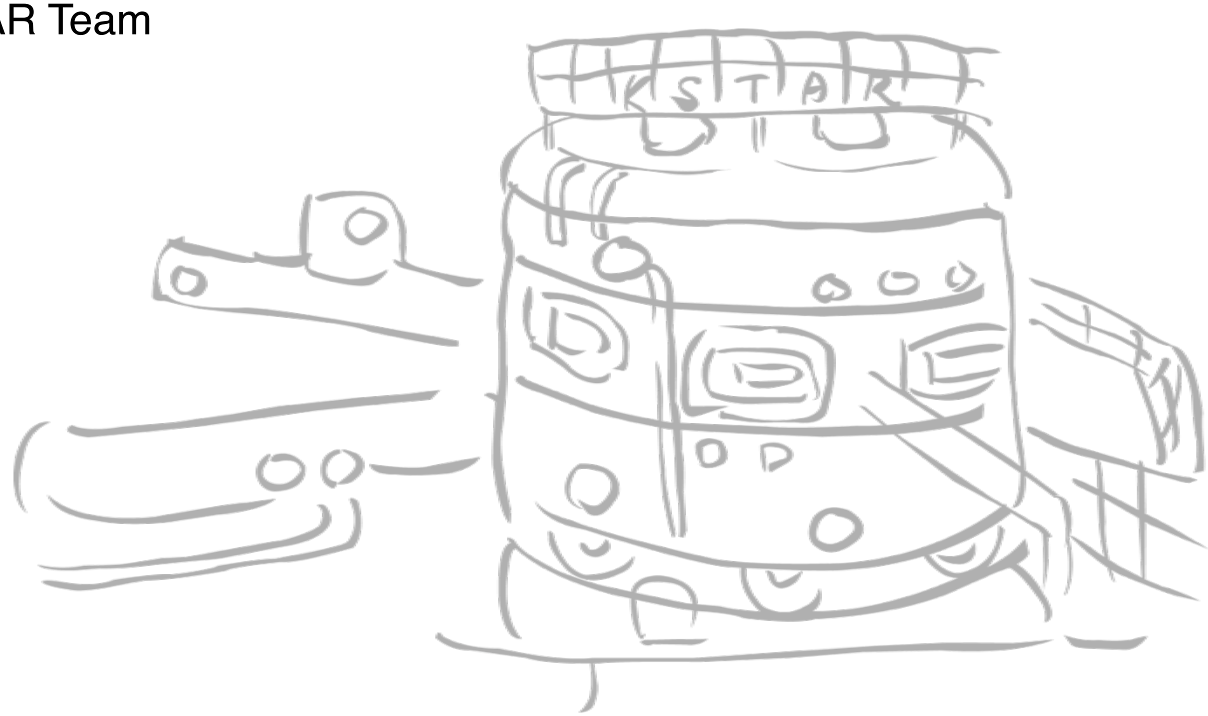
Recent Experimental Results of

KSTAR

National Fusion Research Institute
KSTAR Research Center

M. KWON on behalf of KSTAR Team



국가핵융합연구소
National Fusion Research Institute

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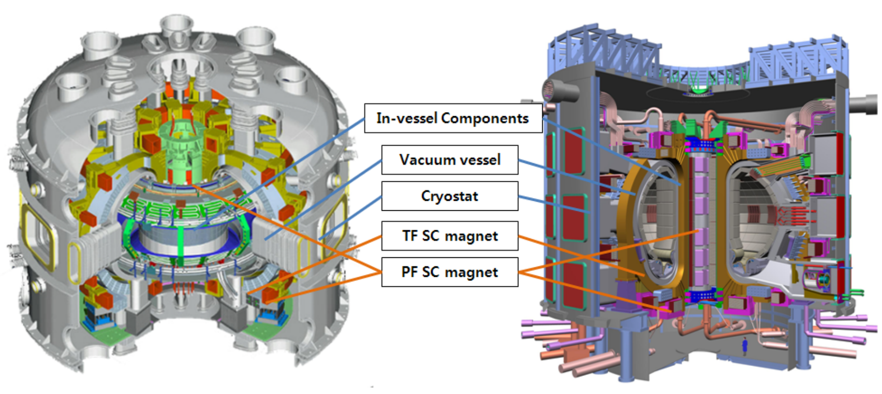
Mission and Achievements

KSTAR Mission

- To achieve the superconducting tokamak construction and operation experiences, and
- To develop high performance steady-state operation physics and technologies that are essential for ITER and fusion reactor development

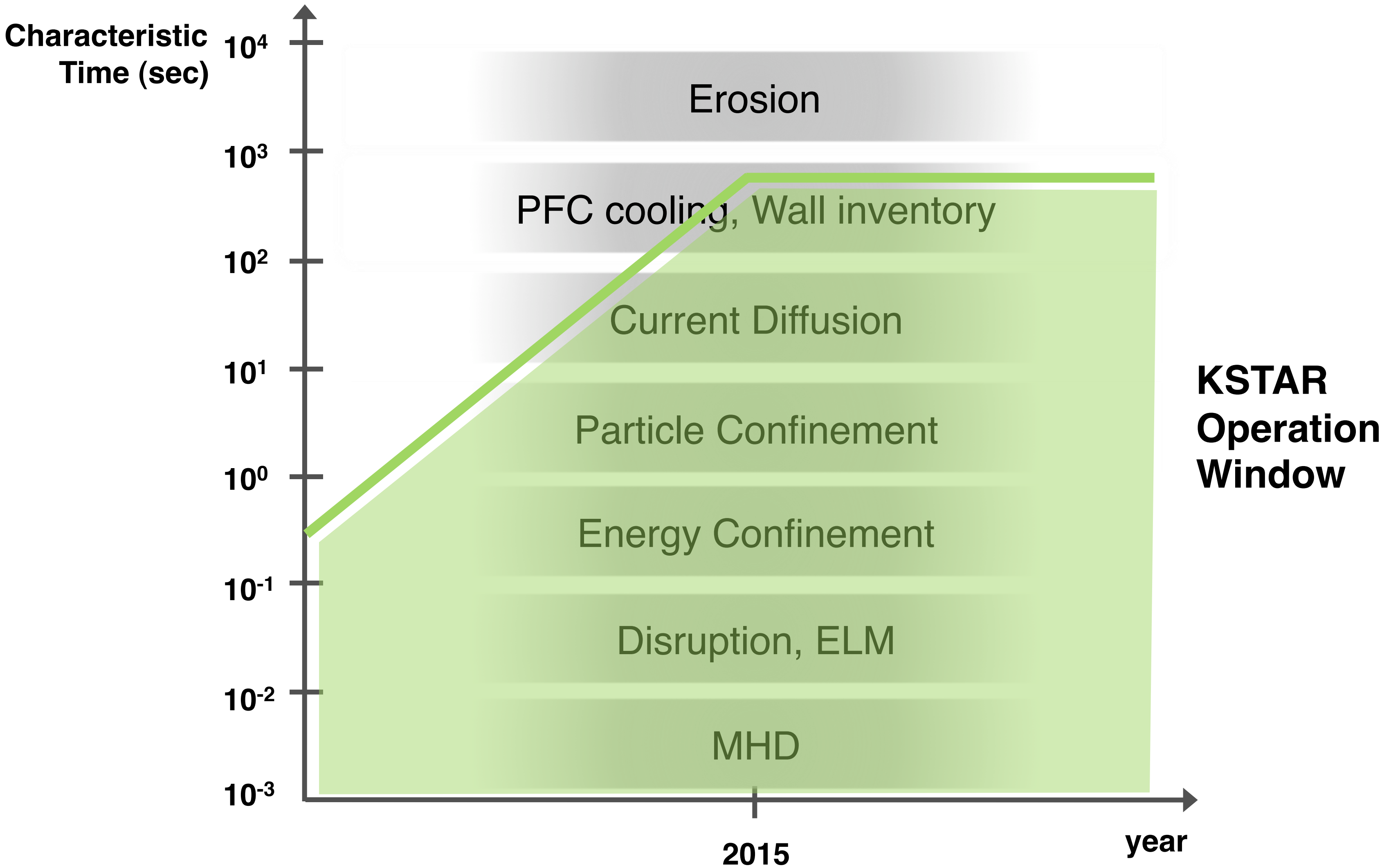


KSTAR Parameters

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	1.8
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
Plasma current, I_P	2.0 MA	1.0 MA
Toroidal field, B_0	3.5 T	3.5 T
Pulse length	300 s	10 s
β_N	5.0	> 1.5
Plasma fuel	H, D	H, D
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Auxiliary heating /CD	~ 28 MW	2.0 MW
Cryogenic	9 kW @4.5K	5 kW @4.5 K

•Black : achieved •Red : by 2011

Long Pulse Operation



Advanced Tokamak

Standard

- Shaping (2010)
- Iso-flux control (2011)
- H-mode (2011)
- $\beta_N < 3$ (2012)
- Current profile control (2013)
- Transport barrier (2013)

Advanced

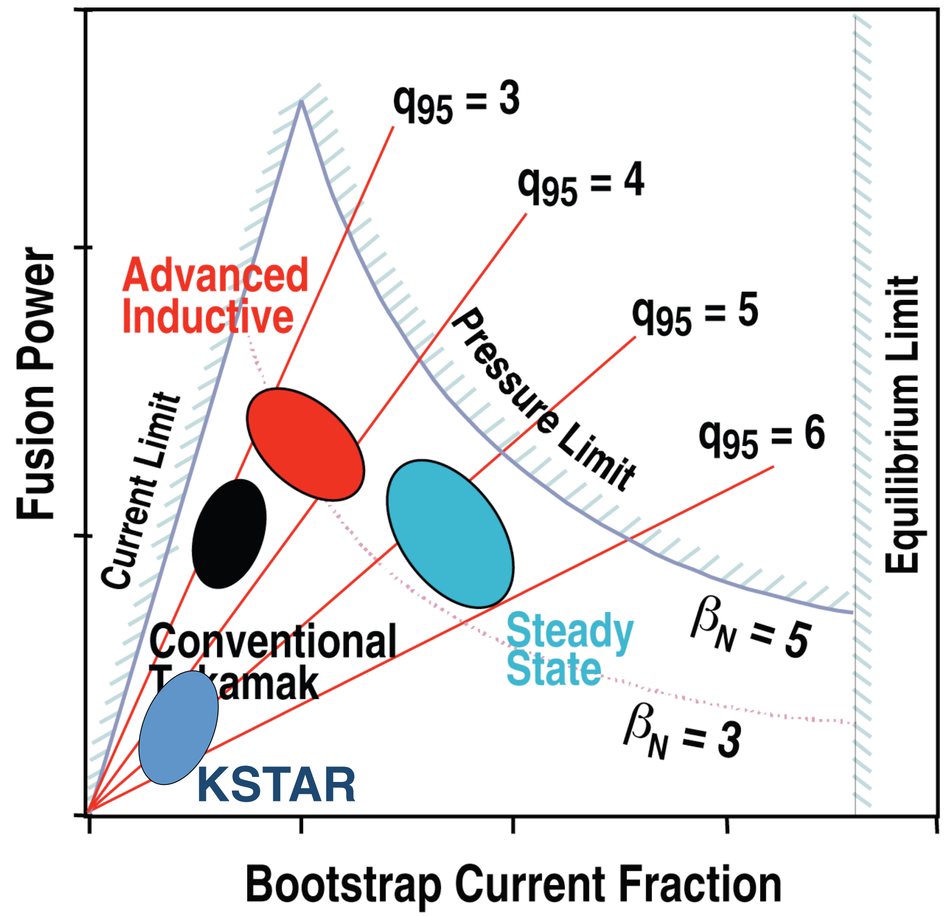
- High β, f_{bs}
- Long-pulse op.

Integrated and Optimized Operation

For steady-state operation,♪

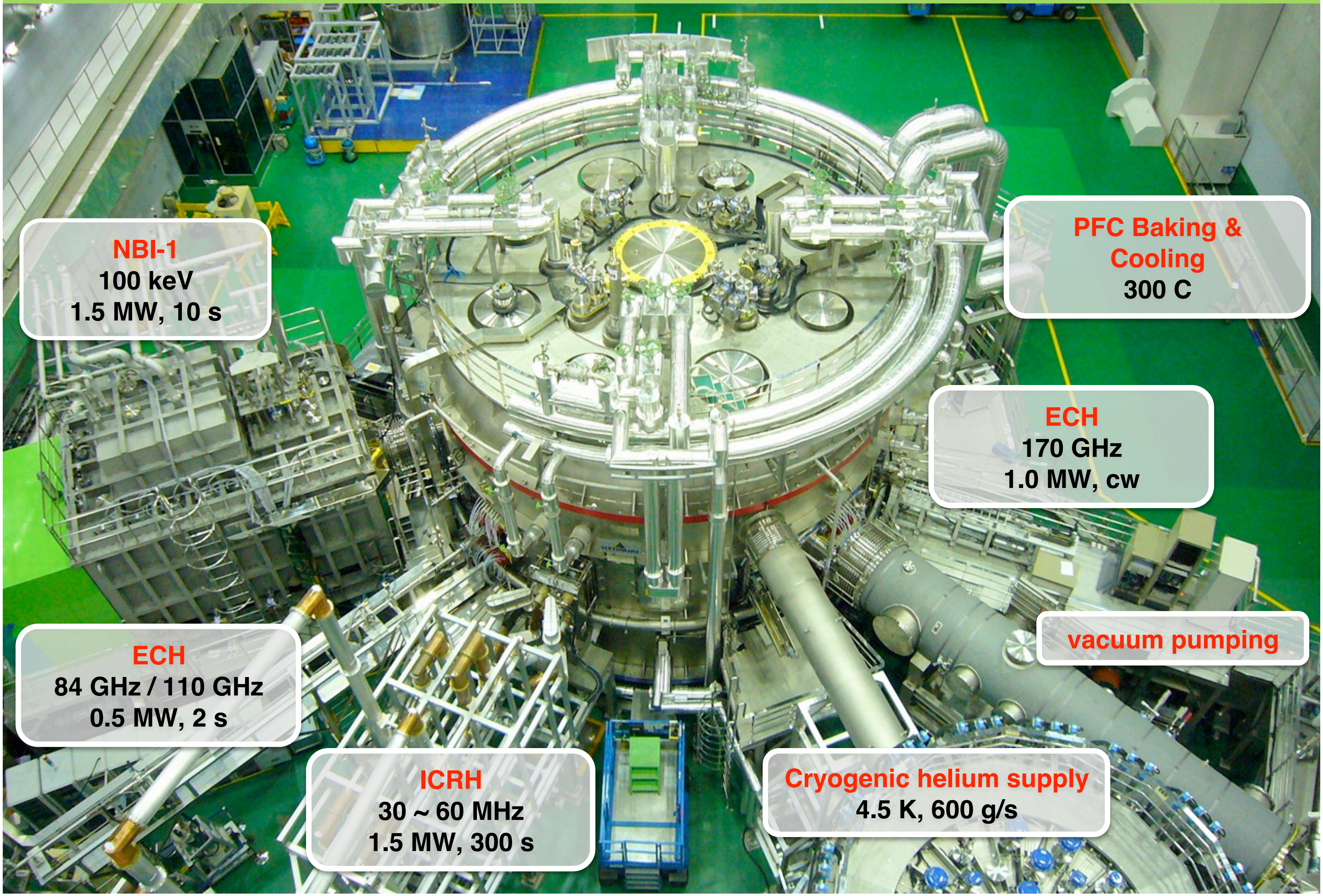
- Heating & Current drive
- Enhanced Performance
- Stability and Control
- Plasma boundary
- Long pulse operation capability

As expanding the operational limit, an integration and opti mization will be pursued with long pulse capability.



