Commissioning and Operation Results of 110 GHz ECH System in KSTAR

Mi Joung, Wonsoon Han, Jongsu Kim, Young-soon Bae, Hyung-yeol Yang
National Fusion Research Institute, Daejeon, Korea

Seungil Park, Heejin Do, Won Namkung, Moohyun Cho
Department of Physics, POSTECH, Pohang, Korea

Yuri Gorelov, John Lohr, and John Doane
General Atomics, P.O. Box 85608, San Diego, CA92186, USA

Victor Orlov, Leonid Popov
GYCOM Ltd., 46 Ulyanov St., Nizhny Novgorod, 603155, Russia

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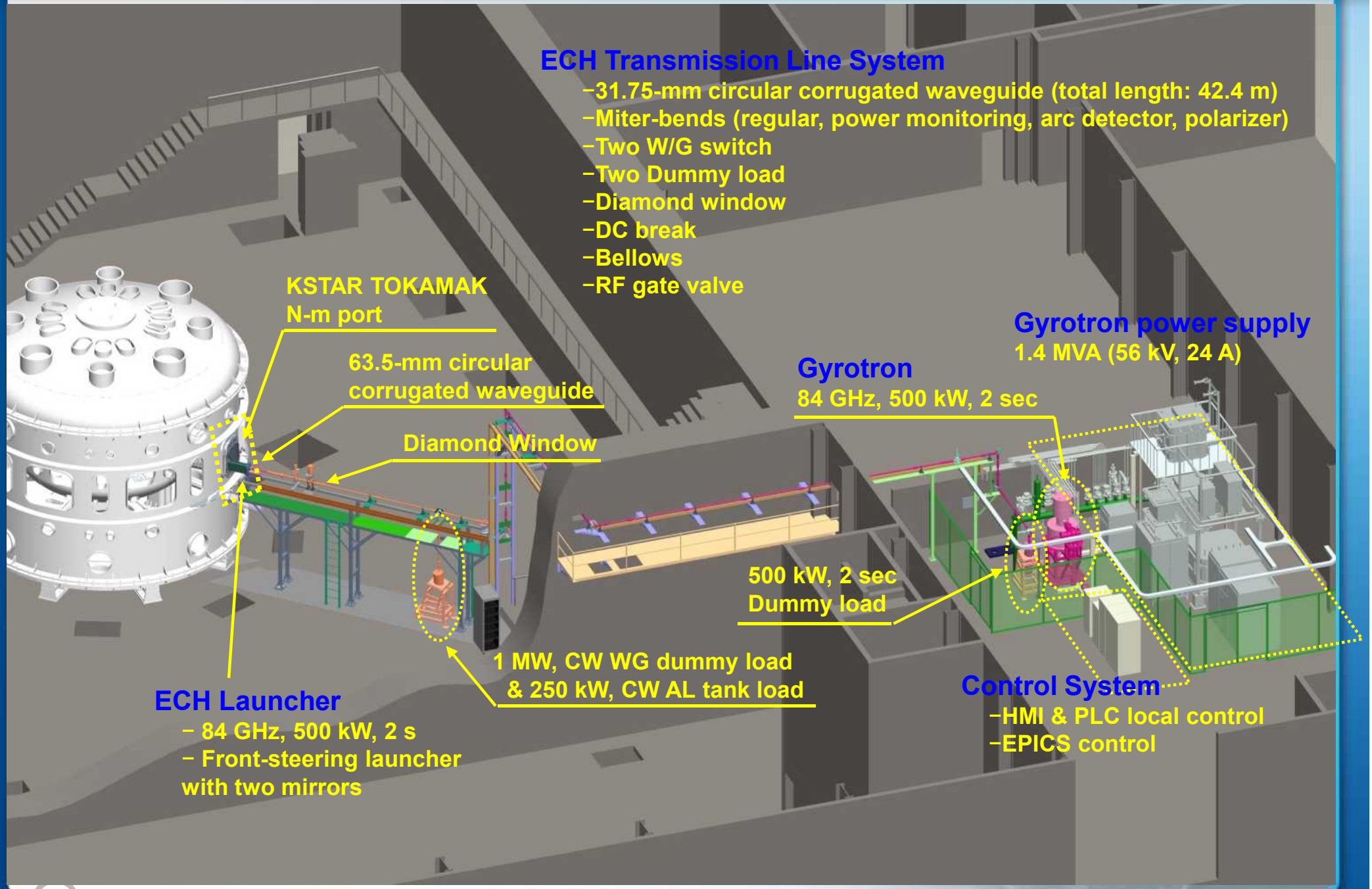
KSTAR ECH Start-up System



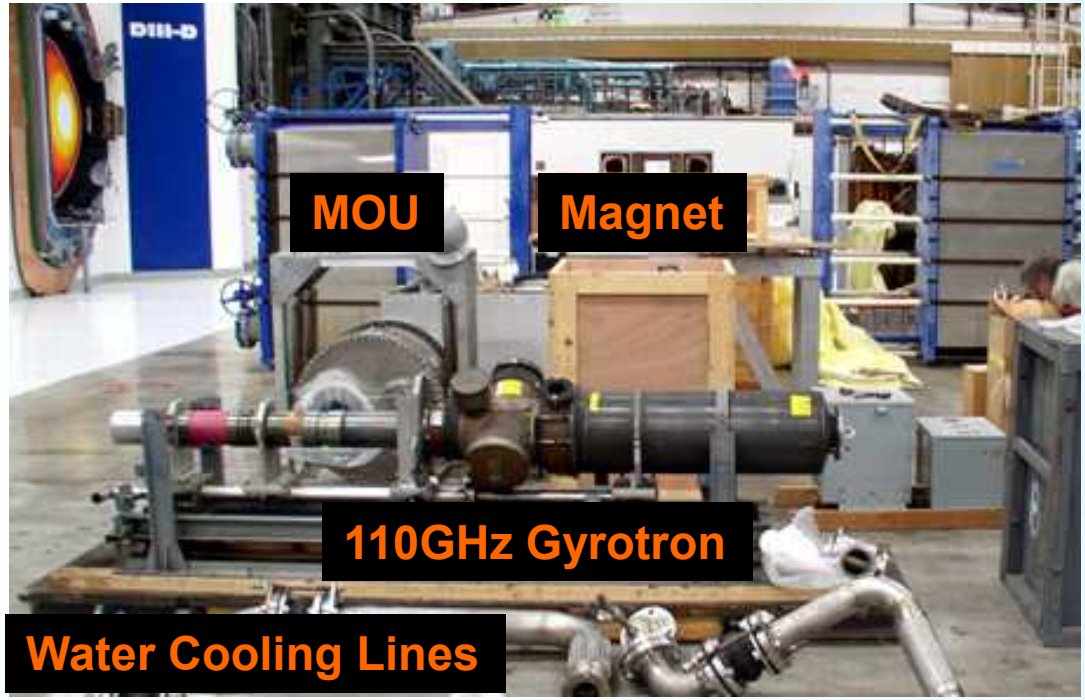
Present status of CPI 84 GHz Gyrotron

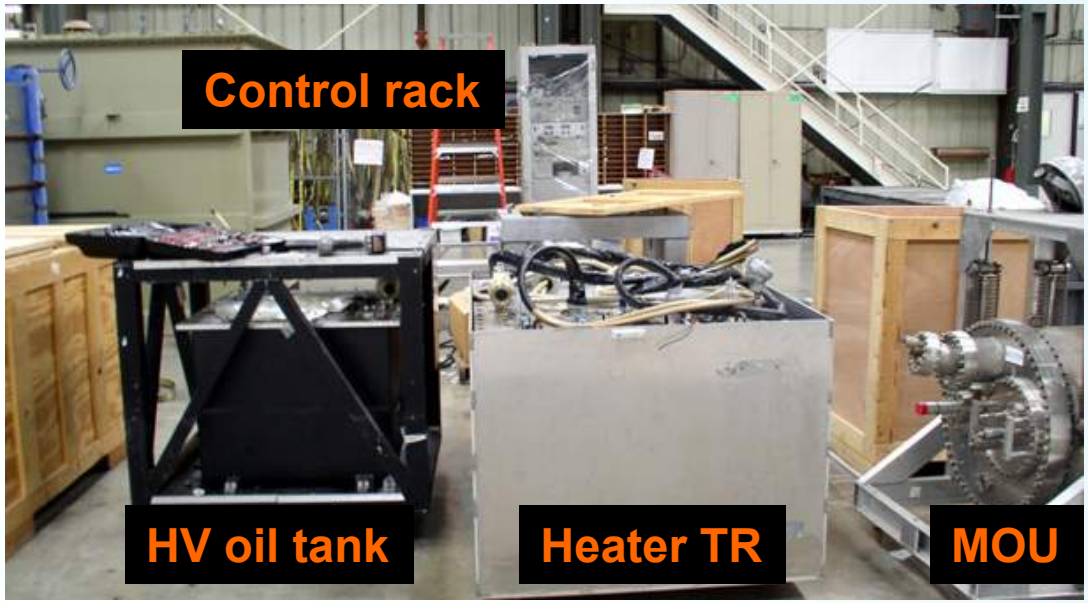
- Jan. 2009: Conditioning (500 kW, 1 - 1.5 s, < 1 % duty)
- Jan. 8, 2009: Vacuum leak found in the collector water channel, surmising hot leak (hot leak is a leak appearing during the operation)

< C P I >

- April 24, 2009: Clear leak found at 300 degrees C. and even at room temp. Tube opened and the big grain growth found in the copper metal surface
- May 7 ~ July 20: Repair the collector part
- July 24 - 28: Tube bakeout. Diamond window leak opened during the bakeout
- July 28 – Aug. 28: Repair at water-to-vacuum braze joint of diamond window
- Sep. 15 – Sep. 30: Finish of the bakeout, pinch-off, cathode activation, attaching RTDs, hi-pot test (high voltage insulation test)
- Sep. 30 – Oct. 4: Hi-pot test and Body leakage current found
- Oct. 6: Serious vacuum leak (Crack in the diamond disk) found during the preparations for shipping
- Jan. 28, 2010: Contract for diamond window and leakage current repair and conditioning
- Now: removed SiN supports and order diamond window and associated parts
- The end of July: move to NFRI

Loan of 110 GHz GYCOM Gyrotron from GA





- Due to the 84 GHz gyrotron troubles, the GA 110 GHz GYCOM gyrotron was loaned.
- NFRI and GA signed the Loan arrangement for the DIII-D 110 GHz GYCOM Gyrotron system on Aug. 20.
- 110 GHz GYCOM Gyrotron system was shipped to NFRI on Sept. 9 and assembled in NFRI.

Loan Items	Remark
110 GHz Gyrotron	
HV oil tank	
Vac-ion pump controller	
Collector coil	P/S, cable, cooling line
MOU	Support, gasket
Superconducting magnet	P/S, LHe & LN2 level sensors, LHe transfer line, level monitor
Gun coil	P/S
Heater P/S	ISO TR, HV cables
19” control rack	PLC

