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

8 - 12 October 2012

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

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Acknowledgement

• Rishi Verma, BARC, Vizag, INDIA
• M. Krishnan, AASC, USA
• Paul Lee, NIE/NTU, SINGAPORE
• S.V. Springham, NIE/NTU, SINGAPORE
• T.L. Tan, NIE/NTU, SINGAPORE
• S. Lee, (NIE/NTU, SINGAPORE + IPFS)
• Alireza Talebitaher, NIE/NTU, SINGAPORE
• S.M. Kalaiselvi, NIE/NTU, SINGAPORE

• NTU ACRF Tier1 Research Grant
Multiple Radiation Source: Avenues for Physics and Applications

Plasma Focus

- High Energy Ions
- Relativistic Electrons
- Soft and Hard x-rays
- EUV Emissions
- Neutron Emission
- Shock Waves
- Plasma Instabilities
- Plasma Turbulence
- Plasmas Dynamics

School & Training Course on DMP, ICTP, Trieste 8-12 October 2012
Rajdeep S Rawat
## Plasma Focus Research – Before 2003

<table>
<thead>
<tr>
<th>Device – location</th>
<th>Energy (kJ)</th>
<th>Peak current (kA)</th>
<th>Neutron Yield (neutrons/shot)</th>
<th>Energy density parameter (J m⁻³)</th>
<th>Speed factor (kA cm⁻¹ mbar⁻¹/²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mega-Joule (≥ MJ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRASCATI – Italy</td>
<td>1000</td>
<td>1850</td>
<td>5 × 10¹¹</td>
<td>5.46 × 10¹⁰</td>
<td>69.10</td>
</tr>
<tr>
<td>TAMU – USA</td>
<td>480</td>
<td>1400</td>
<td>2.6 × 10¹¹</td>
<td>10 × 10¹⁰</td>
<td>76.77</td>
</tr>
<tr>
<td>SPEED2 – Germany</td>
<td>187</td>
<td>4000</td>
<td>1 × 10¹¹</td>
<td>2.42 × 10¹⁰</td>
<td>421.63</td>
</tr>
<tr>
<td>PF-360 – Poland</td>
<td>130</td>
<td>1200</td>
<td>3.8 × 10¹⁰</td>
<td>1.7 × 10¹⁰</td>
<td>84.51</td>
</tr>
<tr>
<td>DENA – Iran</td>
<td>90</td>
<td>2800</td>
<td>1.2 × 10⁹</td>
<td>0.16 × 10⁹</td>
<td>98.23</td>
</tr>
<tr>
<td>DPF-40 – China</td>
<td>18</td>
<td>350</td>
<td>2.1 × 10⁸</td>
<td>1.53 × 10¹⁰</td>
<td>60.20</td>
</tr>
<tr>
<td>7 kJ PF – Japan</td>
<td>7</td>
<td>400</td>
<td>5.8 × 10⁸</td>
<td>3.65 × 10¹⁰</td>
<td>93.31</td>
</tr>
<tr>
<td>Medium (2 – 10kJ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNU/ICTP</td>
<td>2.9</td>
<td>170</td>
<td>1.2 × 10⁸</td>
<td>9.5 × 10¹⁰</td>
<td>61.37</td>
</tr>
<tr>
<td>NX2</td>
<td>2.9</td>
<td>410</td>
<td>7 × 10⁸</td>
<td>5.3 × 10¹⁰</td>
<td>79.72</td>
</tr>
<tr>
<td>BARC – India</td>
<td>2.2</td>
<td>180</td>
<td>14.4 × 10⁷</td>
<td>5.32 × 10¹⁰</td>
<td>68.84</td>
</tr>
<tr>
<td>Sub-kilojoule</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PACO – Argentina</td>
<td>2</td>
<td>250</td>
<td>5 × 10⁸</td>
<td>0.35 × 10¹⁰</td>
<td>81.64</td>
</tr>
<tr>
<td>PF-400-Chile</td>
<td>0.4</td>
<td>127</td>
<td>1.05 × 10⁶</td>
<td>5.2 × 10¹⁰</td>
<td>70</td>
</tr>
</tbody>
</table>

