Long Plasma Source For Proton-Driven PWFA

A Helicon Plasma Cell for AWAKE

Olaf Grulke for the Helicon Cell Team
MPI for Plasma Physics, Greifswald, Germany

What are the Challenges of the Plasma Cell?

1. if plasma generation is not done as extremely short pulses, plasma heating equilibrates with losses and transport processes
2. competition between ionization and radiation losses

   ⇨ choice of gas species important as a compromise between reasonable ionization potential and neutral/ion radiation losses
3. transport time scales

   ⇨ plasma (ion) loss along the discharge tube given by sheath boundary condition

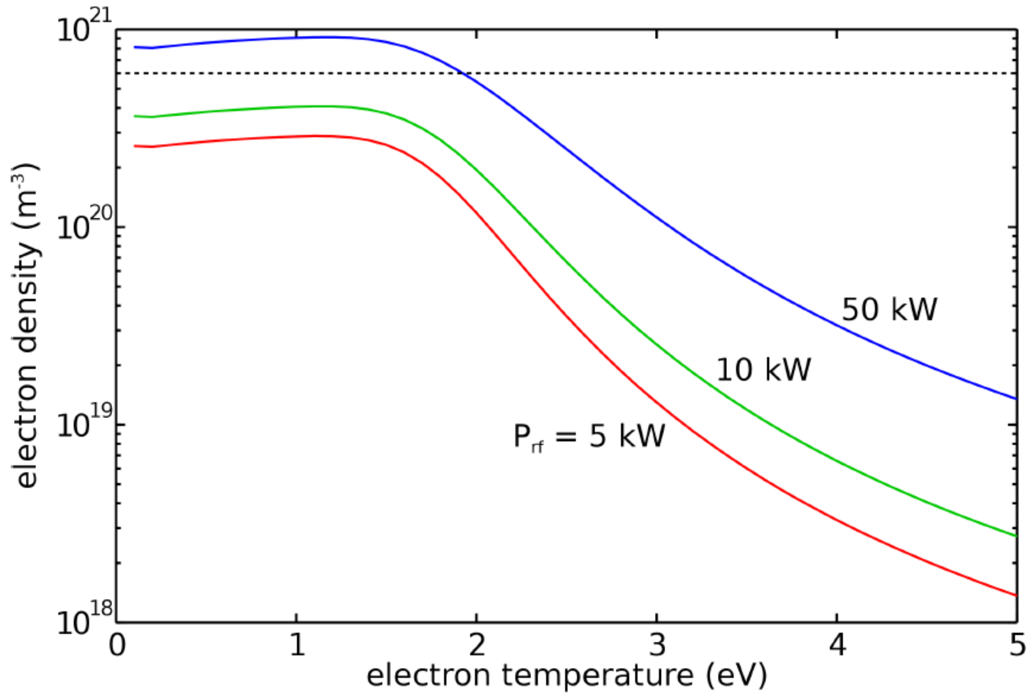
$$t_{||} = \frac{L_{||}}{C_s}$$

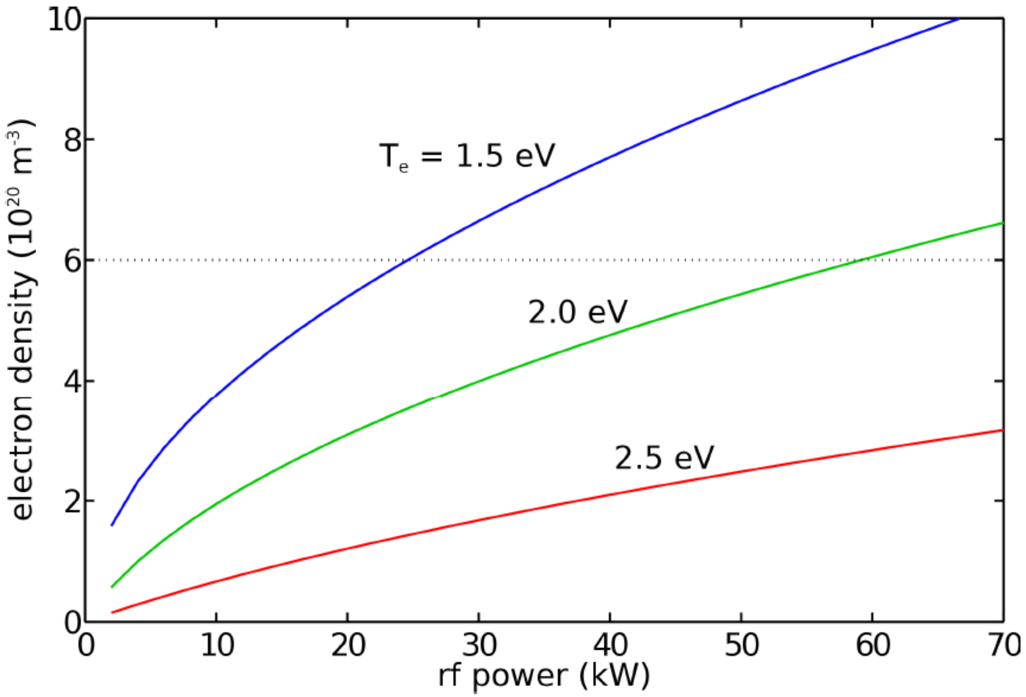
   ⇨ perpendicular ion diffusion

$$t_{\perp} = \left(\frac{L_{\perp}}{\Delta_{step}} \right)^2 \tau$$

Power Balance

example: Ar plasma, r = 1cm, l = 100cm homogeneous plasma density





- ⇨ electron temperature needs to be small T_e ¼ (1-1.5)eV
- ⇨ very high plasma collisionality

$$t_{||} \approx 1\, ms$$

$$t_{\perp} \approx 10^{-5}\, s$$

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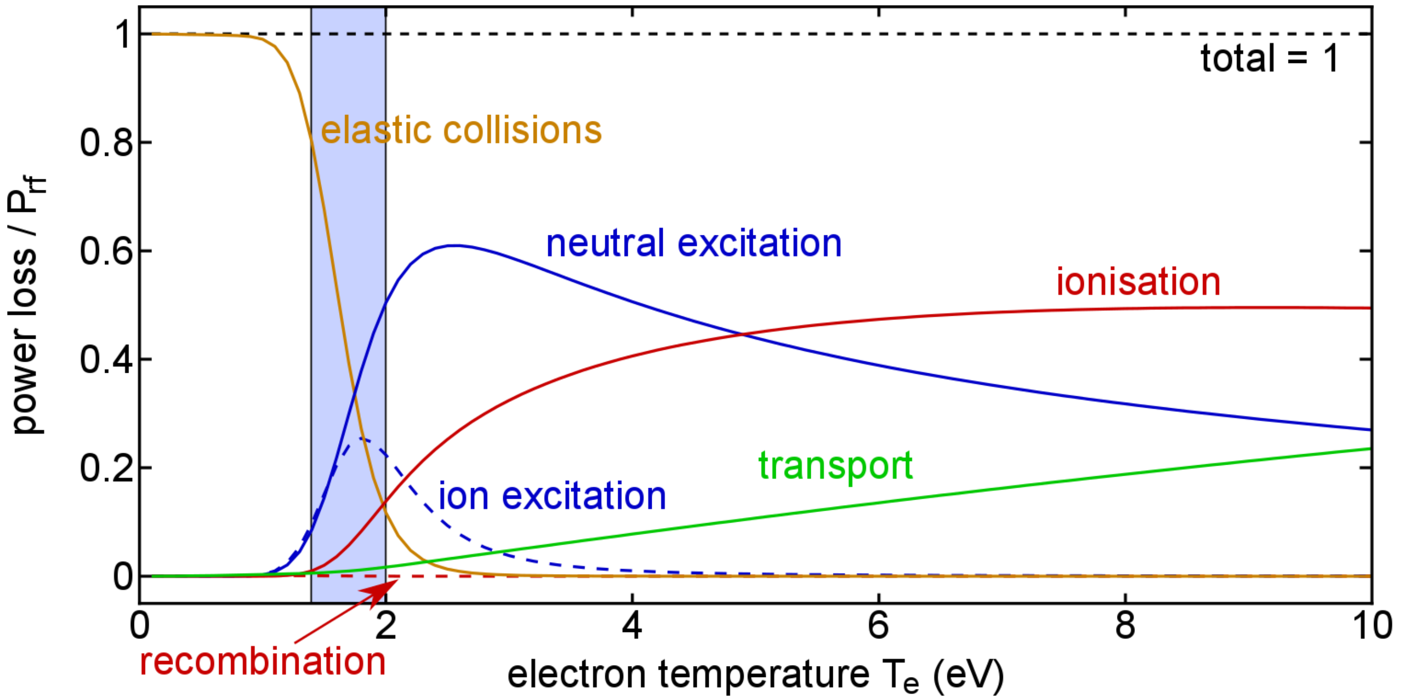

