

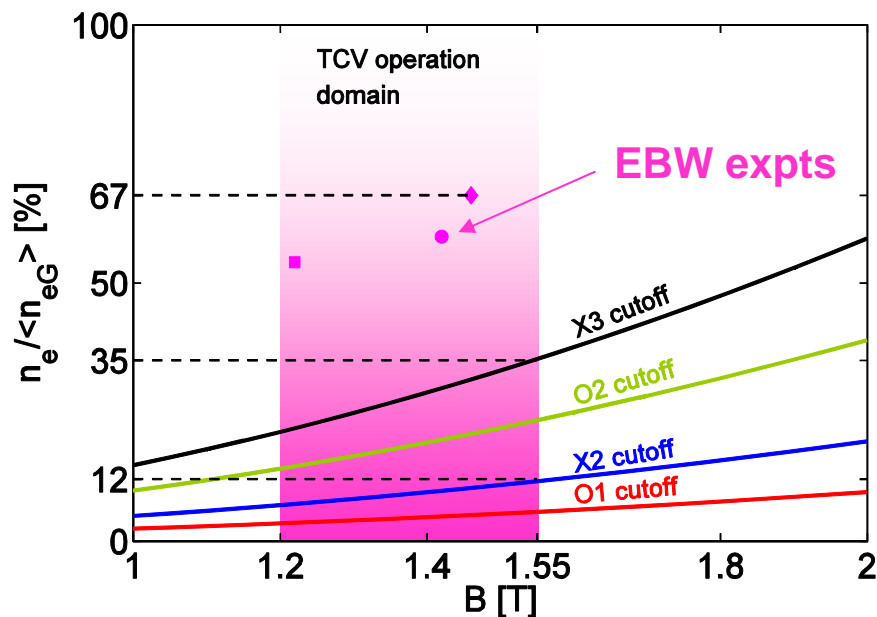
Electron Bernstein wave core deposition via O-X-B double mode conversion in TCV

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Context



Tokamak empirical density limit

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

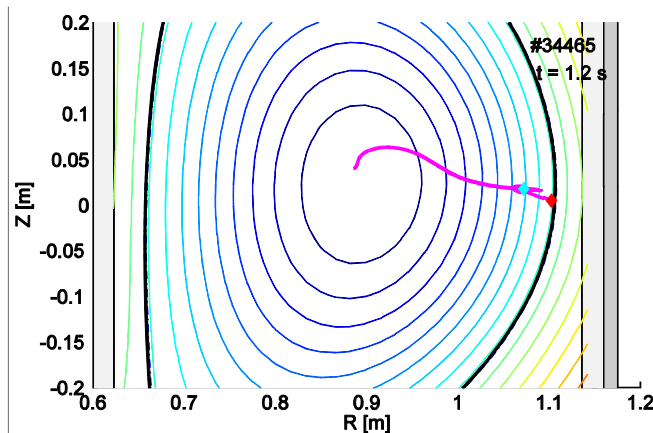
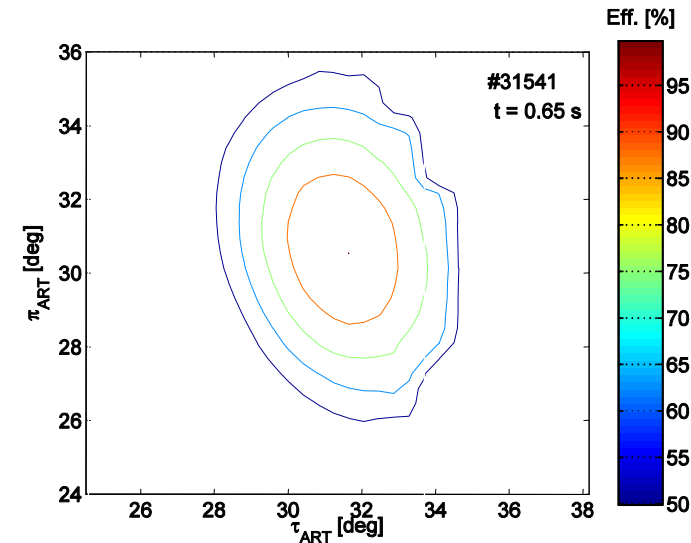
- Electron cyclotron (EC) waves accessibility limitation in medium to low B field tokamaks

