X Ray Detection and Analysis for the PFRC

Alexandra Bosh

7/28/2016

Objectives

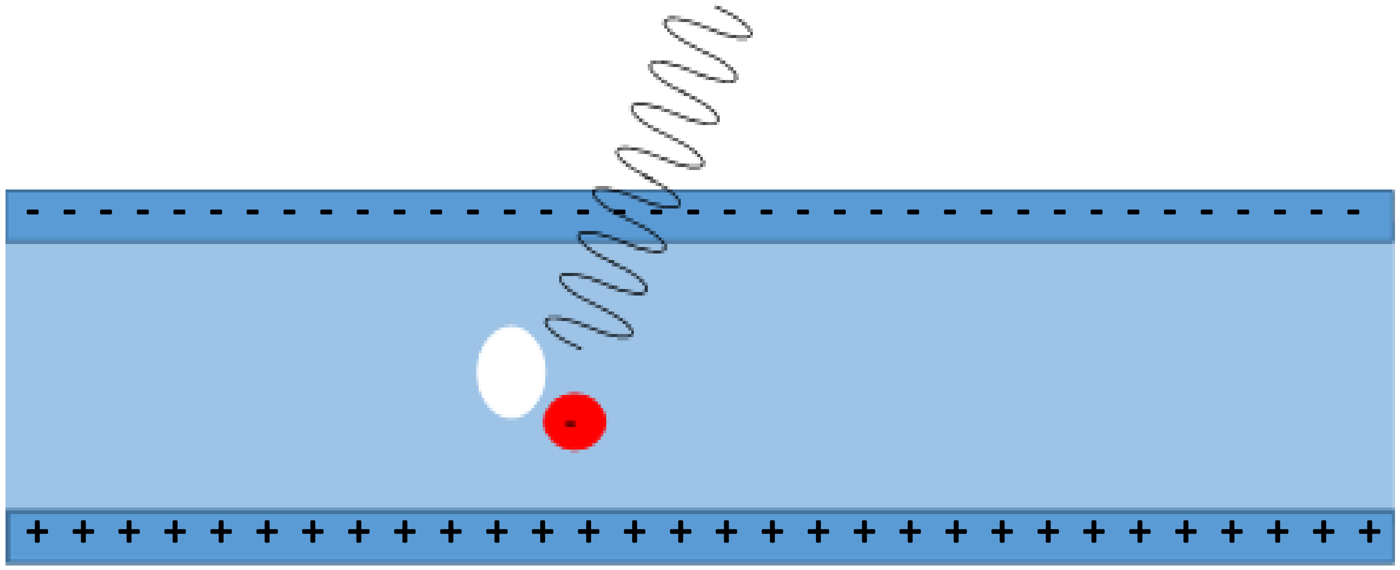
- Background – Purpose of Detecting X Rays
- Detect X Rays
- Calibrate X Ray Detectors
- Analysis

Background – Purpose of Detecting X Rays

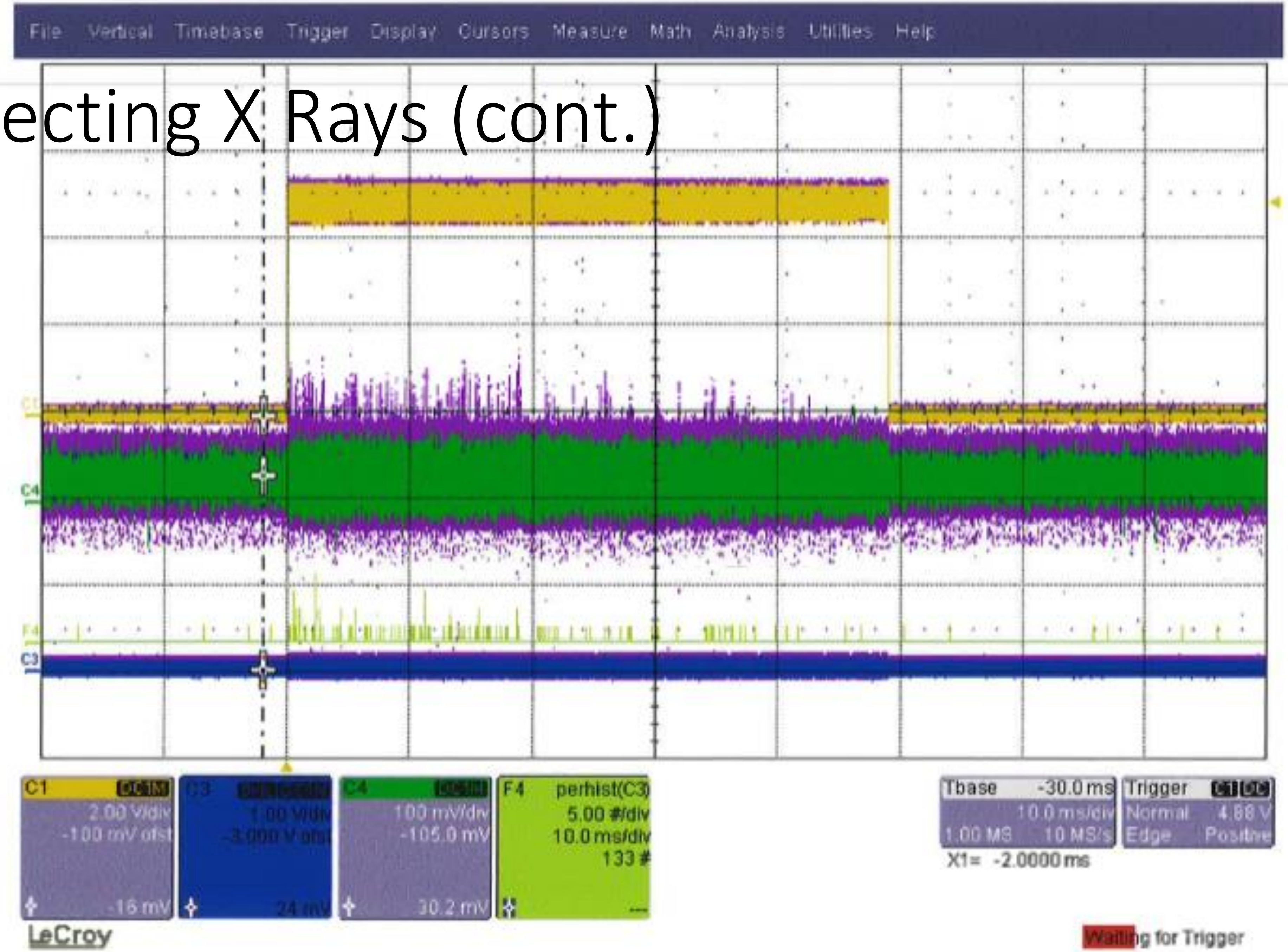
- X ray distribution indicates the temperature of the plasma and can even give more detail, the full distribution function
- Do the electrons follow a Maxwellian distribution or not?
- Plotting count rate versus time determines if x ray production is constant or varying with time
- Energy spectrum of 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

