RMF Plasma Formation in the PFRC-2

Gabriel Gonzalez Jusino[1] , Eric Palmerduca[2] advised by Professor Sam Cohen[2]

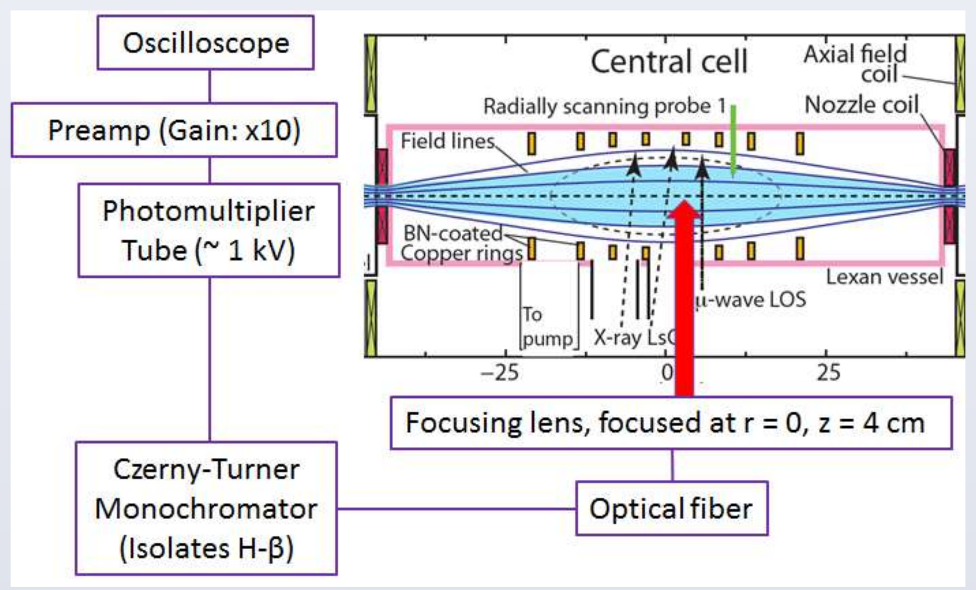
University of Puerto Rico, Rio Piedras[1], Princeton Plasma Physics Laboratory[2]

Objectives

- Describe the effects of seed-plasma parameters on the repeatability of rotating magnetic field (RMF) plasma formation in the PFRC-2.
- Further understand the mechanisms that affect this RMF plasma breakdown time.

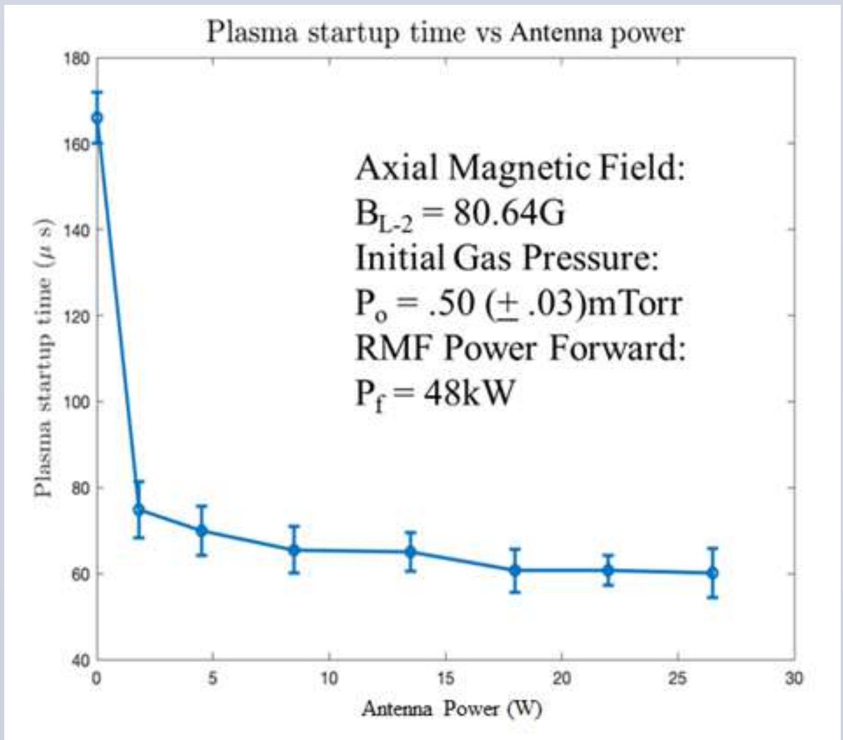
Method

- A non-intrusive method for analyzing plasma is spectroscopy or, in this case, monochrome spectroscopy. The monochromator diffracts visible light and isolates a specific wavelength from the spectrum.
- The observed emission was Hβ light (486nm), photons released as a bound electron in the hydrogen atom falls from the fourth energy level to the second.



