X-ray Measurements during the Plasma Current Start-up Experiments using Lower Hybrid Wave on the TST-2 Spherical Tokamak

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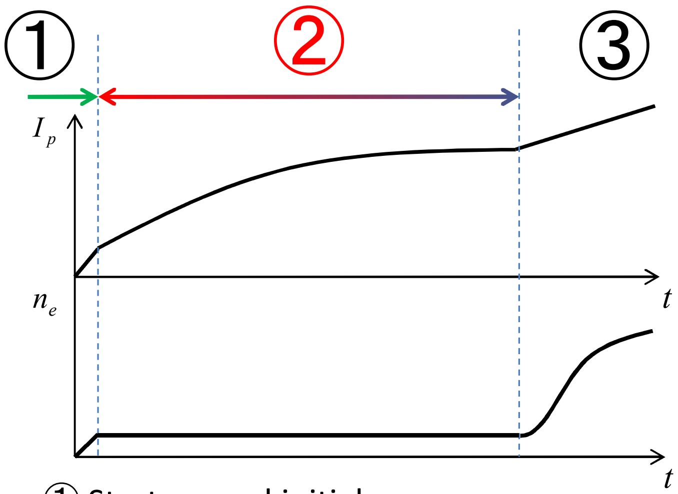
Introduction

- The capability of plasma current start-up and ramp-up using lower hybrid wave (LHW) in spherical tokamak is investigated.



① Start-up and initial ramp up
② Current ramp up by lower-hybrid wave
③ Transition to advanced tokamak

- If the plasma current can be ramped-up by LHW to a sufficient level that is needed for further heating (e.g. NBI), the central solenoid can be eliminated.

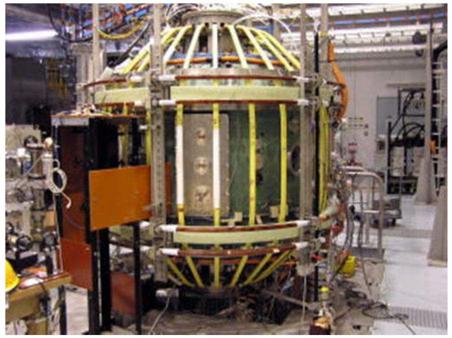
Objectives

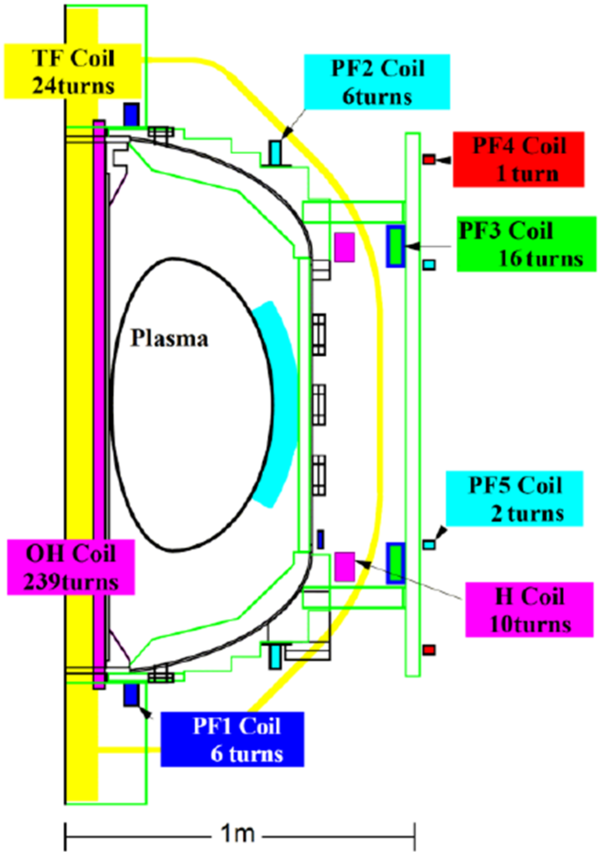
- Demonstrate the feasibility of LHCD ramp-up scenario in ST.
- Measuring the contribution of fast electrons driven by LHW in the plasma current.

Methods

- Measuring fast electron bremsstrahlung in broad energy range (10 eV – 500 keV) using several detectors on the perpendicular and tangential viewing chords.

TST-2 spherical tokamak



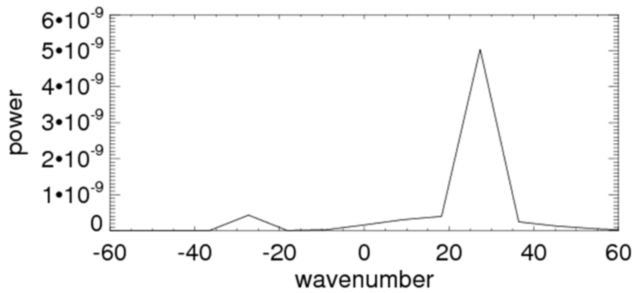


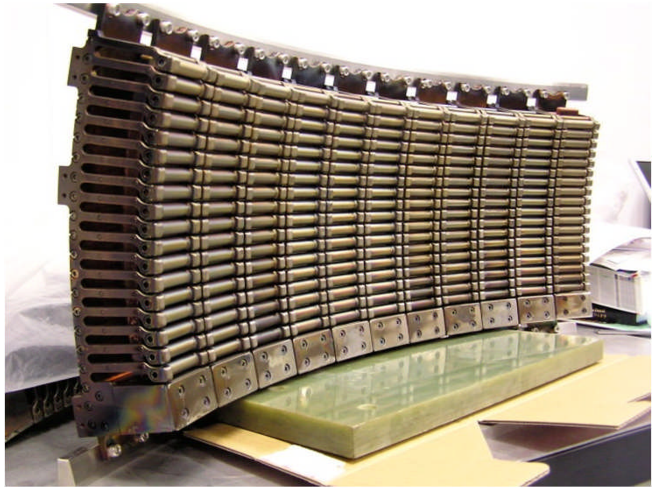
- Major radius R ∼ 0.35 m
- Minor radius a ∼ 0.23 m
- Aspect ratio A = R/a > 1.5
- Toroidal field B_t ∼ 0.1 T

For LHCD ramp-up operation

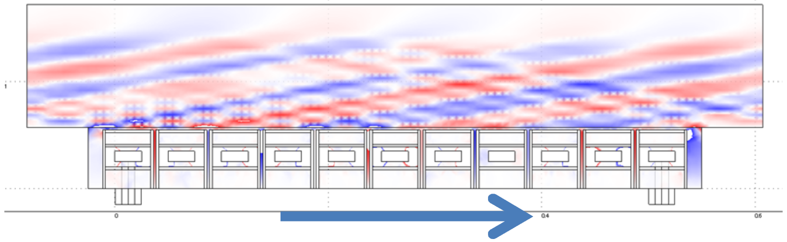
- Plasma current
  - I_p < 15 kA
- Discharge duration
  - Δt < 120 ms

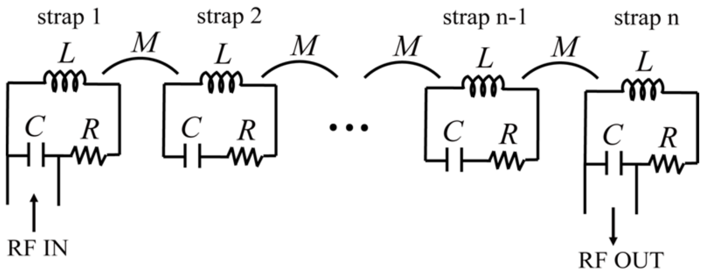
Combline antenna



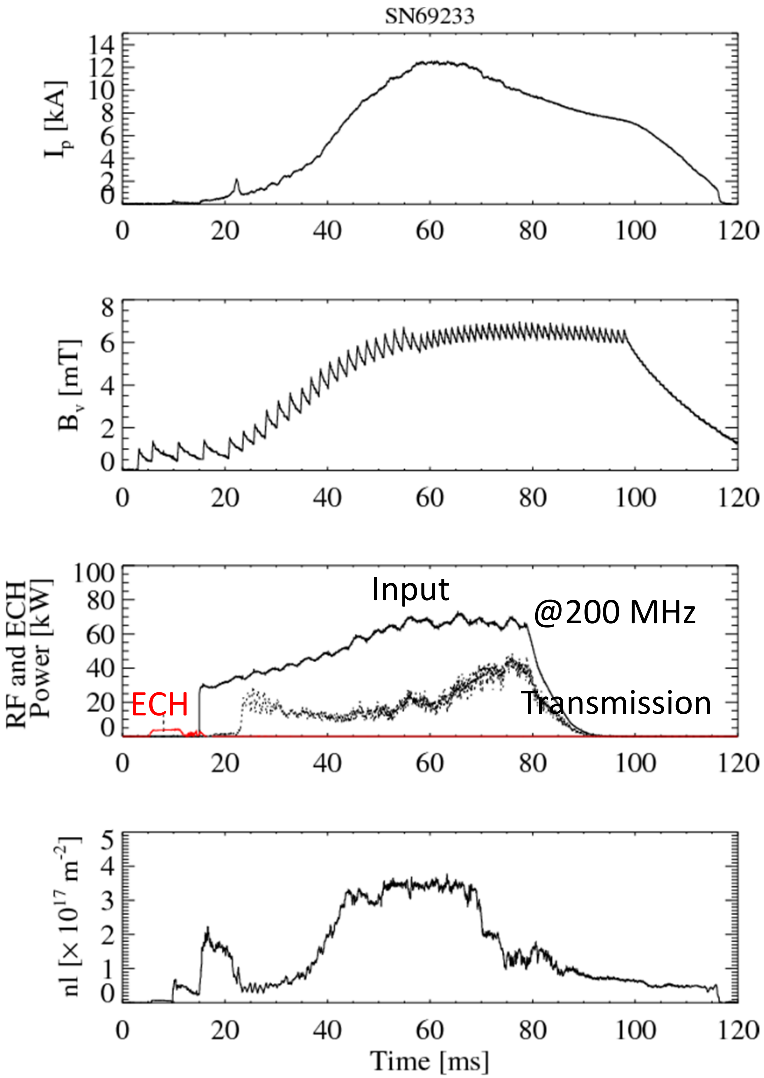


$n_{||} \sim +7.2$
(travelling wave)





