Influence of Krypton gas Admixture on Plasma Focus Deuterium Fusion

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Abstract

A comparative study of DD fusion in a 1.6 kJ plasma focus (PF) device operated in pure deuterium and deuterium-krypton (D₂-Kr) admixture has been performed. Fast-neutron beryllium activation detectors positioned at 0° and 90° to the PF axis measured the time-integrated neutron yield and anisotropy. Typical fusion yields were in the range of 1-3×10⁸ neutrons per shot. The Coded Aperture Imaging (CAI) technique has been employed to image the fusion source using the ~3 MeV protons emitted from D(d,p)T reactions. The coded mask pattern is based on a Singer cyclic difference set with 341 open pixels in 91×15 array, giving a total open area of almost 31 mm². CR-39 polymer nuclear track detectors (filtered with 75 μm Kapton film) recorded the fusion proton image. The proton coded-image was read from the detectors using an automated scanning system. A deconvolution procedure was applied to reconstruct the fusion image. An x-ray pinhole system (with filtering adapted to the D₂ and D₂-Kr cases) was employed simultaneously to image the hot dense plasma column. By comparison with D₂ operation, fusion images for the D₂-Kr case show a significantly narrower and smaller fusion emission region indicating a tighter confinement of the hot plasma interacting with the energetic deuteron beam. Furthermore, no spatial correlation between fusion emission density and micro-pinch formation (as seen particularly in D₂-Kr x-ray images) is evident.
NX2 Plasma Focus Device:

Current sheath driven axially along electrodes by $J \times B$ force $I \approx 300 \text{kA}, B \approx 30 \text{T}$

Pinch $\rightarrow$ Hot Dense Magnetized Plasma, $T_e \approx 1 \text{keV}, n_e \approx 10^{19} \text{cm}^{-3}$

For deuterium filling gas, approximately equal probability of two fusion reactions:

$$d + d \rightarrow p (3.02 \text{MeV}) + T (1.01 \text{MeV}) \quad 50\%$$

$$d + d \rightarrow n (2.45 \text{MeV}) + \text{He} (0.82 \text{MeV}) \quad 50\%$$

Capacitance ($C_0$) $27.0 \mu\text{F}$

Charging voltage $11 \text{kV}$

Energy ($E_0$) $1.6 \text{kJ}$

Inductance ($L_0$) $26 \text{nH}$

Impedance ($Z_0$) $30 \text{m}\Omega$

Anode radius ($a$) $11.5 \text{mm}$

Cathode radius ($b$) $22.0 \text{mm}$

Max. current (at 11 kV) $300 \text{kA}$

Operating Gas Deuterium

Neutron Yield $(1-3) \times 10^{8}$
Proton (fusion product) Imaging

The only possible way for proton imaging is using the pinhole which is quite reasonable for high energy plasma focus device with the neutron yield in range of $10^{11}$ per shot.

But for NX2 as a moderate energy range device with neutron yield of $10^8$ per shot, we cannot achieve a precise image due to lack of proton tracks.

Coded Aperture Imaging solves this problem by using many small pinholes instead of one big pinhole.

✓ Increasing the intensity
✓ Increasing the SNR
× Need the data processing
× More complicated manufacturing
× Less Field of View
Coded Aperture Imaging Approaches

Cyclic Difference Set has a flat side-lobe unlike a Random Set:

1. Hadamard Set: open fraction \( \approx 0.5 \)

\[
p (\text{pixels}) = 4t-1 , \quad h (\text{holes}) = 2t-1 , \quad \lambda (\text{side-lobe}) = t-1
\]

2. Singer Set: variable open fraction \( \approx 1/t \)

\[
p = \frac{t^{m+1} - 1}{t - 1} \quad h = \frac{t^m - 1}{t - 1} \quad \lambda = \frac{t^{m-1} - 1}{t - 1}
\]

e.g. \( t=2 \), \( m=3 \)

First Design with mask-400

Mask-400 (20×20): 57 holes, \( \rho = 1/7 \), Pixel size=(400\(\mu\)m)\(^2\)

Best open area fraction for maximum SNR

$$\text{SNR} = \frac{\text{signal from given pixel}}{\sqrt{\text{variance of signal across image}}} = \sqrt{\frac{N\rho(1 - \rho)}{m(1 + \rho(m - 1))}}$$

$N = \text{total number of particle}, \ \rho = \text{open fraction}, \ m = \text{number of pixels in object}$

The best SNR is obtained using masks based on Singer sets.

By putting some spaced rows, self-supported mask can be obtained.

For Mask-1365 (91×15), 341 holes, $\rho=1/4$,

pixel size=$\text{(300\mu m)}^2$

space factor $k=6$

Blue line: normal mask

Red line: spaced mask

$N = \text{total number of particle}, \ \rho = \text{open fraction}, \ m = \text{number of pixels in object}$
Mask fabrication

Stainless Steel (50 µm thick)
Laser machining with 20µm spot diameter
91×15 pixels (each Pixel: 300µm × 300µm)
341 holes with 25% open area

Fabricated mask (up) and the base (left) for mask and detector
CR-39 (PM355): SSNTD Proton Detection

Using the Kapton film to stop other charge particles (high energy deuterons). The SRIM Simulation has been used for particle penetration in CR-39.