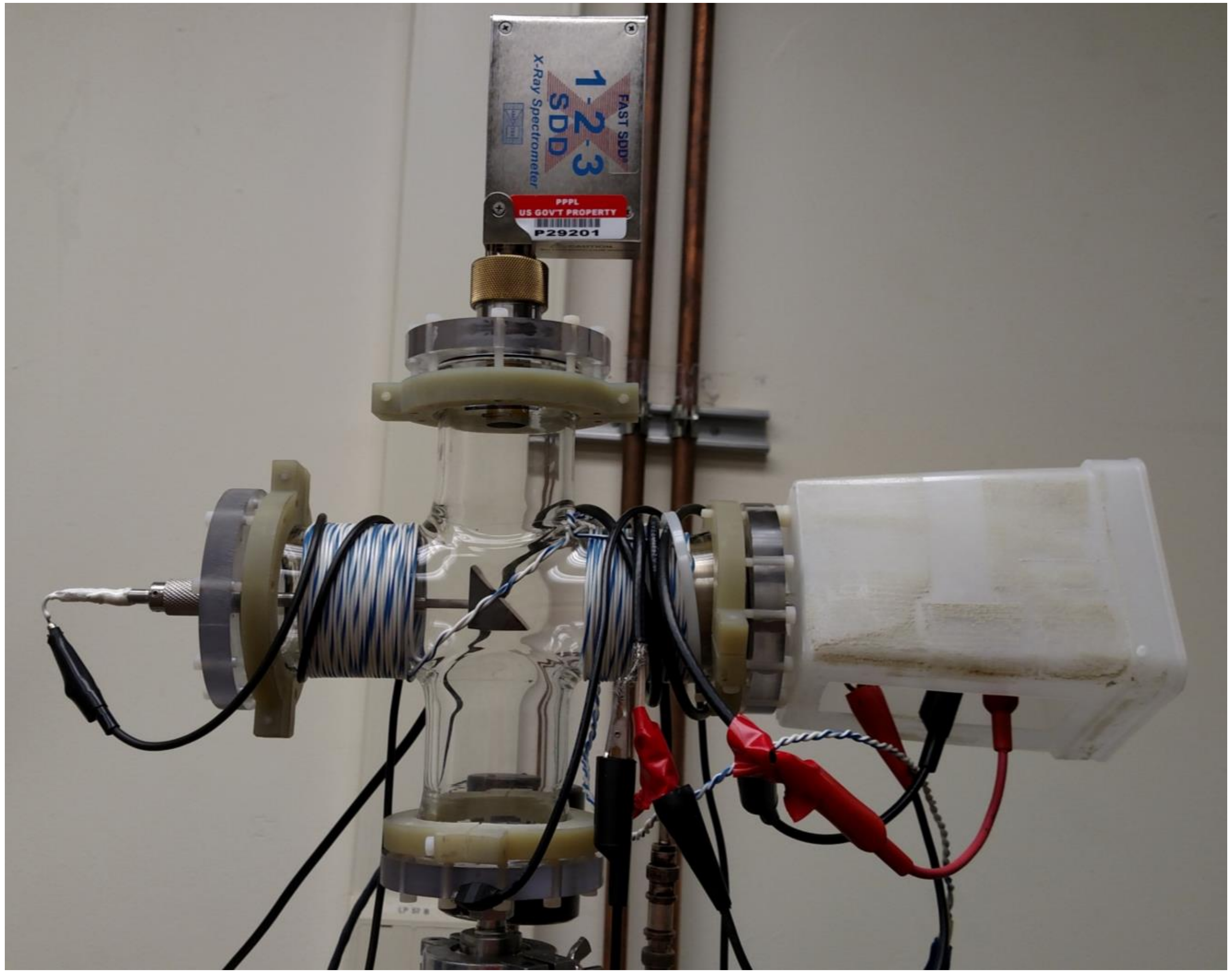


Detecting X Rays (cont.)

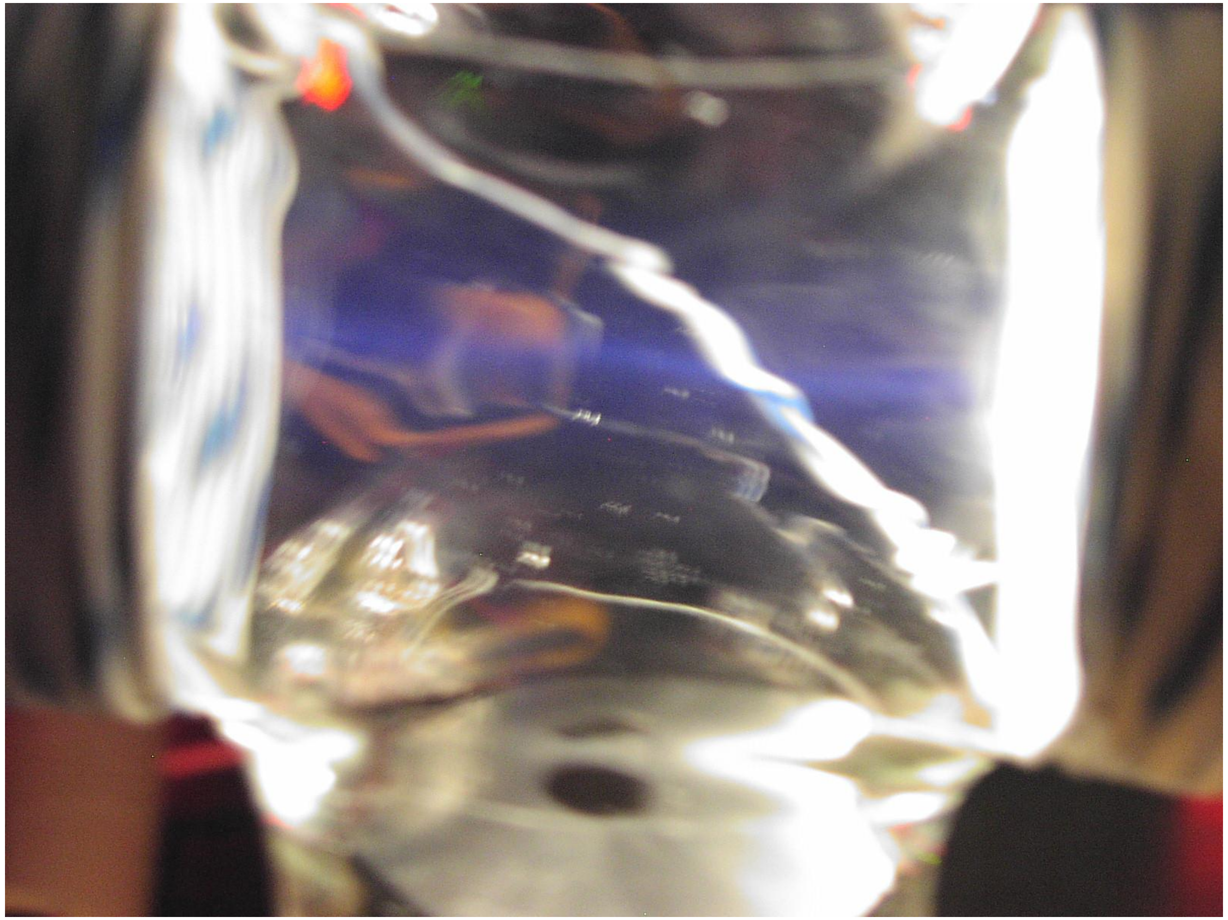


Calibration of X Ray Detector

- 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.



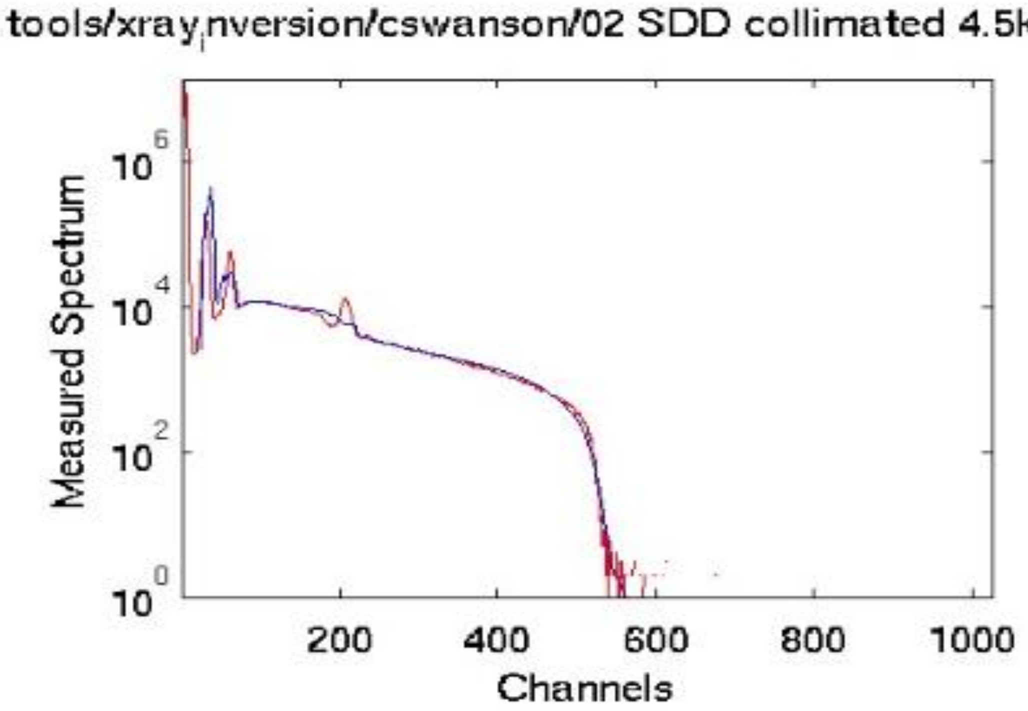
Calibration of X Ray Detector (cont.)

