NSTX-U

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Accessibility enhanced ECCD for plasma current start-up and ramp-up for tokamak reactors

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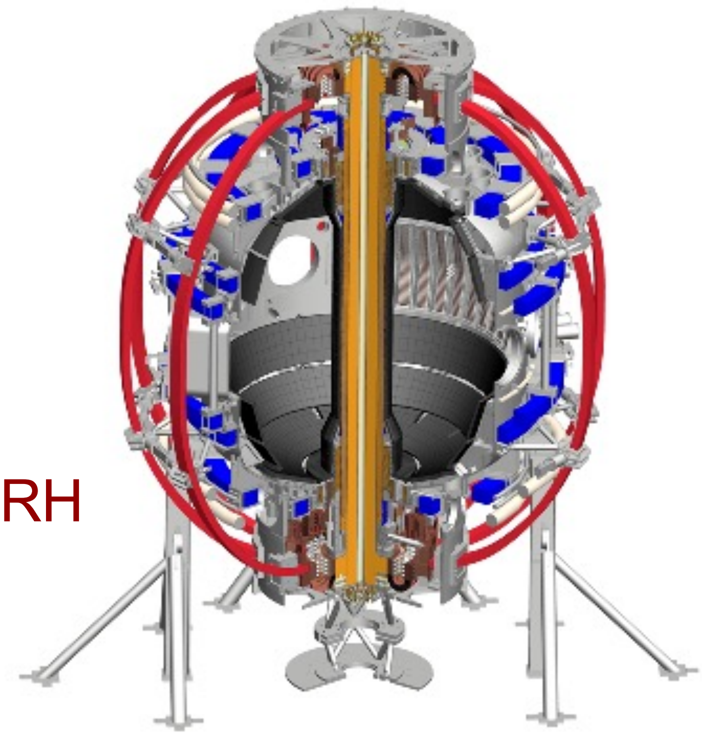


21st joint workshop on ECE and ECRH

June 20-24, 2022

PPPL

Talk Outline

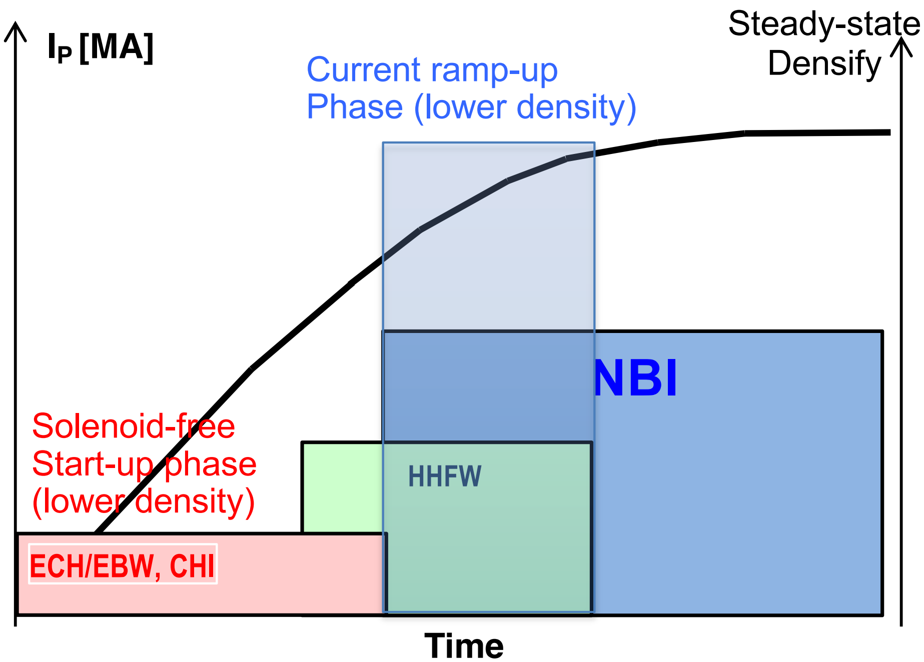
- Motivation of solenoid-free start-up.
- X-I (fundamental X-mode) ECH/ECCD examined for non-inductive start-up and ramp-up:
  - Improved X-I accessibility with magnetic field and electron temperature.
  - Strong absorption of X-I in the low T_e start-up regime.
  - High ECCD efficiency of X-I in the low T_e star-up regime.
- Possible path for 10 MA current non-inductive ramp-up with X-I for SHPD.
- Initial time dependent simulation for 10 MA non-inductive ramp-up for SHPD.
- Summary

M. Ono et al., To be published in a letter in PRE (2022).

Solenoid-free Start-up and Ramp-up are Critical Issues for Compact ST and Tokamak-based Reactors

- ST has been addressing critical issue of central solenoid (CS)-free start-up
  - A compact ST has little space for CS
  - CS-free start-up could significantly simplify ST/ tokamak reactor designs
  - CS-free start-up could save significant amount of V-S which could benefit ITER

- Non-inductive start-up could help achieve current profiles (non-peaked) compatible with advanced ST/tokamak operations



NSTX-U Collaborations:

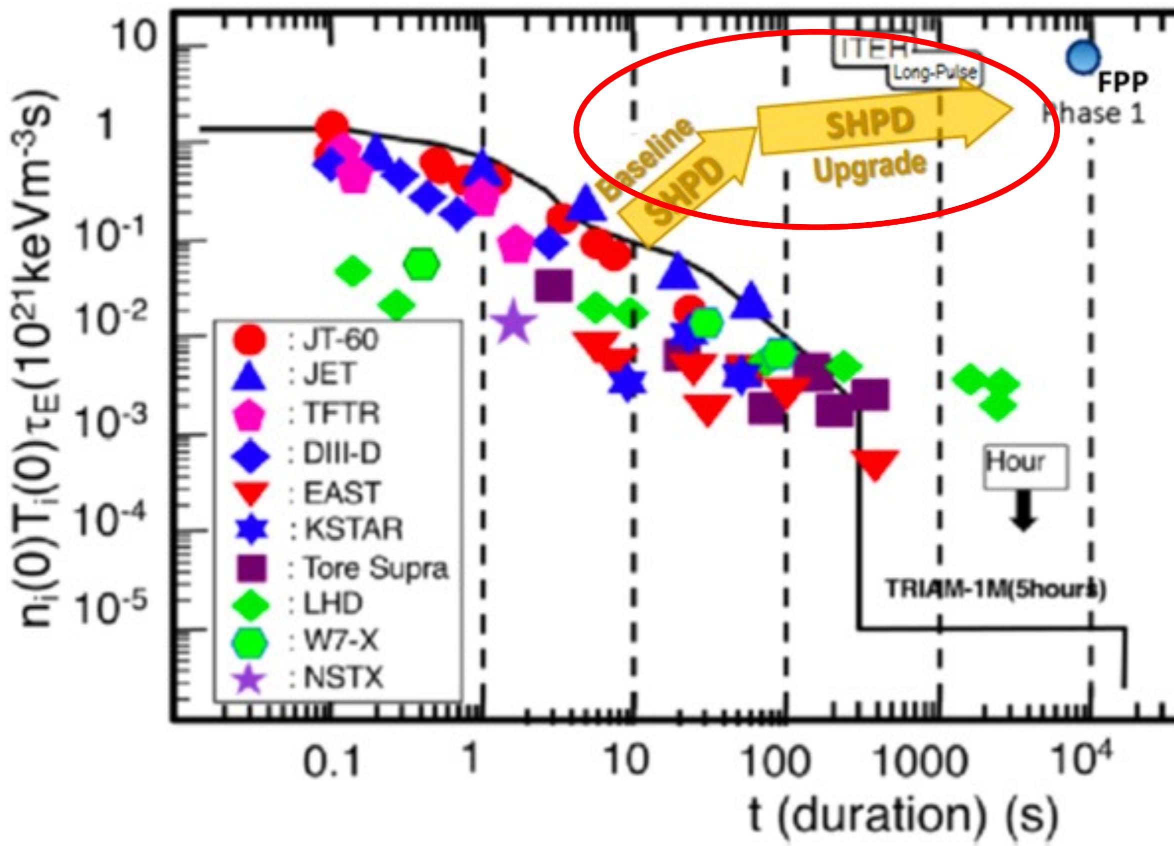
ECH / EBW – QUEST, ST-40

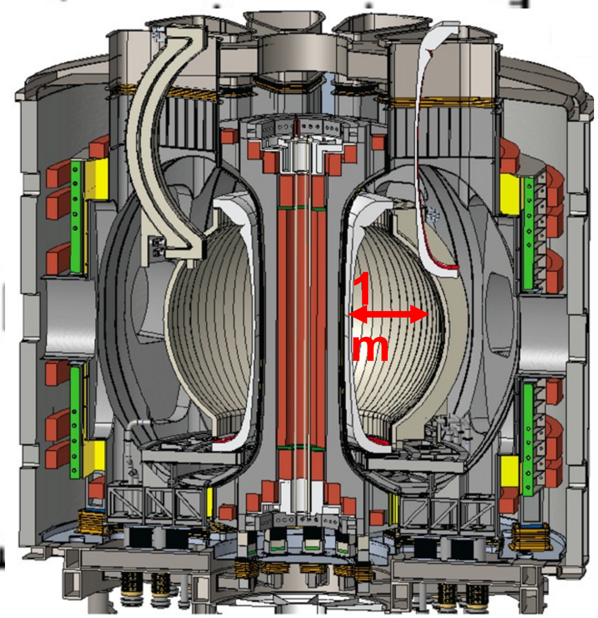
CHI, LHI – QUEST and PEGASUS-III

First demonstration of tokamak formation by ECH: C.B. Forest, et al., PRL 1992

Sustained High Power Density (SHPD) tokamak facility
A compact pilot plant physics demonstration facility

Highly desirable to ramp-up plasma current to ~ 10 MA non-inductively





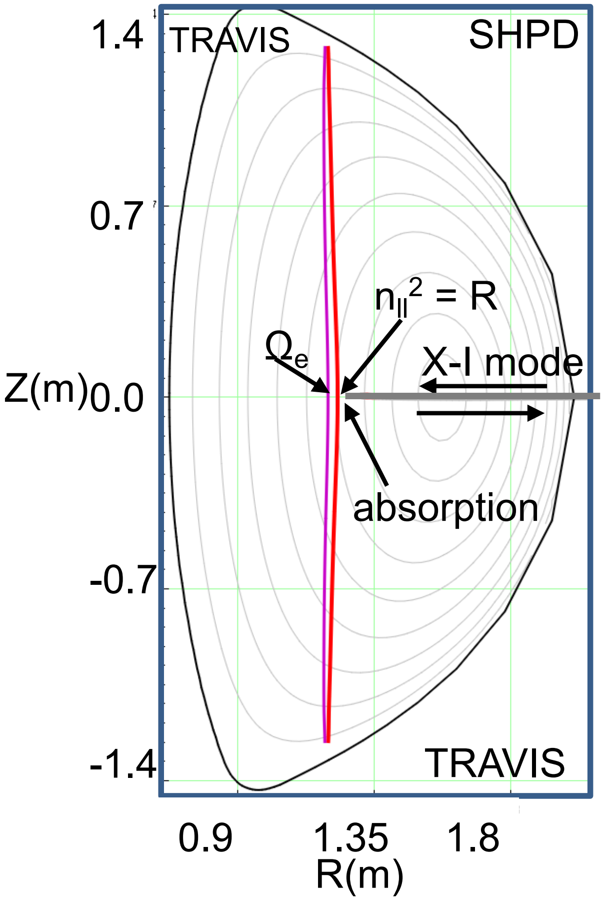
J. Menard et al., NF (2022)

