Overview of Versatile Experiment Spherical Torus (VEST): Progress and Plans

Y.S. Hwang and VEST team

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CARFRE and CATS
Dept. of Nuclear Engineering,
College of Engineering,
Seoul National University

핵융합로공학 선행연구센터
CARFRE
Center for Advance Research in Fusion Reactor Engineering

고성능핵융합로 연구센터
Center for Advanced Tokamak Study
CATS

NFRI 국가핵융합연구소 National Fusion Research Institute
KAERI 한국원자력연구원 Korea Atomic Energy Research Institute
광운대학교 KwangWoon University
AJOU UNIVERSITY
제주대학교 JEJU NATIONAL UNIVERSITY
POSTECH
KAIST
서강대학교 SOGANG UNIVERSITY
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PPPL PRINCETON PLASMA PHYSICS LABORATORY
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
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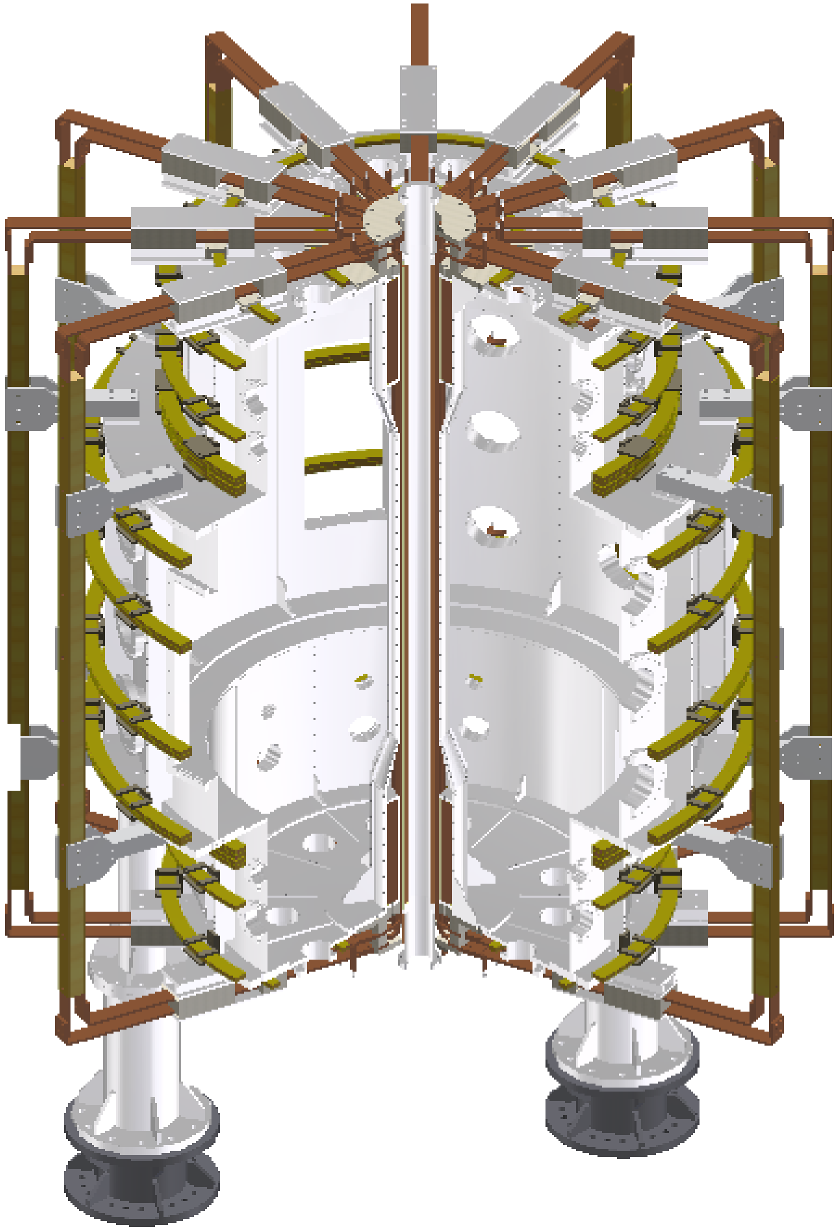


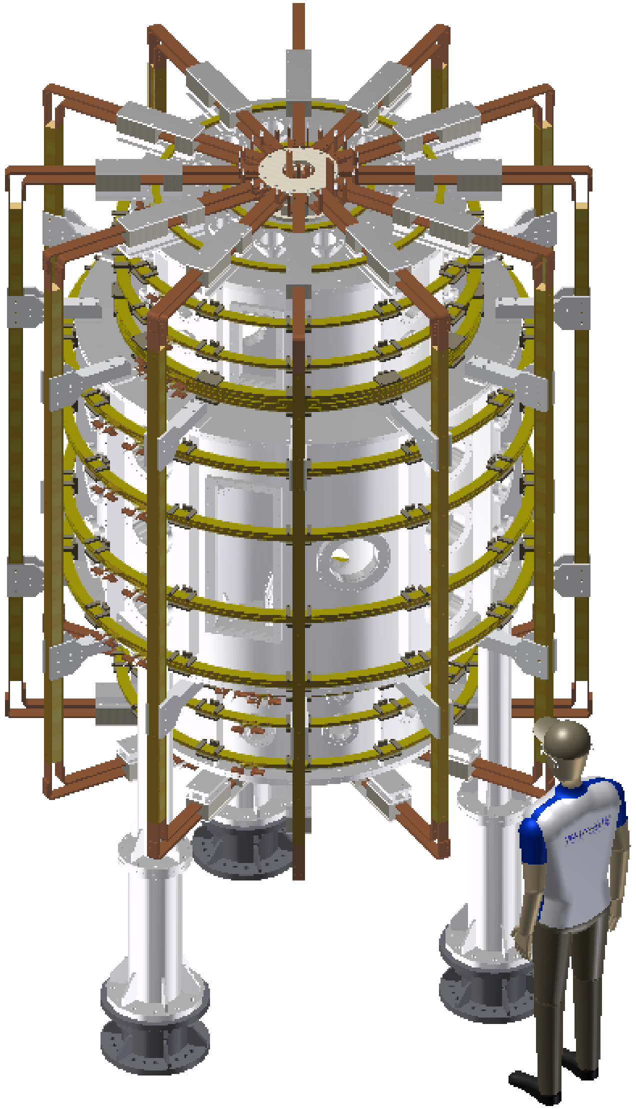
ISTW 2019, October 28-31 2019, ENEA, Frascati, Italy

Outline

- **Introduction : Versatile Experiment Spherical Torus (VEST)**
  - Device and machine status
- **Start-up experiments**
  - Robust start-up method with trapped particle configuration
  - Tearing modes during ramp-up phase
- **Studies for Advanced Tokamak**
  - Research directions for high-beta and high-bootstrap STs
  - Preparation for heating and current drive / diagnostic systems
- **Internal Reconnection Event(IRE) for disruption study**
  - IREs for disruption understanding
  - Rotation acceleration as well as ion heating during IRE
- **Future research plans**
- **Summary**

Introduction:
VEST device and Machine status

VEST (Versatile Experiment Spherical Torus)



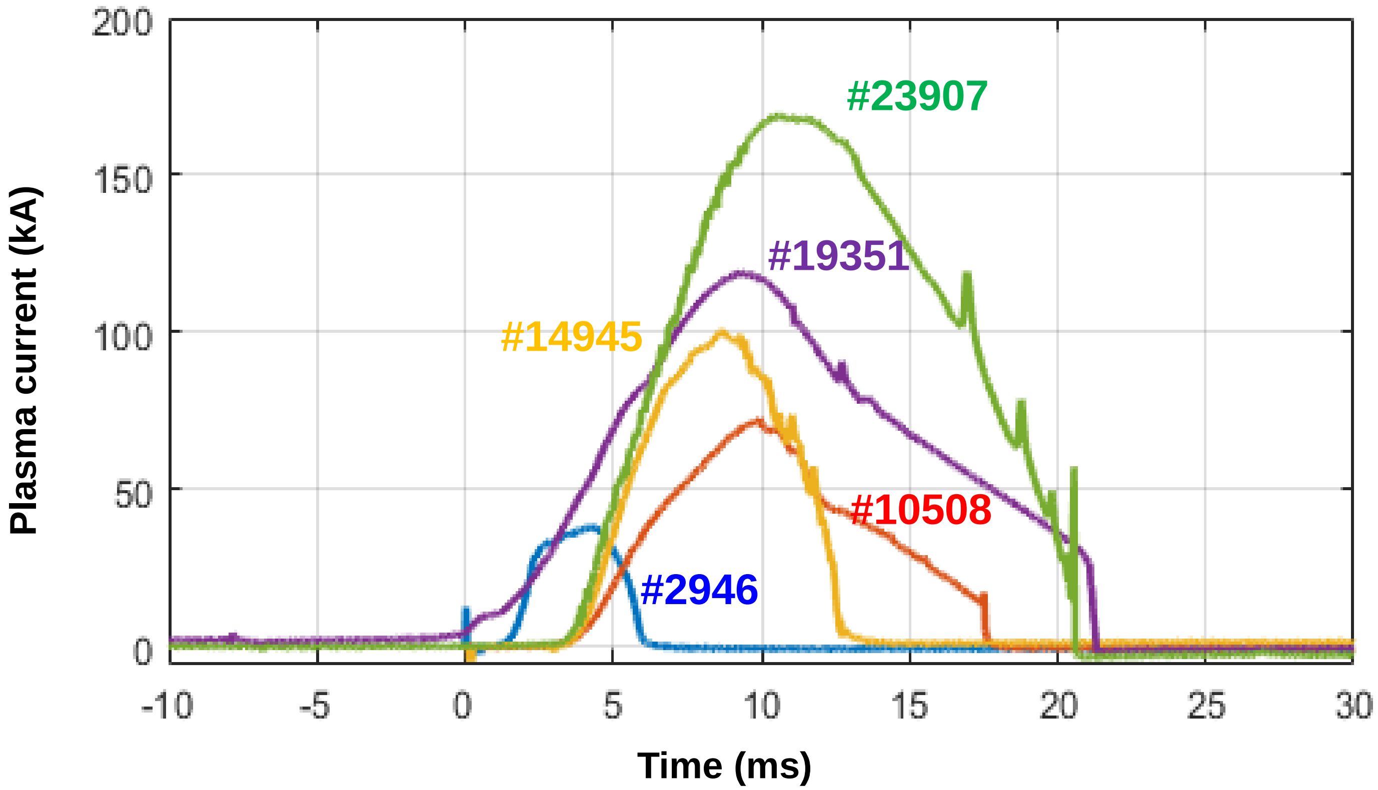
- **The first and only ST device in Korea**
  - Basic research on **a compact, high-β ST (Spherical Torus)**
  - Study on **innovative start-up, non-inductive H&CD, high β, disruption, energetic particle, innovative divertor concept, etc**

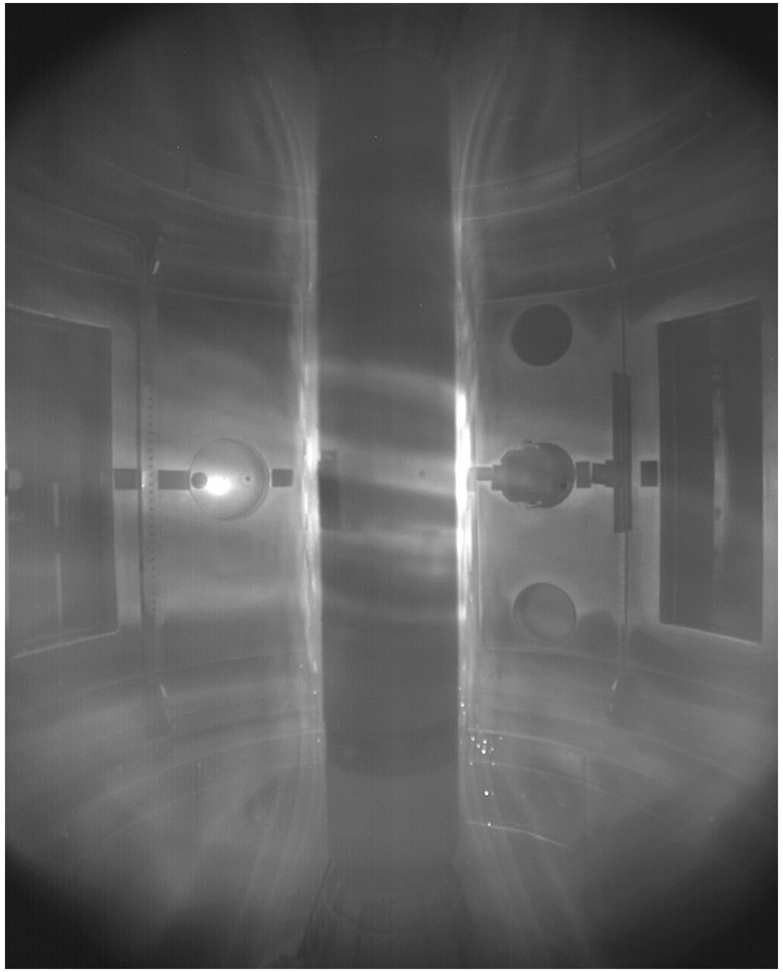
- **Specifications**

	Present	Future
Toroidal B Field	**0.05 – 0.19 T**	<0.3 T
Major Radius	**0.45 m**	0.4 m
Minor Radius	**0.33 m**	0.3 m
Aspect Ratio	**>1.36**	>1.33
Plasma Current	**<170 kA**	<300 kA
H & CD (ECH, NBI, LHFW)	**ECH (7.9GHz, 3kW) ECH (2.45GHz, 15kW) NBI (15keV, 600kW) LHFW (500MHz, 10kW)**	ECH (2.45GHz, 30kW) NBI (20keV, 1.2MW) LHFW (500MHz,200kW)

History of VEST Discharges

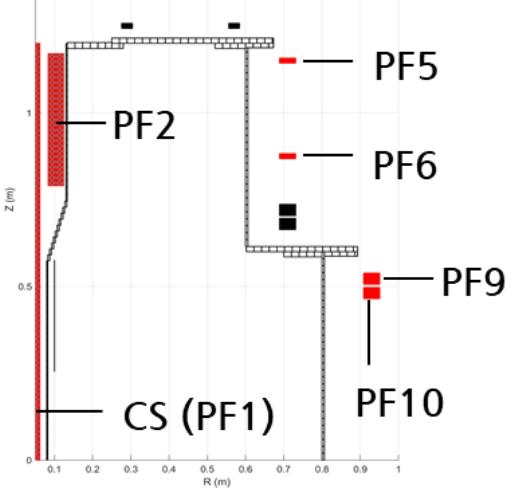
- #2946: First plasma (Jan. 2013)
- #10508: Hydrogen glow discharge cleaning (Nov. 2014)
- #14945: Boronization with He GDC (Mar. 2016)
- #19351: Slower ramp-up and diverted plasma (May. 2018)
- #23907 : Higher TF discharge (Oct. 2019)

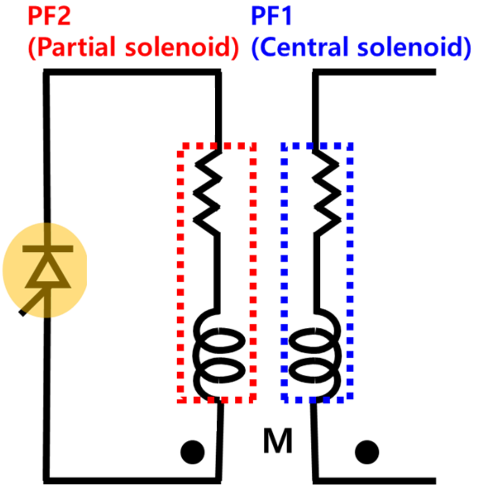


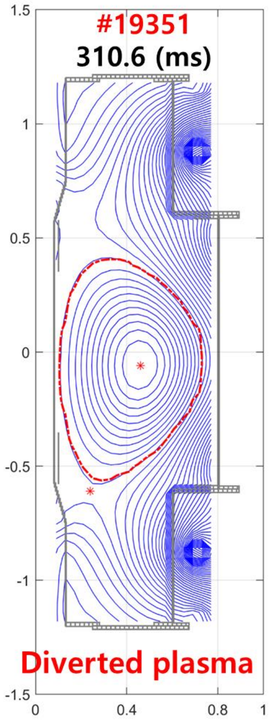


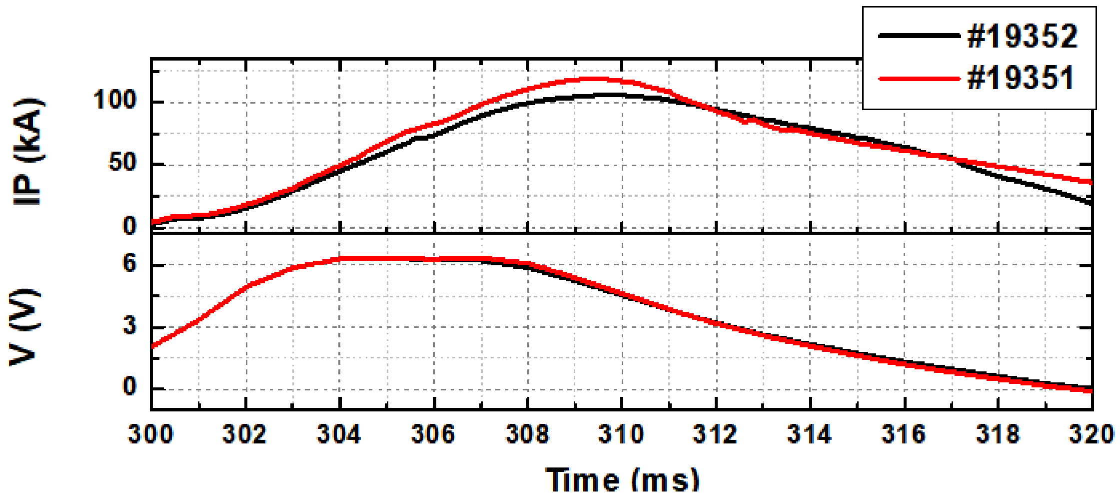
S.C. Kim

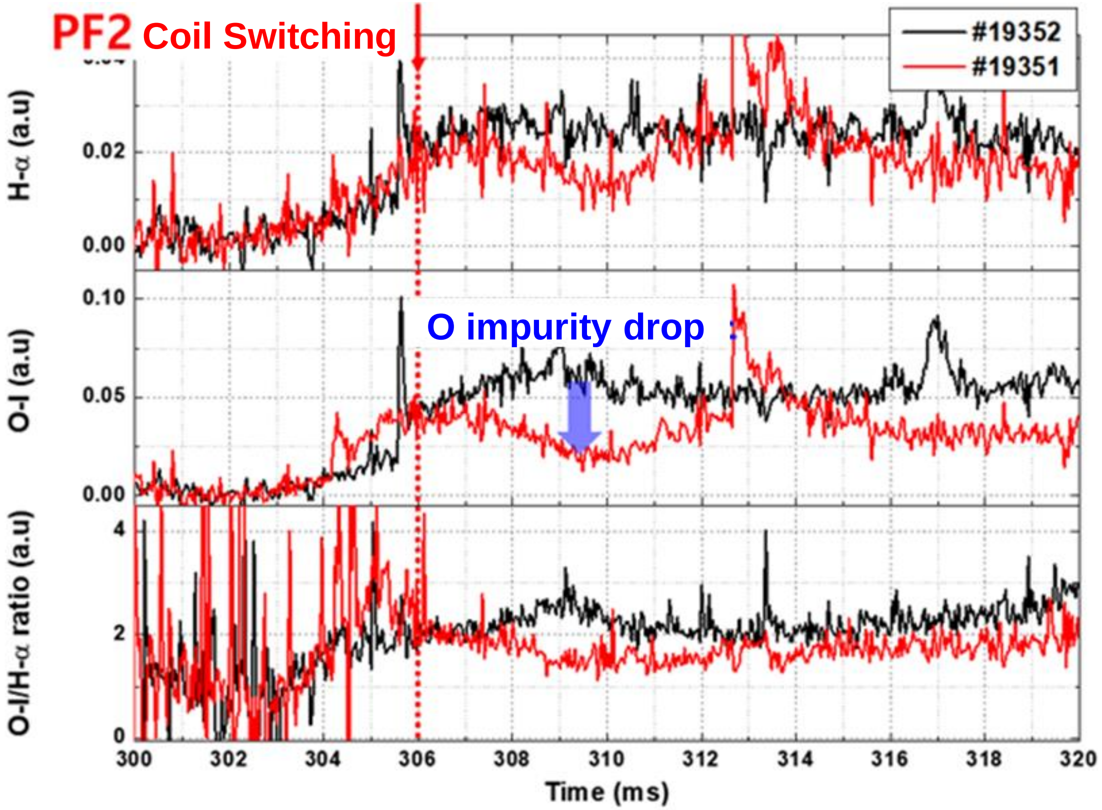
120kA Diverted Plasma (#19351)



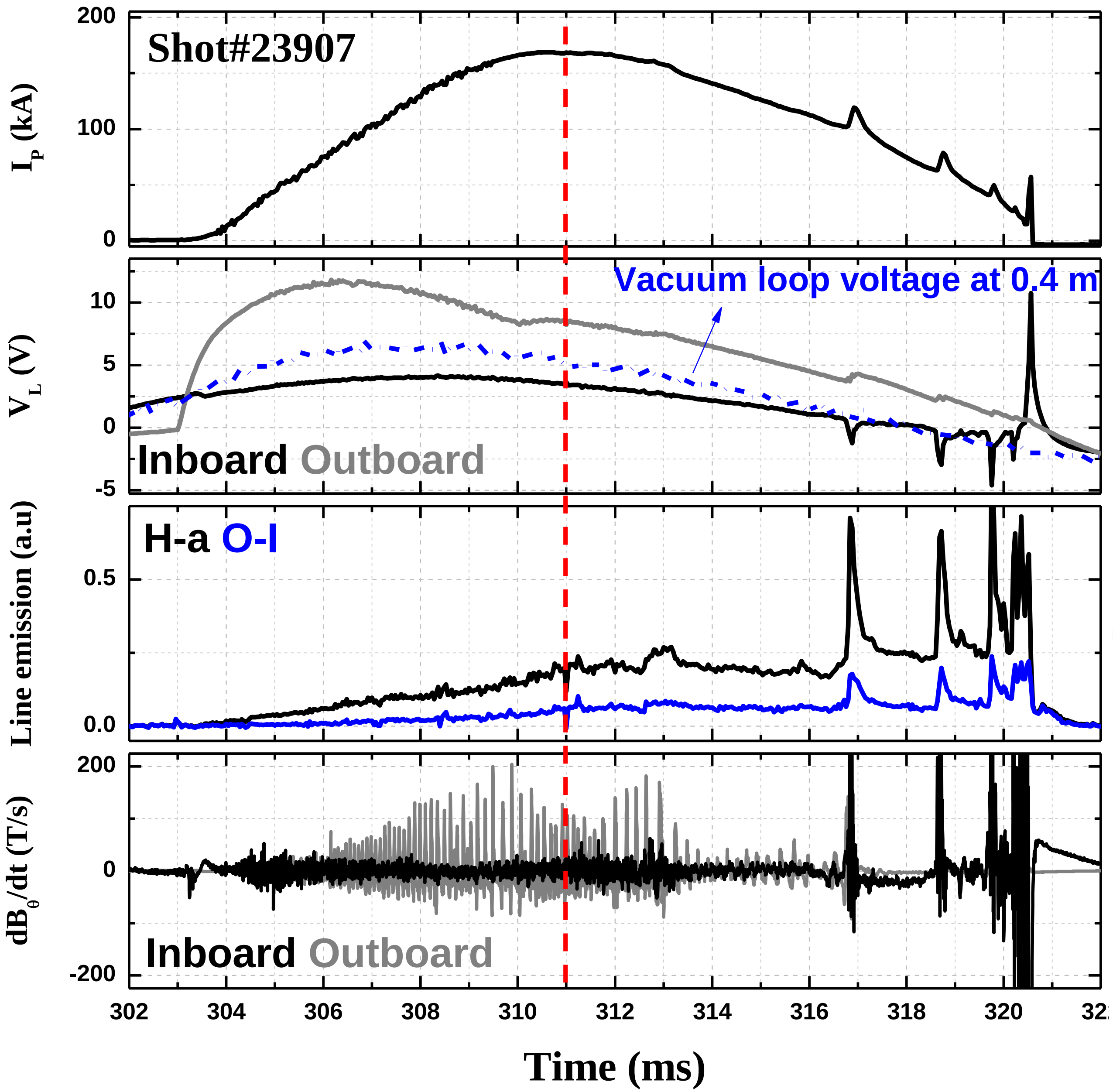




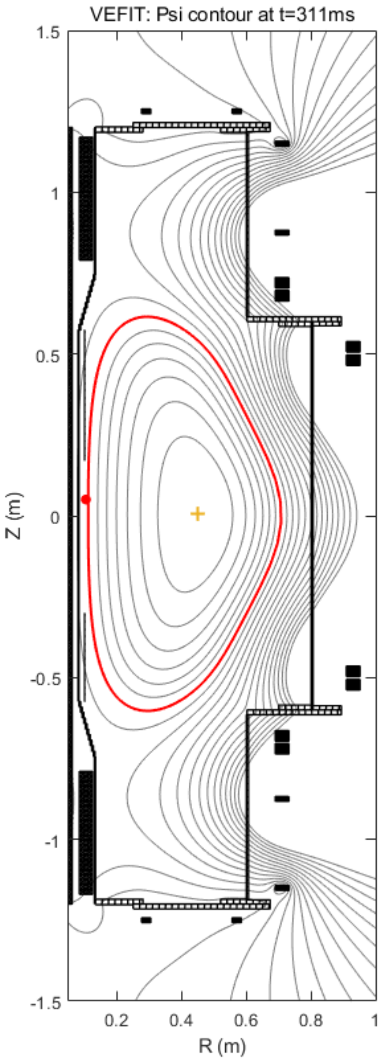




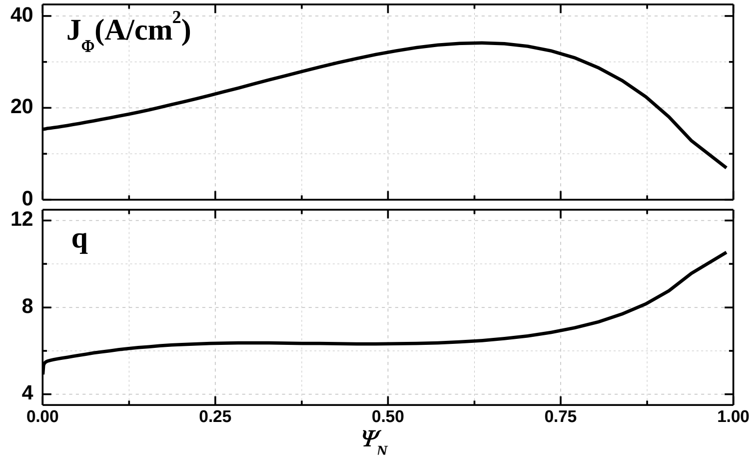
170kA High TF discharge (#23907)



- Toroidal field at machine center (~0.4 m) ~ 0.18 (T)
- Maximum plasma current ~ 170 (kA)
- Pulse duration ~ 16 (ms)



