Physics and Experimental Results of KSTAR ECRH

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Outline

- **Introduction of KSTAR tokamak and ECRH system**
- **Physics issues and experimental results of KSTAR ECRH**
- **Technology issues of 170 GHz ECRH in KSTAR**
- **Summary and plan**

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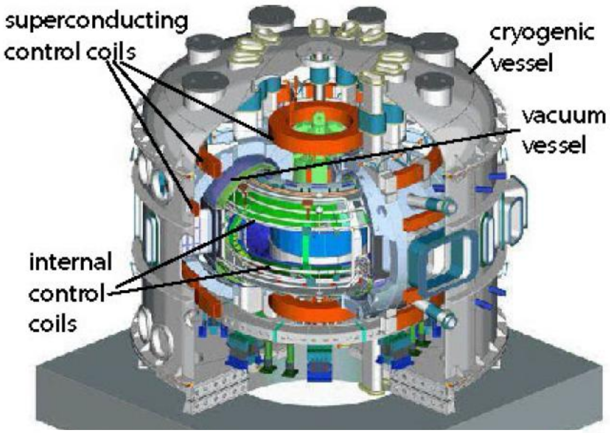
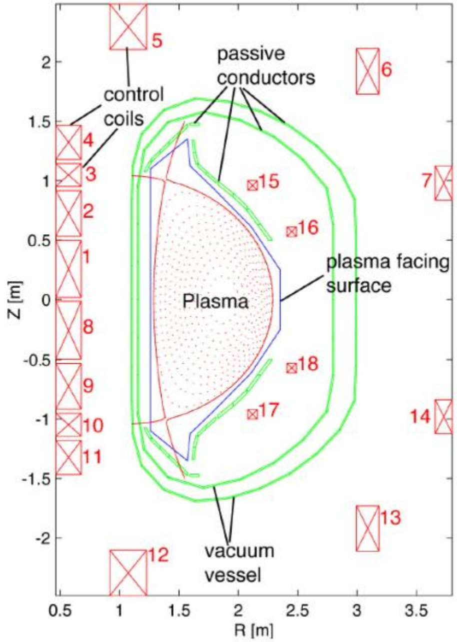
KSTAR tokamak and achievements





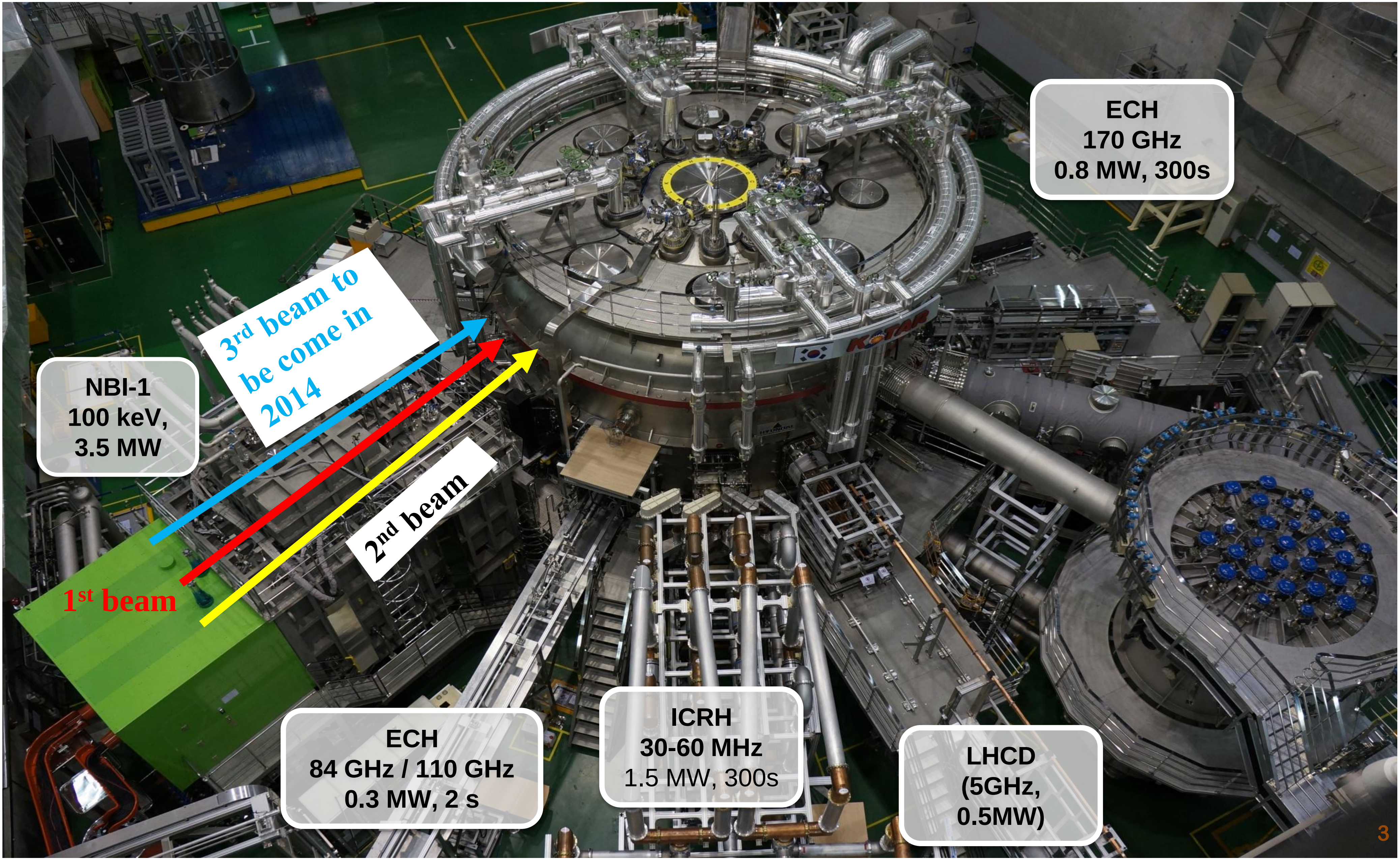
- Cross-section view of KSTAR tokamak

KSTAR Parameters

PARAMETERS	Designed	Achieved
Major radius, R_0	1.8 m	1.8 m
Minor radius, a	0.5 m	0.5 m
Elongation, κ	2.0	2.0
Triangularity, δ	0.8	0.8
Plasma volume	17.8 m^3	17.8 m^3
Bootstrap Current, f_{bs}	> 0.7	-
PFC Materials	C, CFC (W)	C
Plasma shape	DN, SN	DN & SN
Plasma current, I_P	2.0 MA	1.0 MA
Toroidal field, B_0	3.5 T	3.6 T
Pulse length	300 s	20 s (0.6 MA)
β_N	5.0	> 2.5
Plasma fuel	H, D	H, D, He
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Auxiliary heating /CD	~ 28 MW	~5.5 MW
Cryogenic	9 kW @4.5K	5 kW @4.5 K

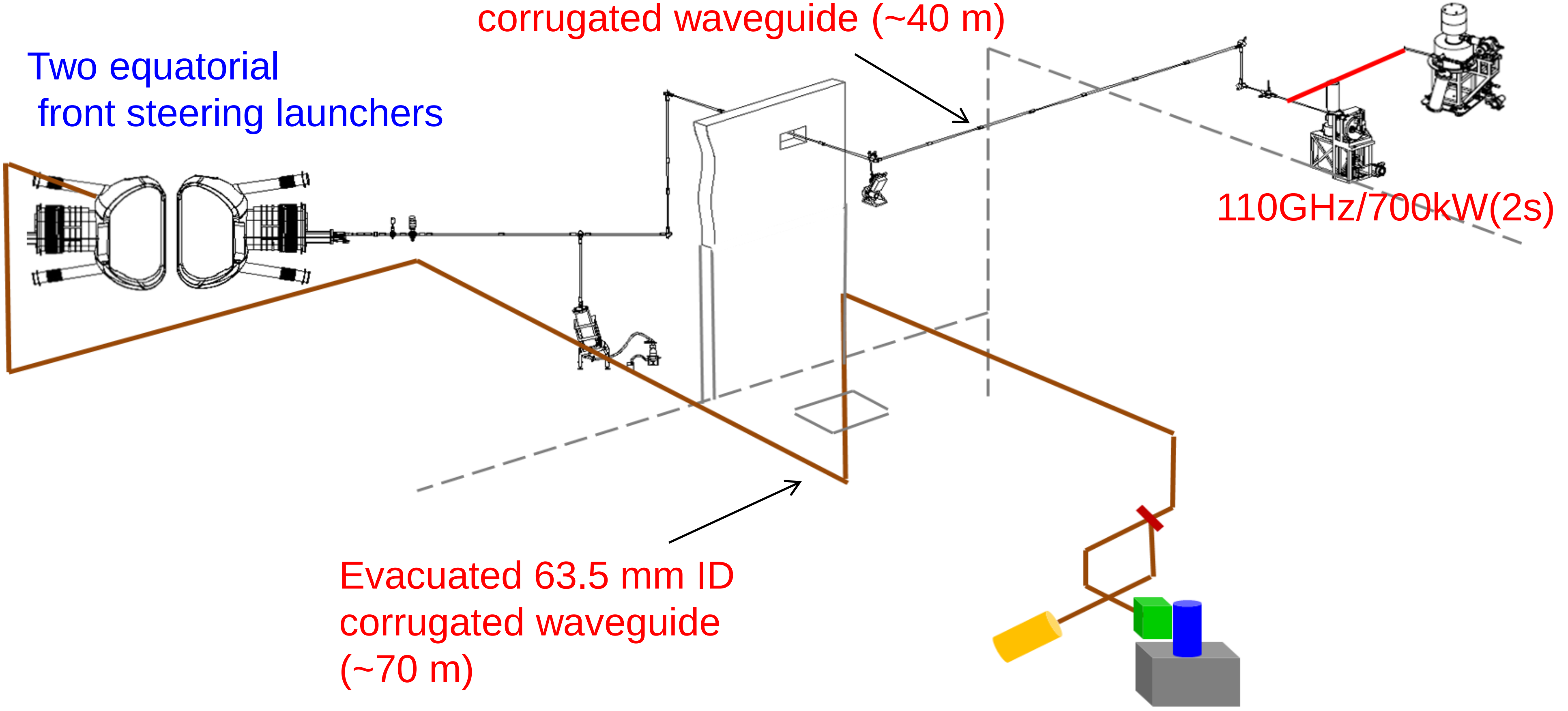
•Black : achieved •Red : by 2012

KSTAR and heating devices



Introduction of KSTAR ECRH system

Layout of KSTAR ECH system



Evacuated 31.75 mm ID
corrugated waveguide (~40 m)

84GHz/500kW(2s)

Two equatorial
front steering launchers

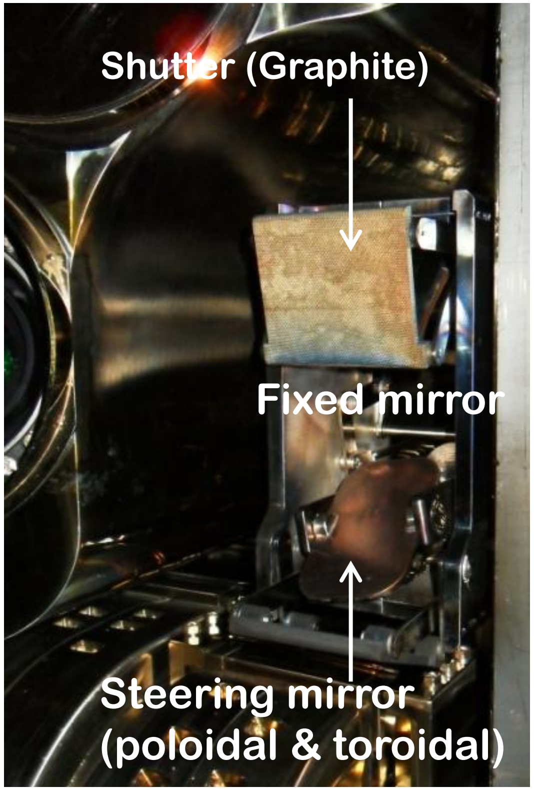
110GHz/700kW(2s)

Evacuated 63.5 mm ID
corrugated waveguide
(~70 m)

170GHz/1MW(20s)

