Modeling Atomic and Molecular Plasma Processes During Startup of PFRC-2

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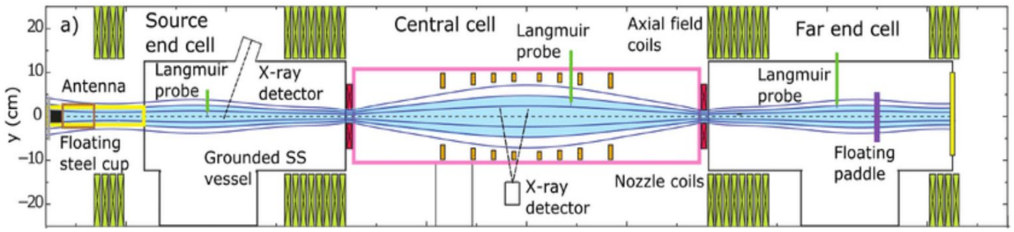
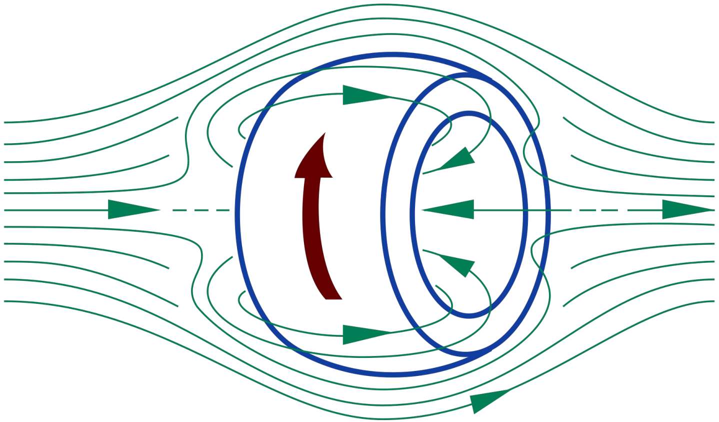
Princeton Field Reversed Configuration-2 (PFRC-2)

What is PFRC-2?

- One of a series of devices to determine the feasibility of a novel compact reactor design
- Uses a rotating magnetic field (RMF) to heat the plasma and form an FRC
- Three major sections: source end cell (SEC), center cell (CC), and far end cell (FEC)





Noteable PFRC-2 phenomena

- Mirror coils between each segment trap particles
- The end plates in the SEC and FEC have changing potentials during operation
  - protons hitting these plates cause secondary electron emission
  - if the potential is highly negative, these electrons are accelerated to several keV

Startup of PFRC-2

- A helicon antenna in the SEC forms a low density ($n_e \sim 10^9$ cm^{-3}) seed plasma
- Seed plasma is transported to the CC where it absorbs RMF power, ionizes the gas in the CC, and forms an FRC
- This process of going from the seed plasma to the high density ($n_e \sim 10^{13}$ cm^{-3}) final plasma is known as densification and is the part of startup we are investigating

Modeling startup

Goals

By modeling startup, we hoped to learn more about:

- the general behavior of the plasma as densification occurs
- how initial conditions affect densification
- the relative importance of different processes
- what role the high energy electrons play in startup

Model simplifications

- 0D model
  - not directly modeling FRC, spatial gradients are free parameters
- Lumped volume
- Excited states wrapped into collisional radiative rate coefficients
- Assume magnetic moment μ is adiabatic
- Assume all distributions are Maxwellian
- Recycling is not delayed

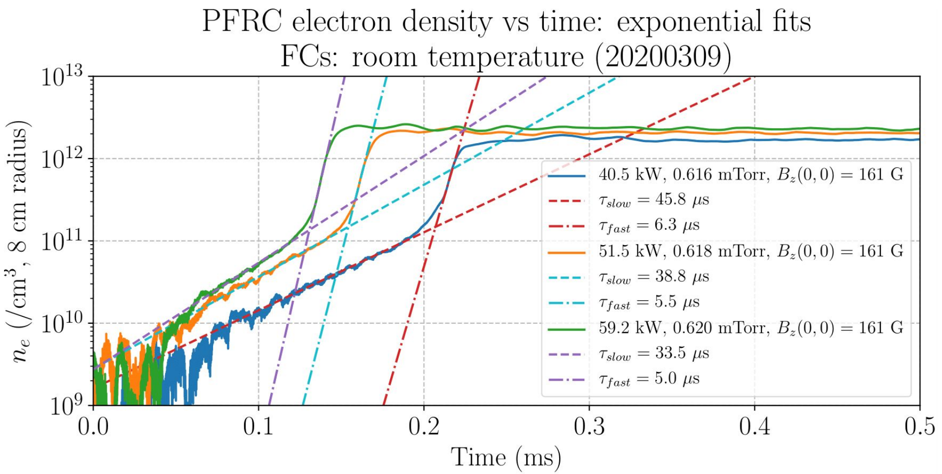
How the model works

- We keep track of the number densities and total energies for the species of interest: low energy e^-, high energy e^-, p^+, H, H_2, and H_2^+
- Then with ODEs for these quantities and some initial values, we use SciPy’s solve_ivp method to evolve them through time

