

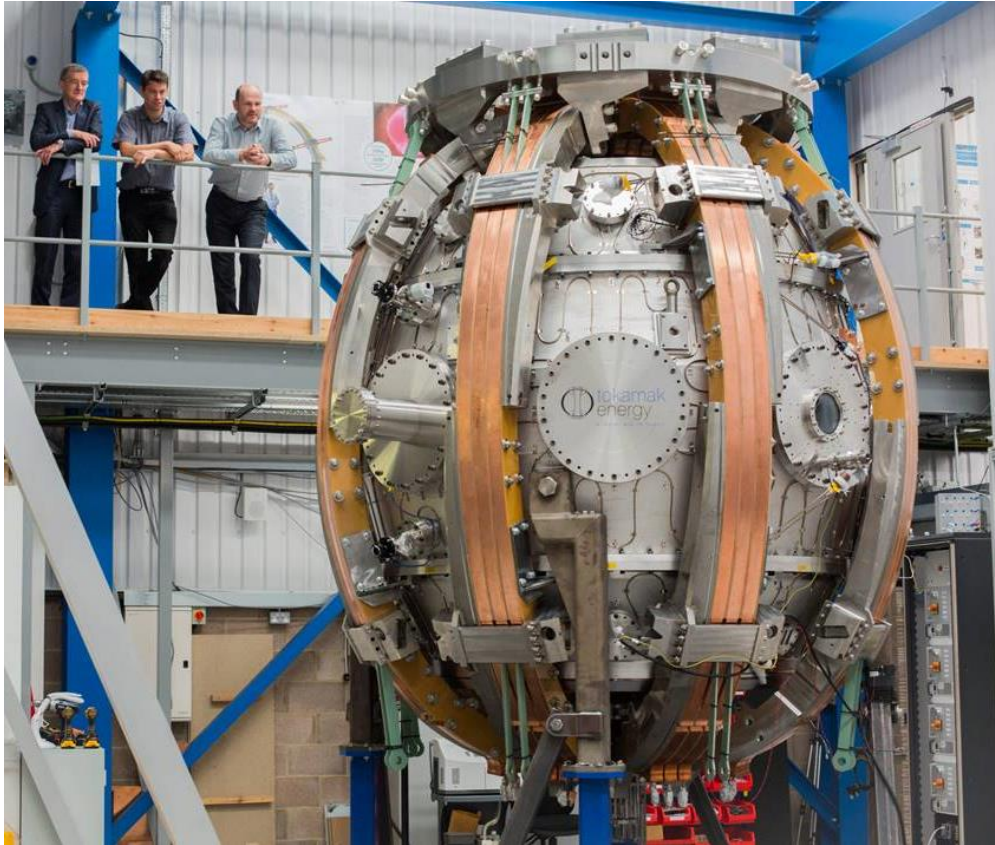
Overview of ECRH and EBW modelling on ST40

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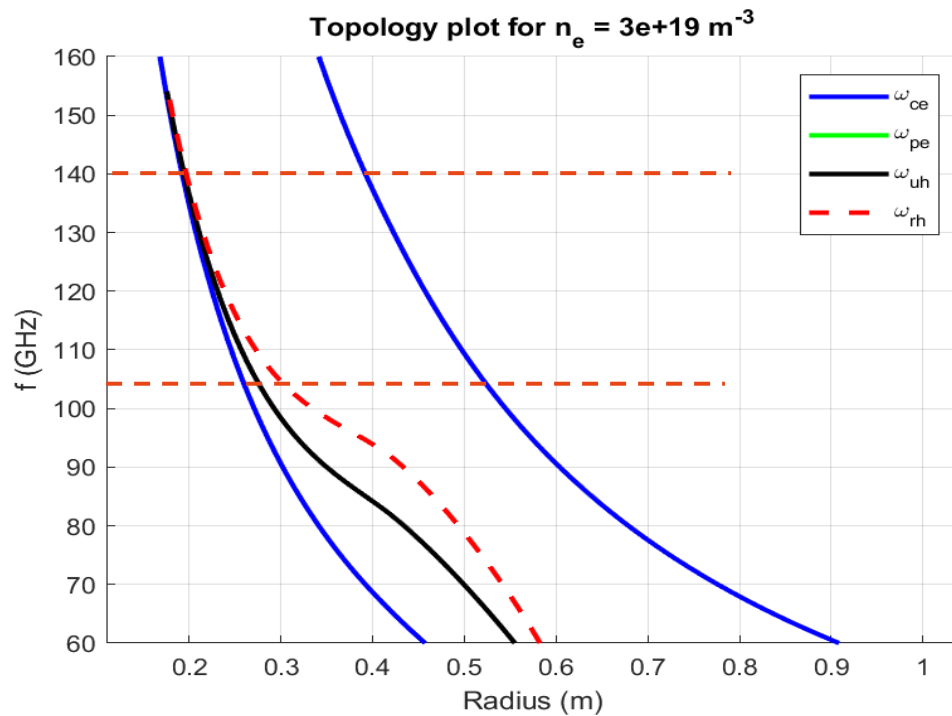
ST40 is a high field spherical tokamak



- ST40 is a high field spherical tokamak (ST) with a nominal maximum $B = 3\text{T}$ and $R_0 = 0.4 \rightarrow 0.6\text{m}$
- To date, plasma currents up to 0.8MA and pulse durations of 200ms have been achieved with $B \sim 2\text{T}$
- 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



Topology plot for ST40 plasma showing the radial locations of the fundamental and 2nd resonance for $B = 2.4\text{T}$ as a function of RF frequency