Current density and q profile



Plasma shape

- $R_0 \sim 0.41\ (m), a \sim 0.30\ (m)$
- $\kappa \sim 2.0,\ \delta \sim 0.40$

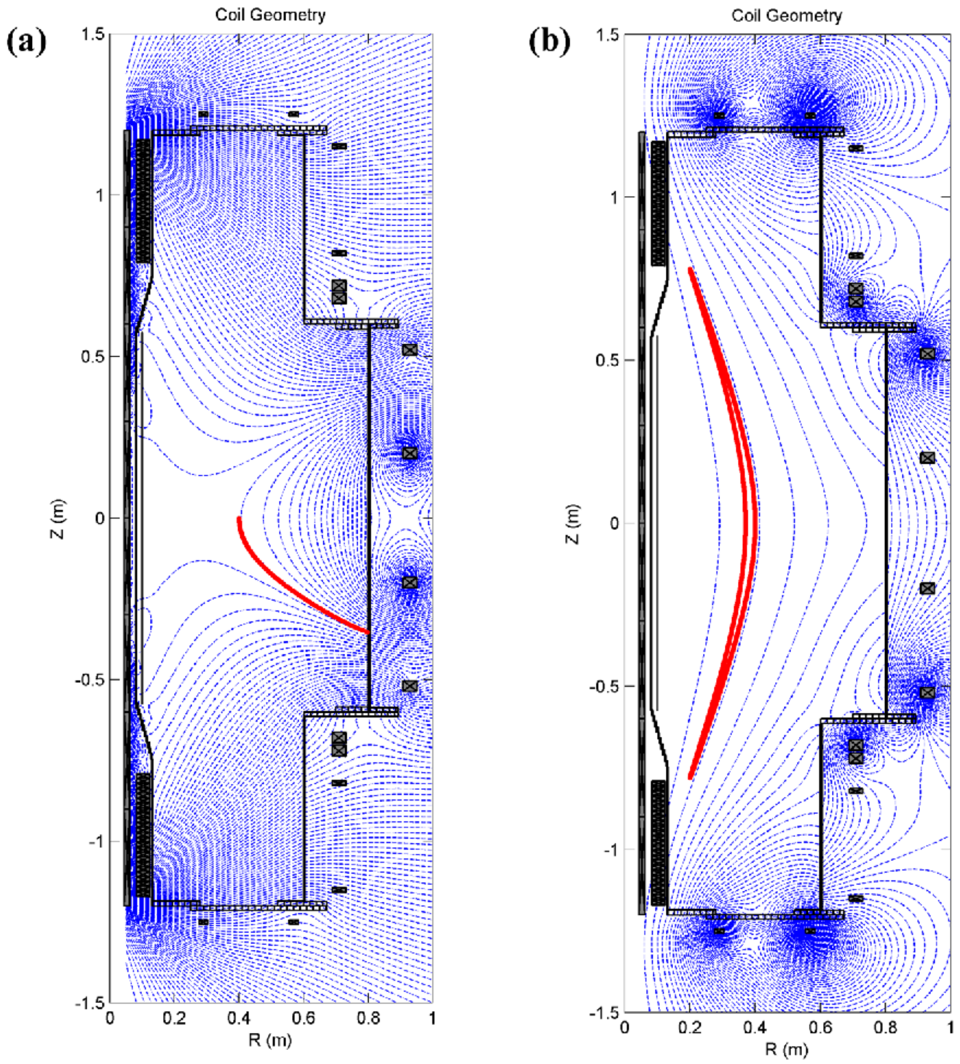
0D-MHD parameters

- $li \sim 0.44$
- $W_{MHD} \sim 244\ (J)$
- $\beta_p \sim 0.068$
- $\beta_t \sim 0.013$

Start-up and Ramp-up Experiments

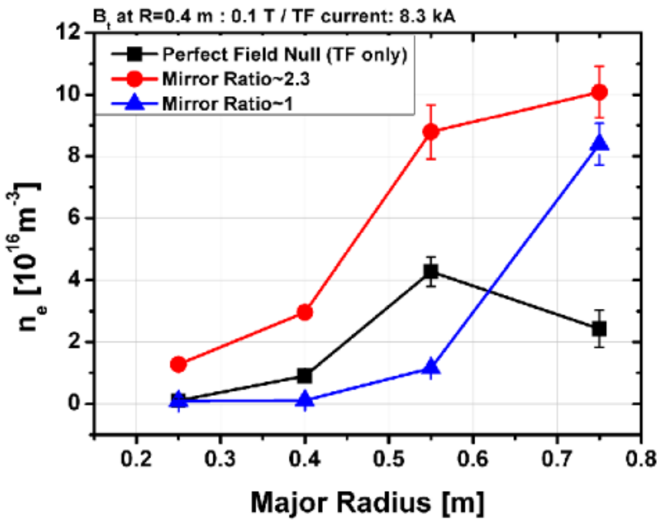
Trapped Particle Configuration (TPC)

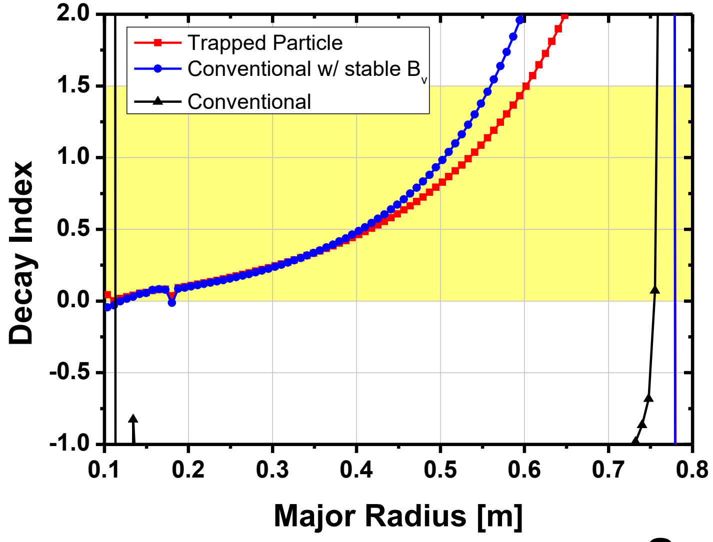
Y. An *et al.*, *Nucl. Fusion* 57 016001 (2017)



- **Efficient and robust tokamak start-up demonstrated with wider operation window at VEST**
  Pressure, ECH power and low loop voltage

- **TPC: Mirror like magnetic field configuration**
  – Enhanced particle confinement
  – Inherently stable decay index structure for Bv

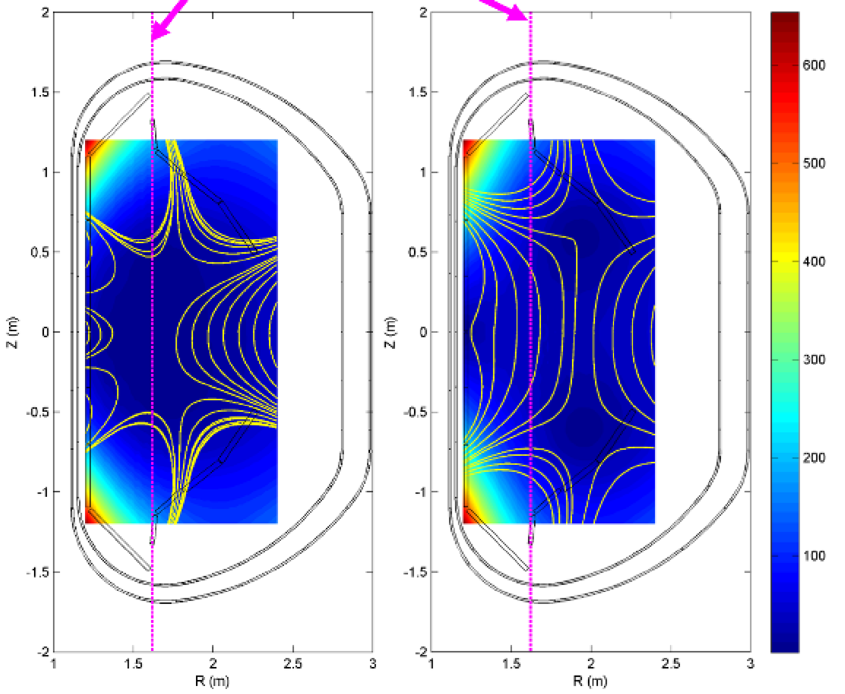


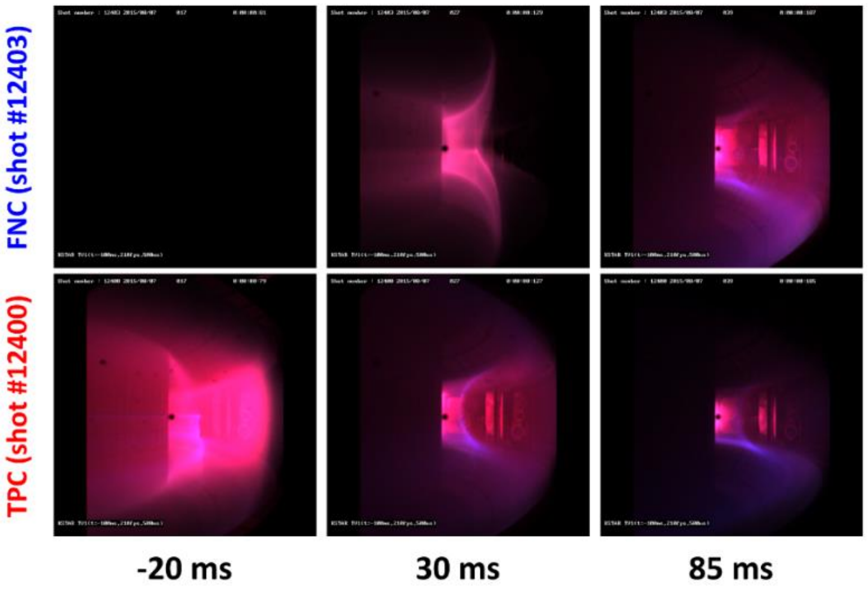


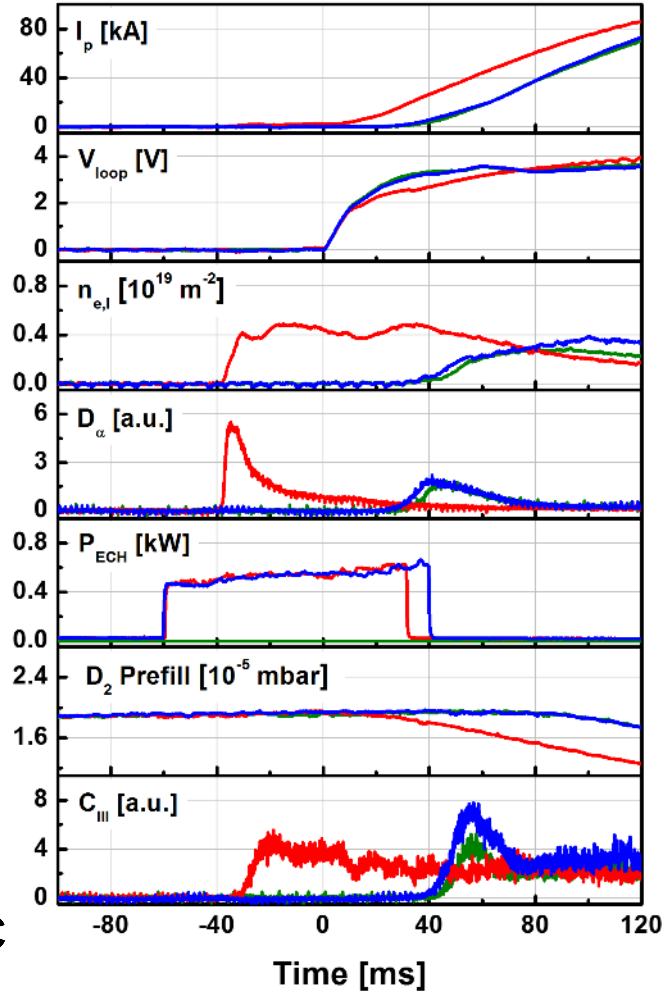
Trapped Particle Configuration (TPC)

J.W. Lee *et al., Nucl. Fusion* 57, 126033 (2017)

Robust and Reliable TPC Start-up Applied to KSTAR Successfully





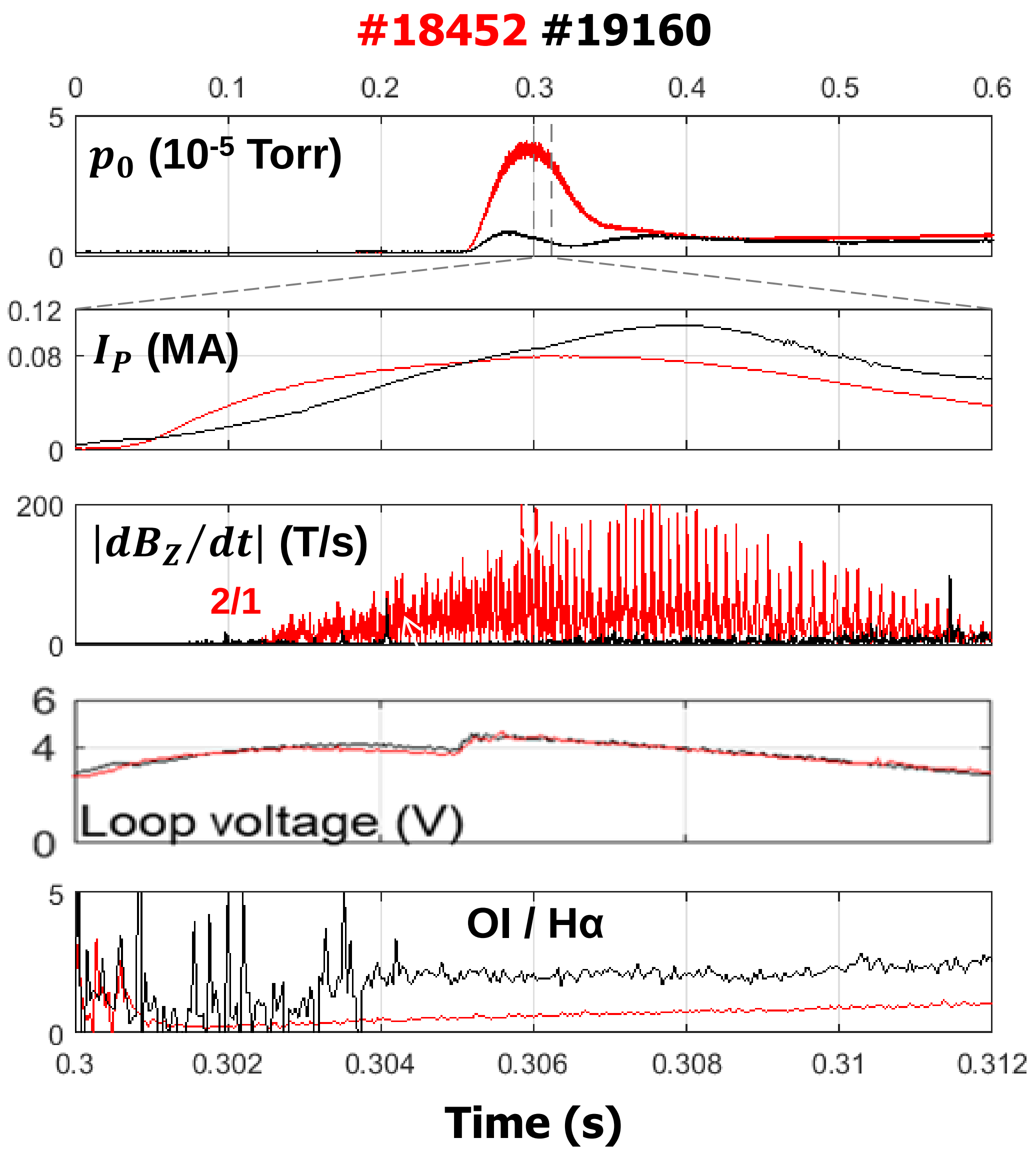


- Feasibility study of TPC in *KSTAR*
  - Even though low mirror ratio than ST, achieving efficient start-up with TPC
  - 2nd harmonic delay of 20 ms and ECH plasma density of 4×10^{18} m^{-2}
  - I_p formation with low E_t *less than 0.2 V/m*

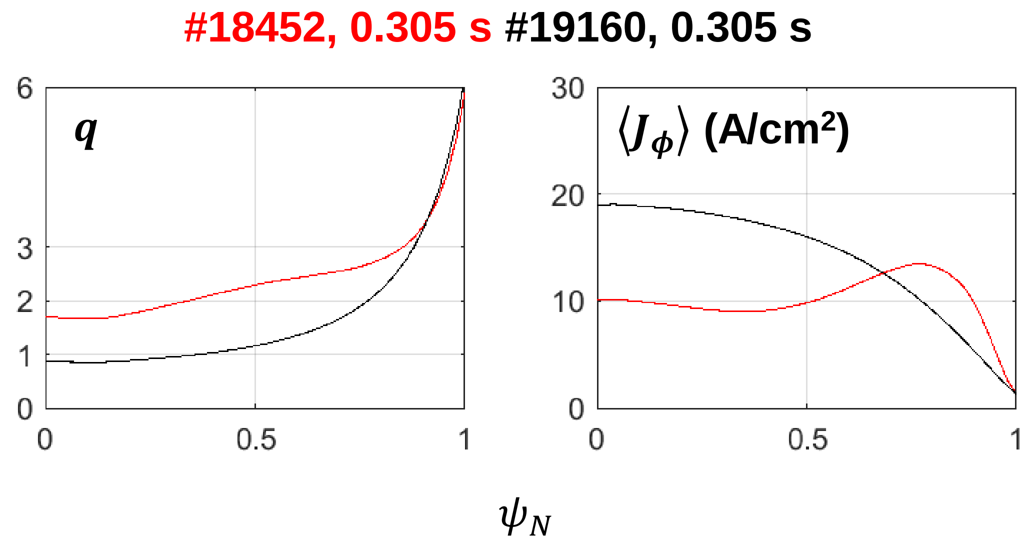
Adjust current density profile for MHD suppression

Poster P11

S.C. Kim/J.H. Yang



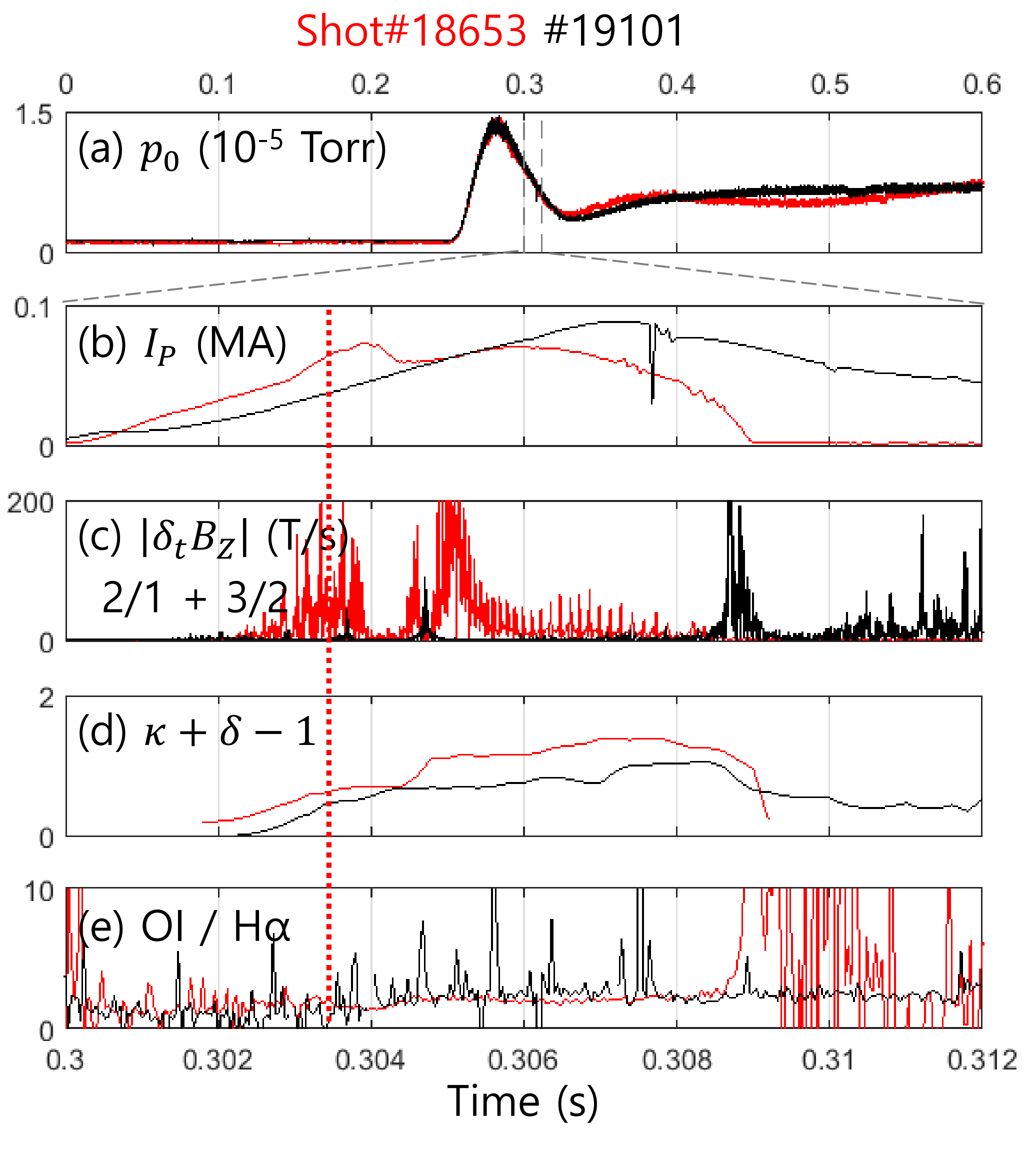
- **Hollow J_ϕ profile with MHD activity**
  - Fast ramp-up rate dI_P/dt
  - High prefill gas pressure with low impurity
- **Peaked J_ϕ profile without MHD activity**
  - Slower ramp=up rate dI_P/dt
  - Low prefill gas pressure with high impurity



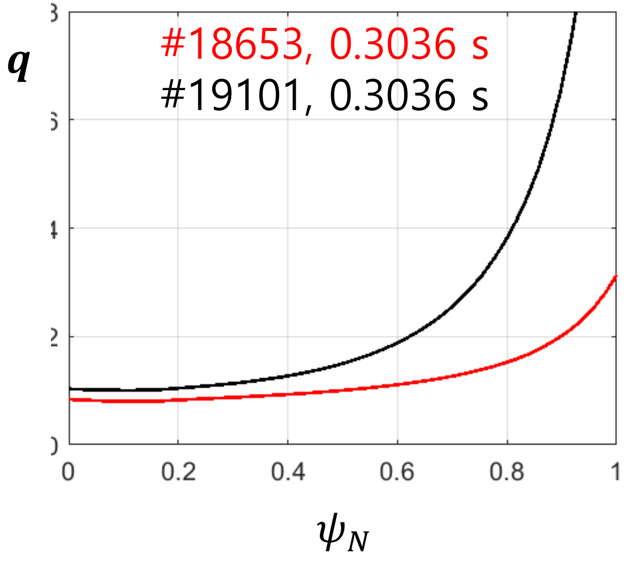
Ramp-up Experiments

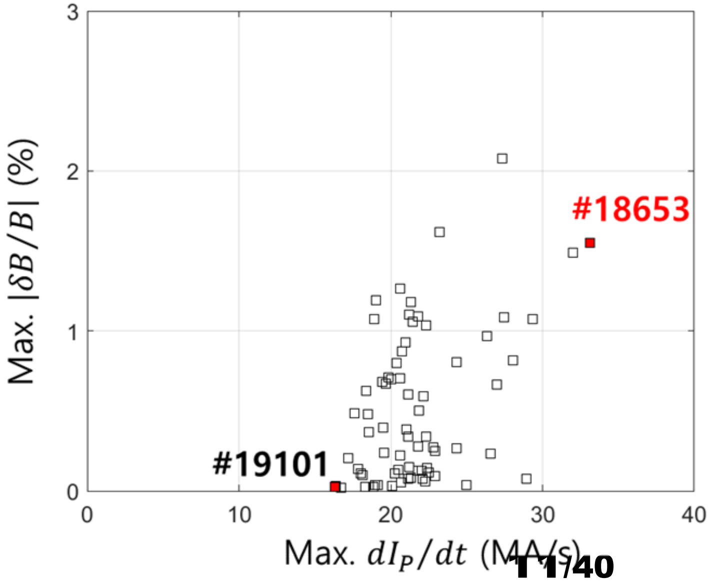
Adjust current density profile with fast ramp-up rate

S.C. Kim



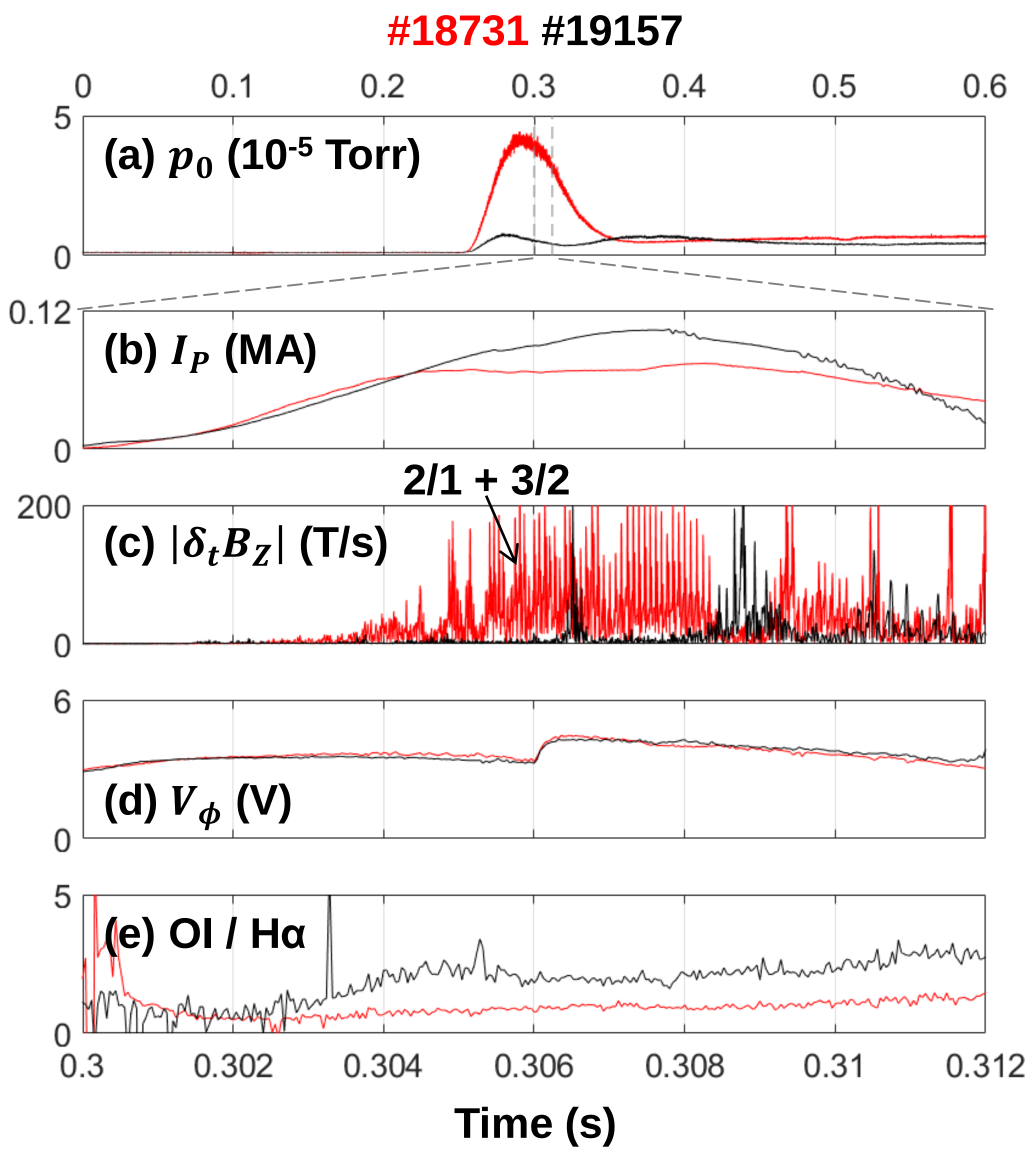
- The same low prefill gas pressure
- **Slow ramp-up rate of ~16MA/sec: TM stable**
  - Peaked current density profile
  - High current achieved
- **Fast ramp=up rate of ~32MA/sec: TM unstable**
  - Hollow current profile
  - Low current achieved
- **Classical feature of TM**