KSTAR ECH launcher

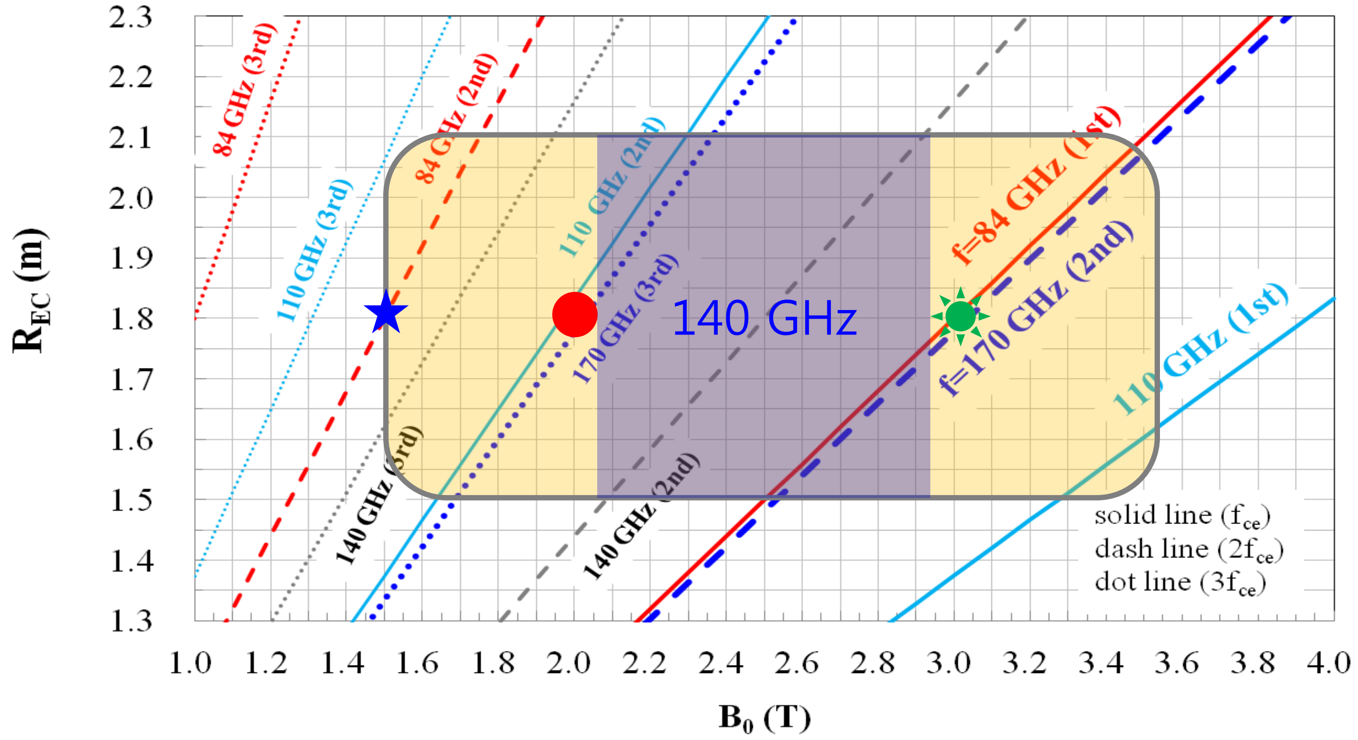
- KSTAR launcher is a just two-mirror front steering launcher
- Steering mirror pivoted at ~30 cm below the equatorial plane, and is steered in both directions (poloidal/toroidal)



- Toroidal range: +/- 30 deg
- Poloidal range: 50 to 90 deg from vertical
  - $0 \leq \rho \leq 0.73$ for the Bt = 2.65 T (170 GHz)
  - Steering is possible during the pulse with an accuracy of +/- 1 deg at a rate of 10 deg/sec

Toray-GA calculation

Operating ranges of Bt considering KSTAR EC frequencies



- 105/140 GHz dual EC frequency is also under consideration for future ECH system

f (GHz)	R_{EC} (m)	B_0 (T)	Remark
84	1.5 ~ 2.1 1.8 ~ 2.1	2.5 ~ 3.5 (O1) 1.5 ~ 1.75 (X2)	No 3rd harm. resonance in shadowed region
110	1.5 ~ 1.6 1.5 ~ 2.1	3.3 ~ 3.5 (O1) 1.65 ~ 2.3 (X2)	No 3rd harm. resonance in shadowed region
170	1.5 ~ 2.1	2.5 ~ 3.5 (X2) 1.7 ~ 2.4 (X3)	

Physics Issues of KSTAR ECRH

- MHDs control
  - Edge localized mode (ELM) control
  - Toroidal rotation control
  - Sawteeth control
  - Tearing mode control for high beta operation
- On-axis electron heating and On/Off-axis ECCD for current profile control
  - Core impurity control and support the advanced operation scenario
- ECH-assisted startup
  - KSTAR is fully superconducting tokamak
  - Slow rising low loop voltage due to limitation of the superconducting poloidal field coil and vessel screening effect
  - In ITER, ECH-assisted startup is very important issue. The inductive electric field is very low, 0.3 V/m with the strong vessel screening effect

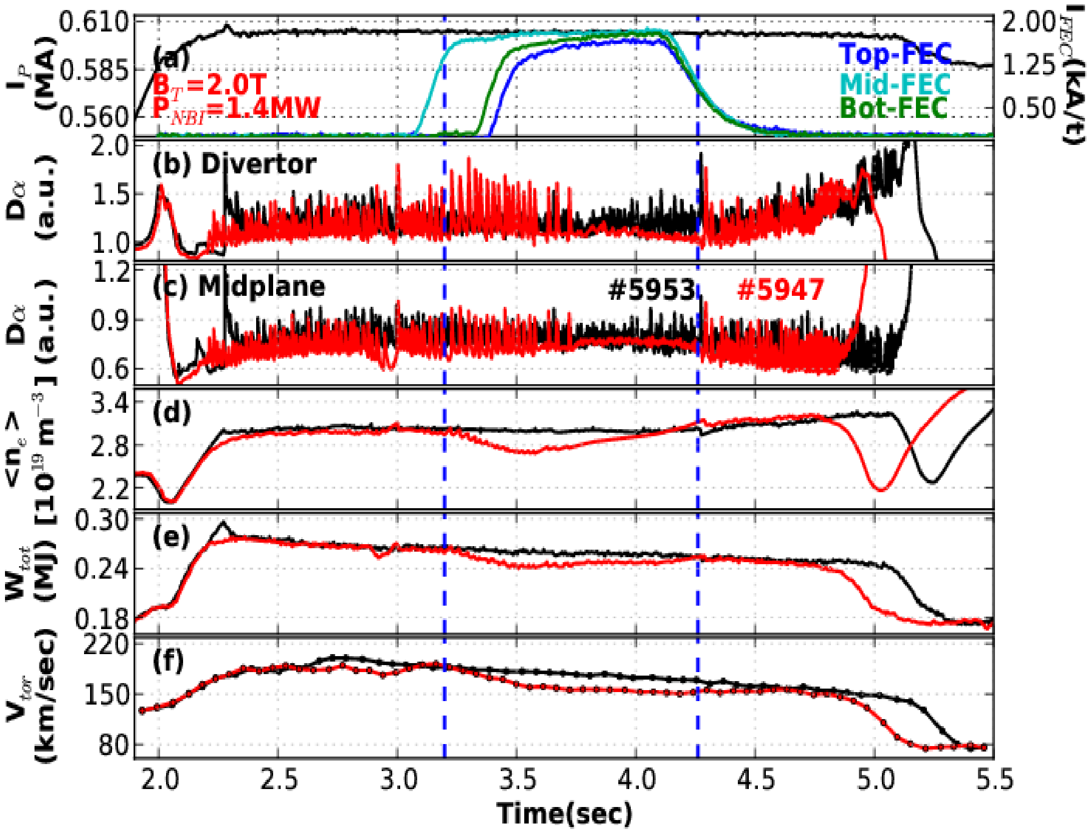
MHD control using KSTAR ECRH

Controllability of Edge Localized Mode (ELM) by edge X2 ECH/ECCD; What is ELM?

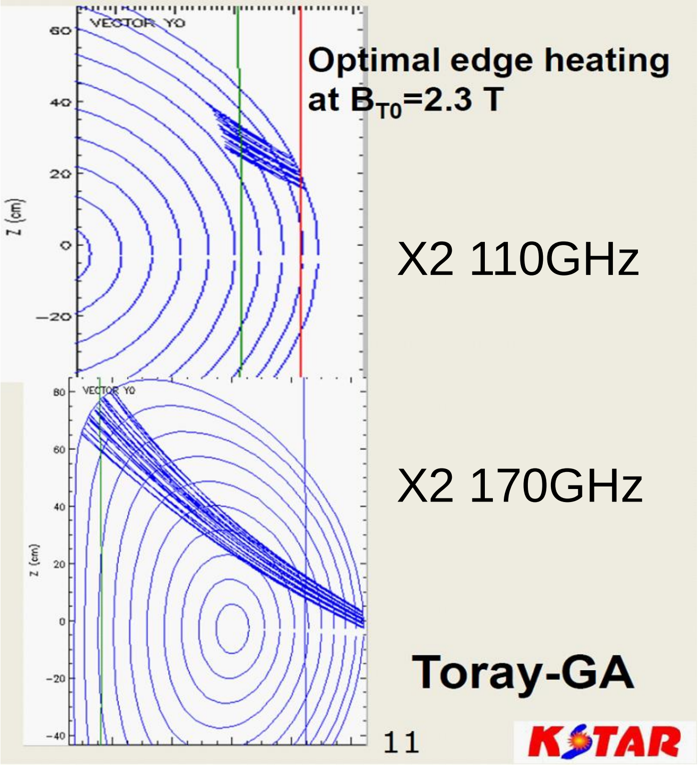
- An **edge-localized mode** ("ELM") is a disruptive instability occurring in the edge region of a tokamak plasma due to the quasi-periodic relaxation of a transport barrier previously formed during an L --> H transition. This phenomenon was first observed in the ASDEX tokamak in 1981.
- Control of edge localized mode (ELM) instabilities in high confinement (H-mode) tokamak plasmas is a critical issue for the operation of future high performance tokamaks including ITER due to predictions of unacceptably high erosion of material surfaces in divertor by heat and particle fluxes during these transient events
- In KSTAR, several methods for ELM control have been conducted such as resonant magnetic perturbations (RMPs), supersonic molecular beam (SMBI) injection, plasma vertical jogging/kicking, and edge-localized current drive by ECCD [Jayhyun Kim, et al., Nucl. Fusion, 52, 114011, 2012].

Experimental results of ELM controllability by RMP and edge X2 ECH/ECCD

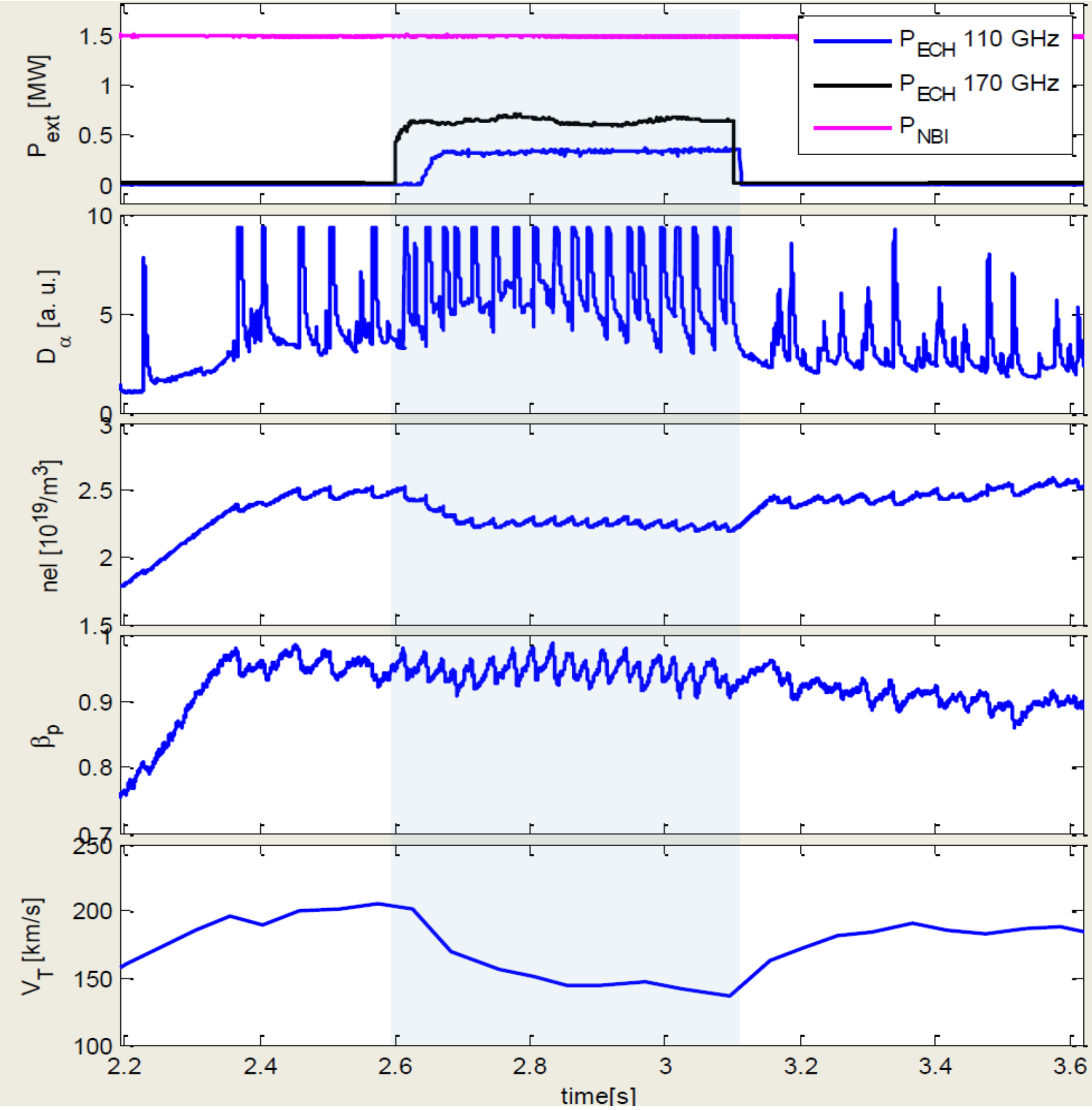
ELM control by Resonant Magnetic Perturbation using IVCC coil



