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Overview of ECRH and EBW modelling on ST40

E. du Toit[1], V. Shevchenko[1], M. Ono[2] and N. Bertelli[2]

[1]*Tokamak Energy, 173 Brook Drive, Milton Park, Oxon, OX14 4SD, UK*

[2]*Princeton Plasma Physics Laboratory, Princeton, NJ, 08543, USA*

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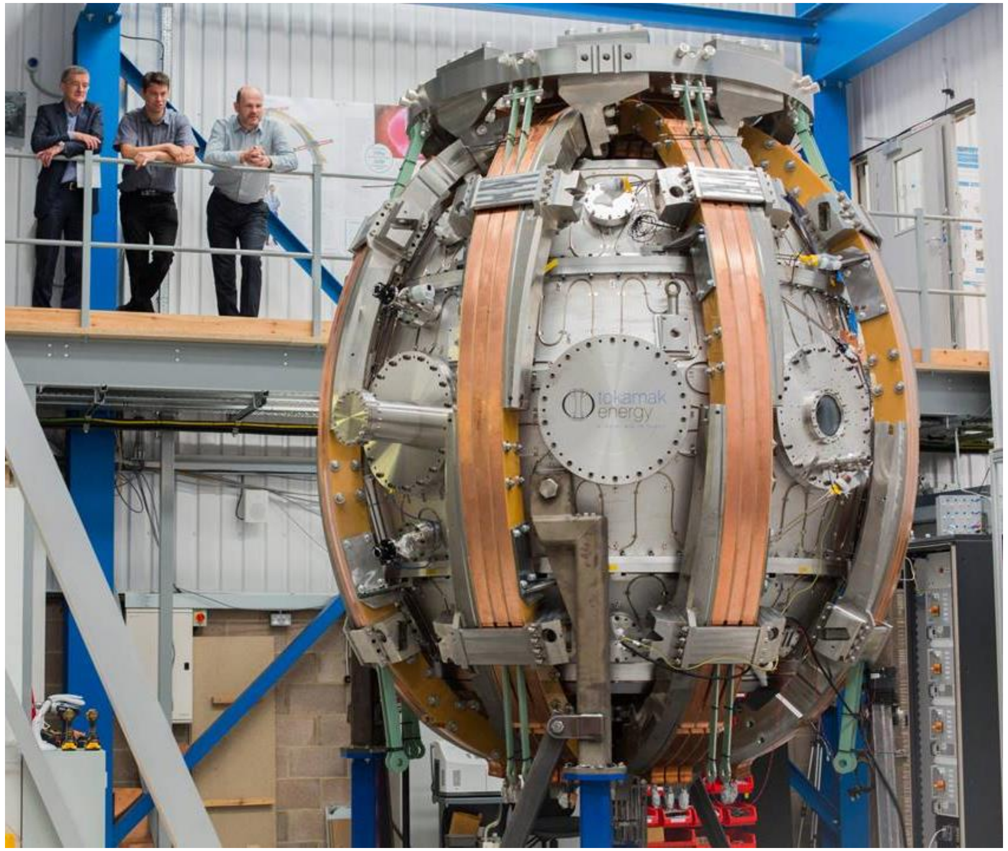
ST40 is a high field spherical tokamak



- ST40 is a high field spherical tokamak (ST) with a nominal maximum $\mathrm{B} = 3\mathrm{T}$ and $R_0 = 0.4 \rightarrow 0.6\mathrm{m}$

- To date, plasma currents up to $0.8\mathrm{MA}$ and pulse durations of $200\mathrm{ms}$ have been achieved with $B \sim 2\mathrm{T}$

- The main research aims for ST40 includes the development of solenoid-free start-up methods

- Electron cyclotron resonance heating (ECRH) and current drive (CD) are planned to be tested in ST40

ECRH system is under construction for ST40

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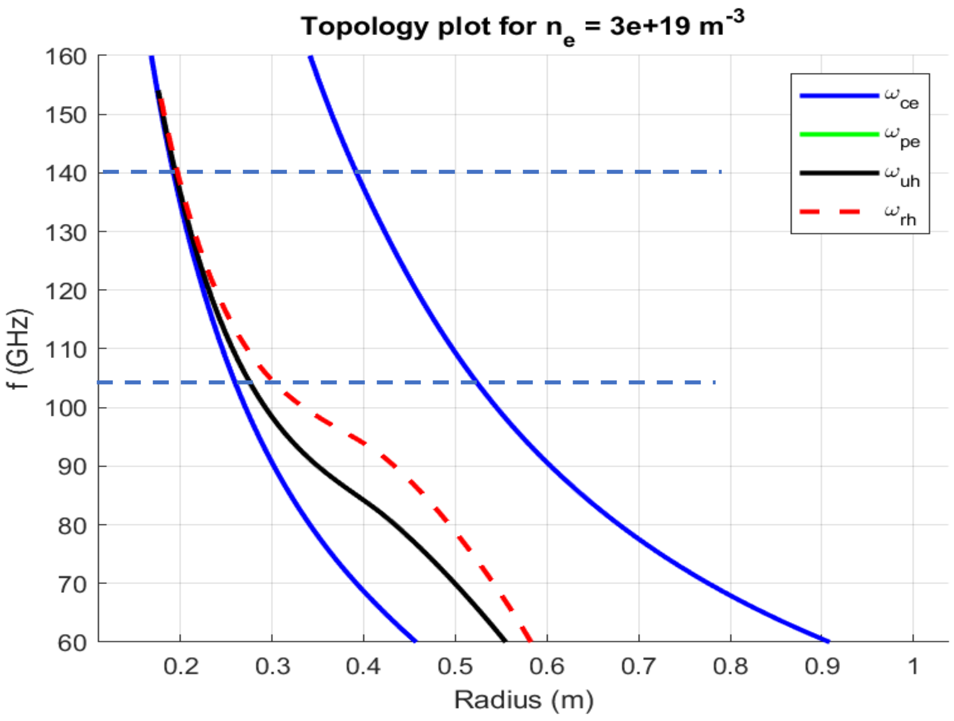
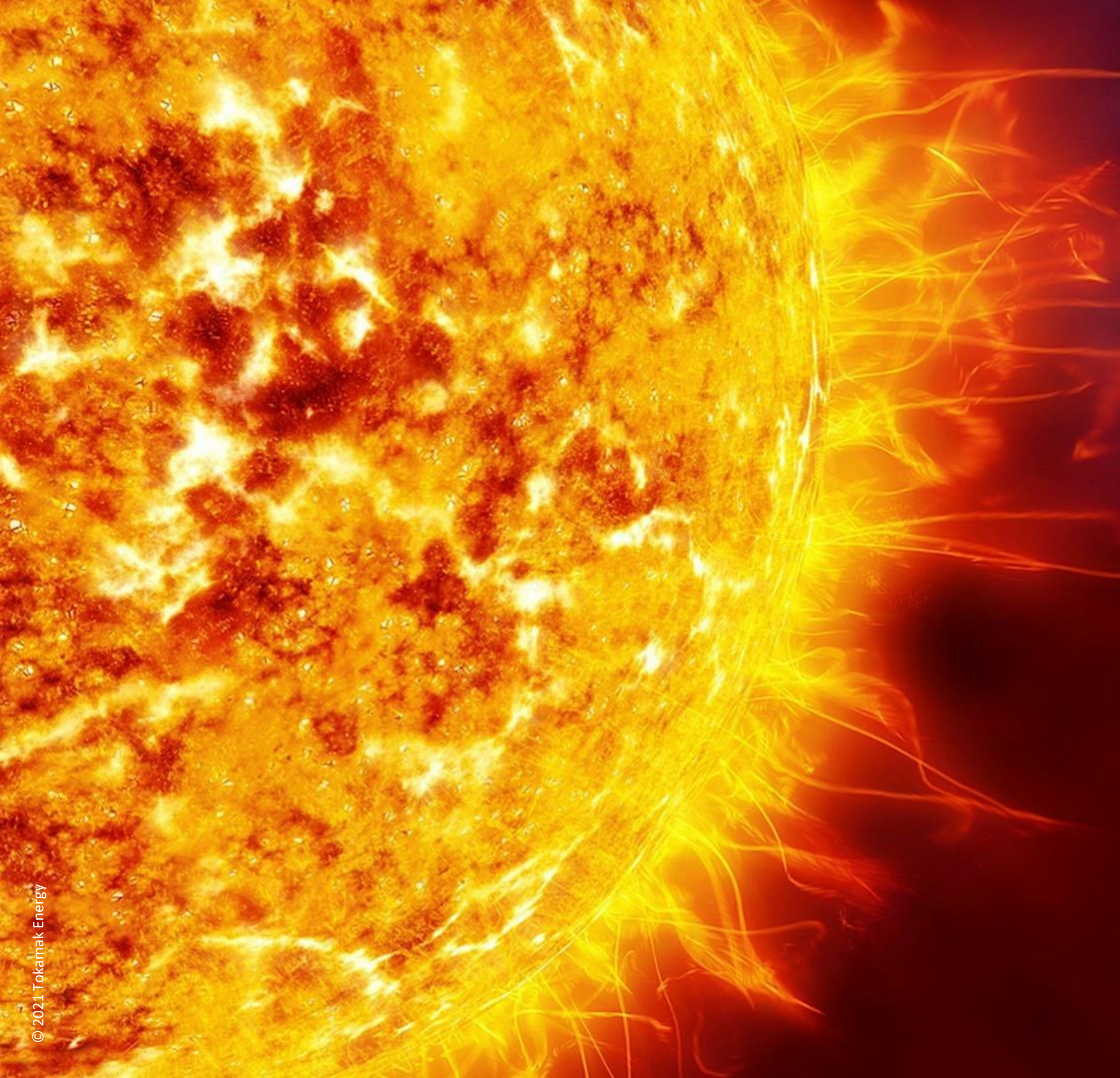
- A multi-frequency ECRH system is currently under construction
  - Consists of two 105/140GHz dual frequency gyrotrons capable of up to 1 MW each
  - This will enable the study of EC heating and current drive, including non-inductive start-up
- This talk will cover three types of heating and current drive:
  1. 2nd harmonic X-mode heating
  2. Excitation of electron Bernstein waves (EBWs)
  3. Fundamental X-mode heating

