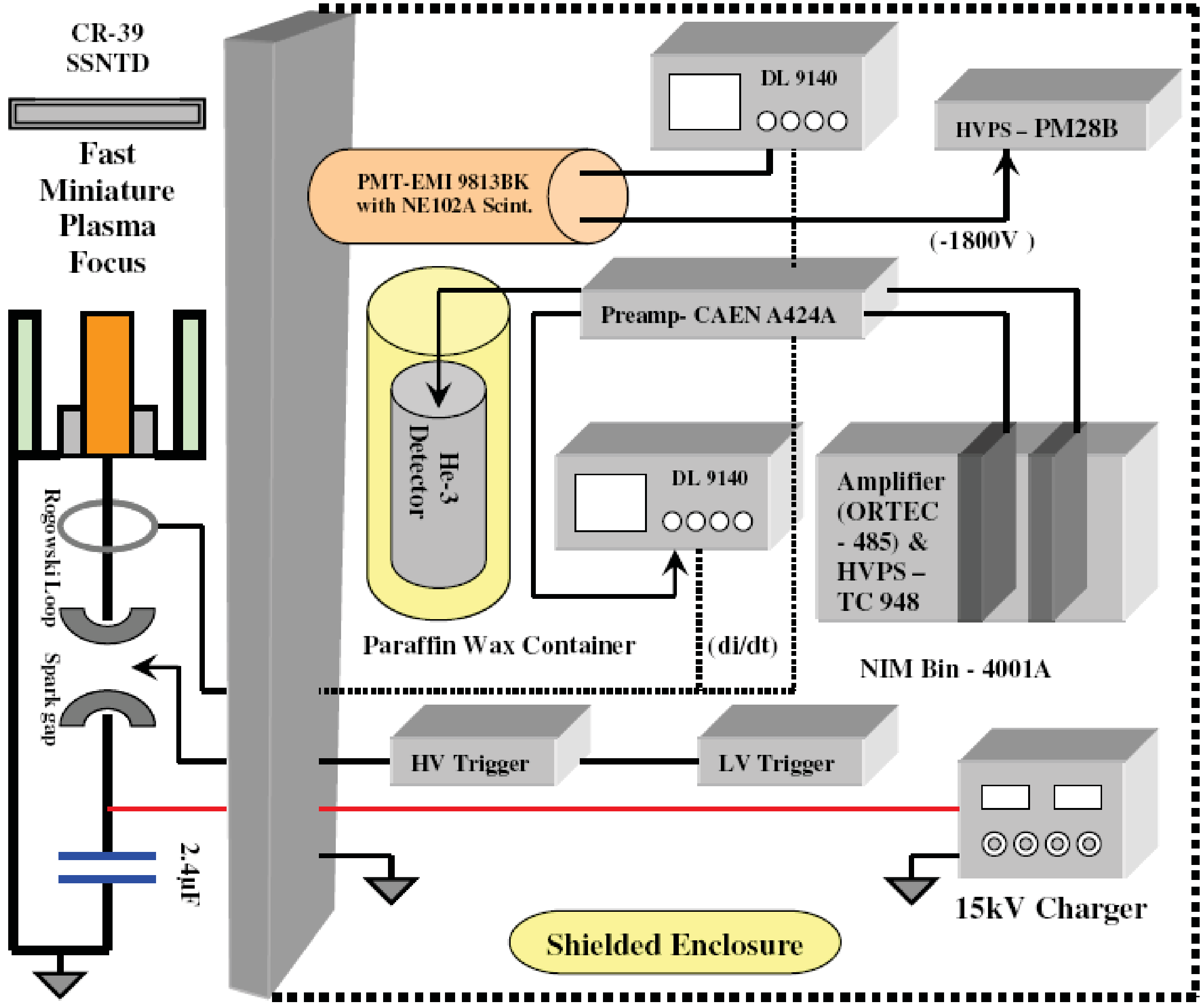
Soft X-rays



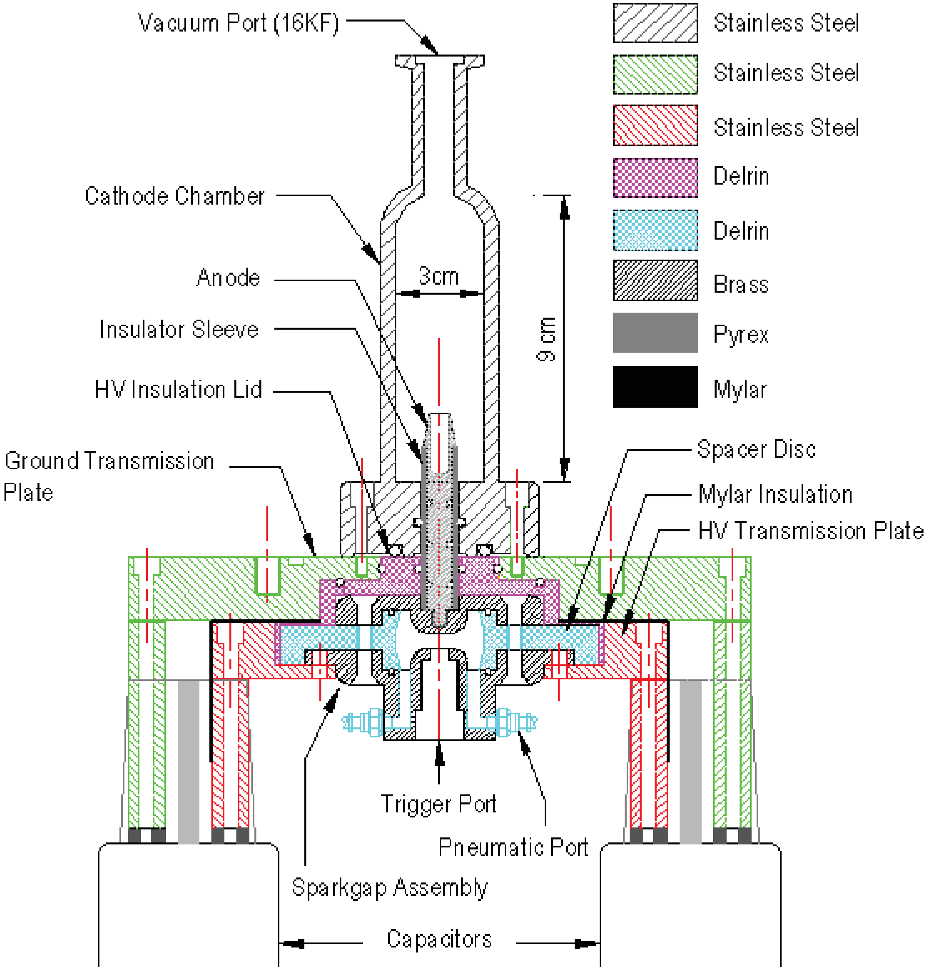
High Rep Rate Shadowgraphy System



Nuclear diagnostics and instrumentation setup

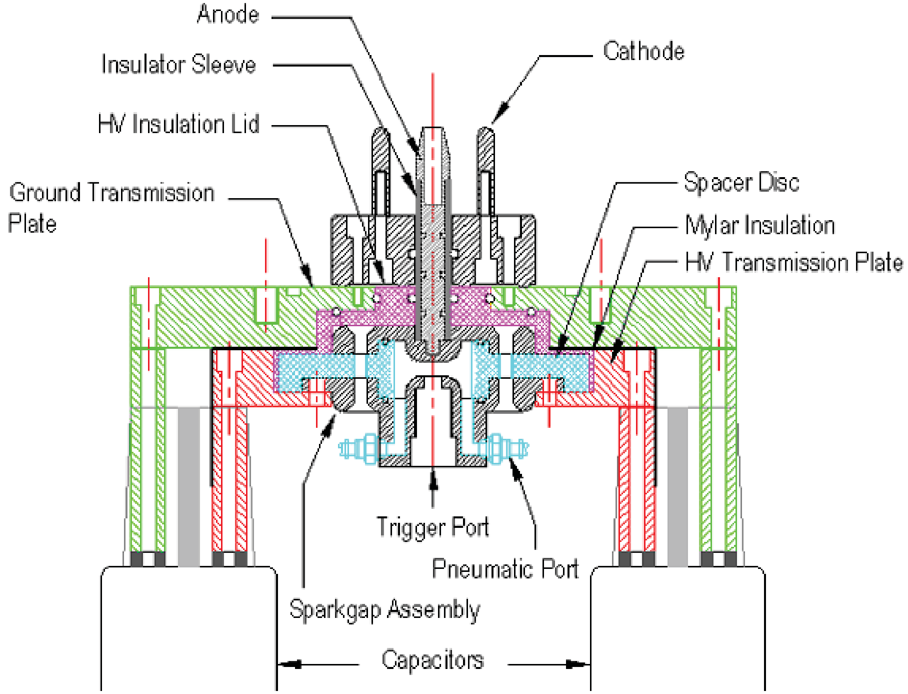


Construction features of 'FMPF-1'



(With tubular cathode)

- No use of cables
- 600μ separation between HV and GND
- Sparkgap embedded within assembly
- Focus tube directly interfaced

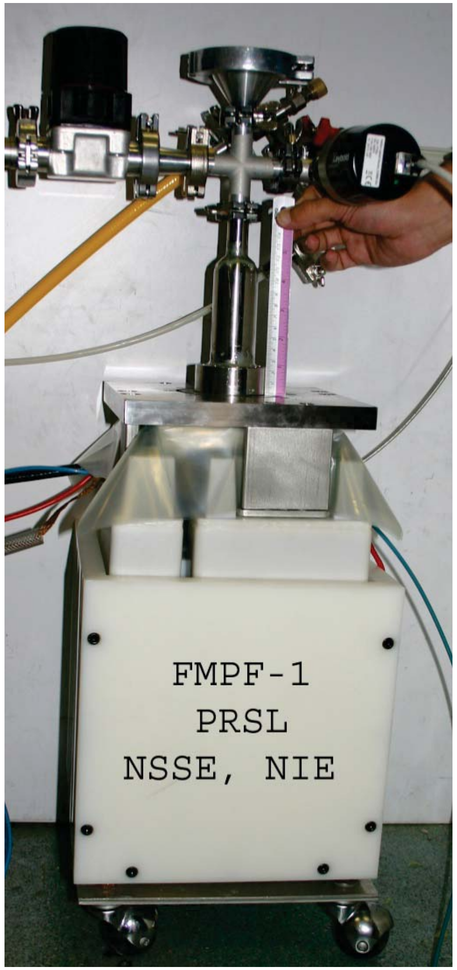


(With squirrel cage cathode)

Rishi Verma, P. Lee, S V Springham, T L Tan and R S Rawat, *High Performance Thyratron Driver with Low Jitter*, Review Scientific Instruments 78 (8), 086107 (2007).

Parameters of ‘FMPF-1’ device

$0.2\text{m} \times 0.2\text{m} \times 0.5\text{m}$

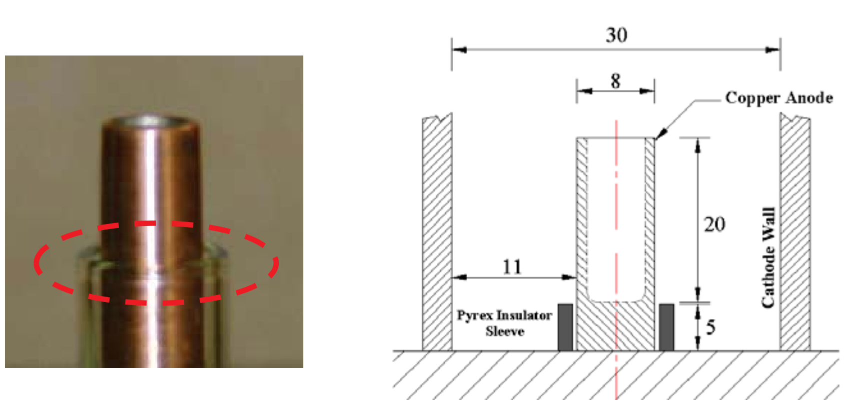


(Total Weight: ~25kgs)

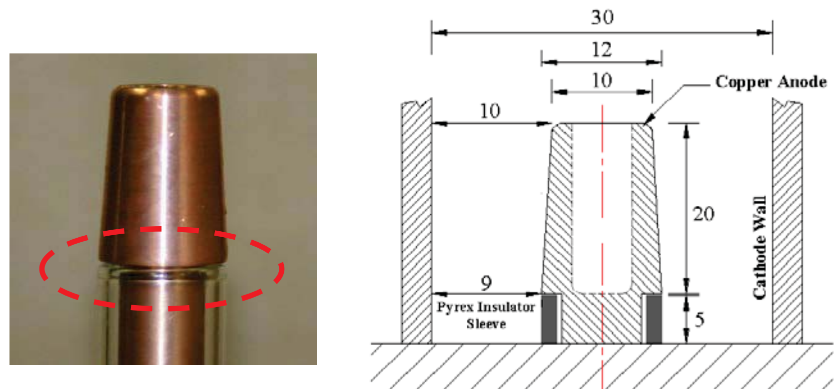
Fully Integrated System

Main electrical characteristics of FMPF-1 device.	
Energy bank capacitance (C_o)	2.4μF
Maximum charging voltage (V_o)	14kV
Maximum stored energy @14kV (E_o)	235J
Maximum current (under short circuit) (I_{sc})	87kA @14kV
Typical operating voltage range	12 – 14 kV
Eq. circuit inductance (L_{eq})	27±2nH
Eq. circuit resistance (R_{eq})	66±3mΩ
Voltage Reversal (k)	33%
Quarter time of discharge ($T/4$)	~400ns
Maximum discharge repetition rate (DRR)	0.5Hz

