ISTITUTO PER LA SCIENZA E TECNOLOGIA DEI PLASMI
Consiglio Nazionale delle Ricerche

21st Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Resonance Heating (ECRH)
20-24 June 2022 – ITER Organization, Saint-Paul-lez-Durance, France

Electron Cyclotron Current Drive Efficiency in the STEP Device

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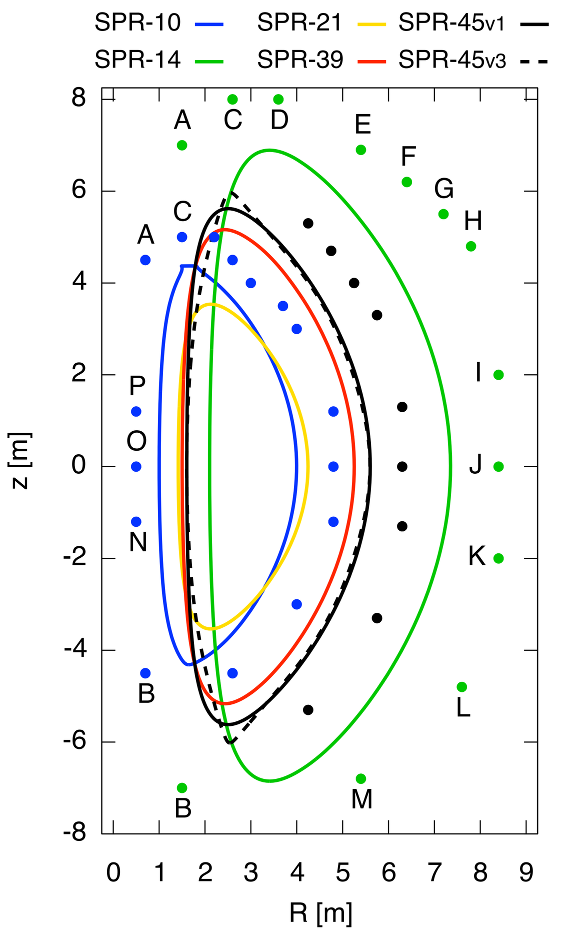
INTRODUCTION

- The UK's Spherical Tokamak for Energy Production (STEP) design program aims at demonstrating the ability to achieve a net electrical gain from fusion reactions in a magnetically confined plasma under reactor relevant conditions.
- A key aspect is the maximization of the plug-to-plasma Current Drive (CD) efficiency of the auxiliary Heating and Current Drive (H&CD) systems.
- The STEP program has recently decided to rely uniquely on mm-wave H&CD actuators, namely Electron Cyclotron (EC) and Electron Bernstein Waves (EBW) [1,2].

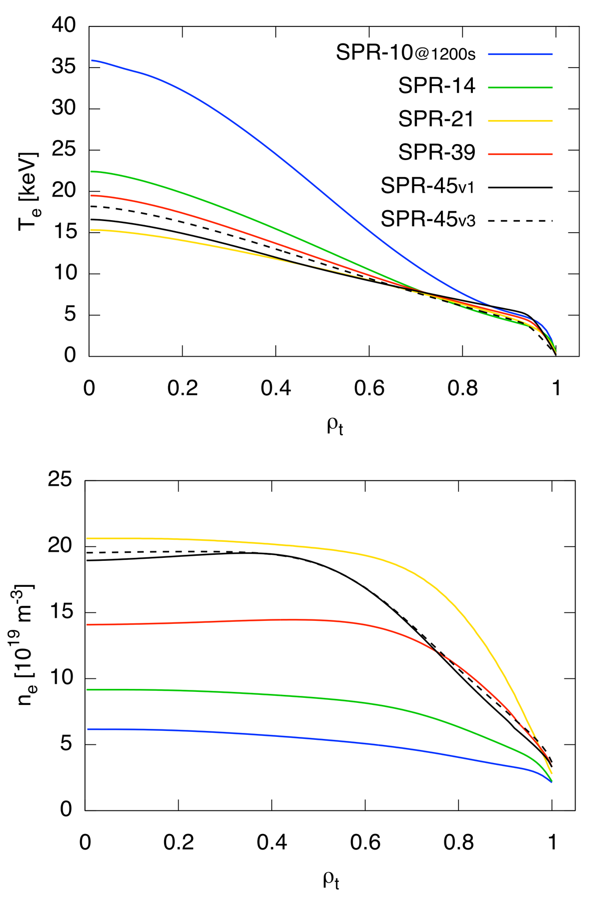
This work outlines the studies done so far: (i) to assess the H&CD capabilities of EC waves in STEP; (ii) to identify the optimal EC beam injection conditions which maximize the CD efficiency; and (iii) to verify their robustness against changes of the plasma parameters and/or changes of the launch conditions.