X-I ECH & ECCD Analysis Tools Used

- Three ray-tracing codes used:
  - RT-4: M. Ono, et al., *AIP Conference Proceedings* (2020).
  - TRAVIS: N. B. Marushchenko et al, *Comp. Phys. Comm*. (2014).
  - Genray: A. P. Smirnov and R. W. Harvey, *Bull. Am. Phys. Soc.* (1995).

- Quasi-linear calculation:
  - CQL3D: Y. V. Petrov and R. W. Harvey, *Plasma Phys. Control. Fusion* (2016).

X-I accessibility is normally limited to very low density
However X-I accessibility improves with increasing B_T and T_e



X-mode at fundamental cyclotron resonance (X - I)

- X-mode is reflected at $n_{||}^2 = R$ cut-off layer

$$R \equiv 1 - \omega_{pe}^2/\big(\omega(\omega - \Omega_e)\big)$$

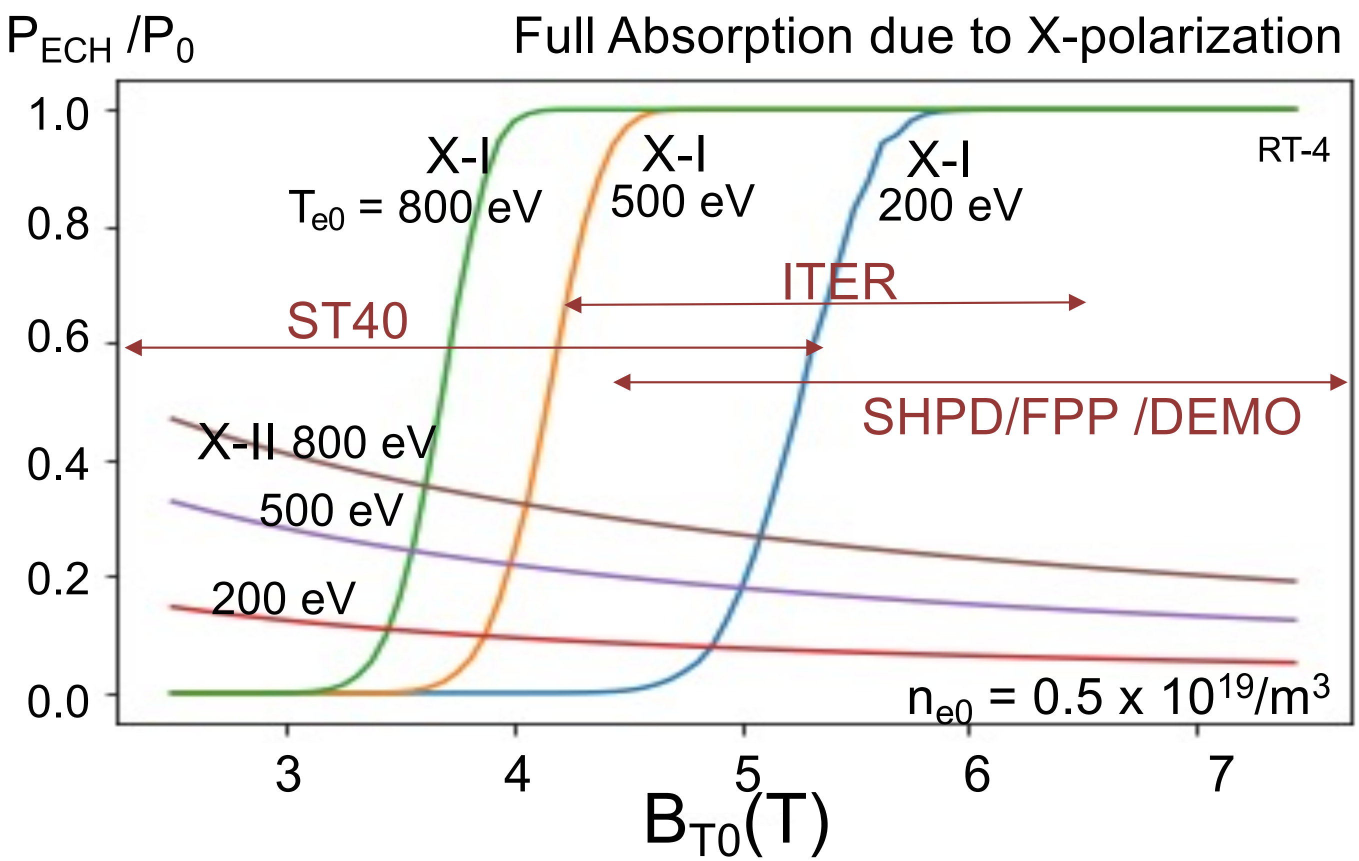
- Resonant interaction possible if the wave fundamental resonance condition $(\omega - \Omega_e)/\big(k_{||}V_{e0}\big) \leq 3$ is satisfied.