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Requirements

- high plasma densities require large heating power ~3MW/100m
- very short radial transport times
  - ⇨ necessity for axially distributed heating
  - ⇨ preferably without staging
- plasma heating via externally excited waves provides these principle boundary conditions
  - ⇨ „classical“ heating mechanisms (electron/ion cyclotron heating) not feasible due to wave cut-off, homogenous discharge, and pimary deposition into particle kinetic energy
  - ⇨ non-resonant (collisional) heating advantageous
- helicon wave-sustained discharge for AWAKE $n = 7 \cdot 10^{20}\mathrm{m}^{-3}$
  - ⇨ demonstrate a plasma density of (order of magnitude larger than conventional helicon discharges)
  - ⇨ scalable to arbitrary discharge lengths without staging
  - ⇨ high axial plasma density homogeneity

Helicon waves

- helicon waves are the low-frequency, bounded version of an R-wave

$$k^2c^2 = \frac{\omega\,\omega_P^2}{\omega_{ce}\cos\theta - \omega - i\nu}$$

plasma density

magnetic field

- discovered by Boswell et al. and noted to be very efficient in plasma density generation

Boswell et al. Plasma Phys. Control. Fusion (1984)

- dispersion relation:

$$\frac{k_{\parallel}k}{\omega} = \frac{n\,e\,\mu_0}{B_0}$$

wave parameters

plasma parameters

$k = \sqrt{k_{\parallel}^2 + k_{\perp}^2}$	helicon wavenumber (1-10cm)
ω	rf range (1-50MHz)
n	plasma density
B	ambient magnetic field (10-500mT)

$$\omega_{ci} \ll \omega \ll \omega_{ce}$$

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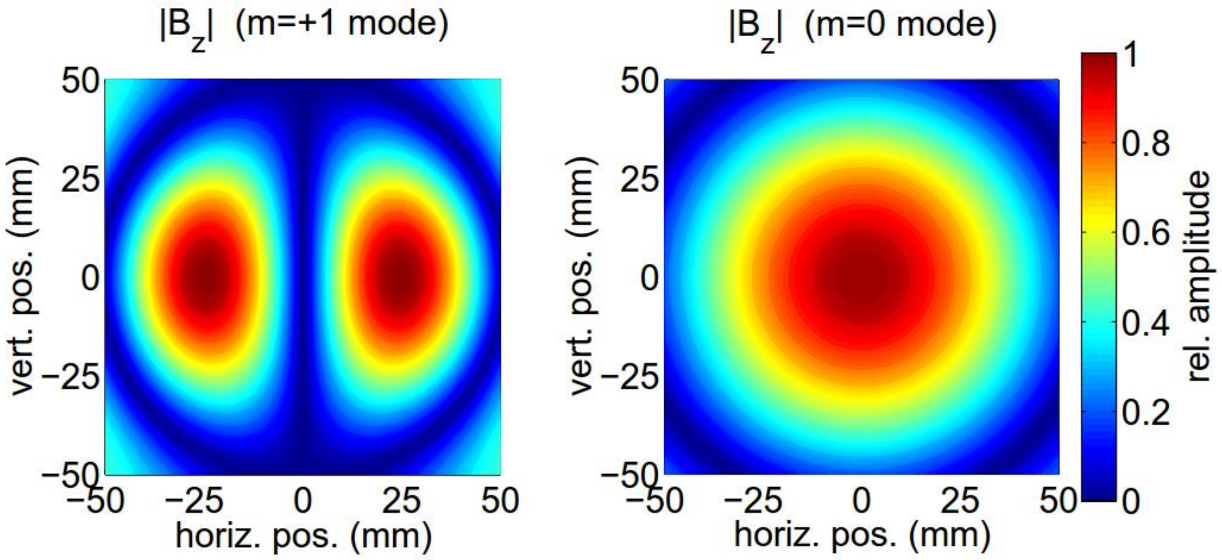
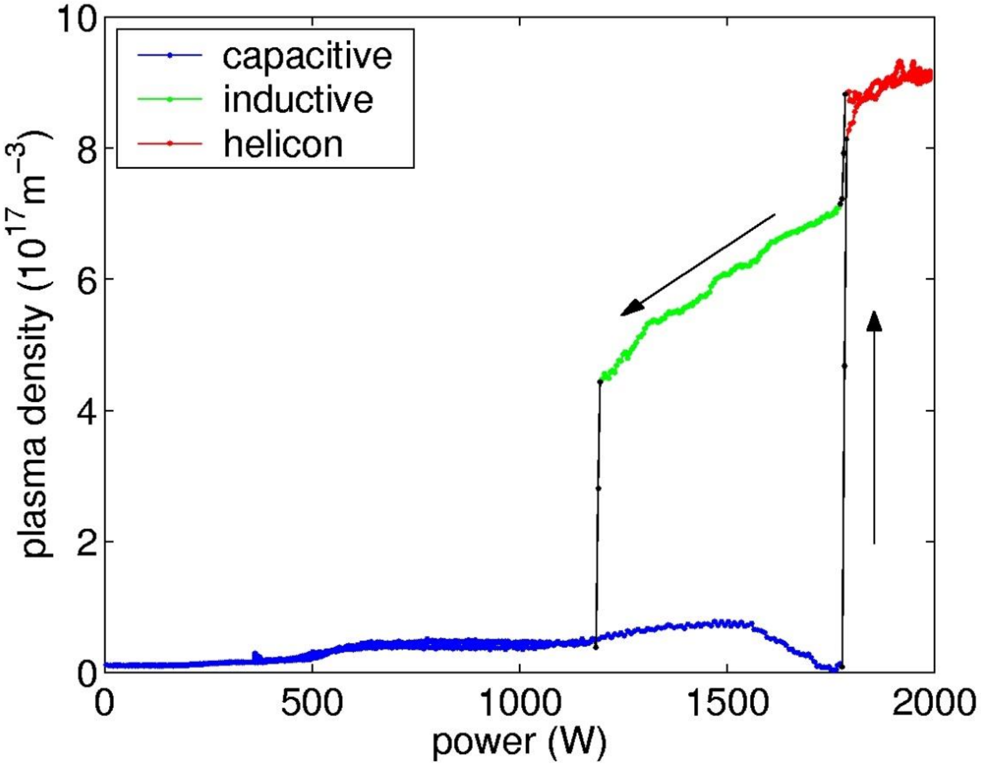
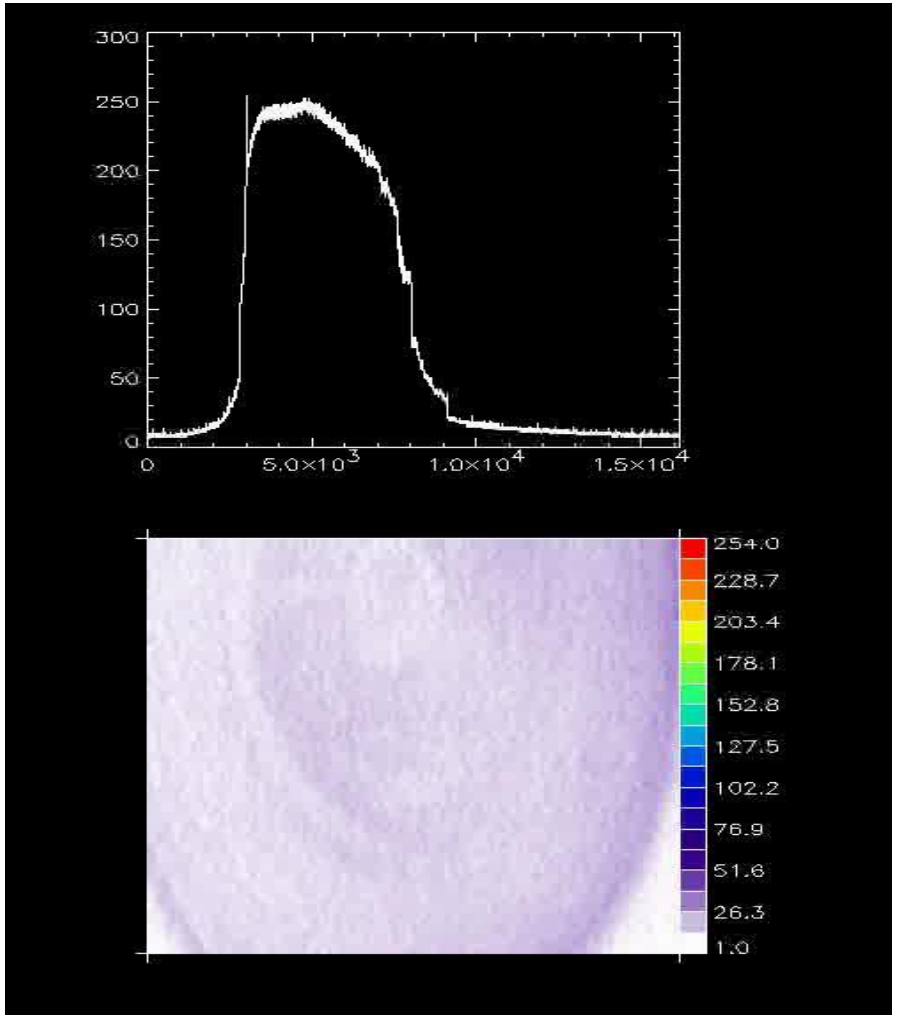
- azimuthal eigenmode structure:



Efficient RF heating Scheme





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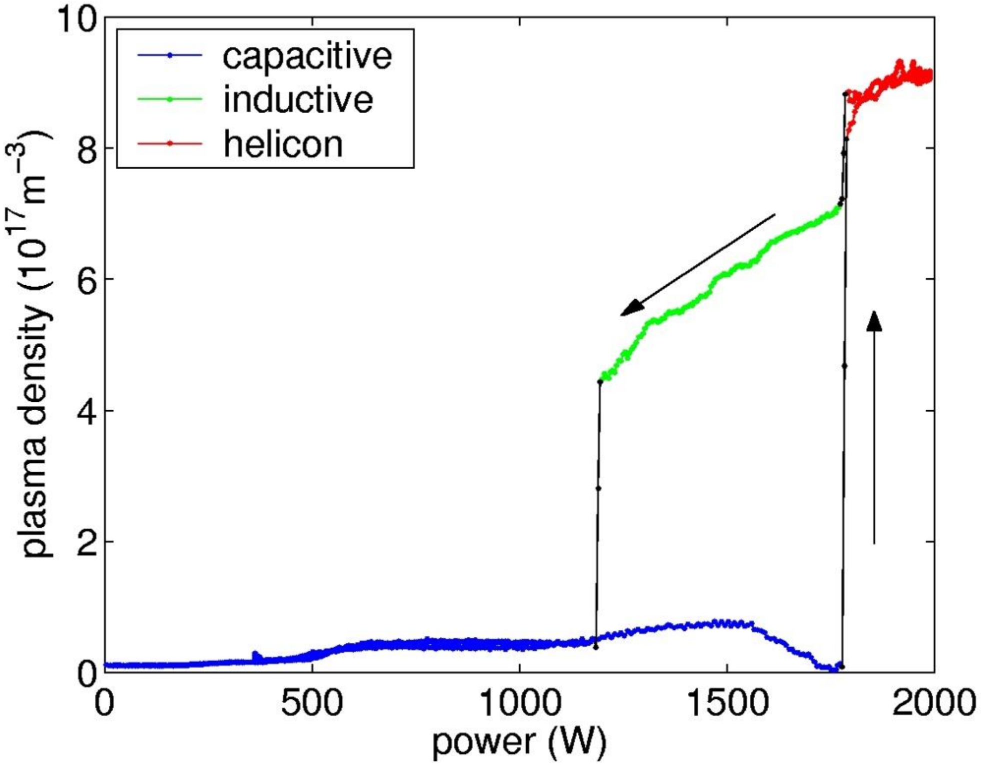
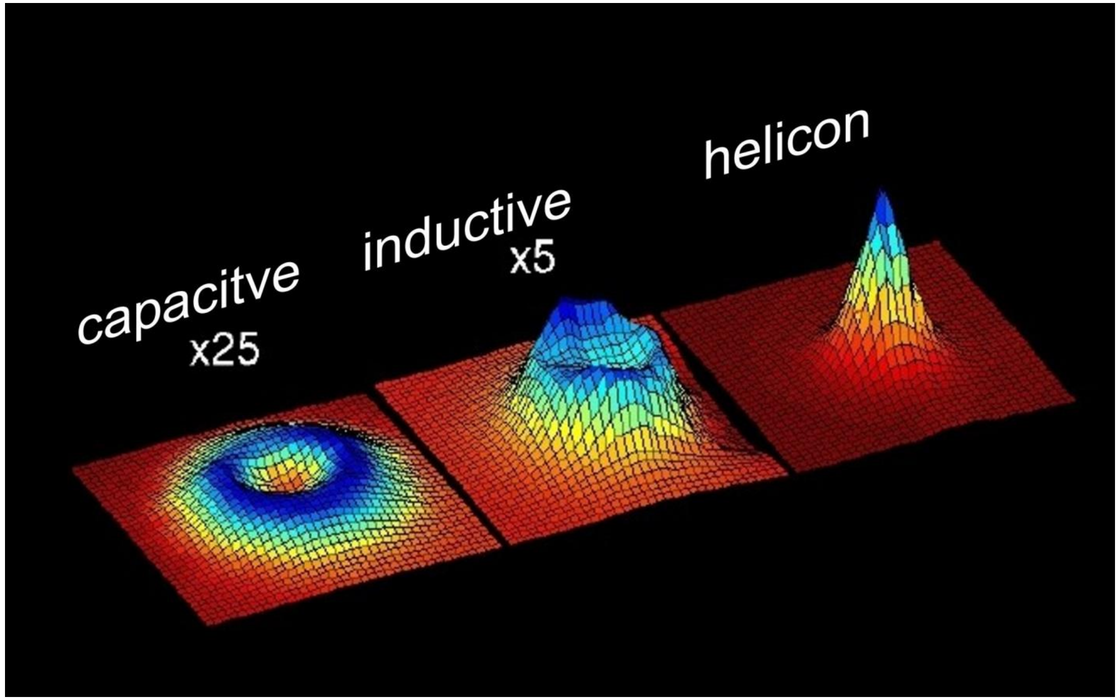


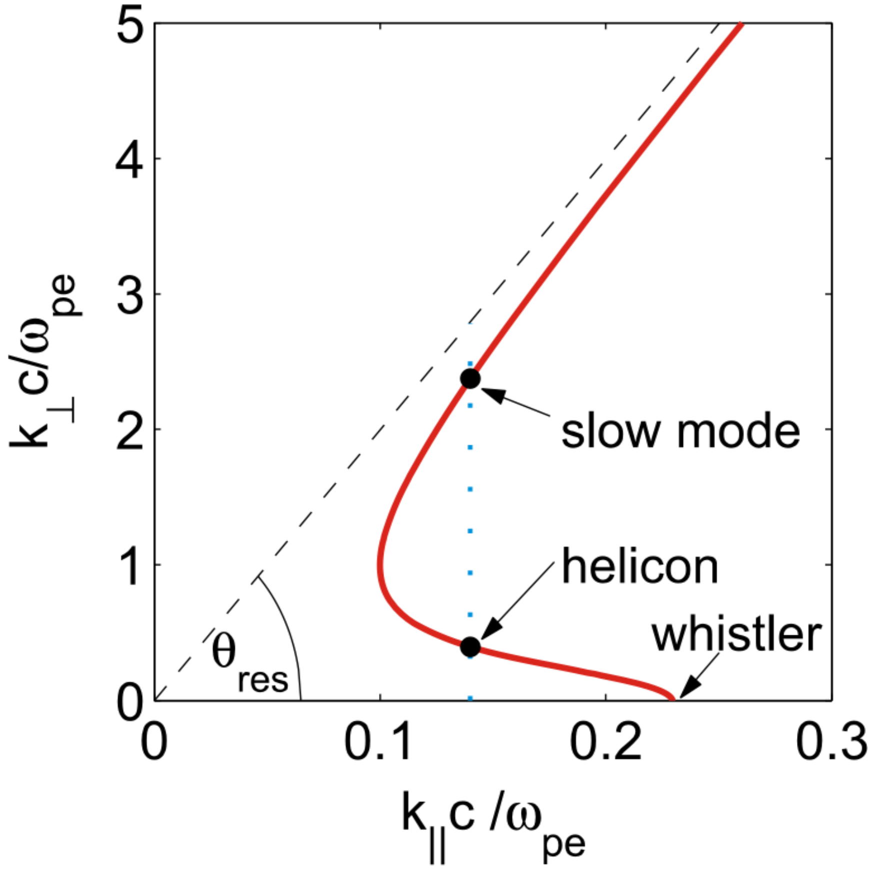


- bifurcation from conventional rf-heating (capacitive/inductive) to high-density helicon wave sustained discharge
- plasma density centrally peaked