From "Realizing Steady-state Tokamak Operation for Fusion Energy" by T. Luce in 2009 APS-DPP

KSTAR Device for 2011 Campaign



Diagnostic Systems for KSTAR

- Installed
- Installed for 2011
- Planned from 2012

•Inspection Illuminator
•TV -2 (Tan.)
•IR TV-2 (Inboard)
•CES (Background)

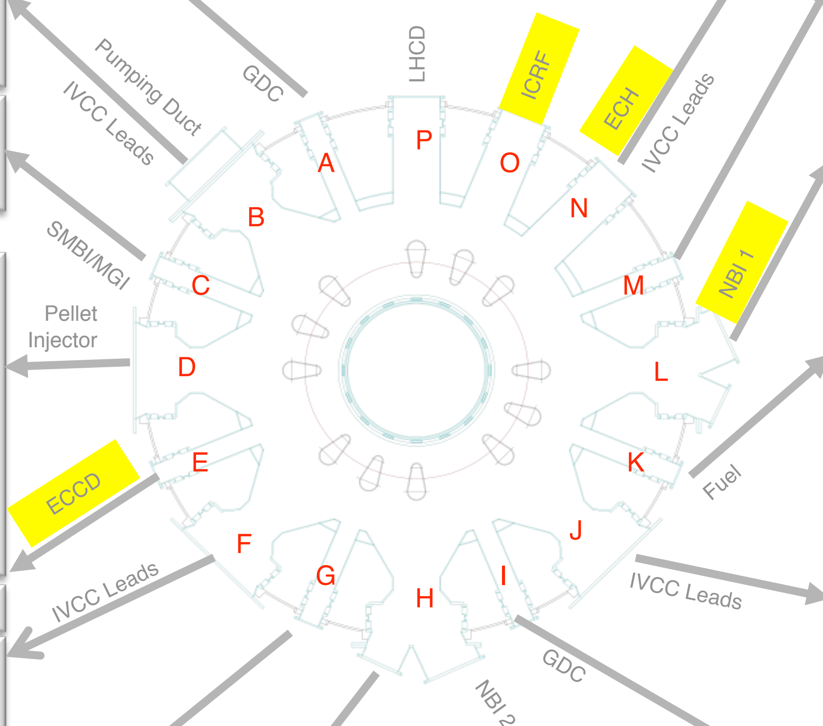
•XICS_perpendicular ('09)
•Thomson S. Dump ('10)
•X-ray Pinhole camera('11)
•(slant) Div. Bolometer ('12)

•Recip. Langmuir Probe
•Fast-ion loss detector ('11)
•Edge probe array ('11)

•Soft X-ray Array ('09)
•TV-3 (from H) ('10~)
•IRTV-1 ('11)
•Imaging Bolometer ('11)
•Ellipsometry ('10)
•Deposition probe ('10)
•mm-Interferometer ('12~)
•Reflectometer ('11)
•X-ray Pulse Height Anal.

•XICS_tangential ('10)
•X-ray Pinhole Camera ('12)
•VUV Survey Spec.

•mm-Interferometer ('08~'11)
•Reflectometer ('09~'11)
•ECEI ('12~)
•MIR ('12)
•(ver) FIR Interferometer



•TV-3 ('08~'09)
•ECEI ('10)

•Hard X-ray ('09)
•Neutron detector ('10)

•Thomson S. Optics ('10)

•Charge Exch. Spec. ('10)
•Coherence Image ('10)
•MSE ('13)
•BES ('13)

•Resistive Bolometer Array
•Thomson S. Laser ('10)
•CX-NPA

•ECE ('08)
•ECE Grating Polychrometer
•(vert) D. Thomson
•(vert) LIF Optics
•(vert) Laser injection

•H-alpha Monitor ('08)
•Visible Spectrometer ('08)
•Visible Filterscope ('08)
•Visible Brems. Array
•(slant) CES-poloidal
•(slant) Recip. Langmuir Probe
•Multi-chord Vis. Spec.

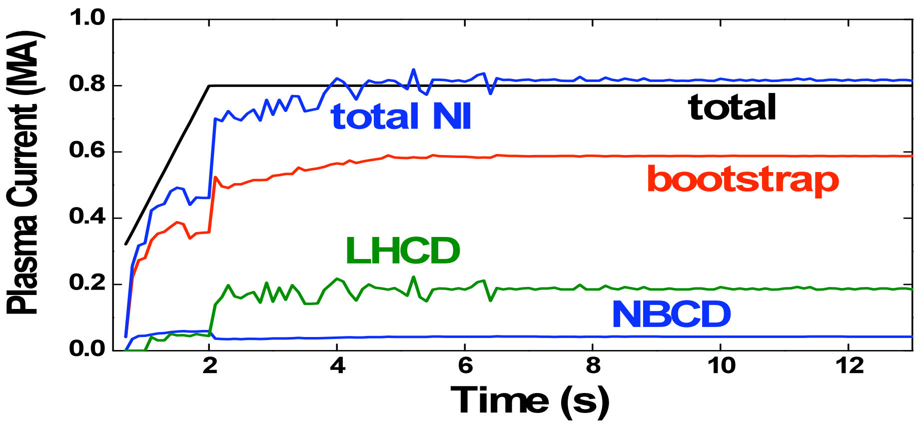
•Inspection Illuminator
•TV-1 (Tan.) ('08)
•IR TV-3 (Inboard)
•*MSE(II)*

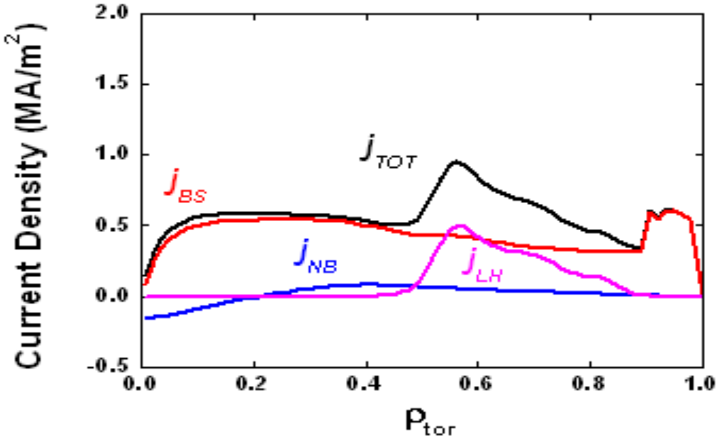
KSTAR Heating and Current Drive Systems

KSTAR	Specification	Role	in 2011
NBI	**14 MW, 300 s** D0/H0 - Two beam lines - Three ion sources per each beam line - Positive based ion source at **120 keV**	- Ion heating & CD - H-mode in initial phase	**1.5 MW** D0 - One beam lines - One ion source - Beam energy : max. **100 keV** - Beam pulse : less than **10 s**
ICRF	30–60 MHz, **8 MW(source), 300 s** - Sources: Four 2MW transmitter	- Ion & electron heating in high density - On- and off-axis CD - Wall cleaning by RF discharge between shot	Frequency : 30 MHz Source power : < **1.5 MW** Pulse : >**10 s** Use 4 straps in the antenna
LHCD	5 GHz**, 2 MW(source), 300 s** - 4 x 500 kW CW klystrons	- Electron heating - Off-axis CD for plasma current profile control - RS-mode	
ECH/CD	84/110 GHz, 0.5 MW(source), 2 s - 84 GHz, 0.5 MW gyrotron 170 GHz, **3 MW(source), 300 s** - 3 x 1 MW CW gyrotrons	▪ 84 (or 110) GHz ECH Startup system - Assisted startup using pre-ionization ▪ 170 GHz ECCD system - 2nd harmonic heating & CD - NTM stabilization leading to high beta - Sawteeth mode control (heating around q=1 surface)	ECH-assisted start up with 110 (and 84) GHz, **0.5 MW (5 s)** Gyrotron ECH and CD with 170 GHz, **1 MW (10 s)**

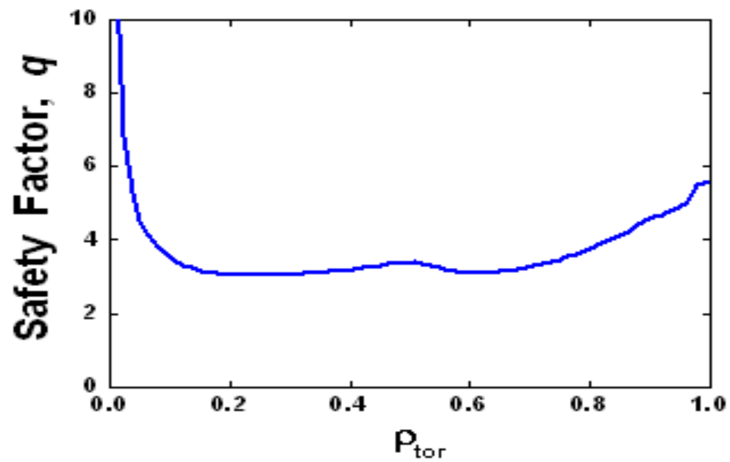
ASTRA Simulation of KSTAR Non-inductive Scenario

- Full non-inductive scenario possible with balanced-NBI & LHCD in RS q-profile plasmas
  - $I_P = 0.8MA$ obtained with $f_{NI} = 100\%$ at $P_{tot} = 8.4MW$



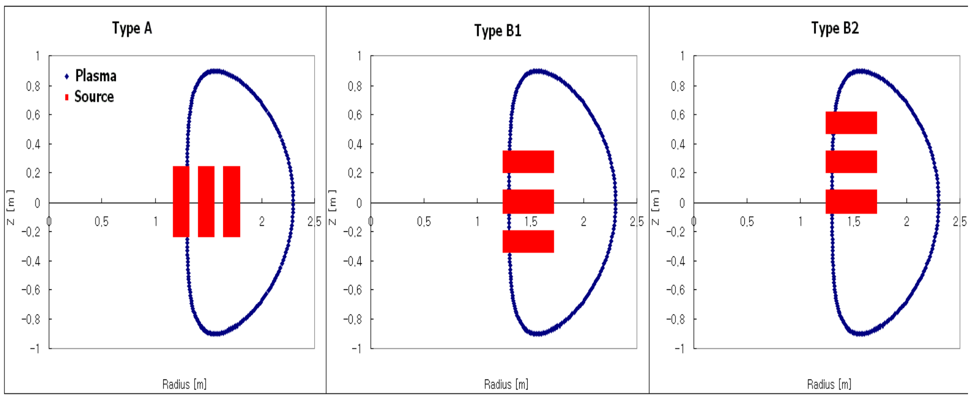


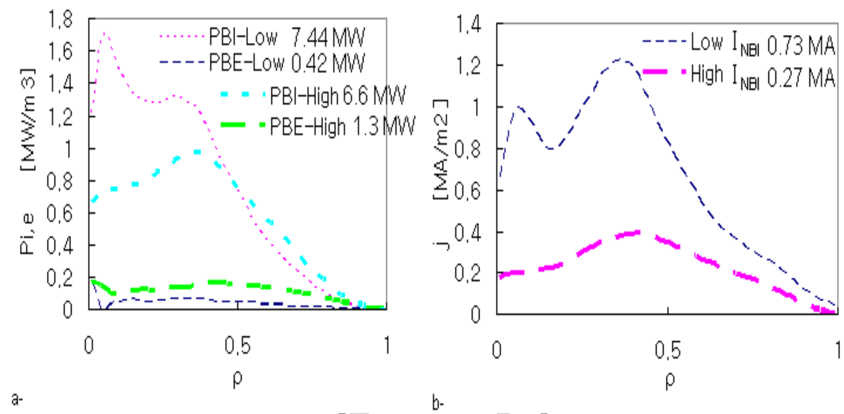
f_{BS} (%)	73.4
f_{NB} (%)	5.3
f_{LH} (%)	23.5
P^{NBI} (MW)	5.4
P^{LH} (MW)	3



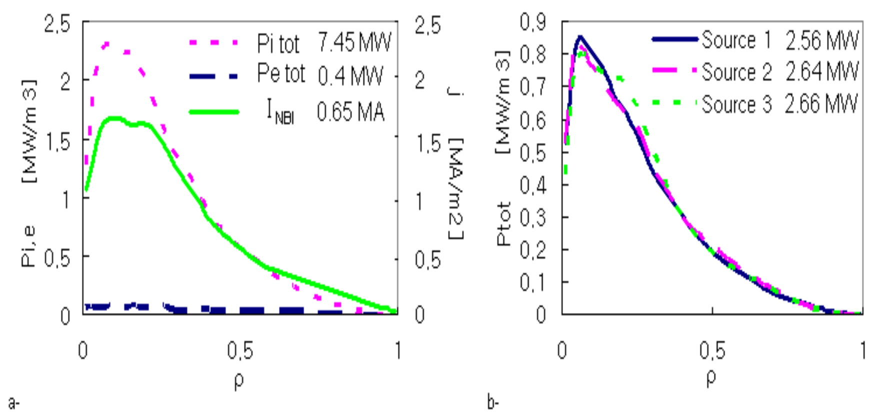
NBI Heating & CD Modeling for KSTAR

- Radial profiles of NBI heating & CD for KSTAR model equilibrium calculated using NUBEAM
  - comparison made of three possible NBI configurations for the 2nd KSTAR NBI system
  - more off-axis heating & CD with the variation of type A → B1 → B2

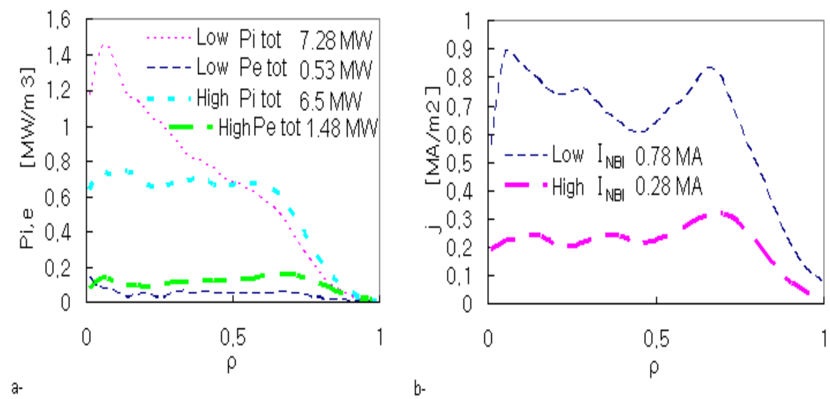




[For type B1]

