Electron Bernstein wave core deposition via O-X-B double mode conversion in TCV

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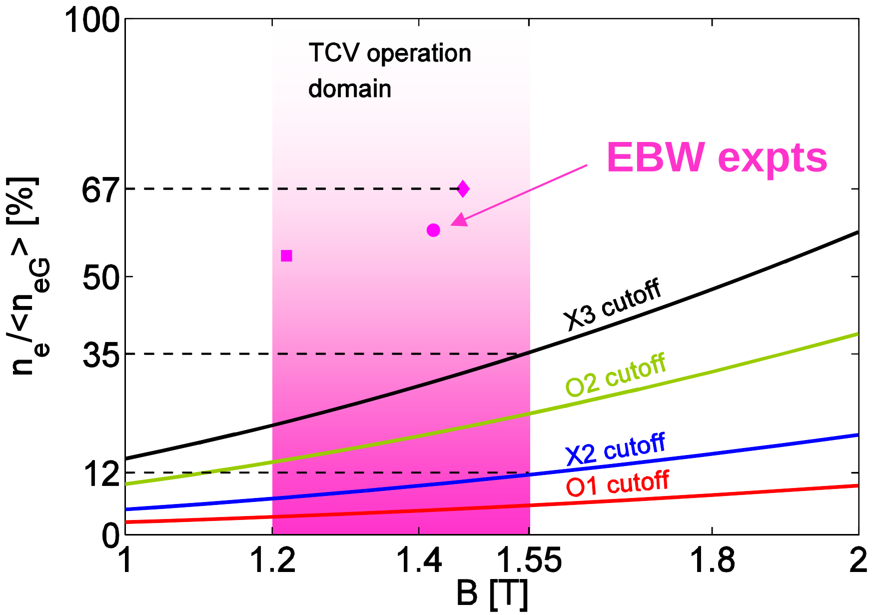
Context



Tokamak empirical density limit

$$\langle n_{eG}\rangle[\mathrm{m}^{-3}] = 10^{20}\cdot\frac{I_p[\mathrm{MA}]}{\pi\cdot(a[\mathrm{m}])^2}$$

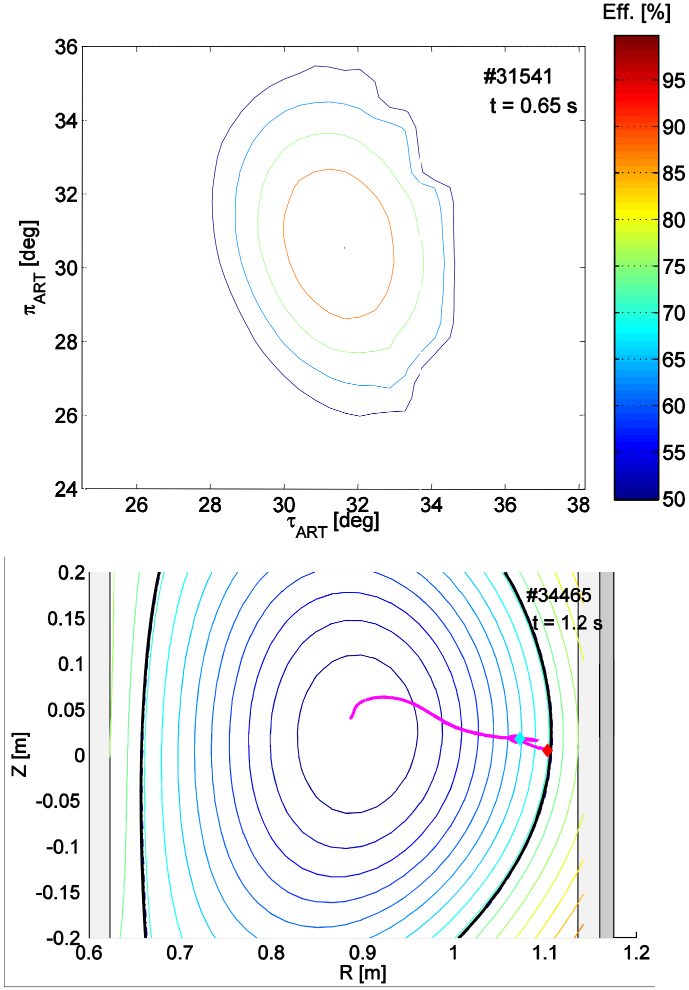
- Electron cyclotron (EC) waves accessibility limitation in medium to low *B* field tokamaks

$$n_{e,cut\text{-}off} \propto B^2$$

- Solutions:
  - Higher harmonics
  - Electron Bernstein waves (EBW)
- In TCV (H-mode, I_p = 0.5 MA, a = 0.2 m)