Results

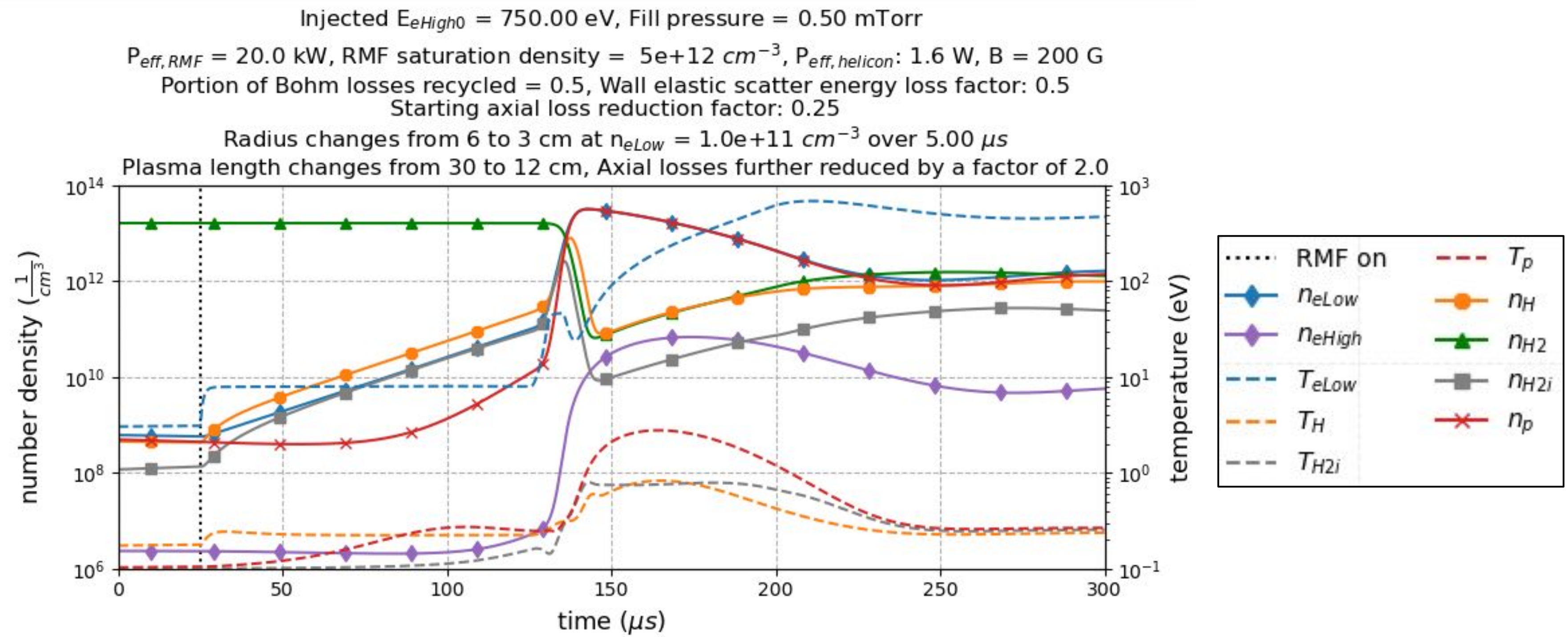
Two timescales of densification

- Experimentally, we find there to be two timescales of densification
- Exact reason unknown
- One hypothesis is that the plasma radius shrinks
    - we trigger a radius change (6 cm to 3 cm) at a density threshold (1e11/cm^3)



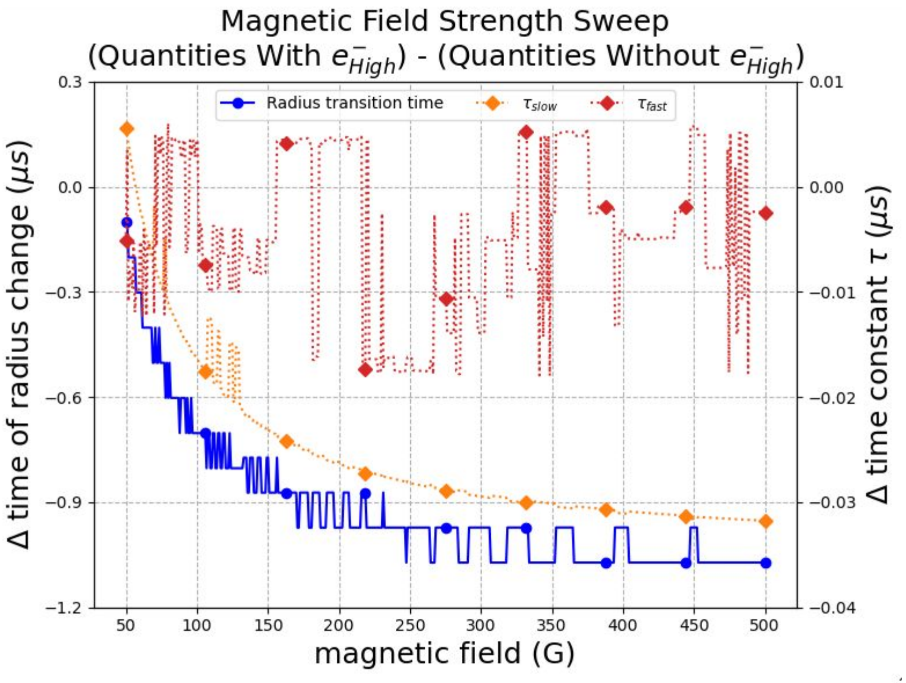
Failing to quantitatively match experimental results