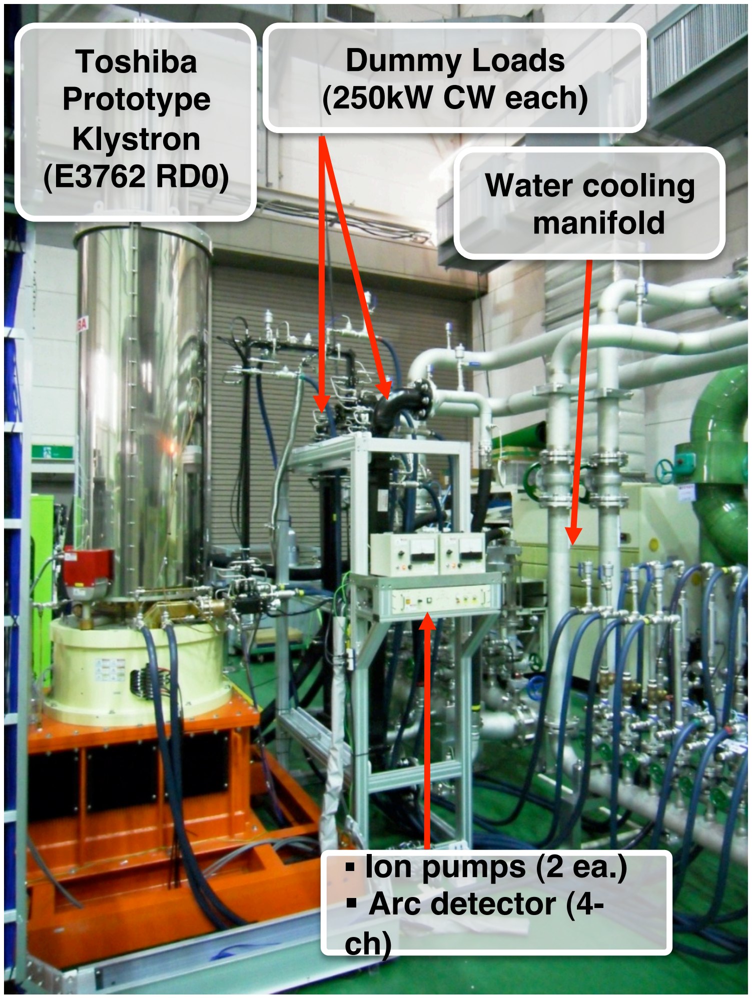


[For type A]

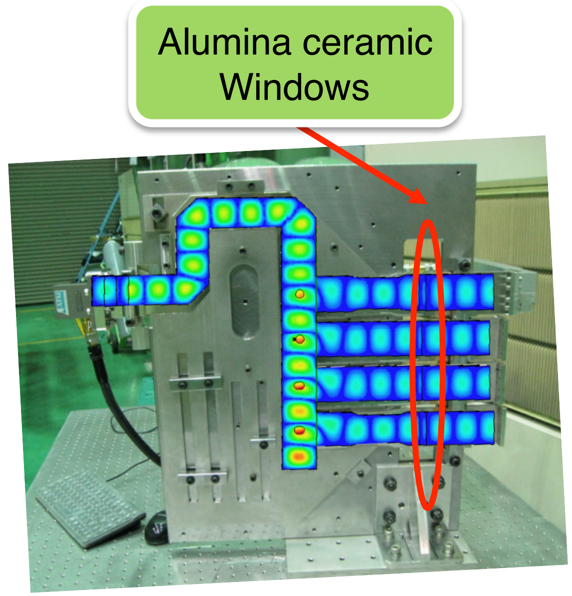


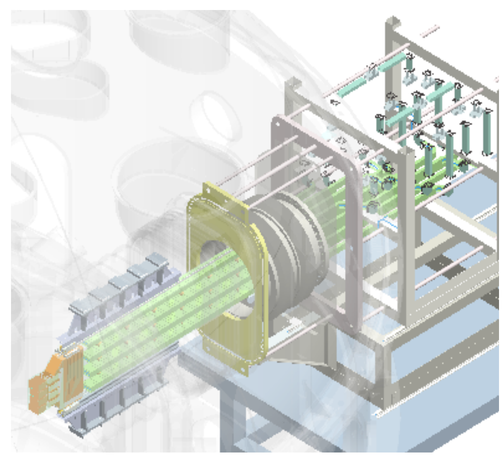
[For type B2]

5 GHz, 500 kW CW Klystron Prototype & Launcher



- Test at KSTAR: 20 s @460 kW, 800 s @300 kW
- Utilization of this test-bed for ITER LH launcher window high power test.



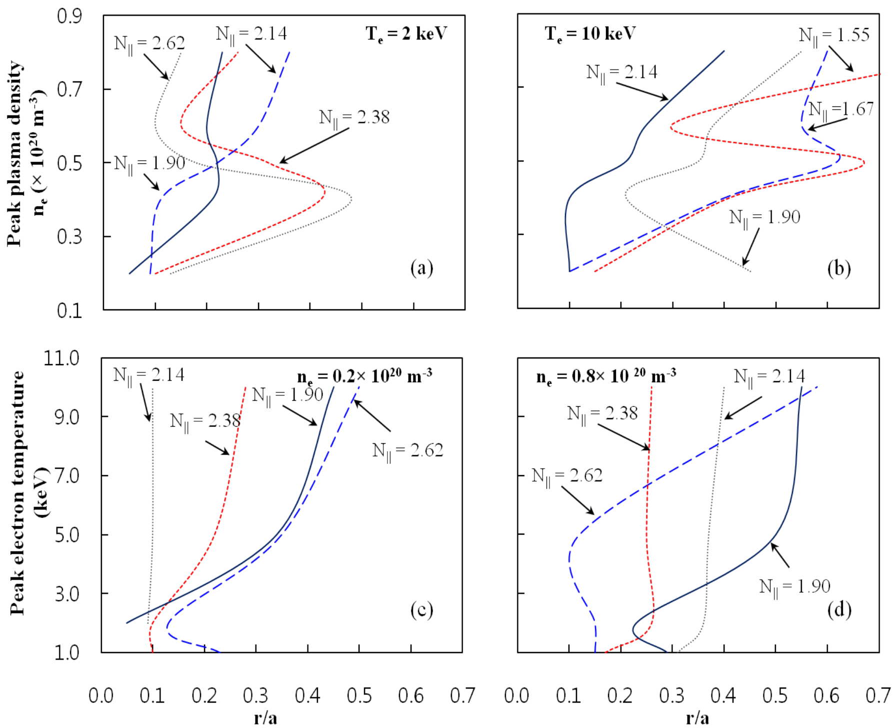


- Design of 8-channel fully active waveguide launcher (no. of waveguide = 32)♪

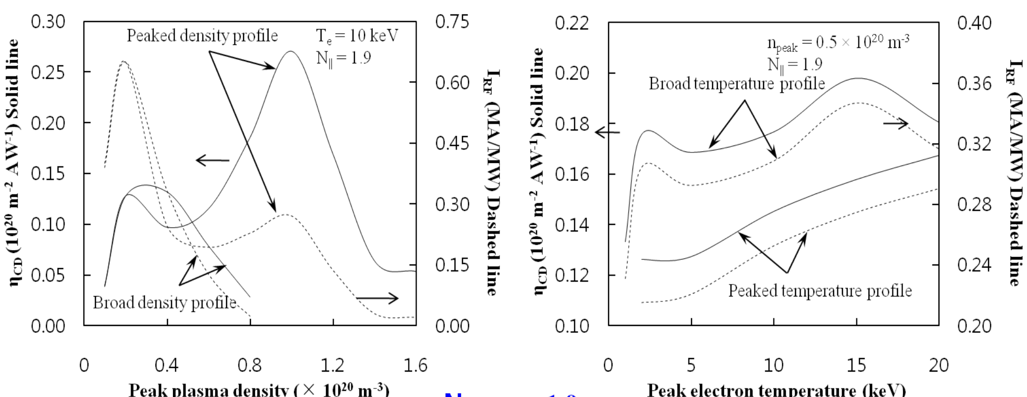
- Prototype of one channel has been fabricated and validated with 4-way RF power splitting
- Un-cooled 8-channel launcher grill will be fabricated for 2012 KSTAR campaign with grill dimensions

➔ width, b = 5.5 mm, septum thickness, d = 1.5 mm, height, h = 55 mm♪

5 GHz LH CD Simulation Results in KSTAR



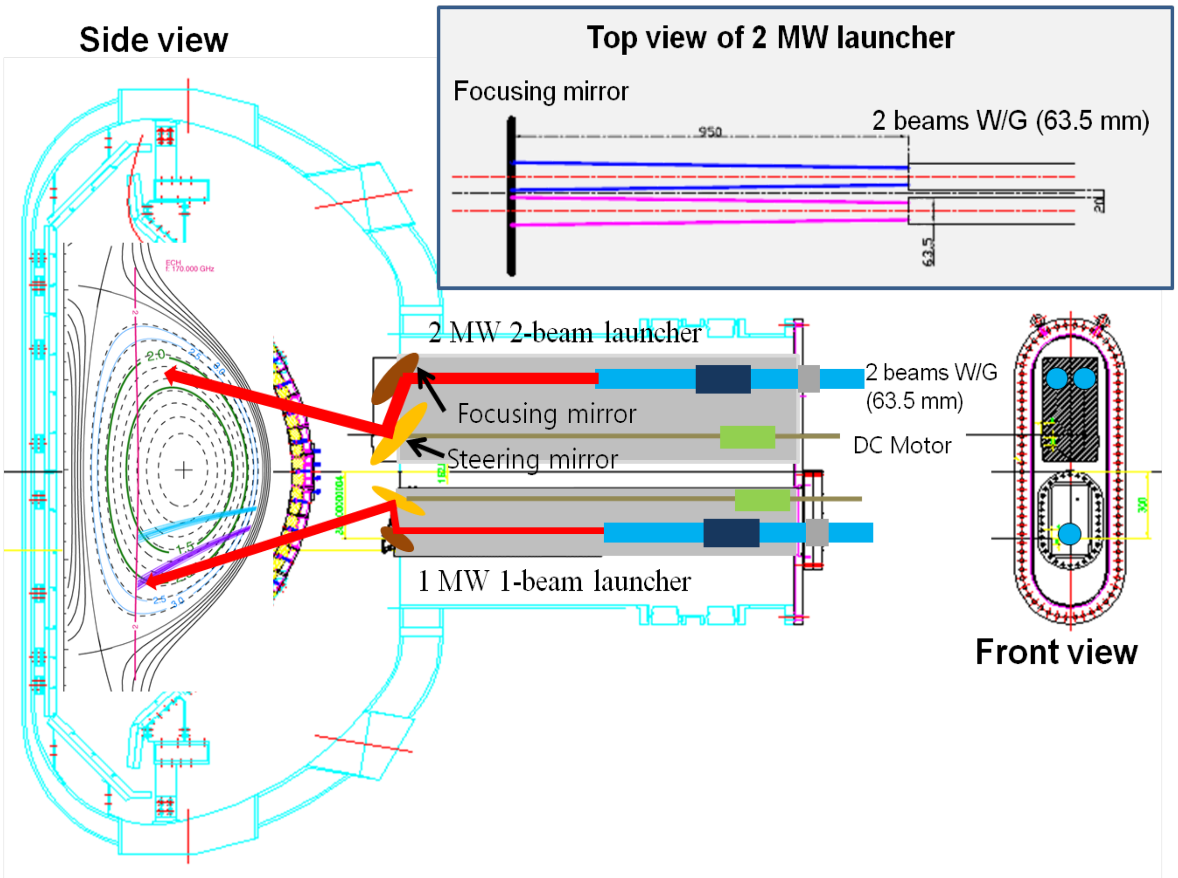
- RF driven current of the order of ~200 kA/MW with efficiency larger than 0.25×10^{20} $AW^{-1}m^{-2}$ when peak n_e~0.6×10^{20} m^{-3} or higher, peak T_e~10 keV, B_T=3.0 T and $N_{||}$ ~1.90 with deposition position is r/*a*≥0.3. with current density ~4×10^{4} A cm^{-2}.



$N_{||\,peak}$ ~ 1.9.

- $N_{||}$=1.9 is optimized for consistent with good coupling, good accessibility, good current profile control and efficient current drive for KSTAR 5 GHz LHCD launcher.

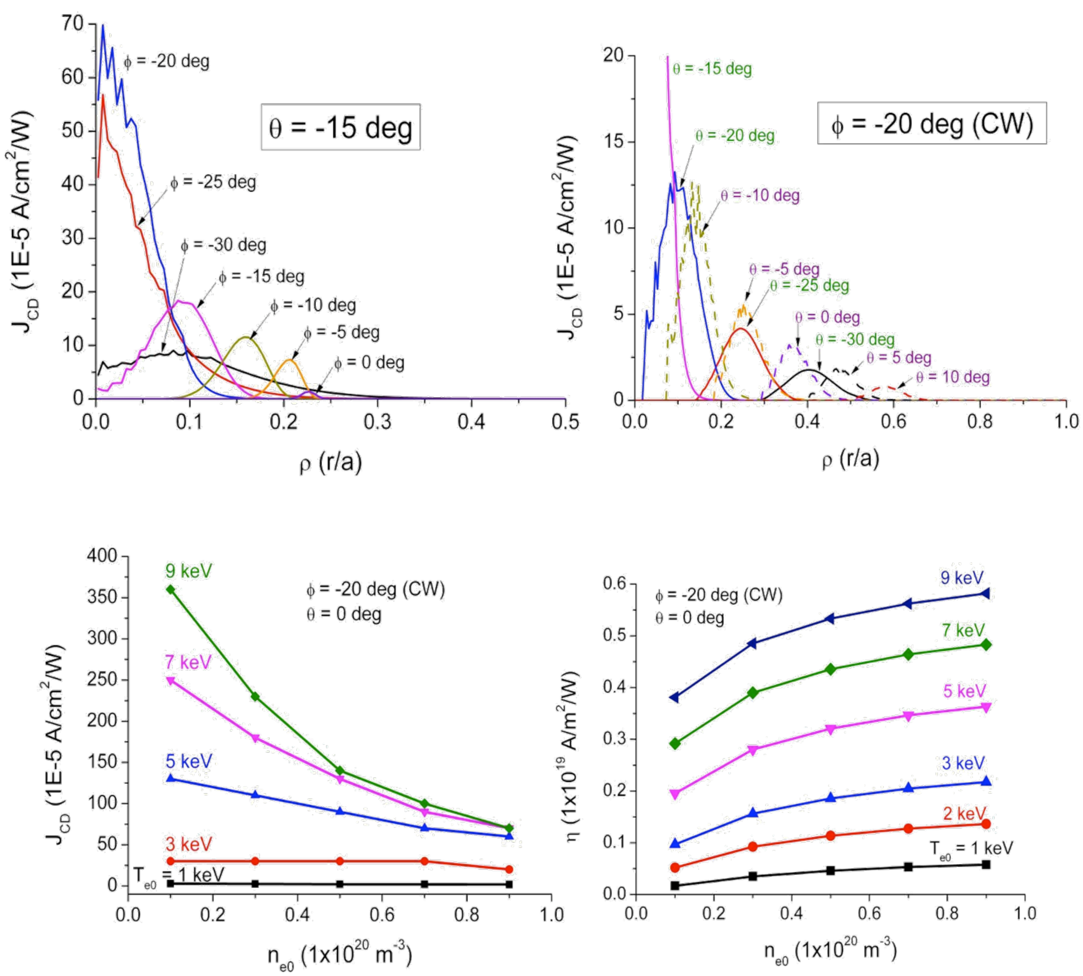
First 170 GHz, 1 MW ECCD Launcher



- **Plan of 170 GHz, 3 MW ECCD Launcher**
  - 1st 1-beam, 1 MW launcher (front-end two mirror system which is same as existing 84/110 GHz EC launcher except the curved surface of the focusing mirror for the beam focusing
  - 2nd 2-beam, 2 MW launcher for the upgrade phase

- First 1 MW 1-beam launcher installed at KSTAR equatorial port (Bay Em)
- Passively cooled mirrors (inlaid Cu bars on back of steering mirror diffuse heat; SS used to reduce eddy current)
- Steering mirror pivoted at -30 cm from the equatorial plane

170 GHz EC CD Simulation Results in KSTAR



Current drive efficiency, $\eta = \langle n_e \rangle R_0 I_{CD}/P_{CD}$♪

- Antenna pivot, z = +30 cm (or -30 cm)
- Beam divergence, FWHM = 1.7 de g
- Maximum driven current is 53.2 kA /MW for ϕ = -25 deg and θ = -15 d eg (or +15 deg).♪

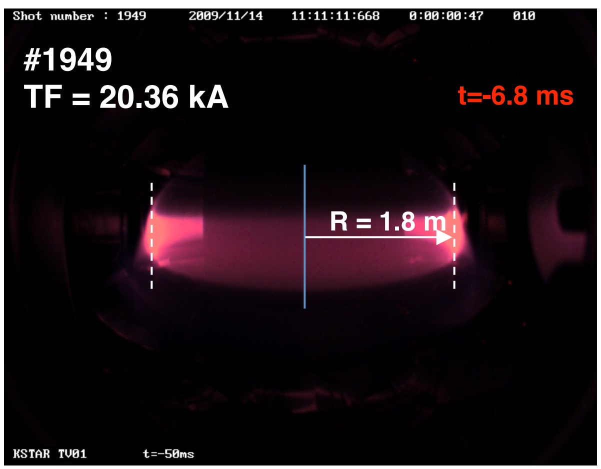
- The current drive efficiency η inc reases as the plasma density an d the electron temperature incre ases, but the peak value of the c urrent density decreases as the plasma density increases.
- For the electron temperature de pendence; both the current drive efficiency and the peak value of the current density increases as the electron temperature increas es.