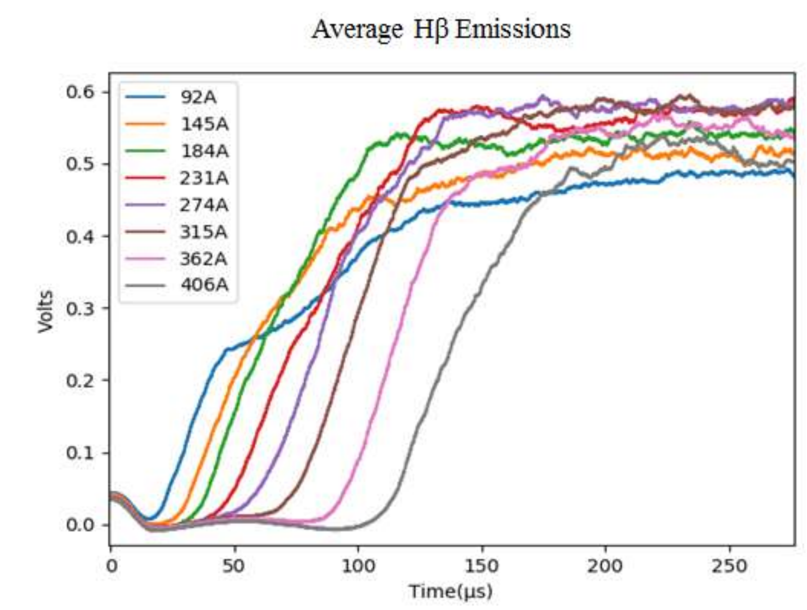
Seed Plasma

- The initial plasma is a steady-state, tenuous (1×10^9 - 1×10^{11} electrons cm^{-3}) hydrogen plasma, formed by an RF capacitively-coupled external antenna in the source chamber of the device.
- Experimental data shows that, for steady conditions, the RMF plasma breakdown time decreases rapidly when there is power into this antenna. However, it does not change much after 5W. This means that, as long as this power exceeds 5W, the RMF power can efficiently couple to it and it is not an object of particular interest.