2003
### Sub-kJ Miniature Plasma Focus Research

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

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


Chilean Nuclear Energy Commission, CCHEN.
Dense plasma focus for production-level EUV lithography

B. Nikolaus, W.N. Partlo, L.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.

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:
  - \( \frac{d_{Mo}}{d_{Mo} + d_{Si}} = 0.4 \)
  - 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 Portable Neutron Generators
- 2001: ~US $60M
- 2006: >US $750M
- By 2010: >US $1.4 billion
Neutrons and $\gamma$-rays have very penetration capability
(Penetration Depth: Suitcases to sea-land containers)

<table>
<thead>
<tr>
<th>Elements</th>
<th>$H$</th>
<th>$C$</th>
<th>$N$</th>
<th>$O$</th>
<th>$Cl$</th>
<th>$C/O$</th>
<th>$C/N$</th>
<th>$Cl/O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explosives</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Very High</td>
<td>Medium</td>
<td>Low &lt;1</td>
<td>Low &lt;1</td>
<td>Very Low</td>
</tr>
<tr>
<td>Narcotics</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High &gt;3</td>
<td>High &gt;1</td>
<td>Very High</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Expected Ratio</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C/O$</td>
<td>$N/O$</td>
</tr>
<tr>
<td>RDX</td>
<td>0.53</td>
<td>1</td>
</tr>
<tr>
<td>TNT</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>C-4</td>
<td>0.71</td>
<td>1</td>
</tr>
</tbody>
</table>

‘fingerprints’ of elements with neutrons?
Neutrons for Active Interrogation

Bombarded neutron → Stable Isotope → Radioactive Isotope

“Characteristic” Prompt $\gamma$ is emitted

Possible Interactions.....

Thermal Neutron (H, N, Cl, S...) Fast Neutron (C, O.....)

- Neutron Capture
  \[ n + ^AX \rightarrow ^{A+1}X + \gamma \]

- 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)

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (MeV)</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{252}\text{Cf}$</td>
<td>2.1</td>
<td>2.6 years</td>
</tr>
<tr>
<td>$^{241}\text{Am(Be)}$</td>
<td>4.5</td>
<td>458 years</td>
</tr>
</tbody>
</table>

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

Sealed Tube Neutron Source (Pulsed)

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

Accelerated hydrogen isotopes impinge on deuterated/ tritium (2-10 Ci) targets
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 ~ 3.6m³

FMPF-1
0.2m x 0.2m x 0.5m
V ~ 0.02m³

2.9kJ ↑
10⁷ - 10⁸ n/s ↑
10⁶ x 10Hz ~ 10⁷ n/s

↓ 0.2kJ
↓ 10⁶ n/s

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

Energy (~200J) -> Selection of operating voltage -> Bank capacitance

Focus tube design

Quarter time period -> Peak current

Estimation of system inductance and resistance

Peak current -> Energy transfer switch

Energy transfer switch -> Layout and connection

Layout and connection

No. of capacitors

Bank capacitance

Voltage

Current

ESL/ESR

Shot life

Peak current

Voltage

Inductance

Jitter

Inductance (Flat plate/Coaxial cable)
Main objectives were to determine:

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

\[
\begin{align*}
L_{eq} &= ? \quad ; \quad R_{eq} = ? \quad ; \quad I_0 = ? \\
k = ? \quad ; \quad T = ?
\end{align*}
\]
Designing of Plasma Focus Tube Assembly

INPUTS

\[ \begin{align*}
I_o & \quad - \text{Peak discharge current amplitude} \\
T/4 & \quad - \text{Quarter time period of the discharge current signal} \\
L_{eq} & \quad - \text{System inductance}
\end{align*} \]

1. Anode radius \((a)\)
   
   **Speed factor**
   
   (90 kA/cm/torr\(^{1/2}\))
   
   \[ \frac{I_o}{a\sqrt{p}} \]

2. Anode length \((z_a)\)
   
   **Typical velocities in axial and radial phases**
   
   \(v_a : 10 \text{ cm/\(\mu\)s}, \ v_r : 25 \text{ cm/\(\mu\)s}\)
   
   \[ z_a = v_a \left[ \frac{T}{4} - \frac{a}{v_r} \right] \]

