U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Modeling of 2nd Harmonic ECH & ECCD Solenoid-free Start-up Experiment in QUEST

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In collaboration with

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RIAM, Kyushu University

NSTX-U / Magnetic Fusion Science Meeting

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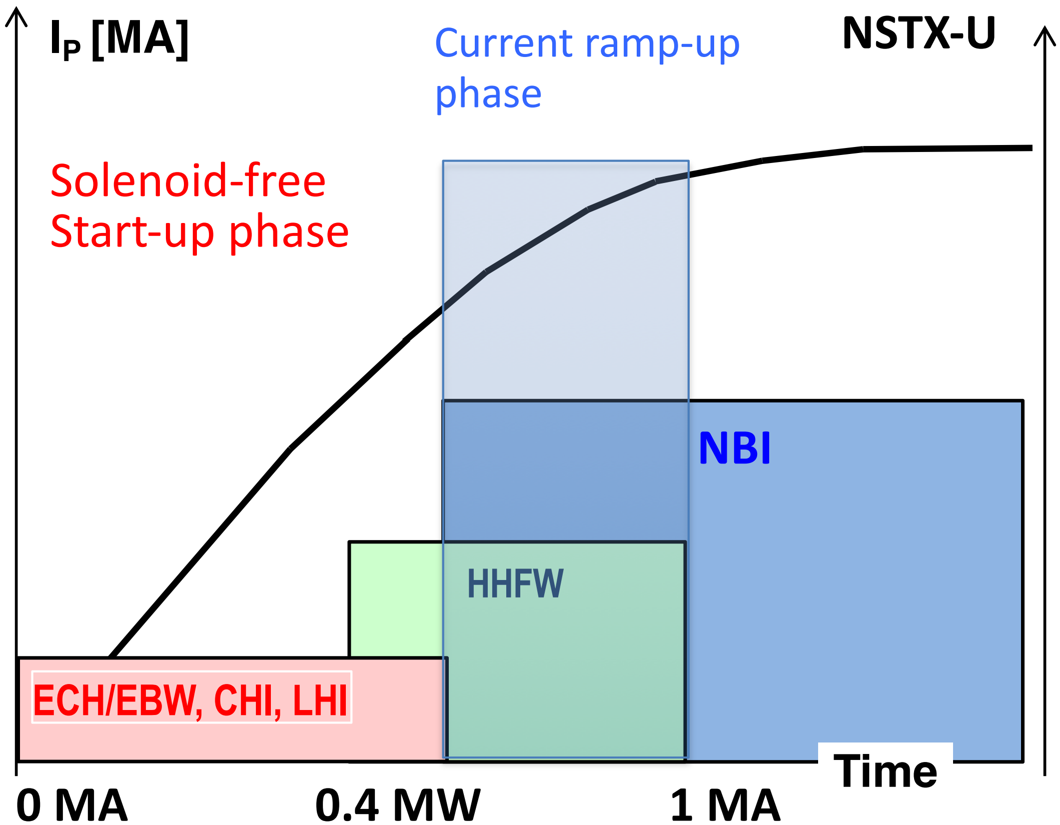
PPPL

Talk Outline

- Introduction and Motivation
- Benchmarking of ECH ray-tracing codes
- High efficiency ECCD for minority hot electron population.
- Pressure-driven currents for closed flux surface formation
- Role of neutral particles for initial breakdown
- Conclusion

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

- ST has been addressing critical issue of solenoid-free start-up
  - A compact ST has little space for a central solenoid
  - Solenoid-free start-up is also attractive for ST/ tokamak reactor designs
- Maximizing solenoid-free start-up currents reduces reliance on less developed non inductive current ramp-up scenarios
- Non-inductive start-up could help achieve current profile compatible with advanced ST/tokamak operations
- Few MA start-up current is projected for reactors
  - Higher currents may be feasible



ECH / EBW – Utilize 1 – 2 MW, 28 GHZ gyrotron

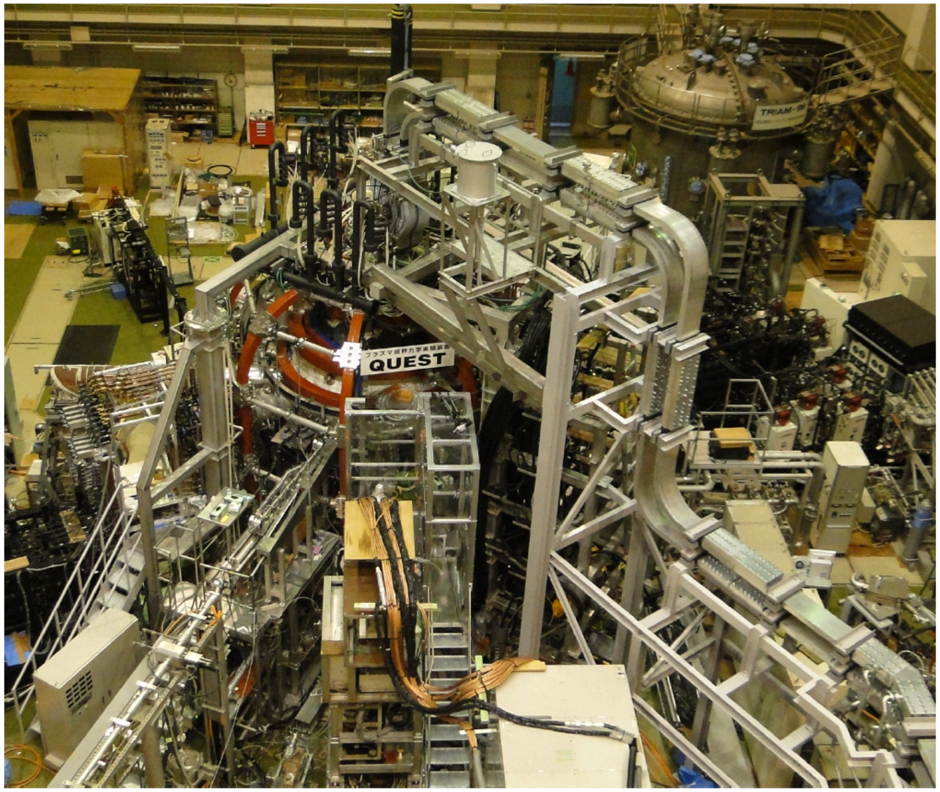
CHI, LHI – Coaxial Helicity Injection and local helicity injection up to ~ 400 kA

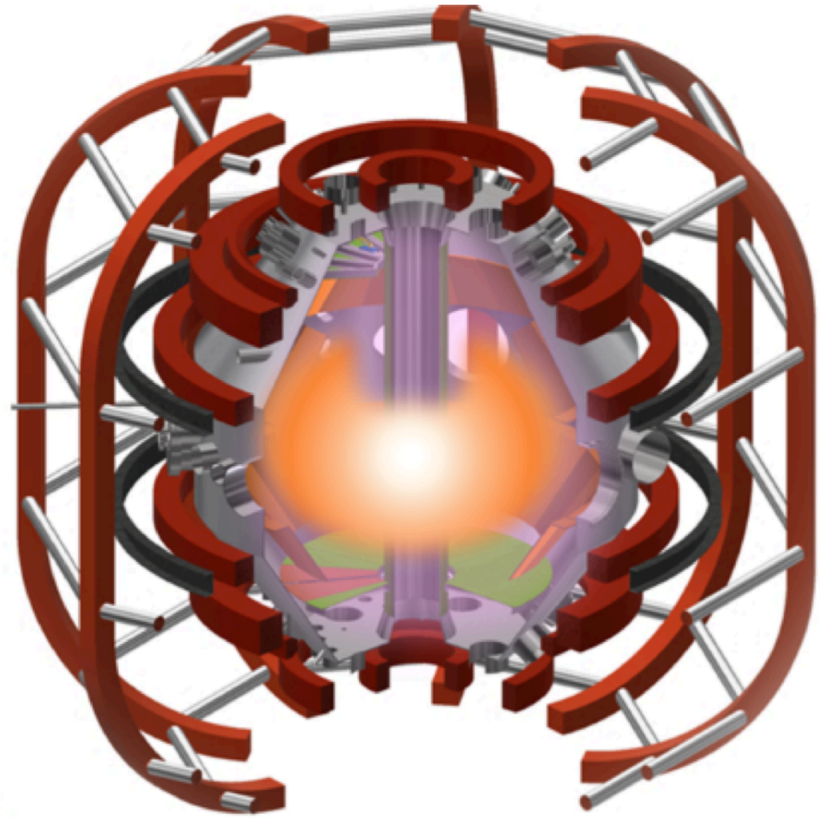
HHFW ~ 4-6 MW 30 MHZ High Harmonic Fast Wave

NBI ~ 10 MW NBI

QUEST - Spherical Tokamak - Largest ST in Japan

Developing solenoid-free start-up concepts including CHI and ECH/EBW





QUEST
R ~ 0.68 m : *a* ~ 0.4 m
B~ *0.25 T* Steady-state!
All metal and hot wall

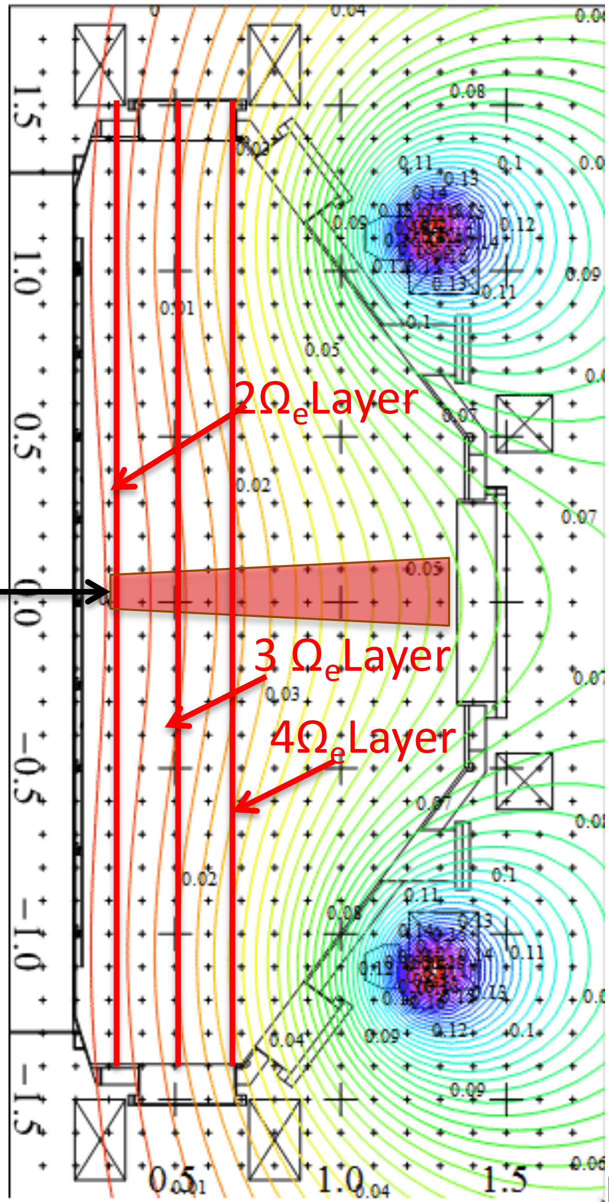
There are no large spaces in the center stack due to spherical tokamak geometry.