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

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

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

O-X-B double mode conversion

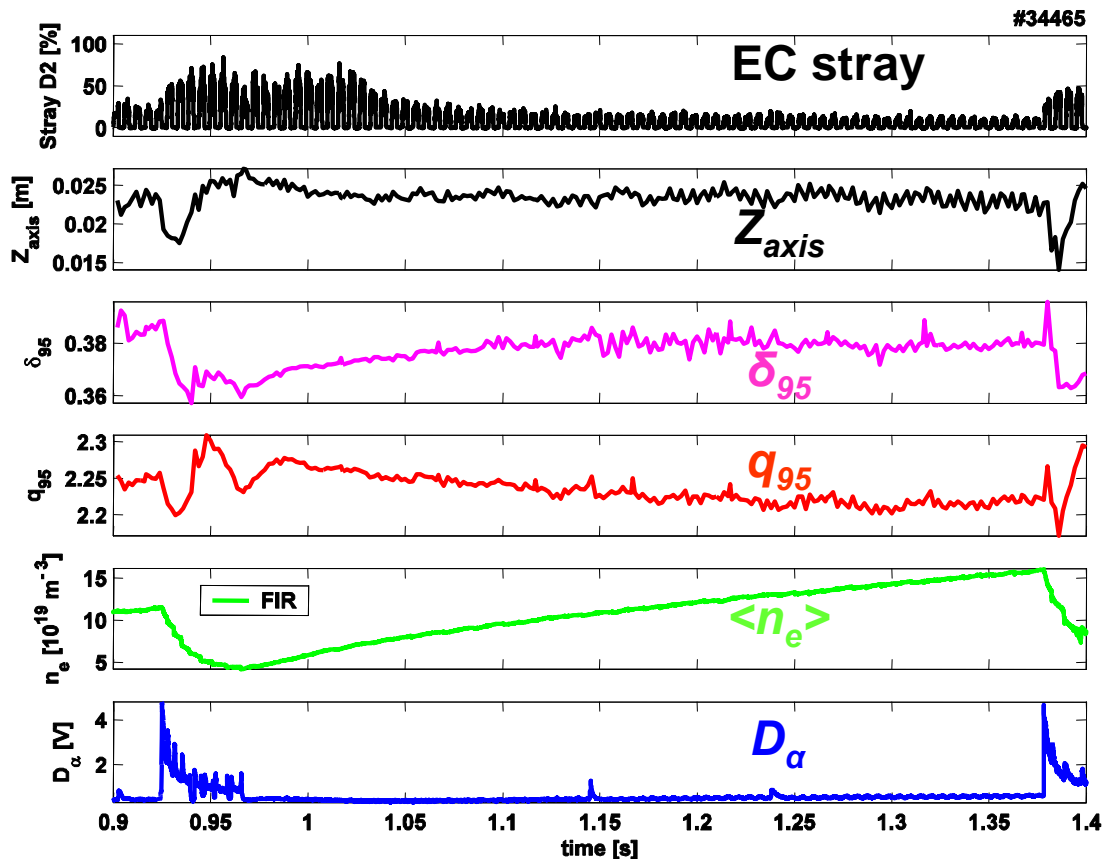


- Bernstein waves are **electrostatic**
 \Rightarrow need a conversion from externally launched e.m. waves in O-mode
- **O-mode to X-mode** conversion at the O-mode cutoff: angular window for the wave injection angles (π and τ) of width T_{O-X}