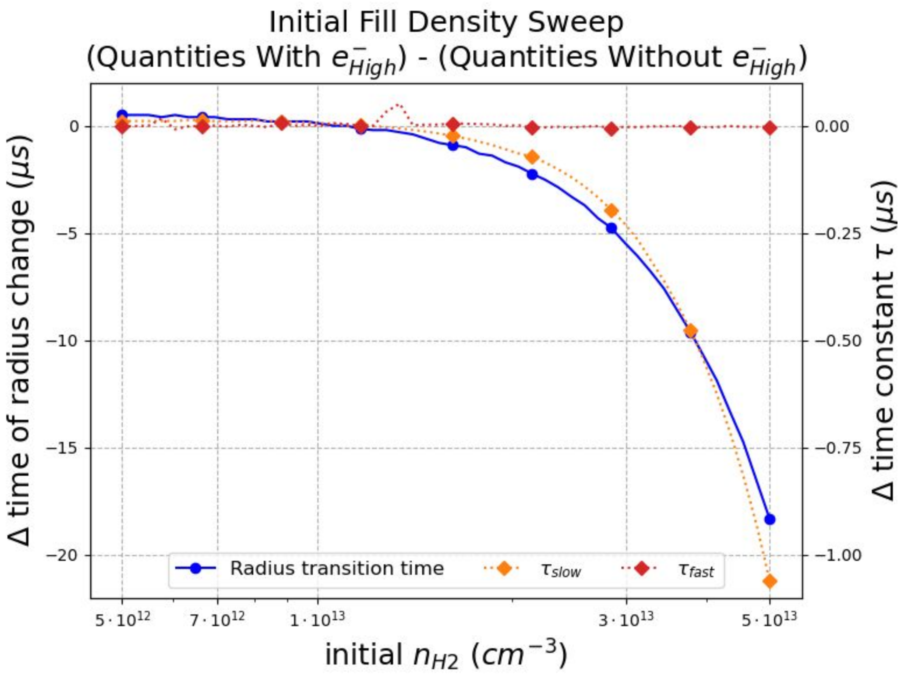
- We’ve only managed to qualitatively match the behavior of two timescales
- Number of possible reasons
  - the effect is not due to a change in plasma radius
  - highly simplified RMF-plasma coupling
  - many free variables
  - lumped volume, maybe distributions are not Maxwellian, ...



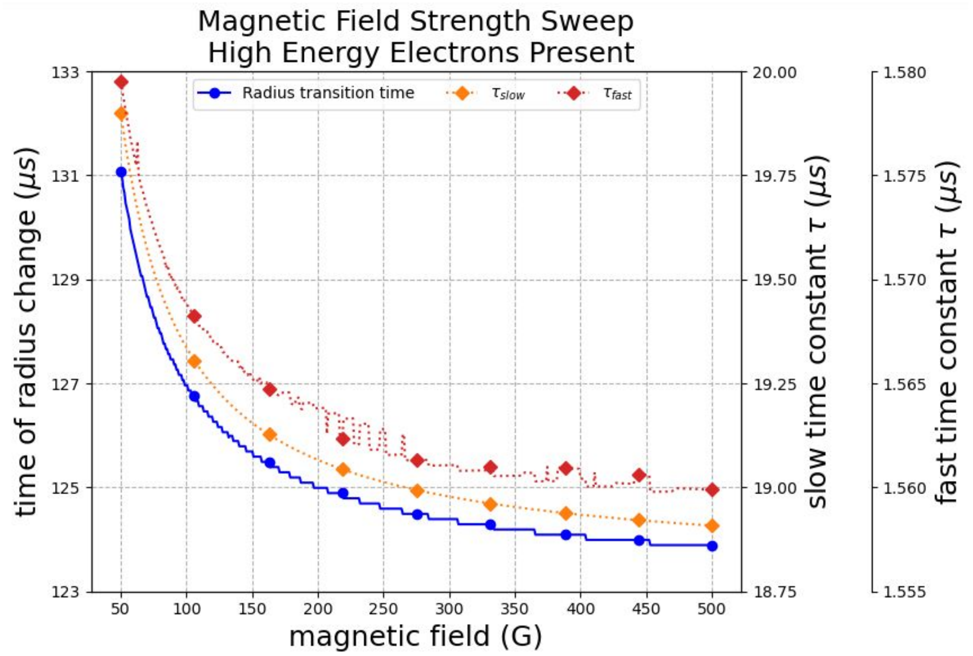
Injected E_{eHigh0} = 750.00 eV, Fill pressure = 0.50 mTorr
$P_{eff,RMF}$ = 20.0 kW, RMF saturation density = 5e+12 cm^{-3}, $P_{eff,helicon}$: 1.6 W, B = 200 G
Portion of Bohm losses recycled = 0.5, Wall elastic scatter energy loss factor: 0.5
Starting axial loss reduction factor: 0.25
Radius changes from 6 to 3 cm at n_{eLow} = 1.0e+11 cm^{-3} over 5.00 μs
Plasma length changes from 30 to 12 cm, Axial losses further reduced by a factor of 2.0
number density ($\frac{1}{cm^3}$)
temperature (eV)
time (μs)
RMF on
n_{eLow}
n_{eHigh}
T_{eLow}
T_H
T_{H2i}
T_p
n_H
n_{H2}
n_{H2i}
n_p