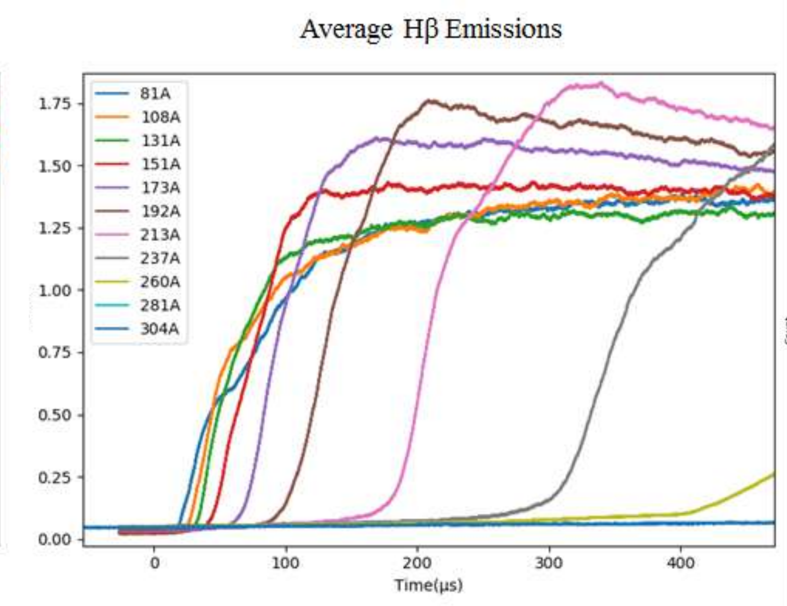


Axial Magnetic Field

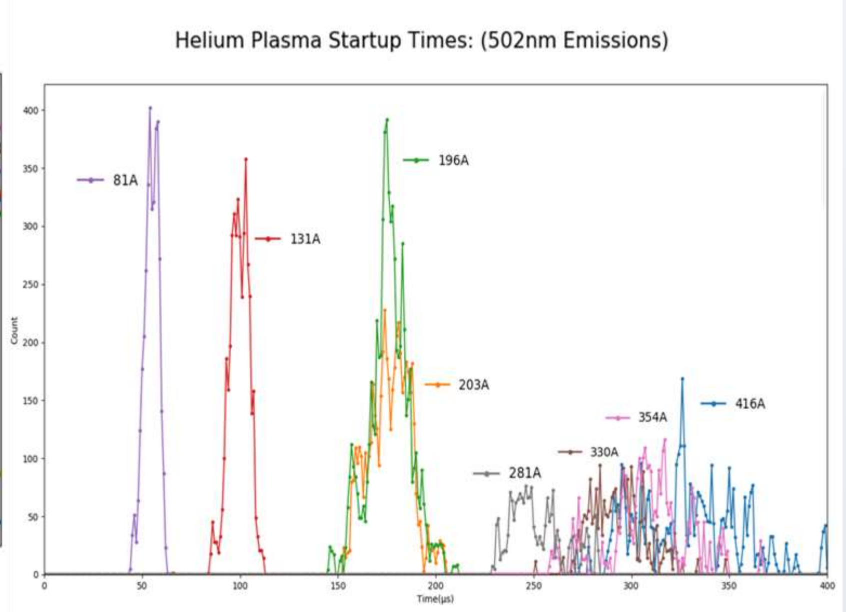
- The axial magnetic field B_a shown in the central cell is induced by electromagnets at each end of the device such that $B_a \sim 0.72i$ (G) on axis, where i is the current in the coils in amperes.
- Experimental data shows that the RMF plasma startup time τ increases as i increases. However, intermediate currents result in higher Hβ emissions (i.e. hotter and/or denser plasma) once it breaks down. Initial gas pressure determines what is considered an intermediate current.
- The τ dependance on i is most likely due to magnetic insulation, which occurs when the gyroradii are small compared to the radial dimension of the machine. The RMF induces an azimuthal electric field in accordance with Faraday's Law. This E field accelerates electrons in the opposite azimuthal direction, but a high B_a turns the electrons around until the magnetic insulation is broken by a current induced by the rate of increase of charge accumulation.



Hydrogen plasma
Antenna Power:
P_f = 11W
Fill Pressure:
P_0 = 0.724mTorr
RMF Power:
P_f = 60kW



Hydrogen plasma
Antenna Power:
P_f = 16W
Fill Pressure:
P_0 = 0.400mTorr
RMF Power:
P_f = 60kW

