Observation of X-Rays from Capacitively Coupled and Field-Reversed Plasma in the PFRC-2

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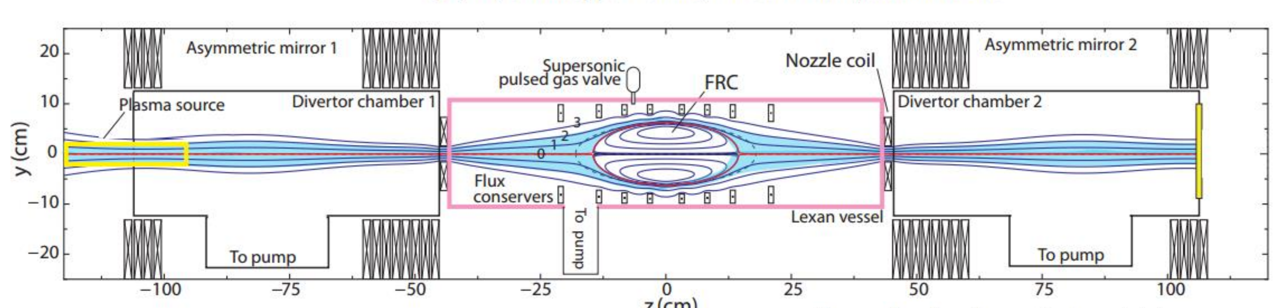
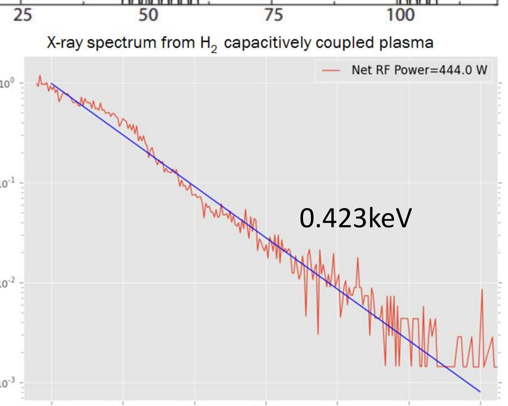
Introduction

The field-reversed configuration (FRC) provides a unique geometry that allows for a small high-β plasma and may one day be a viable option for producing fusion power and propelling rockets throughout the solar system. This work concerns the X-rays emitted from the plasma in a low power capacitively coupled mode as well as when placed in a high power rotating magnetic field (RMF). A 'helicon' RF antenna capacitively couples forming a hydrogen plasma in a static magnetic field. The antenna thus 'heats' electrons. If energetic, electrons will emit X-rays (bremsstrahlung) while decelerating near ions and neutrals. In principle, an FRC can be generated by applying an RMF to the seed plasma. The RMF generates a rotating electric field, which in turn causes a current about the axis of the plasma. This current creates a magnetic field to oppose the initial field and a separatrix forms which encapsulates a region of closed-loop magnetic field lines.

