Observation of minority fast electron dynamics in a low-pressure RF discharge and magnetic nozzle

ExB Workshop
November 2, 2018

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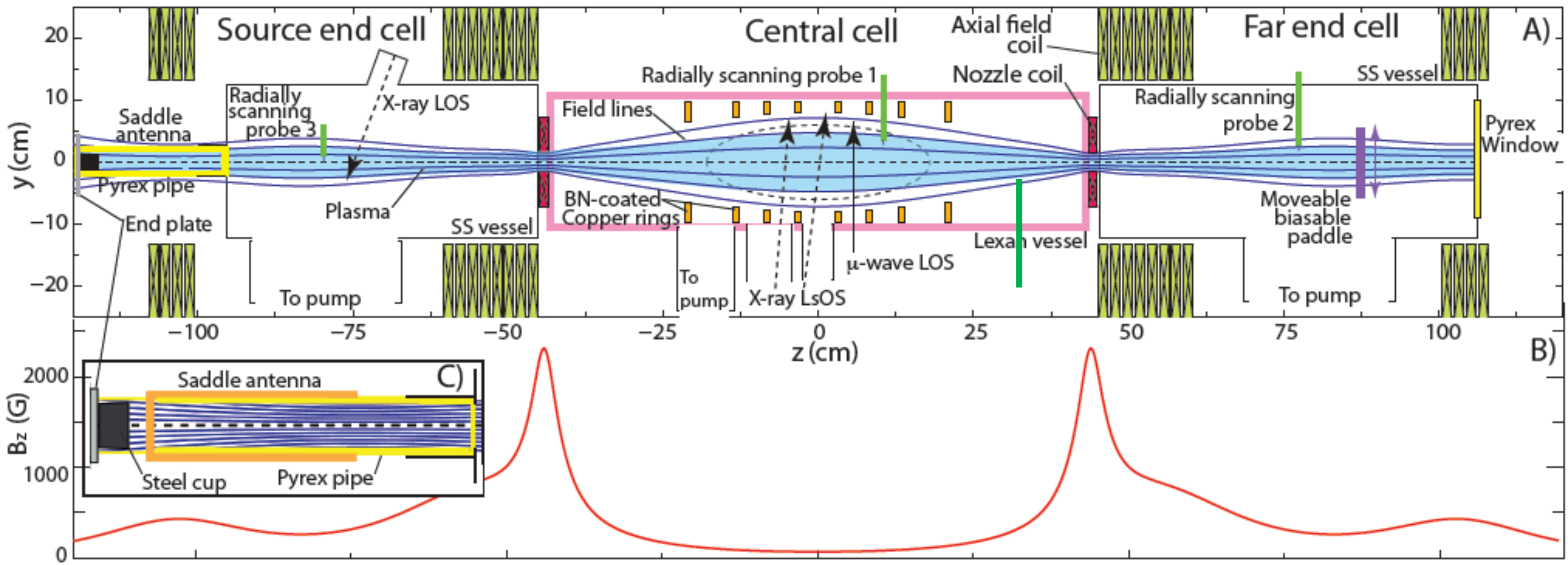
- PFRC-II run as low-pressure RF-coupled magnetic mirror
- 1% minority electrons: 300 – 600 eV (“warm”) temperature near source
  - Surface interaction: RF self bias and ion-induced secondary electron emission
- 0.1% minority electrons: 1 – 3 keV (“hot”) temperature in mirror
  - Fermi acceleration caused by the 1% warm electrons
- Observed to change **potential structures, power balance,** and **discharge properties**

Apparatus

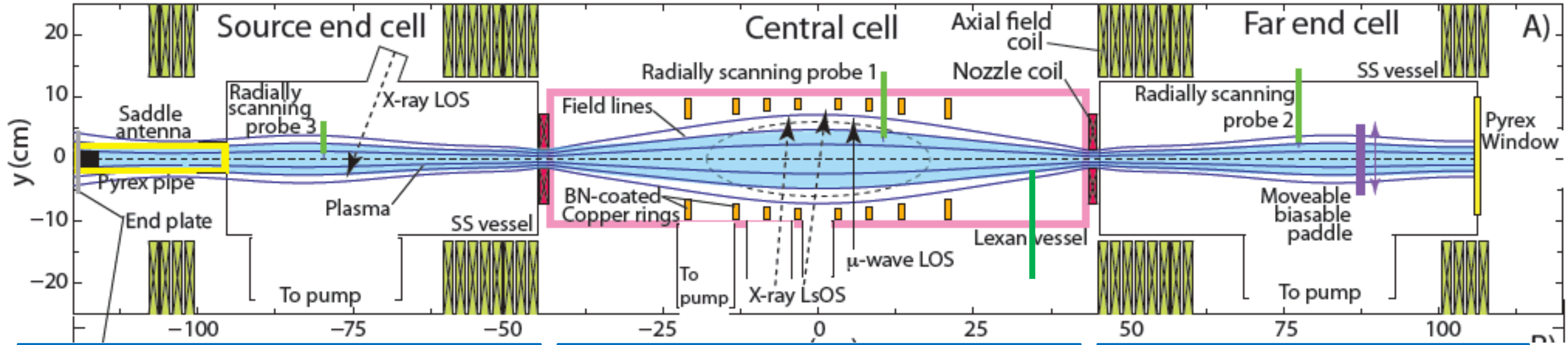
- 1m central mirror cell
- $B_{min} \approx 200\ G$
- Mirror ratio $R \approx 10 - 40$
- Pressure 0.01 – 10 mTorr
- 3 cells: Source, Central, Far

