NSTX-U

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U.S. Department of Energy Office of Science
Fusion Energy Sciences

X-I mode for efficient solenoid-free ECCD plasma current start-up and ramp-up for fusion reactor

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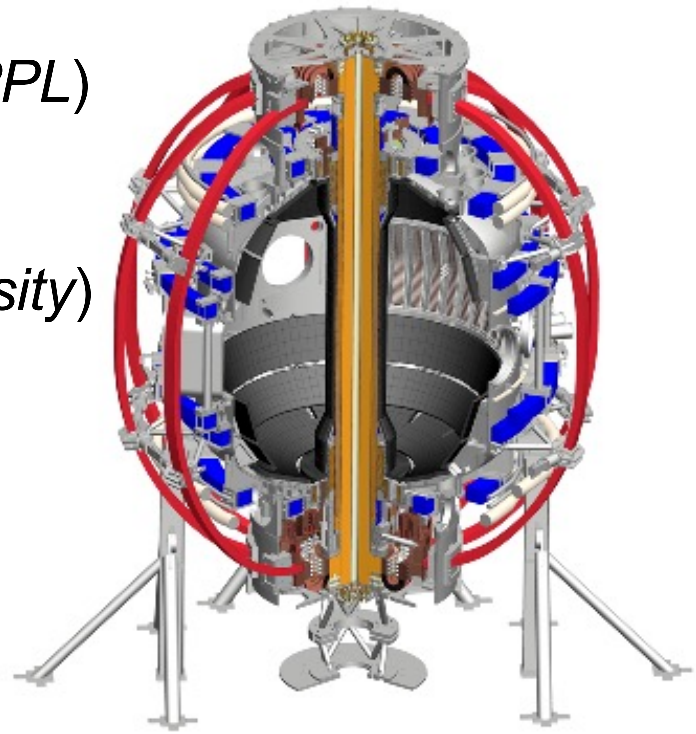


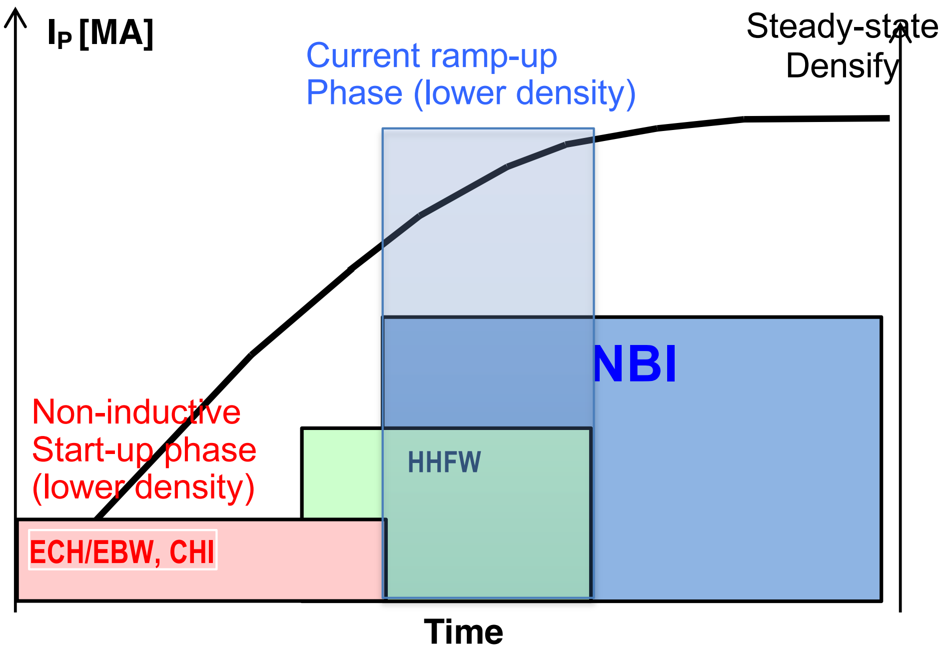
The 21st International Spherical Torus Workshop
October 31 – November 4, 2022

PPPL

Non-Inductive Current Start-up and Ramp-up is a Critical Issue for Compact ST-based Reactors

- ST has been addressing critical issue of non-inductive (NI) start-up
  - A compact ST has little space for Central Solenoid (CS)
  - Elimination or minimization of CS could significantly simplify ST reactor designs
  - CS-free start-up could save significant amount of V-S

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



NSTX-U Collaborations:

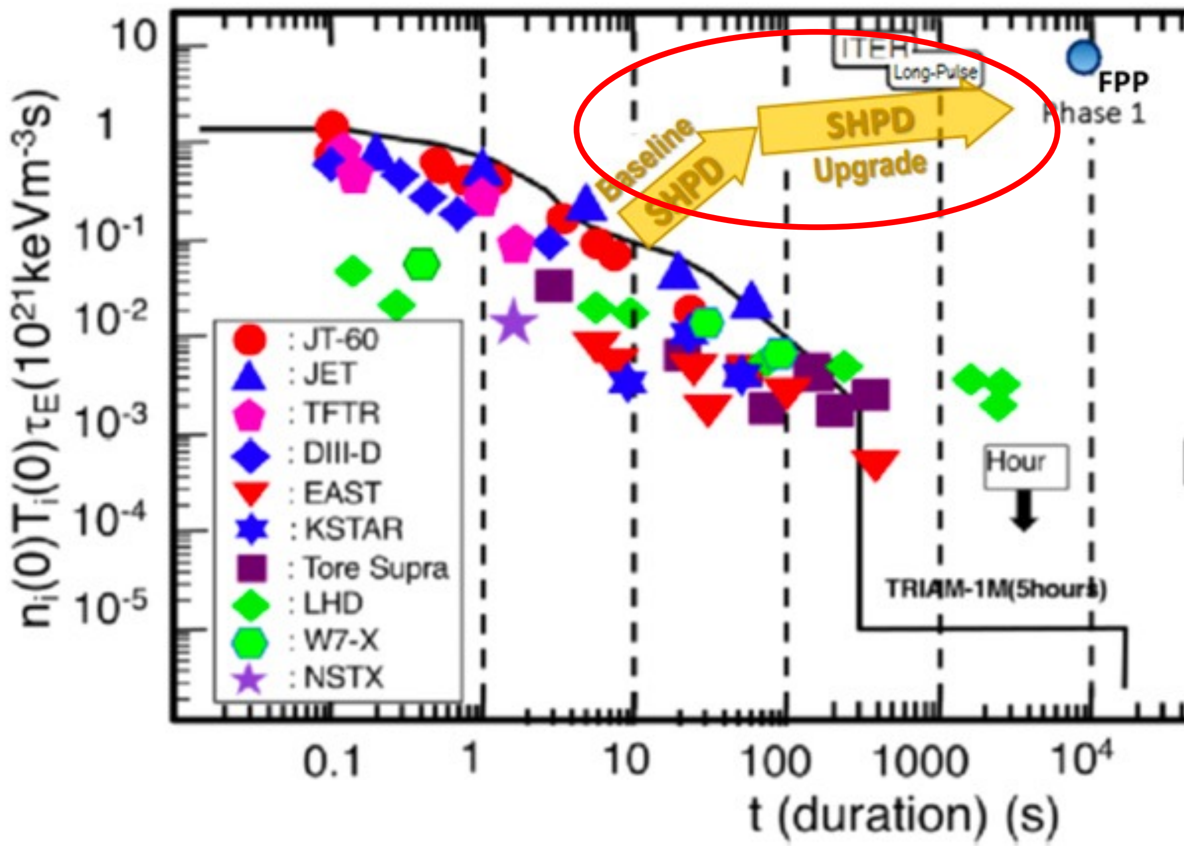
ECH / EBW – QUEST, ST-40

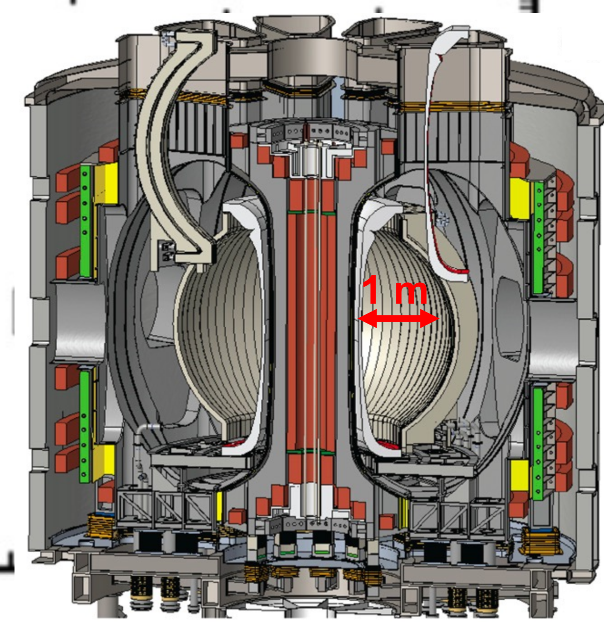
CHI, LHI – QUEST and PEGASUS-III

NI start-up has been quite successful! Can we increase NI ramp up current to ~ a few MA range?

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

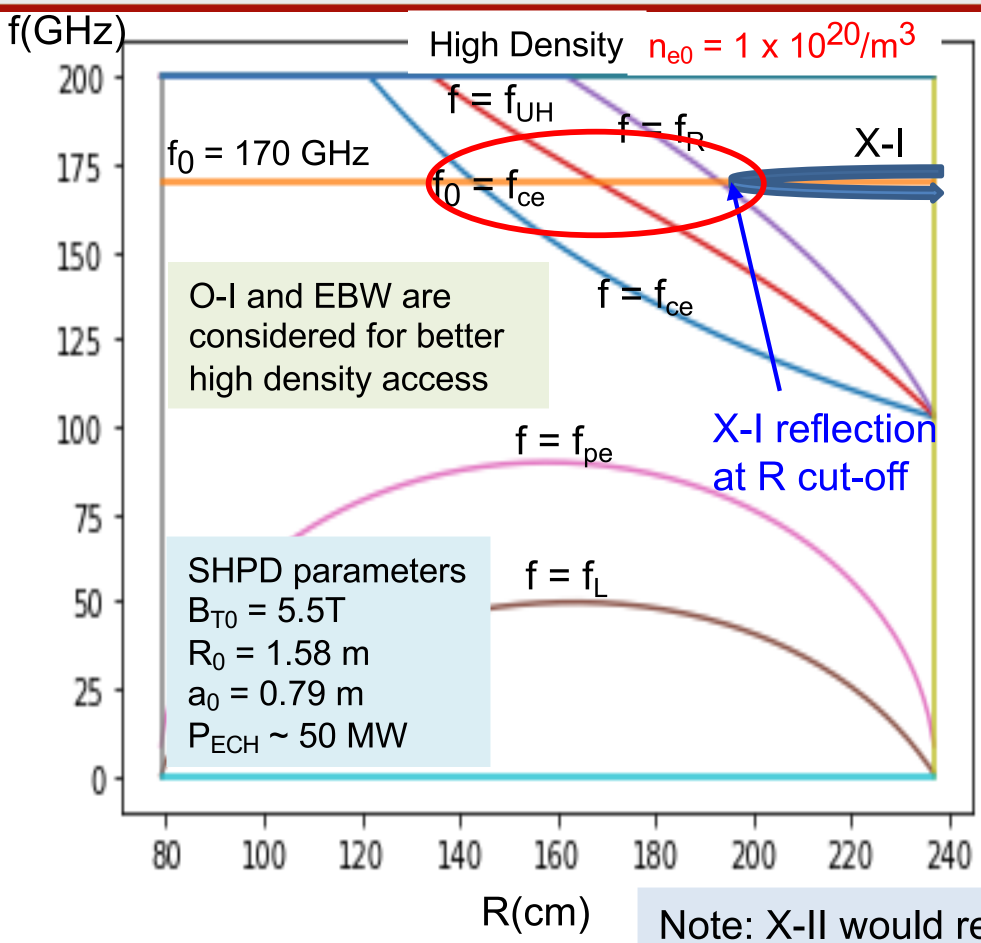
Highly desirable to ramp-up plasma current to ~ 10 MA non-inductively (NI)

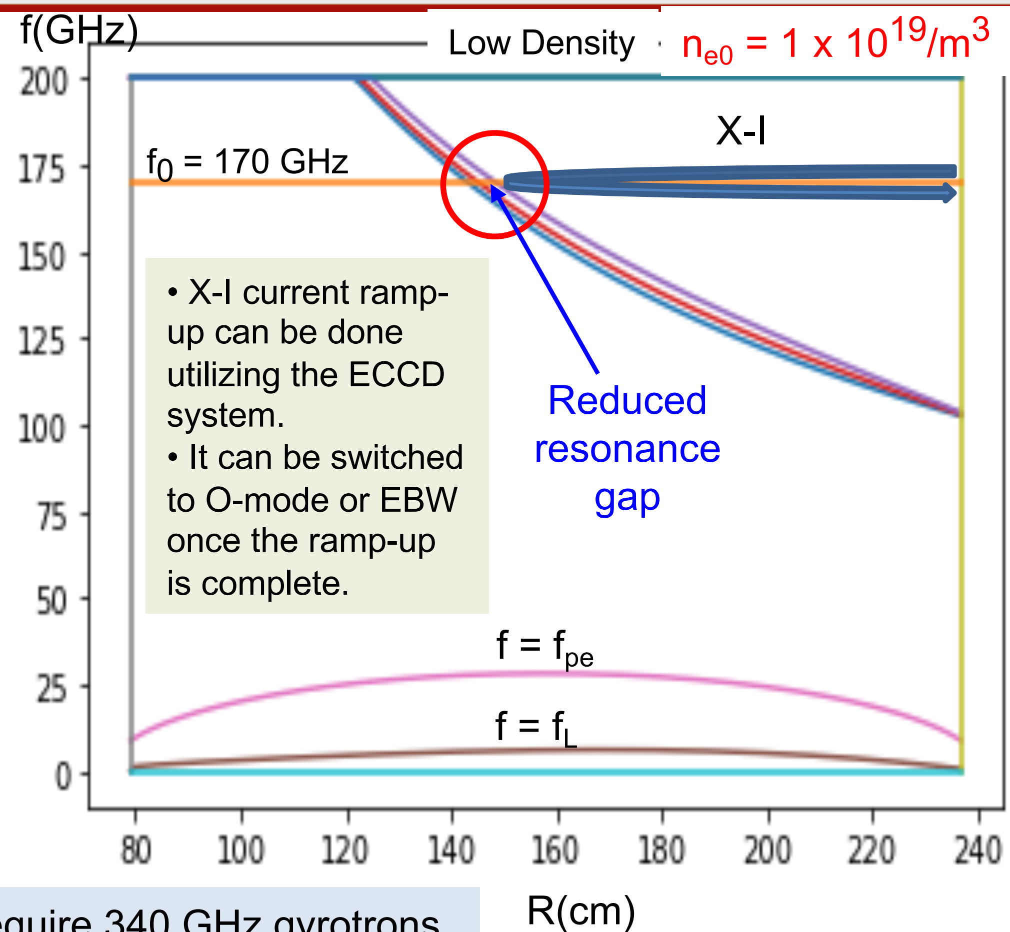




J. Menard et al., NF (2022)

Low-field-side X-I accessibility improves with reduced n_e
X-I can be used to start-up and ramp-up at n_{e0} = 1 x $10^{19}/m^3$ in SHPD