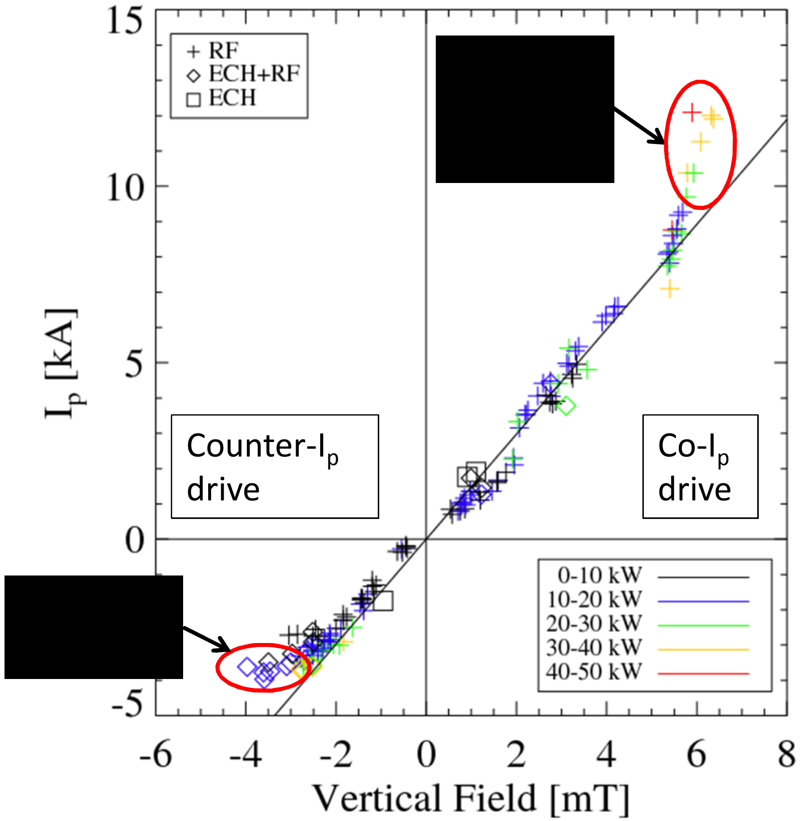
- This antenna is originally designed for fast wave excitation. However, FEM simulation predicts slow wave excitation.
- This is because the fast wave is cutoff for the density we consider.



Discharge waveform

- The plasma current is ramped up with a slow vertical field (B_v) ramp-up.
- Maximum plasma current exceeds 15 kA.
  - I_p < 1.5 kA in the previous experiments using ECH.

Effect of direct current drive



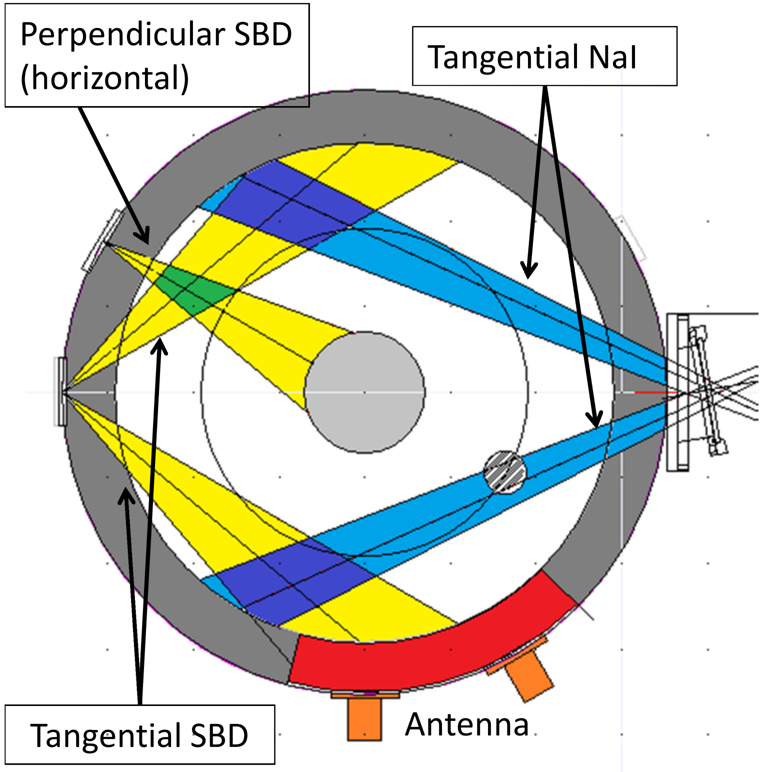
- $I_p \propto B_v$
- The direction of I_p inverts with the reversal of vertical field direction.
- $|I_p| < 4$ kA in the counter drive case.
- This fact shows the effect of direct current drive by the LHW.

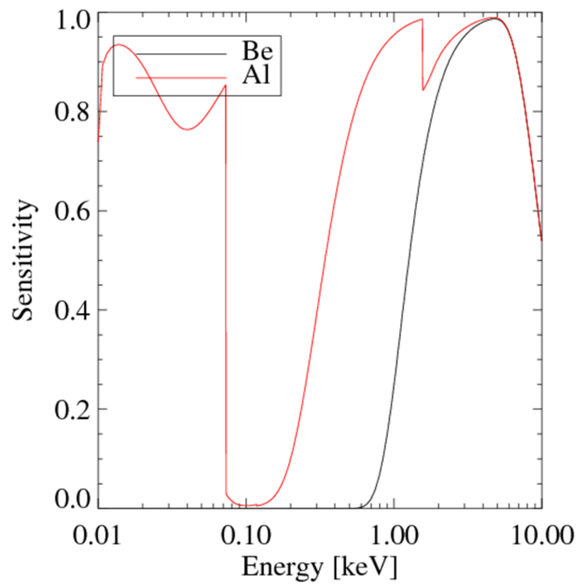
X-ray measurements

X-ray detectors

- SBD (Surface Barriered Diode)
  - Soft X-ray measurement (< 10 keV)
  - We can restrict the energy range of measured photons by changing filters placed in front of the detector.
  - Be filter (1 - 10 keV), Al filter (10 – 70 eV)
  - 2 perpendicular and 2 tangential chords.
- NaI scintillator
  - Hard X-ray measurement (> 10 keV)
  - 2 tangential chords.