- 0 - 500 W at 7 - 27 MHz
- Bulk plasma at $T_e \approx 5\ eV$, $n_e \approx 10^{10-11}/cm^3$
- Probes for 0 – 50 eV
- X-ray for 200 eV – 30 keV



The same chambers as the Princeton Field Reversed Configuration Experiment (PFRC)

MEASUREMENTS



SEC:

- "Warm" electrons:
  - $T_e \sim 300$ eV
  - $n_e \sim 3 \times 10^8/\text{cm}^3$
  - 30 W
- RF self-bias

CC:

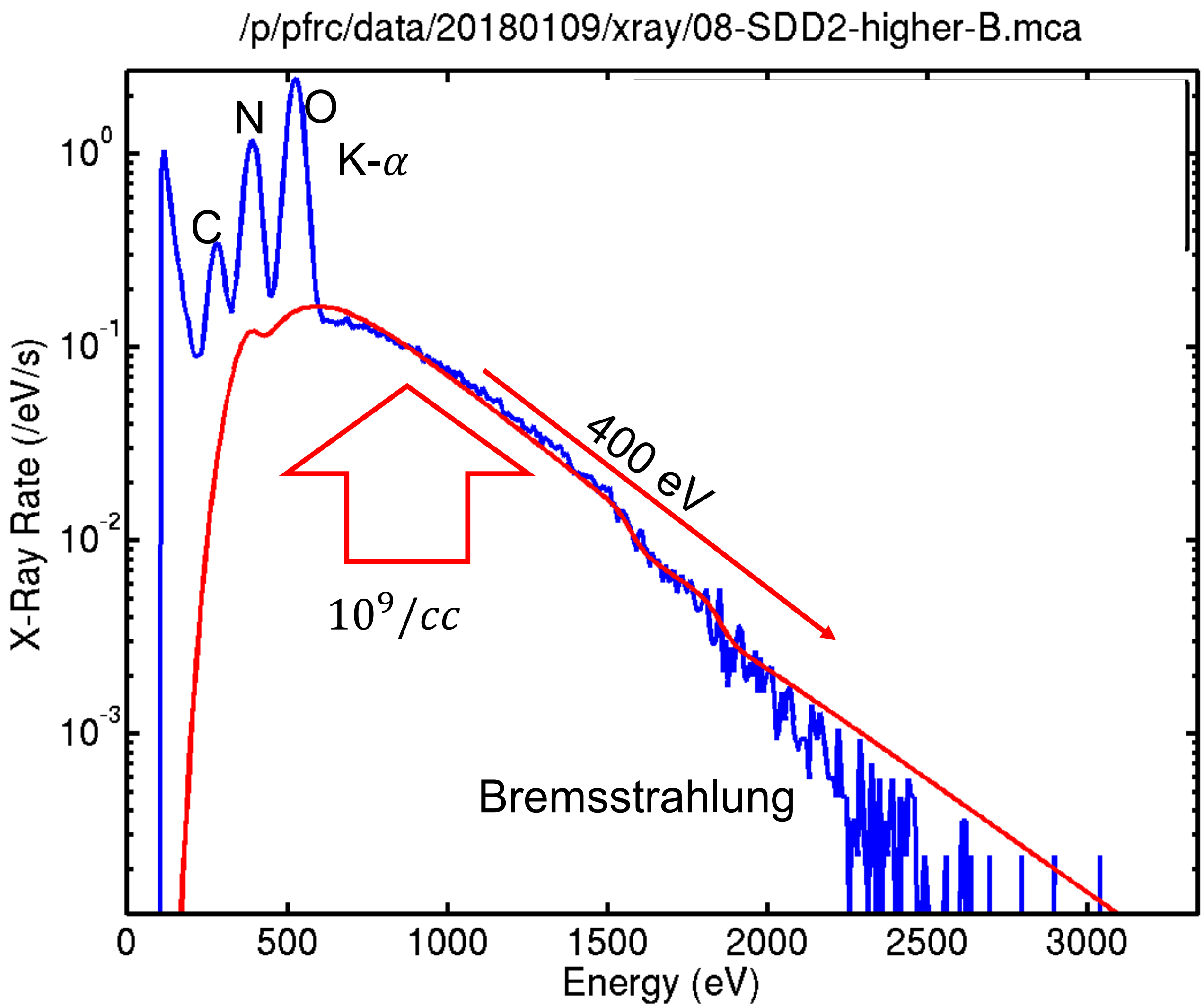
- Warm electrons persist:
  - >300 transits
- "Hot" electrons:
  - $T_e \sim 3$ keV
  - $n_e \sim 3 \times 10^7/\text{cm}^3$
  - 3 W
  - Individual electrons above 30 keV
  - >10,000 transits
- Potential fluctuation:
  - ~ 50 V amplitude
  - ~ 200 MHz frequency

FEC:

- Potential drop:
  - -600 V
- Infer beam
- Sputter of tantalum by hydrogen
- Pressure-dependent heat flux