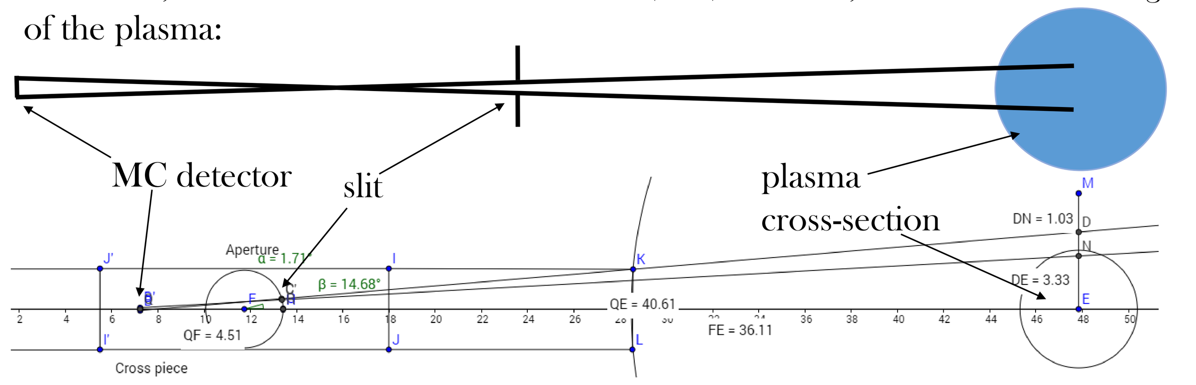




Measuring the X-rays emitted by the PFRC allows us to infer a great deal of information about the plasma, such as what energies the electrons have and the location of the origin of the high-energy electrons leading to X-rays in the first place. We report on the surprising finding that the 'cool' (3eV) capacitively coupled plasma contains 0.1% of keV electrons. Our experiments show that the electrons responsible for the bremsstrahlung are located in the core of the plasma and that the source of the fast electrons is likely due to secondary electron emission resulting from the floating potential on the end plate and on the Pyrex pipe comprising the source.

The PFRC-2 Detector System

This summer we added a detector to the main chamber to investigate the source of the electrons seen earlier. Previously, there was only one detector in expansion region (ER), which scans along central axis of the plasma. We designed, built, calibrated, and installed the main chamber (MC) detector, which scans the height of the plasma:

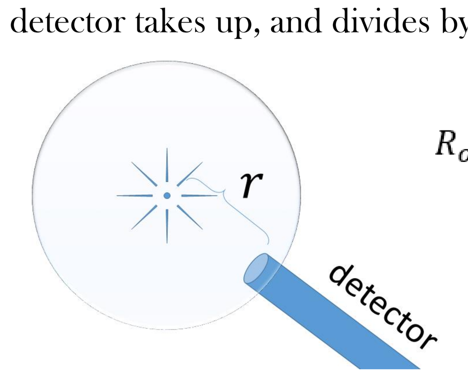


Experiment

- There are two X-ray detectors looking into separate parts of the plasma. By observing the count rates under varying parameters, it is possible to test, verify, and amend our understanding of how electrons behave in the plasma. The parameters we are able to vary include:

- Magnetic field (via current in the L2 and nozzle coils)
- Power to 'helicon' RF antenna (near the end plate)
- Neutral pressure
- Replace H_2 gas with Ar

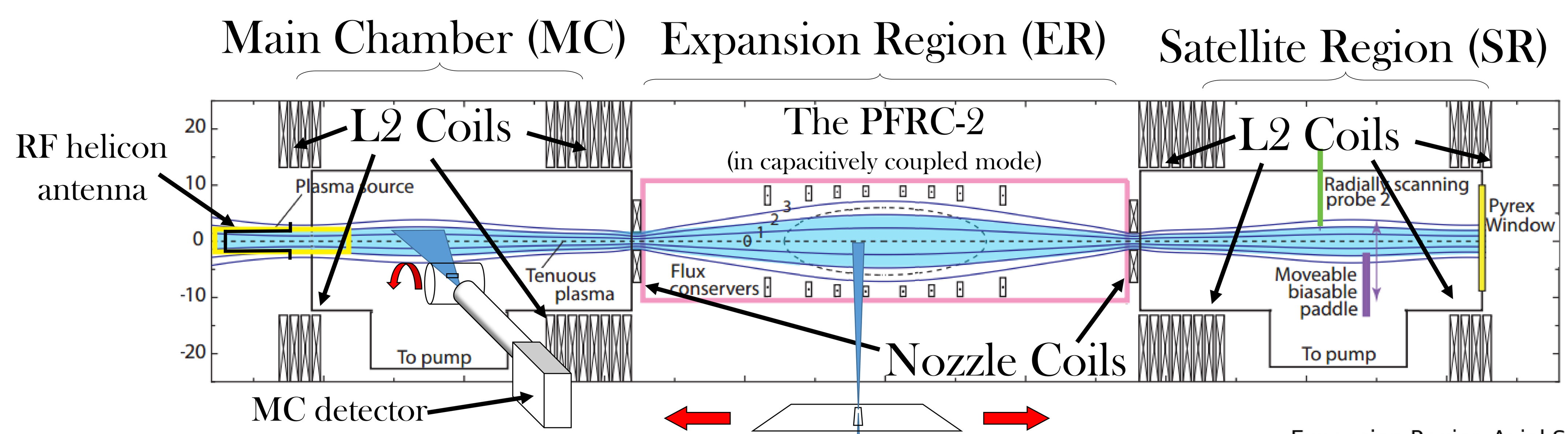
- Measuring X-ray count rates in the MC and ER simultaneously reveals in which region there are more bremsstrahlung-emitting electrons, and therefore can suggest from where they originate. MC and ER X-rays can be compared by finding rate density ρ_R ($s^{-1} \cdot cm^{-3}$): one assumes a point source, uses the solid angle Ω the detector takes up, and divides by the volume of plasma V_p visible to the detector:

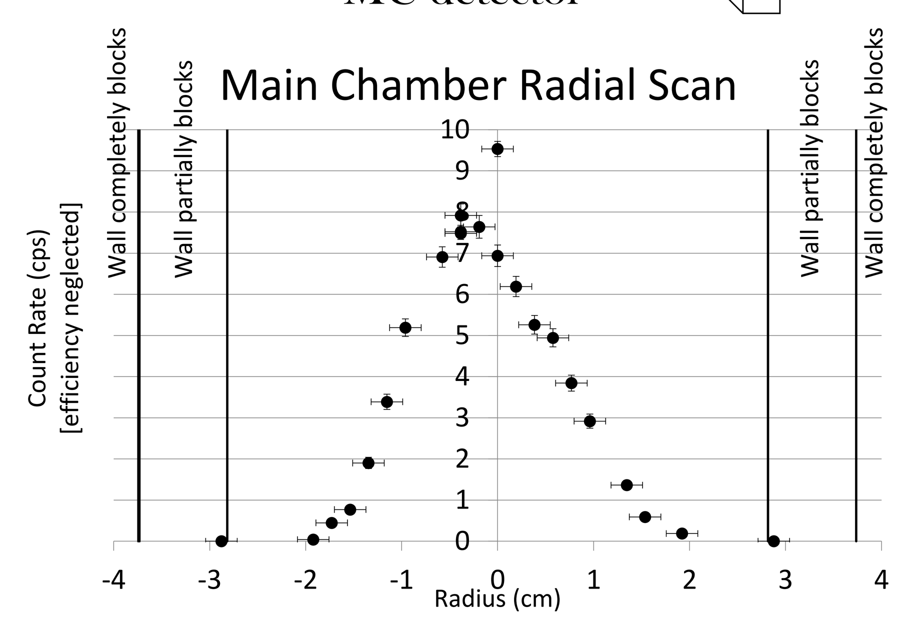


$$R_{obs} = \Omega R = \frac{A_{det}}{4\pi r^2} \cdot \rho_R V_p = \rho_R \left(\frac{\pi r_{det}^2}{4\pi r^2} \cdot \pi r_p^2 l\right)$$

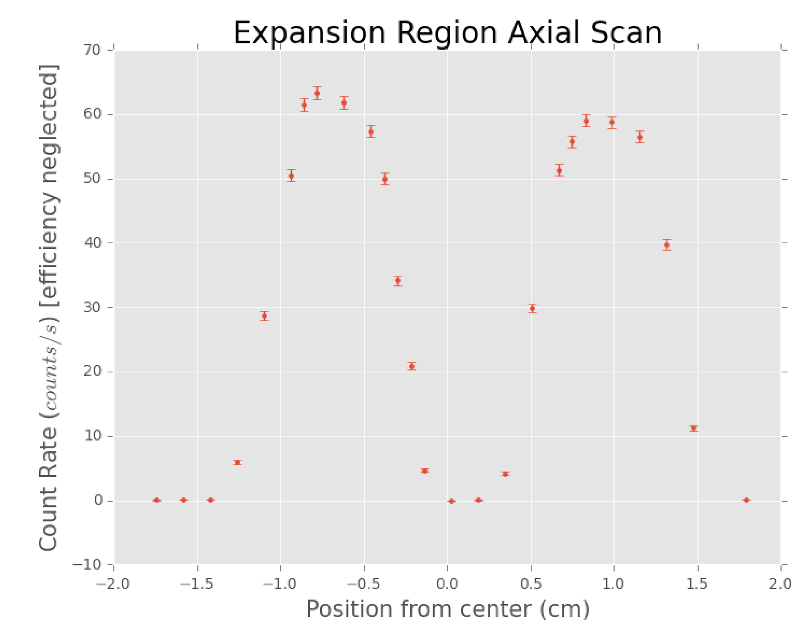
$$\rho_R = \frac{4r^2 R_{obs}}{\pi r_{det}^2 r_p^2 l}$$