Note: X-II would require 340 GHz gyrotrons

X-I accessibility condition

X-I accessible density n_{ea} improves with increasing f_0 and T_e

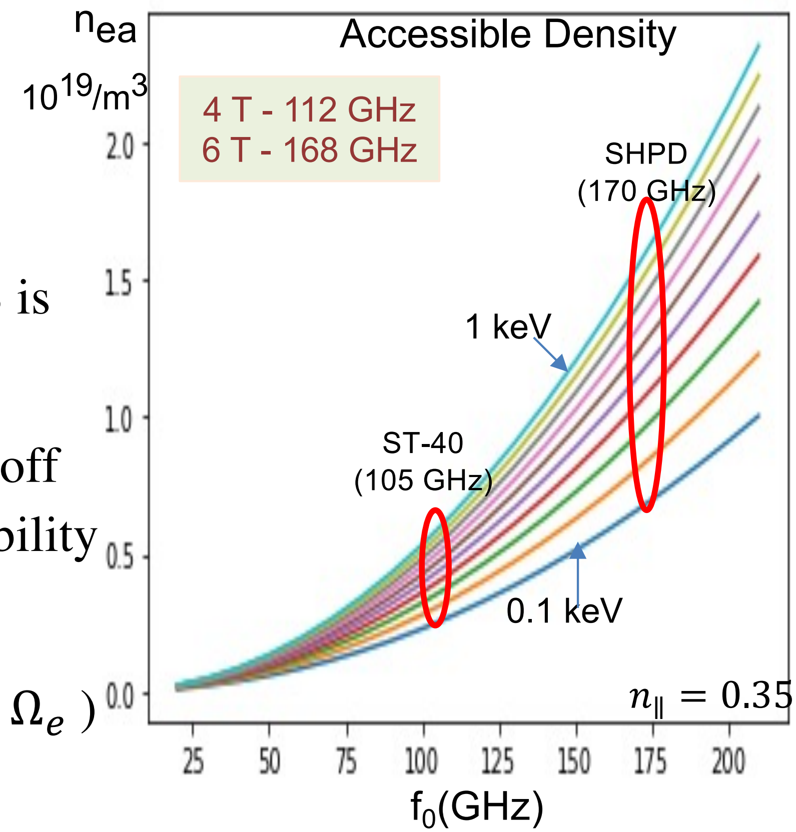
- X-mode is reflected at $n_{||}^2 = R$ cut-off layer

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

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

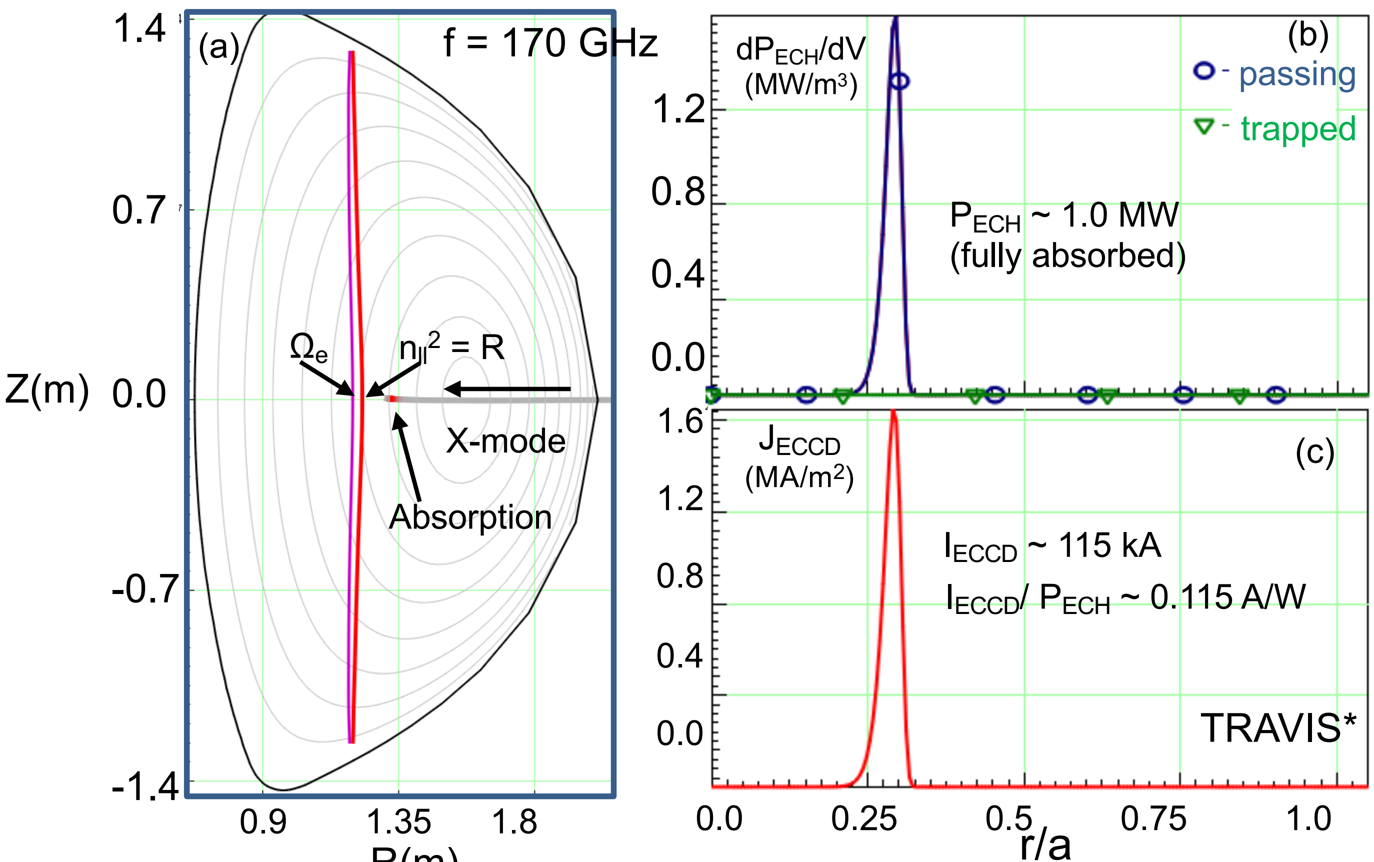
- This resonance condition together with the $n_{||}^2 = R$ cut-off condition yields the following $\omega = \Omega_e$ resonance accessibility condition for plasma density n_{ea} as

$$n_{ea} = 37.5\, f_0^{\,2}\, \frac{V_{e0}}{c} n_{\|}(1 - n_{\|}^2) \qquad f_0 \propto B_{T0}(\omega = \Omega_e)$$



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

R_0 = 1.58 m, R/a ~ 2, B_{T0} = 5.5 T, n_{e0} = $10^{19}/m^3$ and T_{e0} = 1 keV



*N. B. Marushchenko et al, *Comp. Phys. Comm.* 2014)