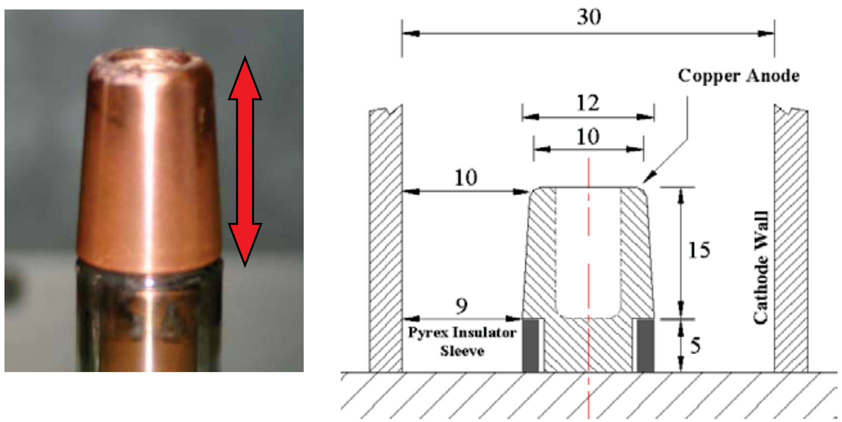
Anode designs experimented



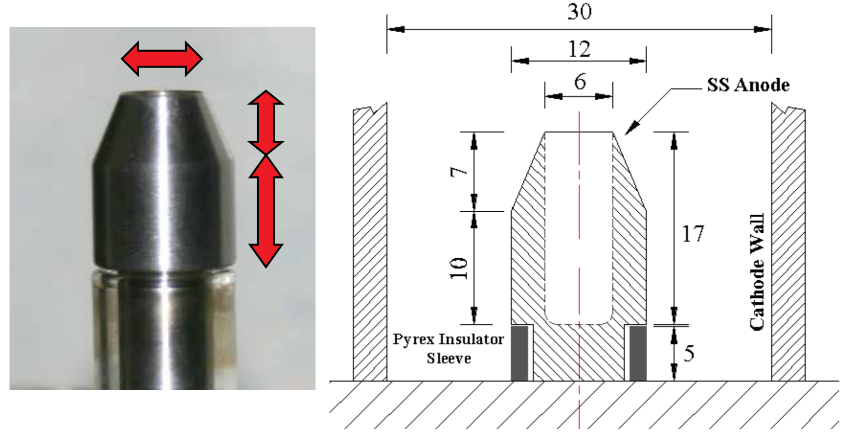
(a) Cylindrical flat-end anode (V1/CFA/20-5/Cu)



(b) Tapered Anode (V2/TA/20-5/Cu)



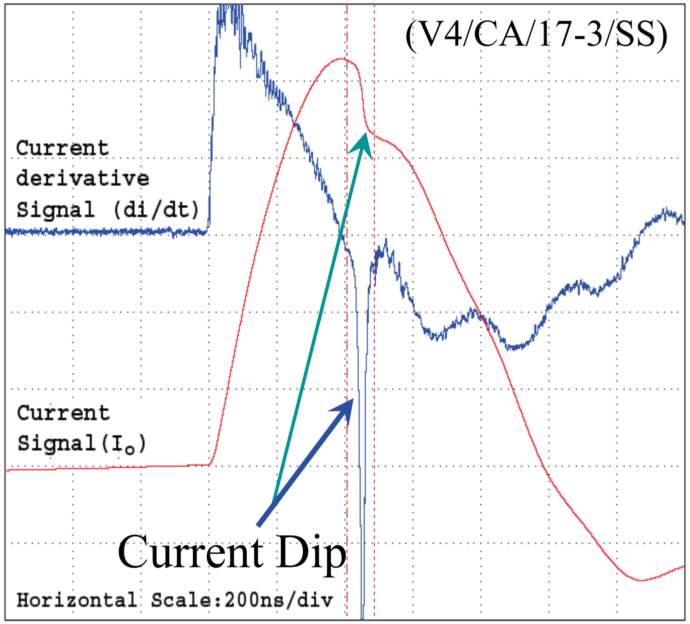
(c) Tapered Anode (V3/TA/15-5/Cu)



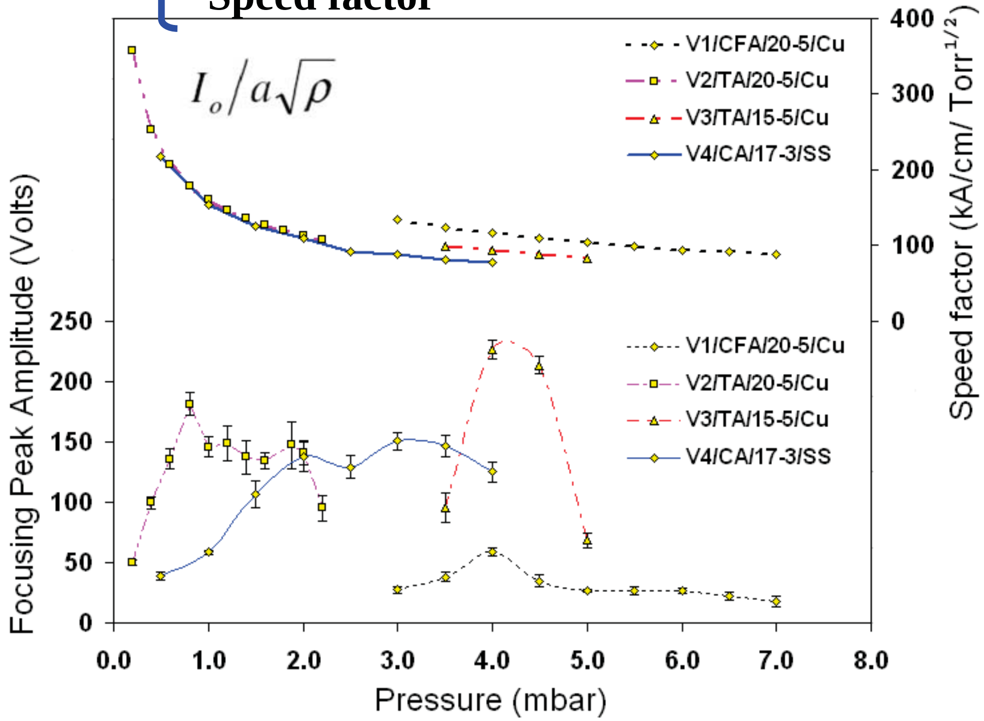
(d) Composite Anode (V4/CA/17-3/SS)

Characterization results of different anode geometries

Figure of merit: Focusing peak amplitude; Speed factor



Typical current/ current derivative signal

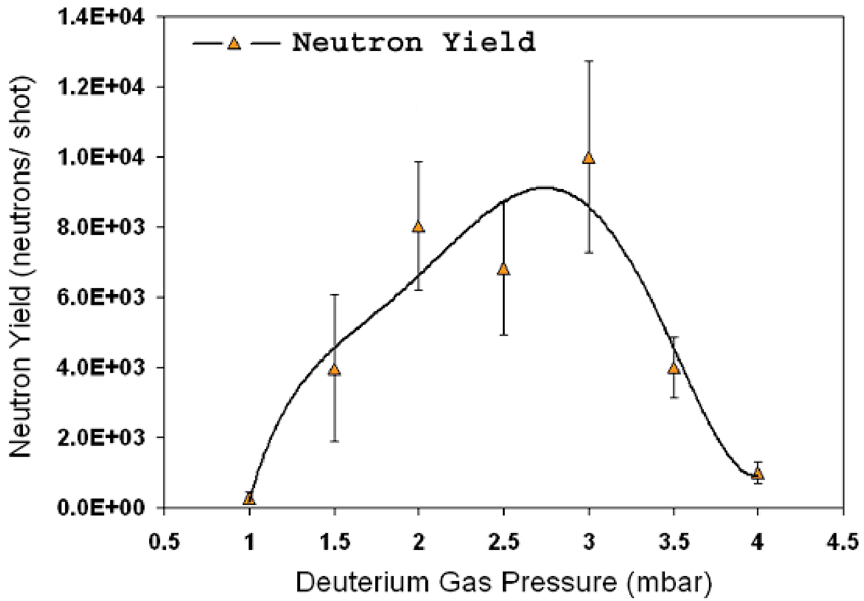


Anode Geometries	Pressure (mbar)	Focus peak (a.u)	Speed factor / Reproducibility
V1/CFA/20-5/Cu	4 mbar	58.5±3.5	115.4/ Poor
V2/TA/20-5/Cu	0.8 mbar	181 ±9.47	179/ Good
V3/TA/15-5/Cu	4 mbar	22.6 ±7.47	92.38/ Low
V4/TA/17-3/SS	3 mbar	166 ±7.1	87.3/ Good

Rishi Verma, M. V. Roshan, F. Malik, P. Lee, S. Lee, S. V. Springham, T. L. Tan, M. Krishnan and R. S. Rawat, *Compact sub-kilojoule range fast miniature plasma focus as portable neutron source*, **Plasma Sources Science and Technology**, 17(4), 045020 (2008).

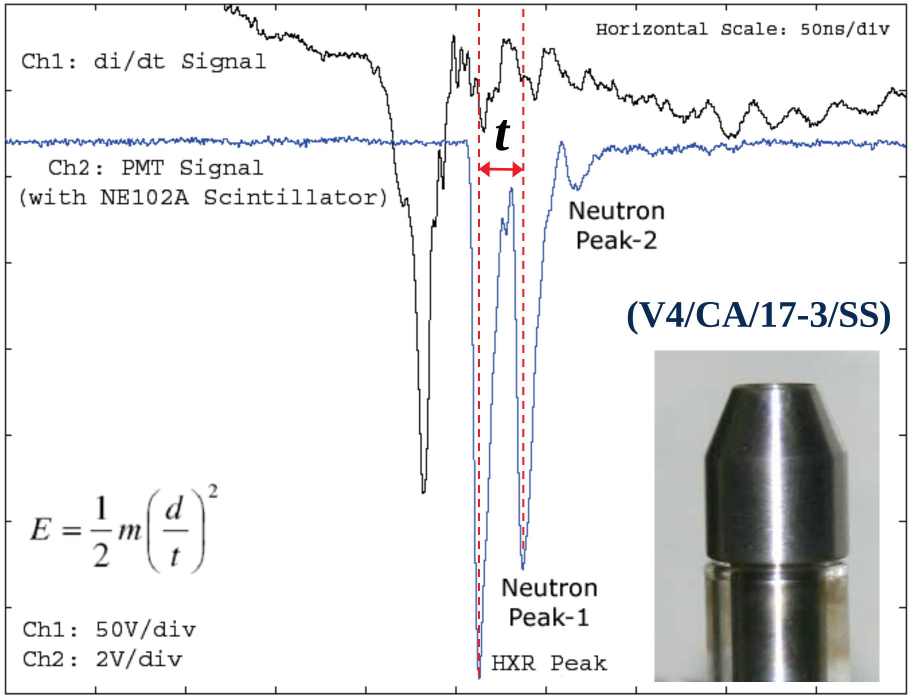
First results of neutrons and hard X-ray emission from FMPF-1

(170J, 12kV, 70kA, composite anode, tubular cathode)



Neutron Yield Measurement
(Using ^{3}He Proportional Counter)

Max. Yield: $1 \pm 0.27 \times 10^{4}$ n/s

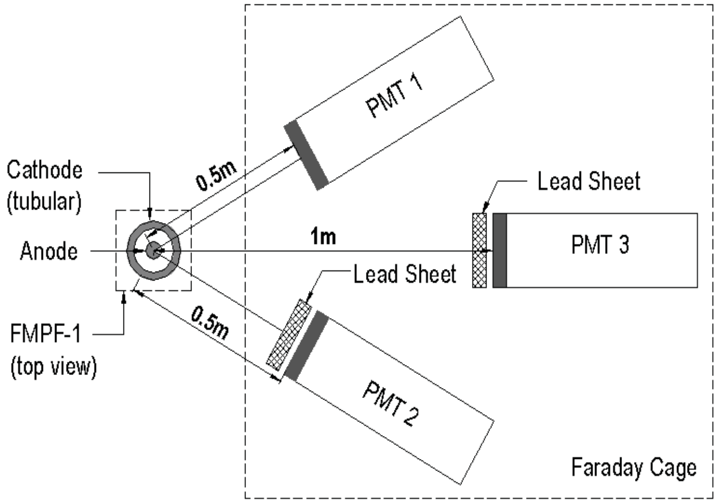


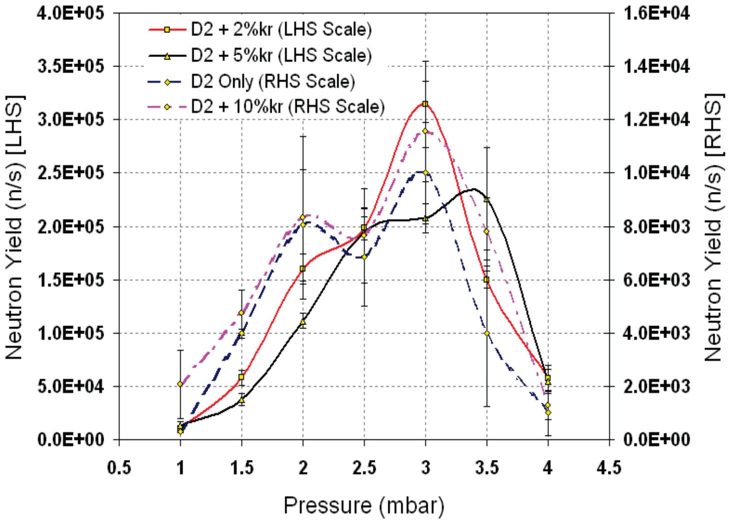
Time of Flight Measurement
(Scintillator Photomultiplier Detector)

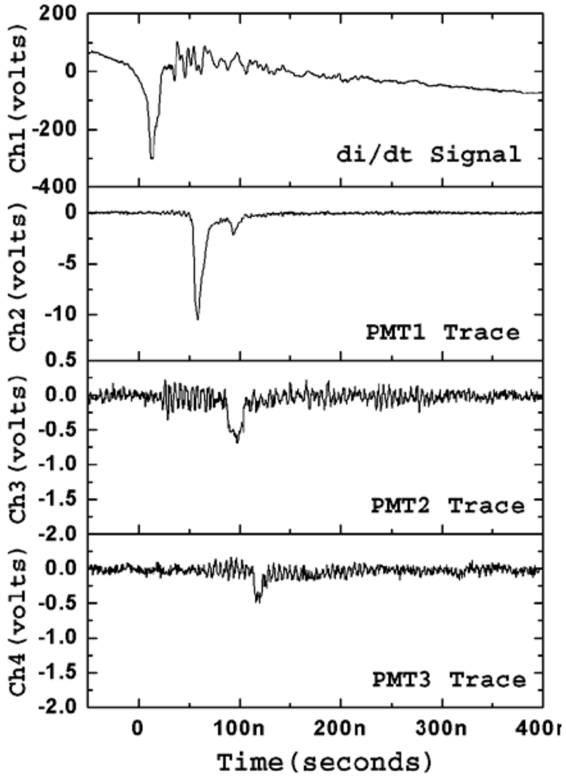
$d = 0.5m,\ t = \sim 24ns$

Rishi Verma, M. V. Roshan, F. Malik, P. Lee, S. Lee, S. V. Springham, T. L. Tan, M. Krishnan and R. S. Rawat, *Compact sub-kilojoule range fast miniature plasma focus as portable neutron source*, **Plasma Sources Science and Technology**, 17(4), 045020 (2008).