Topology plot for ST40 plasma showing the fundamental and 2nd resonance locations for $B = 2.4\mathrm{T}$





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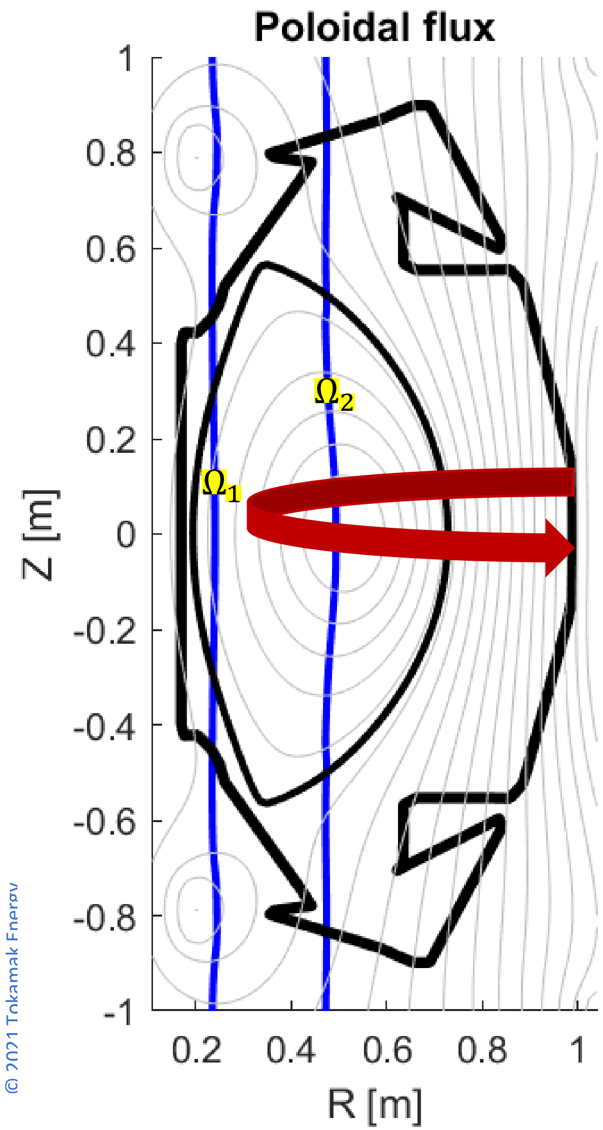
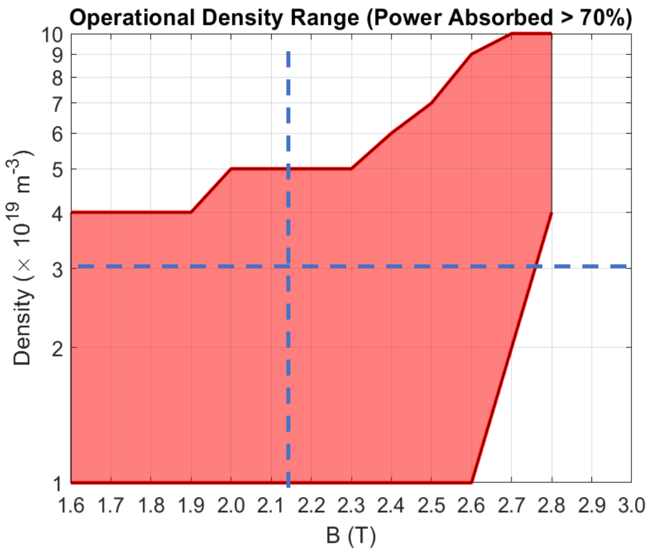
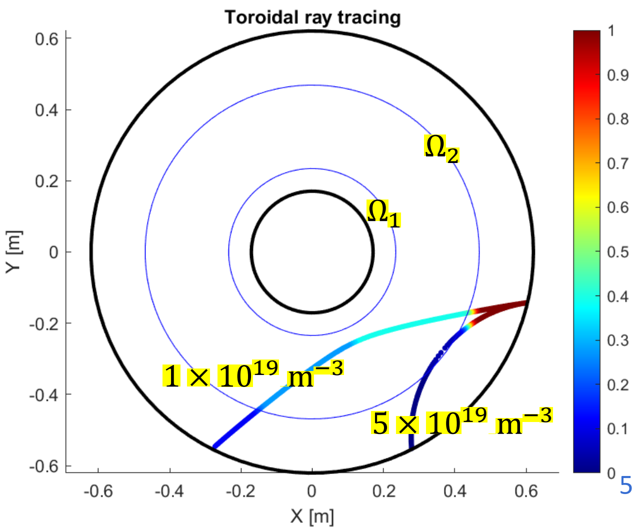
2nd harmonic X-mode

LFS 2nd harmonic X-mode heating with steerable mirror



- 2nd harmonic X-mode ECRH will be studied using a LFS midplane launcher (left)
- The LFS launcher consists of a steerable mirror in the poloidal ($\pm 10°$) and toroidal ($\pm 20°$) directions
- The range of densities for which more than 70% of input power is absorbed is shown for a range of magnetic field strengths (top right), for 105GHz, with $T_e = 1\text{keV}$
- Absorption decreases at higher densities due to refraction, which is illustrated by the wave propagation and absorption in the toroidal plane for $B = 2.2T$ for two densities (bottom right) with $T_e = 1\text{keV}$
- Increasing the magnetic field strength will enable heating at higher densities

