Design of a 2-D X-Ray Imaging System for ECCD/ECH Experiments on DIII-D

By
The Hard X-Ray Camera
- What can it do for DIII-D?

- ECCD physics
  HXC produces 2D intensity map $I(x,y,t)$,
  CQL3D code calculates $f_e(v,r,t)$ & $I(x,y,t)$,
  - adjust D to fit data.

- Electron transport
  Energetic electrons from ECH used as test particles
  traced by the HXC, get $D(E)$.

- MHD studies
  Locate fast electrons during stabilization of NTM.
  Tangential view may reveal high-k MHD near $q=2$. 
Previous results from tangential x-ray imaging in LHCD exp’ts on PBX-M

by Schwick von Goeler et al.
History of Tangential X-ray Imaging  # 2.

PBX-M Hard X-ray Camera

von Goeler, Kaita, Bernabei, Jones.

- Diagnose suprathermal electrons during LHCD.
- Large 23 cm dia. X-ray imaging tube → sufficient intensity.

Conceptual Design Review
GA - San Diego  9/27/00
S. von Goeler
Results from Tangential X-ray Imaging  #2.
Foil Techniques - Hot Electron Temperature.
S.von Goeler and S. Jones on PBX-M.

- Foil techniques are used to determine the energy of suprathermal electrons.
- PBX-M profiles up-down symmmetric.
- Half-foils allow Tphoton-measurement during the same shot.
- Forward paralell temperature (T∥f) from simulation of Tphoton.

Result: T∥f = 100 keV

- Energy of suprathermal electrons measured.
- Simulations show that Tphoton depends on T∥f.

Conceptual Design Review
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Results from Tangential X-ray Imaging #1.
Hollow Hard X-ray Profiles during LHCD.
S. von Goeler and S. Jones on PBX-M.

- Hollow profiles of suprathermal electrons observed during LHCD.
- Excellent agreement with simulations.
Results from Tangential X-ray Imaging  # 4.
Transport of Hot Electrons.
S. Jones and S. von Goeler on PBX-M.

EXPERIMENT
INVERTED X-RAY INTENSITY

DIFFUSION COMPUTATION
RAX - MOREAU MODEL

LH Modulation Experiments

- Hollow profiles imply (Giruzzi code) $D_{HE} < 2 \text{ m}^2/\text{sec}$
- LH modulation experiments show $D > 0.2 \ldots 0.5 \text{ m}^2/\text{sec}$
Results from Tangential X-ray Imaging  # 5.

**MHD Fluctuations - Loss of Hot Electrons.**

S. von Goeler and S. Jones on PBX-M.

- HotSpots (Bremsstrahlung from limiters + walls) seen during MHD.
- MHD causes Loss of Hot Electrons (long before disruption!).

- Wall Loss of suprathermal electrons can be measured.
- Technique was not developed on PBX-M.

Conceptual Design Review
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S. von Goeler
History of Tangential X-ray Imaging  # 3.

Fast Soft X-ray Camera on TEXTOR

Fuchs, von Goeler, Toi, Ohdachi.

- Purpose: 2D imaging of MHD instabilities.
- Fast phosphors (P47). Fast CCD (PSI 1 MHz framing camera),
- Scintillator in vacuum.

Conceptual Design Review
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S. von Goeler
From LHCD to ECCD

- Tangential x-ray imaging technique was successfully used by von Goeler et al. to study LHCD in PBX-M.

- Similar technique can be used for ECCD experiments in DIII-D.
**ECCD Theory**


**Karney & Fisch (NF, 1981)**

2D Fokker-Planck calculation

Trapped particle effect
- (Ohkawa)
- observed in W7-AS, TCV

CQL3D code (3D, bounce-averaged FP code)
$D_e = 0$, cross-field diffusion not fully tested.
Why do we need tangential view?

Bremstrahlung Radiation

\[ N(k, \theta) = \frac{A_1 A_2}{4 \pi b^2} \int \frac{dt}{\Delta t} \int \frac{dk'}{\Delta k} G(k, k') \]

\[ dN(k', \theta') = \alpha \int d^3 p_0 f(p_0, \theta_0) \frac{d\sigma(k', \theta_0, p_0, Z_i)}{dk' d\theta_0} \nu_0 \]

\[ X \int d^2 W(\theta, \theta', \xi) n_e(\xi) n_i(\xi) \int dm_c = \frac{m^3}{E_0} \int_{k'}^{+1} \frac{\pi}{0} \sin(\theta_0) d\theta_0 \left( Z_{\text{eff}} \frac{d\sigma_{ei}}{dk' d\theta_0} + \frac{d\sigma_{ee}}{dk' d\theta_0} \right) + \sum_{i} \left( \frac{n_i}{n_e} \right) \int d\phi f(p_0, \theta_0, \nu) \]

\[ k' = \frac{h \nu}{mc^2} \]

Bremstrahlung Radiation Pattern

(a) Electron/proton  (b) Electron/electron

- forward peaking (co-viewing sees more x-ray)
- extraction of \( f_e \) not straight forward,
- conventional tomography needs modification
- tightly constrained by results from TORAY & CQL3D
Why 2D Imaging?