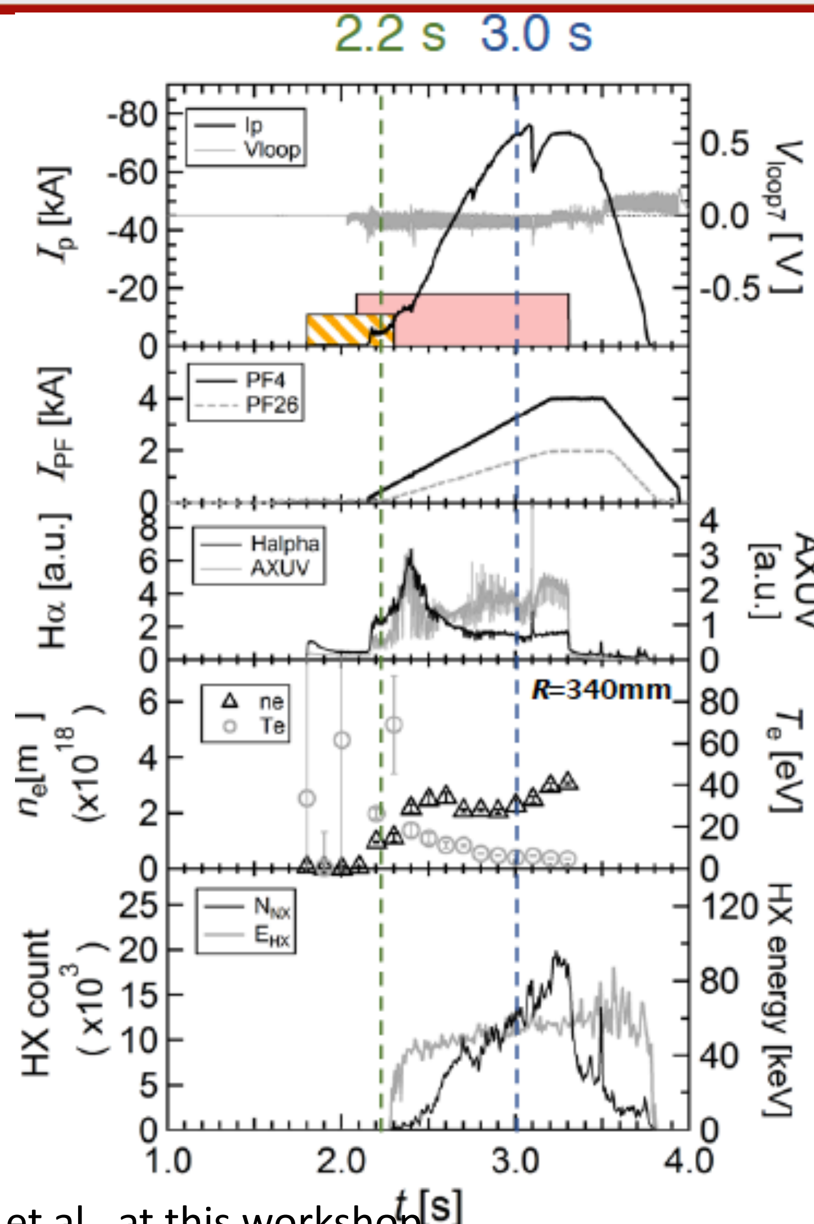
Q-SHU UNIVERSITY EXPERIMENT WITH STEADY-STATE SPHERICAL TOKAMAK

Advanced Fusion Research Center

QUEST ECH provide unique opportunity to understand and optimize ECH based tokamak/ST start-up/ramp-up concept

Strong ECH focusing





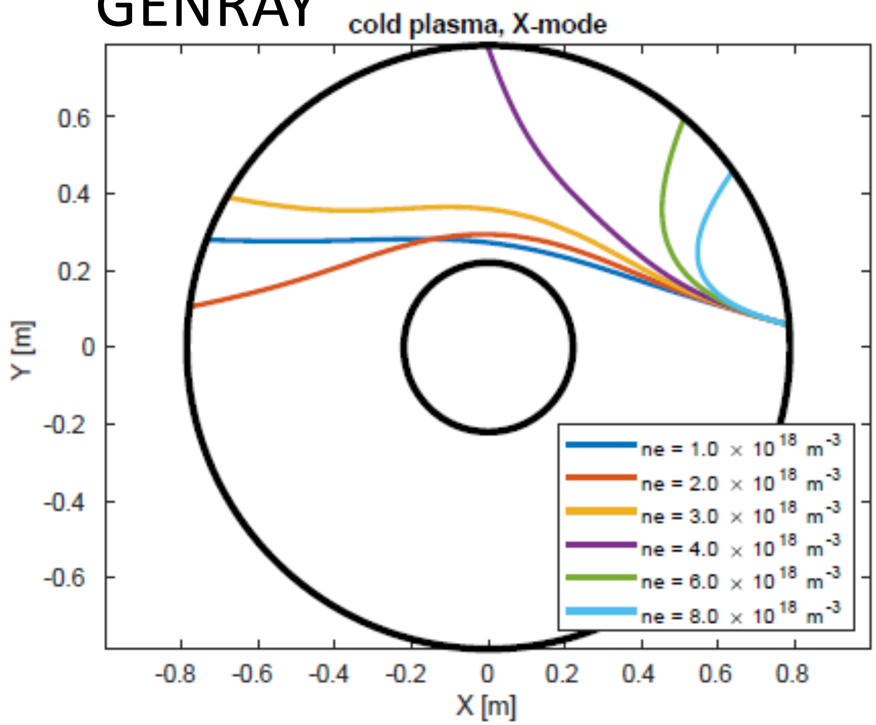
H. Idei, et al., at this workshop

Relatively good agreement obtained for GENRAY and RT4

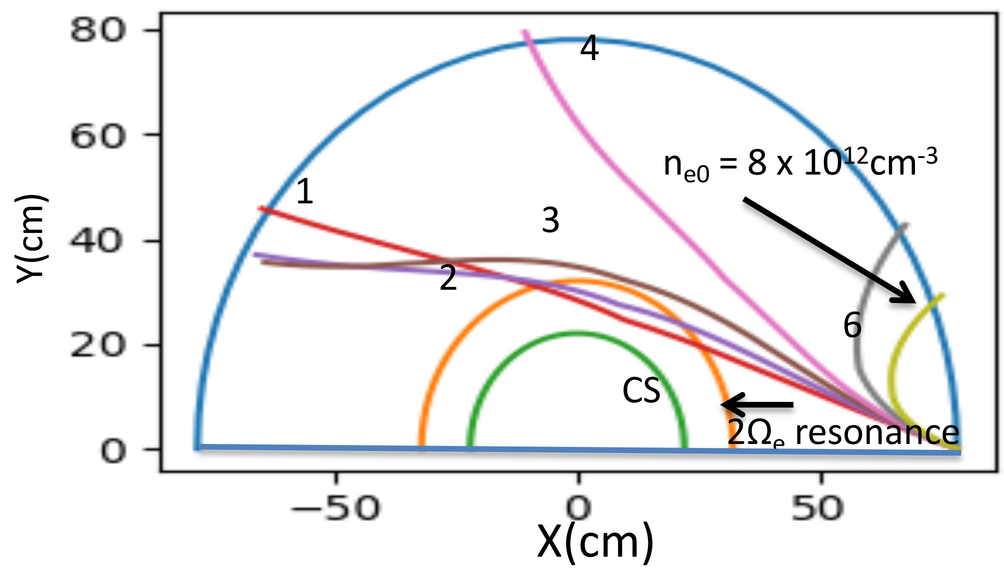
X-mode: $n_e = n_{eo}\,(1 - \rho^2)$,

$n_{||} = 0.32$ at R = 78cm

GENRAY



RT4

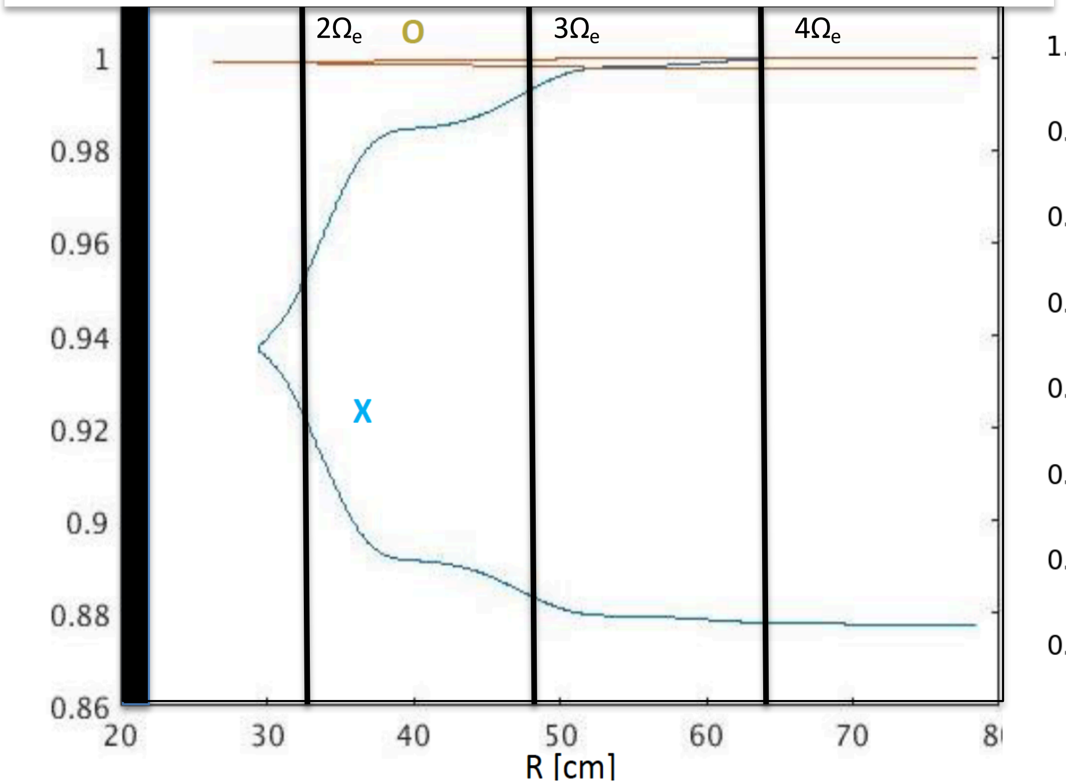


GENRAY and RT4 Harmonic Absorptions Show Good Agreement in QUEST Parameters

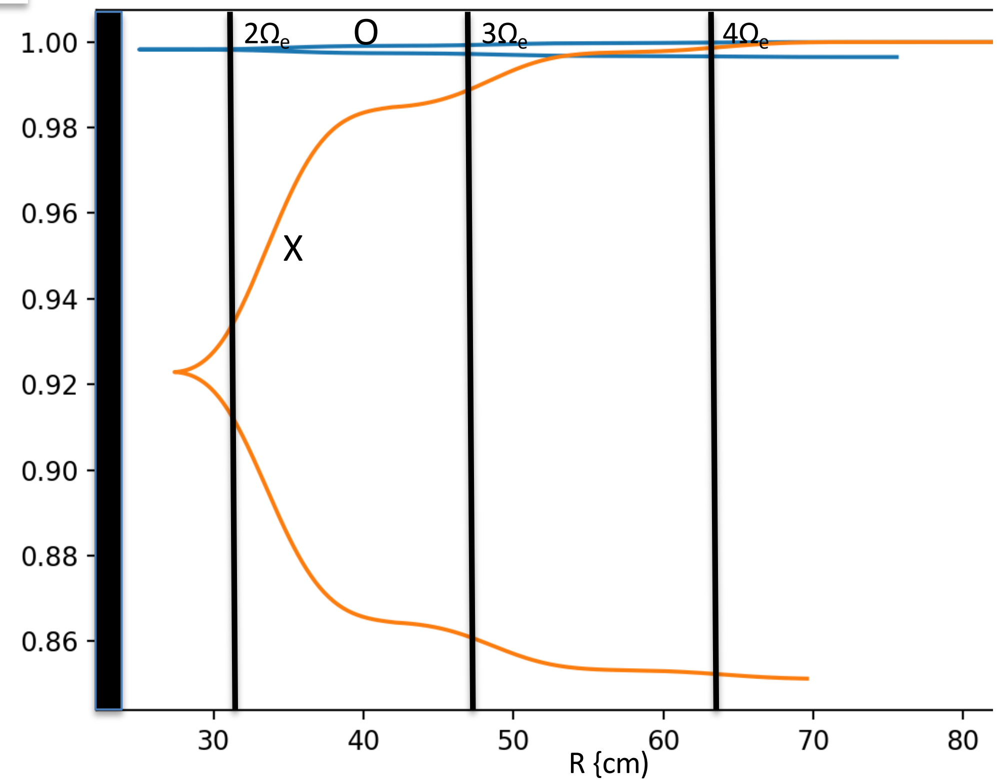
O-X-mode: $n_{||} = 0.3$ at $R = 82$cm $n_{e0} = 2 \times 10^{12}$cm^{-3} $T_{eh0} = 10$ keV