Waves	Max $n_e/\langle n_{eG}\rangle$
X-mode 2nd harm.	~12%
O-mode 2nd harm.	~23%
X-mode 3rd harm.	~35%
EBW via O-X-B	100%, no upper limit

O-X-B double mode conversion



- Bernstein waves are **electrostatic**

⇒ need a conversion from externally launched e.m. waves in O-mode

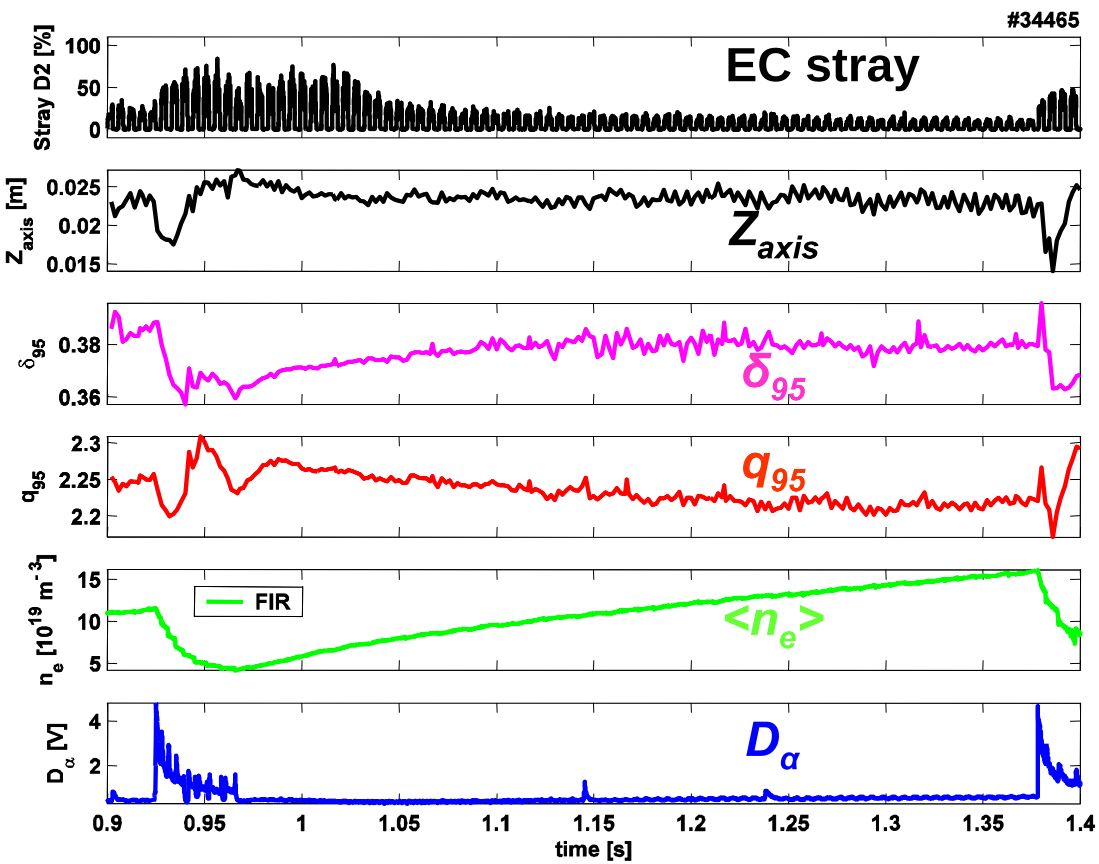
- **O-mode to X-mode** conversion at the O-mode cutoff: angular window for the wave injection angles (π and τ) of width $T_{O\text{-}X}$

$$T_{O-X} \propto \exp(-\pi k_0 L_n); L_n = \left(\frac{dn}{dR} \frac{1}{n} \right)^{-1}$$

⇒ needs a small normalized density scale length $k_0 L_n$ (steep ∇n)

- **X-mode to B-mode** conversion at the upper-hybrid resonance: needs $k_0 L_n > 1$