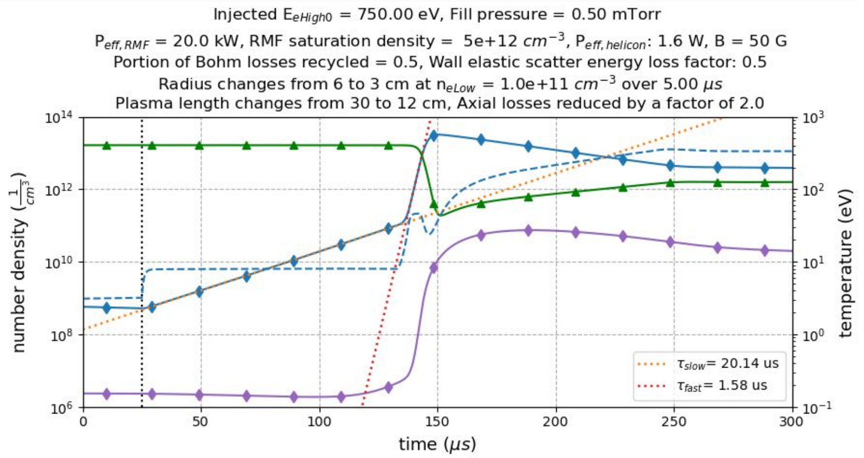
Effects of high energy electrons

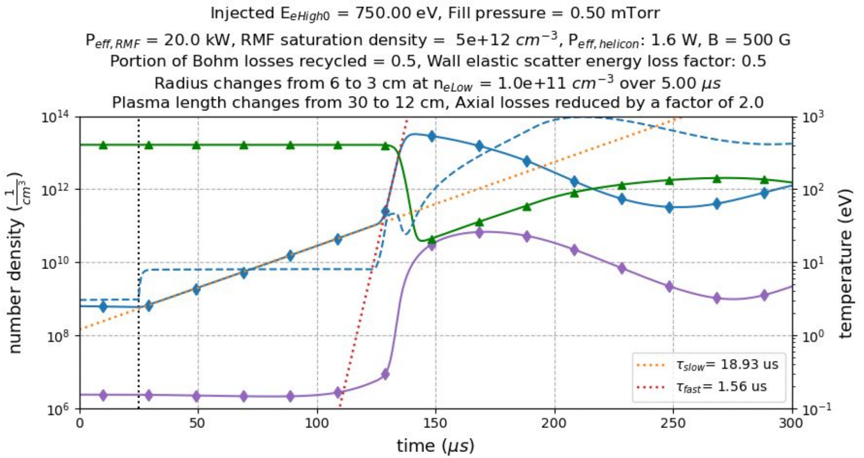




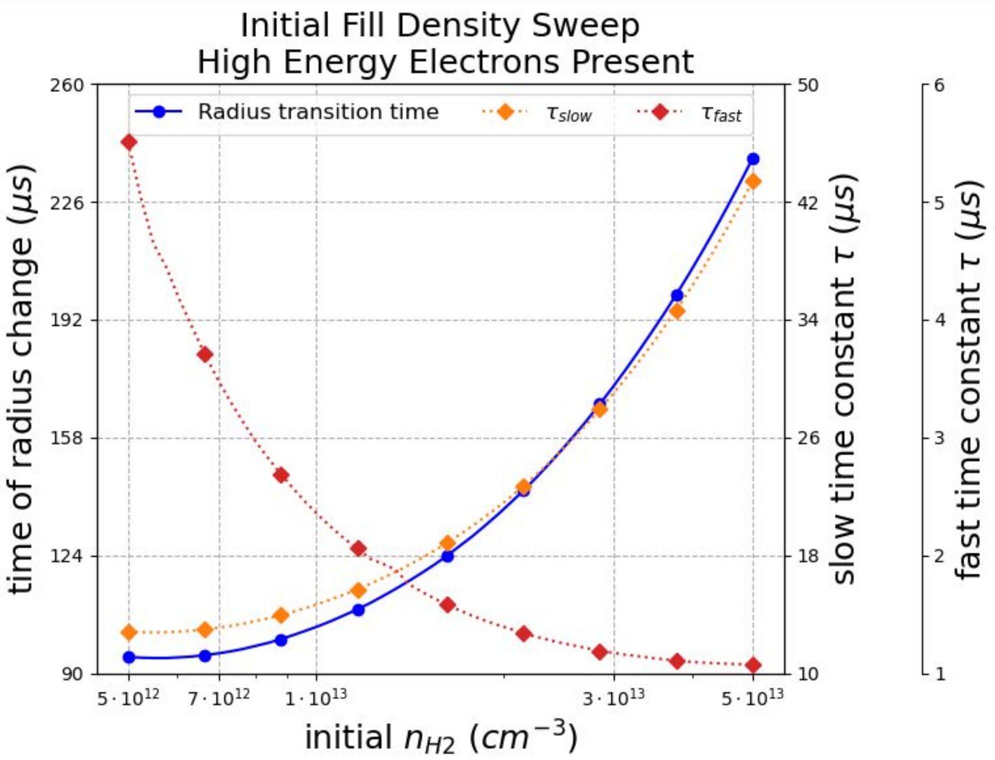
Magnetic field sweep

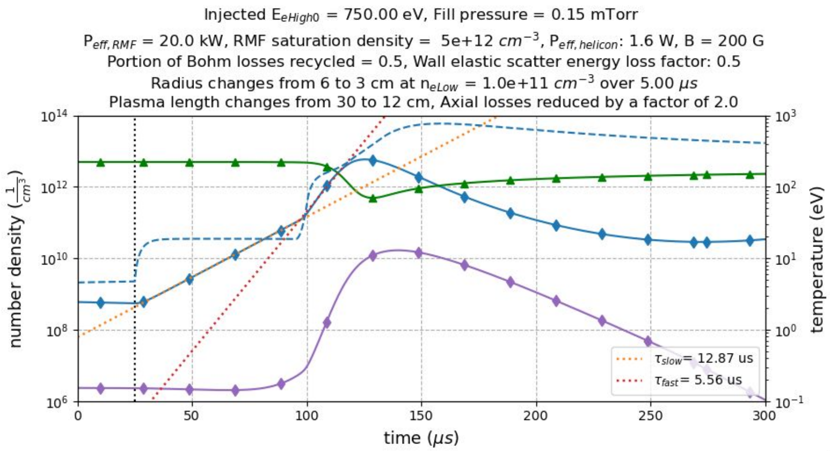


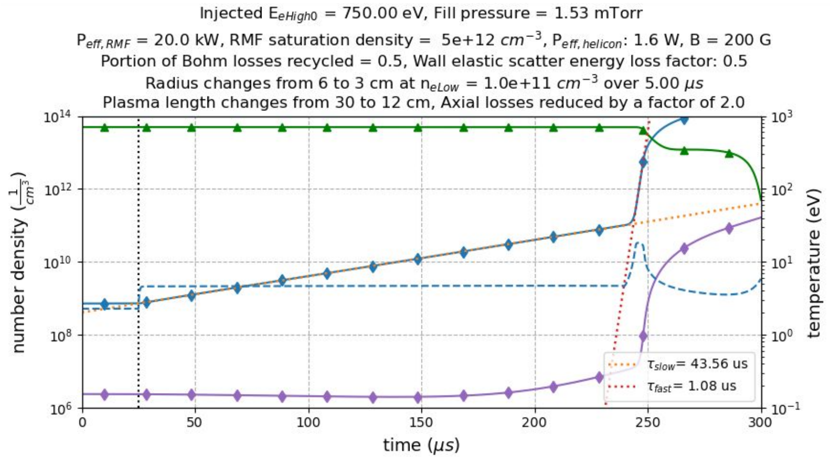




Initial H_2 density sweep







Conclusions

- Some parts of parameter space show differences with and without high energy electrons
  - those that do take longer to reach the fast densification region without high energy electrons
- Increased confinement allows for quicker ionization
- A change in radius does produce two timescales of densification
  - does not imply that is the effect witnessed experimentally

Future work

Future Work