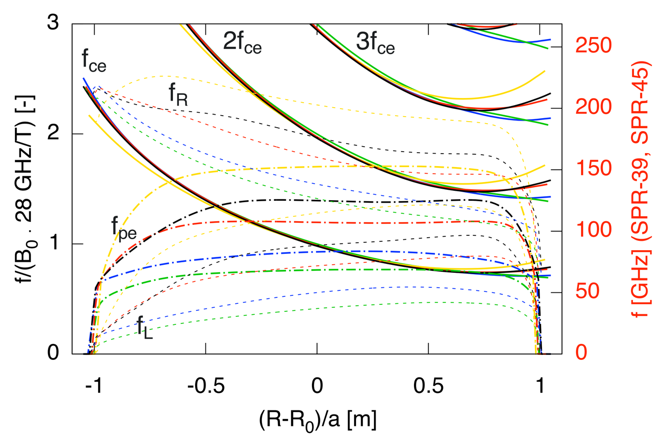
STEP PROTOTYPE CONCEPTS



A number of STEP concepts and candidate launcher positions were selected for investigation

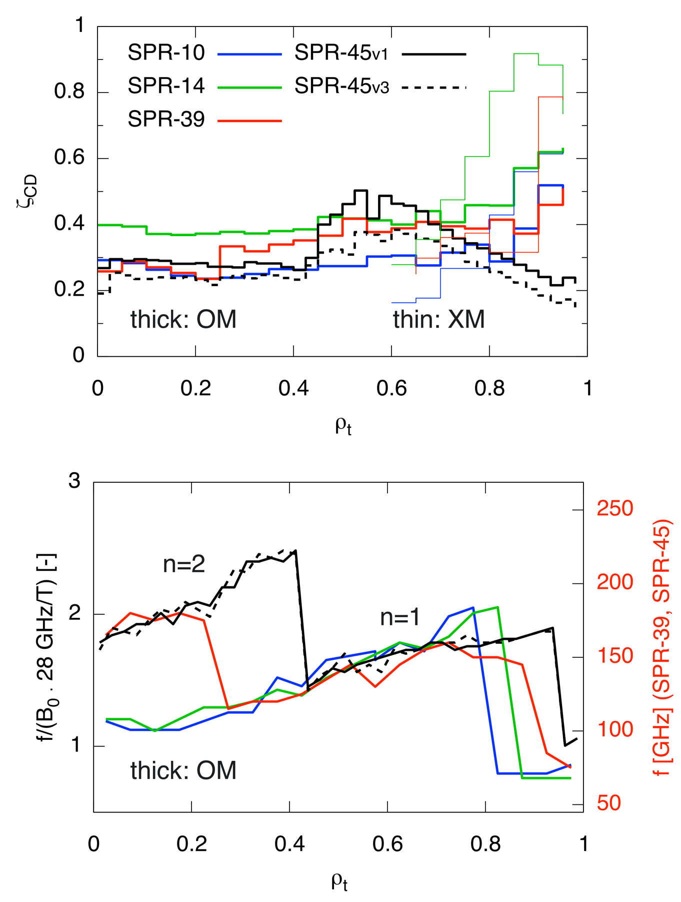
- SPR-14 most favourable to ECCD
  - large T_e/n_e ratio
  - $f_{pe}<f_{ce}$ almost everywhere
  - low B_p/B_ϕ on LFS → easy LFS access
- SPR-45 most recent mm-wave only concept
- Non-conventional vertical and HFS launches included in the study





SPR #	R_0 [m]	B_0 [T]	I_P [MA]	$T_e(0)$ [keV]	$n_e(0)$ [10^{20} m^{-3}]	Z_{eff} [-]
10	2.50	2.4	14	36	0.6	1.7
21	2.83	2.7	14	15	2.1	1.8
39	3.38	3.2	18	19	1.4	1.8
45 (v1)	3.60	3.2	20	17	1.9	1.8
45 (v3)	**3.60**	**3.2**	**20**	**18**	**2.0**	**2.5**
14	4.73	4.0	21	22	0.9	1.7