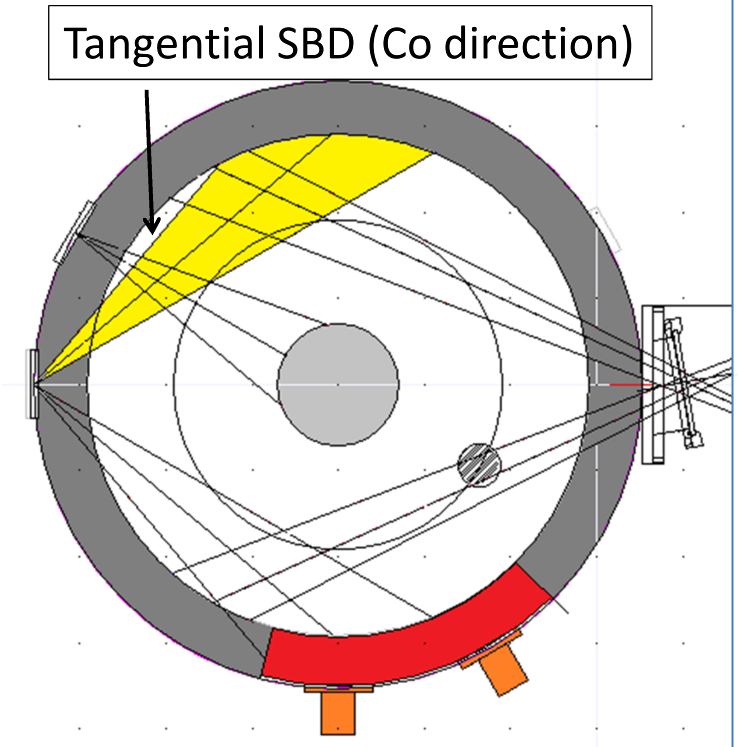
Viewing Chords



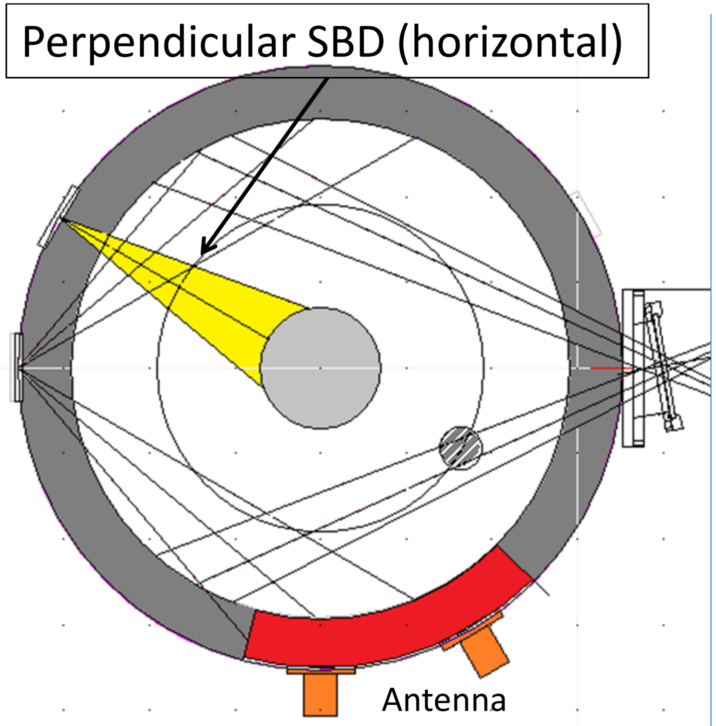


SBD (Al)	SBD (Be)
10-70 eV	1–10 keV

Soft X-ray measurements

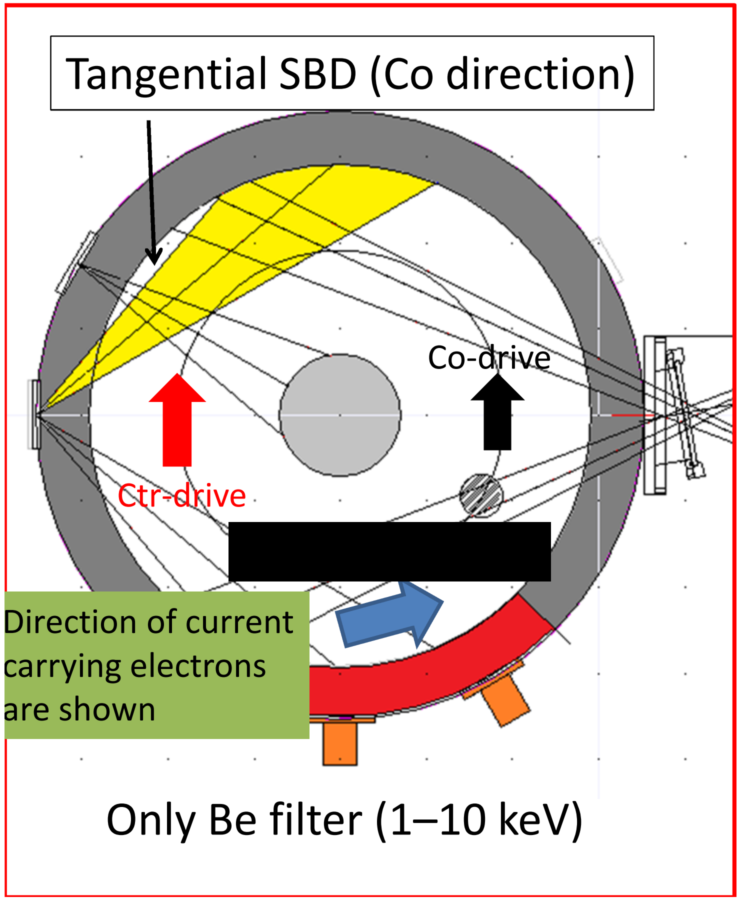


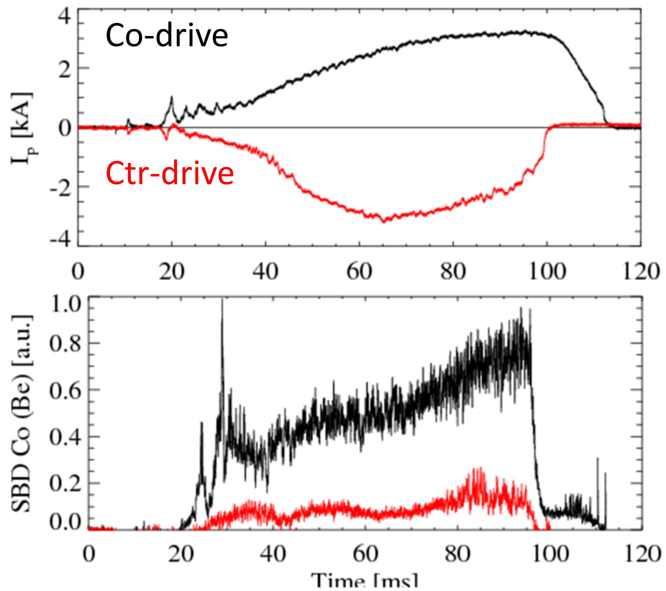
Only Be filter (1–10 keV)



Be filter (1–10 keV) and
Al filter (10-70 eV)

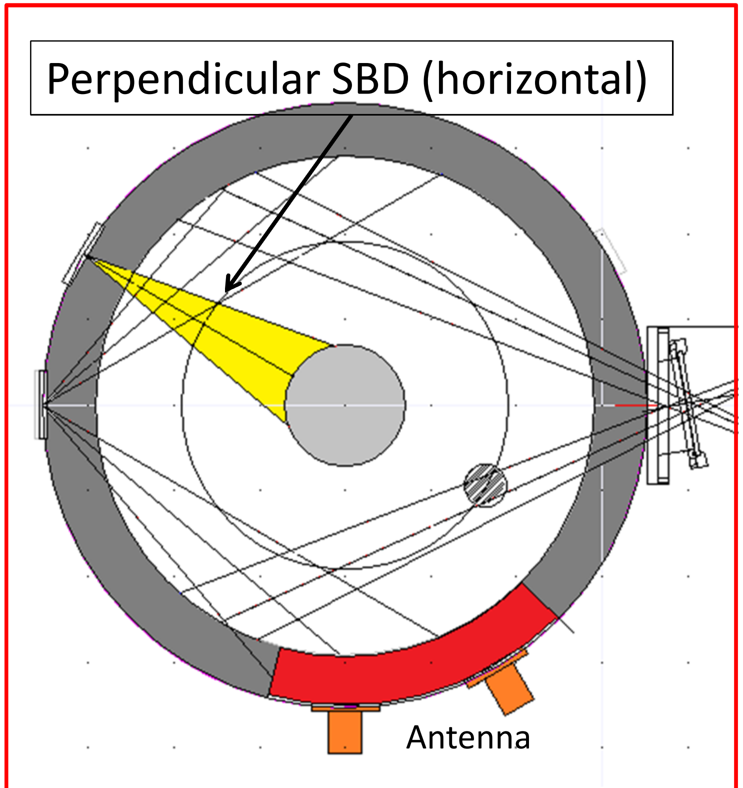
Comparison of SXR in co-direction with co-drive case and ctr-drive case





Stronger emission is measured in co-drive case, which implies the difference in confinement of RF driven fast electrons.

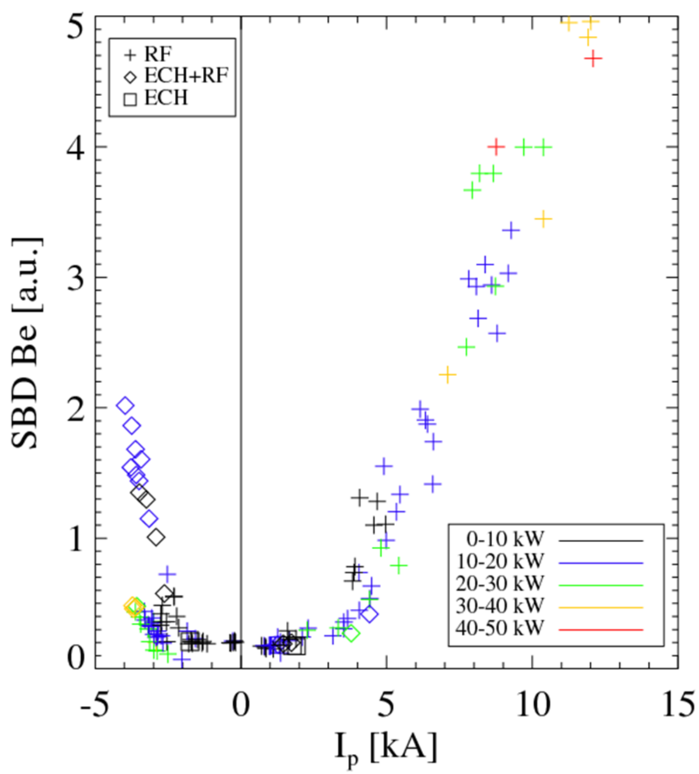
Perpendicular Soft X-ray measurements



Be filter (1–10 keV) and
Al filter (10-70 eV)

- Dependence of the SX on the magnitude of the plasma current is investigated.
- RF amplitude modulation experiments were also performed.

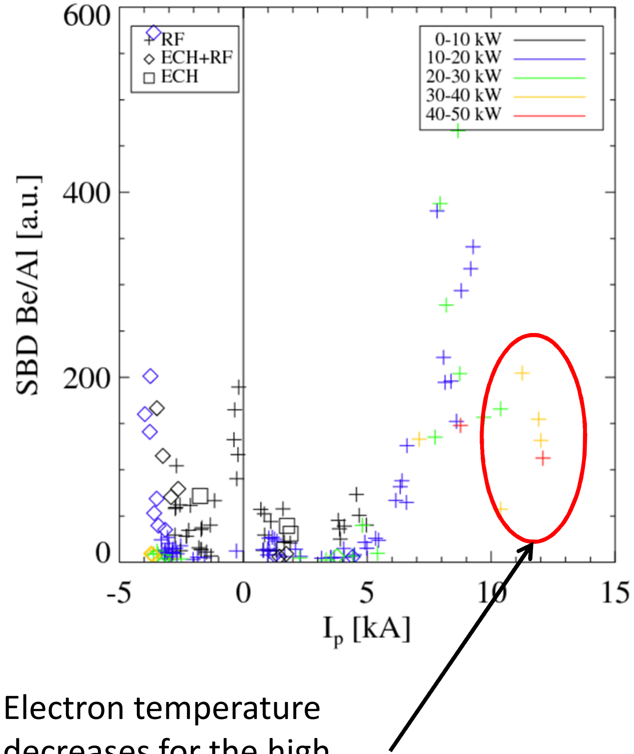
Fast electron contribution to the plasma current



- For the co-drive case, 1-10 keV SX increased as the plasma current increased.