<table>
<thead>
<tr>
<th>Particle Filter</th>
<th>Proton min. energy (MeV)</th>
<th>Deuterion min. energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton (50μm)</td>
<td>1.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Kapton (75μm)</td>
<td>2.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Kapton (100μm)</td>
<td>2.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle Filter</th>
<th>3 MeV proton residue energy (MeV)</th>
<th>Depth of proton in CR-39 (μm)</th>
<th>3 MeV deuteron residue energy (MeV)</th>
<th>Depth of deuteron in CR-39 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton (50μm)</td>
<td>2.1</td>
<td>67</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td>Kapton (75μm)</td>
<td>1.6</td>
<td>41</td>
<td>0.05</td>
<td>~0</td>
</tr>
</tbody>
</table>
Data Analysis

1. Scanning the detector (~12000 frames and ~300,000 proton tracks)
2. Getting the track (x,y) in Image-Pro and filtering
3. Selection of the real track data
4. De-convolution in Visual Basic
5. Plotting in MATLAB
Source Position Calibration

Proton tracks (small)

Alpha tracks (big)
Proton Trajectory in Magnetic Field

\[ B_\phi = \frac{\mu_0 I_p r}{2\pi R_p^2} \quad (r \leq R_p) \]

\[ B_\phi = \frac{\mu_0 I_p}{2\pi r} \quad (R_p < r \leq R_{cs}(z)) \]

\[ B_\phi = 0 \quad (r > R_{cs}(z)) \]
Each detector has been exposed by only one shot!
X-ray Filter

Pure Deuterium

$D_2 + 2\% Kr$

![Graph: Be (20 µm) vs. x-ray energy (eV)]

![Graph: Ti (12.5 µm) + Be (50 µm) vs. x-ray energy (eV)]

![Image: 2 mm scale]

![Image: 2 mm scale]
Neutron yield, Anisotropy and Hard X-ray for pure deuterium discharge

50 shots were fired at 13 mbar and 11 kV (1.6 kJ)

average neutron yield = $1.4 \times 10^8$, anisotropy = 2.0, hard x-ray = 144 (a.u.)
Neutron yield, Anisotropy and Hard X-ray for admixture gas (D$_2$ + 2%Kr) discharge

50 shots were fired at 13 mbar and 11 kV (1.6 kJ)

average neutron yield = 0.84$\times$10$^8$, anisotropy = 1.7, hard x-ray = 114 (a.u.)
<table>
<thead>
<tr>
<th>Neutron Yield</th>
<th>(2.38 \times 10^8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anisotropy</td>
<td>2.41</td>
</tr>
<tr>
<td>HX-ray Integral</td>
<td>257</td>
</tr>
<tr>
<td>(nVs)</td>
<td></td>
</tr>
<tr>
<td>SNR (1365)</td>
<td>23.0</td>
</tr>
<tr>
<td>SNR (4680)</td>
<td>22.6</td>
</tr>
</tbody>
</table>

**Good shot!**

Filter of x-ray: Beryllium 20µm
Fusion Source Imaging
Pure Deuterium

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Yield</td>
<td>$3.15 \times 10^8$</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>2.39</td>
</tr>
<tr>
<td>HX-ray Integral (nVs)</td>
<td>253</td>
</tr>
<tr>
<td>SNR (1365)</td>
<td>21.8</td>
</tr>
<tr>
<td>SNR (4680)</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Filter of x-ray: Beryllium 20µm

Good shot!
Fusion Source Imaging
Pure Deuterium

<table>
<thead>
<tr>
<th>Neutron Yield</th>
<th>$0.83 \times 10^8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anisotropy</td>
<td>1.88</td>
</tr>
<tr>
<td>HX-ray Integral (nVs)</td>
<td>132</td>
</tr>
<tr>
<td>SNR (1365)</td>
<td>13.2</td>
</tr>
<tr>
<td>SNR (4680)</td>
<td>15.2</td>
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</table>

Poor shot!

Filter of x-ray: Beryllium 20µm
### Fusion Source Imaging

**D₂ + 2%Kr**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Yield</td>
<td>2.92×10⁸</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>2.14</td>
</tr>
<tr>
<td>HX-ray Integral (nVs)</td>
<td>266</td>
</tr>
<tr>
<td>SNR (1365)</td>
<td>41.3</td>
</tr>
</tbody>
</table>

**Good shot!**

Filter of x-ray:
Be (50µm) + Ti (12.5µm)
Fusion Source Imaging

D$_2$ + 2%Kr

<table>
<thead>
<tr>
<th>Neutron Yield</th>
<th>4.05×10$^8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anisotropy</td>
<td>2.17</td>
</tr>
<tr>
<td>HX-ray Integral (nVs)</td>
<td>224</td>
</tr>
<tr>
<td>SNR (1365)</td>
<td>50.8</td>
</tr>
</tbody>
</table>

Good shot!
Fusion Source Imaging

D$_2$ + 2\%Kr

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Yield</td>
<td>$0.98 \times 10^8$</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>1.62</td>
</tr>
<tr>
<td>HX-ray Integral (nVs)</td>
<td>123</td>
</tr>
<tr>
<td>SNR (1365)</td>
<td>35.1</td>
</tr>
</tbody>
</table>

Poor shot!

Filter of x-ray:  
Be (50µm) + Ti (12.5µm)
For the first time we have developed and used the Coded Aperture Imaging system to obtain time-integrated good-resolution bright images of the DD fusion source for single shots in a small plasma focus device operated in deuterium and deuterium-krypton gas admixtures.

The m=0 and m=1 instability structures responsible for the break-up of the pinch column are not evident in the fusion source images, indicating that acceleration and gyration of medium-energy deuterons (tens of keV) is distributed along the pinch column.

There is no apparent correlation between the fusion source images and soft x-ray images of the pinch for single PF shots.

There are no hot-spots (E >3keV) for pure deuterium contrary to what is observed very clearly in the D_{2}-Kr gas admixture. There is also no correlation between hot-spot formation in the D_{2}-Kr pinch and fusion source images for single PF shots.

For good shot, the fusion source takes place mostly above the pinch region, in contrary to the poor shot which is mostly inside or around the pinch.