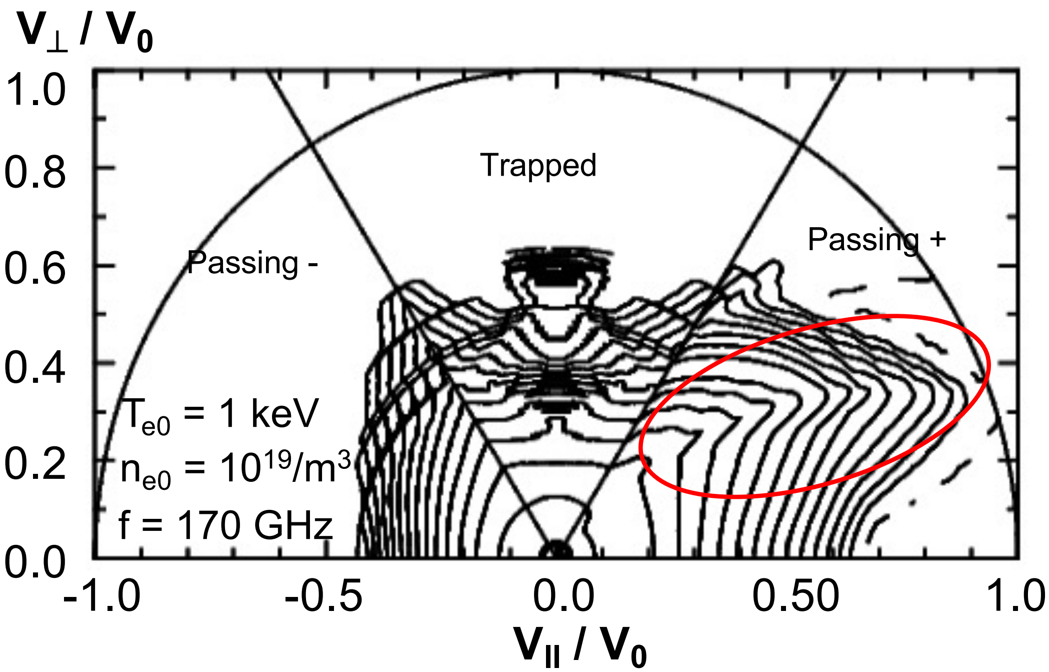
- X-I ECH is highly efficient and highly localized due to wave polarization and unidirectional driven current.
- At 1 keV, X-I is about 200 times more efficient compared to conventional ECCD such as X-II and O-I

M. Ono et al., Phys Rev. E 2022

Quasi-linear X-I ECCD calculations show even higher current drive

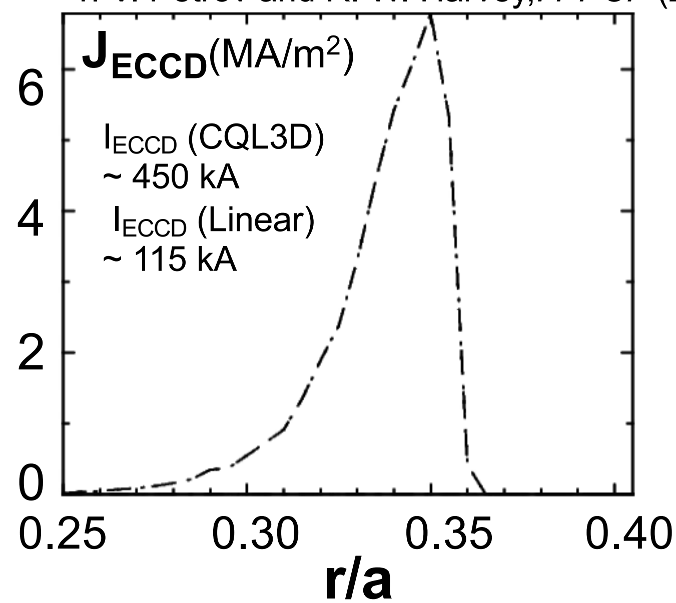
R_0 = 1.58 m, R/a ~ 2, B_{T0}= 5.5 T, n_{e0}= $10^{19}/m^3$ and T_{e0} = 1 keV

CQL-3D shows acceleration of uni-directional passing electrons to higher energy



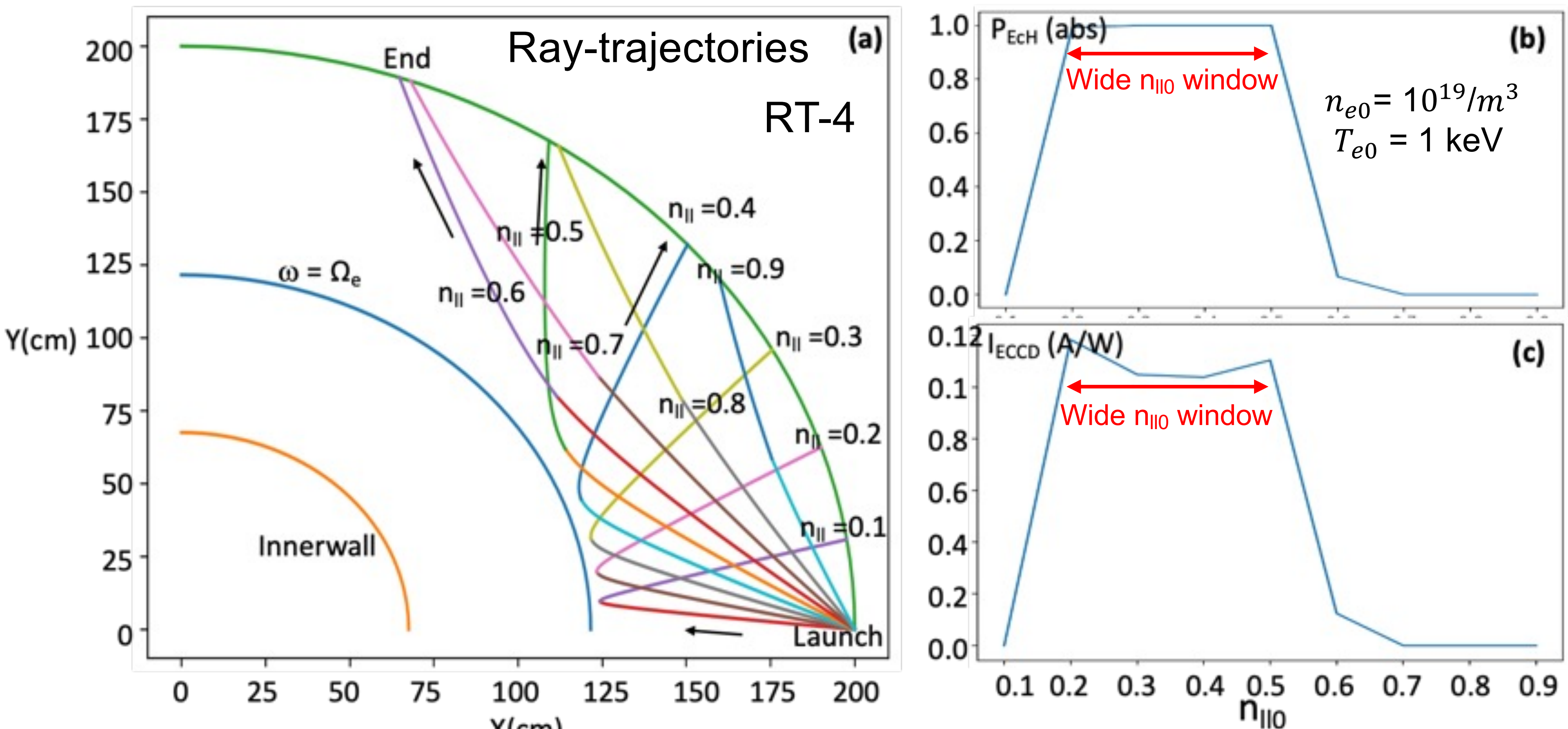
Genray - CQL-3D*

*Y. V. Petrov and R. W. Harvey,. *PPCF* (2016).