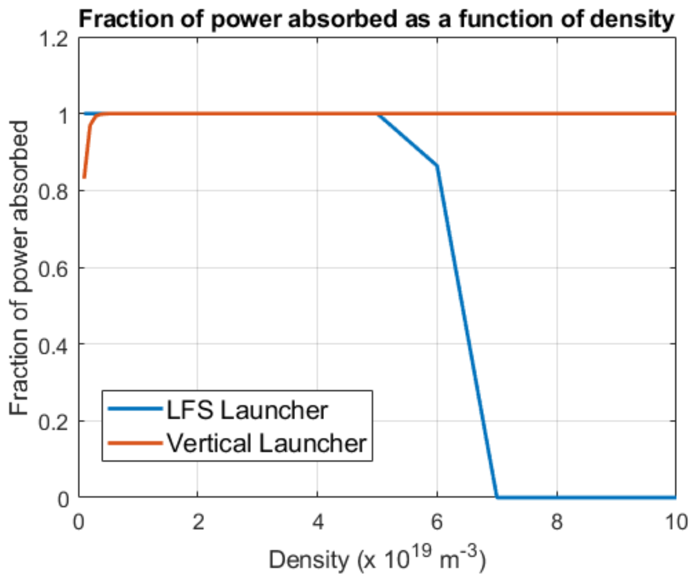


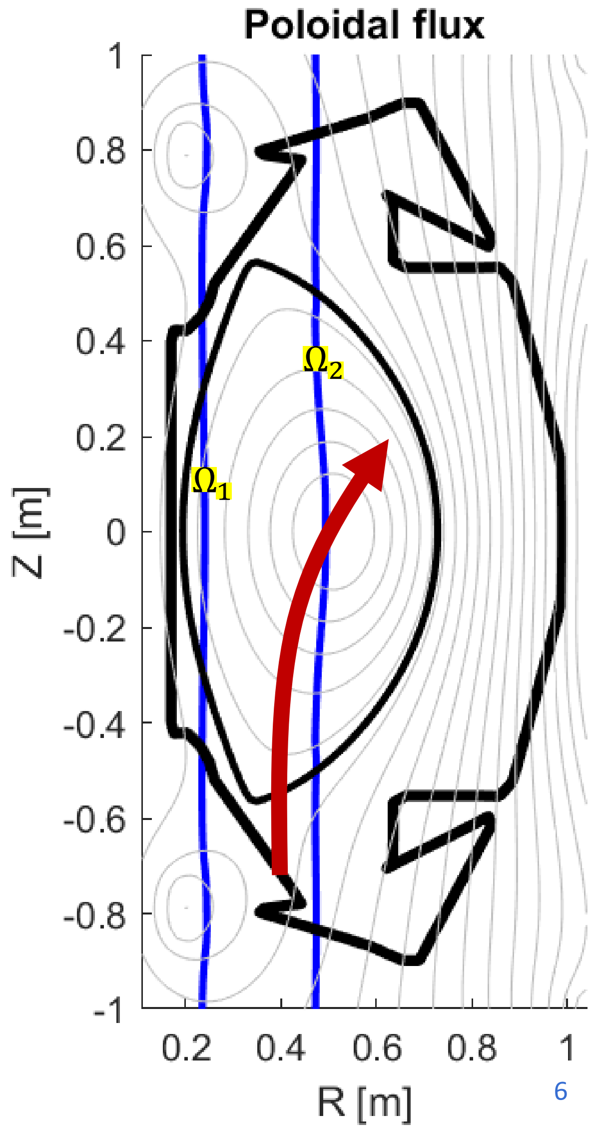


Vertical launcher shows better absorption than LFS launcher at high densities

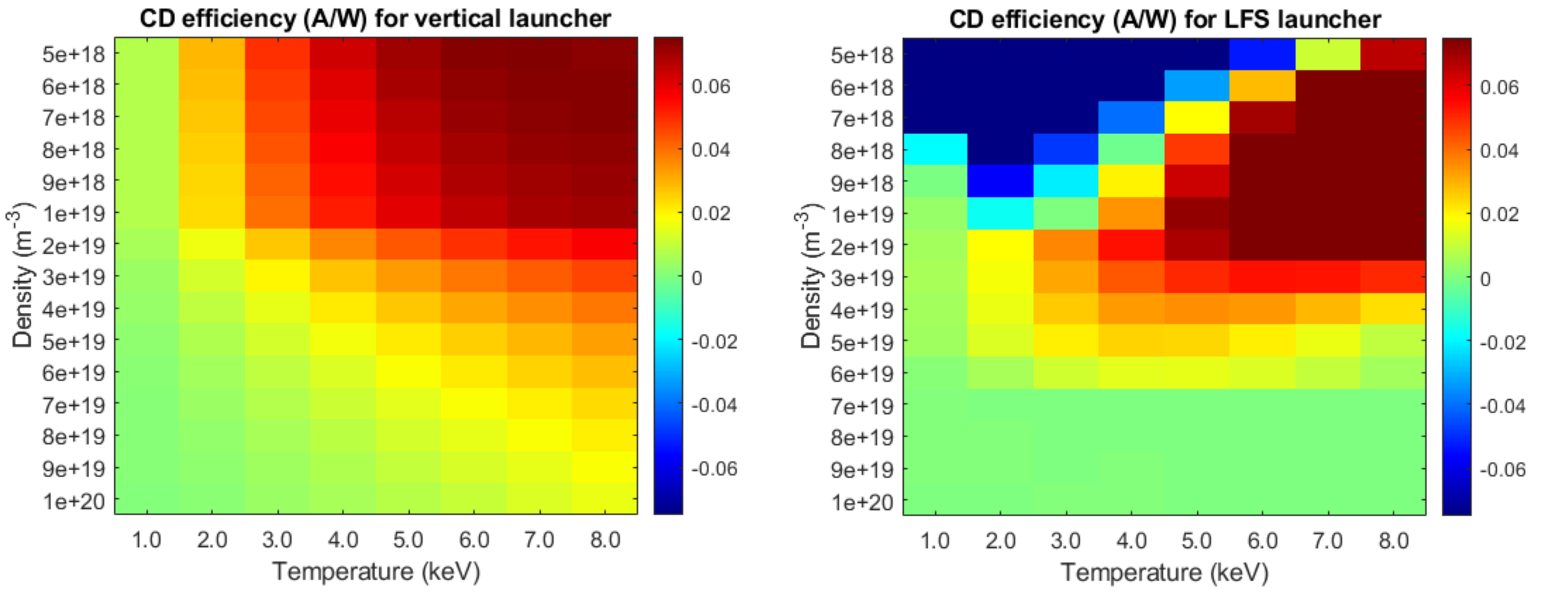
- A vertical launcher can provide additional heating and current drive
- The scheme will make use of 2nd harmonic X-mode heating
- The diagram (right) shows the vertical launcher for a magnetic field strength $B = 2.2T$
- The vertical launcher allows for better absorption at high densities compared to a LFS launcher
- For a LFS launcher, access to the 2nd harmonic resonance is prevented at high densities due to refraction
- For the vertical launcher, refraction forces absorption towards the edge of the plasma at high densities

Fraction of power absorbed as a function of density for a LFS and Vertical launcher, for $T_e = 5\text{keV}$ and $B = 2.2\text{T}$





The LFS and vertical launchers generate similar current drive



CD efficiency (A/W) for different densities and temperatures for a vertical launcher (left) and LFS launcher (right)

- The vertical and LFS launcher show CD efficiencies of $\sim 20 \rightarrow 40\text{kA/MW}$ for relevant densities and temperatures
- The CD efficiency scales like T_e/n_e for the vertical launcher
- The LFS launcher generates negative current at low densities and temperatures
  - It has a higher maximum current drive at low densities and high temperatures
  - The location of absorption varies with density and temperatures, as power can be absorbed in a single or double resonance pass, on the high- or low-field side of the resonance, while some power could also be absorbed at the fundamental resonance at low densities

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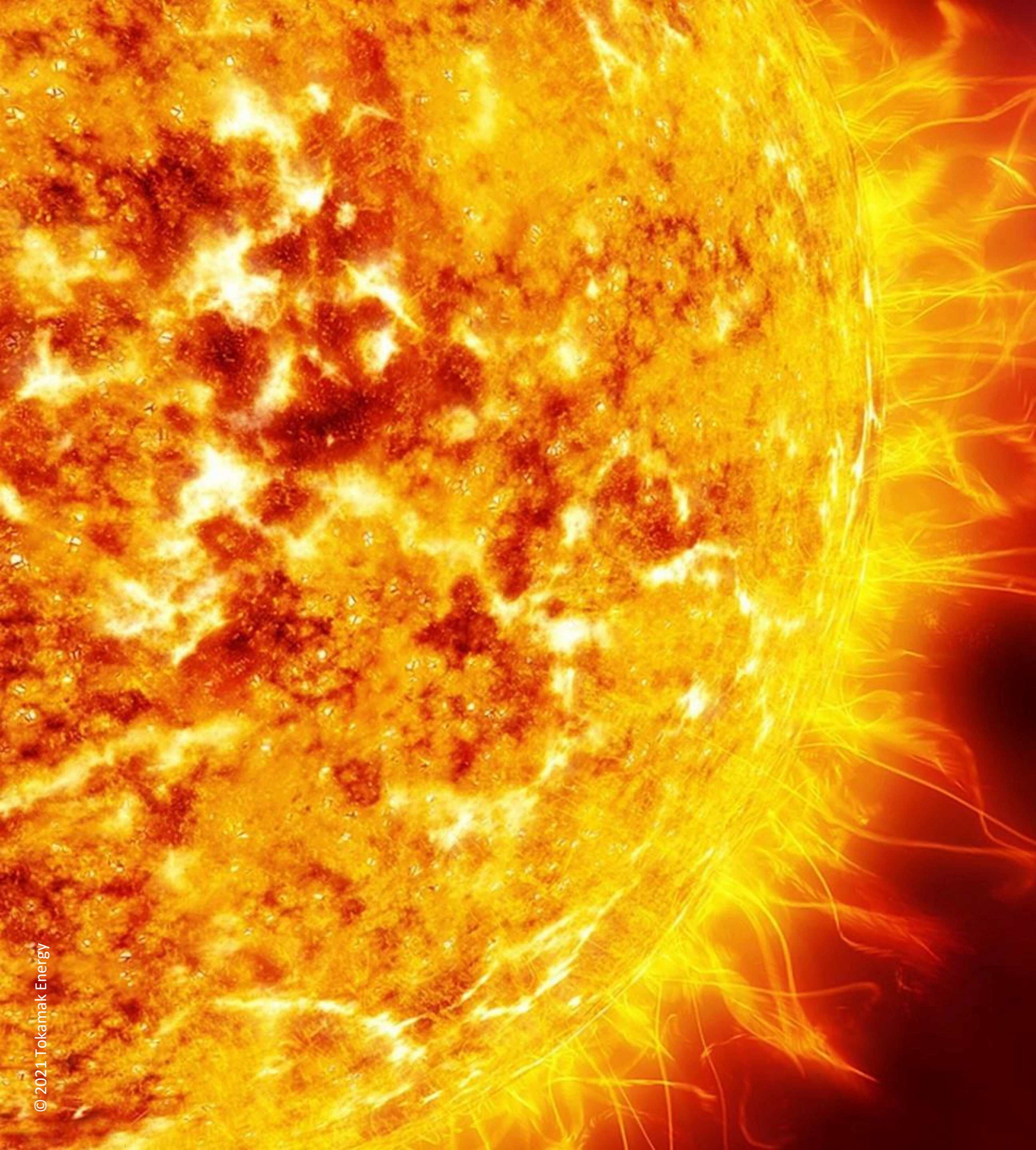
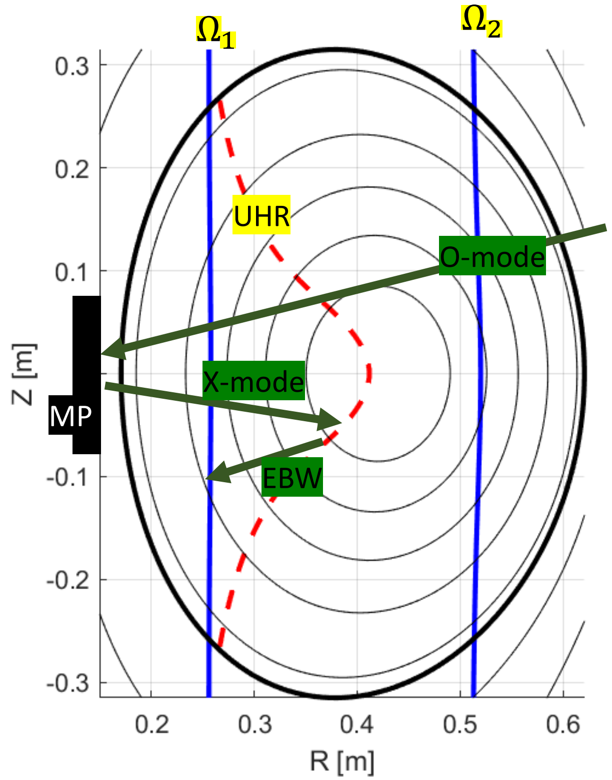
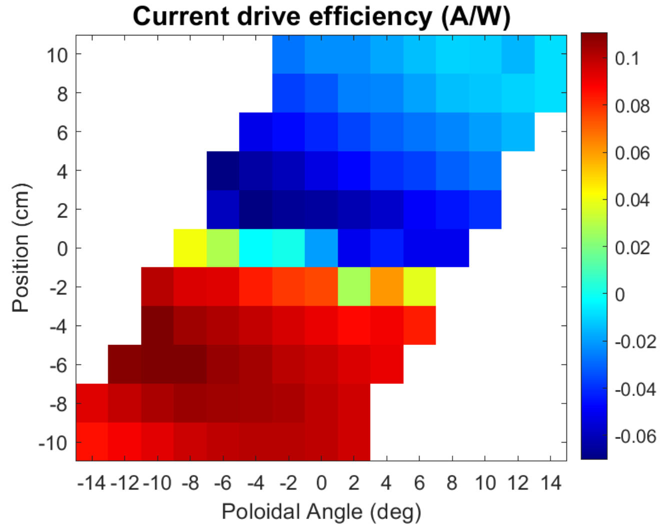