Helicon Wave Energy Dissipation

- heating by collisional dissipation
- linear mode conversion of helicon wave to slow mode (Trivelpiece-Gould wave) with much shorter wavelength and much larger collisional damping

$$Im(\omega)_{HW} = i\nu\frac{k^2c^2}{\omega_P^2} \ll Im(\omega)_{TG} = i\nu$$



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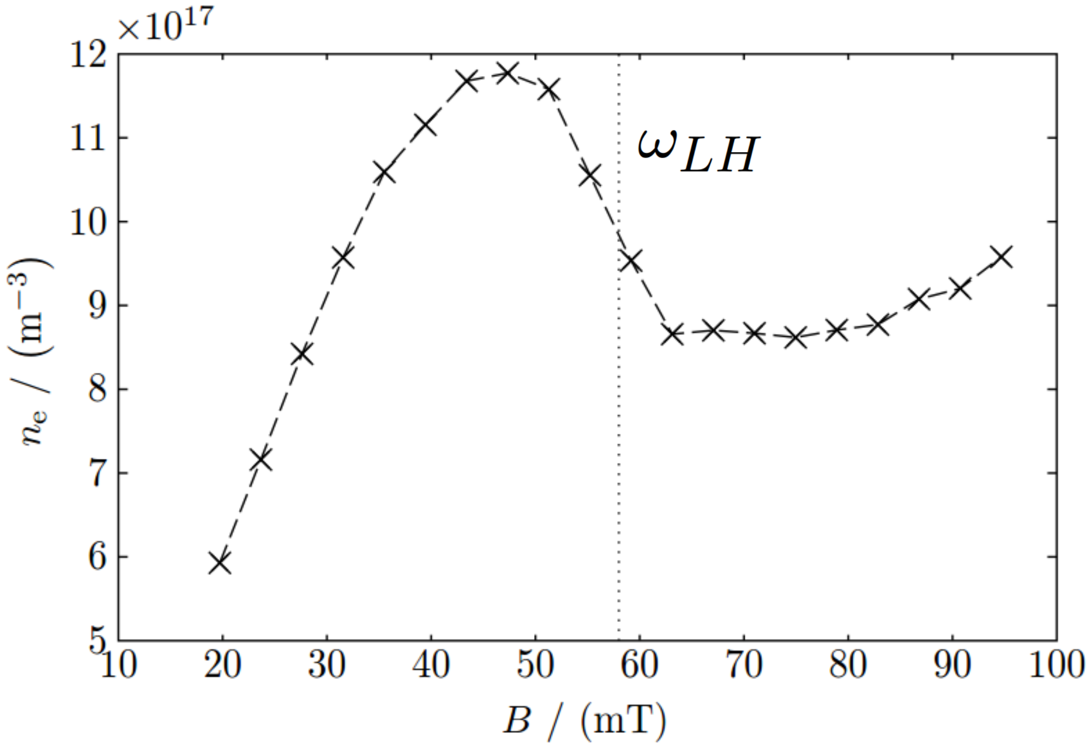

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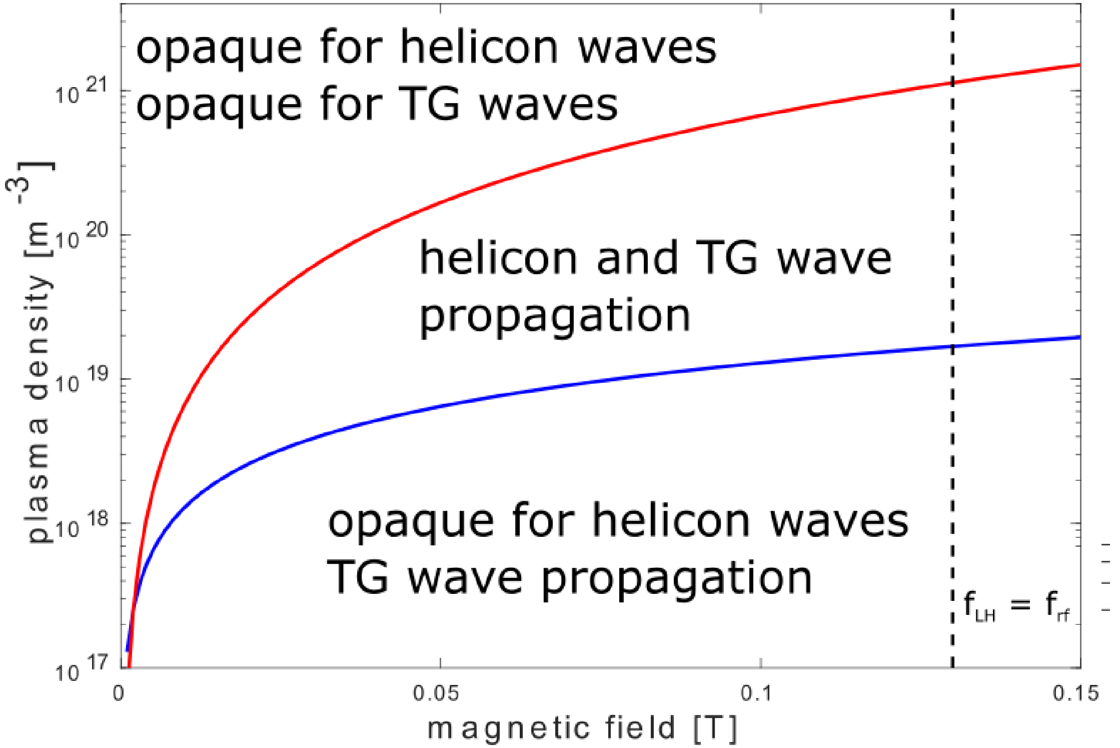
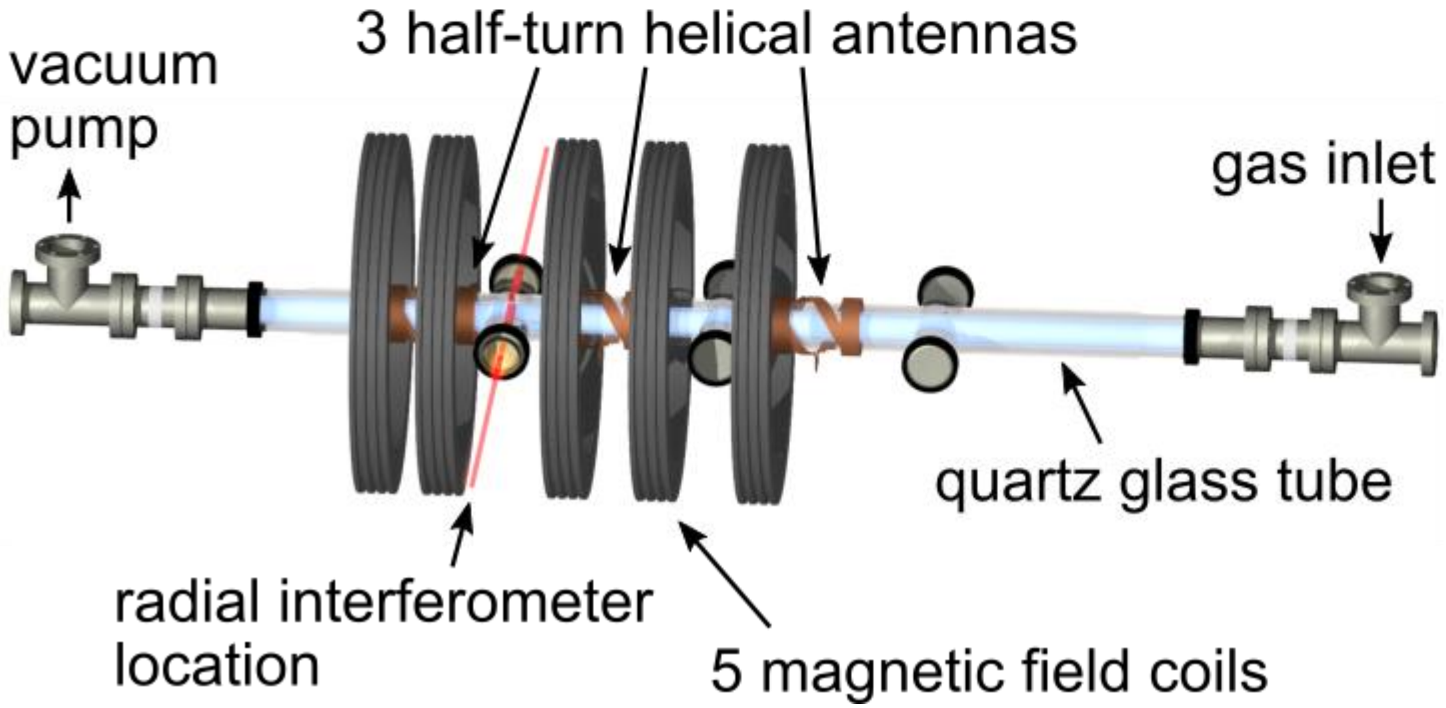
⇨ effective operation limit