110 GHz GYCOM Gyrotron (BORIS)

Cavity Operating mode : $TE_{19,5}$

RF Output mode : TEM_{00}

Beam Voltage : 70 ~ 80 kV

Beam Current : 40 ~ 50 A

Frequency : 109.8~110.15 GHz

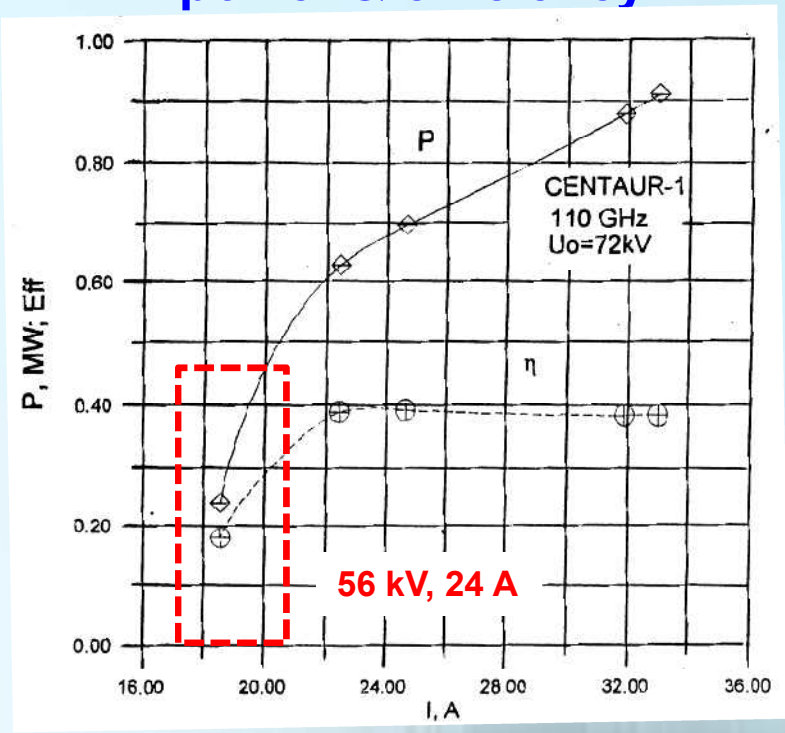
Efficiency : 37.0 %

Gun type : Diode gun

Heater : 10V, 45A

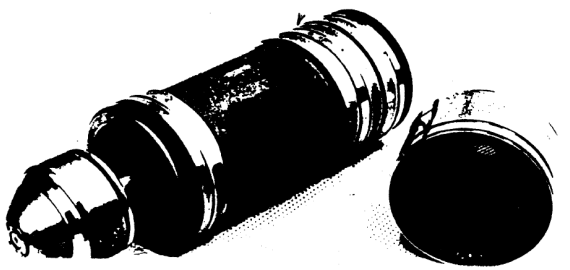
Three Getter Pumps

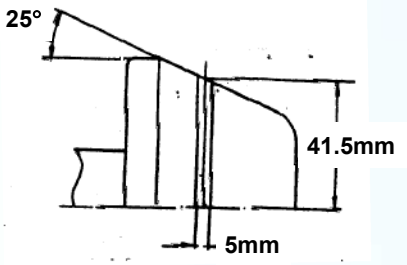
RF power & efficiency



RF output window

Boron nitride (NB) single disk window
- edge cooled by water





Electron Gun

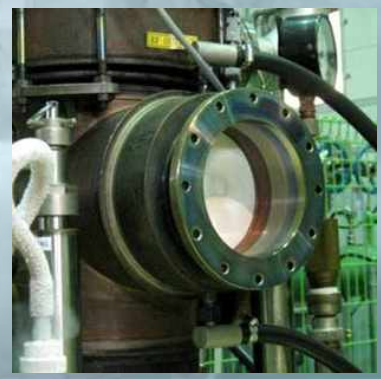
Metal-porous type cathode

j= 3~4 A/cm^2 (up to 10A/cm^2)

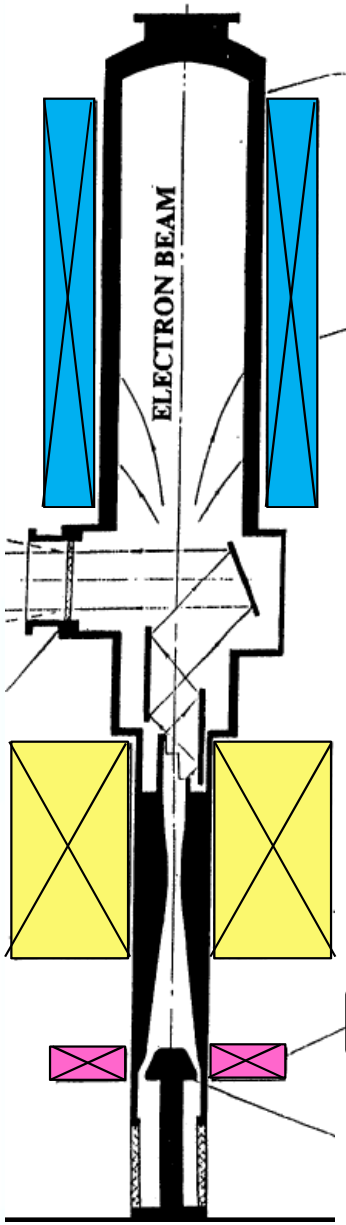
I_{beam}= 40~50 A, $P_{heat} \leq$ 400 W

Velocity ratio ~ 1.3

Magnetic field ratio ~ 22.5



110 GHz GYCOM Gyrotron Magnet



Collector Coil

Normal conductivity coil
Maximum voltage: 60 V
Maximum current: 40 A
Waveform: saw-tooth (5Hz)
Growth time: 0.15 s
R=1Ω, L=1mH

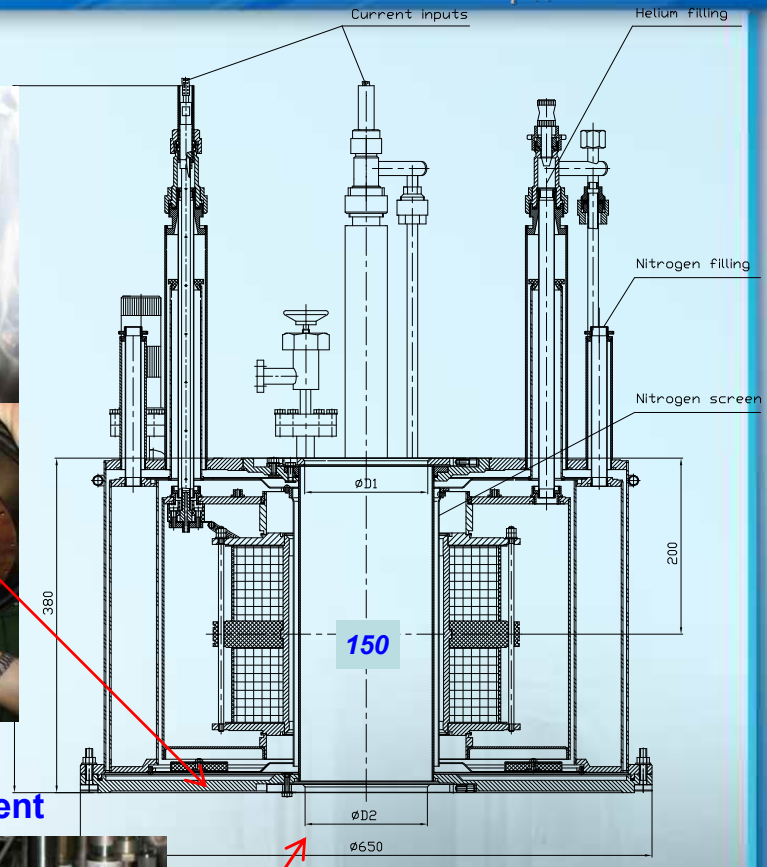
Solenoid

Superconducting coil
Maximum magnetic field: 5 T
Operating current: 40 A ~ 80 A
Bore diameter: 150 mm
LHe(25 l), LN_2(28 l): 0.5 l/h, 1 l/h