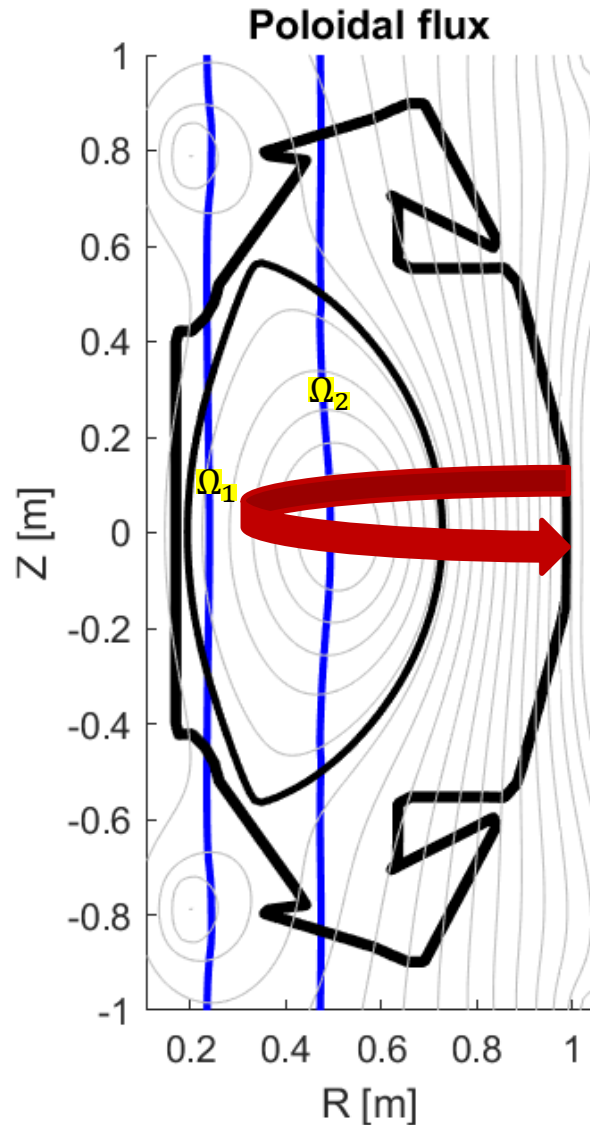
- A multi-frequency ECRH system is currently under construction
- Consists of two 105/140GHz dual frequency gyrotrons capable of up to 1 MW each
- This will enable the study of EC heating and current drive, including non-inductive start-up
- This talk will cover three types of heating and current drive: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



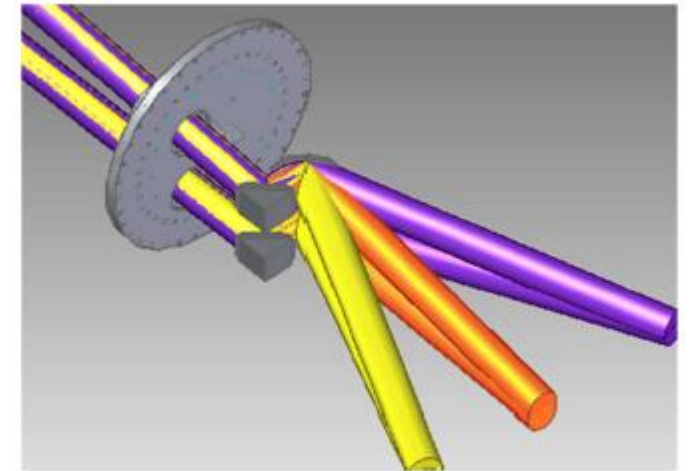
2nd harmonic
X-mode



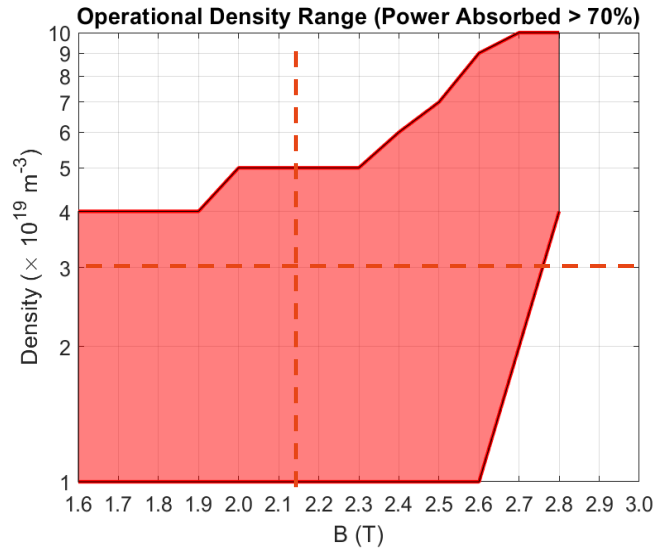
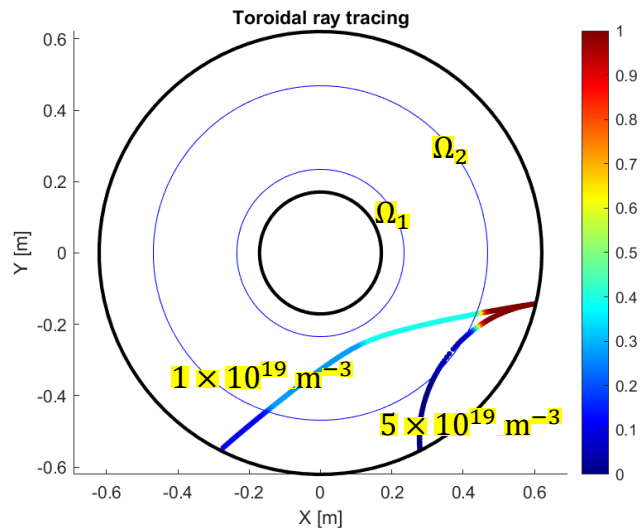
LFS 2nd harmonic X-mode heating with steerable mirror



- A low-field side (LFS) launcher on the midplane will be used for 2nd harmonic X-mode ECRH
- The LFS launcher consists of a steerable mirror in the poloidal ($\pm 10^\circ$) and toroidal ($\pm 20^\circ$) directions, allowing for optimal launcher configurations under different scenarios (right)
- The cut-off densities for this mode of heating is:
 - $7 \times 10^{19} m^{-3}$ for 105GHz
 - $1 \times 10^{20} m^{-3}$ for 140GHz