Even higher ECCD due to acceleration to higher energy range

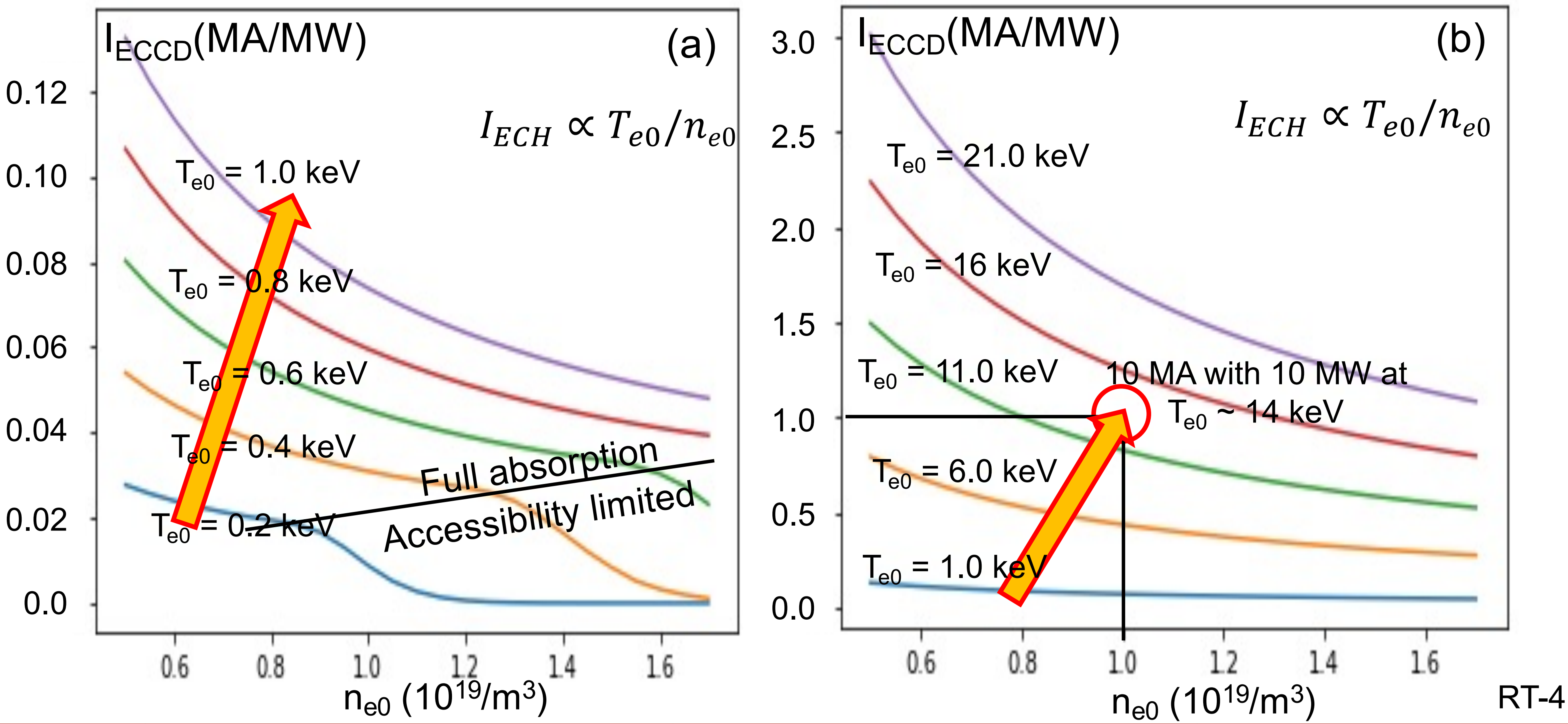
Propagation, absorption, and current driven for X-I in SHPD as a function of launched $n_{||0}$



RT-4: M. Ono, et al., *AIP Conference Proceedings* (2020).

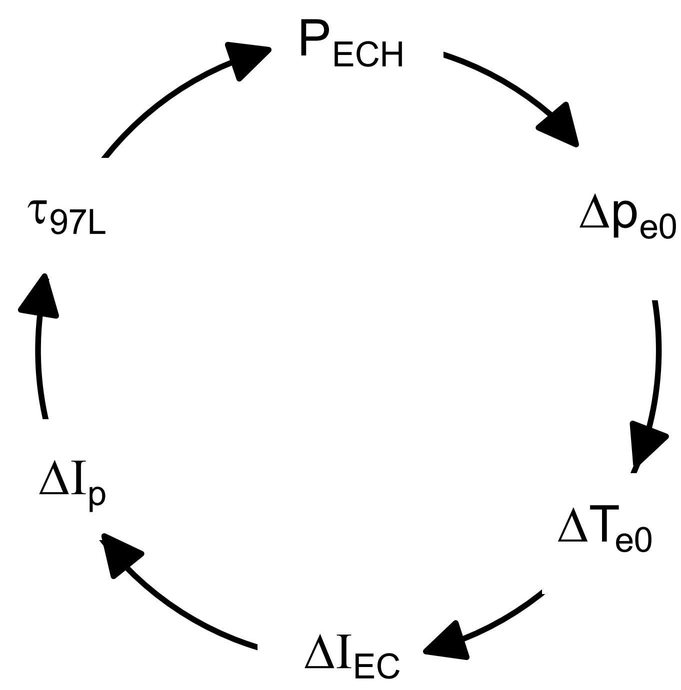
X-I ECCD efficiency improves linearly with T_{e0}/n_{e0}

1 A/W possible for SHPD at T_{e0} ~ 14 keV and $n_{e0} = 10^{19}/m^3$



Time Dependent Model of ECH X-I Current Ramp-up Developed for SHPD
Positive Feedback Cycle of ECH X-I Helps Efficient Current Ramp-up