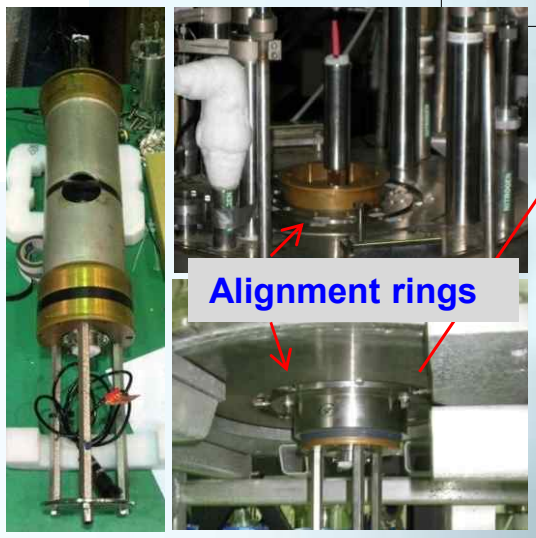
Cathode Coil

Normal conductivity coil
Maximum current : 5 A (< 0.5 kW DC)
No cooling

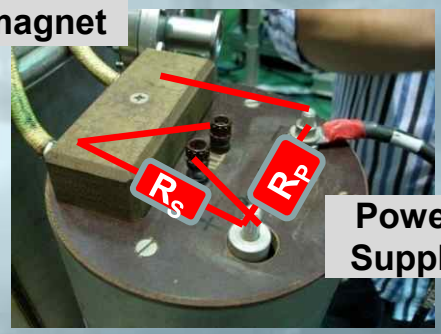
Nitrogen Screen



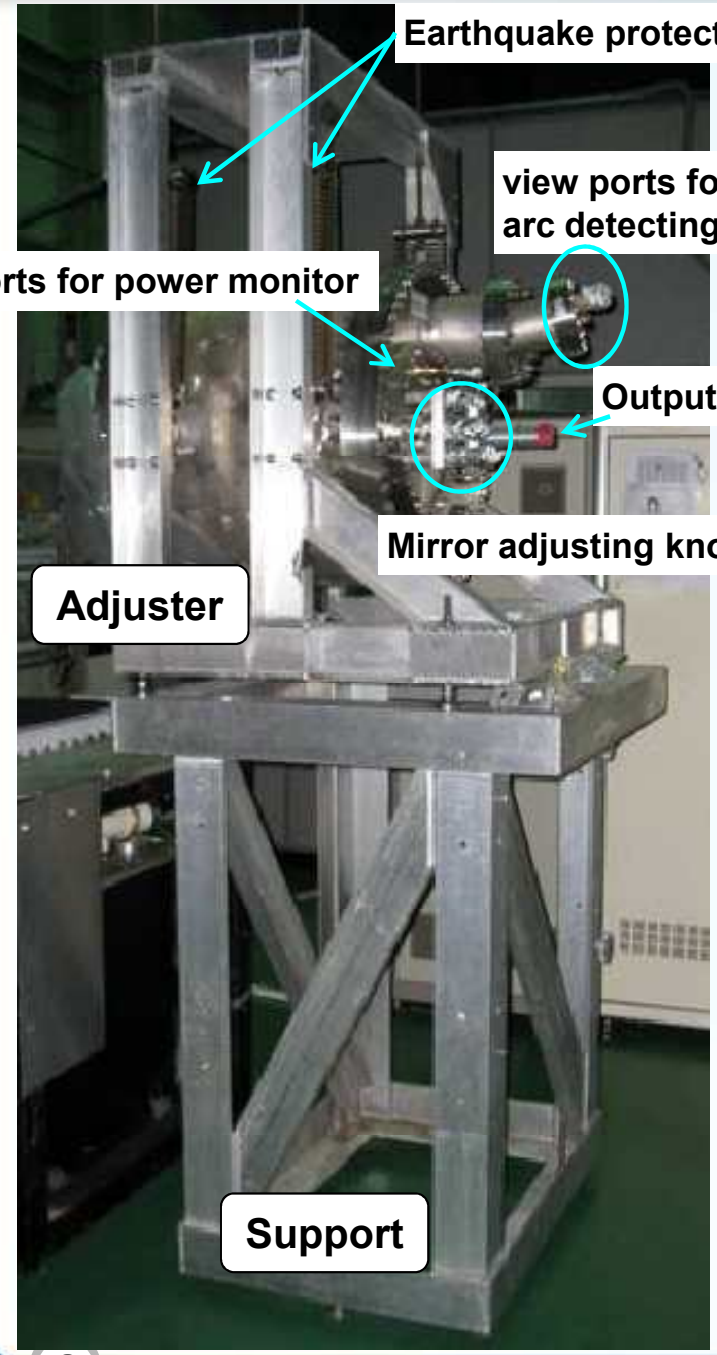
Magnetic field alignment



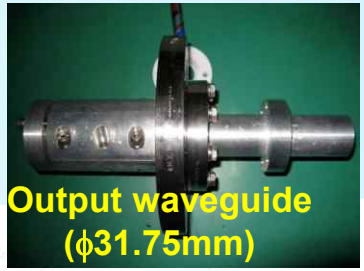
Protection and monitoring resistors

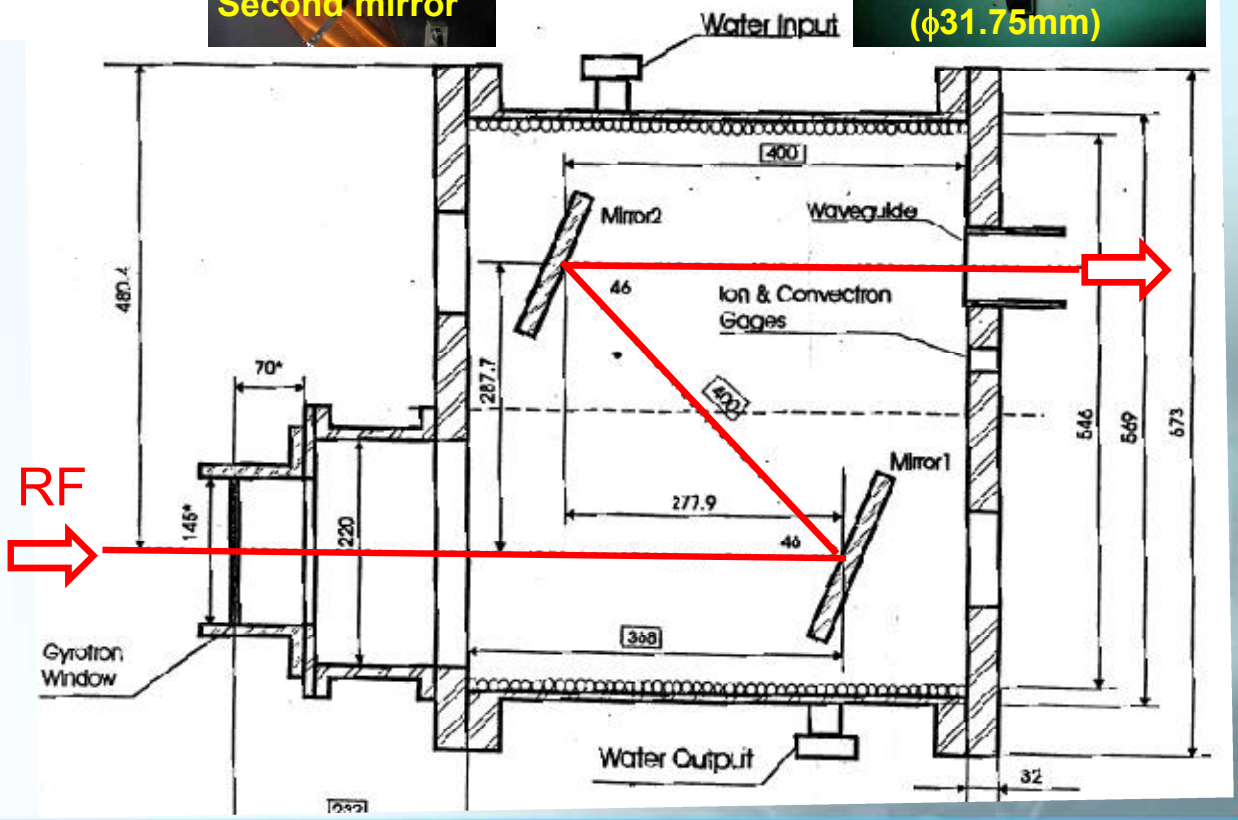


110 GHz GYCOM Gyrotron MOU



MOU consists of two phase correction mirrors. MOU mirrors are adjusted with aligning knobs and cooled by water. MOU chamber has water jacket, arc detecting view ports, and power monitoring WR10 waveguide port. The position of the first mirror is decided from which RF beam size is minimized at this position.

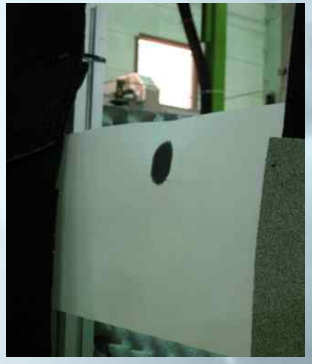




110 GHz GYCOM Gyrotron Installation

- Complete installation during 10 days with GYCOM engineers

  - Oct. 19 : Magnet **LN2 screen** installation, Vac. Pumping, Filling LN2
  - Oct. 20 : Magnet cool down, **Magnet run** (3 quenches at 66 A)
  - Oct. 21 : **Magnet alignment**, Install gyrotron & HV oil filling
  - Oct. 23 : water connection & leak test, Hi-pot test, Heater warm-up & magnet ON, Octanol D/L installation with Eccosorb chamber and RF detector and arc detector, **Gyrotron run** (60kV/15A/up to 20 ms)
  - Oct. 24 : Remove Octanol D/L, **Burn paper exp.** (free space), MOU installation & Burn paper at the end of WG
  - Oct. 25 : Connection MOU to T/L & evacuation
  - Oct. 26 : Water connection to MOU & Miter bends, Run Boris using GA SS D/L, 60kV/22.4A/500ms, P_{RF} at D/L = **213 kW**
  - Oct. 27 : More current at 60 ~ 61kV, up to **1 sec**



Modification of transmission line

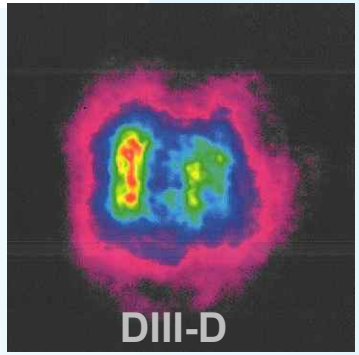
Values of losses in 31.75 mm corrugated circular HE_{11} waveguide

Items	Loss		Value for 84 GHz	Value for 110 GHz	remark
Waveguide	Ohmic (70 GHz to 110 GHz)		~ 5 % (100m)	~ 5 % (100m)	increased
Miter bend	Ohmic ~ $f^{1/2}$	H plane	~ 0.07 %	~ 0.07 %	increased
		E plane	~ 0.15 %	~ 0.15 %	increased
	Mode conversion of plane mirror	With mode mixture	~ 0.28 %	~ 20 %	Remove mode mixture
		Without mode mixture ~ $\lambda^{3/2}$	3 % per bend	~ 1.4 %	
Diamond window	Reflection		< 1 %	~ 45 %	remove
DC break , Pump-out tee, RF gate valve, waveguide switch	Radiation and mode conversion in a gap (0.4 ~ 2.5 mm) ~ $\lambda^{3/2}$		0.01 ~ 0.05 %	0.01 ~ 0.05 %	reduced
W/G up-taper	Mode conversion		< 0.1 %	~ 4.3 %	in HE12

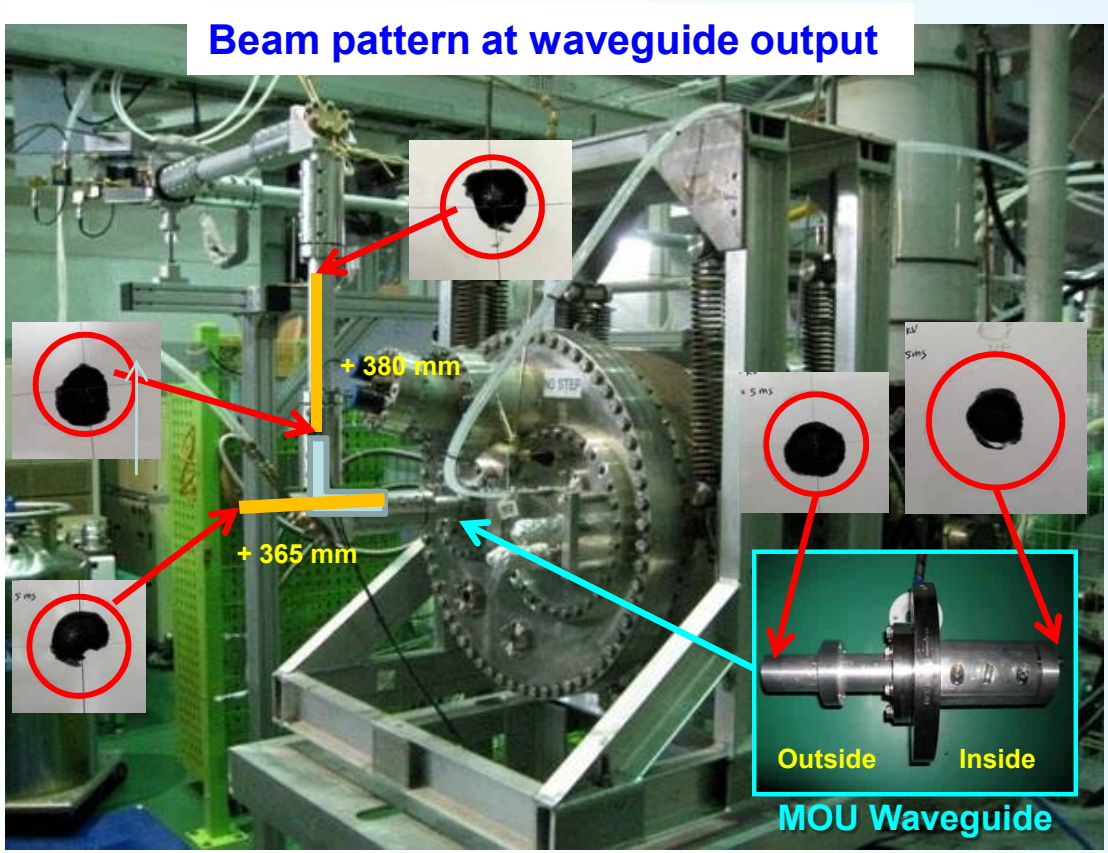
- Most present transmission line components were available to transmit 110 GHz wave .
- The GA large stainless steel load of the dummy loads should be fine at 110 GHz, but it has a long response time.
- Capability of polarizer was confirmed by GA. There is no difficulty in covering the required polarization range at 110 GHz with the existing polarizer mirrors in the same location by using the new Fourier coefficients of the phase shift for the assumed mirror groove geometries at 110 GHz.

RF beam patterns

Beam pattern at gyrotron window



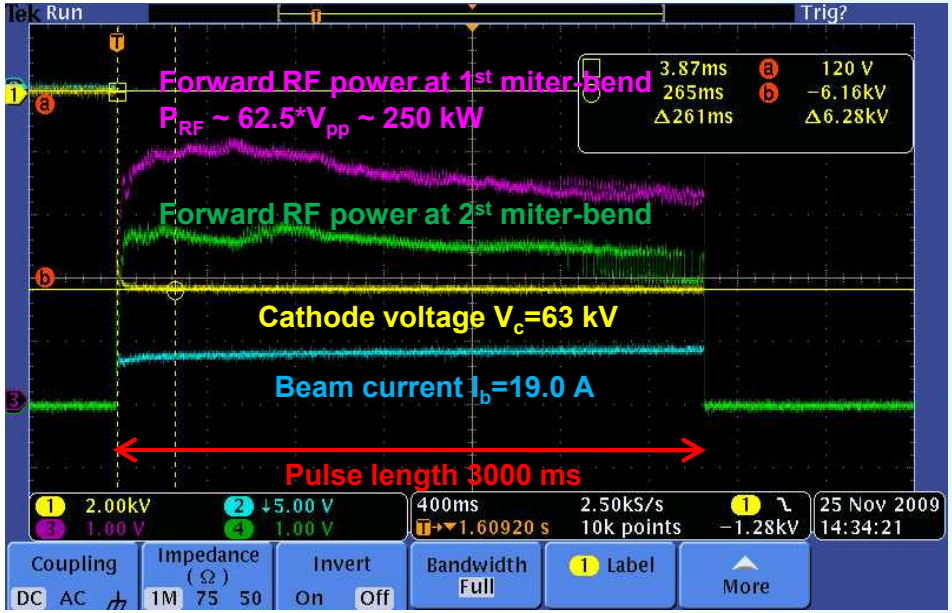
Beam pattern at waveguide output

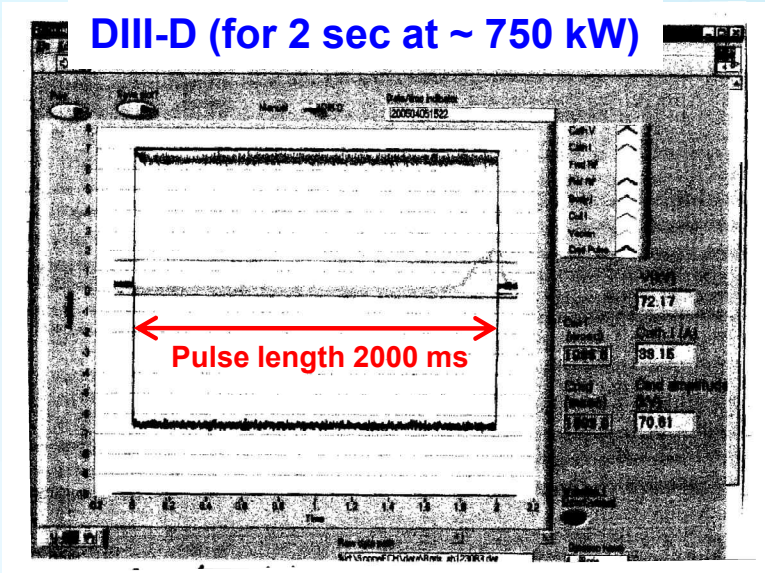


- The RF beam profile outputted at the gyrotron window is peaked at two peaks.
- The measured output beam profile at the window using a burn paper showed a good agreement with those measured in DIII-D.
- A Gaussian-like RF beam profile at the output of the MOU was also observed by using the burn paper measurement.
- The RF beam profiles as a function of traveling length seems to be slightly tilt.