ELM control by edge EC current drive



ECH near pedestal increases f_{ELM}



Shot 6313

At relatively low *v**

f_{ELM} before ECH ~20~30 Hz

f_{ELM} during ECH ~40 Hz

f_{ELM} after ECH ~20~30 Hz

Clear n_e & V_T drop

Similar $\triangle W_{ELM}$

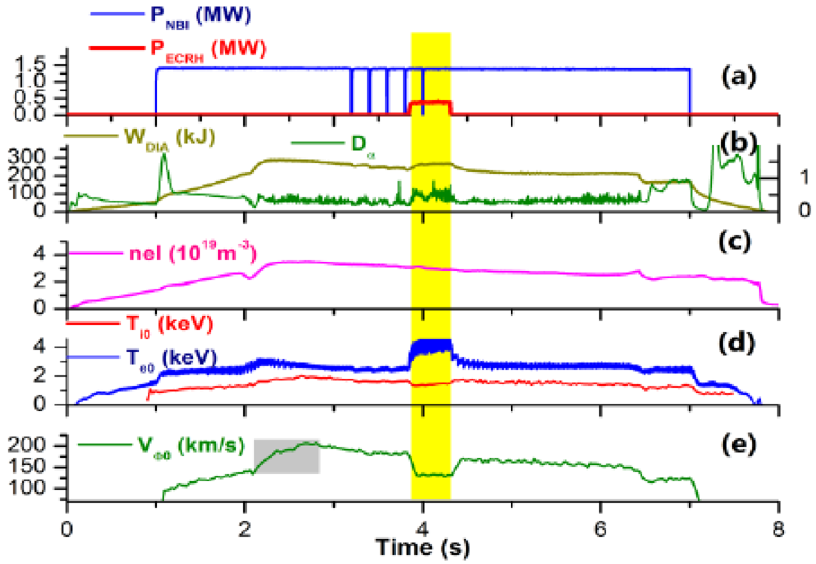
No clear effect of ECCD

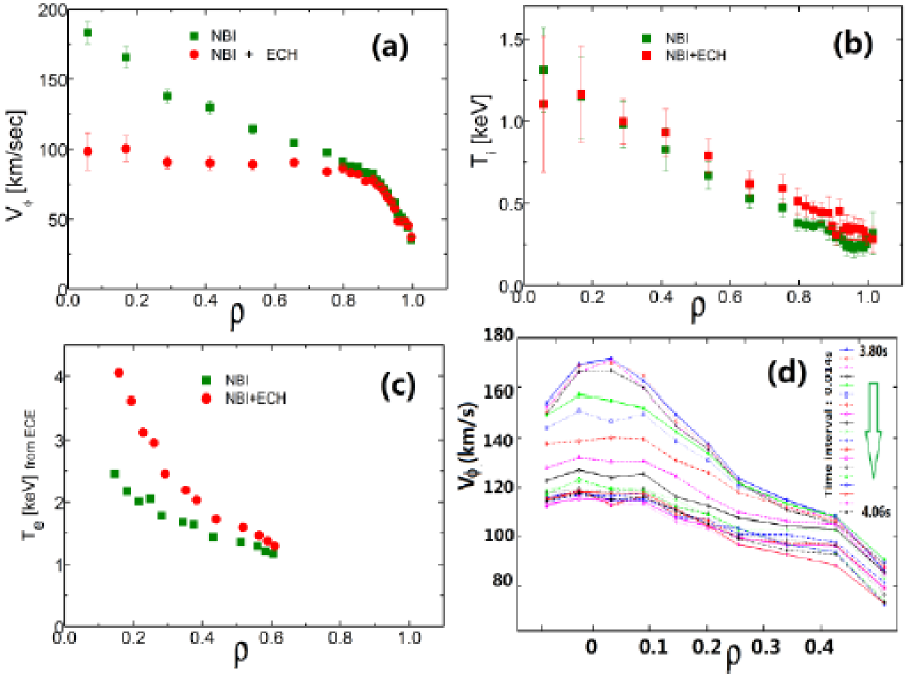
Result in August 2011

1

Alteration of toroidal rotation by ECH

- Toroidal rotation is important for control of stability and transport in tokamaks. While NBI is used widely to control rotation in contemporary tokamaks, it is not a feasible approach for ITER.
- In KSTAR, ECRH heating on NBI heated discharges have been widely investigated and 350 kW ECRH was applied to NBI-heated(1.3MW) H-mode plasmas on KSTAR





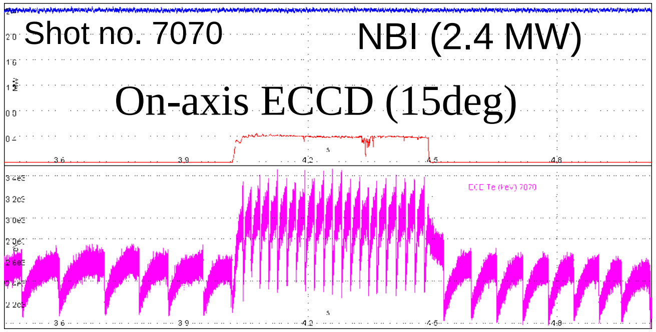
- **On-axis ECH (400kW) to co-NBI plasmas**
  - Counter-current torque in core: – ΔVϕ/Vϕ ~ 30%
  - Strong correlation: –Δ(▽Vϕ) ~ +Δ(▽Te)
- **Hypothesis: core intrinsic torque reversal upon ITG (ion temperature gradient) →TEM (trapped electron mode) by Te steepening**

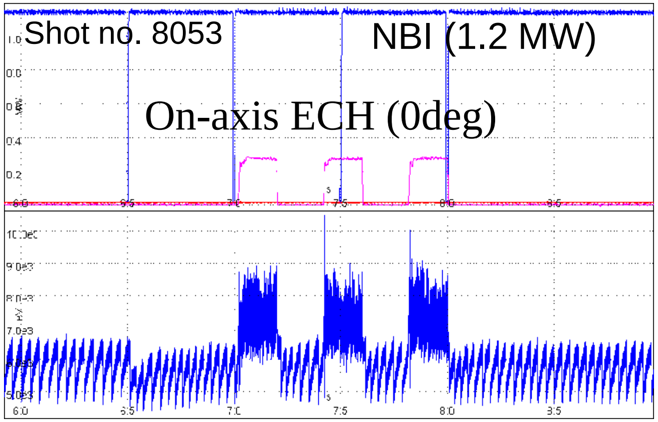
Sawtooth controllability of KSTAR ECH in NB heated plasmas

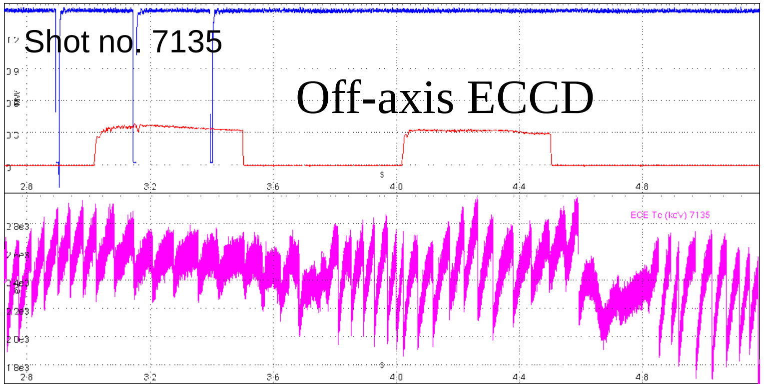
- **Benefits of long period sawteeth: improved performance with gradients build-up and the increase of stored energy.**
- **However, the long sawtooth period create a seed island triggering secondary long-lasting MHD activity, neo-classical tearing mode (NTM) which cause confinement degradation or disruption**

- **The sawtooth control in ITER is very important because the very long sawtooth periods is expected due to large fusion-born alpha particle population in the core**
- **In KSTAR it was found that long period sawteeh were generated with adding second beam (near on-axis) in NBI**

- **Demonstrated that the period of Sawtooth (stabilized by two beams) is shortened in NB-heated plasmas by**
  - **On-axis ~400 kW X2 110 GHz ECCD (100 ms → 20 ms)**
  - **On-axis 270 kW X2 100 GHz ECH) → grassy sawtooth generation**
- **On the other hand, the increase of the sawtooth period with decreased amplitude is observed by Off-axis X2 110 GHz ECCD**
- **We are planning the investigation of sawtooth period with various ECH/ECCD injection conditions and real-time control of Sawteeth (locking, pacing) using modulated 170 GHz X2 ECH/ECCD**





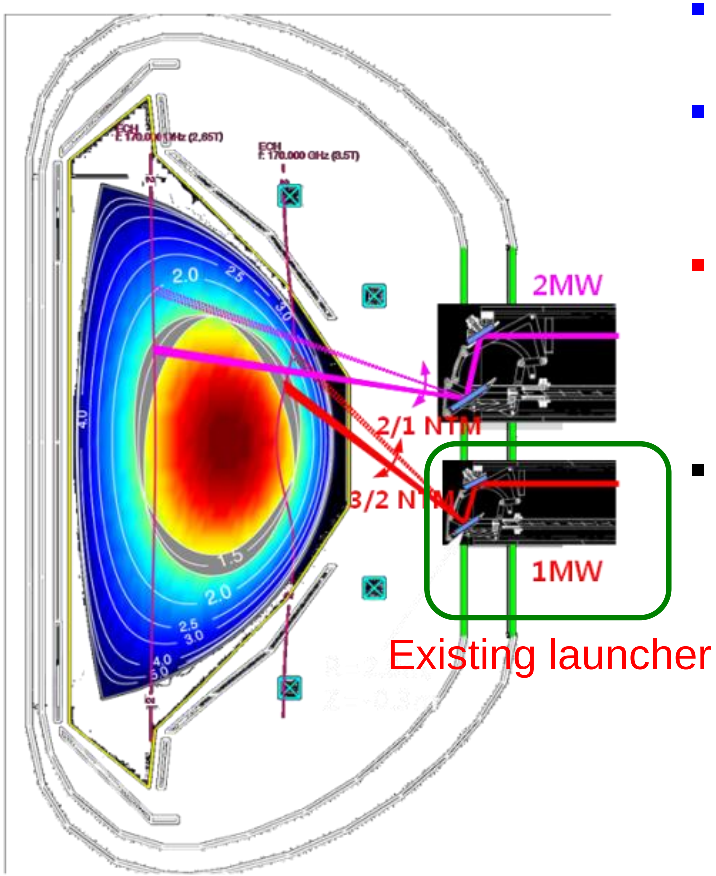


Prospects of application of KSTAR ECH to neo-classical tearing mode (NTM) control

- In recent JET experiment, a long sawtooth triggered an NTM in low-confinement mode
- NTMs degrade plasma confinement by ~15-20% drop and can cause the disruption.