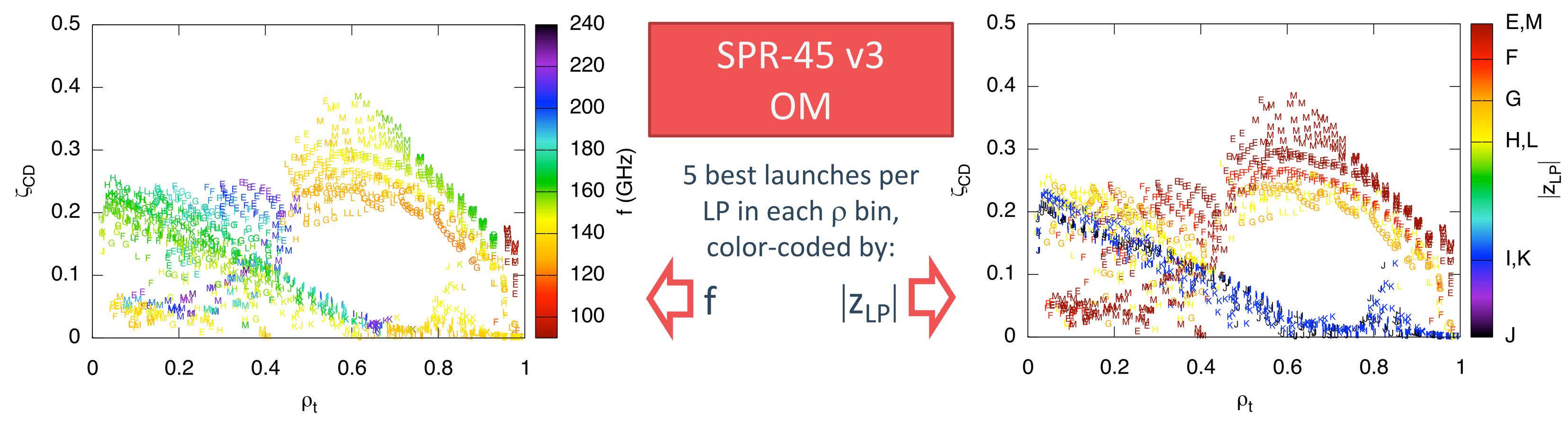
MAXIMAL ECCD EFFICIENCY



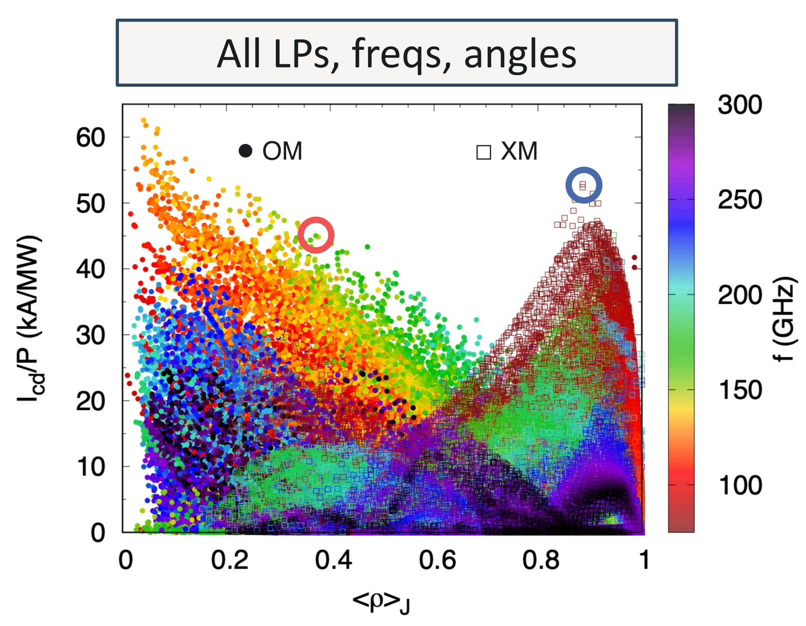
Different SPRs compared via normalized ECCD efficiency [4]

$$\zeta_{CD} = 3.27\frac{R_m n_{19}}{T_{keV}}\frac{I_A}{P_W}$$

- $0.25 \le \zeta_{CD} \le 0.4$ at $\rho < 0.5$ for all SPRs
- $\zeta_{CD} \approx 0.5$ marginally achievable at $\rho \approx 0.6$ in SPR-45, assuming Z_{eff}=1.8. Lower ζ_{CD} in the latest v3 iteration due to higher Z_{eff}=2.5
- OM injection is always preferred up to $\rho < 0.7$
- Far off-axis ($\rho > 0.8$) XM shows large efficiency ($\zeta_{CD} > 0.8$ in SPR-14) but launch condition is not robust (CD via trapped electrons at down-shifted first harmonic close to cut-off condition)
- n=2 resonance preferred only at $\rho < 0.3÷0.5$ in high n_e concepts (SPR-39, SPR-45)
- Optimal LP elevation $|z_{LP}|$ increases with incr. ρ