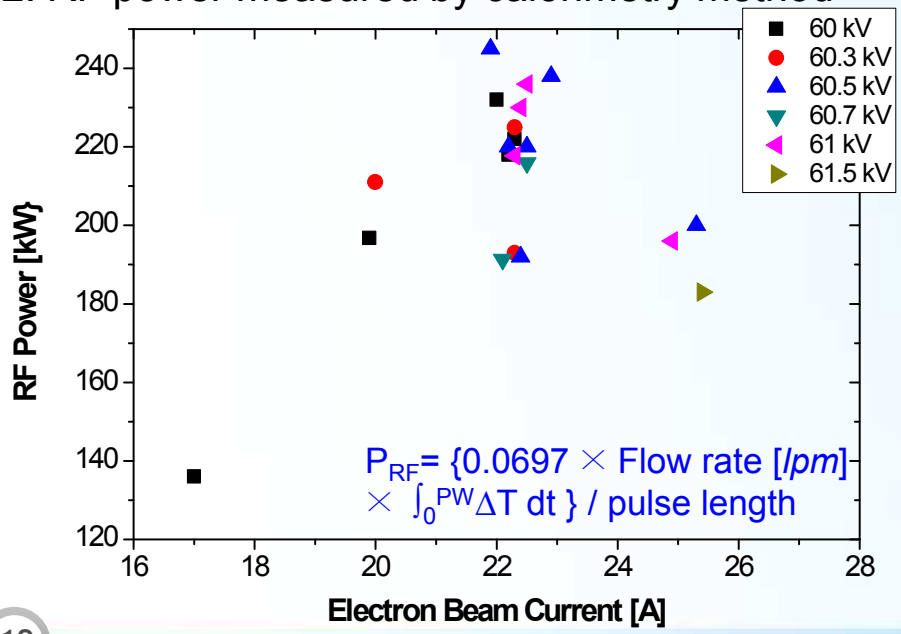
110 GHz GYCOM Gyrotron Commissioning Results

1. Power monitor Miter bend



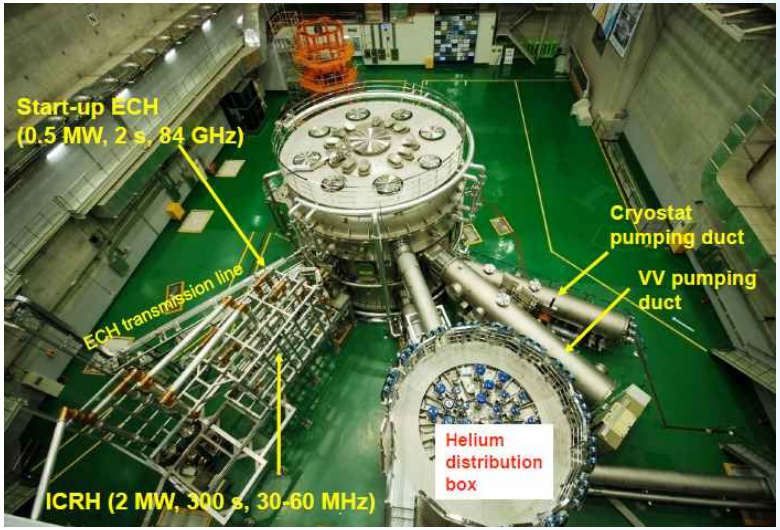


2. RF power measured by calorimetry method



- Averaged RF power is measured by using calorimetry method at dummy load where the water temperature is measured by Resistance Temperature Detectors (RTD-1000). RF power with time is also measured by RF detector at miter-bend.
- The maximum RF power is about 250 kW.
- If transmission efficiency of transmission line is about 20 %, the power outputted the window of the gyrotron is about 450 kW when dummy load, MOU, and cavity are adsorbed about 210 kW, 80 kW, and 24 kW, respectively.
- The current of gun coil and main magnet coil were optimized to maximize the RF power extracted from the gyrotron.

Operation parameters of 2009 KSTAR campaign

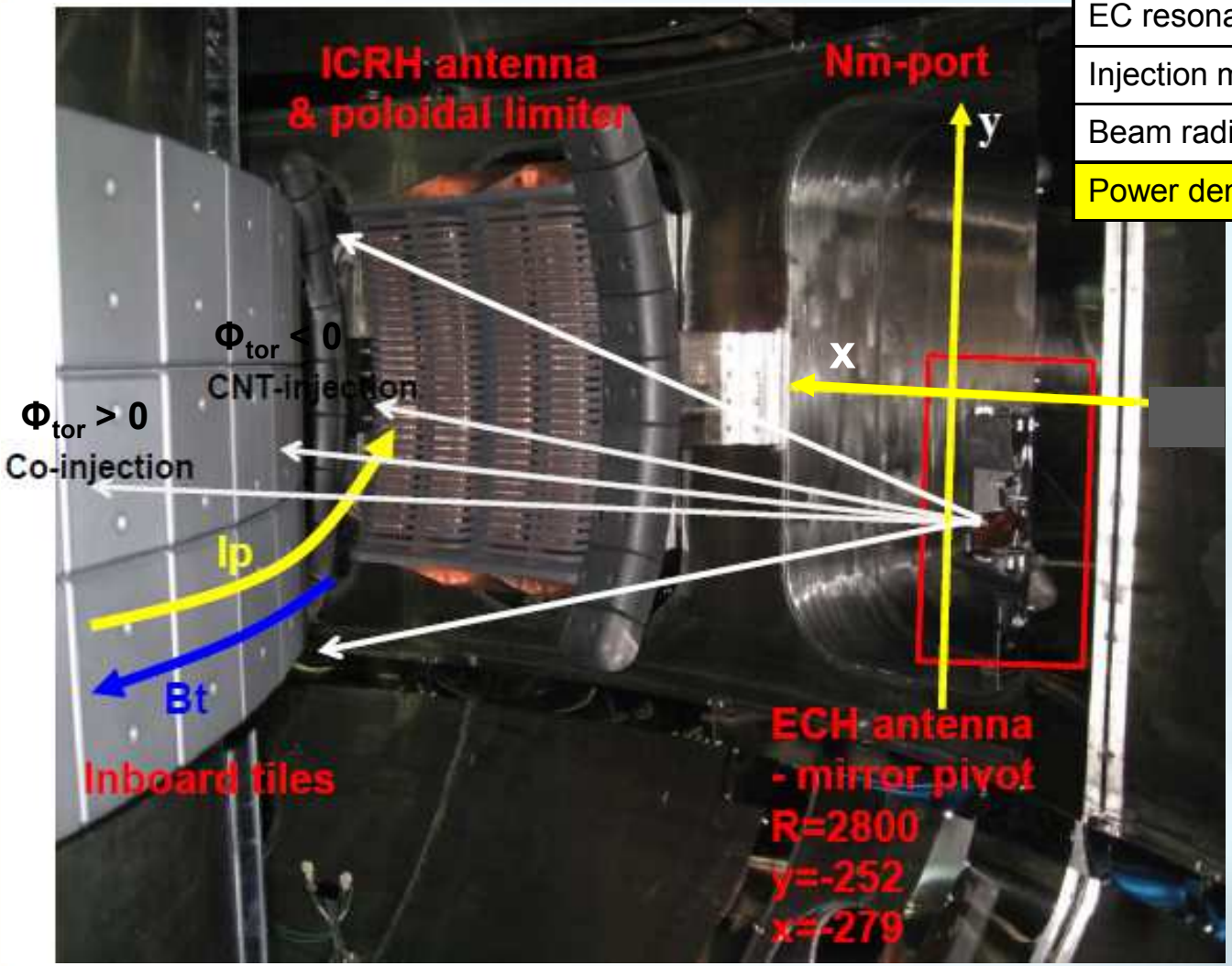


PARAMETERS	KSTAR
Major Radius, R_0	1.8 m
Minor Radius, a	0.5 m
Toroidal Field, B_0	3.5 Tesla
Pulse Length	300 sec
Superconductor	Nb_3Sn, NbTi
Plasma Fuel	H, D-D
Plasma Current, I_P	2.0 MA
Elongation, κ	2.0
Triangularity, δ	0.8

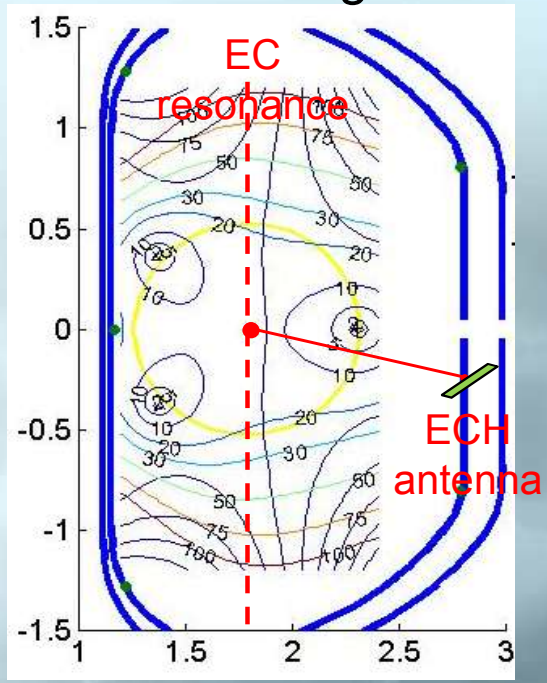
	2008 first campaign	2009 second campaign
Target Operation Parameters	• B_T ~ 1.5 T • I_P > 0.1 MA • t_P > 0.1 s • R = 1.68 m • Flux ~ 1 Wb • Shape ~ circular • Gas: H_2	• B_T ~ 2 T, 3 T • I_P > 0.3 MA • t_P > 2 s • R = 1.8 m • Flux ~ 2 Wb • Shape ~ circular • Gas: D_2
Wall conditioning	• ICWC between shots	• ICWC between shots • Boronization
Magnetic control	• TF : 1.5 T • PF : 4 kA unipolar	• TF : up to 3.5 T • PF : +/-4 kA (zero crossing)
Heating operation	• ECH(84GHz): 500kW, X2,0.4s	• ECH(110GHz): 250 kW, X2, 3s • ICRH(44.2MHz): 300kW, 10 s
Diagnostics	• MD (77 Ch)/ MMWI / ECE / Hα / filterscope / VS / TV	• MD/ MMWI / ECE / Hα / filterscope / VS / TV • PD / XCS (1 set) / Bolometer (resistive) / Reflect. / Soft X-ray

ECH Launcher

	2009 campaign	2008 campaign
Frequency	110 GHz	84 GHz
Injected power	~ 250 kW	~ 350 kW
EC resonance	R = 1.8 m	R = 1.68 m
Injection mode	X2 (O2, X3)	X2 (O2)
Beam radius	58 mm	80 mm
Power density	2.4 kW/cm^2	1.8 kW/cm^2