- This resonance condition together with the $n_{||}^2$ = R cut-off condition yields the following $\omega = \Omega_e$ resonance accessibility condition for plasma density n_e as

$$n_e \leq 37.5\, f^2\, \frac{V_{e0}}{c} n_{\|}(1 - n_{\|}^2) \qquad f \propto B_T(\omega = \Omega_e)$$

T. Maekawa, et al., *Nucl. Fusion* (2018)

X-I can be fully absorbed at start-up temperature of sub-keV! X-I accessibility improves with B_T and T_e for a given n_e



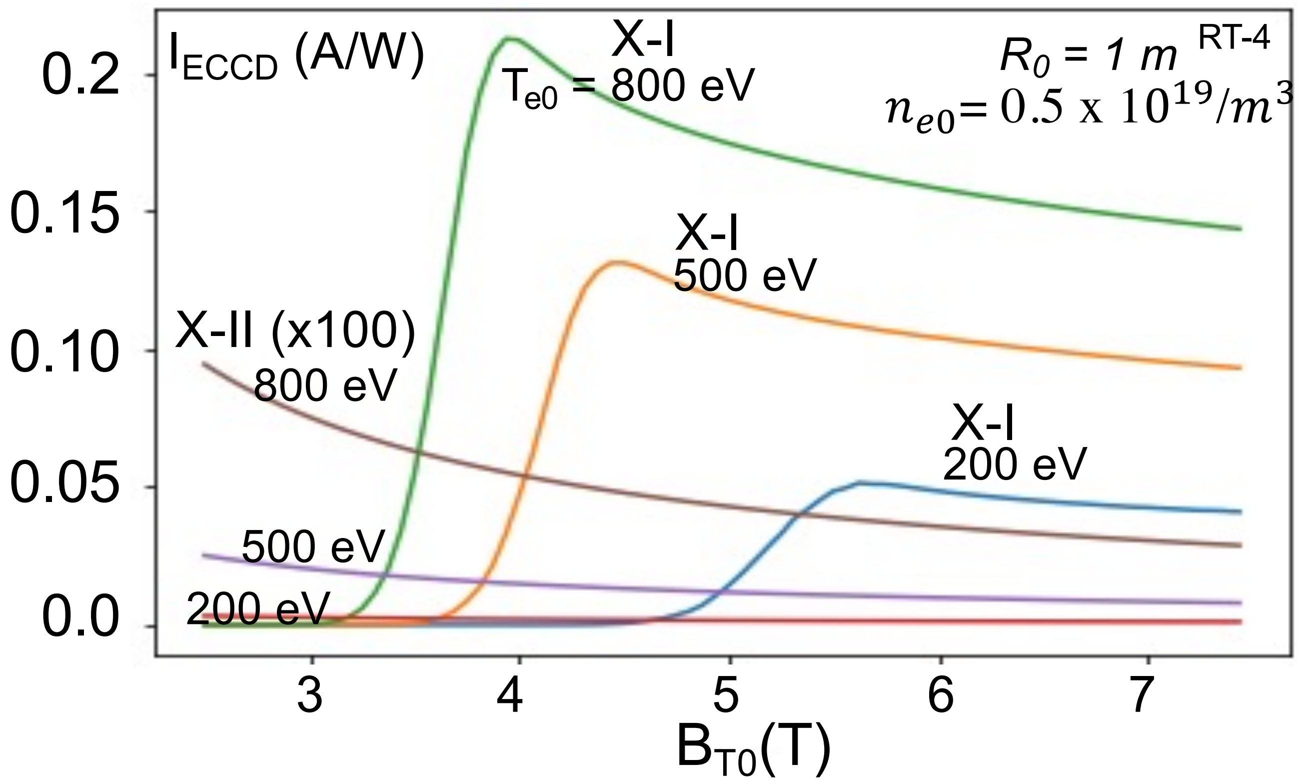
X-I : Ω_e X-mode
X-II : $2\Omega_e$ X-mode

$f \sim \Omega_e$
4 T - 112 GHz
6 T - 168 GHz

RT-4

X-I can drive x 100 larger current for start-up compared to more conventional ECCD X-II, O-I, O-II