SEC X-RAY SPECTRUM

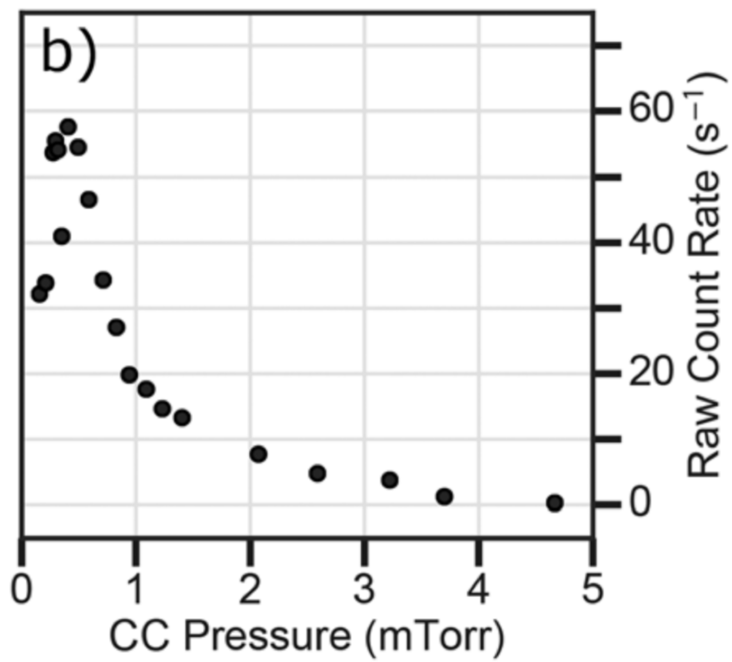
SDD detects $n_e \approx 10^9/cc, T_e \approx 400\ eV$ electrons, 1% amongst the bulk population[3][4]



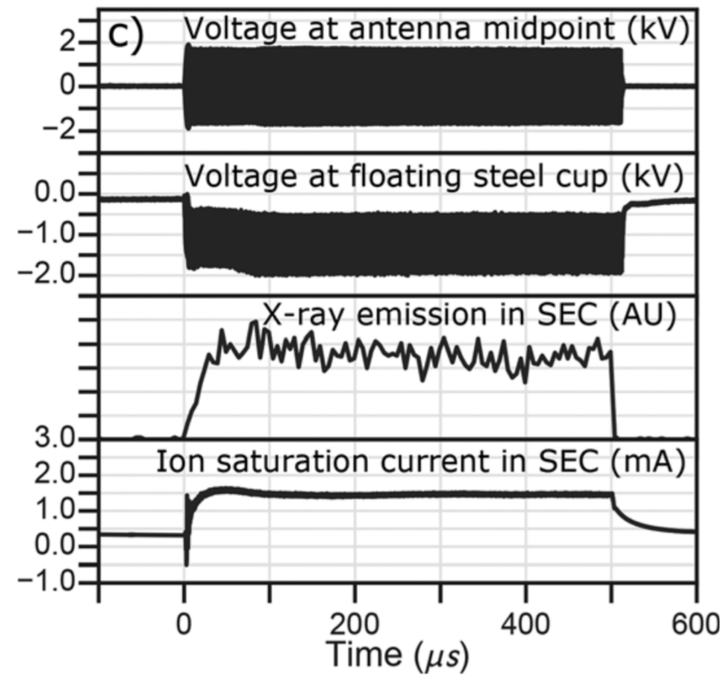
SDD covers energy range of K-α spectral lines from C, N, O, and Bremsstrahlung.
Temperature and density are determined from Bremsstrahlung.

SEC MEASUREMENTS

We deduce: self-bias effect causes very negative potentials on electrode
Ion-induced secondary electron emission causes electrons to be born and accelerated



X-ray count rate from H2 plasma vs gas pressure in the SEC. From [3]