EBW excitation

EBWs are excited in a O-X-B scheme via a mirror polarizer



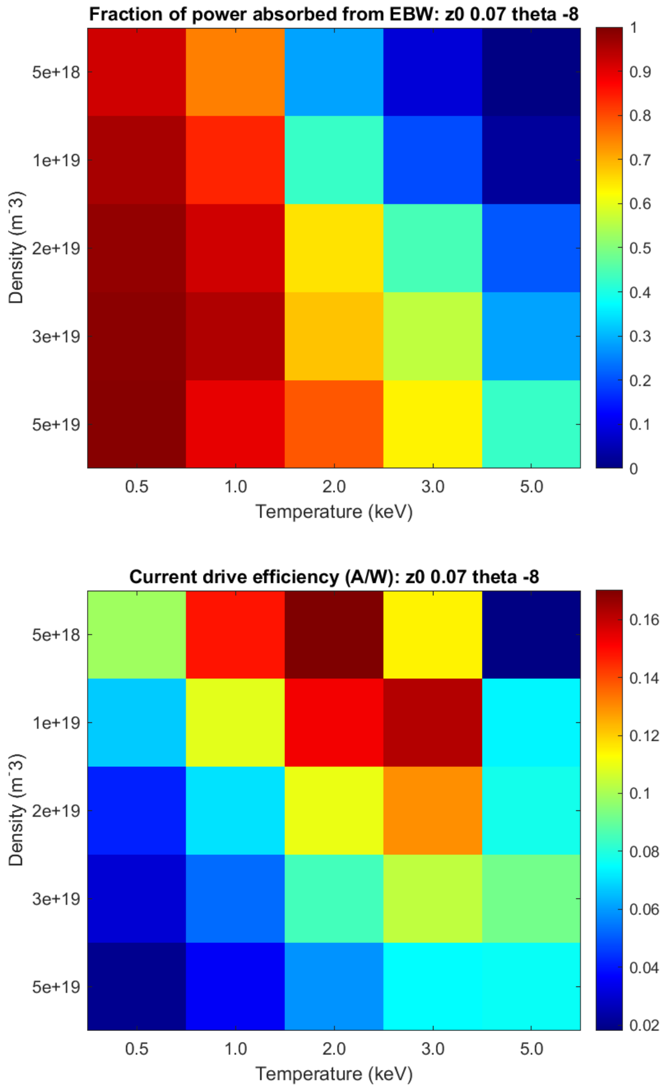
- A scheme for studying plasma start-up and CD using EBWs was developed on MAST [1] and is illustrated in the schematic (left)
- O-mode is launched from the LFS onto a mirror polarizer (MP) located on the centre post to convert the beam to X-mode, which propagates back into the plasma and mode converts to EBW at the UHR
- Current generated (right) is positive below the midplane and negative above the midplane
- The toroidal angle of the launcher is constrained to $4.5°$ to ensure reflection off the MP
- The position and angle of the launchers are determined to maximize current drive



Current drive efficiency (A/W) for different positions and angles of the reflected beam, calculated for 105GHz with $I_P = 300\text{kA}, B = 2.4\text{T}$ $n_e = 10^{19}\text{m}^{-3}, T_e = 1\text{keV}$

[1] V.F. Shevchenko *et al.*, *EPJ Web Conf.* **87**, 02007 (2015).

The fraction of EBW power absorbed scales like n_e/T_e which influences current drive scaling



- The fraction of power absorbed from EBW (top) and the calculated current drive efficiency (bottom) is shown for a range of densities and temperatures calculated for $105\mathrm{GHz}$ ($I_P = 300\mathrm{kA}$, $B = 2.4\mathrm{T}$)

- 100% of power is absorbed for the range of parameters shown, with only the X-B process considered
  - Power is absorbed from X-mode as the beam passes through the ECR, with the remaining power absorbed from EBW

- EBW absorption scales like n_e/T_e
  - X-mode absorption increases with T_e as the resonance layer becomes optically thicker
  - X-mode absorption decreases with n_e as single particle behaviour becomes dominant [2]

- Current drive efficiency normally scales like T_e/n_e
  - X-Mode contribution to current is much less than EBW, due to smaller $N_\parallel$
  - The calculated CD efficiency initially increases with T_e due to the current scaling, but decreases at high T_e as EBW absorption decreases
  - Similar competing effect observed in n_e

- Maximum current drive efficiency of $\sim 0.15\ \mathrm{A/M}$
  - Strong absorption and current drive at a wide range of plasma parameters, including low densities and temperatures, make EBWs ideal for non-inductive start-up studies

[2] V. Petrillo *et al.*, *Plasma Phys. Control. Fusion* **29**, 877 (1987)

Dimensionless current drive efficiency scales like n_e/T_e

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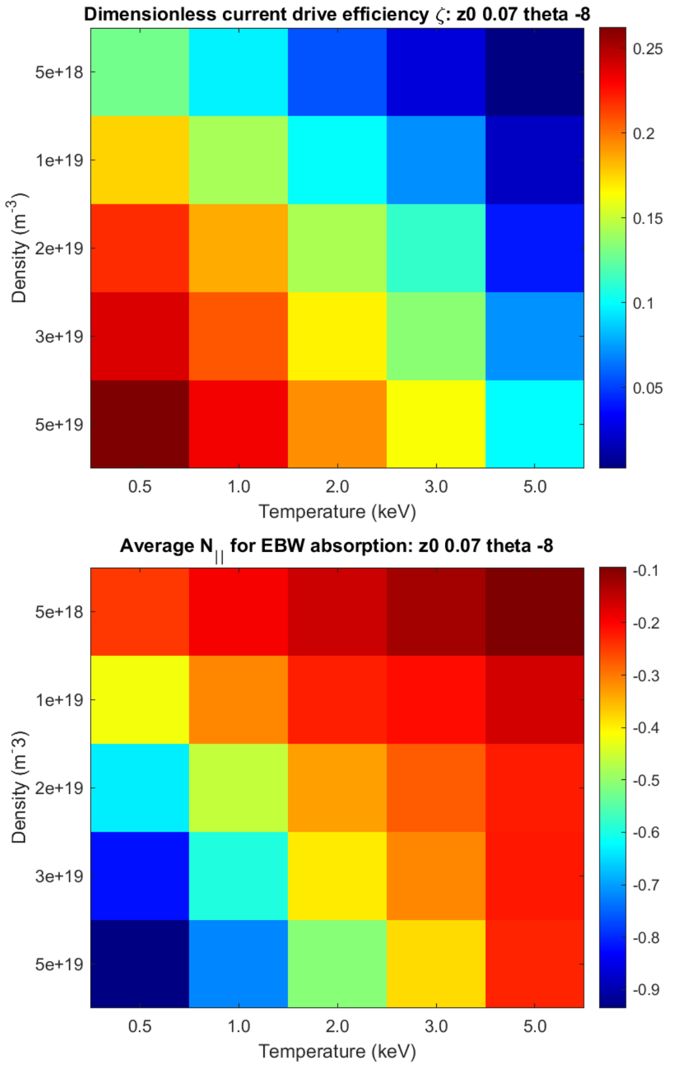