Initial field configuration

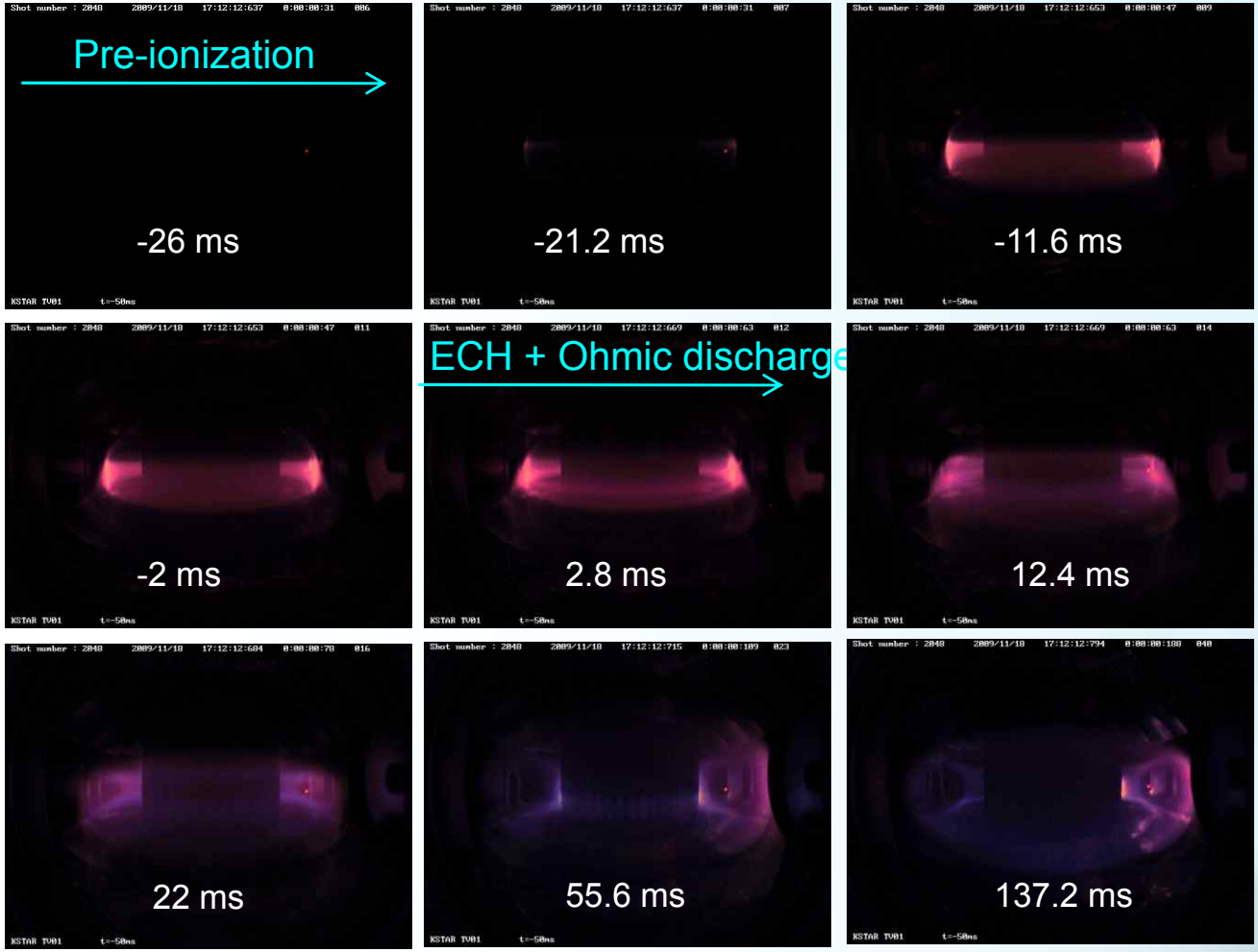


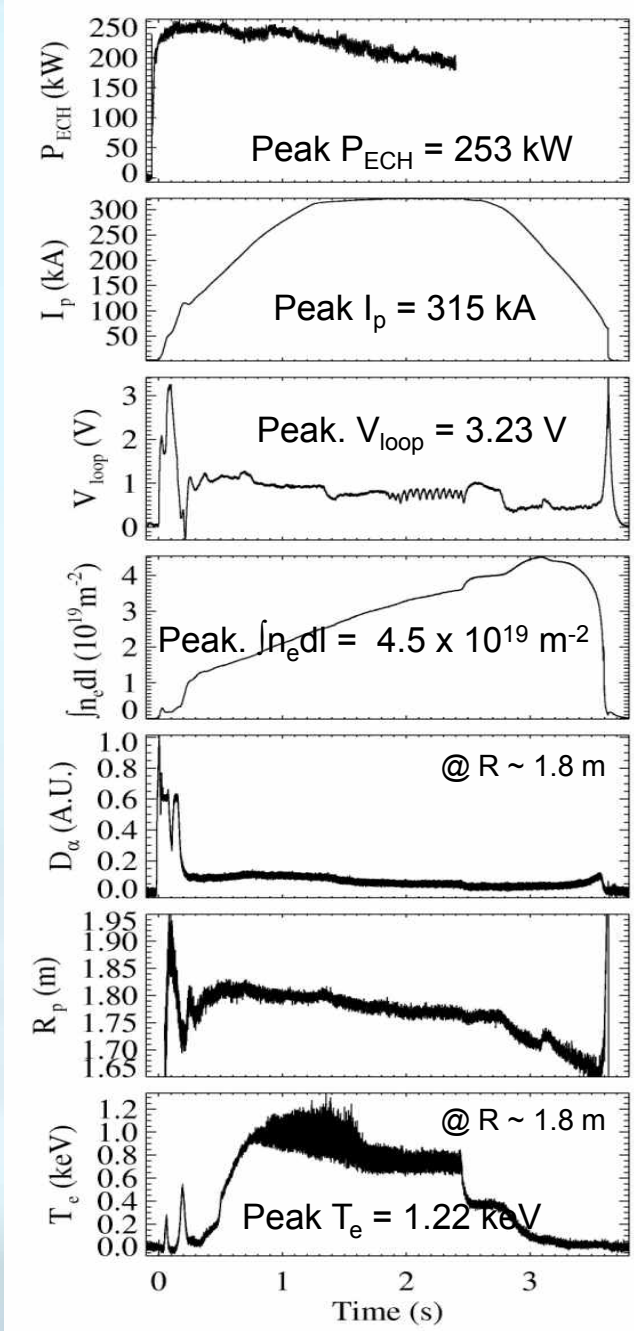
110 GHz ECH-assisted startup in 2009 campaign

Best shot in 2009 KSTAR campaign: KSTAR #2048
Achieved Ip > 300 kA for time ~ 2 s

ICRF: ~30 kW @ -60 ms ~ -30 ms
ECH: ~240 kW, X2
@ -55 ms ~ 2445 ms (2.5 s)
(1.8 m, 0°, 0 mm)

Fast CCD camera image





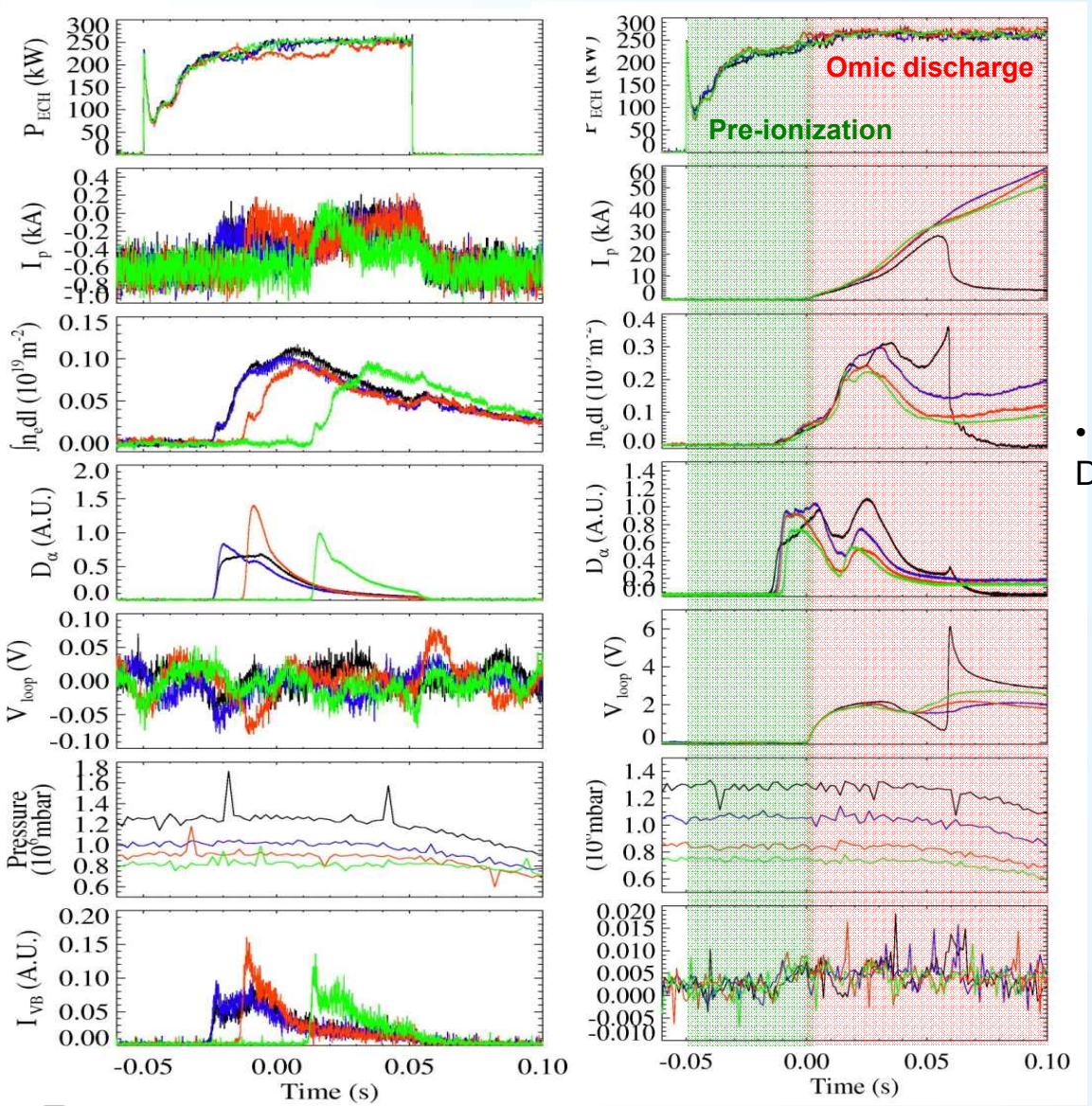
Scanned parameters for 110 GHz ECH

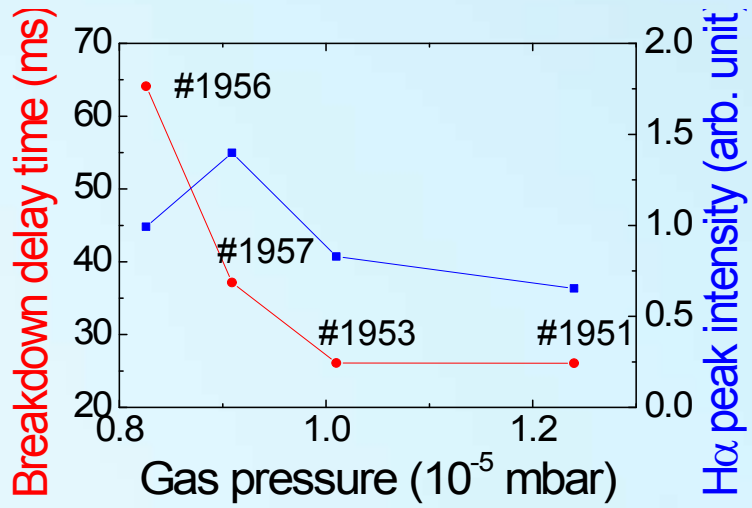
- Pre-ionization (without ohmic discharge)
  - Pre-fill gas pressure
  - Toroidal injection angle
  - Injection mode
  - Vertical magnetic field
- Plasma startup (with ohmic discharge)
  - Pre-fill gas pressure
  - B_z at the EC resonance
  - Additional gas puff in pre-ionization phase
- EC heating effect
  - With/without EC beam

Pre-fill gas pressure

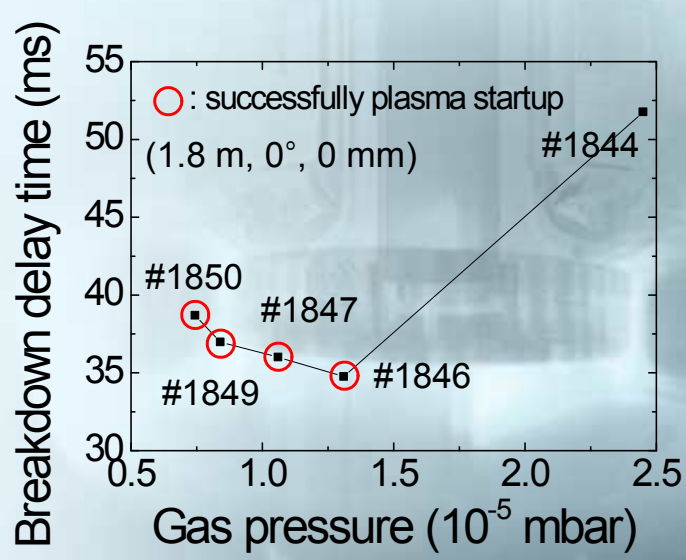
1.24 x 10^{-5} mbar (1.0 V): #1951
1.01 x 10^{-5} mbar (0.9 V) : #1953
0.91 x 10^{-5} mbar: (0.85 V) #1957
0.83 x 10^{-5} mbar (0.8 V): #1956