$N_{eh0} = 0.03\ n_{e0}$, $n_e = n_{eo}\,(1 - \rho^2)$, $T_e = T_{eo}\,(1 - \rho^8)$

GENRAY

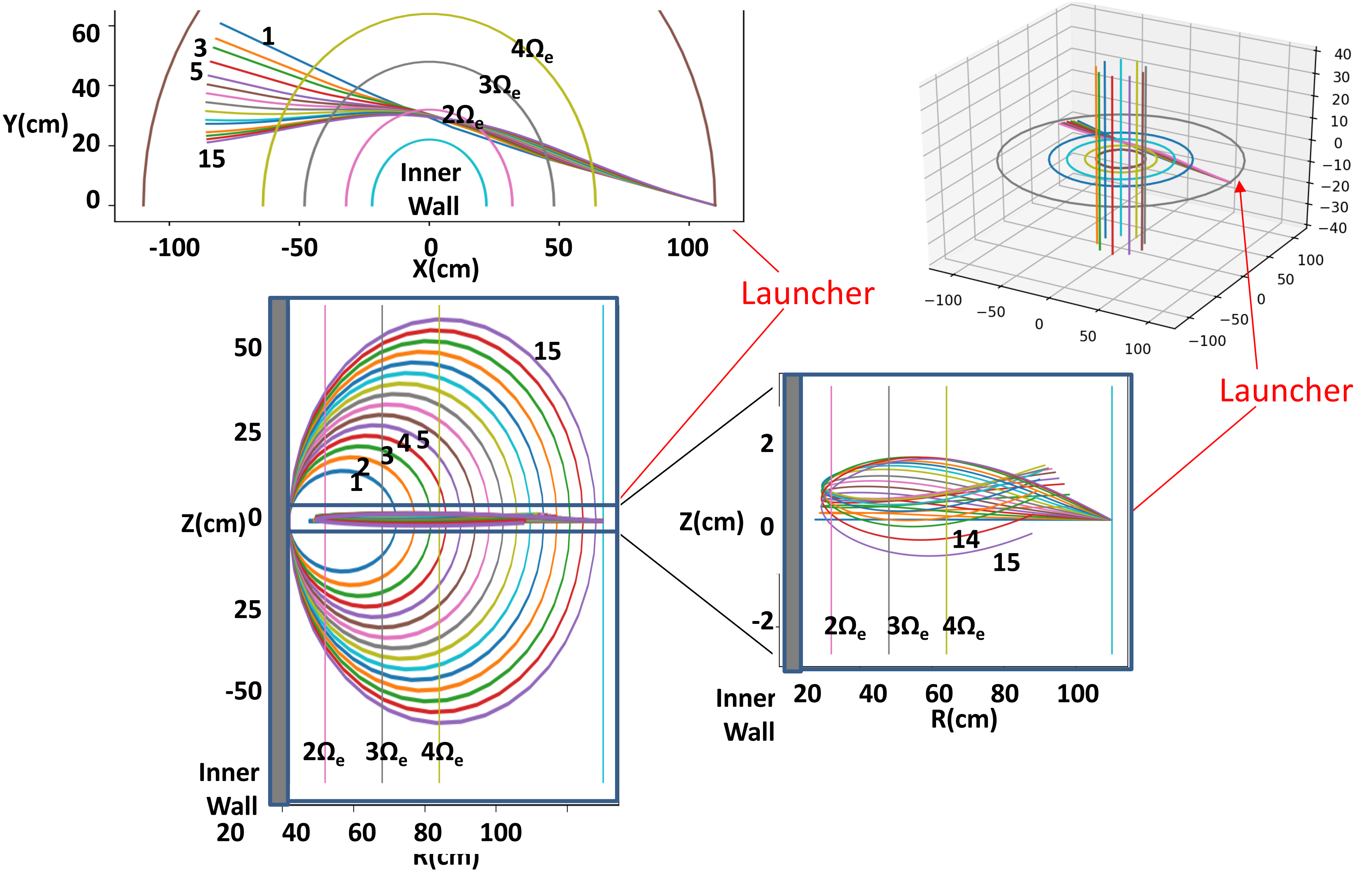


RT4

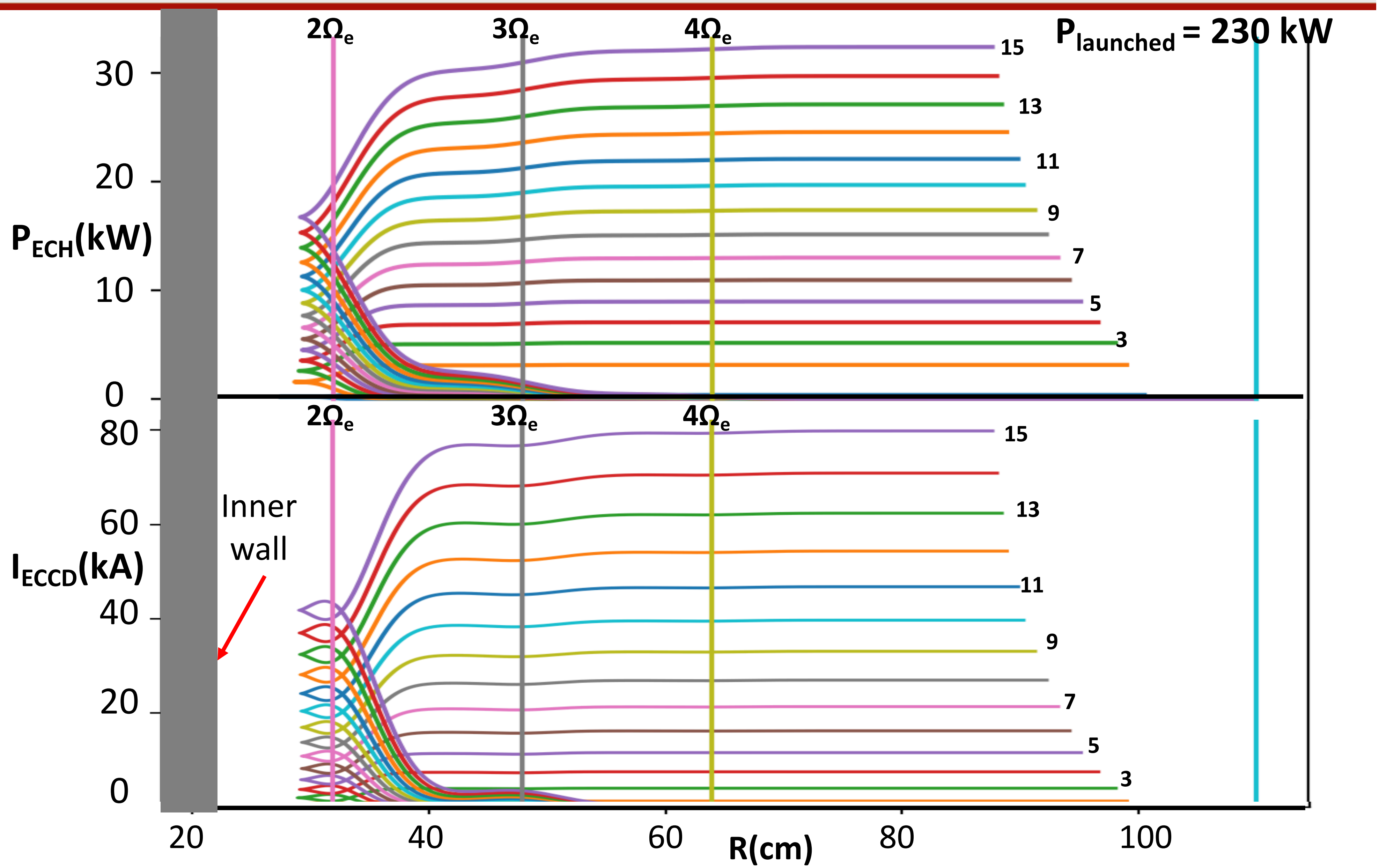


Note: Significant 3rd harmonic absorption observed.

ECCD Ray-Tracing During Current Ramp-up

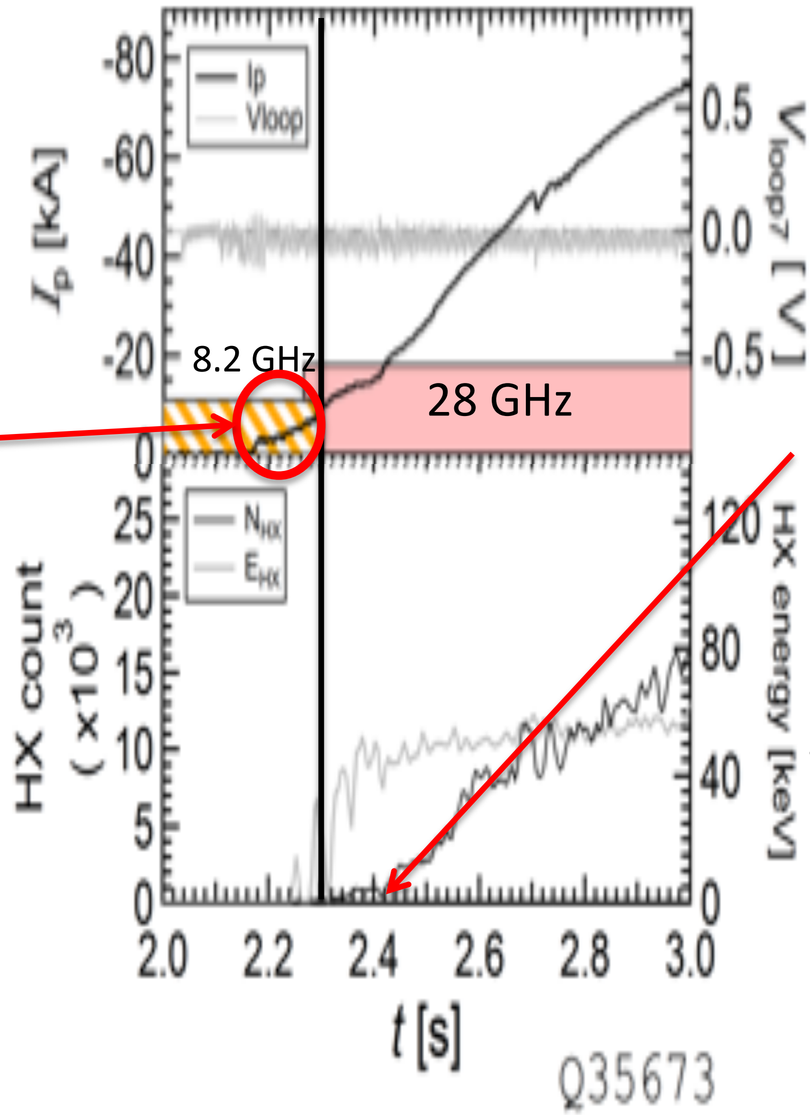


Single-Pass ECH / ECCD Profile Evolution Consistent with 90 +kA current generation