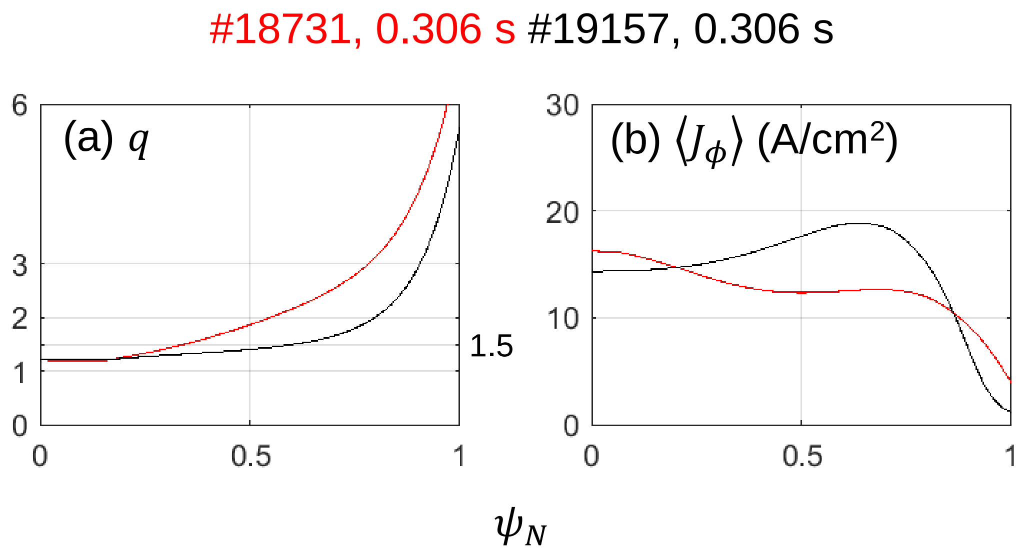


Adjust current density profile with prefill gas pressure control

J.H. Yang

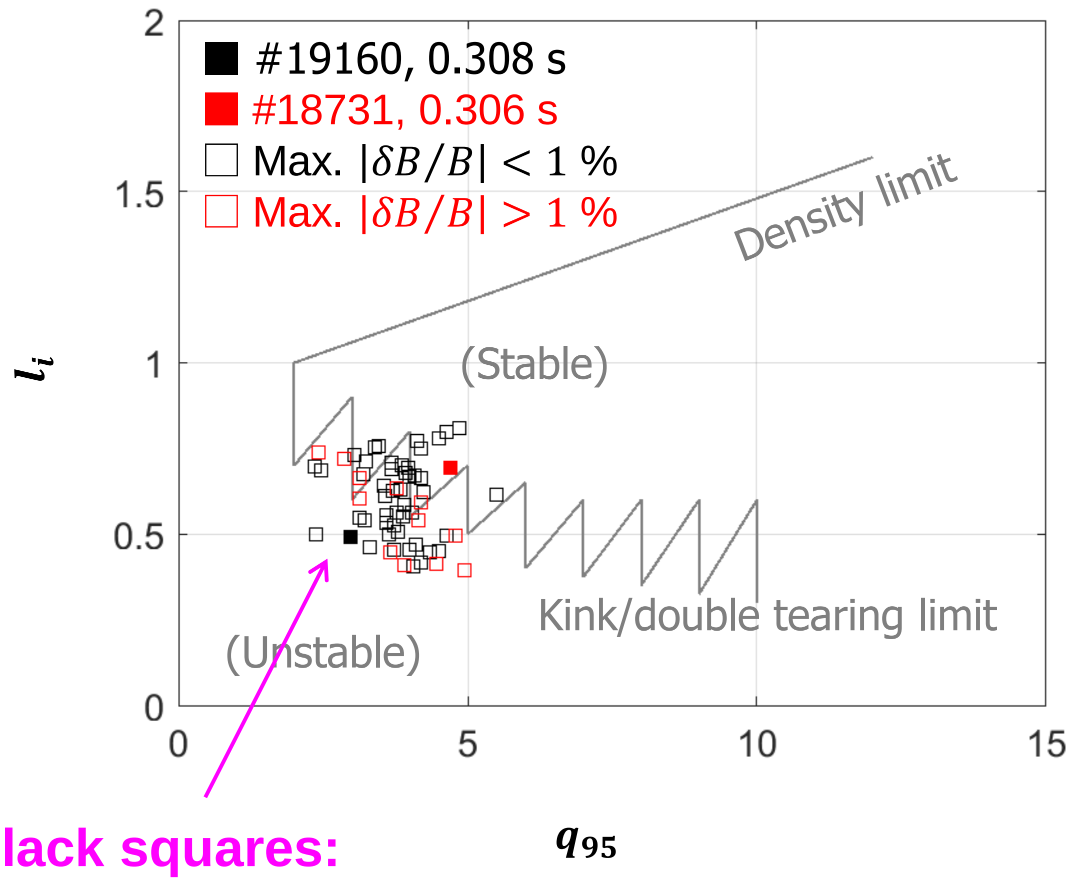


- The same current ramp up rate: Unstable to TM
- **Low prefill gas pressure: TM stable**
  - Hollow current profile
  - High current achieved
- **High prefill gas pressure: TM unstable**
  - Monotonic current profile
  - Low current achieved
- **Neoclassical feature** of TM?



Lower l_i startup by tearing mode suppression

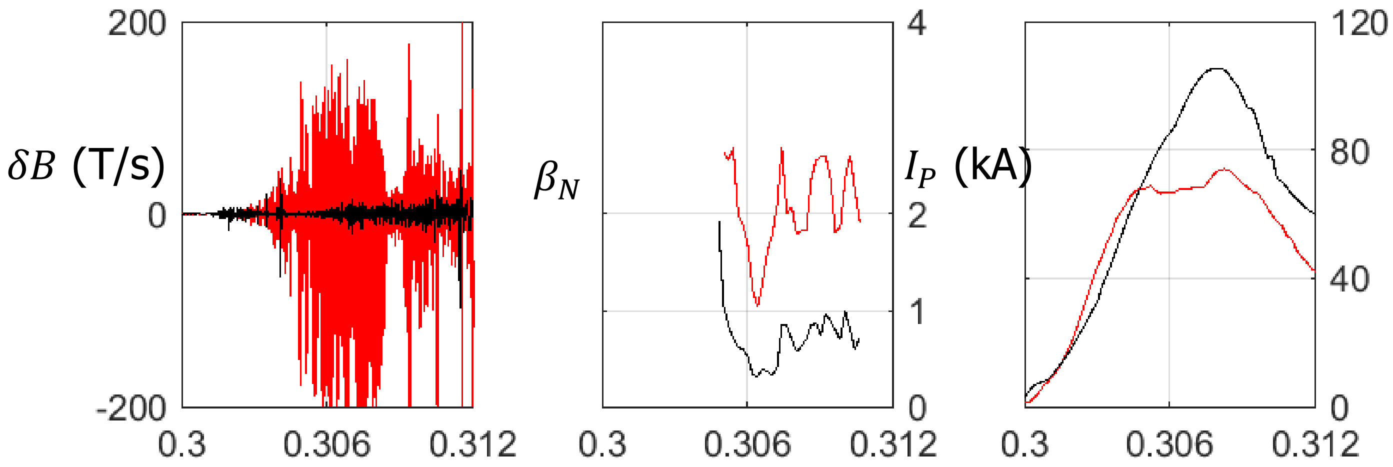
J.H. Yang



Black squares:
Stable shots at unstable region

Suppress TM by e.g. lower β_N

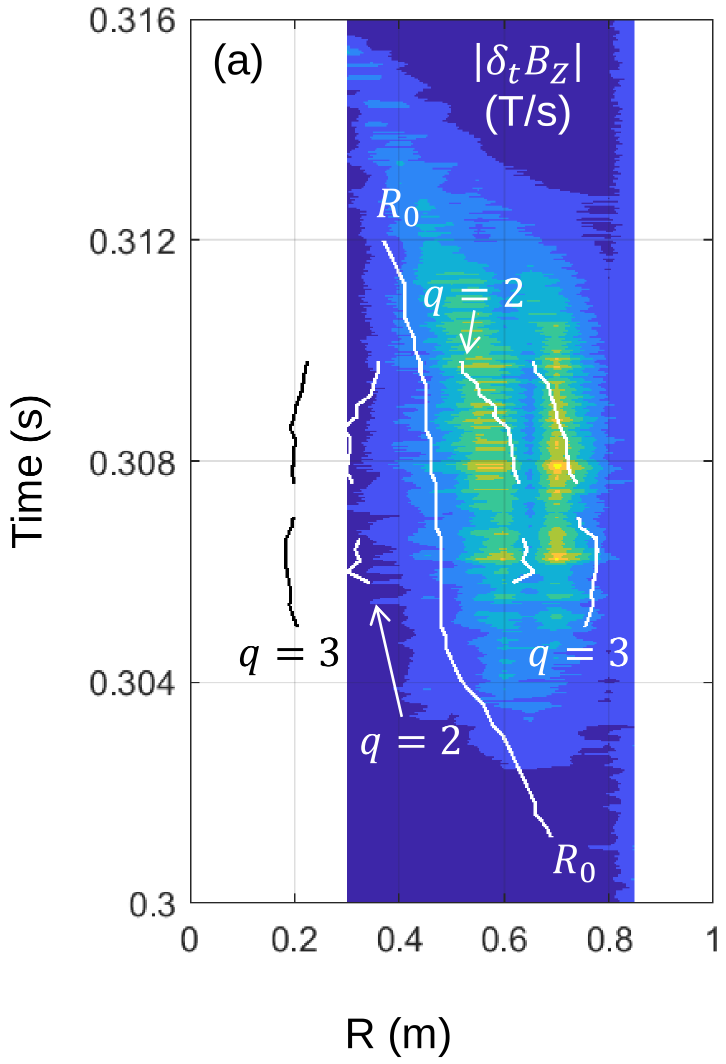
Startup at l_i ~ 0.5 without MHD activity available



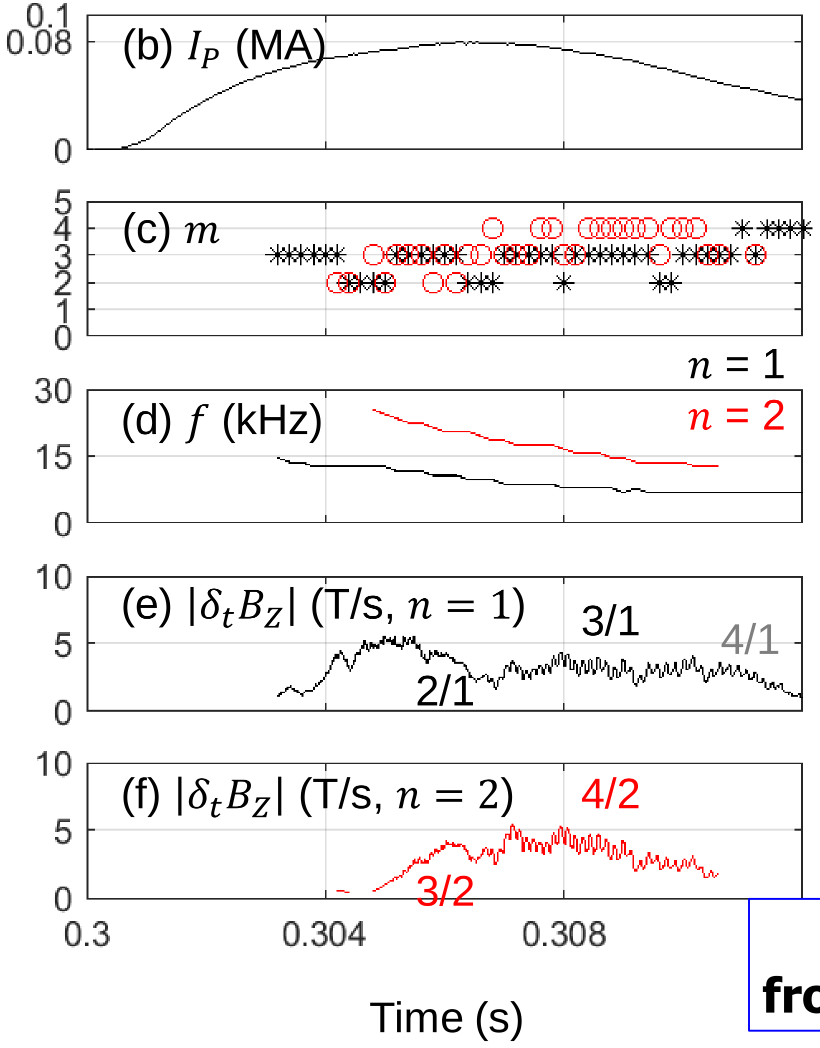
Inboard-Outboard Fluctuation Asymmetry

J.H. Yang

Shots #18452 – 18457

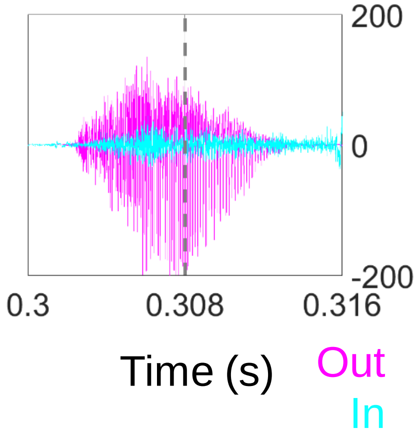


Shot #18452



Theory (Fitzpatrick):
NTM islands are phase locked

Mirnov coil signal



VEST Typical:

2/1 + 3/2 → 3/1 + 4/2

Nonlinear coupling

Linear coupling

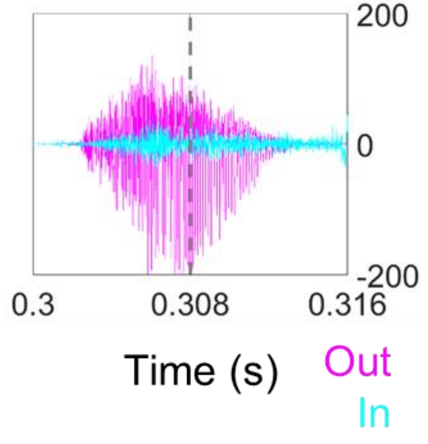
Fluctuation asymmetry may results from phase lock of two magnetic islands

Ramp-up Experiments

Inboard-Outboard Fluctuation Asymmetry

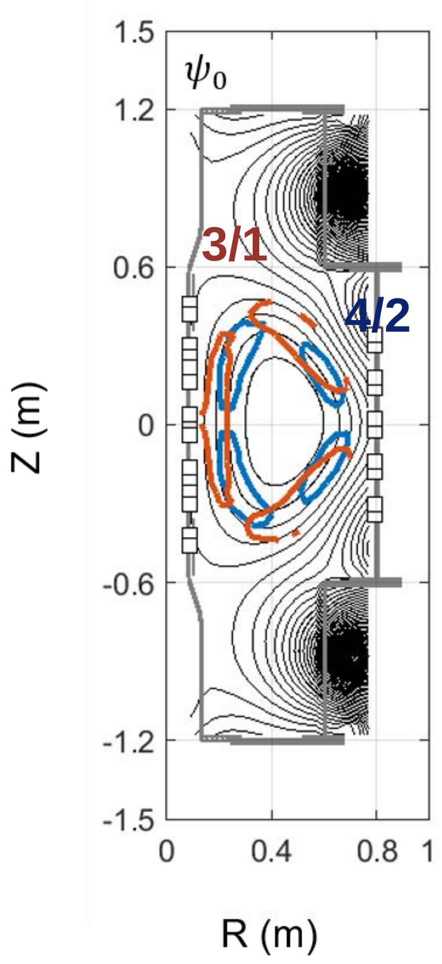
Fluctuation asymmetry may results from phase lock of two magnetic islands

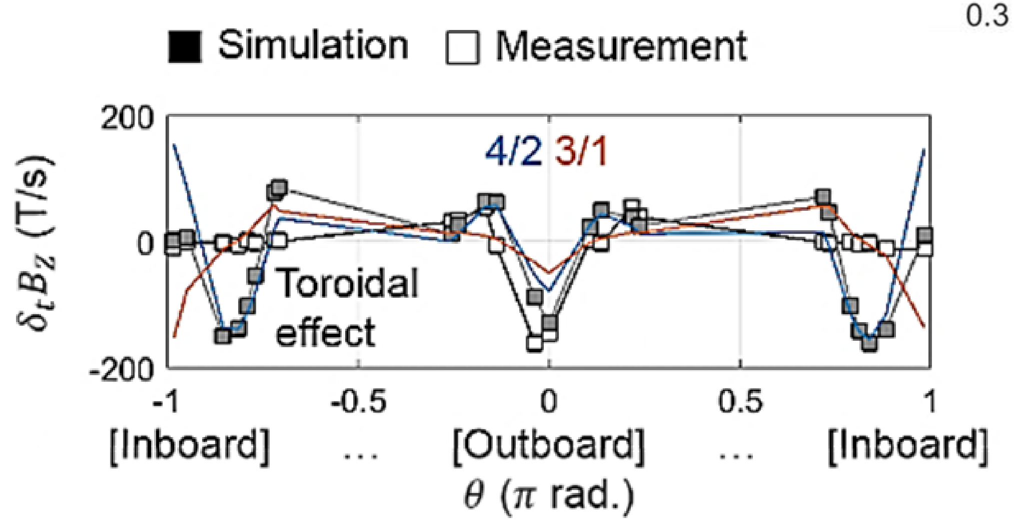
Mirnov coil signal

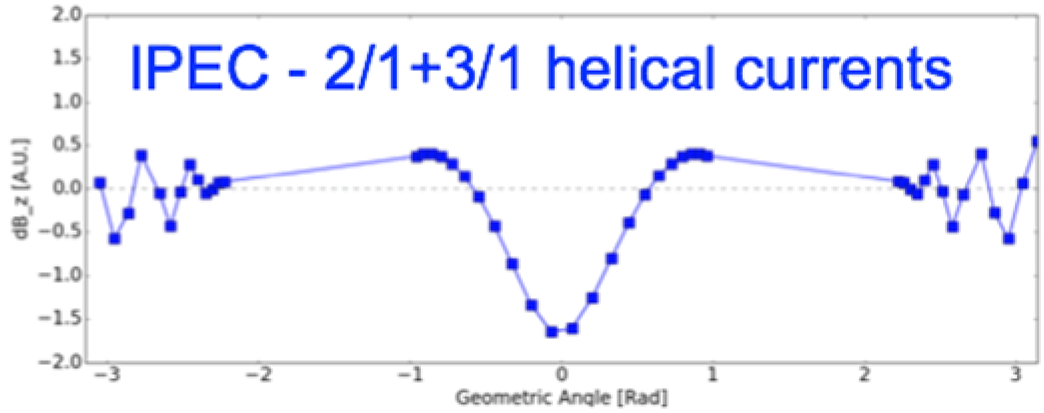


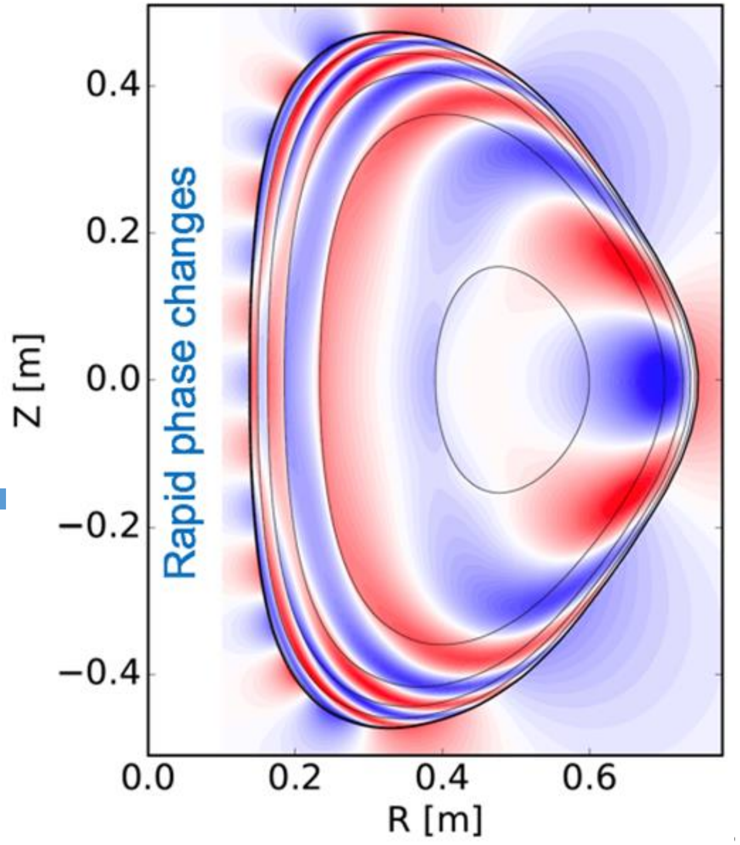
J.K. Park (PPPL)

kink + tearing









Studies for Advanced Tokamak

Scopes of Advanced Tokamak Studies in VEST

Fusion reactor requires
high beta (or Q) and high bootstrap current
Simultaneously

Alpha heating dominant (high Q)
→ Centrally peaked pressure profile

High Bootstrap current fraction (high f_b)
→ Hollow current density profile (low li)

Confinement and Stability?

Profile diagnostics

High power neutral beam heating

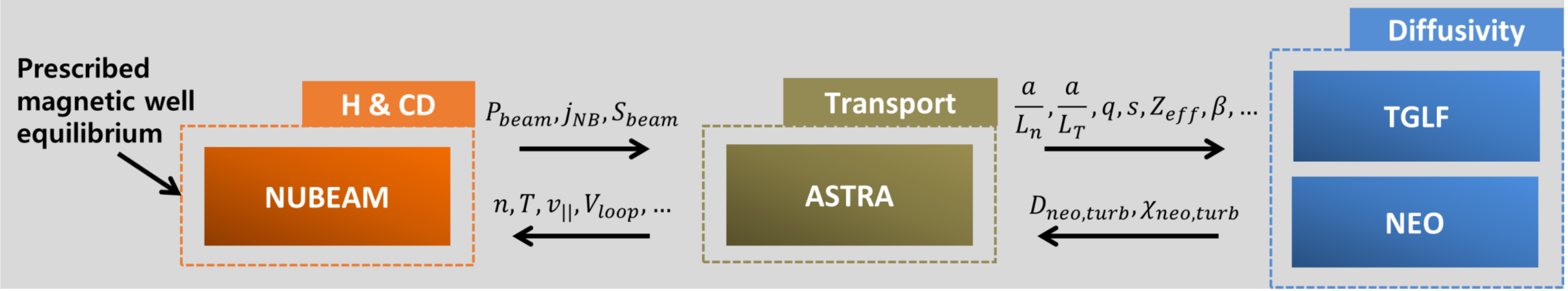
Current density profile control
Bootstrap/EBW/LHFW

Simulations for the VEST Advanced Tokamak Scenario

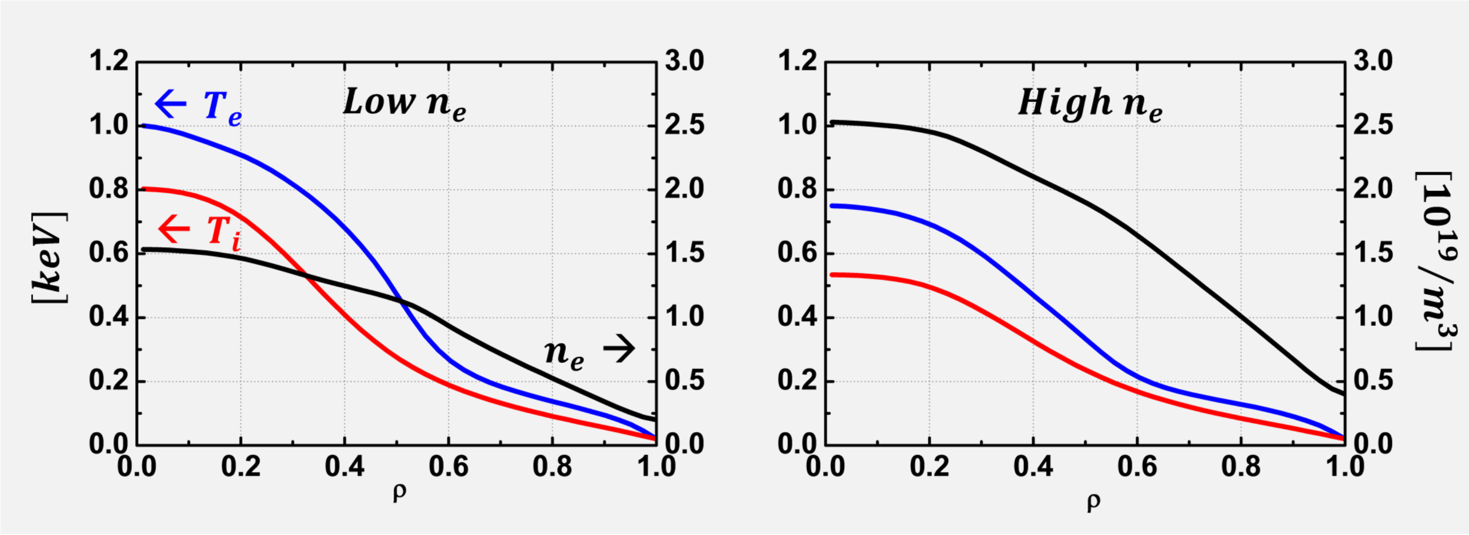
C.Y. Lee

- **The integrated modeling system constructed.**

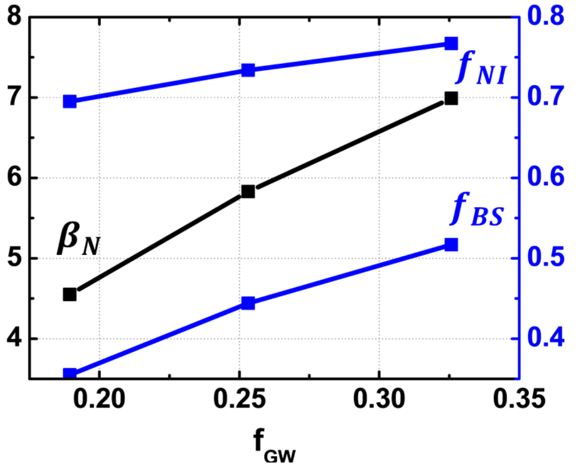
- ASTRA+TGLF and NEO for heat & particle transport: Valid even in low aspect ratio tokamak



- **The steady state solution of beam discharges showing that T_{e0}~$0.8\ keV$, T_{i0}~$0.5\ keV$ can be achieved by considering beam heating & fueling simultaneously.**