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

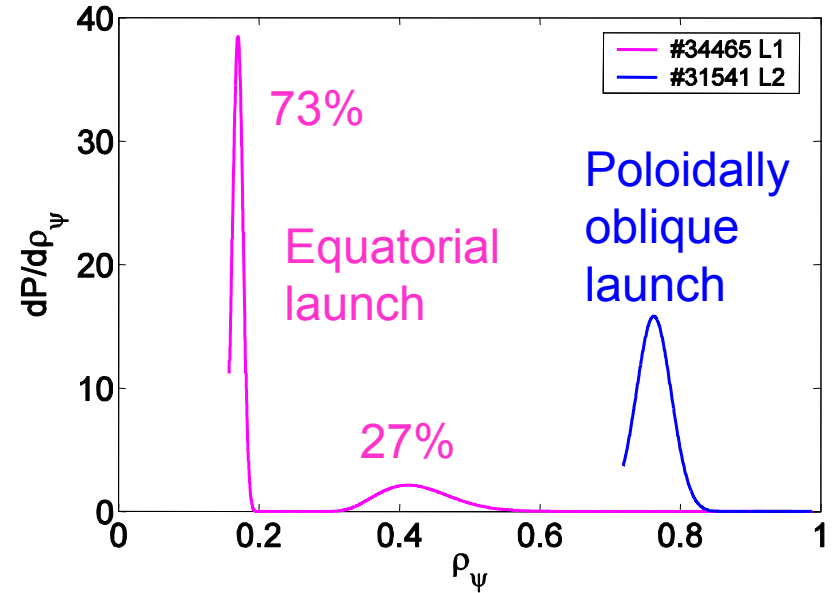
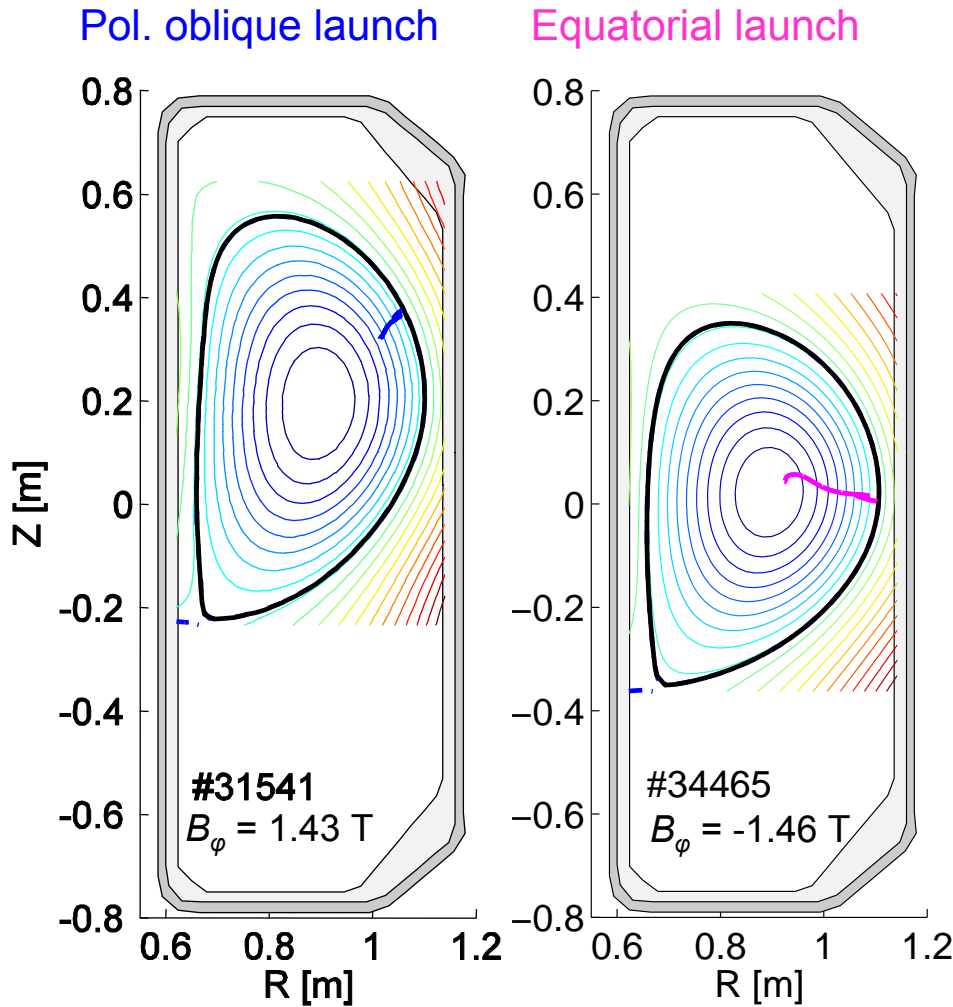
- \Rightarrow needs a small normalized density scale length $k_0 L_n$ (steep ∇n)
- **X-mode to B-mode** conversion at the upper-hybrid resonance: needs $k_0 L_n > 1$