Helicon Plasma Cell Setup



- homogenous magnetic field B·130mT @ ω=13.56 MHz
- multiple (up to 3) m=+1 antennas to distribute heating (modular)
- chief diagnostics are a CO_2 laser interferometer and LIF

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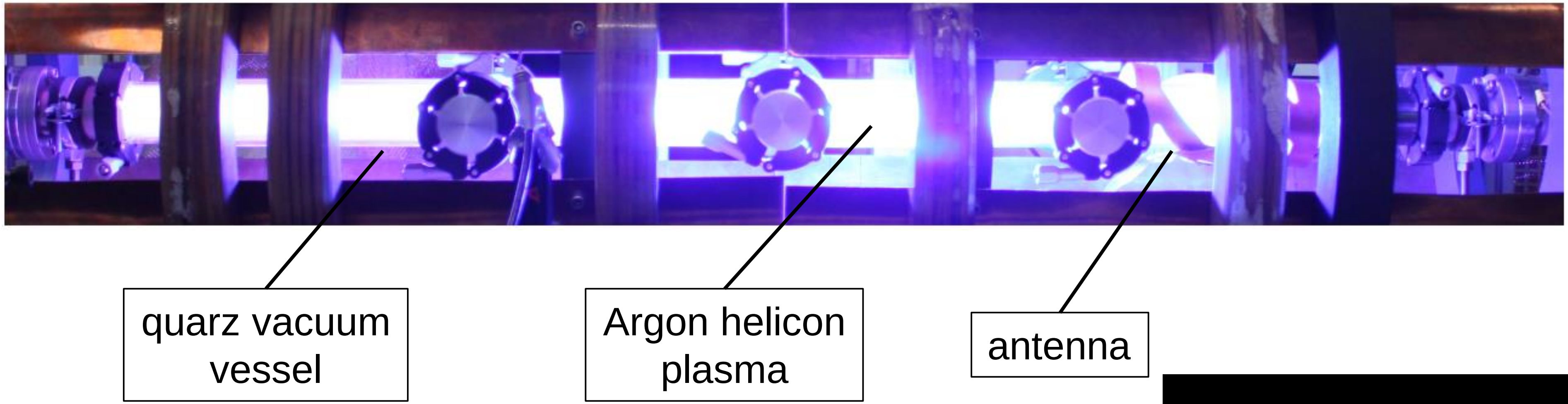

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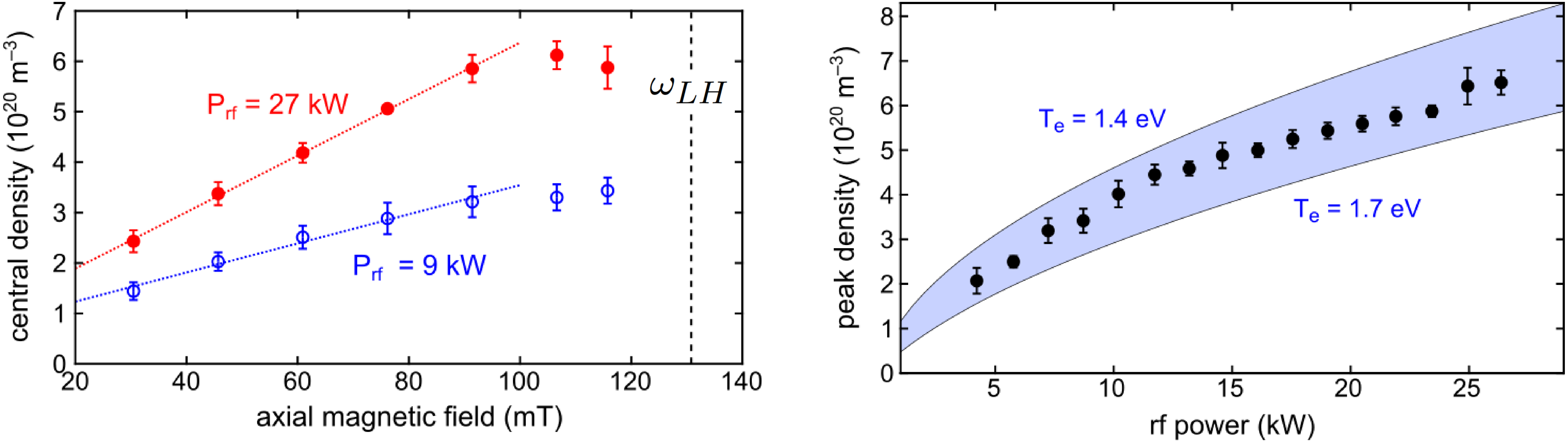
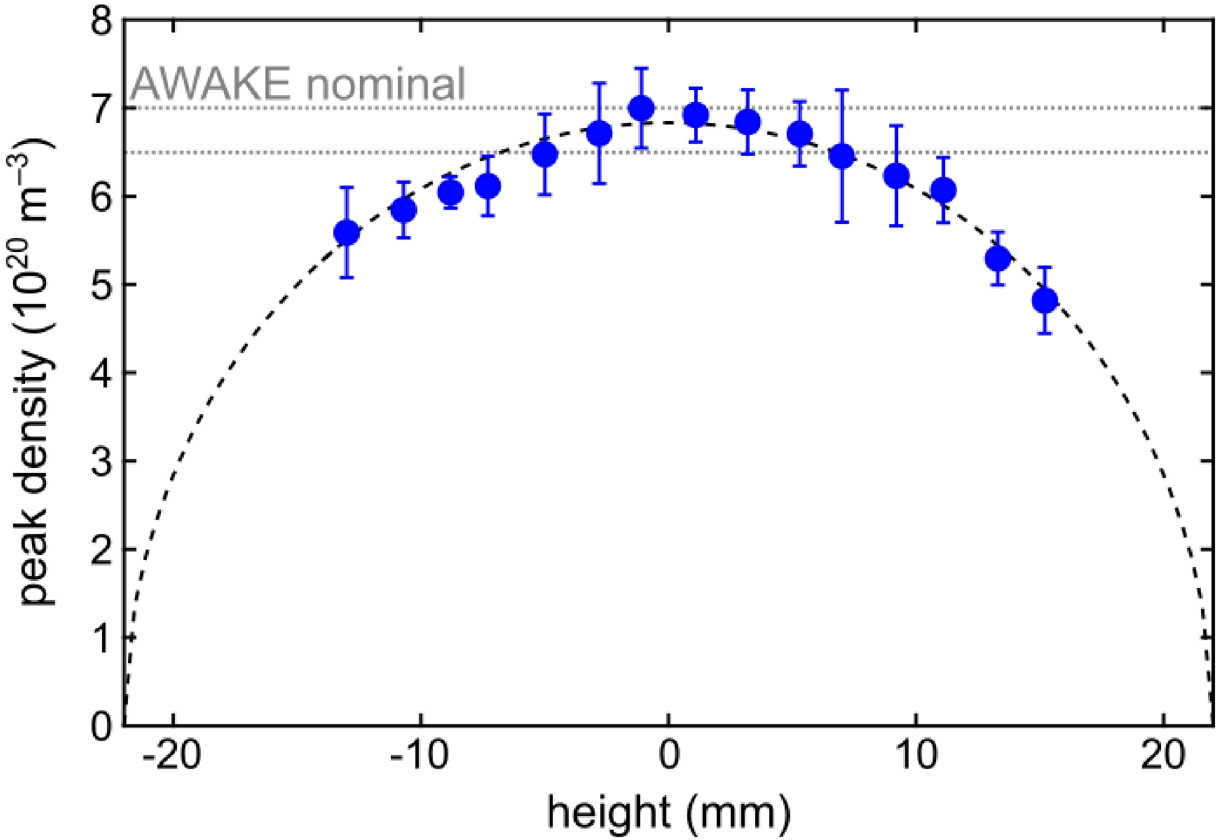
Helicon Dispersion Measurements



- linear scaling of helicon dispersion fulfilled for various rf heating power levels
- peak plasma density in agreement with power balance calculations
- role-off of plasma density when approaching ω_{LH}