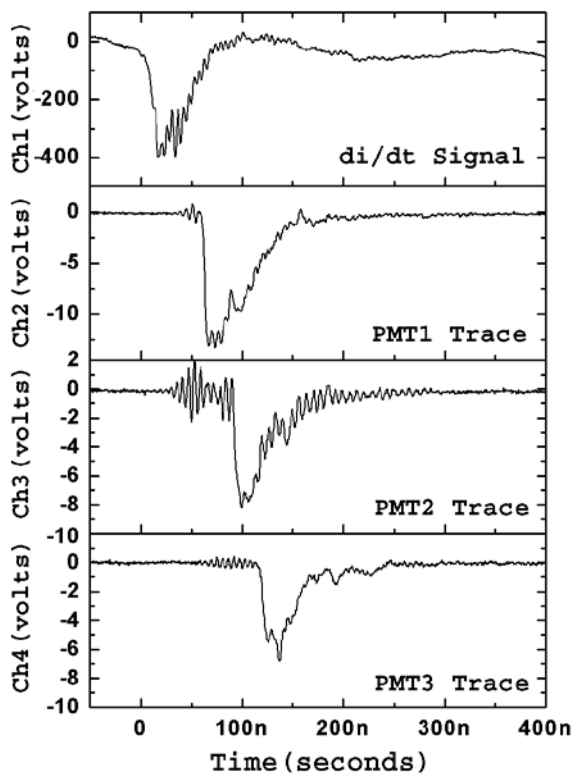
Neutron yield enhancement:
D2-Kr admixture operation







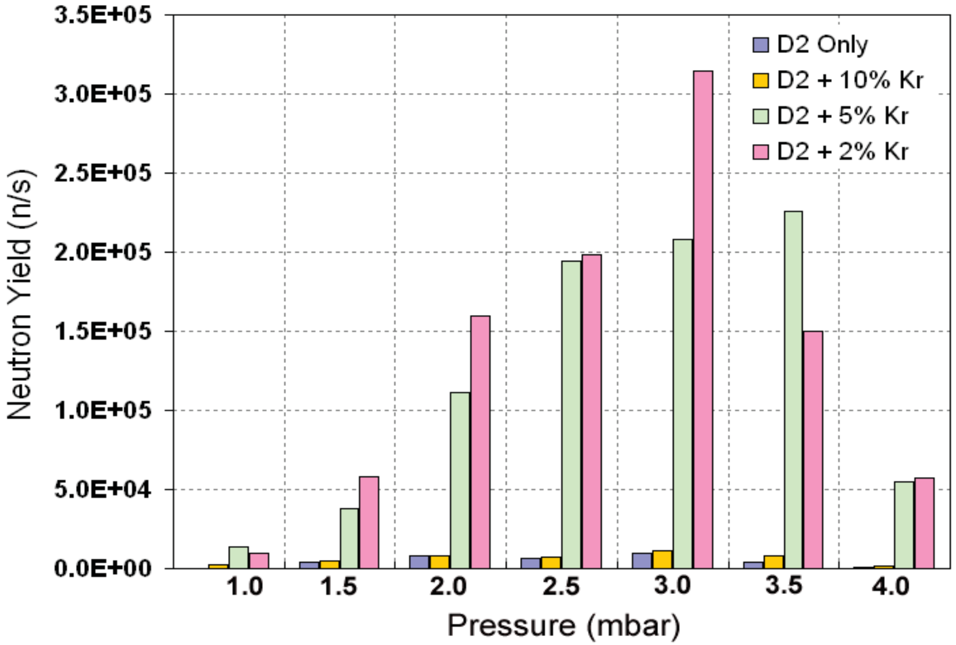
(a) D_2 discharge at 3mbar



(b) D_2+5%Kr admixture discharge at 3mbar

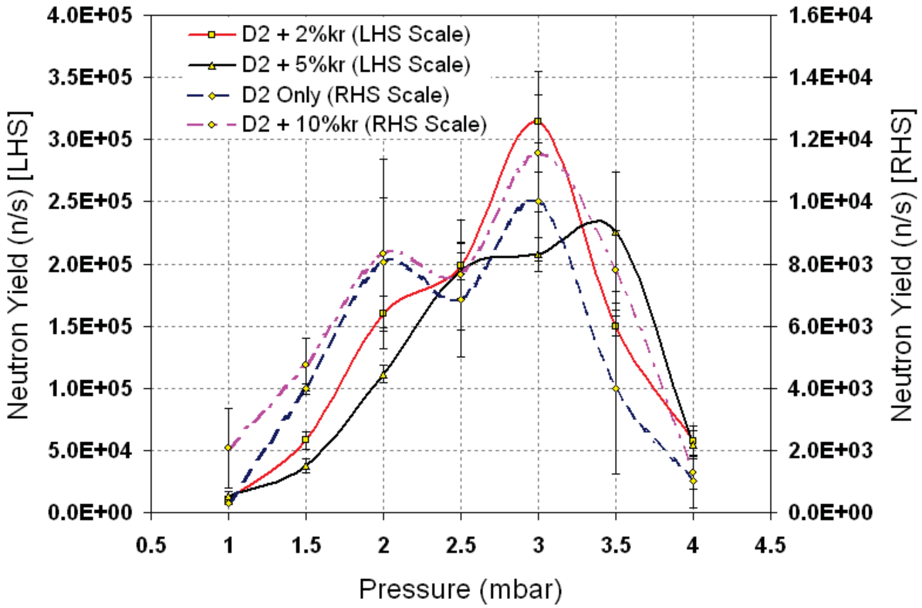
Rishi Verma, P. Lee, S. Lee, S.V. Springham, T.L. Tan, M. Krishnan and R.S. Rawat, *Order of magnitude enhancement in neutron emission with Deuterium-Krypton admixture operation in miniature plasma focus device*, Applied Physics Letters **93** (10), 101501 (2008).

Experiments with Deuterium-Krypton Admixtures
(Anode: composite, cathode: tubular)



Gains
- **30X** - for D_2+2%Kr
- **20X** - for D_2+5%Kr
- **1.2X** - for D_2+10%Kr

Concentration Ratio	Neutron Flux
D_2 + 2%Kr	$3.14 \pm 0.4 \times 10^5$ n/s
D2 + 5%Kr	$2 \pm 0.18 \times 10^5$ n/s
D2 + 10%Kr	$1.16 \pm 0.18 \times 10^4$ n/s
D2 (Pure)	$1 \pm 0.27 \times 10^4$ n/s



X-ray yield enhancement: D2-Kr admixture operation

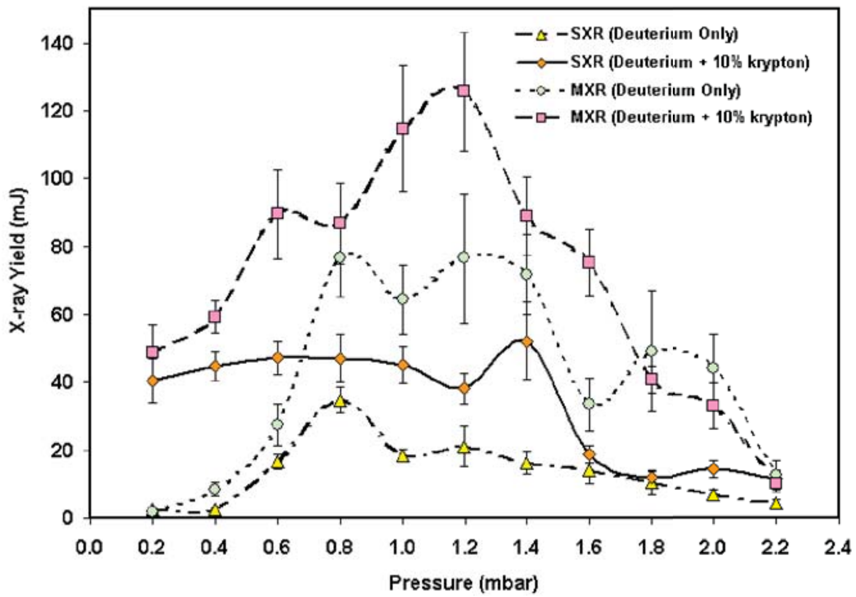


Figure 2. X-ray yields in the spectral range of 0.9keV to 1.6keV (SXR) and 3.2keV to 7.7keV (MXR) for D_2 and D_2-kr admixture at different filling pressures

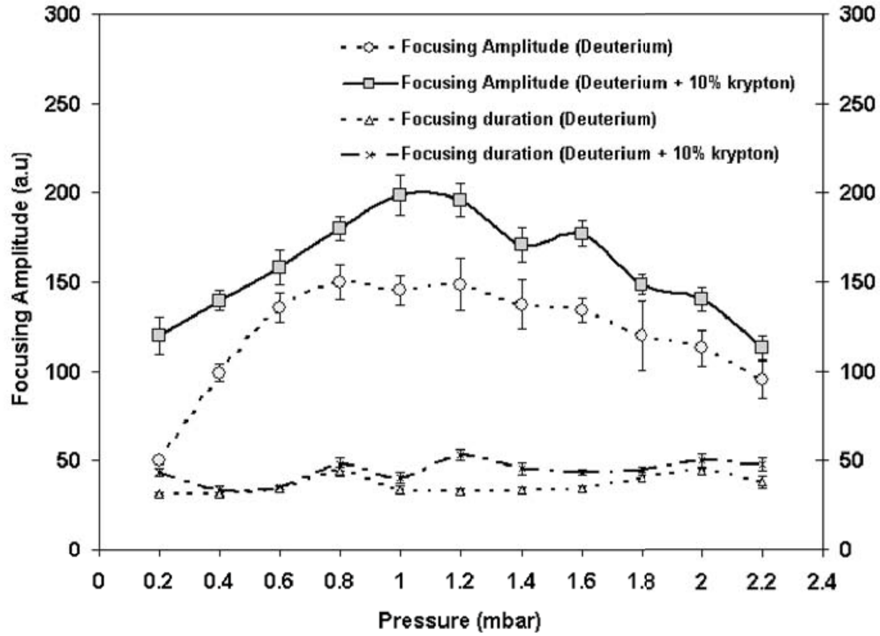


Figure 3. Focusing peak amplitude and Focusing duration for D_2 and D_2-kr admixture

APPLIED PHYSICS LETTERS **92**, 011506 (2008)

Order of magnitude enhancement in x-ray yield at low pressure deuterium-krypton admixture operation in miniature plasma focus device

Rishi Verma,[a] P. Lee, S. V. Springham, T. L. Tan, and R. S. Rawat[b]
NSSE, National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, Singapore

Neutron yield enhancement:
Squirrel Cage Cathode

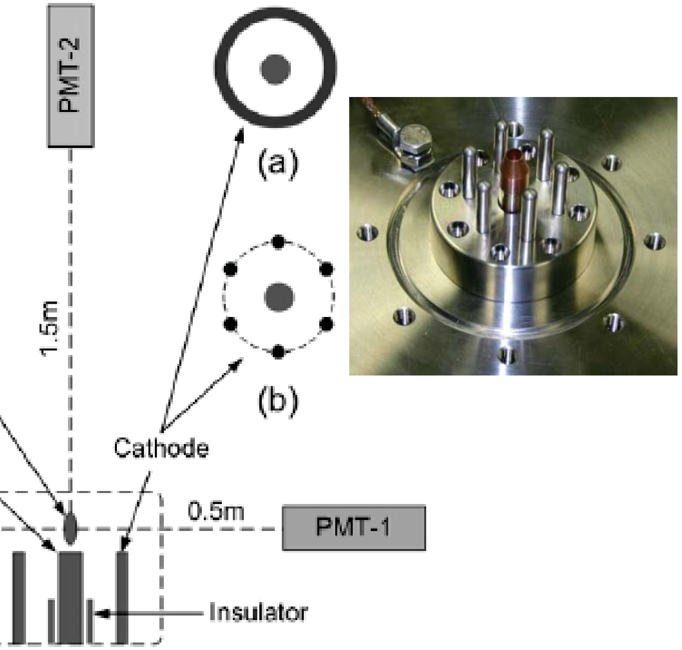



Fig. 1. Layout of time resolved and time integrated neutron diagnostic set-up.

Physics Letters A 373 (2009) 2568–2571

Effect of cathode structure on neutron yield performance of a miniature plasma focus device

Rishi Verma [a,1], R.S. Rawat [a,*], P. Lee [a], S. Lee [a], S.V. Springham [a], T.L. Tan [a], M. Krishnan [b]

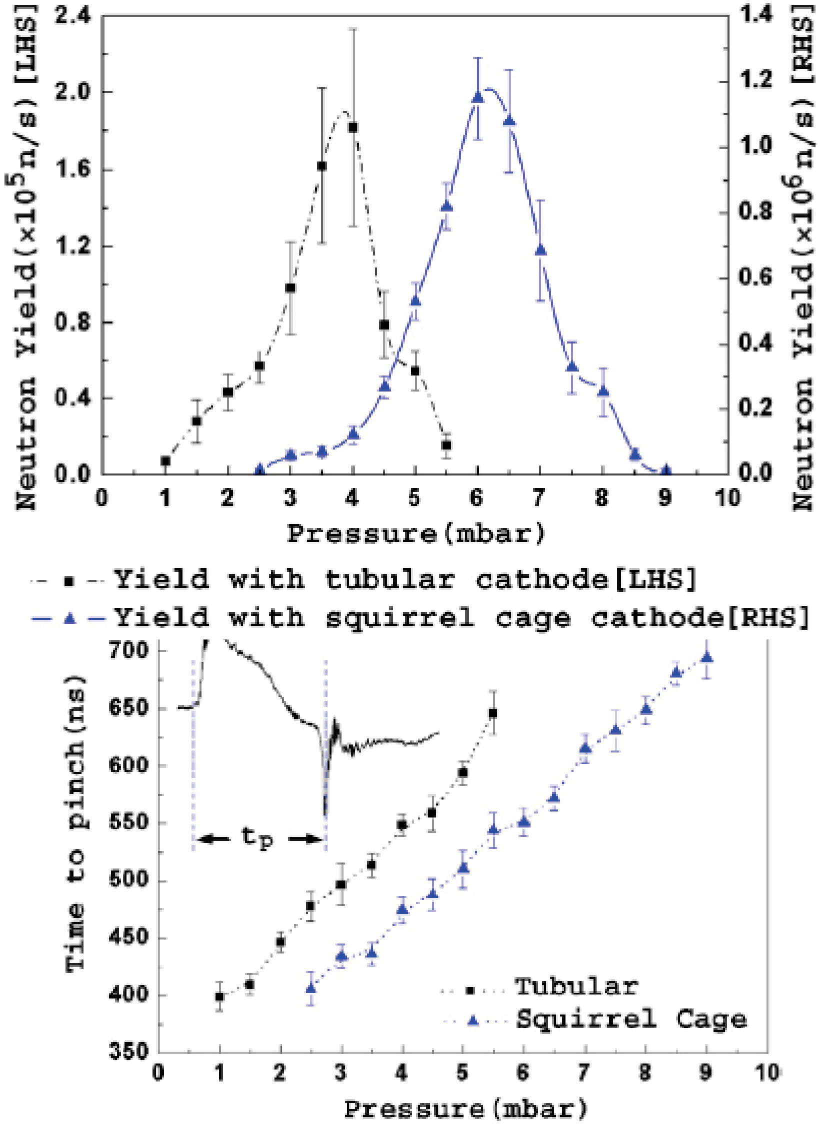


Fig. 4. Time to pinch versus D_2 filling gas pressure for tubular and squirrel cage cathode operation.