- When running the machine with the RMF, the detectors can be gated to register X-rays just when the RMF is on as well as just when it is off, allowing comparison between X-rays from the two resulting plasmas.





A scan across the radius of the plasma from the main chamber. That there is a sharp peak and not a flat rectangle (well within where the walls are expected to interfere) indicates X-rays originate from the core of the plasma rather than the surface.

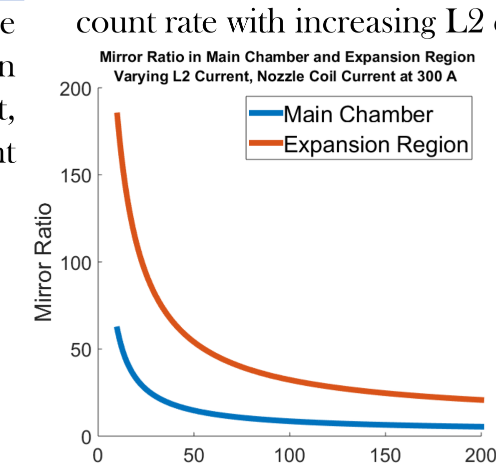


A scan across the axis of the plasma in the expansion region. Because the detector is partially blocked by a flux conserver (slightly to the right of zero), there is a valley in the middle of the two peaks where the count rate decays to zero.

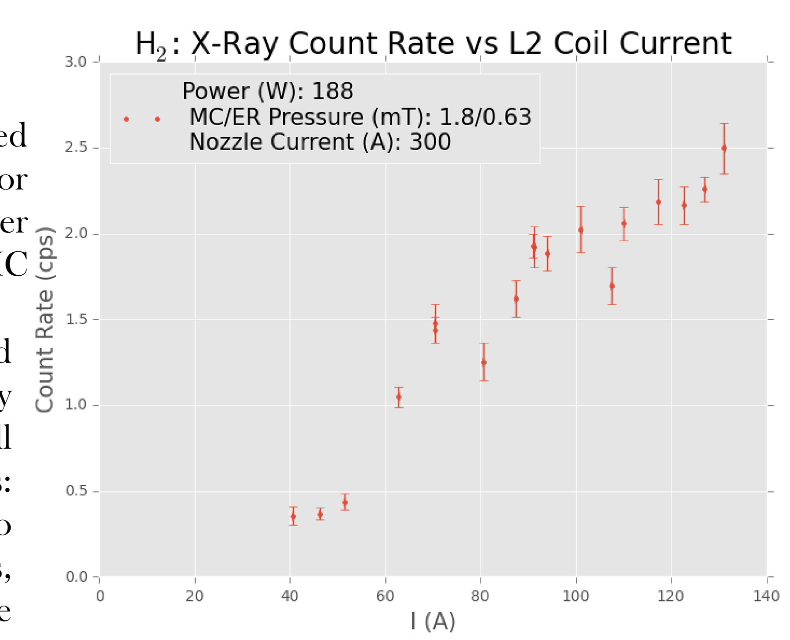
Results from capacitively coupled mode in the main chamber