I-X ECCD generate uni-directional currents due to accessibility



$f \sim \Omega_e$

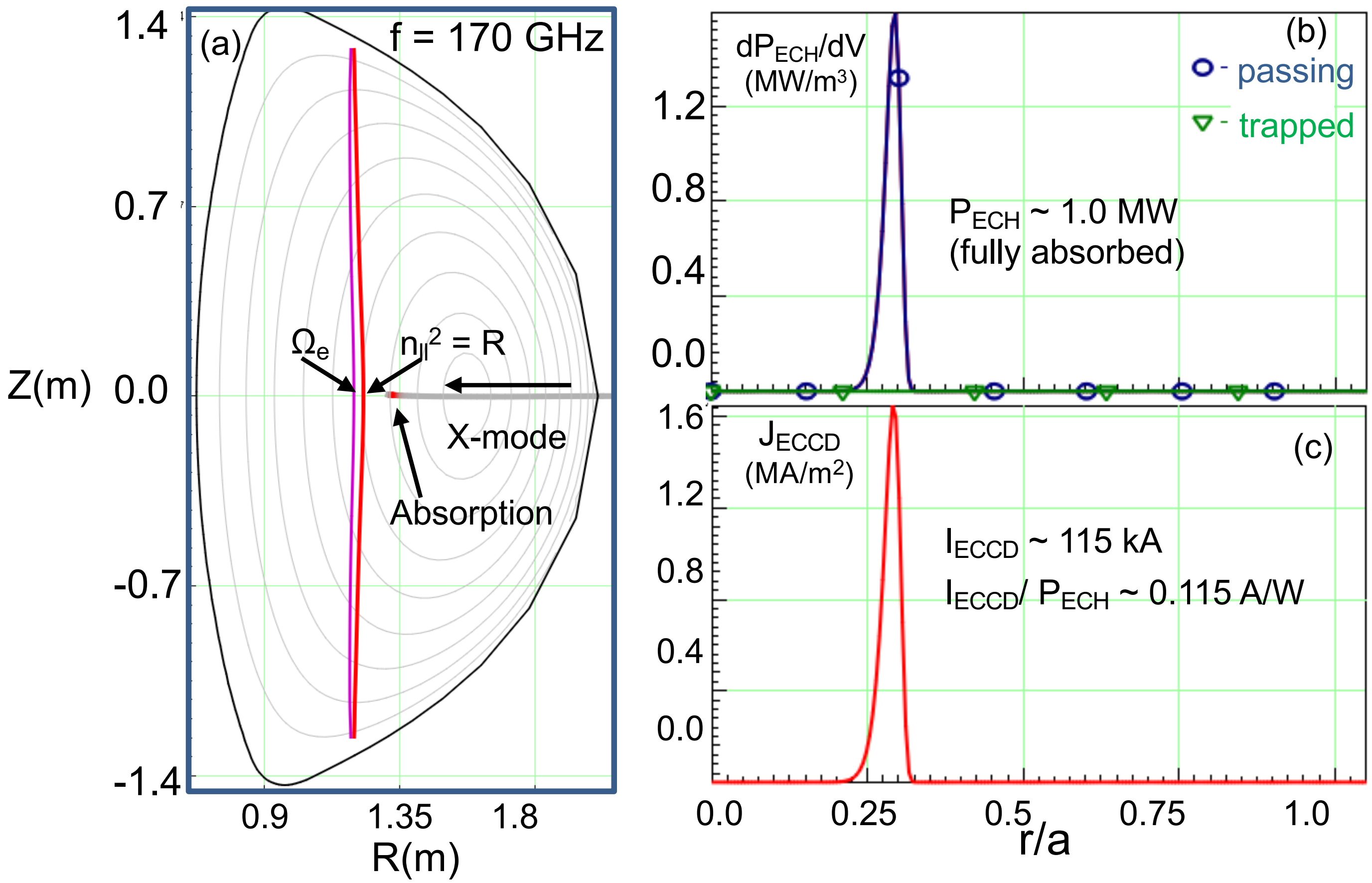
4 T - 112 GHz

6 T - 168 GHz

RT-4

Propagation, absorption and current drive of X-I-mode in SHPD

R_0 = 1.58 m, R/a ~ 2, B_{T0}= 5T, n_{e0}= $10^{19}/m^3$ and T_{e0} = 1 keV

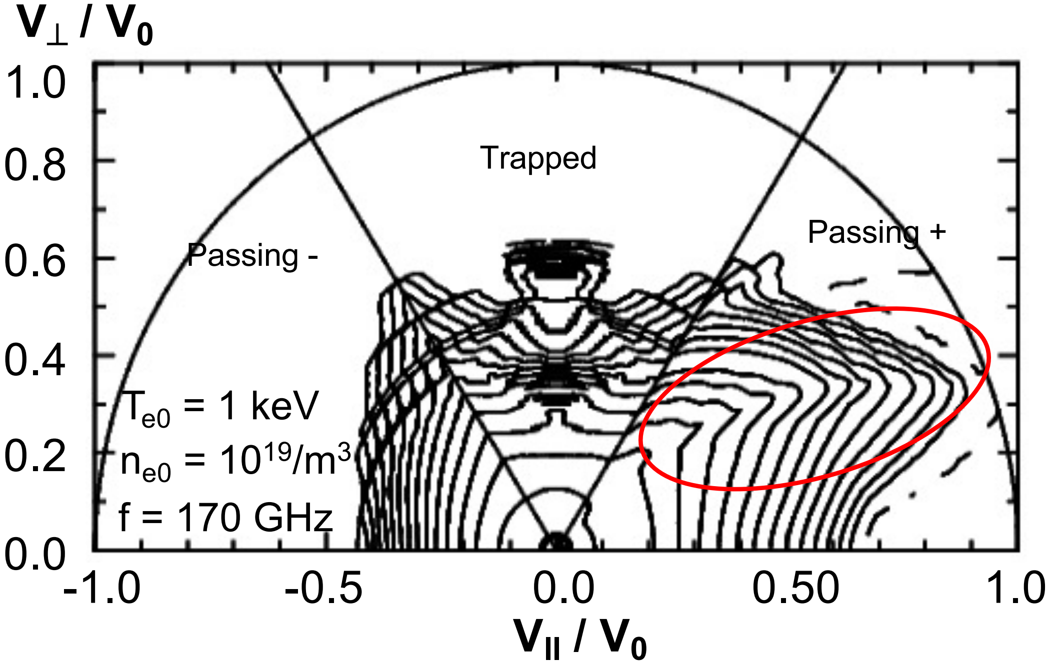


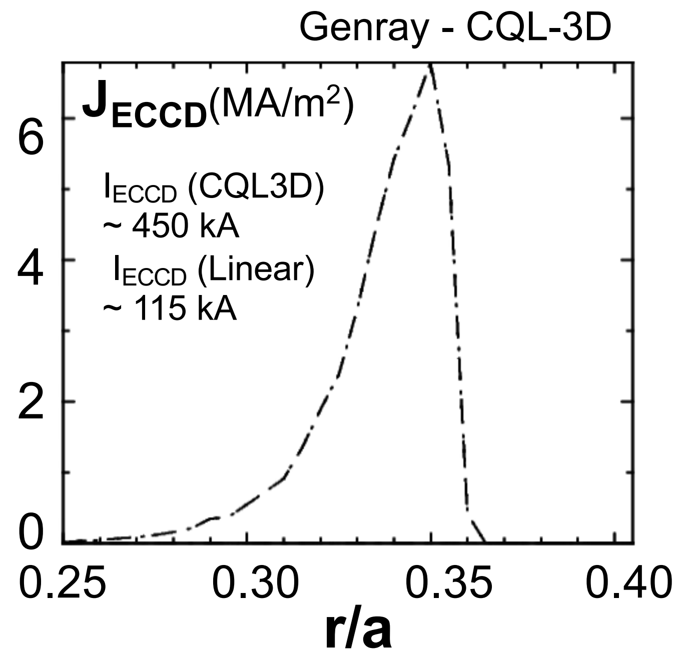