- So, the application of KSTAR ECH to NTM control is very important issue to achieve the high beta long-pulse high-confinement mode

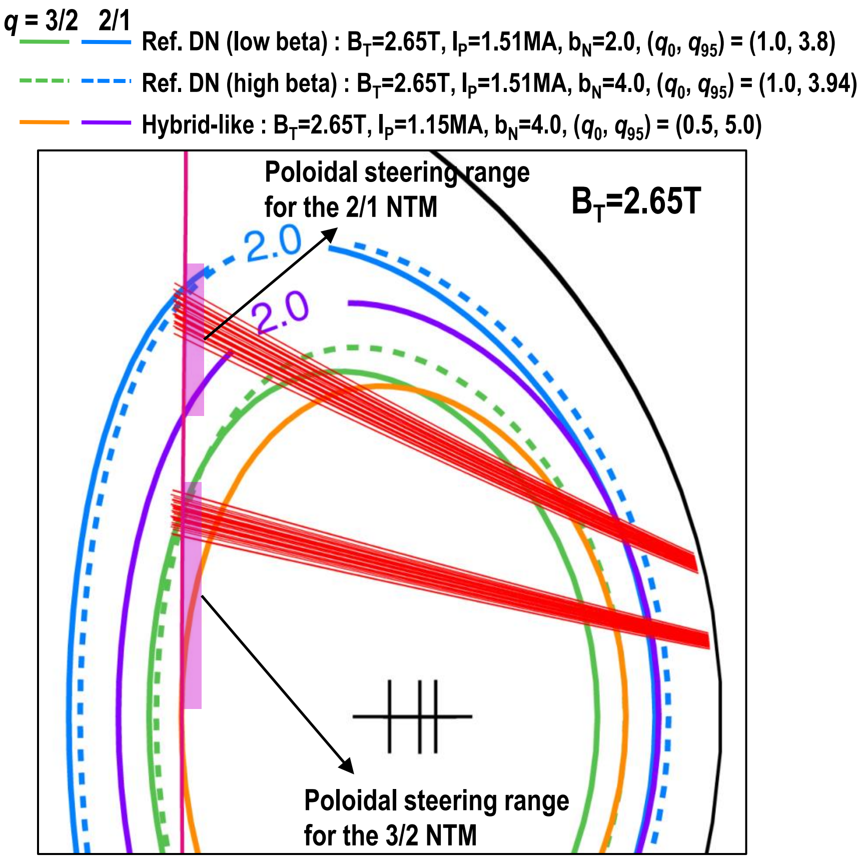
- Scheme of NTM control in KSTAR
  - ➢ Installation of two vertically separated front steering launchers (FSLs) is to handle 3MW(2MW+1MW) EC-wave power.
  - ➢ In the simulation, radial location of steering mirror is fixed at 2.8 m and wave can be poloidally steered in a range of 50~90^{o} for upward injection case and 90~110^{o} for downward injection case.
  - ➢ In case of EC-wave deposition on the outboard region (red beams), narrow current density profiles can be driven on the m/n = 3/2 & 2/1 NTM resonant surfaces, but amount of driven current is low due to strong e-trapping effect.
  - ➢ **In case of EC-wave deposition on the Inboard region is more favorable for NTM control**



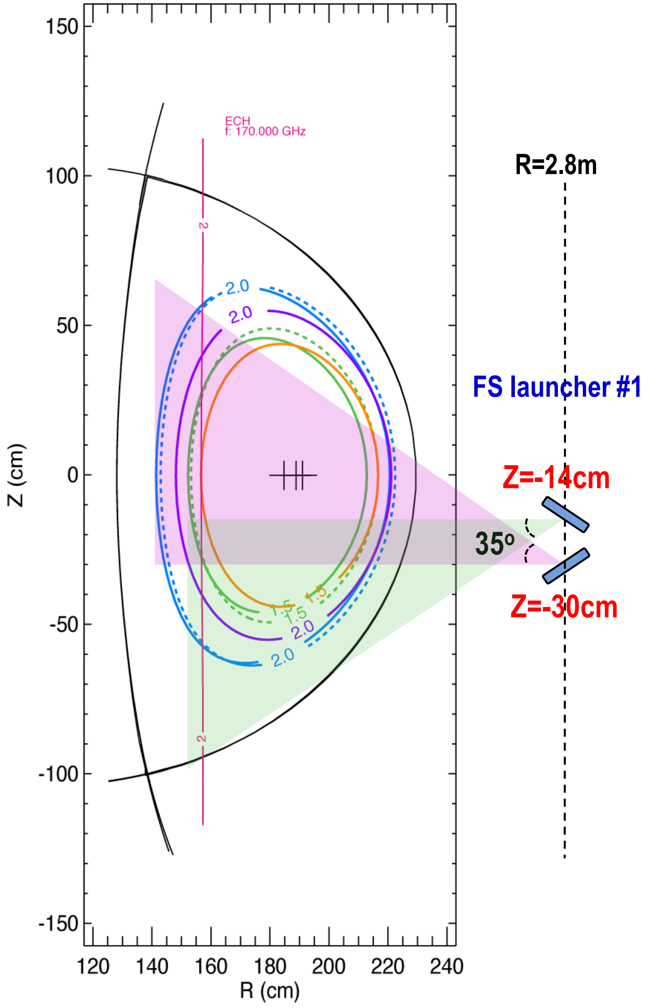
- Schematics of NTM suppression by ECCD in KSTAR (Y.S. Park and Y.S. Hwang, Fus. Eng. Design 83, 2008)

B_T=2.65T Exhibits Favorable ECCD Conditions for NTM Suppression (Toray-GA calculation)

- **B_T=2.65T is adequate to align the ECCD to NTM flux surfaces of various KSTAR equilibria**

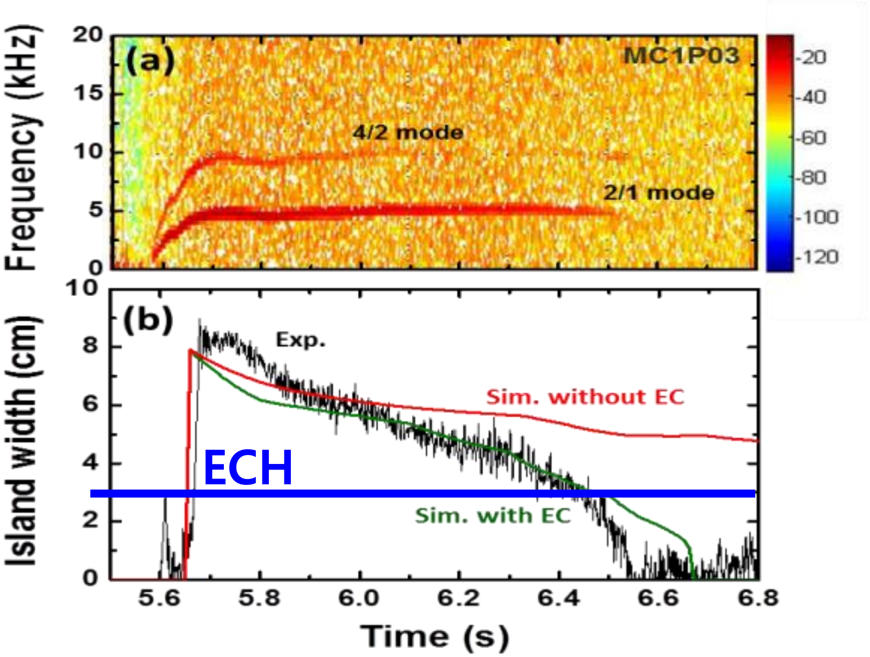


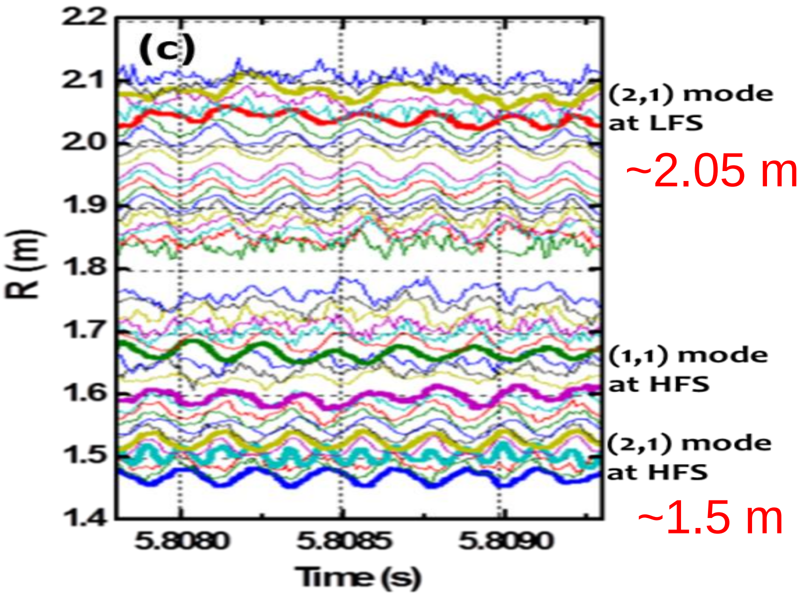
- q=3/2 & 2/1 flux surfaces of the 3 different KSTAR equilibria



Experimental results of tearing mode control by ECCD

- 110GHz X2 and 170 GHz X3 ECCD
- The island width and mode number were identified by Mirnov coil arrays and the island location was estimated by ECE.
- The FFT frequency spectrum and the island width taken from Mirnov coil signals.
- After being triggered with a small island width around 5.6 s, the tearing mode grows rapidly to the maximum island width of ~8 cm, then gradually shrinks and terminates around 6.6 s



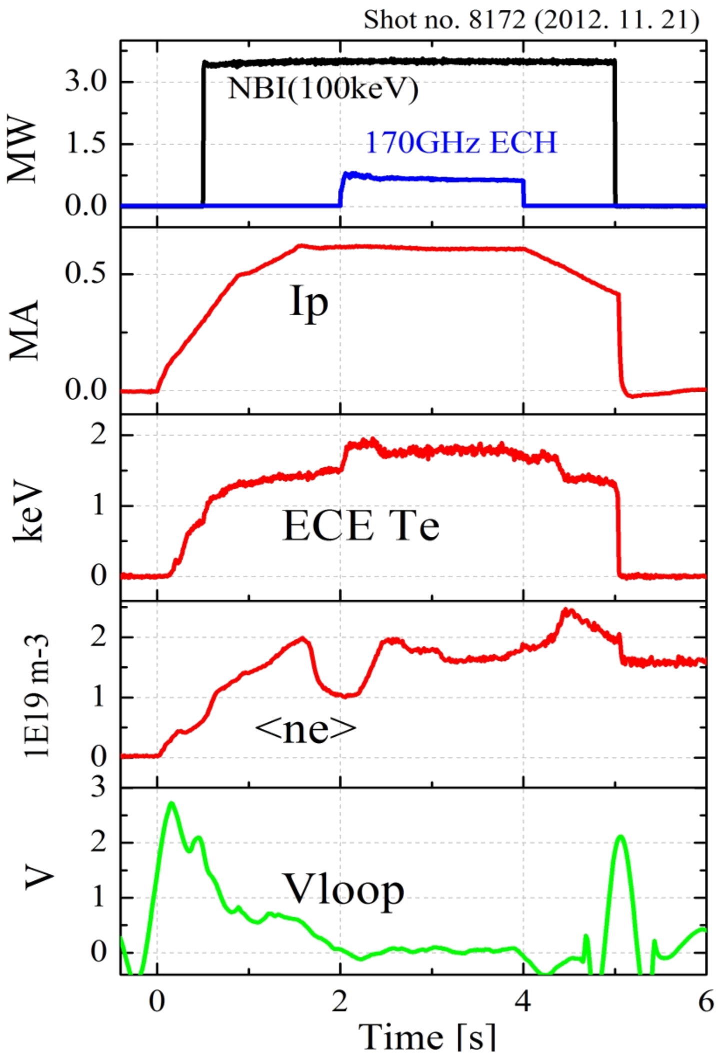


ECE signals shows the position of island where phase inversion of Te oscillation

On-axis electron heating using KSTAR ECRH

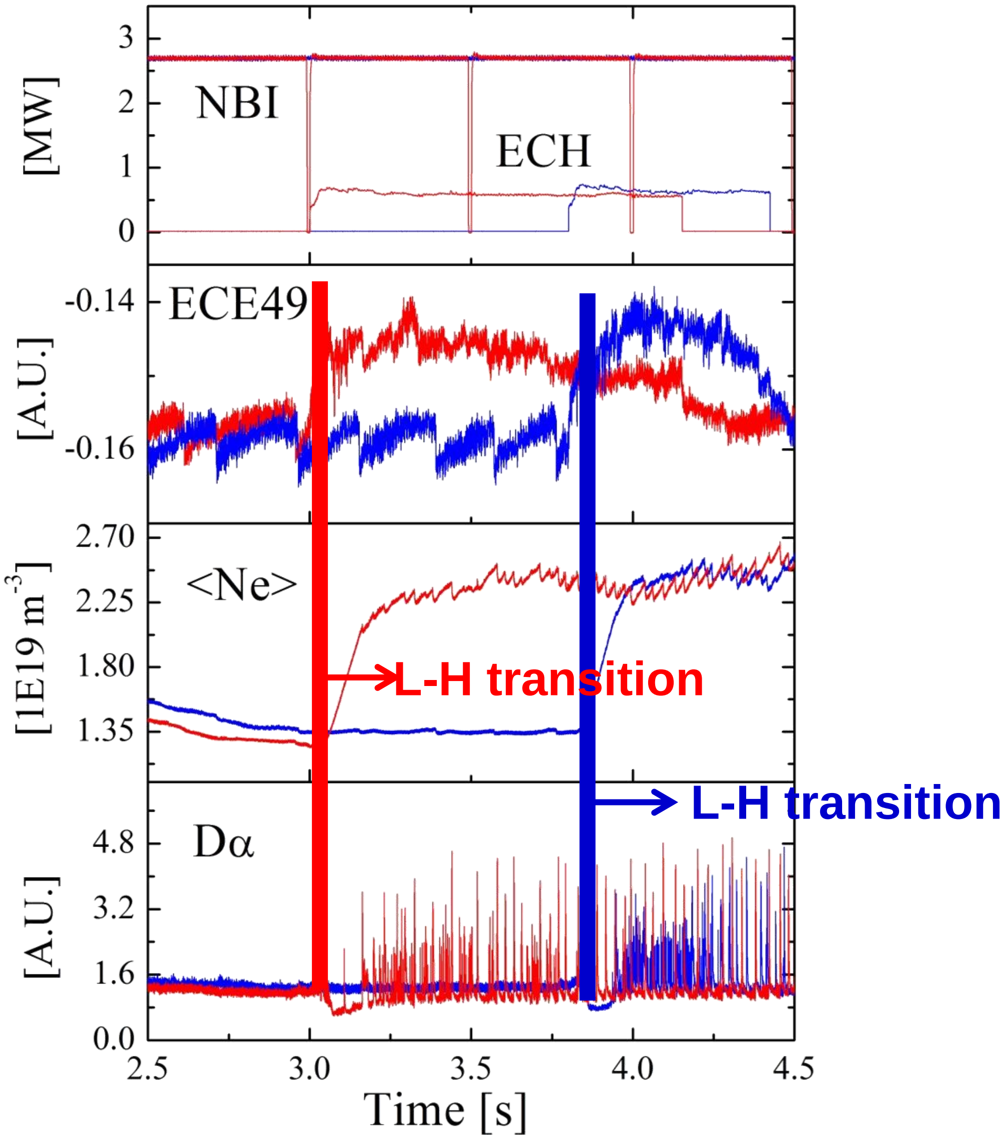
170 GHz, 0.8 MW, 2s 170 X2 on-axis ECH heating in NBI-heated L-mode discharge with Bt = 3 T, the plasma current of 0.6 MA