1.31 x 10^{-5} mbar (1.0 V): #1846
1.06 x 10^{-5} mbar (0.9 V): #1847
0.84 x 10^{-5} mbar (0.8 V): #1849
0.84 x 10^{-5} mbar: (0.75 V): #1850

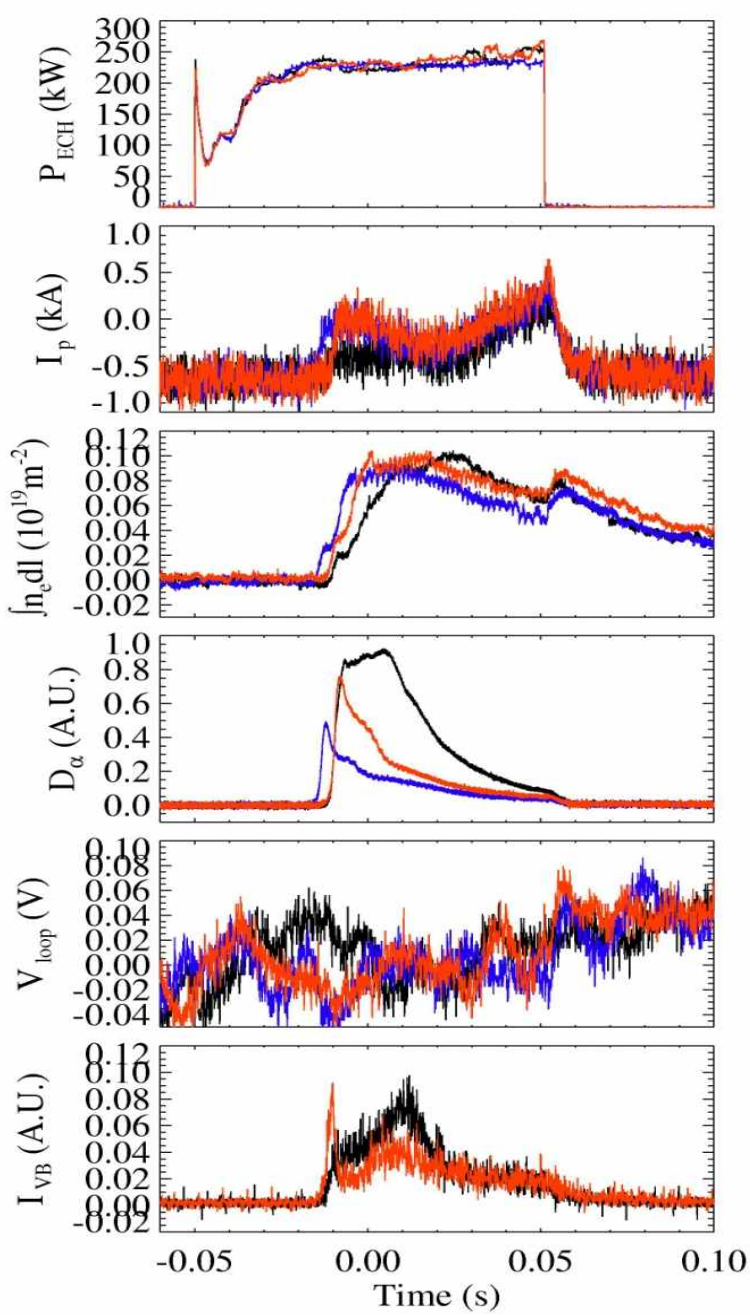




- Breakdown delay time:
Delay time to increase the Hα signal after ECH injection



Pre-ionization – Toroidal injection angle



0°: #1949
-10° (counter): #1948
-20° (counter): #1950

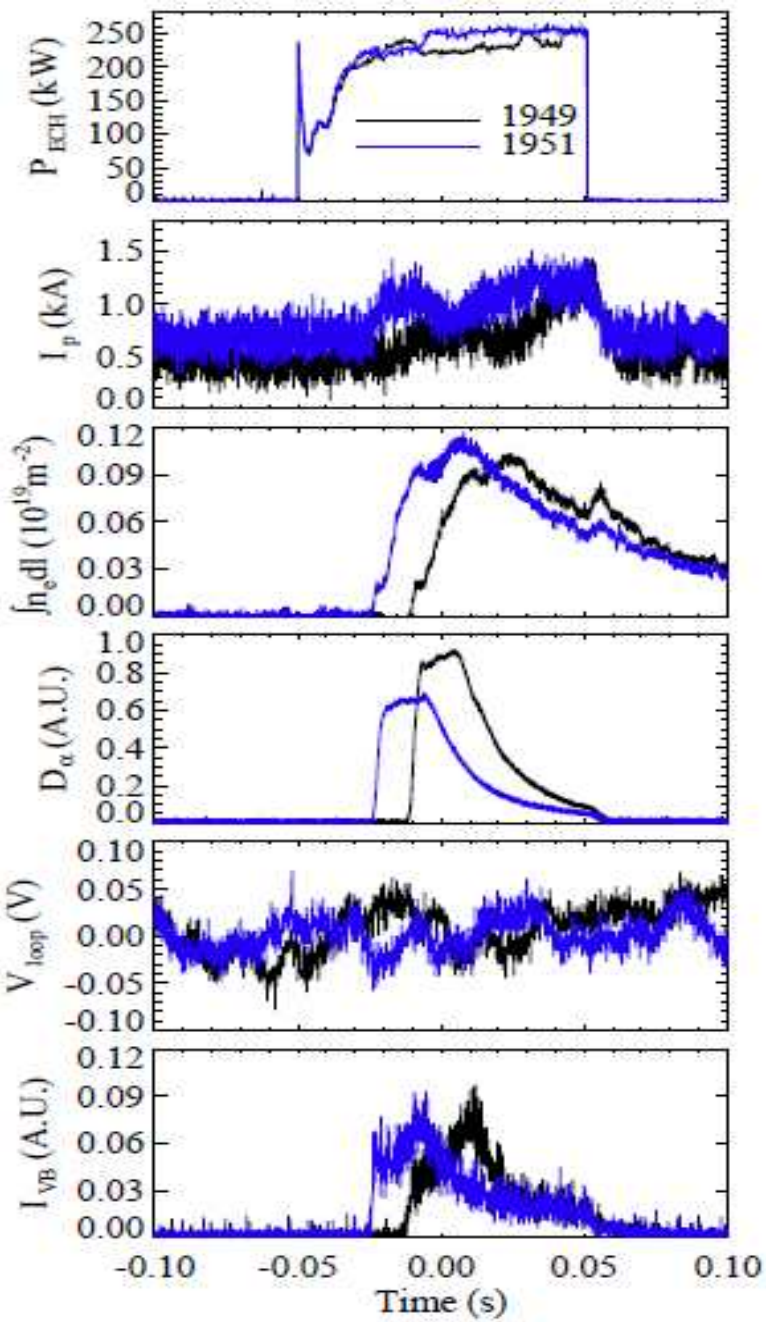
ECH power [kW]	250 kW
Pre-ionization time [ms]	36.98 (#1949) 34.17 (#1948) 37.06 (#1950)
ECH on-time [ms]	- 50
Resonance position	R = 1.8
Resonance field [T]	2
ECH beam target position [m]	R = 1.8, Z = 0
Gas pressure [10^{-5} mbar]	D2 gas, 1.25

- The **counter oblique EC beam launch** was most favorable for the pre-ionization and burn-through during KSTAR first plasma campaign.

- Breakdown delay time was minimized at the toroidal injection angle of -10 degree. But the line integrated electron density at the perpendicular injection was more increased than at the toroidal injection angle of -10 degree.

- In the case of the injection angles of -20°, ECH pre-ionization was also observed.

Pre-ionization – Poloidal injection position



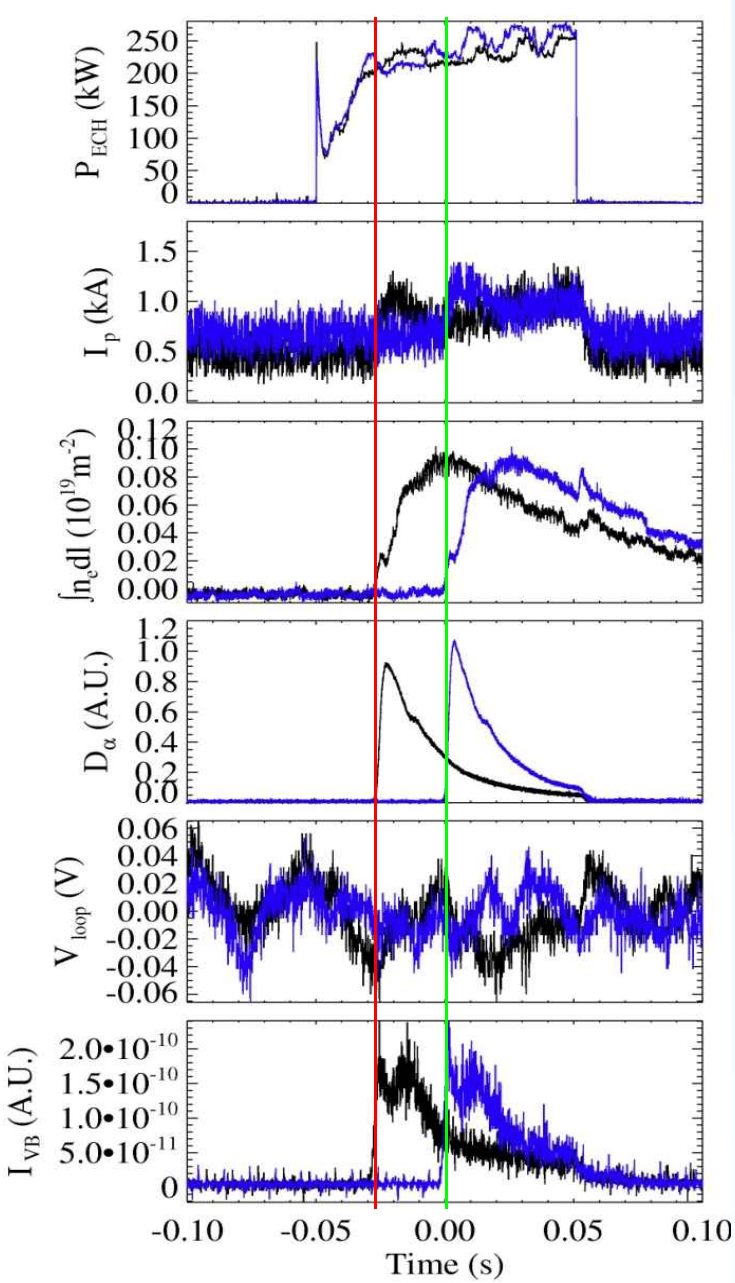
0 mm: #1949
-100 mm: #1951

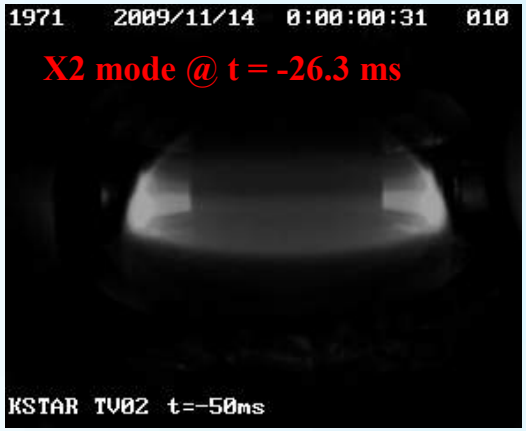
Shot # (line color)	1949 (black)	1951 (blue)
ECH power [kW]	250	
ECH power on time [ms]	-50	
ECH tor. Injection angle [deg.]	0.0 deg. (perpendicular injection)	
ECH beam target position (pol.) [cm]	0.0	-0.1 m
Gas pressure [10^{-5} mbar]	D2 gas, 1.24	
Delay time [ms]	38.22	26

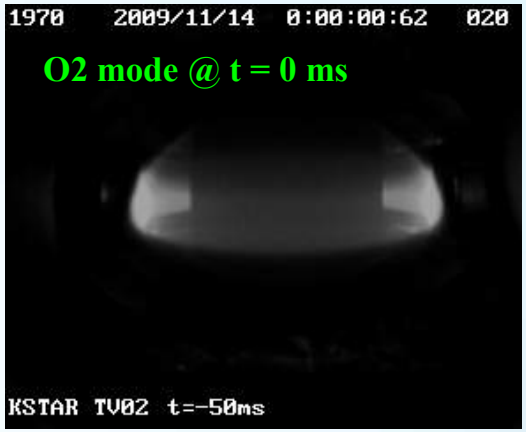
- **Downward launch from the medium plane was efficient** for pre-ionization, like the first KSTAR operation result.