O-X-B EBH plasma target in TCV

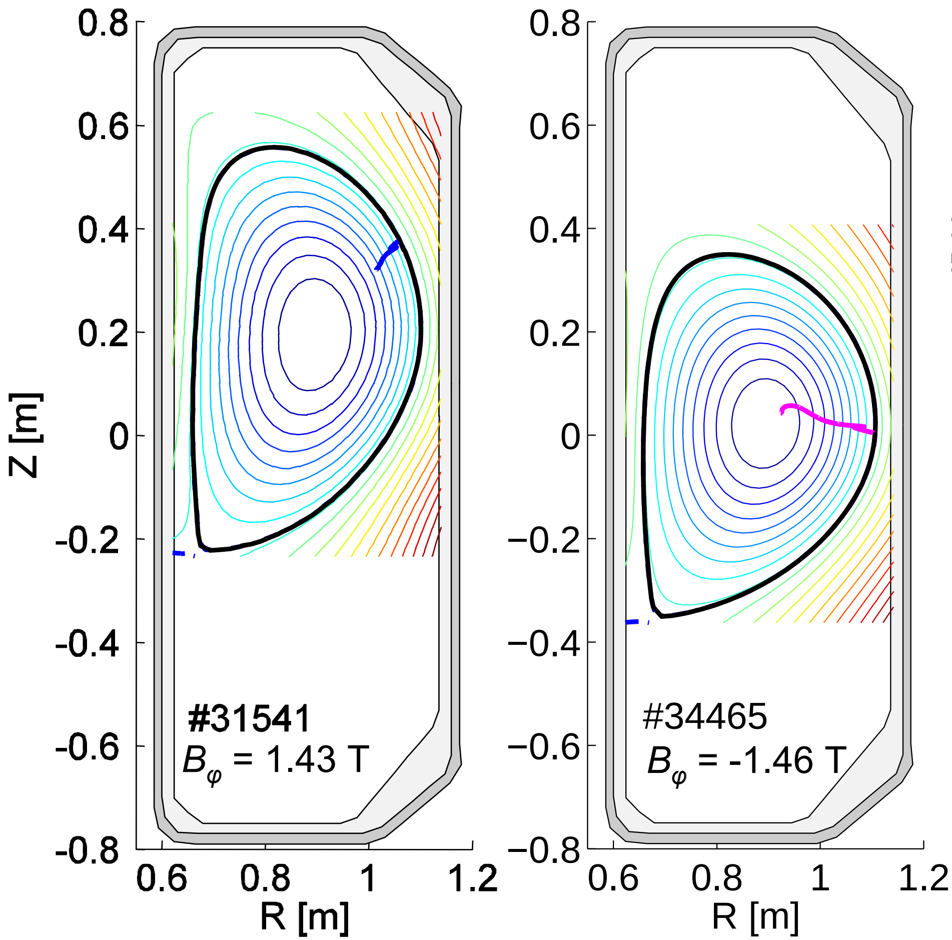


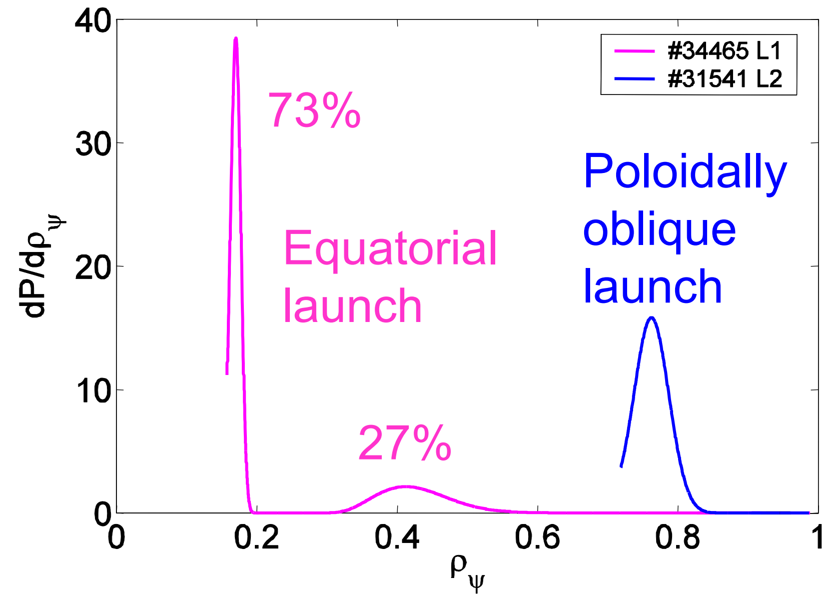
- High-confinement mode provides the adequate ∇n conditions ($k_0 L_n$ ~ 10 at the edge)
  - Medium δ_{95} ~ 0.4
  - High κ_{95} ~ 1.5
  - Low q_{95} ~ 2.2
  - Thus high I_p ~ 400 kA
- Strong central sawtooth activity
- EC power
  - ON/OFF modulation
  - 181 Hz
  - 50% duty cycle