1. Much more spatial information:
   
   5000 pixels vs 30 detectors.

2. ECCD/ECH produce energetic electrons with poloidally asymmetric distribution.
   - 1D imaging at $B_{\text{min}}$ not enough.
**ECCD Experiments**

Loop voltage measurement:
- TFR, DITE, TCA, DIII-D, TCV ...
- W7-AS, CLEO,
- no direct $j(r)$ data

MSE measurements for $j(r)$ & $q(r)$:
- DIII-D, JT-60U
- no velocity space information

For better understanding of ECCD physics, better extrapolation to future experiments, we need to study the velocity space dynamics,
- measurement of $f_e(v,r,t)$ - HXC

Russian PHA system on DIII-D:
- single channel, no spatial profile info’.

Array of CdTe detectors:
- TCV tokamak (Laussane), 14 chords,
- 8 energy channels/chord, $\Delta r \sim 2\text{cm}$, $\Delta t \sim 5\text{ms}$

**DIII-D HXC - 2D X-Ray Imaging System**
HXC produces 2D intensity map  \( I(x,y,t) \).

CQL3D code calculates \( f_e(v,r,t) \) & \( I(x,y,t) \).

Adjust \( D_e \) to get best fit
- provides estimate on \( D_e \).

Simple analytic functions will be much faster – needs experience.

LHCD was analyzed by von Goeler:
\[
f_e = f_e \left( T_\perp, T_{\|f}, T_{\|b} \right) \text{ works well.}
\]

\( f_e \) will take a different form for ECCD.
Other Possible Experiments

1. Co/counter asymmetry
   asymmetric resistivity becomes
   asymmetric x-ray emissivity

2. Image of trapped electrons.

3. Estimates on $D_e(E)$ from:
   a. $f_e(v,r,t)$
   b. energetic electrons moving
      across B

4. Effects of fluctuations on $D_e(E)$
   in plasmas with MHD, shear flow,
   impurity injection etc.

5. New MHD activities.
Asymmetric emissivity

\[ P_{ECH} \]

\[ \text{Co-ECCD} \quad \text{Ctr-ECCD} \]

Brightness

\[ t \]

Trapped electron image

\[ ECH \]

\[ \text{Brightness} \quad \Rightarrow \quad V_e^* \]
Magnetic stochasticity aggravated by MHD?

sawteeth:

$P_{\text{ech}}$
(core/off-axis heating)

Thin foil selects photon energy, spread of photon intensity gives $D(E)$.

Find $D(E)$ with or without $m=1$, before/during sawtooth crash.
Engineering design for the tangential x-ray camera
Selection of DIII-D Port Location

Tangential Co-View Of Plasma Current

Plan View of DIII-D Ports, Looking Down from Above Machine

75 R0
Initial Proposal

90 R0
"Best" Location

B.E.S.
T.C.T.S.

BLOCKED BY THOMSON TOWER AND STRUTS
Hard X-Ray Camera Design System Overview

NEAR MACHINE COMPONENTS
- Vacuum Interface Cone and Beryllium Window
- Pin Hole Camera w/ Variable Lead Apertures and Foils
- Fiber Optic Face Plate and Scintillator
- X-Ray and Neutron Shielding

In-Vessel Graphite Neutron Shielding

DIII-D Structural Upgrades
Near Machine Shielding
Total Dead Weight: 2,375 lbs

“Remote” Shielding
Total Dead Weight: 7,100 lbs

“REMOTE” COMPONENTS
- Coherent Fiber Optic Bundle
- Image Intensification and Demagnification Tube
- High Speed CCD
- X-Ray, Neutron and Magnetic Field Shielding
- Data Acquisition and Power Supply Equipment (Not Shown)
“Compact” TEXTOR Design System Components Overview

100 mm Fiber Optic Bundle

Vacuum Interface Cone
Beryllium Window

12" CF Flange

Pin-Hole Camera
Variable Lead Aperture and Foils
Scintillator Fiber Optic Face Plate