EC LAUNCH PARAMETRIC SCAN

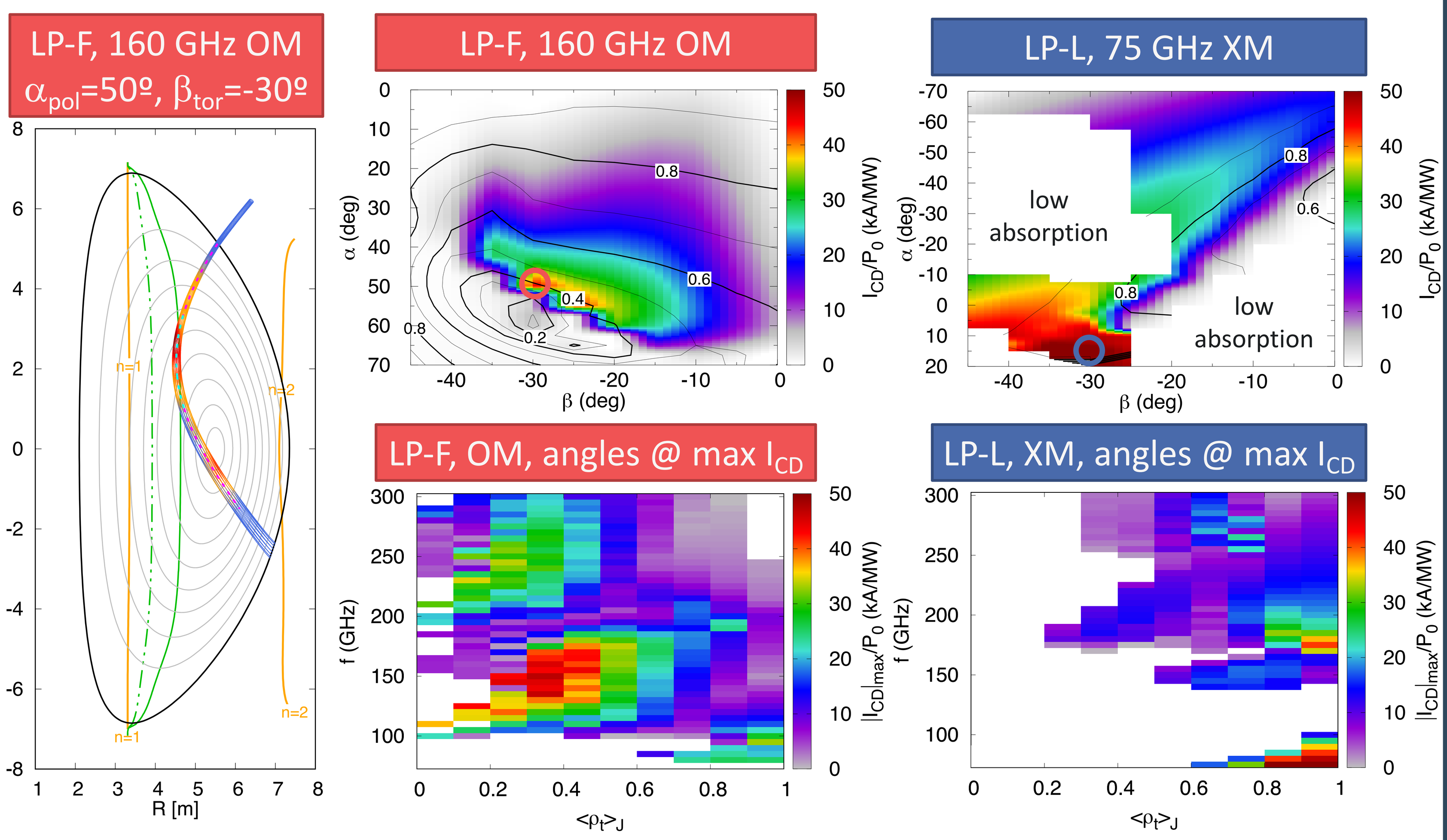


Extensive parametric analysis (≈10^7 runs per SPR) via quasi-optical beam-tracing code GRAY [3]