→ This fact suggests that fast electrons produced by LHW have some contributions to the plasma current.

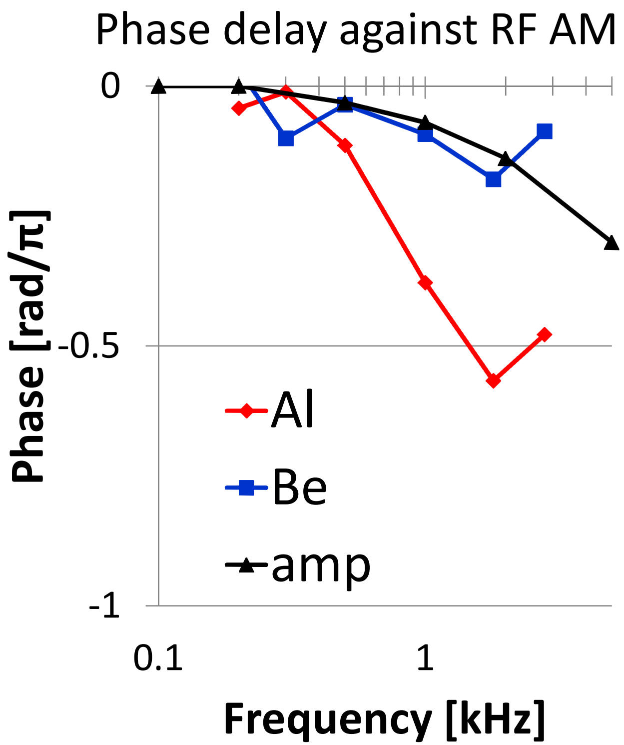
Electron temperature increased as the plasma current increased



Electron temperature decreases for the high filling pressure sequence

- The ratio of high energy SX (1-10keV) to low energy SX (10-70 eV) can be used as qualitative measure of electron temperature.
- The effective electron temperature increases as the plasma current increases.

Amplitude modulation



- Phase of low energy photon emissions delayed against RF AM from 0.5 kHz.
- Estimated slowing down time for low energy electrons is 0.2 ms
- While, phase delay of high energy photon emission was not observed.

Short life time of high energy electron

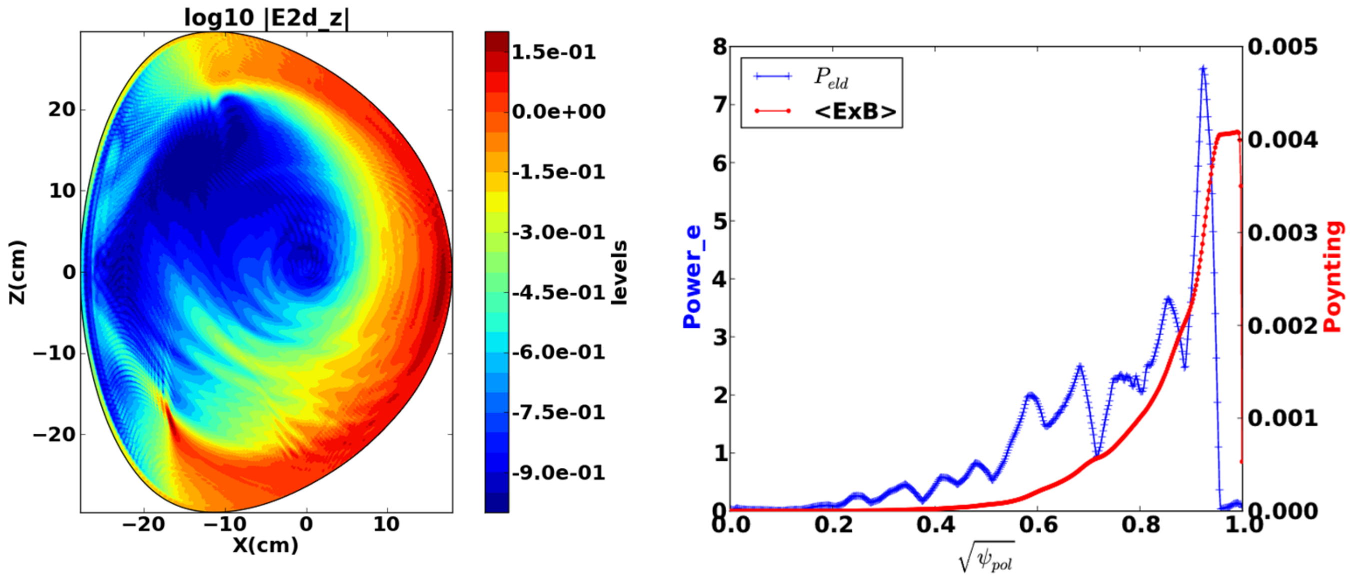
Slowing down　Rapid loss　RF source

$$\frac{\partial n_H}{\partial t} = -\frac{n_H}{\tau_H} - \frac{n_H}{\tau_{loss}} + S_0 e^{i\omega t}$$

- If no loss term presents, the phase of high energy photon emissions start to delay at lower frequency than low energy photon emission because $\tau_H > \tau_L$.
- More rapid loss term should present. ($\tau' < 0.1$ ms)
- Orbit drift size $\Delta = r_{Le}\, q \sim 30$ mm
- Observed fast electrons may reside mainly near the edges.

$$\tau' = \frac{\tau_H \tau_{loss}}{\tau_H + \tau_{loss}},\ \phi_H = \mathrm{Arctan}\left(-\omega \tau'\right)$$

Simulation predicts strong edge absorption



- Wave simulation using TORLH full wave code and CQL3D Fokker-Planck code predicts that edge absorption is very strong.

Response of lower energy component

$$\frac{\partial n_L}{\partial t} = -\frac{n_L}{\tau_L} + a\frac{n_H}{\tau_H} + bS_0 e^{i\omega t}$$