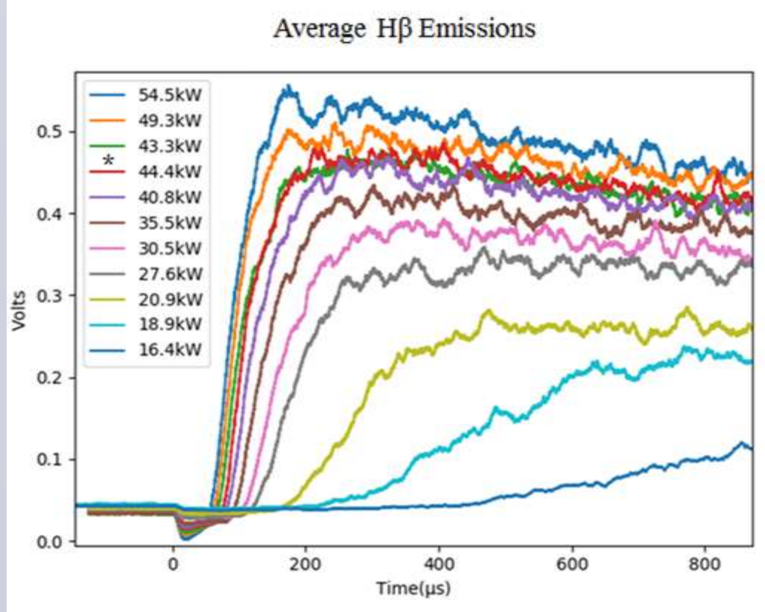


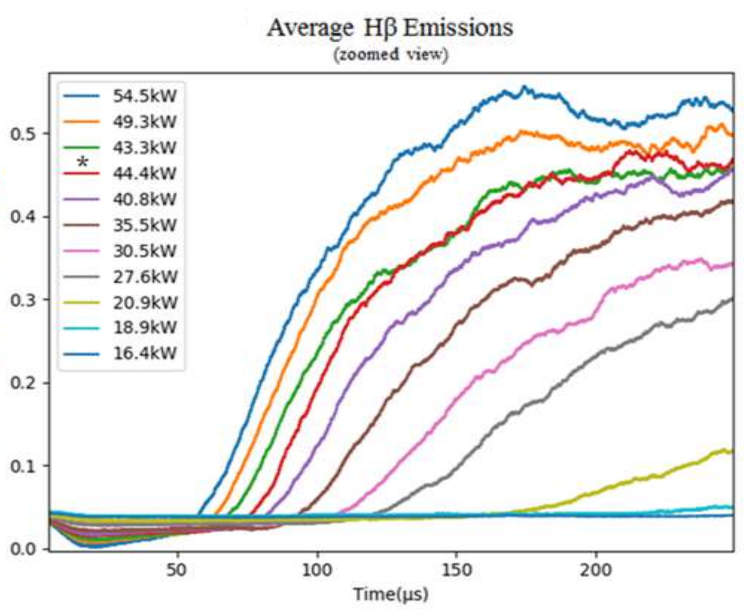
70% Helium 15-30% Hydrogen plasma
Fill Pressure:
P_0 = 0.446mTorr
RMF Power:
P_f = 46kW

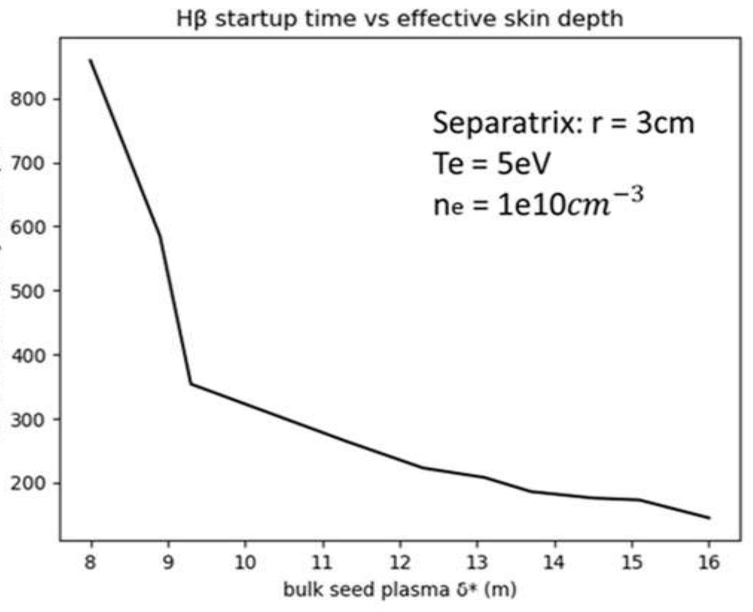
Plasma Formation and RMF Penetration

- Further theoretical and experimental analysis is required to accurately predict RMF penetration for an odd-parity RMF such as the one induced in the PFRC-2. We can however use the existing models for even-parity RMFs to get an estimate of the effective skin depth and penetration criteria.
- Using the effective skin depth $\delta^* = \frac{\omega_{ce}}{\nu_{ei\perp}}\left(\frac{\eta_\parallel}{\mu_o \omega_{RMF}}\right)^{1/2}$ (W. N. Hugrass and R. C. Grimm) it is evident, and not at all surprising, that the tenuous seed plasma is fairly transparent to the RMF.
- However, once there is RMF breakdown of the seed plasma, the electron density goes up, thus increasing the electron-ion collision frequency and decreasing the effective skin depth. These effective skin depths go from 19cm to 54cm for our RMF plasma conditions. The diameter of the flux conservers is 16cm.
- Increasing the forward power into the RMF antennas increases the field magnitude by $B_{RMF} \sim 1G\left(\frac{P_f(kW)}{0.934}\right)^{1/2}$ thus linearly increasing the electron cyclotron frequency, which gives better penetration.
- Better penetration affects not only how far B can travel into the plasma, but also the time it takes for full penetration. This effect was also observed in the time it takes the Hβ emissions to reach a steady state.