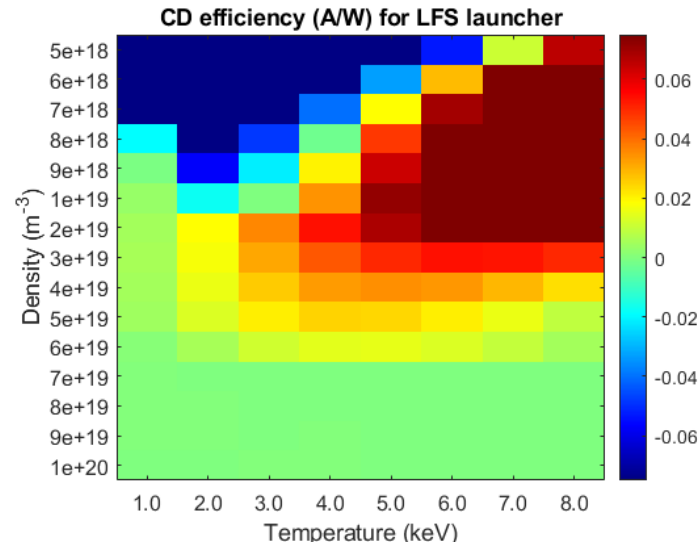
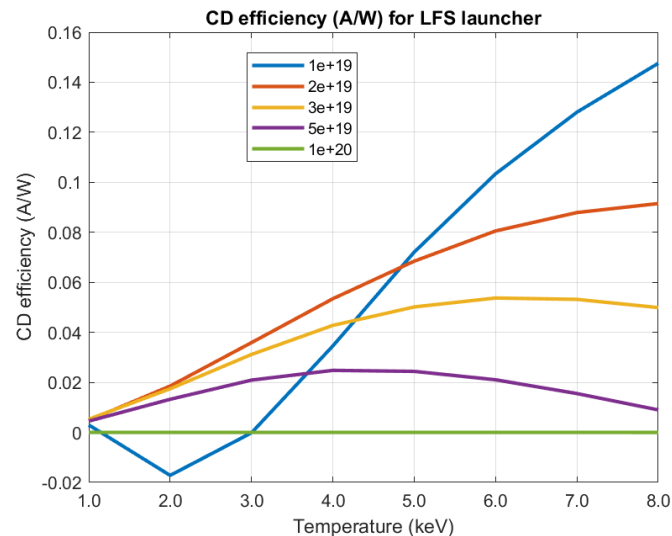
Refraction reduces absorption at high densities



- The range of densities for which more than 70% of input power is absorbed is shown for a range of magnetic field strengths (top), for 105GHz, with $T_e = 1\text{keV}$
- Typical operating densities and magnetic field is indicated by the dashed lines
- Absorption decreases at higher densities due to refraction
- This is illustrated by the wave propagation and absorption in the toroidal plane for $B = 2.2\text{T}$ for two densities (bottom) with $T_e = 1\text{keV}$
- Increasing the magnetic field strength will enable heating at higher densities



Moderate current drive efficiencies are expected



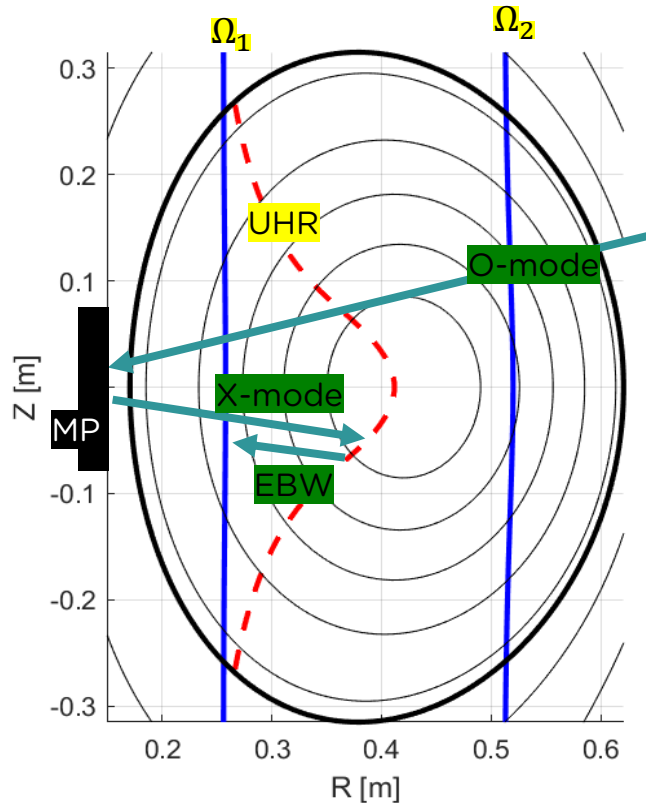
- CD efficiencies of $\sim 20 \rightarrow 40$ kA/MW can be achieved for relevant densities and temperatures, shown here for $B = 2.2T$
- At low densities, negative current drive is generated at low temperatures and large positive current drive at high temperatures
- CD scales like T_e/n_e , but the direction and magnitude can vary as the location of absorption changes
 - 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 (and high temperatures)



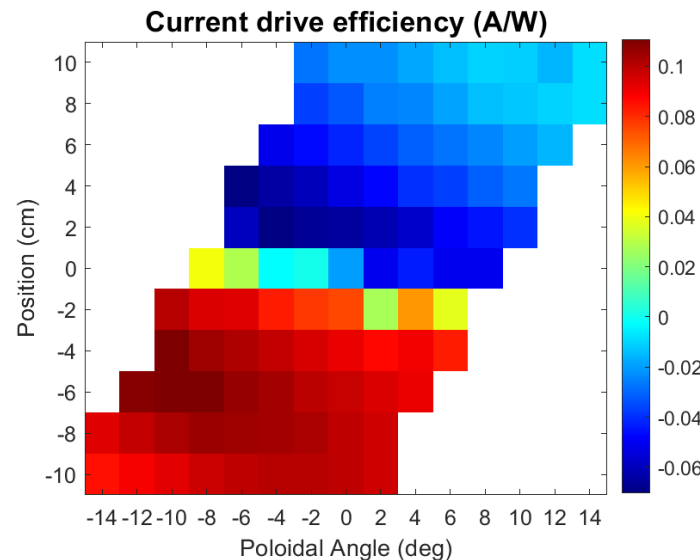
EBW
excitation



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 (below) is positive below the midplane and negative above the midplane
- The position and angle of the launchers are determined to maximize current drive



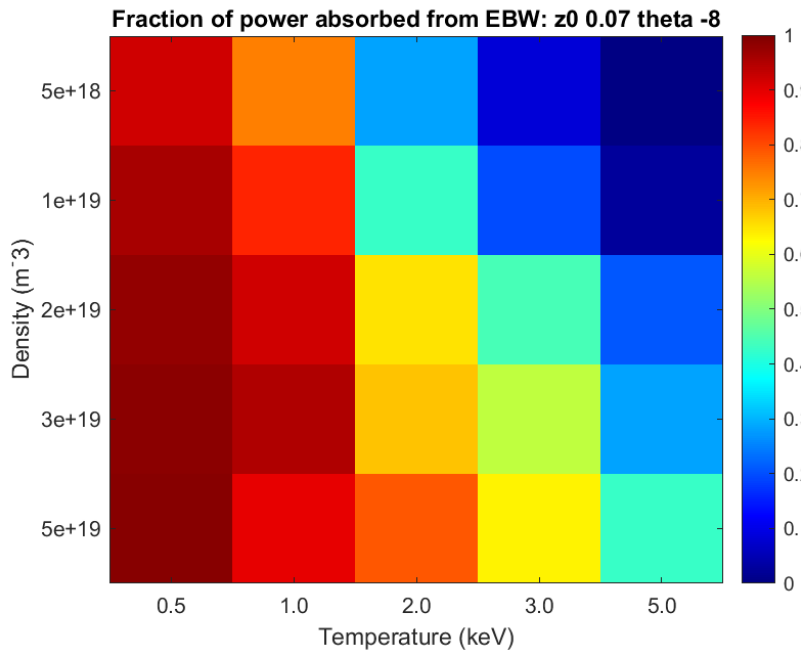
Current drive efficiency (A/W) for different positions and angles of the reflected beam, calculated for 105GHz with

$$I_p = 300\text{kA}, B = 2.4\text{T}$$
$$n_e = 10^{19}\text{m}^{-3}, T_e = 1\text{keV}$$