- The dimensionless current drive efficiency ζ_{CD} (top) and the average parallel refractive index $N_{\parallel}$ (bottom) is shown for a range of densities and temperatures calculated for 105GHz ($I_P = 300\text{kA}$, $B = 2.4\text{T}$)

- The dimensionless current drive efficiency is calculated from [3],

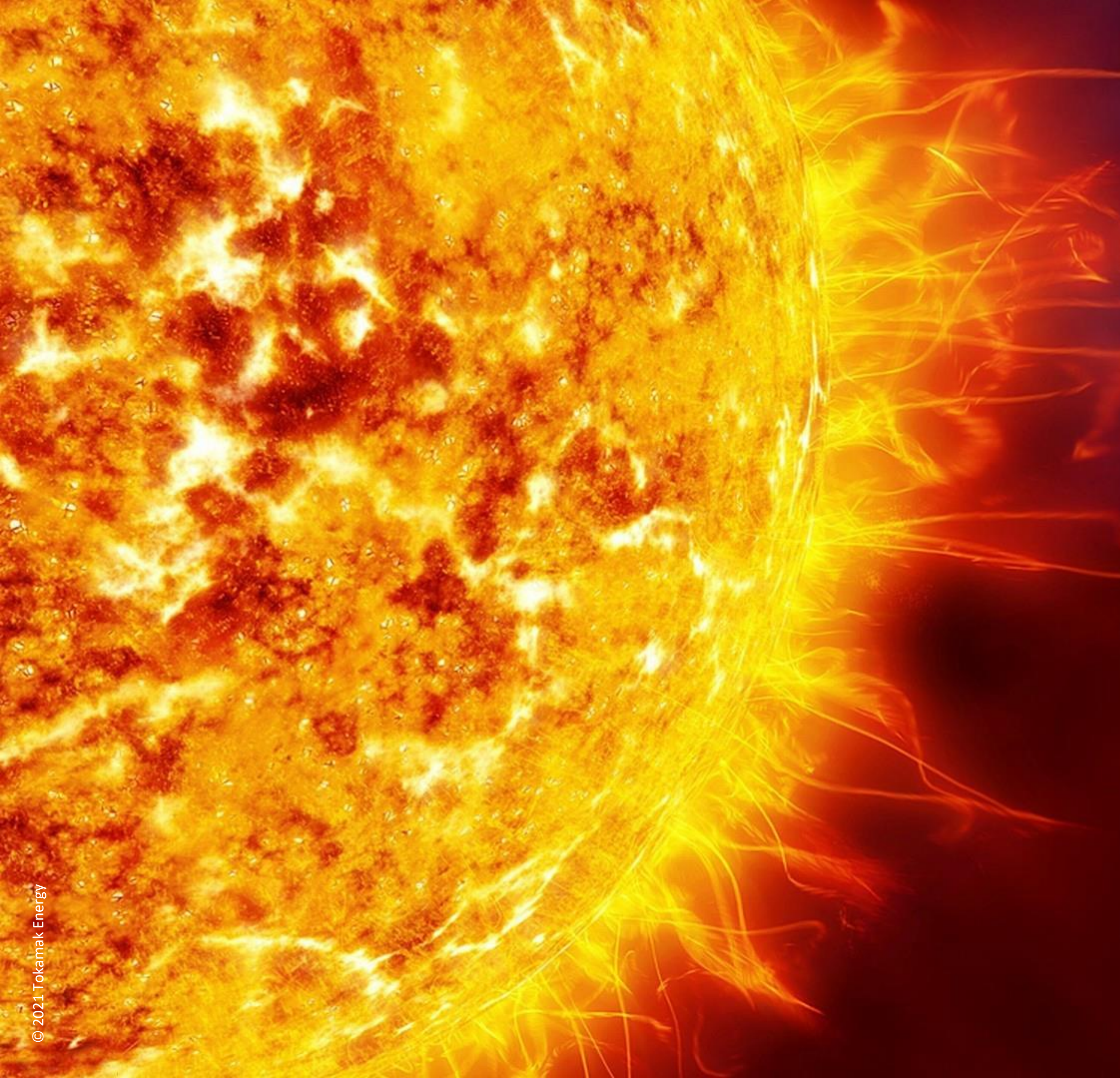
$$\zeta_{CD} = 3.27 \frac{I_P(A)\ R(m) n_e(10^{19} m^{-3})}{P(W)\ T_e(keV)}$$

- It is known that ζ_{CD} depends on:
  - The type of RF current drive
  - Effective charge
  - Magnetic field configuration and location of absorption
  - Wave parameters and wave/particle interaction

- Both ζ_{CD} and $|N_{\parallel}|$ scales like n_e/T_e
  - The dimensionless current drive efficiency depends on the wave parameters
  - In general, larger values for $|N_{\parallel}|$ generates larger current

- Dimensionless current drive efficiencies of $\zeta_{CD} \sim 0.1 \rightarrow 0.2$ are observed

[3] T.C. Luce et al., *Phys. Rev. Lett.* **83**, 4550 (1999).



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Fundamental X-mode

High frequency allows the study of fundamental X-mode absorption with LFS launcher

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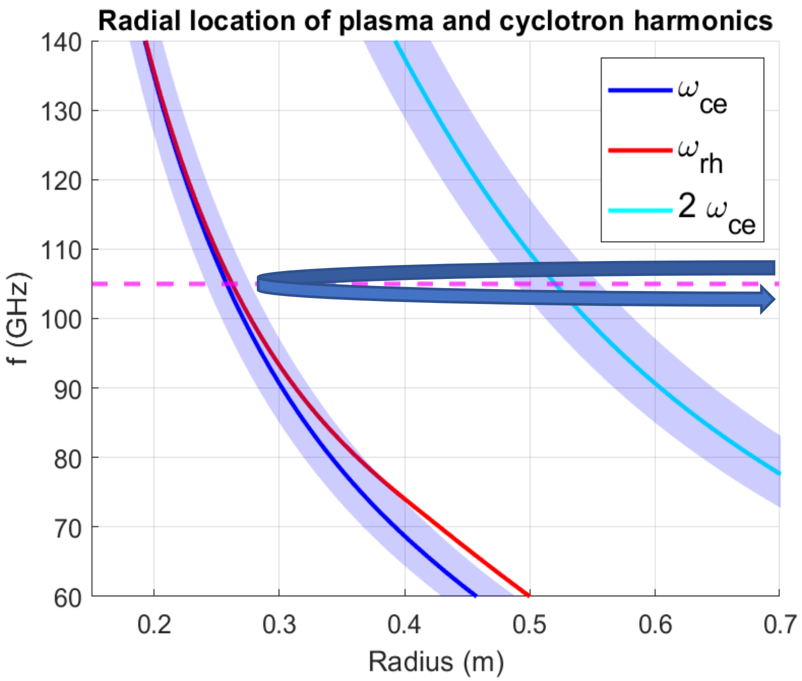
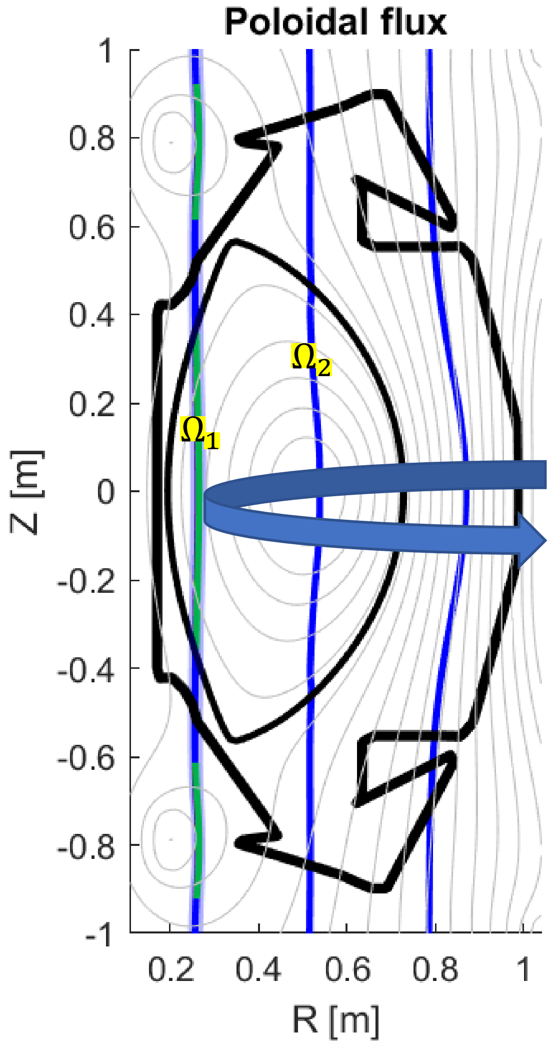
- Fundamental X-mode ECRH and CD could be used to significantly improve current start-up and ramp-up
- X-mode injected from the LFS is reflected at the ω_{rh} cut-off
- At low densities, absorption can occur before the cut-off is reached
- The accessibility condition for plasma density scales like $n_e \sim f^2$, such that higher frequencies allow absorption at higher densities