ECH and ECH highly efficient and highly localized

TRAVIS

Quasi-linear calculation shown even higher current drive compared to linear case
R_0 = 1.58 m, R/a ~ 2, B_{T0}= 5T, n_{e0}= $10^{19}/m^3$ and T_{e0} = 1 keV

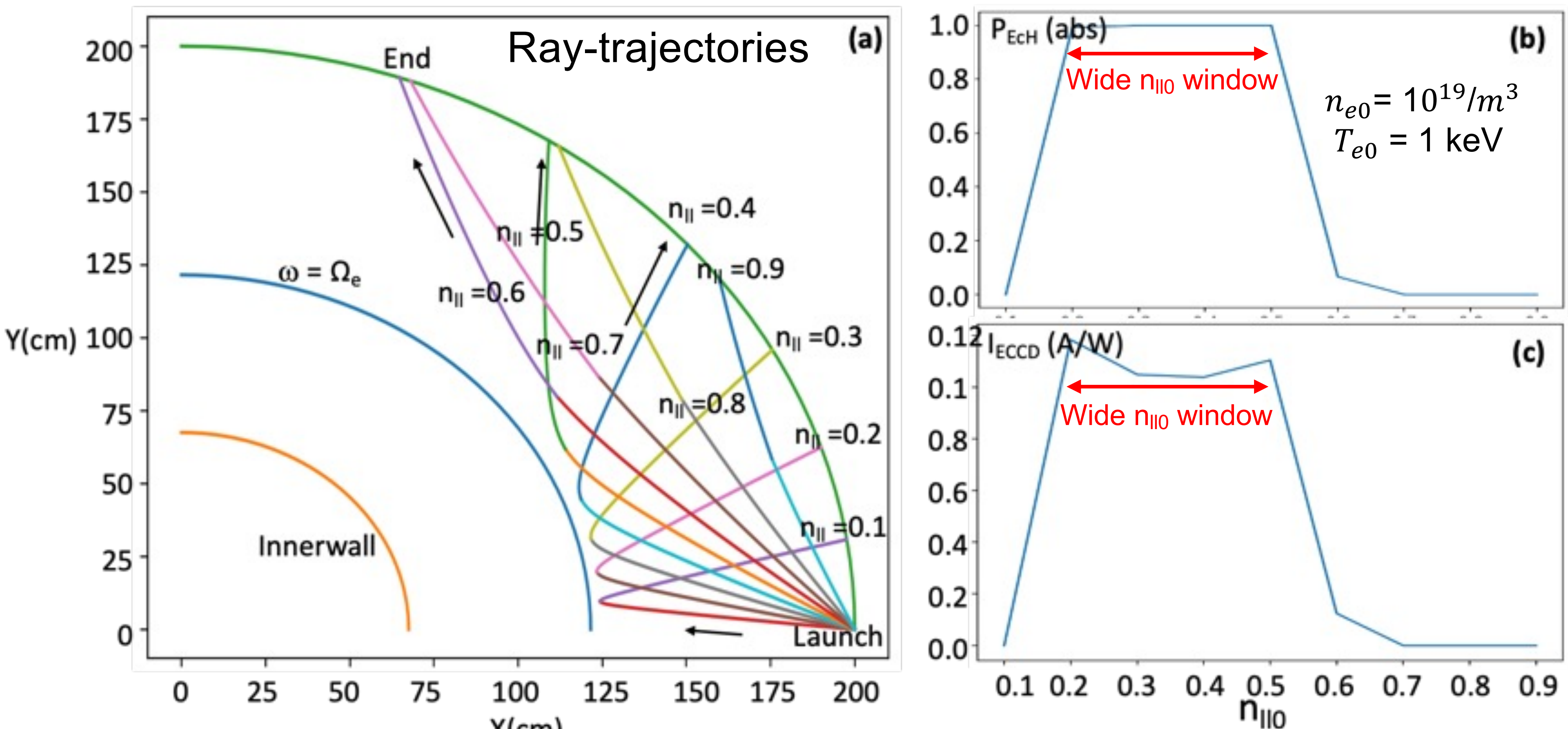
Quasi-linear X-I calculation shows interaction with uni-directional passing electrons