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

4. Insulator length \((z_l)\)
   
   \(z_l < (b-a), \text{ paschen minima}\)
Optimization using Lee Code

Short Circuit Oscillogram \( \rightarrow k, T \) \( \rightarrow \) Rogowski Coil Calibration Factor

Calibrated Current Trace from Experiment

Simulated Trace \( \rightarrow L_0, R_0 \) \( \rightarrow a, b, z_0, p, C_0, V_0 \) \( \rightarrow \)

Fitting by adjusting mass And current shading factors

\[ k = \text{reversal ratio} \]
\[ T = \text{time period} \]
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.
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**
**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

(0.6\mu F \times 4 \approx 2.4\mu F)

Capacitor bank  Integrated System

Schematic View

The FMPF-2 device

Layout of the capacitor bank

Constructional layout of FMPF-2 device

The FMPF-3 device

Fully Integrated System


Schematic View
## Hardware configuration summary of FMPF devices

<table>
<thead>
<tr>
<th>Specifications</th>
<th>FMPF-1</th>
<th>FMPF-2</th>
<th>FMPF-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacitance</td>
<td>2.4μF</td>
<td>2.4μF</td>
<td>2.4μF</td>
</tr>
<tr>
<td>Capacitance ($C_o$) $\times$ No. of Capacitors</td>
<td>0.6μF $\times$ 4</td>
<td>0.3μF $\times$ 8</td>
<td>0.3μF $\times$ 8</td>
</tr>
<tr>
<td>Max. charging voltage ($V_o$)</td>
<td>30kV</td>
<td>30kV</td>
<td>30kV</td>
</tr>
<tr>
<td>ESL/ESR of capacitor(s)</td>
<td>~70nH/ ~250mΩ</td>
<td>~20nH/ ~80mΩ</td>
<td>~20nH/ ~80mΩ</td>
</tr>
<tr>
<td>No. of energy transfer switch(s)</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Switch type/Model</td>
<td>Trigatron/Indigenous</td>
<td>Trigatron/SG-101M-75C</td>
<td>Pseudospark/TDI11-150k/25</td>
</tr>
<tr>
<td>Operating voltage range/Maximum current handling limit</td>
<td>8 – 18kV/100kA</td>
<td>10 – 40kV/100kA</td>
<td>3 – 20kV/150kA</td>
</tr>
<tr>
<td>Max. discharge repetition rate (PRR)</td>
<td>0.5Hz</td>
<td>10Hz</td>
<td>10Hz</td>
</tr>
</tbody>
</table>
**Major electrical characteristics of FMPF devices**

<table>
<thead>
<tr>
<th>Electrical Parameters</th>
<th>FMPF-1</th>
<th>FMPF-2</th>
<th>FMPF-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy bank capacitance ( (C_o) )</td>
<td>2.4 µF</td>
<td>2.4 µF</td>
<td>2.4 µF</td>
</tr>
<tr>
<td>Max. charging voltage ( (V_o) )</td>
<td>14kV</td>
<td>14kV</td>
<td>14kV</td>
</tr>
<tr>
<td>Max. stored energy ( (E_o) )</td>
<td>235J</td>
<td>235J</td>
<td>235J</td>
</tr>
<tr>
<td>Peak short circuit current ( (I_{sc}) ) @ 14kV</td>
<td>87kA</td>
<td>89kA</td>
<td>103kA</td>
</tr>
<tr>
<td>Eq. circuit inductance ( (L_{eq}) )</td>
<td>27±2nH</td>
<td>56±3nH</td>
<td>34±2nH</td>
</tr>
<tr>
<td>Eq. circuit resistance ( (R_{eq}) )</td>
<td>66±3mΩ</td>
<td>26±3mΩ</td>
<td>23±3mΩ</td>
</tr>
<tr>
<td>Driver impedance ( (Z_o) )</td>
<td>~161mΩ</td>
<td>~157mΩ</td>
<td>~106mΩ</td>
</tr>
<tr>
<td>Reversal factor ( (k) )</td>
<td>33%</td>
<td>77%</td>
<td>78%</td>
</tr>
<tr>
<td>Quarter time period ( (T/4) )</td>
<td>~400ns</td>
<td>~575ns</td>
<td>~458ns</td>
</tr>
<tr>
<td>Max. discharge repetition rate ( (PRR) )</td>
<td>0.5Hz</td>
<td>10Hz</td>
<td>10Hz</td>
</tr>
</tbody>
</table>
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
   \( t_{1/4} \sim 400\text{ns} \) and \( t_{\text{pinch}} \sim 10 – 15\text{ns} \)