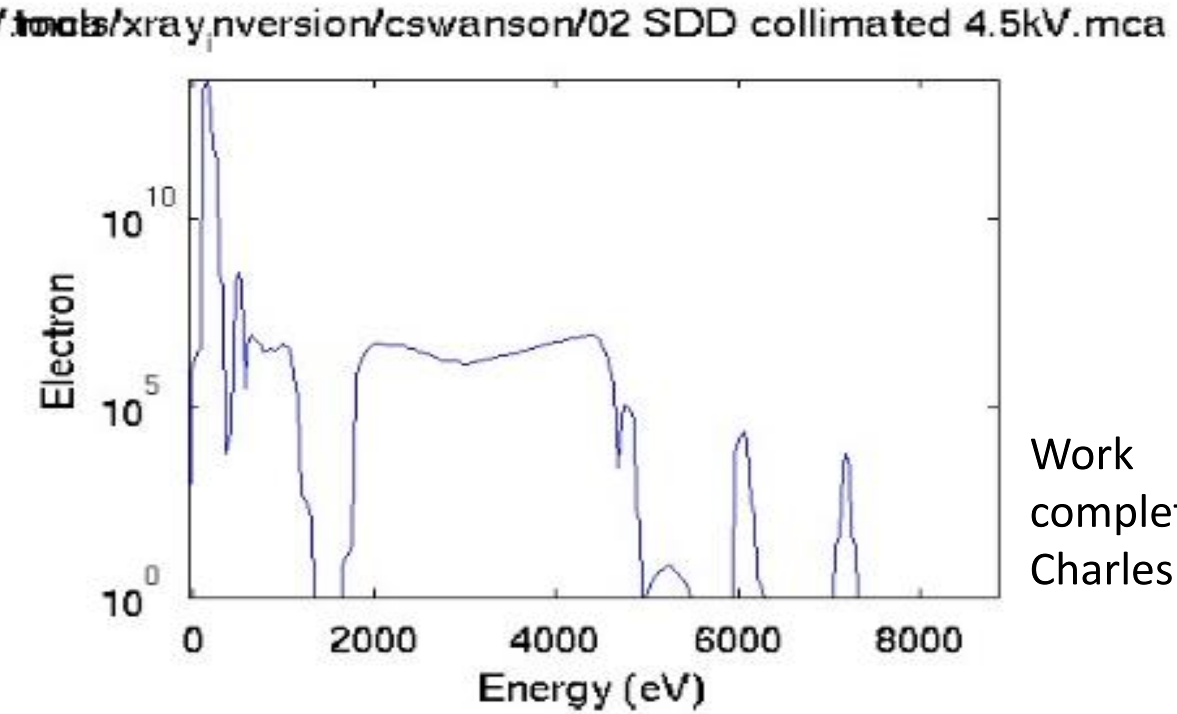


Thanks Sam!

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.

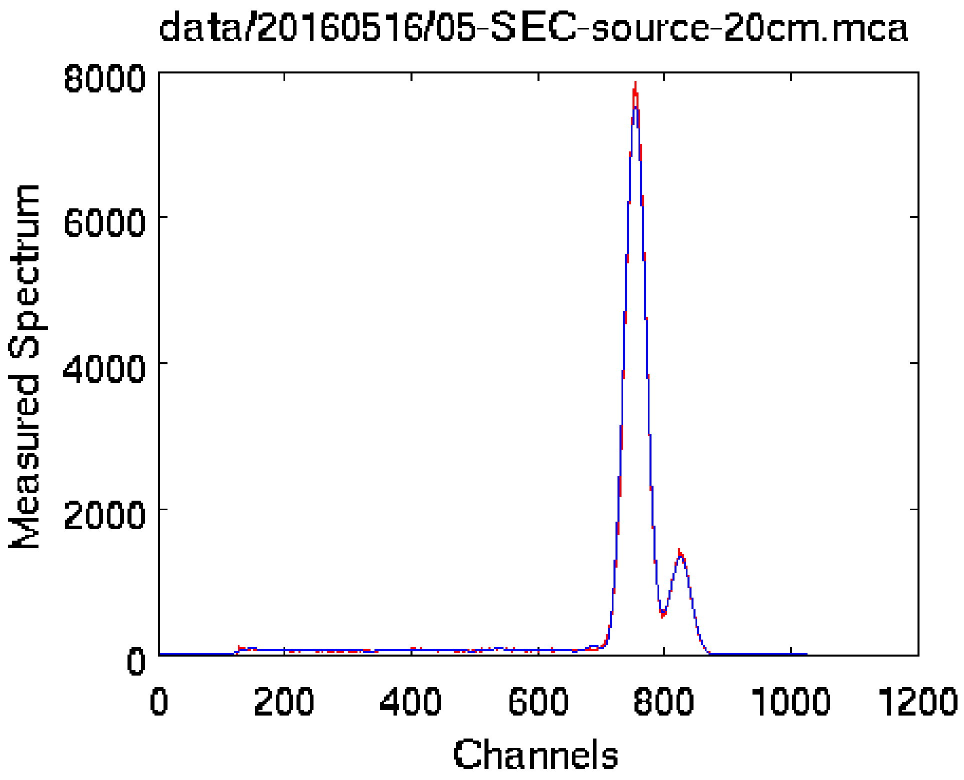


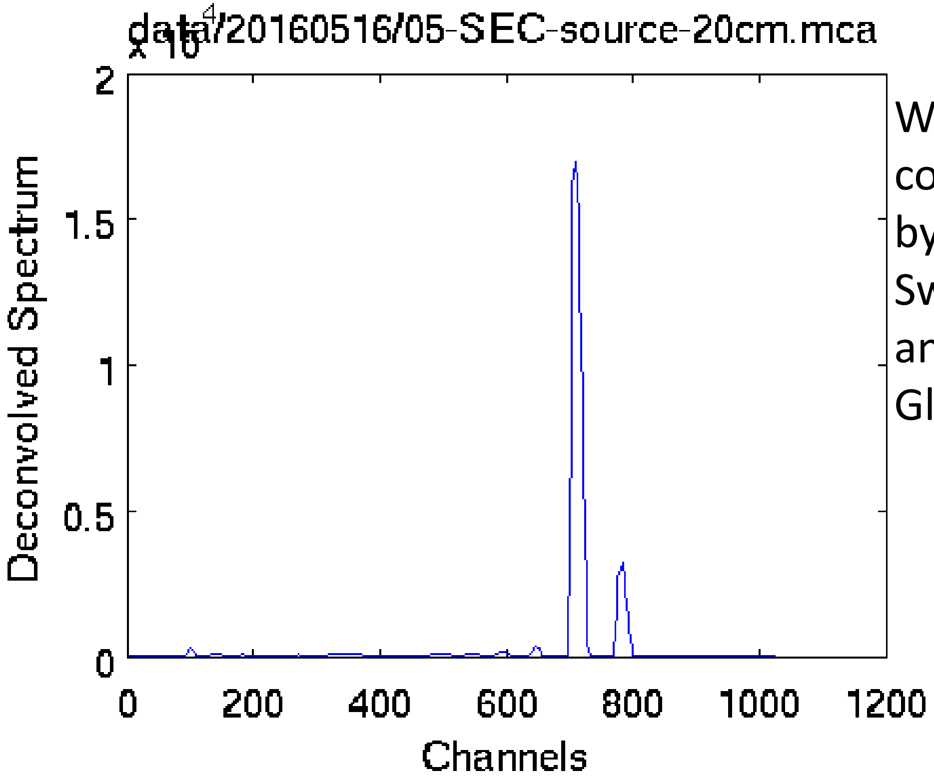


Work completed by Charles!

Calibration of X Ray Detector - Resolution

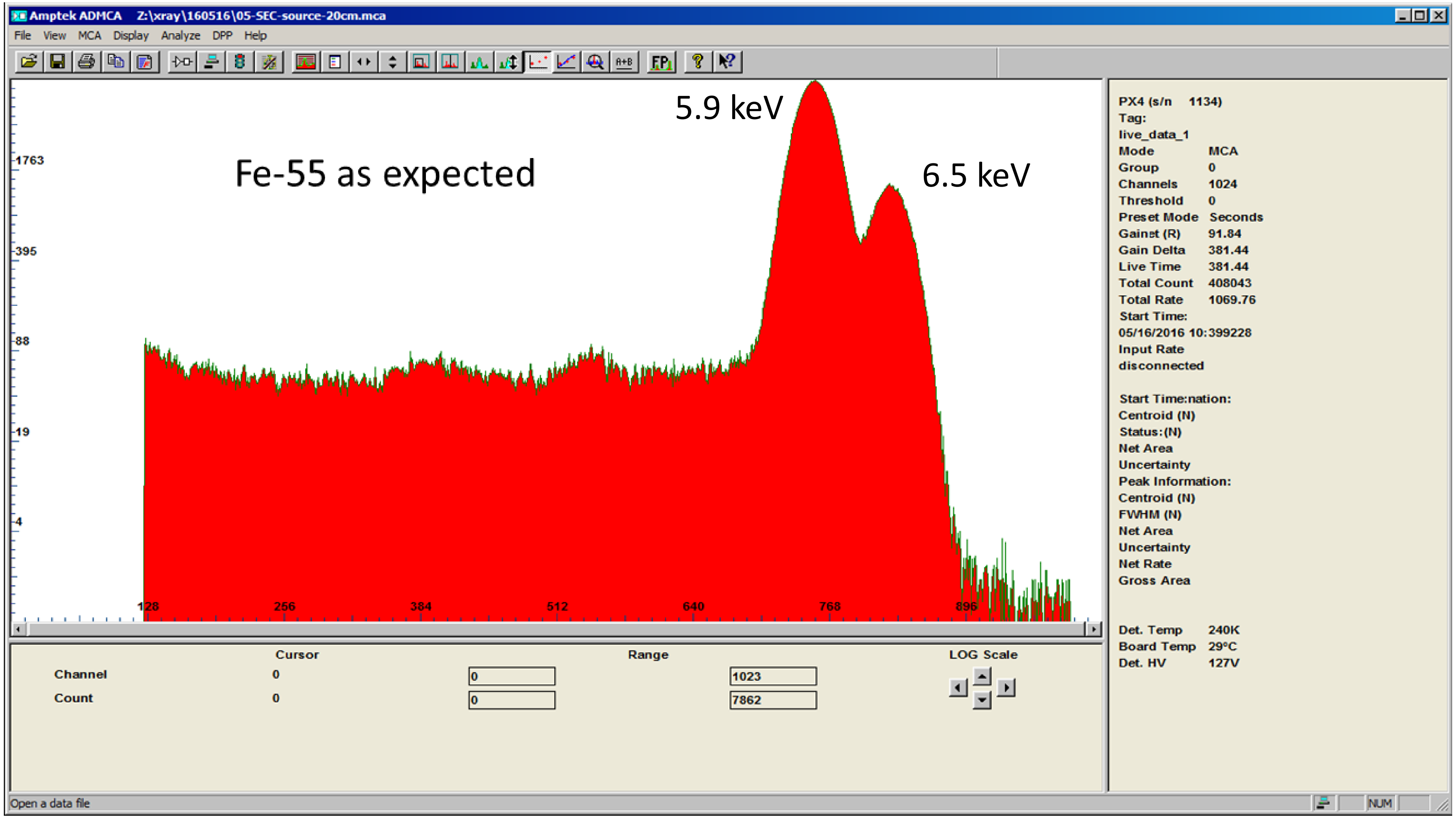
- Resolution of detectors can be determined by taking into account the background noise