-Probably the electron meets longer path length along vertical gradient B drift, Or larger vertical stray magnet field at the lower position from the field null center could align electrons at the resonance position

Pre-ionization – EC wave mode





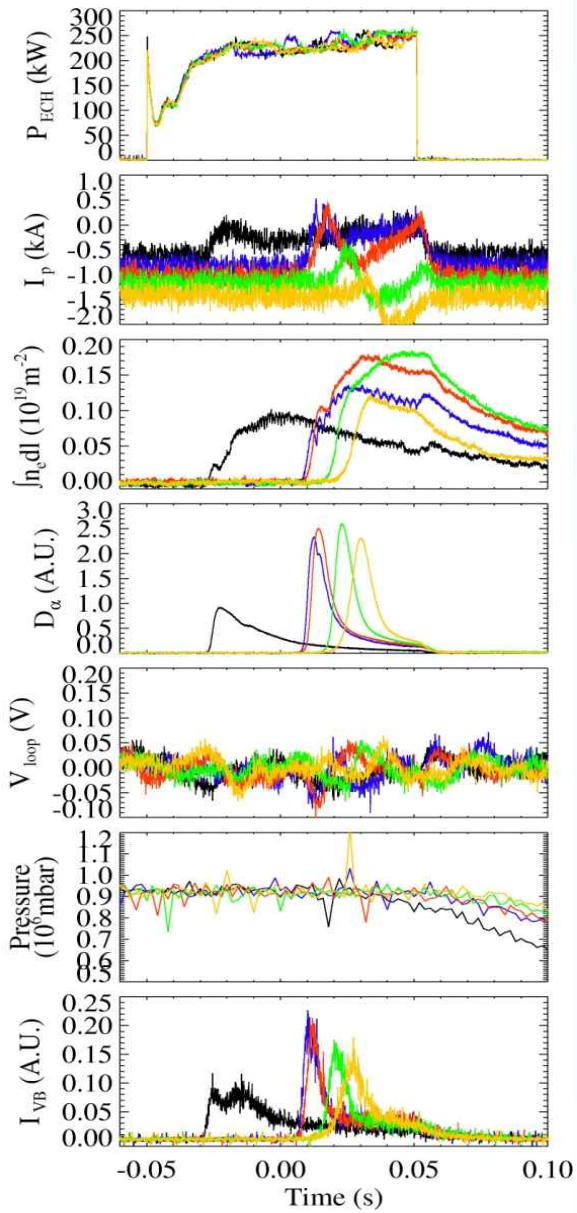


ECH power [kW]	250 kW
ECH injection angle (tor.) [deg.]	0.0 deg. (X2 perp.)
ECH injection mode	**X2 (#1971, black)** **O2 (#1970, blue)**
Pre-ionization time [ms]	22.45 (X2 mode) 50 (O2 mode)
ECH on-time [ms]	-30
TF current [kA]	13.3
Resonance position	R=1.6
Resonance field [T]	1.5
ECH beam target position [m]	R=1.6, Z=0
Gas pressure [10^{-5} mbar]	2.9

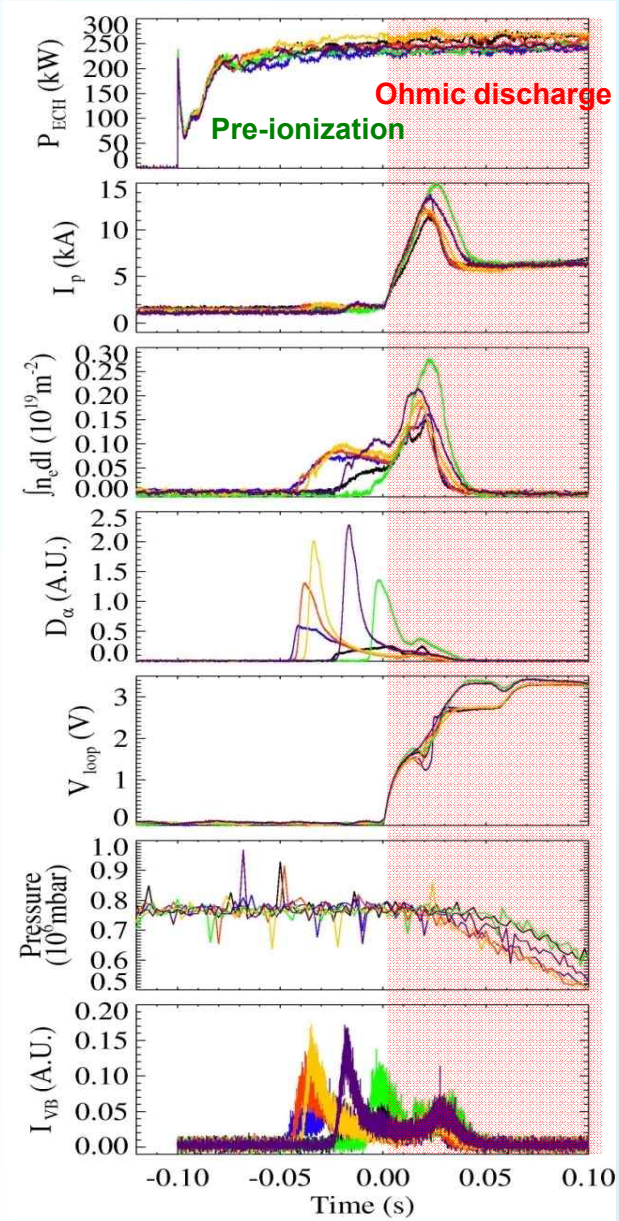
- X2 mode is best condition for pre-ionization.
- O2 mode pre-ionization was ignited very late.
- X3-mode injection (#2116) in B_T = 1.3 T and pre-ionization in the pure TF field was attempted but failed.

B_z dependence

Pre-ionization

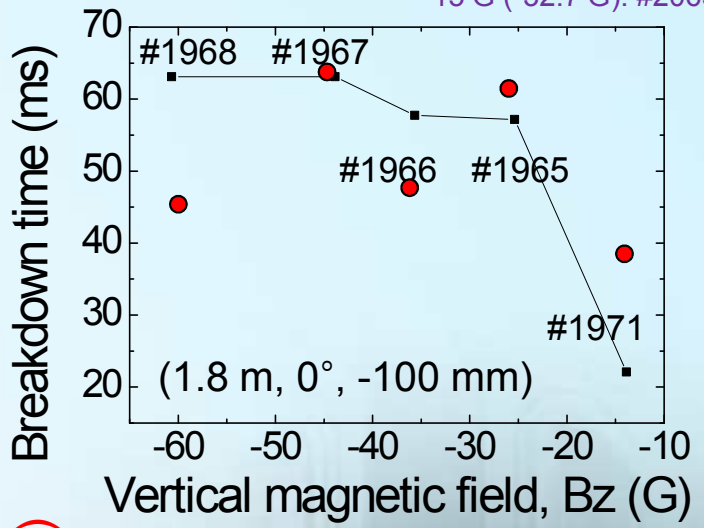


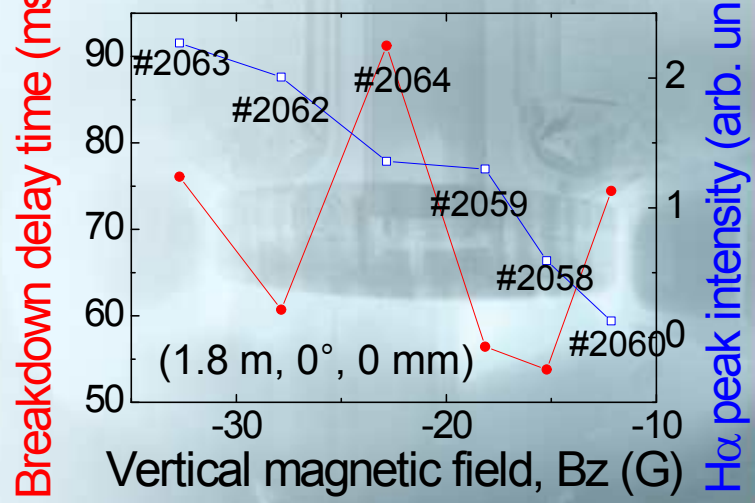
ECH-assisted startup



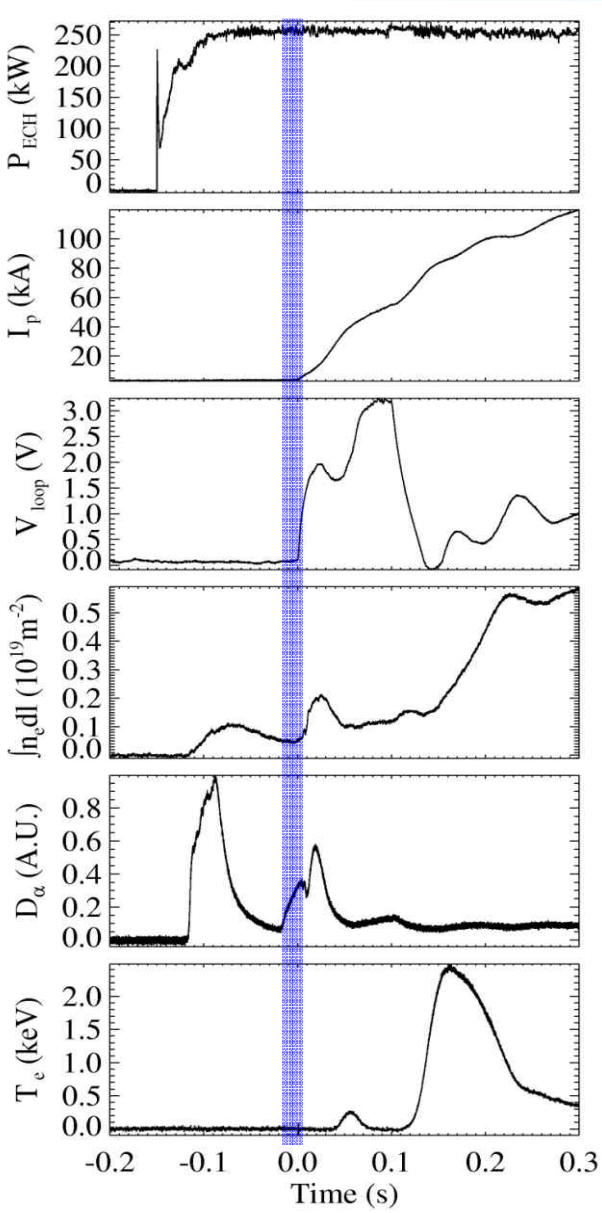
Pre-ionization
Bz (incoloy effect)
0 G (-13.87 G): #1971
-10 G (-25.37 G): #1965
-20 G (-35.65 G): #1966
-30 G (-43.86 G): #1967
-50 G (-60.67 G): #1968

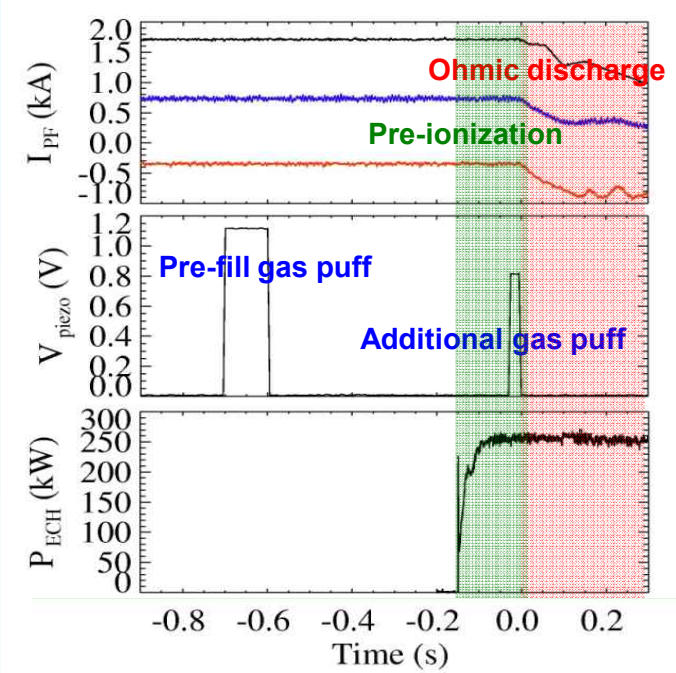
ECH-assisted startup
Bz (incoloy effect)
5 G (-12.15 G): #2060
0 G (-15.22 G): #2058
-5 G (-18.15 G): #2059
-7.5 G (-22.84 G): #2064
-10 G (-27.86 G): #2062
-15 G (-32.7 G): #2063