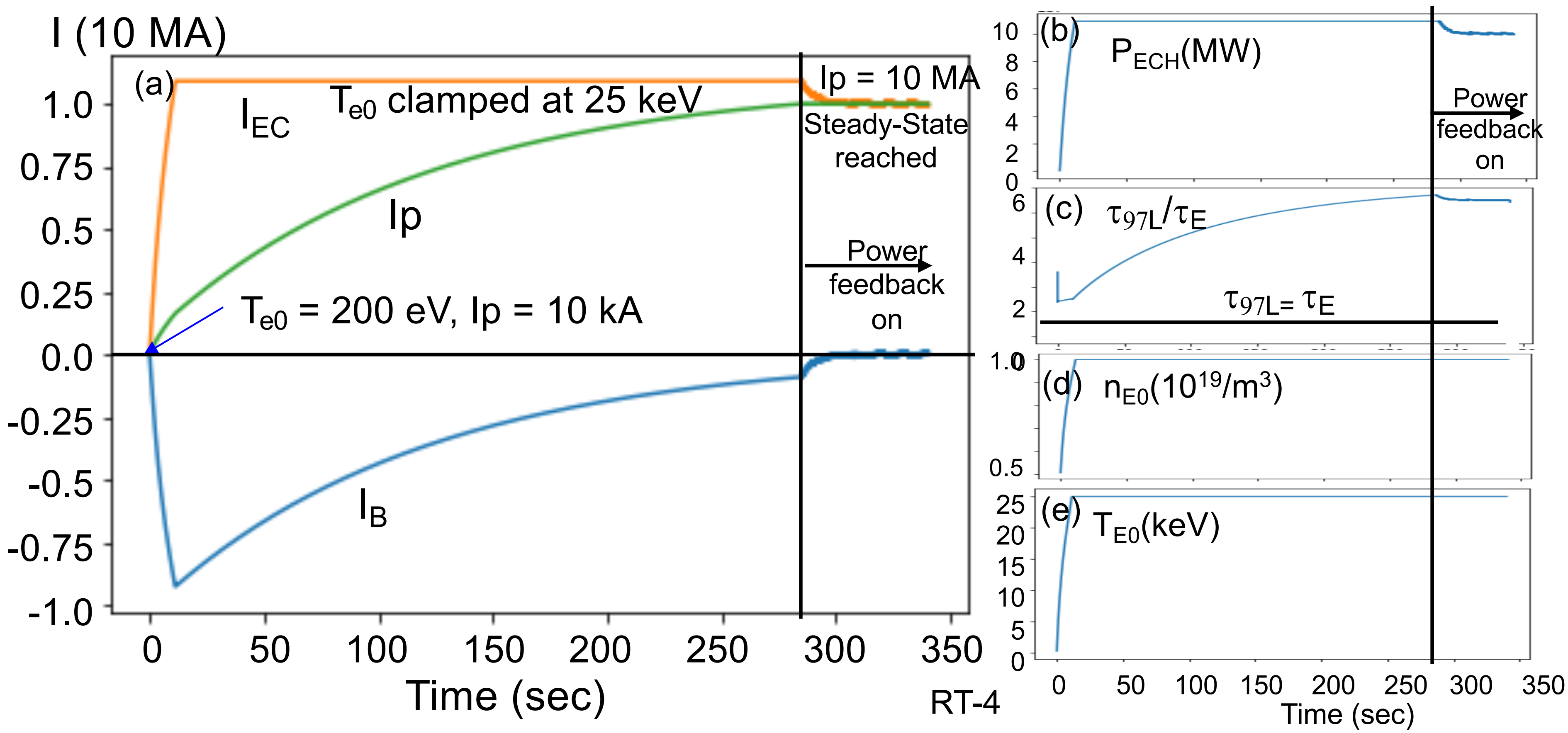
- ECH heating power P_{ECH} raises electron plasma pressure, Δp_{e0}.
- With constant plasma density, the electron plasma pressure increase would increase electron temperature ΔT_{e0}.
- Increased temperature increases the ECCD current drive ΔI_{EC} as the current drive efficiency increases with T_{e0}.
- Increased ECCD current drive increases the plasma current ΔI_p.
- Finally, increased ΔI_p increases the plasma confinement time τ_{97L} per L-mode scaling* which would increase Δp_{e0}, completing the positive feedback heating and current drive cycle.



*S. M. Kaye et al., *NF* (1997)

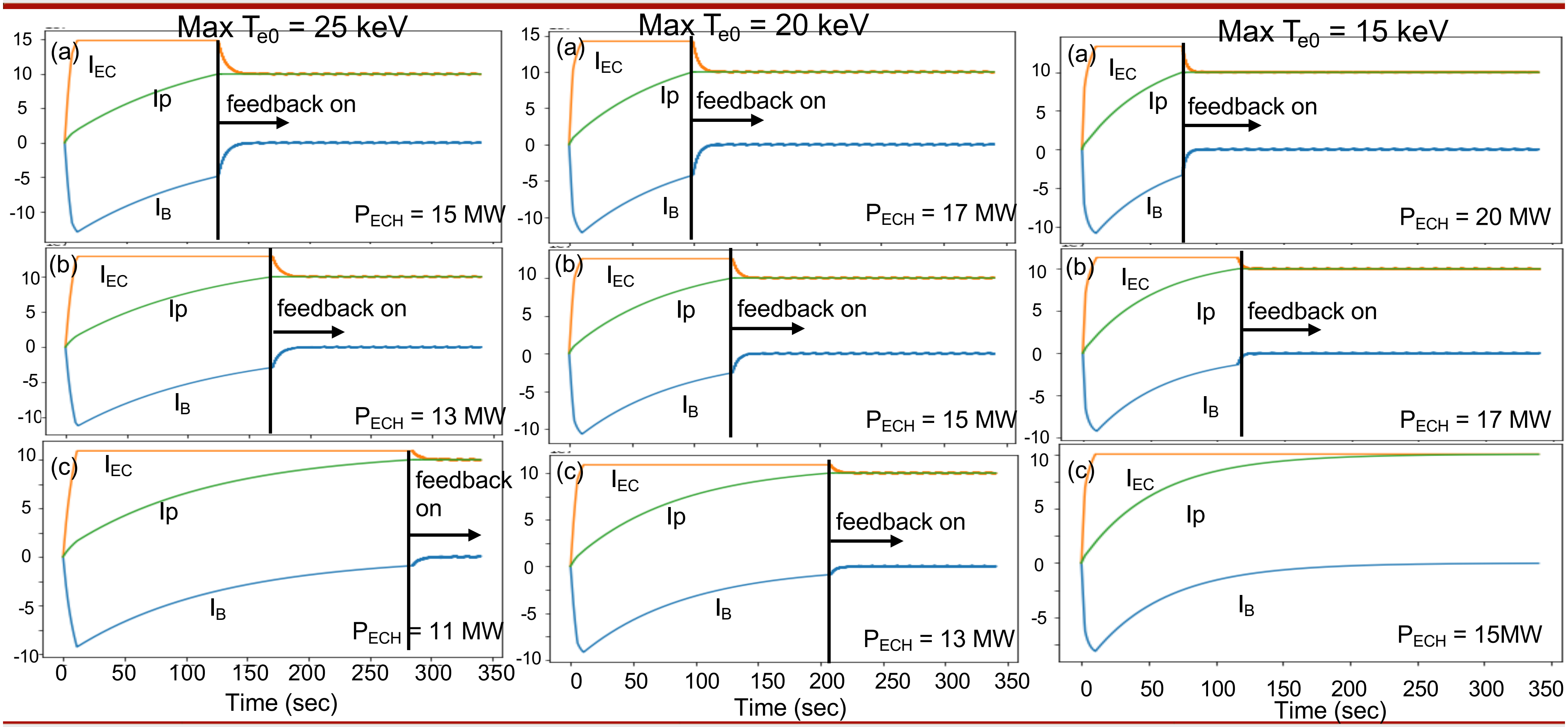
Current Ramp-up to 10 MA with T_{e0} clamped at 25 keV with feedback

SHPD: R_0 = 1.58 m, R/a ~ 2, B_{T0} = 5.5 T, n_{e0} = $10^{19}/m^3$



SHPD Current Ramp-up to 10 MA with various Max T_{e0} and P_{ECH}

Lower Max T_{e0} and higher P_{ECH} reduces the ramp-up time



Current ramp-up model is developed for SHPD using X-I

Non-inductive current ramp-up to 10 MA with 10 – 20 MW

- X-I 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 200 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 values due to uni-directional electrons accelerating to higher energy.
- For SHPD tokamak facility, X-I ECCD ramp-up to full current I_{ECCD} ~ 10 MA appears feasible with only P_{ECH} ~ 10 - 20 MW. After ramp-up, the X-I can be switched to O-I and/or EBW.
- Initial time dependent model of the X-I ECH/ECCD current ramp-up was presented.
- We introduced the clamped electron temperature model at T_{e0} = 15, 20, 25 keV. The ramp-up time is reduced at higher power and lower max T_{e0}. The temperature control such as impurity injection may be used if faster ramp-up is needed.
- X-I ECCD ramp-up can be tested in ST-40 and other devices with the fundamental resonance.