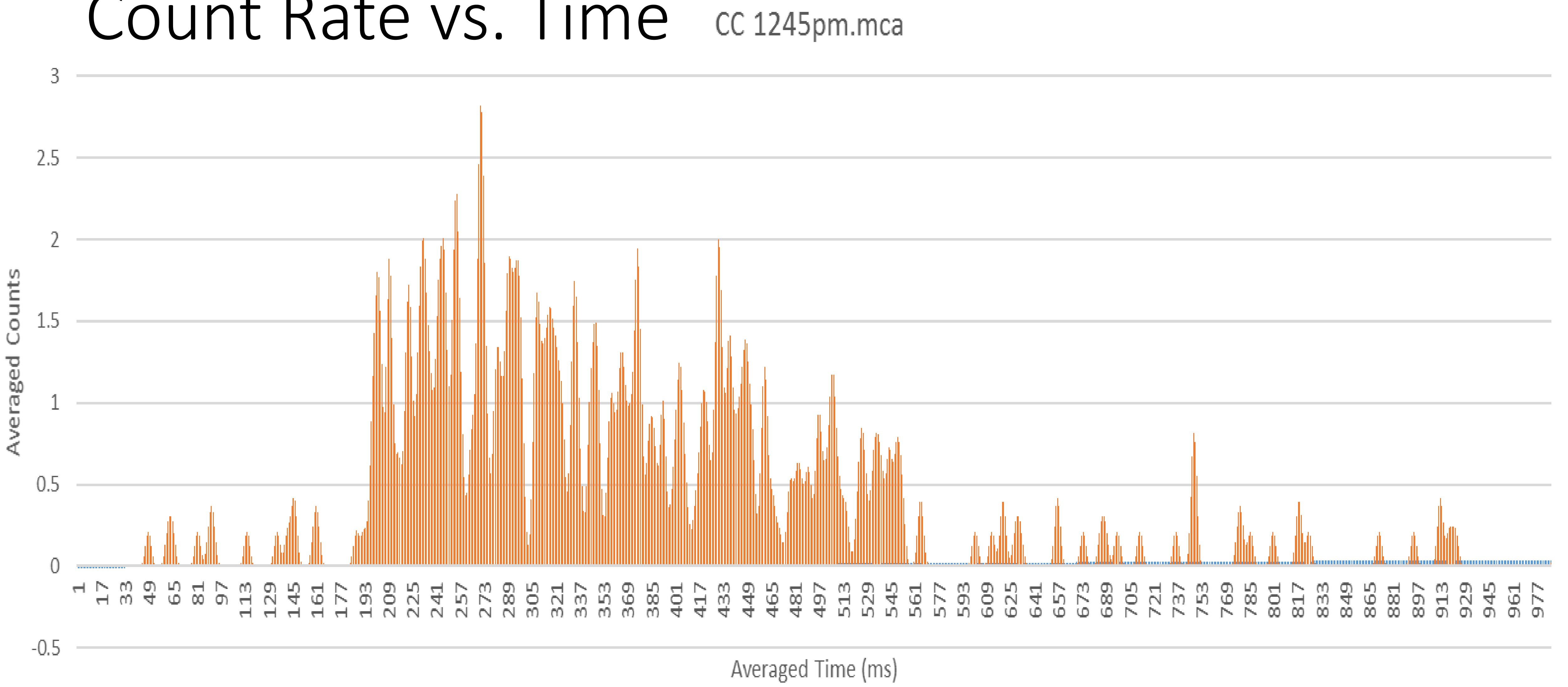
Work completed by Charles Swanson and Alex Glasser!

Calibration of X Ray Detector – Scale



Work completed by Charles Swanson, Alex Glasser and Peter Jandovitz!

Count Rate vs. Time



Analysis

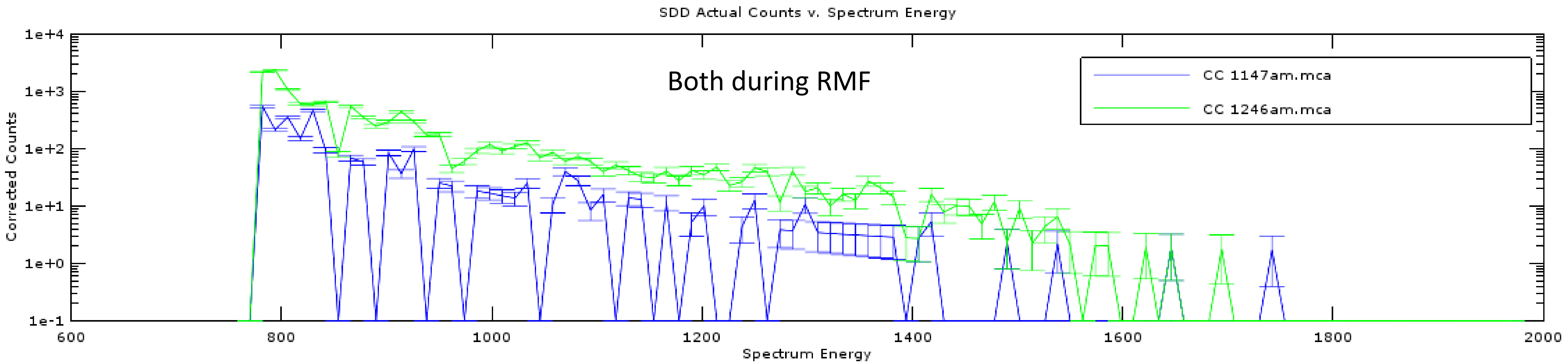
- Analysis of data collected would allow for determination of FRC bulk properties
  - Raw Data → X Ray Temperature & Count Rate
  - Count Rate → Electron Density
  - Electron Density & Temperature → Plasma Pressure
  - Plasma Pressure → β
  - Plasma Pressure & Total Volume → Stored Energy
  - Stored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

Analysis – X Ray Temperature

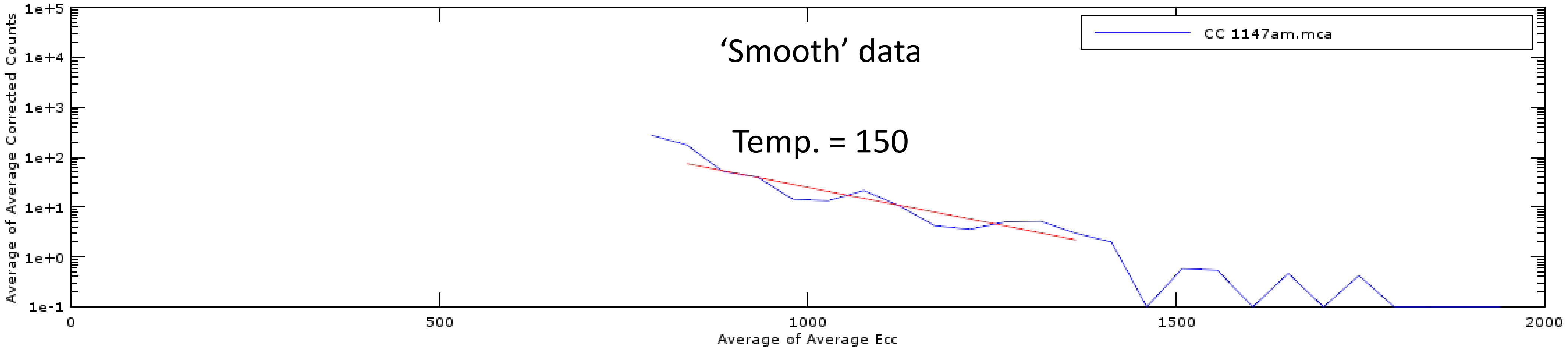
- Plot corrected counts vs. spectrum energy on a logarithmic-linear plot
- Linear regression: $y = mx + b$.
- Temperature is the negative inverse of log slope
- $T = -\frac{1}{m}$