- Tangential neutral beams from two ion sources
  - No. 1 IS: 100keV, 1.7 MW
  - No. 2 IS: 100keV, 1.8 MW
- 170 GHz on-axis heating with perp. angle
  - 1 MW output power at the gyrotron window
  - Pulse width: 2 s
  - Loop voltage drops to zero by addition of 170 GHz ECH
  - Te increases by ~30%
  - <ne> increases by factor of 2

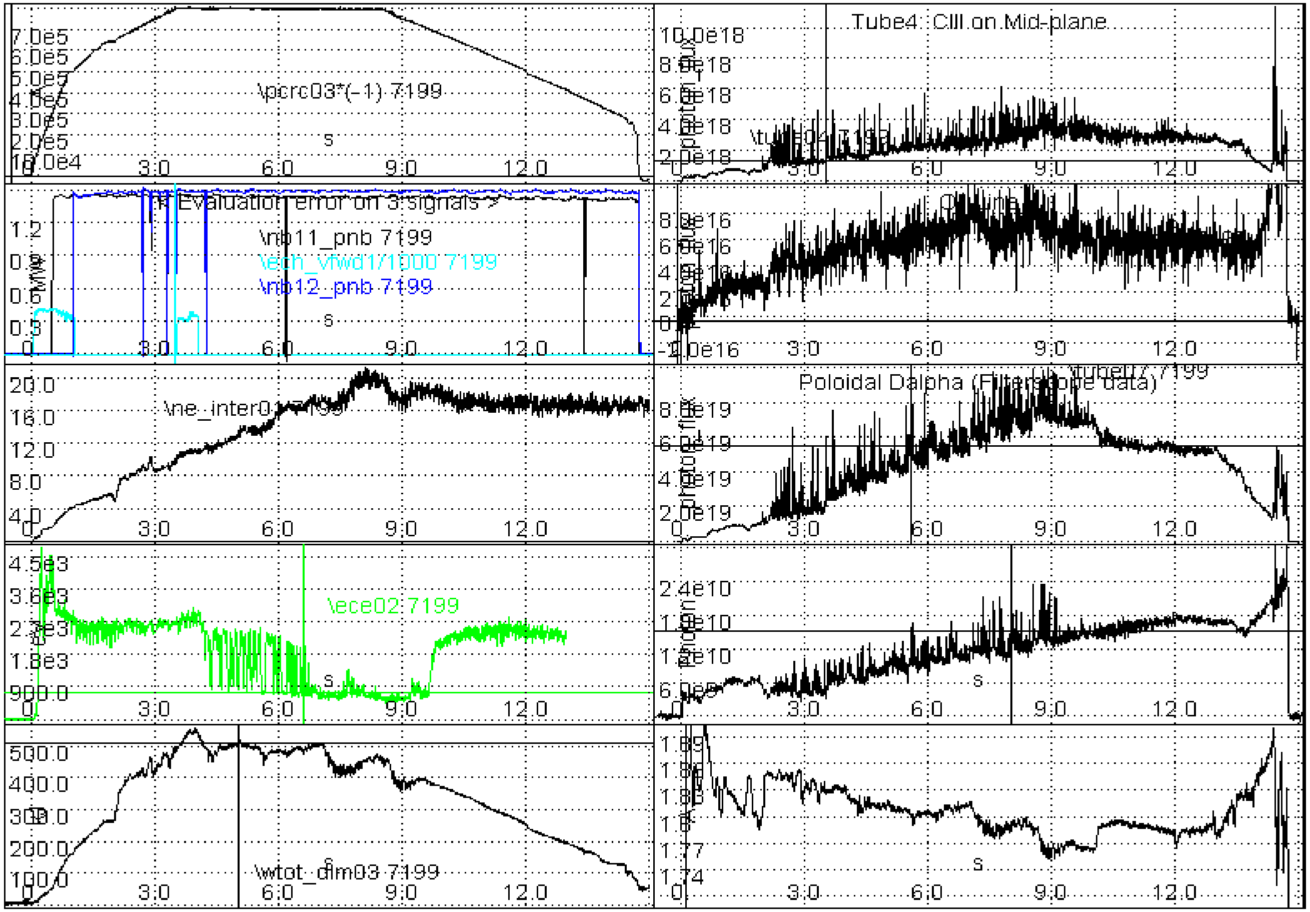

Shot no. 8172 (2012. 11. 21)

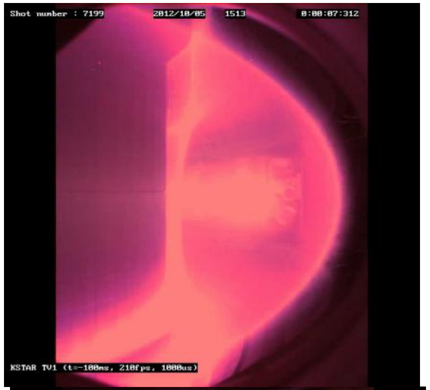
LH transition by 170 GHz X2 on-axis ECH at Bt = 3 T

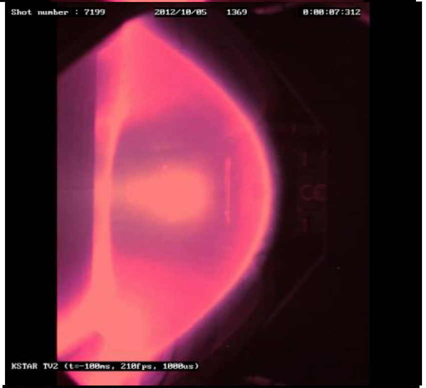
- 2.7 MW beam power was not enough for L-H transition for Bt = 3 T and <ne> ~ 2E19 m^{-3}
- ~0.7 MW 170 GHz X2 ECH turned on L-H transition
- Turn-on of L-H transition is determined by the switching time of ECH

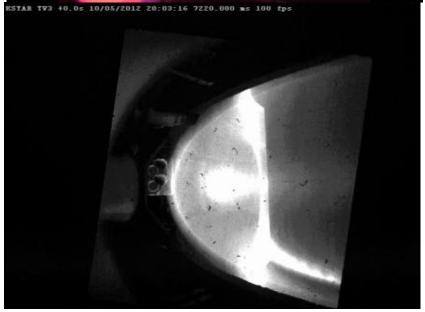


Issue of impurity accumulation at the core; ECH would be helpful to cure the core impurity accumulation in upcoming KSTAR operation









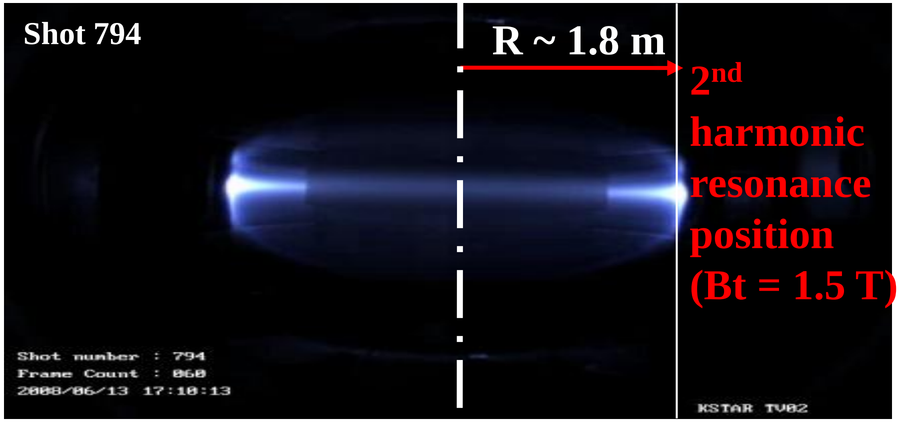
ECH-assisted startup in KSTAR

Why ECH-assisted startup is important in superconducting devices?

- Electron heating by EC beam before/after applying the inductive voltage (loop voltage) is able to reduce the required breakdown loop voltage particularly in large superconducting tokamaks which has limitation of loop voltage due to thick VV and engineering limitations of superconducting coils…
- ITER is strongly considering ECH-assisted startup due to the slow rise of E_{tor} which may result from strong vessel screening, so ITER-relevant ECH-assisted startup experiment is being performed as the ITPA activity (IOS2.3)
- Keeping ECH heating after the breakdown reduces the resistive power consumption ($\propto Te^{-3/2}$) leading to the flux saving
- Reliable startup even for bad wall conditions and startup without runaway electrons which can damage the walls
- Main Three Approaches of ECH-assisted startup in superconducting devices
  - ECH pre-ionization with **poloidal magnetic field null** before the onset of the inductive voltage
  - ECH switching on after the onset of the inductive voltage
  - Non-inductive current startup forming initial closed flux surfaces by ECH under a weak Bv
  - In KSTAR first plasma campaign, 84GHz X2 ECH pre-ionization was attempted, and the successful startup is obtained with loop voltage of 2.0 V

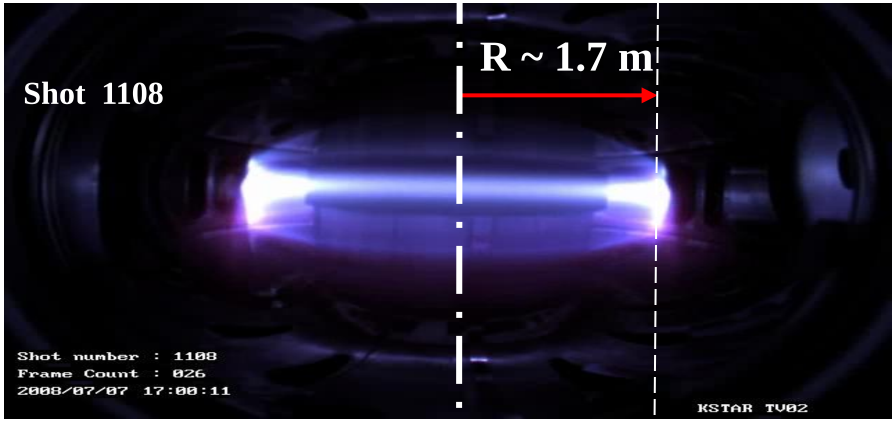
Pre-ionization with poloidal magnetic field null

- X2 84 GHz ECH is used for ECH-assisted startup using pre-ionization in KSTAR first plasma campaign



2nd harmonic resonance position (Bt = 1.5 T)

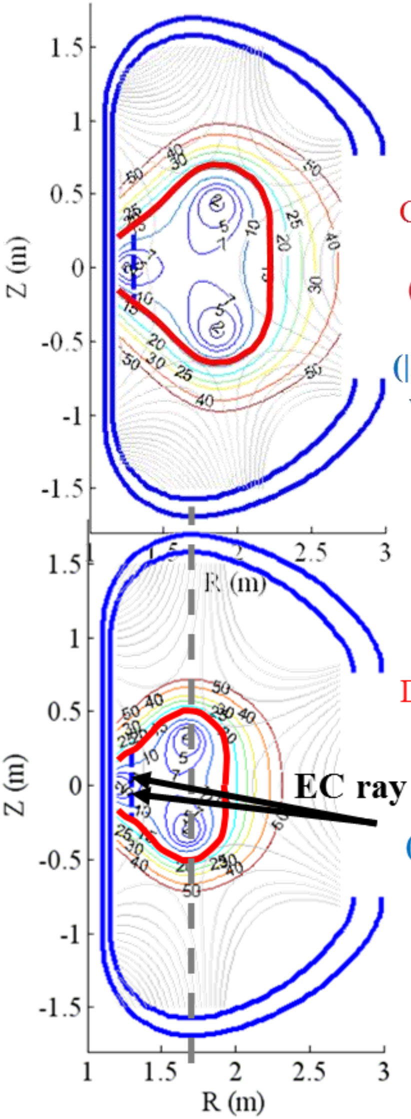
Conventional mode
Perpendicular launch
EC beam target:
Z=0m, R=~1.8 m