Neutron yield anisotropy in FMPF-1

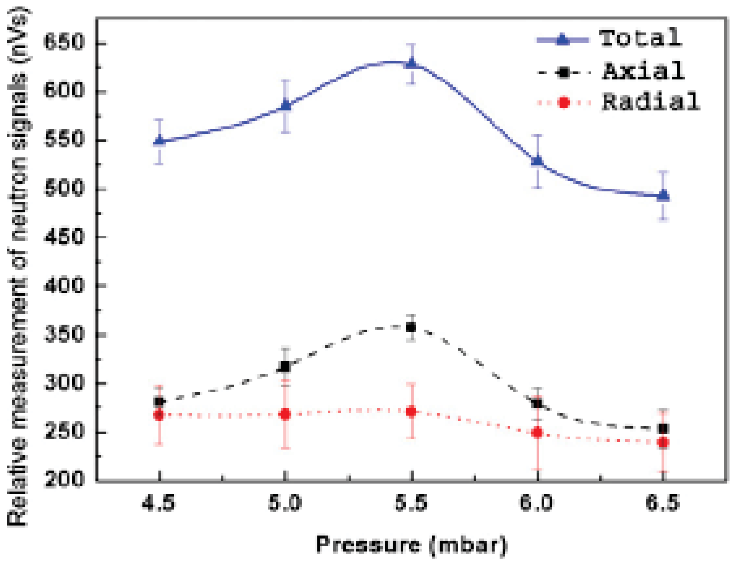


Figure 5. Variation in axial, radial and total neutron flux with filling gas pressure.

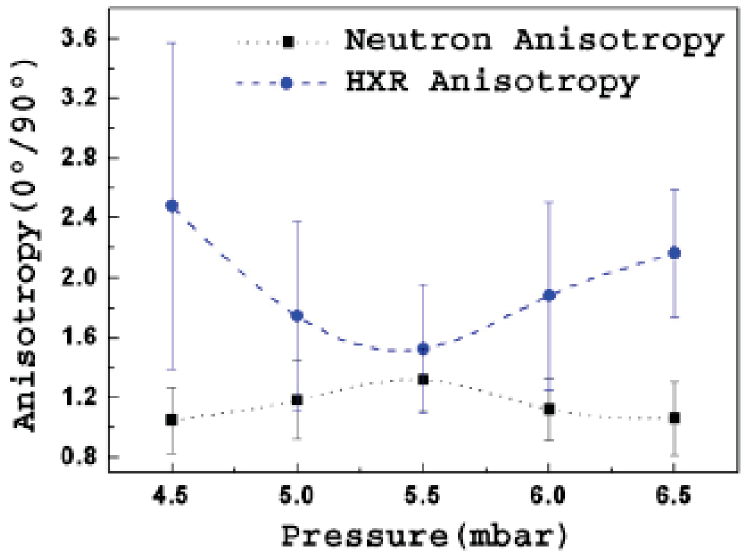
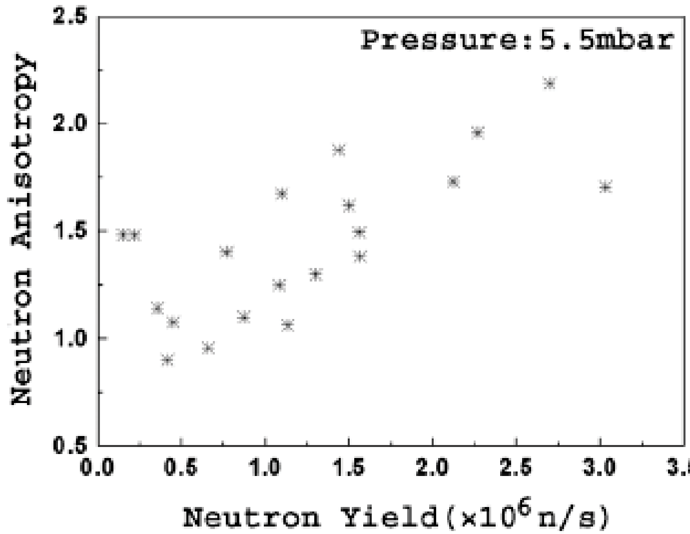


Figure 8. Variation of HXR and neutron anisotropy as a function of pressure.

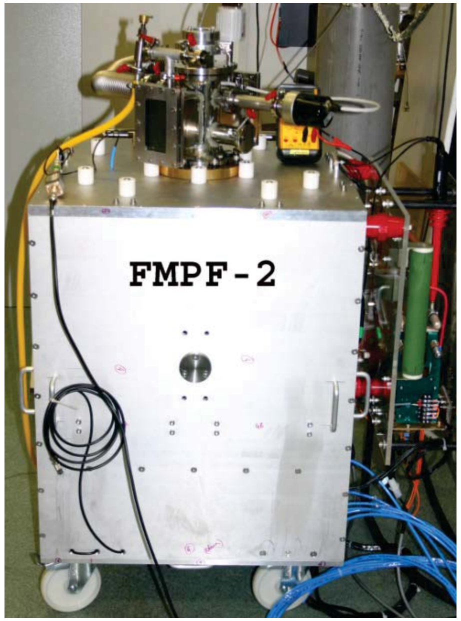


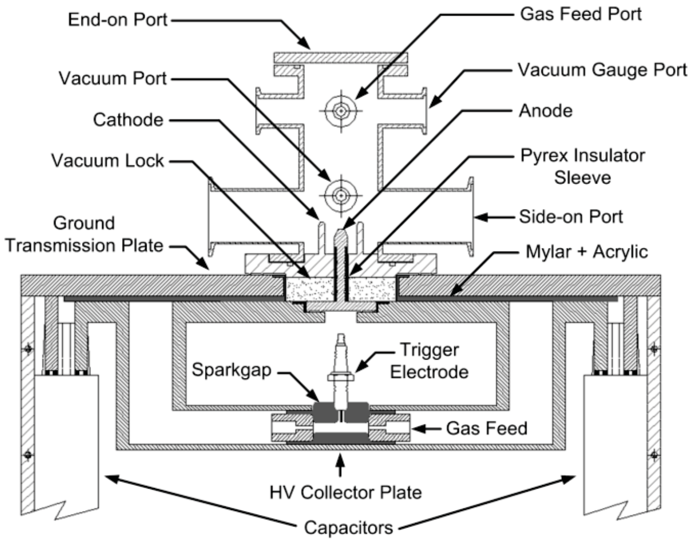
Plasma Phys. Control. Fusion 51 (2009) 075008 (16pp)

Experimental study of neutron emission characteristics in a compact sub-kilojoule range miniature plasma focus device

Rishi Verma[1,2], R S Rawat[1,4], P Lee[1], M Krishnan[3], S V Springham[1] and T L Tan[1]

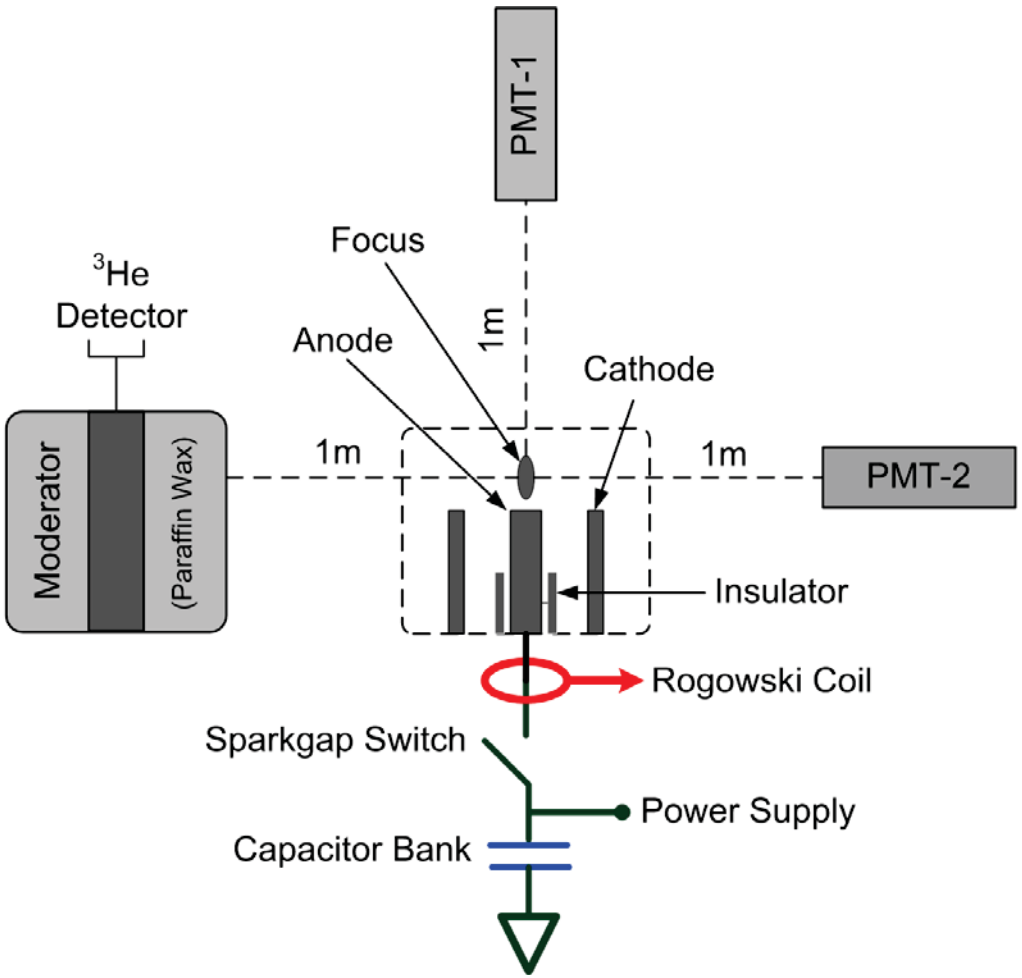
Parameters of 'FMPF-2' device

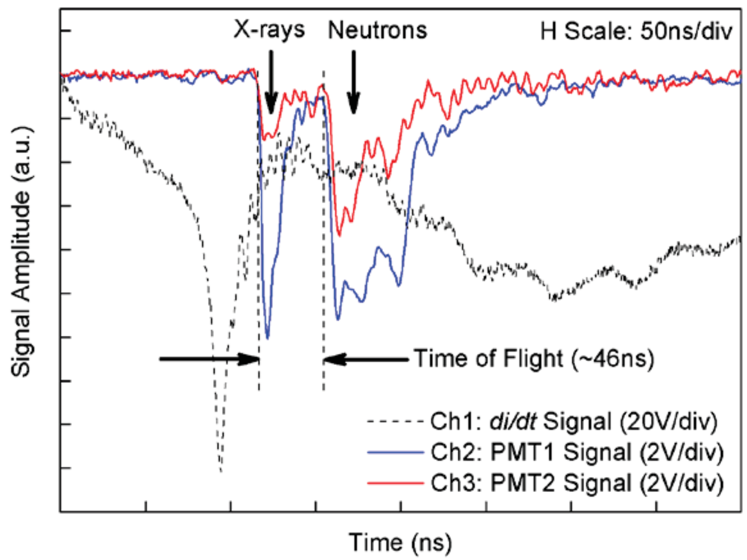


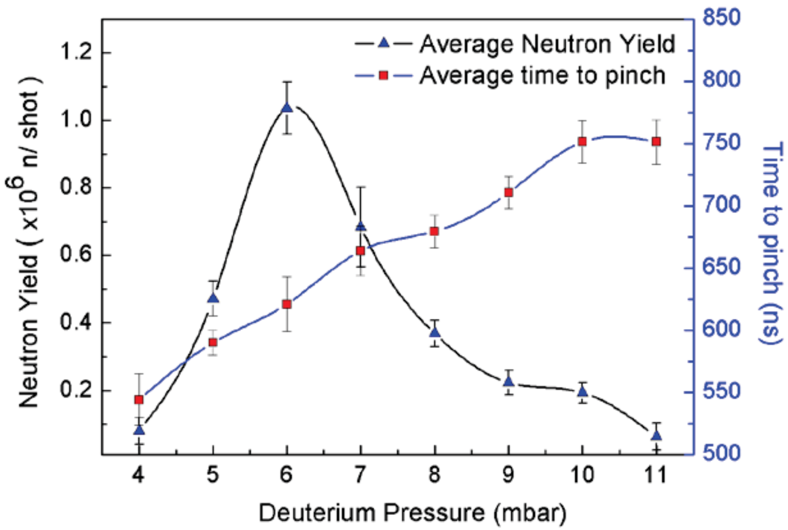


Main electrical characteristics of 'FMPF-2' device.	
Energy bank capacitance (C_o)	2.4μF
Maximum charging voltage (V_o)	14kV
Maximum stored energy @14kV (E_o)	235J
Maximum current (under short circuit) (I_{sc})	89kA @14kV
Typical operating voltage range	12 – 14 kV
Eq. circuit inductance (L_{eq})	56±3nH
Eq. circuit resistance (R_{eq})	26±3mΩ
Voltage Reversal (*f*)	77%
Quarter time of discharge (*T/4*)	~575ns
Maximum discharge repetition rate (DRR)	10Hz

Results from FMPF-2







Time Average Neutron Yield from FMPF-2

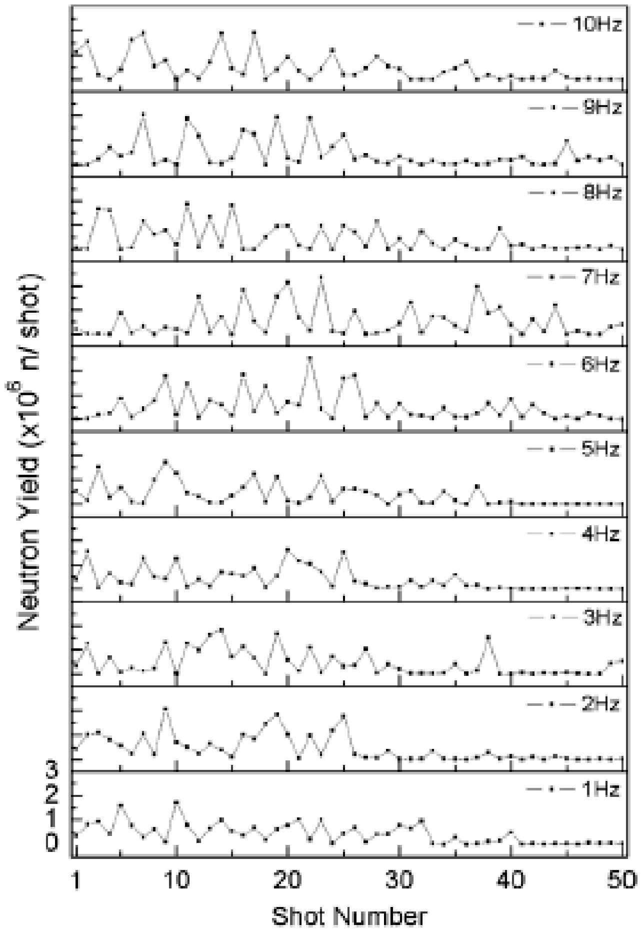


Figure 3. Neutron output per shot at different repetition rates for 6 mbar D_2 filling gas pressure.