Radial Plasma Profiles



- AWAKE central plasma density achieved!
- shallow core density gradients

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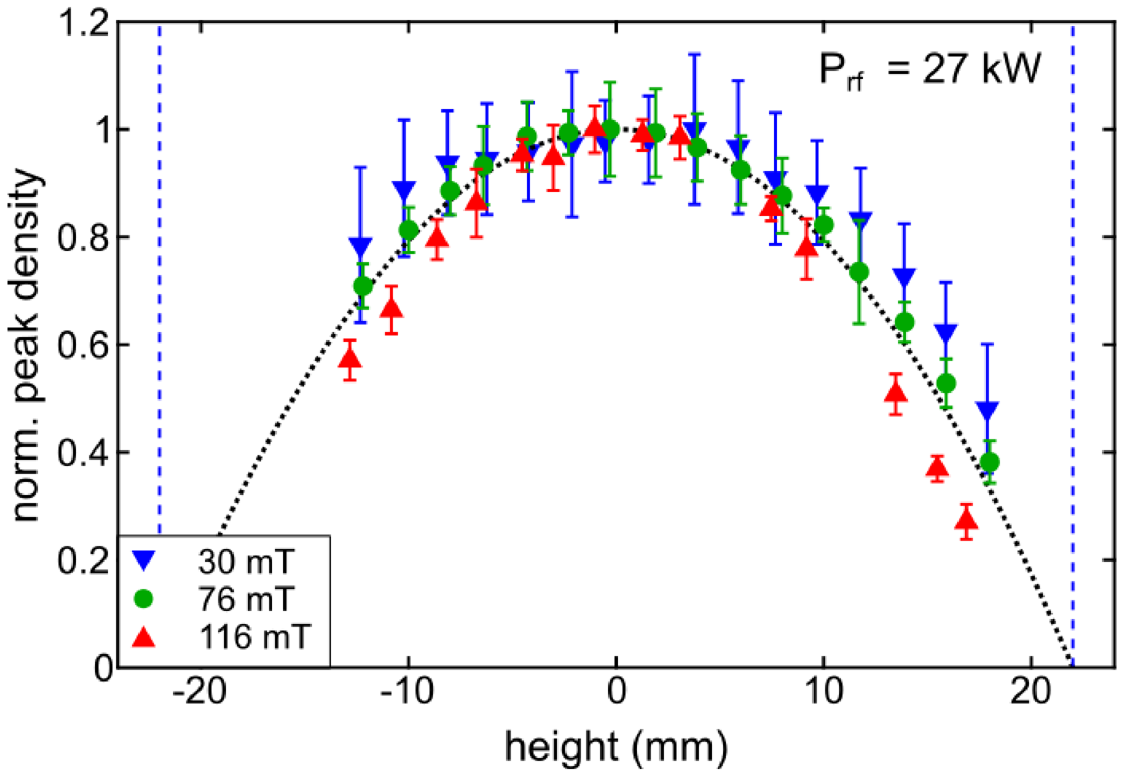

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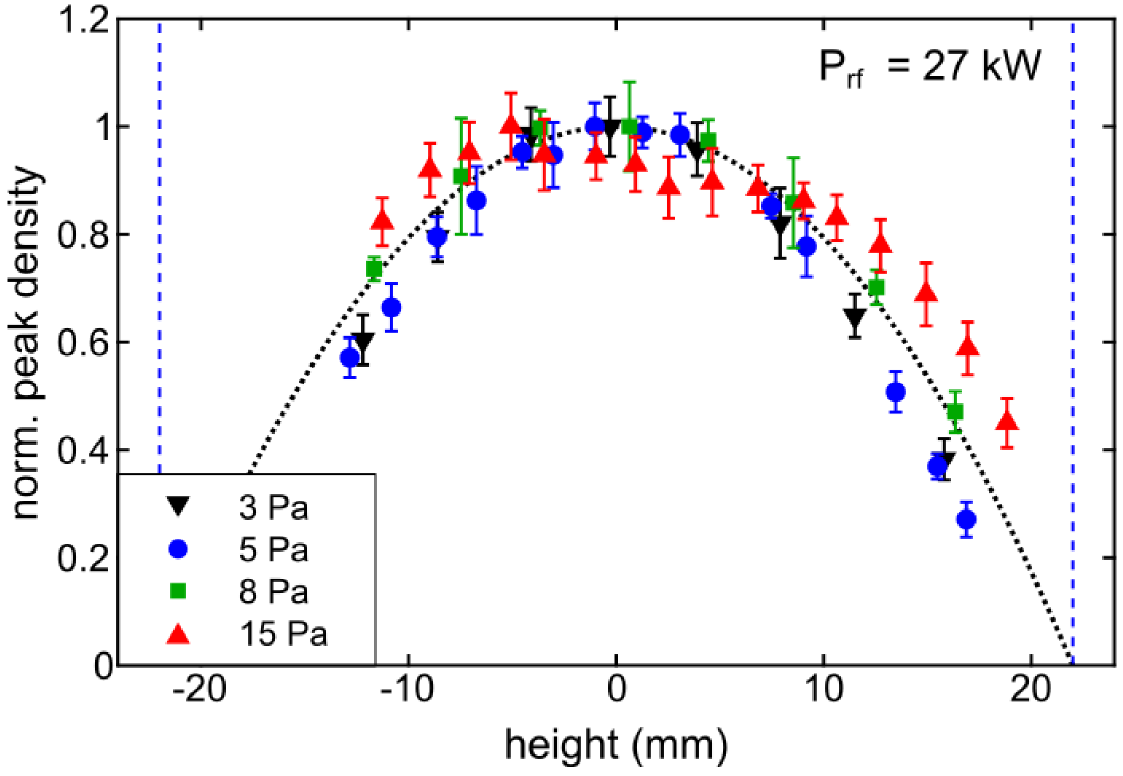
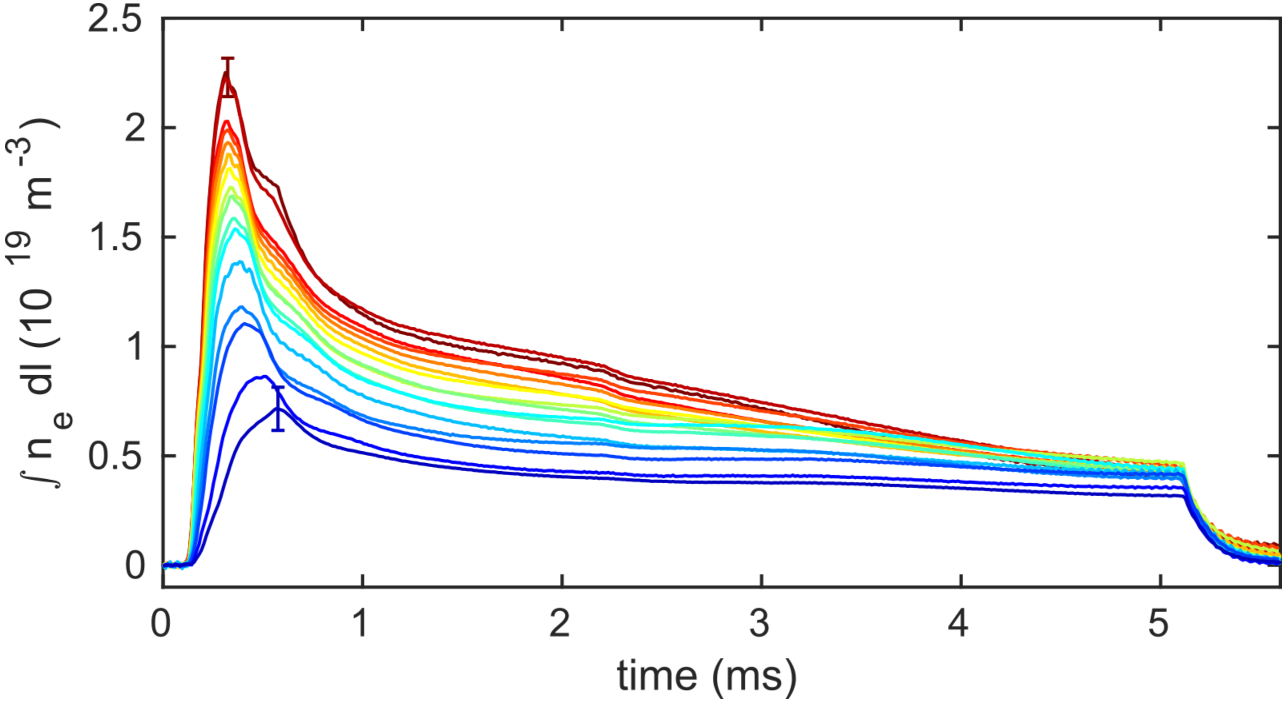