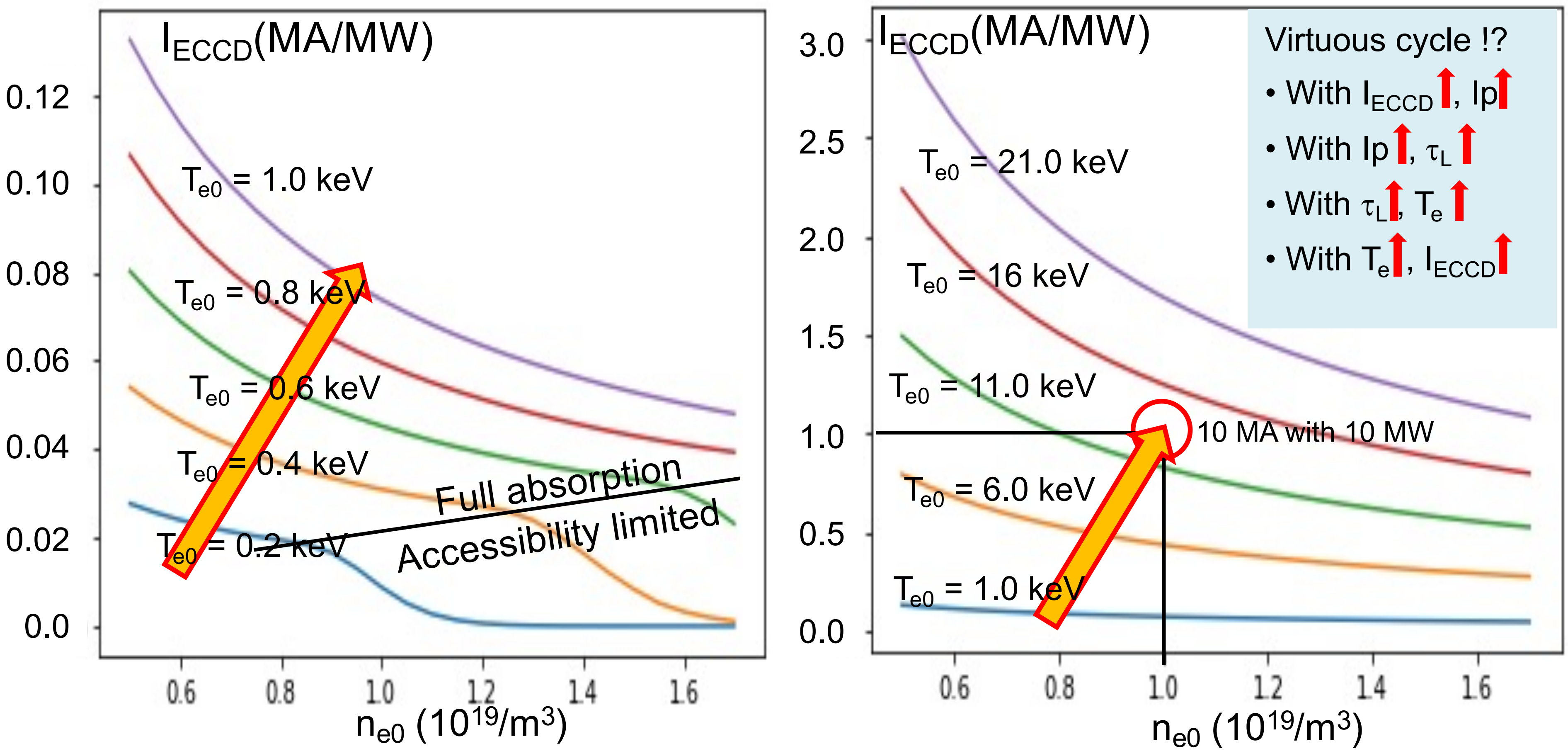
Even higher ECCD due to acceleration to higher energy range

Propagation, absorption, and current driven for X-I in SHPD as a function of launched $n_{||0}$