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

2. Measuring Neutron Yields \( \leq 10^6 \text{ n/s} \)

   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

Indium Foil Activation Detector
(for single shot operations)

Beryllium Activation Detector
(for repetitive; up to 3 Hz)

Solid State Nuclear Track Detector

Time resolved neutron and HXR

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

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

Diagnostics

**Electrical**

- Strip winding
  - (Showing installation of Rogowski coil)

**Soft X-rays**

- High Rep Rate Shadowgraphy System
  - Diagram showing components such as mirror, laser, photodiode, voltage probe, oscilloscope, and PC.
Nuclear diagnostics and instrumentation setup
Construction features of ‘FMPF-1’

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

Parameters of ‘FMPF-1’ device

<table>
<thead>
<tr>
<th>Main electrical characteristics of FMPF-1 device.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy bank capacitance ($C_o$)</td>
</tr>
<tr>
<td>Maximum charging voltage ($V_o$)</td>
</tr>
<tr>
<td>Maximum stored energy @14kV ($E_o$)</td>
</tr>
<tr>
<td>Maximum current (under short circuit) ($I_{sc}$)</td>
</tr>
<tr>
<td>Typical operating voltage range</td>
</tr>
<tr>
<td>Eq. circuit inductance ($L_{eq}$)</td>
</tr>
<tr>
<td>Eq. circuit resistance ($R_{eq}$)</td>
</tr>
<tr>
<td>Voltage Reversal ($k$)</td>
</tr>
<tr>
<td>Quarter time of discharge ($T/4$)</td>
</tr>
<tr>
<td>Maximum discharge repetition rate (DRR)</td>
</tr>
</tbody>
</table>
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)
Focusing peak amplitude

Speed factor

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/CA/17-3/SS | 3 mbar | 166 ±7.1 | 87.3/ Good

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)

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

Neutron yield enhancement: D2-Kr admixture operation


(a) D$_2$ discharge at 3mbar

(b) D$_2$+5%Kr admixture discharge at 3mbar
Experiments with Deuterium-Krypton Admixtures
(Anode: composite, cathode: tubular)

**Gains**
- 30X - for $\text{D}_2 + 2\%\text{Kr}$
- 20X - for $\text{D}_2 + 5\%\text{Kr}$
- 1.2X - for $\text{D}_2 + 10\%\text{Kr}$

### Neutron Flux

<table>
<thead>
<tr>
<th>Concentration Ratio</th>
<th>Neutron Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{D}_2 + 2%\text{Kr}$</td>
<td>$3.14 \pm 0.4 \times 10^5$ n/s</td>
</tr>
<tr>
<td>$\text{D}_2 + 5%\text{Kr}$</td>
<td>$2 \pm 0.18 \times 10^5$ n/s</td>
</tr>
<tr>
<td>$\text{D}_2 + 10%\text{Kr}$</td>
<td>$1.16 \pm 0.18 \times 10^4$ n/s</td>
</tr>
<tr>
<td>$\text{D}_2$ (Pure)</td>
<td>$1 \pm 0.27 \times 10^4$ n/s</td>
</tr>
</tbody>
</table>
**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 D₂ and D₂-Kr admixture at different filling pressures.

**Figure 3.** Focusing peak amplitude and Focusing duration for D₂ and D₂-Kr admixture.

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**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.


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 D2 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.