β_N~7, f_{BS}~0.5, f_{NI}~0.75



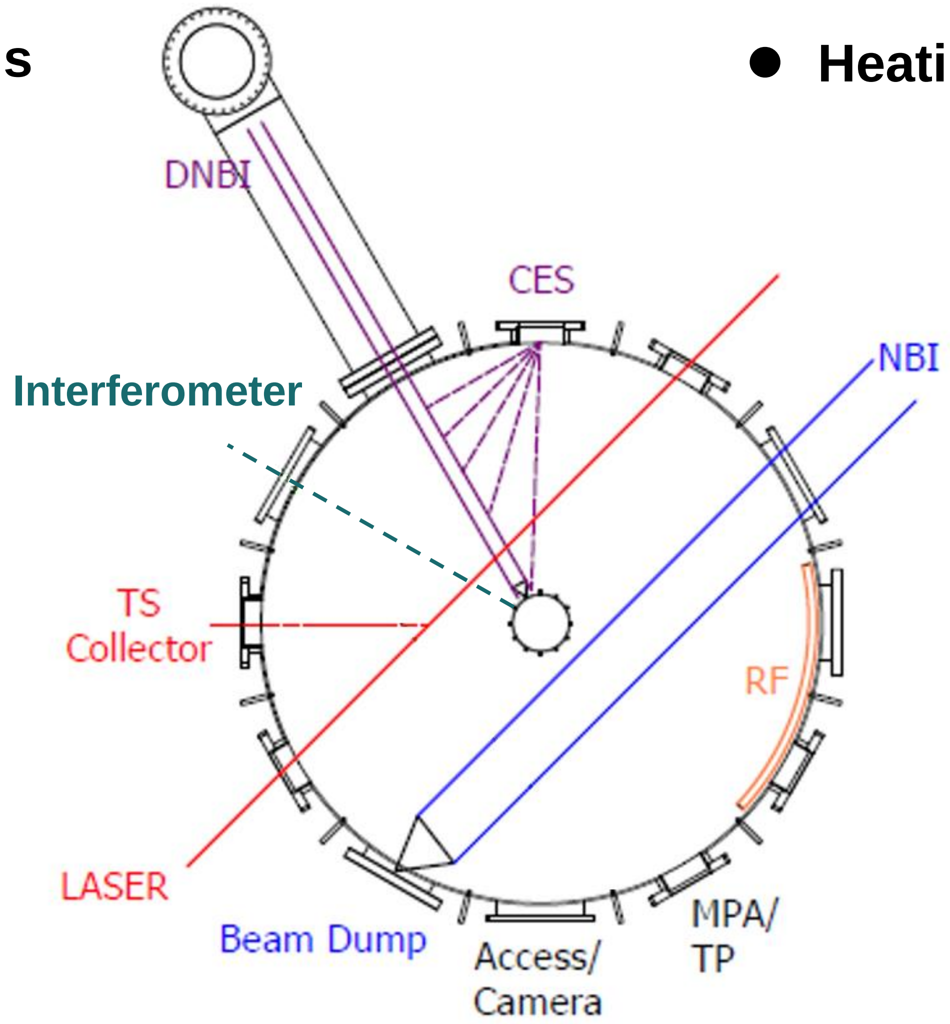
Diagnostics, Heating and Current Drive Systems in VEST

- **Profile Diagnostic Systems**

Magnetics and Visible Spectroscopy

Interferometry with 94GHz, multi-channel from SNU/UNIST

Thomson Scattering with Nd:YAG laser from SNU/NFRI/JNU/SogangU



- **Heating and Current Drive Systems**

Neutral Beam Injection System with ~600kW at 15keV from KAERI

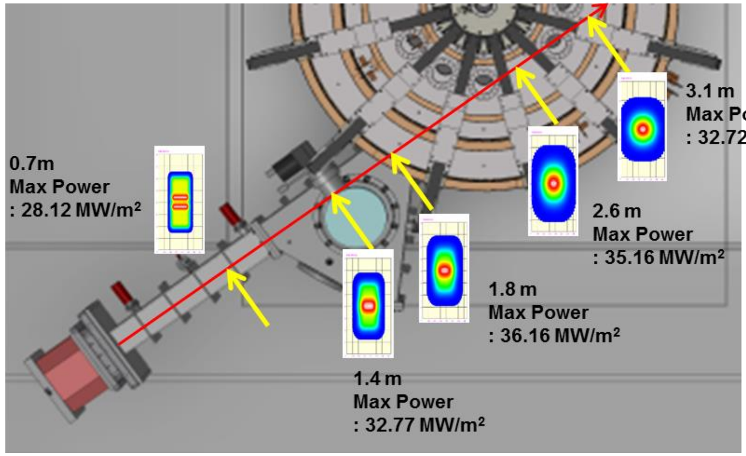
Low Hybrid Fast Wave H/CD with ~10kW at 500MHz from KAERI/KAPRA/KWU

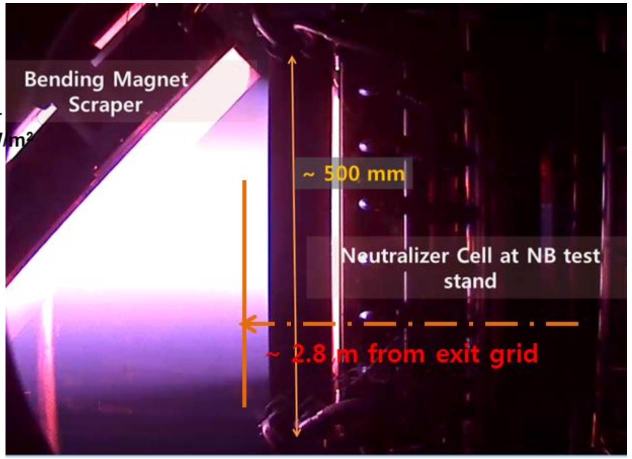
Electron Cyclotron/Bernstein Wave H/CD with ~15kW at 2.45GHz 3kW at 7.9GHz from SNU/KAPRA

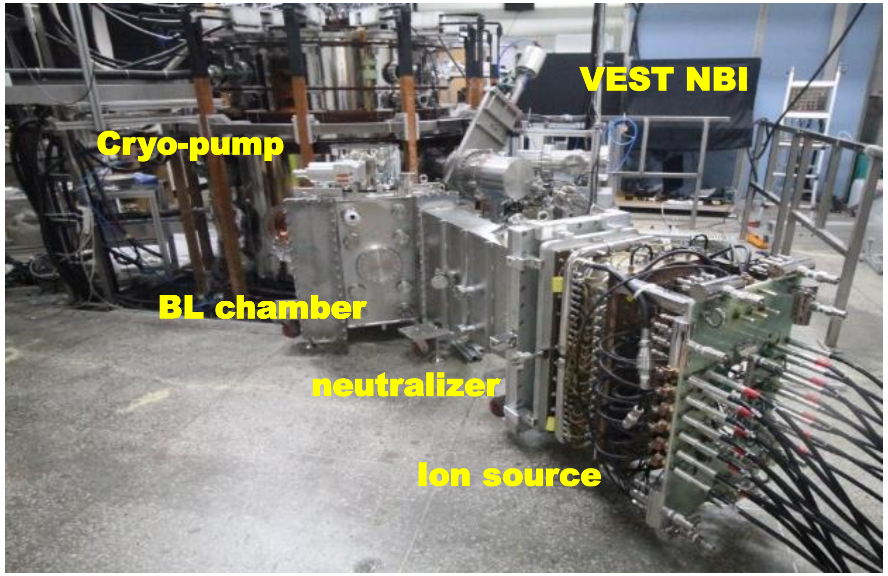
High power central heating

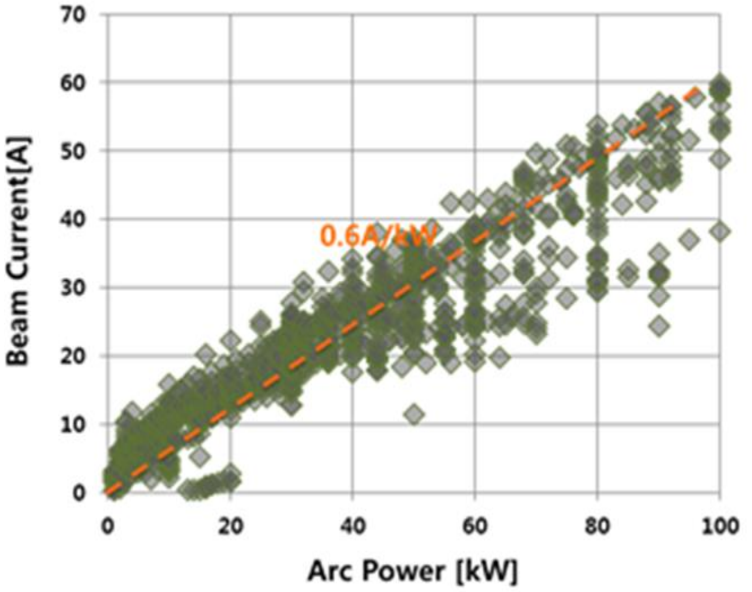
High Power NBI System : High Perveance (~15kV,~50A) Ion Source Installed on VEST

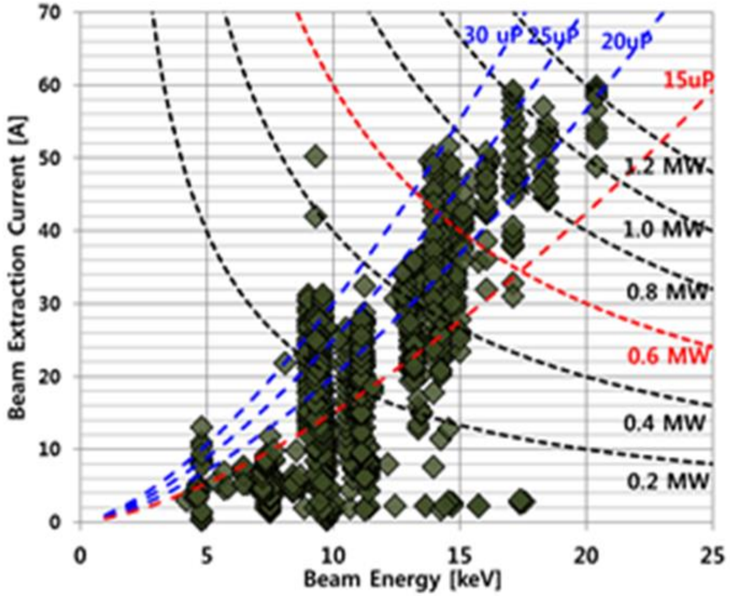
VEST NBI: Beam extraction experiments of NBI ion source











B.K. Jung

- 15keV-40A /0.6MW
- 20keV-60A /1.2MW

한국원자력연구원
Korea Atomic Energy Research Institute

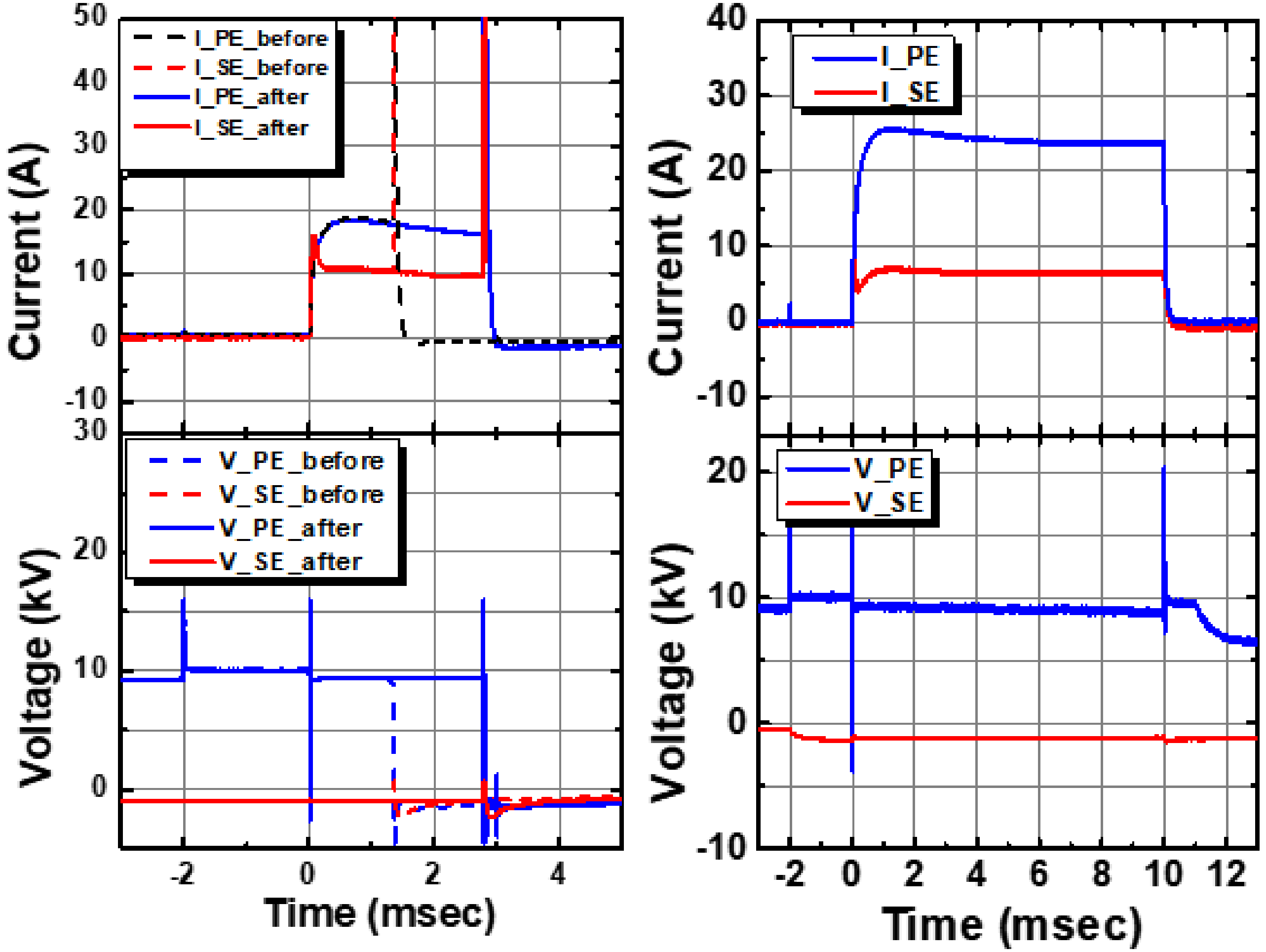
High power central heating

NBI System Commissioning in VEST

Poster P10

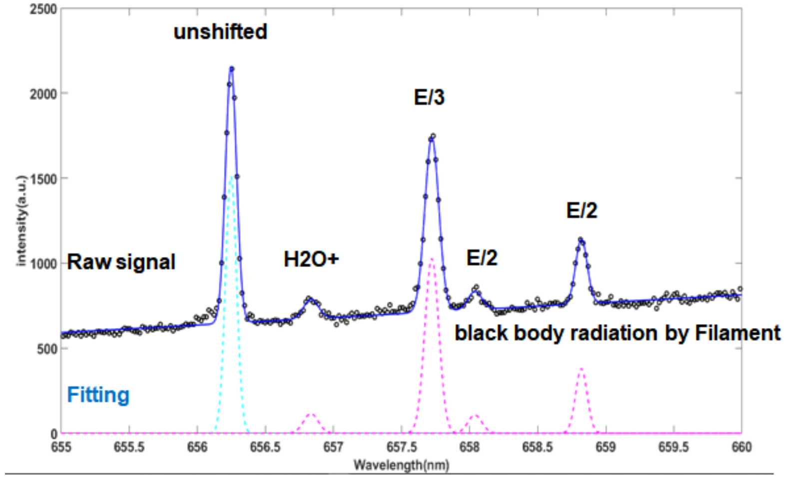
K.H. Lee

Commissioning up to 200 kW (10 kV/20 A, 10 msec)

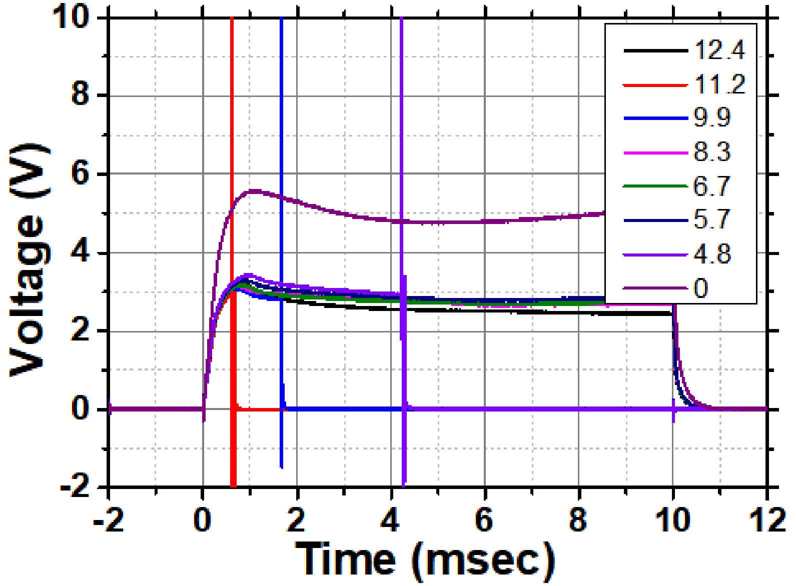


Injected NBI power up to 120 kW / 10 msec
with average beam energy of 6.5kV

Beam fraction E : E/2 : E/3 = 45 % : 7 % : 47 %



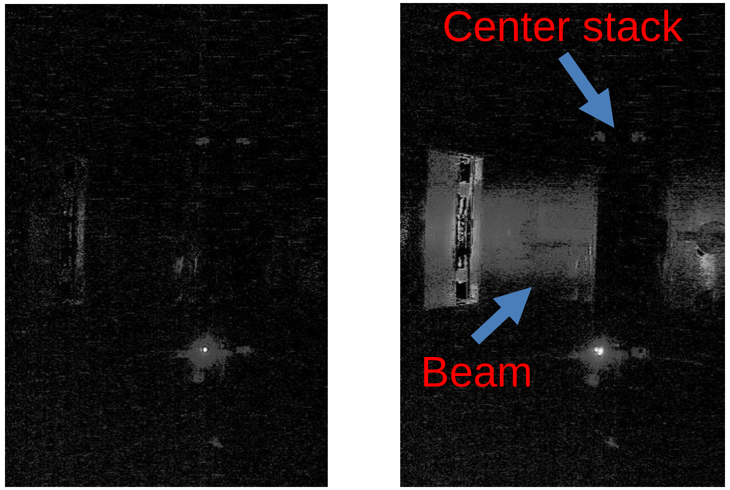
Neutralization efficiency: ~60%



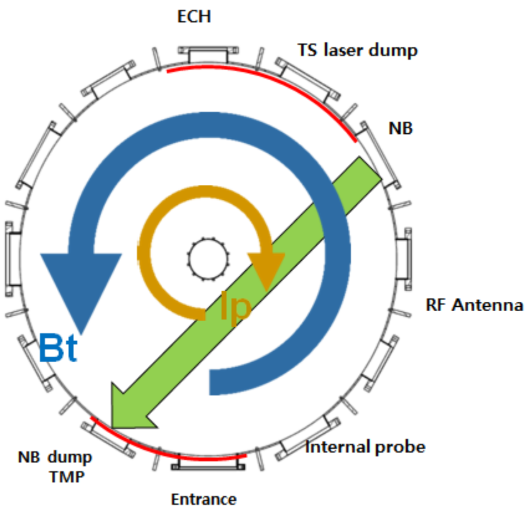
NBI Coupling Experiments in VEST

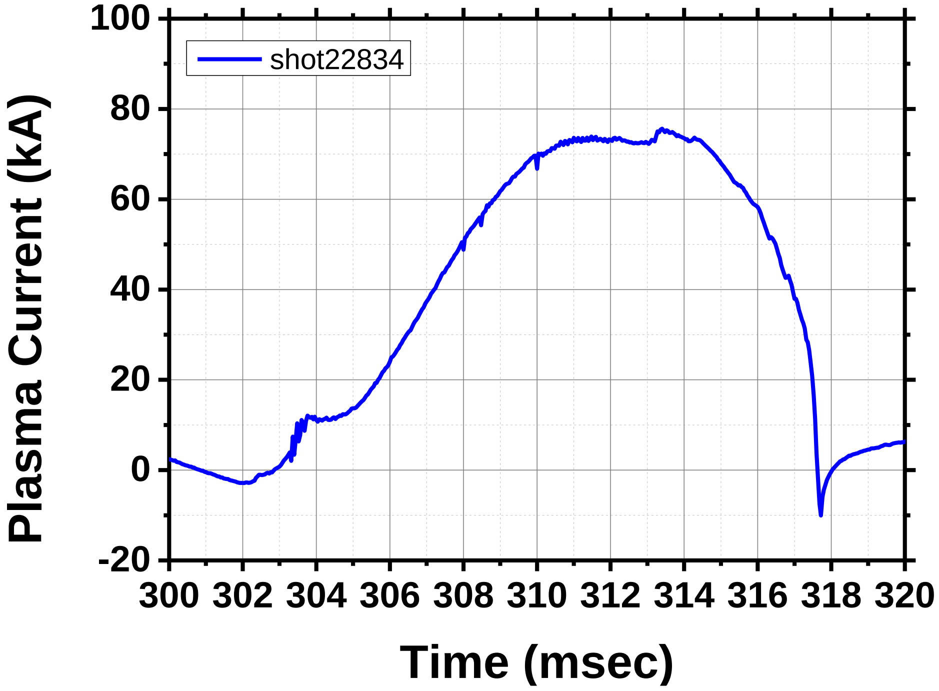
K.H. Lee

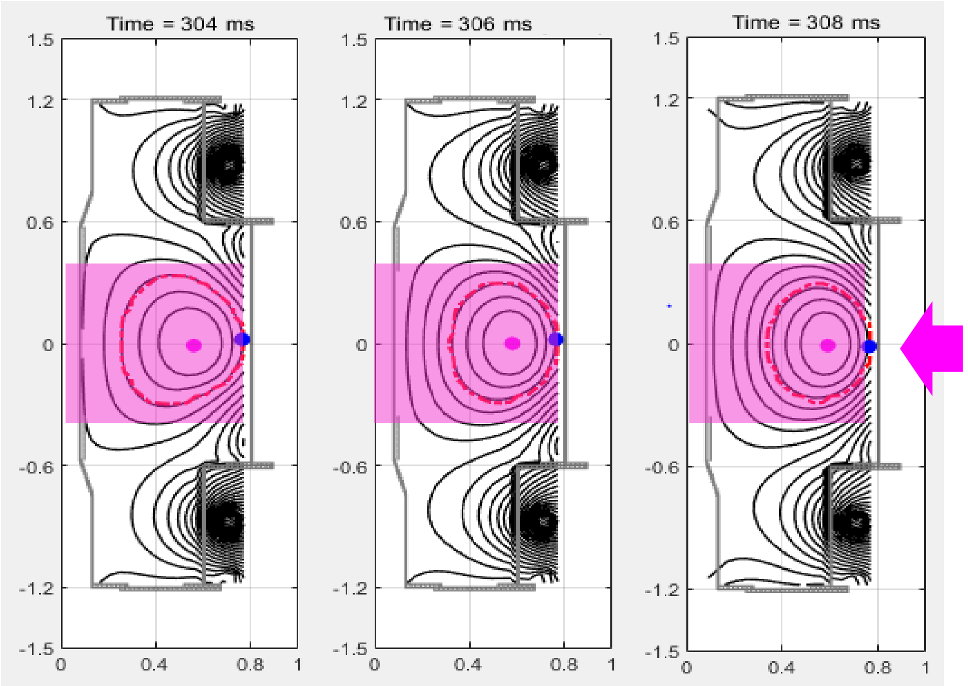
- Target plasma : #23834
- Plasma peak current : 75kA
- TF : 0.15T (= 12.5kA)
- Wall conditioning by GDC, Boronization
- NB power : 120kW