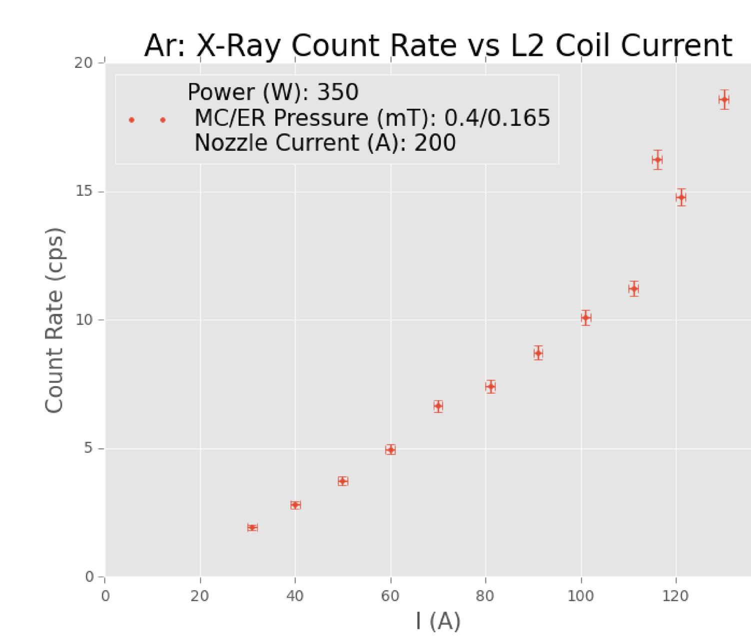
Magnetic Field

The axial component of the magnetic field can be varied via current in the L2 and nozzle coils. Based on the mirror ratios (shown below), the ER mirror ratio decays slower than the MC ratio. This would suggest a decreasing MC count rate with increasing L2 current.



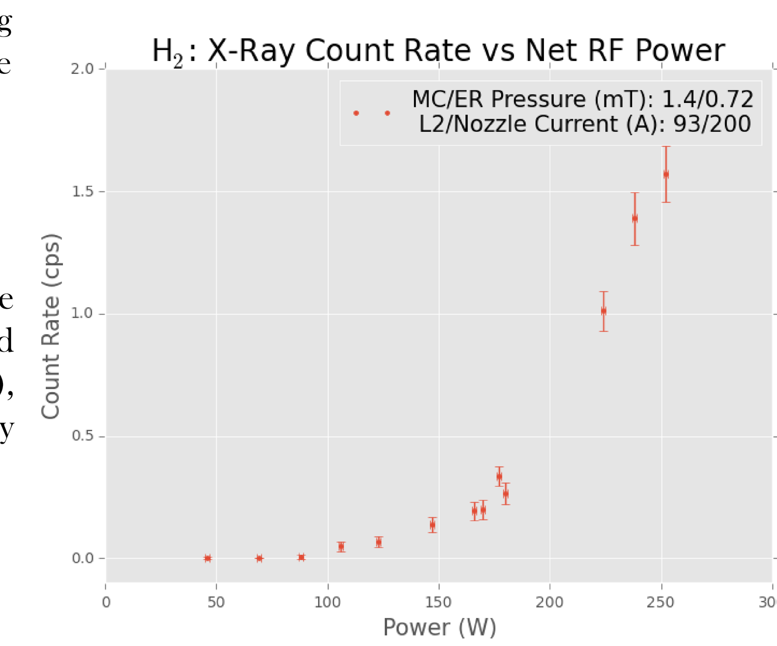
Instead, the observed increasing count rate may be explained by the small opening in the nozzle coils: the decreasing mirror ratio expands the field lines, leading to wider particle trajectories and causing particles to spiral into the wall.