From off-axis to core EBW deposition

Pol. oblique launch

Equatorial launch



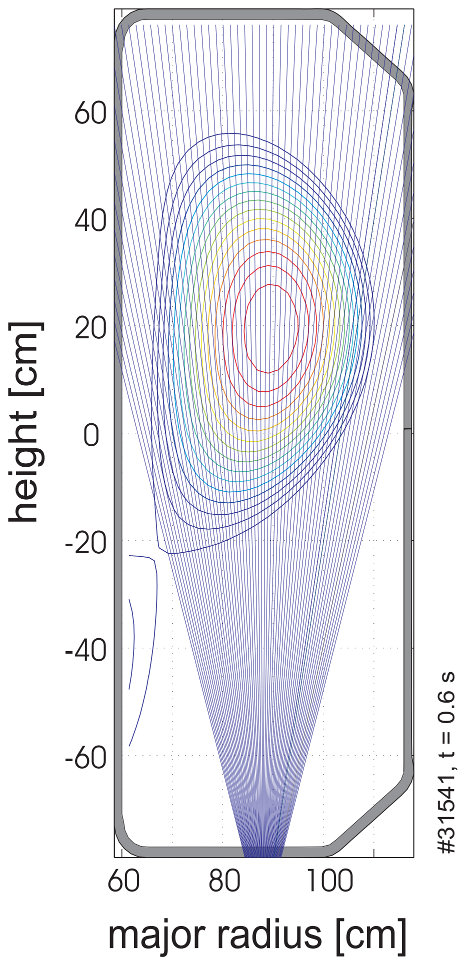


ART non-relativistic ray-tracing:

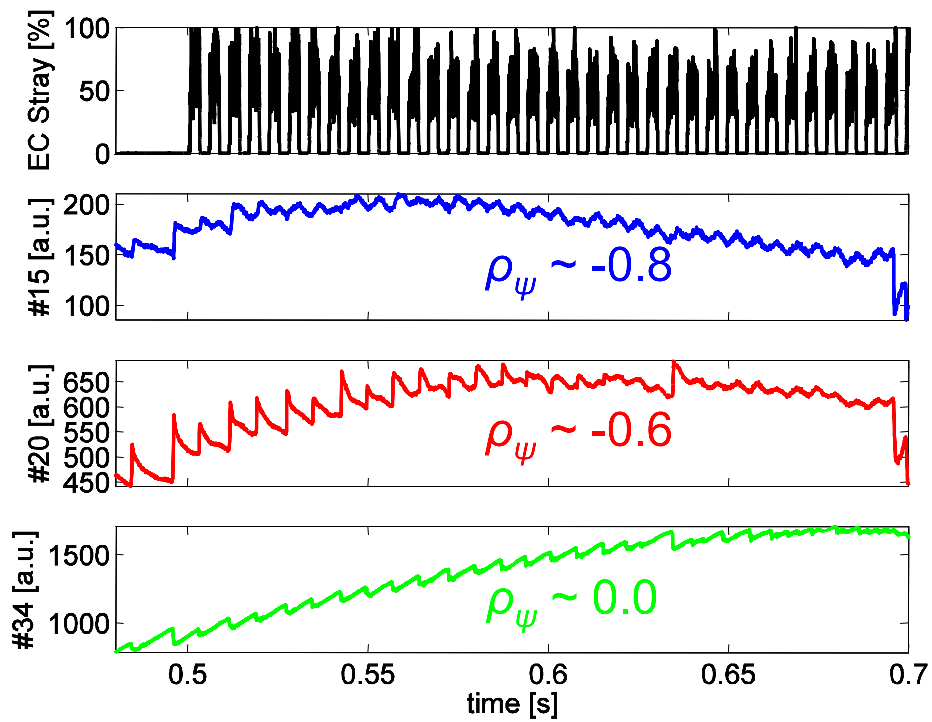
- Oblique launch: $\rho_{\psi dep}$ ~ 0.76
- Equatorial launch: $\rho_{\psi dep}$ ~ 0.17 (~73% of power)

Duplex Multiwire Proportional soft X-ray detector (DMPX)