Early Phase is Consistent With Pressure Driven Current ECCD Phase Starting Only After I_p ~ 5 - 10 kA

- No X-ray
- No ECCD
- Pressure Driven Current



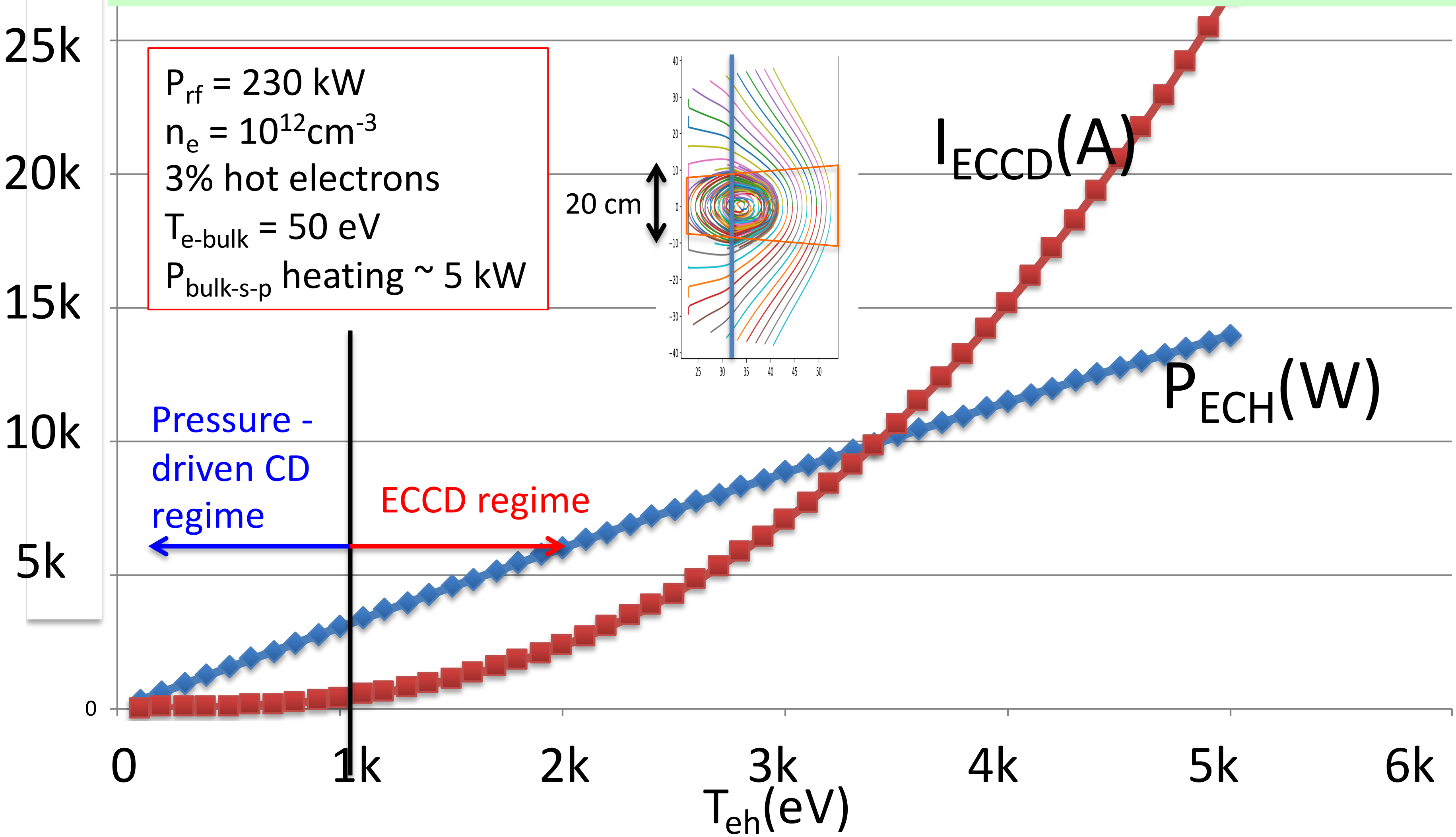
- Increasing X-ray – energetic electrons
- $I_p \propto I_{X\text{-}ray} \propto n_{eh}$
- Minority energetic particle population
- ECCD

- How does the field line closure occurs with 2nd Harmonic ECH as $P_{ECH} \propto T_{e0}$?

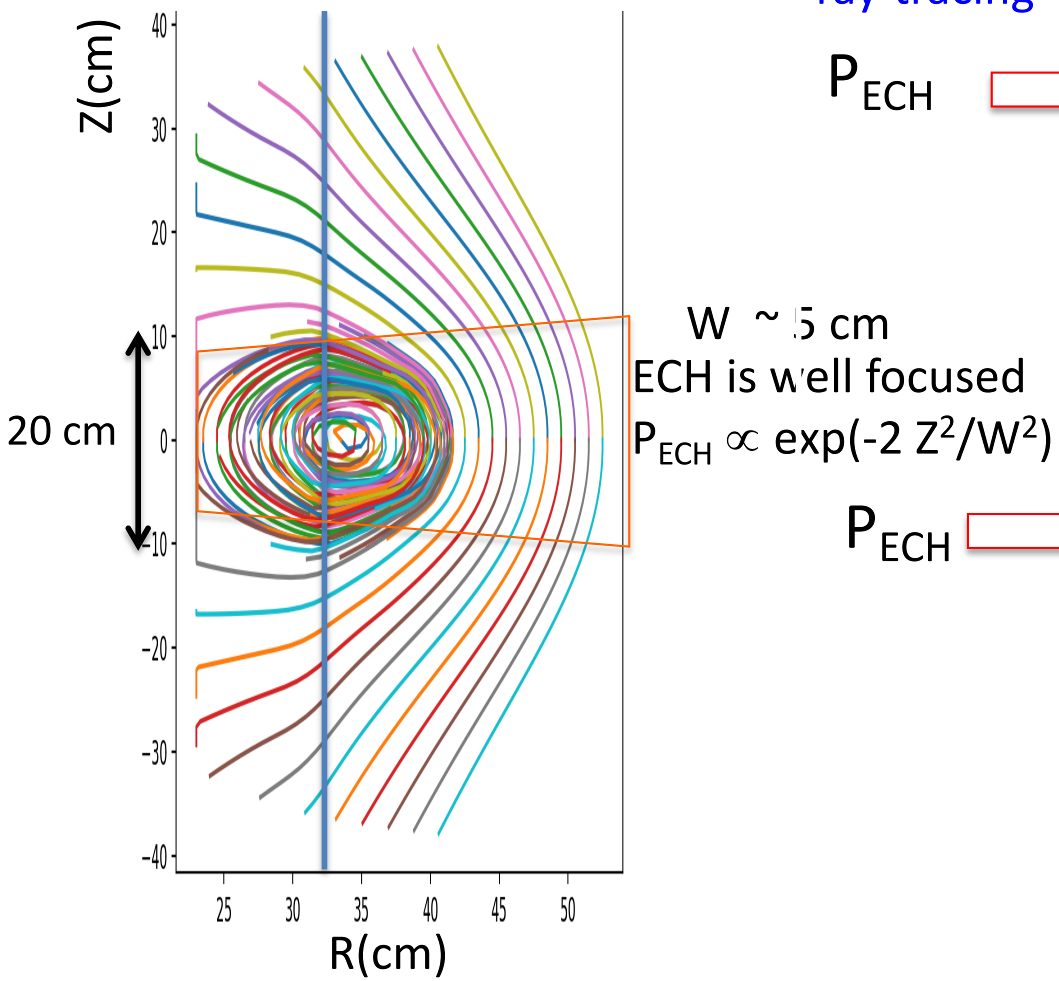
- How does the plasma transition from pressure driven to ECCD phase? Pressure driven current can generated with ~ 50 eV plasma but ECCD will require ~ keV plasma.

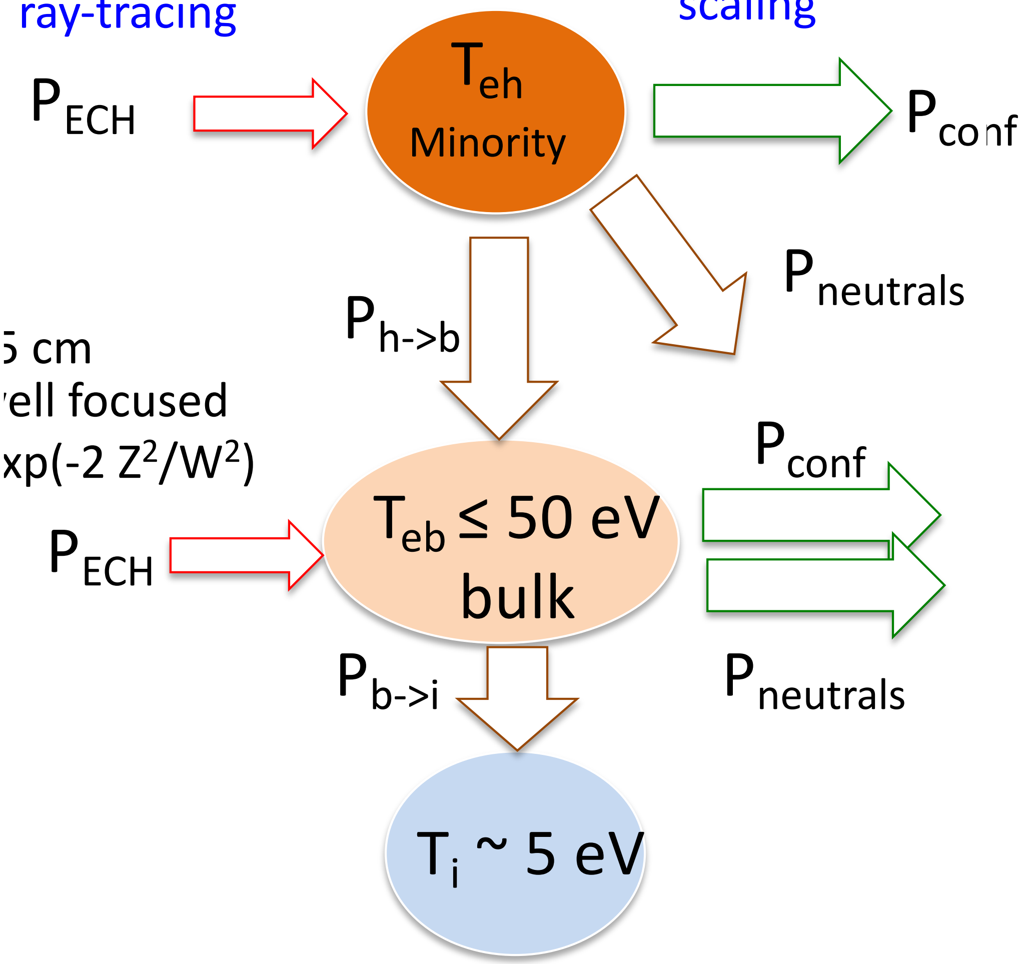
Single Pass 2nd Harmonic ECCD and ECH Calculated Using Ray-Tracing Code (RT-4)

For ECCD, T_{eh} must be heated to > 1keV with 2nd harmonic ECH.
Question: Can T_{eh} be heated to > 1keV from ~ 50 eV with ECH?