- Nonadiabaticity of magnetic moment for mirror confined particles
- Add a spatial dimension
- Further investigate how RMF interacts with the plasma

Any questions?

Acknowledgements

- Eugene for answering many, many questions
- The PFRC group for providing useful feedback
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Inter-particle processes included in the model

- Ionization:

  $e^- + H \rightarrow 2e^- + p^+$, $H_2 + e^- \rightarrow H_2^+ + 2e^-$

- Dissociative Ionization:

  $H_2 + e^- \rightarrow H + p^+ + 2e^-$, $H_2^+ + e^- \rightarrow 2p^+ + 2e^-$

- Recombination:

  $p^+ + e^- \rightarrow H$

- Dissociative Recombination:

  $H_2^+ + e^- \rightarrow 2H$

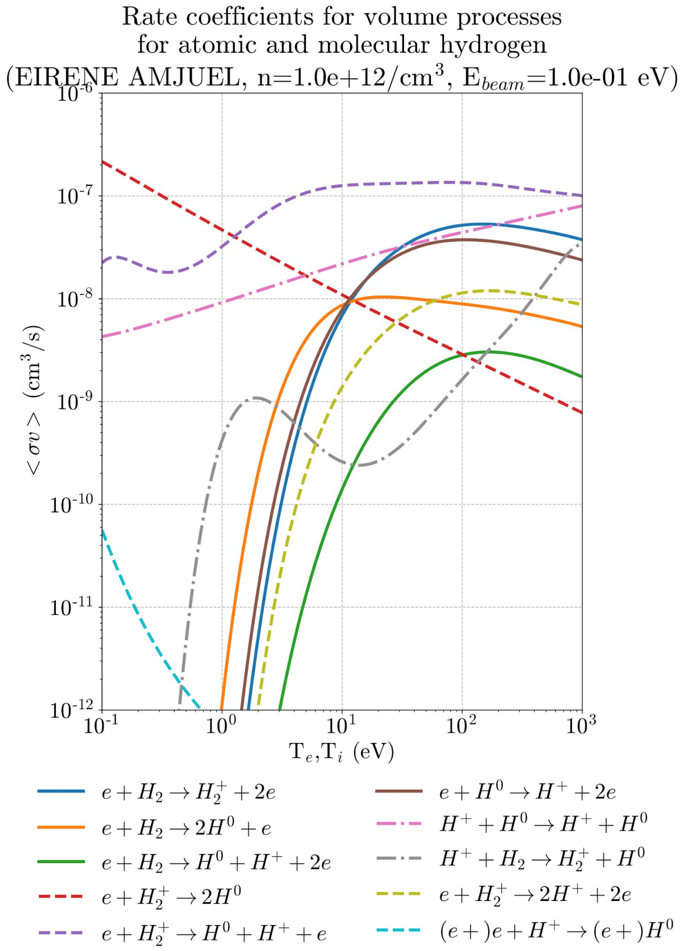
- Dissociation:

  $H_2 + e^- \rightarrow 2h + e^-$, $H_2^+ + e^- \rightarrow H + p^+ + e^-$

- Charge Exchange:

  $H_2 + p^+ \leftrightarrow H_2^+ + H$, $H + p^+ \rightarrow p^+ + H$

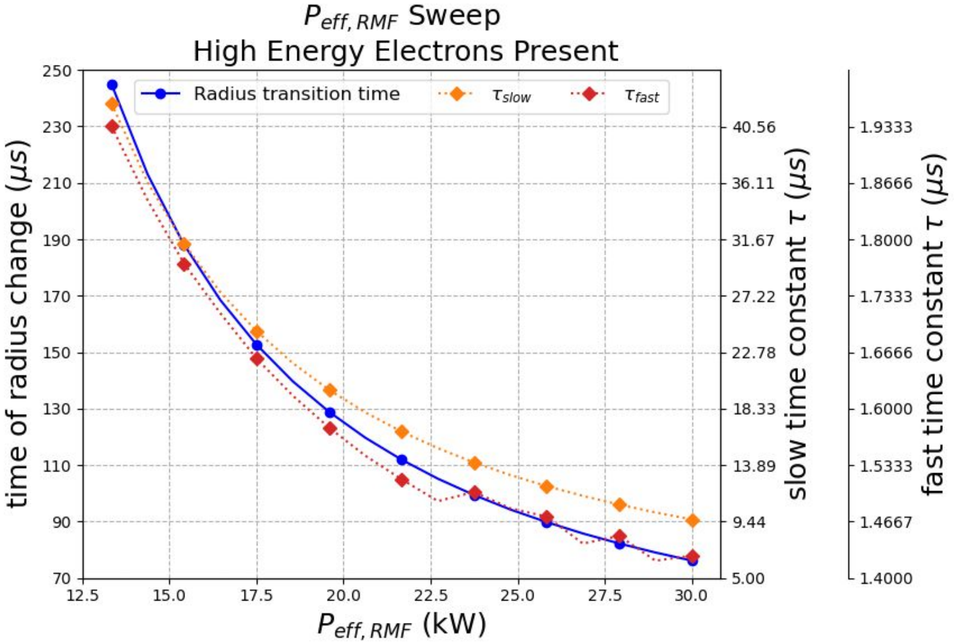
- Thermalization

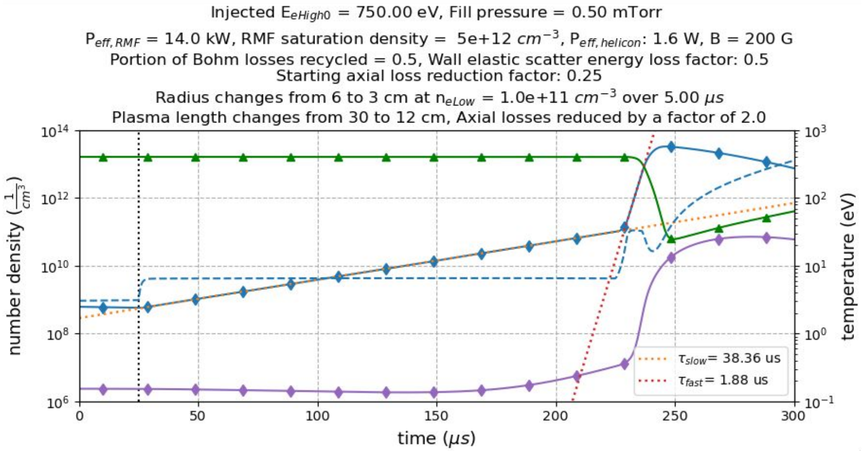