Dipole-like mode
Perpendicular launch
EC beam target:
Z= 0 m, R=~1.7 m

Fast CCD camera (200 fps) image

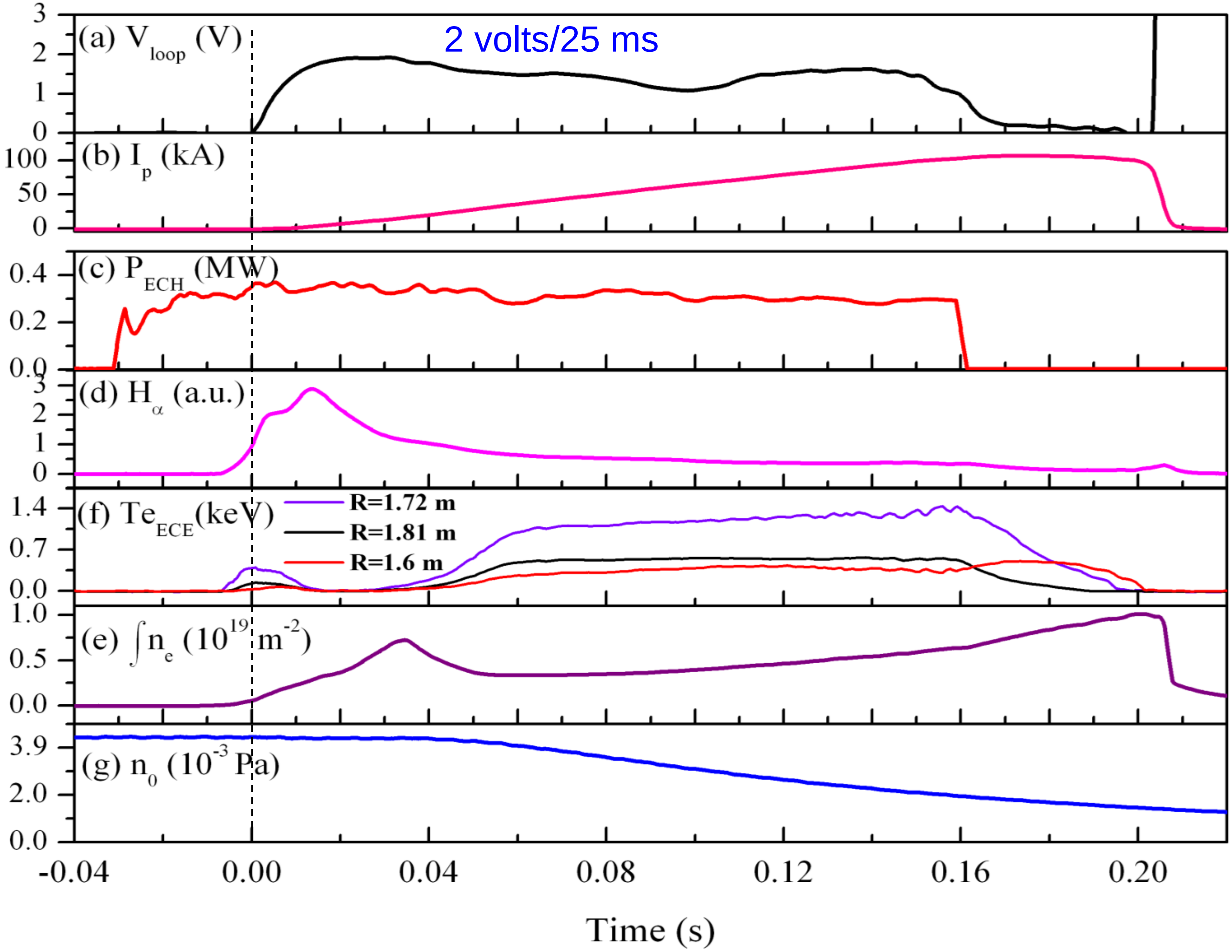
Field Null (FN) configuration



Conventional mode (used for 1st plasma) (|Bz| = 0~5 G) with Incoly effect

Dipole-like mode (used for higher plasma current ramp-up) (|Bz| = 20~25 G) with Incoly effect

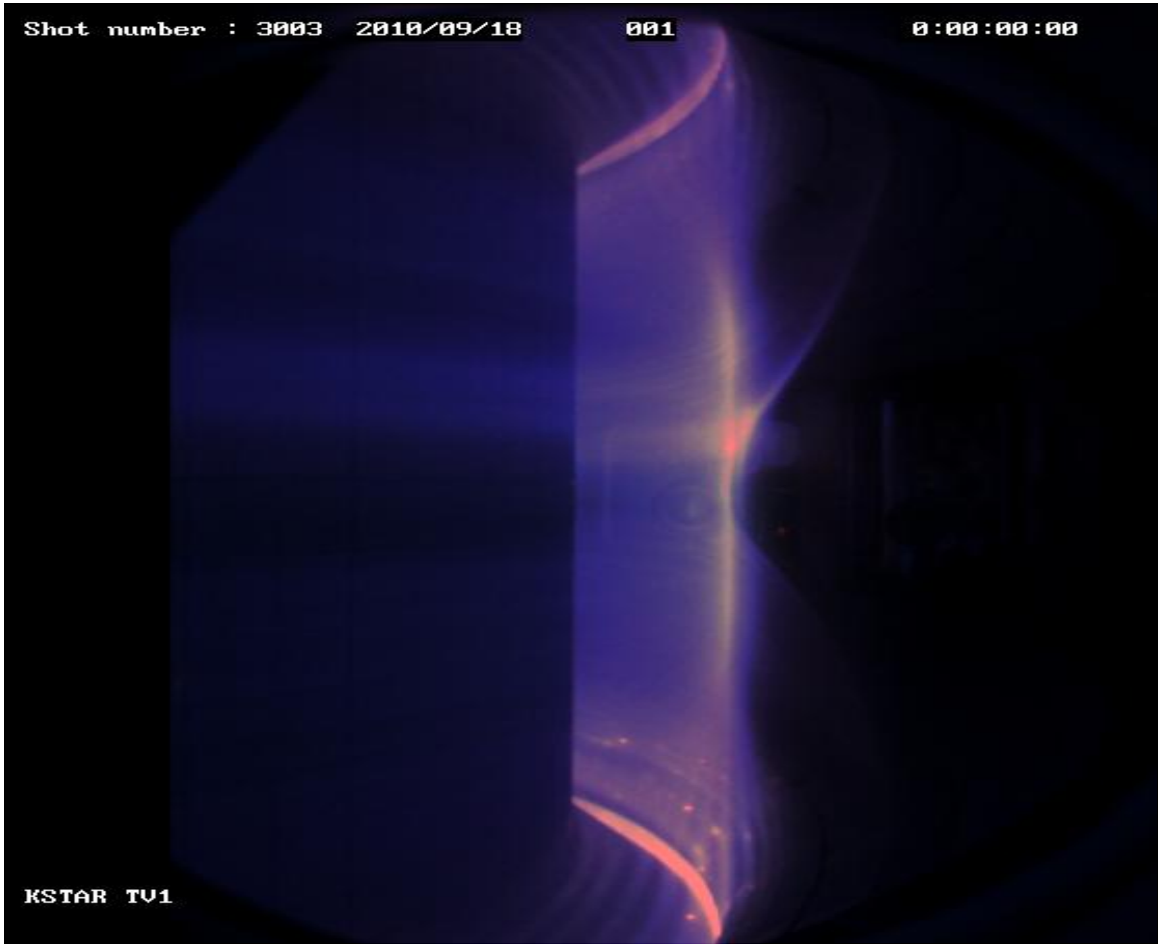
KSTAR 1^{ST} Plasma (2008. 6. 13) is successfully achieved with 84 GHz X2 ECH-assisted startup using pre-ionization



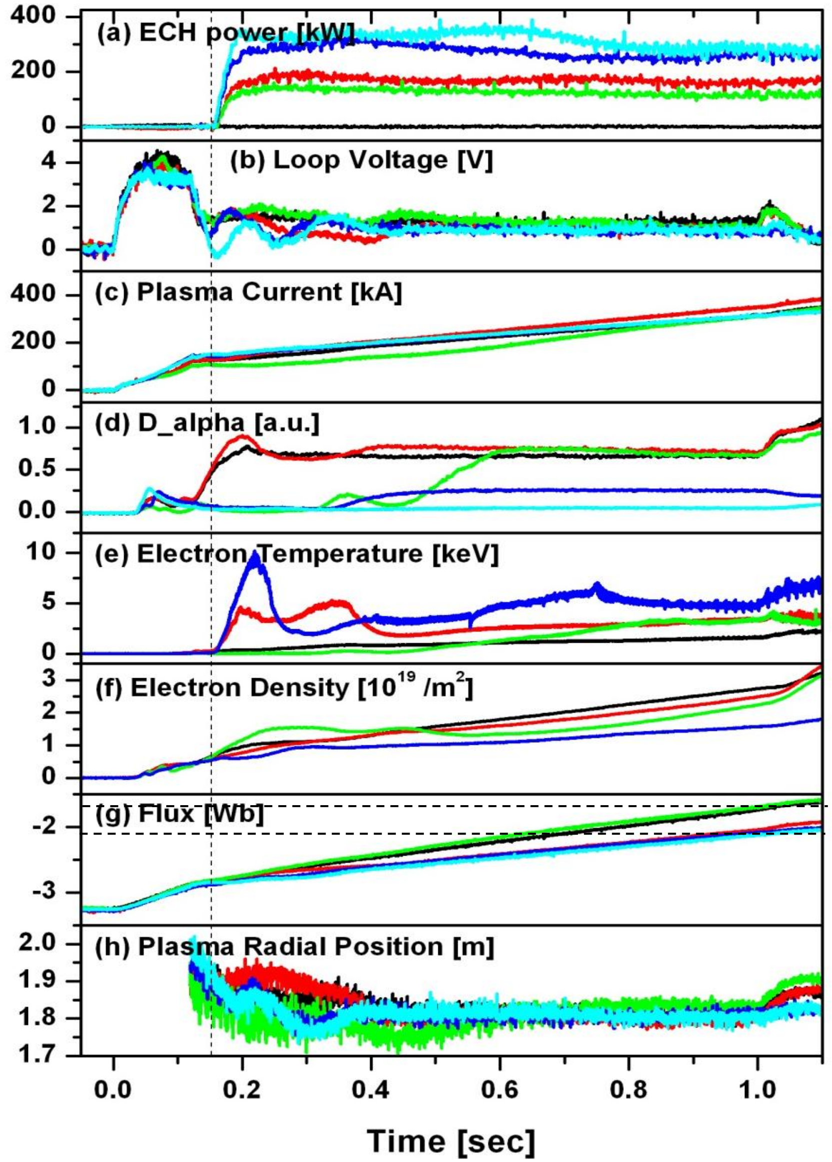
2 volts/25 ms

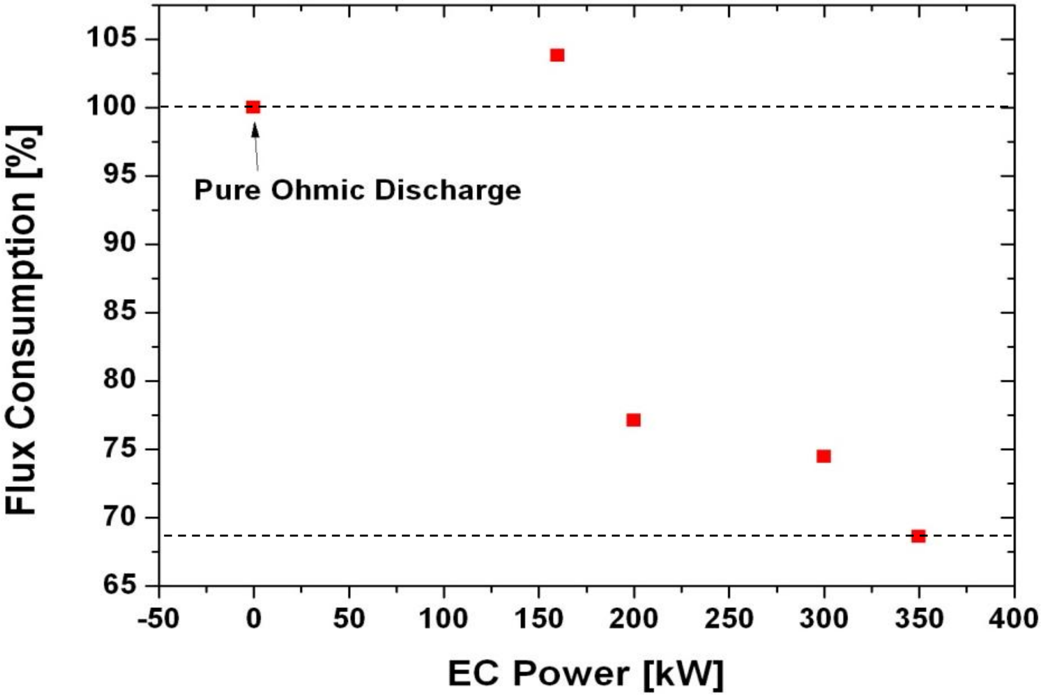
- ECH power ~ 350 kW
- ECH power on t=-30 ms and inductive voltage begins t = 0 s.
- Bt = 1.5 T, R_{X2} = 1.8 m
- Vloop = 2 Volts (at inboard mid-plane)
- Line average density = 1×10^{19} m^{-2} (peak)
- Pre-ionization starts at t=-7.5 ms
- H_2 pre-fill gas pressure: 4.6 x 10^{-3} Pa (at pumping duct)
- No plasma position control