ECH-assisted Startup

Successful pre-ionization with 2nd harmonic ECH

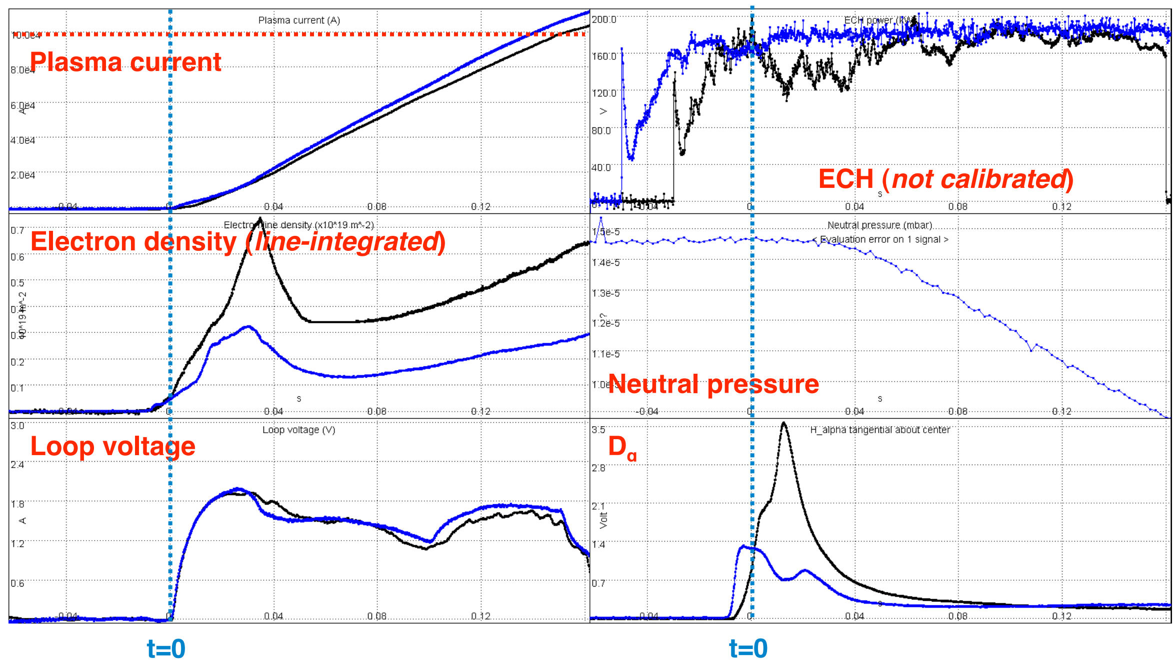
- 2nd harmonic ECH pre-ionization : 1.5 T with 84 GHz and 2.0 T with 110 GHz
- Loop voltage for startup was lowered to 2 V (~15% decrease).
- Pre-ionization was characterized by scanning the injection angle, gas pressure and ECH power. Power threshold was about 250 kW.
- 2nd harmonic ECH pre-ionization could be applicable to ITER startup.

ECH-assisted startup



ECH pre-ionization for 84 GHz and 110 GHz

Black: 84 GHz in 2008 (#794)
Blue: 110 GHz in 2009 (#1767)



First H-modes in KSTAR

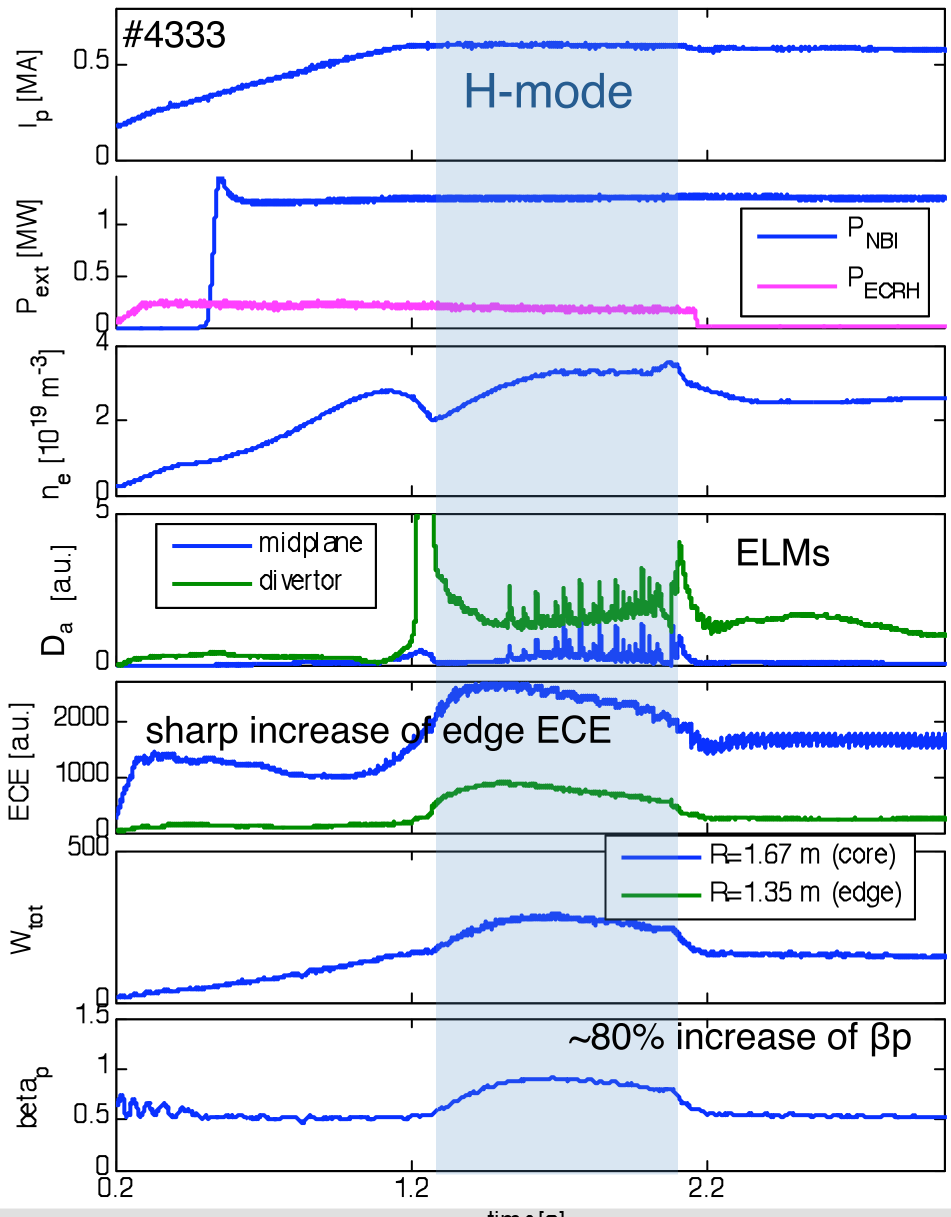
- Typical ELMy H-mode discharges achieved in KSTAR with NB I and ECRH
  - One year earlier than our plan (last days in the campaign)

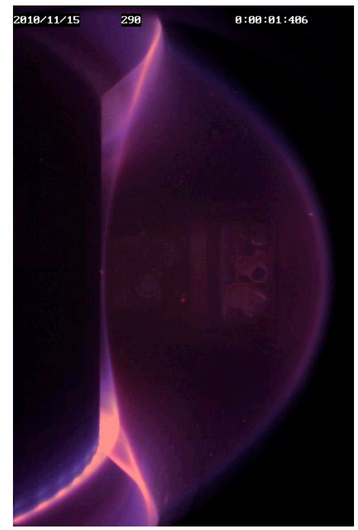
- Total 30 shots obtained for non-adjacent 5 days
  - Ip=0.6 MA at B_T=2.0 T with DN diverted shape (kappa>1.7)
  - Relatively low density regime ($n_e < 4.0 \times 10^{19}$ m^{-3})
  - With ~1.5 MW available power (NBI+ECRH)
  - After boronization with carborane

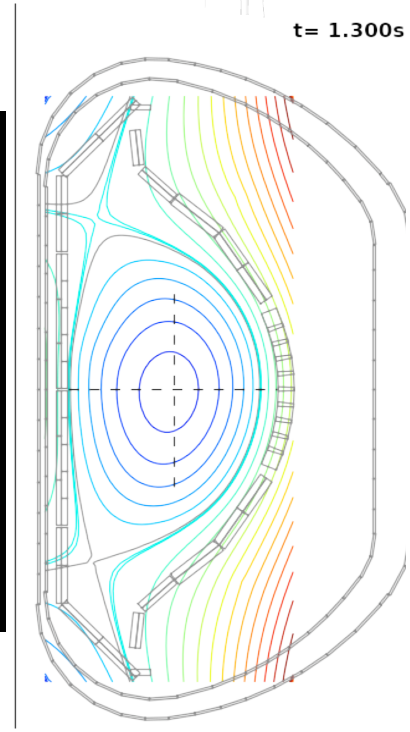
- Marginal powers for L/H transition
  - Slow L/H transitions and dithering
  - Often synchronized with sawtooth crashes

- Under limited controllability of plasma shape and vertical stabil ity
  - H-mode phase lasted for ~1.0 sec

Typical H-mode Shot in KSTAR







~30 shots observed in 5 days

B_T=2 T, I_p~0.6 MA, N_e~2e19 m^{-3}

P_{NBI}~1.3 MW (80 keV, co-NBI)

P_{ECH}~0.25 MW (cntr-injection to Ip)

P_{OH}~0.2 MW

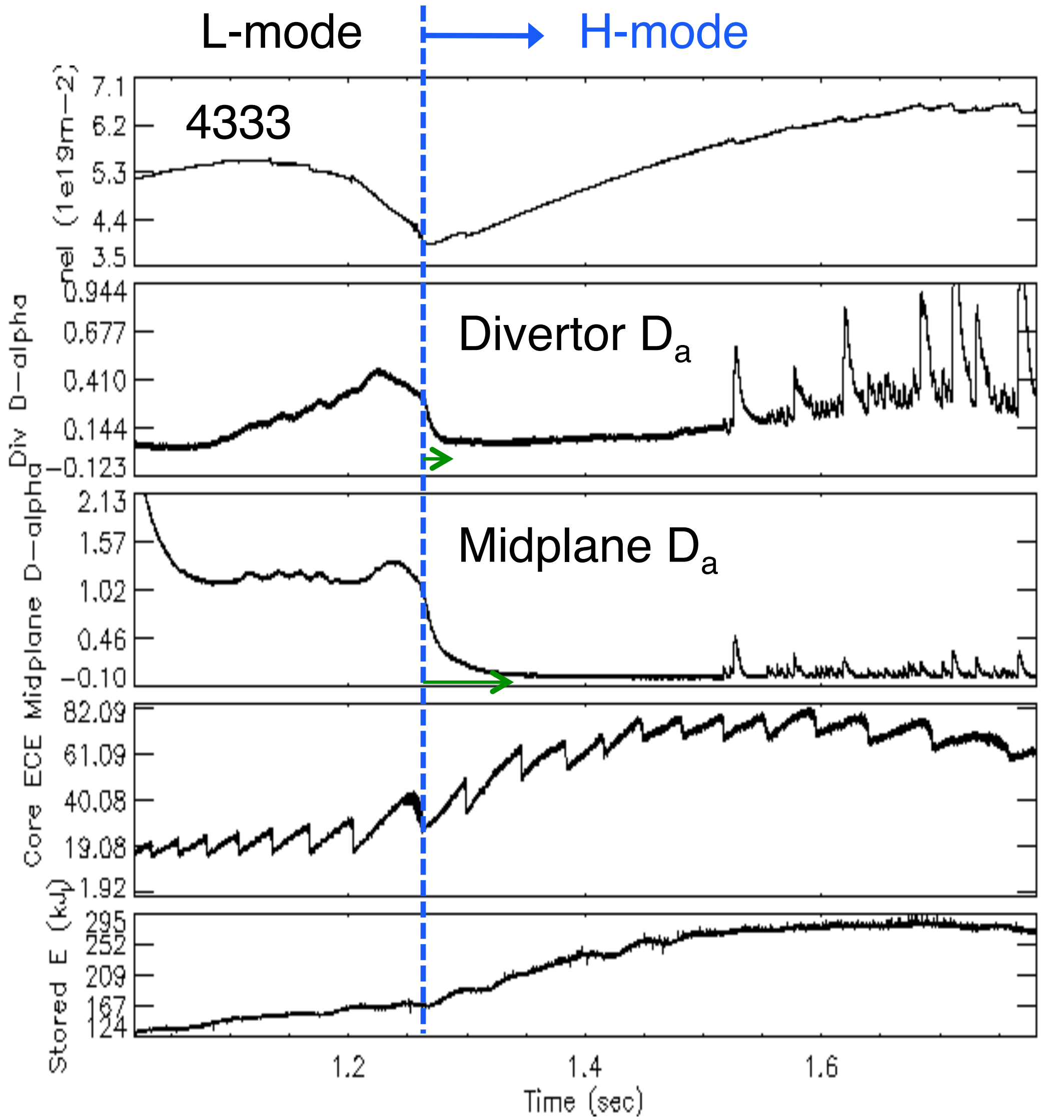
Double null, κ~1.8, R~1.8 m, a~0.5 m

Boronization with carborane

P_{thres} ~1.1 MW

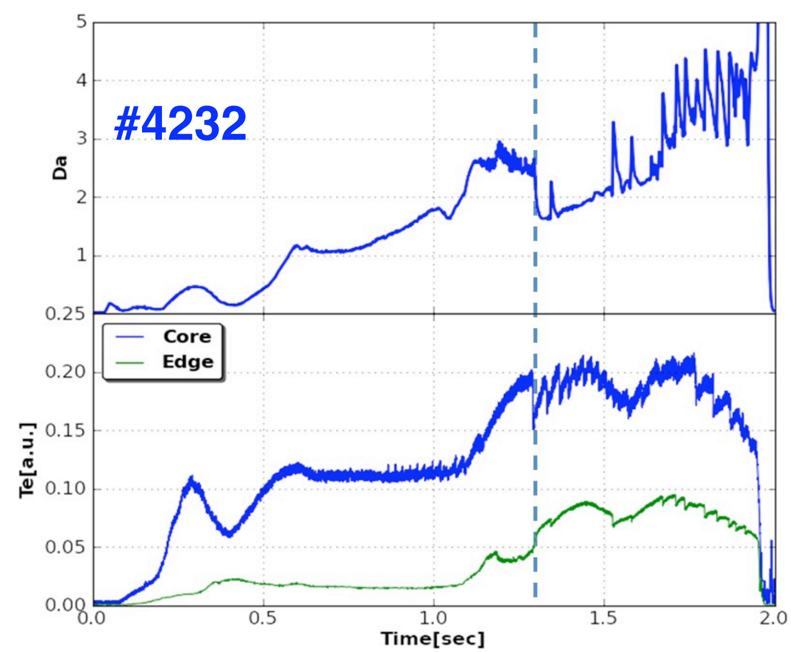
(ITER physics basis, 1999)