Radial location of the cyclotron harmonics and X-mode cut-off for $n_e = 5 \times 10^{18} \mathrm{m}^{-3}$ as a function of wave frequency. The shaded region indicates the Doppler broadening for $T_e = 500\mathrm{eV}$ and $N_{\parallel} = 0.5$



[4] M. Ono, N. Bertelli and V. Shevchenko, *Nucl. Fusion* (submitted)

ECRH and ECCD is relatively flat as a function of $N_\parallel$

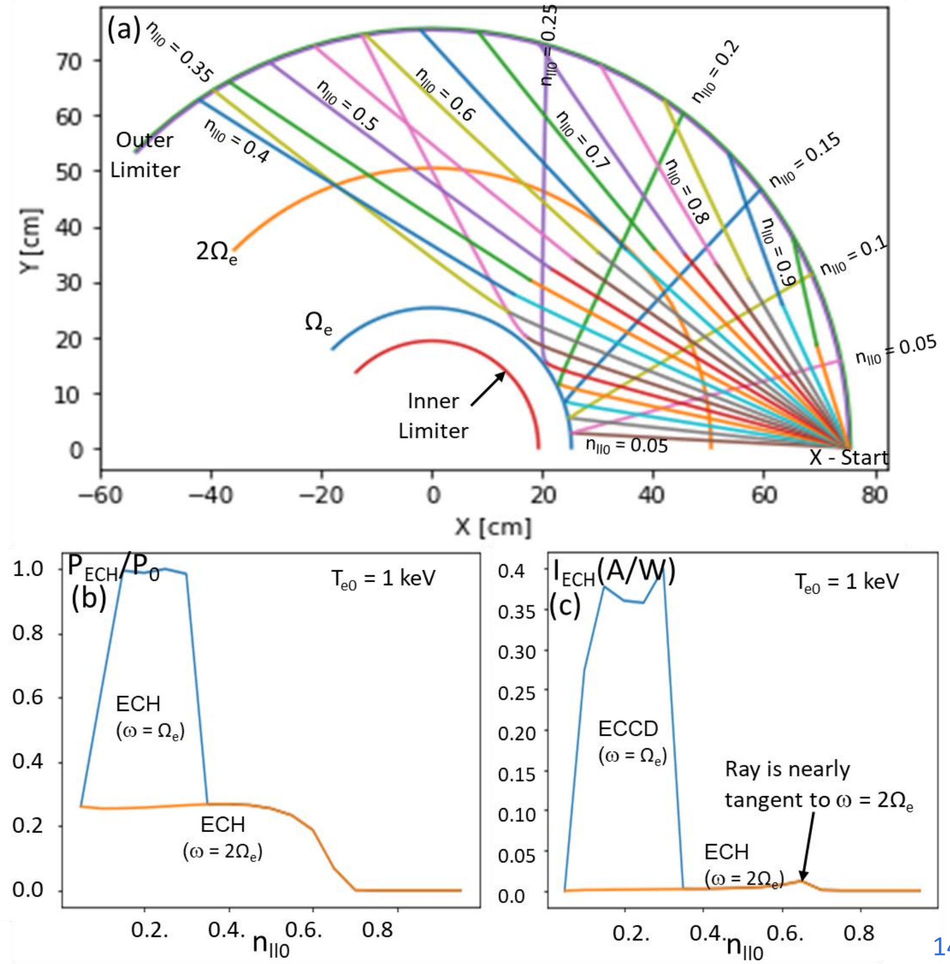
- The parallel refractive index $N_\parallel$ can be adjusted through the toroidal angle $(\pm 20°)$ of the launcher

- The LFS X-mode is reflected before it reaches the resonance, but can be absorbed if the Doppler shifted resonance condition is satisfied, i.e.

$$\frac{\omega - \Omega_e}{k_\parallel v_{th}} \leq 3$$

- The wave absorption and current drive is shown as a function of $N_{\parallel 0}$
  - The wave is fully absorbed for $0.15 < N_{\parallel 0} < 0.3$ before it decreases as the wave passes Ω_e and eventually does not reach $2\Omega_e$
  - Fundamental ECCD is far more efficient than 2nd harmonic current drive, with current drive efficiencies up to ~ 0.4 A/W

The dependence of ECRH and ECCD on $N_\parallel$ is shown for Ω_1 and Ω_2
$B_T = 2.3\text{T}$, $f = 105\text{GHz}$, $n_{e0} = 5 \times 10^{18}\text{m}^{-3}$ and $T_{e0} = 1\text{keV}$

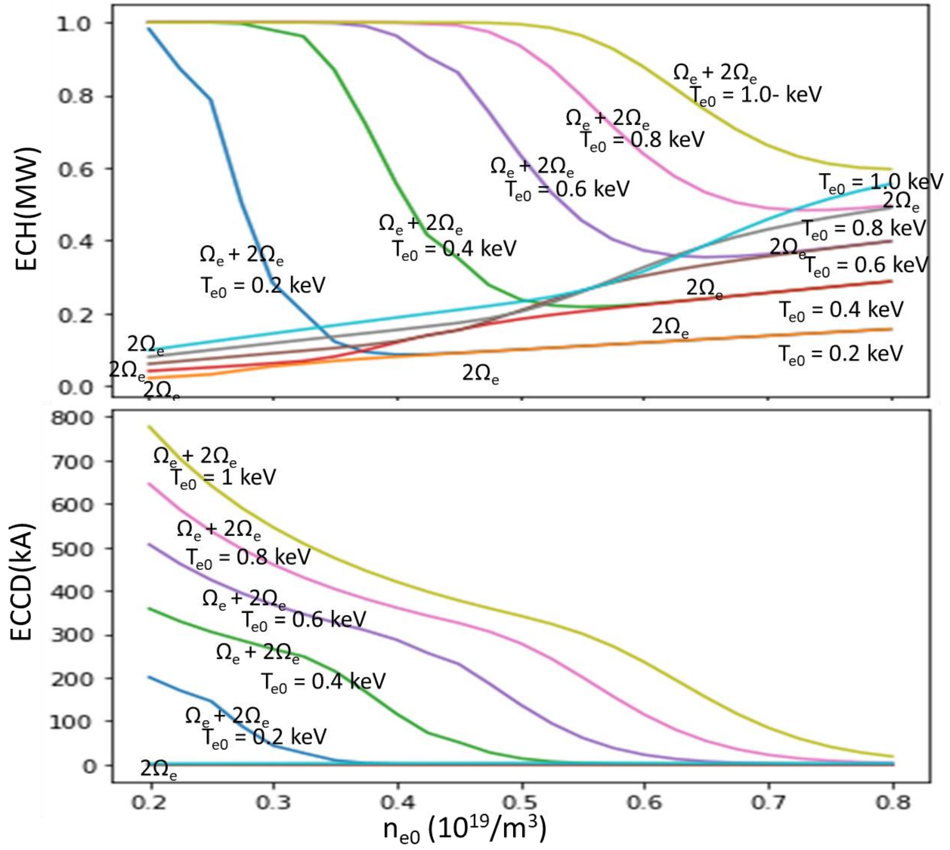


[4] M. Ono, N. Bertelli and V. Shevchenko, *Nucl. Fusion* (submitted)