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



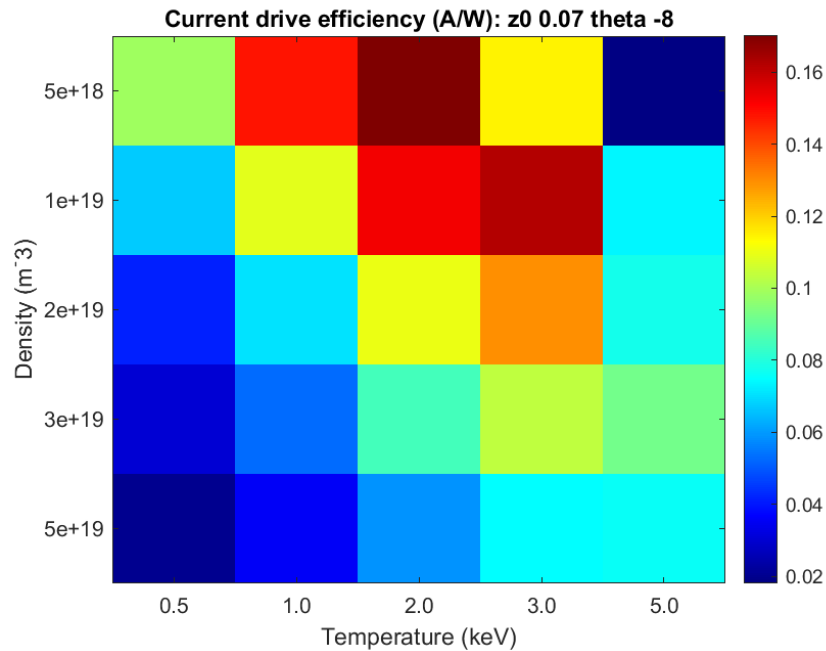
The fraction of EBW power absorbed scales like n_e/T_e which influences current drive scaling



- The fraction of power absorbed from EBW is shown for a range of densities and temperatures calculated for 105GHz ($I_p = 300\text{kA}$, $B = 2.4\text{T}$)
- 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]



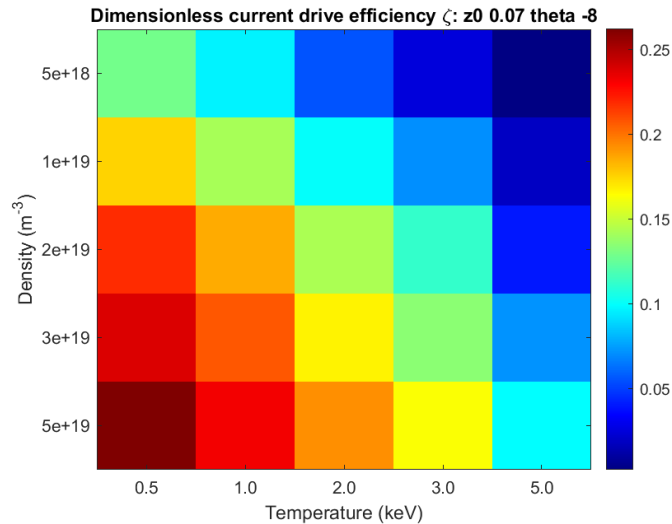
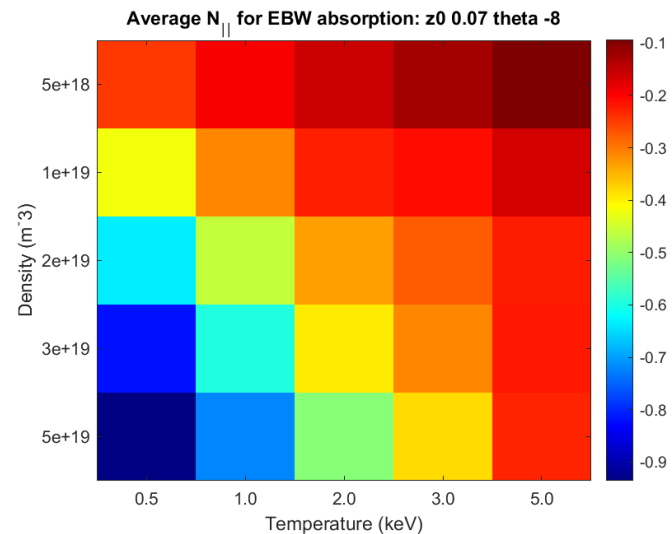
The fraction of EBW power absorbed scales like n_e/T_e which influences current drive scaling



- The current drive efficiency is shown for a range of densities and temperatures calculated for 105GHz ($I_p = 300\text{kA}$, $B = 2.4\text{T}$)
- 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 $\sim 0.15 \text{ A/W}$
 - 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



Dimensionless current drive efficiency scales like n_e/T_e



- 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],

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

- It is known that ζ_{CD} depends on, amongst others:

- The type of RF current drive
- Wave parameters and wave/particle interaction

- Both ζ_{CD} and $|N_{\parallel}|$ scales like n_e/T_e

- ζ_{CD} 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

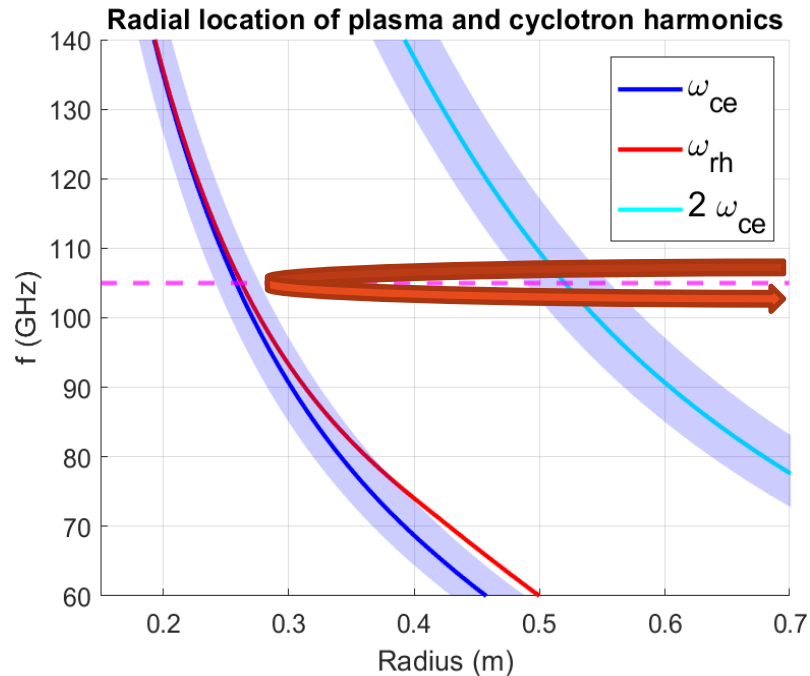
[3] T.C. Luce et al., *Phys. Rev. Lett.* **83**, 4550 (1999).



Fundamental X-mode



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



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

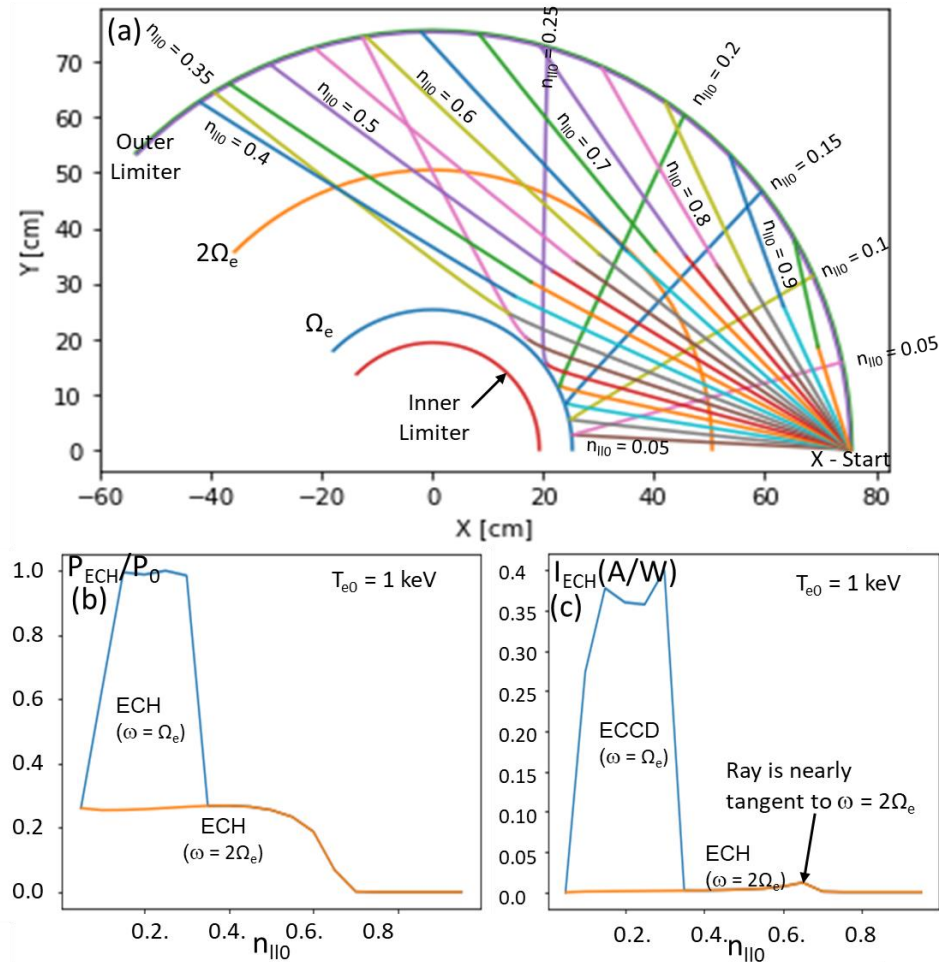
- Fundamental X-mode ECRH and CD could be used to significantly improve current start-up and ramp-up
- BUT**, X-mode injected from the LFS is reflected at the ω_{rh} cut-off
- HOWEVER**, at low densities, absorption can occur before the cut-off is reached
- The accessibility condition for plasma density scales like $n_e \sim f^2$, such that higher frequencies allow absorption at higher densities
- The LFS X-mode is reflected before it reaches the resonance, but can be absorbed if the Doppler shifted resonance condition is satisfied [4], i.e.