DMPX lines of sight

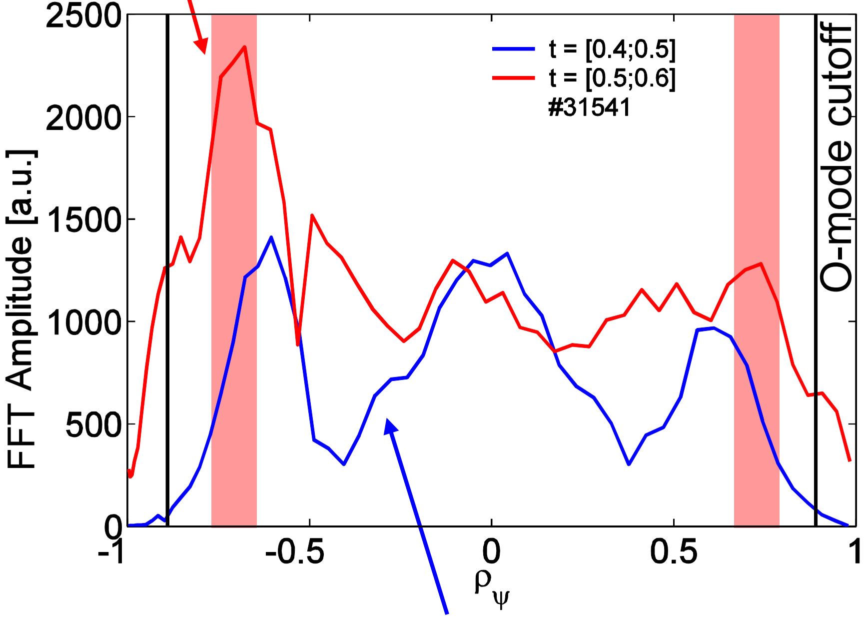


- High spatial resolution (64 vertical lines of sight)
- High time resolution (200 kHz)



Off-axis deposition: FFT analysis

EBW deposition profile



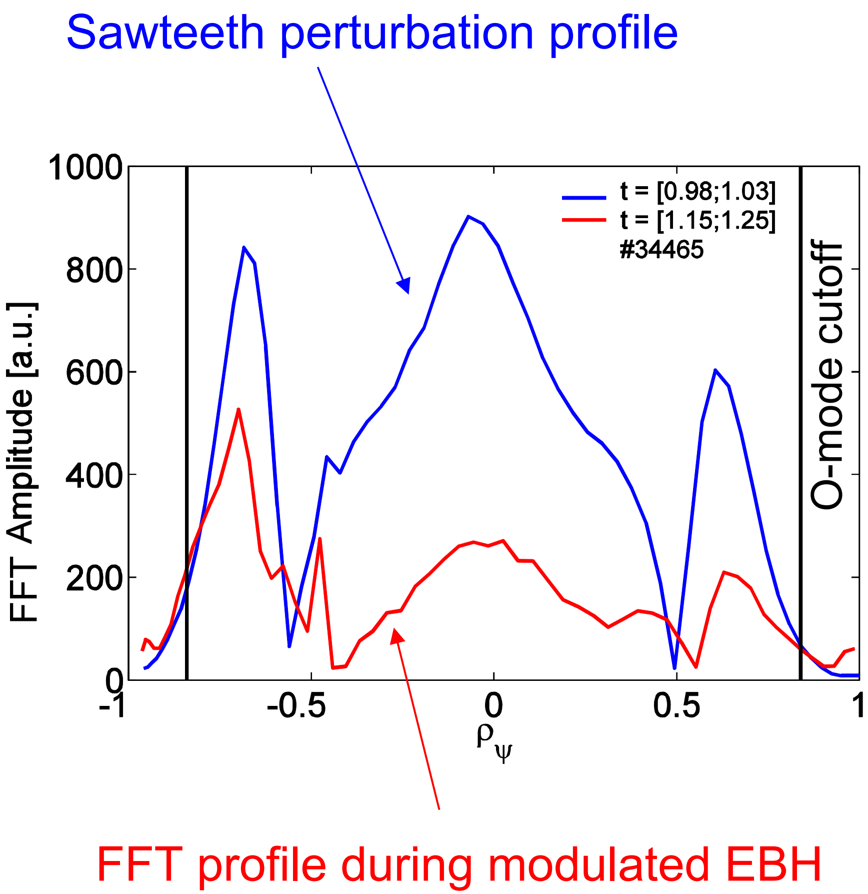
Sawteeth perturbation profile in OH

- Z_{axis} ~ 20 cm, UL launchers
- Off-axis deposition to avoid the strong central sawteeth

- Total energy from Diamagnetic Loop (DML) shows up to 60% global absorption
- Clear perturbation on edge soft X-ray channels (DMPX) for each EC power pulse

- Fast Fourier Transform (FFT) analysis can be used
- FFT → $\rho_{\psi dep}$ ~ 0.71
- ART → $\rho_{\psi dep}$ ~ 0.76
- Successful EBW deposition demonstrated

Core deposition: FFT analysis



- Z_{axis} ~ 0 cm, equatorial launchers
- DML shows up to 60% global absorption
- Slight but visible perturbation on soft X-ray channels (DMPX)
- Strong sawtooth activity hampers FFT analysis for $\rho_{\psi dep} < 0.7$

Break-in-slope (BIS) analysis

- Method for the power deposition localization **excluding the time of the fast sawtooth crash perturbation**