- AWAKE central plasma density achieved!
- shallow core density gradients
- radial profiles stiff against changes of magnetic field and neutral gas pressure

Temporal Plasma Density Evolution



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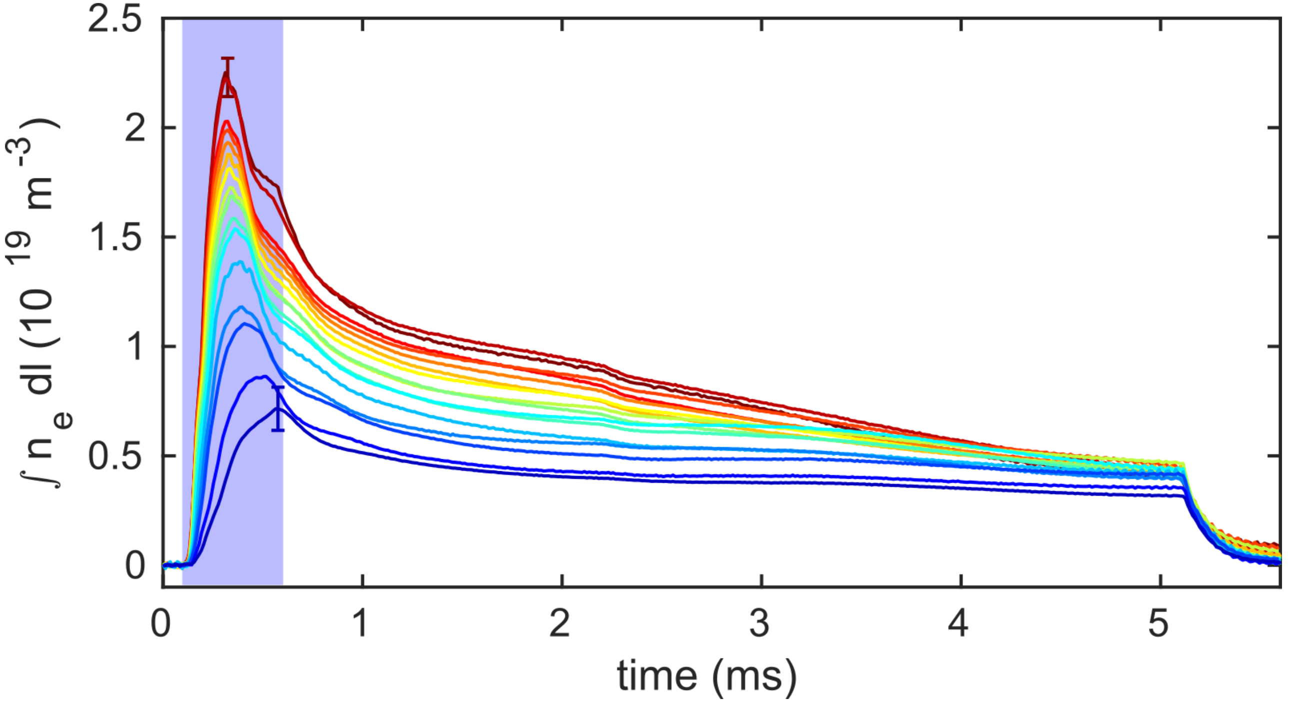

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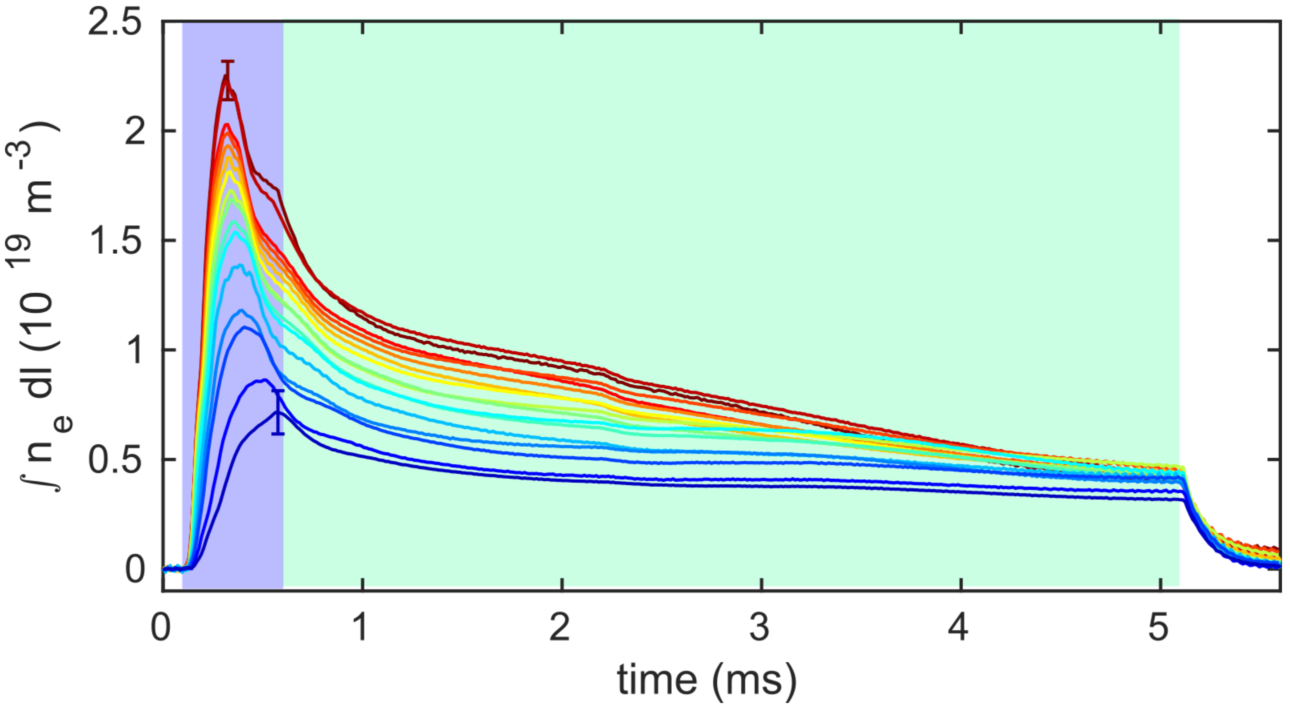

