X Ray Detection and Analysis for the PFRC

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Objectives

• Background – Purpose of Detecting X Rays
• Detect X Rays
• Calibrate X Ray Detectors
• Analysis
Background – Purpose of Detecting X Rays

• X ray distribution indicates the temperature of the plasma and can even give more detail, the full distribution function
• Do the electrons follow a Maxwellian distribution or not?
• Plotting count rate versus time determines if x ray production is constant or varying with time
• Energy spectrum of x rays is determined from raw data collected from detectors. This information is crucial for determination of various properties of the plasma
Detecting X Rays

• Amptek XR – 100SDD Silicon Drift Detector (SDD)
  • Allows for a higher count rate
• Amptek XR – 100CR Si-PIN Detector
Detecting X Rays (cont.)
Calibration of X Ray Detector

• In order to calibrate detector, the scale (x-axis), sensitivity (y-axis) and resolution for each detector must to be determined over all energy levels.
Calibration of X Ray Detector (cont.)

Thanks Sam!
Calibration of X Ray Detector – Sensitivity

- The sensitivity of the detectors, up to this point, has been trusted to be that of the written values from manufacturer. Charles is currently working on solving an issue that has been found.

Work completed by Charles!
Calibration of X Ray Detector - Resolution

- Resolution of detectors can be determined by taking into account the background noise.

Work completed by Charles Swanson and Alex Glasser!
Calibration of X Ray Detector – Scale

Work completed by Charles Swanson, Alex Glasser and Peter Jandovitz!
Count Rate vs. Time

CC 1245pm.mca
Analysis

• Analysis of data collected would allow for determination of FRC bulk properties
  • Raw Data → X Ray Temperature & Count Rate
  • Count Rate → Electron Density
  • Electron Density & Temperature → Plasma Pressure
  • Plasma Pressure → $\beta$
  • Plasma Pressure & Total Volume → Stored Energy
  • Stored Energy & Power → Confinement Time
Analysis – X Ray Temperature

• Plot corrected counts vs. spectrum energy on a logarithmic-linear plot
• Linear regression: $y = mx + b$.
• Temperature is the negative inverse of log slope
• $T = -\frac{1}{m}$
• Comparison of analysis of ‘smooth’ data with data containing many zeros
Analysis – X Ray Temperature (cont.)

‘Smooth’ data
Temp. = 150

Data with plenty of zeros
Temp. = 185
Temp. = 73
Analysis – X Ray Temperature (cont.)

• Comparison of the temperatures during Helicon only run and RMF run with same parameters of machine during each run
Analysis – X Ray Temperature (cont.)

RMF run

Temp. = 201 eV

Helicon only run

Temp. = 145 eV
Analysis – Count Rate

- Count Rate = \frac{\text{corrected counts}}{\text{time collected}}

Count Rate \approx 2 \frac{\text{counts}}{\text{sec}}

Count Rate \approx 58 \frac{\text{counts}}{\text{sec}}
Analysis – Electron Density

• Two ways:
  • Complicated-ish math or simplistic math
  • Interferometer measurements
Analysis – Electron Density

• Two ways:
  • *Complicated-ish math* or simplistic math
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Analysis – Electron Density

• Bremsstrahlung Reaction Rate

• From *Principles of Plasma Diagnostics* by I. H. Hutchinson, Eq’ns 5.3.6 & 5.3.11

\[
\left\langle \sigma \nu \right\rangle_{T} = \frac{16\alpha c^{2}\pi Z^{2}r_{e}^{2}}{3\text{sqrt}(3)} \cdot \frac{1}{E_{\text{Xray}}} \int dE_{e} \cdot \frac{G(E_{\text{Xray}}, E_{e})}{\nu_{e}} \cdot f_{T}(E_{e}) =
\]

\[
5.0 \times 10^{-6} \text{ cm}^{4} / \text{s}^{2} \cdot \frac{1}{E_{\text{Xray}}} \int dE_{e} \cdot \frac{G(E_{\text{Xray}}, E_{e})}{\nu_{e}} \cdot f_{T}(E_{e})
\]

• Assuming constant Gaunt factor (~2x error)

\[
\left\langle \sigma \nu \right\rangle_{T} = \left( 9.6 \times 10^{-14} \text{ cm}^{3} \cdot \text{eV}^{2} / \text{s} \right) \cdot e^{\frac{E_{\text{Xray}}}{T}} \frac{1}{\sqrt{TE_{\text{Xray}}}}
\]

Thanks Charles!
Analysis – Electron Density

• **CC Detector Effective Emission Volume**
  
  - Actual volume, as if seen from a point sourch through the slit mask:
    
    \[ V_{\text{tot}} = A_3 L = A_2 \left( \frac{r_2^2}{r_1^2} \right) \cdot L \]

  - Solid angle reduction factor
    
    \[ \frac{\Omega}{4\pi} = \frac{A_1}{4\pi r_2^2} \]

  - Total effective volume
    
    \[ V_{\text{eff}} = \frac{V_{\text{tot}} \Omega}{4\pi} = \frac{A_1 A_2 L}{4\pi r_1^2} = 5.8 \times 10^{-4} \text{ cm}^3 \]