$\Rightarrow$ Quantify the break in the slope of soft X-ray traces due to EC power modulation

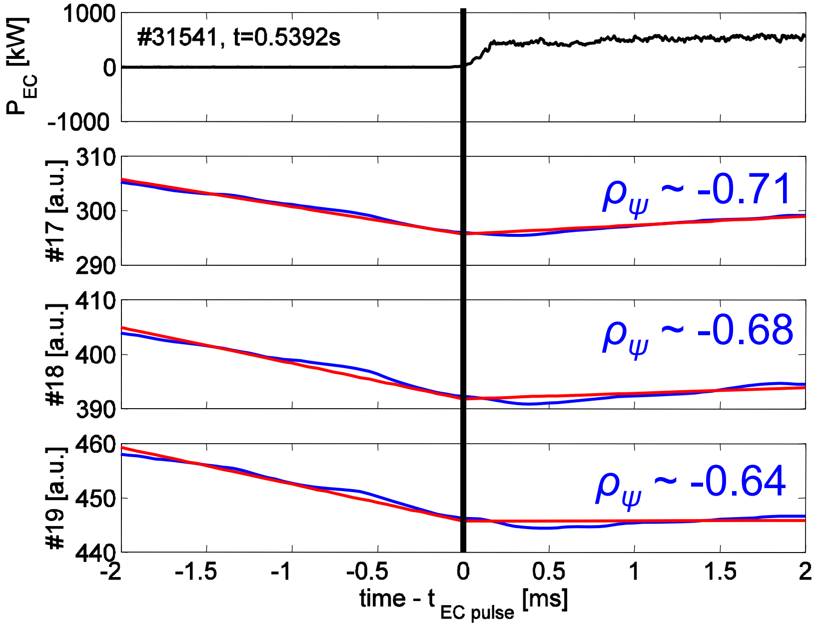
- Automatic detection of sawtooth crashes
- Select the EC power modulations excluding the sawtooth crashes and their propagation
- Linear fit of soft X-ray traces before/after EC switch-ONs
- Calculate the change in slope for each DMPX channel

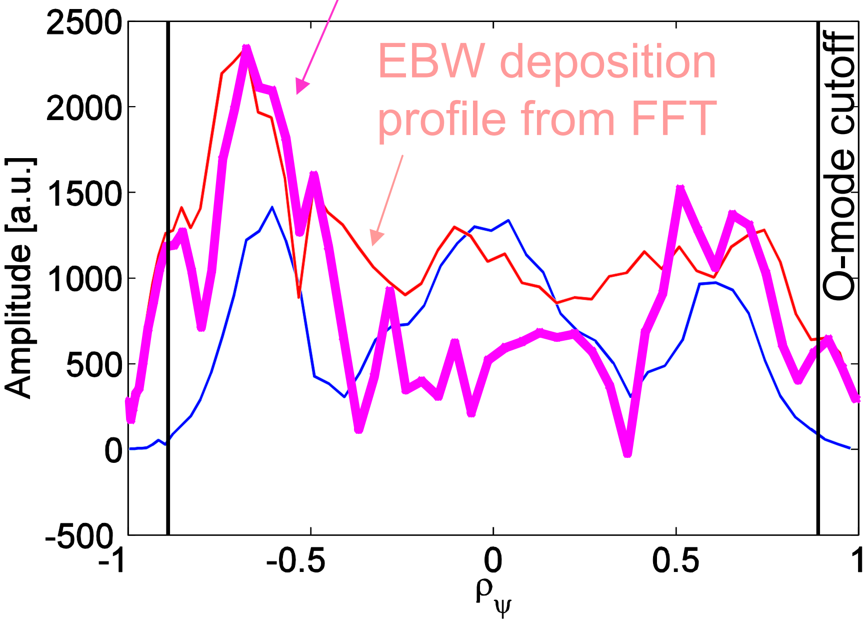
$\Rightarrow$ Break-in-slope profile

Advantages:

- BIS analysis provides information **for each EC power switch-ON** non-perturbed by the sawtooth
- Can be used where FFT is dominated by the sawtooth perturbation