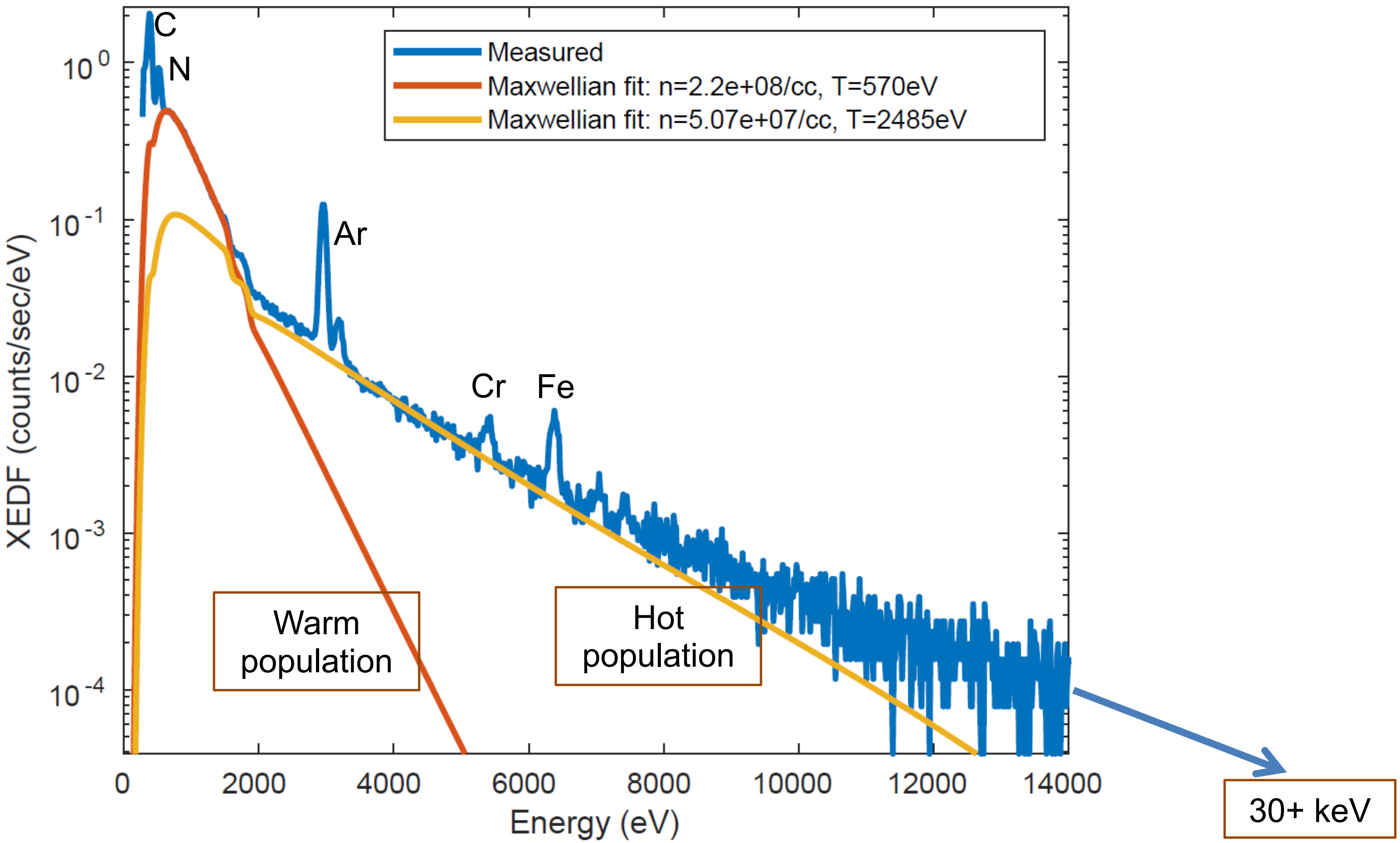


Profiles in time: antenna voltage, steel cup voltage, x-ray count rate, Langmuir ion saturation current. From [3]

This process is more likely to happen:
When discharge is more **capacitive** than **inductive**.
When **pressure is low** so electron **mean free path is long**.

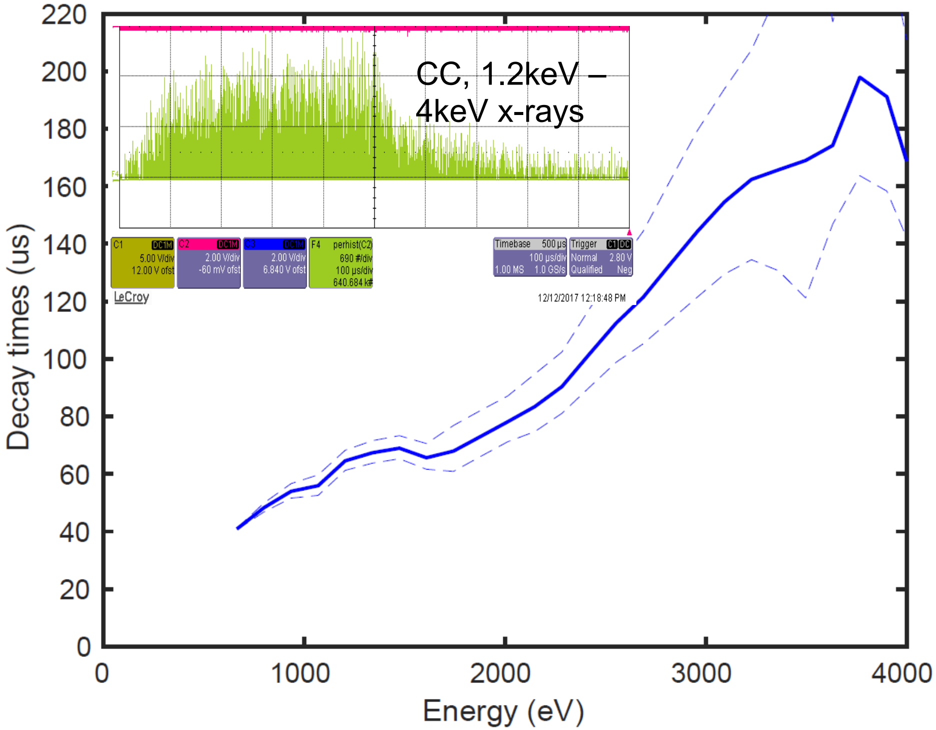
CC X-RAY SPECTRUM

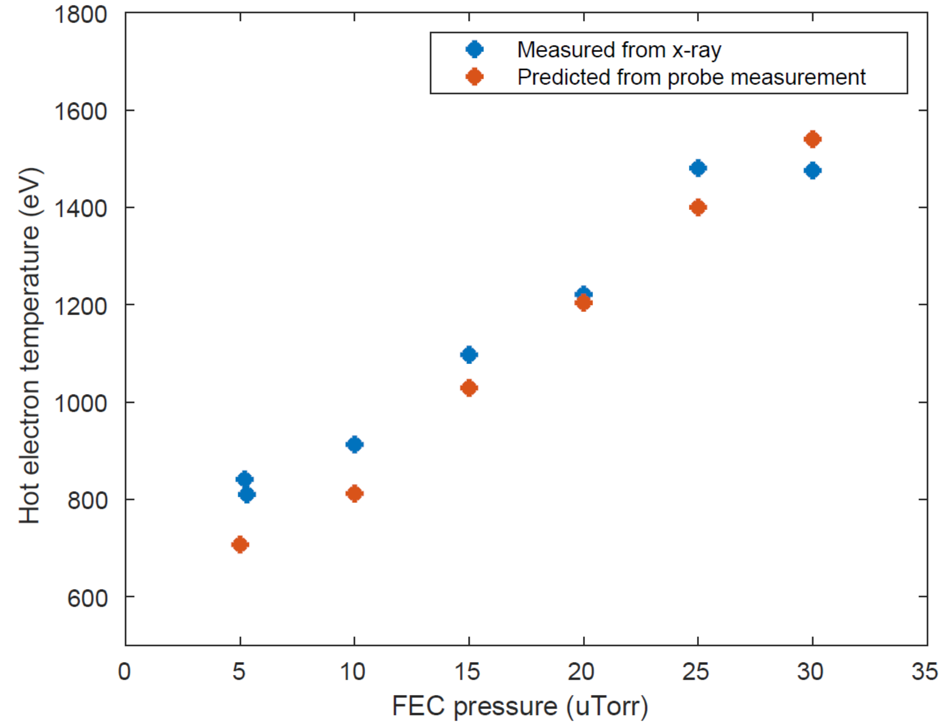
SDD detects $n_e \approx 10^8/cc, T_e \approx 3\ keV$ electrons, 0.1% amongst the bulk population [4]