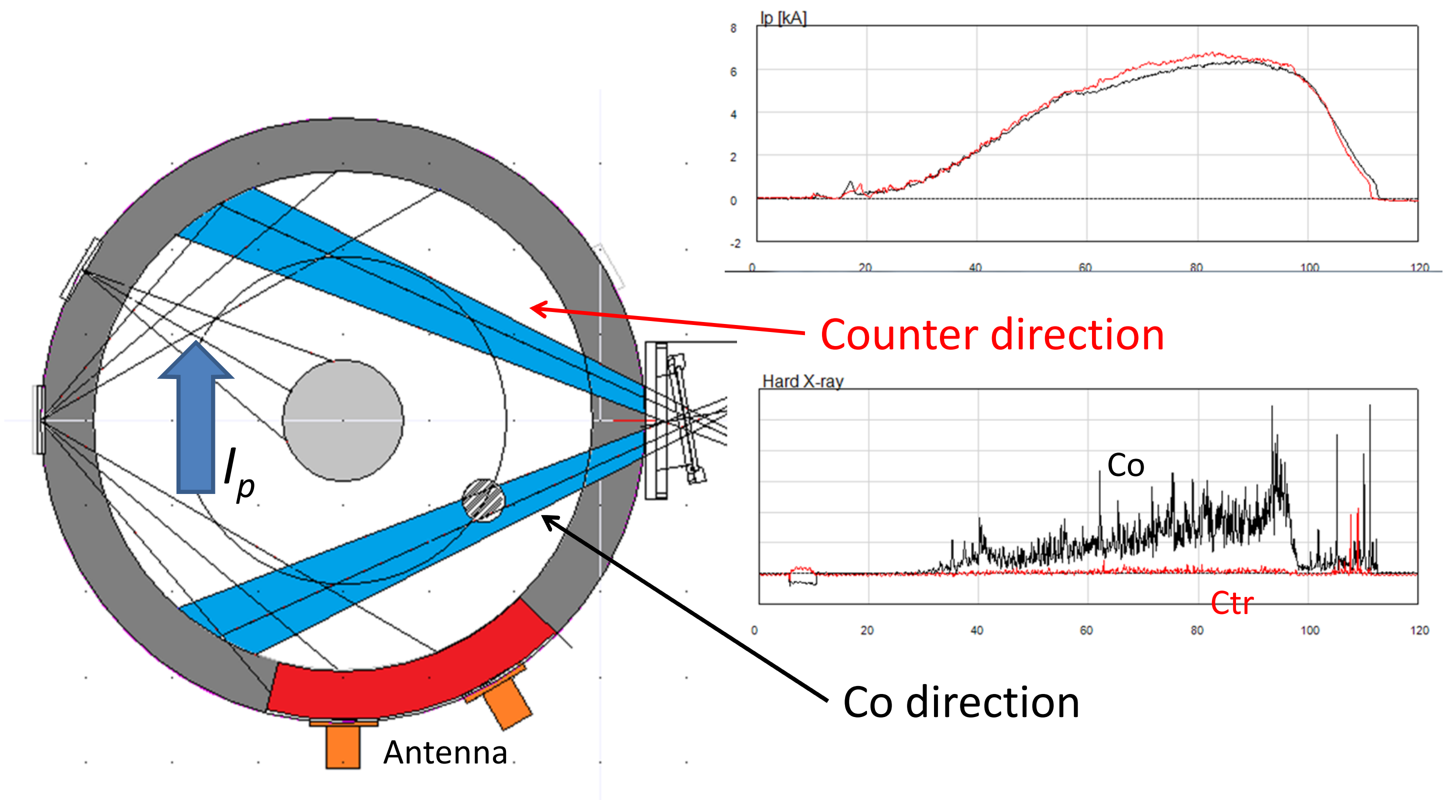
Slowing down term

Source term from relaxation of high energy electrons

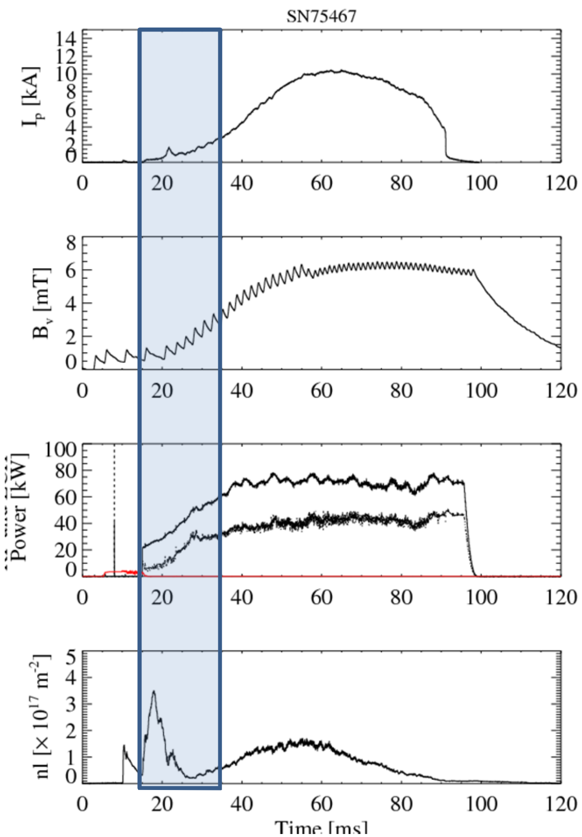
RF source term

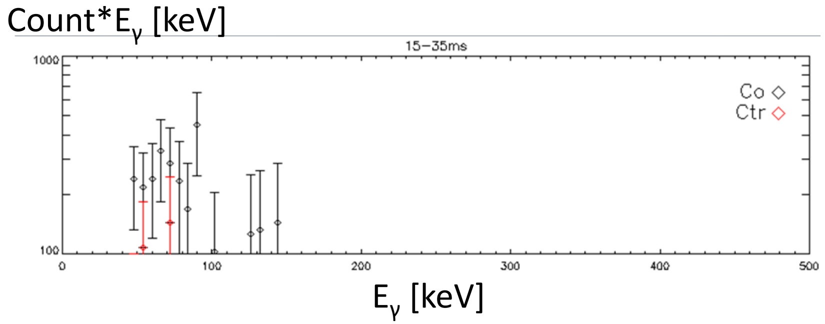
- If a << b, $\phi_L = \mathrm{Arctan}\left(-\omega\tau_L\right)$
- If a >> b, phase starts to delay at $f_H = 1/\tau_H$.
- 0.2 ms is comparable to collisonal slowing down time of low energy electrons (E ~ 10-70 eV).

Hard X-ray measurements



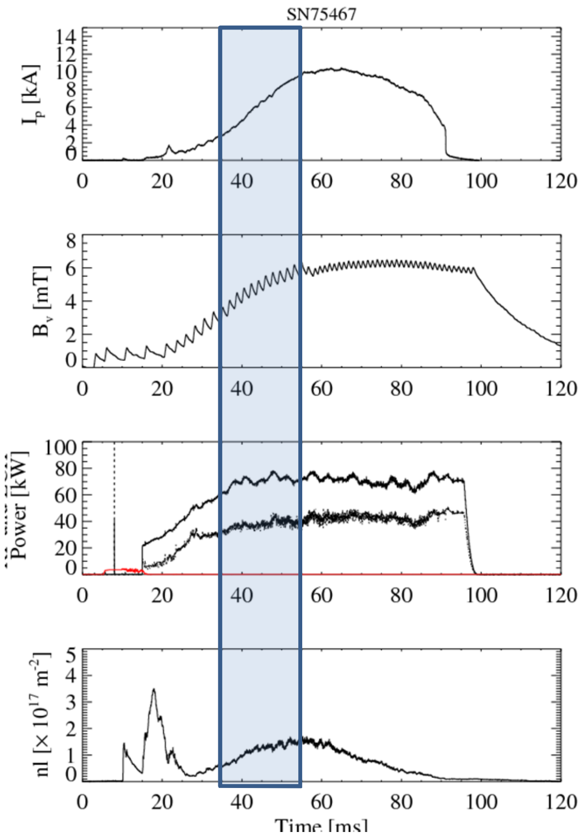
Fast electron build up

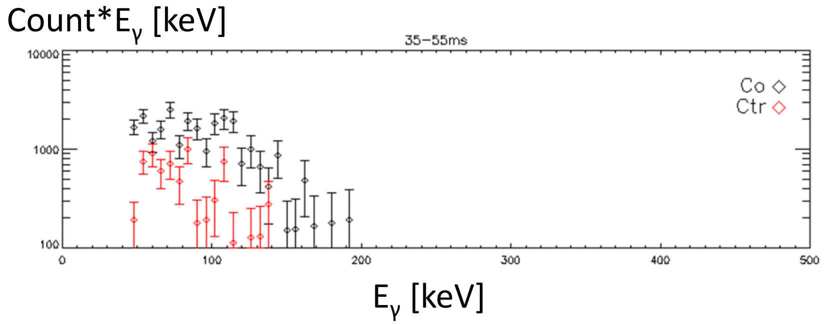




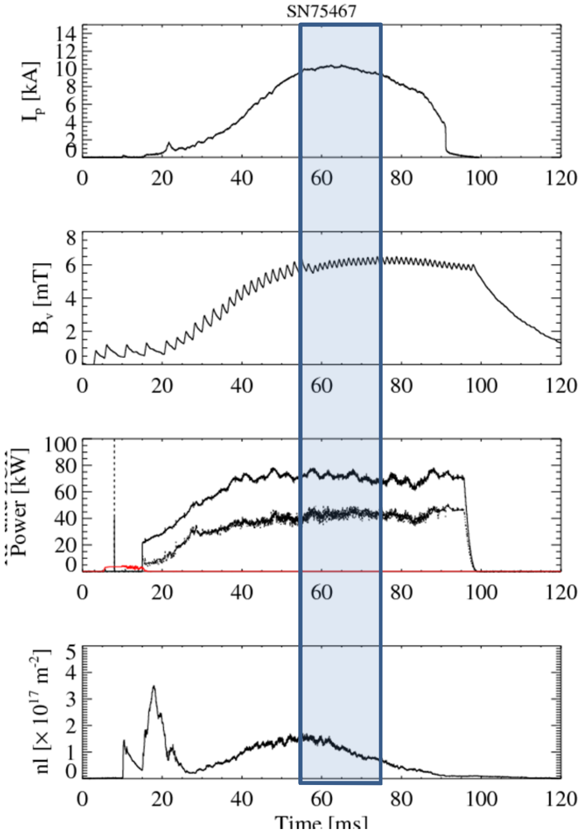
- At the current start-up phase, hard X-ray intensity (E_γ > 100 keV) is very low.

Fast electron build up

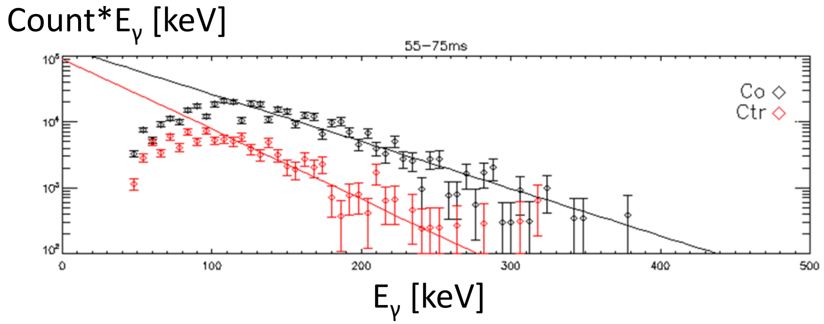




- Fast electron build up was observed as the plasma current increased.
- Hard X-ray from co-direction is always stronger than that from counter direction.



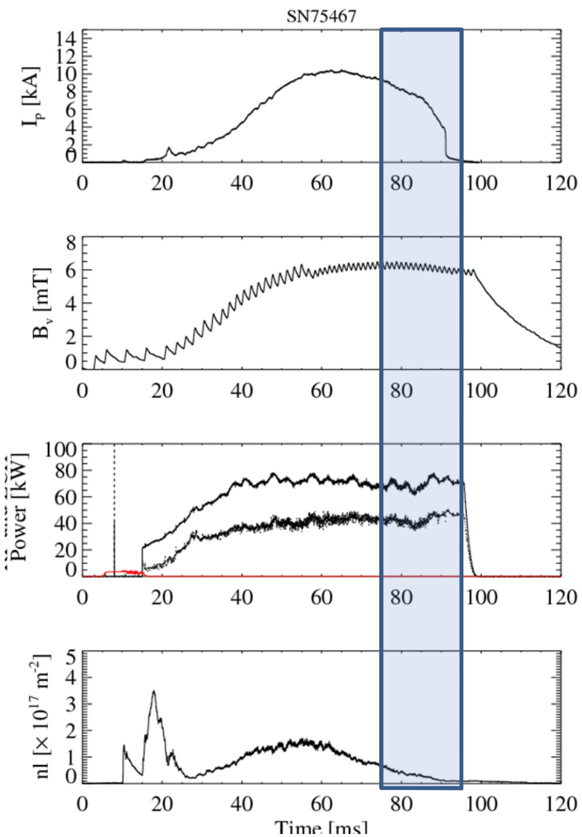
Fast electron build up

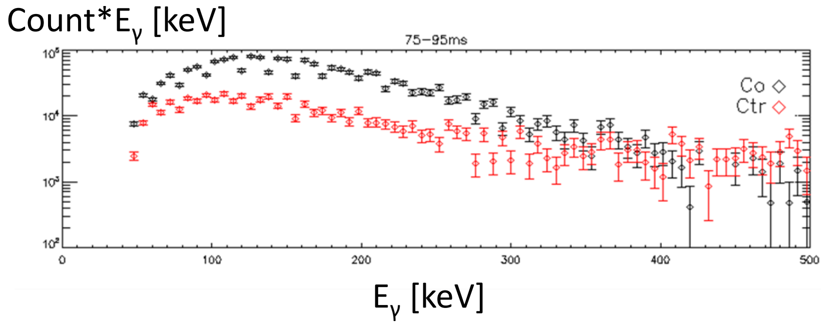


- A slight difference in effective temperature of Hard X-ray can be seen.

