The Initial Design of Bremsstrahlung X-ray Source for Radiation Effect Study

Tiancheng Zhong
KIP, Heidelberg University
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Master thesis finished in China academy of Engineering Physics (CAEP)
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◆ Problem analysis
◆ Diode design
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What it is used for?

Electronics used in radiation environment. High dose X-ray will damage them.

Character of simulated X-ray
- High dose
- Large area

system level for electronics
Ways to produce X-ray

Characteristic radiation

Bremsstrahlung

High energy in EM field

Energy: few keV to few 10keV

Energy: related to $E_e$

High quality X-ray

High energy electrons are needed.
High $E_e$: 1. Accelerator based

But, **High dose and large area** are the most important things!

**High quality X-ray is not necessary.**
High $E_e$: 2. Pulsed Power Machine (PPM) based

- **Marx generators**
- **Water Insolation Transmission line**
- **converter**
- **Magnetic Insolation Transmission Line (MITL)**

Voltage input
Few 10kV

High voltage output
Few MV to few 10 MV

R:~20m
center
High $E_e$ : 2. Pulsed Power Machine based

How to get high voltage

$U = nU_0$

few 10 channels of Marx generator output to one

Marx generators → Water Insolation Transmission line → converter → Magnetic Insolation Transmission Line (MITL) → High voltage output

In

Out

10MegaOhms

In

U= nU0

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T. Zhong, LAB X-ray source
Three ways to produce X-ray based on PPM

- Z-pinchar
- Rod-pinch diode
- LAB diode
Z-pinch: what is z-pinch

Force:
\[
\vec{F} = \vec{J} \times \vec{B} - \nabla p = -\left( \frac{d}{dr} \left( p + \frac{B_\theta^2}{2\mu_0} \right) + \frac{B_\theta^2}{\mu_0 r} \right)
\]

p: plasma pressure
B: magnetic caused by current

When: \( r \geq r_0 \); \( \vec{F} < 0 \)

Plasma will be force to the z axis: z-pinch.

Outward

Inward

T. Zhong, LAB X-ray source
Z-pincher: stability

\[ H = W + K \]

\( H \): total energy; \( W \): potential; \( K \): kinetic

Fluctuation: \( \delta H = \delta W + \delta K = 0 \)

\[ \delta W = -\frac{1}{2} \int dr \cdot \xi^* \cdot F(\xi) \]

Stable: \( \delta K \leq 0; \ \delta W \geq 0 \)

\[ \mathbf{B}_0 = (0, B_\theta(r), 0), \quad J_0 = (0, 0, J_z(r)) \]

Displacement: \( \xi = \xi(r) \exp[i(m\theta + kz)] \)

When \( m = 0 \),

\[ \delta W_\parallel = \int dr \cdot \gamma p \cdot |\nabla \cdot \xi_\perp|^2 > 0 \]

Instability only exist in \( r \) direction
Z-pinchn: x-ray source

Metal wires array

Metal wires $\rightarrow$ plasma $\rightarrow$ Z-pinchn

High density and temperature

Characteristic radiation (main)
Rod-pinchn diode

$I$ increasing:

$r_B \gg r_c$  Space charge limit

$r_B \sim r_c$  Magnetic limit

Difficult to high current!
Fill plasma in diode before load voltage:
• improve $I$ (faster from a to c; hit point will be focused on the peak)
Large-area-Bremsstrahlung (LAB) Diode

Normal X-ray diode

X-ray dose is not high enough. Mainly limited by current.

A: Anode  K: cathode
Large-area-Bremsstrahlung (LAB) Diode

**Motivation:** High dose of X-ray > few $10^3$R

Difference to normal diode:
- Much higher Voltage: ~MV
- Much larger current: ~MA
- Transmission line used to load voltage
- Much smaller A-K gap: ~few mm
- Bigger cathode and anode:
- No heating
- Thin target ~few 100um

Bremsstrahlung: X-ray (photon) for higher energy than z-pinch
Large-area-Bremsstrahlung (LAB) Diode

Field electron emission: $E > 100\text{MV/cm}$

Whisker on metal surface

Needed $E$ decreased to $\sim \text{MV/cm}$
Large-area-Bremsstrahlung (LAB) Diode

Field emission current

\[ j = ve \int n(\varepsilon_z) \cdot P(\varepsilon_z) \cdot d\varepsilon_z \]

- \( n(\varepsilon_z) \): electron density at energy state \( \varepsilon_z \)
- \( P(\varepsilon_z) \): escape possibility

Space-charge-limit current

\[ j = n_p e v_p \]

- \( n_p \): electron density in plasma
- \( v_p \): velocity of electrons in plasma
Why LAB diode?