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

- Increasing $k_{\parallel}$ and/or v_{th} will improve absorption



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

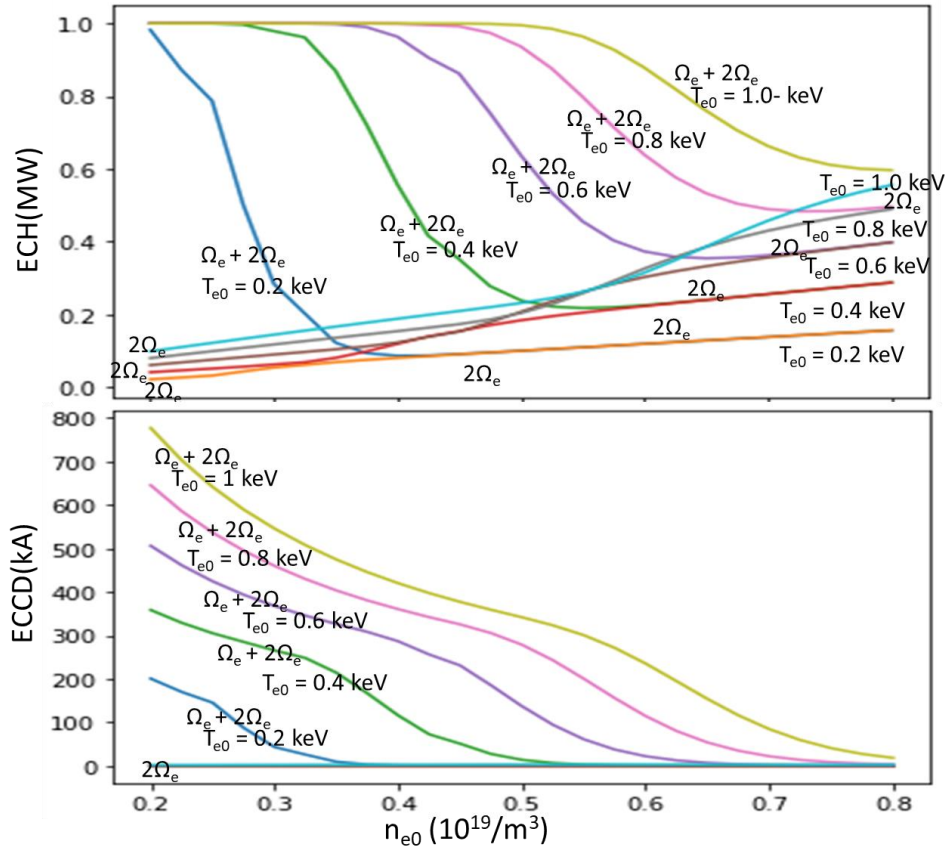


- The parallel refractive index $N_{\parallel}$ can be adjusted through the toroidal angle ($\pm 20^\circ$) of the launcher
- The wave absorption and current drive is shown as a function of $N_{\parallel 0}$
- The wave is fully absorbed for $0.15 < N_{\parallel 0} < 0.3$ before it decreases as the wave 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 $\sim 0.4 \text{ A/W}$

$$B_T = 2.3\text{T}, f = 105\text{GHz}, n_{e0} = 5 \times 10^{18} \text{m}^{-3} \text{ and } T_{e0} = 1\text{keV}$$



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



- High current drive efficiency up to 0.8 A/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

$$B_T = 2.3T, f = 105\text{GHz}, \text{ and } N_{\parallel 0} = 0.3$$

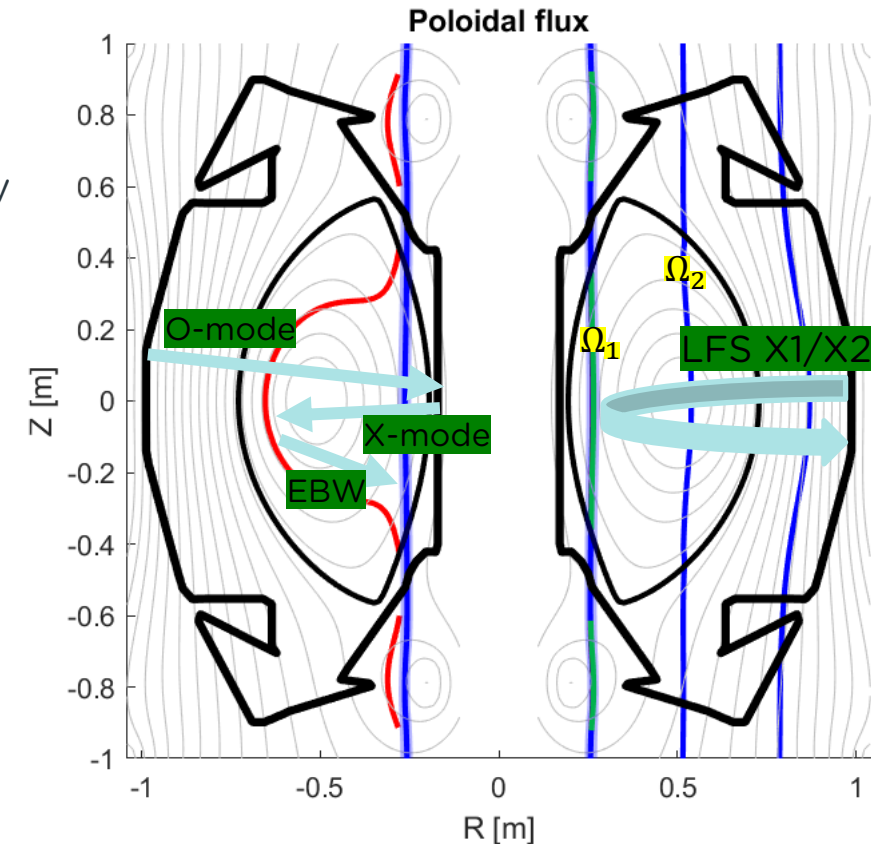


Conclusions



Strong absorption and current drive can be achieved with different schemes

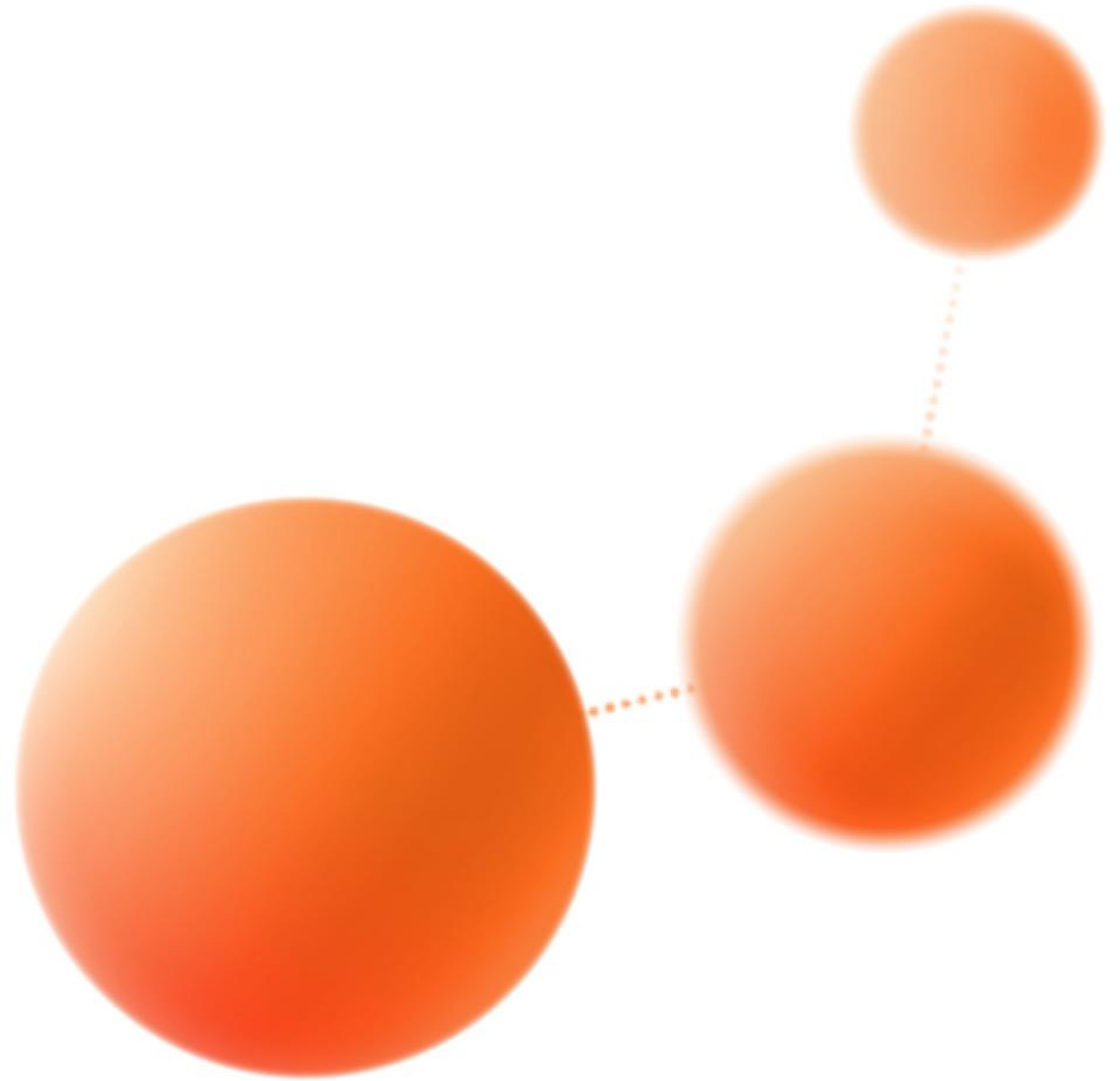
- 2nd harmonic X-mode ECRH using a LFS launcher is ideal for heating during flat-top phase
 - Strong absorption is expected over a wide range of plasma parameters
 - Increasing magnetic field strength increases the maximum operational density
 - Current drive efficiency are $\sim 20 \rightarrow 40\text{kA/MW}$
- EBW and fundamental X-mode ECRH are ideal candidates for studying non-inductive start-up
 - 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, with CD efficiencies of $\sim 100\text{kA/MW}$
 - Fundamental X-mode ECRH with a LFS launcher
 - Strong ECCD can be provided at low densities and high temperatures, with CD efficiencies up to 800kA/MW