This is **quite hot**

CC FLUCTUATION AND X-RAY PROPERTIES



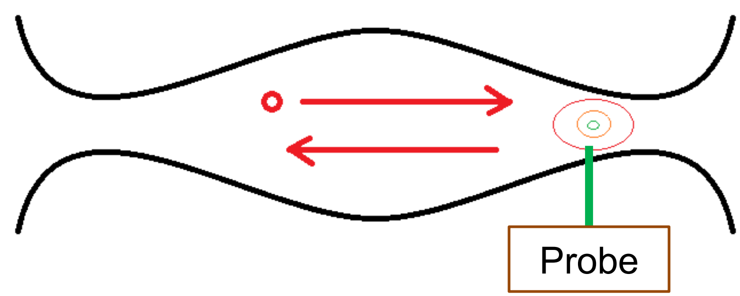


Electrons of higher energy persist for longer time after RF cessation. These are tens of thousands of mirror transits, hundreds of microseconds

$$T_{eff} = \Delta E \sqrt{\frac{\tau}{t_t}}$$

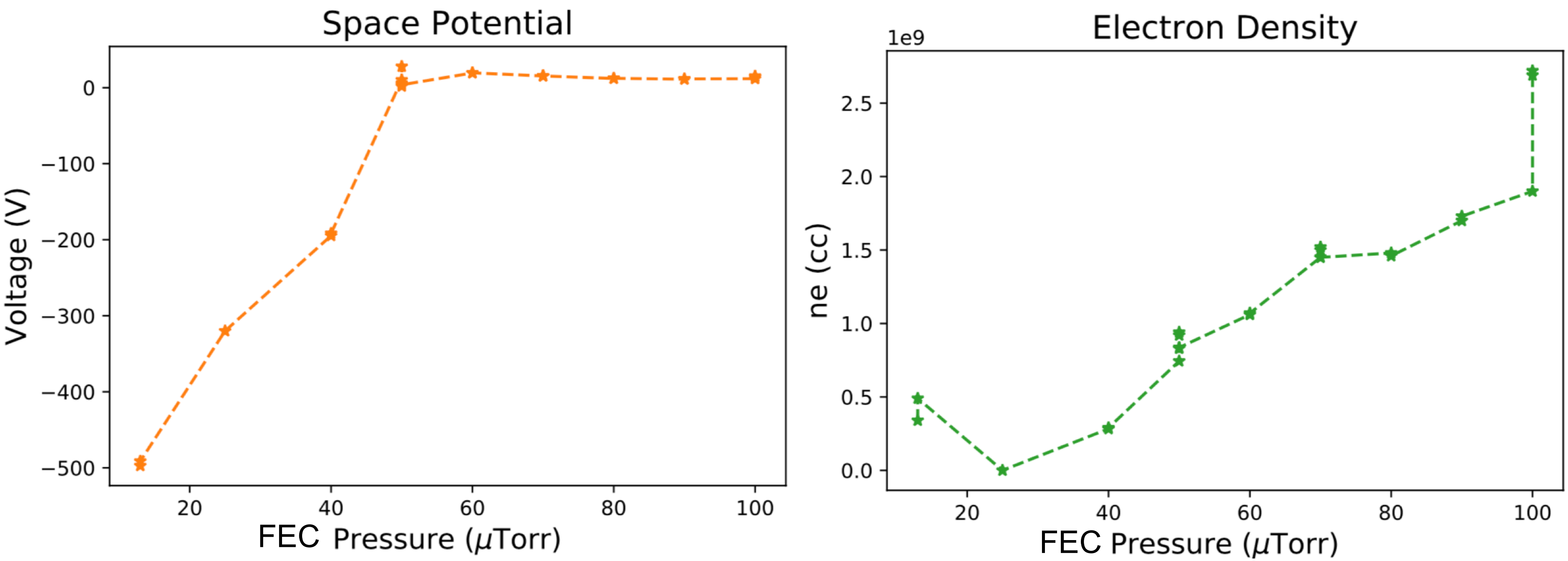
Increasing the FEC pressure:

1. Increases the amplitude of the ~200 MHz fluctuation (~50 V)
2. Increases the hot electron temperature proportionally.



FEC CONDITIONS

Far End Cell (FEC, termination of plasma column) has a Langmuir probe and a Tantalum (low-sputtering) paddle whose floating potential can be measured.[4]



Plots and measurements by Tony Qian for SULI internship

- Space potential is measured to be < - 600 V
- Electron density is measured to increase with increasing FEC pressure (ionization)
- We suppose these ionization-born electrons are responsible for the fluctuation in the CC