Image Intensifier Tube
High Speed CCD
Iron Box Shield and Mount

3D View of System Components, Shielding Removed

DIII-D HARD X-RAY CAMERA
Pin Hole Camera Design

Bellows

Scintillator
Fiber Optic Face Plate

Beryllium Window

Lead Shielding

Tungsten X-Ray Shielding
Flange

Vacuum Canister
DIII-D HARD X-RAY CAMERA

Lead Aperture Strip
Energy Cut-Off Foil Strip

Energy Comparison Foil Strips
**Bellows**
- Change of Face Plate
- Misalignments

**Design Criterion**
- Couple Scintillator to Fiber Optic Bundle
- Interchangeable Face Plates
- Vacuum Interface

**Fiber Optic Face Plate**
- 130 mm Dia (100 mm useful) x 6.35 mm thk
- NA 1.0, 15-18 Micron Fiber Size
- Vacuum Safe to 2E-10

**Preferred Phosphor, P47:**
Fast Decay (<1 μsec)
- Good Efficiency (tested in Juelich)
- Blue Phosphor (match photocathode)
- Disadvantage: Strong K-edge at 17 keV

**Thickness**
- 400 μm
  - Registers X-Rays below 50 keV
  - Sensitive to neutrons
- 20 μm
  - Registers photons below 10 keV (thermal x-rays)
  - 20x less sensitive to neutrons
X-Ray Optics Layout

- .005" Beryllium Window
- Lead Aperture Strip
- Energy Cut-Off Foils
- Energy Comparison Foil Strips
- Scintillator Fiber Optic Face Plate

Pin-Hole Camera Design

DIII-D HARD X-RAY CAMERA

REF 9/27/00
Stainless Steel Aperture and Foil Vacuum Canister

Flexible Metal Bellows
Energy Comparison Foil Shaft
Lead Aperture and Energy Cut-Off Foil Shaft
Fiber Optic Plate Interface Flange

Vacuum Canister Weldment

PPPL
DIII-D HARD X-RAY CAMERA

Pin-Hole Camera Design

REF 9/27/00
Lead Aperture and Energy Cut-Off Foils

Outline of Linear Actuator
Lead Aperture Strip
Cut-Off Foil Strip
Vacuum Canister Walls

PLAN VIEW

1 mm
2 mm
4 mm

BLOCK

Pin-Hole Camera Design
Blank
Possible other Foil
Be-Al
Al
Al-Cu

DIII-D HARD X-RAY CAMERA

PPPL
Princeton Plasma Physics Laboratory

REF 9/27/00
## Cut-Off Foil Range

<table>
<thead>
<tr>
<th>Measurement Objective</th>
<th>Plasma Electron Temperature</th>
<th>X-Ray Energy Cut-Off</th>
<th>Foil Material (+.005” Be Window)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>Full Range</td>
<td>2.4 keV</td>
<td>Blank</td>
</tr>
<tr>
<td>Suprathermal</td>
<td>1 keV</td>
<td>6 keV</td>
<td>.001” Al</td>
</tr>
<tr>
<td>Suprathermal</td>
<td>2 keV</td>
<td>12 keV</td>
<td>.010” Al</td>
</tr>
<tr>
<td>Suprathermal</td>
<td>4 keV</td>
<td>24 keV</td>
<td>.010” Al + .002” Cu</td>
</tr>
</tbody>
</table>

![Graph showing the change in dn/dE with energy (E) and electron density](image)
Energy Comparison Foil Strips

.1 mm Thick Aluminum Foil $\Rightarrow$ 20 keV Cut-Off
.5 mm Thick Copper Foil $\Rightarrow$ 50 keV Cut-Off

Interpolate X-Ray Signal

Field of View

$\phi 2.7$ [$\phi 68.6$]

Interpolation Between Signal Peaks
**Linear Actuators**

- Capable of Multiple Positions with Fine Resolution and Repeatability
- Method for sensing position of each aperture and foil
- Foil Strip Actuation Only Needs to be On/Off

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**Pin Hole Camera Assembly**

- Lead X-Ray Shielding
- Vacuum Canister
- Scintillator Fiber Optic Face Plate

**DIII-D HARD X-RAY CAMERA**

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**Pin-Hole Camera Design**

- The Vacuum Canister Will Be Encased In A Block of Lead and Have a Forward Lead Disc.
Neutron noise is the major difficulty

1. H-plasma & H-beams: undesirable because it takes days to clean up carbon tiles.
2. Thick neutron shielding: limited by available space.

The present design should have no problem for MHD studies – plenty of photons at $E \sim T_e$.

At high beam power, neutron noise will be a problem for $E \sim 50$ keV. Expect 2D imaging system to work at $S_n < 5 \times 10^{14}$ n/s.

1-D CdZnTe array is the only hope to operate at $S_n > 10^{15}$ n/s.
Conclusion

- The Hard X-Ray Camera is a valuable addition to DIII-D.
- It fits well with the ECCD program (unique).
- It opens up new frontiers
  - electron transport - pertinent to the Advanced Tokamak program.