NB injection to VEST



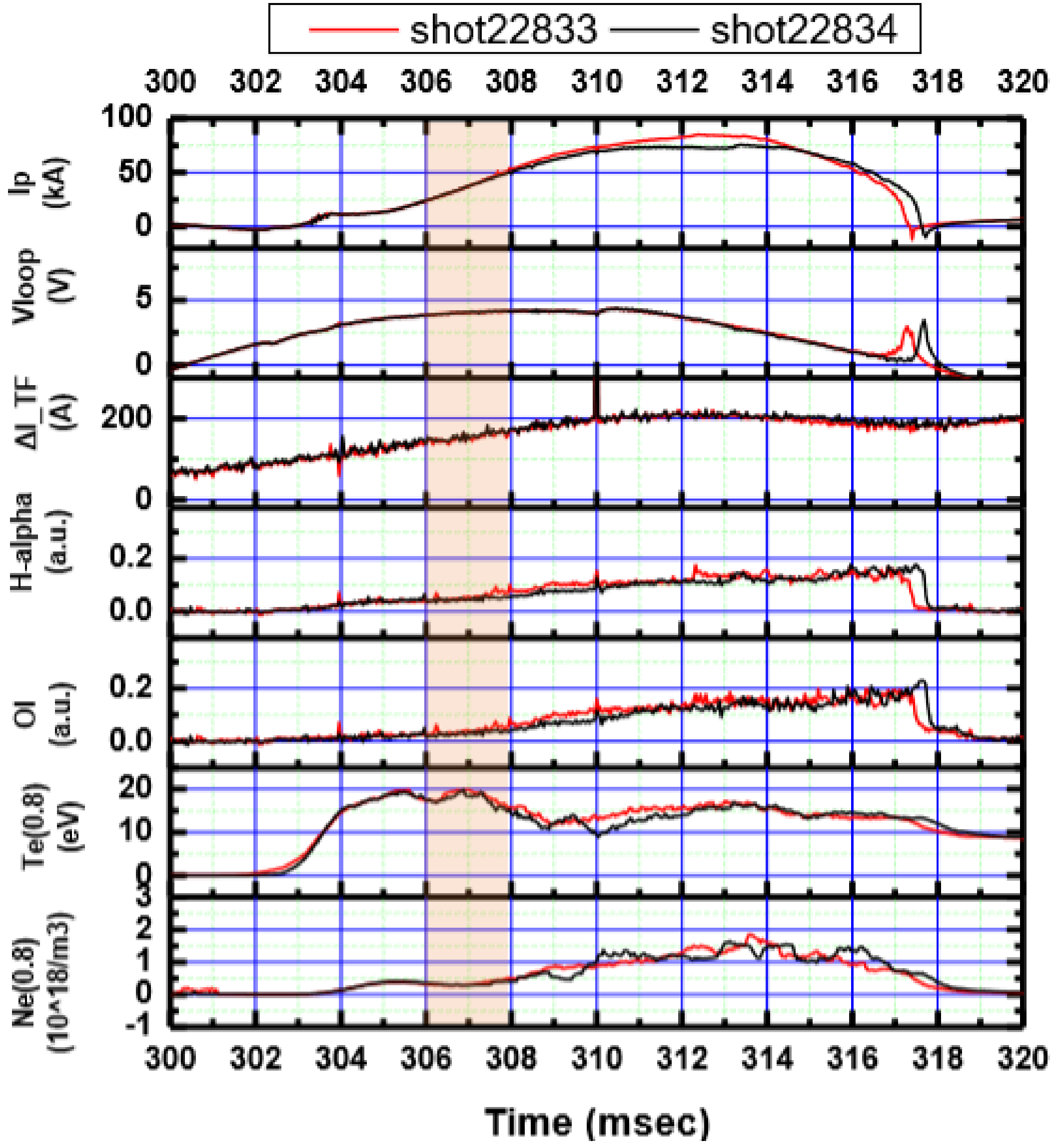




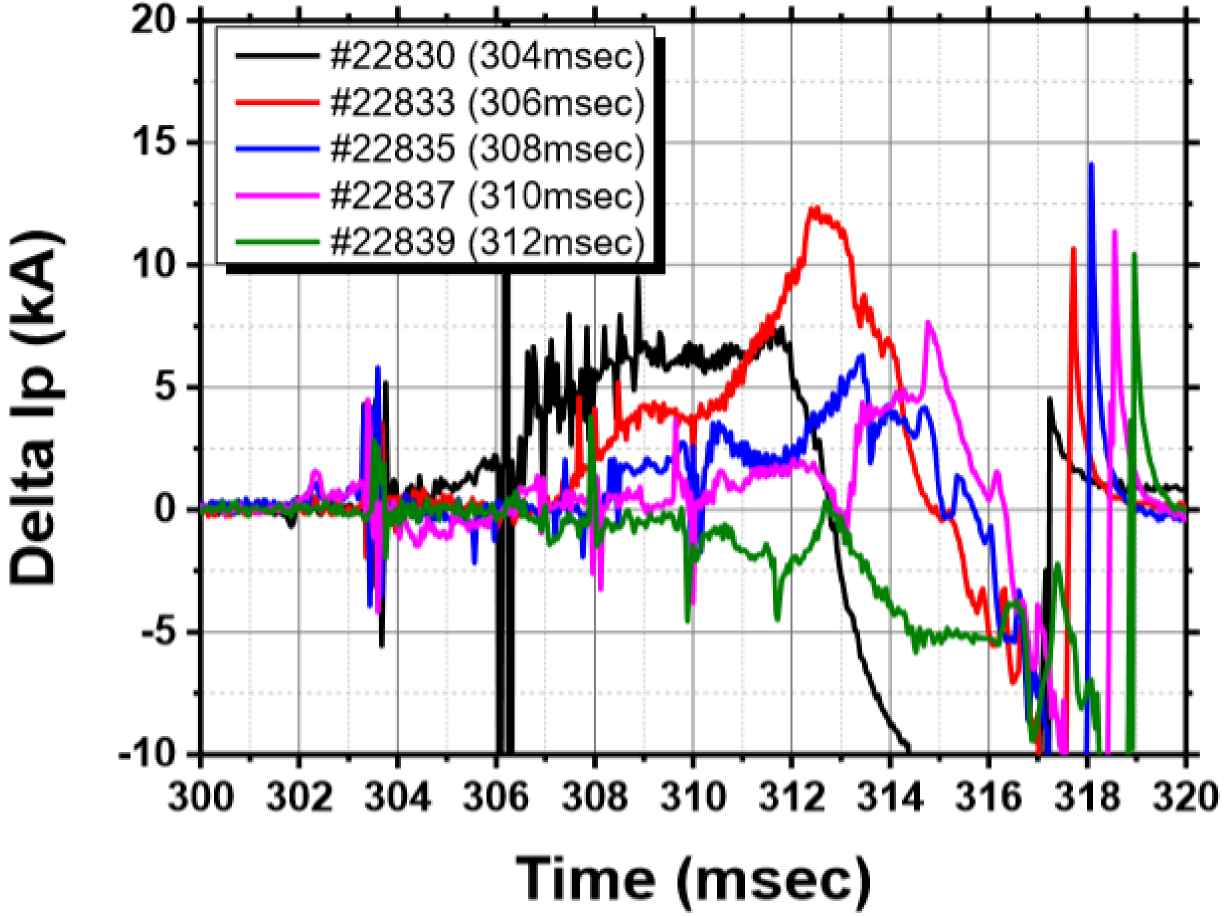
High power central heating

NBI Coupling Experiments with 2msec Beam in VEST

K.H. Lee



Changes of plasma current by NBI



- Coupling at different time with different plasma current

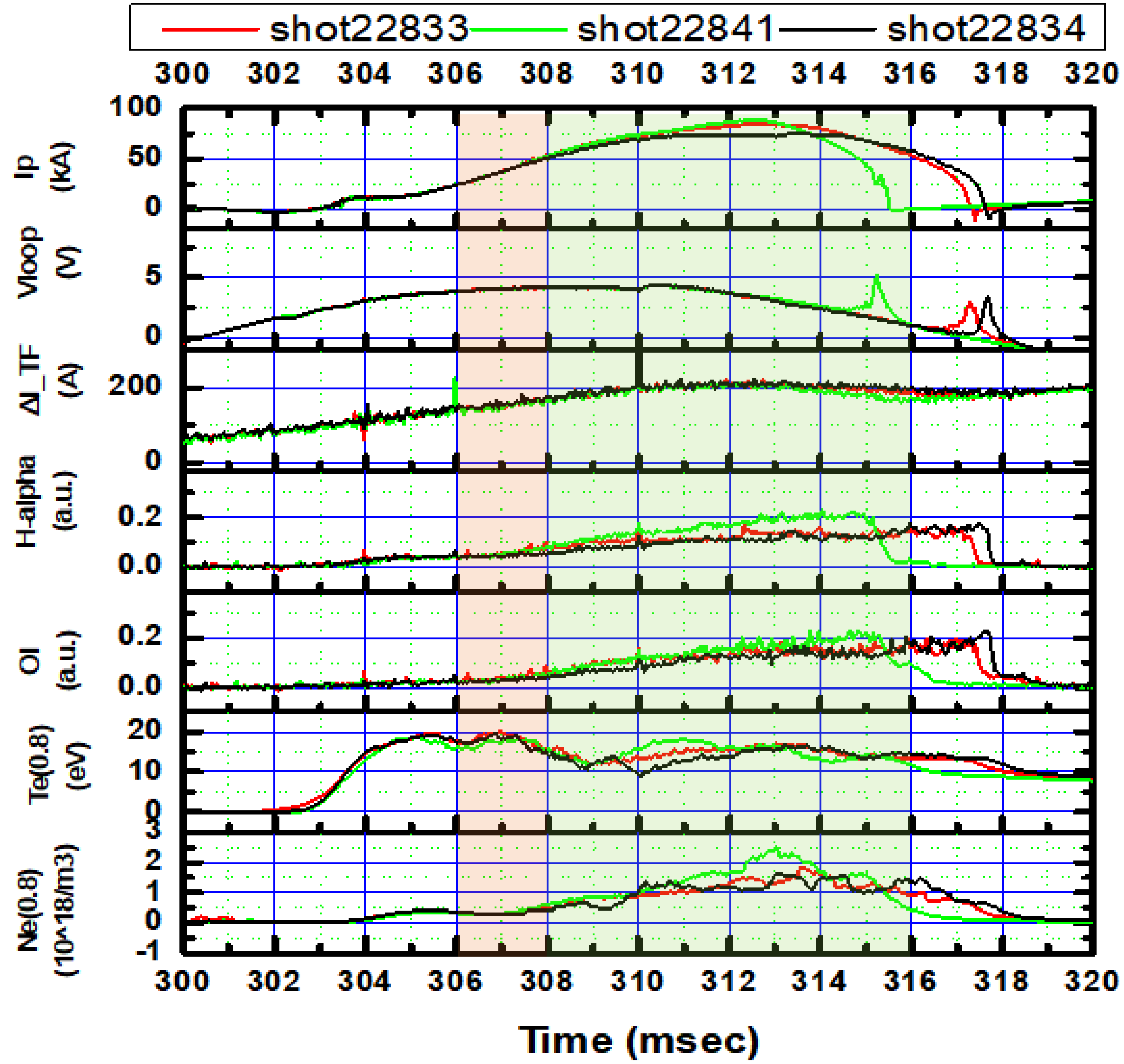
→ Better coupling with Ip < 50kA: low beam energy?

- Current drop with Impurity influx by equilibrium change

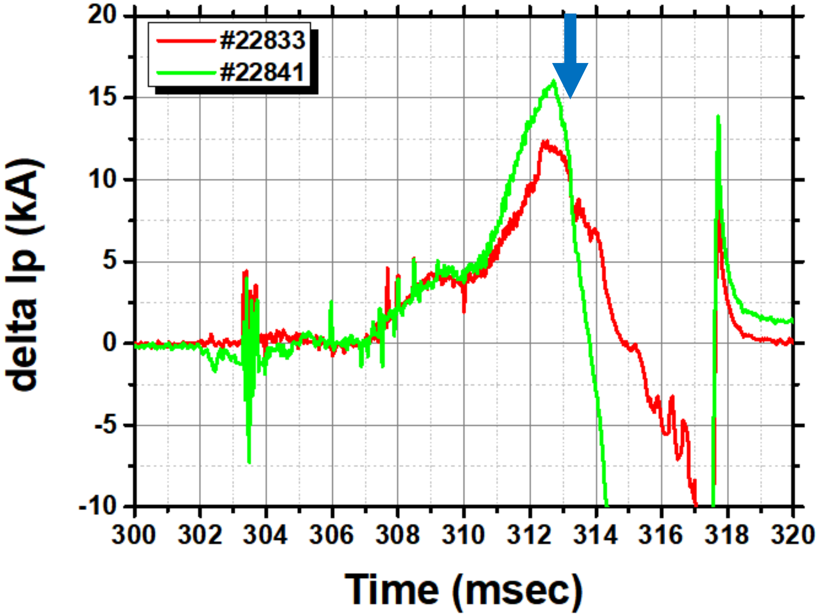
High power central heating

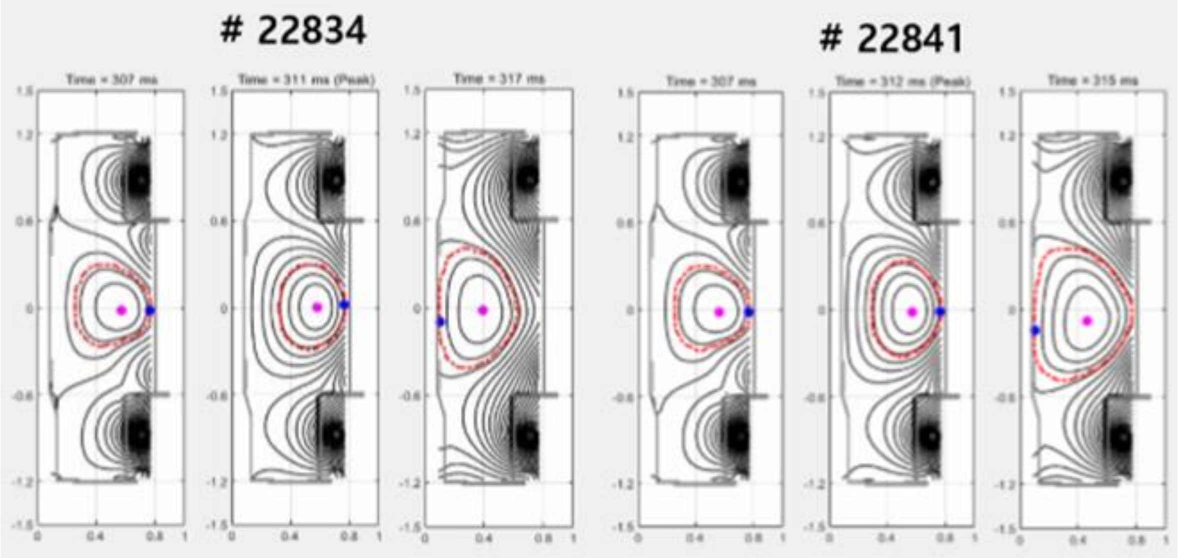
NBI Coupling Experiments with 2msec vs 10msec Beam in VEST

K.H. Lee



Changes of plasma current by NBI

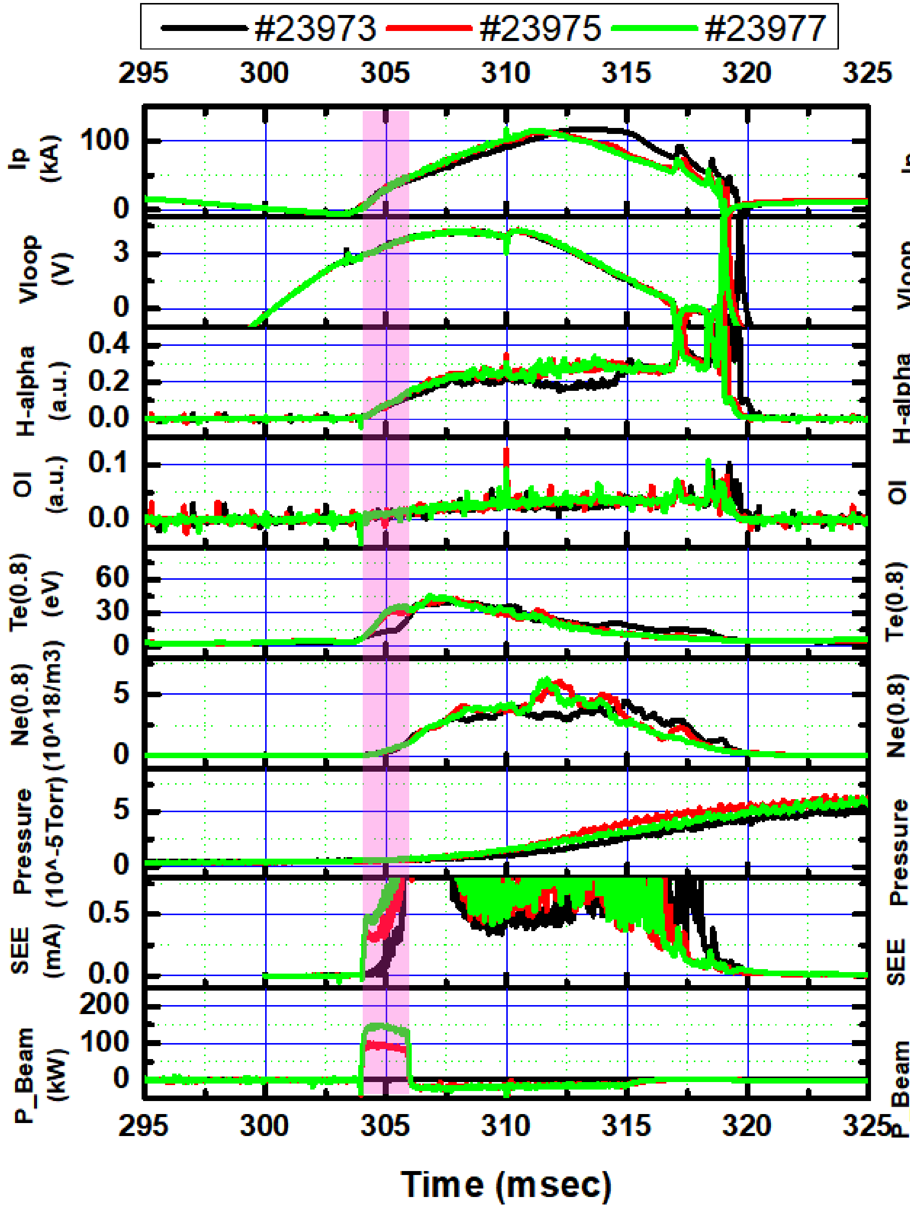


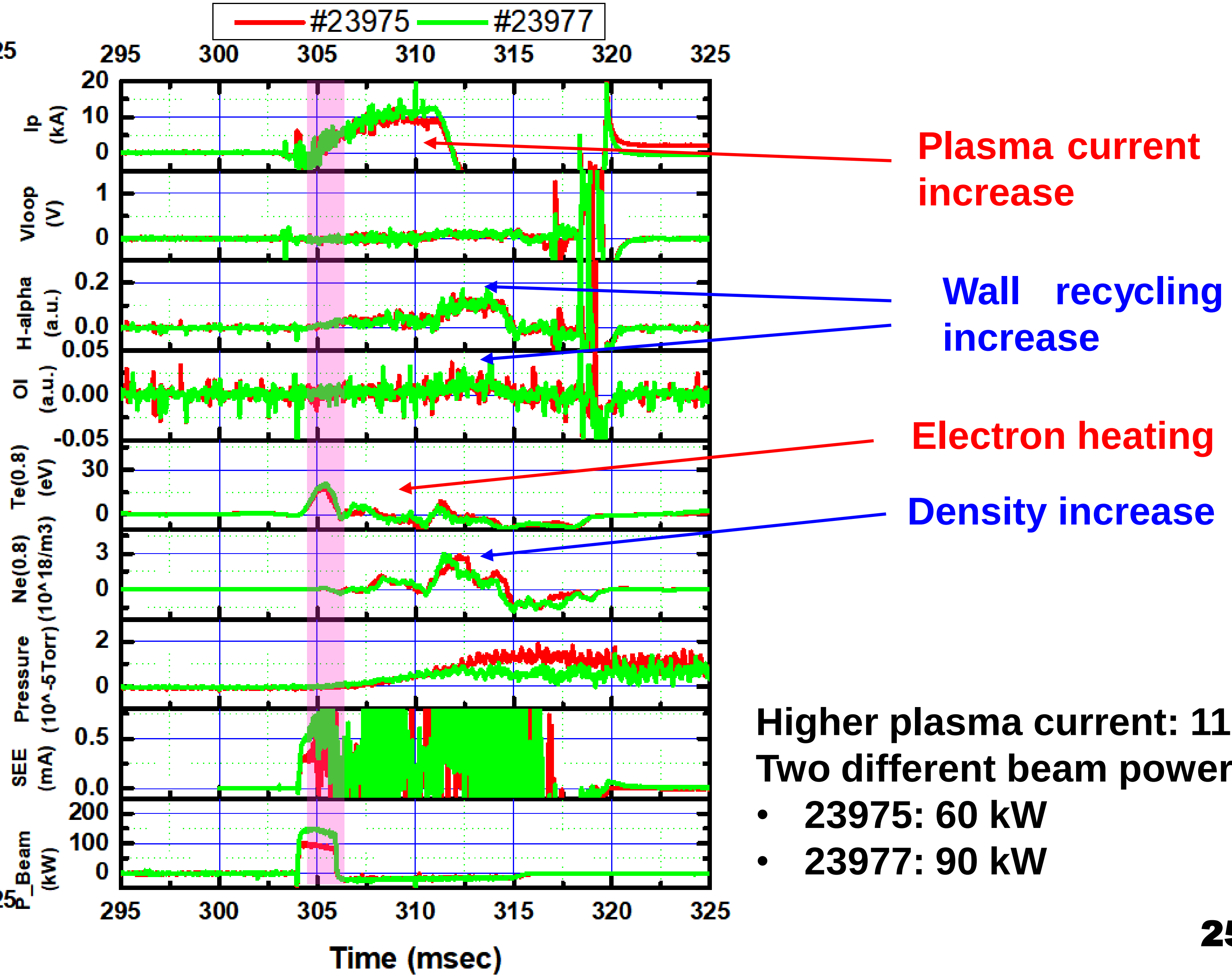


High power central heating

NBI Coupling Experiments with 2msec Beam in VEST

K.H. Lee





Higher plasma current: 110kA

Two different beam powers

- 23975: 60 kW
- 23977: 90 kW

Profile Diagnostic Systems

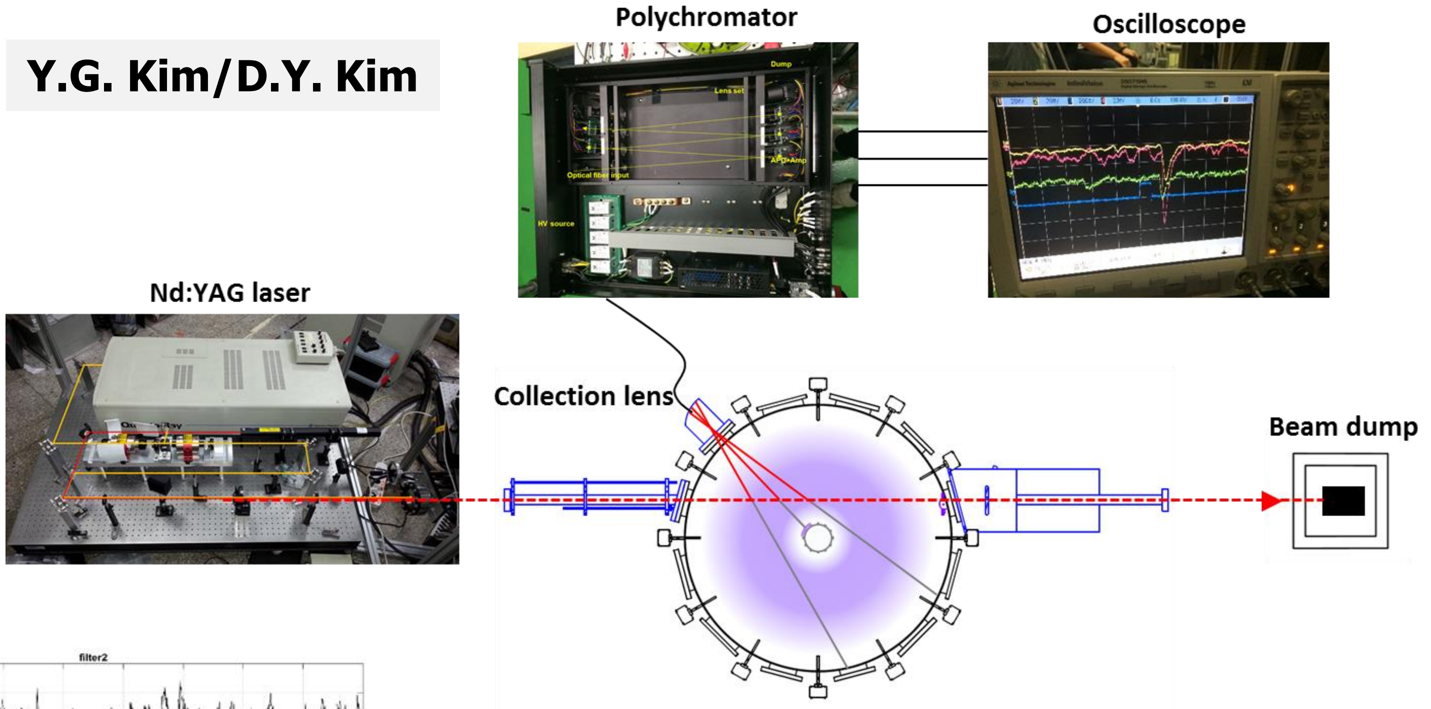
Profile diagnostics

Thomson Scattering System

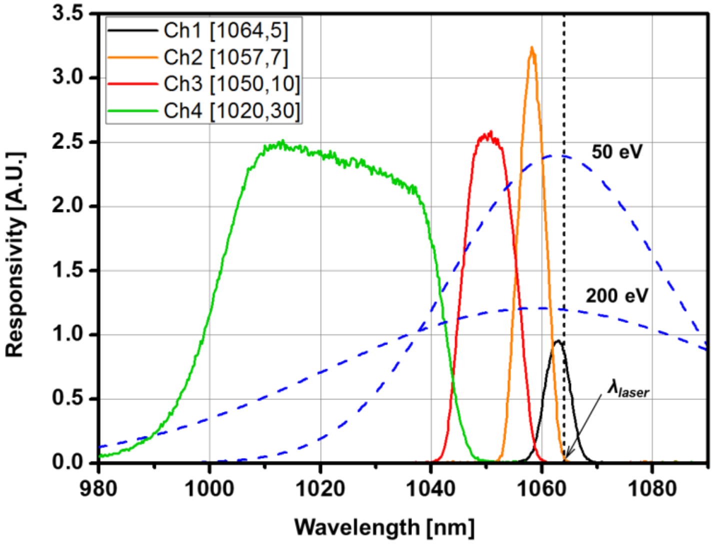
In collaboration with NFRI 서강대학교 Sogang University

Y.G. Kim/D.Y. Kim

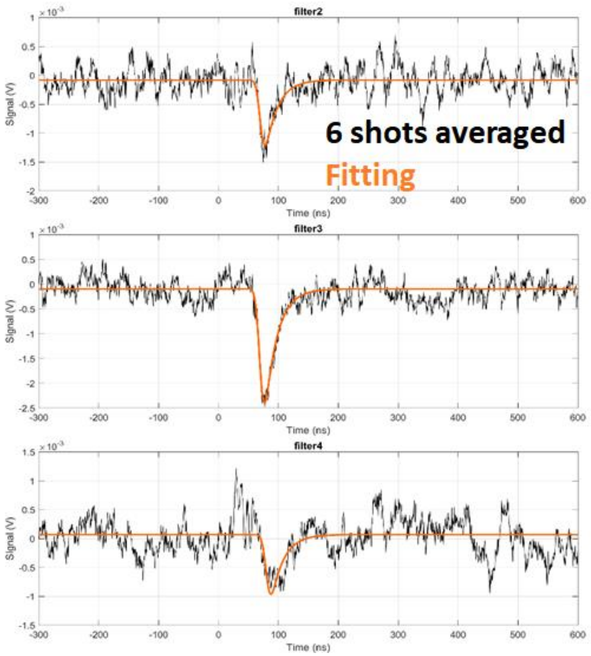
- Measurement target
  - n_e: > 5×10^{18} m^{-3}
  - T_e: 10-500 eV
  - core plasma
- Laser: 0.65 J/pulse, 1064 nm
- Collection solid angle: ~50 msr
- Scattering length: ~5 mm
- Filter polychromator: 4 channels

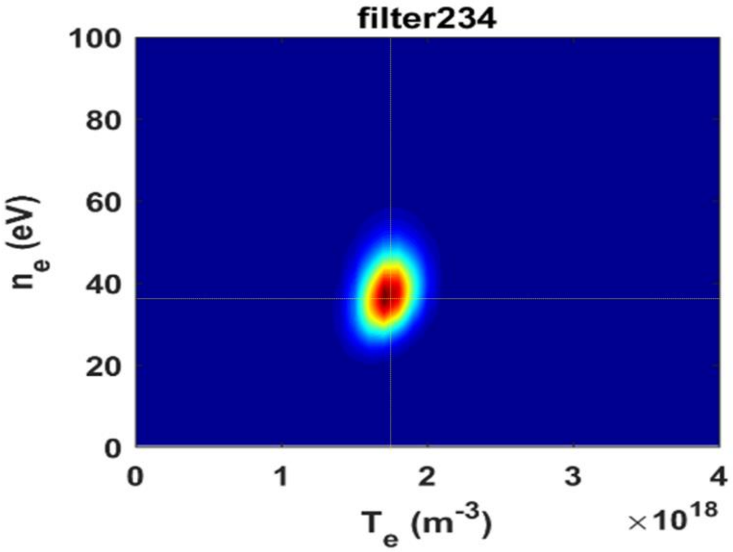


Schematic of the TS system



Spectral Response of the polychromator





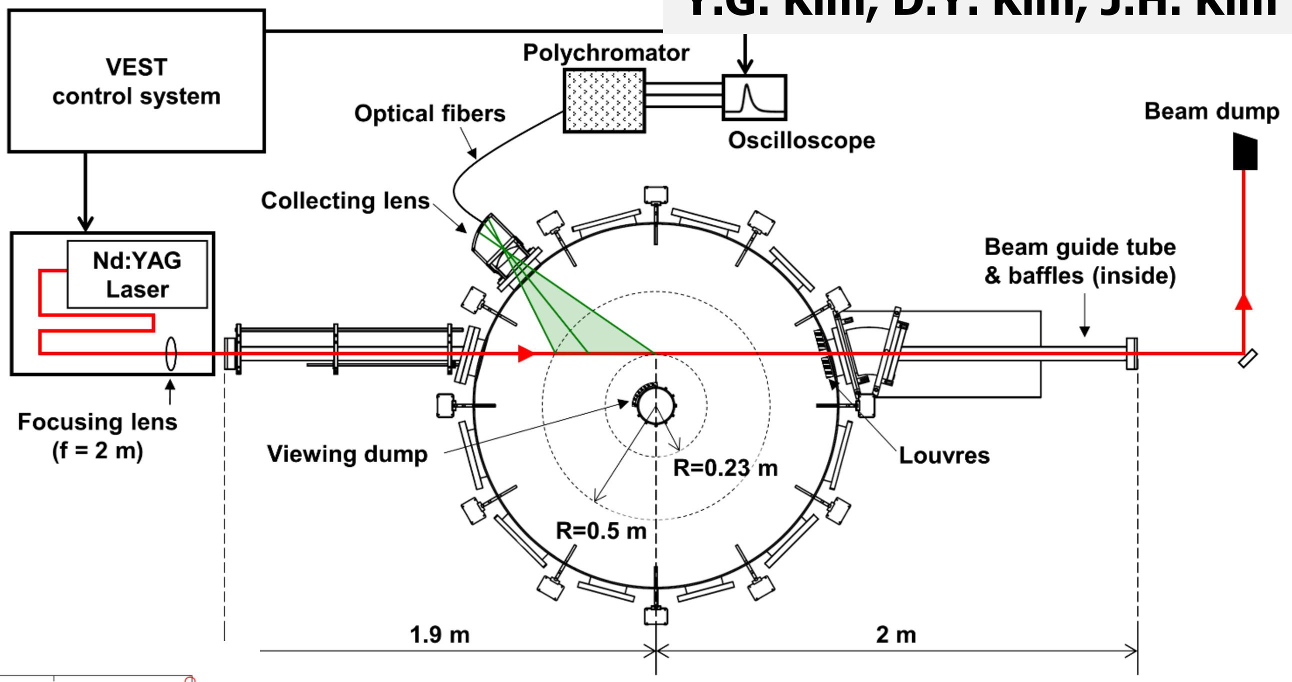
Profile diagnostics

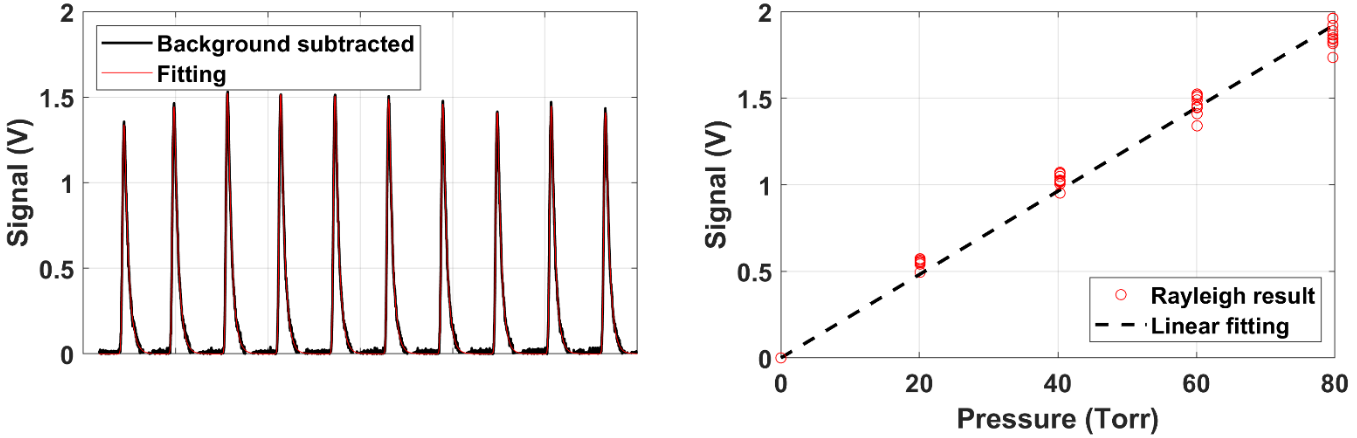
Thomson Scattering System Upgrade

In collaboration with NFRI National Fusion Research Institute

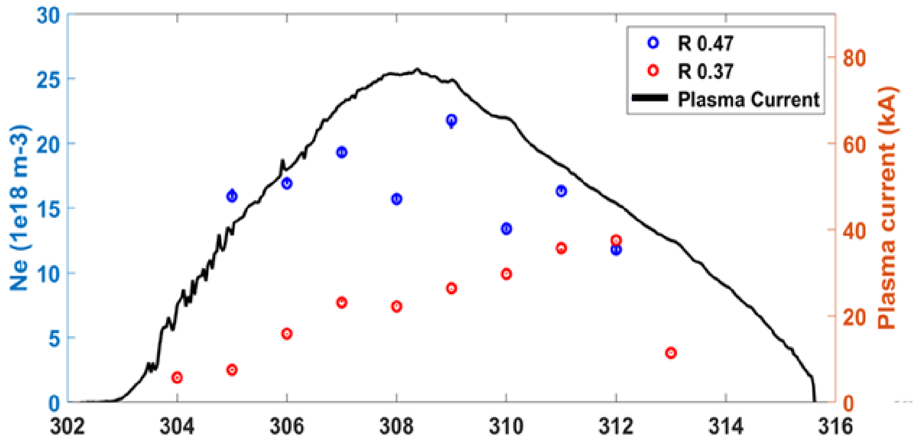
Y.G. Kim, D.Y. Kim, J.H. Kim

- **Nd:YAG laser system** (BeamTech Inc. SGR-20)
  - ✓ Laser energy: 0.85 J ➔ 2.0 J
  - ✓ Repetition rate: 10 Hz ➔ 1 kHz (10 pulses)
  - ✓ Optical loss: 23% ➔ 4%
- **Additional polychromator**
  - ✓ 2 points measurement
- **New fast digitizer (CAEN V1742)**
  - ✓ 5 GS/s × 32 ch.