FEC PADDLE BEHAVIOR

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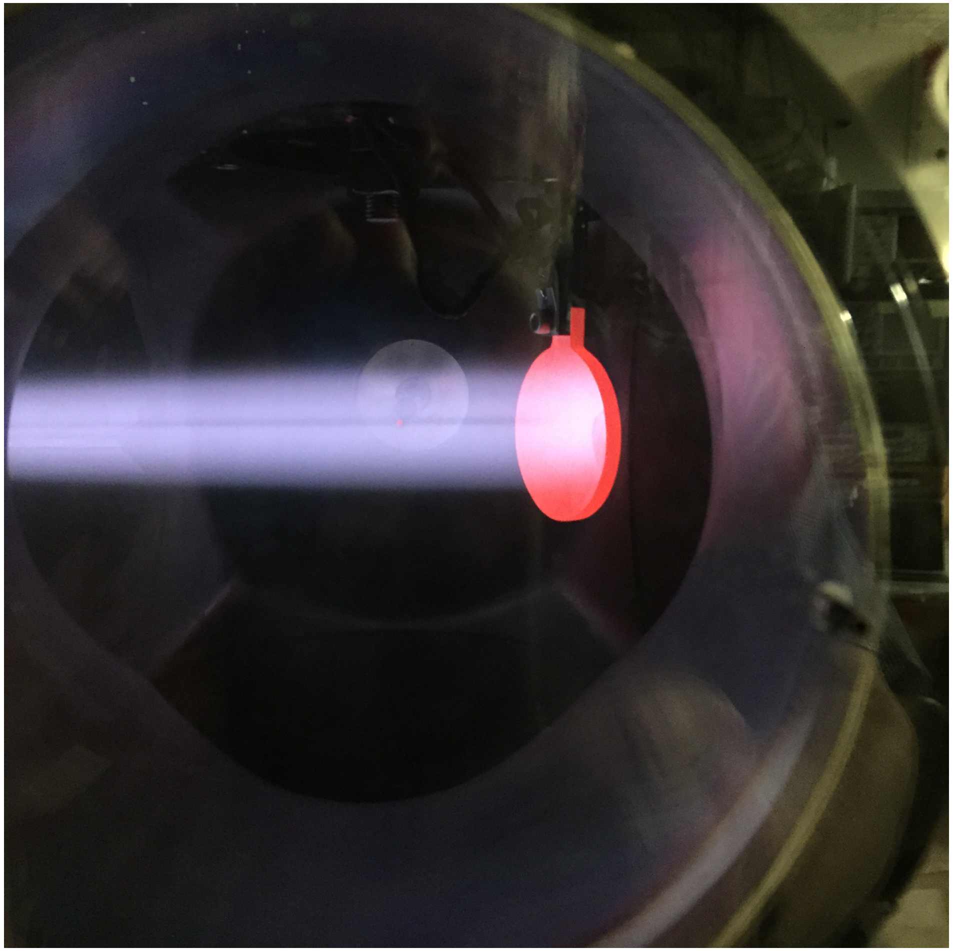

Photo by S. A. Cohen

- Paddle floating potential is measured to be < -1 kV
- Tantalum sputter-coats the FEC regularly (feed gas is Hydrogen)
- Paddle glow is observed under specific circumstances (wait 2 slides)