T_{eff_Co}	T_{eff_Ctr}
61±6 keV	41±5 keV

Fast electron build up





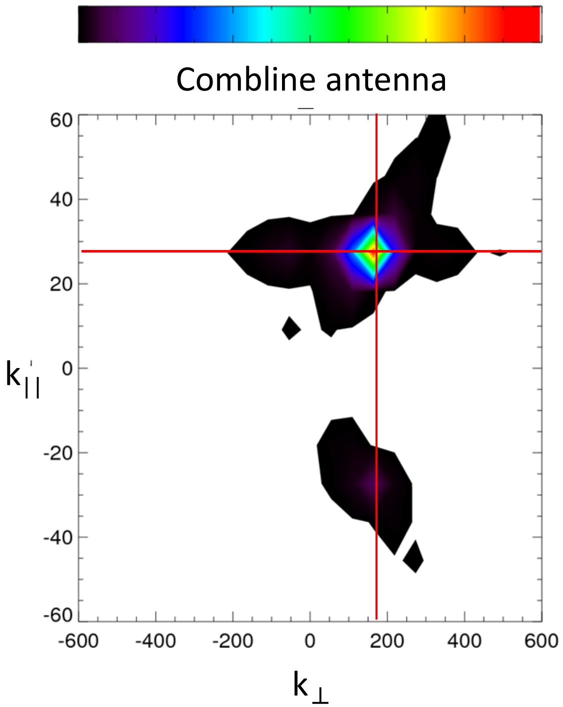
- At the current decreasing phase, the hard X-ray emission increases because the electric field due to the plasma inductance accelerates fast electrons.

Summary

- There are more RF driven fast electrons (1-10 keV) in co-drive case compared with ctr-drive case.
- Fast electron population significantly increased as the plasma current increases.
- However, the confinement time of these fast electrons seems to be very short compared to the collisional slowing down time.
- The higher intensity and the higher effective temperature of co-direction hard X-ray emission confirm the existence of RF driven fast electrons (> 100 keV).

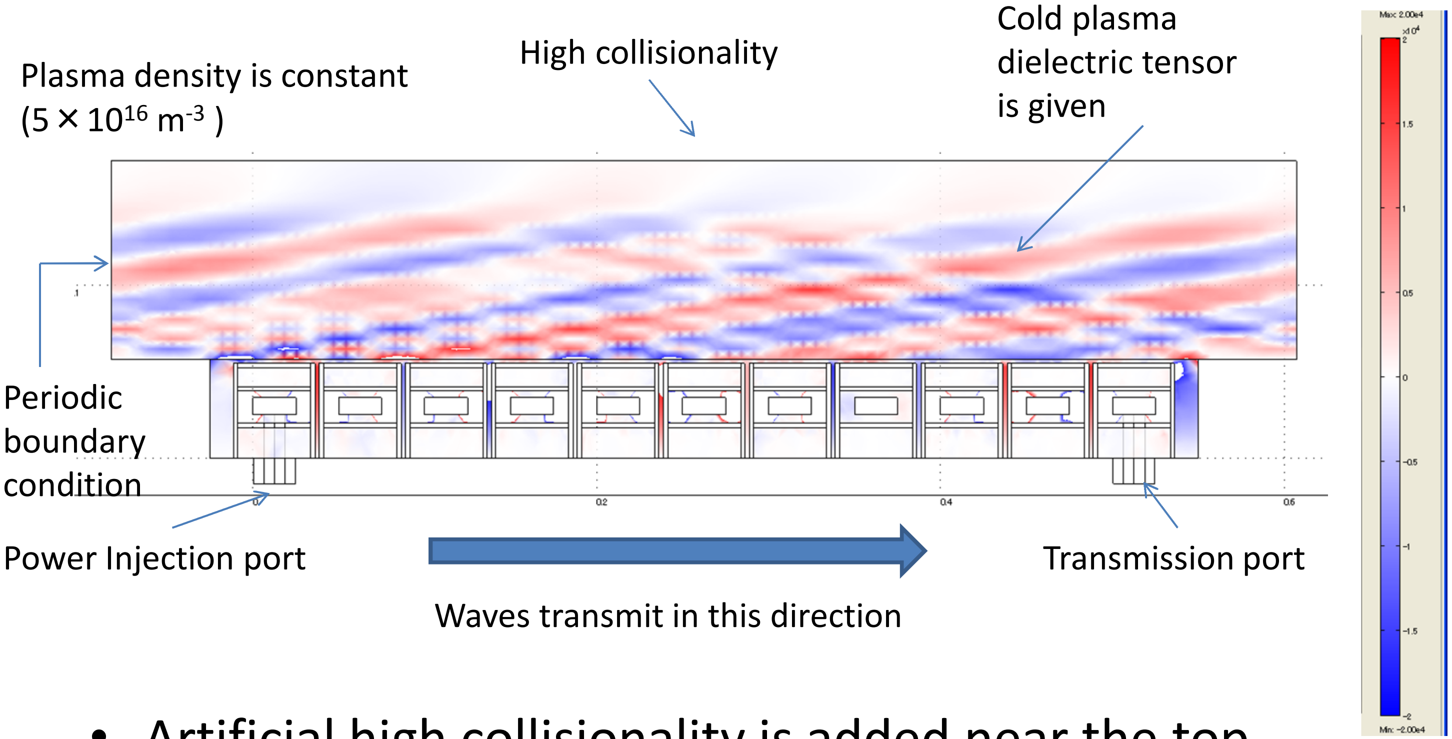
Back up slides

Slow wave excitation by combline antenna



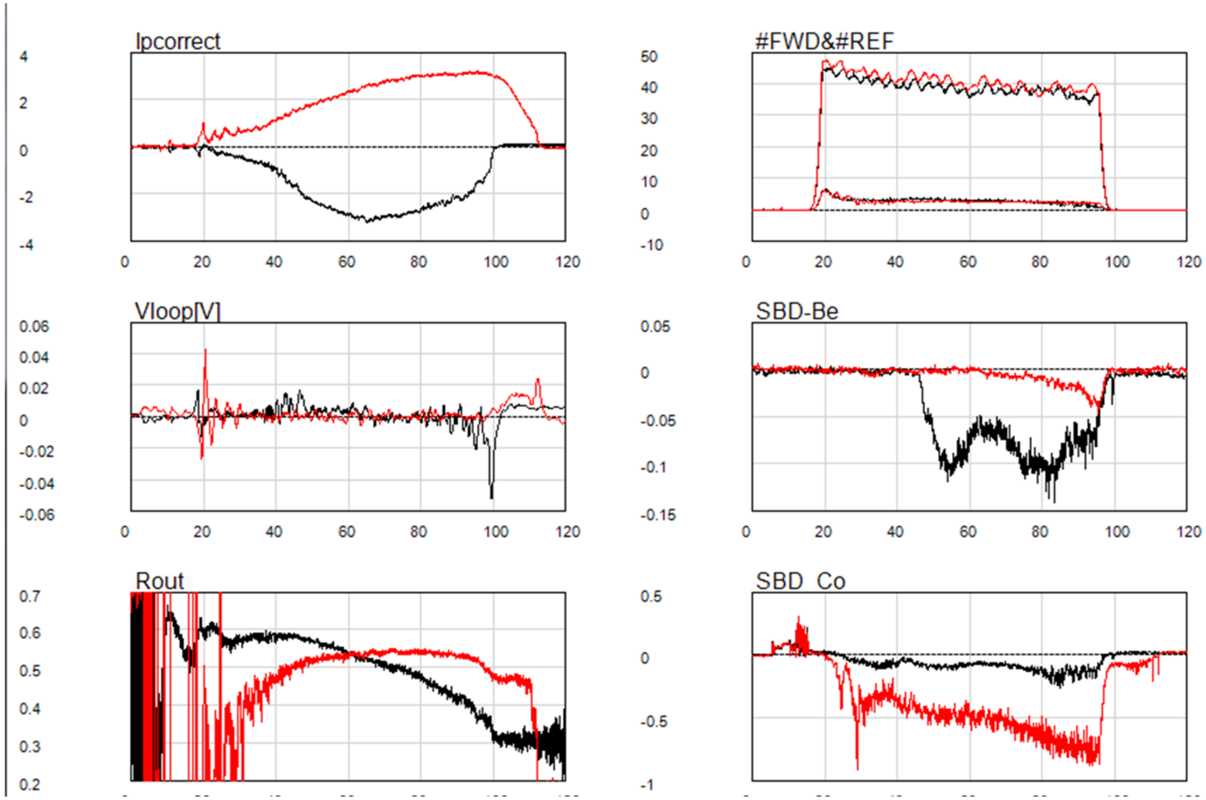
- Wave excitation simulation is performed using versatile FEM solver, COMSOL.
- The excited wave has
- $k_{||}$ =30 ($n_{||}$ = 7.2), $k_\perp$ ∼150, which satisfies slow wave dispersion relation.
- This is because the fast wave is cutoff for the density we consider