Slow L/H Transition and Synchronization with ST Crash

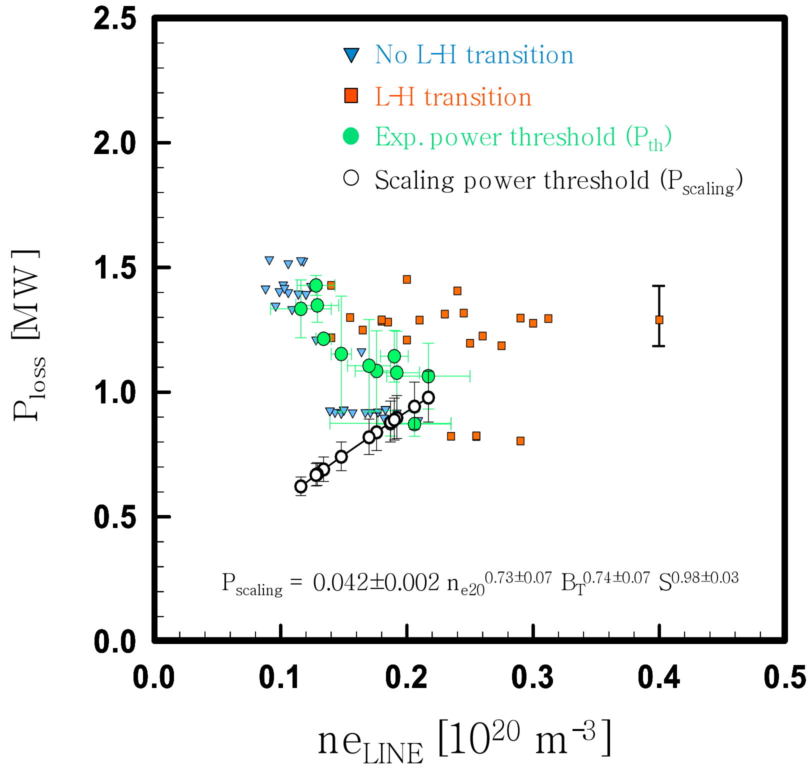


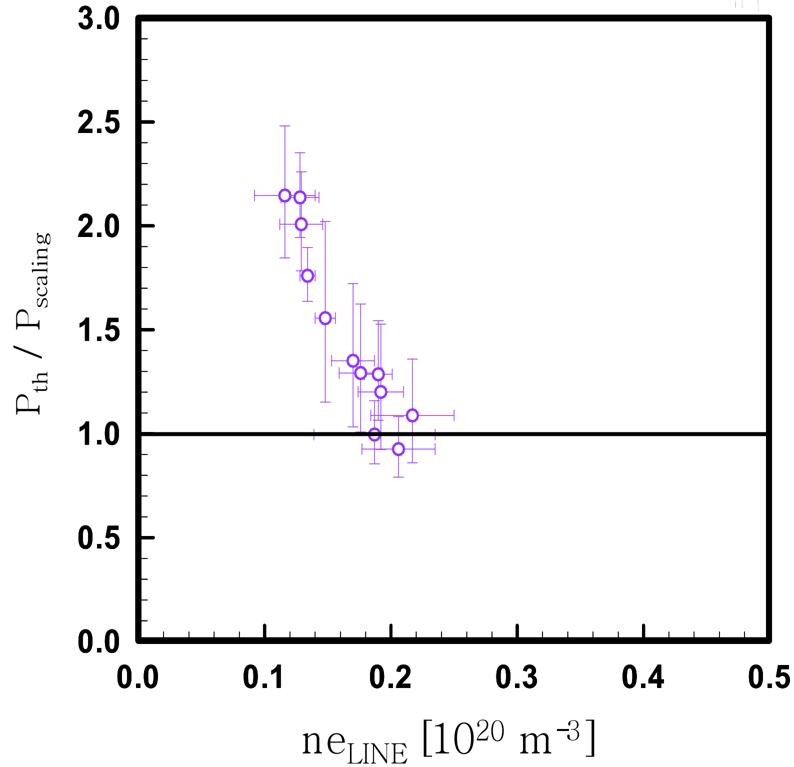
Courtesy by J.W. Ahn (ORNL)

- **Slow L-H** transition for most KSTAR H-mode shots:
  - Transition time from midplane D_a (~50ms) is longer than divertor D_a (~10ms)
- **Sawtooth crash is synchronized** with the L-H transition in many cases



Threshold Power for L/H Transition Was Rolled Over In Low Density Regime





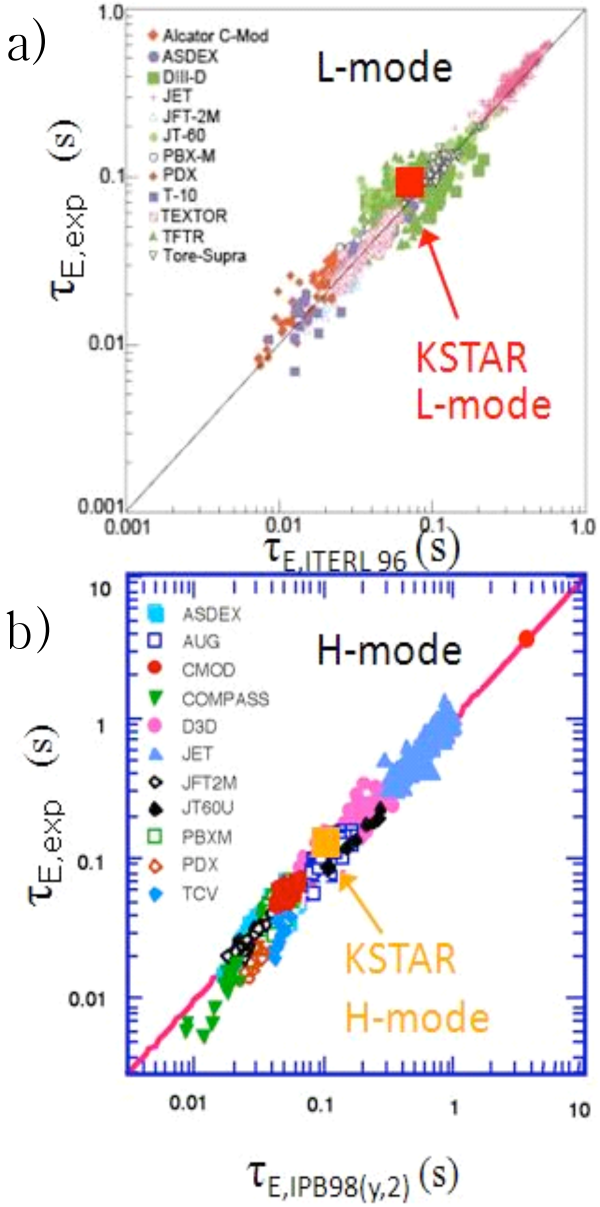
- Most of H-modes were obtained in the range
  - **$0.14 \leq n_{e,line} \leq 0.31 \times 10^{20} m^{-3}$ ($13\% \leq n_e/n_{GW} \leq 40\%$)** with ext. power of **$1.1 \leq P_{in} \leq 1.5$MW**
  - Corresponding to **$n_{e,min}$ for L/H threshold** (*ITER physics basis, 1999*)

- In the **low density below $0.2 \times 10^{20} m^{-3}$**, **the threshold power increased** (**rolled over**) as the density decreased like as previous reports from JT-60U[1] and ASDEX-U[2]

  [1] Fukuda T. *et al 2000 Plasma Phys. Control. Fusion* ***42*** *A289*

  [2] Ryter F. *et al 2009 Nucl. Fusion* ***49*** *062003*

Energy Confinement Time Is in Line with Multi-Machine Database for L- and H-mode



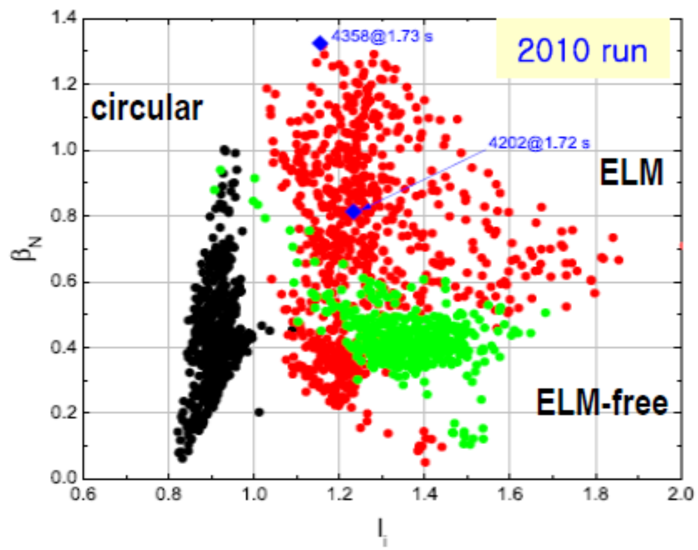
- τ_E estimated using measured stored energy and ASTRA simulation with some assumptions

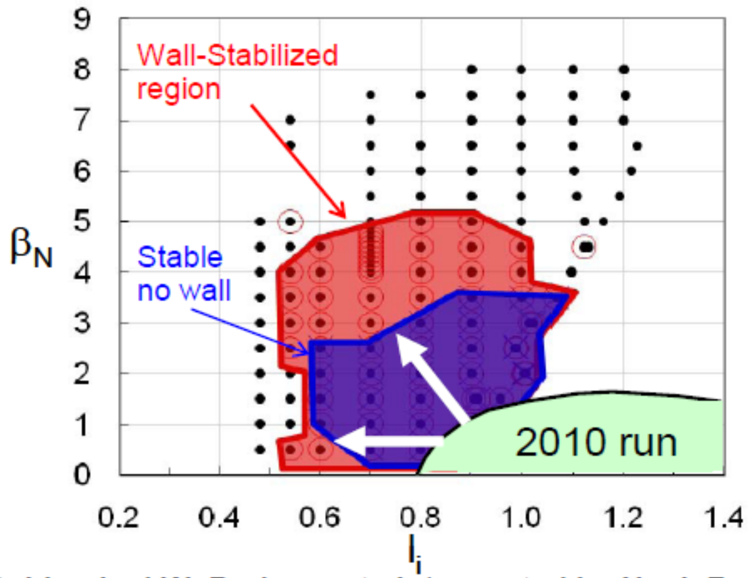
$$\tau_{E,\exp} \equiv (W_{tot} - W_{fast}) / P_{loss}$$

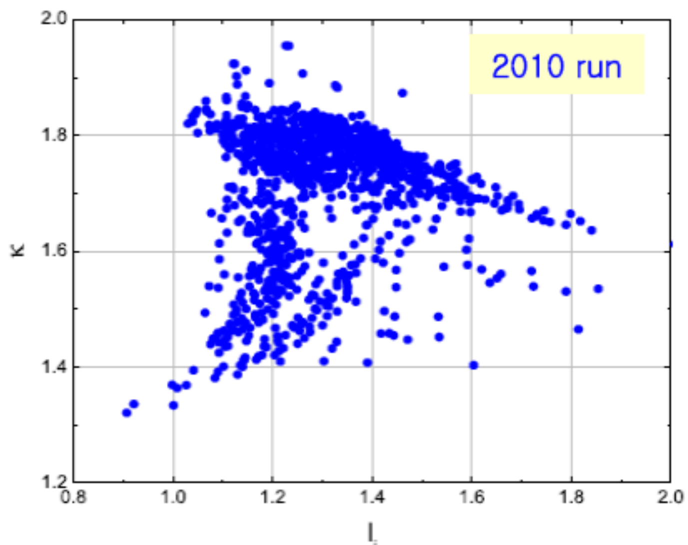
$$P_{loss} = P_{Ohm} + P_{aux} - P_{rad} - P_{fastion} - dW_{tot}/dt$$

- Assuming 20% (due to low density regime) fast ion fraction in the stored energy, the experimental τ_E was estimated
  - L-mode: τ_E= ~86ms, **H_{L96}=1.3**
  - H-mode: τ_E=~130ms, **H_{H98}=1.1**

Extended Operation Window



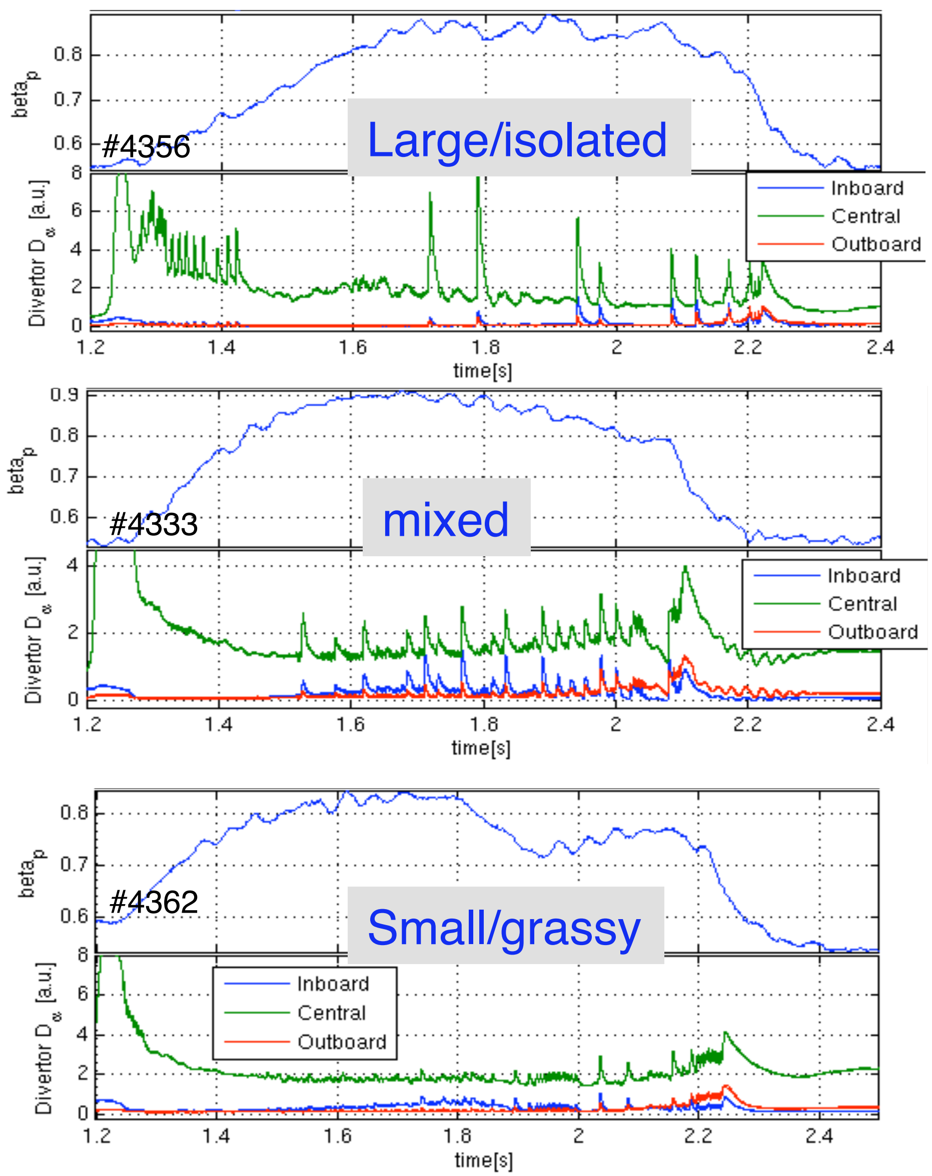




* Y.S. Park, S.A. Sabbagh, J.W. Berkery, et al. (accepted by Nucl. Fusion) (2011)