**Z-pinch:**
- Characteristic radiation
- Energy of X-ray limited by energy state of material
- Difficult to reach high energy ($>100\text{keV}$)

**Rod-pinch diode:**
- Bremsstrahlung at peak of anode rod
- Difficult to get large area X-ray

LAB diode
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Requirement of X-ray field

High dose and large area (uniformed) X-ray field is needed!

High dose: >few $10^3$R

Large area: $r > 10$cm

level of test object

uniformity: 2:1

Dose: Highest $<$2*lowest

Uniformed: uniformed flat

Uniformed: uniformed volume
Main problem

Why difficult to get large and uniformed x-ray field?

\[ I > 300\text{kA}; F_B > F_e \]

Else: electron emission is not stable
Successful approaches

1. Outer control system

Problem: Complicated structure

outer $B_\theta$ → Uniformed electrons → Uniformed X-ray

Al: 1um+PET: 12um

Target (Tantalum)
Successful approaches

2. Multi-diode

**Saturn:** Coaxial ring diodes

**DECADE:** Rings diode array

Simple structure for each diode, but should be powered *respectively.*
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My idea

• Innovation: non-uniformed electrons to uniformed X-ray;

Hole on cathode & tapered part

Uniformed X-ray area

Character of electrons
• Inject large radius
• Suitable angle
• Distributed at range
Build platform to design

Voltage \( U_{in} = 2 \sin \left( \frac{2\pi t}{300} \right) \)

Time (ns) \n
0 20 40 60 80 100 120 140

Voltage (MV) \n
0 0.5 1.0 1.5 2.0

Distance to diode (cm) \n
960.0 1883 2805 3728 4650 5573 6495 7418 8340

Dose (R) \n
-27 -18 -9 0 9 18 27

Voltage X-ray output

Electronic simulation

MCNP simulation

Pt, 125

\( r = 27 \text{ cm} \)

\( z = 2 \sim 24 \text{ cm} \)

Interested field

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Verify the platform

Mercury

<table>
<thead>
<tr>
<th>Angle (@1m)</th>
<th>Exp.</th>
<th>Sim.</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>445rad</td>
<td>471rad (±6.20%)</td>
<td>5.84%</td>
</tr>
<tr>
<td>20°</td>
<td>378rad</td>
<td>413rad (±2.30%)</td>
<td>9.26%</td>
</tr>
</tbody>
</table>
Two parts of the design

Structure design (PIC)
- Impedance
- Electrons on anode

Target design (MCNP)
- Thickness vs. output X-ray
- Escaped electrons
Structure design

✓ Structure design (PIC):
  1. Propose **initial** structure (exp. equation);
  2. Study the parameters **effect** on the electrons;
  3. **Optimize** it to get better result;
  4. 7 middle structures to the **final**.

Data collection

- Structure design (PIC):
  1. Propose **initial** structure (exp. equation);
  2. Study the parameters **effect** on the electrons;
  3. **Optimize** it to get better result;
  4. 7 middle structures to the **final**.

**Electron distribution**

**Electron angle distribution**

Particle-In-Cell Software simulation

Voltage

Voltage

Voltage

Final structure
Target design

Target design (MC Method):
1. Efficiency (converter: Tantalum)
2. Electron absorption: graphite

X-ray dose vs. thickness of Tantalum

Escaped electrons vs. graphite

Target: Radius=19 cm Ta(200um)+C(5mm)
**results**

✓ **X-ray output:**

![X-ray distribution](image)

**Results better than requirement:**

**Area:** Radius=22.1 cm; Dose=6457 R

**Volume:** Radius=12 cm; Δz=14 cm; Dose=5652 R
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Summary

• Investigated the main ways to produce intensive X-ray.
• Build platform and summarized approach to design LAB diode.
• Propose a structure of LAB diode based on the pulsed power source in CAEP.
Thanks for your attention!