110GHz O1 ECH pre-ionization is well vertically aligned with conventional field null configuration

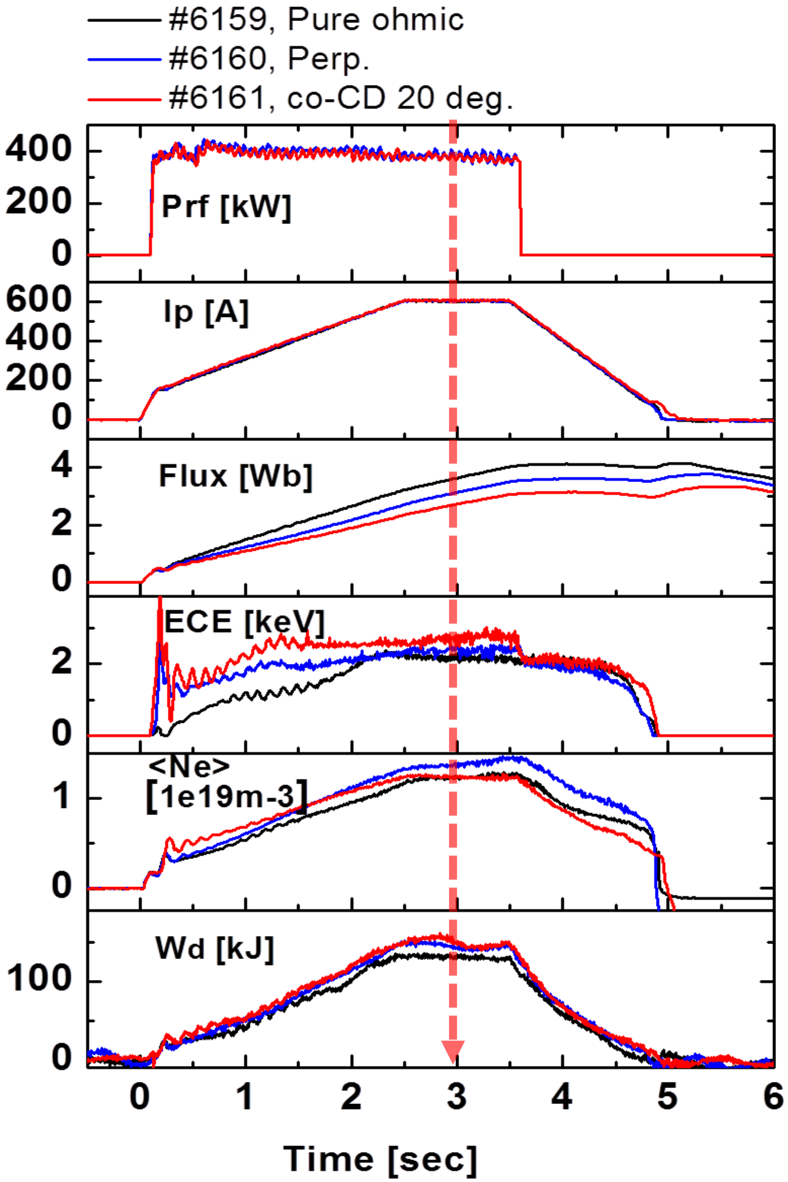


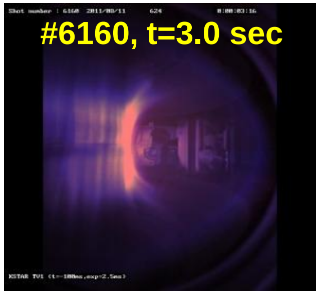
Flux consumption by ECH; 350 kW, 110 GHz X2 ECH in the ramp-up phase (2009-2011) saved flux consumption by 33%

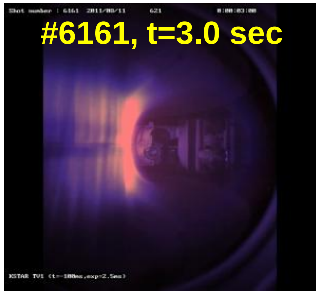




400 kW, 170 GHz X2 ECH-assisted start-up saved maximum 24% flux consumption







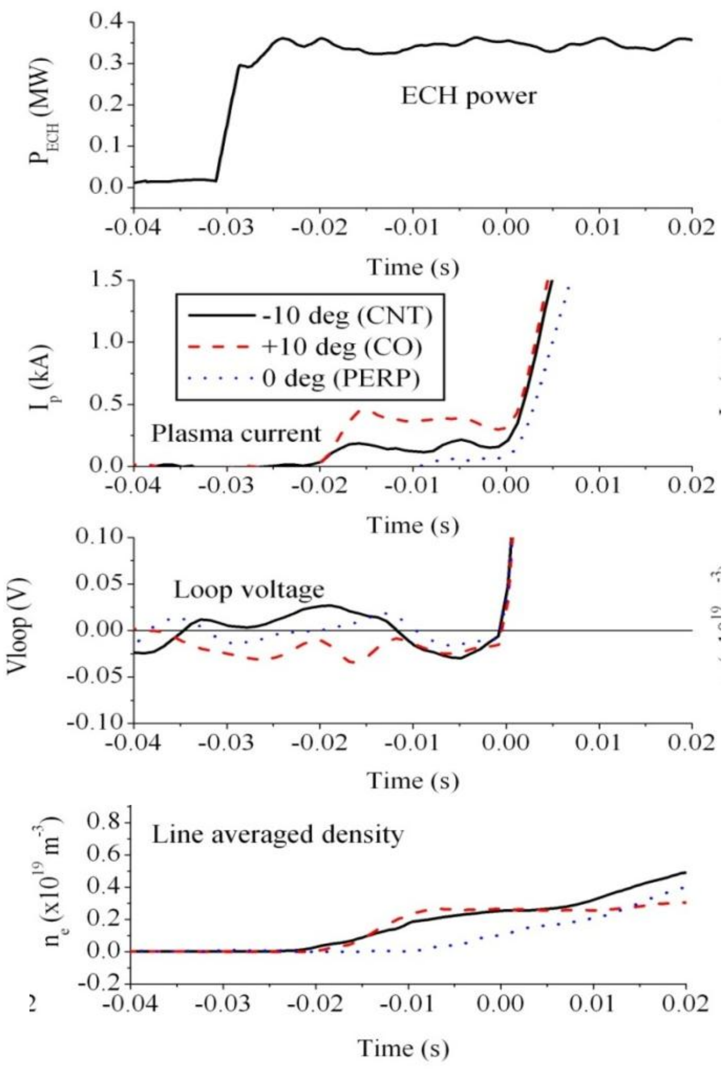
- Operation conditions

  - B_T = 3 T
  - I_P = 600 kA (0.24 MA/s), Rp = 1.8 m
  - P_{ECH} (167.3 GHz, X2) ~ 400 Kw
  - on-axis injection (@ t=100 ms)

- At t = 3.0 sec

	Pure-Ohmic	**Perp. ECH**	**20-deg Co. ECH**
Te [keV, max.]	**2.2 keV**	**2.3 keV**	**2.75 keV**
Consumed Flux [Wb]	**4.13 Wb**	**3.62 Wb**	**3.14 Wb**
Stored E	**132 kJ**	**148 kJ**	**156 kJ**
Ne [$1e^{19}m^{-3}$]	**1.17**	**1.31**	**1.24**
V_{Loop}	**1.29 V**	**1.06 V**	**0.92 V**

Non-inductive current ramp-up by ECH; observations of EC driven non-inductive current (pressure driven Pfirsch-Schlüter current) in pre-ionization phase



Toroidal Equilibrium

B_v field to hold toroidal plasma in equilibrium

$$B_v = \frac{\mu_0 I_p}{4\pi R}\left(\ln\frac{8R}{a}+\frac{l_i}{2}-\frac{3}{2}+\beta_p\right)$$

Here, $\beta_p = \frac{2\mu_0\langle p\rangle}{B_a{}^2} \propto \frac{\langle p\rangle}{I_p{}^2}$, $B_a = \frac{\mu_0 I_p}{2\pi a}$

By normalizing Bv and Ip as: $\overline{B_v} = \sqrt{\frac{2}{\mu_0}}\frac{(R/a)\cdot B_v}{\sqrt{\langle p\rangle}}$, $\overline{I_p} = \sqrt{\frac{\mu_0}{8}}\frac{I_p}{\pi a\sqrt{\langle p\rangle}}$

$$\overline{B_v} = \left(\ln\frac{8R}{a}+\frac{l_i}{2}-\frac{3}{2}\right)\cdot\overline{I_p} + \frac{1}{\overline{I_p}}$$

Current Hoop Force **Pressure Hoop force**

At the initial stage of discharge, Ip is low and pressure term is dominant ;

$$\overline{B_v} = 1\Big/\overline{I_p} \quad \text{or} \quad \overline{I_p} = 1\Big/\overline{B_v}$$

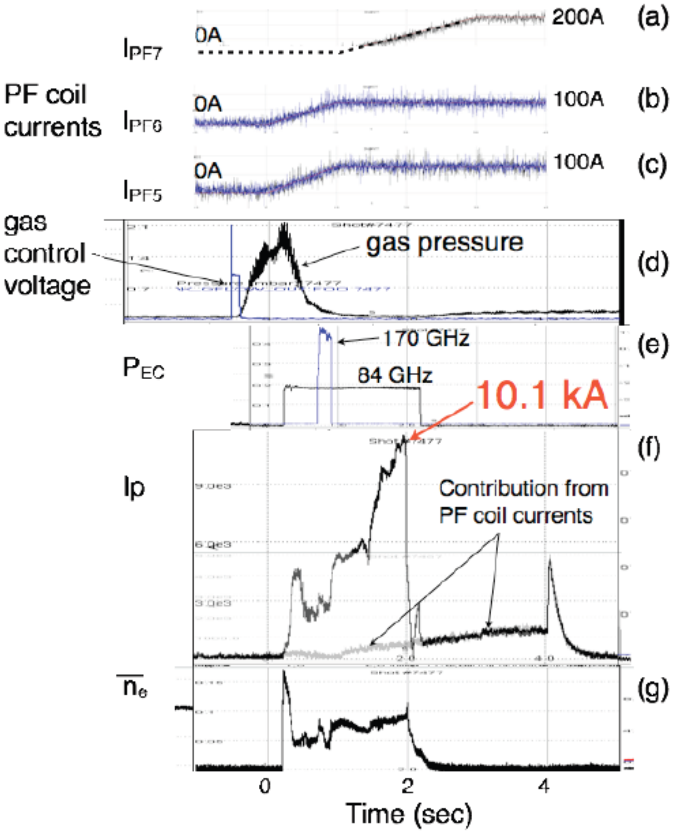
that is, $I_p = 2\pi a^2\langle p\rangle\big/RB_v$

Toroidal current for equilibrium is able to be driven by the plasma pressure under the external fields of Bt and Bv.

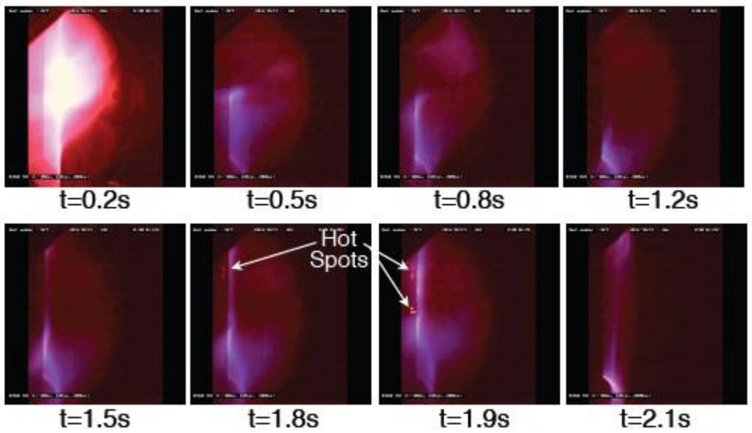
Cf: T. Maekawa, 3rd KO-JA Joint Workshop on RF Heating Physics, NFRI (Jan. 14-15, 2008)

First experiments of non-inductive startup and initial closed field equilibrium by 200 kW 84 GHz O1, 700 kW X2 170 GHz ECH under steady Bv in 2012 KSTAR campaign (Kyoto Univ.)