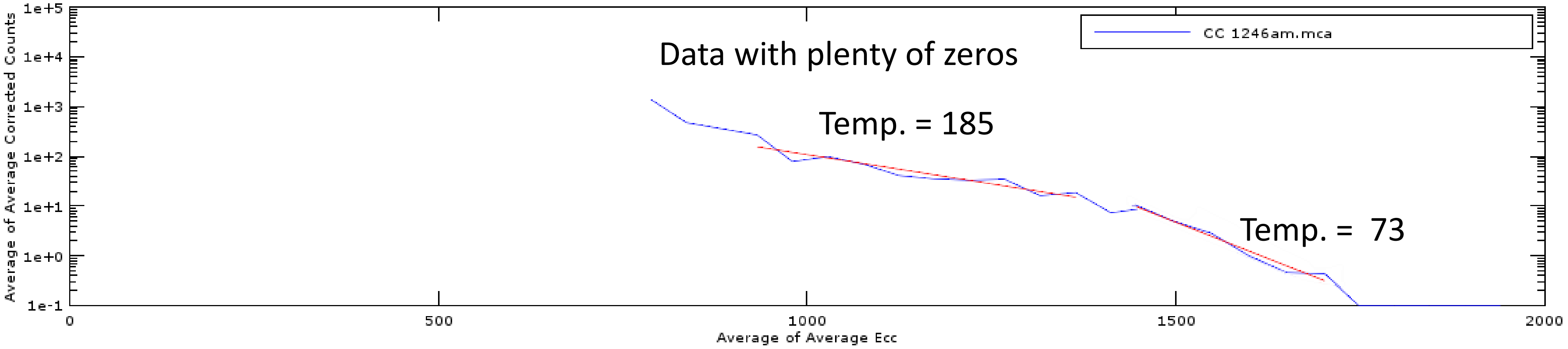
Analysis – X Ray Temperature (cont.)

- Comparison of analysis of ‘smooth’ data with data containing many zeros



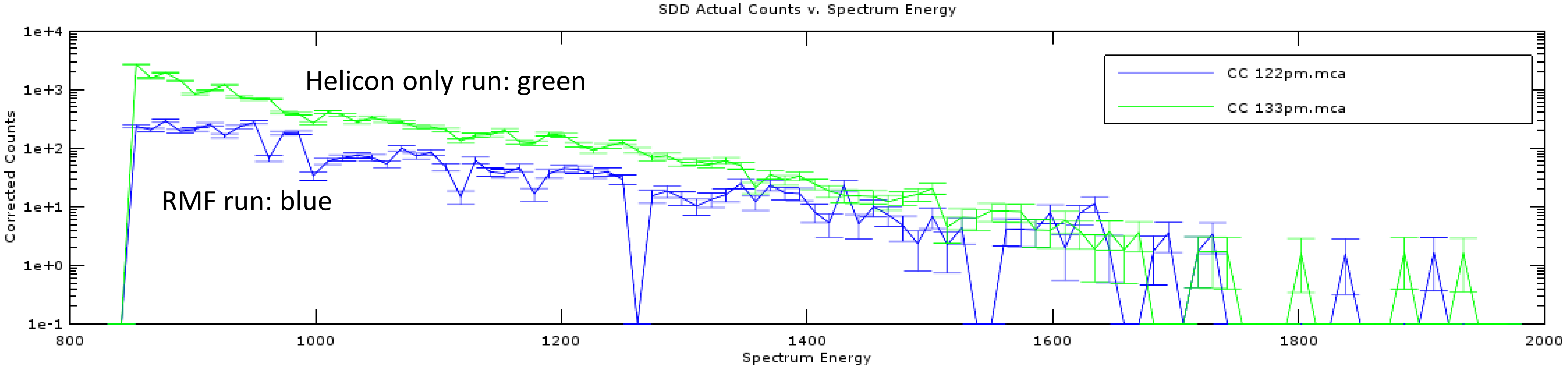
Analysis – X Ray Temperature (cont.)



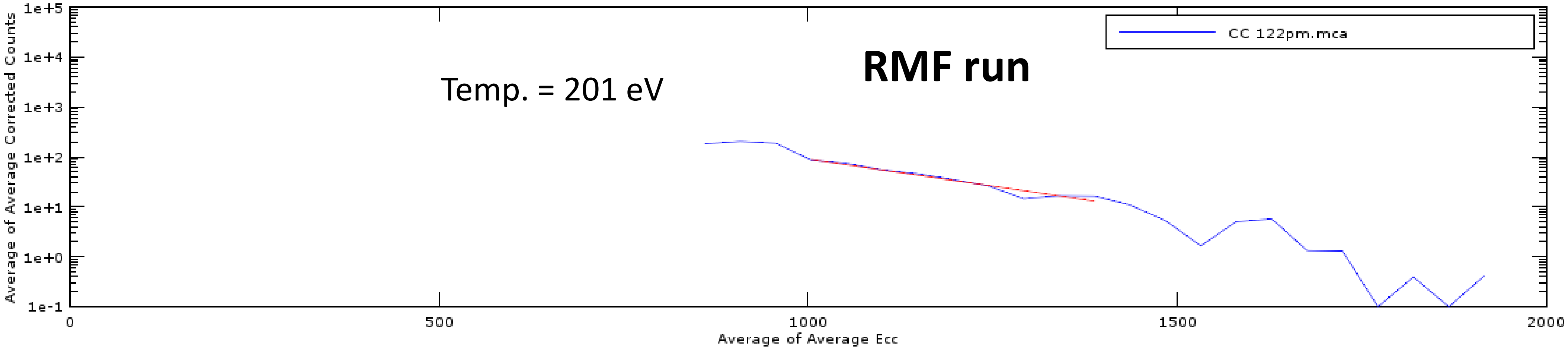


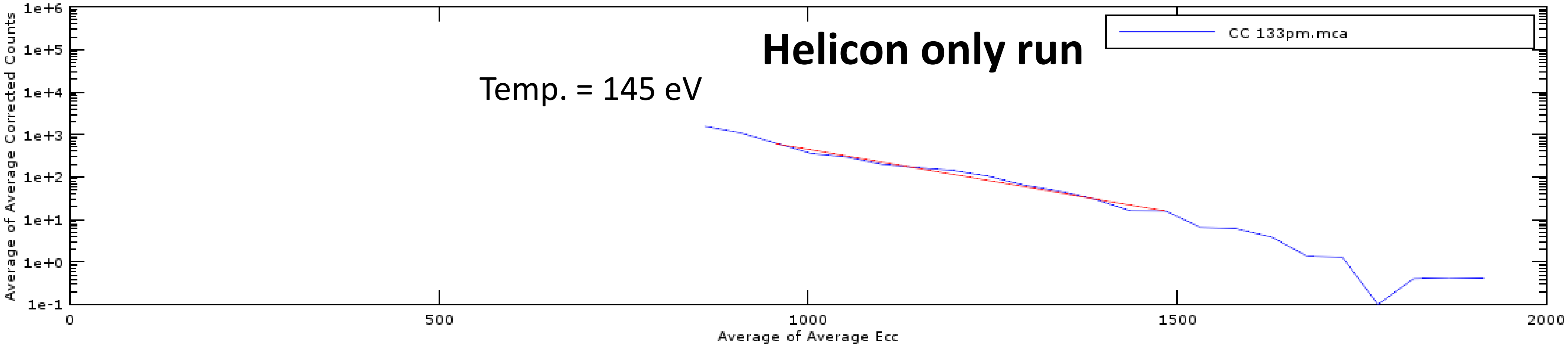
Analysis – X Ray Temperature (cont.)

- Comparison of the temperatures during Helicon only run and RMF run with same parameters of machine during each run



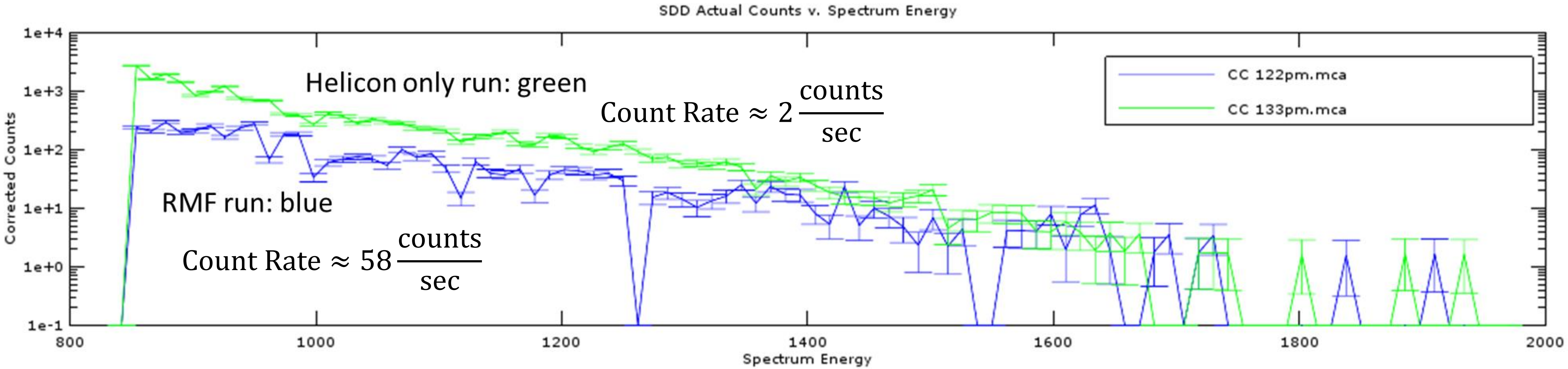
Analysis – X Ray Temperature (cont.)