Simulation conditions

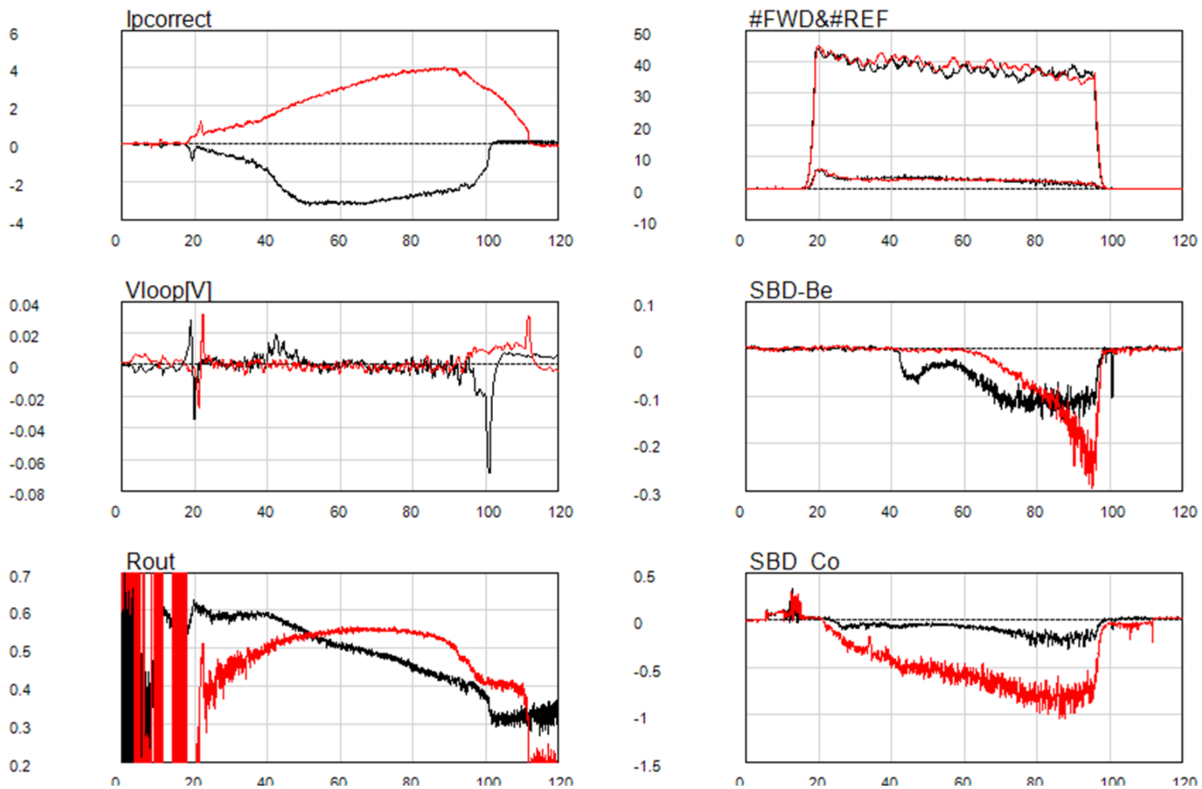


- Artificial high collisionality is added near the top boundary to suppress unwanted reflection.