O-X-B EBH plasma target in TCV



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

From off-axis to core EBW deposition



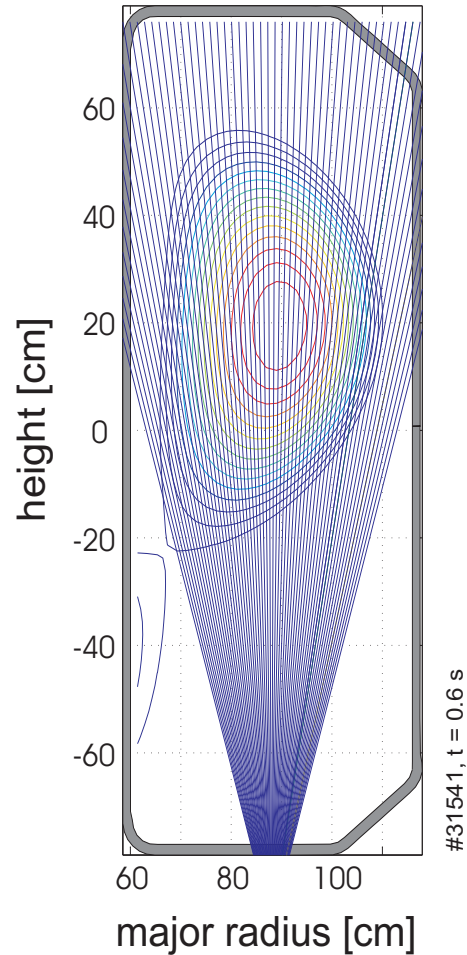
ART non-relativistic ray-tracing:

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

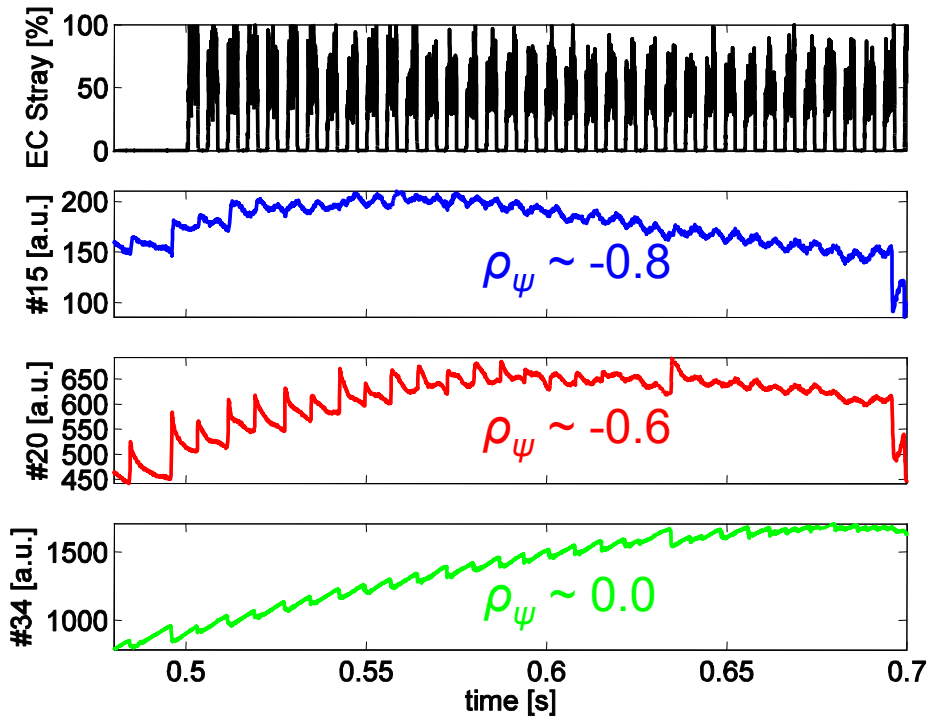


Duplex Multiwire Proportional soft X-ray detector (DMPX)

