# Electron Bernstein Wave Heating and Emission in the TCV Tokamak

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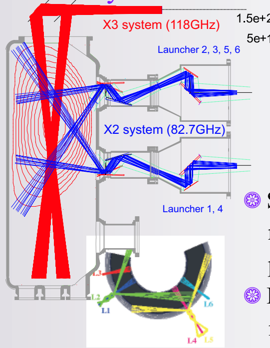
## Introduction

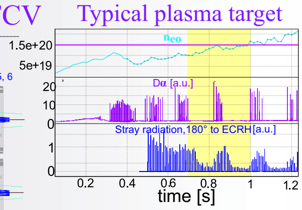
- ECRH LFS accessibility is limited by cut-offs at high $n_e$. X-mode: right hand cut-off; O-mode: plasma cut-off
- O-X-mode conversion at plasma cut-off
- O-X power transmission: $T(N_\perp,N_\parallel)=\exp(-\pi k_0 L_n[(Y/2)^{1/2}[2(1+Y)(N_{\parallel,opt}-N_\parallel)^2+N_\perp^2])$
- At upper hybrid layer → second mode conversion into Bernstein mode → **O-X-B scheme**.
- Absorption at harmonics of the cyclotron resonance
- **B-X-O emission** inverse process of OXB

## Experimental Determination of Optimum Angle

### ECRH System in TCV

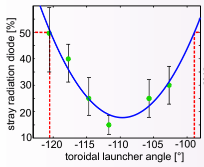



### Typical plasma target

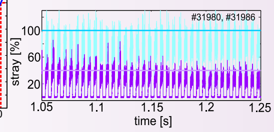



- Strong decrease of stray radiation in ELM free phases ⇒ high absorption
- ELM behaviour plays an important role in O-X conv.

### Toroidal angle scan



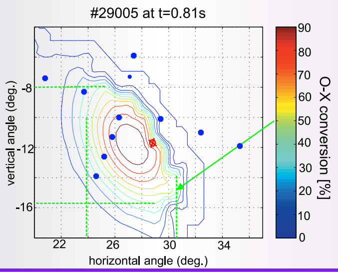

### Comparison O- and X-mode injection




- Tor. and pol. angular dependence as expected for O-X conversion
- Similar behaviour for equatorial and upper lateral launchers
- No angular dependence in stray in X-mode

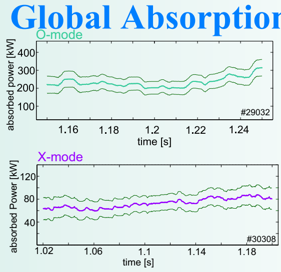
## Ray Tracing with ART Code

- ART: calc. of angular window for O-X conv., propagation, deposition, absorp.
- Simulated angular window reproduces well measured angle dependence (~2°)!

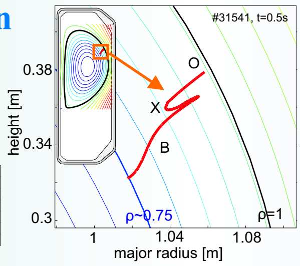



## Global and Local Heating Experiments

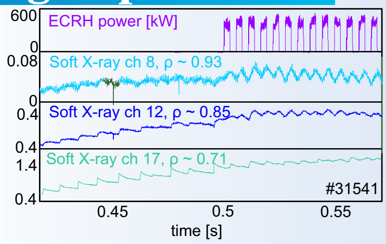
### Global Absorption




- Global central abs. from DML
- O-mode absorption: ~ 60%
- X-mode absorption: < 10%
- → multipass absorption ~ 10%

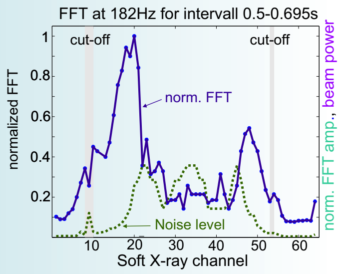


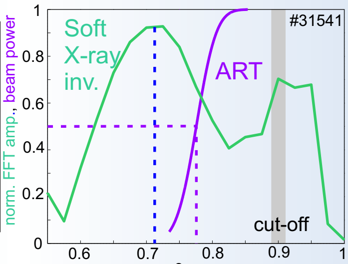

- Due to interference of sawteeth, deposition chosen close to edge
- Edge absorption achieved via upper lateral injection & z=20cm




- Clear response in soft X-ray signal due to modulated ECRH → EBW heating!
- $f_{mod}$ = 182 Hz, $f_{ST}$ ~ 110 Hz
- FFT of all 64 soft X-ray channels

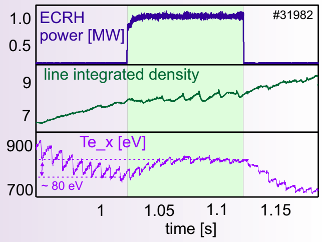
## Local Absorption from soft X-rays



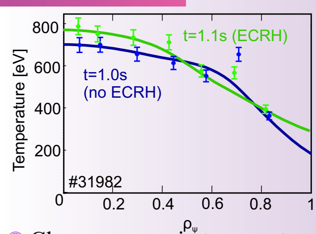




- FFT amplitude over SXR channels
- Clear maxima above noise level show EBW deposition location!
- Deposition at channels 20, 52
- SXR line integrated → inversion
- Deposition SXR: $\rho_\psi$ ~ 0.72
- ART absorption: $\rho_\psi$ ~ 0.78
- → good agreement within 10%

## Temperature increase

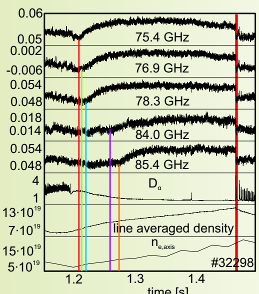



- Long ECRH pulses of 100ms, 1MW
- Additional heating: $P_{Ohm}$ ~ 0.6MW, $P_{ECRH}$ ~ 1MW
- ART deposition location $\rho_\psi$ ~ 0.4



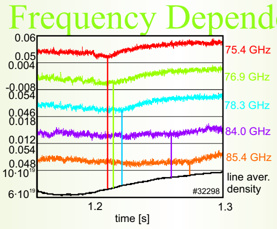

- Clear response in temperature of ~ 80eV via SXR absorber method
- Central temperature increase of ~ 100eV via Thomson scattering
- → Central $T_e$ increase via EBWH!

## Electron Bernstein Wave Emission




- Emission observed with new reception launcher in overdense plasmas → EBE
- Emission is angle dependent!

### Frequency Dependence of O-mode Cut-off




| f [GHz] | cut-off calc. [e19] | FIR EBE onset [e19] | $n_{e,axis}$ EBE onset [e19] |
|---|---|---|---|
| 75.4 | 7.0 | 6.7 | 6.8 |
| 76.9 | 7.35 | 7.1 | 7.3 |
| 78.3 | 7.6 | 7.5 | 7.7 |
| 84.0 | 8.8 | 9.1 | 9.7 |
| 85.4 | 9.1 | 9.5 | 10 |

- EBE interrupted by ELM like for heating!
- EBE onset shifted to higher densities with increasing frequency, as expected
- Error between calculated cut-off densities and measured density 5-10% → good agreement!

## Conclusions

- For first time EBWH via O-X-B conversion demonstr. in standard aspect-ratio tokamak (overdense plasmas)!
- Angle dependence of O-X conversion confirmed
- Localized heating deposition location at $\rho_\psi$~0.7
- Temperature increase due to EBWH observed with wire chamber SXR and Thomson
- First successful density and angle dependent EBE measurements

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