Analysis – Count Rate

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



Analysis – Electron Density

- Two ways:
  - Complicated-ish math or simplistic math
  - Interferometer measurements

Analysis – Electron Density

- Two ways:
  - **Complicated-ish math** or simplistic math
  - Interferometer measurements

Analysis – Electron Density

- **Bremsstrahlung Reaction Rate**
- From *Principles of Plasma Diagnostics* by I. H. Hutchinson, Eq'ns 5.3.6 & 5.3.11

$$\left\langle \partial_{E_{xray}} \sigma v \right\rangle_T = \frac{16\alpha c^2 \pi Z^2 r_e^2}{3sqrt(3)} \cdot \frac{1}{E_{xray}} \int dE_e \cdot \frac{\left(G\left(E_{xray}, E_e\right)\right)}{\nu_e} \cdot f_T(E_e) =$$

$$5.0 \times 10^{-6} \frac{\mathrm{cm}^4}{\mathrm{s}^2} \cdot \frac{1}{E_{xray}} \int dE_e \cdot \frac{G\left(E_{xray}, E_e\right)}{\nu_e} \cdot f_T(E_e)$$

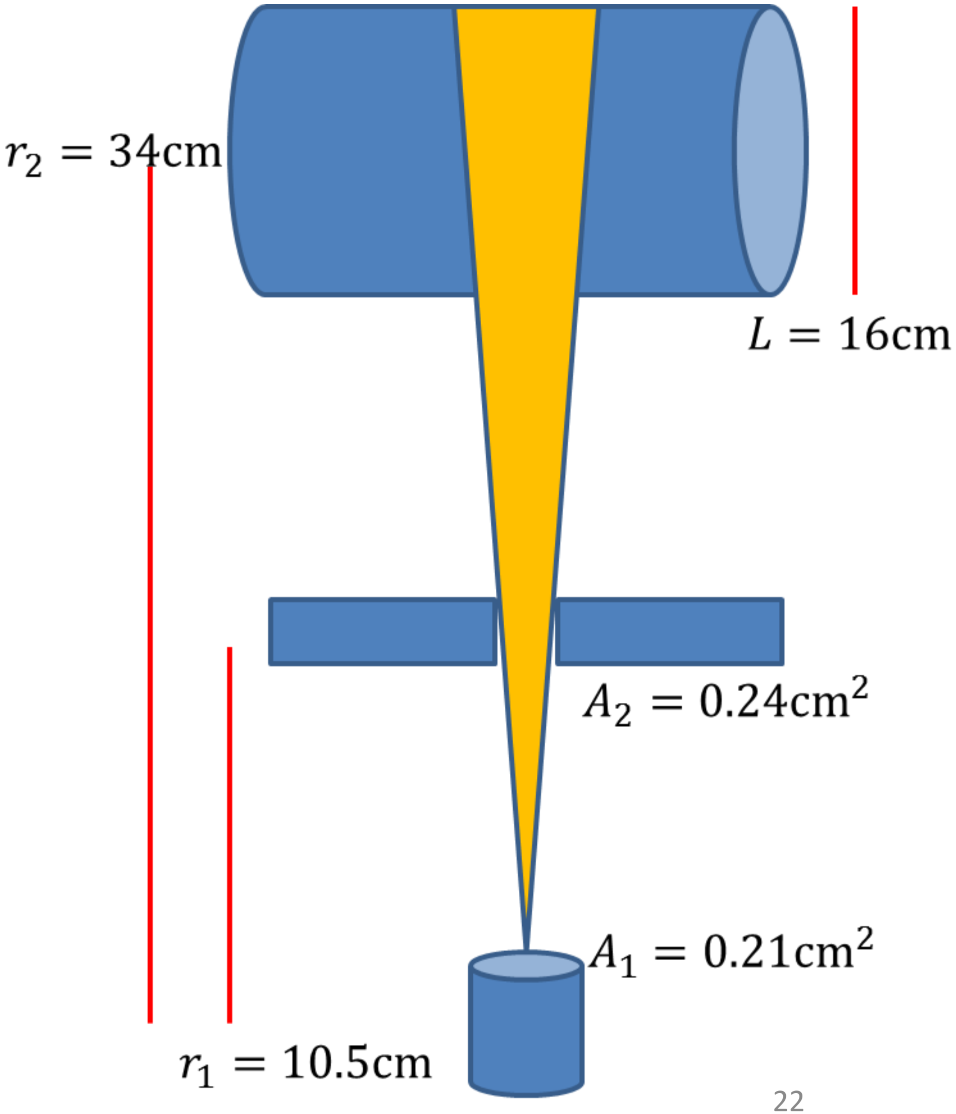
- Assuming constant Gaunt factor (~2x error)
  - $\left\langle \partial_{E_{xray}} \sigma v \right\rangle_T = \left(9.6 \times\ 10^{-14} \frac{\mathrm{cm}^3 \cdot \mathrm{eV}^{\frac{1}{2}}}{\mathrm{s}}\right) \cdot \frac{e^{-\frac{E_{xray}}{T}}}{\sqrt{T} E_{xray}}$

Thanks Charles!

Analysis – Electron Density

- **CC Detector Effective Emission Volume**
- Actual volume, as if seen from a point sourch through the slit mask:
  - $V_{tot} = A_3 L = A_2 \left(\frac{r_2^2}{r_1^2}\right) \cdot L$
- Solid angle reduction factor
  - $\frac{\Omega}{4\pi} = \frac{A_1}{4\pi r_2^2}$
- Total effective volume
  - $V_{eff} = \frac{V_{tot}\Omega}{4\pi} = \frac{A_1 A_2 L}{4\pi r_1^2} = 5.8 \times 10^{-4}\text{cm}^3$

Thanks Charles!



Analysis – Electron Density

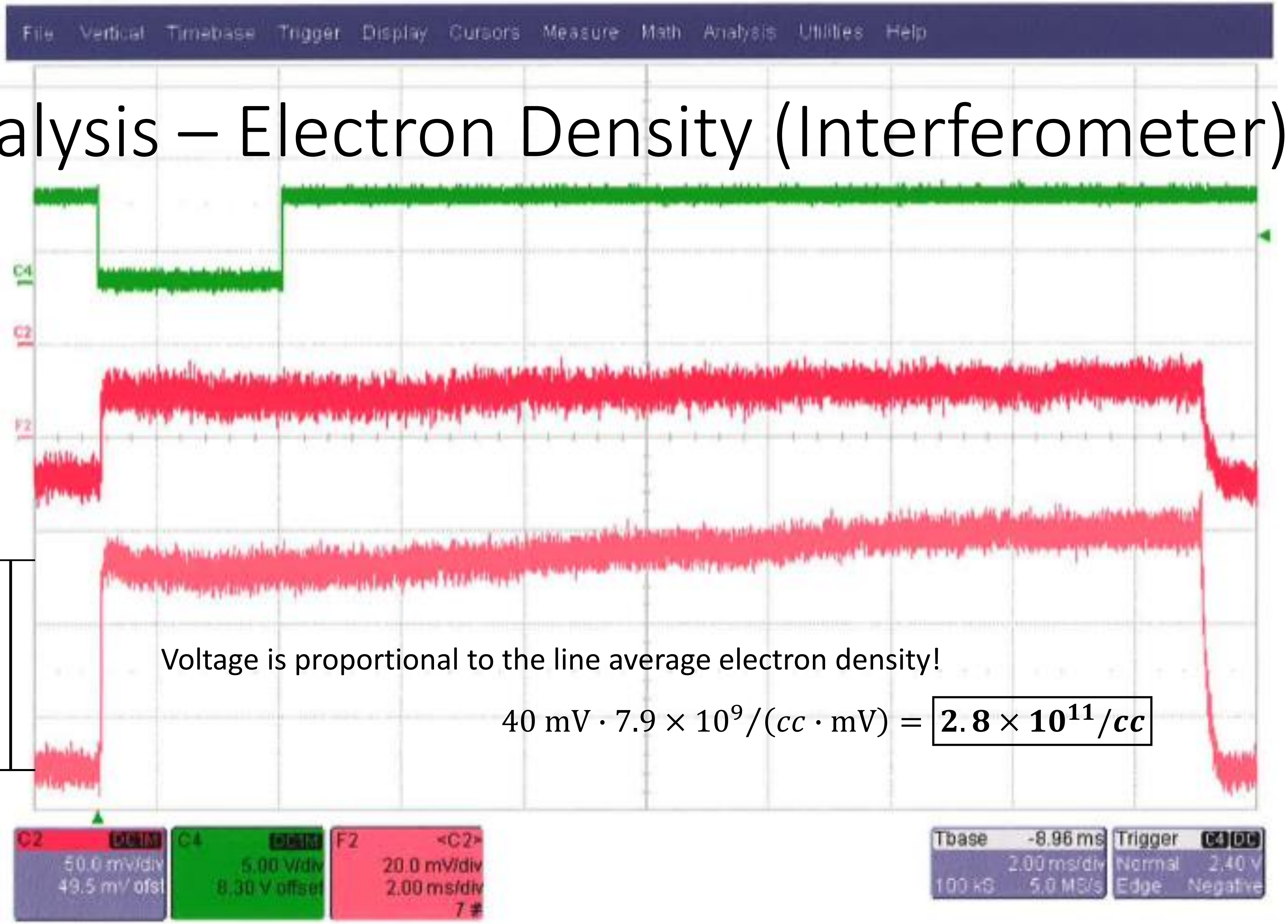
- **Bremsstrahlung Rate Density**
- Rate density η from reaction rate
  - $\partial_{E_{xray}}\eta = n_e n_\sigma \left\langle \partial_{E_{xray}} \sigma v \right\rangle$
- Rate density from measure count rate
  - $\partial_{E_{xray}} CR = \partial_{E_{xray}} \eta V_{eff}$