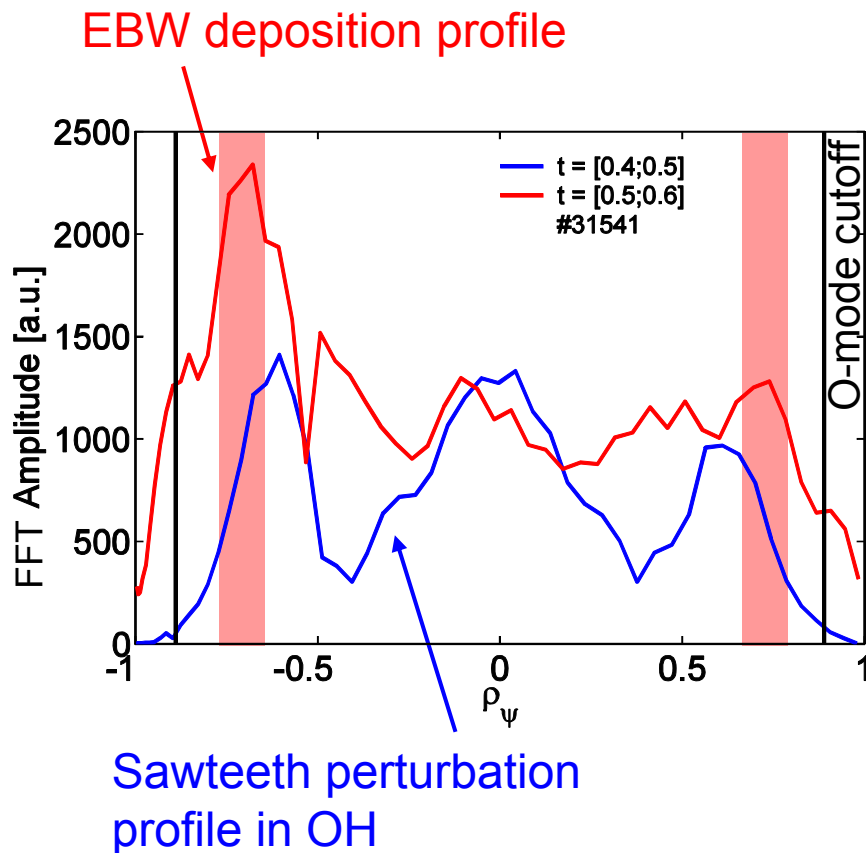
DMPX lines of sight



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



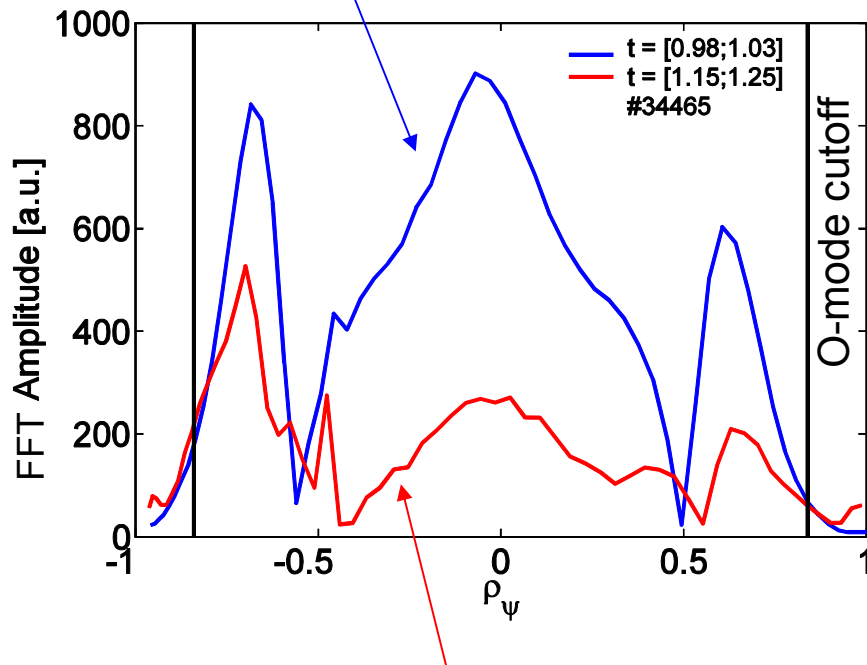
Off-axis deposition: FFT analysis



- $Z_{axis} \sim 20$ 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 $\rightarrow \rho_{\psi dep} \sim 0.71$
 - ART $\rightarrow \rho_{\psi dep} \sim 0.76$
- Successful EBW deposition demonstrated