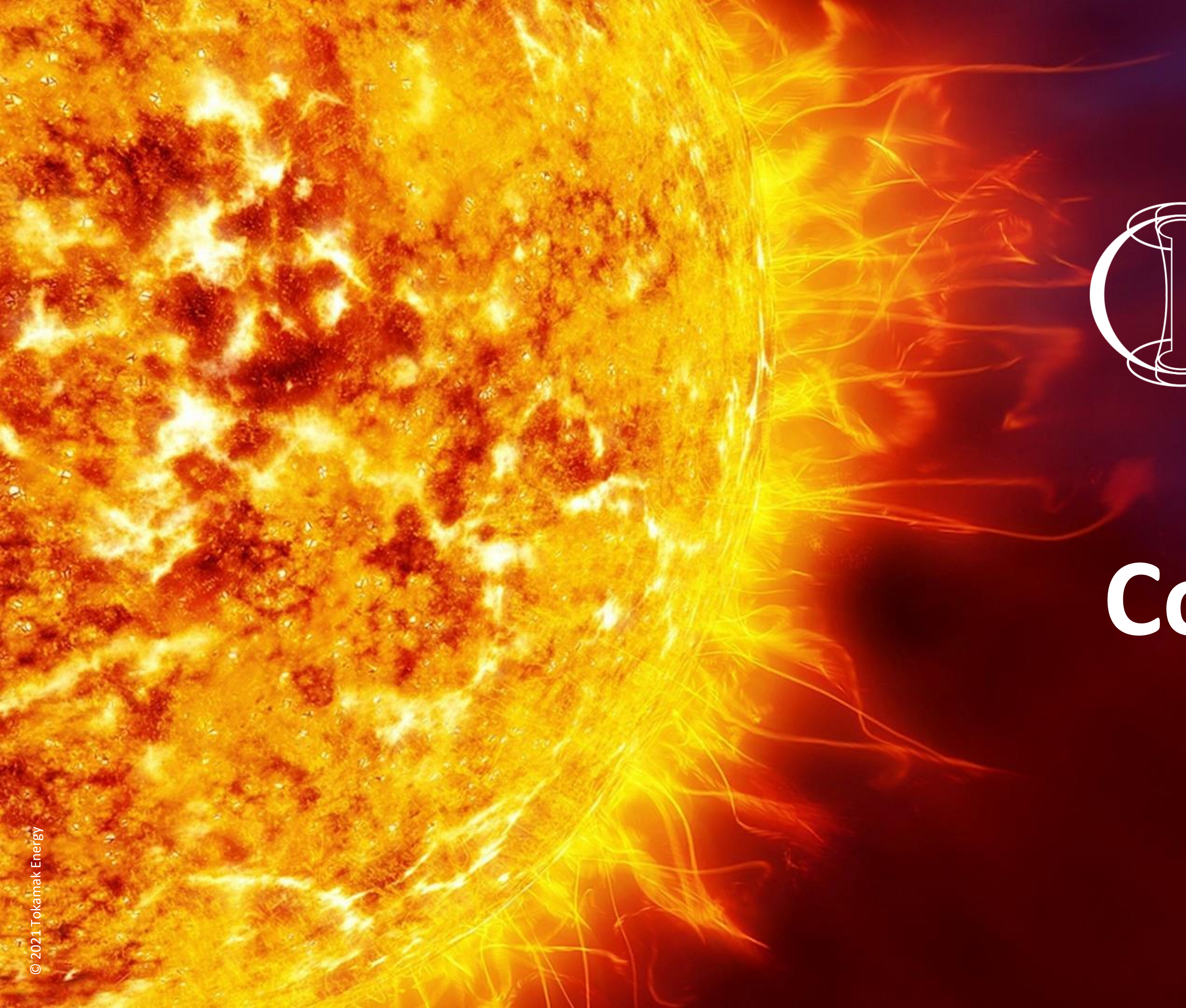
Fundamental X-mode heating can provide strong ECRH and ECCD at low T_e and n_e

- High current drive efficiency up to $0.8A/W$ can be achieved at low density and high temperature
- At $B = 2.3T$ absorption occurs at both the 2nd and fundamental resonance
- The ECRH and ECCD is shown as a function of density for different temperatures
  - Total absorption $(\Omega_e + 2\Omega_e)$ initially decreases with density, as absorption at Ω_e decreases, before it increases due to increased absorption at $2\Omega_e$
  - Absorption at Ω_e and $2\Omega_e$ increase with temperature
  - The current drive efficiency decreases with density, but increases with temperature

The dependence of ECRH and ECCD on n_e is shown for different T_e by separating it into $2\Omega_e$ and $\Omega_e + 2\Omega_e$ absorption
$B_T = 2.3\text{T}$, $f = 105\text{GHz}$, and $N_{\parallel 0} = 0.3$



[4] M. Ono, N. Bertelli and V. Shevchenko, *Nucl. Fusion* (submitted)



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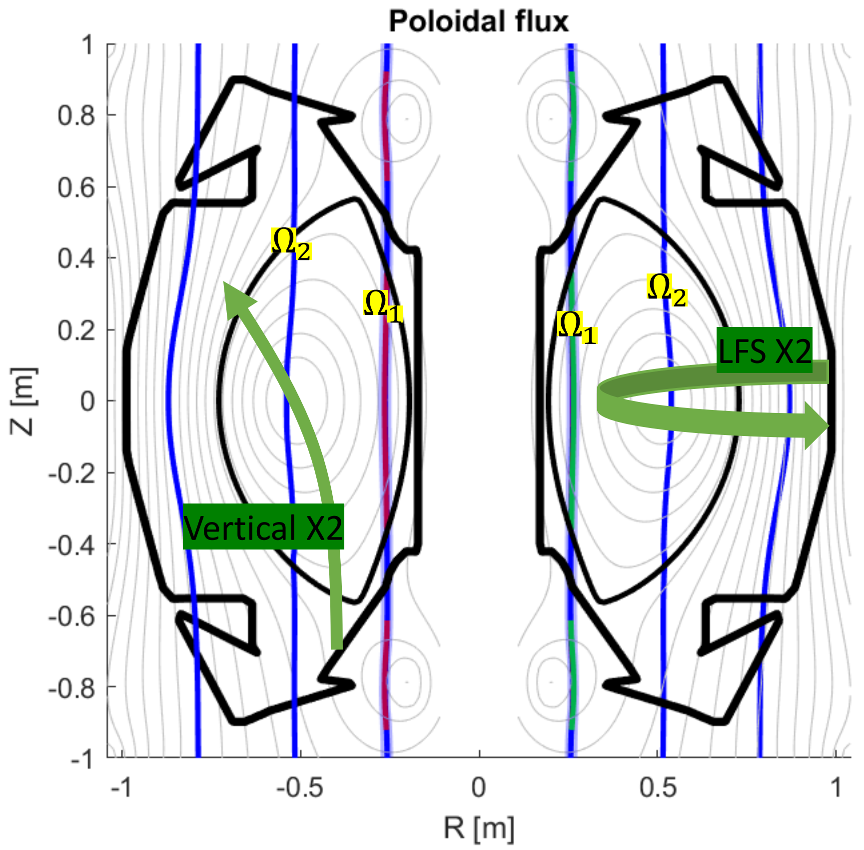
Conclusions

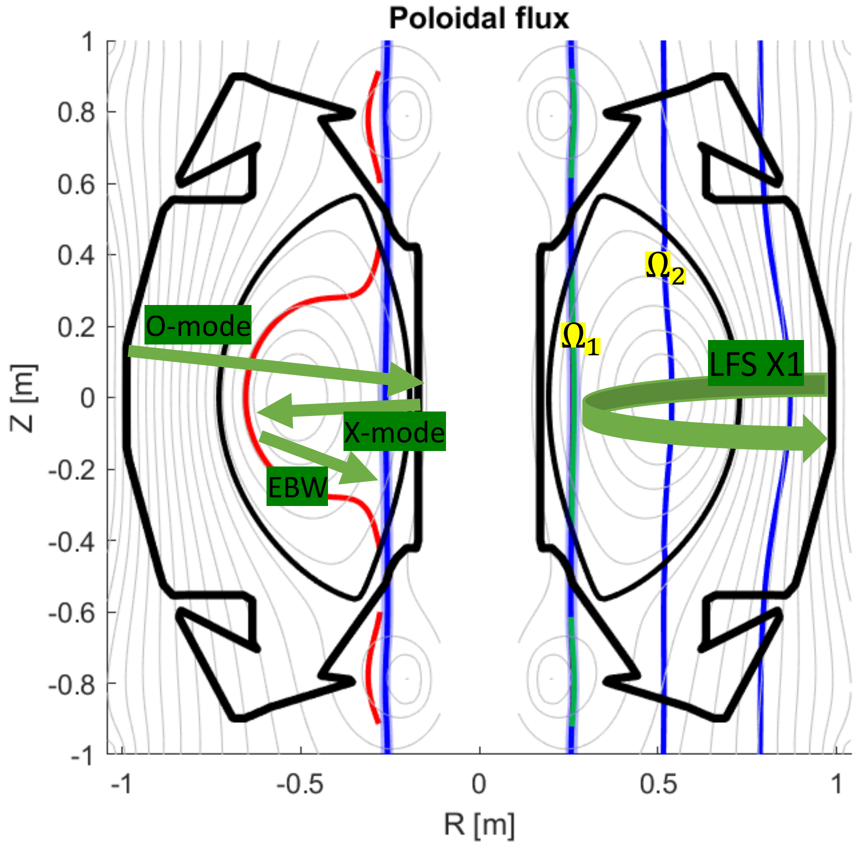
Strong absorption can be achieved with a LFS and/or vertical launcher