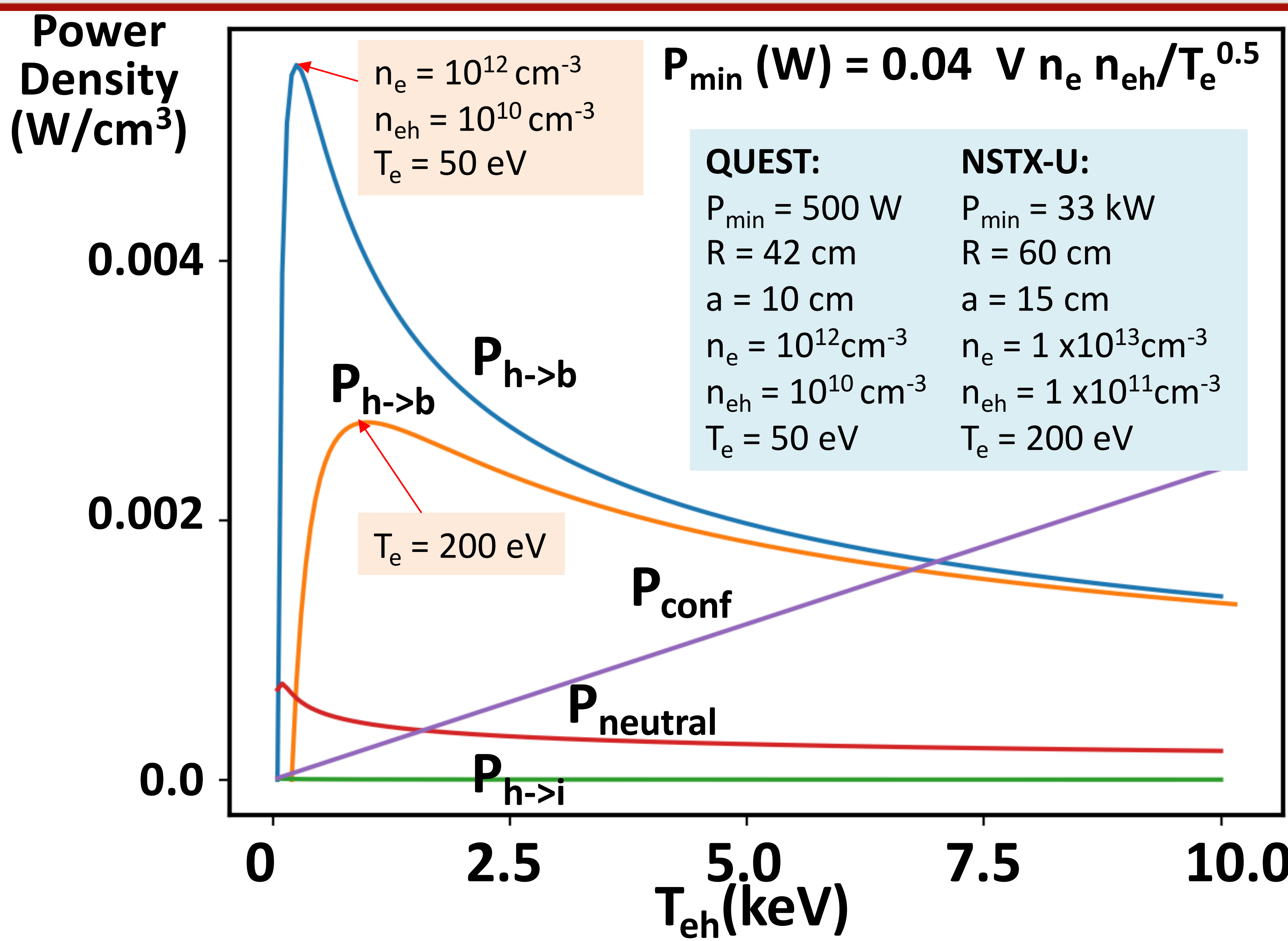


ECH heats T_{eh} which heats T_{eb} through collisions T_{eb} cools via collisions with cold ions and neutrals





Minority Hot Electron Efficient Way to Achieve High T_{eh}!
Minimum Power is needed to form hot T_e population



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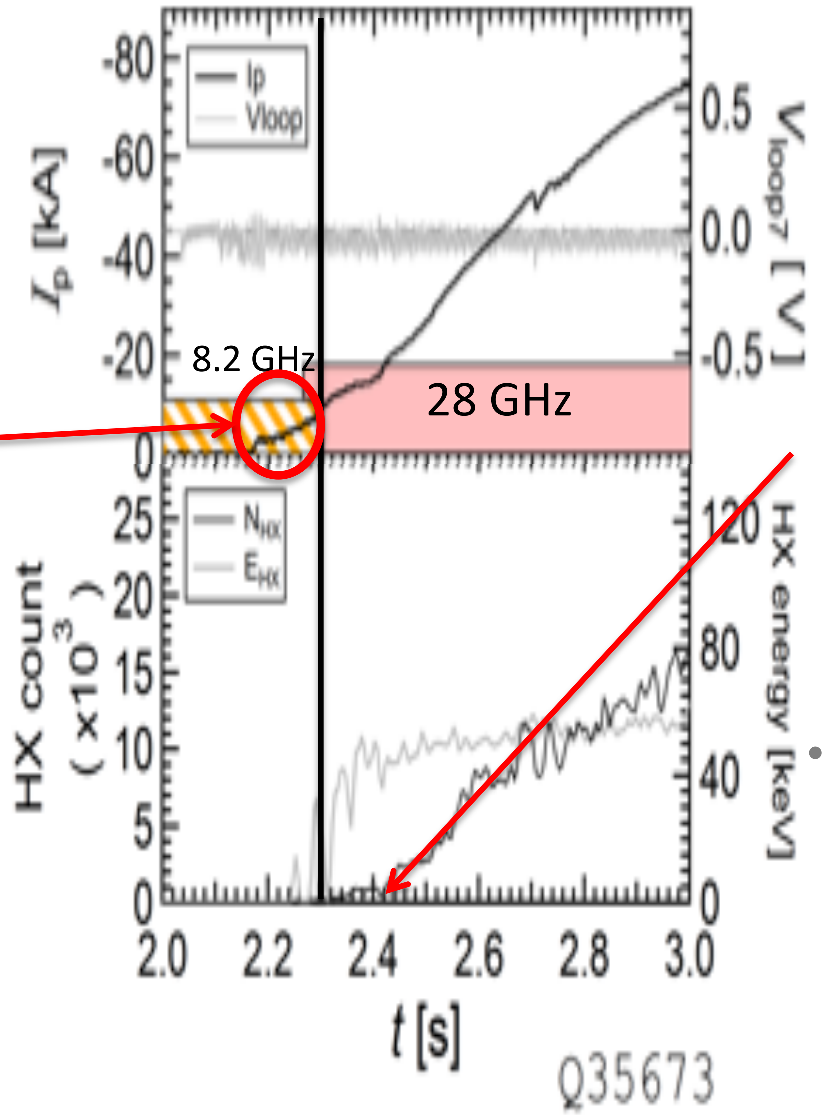

- Increasing X-ray – energetic electrons
- $I_p \propto I_{X\text{-ray}} \propto n_{eh}$
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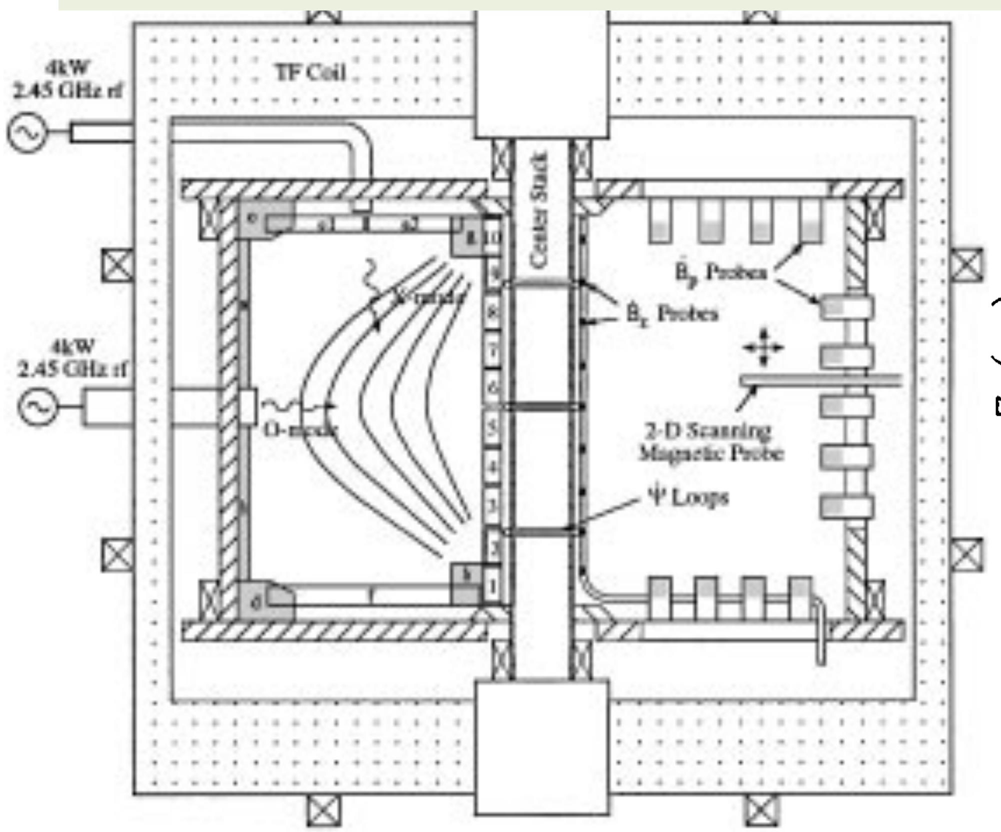
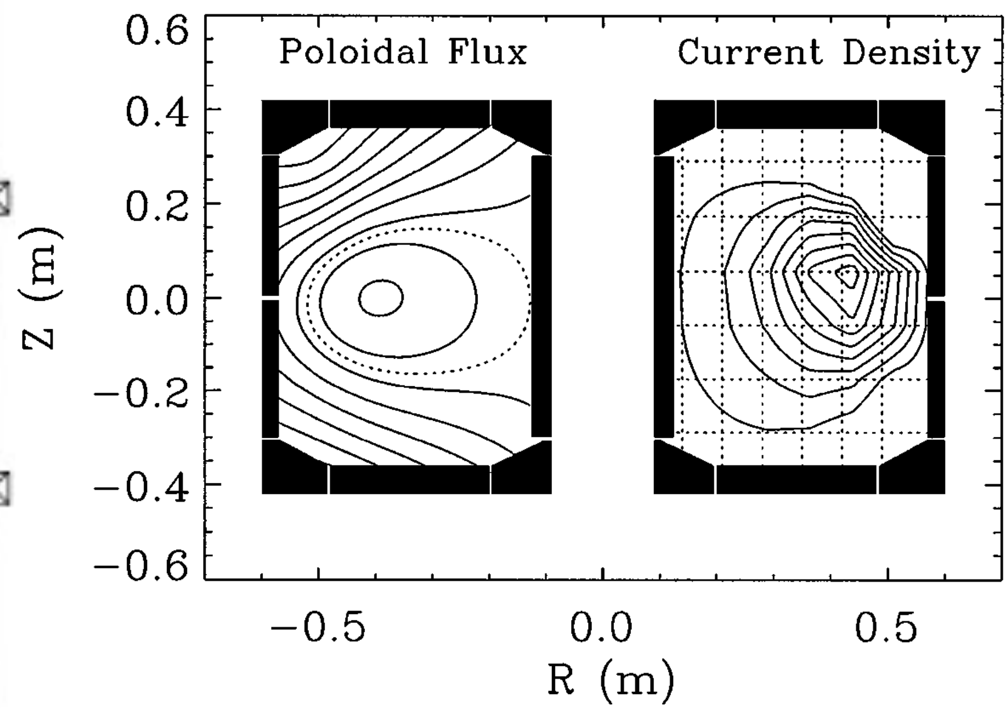
Early ECH tokamak start-up experiments performed on CDX-U (now LTX-β!)