FEC PADDLE BEHAVIOR

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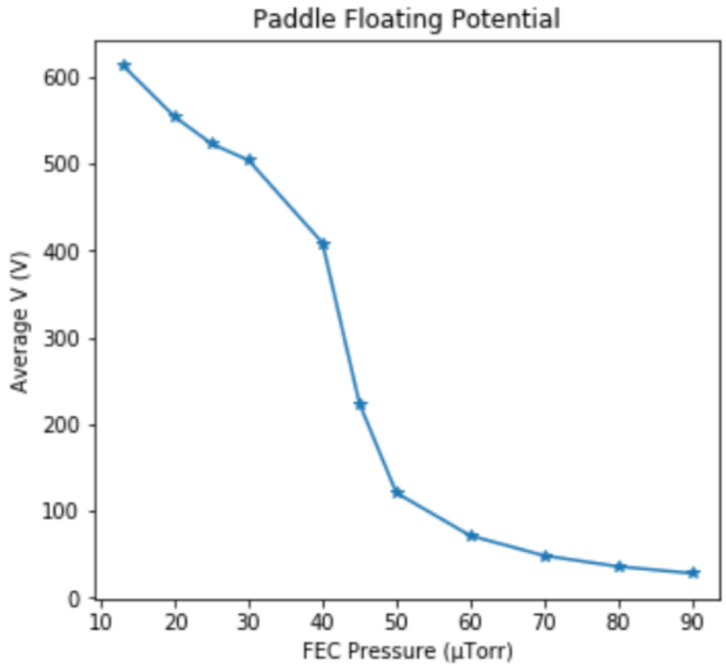
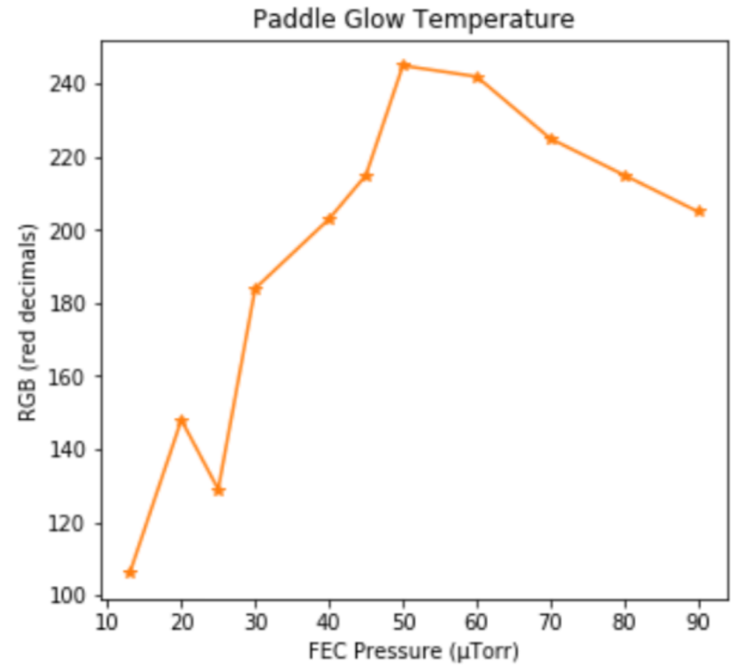
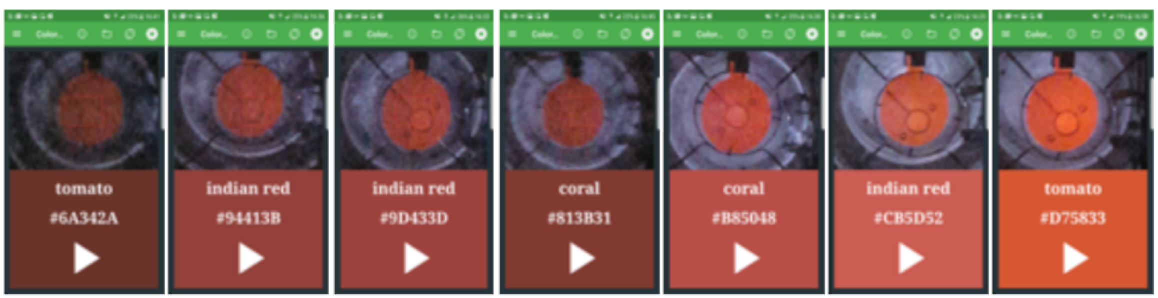
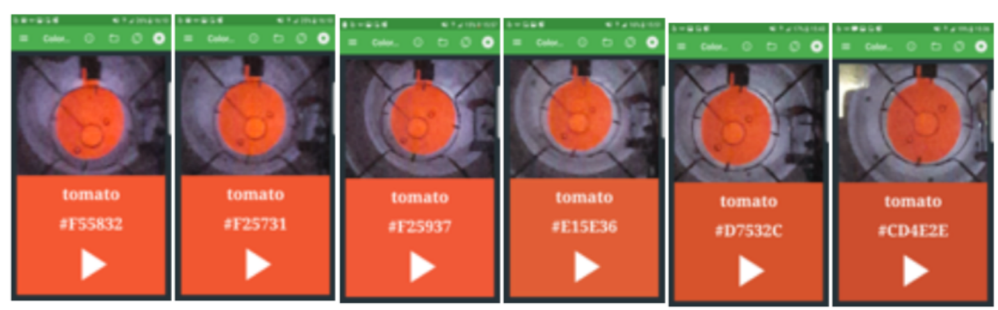
Photos by S. A. Cohen

- When plasma is terminated on a sapphire plate: Visibly hollow light emission profile









Reproduced from Tony Qian's presentation to the PFRC group, April 27, 2018

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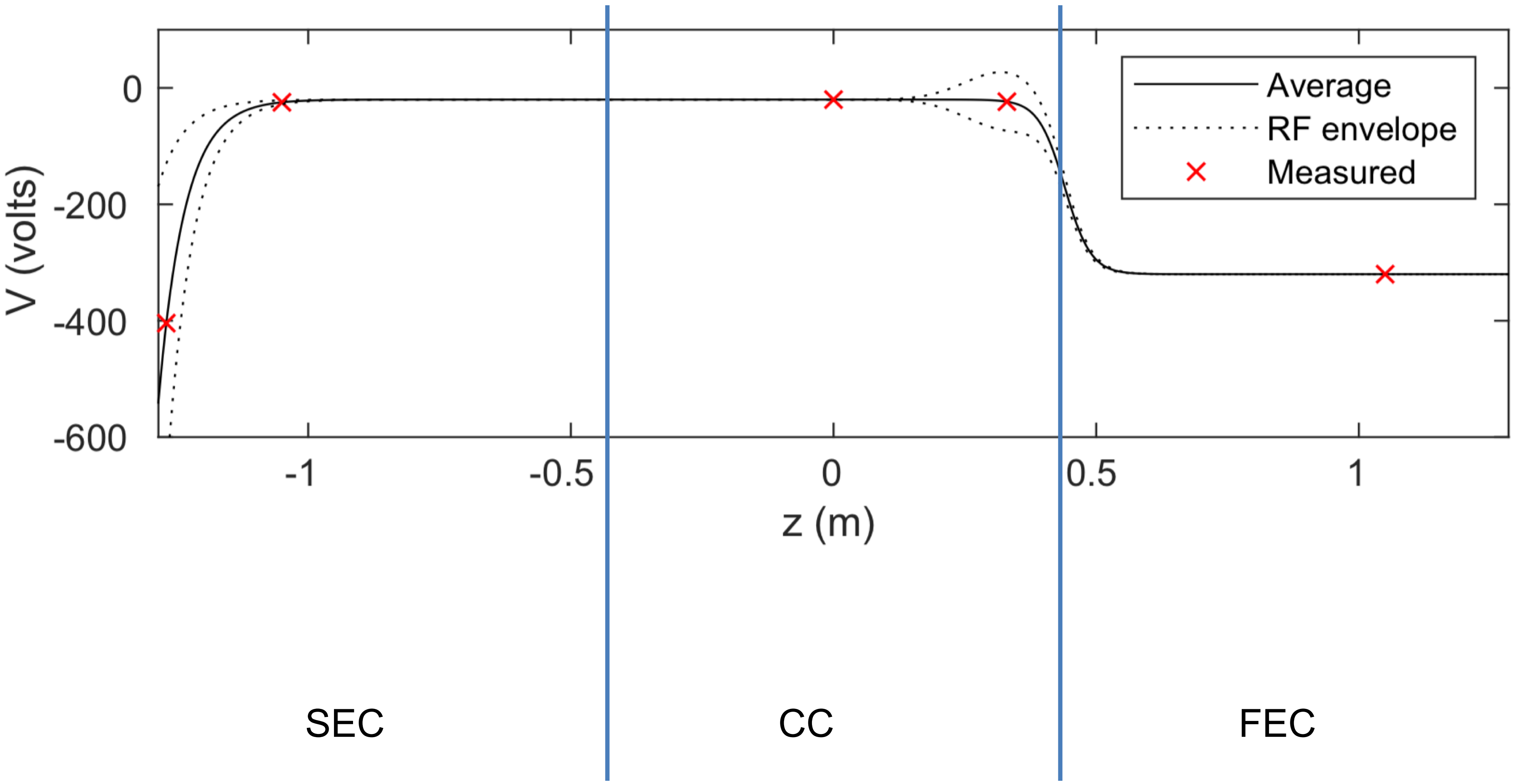
SUMMARY: GLOBAL POTENTIAL PROFILE