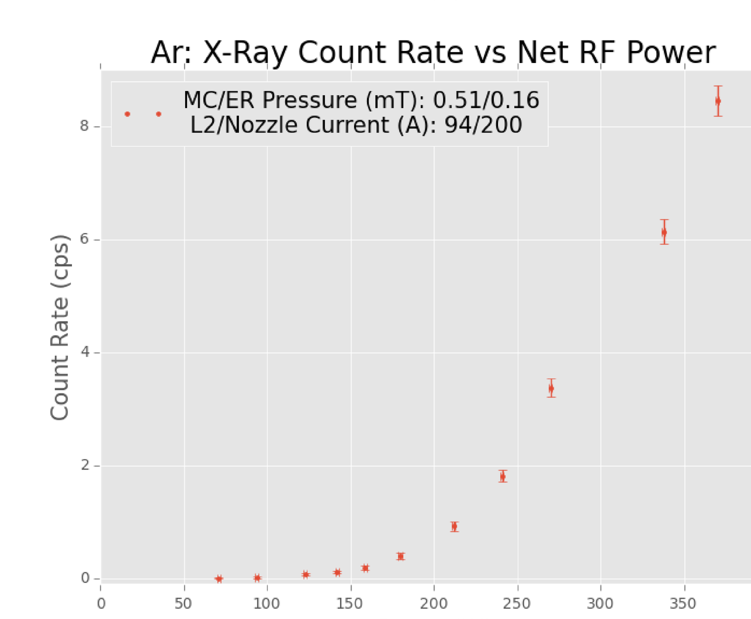




RF Power

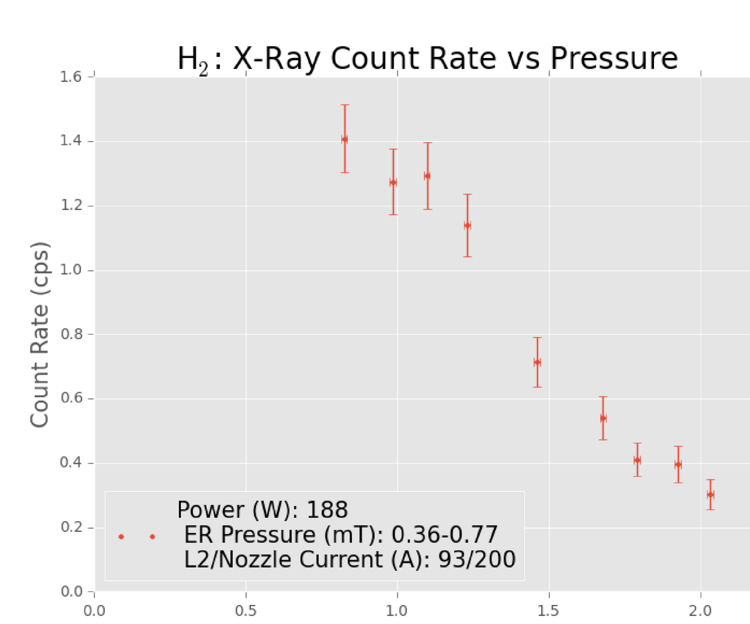
X-ray count rates were also observed while varying the net power to the 'helicon' RF antenna (near the end plate). The result was an apparent power law ($R \propto P^4$), observed in both hydrogen and argon. We are currently investigating the exact reasons for this correlation.