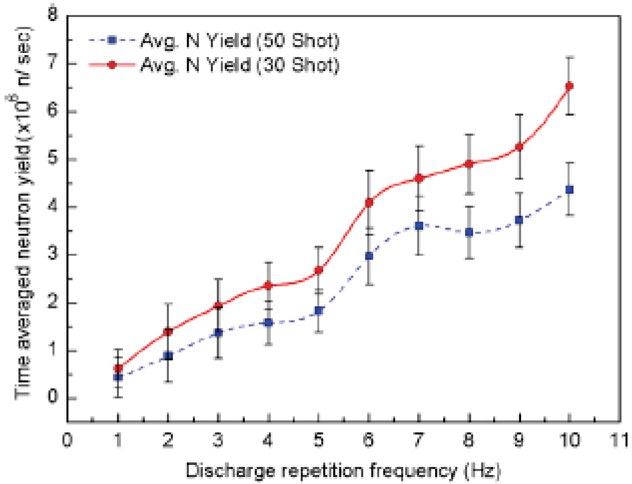


Figure 4. Time averaged neutron output at different discharge repetition rates for 6 mbar D_2 filling gas pressure.

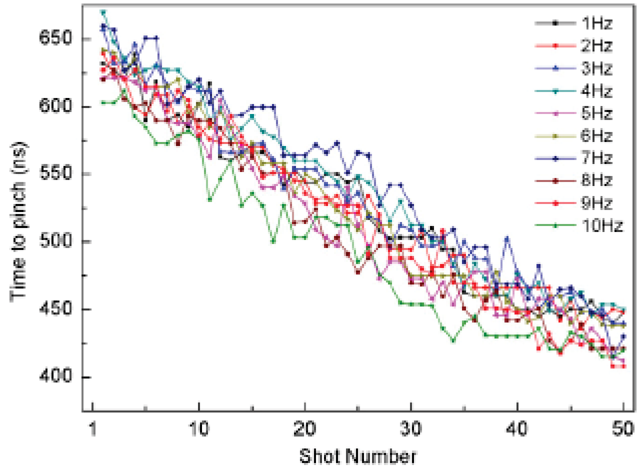
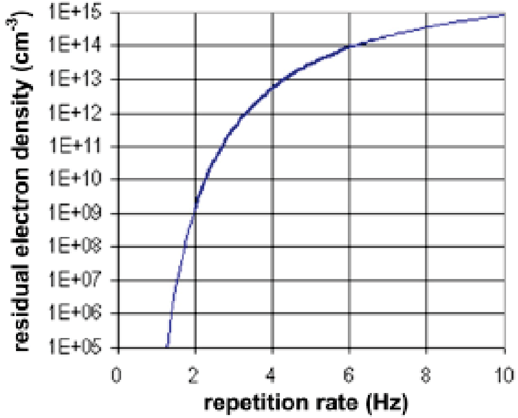
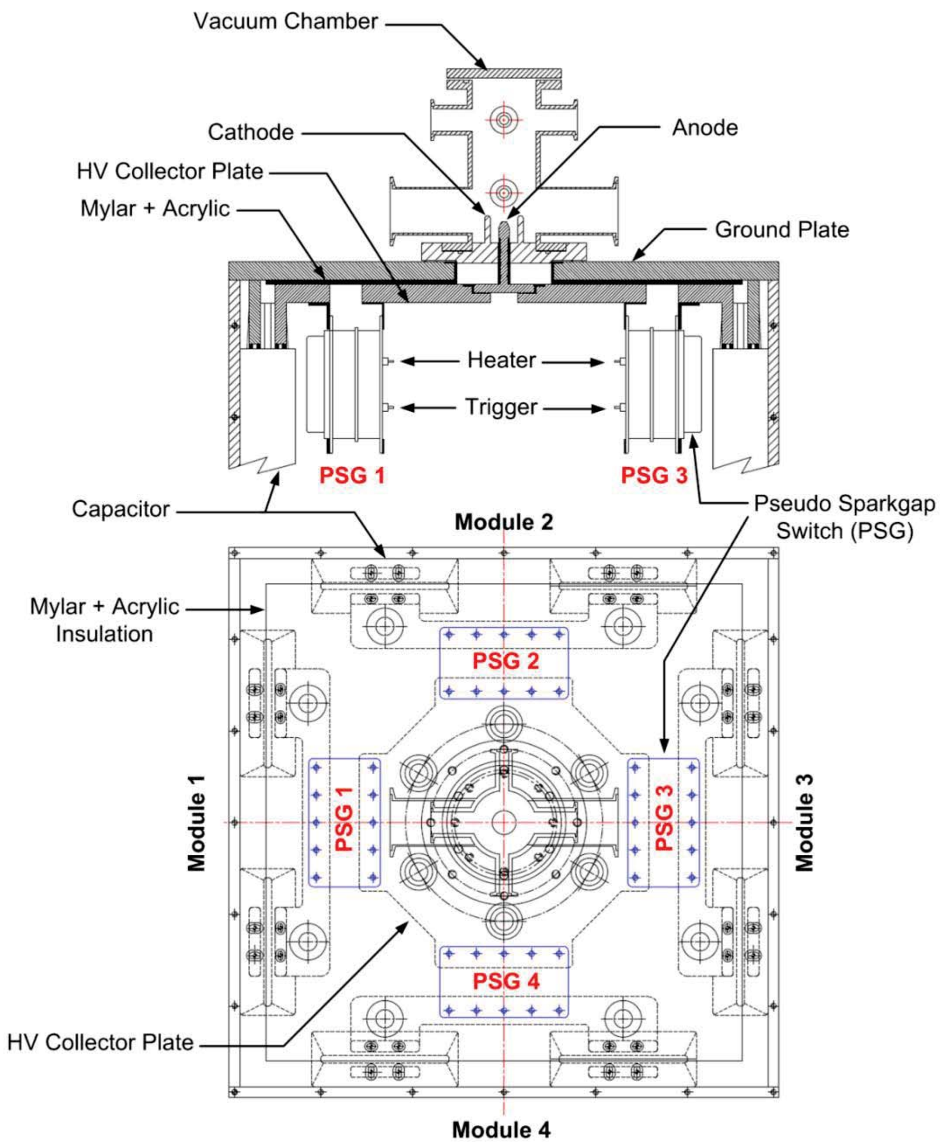


Figure 5. Time to pinch at different repetition rates for 6 mbar D_2 filling gas pressure.



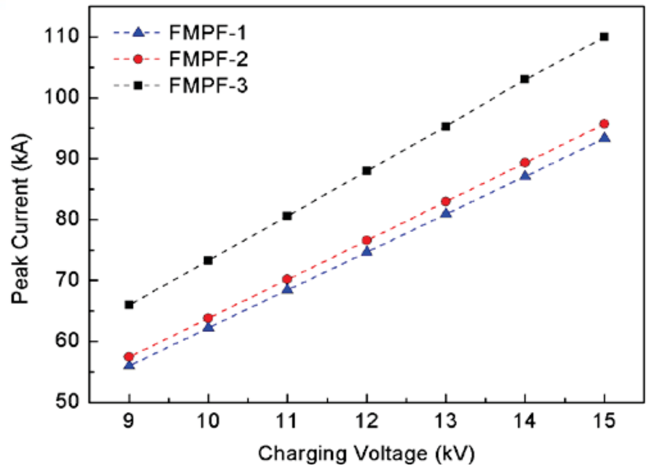
Rishi Verma, R. S. Rawat, P. Lee, S. V. Springham, T. L. Tan and M. Krishnan, *Realization of enhancement in time averaged neutron yield by using repetitive miniature plasma focus device as pulsed neutron source*, Journal of Physics D: Applied Physics **42**, 235203 (2009).

Parameters of ‘FMPF-3’ device

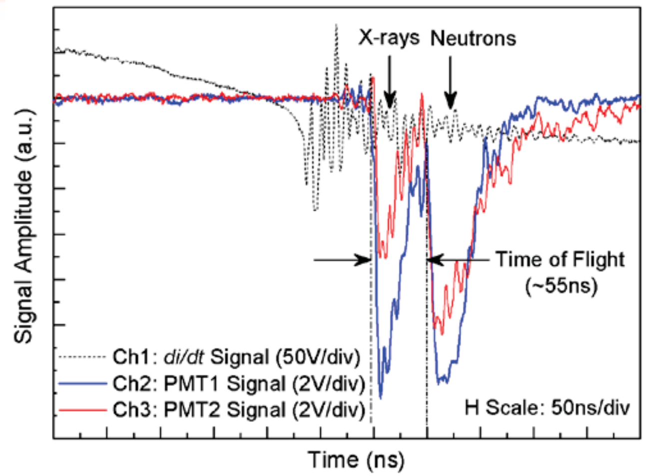


Main electrical characteristics of ‘FMPF-3’	
Energy bank capacitance (C_o)	2.4μF
Maximum charging voltage (V_o)	14kV
Maximum stored energy @14kV (E_o)	235J
Maximum current (under short circuit) (I_{sc})	103kA @14kV
Typical operating voltage range	10 – 14 kV
Equivalent circuit inductance (L_{eq})	34±2nH
Equivalent circuit resistance (R_{eq})	23±3mΩ
Voltage Reversal (f)	78%
Quarter time of discharge ($T/4$)	~458ns
Maximum discharge repetition rate (DRR)	10Hz

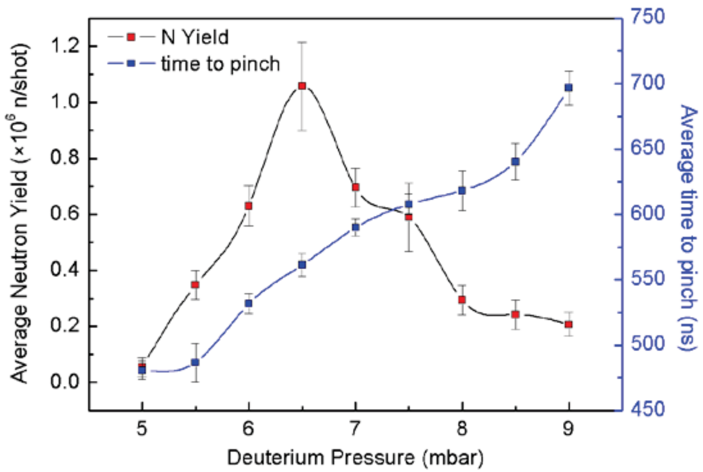
Some Results from FMPF-3



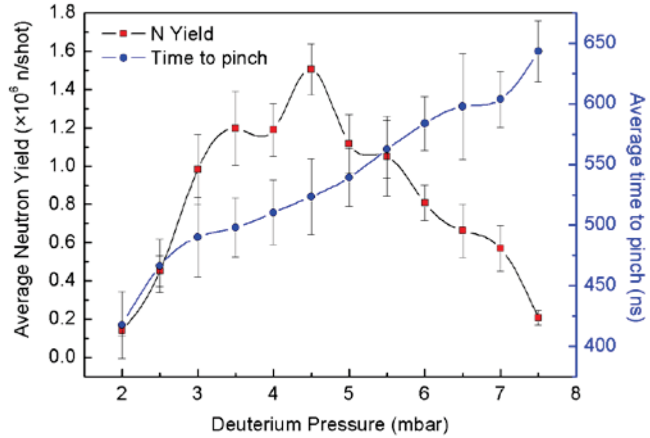
Maximum peak currents (under short circuit test conditions) in FMPF devices at different charging voltages.



Current derivative (*di/dt*) and scintillator photomultiplier (PMT) detector signals at 4.5mbar D_2 filling gas pressure.



Average neutron yield and time to pinch/ focus for FMPF-3 for composite anode that provided optimum yield for FMPF-2.



Average neutron yield and time to pinch/ focus at different D_2 gas filling pressures for FMPF-3 device with cylindrical anode.

Record Time Averaged Neutron Yield from FMPF-3

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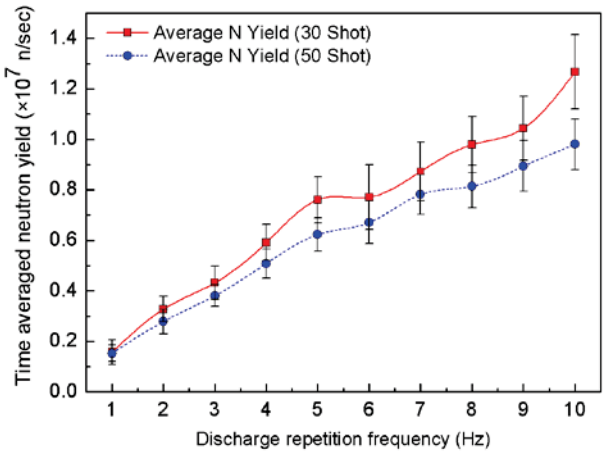
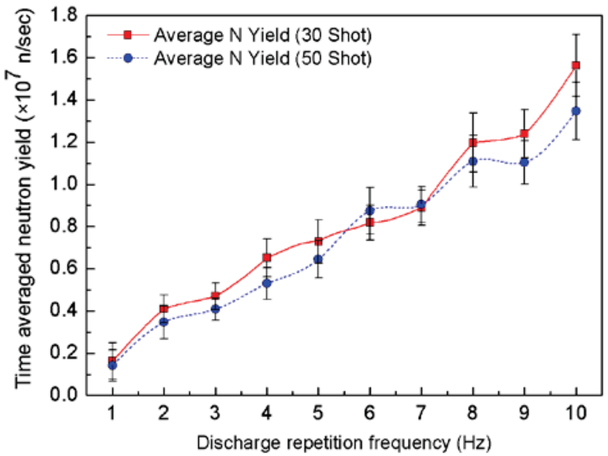
NATIONAL INSTITUTE OF EDUCATION SINGAPORE