Recent result of N2 Rayleigh scattering measurement

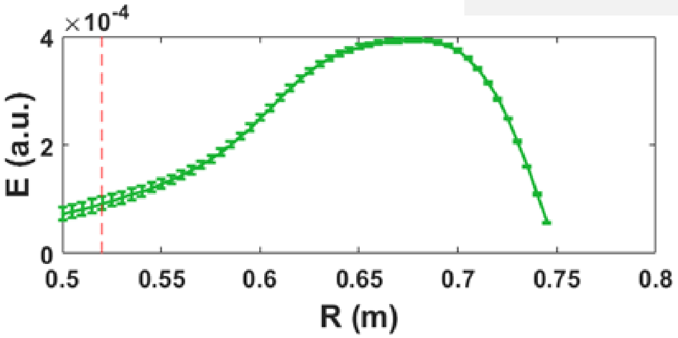


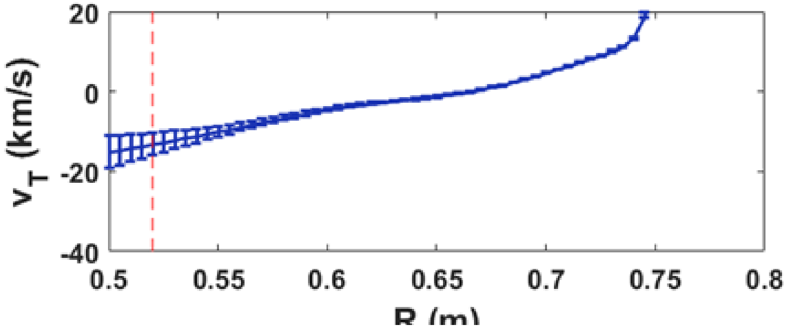
Young-Gi Kim, *et al.*, Fusion Engineering and Design 143, 130-136 (2019)
Doyeon Kim, *et al.*, Fusion Engineering and Design 146 Part A, 1131-1134 (2019)

Profile diagnostics

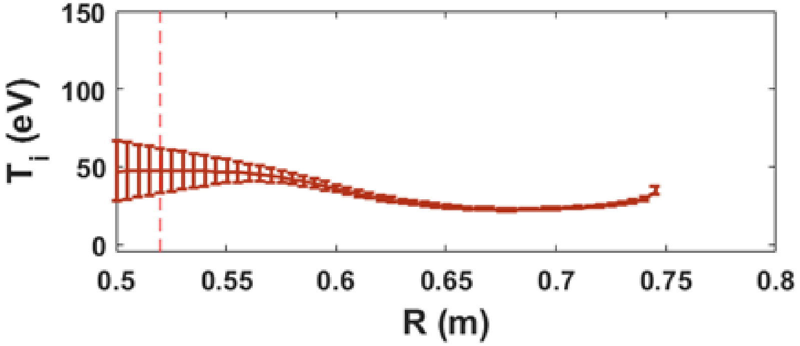
Visible optical spectroscopy

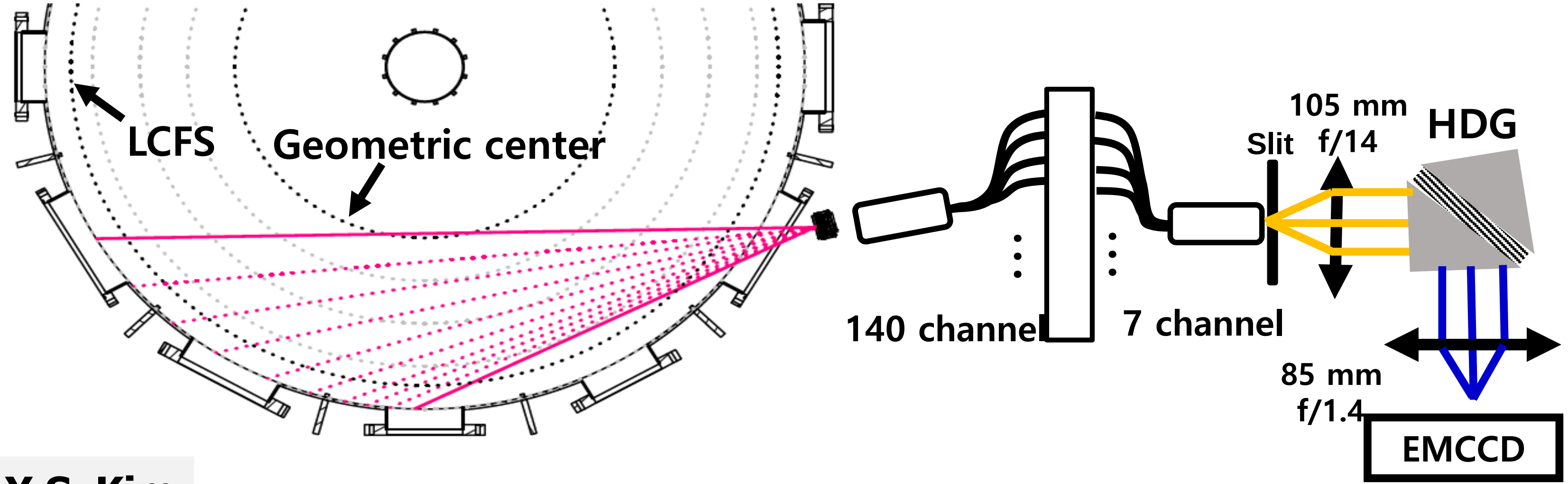
In collaboration with AJOU UNIVERSITY KAIST

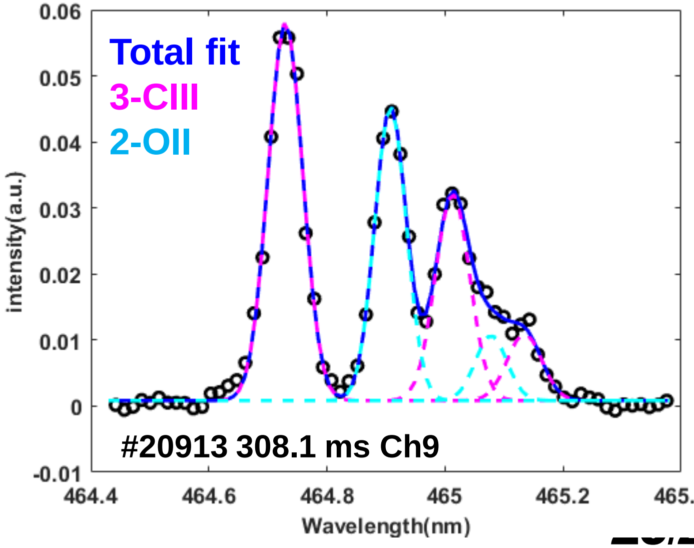




- Measurement quantities : T_i, v_T, n_Z
- Passive emission spectroscopy
  - ✓ CIII 464.74 nm and OII 464.90 nm
  - ✓ Line-integrated spectra → spectral inversion
- Specification
  - ✓ Detection range : 0.39 m< R <0.71 m
  - ✓ Spatial resolution : 20-22 mm
  - ✓ Temporal resolution : 2 ms for 9ch, 0.2 ms for 1ch
- CES/BES combined system is in preparation







Y.S. Kim

YooSung Kim *et al.*, Fusion Engineering and Design 123, 975-978 (2017)

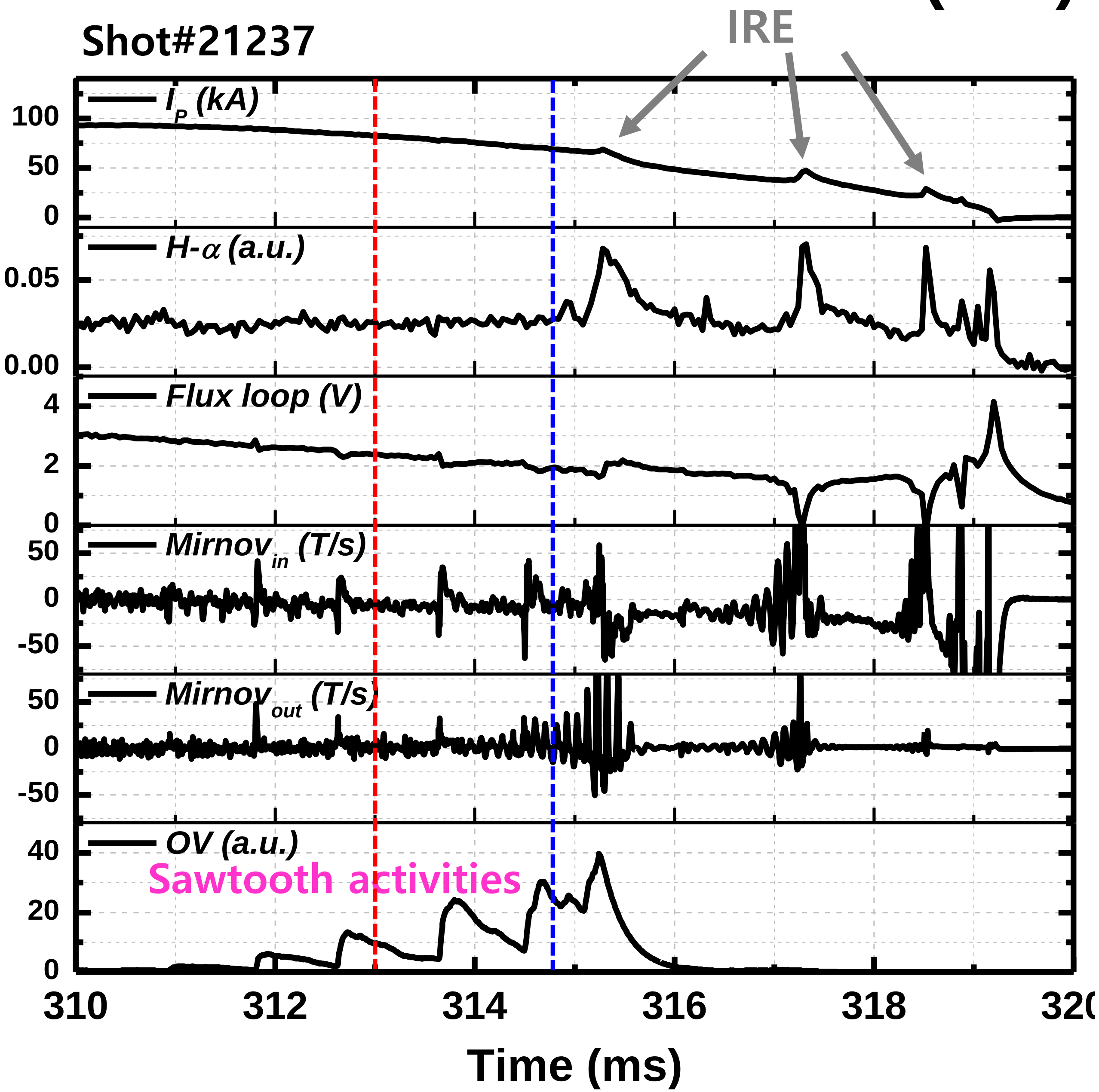
Internal Reconnection Event (IRE) for Disruption Study

IRE & Disruption

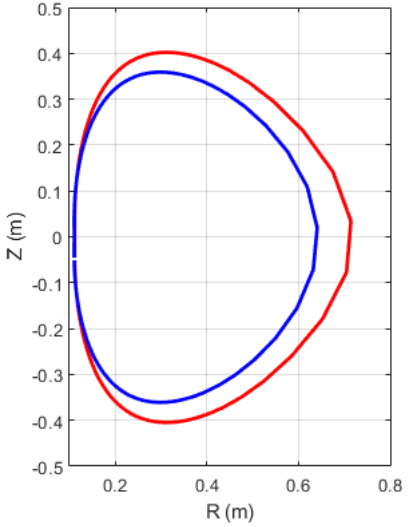
Internal Reconnection Event (IRE) after Sawtooth

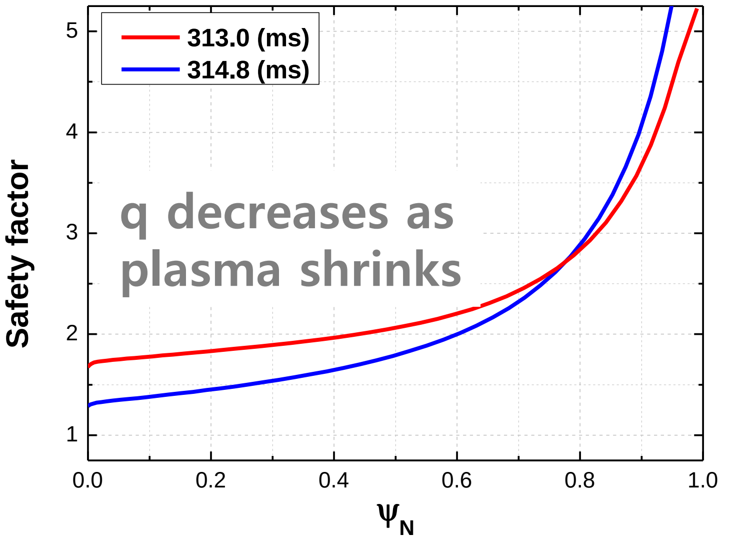
Poster P11

Y.S. Kim/S.C. Kim



- **Before the IRE, sawtooth-like activities are observed in Mirnov and OV signals even though q_0 is calculated to be higher than 1**



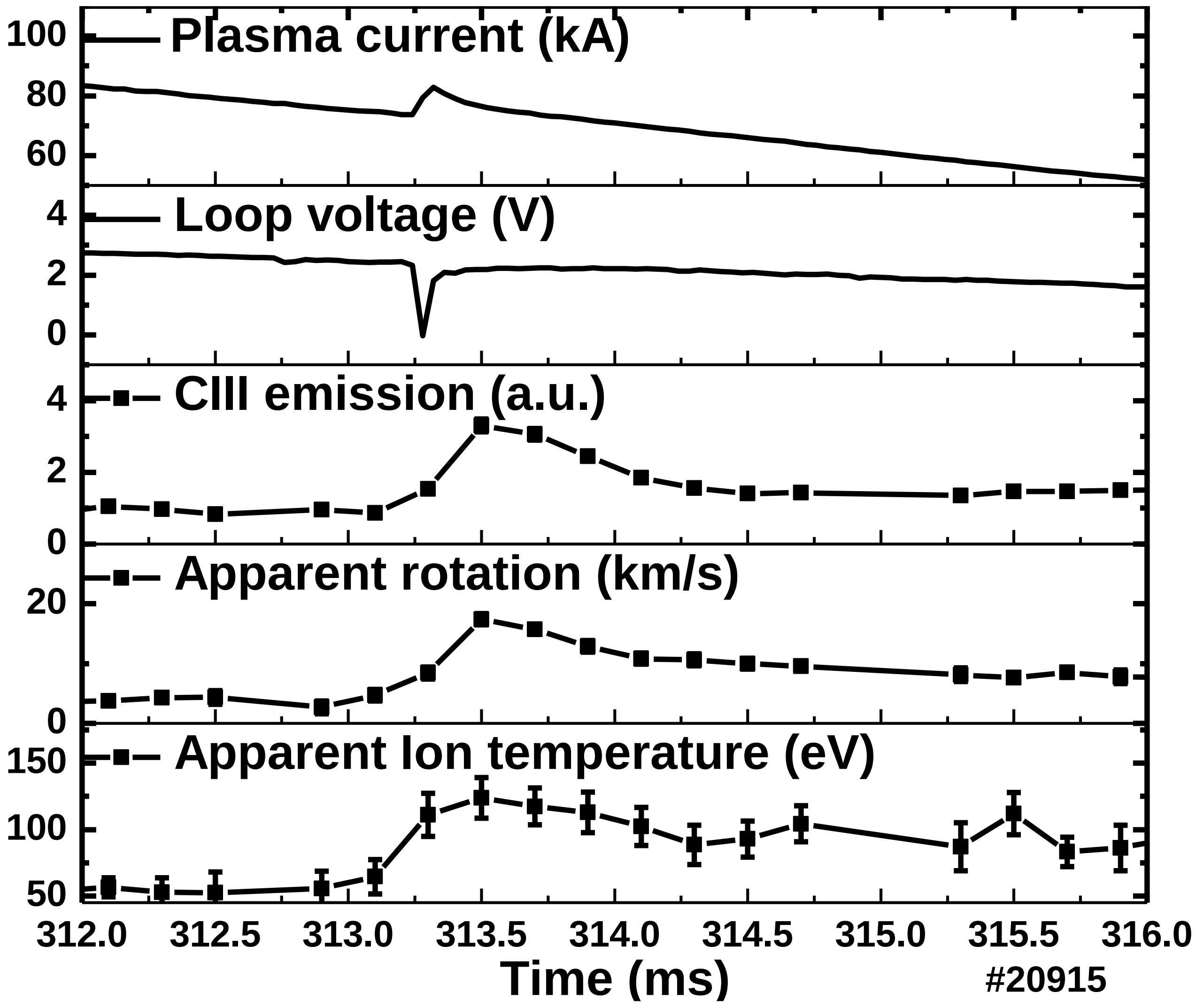


- **After the sawtooth activities, several IRE bursts are observed in I_P, Hα and magnetic signals**
- **IRE looks like…**
  - ➢ **Mode coupling between one internal mode (sawtooth) and the other internal mode (or external mode)**

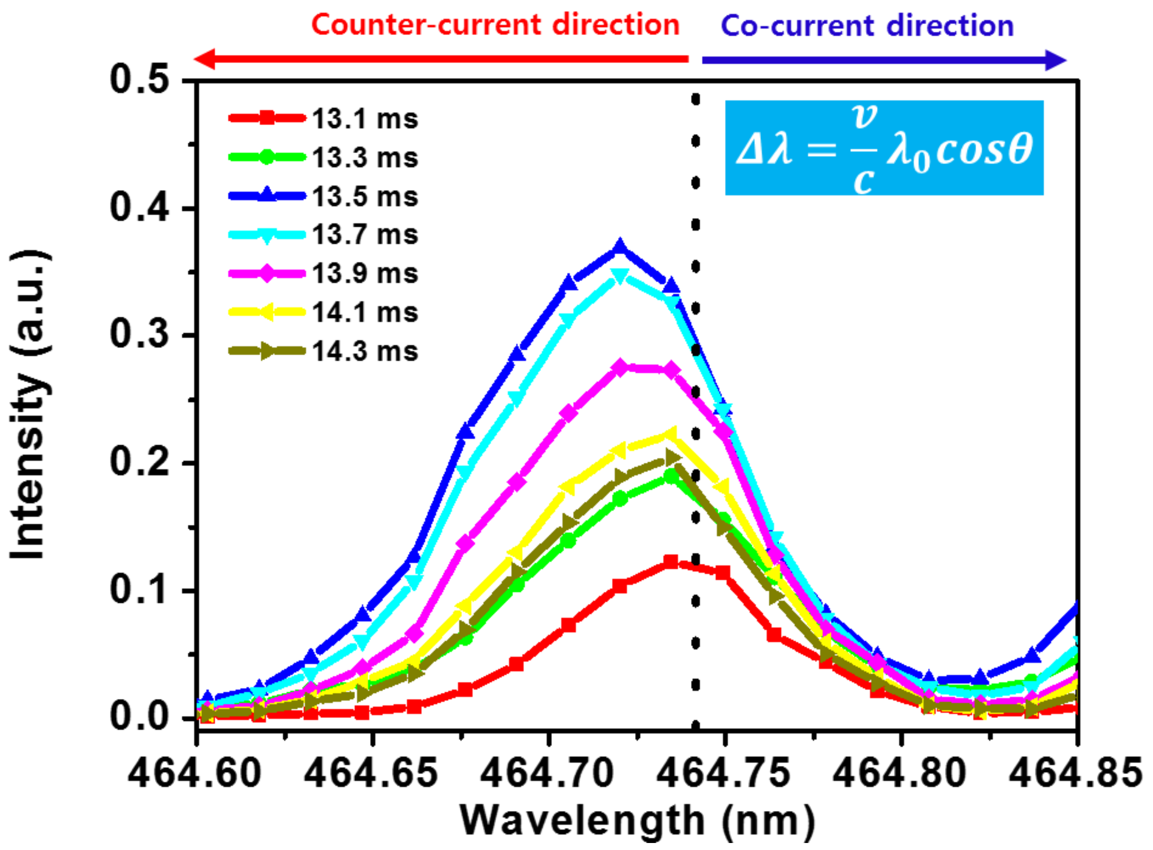
→ need further study including mode identification!

Rotation Acceleration as well as Ion Heating with IRE

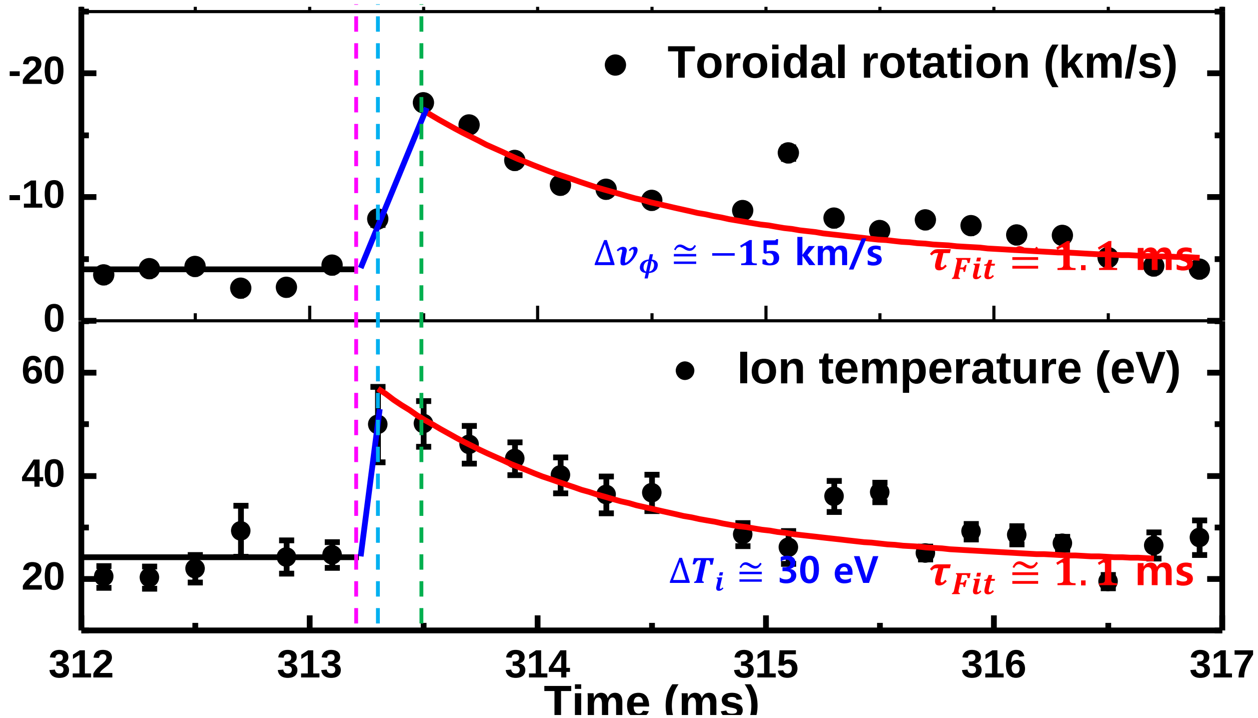
Y.S. Kim

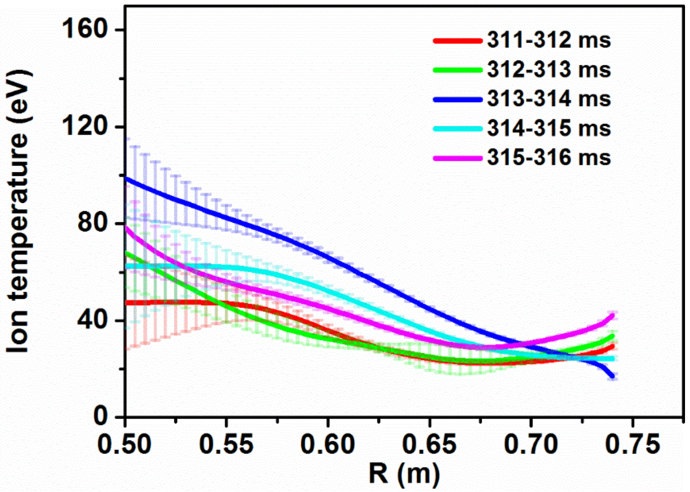


Accelerated rotation in counter-Ip direction after strong ion heating during an IRE

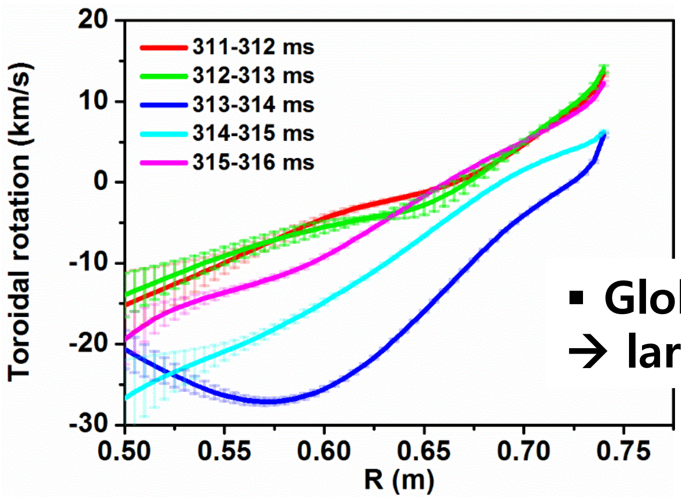


Global Rotation Acceleration as well as Ion Heating with IRE





Y.S. Kim



MHD crash
→ Prompt ion heating
→ (relatively) slow rotation acceleration

Sequence discrepancy
→ Inconsistent with reconnection outflow mechanism
→ different drive mechanism?