- In 2010, KSTAR operation regime was widely extended
  - β_N up to 1.3, Elongation up to 1.9
  - Triangularity up to 1.0
  - l_i covered: 0.8 to 1.9, but only circular has l_i<1.0
- For n=1 RWM and vertical stabilities, li should be decreased more

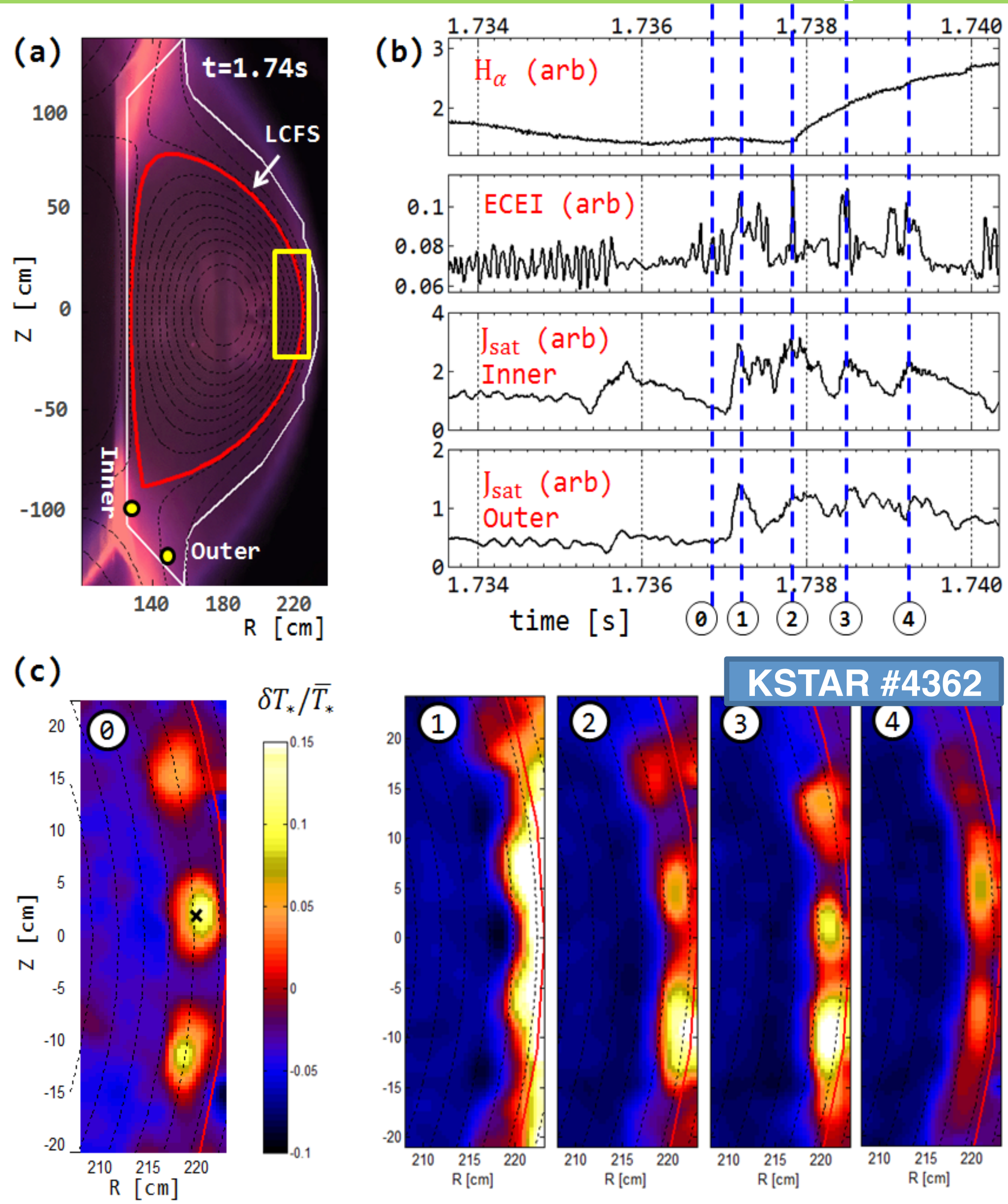
Variety of ELM phenomena found: mixing EC heating changes ELM characteristics



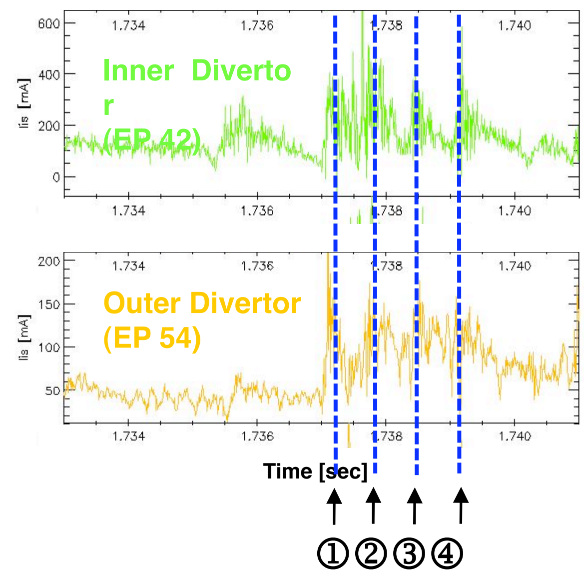
- **Large/isolated bursts** (#4356)
  1.5 MW of NB injections makes a dithering/small ELM first, and isolated, large bursts appear after a long ELM-free period (>0.2 s)

- **Small/grassy or mixed** (#4333,4362)**:**
  - Any deposition of EC heating eliminates first dithering
  - Either small "grassy" ELMs or mix of small & large bursts appears after the ELM-free period

2D ECEI Observation: A Single Large ELM Crash Event Consisted of A Series of Multiple Filament Bursts

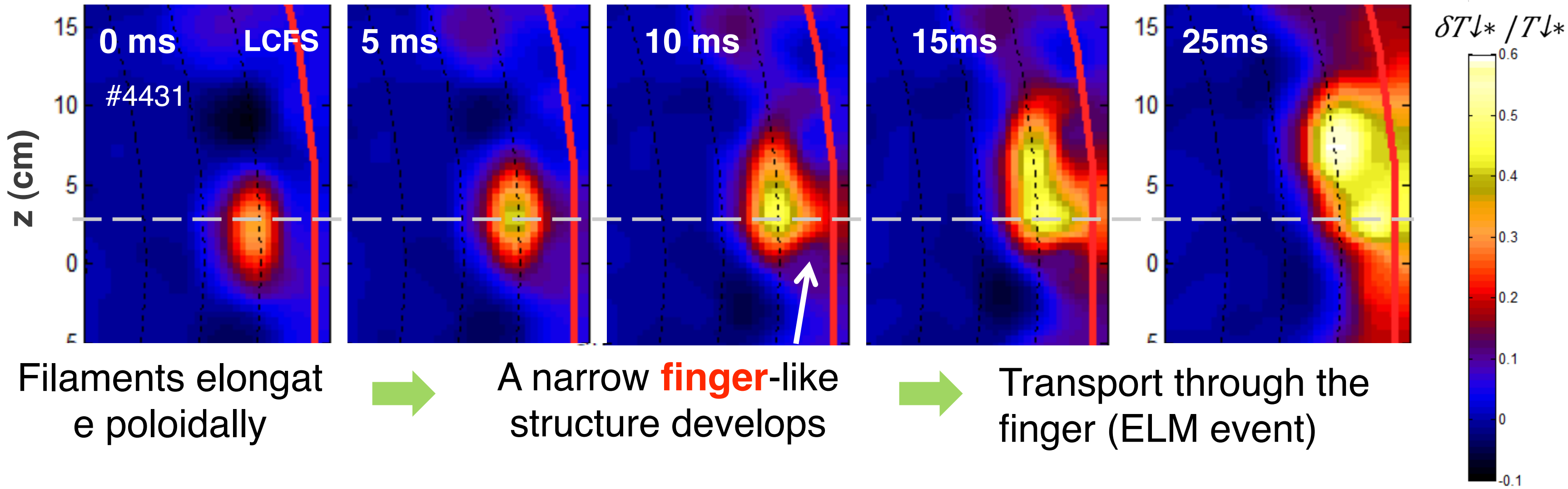


- A single large ELM crash was consisted of a series of multiple filament bursts
- Similar observations on ion saturation currents measured from divertor probes

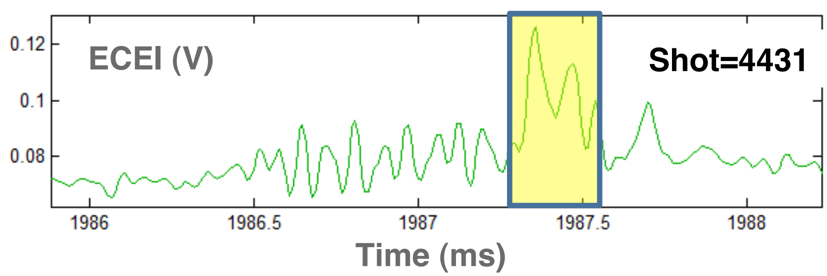


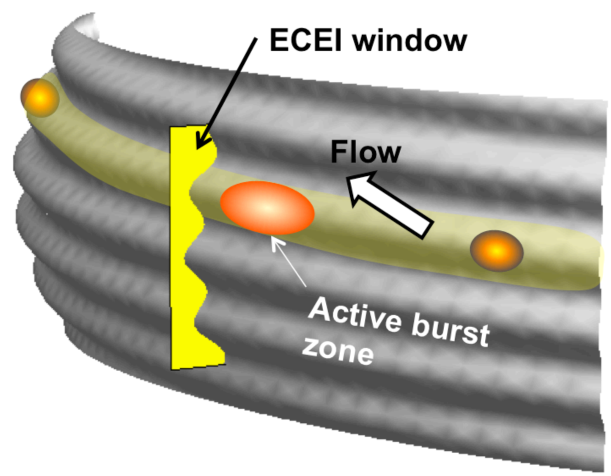
Courtesy by G.S. Yun (Postech) and J.G. Bak (NFRI)
Accepted for publication in PRL (2011)

Filament Burst in A Large ELM Crash: Finger-Like Structure Formation and Its Evolution to A Burst



Filaments elongate poloidally → A narrow **finger**-like structure develops → Transport through the finger (ELM event)



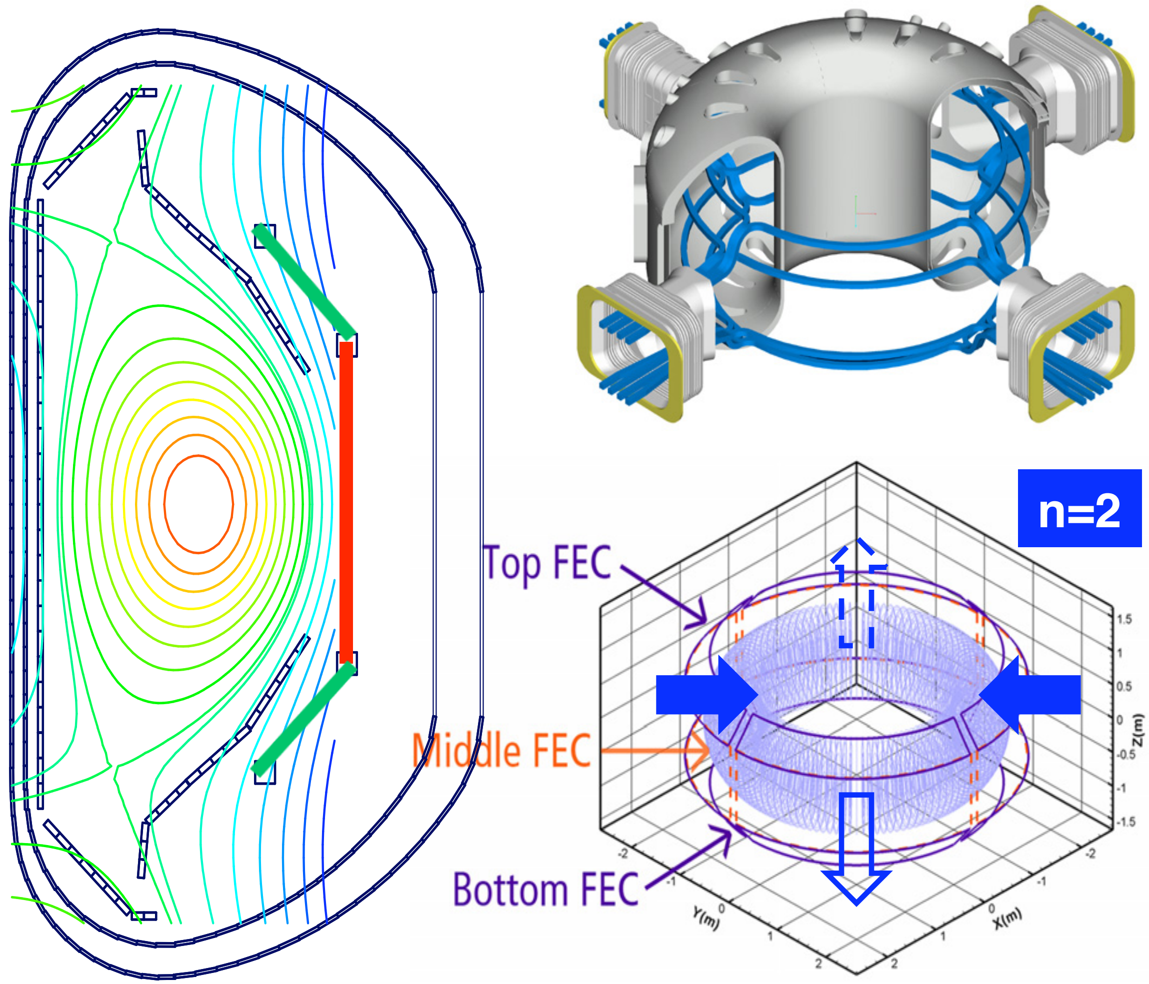


- Elongation of filament suggests an increased shear in the poloidal flow
- Fast burst < 50 ms, localized burst zone
- Finger connection to LCFS initiates the ELM