Core deposition: FFT analysis

Sawteeth perturbation profile



FFT profile during modulated EBH

- $Z_{axis} \sim 0$ 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

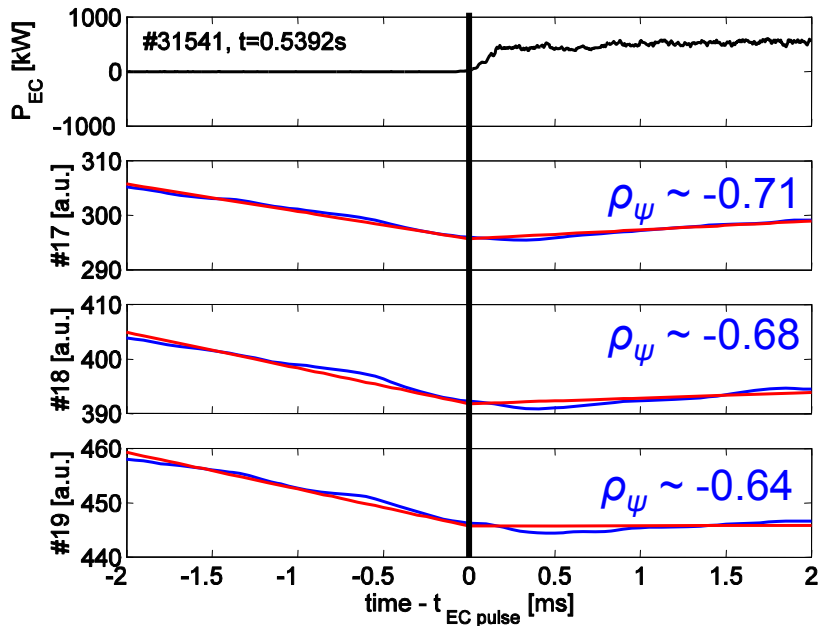
- Method for the power deposition localization **excluding the time of the fast sawtooth crash perturbation**
- ⇒ Quantify the break in the slope of soft X-ray traces due to EC power modulation

- 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
- ⇒ Break-in-slope profile

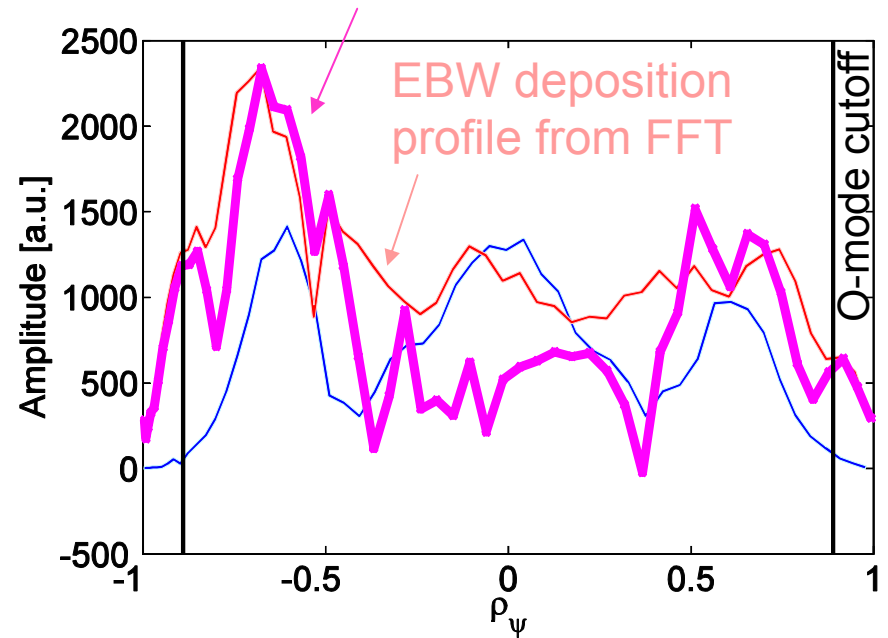
Advantages:

- 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

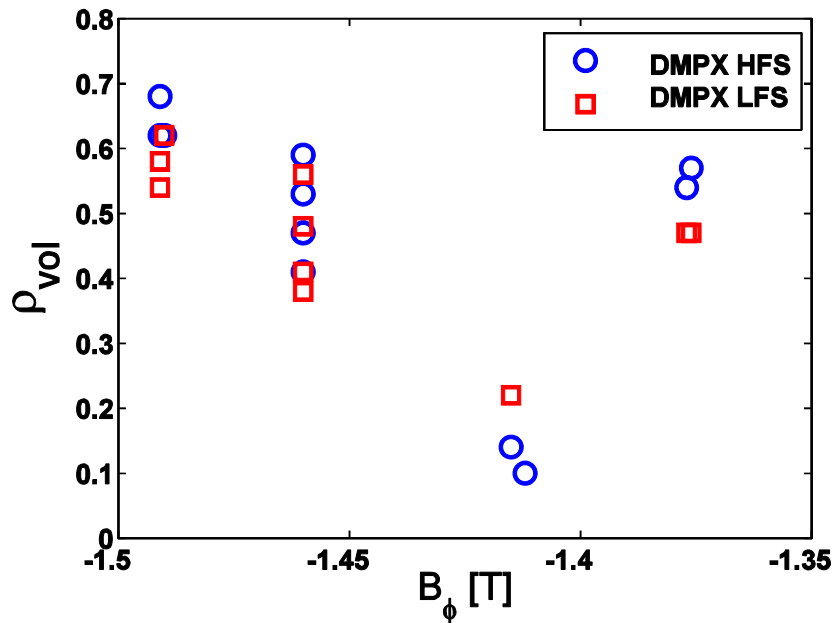


EBW deposition profile from BIS



- BIS → $\rho_{\psi dep} \sim 0.70$
 - FFT → $\rho_{\psi dep} \sim 0.71$
 - ART → $\rho_{\psi dep} \sim 0.76$
- } 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 $B_\phi \sim 1.42$ T found for central heat deposition
- ART agrees on the trend and on typical $B_{\phi,opt}$ 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