Thanks Charles!

Analysis – Electron Density (cont.)

- Example: July 19, 2016 at 12:45pm (filename indicates 12:46am…), spectrum measured
  - Rate density measured: $\partial_{E_{xray}}\eta(800\mathrm{eV}) = 1.6 \times 10^{3}\,\frac{1}{\mathrm{cm}^3\cdot\mathrm{eV}\cdot\mathrm{s}}$
  - Reaction rate calculated: $\left\langle \partial_{E_{xray}}\sigma v \right\rangle_{T=150eV}(800\mathrm{eV}) = 4.7 \times 10^{-20}\,\frac{\mathrm{cm}^3}{\mathrm{eV}\cdot\mathrm{s}}$
  - Scattering density measured: $n_\sigma = P_{cc} \cdot 3 \times 10^{13}\,\frac{1}{\mathrm{cm}^3\cdot\mathrm{mTorr}} = 1.5 \times 10^{13}\,\frac{1}{\mathrm{cm}^3}$
  - Electron density inferred: $\boxed{n_e = 3.4 \times 10^{9}\,\frac{1}{\mathrm{cm}^3}}$

Analysis – Electron Density (Interferometer)



$\approx$ 2 div

Voltage is proportional to the line average electron density!

$$40\ \mathrm{mV} \cdot 7.9 \times 10^{9}/(cc \cdot \mathrm{mV}) = \boxed{\mathbf{2.8 \times 10^{11}/cc}}$$

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 – β

- For FRC: $\beta \ \cong 0.5 \ - 1$ (tokomak: $\beta \cong 0.05$)
- $\beta = \frac{plasma\ pressure = n_e \cdot k_b \cdot T}{magnetic\ field\ pressure = \frac{B^2}{8\pi}} = 1$
- $n_e \cdot k_b \cdot T_{xray} = \frac{B^2}{8\pi}$ → $nT = \frac{B^2}{4\mu_0}$
- 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 - β (cont.)

- $nT = \frac{B^2}{4\mu_0}$
- In general $B: 50 \ - 100G, T \approx 150 - 300 \ eV$

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

Maxwellian Distribution?

- Maybe?
- Previous machine (PFRC-1)
- Single particle simulation
- Electron collision rate
  - $\nu_e = 2.91 \times 10^{-6} n_e \ln \Lambda \, T_e^{-\frac{3}{2}} \sec^{-1}$
- At $200eV, \tau_{ee} \approx 2 \; sec$
- Other ways to reach Maxwellian
- RMF *only* runs for 5 ms with water coolant or 250 ms with LN_2!

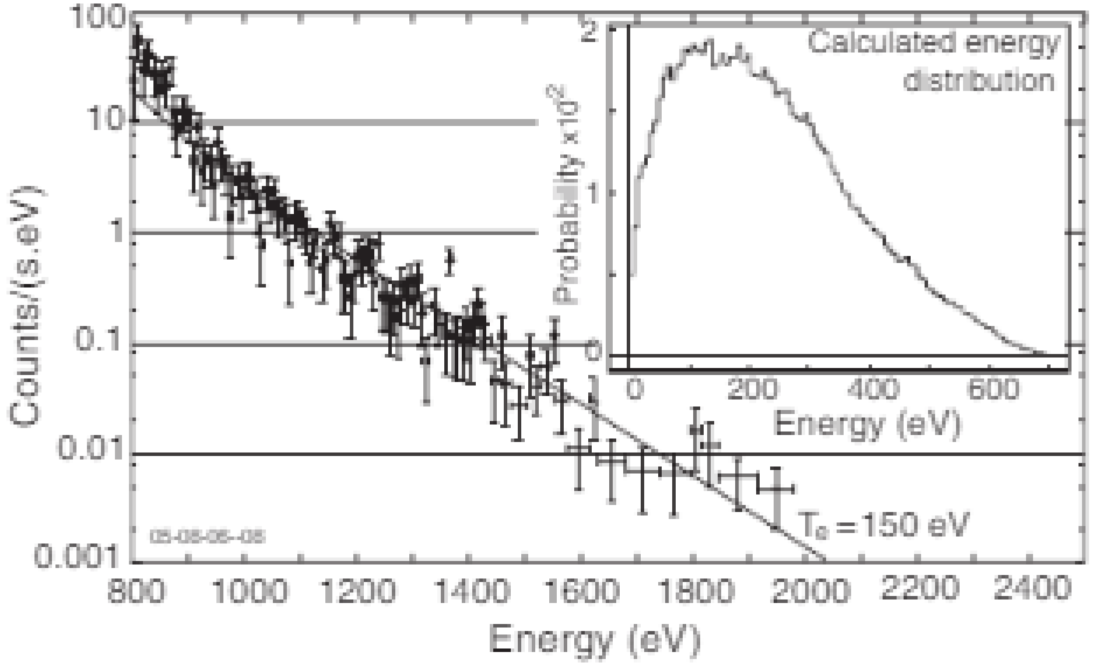


FIG. 4. Measured x-ray spectrum: ${}_mP_{\rm rf} = 9.6$ kW; ${}_mn_e = 1.6 \times 10^{12}$ cm^{-3}; ${}_m\Phi_{\rm DL} = 5\ \mu$Vs; $f_s = 14.000$ MHz (no FM); $P_{\rm H_2} = 1.09$ mTorr; $B_0 = 56$ G; $B_M = 2900$ G, where subscript m means maximum value. The spectrum shape is fit by $T_e = 150$ eV.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

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

What do we expect?
RMF code

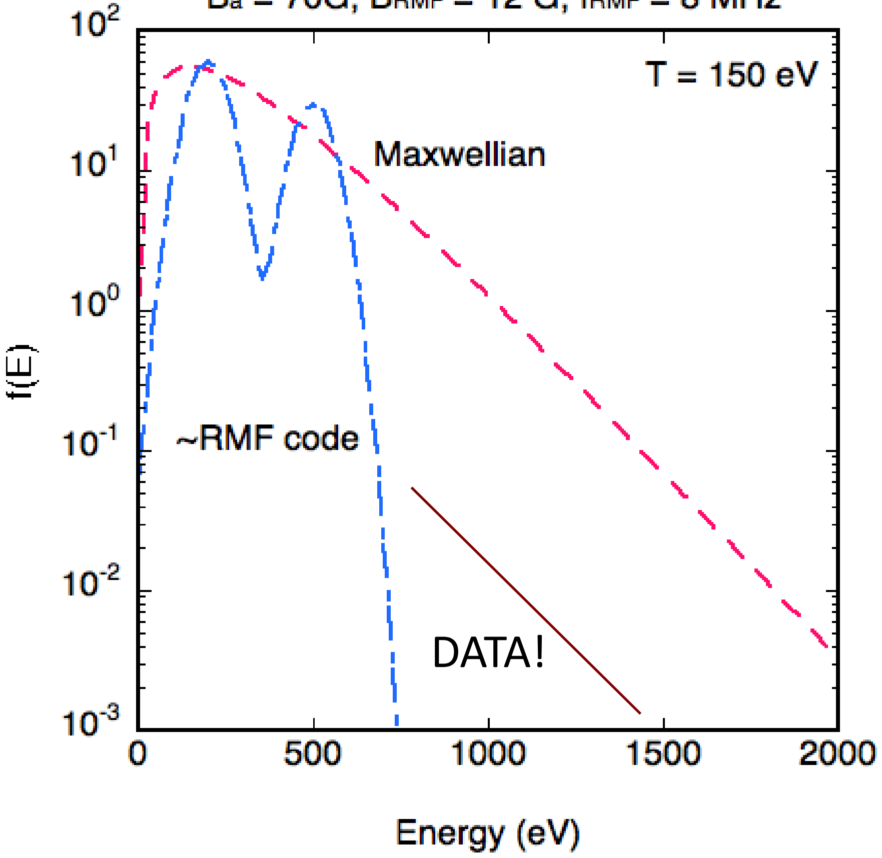
Possible causes:

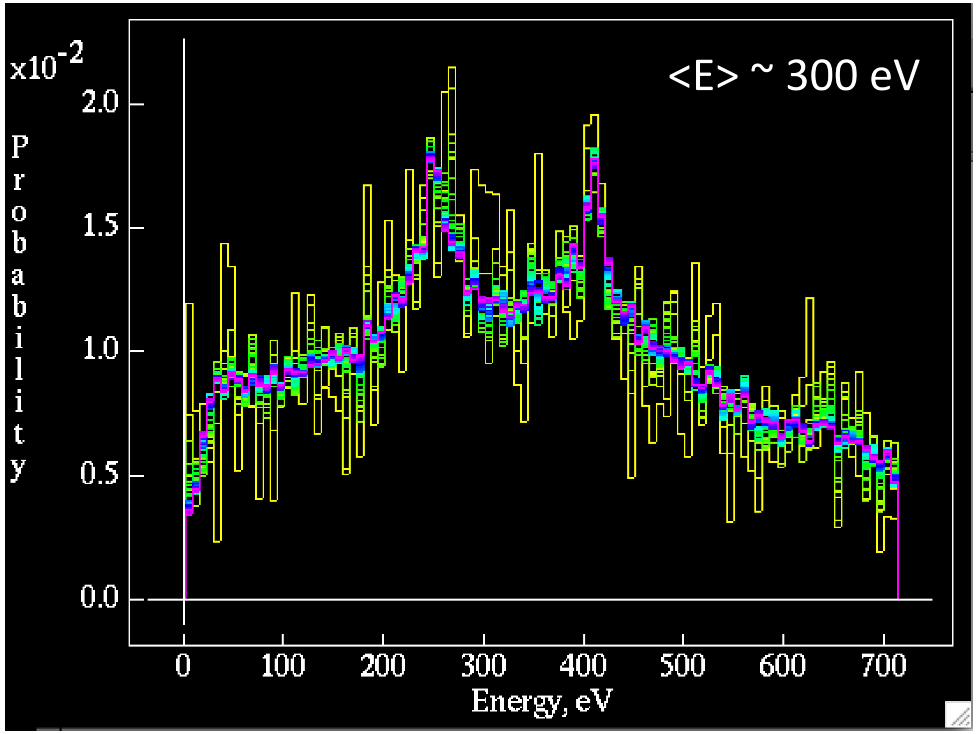
a) Pulse pile-up

b) Scattering off (mirror) field

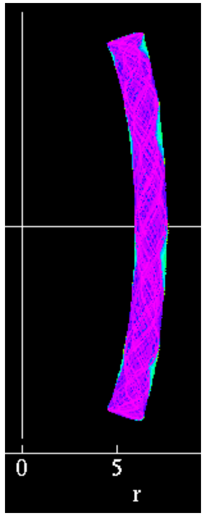
c) Plasma instabilities

RMF code: r_s = 6 cm, κ = 4,
B_a = 70G, B_{RMF} = 12 G, f_{RMF} = 8 MHz

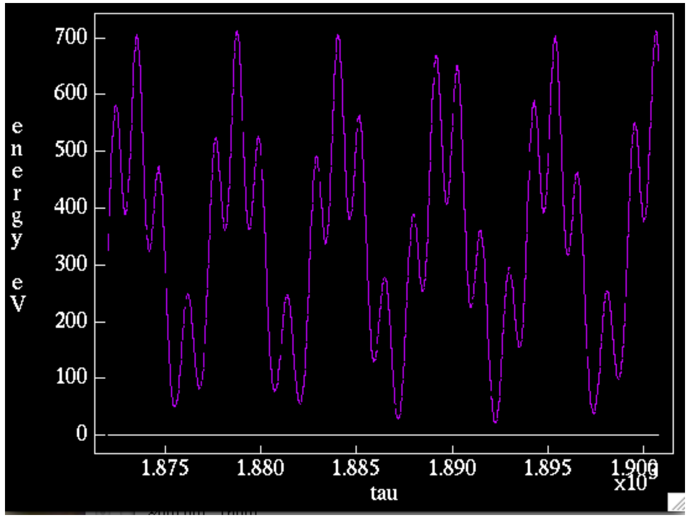




r vs z



E vs t



X-ray Emission vs. Source Power

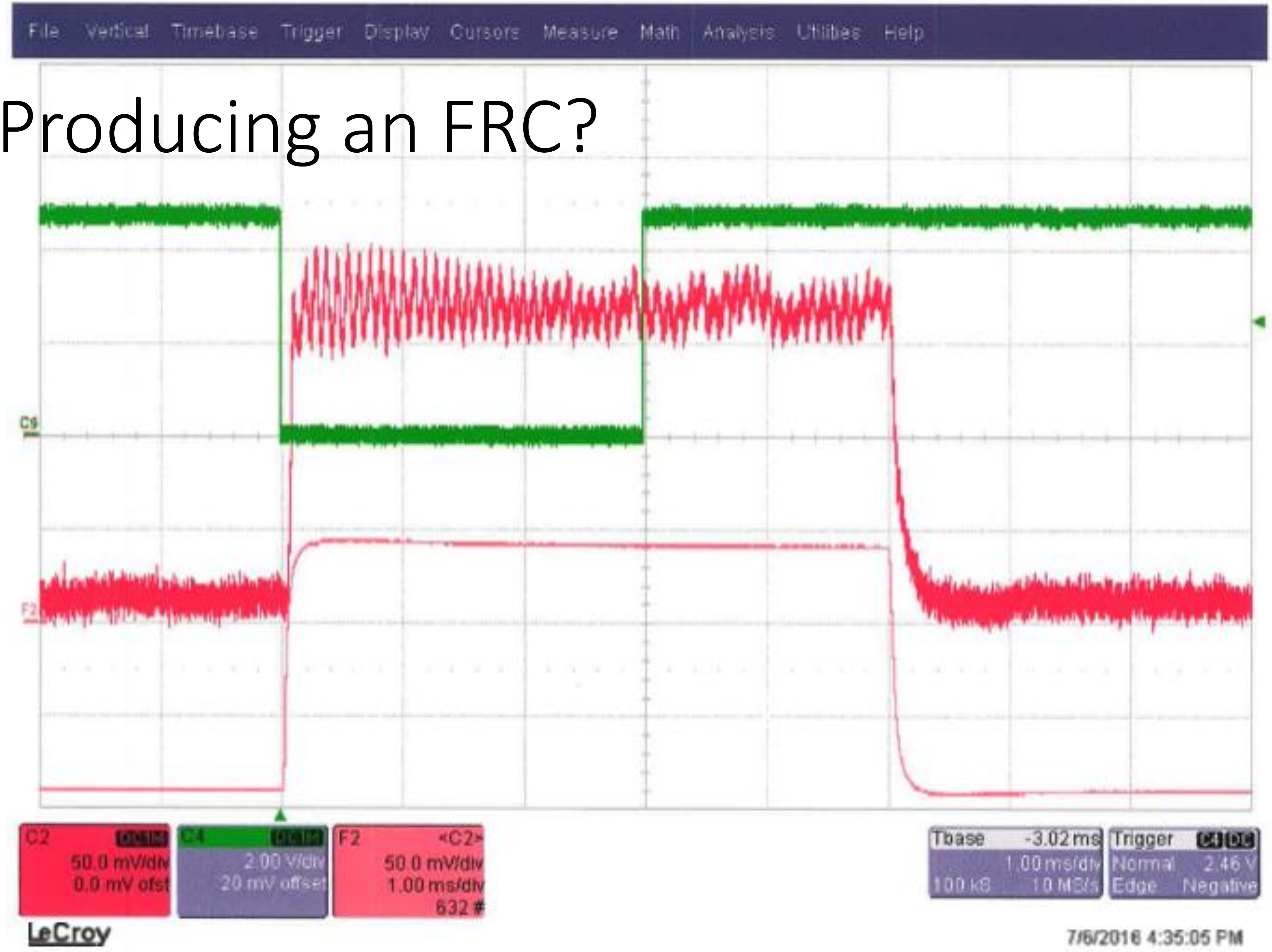
X-ray emission during the RMF pulse steadily and significantly increases as the power for the seed plasma antenna increases. The most significant change in the seed plasma as the source power increases is an increase in the number of very energetic secondary electrons in the bulk plasma, seen here as 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.

Peter Jandovitz's Poster Presentation, *0.8-5.0 keV X-ray Emission from the PFRC-2 Plasma*

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

Acknowledgements

- CHARLES SWANSON!!
- Peter Jandovitz
- Sam Cohen
- Alex Glasser
- All other SULI interns
- SULI, PPPL, DOE