POSTECH
FOM UCDAVIS

Courtesy by G.S. Yun (Postech) Accepted for publication in PRL (2011)

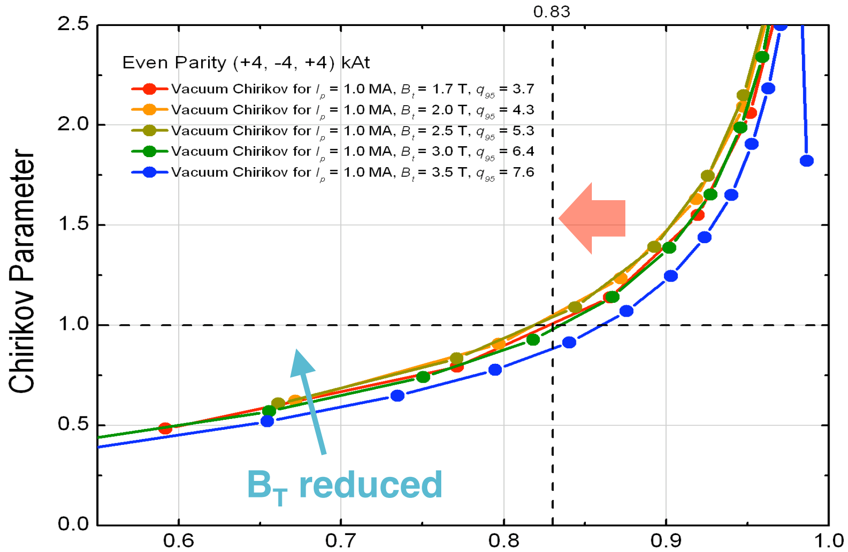
N=2 RMP Applicable for KSTAR 2011 ELM Control



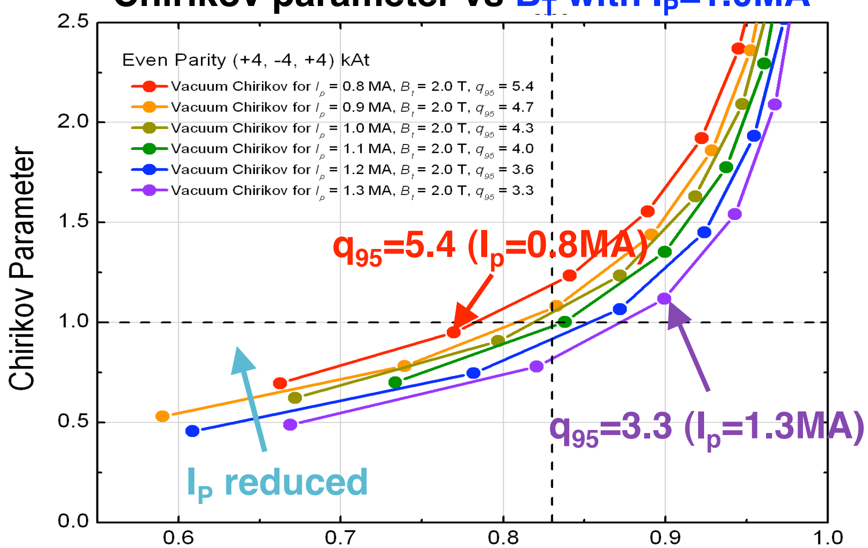
KSTAR Picture-Frame RMP Coils

- n=2 magnetic perturbatio n applicable
- Poloidally three coils avail able for changes of even/o dd parity and phasing
- Note that these are all inn er coils close to plasma. A nd the middle coil is very u seful for variations of mag. perturbation.

Preliminary Analysis of ELM Control by RMP for KSTAR 2011
: ELM Suppression May Possible



Chirikov parameter vs B_T with I_P=1.0MA



Chirikov parameter vs I_P with B_T=2.0T

***** *Y.S. Park, KSTAR RMP meeting, Jan. (2011)***

- Reducing B_T doesn't change much, but helpful due to reducing q_{95}
  - ψ_N >0.83 can be met
  - q_{95}=3.7 with B_T=1.7 T

➔ ELM could be suppressed

- I_P can make large changes on
  - RMP penetration
  - q_{95}

➔ I_p optimization with lowest B_T needed for ELM suppression

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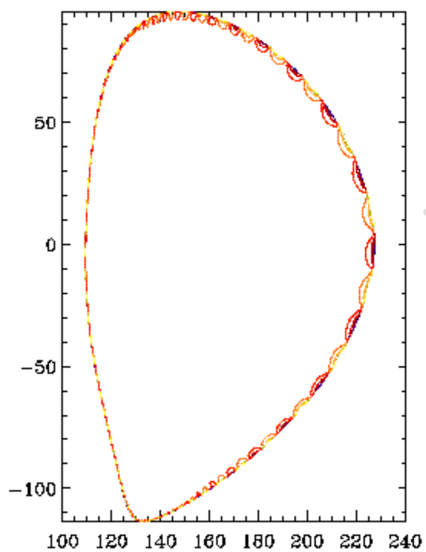
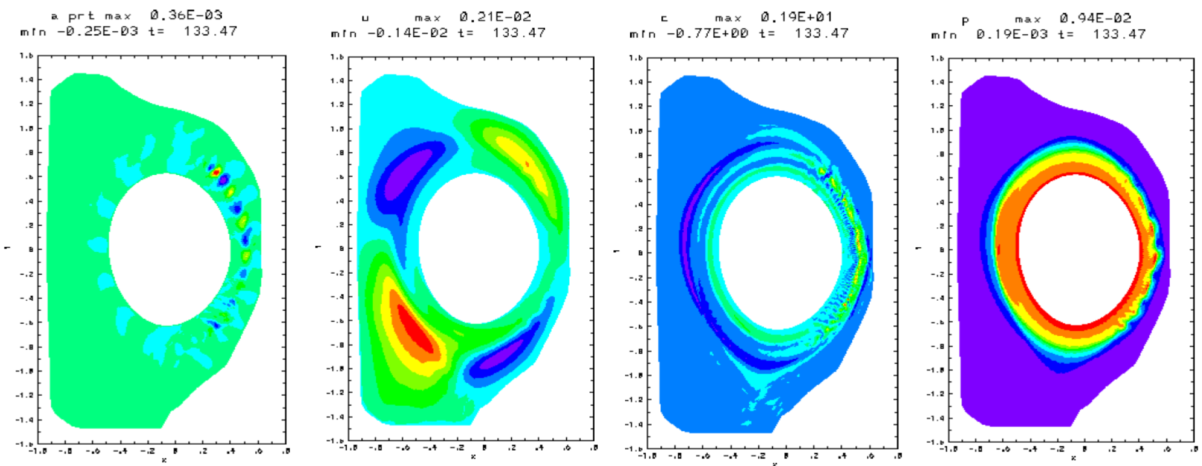
ELM and its Control Simulation using M3D code etc.

Calculation of the growth rate and mode structure of unstable ELM using a linear ELM stability code, ELITE

Nonlinear simulation of ELM evolution using M3D code

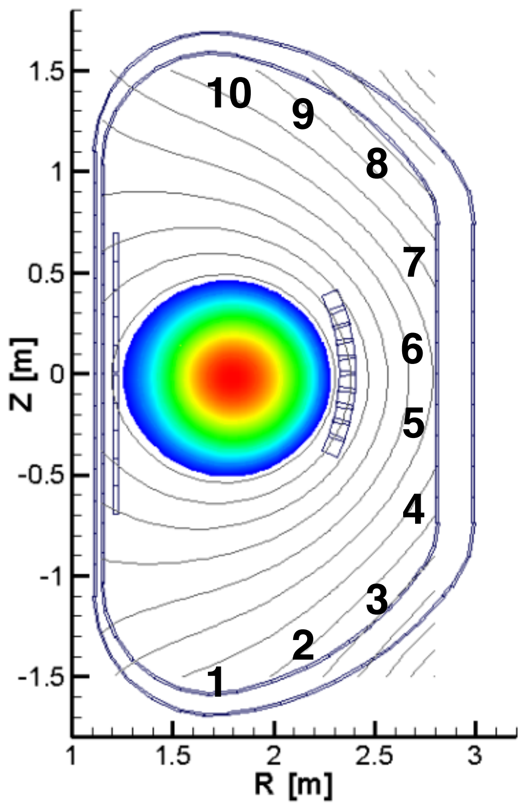


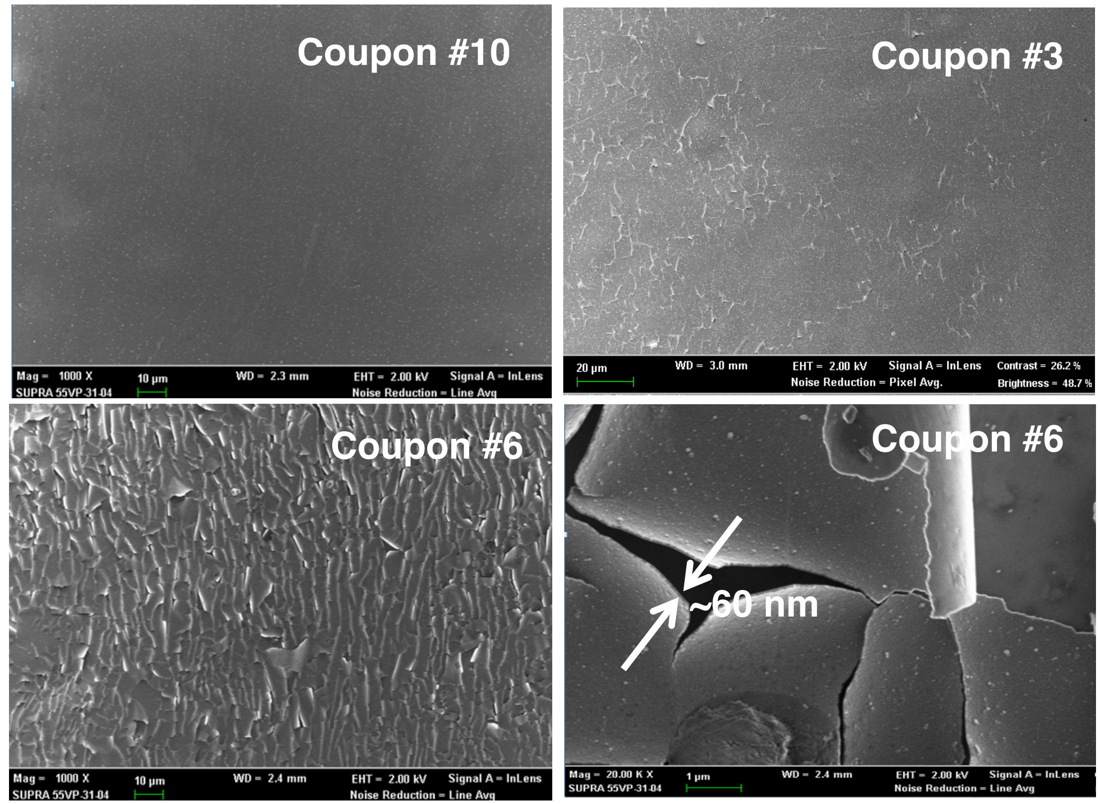


Poloidal flux pert urbation | Velocity stream f unction | Toroidal current | Pressure

- Simulation studies of ELM control mechanisms using RMP or Pellet pace-making method are also being performed using the M3D, XGC0 codes

Dust conversion from layers

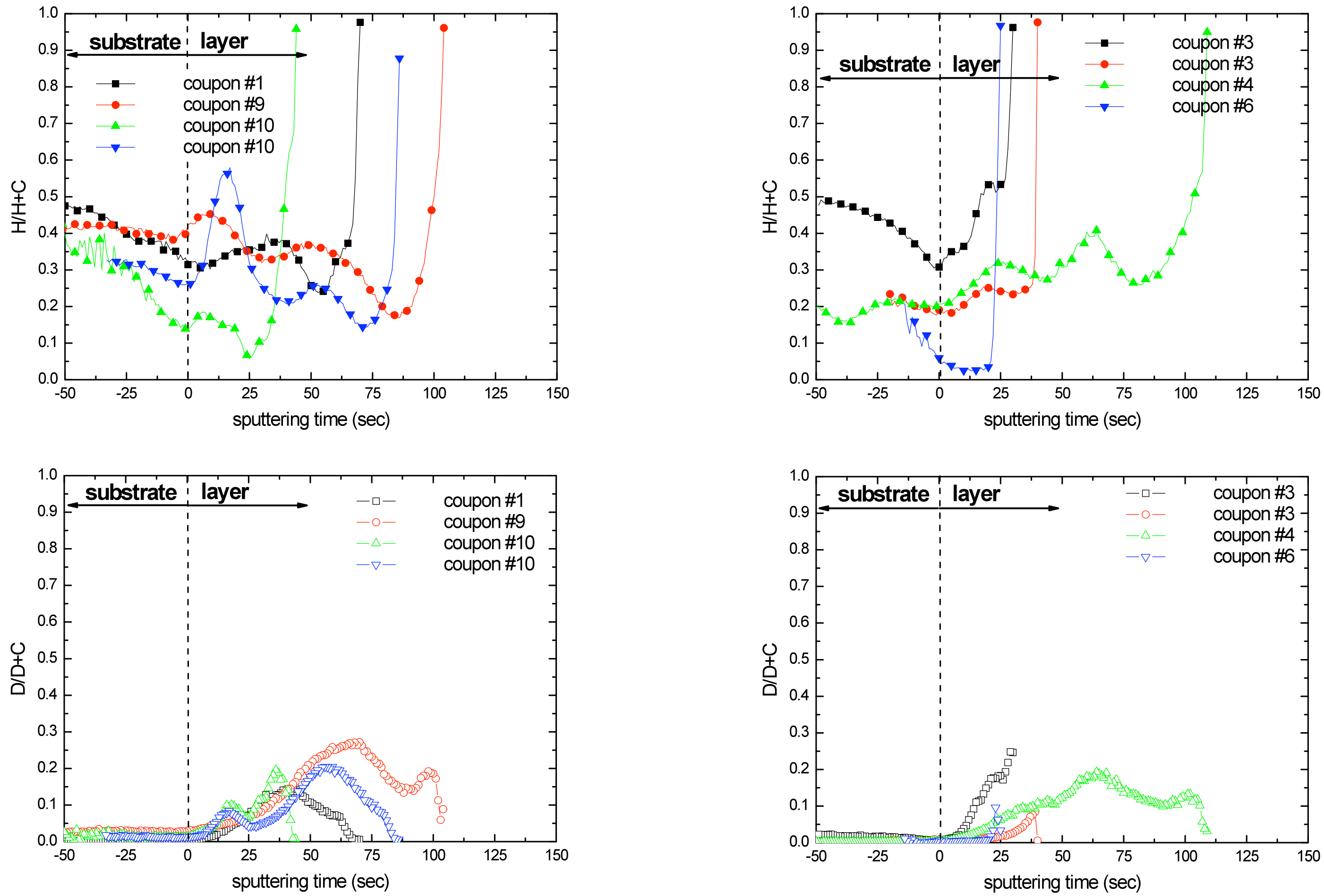




1. Stable layers at far distance.
2. Flake formation at coupon #3, #6 is observed (several weeks after vent).
3. Connected to internal stress and adhesion.