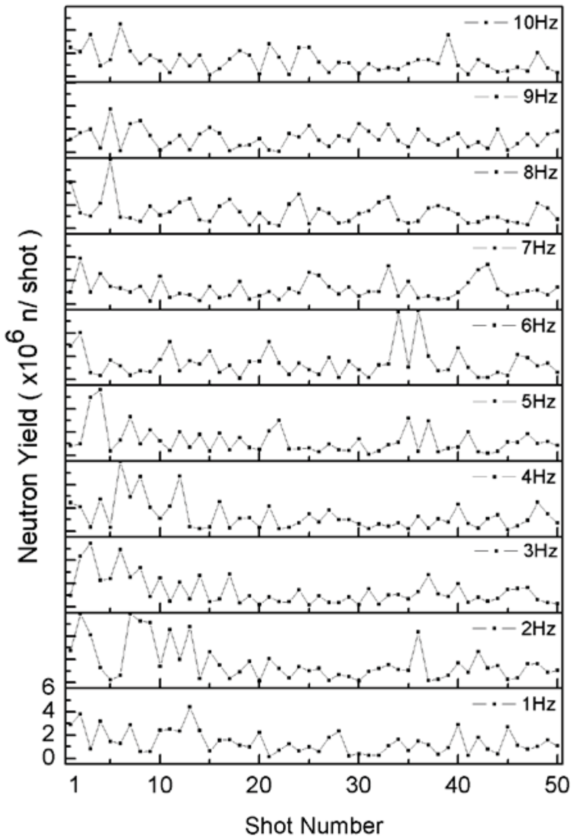
NANYANG TECHNOLOGICAL UNIVERSITY

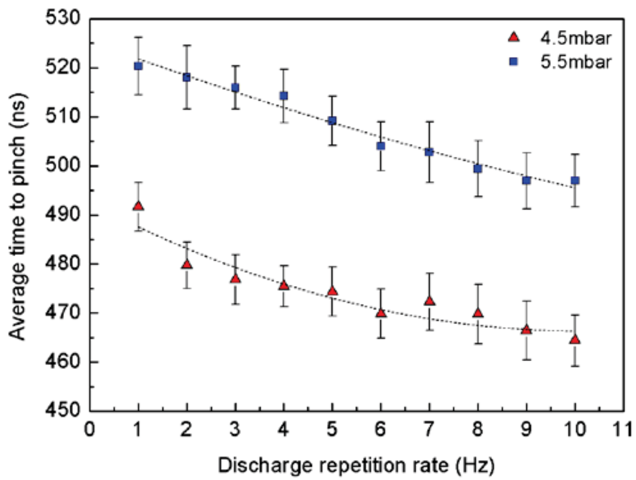


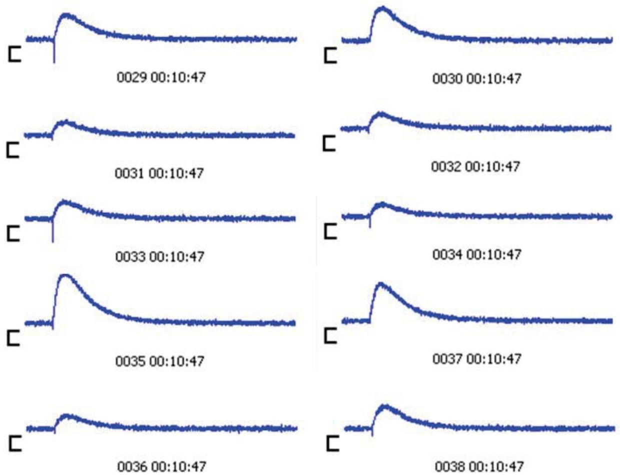
(a) at 4.5mbar D_2 filling gas pressure



(b) at 5.5mbar D_2 filling gas pressure

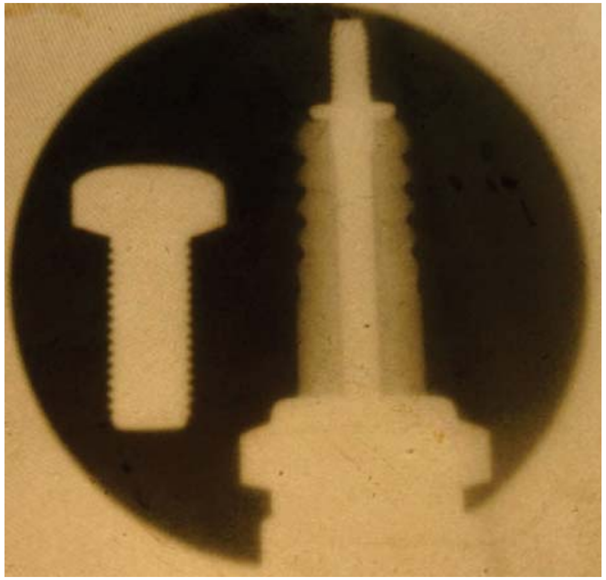


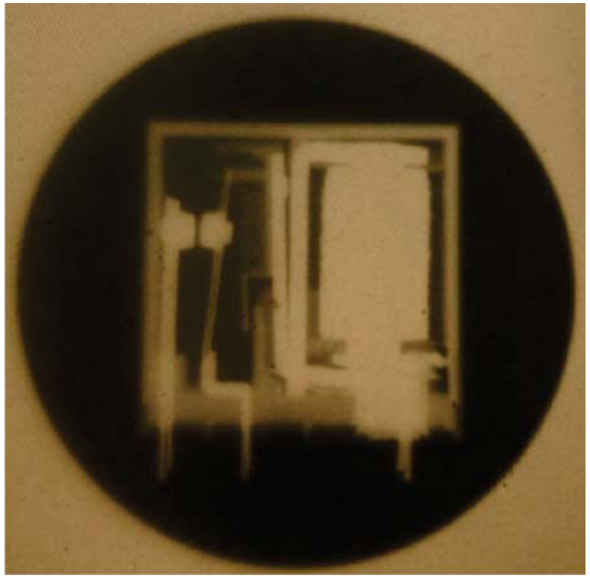


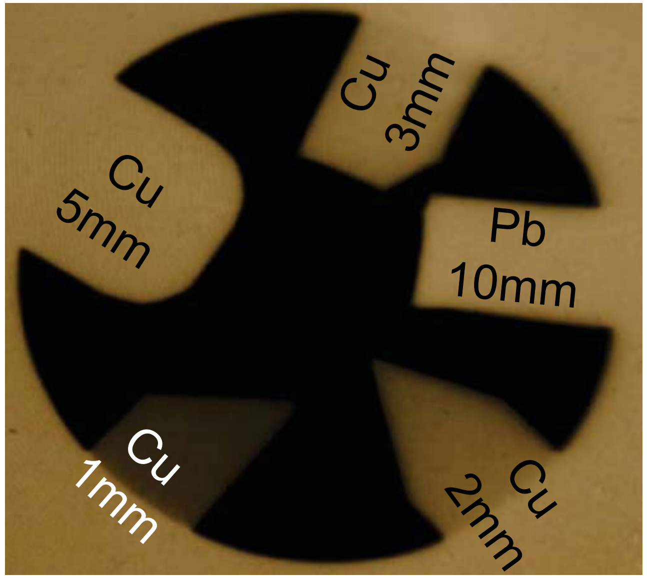


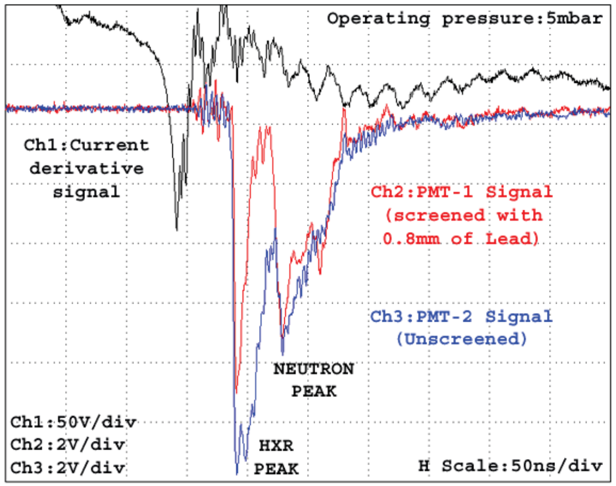
Rishi Verma, R. S. Rawat, P. Lee, S. V. Springham and T. L. Tan, *High performance high repetition rate miniature plasma focus device: Record time averaged neutron yield at 200 J with enhanced reproducibility*, Journal of Fusion Energy, In Press (2012).: DOI: 10.1007/s10894-012-9517-5.

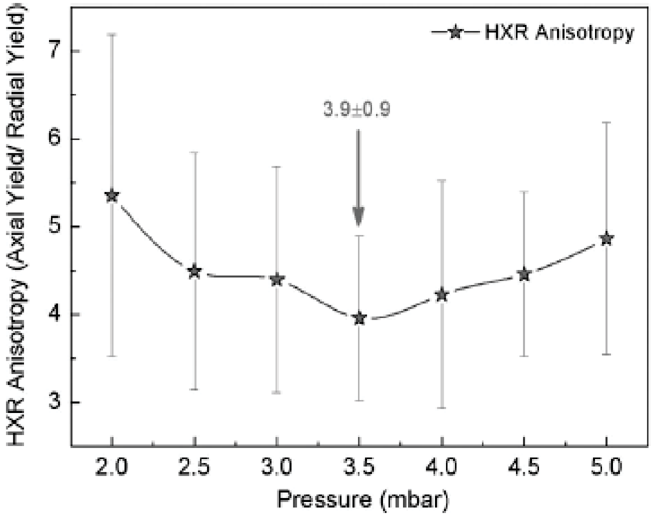
Applications: HXR radiography source

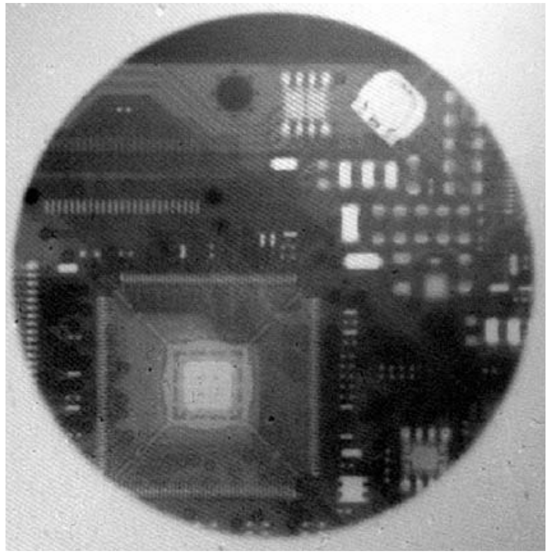












Rishi Verma, R. S. Rawat, P. Lee, M. Krishnan, S.V. Springham, and T.L. Tan, *Miniature plasma focus device as a compact hard X-Ray source for fast radiography applications*, IEEE Transanctions on Plasma Science **38**(4), 652-657 (2010).

Applications: Nanophase Soft Magnetic FeCo Thin Films

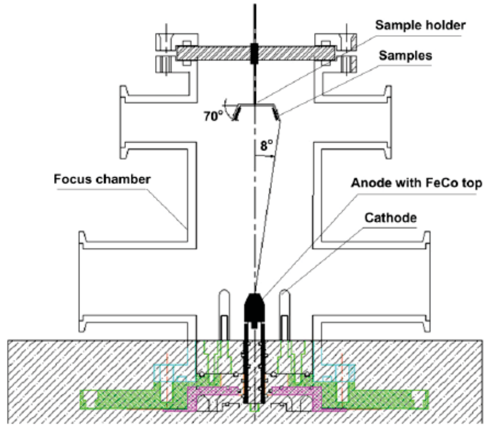


Fig. 1. Schematic of fast miniature plasma focus device (FMPF-1) for thin film deposition

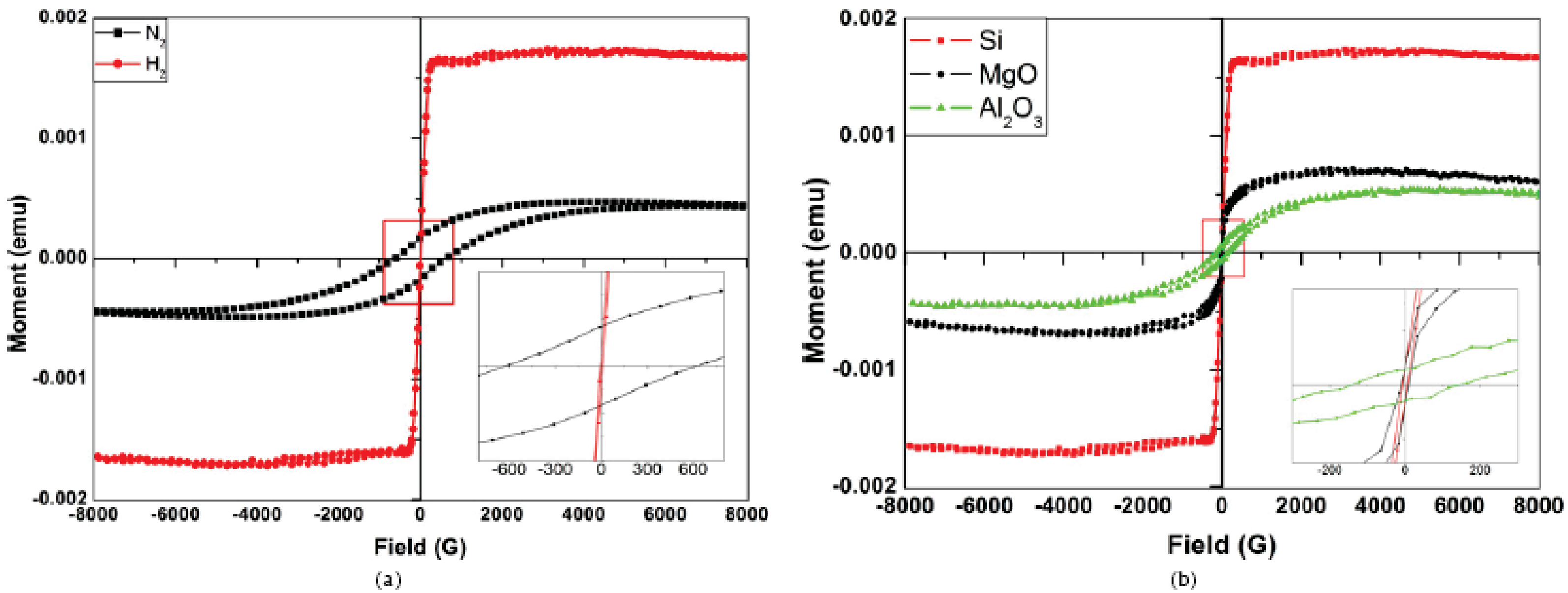


Fig. 2. Hysteresis loops of (a) samples deposited on $Si_{(100)}$ substrate using hydrogen (-●-) and nitrogen (-■-) gases, and (b) samples deposited on $Si_{(100)}$ (-■-), $MgO_{(100)}$ (-●-) and amorphous Al_2O_3 (-▲-) using hydrogen as filling gas.

Z.Y. Pan, R.S. Rawat, R. Verma, J.J. Lin, H. Yan, R.V. Ramanujan, P. Lee, S.V. Springham, T.L. Tan, *Miniature plasma focus as a novel device for synthesis of soft magnetic FeCo thin films*, Physics Letters A **374**, 1043-1047 (2010).