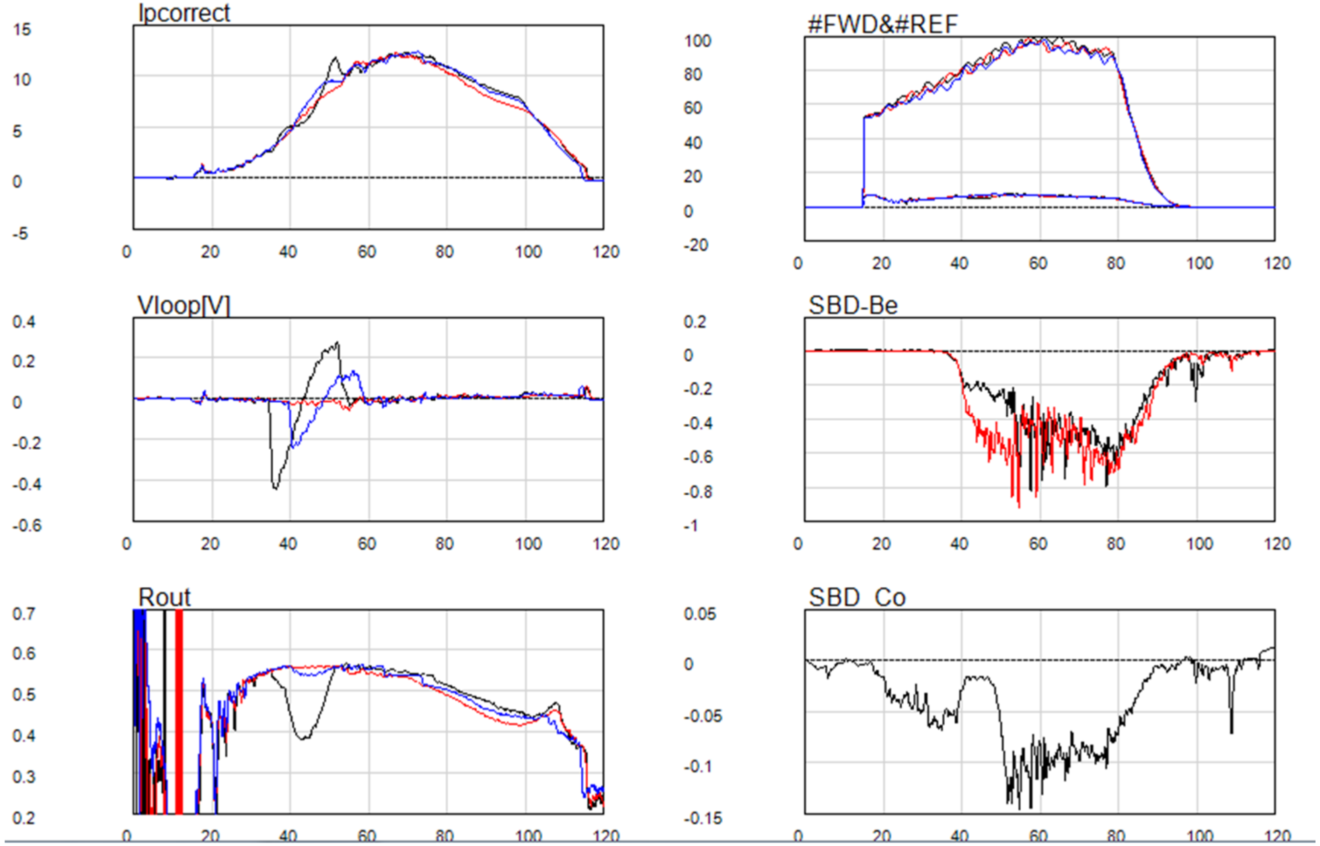
Co-drive and Ctr-drive



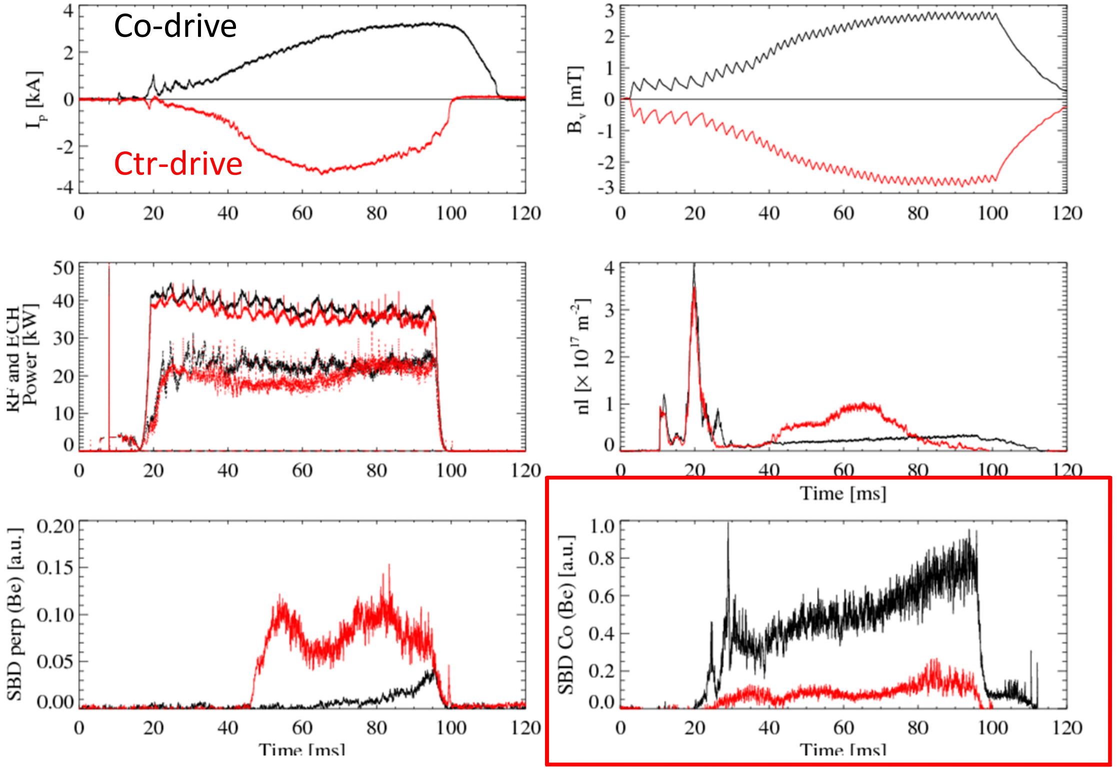
Co-drive and Ctr-drive



Effect of loop voltage



Increase in the tangential X-ray emission

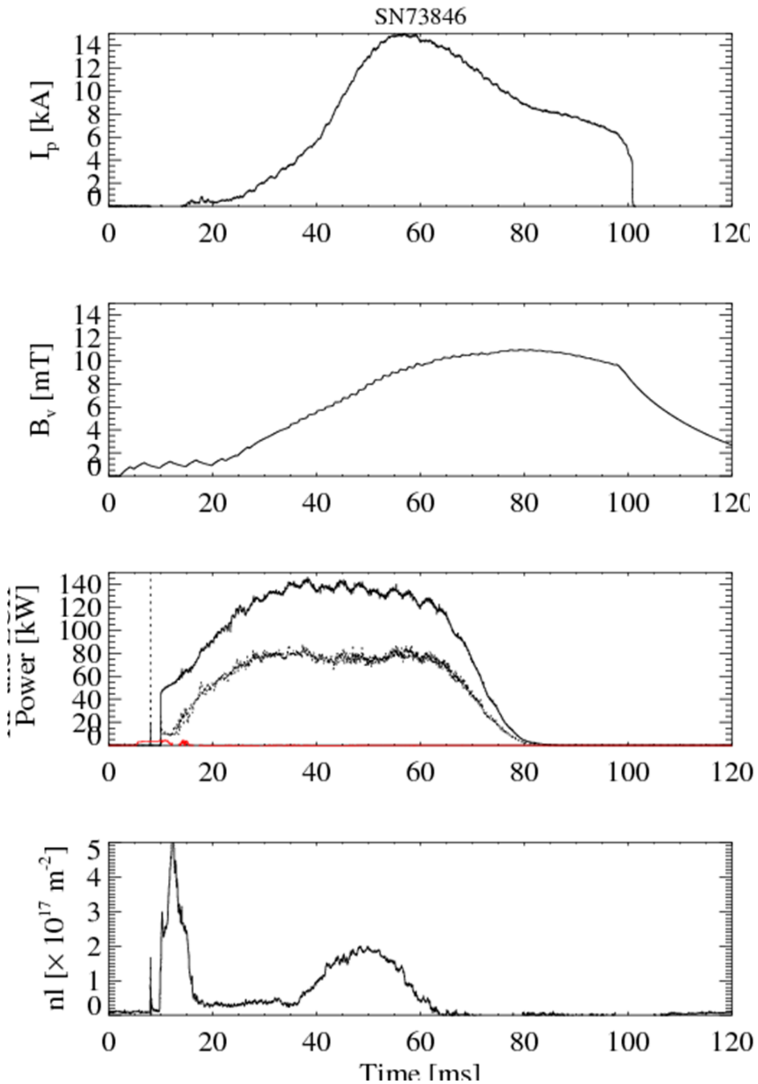


- In case of co-drive, tangential X-ray emission (E_γ ~ 1-10 keV) increases, which suggests the difference in confinement of RF driven fast electrons.

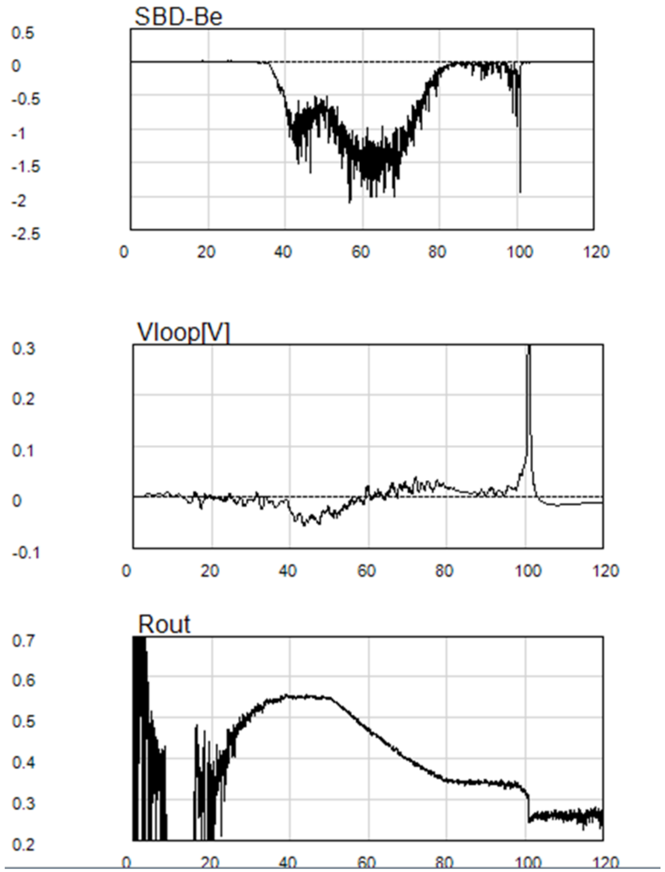
$$\begin{cases} \dfrac{\partial n_H}{\partial t} = -\dfrac{n_H}{\tau_H} - \dfrac{n_H}{\tau_{loss}} + S_0 e^{i\omega t} \\ \dfrac{\partial n_L}{\partial t} = -\dfrac{n_L}{\tau_L} + a\dfrac{n_H}{\tau_H} + bS_0 e^{i\omega t} \end{cases}$$

$$\tau' = \frac{\tau_H \tau_{loss}}{\tau_H + \tau_{loss}}, \phi_H = \mathrm{Arctan}\left(-\omega\tau'\right)$$

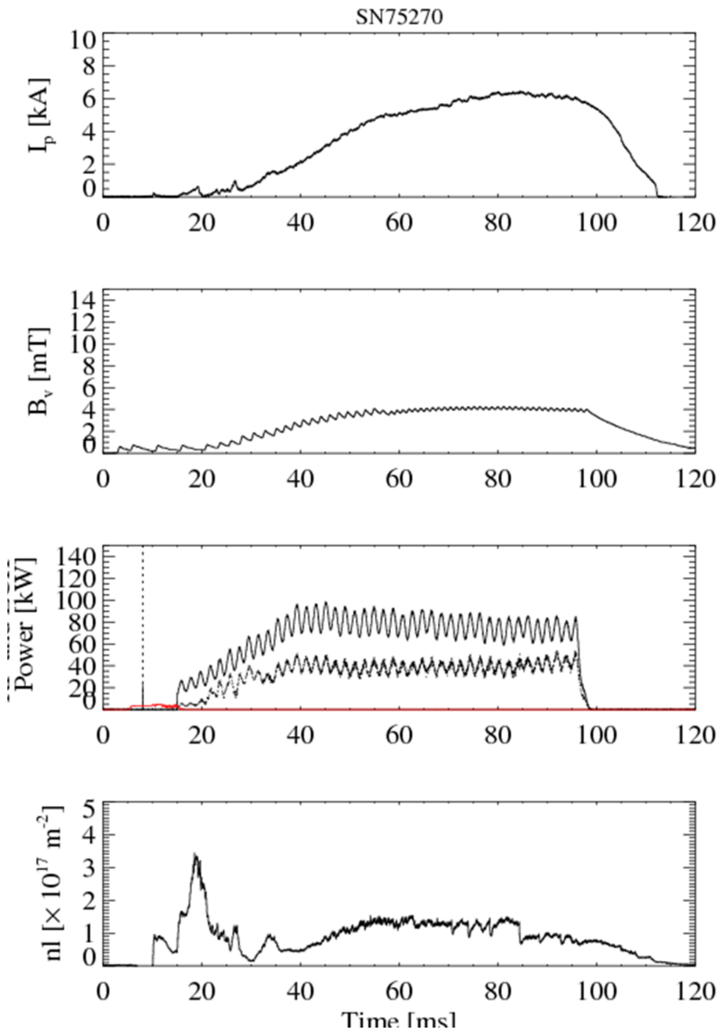
15 kA Shot



SN73846
I_p [kA]
B_v [mT]
Power [kW]
nl [× 10^17 m^-2]
Time [ms]
0 20 40 60 80 100 120



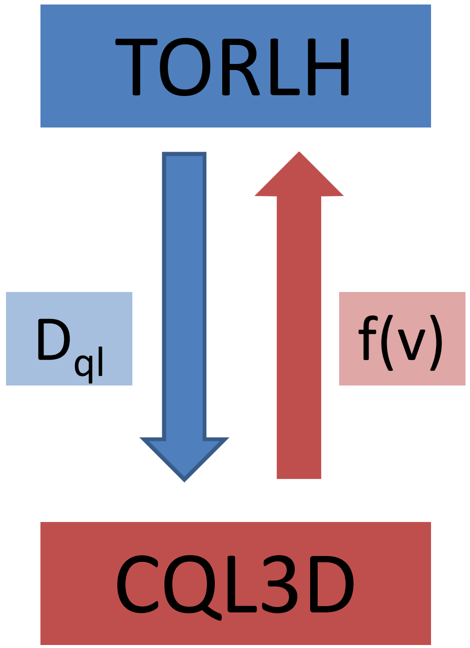
SBD-Be
0.5
0
-0.5
-1
-1.5
-2
-2.5
Vloop[V]
0.3
0.2
0.1
0
-0.1
Rout
0.7
0.6
0.5
0.4
0.3
0.2
0 20 40 60 80 100 120



Modulation Exp.

Iteration between TORLH/CQL3D

RF fields and quasilinear flux D_{ql} are calculated for the dielectric of the deformed distribution function.



New distribution function f(v) is calculated from RF quasilinear flux.

- After several iterations, self-consistent solution is obtained.