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

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

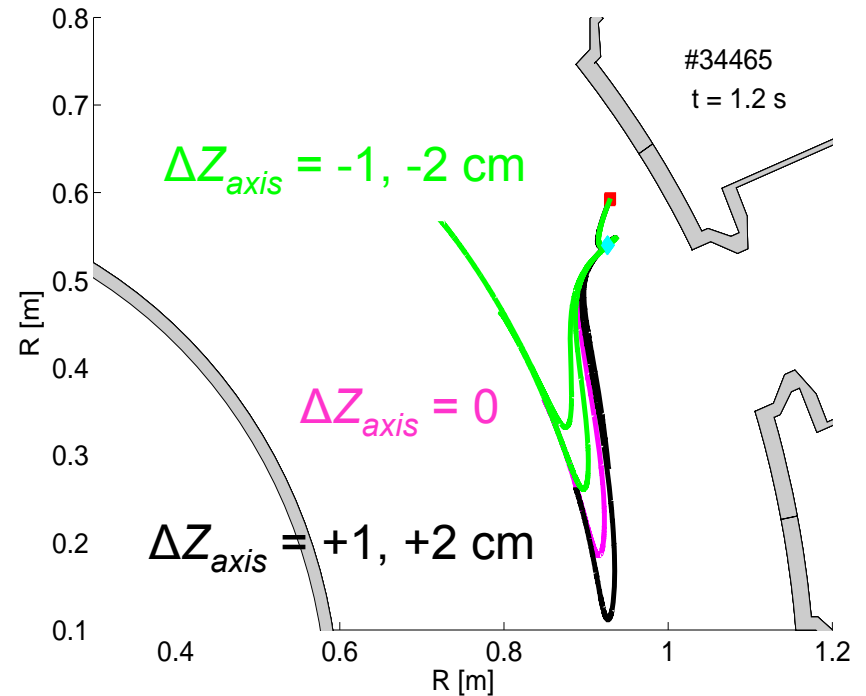
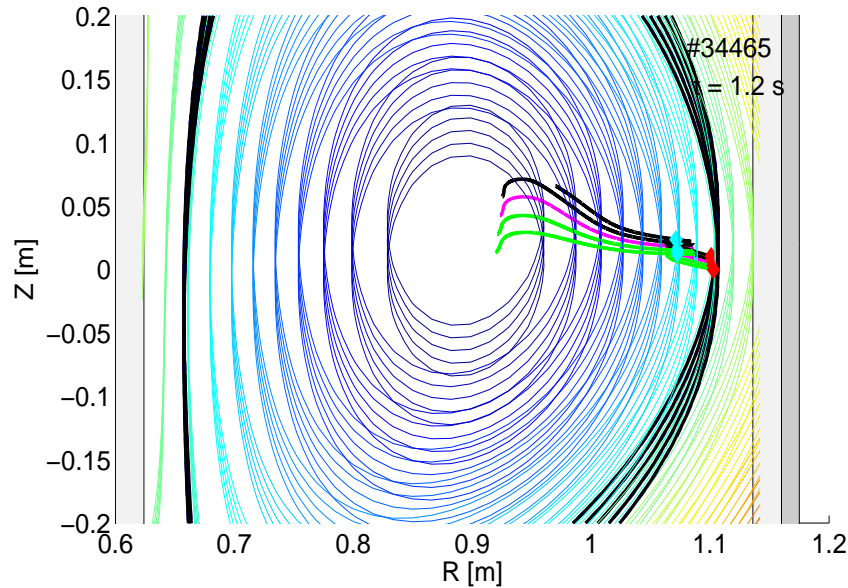
- X-B conversion transmission function (neglecting non-linear effects)

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

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

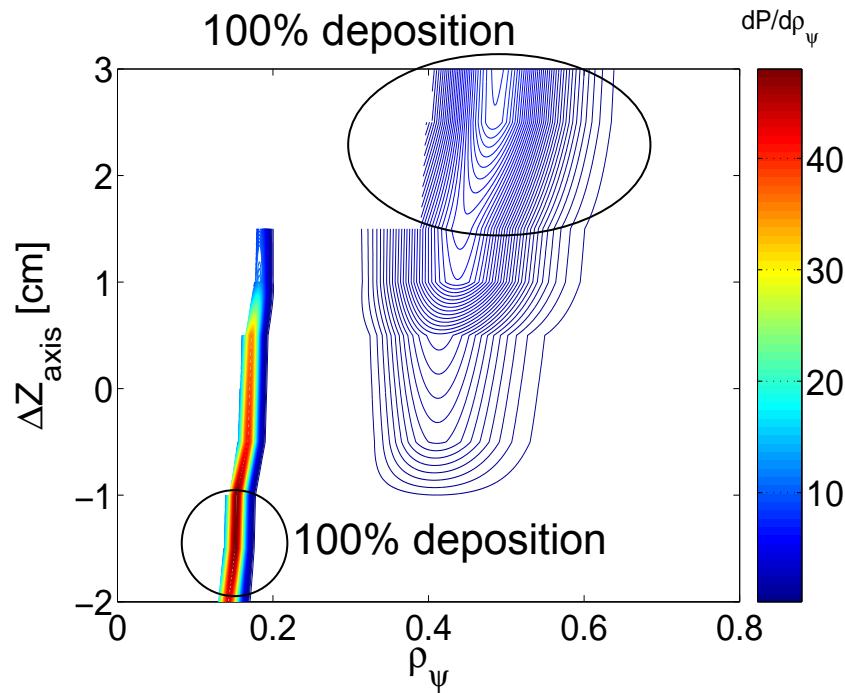
- Thus, required normalized density scale length is typically $k_0 L_n \sim 10$ in TCV

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 $Z_{inj} \sim -2.1$ cm ($Z_{axis} \sim 2.3$ cm, $\Delta Z_{axis} > 0$), the more power is absorbed at the outer location