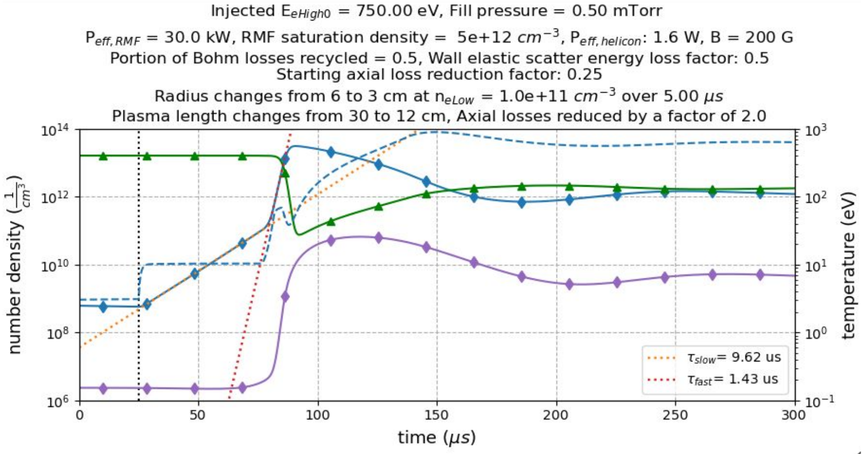
Other processes included

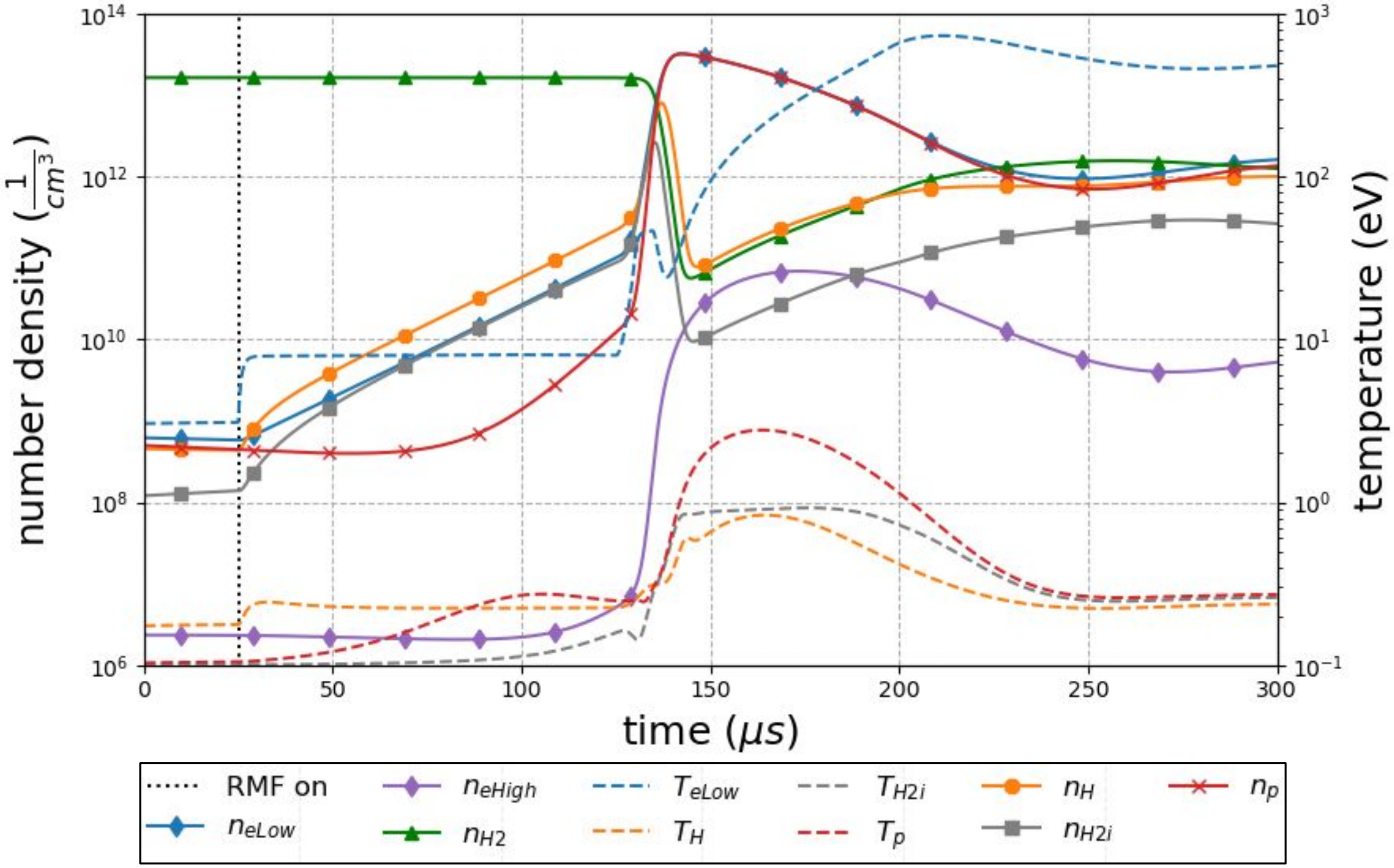
- Bohm losses
- Axial losses reduced by mirror effects
- Bremsstrahlung losses
- Recycling and elastic collisions with the chamber
- Influx of H_2 gas