Trapped particle and bootstrap current played important role in formation of robust closed flux ST/tokamak configuration!

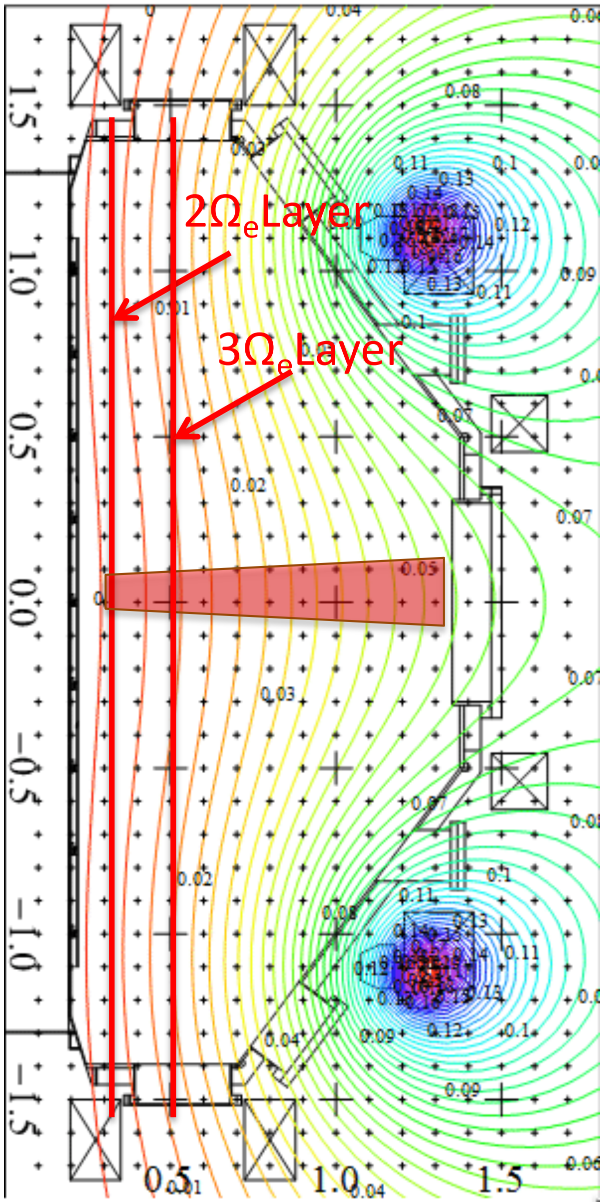
With limited ECH power, lowering of neutral pressure was critical!



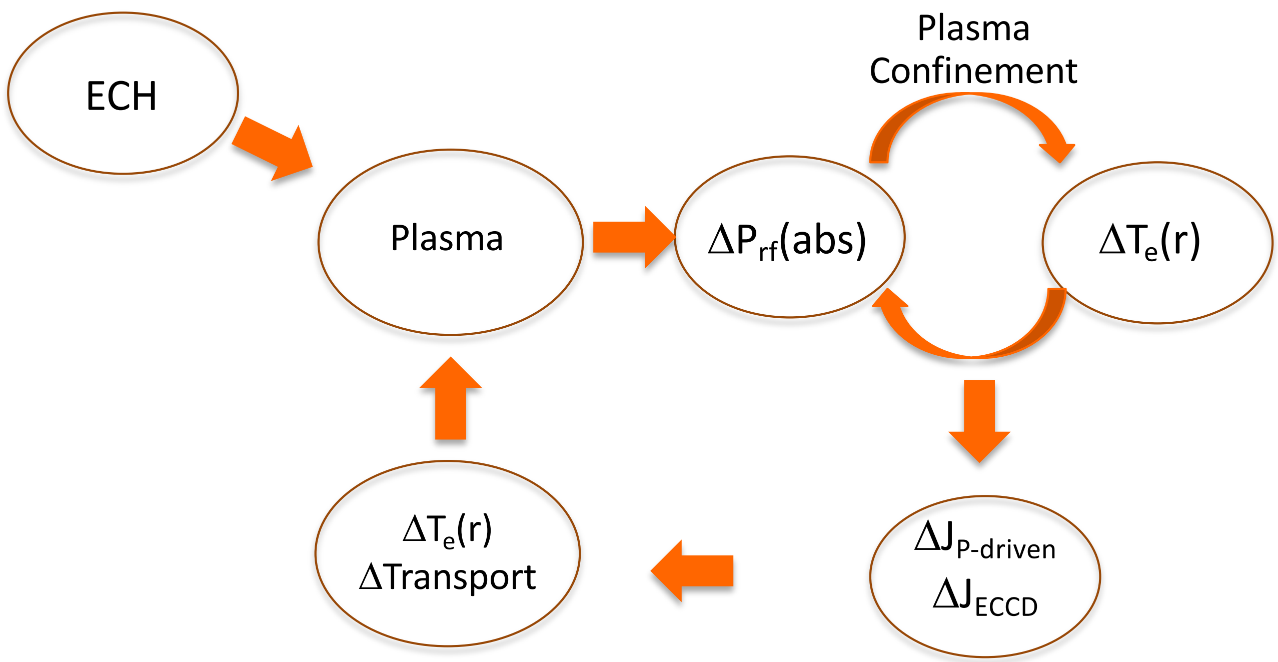


*C.B. Forest, et al., PoP 1994, Y.S. Hwang, et al., *PRL 1996*

A Grid-based Tokamak Start-up Modeling being Developed Tracking from open to closed field line configurations

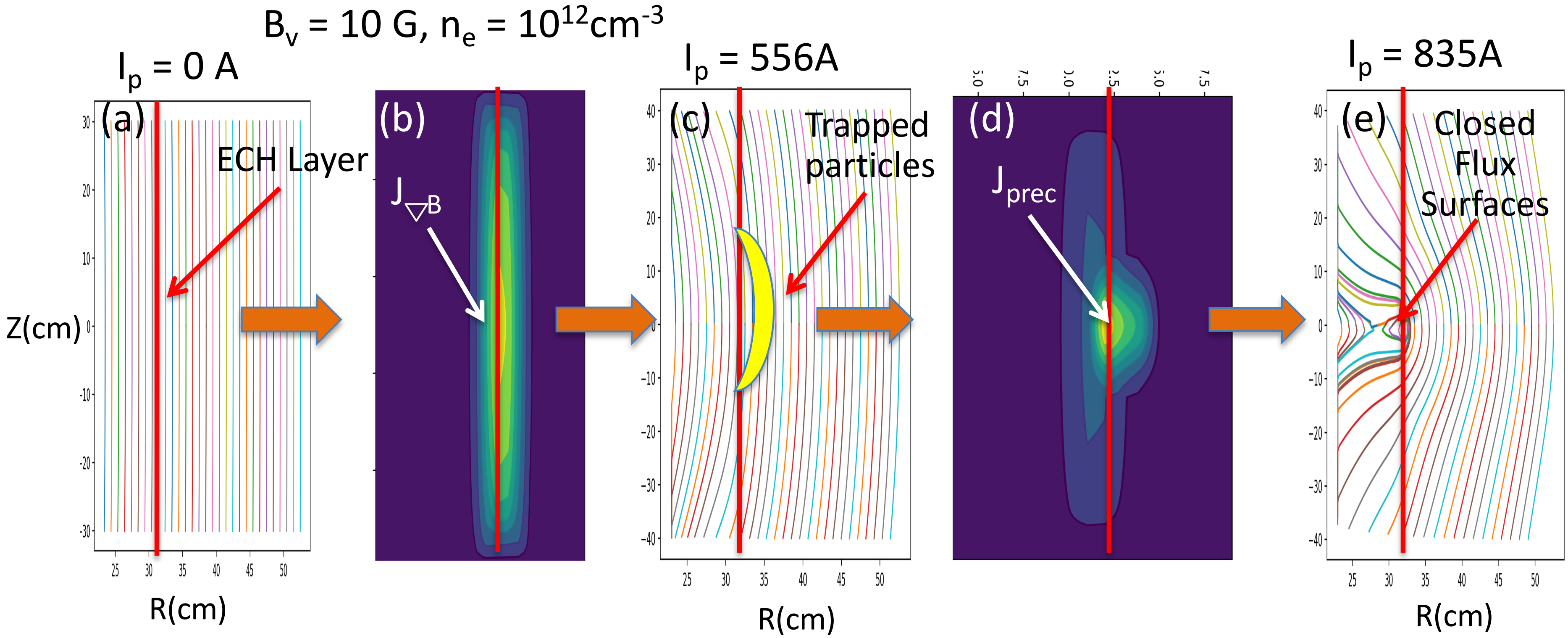


Plasma and current 2-D grids are evolved in steps from open to closed field line configuration starting with pure vertical field. Electron energy parallel transport was used for open field line and L-mode scaling was used for closed flux volume.
ECH/ECCD is well suited for modeling due to the well defince heating and CD region.



Precessional Driven Currents Can Create Closed Flux

Trapped particles are robustly confined in open and closed fields



- Trapped particles precessional toroidal drifts generate toroidal current ~ $P_e / RB_{v\text{-midplane}}$
- Electron heating of trapped particles is quite efficient - power loss actually decreases with T_e
- Mid-plane J-precession location is effective in creating small closed flux surfaces.
- J-precession continues to exist even within the closed flux surfaces.