Thank You



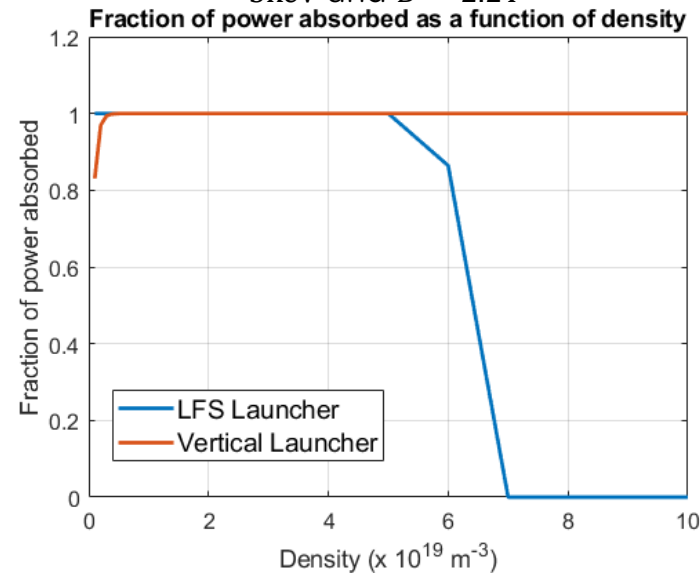
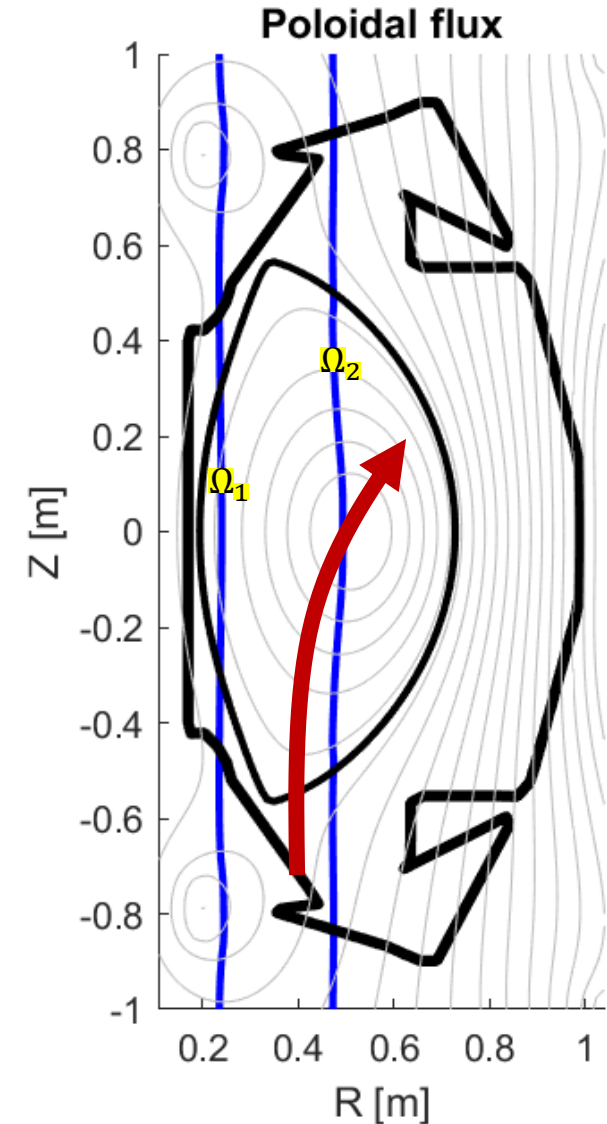
Additional Slides