Test BIS analysis on off-axis case

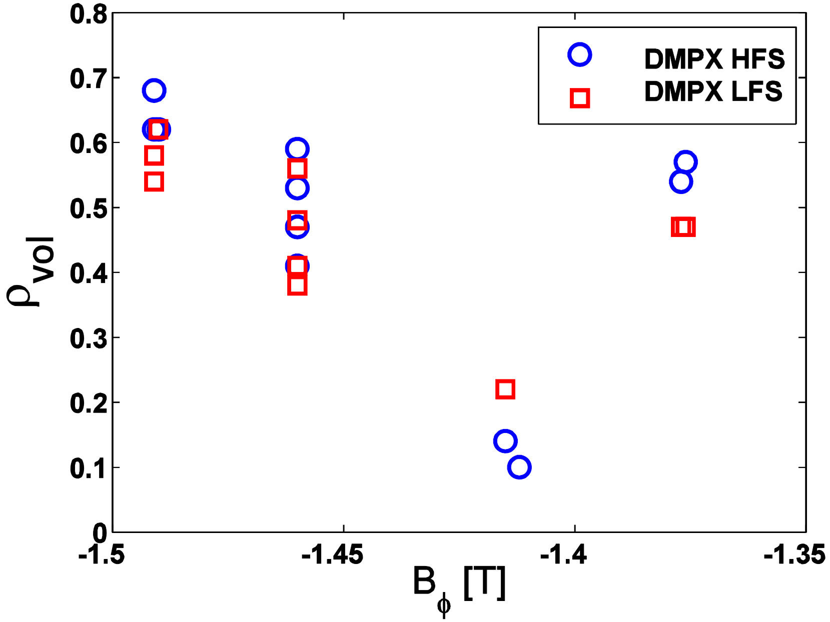




- BIS → $\rho_{\psi dep}$ ~ 0.70
- FFT → $\rho_{\psi dep}$ ~ 0.71
- ART → $\rho_{\psi dep}$ ~ 0.76

BIS agrees with FFT and ART

BIS deposition location in B_φ-scan



- B_φ scan to change the radial position of the resonance
- Power deposition location determined with BIS method applied on the DMPX channels
- Small database
  - 5 shots
  - 4 values of B_φ
- Optimum B_φ ~ 1.42 T found for central heat deposition
- ART agrees on the trend and on typical $B_{\varphi,opt}$ but significant radial discrepancies

Conclusions

- Successful assessment of a break-in-slope method for the detection of power deposition location in presence of strong sawteeth perturbation.
- This method now allows central power deposition measurements, not accessible with FFT.
- From yet a small database, initial experimental trend and field for a central EBH optimization was determined.
- Work in progress
  - Take into account the heat pulse propagation delay in the break-in-slope method
  - Use of a Drift-kinetic-equation solver and a fully-relativistic ray-tracing simulation (collaboration with J. Decker, CEA Cadarache) for evaluation of relativistic effects on the power deposition location.

Spare slides

O-X-B double mode conversion

- O-X conversion angular window for the wave injection directions

$$T_{O\text{-}X} = \exp\left\{-\pi \mathbf{k_0 L_n} \sqrt{Y/2}\left[2(Y+1)(N_z - \mathbf{N_{z,opt}})^2 + N_y^2\right]\right\}$$

$$L_n = \left(\frac{dn}{dR}\frac{1}{n}\right)^{-1} \qquad Y = \frac{\omega_{ce}}{\omega} \qquad N_{z,opt}^2 = \frac{Y}{Y+1} = \cos^2(\theta_c)$$

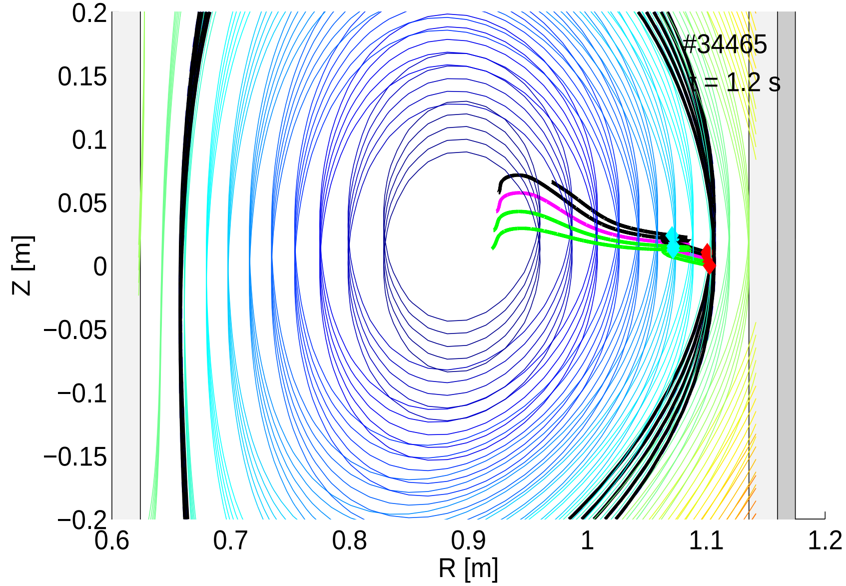
- X-B conversion transmission function (neglecting non-linear effects)