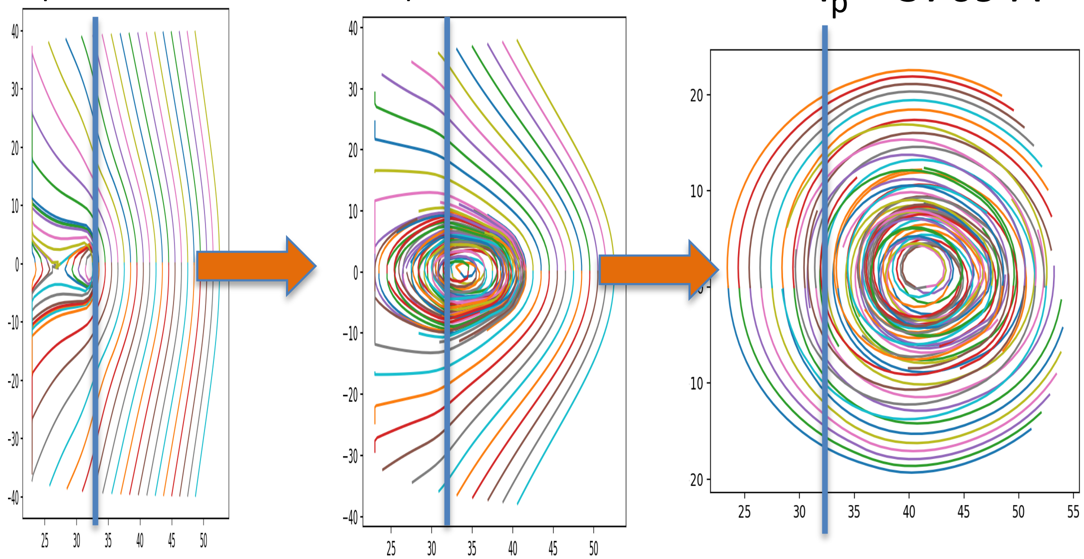
*C.B. Forest, et al., PoP 1994

Bootstrap Currents Can Enhance Closed Flux Surfaces

Bootstrap current can rapidly increase the plasma current

P_{ECH} = 100 kW
B_v = 10 G
n_e = 10^{12}cm^{-3}

I_p = 835A I_p = 1706 A I_p = 3769 A

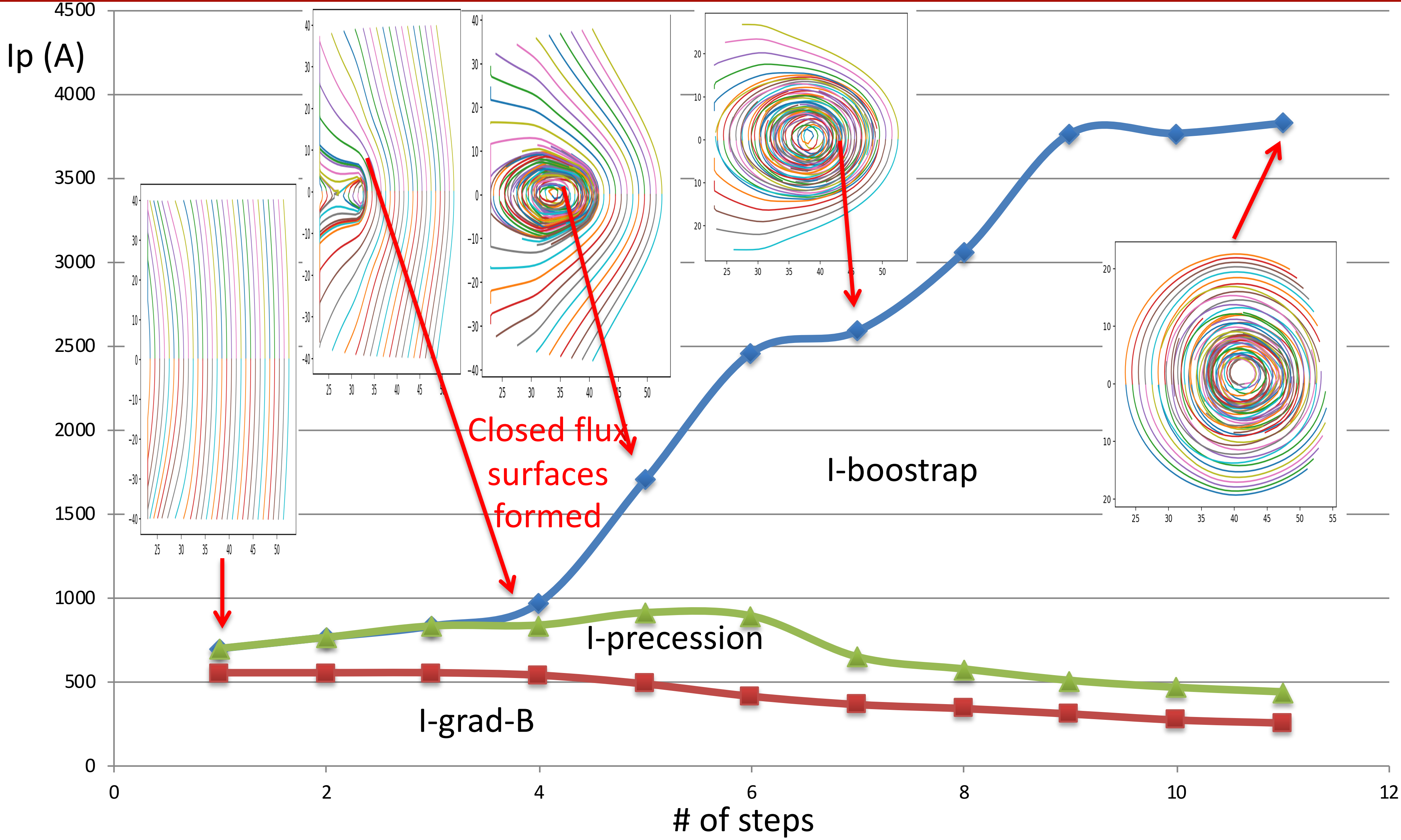


P_{ECH} = 3.35 kW P_{ECH} = 30 kW P_{ECH} = 61 kW

- With closed flux surfaces, bootstrap currents (J_{bt}) are generated. *
- J_{bt} was investigated in CDX-U and DIII-D, and J_{bt} scaling using ITER 89P confinement scaling was developed and being used here. *
- J_{bt} increases I_p and confinement, and expanded closed flux region generates more J_{bt}.
- J_{bt} eventually reaches saturation since the increasing J_{bt} reduces poloidal beta.

*Y.S. Hwang, et al., *PRL 1996*, C.B. Forest, et al., *PoP 1994*

Formation of Flux Surface Formation Possible With Only Pressure-Driven Currents Without ECCH

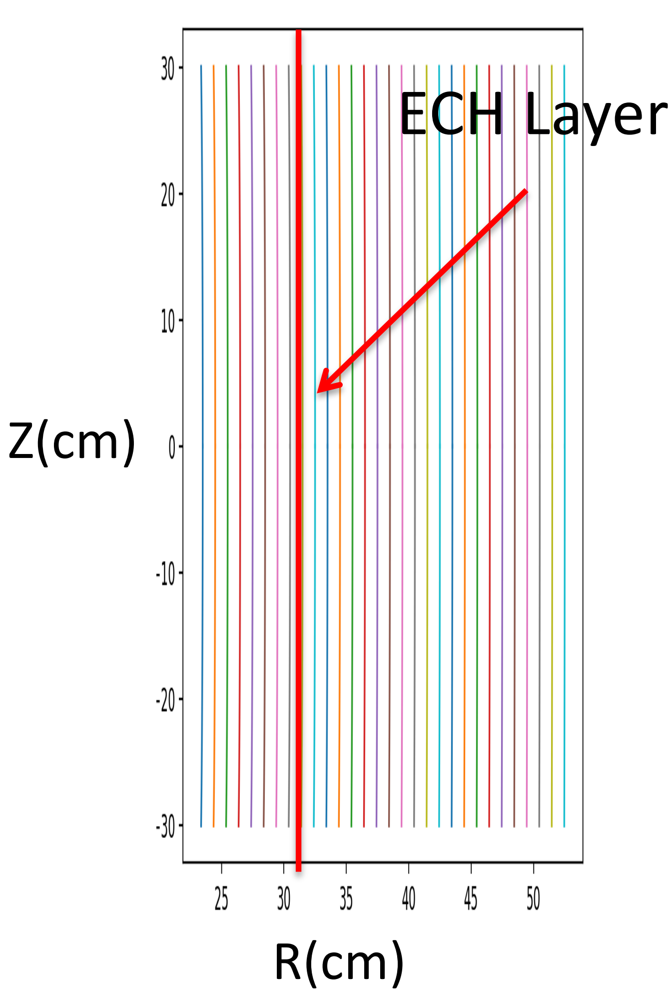


Initial ECH break-down phase

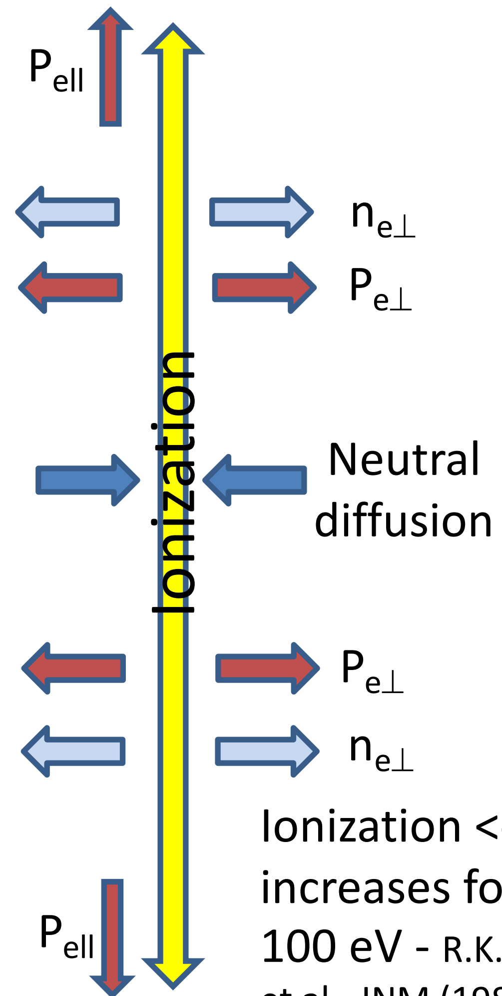
Neutral Particle / Ionization Dominates Power Balance

One ionization consumes E ~ 13 eV and produces one cold "e" and "i" reduces one "n"

Ionization produces plasma but consumes considerable amount of power – "dominant" in PB



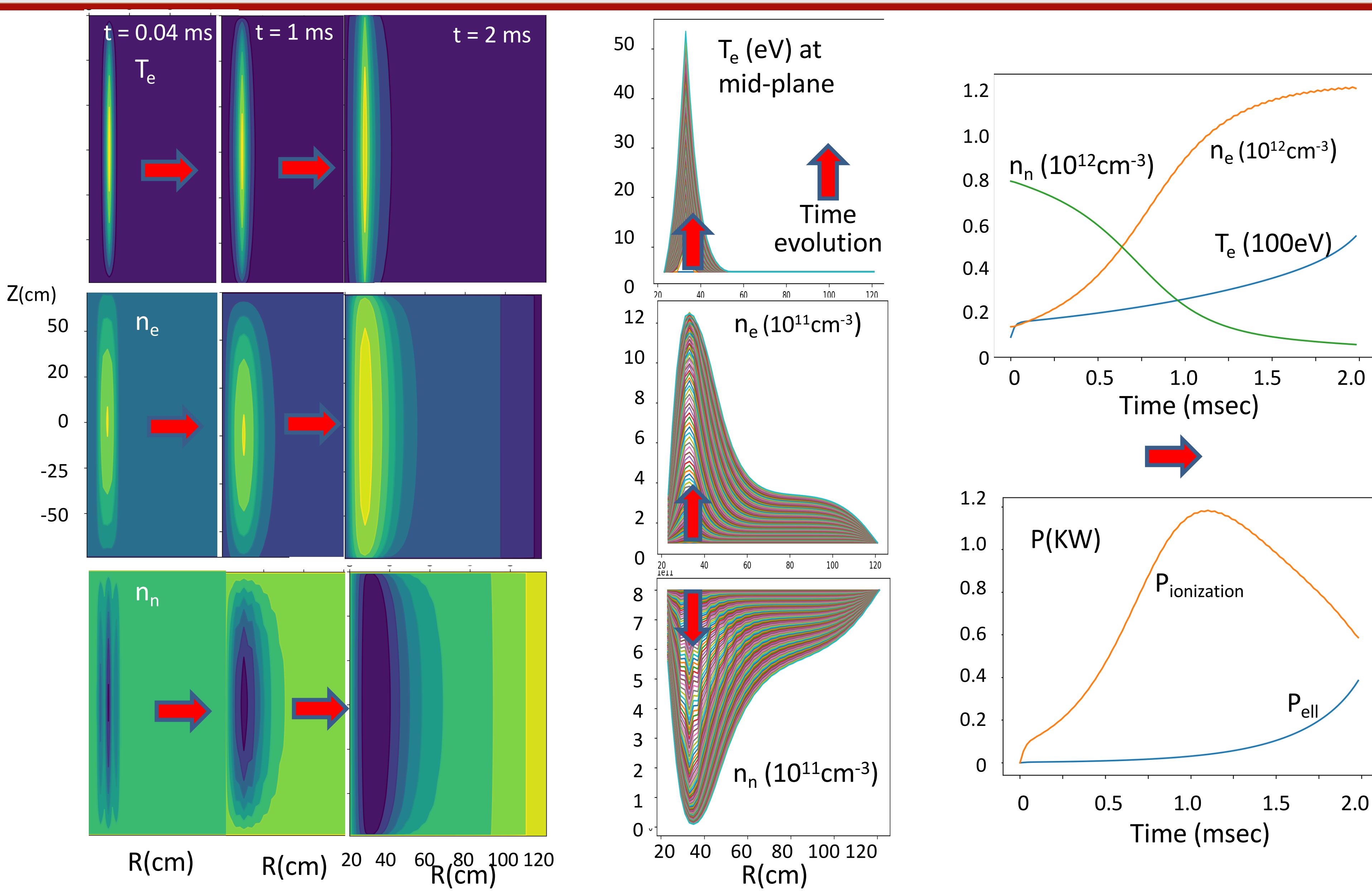
$P_{ell} \propto T_e^{7/2}$



Ionization <σv> increases for T_e < 100 eV - R.K. Janev et al., JNM (1984)