- 9-16 Different **launch points** (LP)
- 2 possible **polarizations** (OM, XM)
- **frequency** scan from f_L up to $>3f_{ce}$
- wide range of **poloidal** (α) and **toroidal** (β) launch **angles**

Assessment of

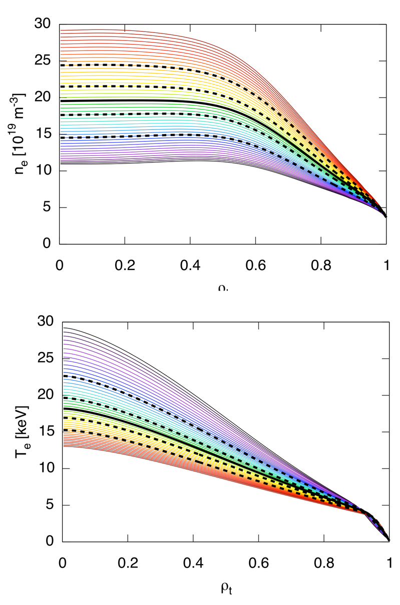
- max(I_{CD}) & optimal launches vs ρ
- launch angles and frequency tolerances



SENSITIVITY TO DENSITY

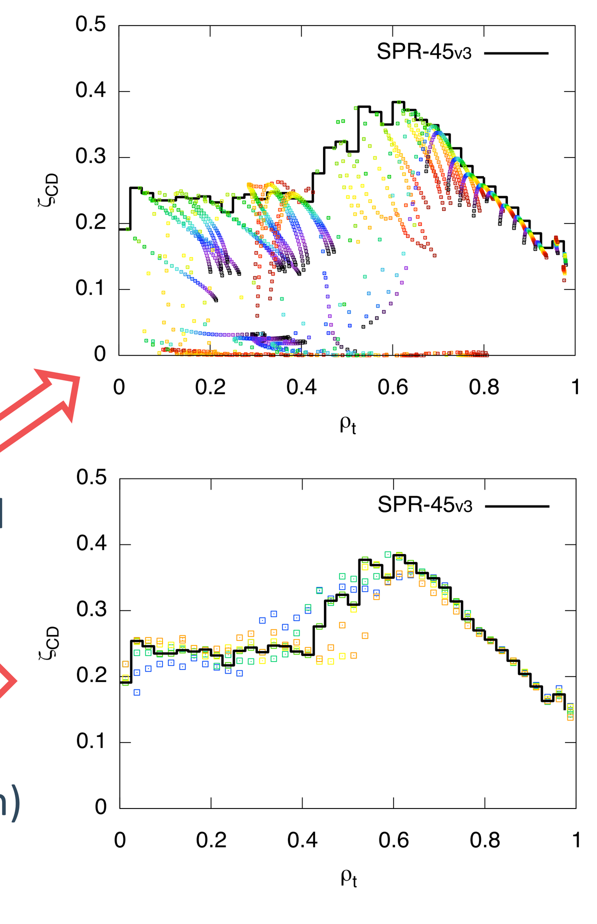
Motivation of the analysis:

a. Assess sensitivity to variations of plasma parameters (robustness of launch conditions)
b. Investigate possibility to operate at higher ne (beneficial for EBW)



Preliminary results:

a. Quantified changes in J_{CD} location and ζ_{CD} for the nominal optimal launches
b. Performed re-optimization at ±10%, ±25% n_e
   - ζ_{CD} mostly affected around $\rho \approx 0.6$ (n=1 to n=2 transition)



CONCLUSIONS

- A maximum normalized ECCD efficiency $0.25 < \zeta_{CD} < 0.4$ was typically found at $\rho < 0.6$ in all the SPRs assessed in this study, via OM absorption at the n=1 or n=2 harmonics.
- Far off-axis ($\rho > 0.8$), $\zeta_{CD} > 0.5$ can be achieved via XM absorption at the down-shifted first harmonic resonance, but with a narrow operational space
- Maximization of ECCD over the whole radial range requires LPs at different elevations $|z_{LP}|$
- High n_e limits the exploitation of n=1 resonance at mid-radius. Otherwise, the maximum achievable ζ_{CD} is fairly insensitive to n_e variations (meaning max(I_{CD})/P ∝ T_e/n_e)
- The trade-off between maximum performance and reliable operation needs a careful evaluation before a final choice is made for the optimal EC launch configuration

ACKNOWLEDGEMENTS

This work has been carried out under a contract (PO #2053810) signed between UKAEA and ISTP-CNR

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