$P_{eff,\,RMF}$ sweep

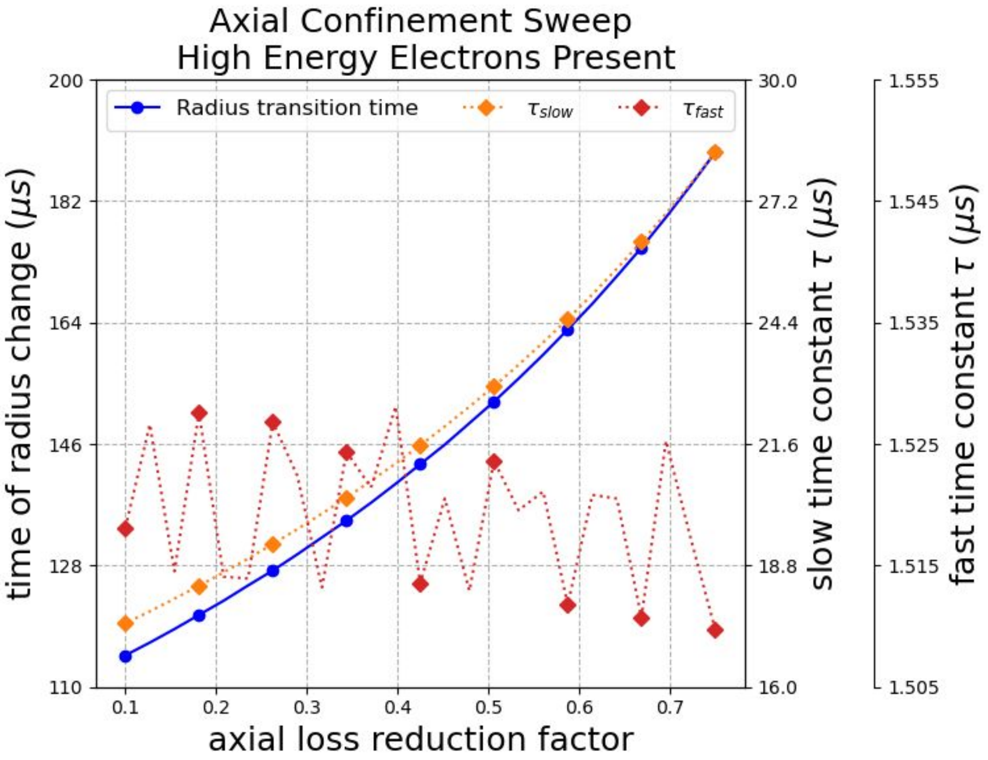


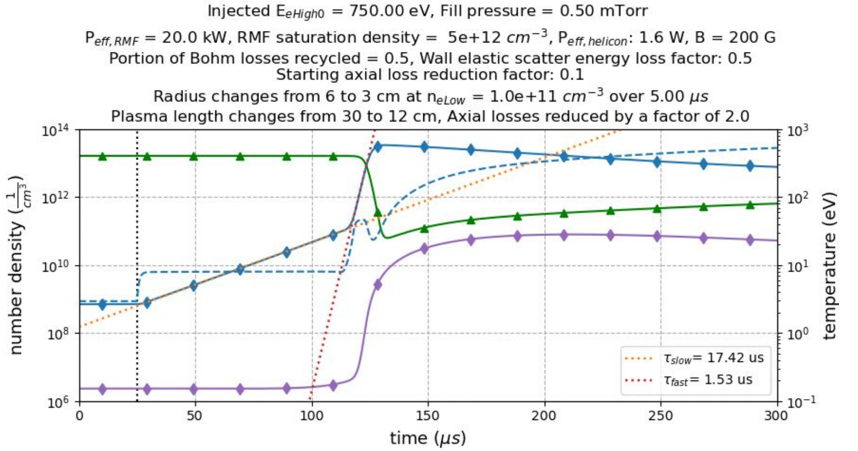


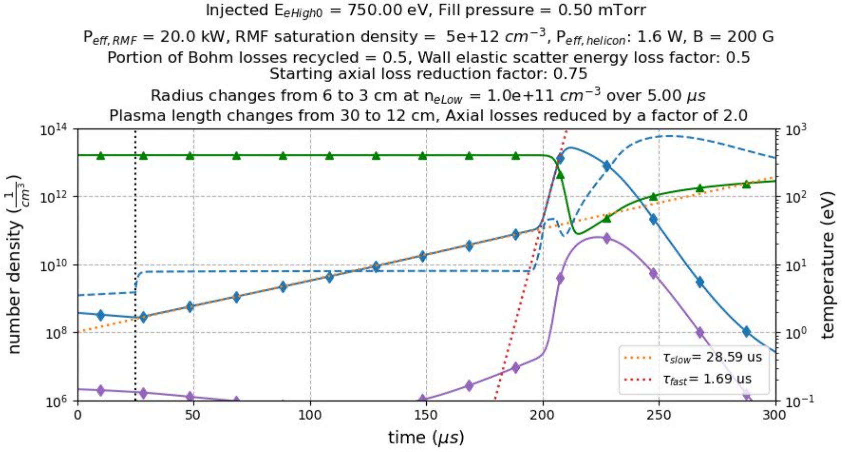




number density ($\frac{1}{cm^3}$)
temperature (eV)
time (μs)
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
50
100
150
200
250
300
RMF on
n_{eLow}
n_{eHigh}
n_{H2}
T_{eLow}
T_H
T_{H2i}
T_p
n_H
n_{H2i}
n_p







$$\Gamma_{axial\ loss} = \frac{r_{reducing} \cdot m_{escape} \cdot c_s}{\ell_{plasma}}$$

Axial loss sweep 2