Applications: Nanophase Soft Magnetic FeCo Thin Films

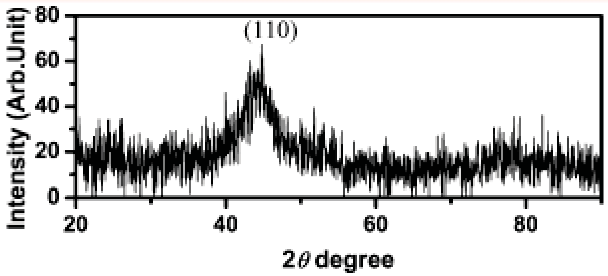


Fig. 5. XRD pattern of the sample deposited on the $Si_{(100)}$ substrate using hydrogen as filling gas.

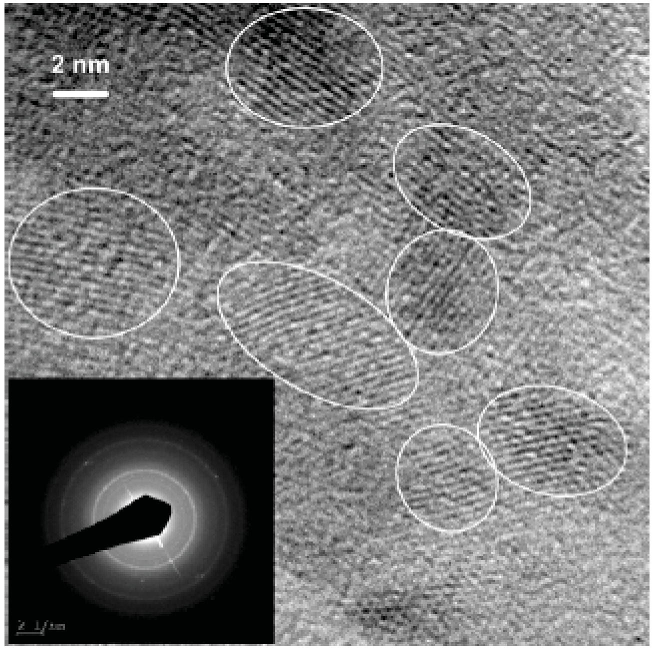


Fig. 6. HRTEM image of the sample deposited on the $Si_{(100)}$ substrate using hydrogen as filling gas and corresponding SAD pattern in the inset.

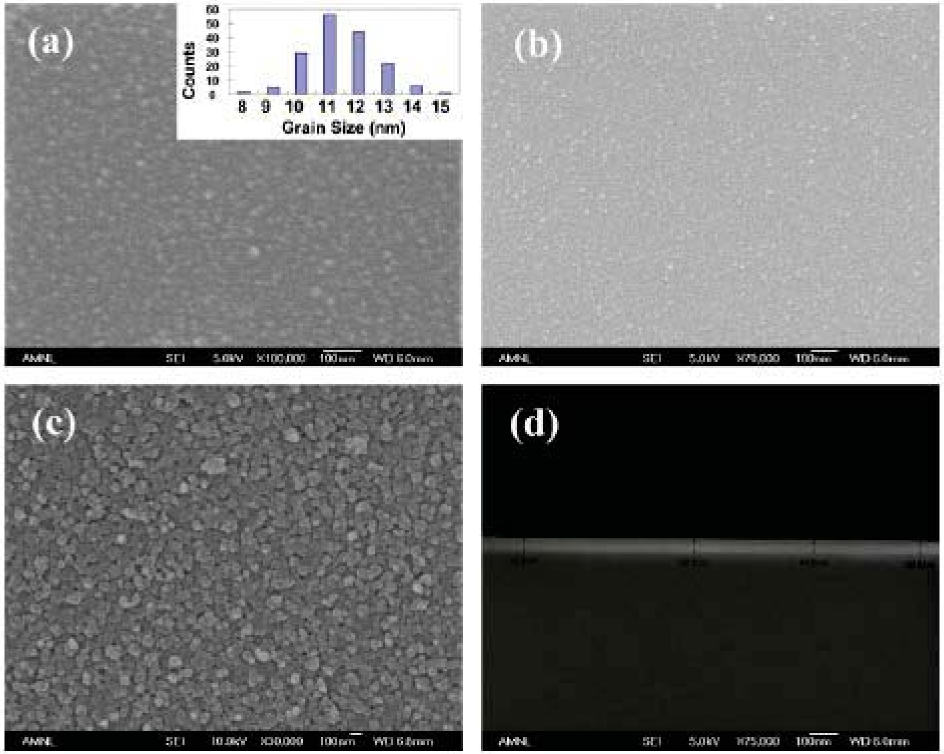


Fig. 3. The morphological images of the FeCo samples deposited on
(a) Si(100), (b) MgO(100), (c) amorphous Al2O3 substrates, and (d) the cross sectional view of the sample deposited on Si(100) using hydrogen as filling gas.

Z.Y. Pan, R.S. Rawat, R. Verma, J.J. Lin, H. Yan, R.V. Ramanujan, P. Lee, S.V. Springham, T.L. Tan, *Miniature plasma focus as a novel device for synthesis of soft magnetic FeCo thin films*, Physics Letters A **374**, 1043-1047 (2010).

Applications: High Deposition rate DLC Film Synthesis using FMPF-2

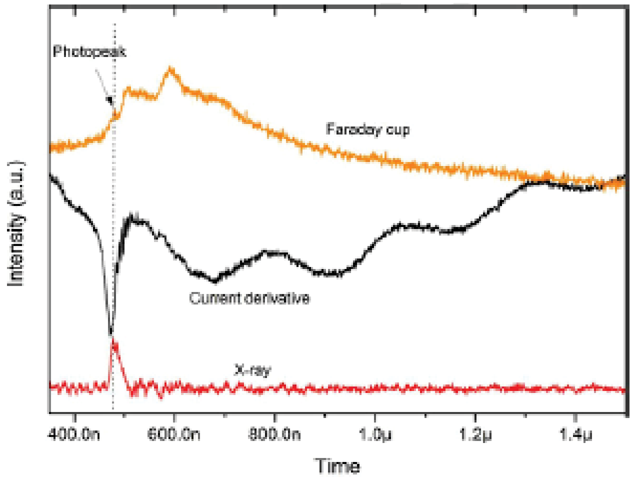


Fig. 2. Typical signals from PIN diode, Rogowski coil and Faraday cup.

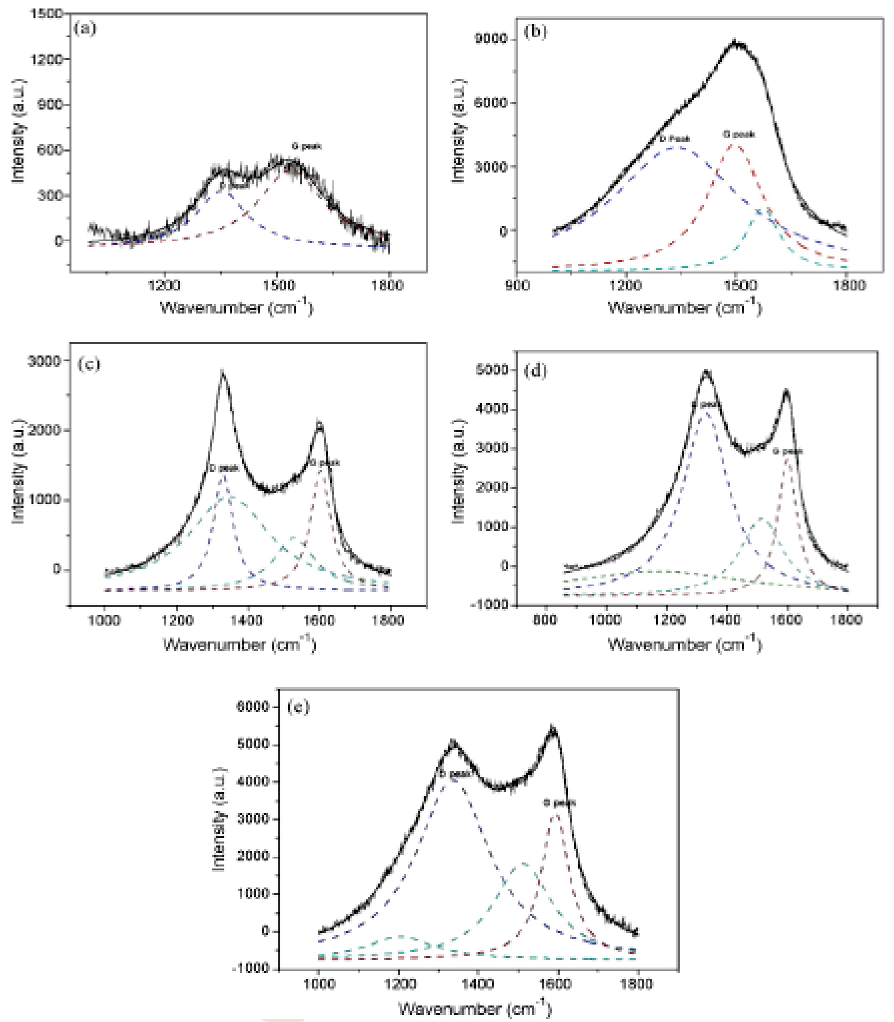


Fig. 3. Raman Spectra of the DLC films deposited using (a) 10, (b) 20, (c) 50, (d) 100 and (e) 200 focus deposition shots.

E. Gharshebani, R. S. Rawat, R. Verma, S. Karamat, and S. Sobhanian, *Low energy repetitive miniature plasma focus device as high deposition rate facility for synthesis of DLC thin films*, Applied Surface Science 256(16), 4977-83 (2010).

Applications: High Deposition rate DLC Film Synthesis using FMPF-2

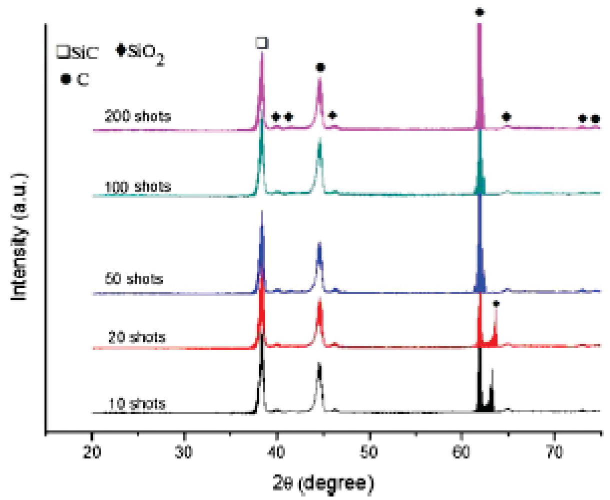


Fig. 5. XRD patterns obtained for DLC films deposited at a distance of 6 cm using different number of focus deposition shots.

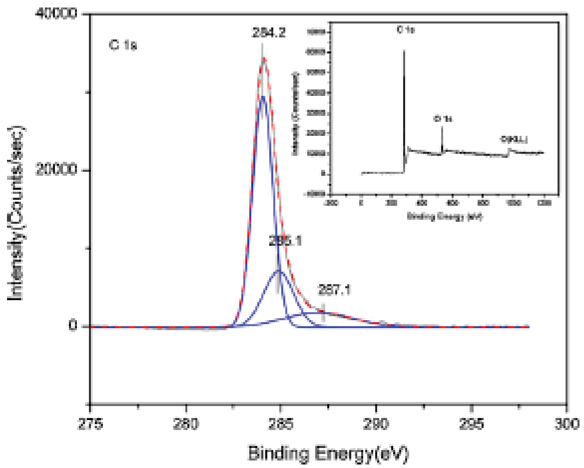


Fig. 7. De-convolution of the C 1s binding energy peak of XPS spectrum of the deposited with 100 shots. The inset shows the typical XPS Survey spectrum of the same sample.

E. Gharshebani, R. S. Rawat, R. Verma, S. Karamat, and S. Sobhanian, *Low energy repetitive miniature plasma focus device as high deposition rate facility for synthesis of DLC thin films*, Applied Surface Science 256(16), 4977-83 (2010).

Atomic percentage			
No. of shots	C	O	Si
10	95.89	3.44	0.67
20	89.96	8.85	1.19
50	93.94	5.96	0.10
100	93.12	6.81	0.07
200	93.55	6.38	0.07

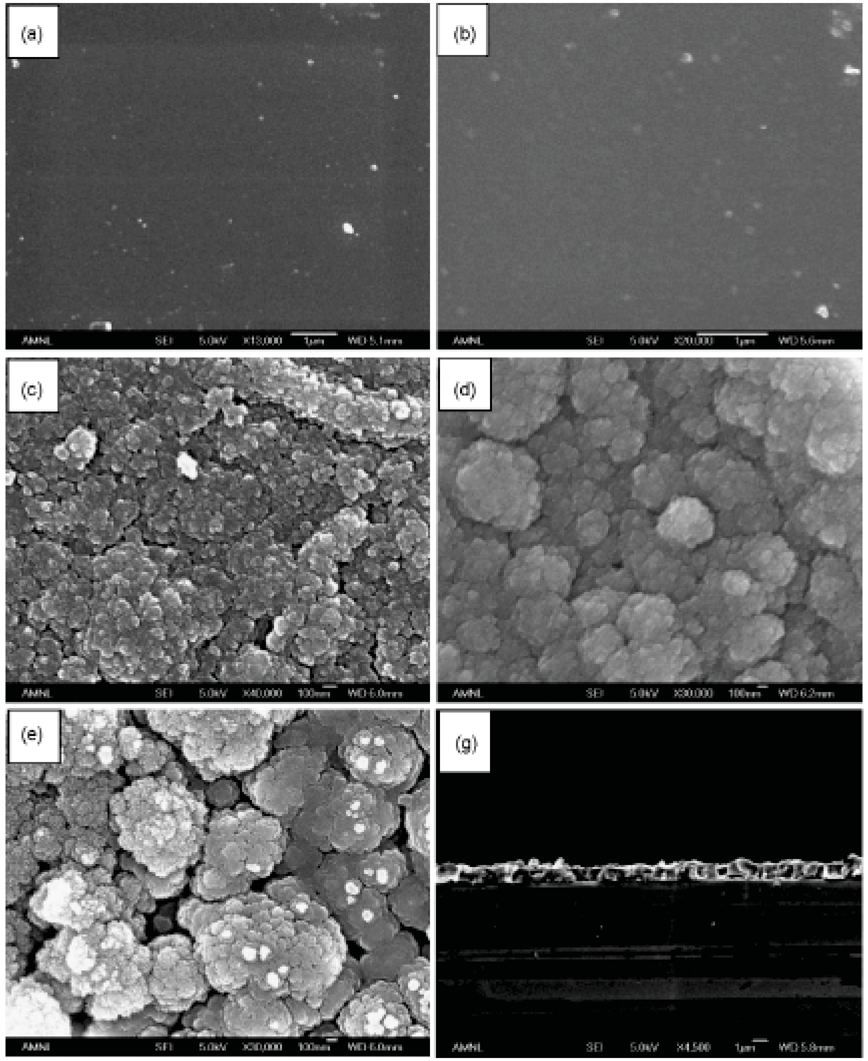
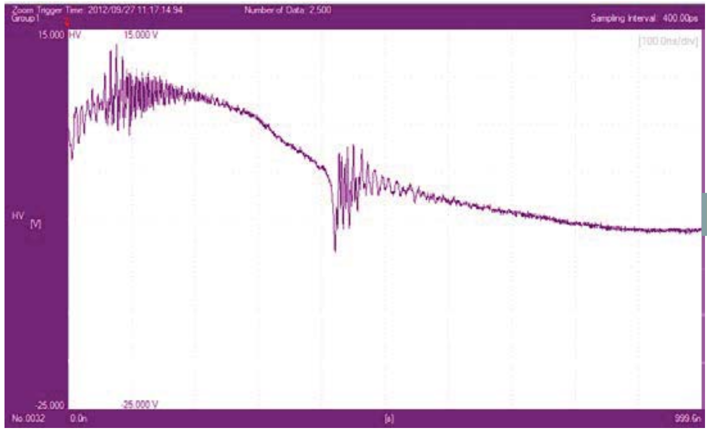


Fig. 6. (a) 10, (b) 20, (c) 50, (d) 100 and (e) 200 focus deposition (g) cross-sectional SEM for 200 focus deposition shots.