Backup Slides

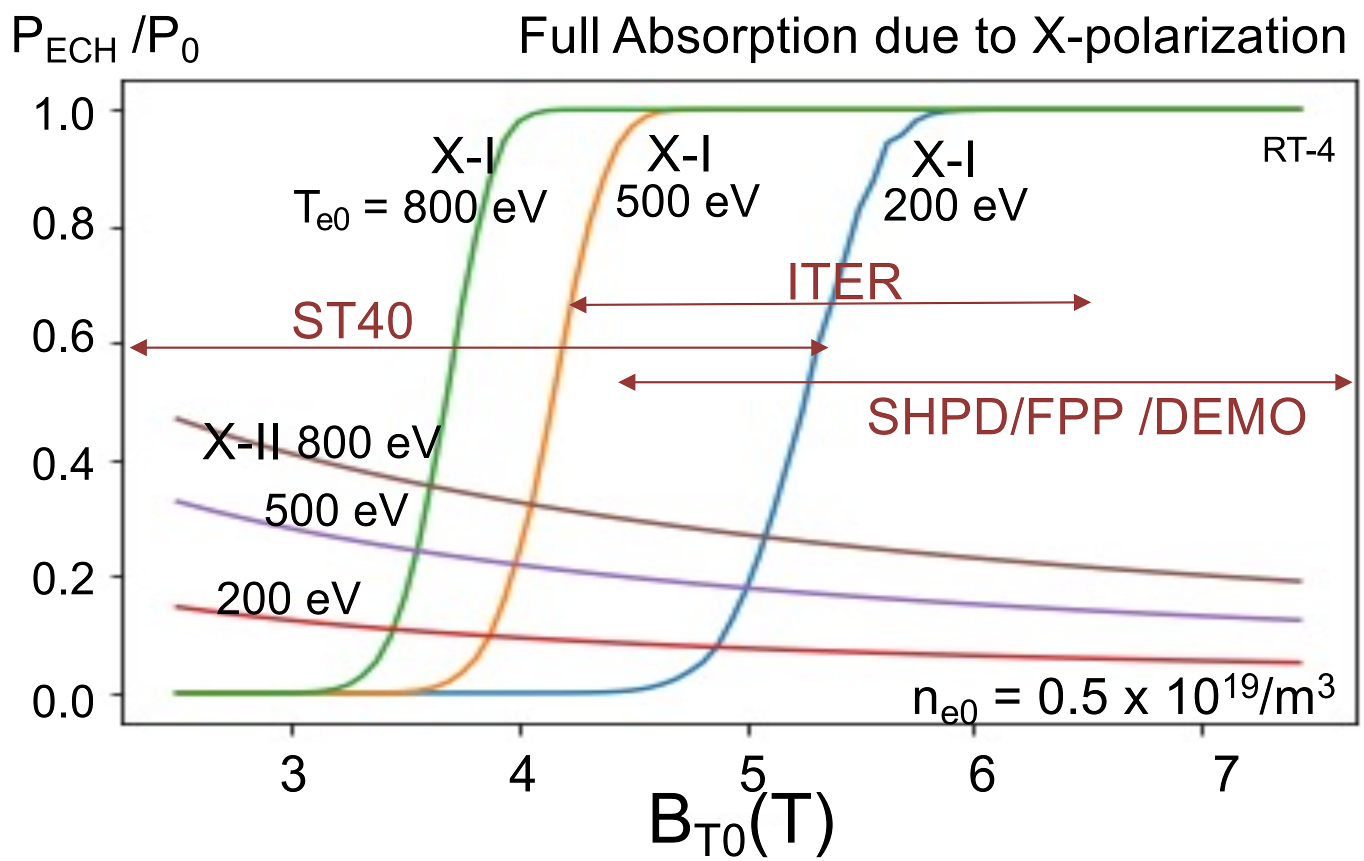
Time Dependent Model of X-I ECCD Non-inductive Current Ramp-up

- Time dependent model:

$$\boldsymbol{V_l = 0 = I_B R_B + \ L_B \frac{dI_B}{dt} + M_{EC} \ \frac{dI_{EC}}{dt}}$$

- $\boldsymbol{I_{EC}}$ is the current driven by ECCD.
- $\boldsymbol{I_B}$ is the induced negative current by back EMF .
- $\boldsymbol{M_{EC}}$ is the mutual inductance between ECCD current I_{EC} and induced plasma current $\boldsymbol{I_B}$.
- $\boldsymbol{R_B}$ is the plasma resistivity for the induced current, $R_B = 5\ x\ 10^{-7}\ ln\Lambda\ Z_B\ \left({}^{2R}/_{a^2}\right) T_e^{-3/2}$
- $\boldsymbol{L_B}$ is the plasma inductance of induced current, $L_B = \mu_0\ R\ (ln\ {}^{8R}/_a + {}^{l_E}/_2 - 2)$
- $\boldsymbol{V_l}$ is the loop voltage which is zero for the present non-inductive plasma ramp-up study

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



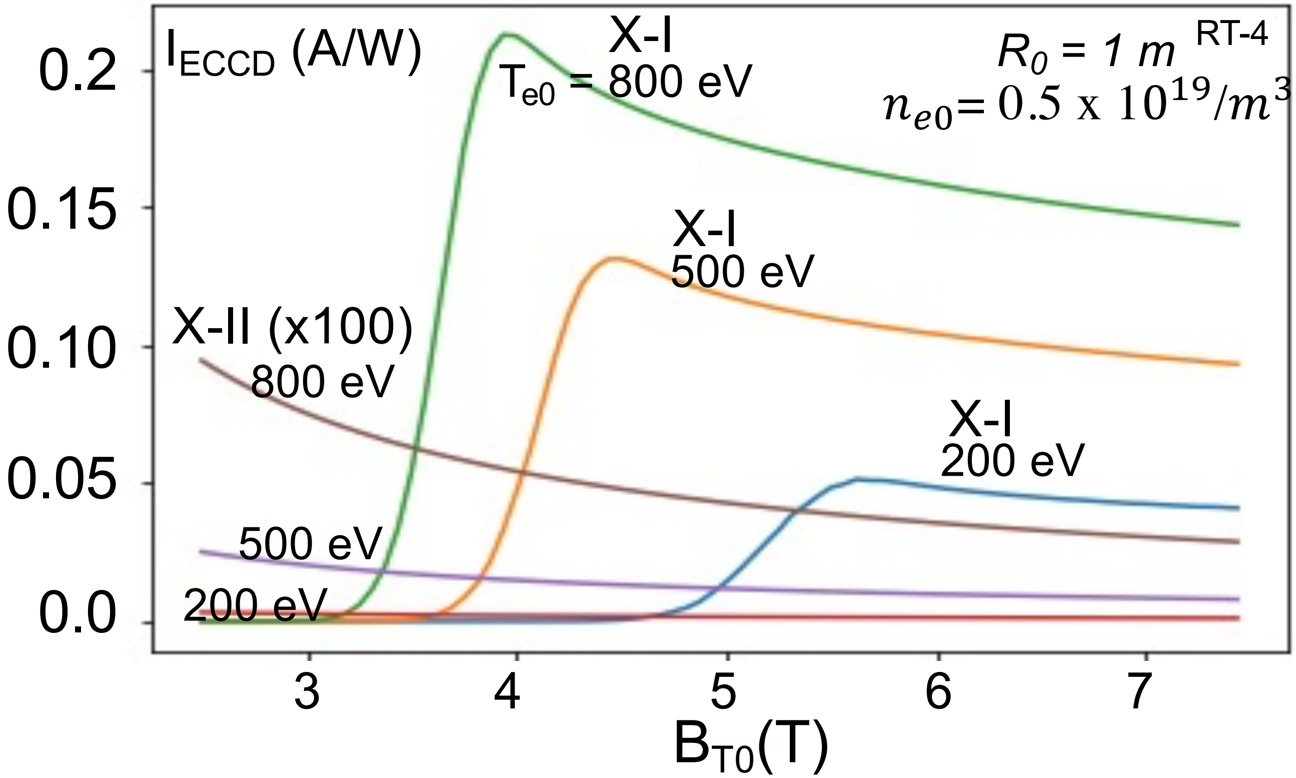
X-I : Ω_e X-mode
X-II : $2\Omega_e$ X-mode