  Thanks Charles!
Analysis – Electron Density

• Bremsstrahlung Rate Density
• Rate density $\eta$ from reaction rate
  • $\partial_{Exr_ay}\eta = n_e n_\sigma \left( \partial_{Exr_ay} \sigma \nu \right)$
• Rate density from measure count rate
  • $\partial_{Exr_ay} CR = \partial_{Exr_ay} \eta V_{eff}$

Thanks Charles!
Example: July 19, 2016 at 12:45pm (filename indicates 12:46am...), spectrum measured

- Rate density measured: \( \frac{\partial E_{\text{X-ray}} \eta(800\text{eV})}{\partial x} = 1.6 \times 10^3 \frac{1}{\text{cm}^3\cdot\text{eV}\cdot\text{s}} \)

- Reaction rate calculated:
  \[
  \left( \frac{\partial E_{\text{X-ray}} \sigma v}{\partial x} \right)_{T=150\text{eV}} (800\text{eV}) = 4.7 \times 10^{-20} \frac{\text{cm}^3}{\text{eV}\cdot\text{s}}
  \]

- Scattering density measured: \( n_\sigma = P_{cc} \cdot 3 \times 10^{13} \frac{1}{\text{cm}^3\cdot\text{mTorr}} = 1.5 \times 10^{13} \frac{1}{\text{cm}^3} \)

- Electron density inferred: \( n_e = 3.4 \times 10^9 \frac{1}{\text{cm}^3} \)
Voltage is proportional to the line average electron density!

\[ 40 \text{ mV} \cdot 7.9 \times 10^9/(\text{cc} \cdot \text{mV}) = 2.8 \times 10^{11}/\text{cc} \]
Analysis – Electron Density (cont.)

- From interferometer: \( n_e = 2.8 \times 10^{11} \approx 1 \times 10^{11} \)
- From analysis: \( n_e = 3.4 \times 10^9 \approx 1 \times 10^9 \) too low!
Analysis – $\beta$

• For FRC: $\beta \cong 0.5 - 1$ (tokomak: $\beta \cong 0.05$)

• $\beta = \frac{\text{plasma pressure} = n_e \cdot k_b \cdot T}{\text{magnetic field pressure} = \frac{B^2}{8\pi}} = 1$

• $n_e \cdot k_b \cdot T_{xray} = \frac{B^2}{8\pi} \rightarrow nT = \frac{B^2}{4\mu_0}$

• B – field is measured during experiments. Analysis leads to determining the values of $n_e$ and $T_{xray}$, values that are required in order to classify an FRC.

• If ions were more energetic their temperature would have to be taken into account
Analysis - $\beta$ (cont.)

• $nT = \frac{B^2}{4\mu_0}$

• In general $B: 50 - 100 G$, $T \approx 150 - 300$ eV

$$1 = 4 \times 10^{-11} \frac{nT}{B^2} = 4 \times 10^{-11} \cdot \frac{10^9}{cc} \cdot \frac{2 \times 10^2 eV}{10^4 G} = 8 \times 10^{-4}$$
Maxwellian Distribution?

• Maybe?
• Previous machine (PFRC-1)
• Single particle simulation
• Electron collision rate
  • \( \nu_e = 2.91 \times 10^{-6} n_e \ln \Lambda T_e^{3/2} \) sec\(^{-1} \)
• At 200 eV, \( \tau_{ee} \approx 2 \) sec
• Other ways to reach Maxwellian
  • RMF only runs for 5 ms with water coolant or 250 ms with LN\(_2\)!

S.A. Cohen; Berlinger, B.; Brunkhorst, Christopher; Glasser, A.H., (2007), Formation of Collisionless High-\( \beta \) Plasmas by Odd-Parity Rotating Magnetic Fields, Physical Review Letters

FIG. 4. Measured x-ray spectrum: \( mP_{rf} = 9.6 \) kW; \( m n_e = 1.6 \times 10^{12} \) cm\(^{-3} \); \( m \Phi_{DL} = 5 \) \( \mu \)Vs; \( f_s = 14.000 \) MHz (no FM); \( P_{H_2} = 1.09 \) mTorr; \( B_0 = 56 \) G; \( B_M = 2900 \) G, where subscript \( m \) means maximum value. The spectrum shape is fit by \( T_e = 150 \) eV. Inset: electron energy distribution calculated with the RMF code.
What do we expect?
RMF code

Possible causes:
  a) Pulse pile-up
  b) Scattering off (mirror) field
  c) Plasma instabilities
X-ray emission during the RMF pulse steadily and significantly increases as the power for the seed plasma antenna increases. The most significant change in the seed plasma as the source power increases is an increase in the number of very energetic secondary electrons in the bulk plasma, seen here as an increase in x-ray emission without RMF. Perhaps this means that these energetic seed electrons significantly improve the coupling of the RMF to the plasma, but further experimental and theoretical investigation is required.
What Have We Determined Thus Far?

• We are not looking at the bulk distribution
• Questions
  • Maybe Heating minority population?
  • Not producing an FRC?
Not Producing an FRC?
Future Work

• Why does the RMF amplify the count rate?
• What is the effective temp of the bulk?
• Put on the new detector → 400 eV
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