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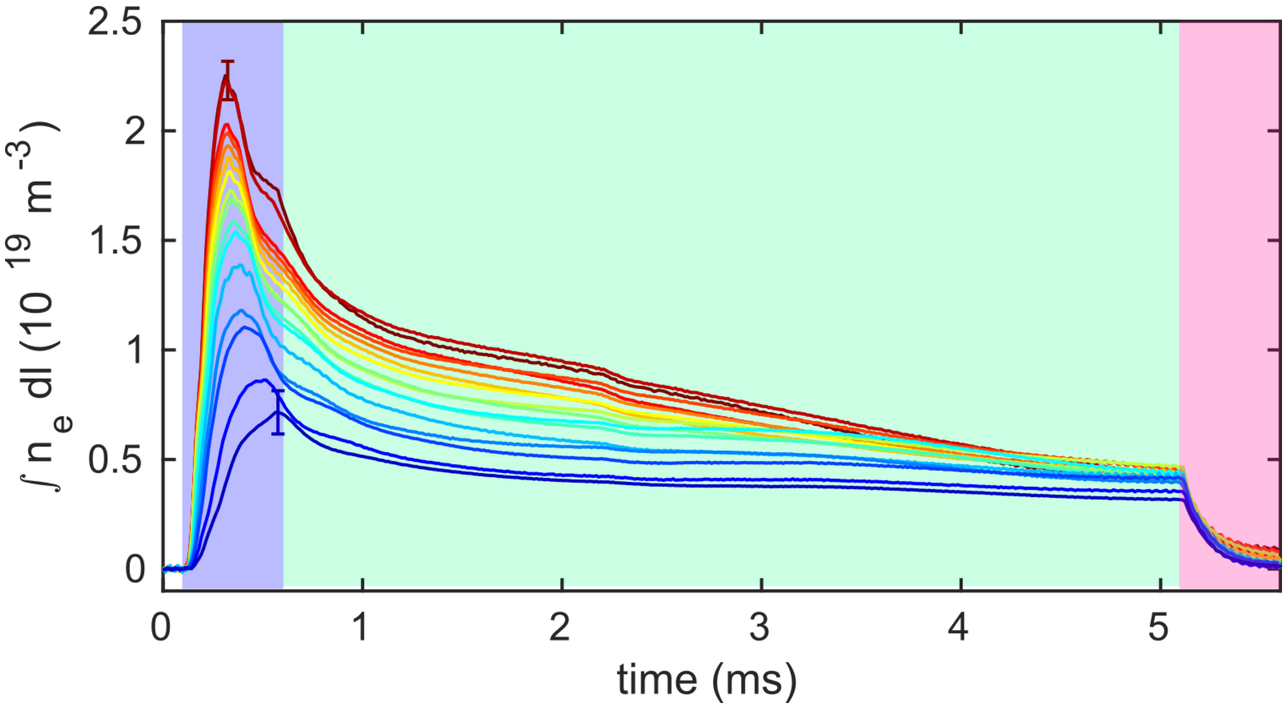
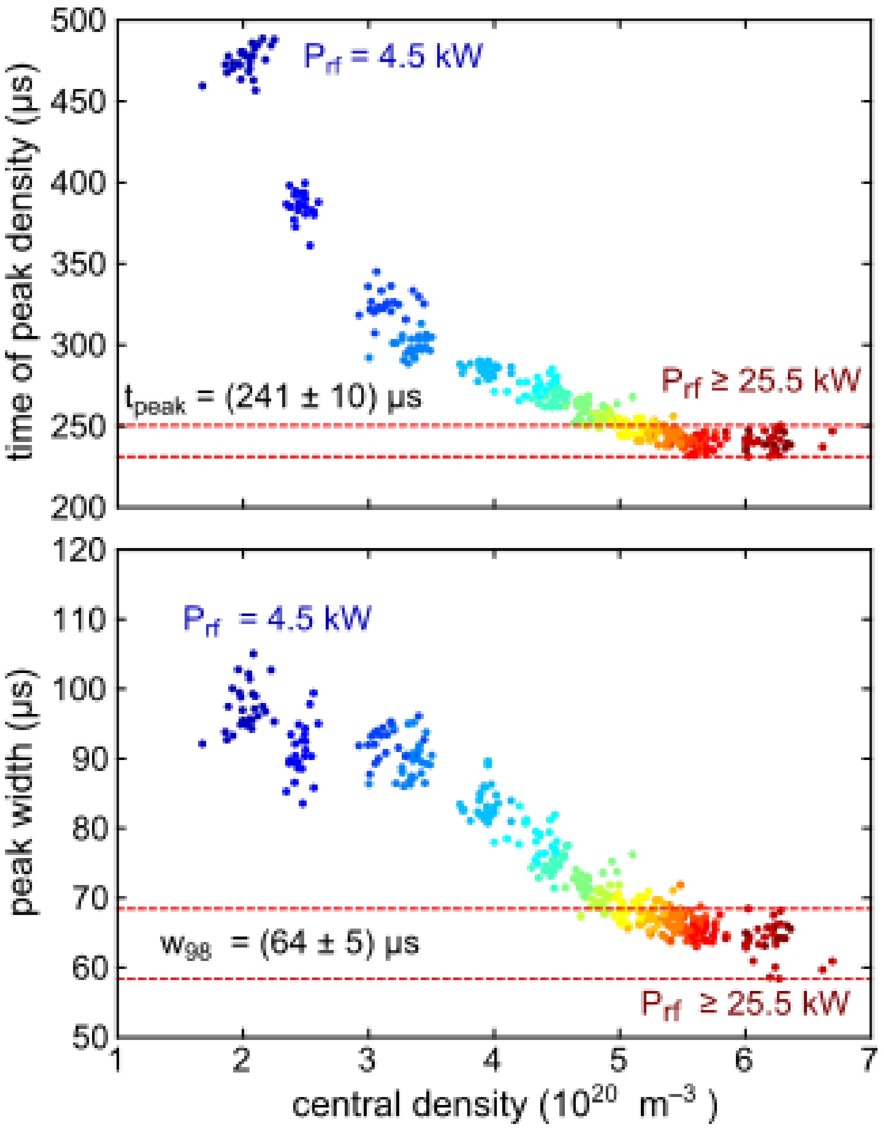


- plasma density is not stationary
- initial high density peak
- plasma density decay despite constant rf heating power
- after power switch-off 1/e plasma decay

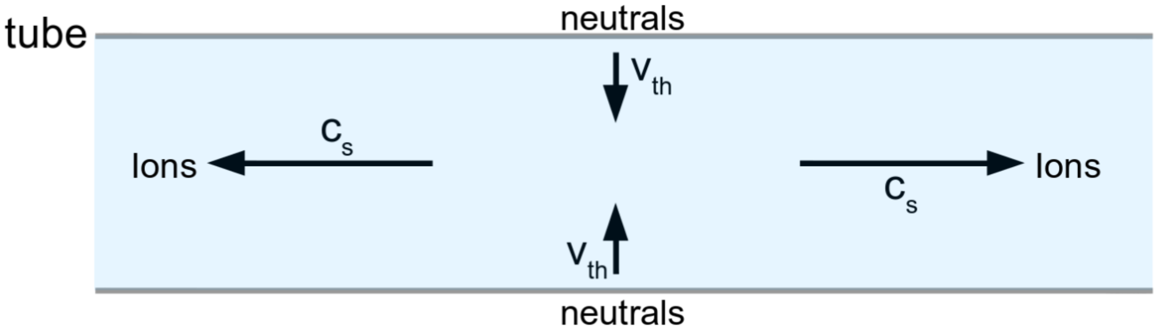
High-Density Peak Timing



- high-density peak is delayed w.r.t. power switch-on
- delay decreases with increased rf power levels
  - ⇨ discharge breakdown supported by large rf powers
  - ⇨ delay reproducible within 10 µs
- width of high-density peak exceeding nominal AWAKE density is relatively broad
  - ⇨ larger than the delay jitter
- we can provide the high-density phase accurately for Δt ¼ 50 µs

Transient Plasma Density Decrease

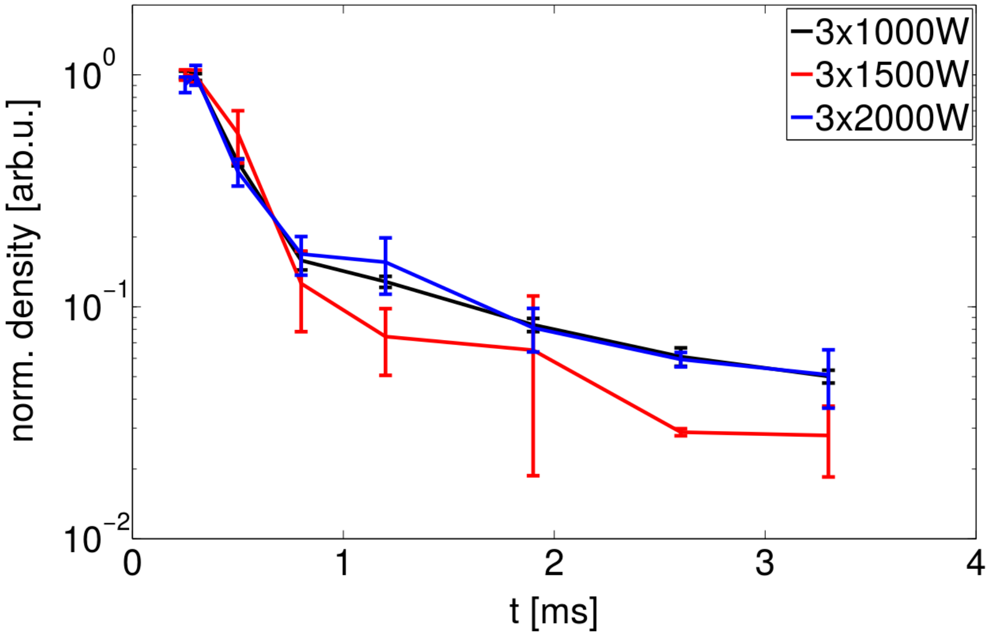
- centrally peaked plasma density prohibits central neutral gas fueling



- direct LIF measurements of central neutral gas density indicates depletion

⇨ timescale determined by ion losses (1ms)

⇨ advanced central gas fueling schemes are expected to stabilize the discharge



Summary

- helicon discharges are shown to provide plasma densities of n ¼ 10^{21} m^{-3}
  - ⇨ unparalleled helicon plasma density
  - ⇨ rf power requirements in agreement with balance calculations
- distributed plasma heating easily achieved via multiple antenna operation
  - ⇨ helicon damping length leads to $\sim$3 antennas per m discharge
  - ⇨ the principle is readily scalable to large discharge lengths
- for discharges ($>$1ms) neutral gas dynamics affect the density evolution
  - ⇨ neutral pumping in plasma core
  - ⇨ central fueling essential to stabilize temporal plasma density behavior (if needed)

- pending: axial plasma density homogeneity not yet quantified

Schematics of a Long Helicon Plasma Cell