RT-4

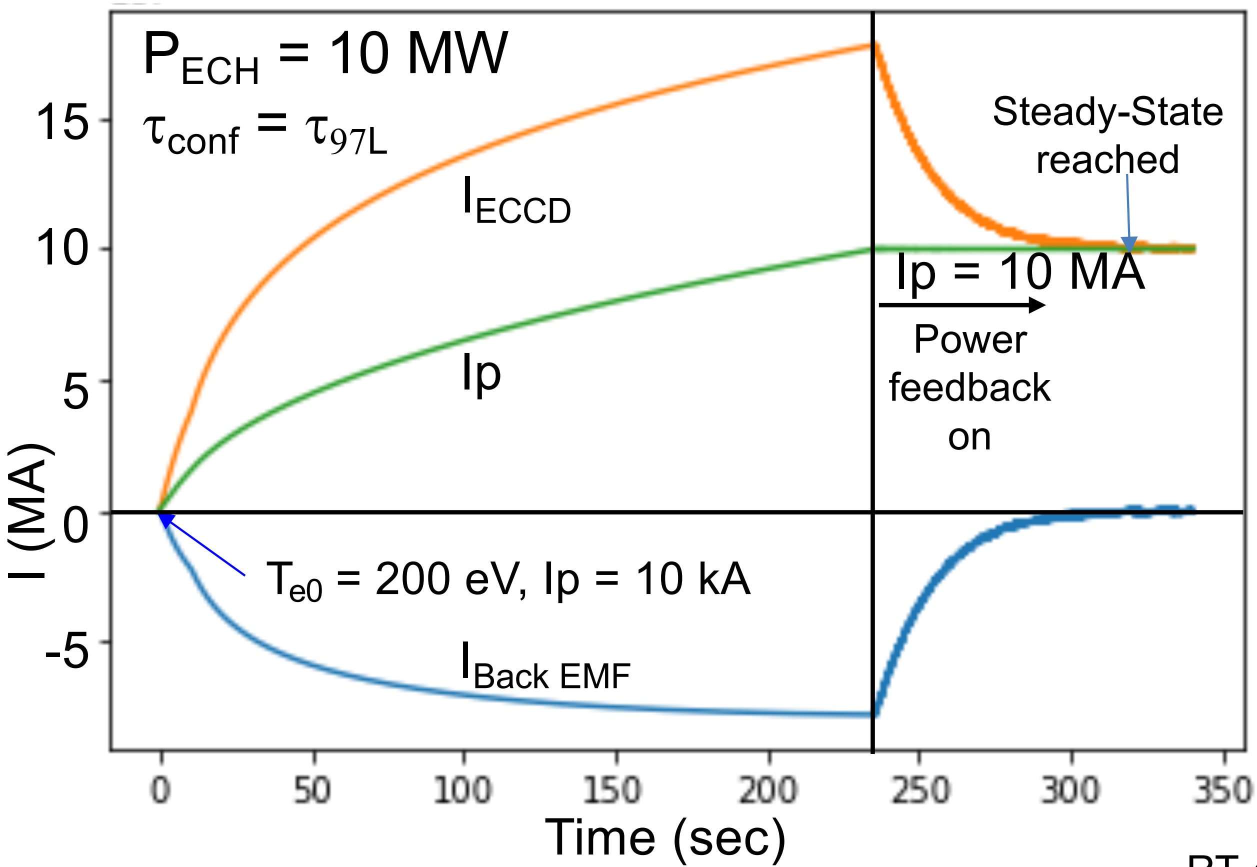
X-I can drive 10 MA of CS-free current ramp-up possible with P_0 ~ 10 MW in SHPD*

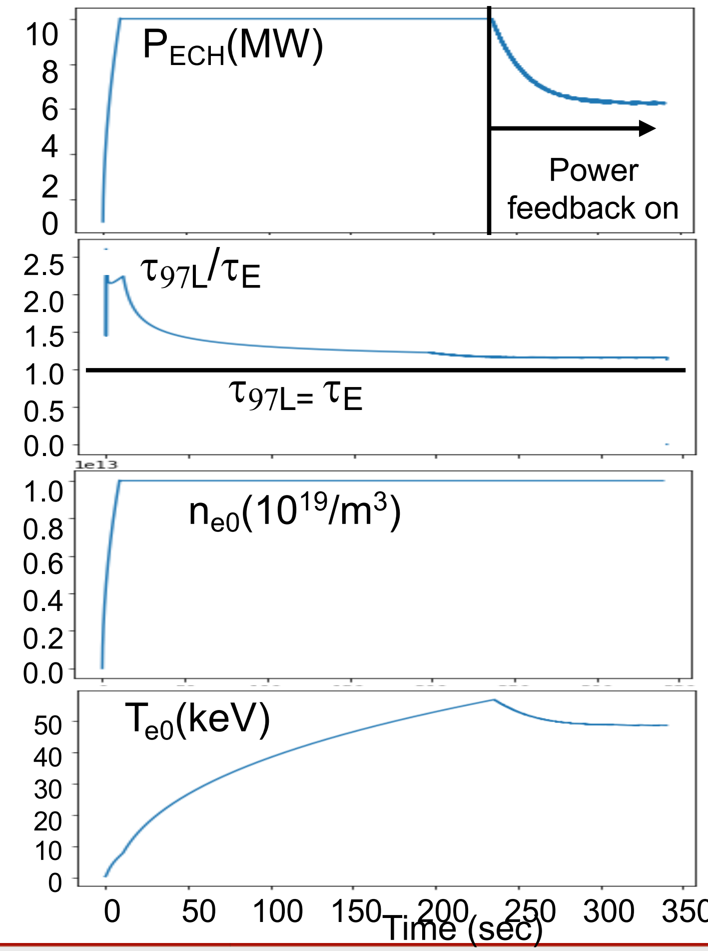


RT-4

Preliminary Time Dependent Results of Solenoid-free Start-up and Ramp-up

SHPD: R_0 = 1.58 m, R/a ~ 2, B_{T0}= 5T, n_{e0}= $10^{19}/m^3$





RT-4

I-X ECH/ECCD Looks Attractive for Fusion Reactor Regime

- I-X accessibility improves with toroidal magnetic field, well suited for fusion reactor regime.
- In the lower temperature start-up regime (T_{e0} = 0.2 – 1 keV), X-I ECCD is x 100 more efficient compared to more conventional X-II, O-I, and O-II ECCD due to strong interactions provided by the fundamental X-polarization with accessibility constrained uni-directional electron population.
- CQL-3D calculations suggest even more ECCD compared to the linear value due to electrons accelerating to higher energy.
- For SHPD tokamak facility, X-I ECCD ramp-up to full current I_{ECCD} ~ 10 MA appears possible with only P_{ECH} ~ 10 MW.
- Initial time dependent model of the X-I ECH/ECCD current ramp-up presented.
- ST-40 with MW-class 140/105 GHz gyrotrons offers the near-term opportunities for MA-class demonstration of CS-free I-X current ramp-up (E. du Toit, this conference).
- WEST with three MW-class 105 GHz gyrotrons with B_{T0} = 3.7 T can also investigate X-I. (Lena Delpech, Remi Dumont, this conference)