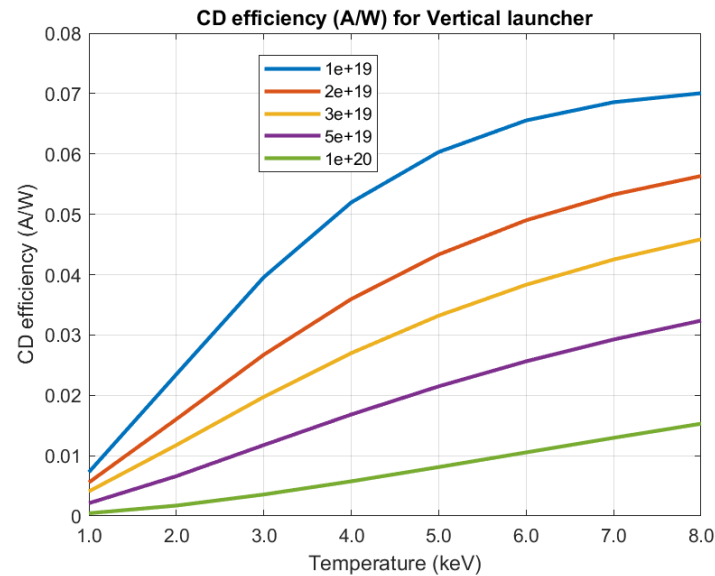
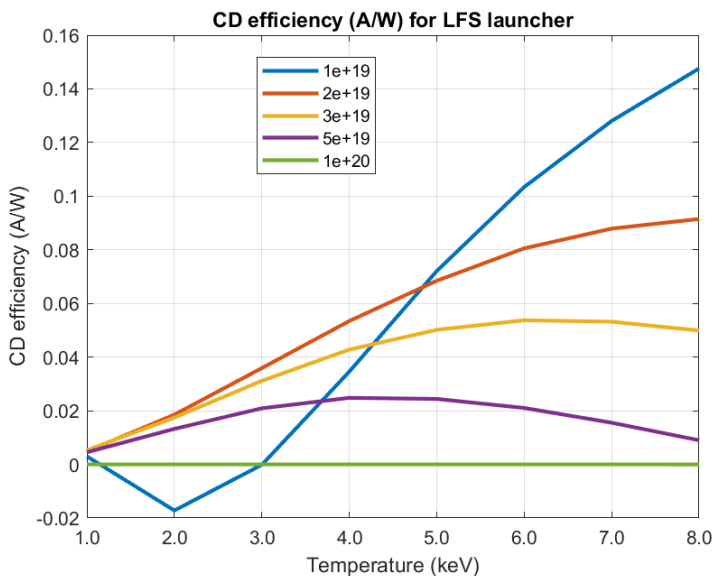
Vertical launcher shows better absorption than LFS launcher at high densities

- 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 $B = 2.2T$



Vertical launcher shows similar current drive to LFS launcher, with less flexibility

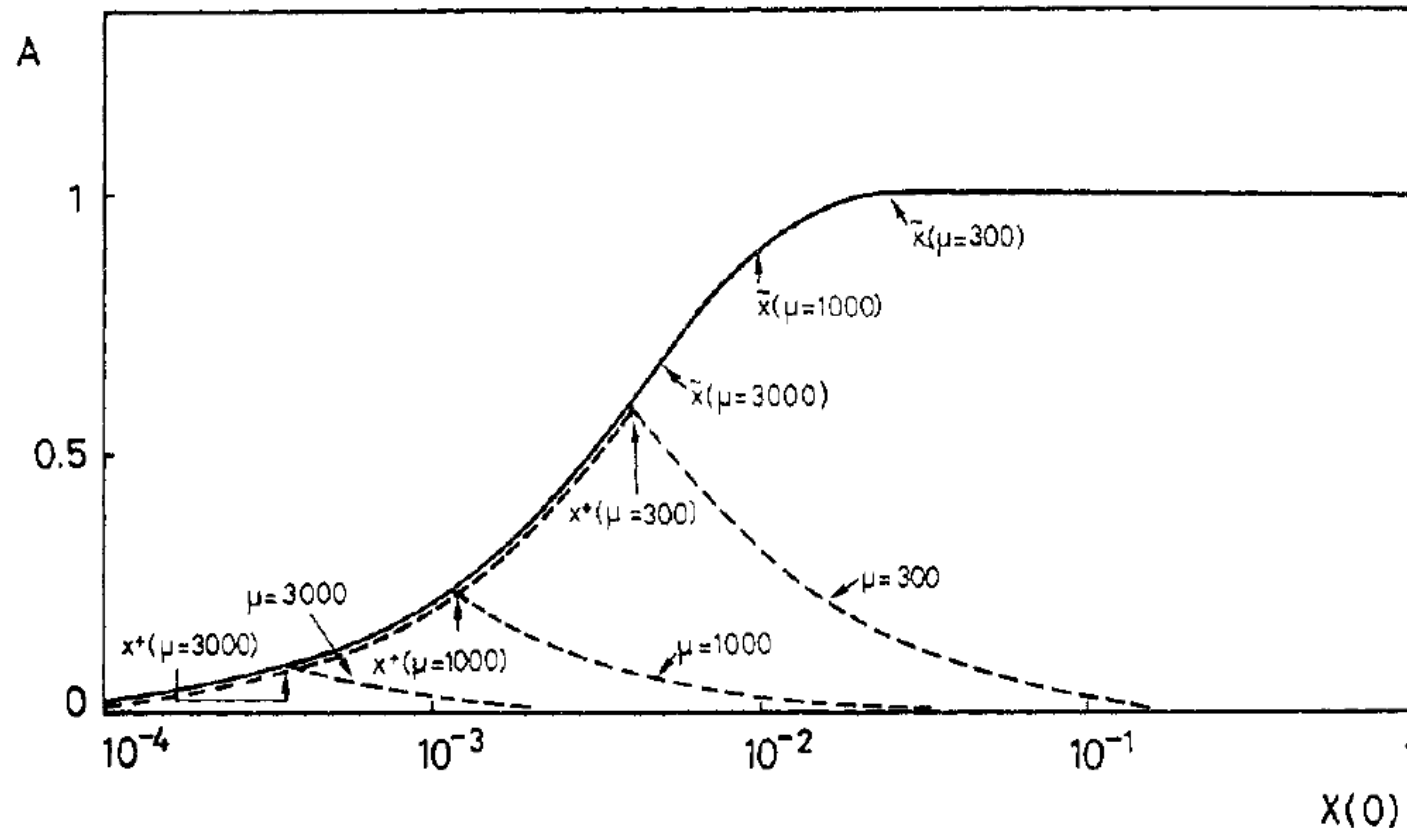


- The vertical (top) and LFS (bottom) launchers show CD efficiencies of $\sim 20 \rightarrow 40 \text{ kA/MW}$ for relevant densities and temperatures
- The vertical launcher is less flexible compared to the LFS launcher
 - The optimal launcher direction can be calculated for a given scenario
 - An increase (or decrease) in the density can have a large impact on the CD due to refraction
 - A change in the plasma equilibrium, due to vacuum field or plasma current, can have a large impact on CD
- Steerability is required for a useful vertical launcher, which is complex to install



Higher frequency requires higher density

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



- Total power absorption increases with density ($X(0) = \omega_{pe}^2/\omega^2$)
- 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 ($X(0) \rightarrow 1$)