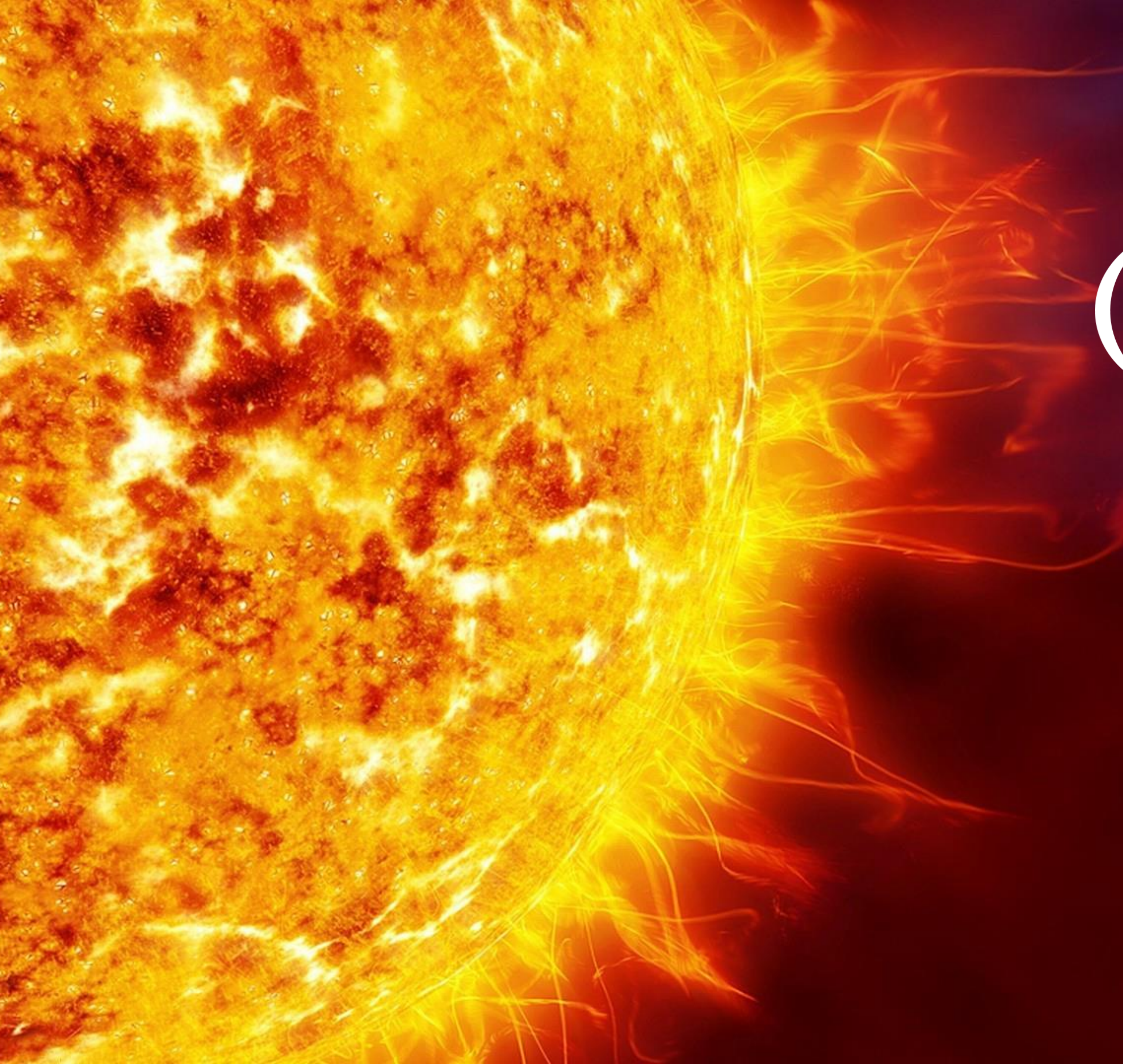
- 2nd harmonic X-mode ECRH using a LFS launcher
  - Strong absorption is expected over a wide range of plasma parameters
  - Increasing magnetic field strength increases the maximum operational density
- 2nd harmonic X-mode ECRH using a vertical launcher
  - Strong absorption is expected over a wide range of plasma parameters
  - Higher density limit compared to LFS launcher
- Current drive efficiency for both launchers are $\sim 20 \rightarrow 40\text{kA/MW}$
- Both these schemes are ideal candidates for heating during the flat-top phase



Strong current drive can be achieved with EBW or fundamental X-mode

- EBW can be excited in an O-X-B scheme using a LFS launcher and mirror polarizer
  - Strong absorption is expected, even at low densities and temperatures
  - Modelling shows current drive efficiencies of $\sim 0.1\ \mathrm{A/W}$
- Fundamental X-mode ECRH with a LFS launcher
  - Strong ECCD can be provided at low densities and temperatures
  - Modelling shows current drive efficiencies up to $0.8\mathrm{A/W}$
- These schemes are ideal candidates for studying non-inductive start-up





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Thank You

Additional Slides

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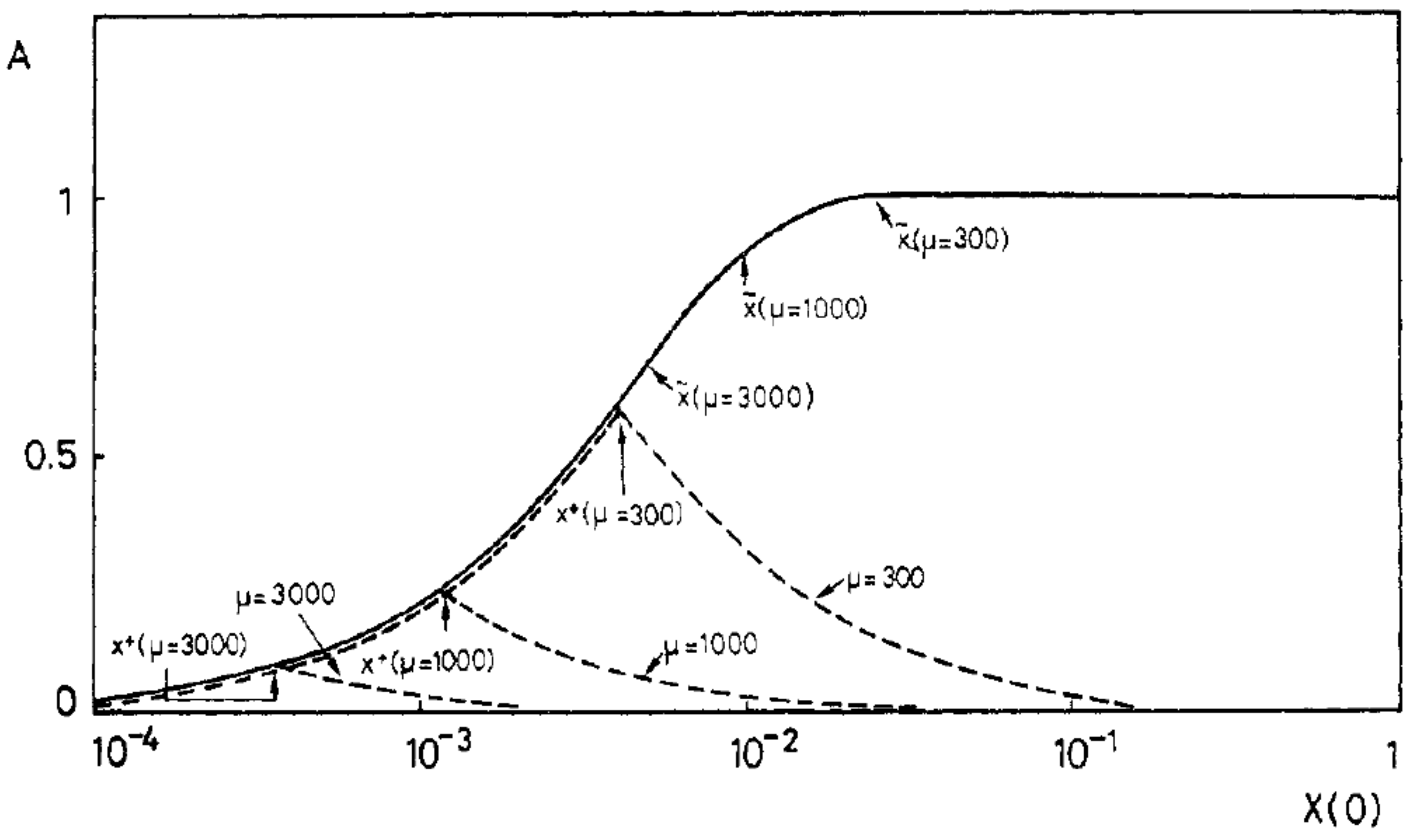
Higher frequency requires higher density

Global wave absorption coefficient for X-B mode conversion as a function of density $\left(X(0) = \omega_{pe}^2/\omega^2\right)$. The dashed lines indicate the amount of power absorbed from X-Mode [2]



- Total power absorption increases with density $\left(X(0) = \omega_{pe}^2/\omega^2\right)$
- X-Mode absorption (dashed line) decreases with density, but increases with temperature $(\mu = m_e c^2/T_e)$
- X-Mode absorption scales like T_e/n_e
- EBW absorption scales like n_e/T_e
- Higher frequency requires higher density for EBW absorption $(X(0) \to 1)$

[2] V. Petrillo *et al.*, *Plasma Phys. Control. Fusion* **29**, 877 (1987)