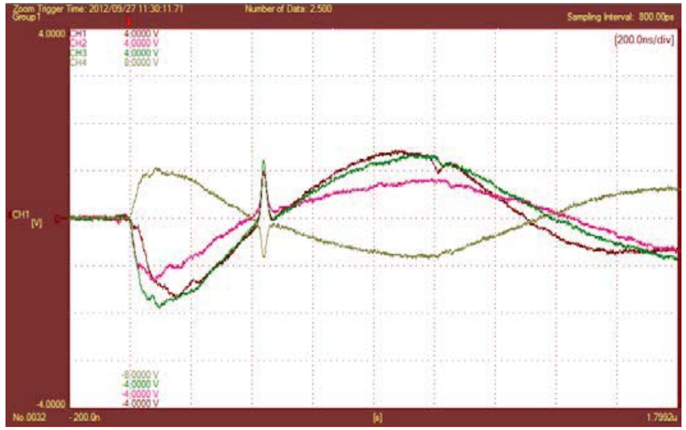
Other Critical Issues in High Rep Rate High Performance PF Devices: Synchronization of Switches

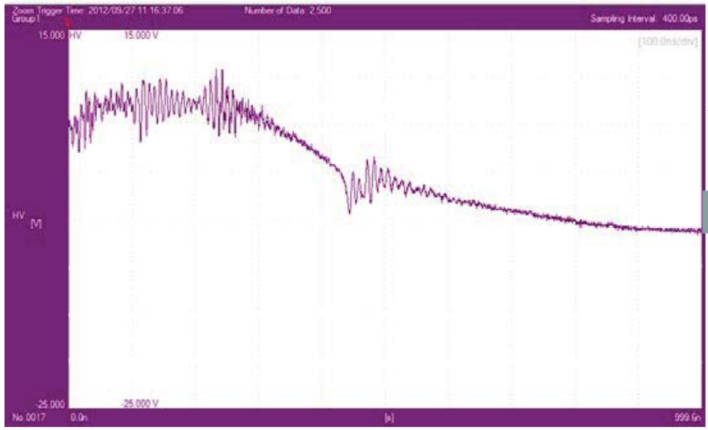
di/dt

4 PSG signals

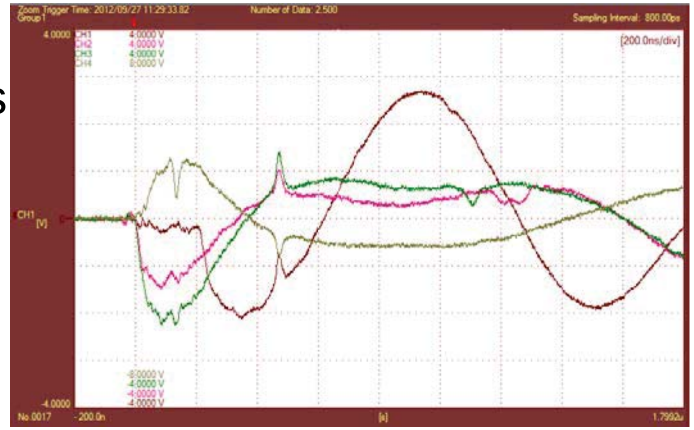


Synchronous signal

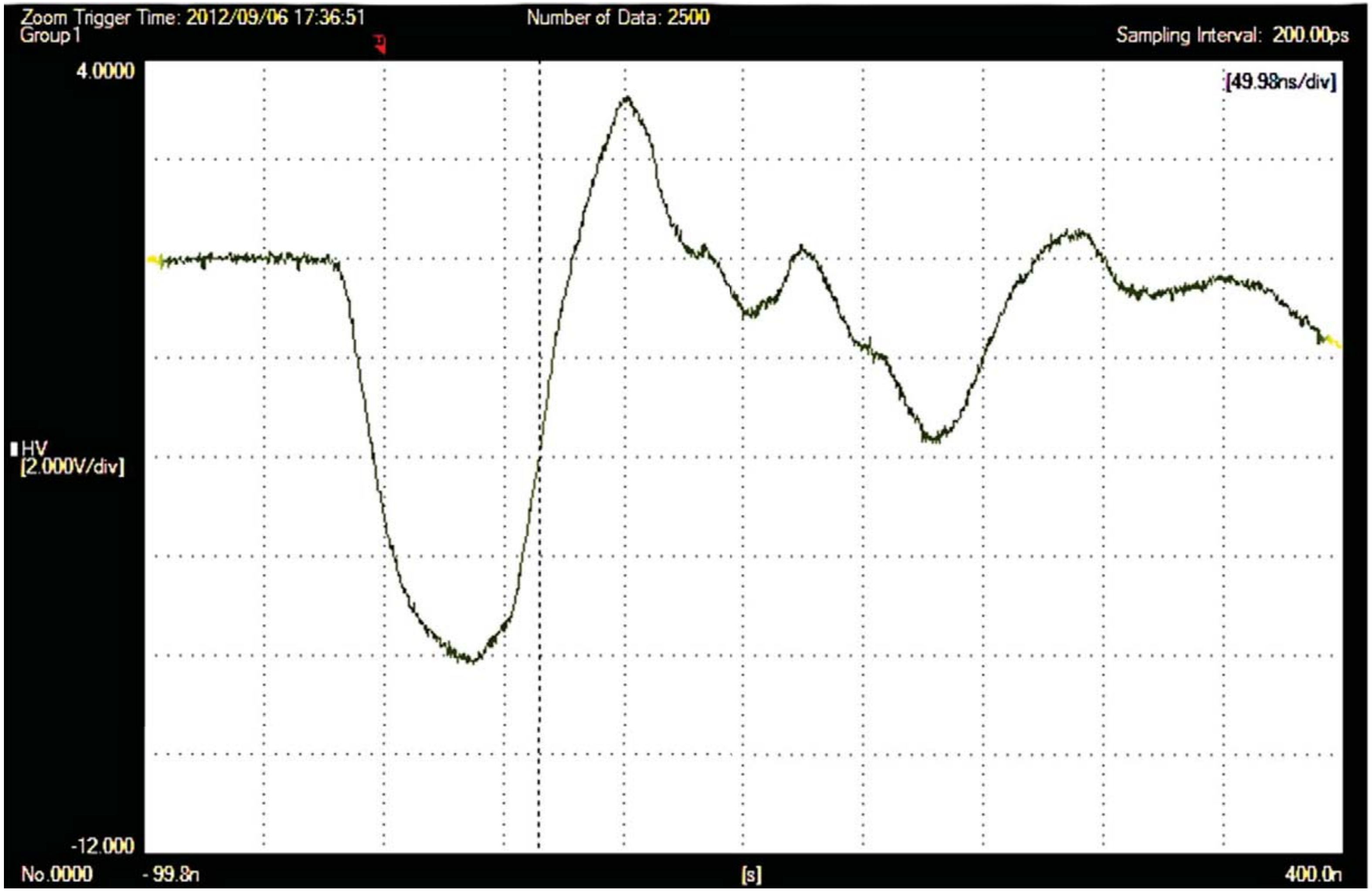




Asynchronous signal



Other Critical Issues in High Rep Rate High Performance PF Devices: Synchronization of Switches

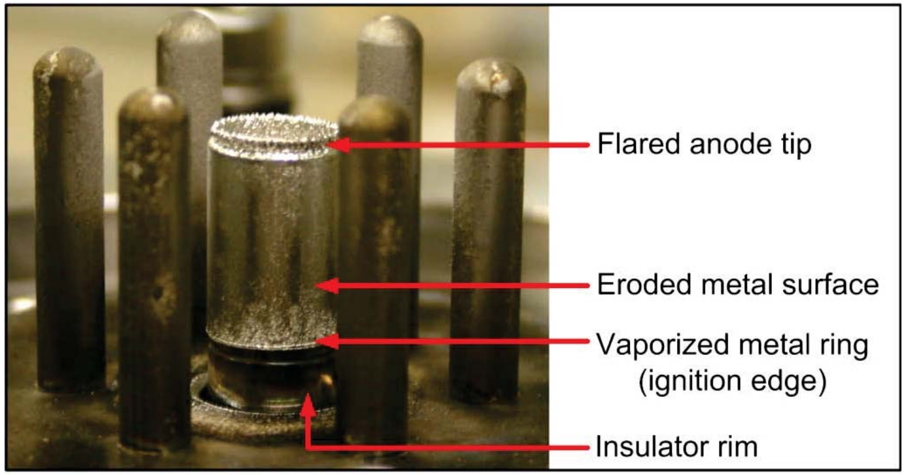


Trigger pulse signal

Other Critical Issues in High Rep Rate High Performance PF Devices: Thermal Load Management

Operation at high rep-rate is needed to be compensated for lower yield related for Low Energy PF devices. But higher operating frequency

- Introduces thermal management problems in the electrodes and chamber walls
- Ablation of anode tip material by electron beam and hot dense plasma
- Coaxial geometry with multiple cathode rods and a single anode

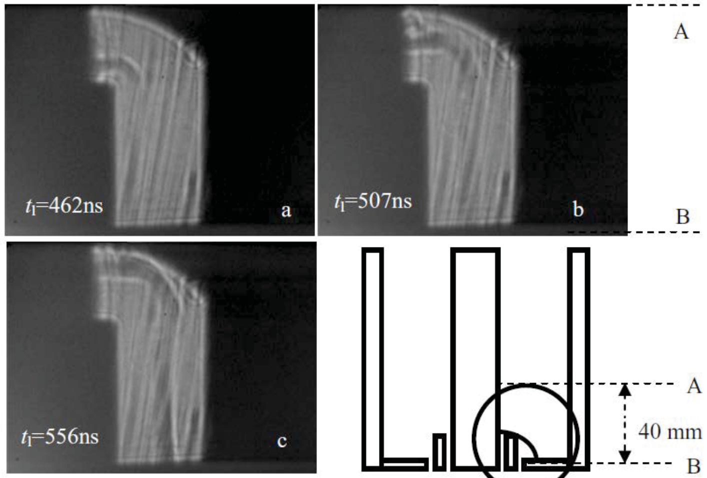


Anode thermal management is an important first step to high rep-rate operation

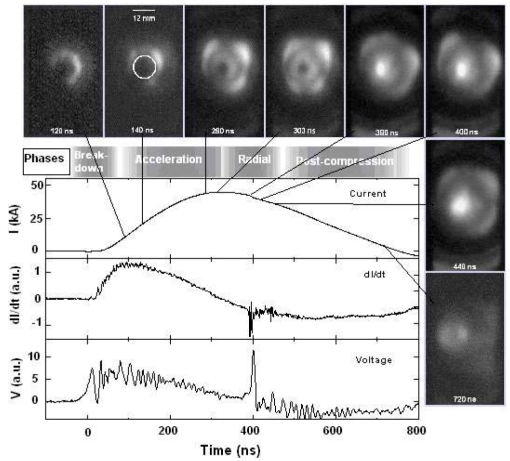
Other Critical Issues in High Rep Rate High Performance PF Devices: Thermal Load Management

- Simple geometry relies on thermal conductivity of anode material (Cu or SS) to conduct heat to large flange to which anode is connected. The flange holding anode act like the heat sink.
- The 2 kW FMPF facility (200J @ 10 Hz repetition rate) with assumption of about 20% being used up in heating up the anode top gives approximately 400 W/cm^2 thermal load into anode. But at 100 Hz operation the same will go to 4 kW/cm^2.
- Very little heat transfer to the low pressure gas.
- The annular design of anode also impedes the heat flow
- Active cooling would be essential

Other Critical Issues in High Rep Rate High Performance PF Devices: High Sensitivity to Gas-fill Type



T. Zhang, X. Lin, K. A. Chandra, T.L. Tan, S.V. Springham, A. Patran, P. Lee, S. Lee and **R.S. Rawat**,, Plasma Source Science and Technology **14** (1), 368-374, 2005.



S.M. Hassan, T. Zhang, A. Patran, **R. S. Rawat**, S. V. Springham, T. L. Tan, D. Wong, W. Wang, S. Lee, V.A. Gribkov, S.R. Mohanty and P. Lee, Plasma Sources Science and Technology **15** (4), 614-619 (2006).

About 20-30% of total time to pinch (breakdown to pinch) is spent in formation of well defined current sheath at the insulator sleeve.

So the time available for the formation of current sheath decreases with the decrease in the time to pinch for low energy fast PF devices.

For very fast extremely low energy plasma focus the smaller time may not be sufficient for proper current sheath formation and hence pinching efficiency will also be poor.

The smaller time available for current sheath formation may also have significant affect on the degree of ionization of various gases used. The optimized electrode dimensions may differ significantly for gases.

Summary

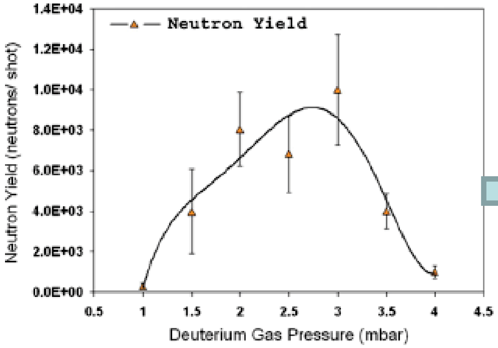


Figure 9. Total neutron yield versus deuterium filling pressure.