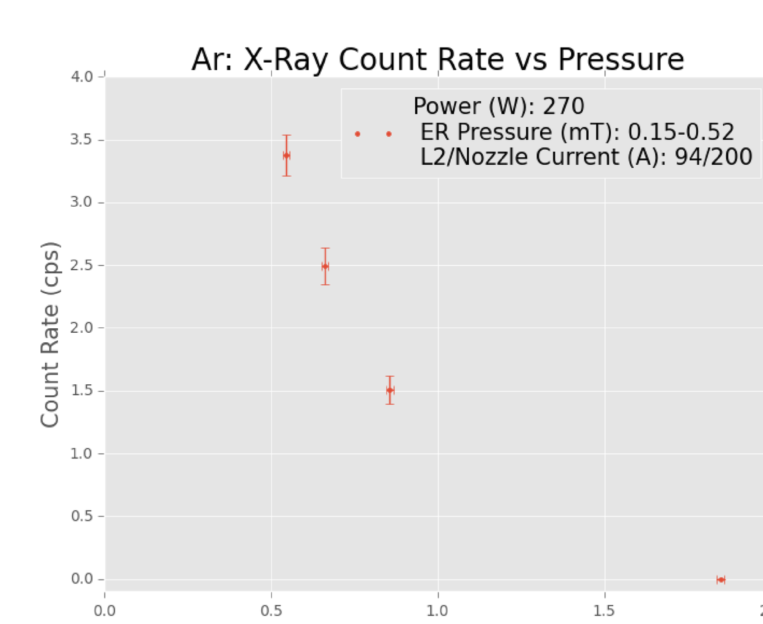


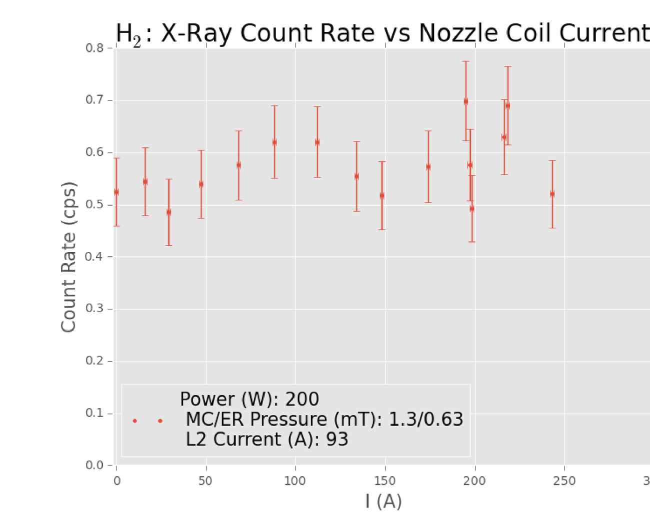


Neutral Pressure

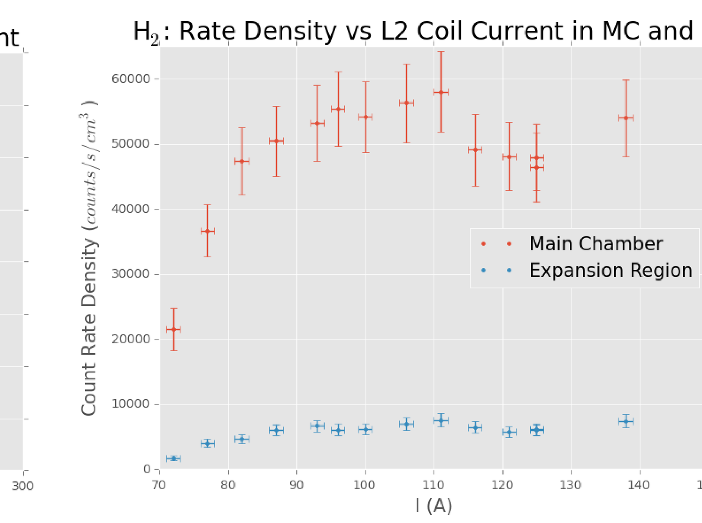
The amount of gas in the machine could be controlled, and thus the pressure could be varied. As this is neutral pressure, it was expected that the X-ray count rates should increase, particularly because in the capacitively coupled plasma it is the neutral particles which are responsible for most of the bremsstrahlung. Instead, the count rate is observed to decrease with increasing pressure, suggesting that the pressure may be interfering with the fast electron generation.