- Global profile change
→ large scale MHD activity

Neoclassical toroidal viscosity (NTV) torque from the fluctuating magnetic field

NTV Torque from the Fluctuating Magnetic Field

Y.S. Kim

- In the presence of non-axis symmetric magnetic perturbation, neoclassical transport theory predict the NTV torque [1-3]
- MHD activity → strong magnetic perturbation
- Offset rotation is counter-I_P direction
- NTV torque can accelerate plasma rotation to offset velocity

- Similarity with experimental observation
  - Rotation in counter-I_P direction
  - Relation with magnetic fluctuation

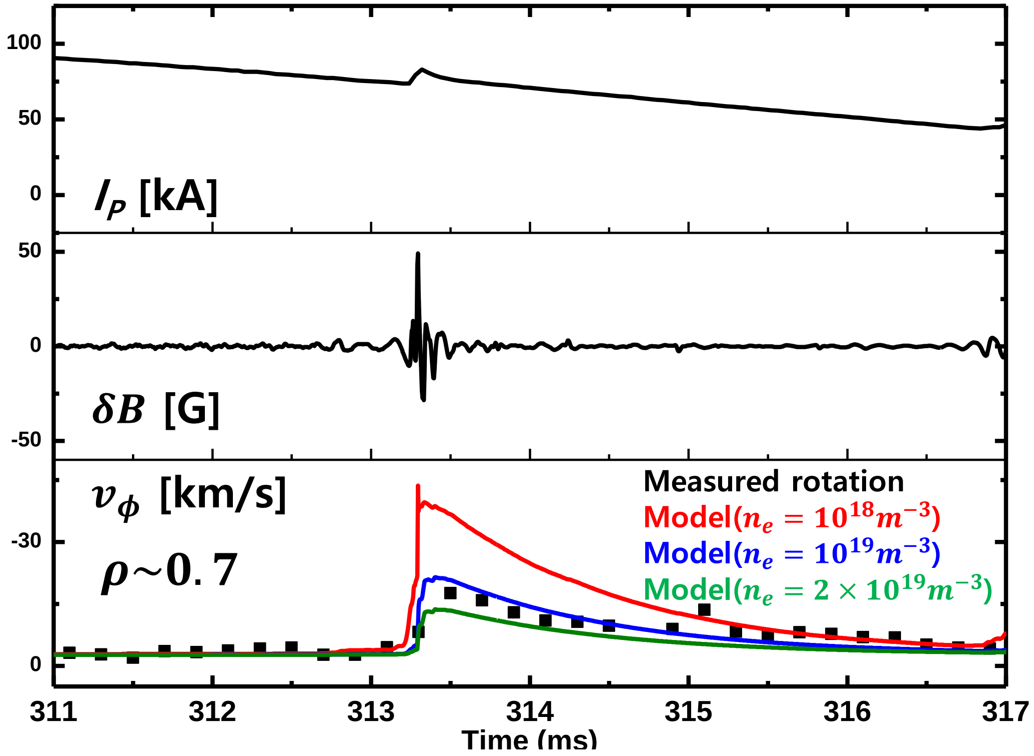
❖ Simple 0D momentum balance equation

$$m_i n_i R \frac{d\Delta v_\phi}{dt} = S_{NTV} - \frac{m_i n_i R \Delta v_\phi}{\tau_M}$$

where $S_{NTV}[4] \cong 6.1 n_i m_i v_{ti}^2 \frac{\epsilon^{\frac{3}{2}}}{v_i R} (\delta B/B)^2 (v_\phi - v_{\phi,NTV})$

$|\delta B|[5] \cong \frac{1}{2}\left(\frac{b}{r}\right)^{m+1} |\delta B_z|_{wall}$

$v_{\phi,NTV} = -40 km/s,$

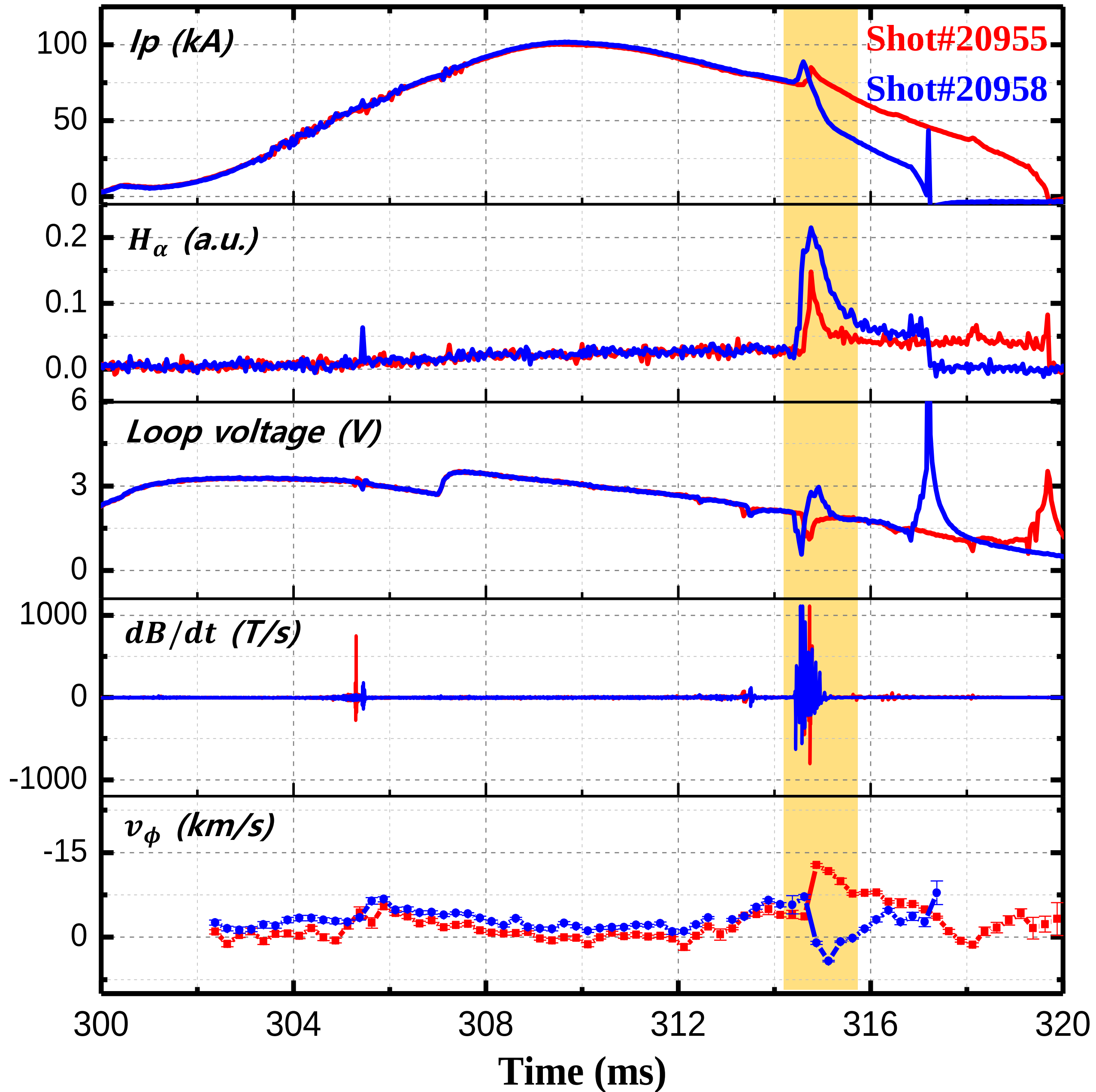


NTV torque by magnetic is reasonably agreement with experimental observation

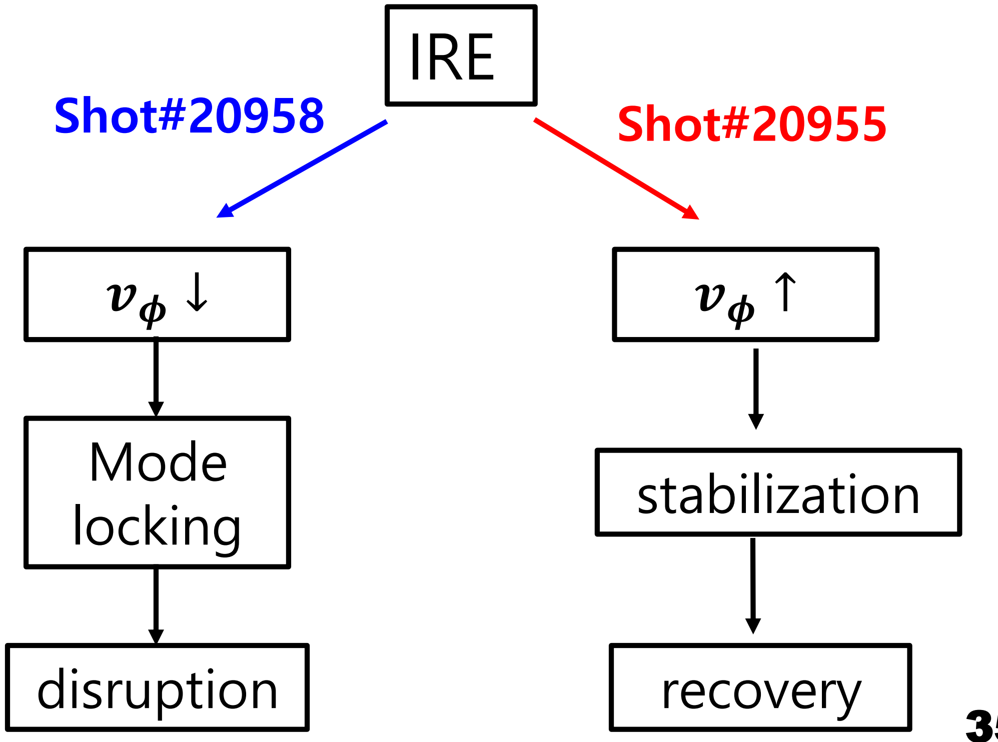
[1] A.J. Cole, C. C. Hegna, and J. D. Callen, *Phys. Plasmas* 15 056102 (2008)
[2] J.D. Callen, *Nucl. Fusion* 51 094026 (2011)
[3] A.M. Garofalo et al., *Phys. Rev. Lett* 101 195005 (2008)
[4] J. Seol et al., Phys. Rev. Lett. 109 195003 (2012)
[5] R. J. La Haye et al., Phys. Plasmas 7 3349 (2000)

Two Different IREs with Opposite Rotational Kick

Y.S. Kim



- Discharges with the same operating conditions
  - Shot#20955: Recovery
  - Shot#20958: Termination (disruptive)
- Before the IRE activity, discharge characteristics are almost same in both cases
- However, different behaviors after the IRE



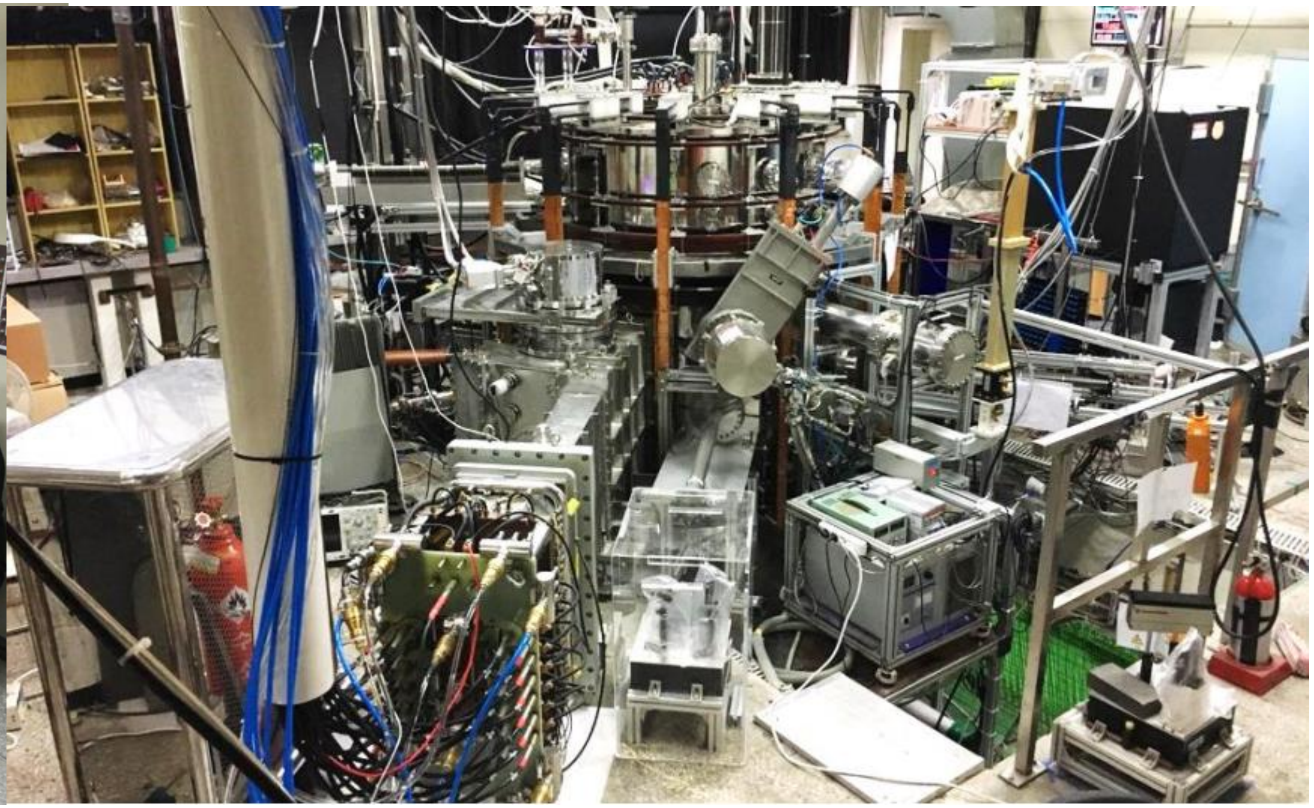
Long-term Research Plans

- **Reactor-relevant Advance Tokamak research**
  - ➢ **AT scenario for high beta and steady-state operation**
  - ➢ **Disruption mechanism and control**
  - ➢ **Energetic particle transport**
  - ➢ **Innovative divertor to handle long-pulse high-performance operation**
  - ➢ **…**

Summary

- **Ohmic operation with I_P < 170 kA, κ < 2 and q_{95} < 5 achieved**
  - MHD suppression and diverted configuration at higher TF field
- **Efficient start-up with TPC (Trapped particle configuration) and MHD control**
  - Robust TPC start-up applied to KSTAR successfully
  - TM during ramp-up suppressed by low prefill gas pressure (neoclassical)
  - Lower l_i startup by tearing mode suppression
- **Preparation for the study of Advanced Tokamak with strong central heating**
  - Scenario for advanced tokamak study established
  - High power (>600 kW) NBI coupling experiments on-going
  - Various diagnostics are under preparation
- **MHD activity study during ramp-up/ramp-down**
  - IRE (Internal reconnection event) study to understand disruption
  - Rotation acceleration as well as ion heating during IRE
- **Various long-term research plans will be pursued**

Thank you for your attention !



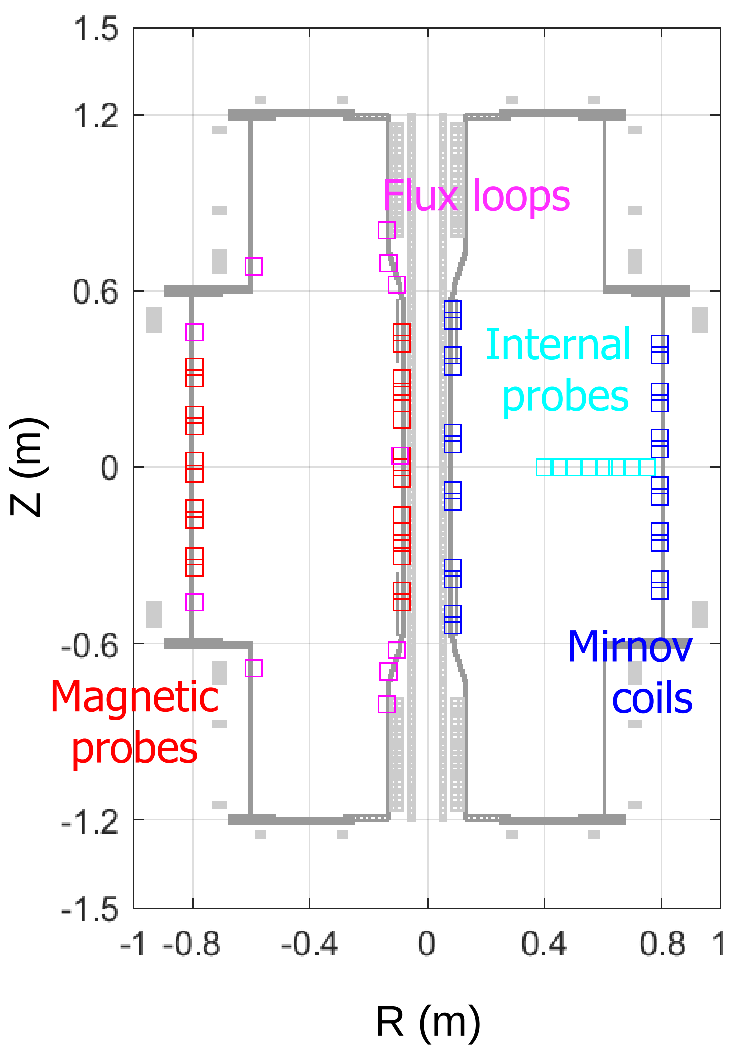
Diagnostic Systems

Diagnostic Method		Purpose	Remarks
Magnetic Diagnostics	Rogowski Coil	Plasma current & eddy current	in-vessel coils
	Pick-up Coil & Flux Loop	B_z, B_r & Loop voltage, flux	65 pick-up coils 11 loops
	Magnetic Probe Array	**B_z, B_r, MHD**	**Movable array**
Probes	Electrostatic Probe	Radial profile of T_e, n_e	Triple Probes
Optical Diagnostics	Fast CCD camera	Visible Image	20kHz
	H_α monitoring	H_α	H_α filter+ Photodiode
	Impurity monitoring	O & C lines	Spectrometer
	Thomson Scattering	**T_e, n_e profile**	**Nd:YAG laser, 1kHz**
	Imaging Fabry-Pérot Interferometer	**edge T_i**	**Multi-channel with fiber array**
	Visible Optical Spectroscopy	**Rotation and T_i**	**CES/BES with DNB**
	Interferometry	**Line averaged n_e**	**94GHz, multi-channel**
	Soft X-ray Array	**MHD**	**2-D**

Magnetic diagnostics

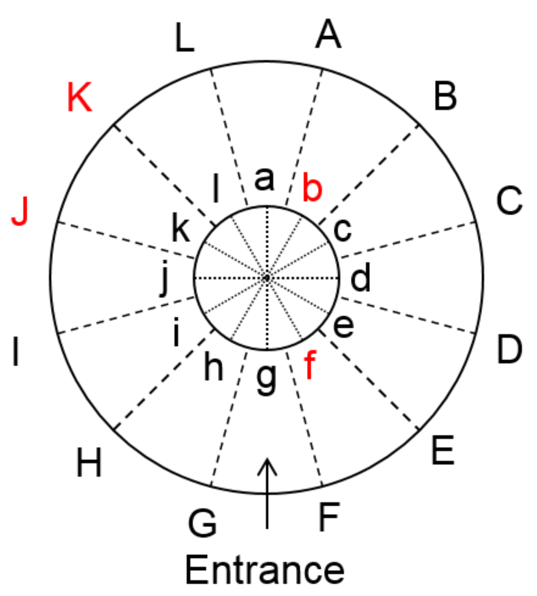
J.H. Yang

VEST magnetic diagnostics

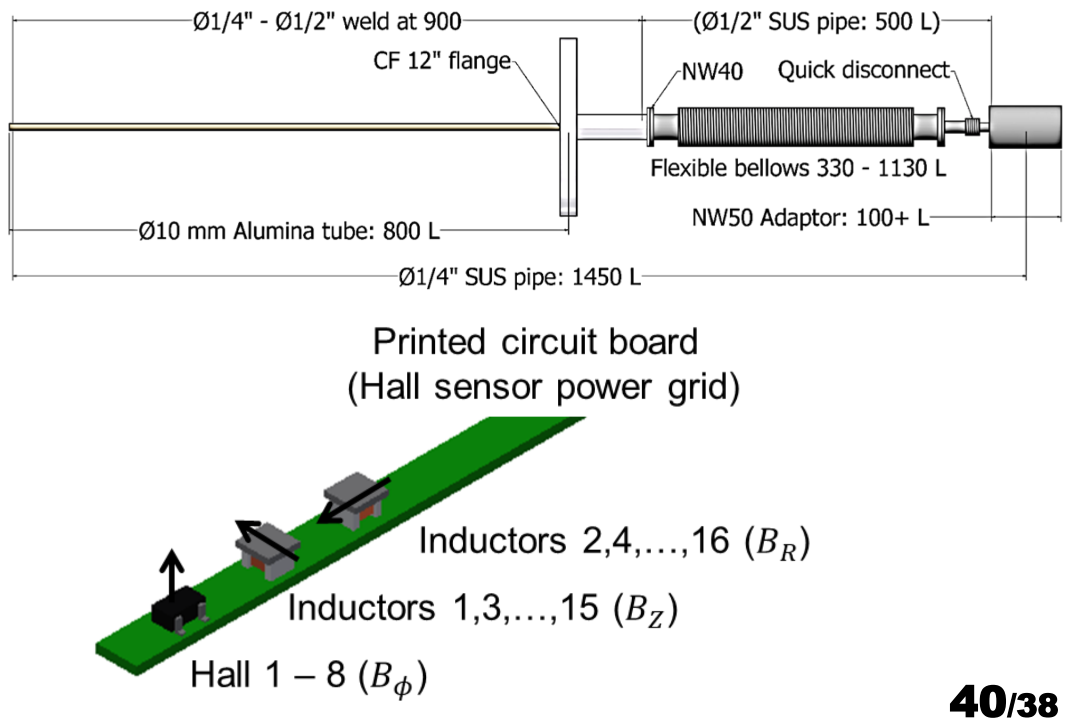


- Flux loops 11 EA
- Magnetic probes 25 EA (inboard: b, outboard: J)
- Mirnov coils 24 EA (inboard: b, outboard: J, off-plane: K)
  - Cutoff 94 kHz limited by stainless steel shield
- Internal probes 8 EA (movable R > 0.30 m, ΔR = 5 cm)
- Digitizer Sample fast: 250 kS/s, slow: 25 kS/s

VEST top view



Internal magnetic probe



* TF coils are used as a diamagnetic flux sensor for stored energy

Start-up Experiment

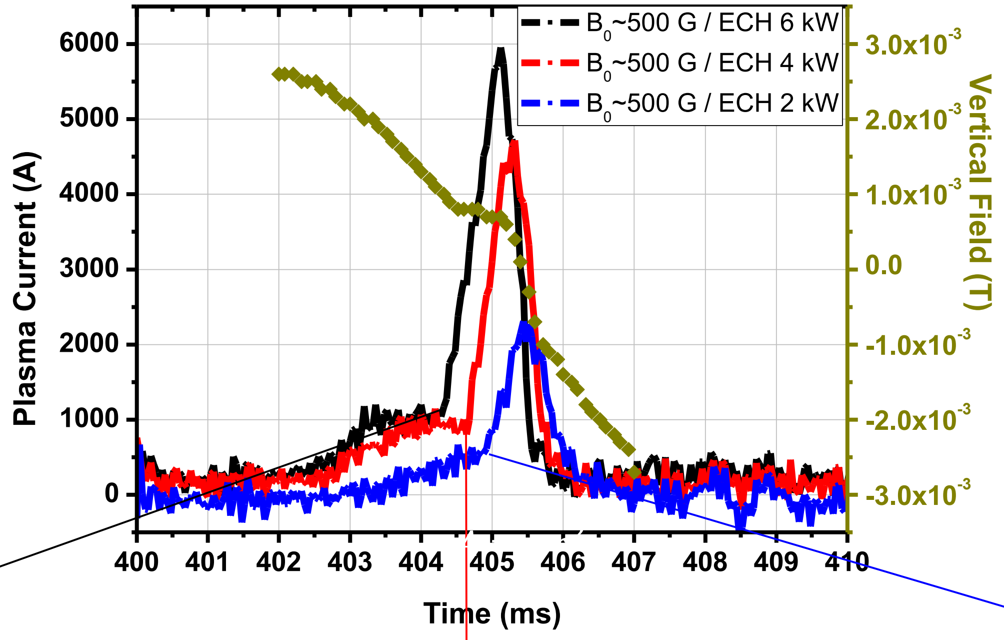
Closed Flux Surface Formation for Successful Start-up in TPC