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

RT-4

M. Ono et al.,Physical Review E 2022

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



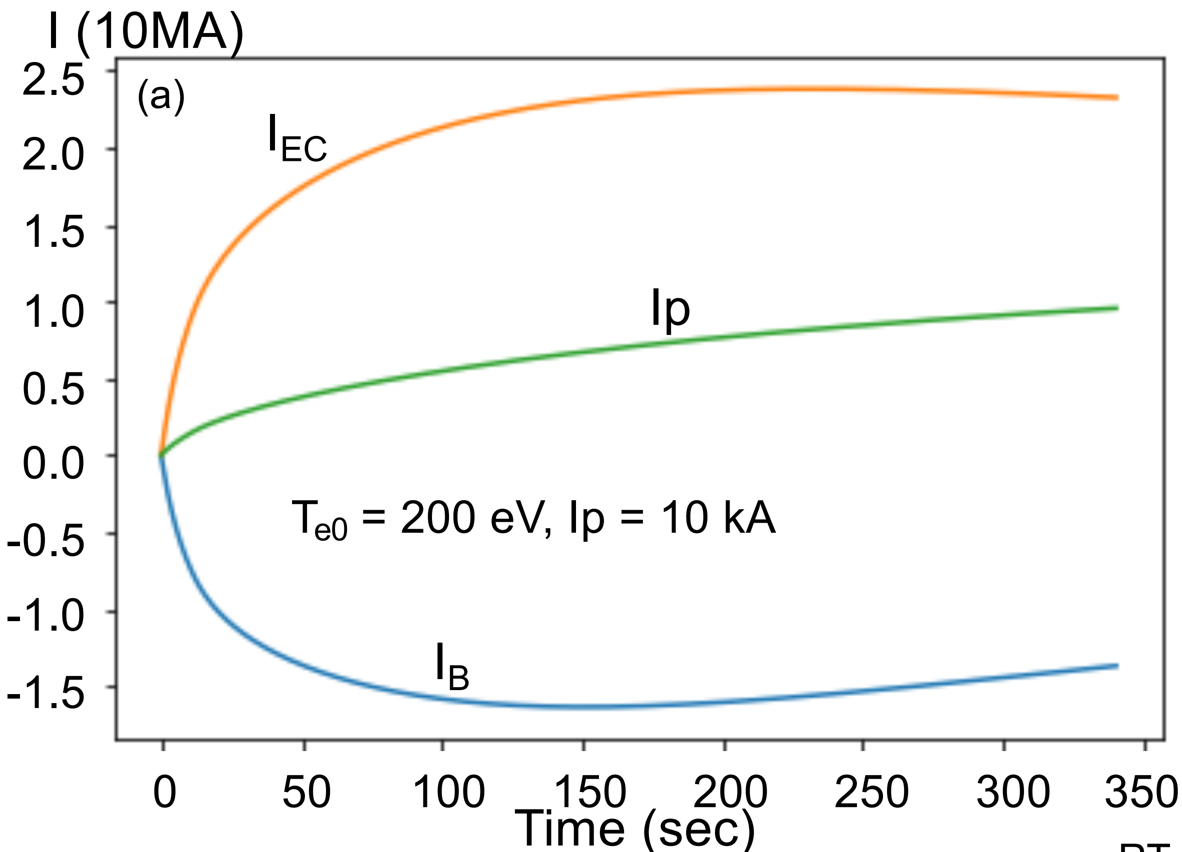
$f \sim \Omega_e$
4 T - 112 GHz
6 T - 168 GHz

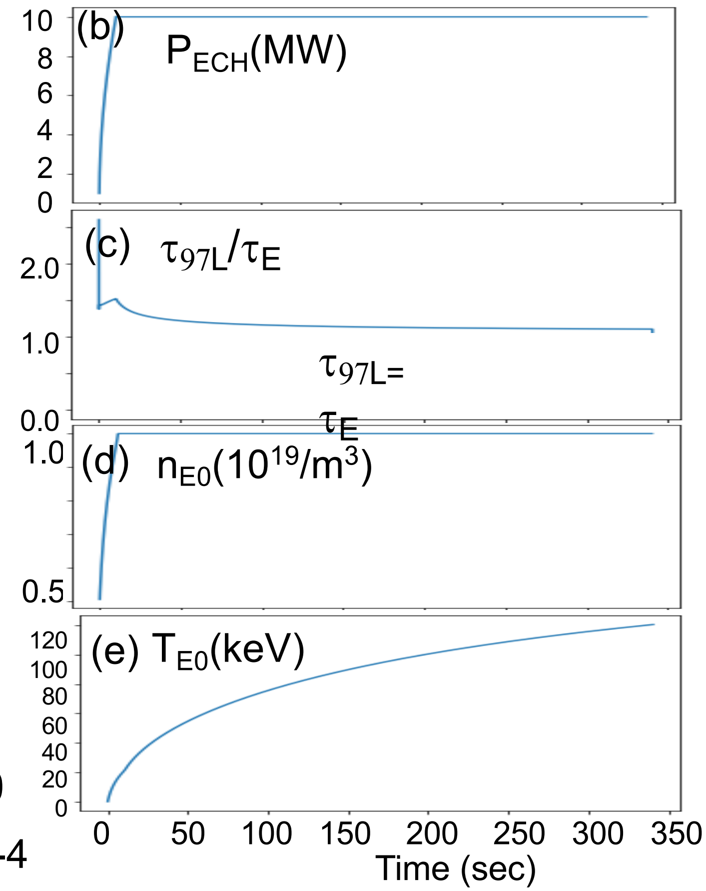
I-X ECCD generates uni-directional currents due to accessibility constraint

RT-4

Current Ramp-up to 10 MA with T_{e0} Unclamped

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





RT-4

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).

Tokamak Confinement Scalings

$$\tau_{97L} = 0.023\ I_p^{0.96} B_T^{0.03} \kappa^{0.64} R^{1.83} (\frac{R}{a})^{0.06} n_e^{0.40} M_{eff}^{0.2} P^{-0.73}$$

Table XVI. Comparison of L and H Mode $\tau_{E,th}$ scaling parameters

Parameter	L mode	ELM-free	ELMy H
Constant	0.023	0.036	0.034
I_p	0.96	1.06	0.90
B_T	0.03	0.32	0.05
κ	0.64	0.66	0.80
R	1.83	1.79	2.10
R/a	0.06	0.11	−0.20
M_{eff}	0.20	0.41	0.40
$\bar{n}_e$	0.40	0.17	0.30
P	−0.73	−0.67	−0.65

S. Kaye et al., NF(1997)

Plasma Evolution Assumptions

Prescribed:

- $n_{e0}(t)$ plasma density and profile
- $T_{e0}(t)$ computed but profile prescribed
- Plasma position and size evolution for *R(t)*, *a(t)*, and elongation *κ(t).*
- Z_B = 4 is the effective plasma resistivity

$$T_e(r) = (T_{e0} - T_{ee})\left(1 - (r/a)^2\right)^3 + T_{ee}$$

$$n_e(r) = (n_{e0} - n_{ee})\left(1 - (r/a)^2\right) + T_{ee}$$