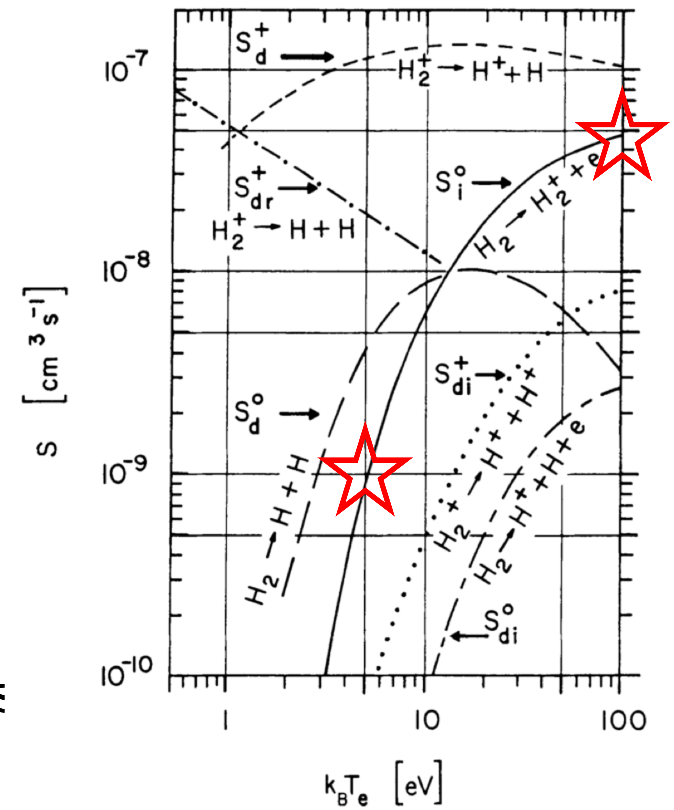
CONCLUSION

"Might I have fast electrons in my device?"

- Maybe, if you haven't looked for them (x-rays, etc)

"When are fast electrons important?"

- If $n_f\sqrt{T_f} \sim n_b\sqrt{T_b}$: Fast particle flux is significant.
  - Potential structures at the nozzles and sheaths
- If $n_f T_f/\tau_f \sim n_b T_b/\tau_b$: Power from fast electrons is significant
  - Power balance
- If $n_f\langle\sigma v\rangle_f \sim n_b\langle\sigma v\rangle_b$: Ionization from fast electrons is significant
  - Discharge sustained by different process
  - Plasma where you don't expect it



Rate constants, including for ionization, for thermal electrons in Hydrogen. Fast electrons ionize H_2 >50x more easily. [5]

REFERENCES

[1] http://amptek.com/
[2] Swanson, C., P. Jandovitz, and S. A. Cohen. "Using Poisson-Regularized Inversion of Bremsstrahlung Emission to Extract Full Electron Energy Distribution Functions from x-Ray Pulse-Height Detector Data." *AIP Advances* 8, no. 2 (February 1, 2018): 025222. https://doi.org/10.1063/1.5019572.
[3] Jandovitz, P., C. Swanson, J. Matteucci, R. Oliver, J. Pearcy, and S. A. Cohen. "Demonstration of Fast-Electron Populations in a Low-Pressure, Low-Power, Magnetized RF Plasma Source." *Physics of Plasmas* 25, no. 3 (March 1, 2018): 030702. https://doi.org/10.1063/1.4998735.
[4] Swanson, C. "Measurement and Characterization of Fast Electron Creation, Trapping, and Acceleration in an RF-Coupled, High-Mirror-Ratio Magnetic Mirror." Doctoral thesis, Princeton University, 2018.
[5] Harrison, M. F. A. "Atomic and Molecular Collisions in the Plasma Boundary." In *Physics of Plasma-Wall Interactions in Controlled Fusion*, edited by D. E. Post and R. Behrisch, 281–349. Boston, MA: Springer US, 1986. https://doi.org/10.1007/978-1-4757-0067-1_7.