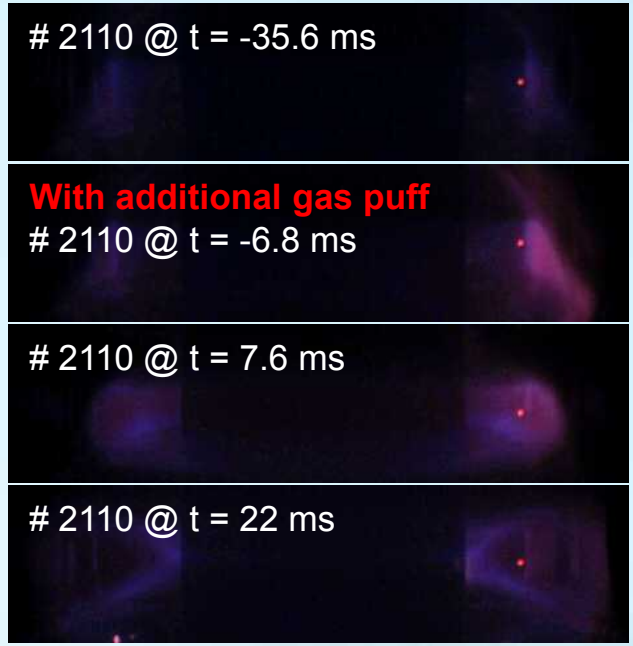




Additional gas puff in pre-ionization phase



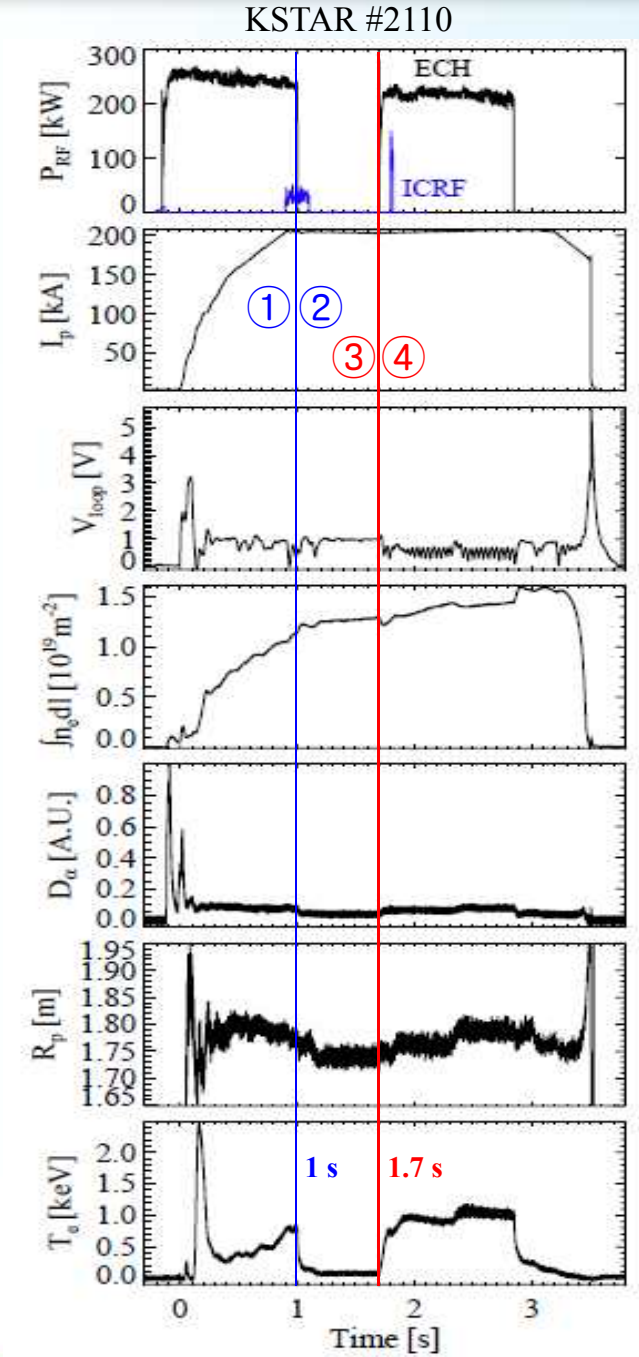


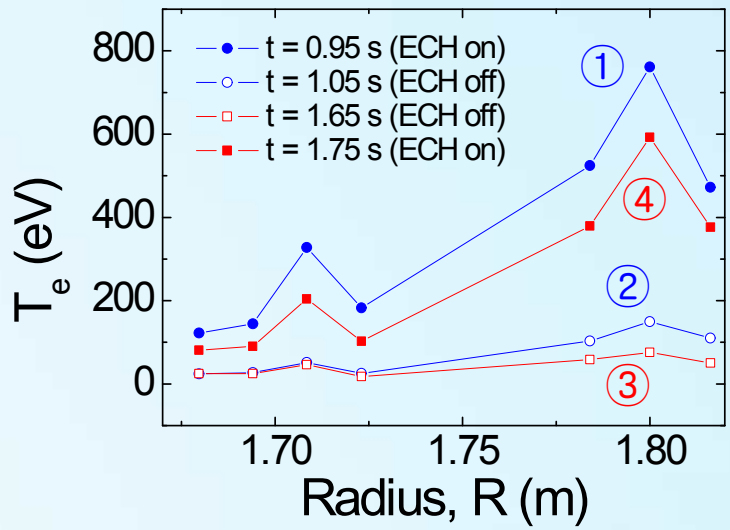


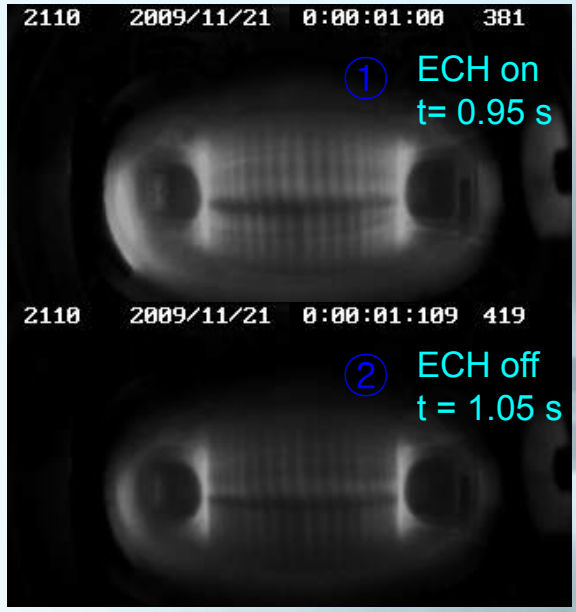
Additional gas puff during -25 ms to -5 ms

- After boronizations, we had suffered lots of difficulties on plasma startup.
- Additional gas puff during the pre-ionization phase was suggested to improve the reliability of plasma startup.
- Indeed, with startup configuration of 2271(Nov. 30), we got total 7 successful shots (2271~2277) continuously until the end of plasma experiments

EC heating effect







Red spot & coating of steering mirror of ECH launcher

Before the campaign

After the campaign

- During the second campaign, red spot was detected on the steering mirror of ECH launcher by the fast CCD camera.

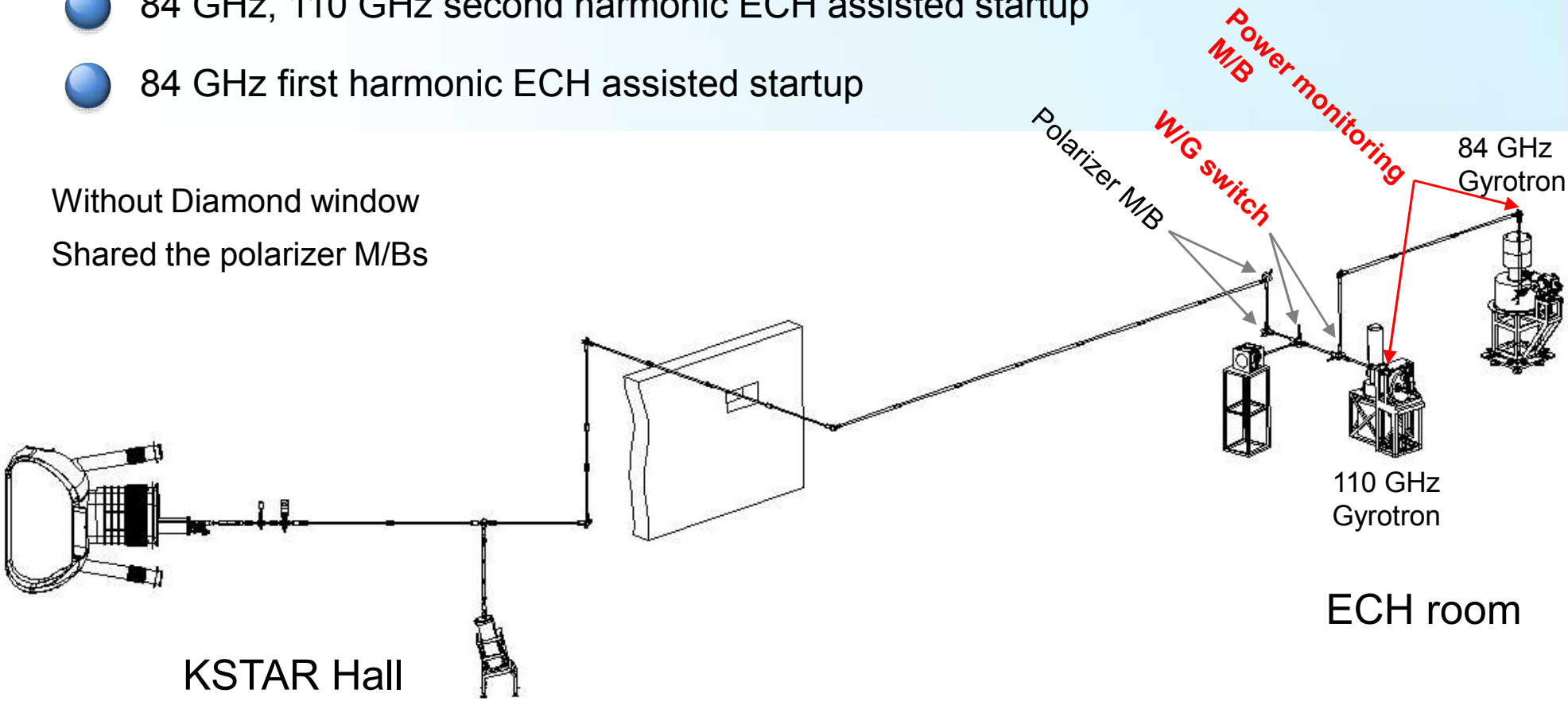
- After the plasma campaign, we found the white powder on the ECH launcher.

2010 ECH plan

- Power supply upgrade (70kV/30A, RF power ~ 800 kW)
- Rearrangement for selective operation of 84GHz/110GHz gyrotron
- RF beam alignment with MOU
- ECH antenna motor, fixed mirror, steering mirror upgrade
- 84 GHz, 110 GHz second harmonic ECH assisted startup
- 84 GHz first harmonic ECH assisted startup

Without Diamond window

Shared the polarizer M/Bs



Summary

- In a short period of time, the 110 GHz Gyrotron system is successfully installed for the ECH-assisted startup in 2009 KSTAR campaign.
- The measured output beam profile at the window using a burn paper showed a good agreement with those measured in DIII-D. A Gaussian-like RF beam profile at the output of the MOU was also observed using the burn paper measurement.
- RF power is measured at the terminal dummy load near the tokamak by using the calorimetry method as a function of pulse duration and main magnet current. The maximum measured RF power was 250 kW with beam voltage 63 kV and beam current 20 A.
- 110 GHz 2nd harmonic pre-ionization

  Breakdown delay time decreased with high neutral pre-fill pressure, toroidal injection angle of -10 degree, downward injection, X-mode injection, and low vertical magnetic field at the field null center.
- ECH-assisted startup

  For reliable plasma startup, several recipes are suggested.

  With additional gas puff in the pre-ionization phase, the plasma startup was reliable and reproducible (#2109~#2153).