Deposition in the gap in KSTAR

SIMS analysis



1. H/H+C ratio ~ 0.2-0.4 while D/D+C ratio ~0-0.3 at top and bottom.
2. H/H+C ratio ~ 0.1-0.6 while D/D+C ratio ~0-0.3 at midi-plane. H/H+C ratio ~ 0.02 at coupon #6.

Deposition in the gap in KSTAR

1. (Average) total carbon flux towards outer wall in 2009 campaign is about ~2.94×10^{16} atoms/cm^2/s.
2. KSTAR vacuum vessel has surface area of 80 m^2 with 11 m^2 covered by graphite PFC tiles in 2nd campaign.
3. Assuming that the erosion source of the carbon is only in-board PFCs (effective erosion area 8.8 m^2), an erosion flux of 2.32×10^{17} atoms/cm^2/s.
4. Total carbon atoms eroded from PFC during the campaign would be ~4.1×10^{24} atoms (82 g).
5. (Average) hydrogen (deuterium) retention (inside layers) of ~7.5×10^{23} H (D) atoms (1.26g H + 2.51g D = 3.77g) in 2009.

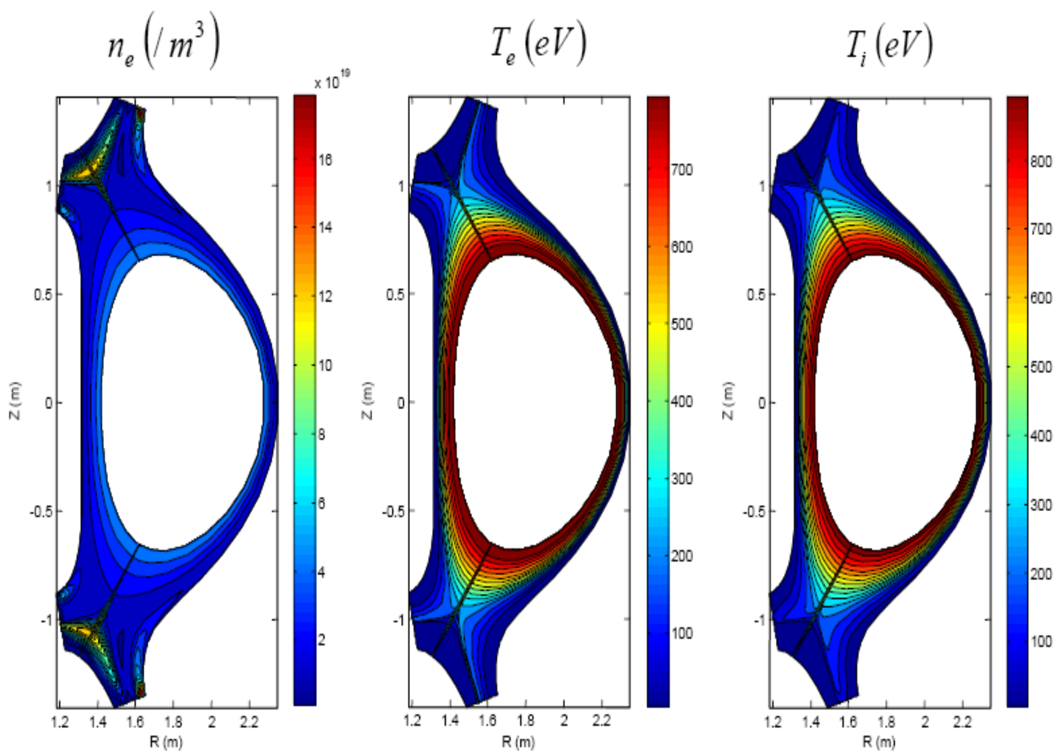
Tore Supra

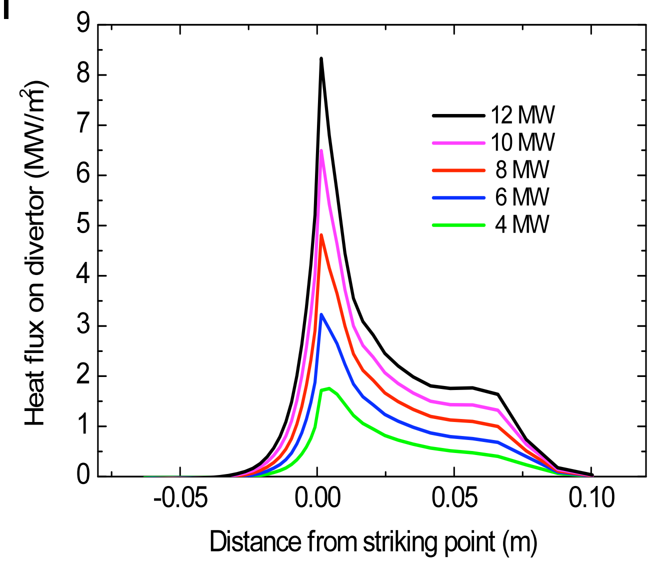
Gross erosion (TPL) from spectroscopy (per campaign)	60 – 160 g $\Gamma_{C^0}^{in} = 1.5\text{-}3.5\times10^{20}$ C/m^2/s
Estimated deposits mass (per campaign)	15 – 30 g
Estimated distant redeposition	20 – 50 %
Estimated local redeposition	80 – 50 %
Integrated D quantity retained in the vessel	4.10^{23} D
Integrated D content in analysed deposits	5.10^{22} D
D/C ratio in the deposits	0.01 – 0.10

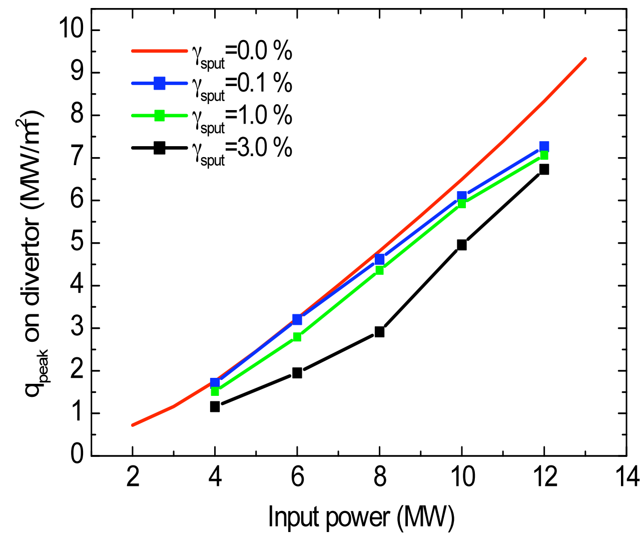
Table 1 : *Summary of carbon and deuterium balances for one campaign.*

Divertor Transport Simulation for KSTAR

- Divertor heat fluxes calculated using B2 code for various operation powers an d C^+ impurity condition for KSTAR divertor model







- Peak heat flux on divertor being reduced wit h increasing C^+ impurity fraction

ITER High Priority Research Topics (IEA/ITPA)

Keywords of key issues :
Shaping / H-mode / rotation / disruption
ECRH breakdown / ICRF conditioning / runaway / dust

- TC-2 Power ratio – Hysteresis and access to H-mode with H~1
- TC-3 Scaling of the Low-Density Limit of the H-mode threshold
- TC-9 Scaling of intrinsic plasma rotation with no external momentum input
- TC-14 RF rotation drive
- PEP-22 Controllability of pedestal and ELM characteristics by edge ECH/ECCD/LHCD
- PEP-28 Physics of H-mode access with different X-point height
- DSOL-8 ICRF conditioning
- DSOL-9 C injection experiments to understand C migration
- DSOL-13 Deuterium co-deposition with carbon in gaps of plasma facing components
- MDC-13 Vertical stability physics and performance limits in Tokamaks with highly elongated pla smas
- MDC-15 Disruption database development
- MDC-16 Runaway electron generation, confinement, and loss
- IOS-2.1 ECRH breakdown assist at 20-degree toroidal angle
- IOS-2.2 Ramp-down from q95=3
- IOS-5.2 Maintaining ICRH coupling in expected ITER Regime.
- IOS-6.2 li controller (Ip ramp) with primary voltage / additional heating
- DIAG-3 Resolving the discrepancy between ECE and TS at high Te
- DIAG-4 Field test of a Capacitance diaphragm Gauge as a dust monitor for ITER

5-Year Operation Plan (Phase I)

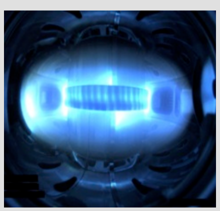
Campaign	2008	2009	2010	2011	2012
Operation Time	'08. 3 ~'08. 8	'09. 8 ~'09.12	'10.6 ~'10. 12	'11. 4 ~'11. 9	'12. 3 ~'12. 8
Experimental goals	• First plasma startup • 2^{nd} Harmonic ECH pre-ionization	• Startup stabilization • ECH pre-ionization • ICRF wall conditioning	• Shape control • L-mode • MHD study • Wall conditioning	• H-mode • MHD • ELM & Disruption • Wall interaction	• Profile control • ITER shape • ELM & disruption
Operation Parameters	• $B_T \sim 1.5$ T • $I_P > 0.1$ MA • $t_P > 0.1$ s • Te ~ 0.3 keV • Shape ~ Circular • Gas : H_2	• B_T : 2 ~ 3.5 T • $I_P > 0.3$ MA • $t_P > 2$ s • Te ~ 1 keV • Shape ~ Circular • Gas : D_2	• B_T : 2 ~ 3.5 T • $I_P > 0.5$ MA • $t_P > 5$ s • Ti ~ 1 keV • Shape ~ DN (κ2.0) • Gas : D_2	• B_T : 2 ~ 3.5 T • $I_P > 1$ MA • $t_P > 10$ s • Ti ~ 3 keV • Shape ~ DN & SN • Gas : D_2	• B_T : 2 ~ 3.5 T • $I_P > 1$ MA • $t_P \sim 20$ s • Ti ~ 5 keV • Shape ~ DN & SN • Gas : D_2
Magnetic Control	• TF : 15 kA [1.5T) • PF : 4 kA (~1 Wb) • Grid : 50 MVA	• TF : 35 kA [3.5 T] • PF : +/-4 kA (~2 Wb) • Grid : 50 MVA	• TF : 35 kA [3.5 T] • PF : +/-10 kA (~4 Wb) • IVCC : VS • Grid: 100 MVA	• TF : 35 kA [3.5 T] • PF : +/-15 kA (~6Wb) • IVCC : VS • Grid: 100 MVA	• TF : 35 kA [3.5 T] • PF : +/-20 kA (~8Wb) • IVCC : FEC,RMP,RWM • Grid: 100 MVA
Vacuum Conditioning	• Inboard limiter (belt) • Gas puff • Glow DC	• Inboard limiter + Boronization + ICRF DC	+ Divertor + Passive stabilizer + In-vessel coil + PFC baking	+ PFC cooling	+ Cryopump operation
Heating & Current Drive	• ECH(84G):0.3MW, 0.4s	• ECH(110G):0.2MW, 2s • ICRH: 0.3MW, 1s	• ECH(110G):0.5MW • ICRH: 1MW • NBI: 1MW	• ECH(84/110G):0.5MW • ECCD(170G): 1MW • ICRH : 1.5MW • NBI: 1.5MW	• ECH(84/110G):0.5MW • ECCD(170G): 1MW • ICRH : 1.5MW • NBI : 3MW • LHCD : 0.3MW
Diagnostics	• Magnetic Diagnostics / MMWI / ECE / Hα / VS / filterscope / TV / • Hall probe array	+ XICS / Soft X-ray / Hard X-ray/ Resistive Bolometer / Probe / Reflectometer • e-beam	+ Thomson (5ch)/ ECEI / IRTV / Image Bolometer / CES / neutron / XICS-2 / Ellipsometry /	+ FIR / Div. bolometer /X-ray pinhole / Coherence imaging/ fast-ion / etc	+ MSE / MIR / BES / VUV / CX-NPA /etc

Long-term Operation Plan

KSTAR will be operated as an international collaboratory to exploit the key scientific and technological issues for the ITER and attractive fusion reactor.

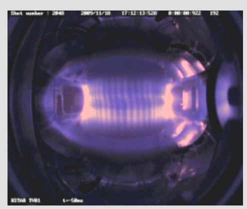
Operation Phase I 2008 ~ 2012	Operation Phase II 2013 ~ 2017	Operation Phase III 2018 ~ 2022	Phase IV 2023 ~
SC Tokamak operation	**Long-pulse operation**	**High performance operation**	**DEMO test bed**
• **Superconducting tokamak operation** • First plasma & inductive current ramp (2 MA) • Plasma shaping & heating (DN & SN, H-mode)	• **Steady-state operation & ITER pilot device roles (300 s+)** • **Plasma heating & non-inductive current drive** • **Instability control in H-mode and AT-mode**	• **Advanced scenario for DEMO beyond ITER** • **High-beta and high bootstrap current scenario** • **Extreme operation of the superconducting tokamak**	• **DEMO Engineering** • **DEMO simulator** • **Reactor material test**

First Plasma ('08)



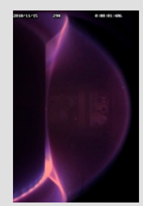
133kA
0.25sec
1.5Tesla♪

Second Campaign ('09)



320kA
3.6sec
3.0Tesla♪

Third Campaign ('10)



720kA
7.5sec
3.5Tesla♪

Summary: Toward Steady-State Operations

SC magnet system for steady-state :

- Reliable operations of SC magnet & cryogenic facility for long pulse operatio n

Divertor & PFC :

- Active-cooling on PFC & divertor will be prepared for long pulse operation
- Particle and flow control (fueling, wall conditioning, pumping)
- Dust characterization as a ITER safety issue

Heating & Current drive optimization :

- Simulation study with ASTRA, ONETWO, TSC/TRANSP predicts possible ste ady-state operation scenarios
- Long-pulse, non-inductive NBCD, LHCD, ECCD being installed

Advanced confinement by active plasma control:

- ELMy H-modes were achieved in the 2010 campaign, although the controllability of plasma shape and vertical stability was limited.
- Extensive experimental program will be done for advanced confinement phys ics using profile diagnostics, heating and current drive systems and IVCC

KSTAR Presentations in SOFE 2011

- SO1B-2 (invited) Key Features in the Operation of KSTAR J.G. Kwak
- SO4C-2 (invited) The Construction of ITER, Viewed from Lessons Learn ed from KSTAR Project H. Y. Yang
- SP3-39 Current Control Method of Thyristor Converter for PF Supercond ucting Coil in KSTAR, H. -S. Ahn
- SP3-40 Development of in-Vessel Vertical Coil (ivc) Power Supply J. K. Jin
- SP1-15 Design Feature & Operation Results of Kstar PFC GN2 Baking System S. -T. Kim
- SP1-32 Temporal and Spatial PFC Temperature Profiles in KSTAR 2010 Campaign E. N. Bang