Hydrogen plasma
Seed Power: P_f = 11W
Axial Field: B_a = 180.72G (251A)
Fill Pressure: P_0 = 0.610mTorr
RMF Power: Varied from 16.4kW to 54.5kW

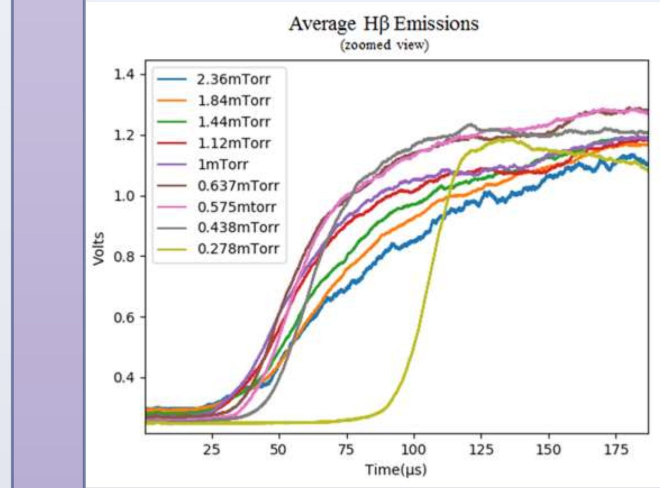


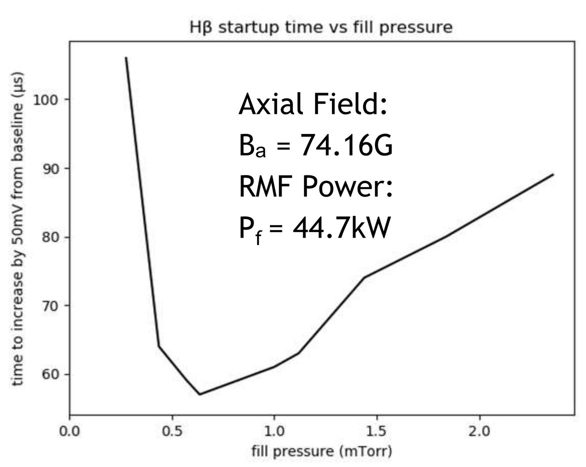




Initial Pressure

- The pressure dependence can be thought of in analogy to Paschen's law.
- The ionization rate of the seed plasma will be determined by $\frac{\partial n_e}{\partial t} = n_o n_e \langle \sigma v \rangle$, where the velocity averaged ionization cross section ($\langle \sigma v \rangle$) depends on the electron temperature.
- At high pressures, the electron-neutral collision rate ($n_o \langle \sigma v \rangle$) is high, which keeps the electrons from accumulating much kinetic energy.
- At medium pressures, $n_o \langle \sigma v \rangle$ is such that the electrons can gain more energy and n_e is still high enough to create a chain reaction relatively quickly.
- At low pressures, the electrons gain a lot of energy before they collide. The breakdown has a delayed initiation, but a rapid increase once initiated.





Conclusions

- Although breakdown occurs without it, presence of a seed plasma is essential for good RMF power coupling, but the RMF plasma behavior appears largely insensitive to seed plasma powers above 10W.
- Low axial magnetic fields allow fast RMF plasma breakdown, but low Hβ emissions. High axial magnetic fields impede azimuthal current induction for a short time and also result in moderate to low emissions. For a given pressure, there exists an intermediate axial field that allows high Hβ emissions without compromising τ.
- According to the current model for RMF penetration, the PFRC-2 is well within the thresholds for very good penetration, which is promising for further upscaling.
- The effects that the initial gas pressure has on the plasma are very complex, but during RMF breakdown, the electron-neutral collision rate is a dominating factor.

References and Acknowledgments

(Special thanks to Eugene Evans for his programming expertise and tech savvy.)

[1] S.A Cohen, B. Berlinger, C. Brunkhorst, A. Brooks, N. Ferraro, D.P. Lundberg, A. Roach, and A.H. Glasser, "Formation of Collisionless High-β Plasma by Odd-Parity Rotating Magnetic Fields", Phys. Rev. Lett. 98, 145002 (2007)

[2] K. Papadopoulos, A. Zigler, D. L. Book, C. Cohen, and D. Hashimshony. "Breakdown of Magnetic Insulation in Semiconductor Plasmas". IEEE Transactions on Plasma Science. vol.24, Issue 3, Jun 1996.

[3] W. N. Hugrass, R. C. Grimm. "A numerical study of the generation of an azimuthal current in a plasma cylinder using a transverse rotating magnetic field". Journal of Plasma Physics (1981), vol. 26, part 3, pp. 455-464.

Contacts

- Gabriel Gonzalez Jusino: gabriel.gonzalez38@upr.edu
- Sam Cohen: scohen@pppl.gov