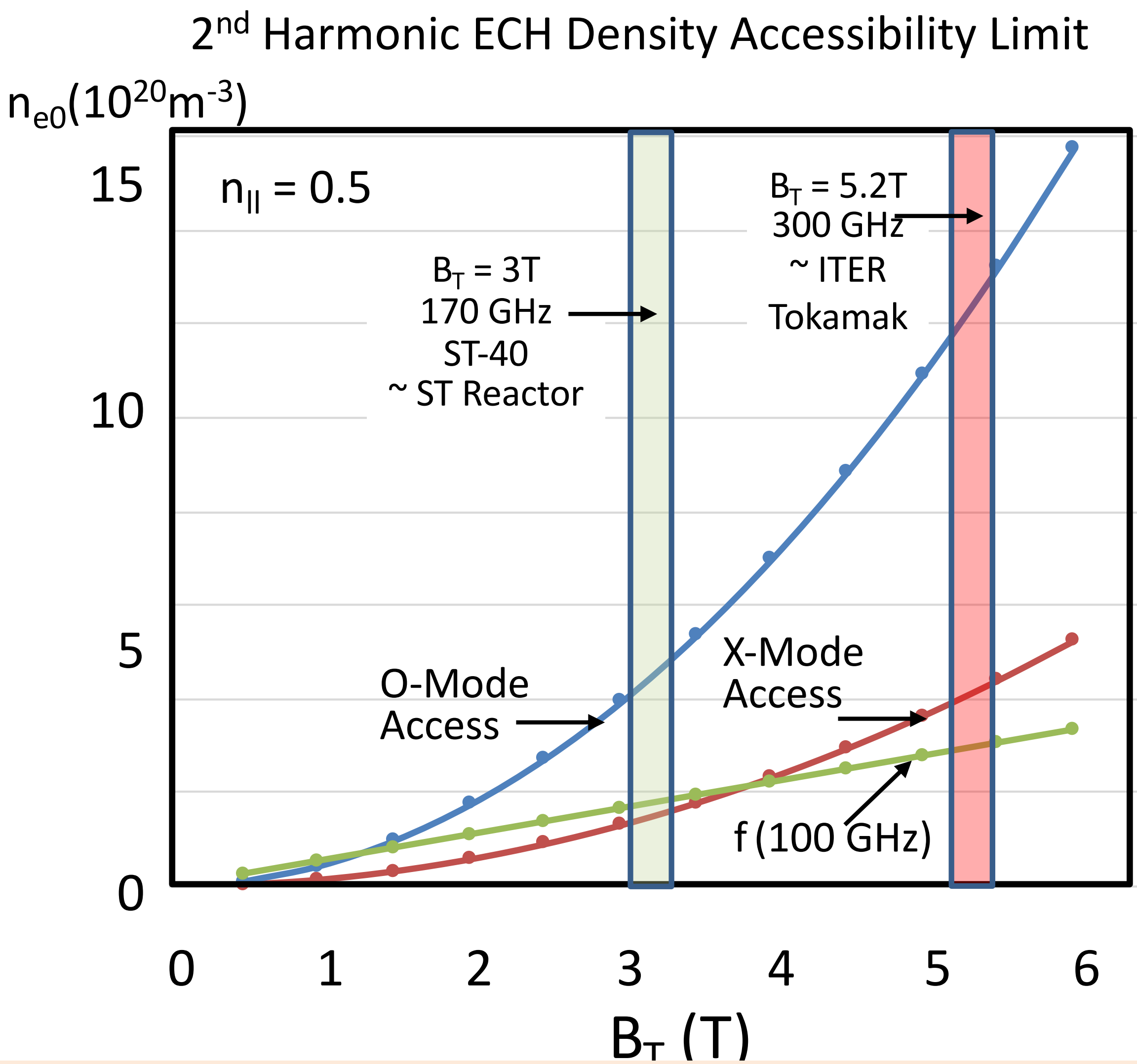
Ionization is dominant power balance initially

But peaks at T_e ~ 30 eV due to neutral particle reduction



Excellent 2nd Harmonic ECH Density Access

4 x $10^{20}m^{-3}$ for X-mode and higher for O-mode at 300 GHz



Reactor needs ~ 50 MW of Auxiliary Power

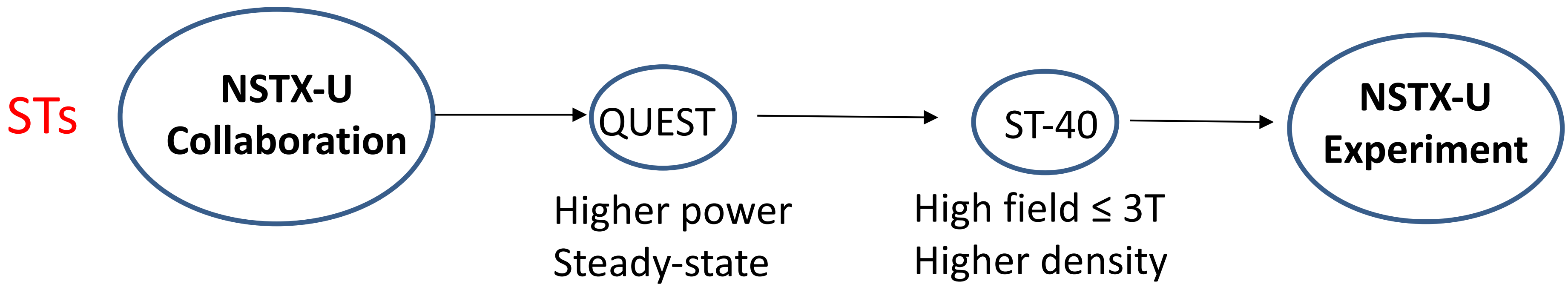
ECH power for

- Heating
- Current Drive
- NTM Stabilization
- Profile control
- Disruption Avoidance
- ….

2nd harmonic ECH power can be also utilized for tokamak/ST start-up

NSTX-U 2nd Harmonic ECH Start-up Research Strategy

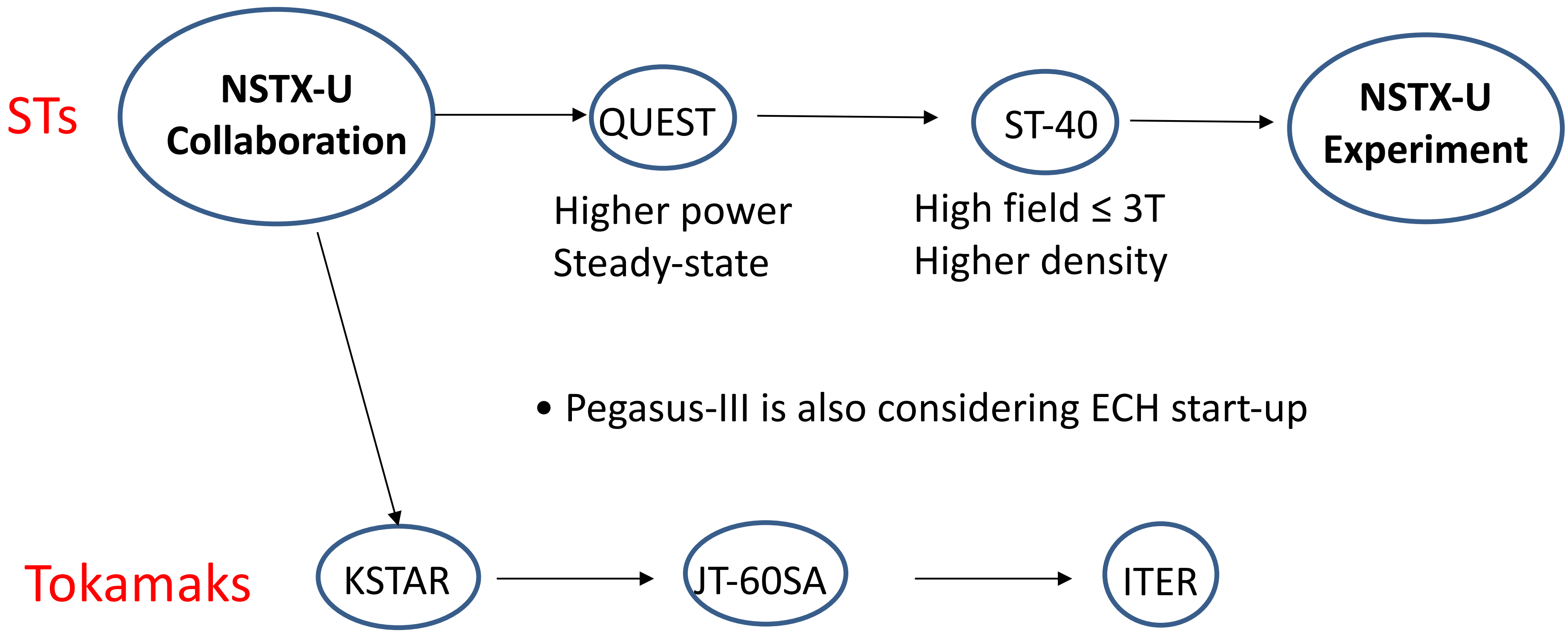
- Need to develop the solenoid-free start-up actuator for ST reactors



- Pegasus-III is also considering ECH start-up

NSTX-U 2nd Harmonic ECH Start-up Research Strategy

- Need to develop the solenoid-free start-up actuator for ST reactors
- Solenoid-free start-up could also help large SC tokamaks such as ITER and also the advanced/compact tokamak reactors



- Pegasus-III is also considering ECH start-up

2nd harmonic ECH start-up could help large SC tokamaks

Summary of Modeling of the QUEST 28 GHz 2nd Harmonic ECH Plasma Start-up Experiment

- ~ Significant first pass absorption at 2 Ω_e, 3 Ω_e and 4 Ω_e resonances consistent with generation of ~ 100 kA currents observed in the experiment.
- Strong focusing of ECH in early phase of start-up with relatively small closed flux volume enables heating of hot electron minority population to over 1 keV needed for efficient ECCD.
- Minority hot electron-based QUEST 2nd harmonic ECH start-up scenario looks attractive for NSTX-U and future devices.
- Grid-based start-up code being developed to simulate open to closed flux surface transition with pressure driven current.
- Grad-B, precessional drifts, and bootstrap current provide sufficient plasma current for an initial closed flux configuration ~ 5 – 10 kA.
- Important role of ionization of neutrals for initial breakdown phase of the start-up investigated.
- 2nd Harmonic ECH looks promising to support future reactor development path without suffering density accessibility limit. This power can be used for soleoid-free start-up.

Plasma Evolutions During ECCD Current Ramp-up

~2% hot electron population accounts for much of plasma stored energy