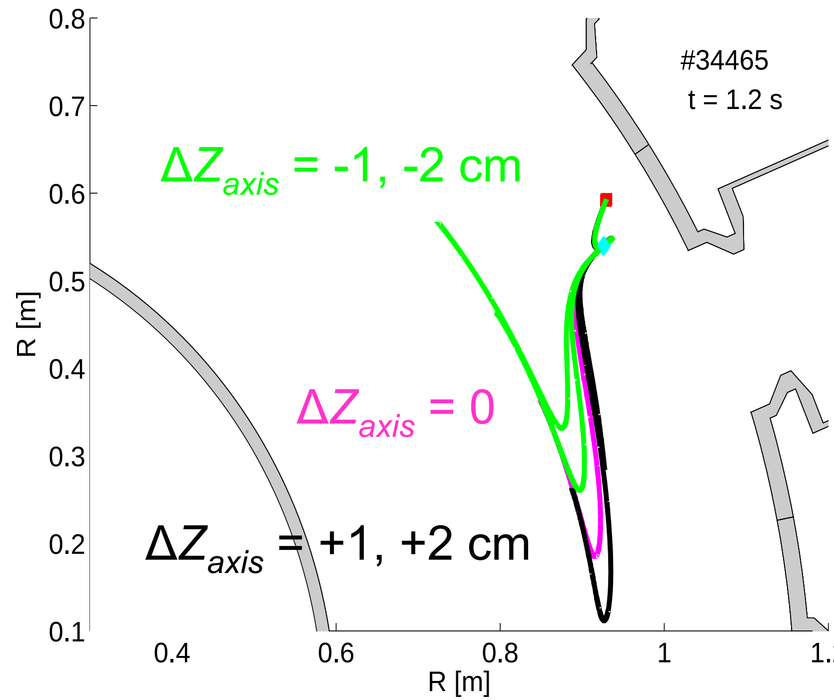
$$T_{X-B} = 1 - \exp\left\{-\pi k_0 L_n Y^2 \sqrt{\left(\omega_{UH}/\omega_c - 1\right)/X}\right\}$$

$$X = \frac{\omega_{pe}^2}{\omega^2}$$

- Thus, required normalized density scale length is typically $k_0 L_n \sim 10$ in TCV

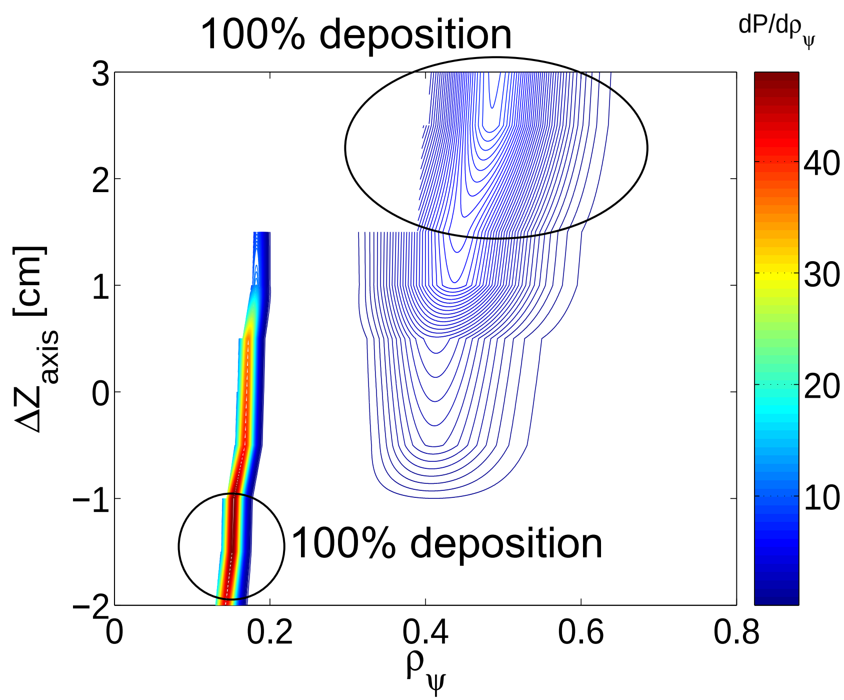
Test ray propagation sensitivity to Z_{axis}





- Difficulty for the power localization could come from the presence of a double absorption location

Power deposition sensitivity to Z_{axis}



- The more the plasma moves away from Z_{inj} ~ -2.1 cm (Z_{axis} ~ 2.3 cm, ΔZ_{axis} > 0), the more power is absorbed at the outer location