- Main motivation is to study CS-free startup by ECH in future reactor regarding the economical requirement (plasma beta increases as A=R/a decreases and as κ increases)
- Recent experiments in small devices (LATE) show successful start-up by ECH without induction from the central solenoid. However, this start-up scheme has not been tested in the superconducting-magnet device.



- Time evolution of the discharge of shot 7477 in KSTAR



- Under analyzing the flux loop signals whether the closed flux surface is formed in Kyoto Univ.

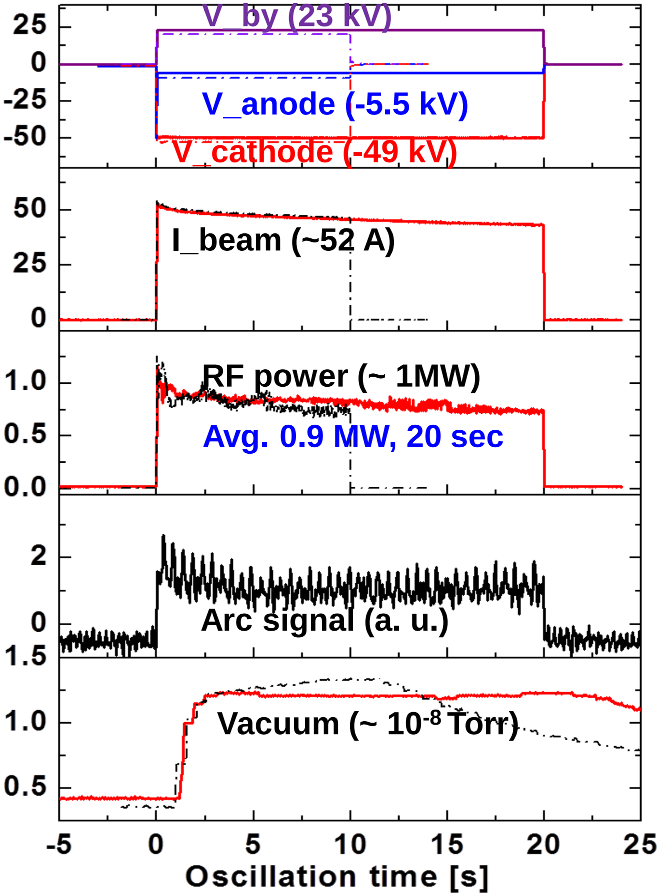
c.f. 33 kA with 2 MW in DIII-D
20 kA with 2.6 MW in JT-60U
With poloidal coils inside the toroidal coils

(G. L. Jackson et al., Nucl. Fusion 51 (2011) 083015
M. Uchida et al., Nucl. Fusion 51 (2011) 063031)

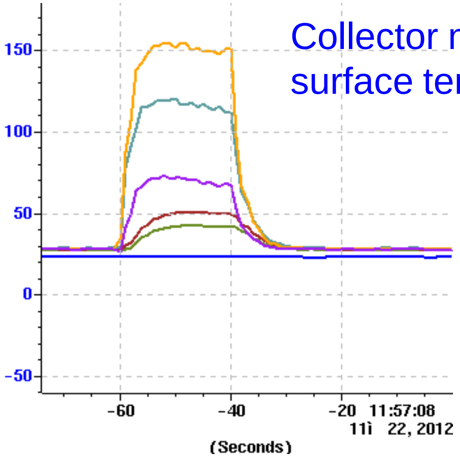
Technology issues for 170 GHz steady-state ECH system

Achievement of 20-s long pulse at the output power of 1 MW of 170 GHz JAEA gyrotron which is considered as important milestone for long pulse KSTAR operation

- **RF output power is 1 MW with duration of 20 sec (avg. power is about 900 kW)**
- **Total electrical efficiency is about 40% and oscillation efficiency ~ 30%**



Channels	**Absorption power [kW]**	**Loss rate [%]**
Main load Load mirror Pre-load	797 6 48	89.6 0.6 5.4
MOU mirror MOU chamber	3 23	0.3 2.6
DC break	12	1.4
Window	1	0.1
Total	**890**	**100**

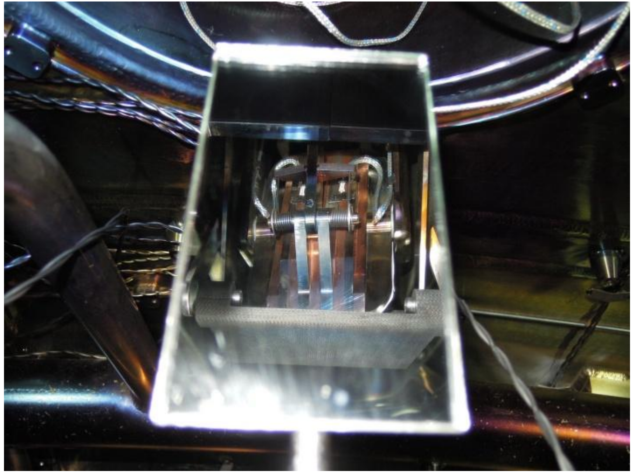


Collector metal surface temperature

Temperature monitoring of passively cooled launcher mirrors by thermocouple sensors installed behind the mirrors; this is first step toward the steady-state launcher development

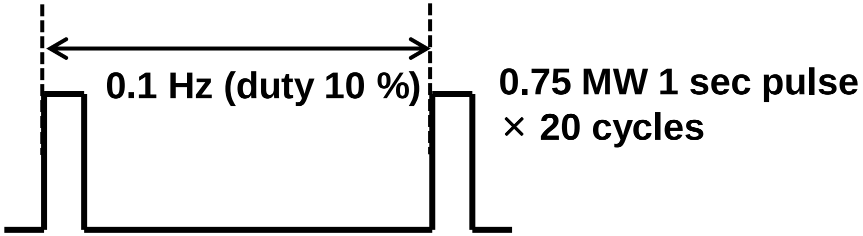
Focusing mirror

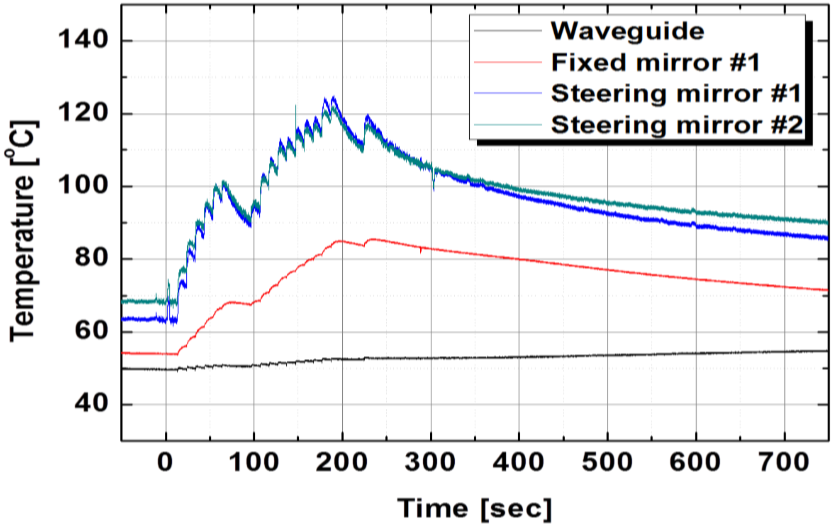
Steering mirror



❖ Temperature rise of the launcher during the ECWC

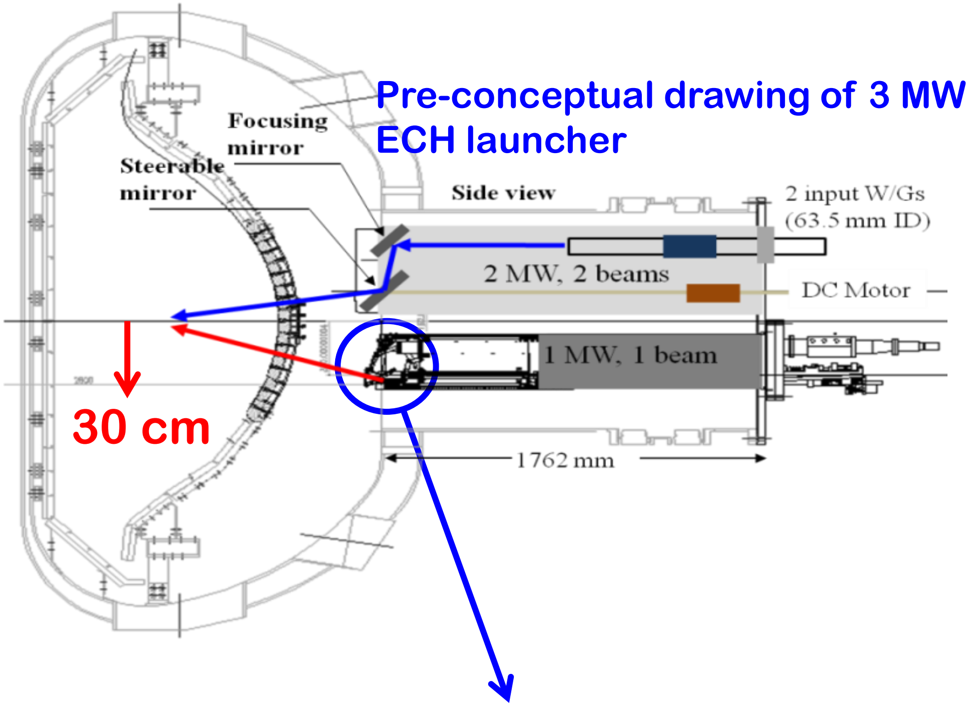
- 0. 75 MW 1 sec pulse × 20 times
- 0.1 Hz operation





Maximum temperature of the front surface of steering mirror is estimated by 540 C (should not be a problem)

Plan for 170 GHz steady-state MW launcher (collaboration with PPPL and POSTECH)



Pre-conceptual drawing of 3 MW ECH launcher

Fixed Mirror

Steering Mirror

- **170 GHz, 1 MW present ECCD launcher**
  - **Power handling – 1MW pulse for 5 ~10sec duration every 15 minutes**
  - **Passively cooled mirrors same as GA launcher**
  - Fixed focusing mirror made of solid Glidcop front surface and a center section brazed to a SS backing plate
  - Steerable mirror made of inlaid copper bars with SS blocks to maximize the radiation cooling and reduce eddy currents
- **Upgrade to 3MW ECCD**
  - **2-beam 2 MW launcher is under conceptual design in collaboration with POSTECH and PPPL**
- **Plan for steady-state launcher development**
  - **1st step is replacing existing focusing mirror by water-cooled mirror to gain experience, which is relatively easier than steerable mirror, and steering mirror by recently upgraded passively cooled mirror**
  - **Fully actively water cooling toward 300 s mirrors will be applied to both mirrors in future**

Summary

◆ **ECRH is being considered as a very attractive tool for important physics issues and steady-state operation in KSTAR. Steady-state operation scenario using ECRH in KSTAR is under development**

◆ **Physics**

- KSTAR ECH has the sawtooth controllability, and its further experiments (stabilization/destabilization, period locking, pacing) will be performed at higher Bt using modulated 170 GHz X2.
- It is observed that KSTAR ECH/ECCD is has a function of controllability of toroidal rotation and pedestal and ELM characteristics
- Examined NTM controllability using 170 GHz ECH system in Toray-GA calculation for KSTAR future campaign, and TM control by 110/170 GHz ECRH in L-mode plasma was experimentally observed.
- ECH-assisted startup using 110 GHz X2 and 170 GHz ECH X2 is routinely applied for the reliable startup and flux saving in KSTAR.

Summary (continued)

◆ Technology

- 170 GHz gyrotron is operated at 1MW/20-s long pulse output using the dummy load with supports from JAEA
- For steady-state 170GHz ECRH system; launcher with active water-cooled mirrors, water cooling of transmission line, long pulse gyrotron operation with heater control
- For high frequency modulation (e.g. 5kHz) in 170 GHz ECRH, examination of operation conditions of 170 GHz gyrotron and power supply upgrade may be needed
- Real-time NTM control requires SW/HW modifications in plasma control system (PCS) and ECRH

Plan

- Investigation of 170 GHz X2 ECCD effect by changing poloidal/toroidal launching angles with long pulse duration (max 10 s) in 2013 campaign
- Further experiments for pedestal and ELM characteristics using 170 GHz X2 ECH/CD
- Control of core impurity accumulation using ECRH for ELMy H-mode
- ITER-relevant ECH-assisted startup; 170 GHz EC beam switching on during the slow increasing low loop voltage (< 2V) by active control of central solenoid coil power supply in 2013 campaign
- 170 GHz gyrotron longer pulse operation to 300 s with stationary output power by heater boosting
- 170 GHz ECH power upgrade to 3 MW until ~2017 in KSTAR 3rd phase with steady-state launcher
- New gyrotron of 105/140 GHz dual-frequency at 1 MW output power (100s) for core-electron heating (control of core impurity accumulation) and startup in wide operation range of Bt with 1.8 T < Bt < 2.8 T.