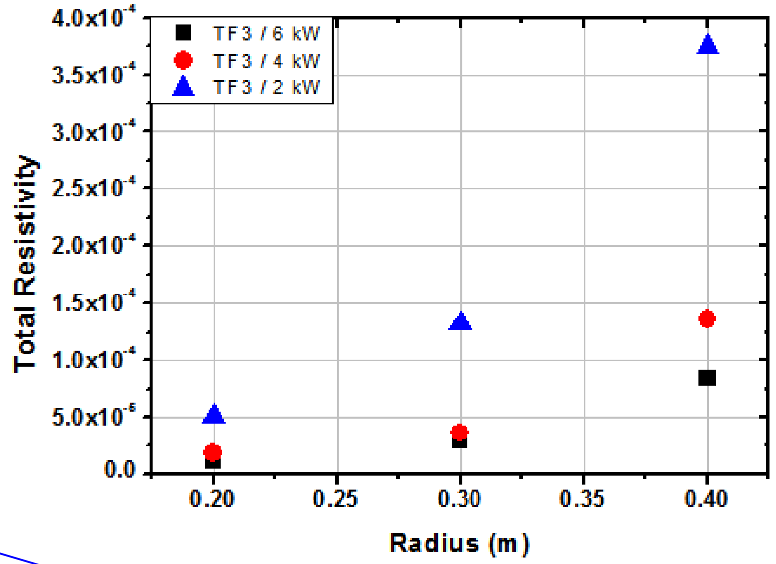
H.Y. Lee

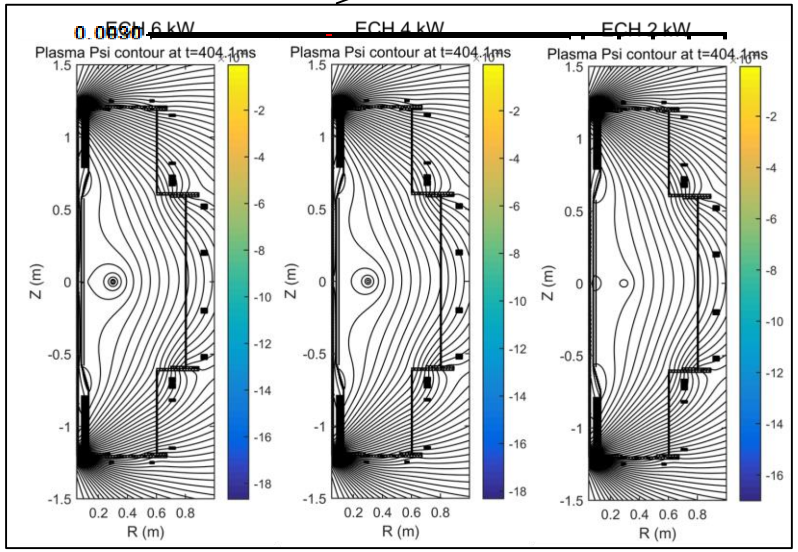
- Successful ohmic start-up at low loop voltage in TPC depends on vertical field strength, loop voltage, and plasma resistivity
- Close flux formation criterion decides the size of initial plasma when poloidal field from initial current exceeds vertical field

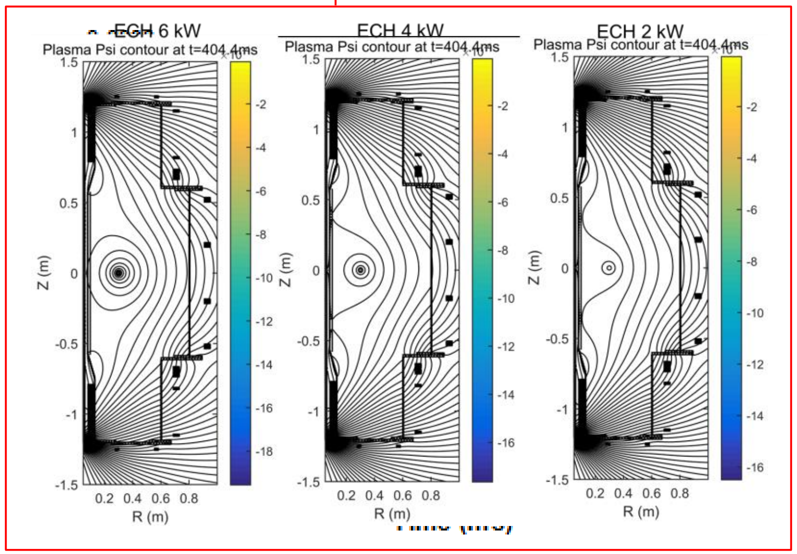
Bv (G) < Bp = 2*Ip(kA)/a(m)

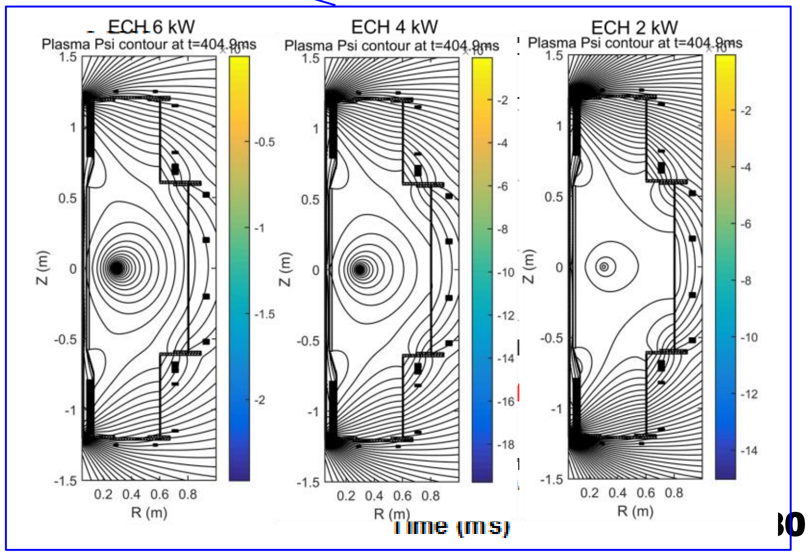
$$\frac{E_t a}{B_v \rho} > 1.6 \times 10^2 \ [\frac{V}{G\ \Omega m}]$$









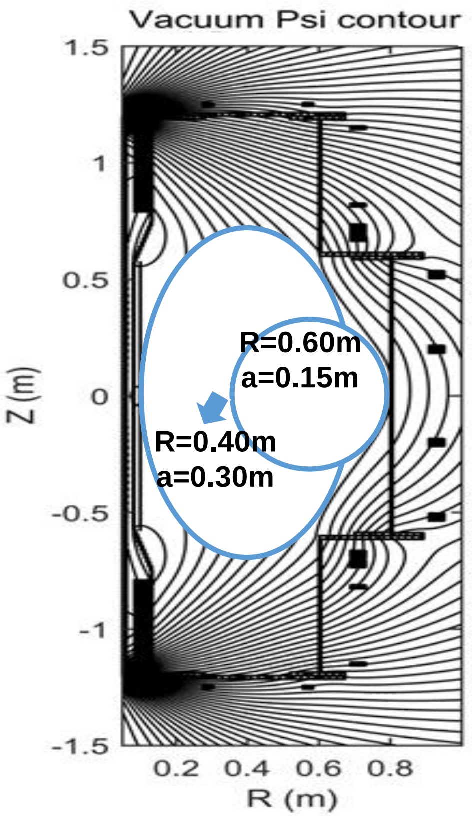


Solenoid-free Start-up from Outboard with Outer Poloidal Field Coils

Solenoid-free Startup using outer PF coils assisted by enhanced 2.45 GHz EBW pre-ionization

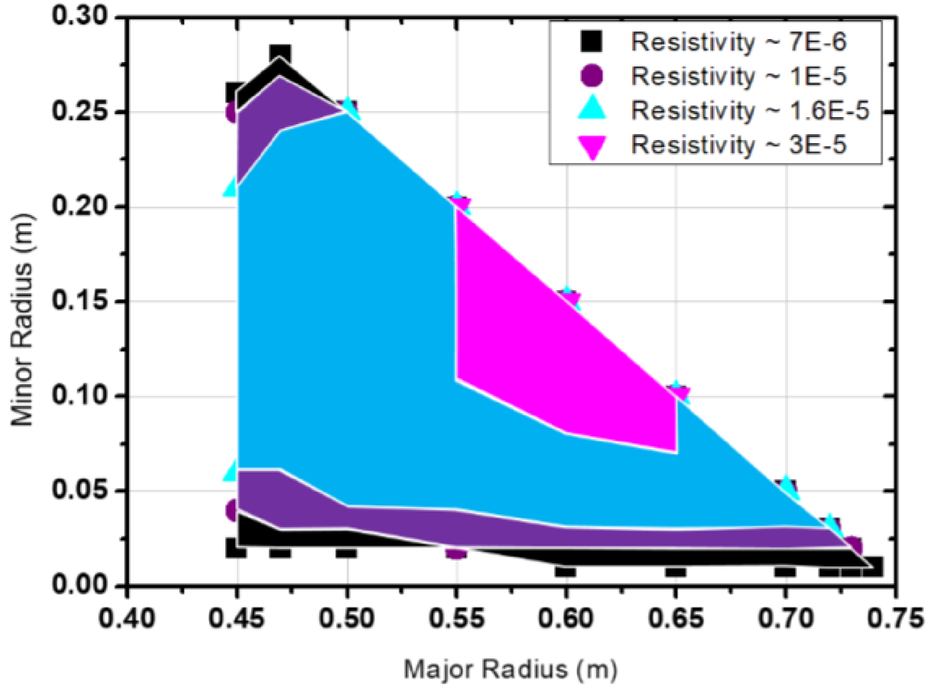
Startup criteria for Closed Flux Surface (CFS) formation

$$\boxed{\frac{E_t a}{B_v \eta} > 1.6 \times 10^2 \left[\frac{V}{G\Omega m}\right]}$$

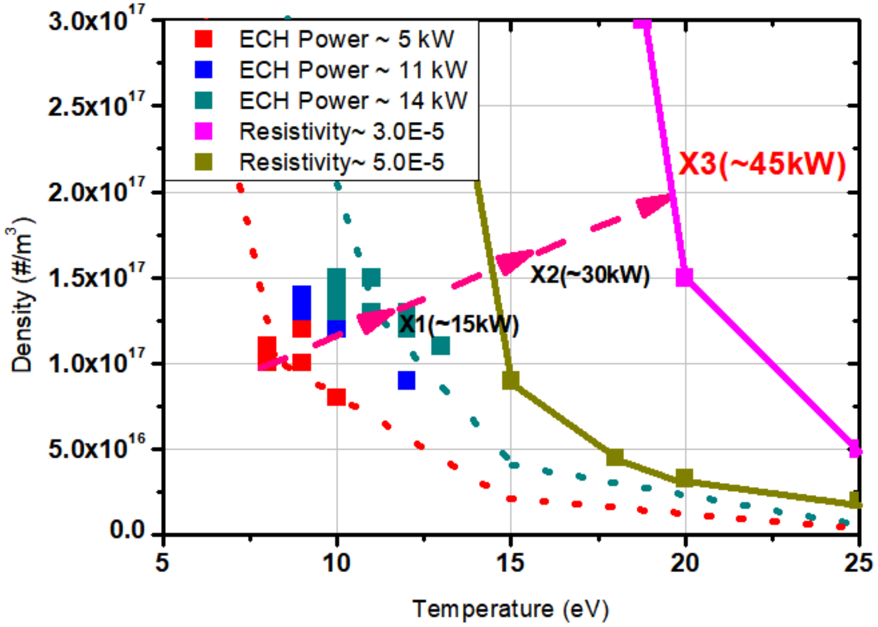


Successful outer PF Startup region of CFS location & size

$$L\frac{dI_p}{dt} = V_l - I_p\left(\frac{dL}{dt} + R_p\right) > 0$$



Lowering plasma resistivity by optimizing EBW pre-ionization



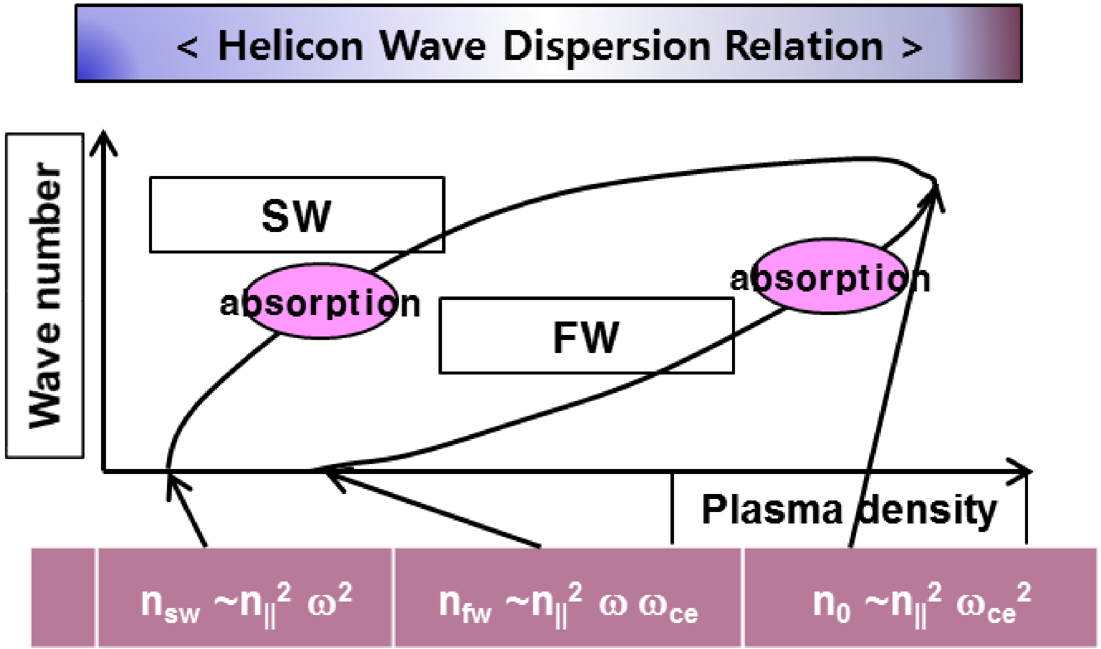
$$\frac{dR_o}{dt} < 0 \rightarrow \frac{dL}{dt} < 0$$

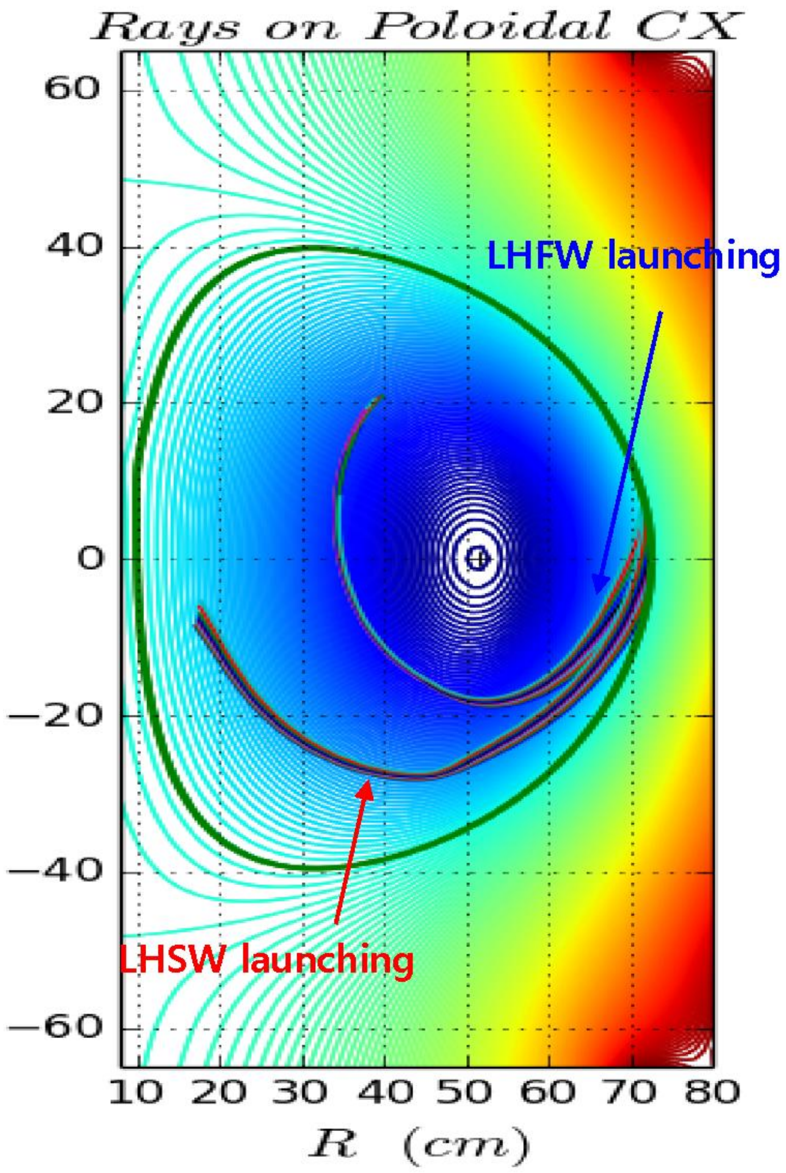
$$L = \mu_o R_o \left(\ln\frac{8R_o}{a} + \frac{l_i}{2} - 2\right)$$

- **To reach target resistivity, higher ECH power of ~45kW may be needed to have sufficient density and temperature in the pre-ionization phase.**
- **Required ECH power will be reduced by optimizing EBW pre-ionization**

Current density profile control

Core Heating and Current Drive with LHFW





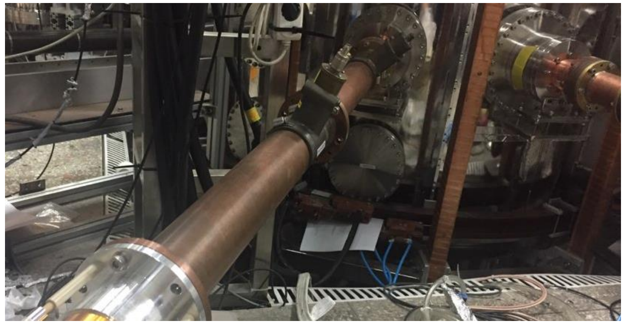
- **For high density plasma in fusion reactor**
  - Slow wave branch of LHW
    → Absorbed at the edge region
  - **Fast wave branch of LHW**
    → Possible absorption at the core region

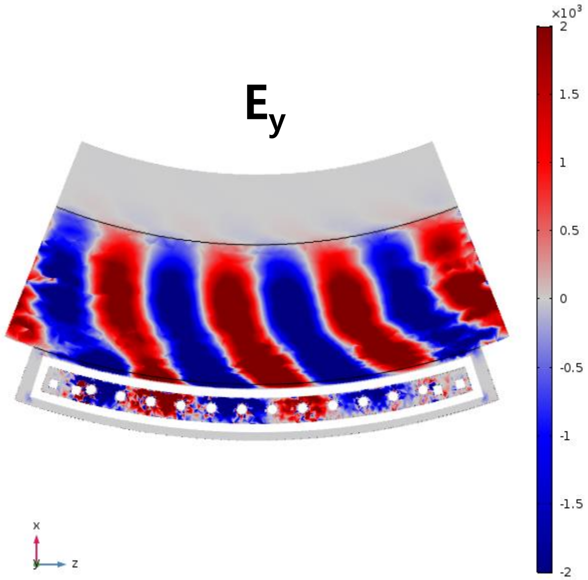
- **Proof of principle for current drive scheme by fast wave branch of LHW in VEST**

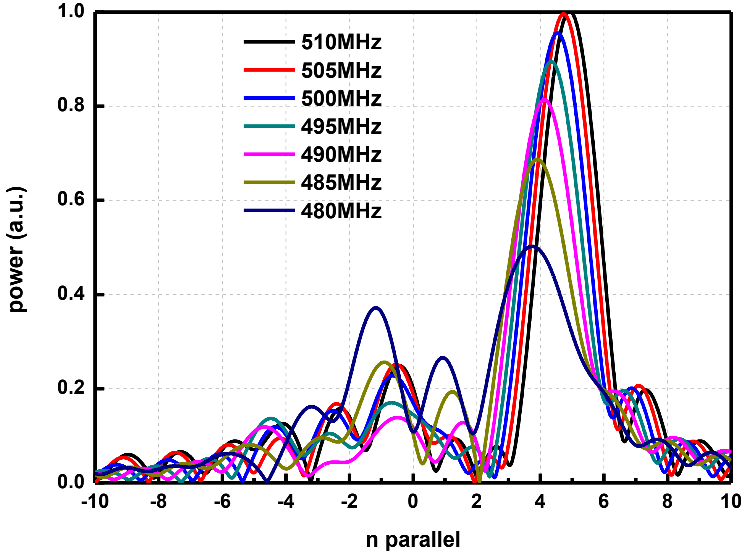
Current density profile control

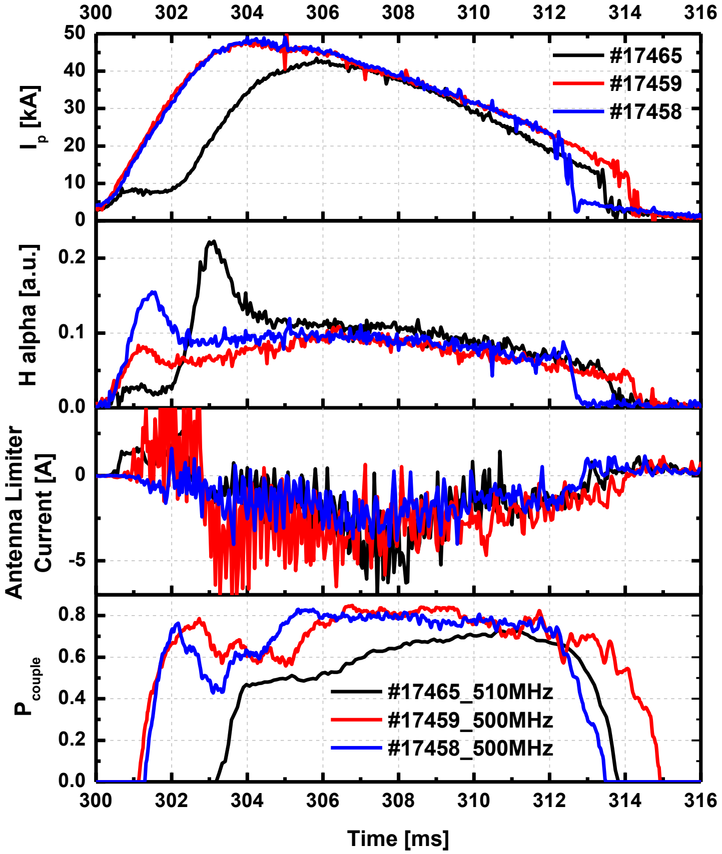
In collaboration with KAERI and Kwangwoon Univ.

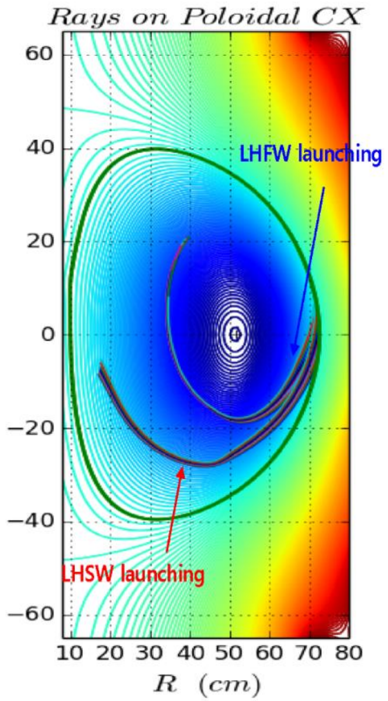
LHFW H/CD Coupling simulation and experiment











- **LH Fast Wave**
  - Good core accessibility
  - Efficient plasma coupling of combline antenna
- **Hardware**
  - UHF Klystron (10kW), Combline antenna
  - $N_{||}$ = 3-5 / 470~510 MHz

S.H. Kim/J.G. Jo

JongGab Jo *et al.*, Physics of Plasmas 25, 082511 (2018)

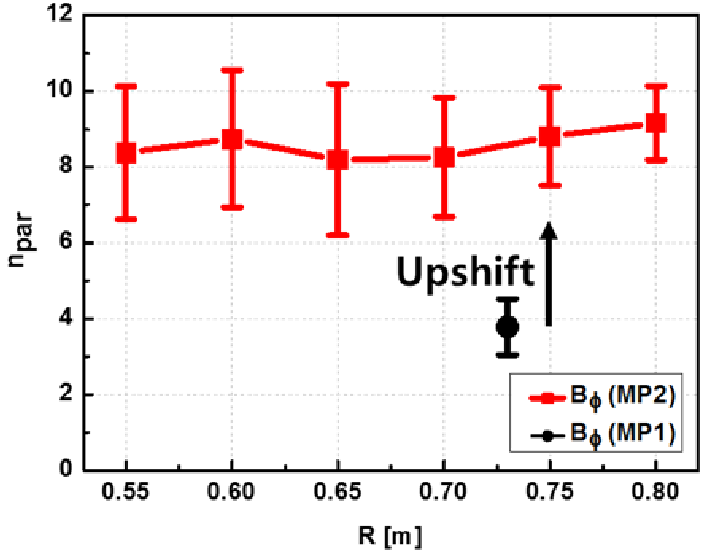
Feasibility study of LH Fast Wave (500MHz, 10kW)

In collaboration with KAERI and Kwangwoon Univ.

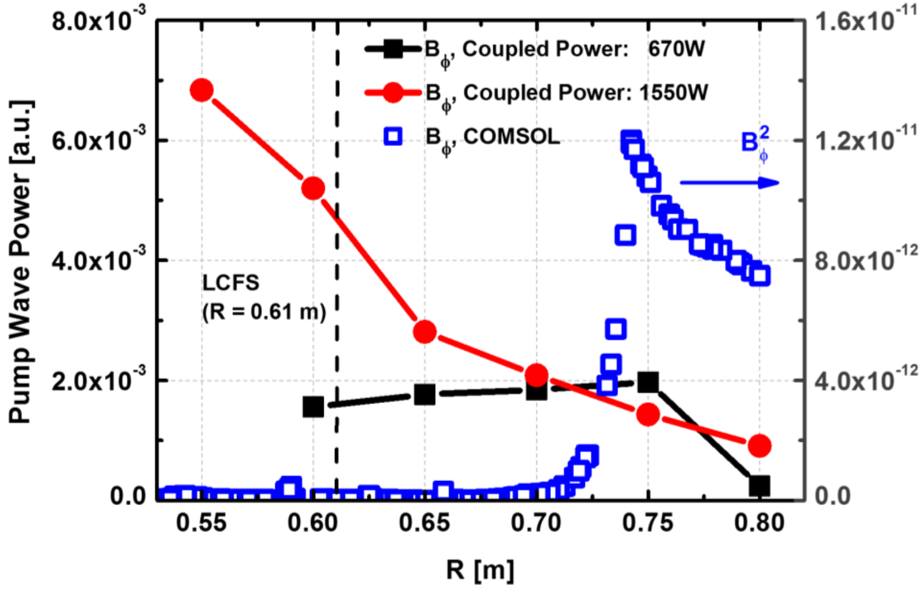
$$2\omega_{lh} < \omega \ll \omega_{ce}$$

Modified accessibility condition of LHFW by $n_{\|}$-upshift via microwave scattering

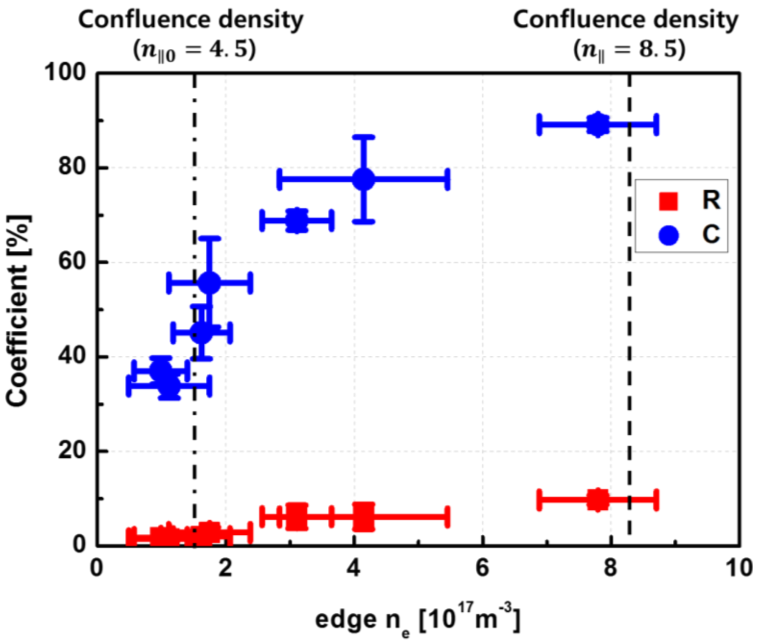
$n_{\|}$-upshift via wave scattering measured during propagation in edge region



Modification of wave propagation into more radially inward region



Expanded coupling regime in high density plasma



S.H. Kim/J.G. Jo

JongGab Jo *et al.*, Physics of Plasmas 26, 012506 (2019)