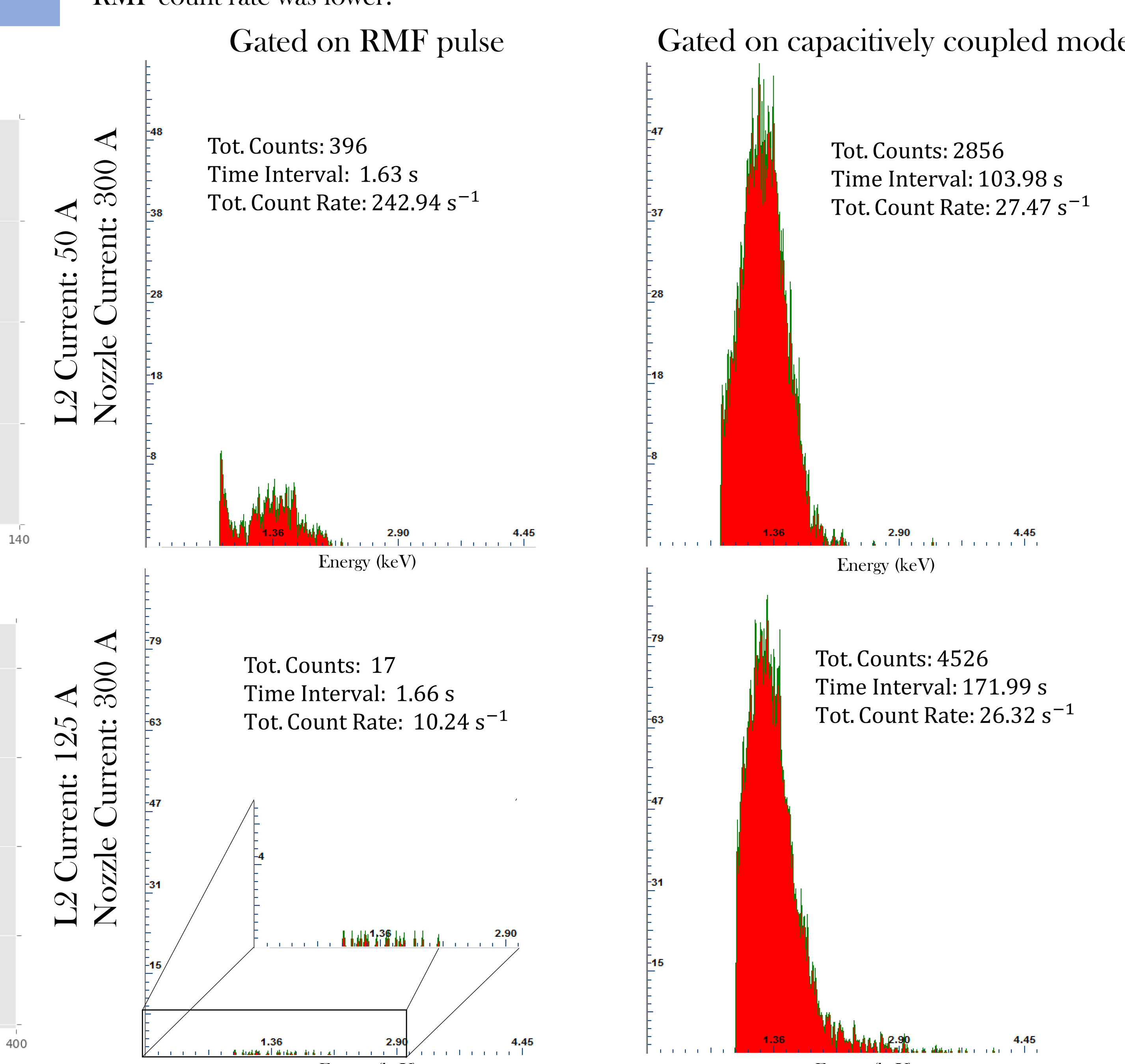
The magnetic field can also be changed by varying the current through the nozzle coils. The above plot shows count rates for various nozzle coil currents from the MC. No strong correlation was evident.



In the above, L2 current was varied with the ER and MC detectors recording X-rays simultaneously. To compare the count rates, the total count rates were converted to rate densities, showing a far greater source of X-rays in the MC. This could be due to mirror ratios or the plasma radius.

Results from the RMF in the expansion region

X-ray spectra were taken from the ER while pulsing the rotating magnetic field (RMF). The detector was gated on each pulse such that X-rays could be counted only during the RMF part of the pulse or only during the capacitively coupled portion of the pulse. In this way, spectra taken with the RMF could be compared to those taken in the background capacitively coupled seed plasma. For lower L2 current, the RMF count rate was higher than that from the cap. coupled plasma, but for higher currents, the RMF count rate was lower:



Conclusions

- The radial scan from the main chamber (peaked and not square) indicates that the source of X-rays lies in the volume of the plasma when cap. coupled.
- When capacitively coupled, a higher rate density is observed in the MC than in the ER, indicating the energetic electrons originate in the MC.
- At lower L2 coil currents, we observed a higher count rate during the RMF pulse than during the capacitively coupled mode, but this relationship reversed when the L2 current rose. These findings suggest much more can be learned from further investigation using the method of gating on RMF pulses.

Acknowledgements

Thanks to Peter Jandovitz, Charles Swanson, Jack Matteucci, Jackey Liu, and Prof. Sam Cohen. This work is supported by the US DOE Contract No. DE-AC02-09CH11466 and the Princeton Environmental Institute.