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

Rishi Verma1,2, R S Rawat1,4, P Lee1, M Krishnan3, S V Springham1 and T L Tan1
Parameters of ‘FMPF-2’ device

Main electrical characteristics of ‘FMPF-2’ device.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy bank capacitance ($C_o$)</td>
<td>2.4 μF</td>
</tr>
<tr>
<td>Maximum charging voltage ($V_o$)</td>
<td>14kV</td>
</tr>
<tr>
<td>Maximum stored energy @14kV ($E_o$)</td>
<td>235J</td>
</tr>
<tr>
<td>Maximum current (under short circuit) ($I_{sc}$)</td>
<td>89kA @14kV</td>
</tr>
<tr>
<td>Typical operating voltage range</td>
<td>12 – 14 kV</td>
</tr>
<tr>
<td>Eq. circuit inductance ($L_{eq}$)</td>
<td>56±3nH</td>
</tr>
<tr>
<td>Eq. circuit resistance ($R_{eq}$)</td>
<td>26±3mΩ</td>
</tr>
<tr>
<td>Voltage Reversal ($f$)</td>
<td>77%</td>
</tr>
<tr>
<td>Quarter time of discharge ($T/4$)</td>
<td>~575ns</td>
</tr>
<tr>
<td>Maximum discharge repetition rate (DRR)</td>
<td>10Hz</td>
</tr>
</tbody>
</table>
Results from FMPF-2

Diagram:
- Moderator
- Parafin Wax
- ^3He Detector
- Focus
- Anode
- Cathode
- Rogowski Coil
- Sparkgap Switch
- Capacitor Bank
- Power Supply
- PMT-1
- PMT-2

Graphs:
1. X-rays, Neutrons
   - Time of Flight (~46ns)
   - Ch1: d/dt Signal (20V/div)
   - Ch2: PMT1 Signal (2V/div)
   - Ch3: PMT2 Signal (2V/div)
   - H Scale: 50ns/div

2. Neutron Yield vs. Time to Pinch
   - Average Neutron Yield
   - Average time to pinch

3. Neutron Yield vs. Deuterium Pressure
   - Deuterium Pressure (mbar)
   - Time to pinch (ns)

Caption:
School & Training Course on DMP, ICTP, Trieste 8-12 October 2012
Rajdeep S Rawat
Parameters of ‘FMPF-3’ device

Main electrical characteristics of ‘FMPF-3’

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy bank capacitance ( (C_o) )</td>
<td>2.4( \mu )F</td>
</tr>
<tr>
<td>Maximum charging voltage ( (V_o) )</td>
<td>14kV</td>
</tr>
<tr>
<td>Maximum stored energy @14kV ( (E_o) )</td>
<td>235J</td>
</tr>
<tr>
<td>Maximum current (under short circuit) ( (I_{sc}) ) @14kV</td>
<td>103kA</td>
</tr>
<tr>
<td>Typical operating voltage range</td>
<td>10 – 14 kV</td>
</tr>
<tr>
<td>Equivalent circuit inductance ( (L_{eq}) )</td>
<td>34±2nH</td>
</tr>
<tr>
<td>Equivalent circuit resistance ( (R_{eq}) )</td>
<td>23±3mΩ</td>
</tr>
<tr>
<td>Voltage Reversal ( (f) )</td>
<td>78%</td>
</tr>
<tr>
<td>Quarter time of discharge ( (T/4) )</td>
<td>~458ns</td>
</tr>
<tr>
<td>Maximum discharge repetition rate (DRR)</td>
<td>10Hz</td>
</tr>
</tbody>
</table>
Some Results from FMPF-3

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

Current derivative \((\frac{di}{dt})\) 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

(a) at 4.5mbar D₂ filling gas pressure

(b) at 5.5mbar D₂ filling gas pressure

Applications: HXR radiography source

Applications: Nanophase Soft Magnetic FeCo Thin Films

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.


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. HREM image of the sample deposited on the Si(100) substrate using hydrogen as filling gas and corresponding SAD pattern in the inset.
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.
Applications: High Deposition rate DLC Film Synthesis using FMPF-2


Fig. 6. (a) 10, (b) 20, (c) 50, (d) 100 and (e) 200 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.

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

\[ \frac{di}{dt} \]

4 PSG signals

Synchronous signal

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

Trigger pulse signal
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/cm² thermal load into anode. But at 100 Hz operation the same will go to 4 kW/cm².

- 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


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.

[Graph showing neutron yield vs. deuterium gas pressure]

[Graph showing neutron yield vs. pressure at 5.5 mbar]

[Graph showing time-averaged neutron yield vs. discharge repetition frequency]

[Graph showing neutron yield vs. pressure for different conditions]

[Image of cathode structure]

[Image of SEM micrograph of cathode material]