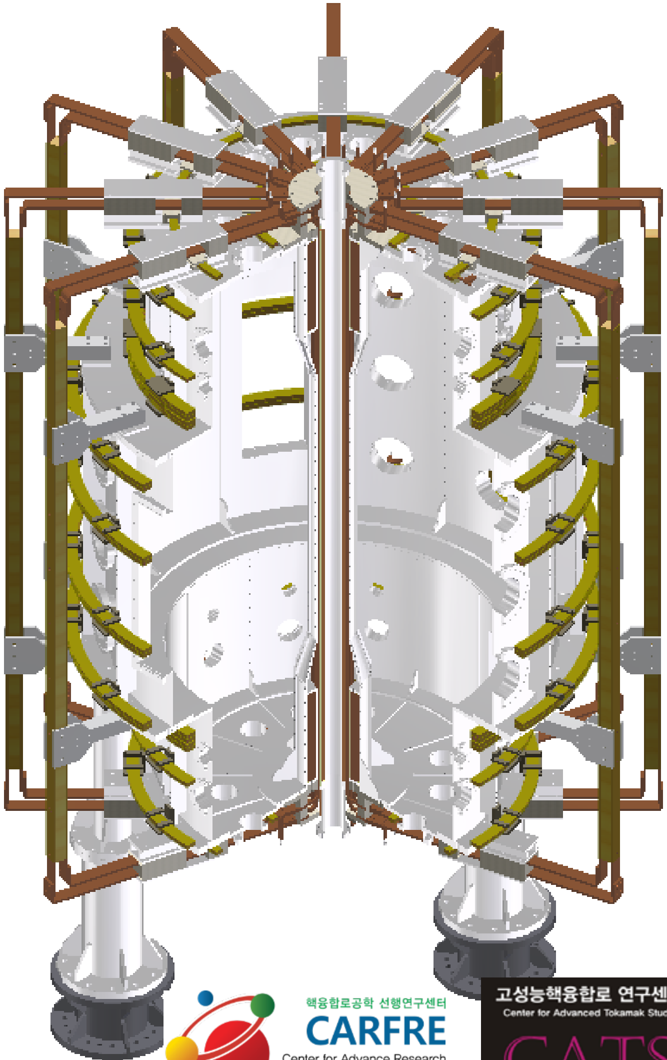
Status and Plan for VEST

Y.S. Hwang and VEST team

Nov. 6, 2015

Dept. of Nuclear Engineering
Seoul National University



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KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

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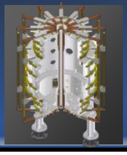
18th International Spherical Torus Workshop,
Nov. 2-6, 2015, Princeton, NJ, USA

핵융합로공학 선행연구센터 CARFRE Center for Advance Research in Fusion Reactor Engineering

고성능핵융합로 연구센터 Center for Advanced Tokamak Study CATS

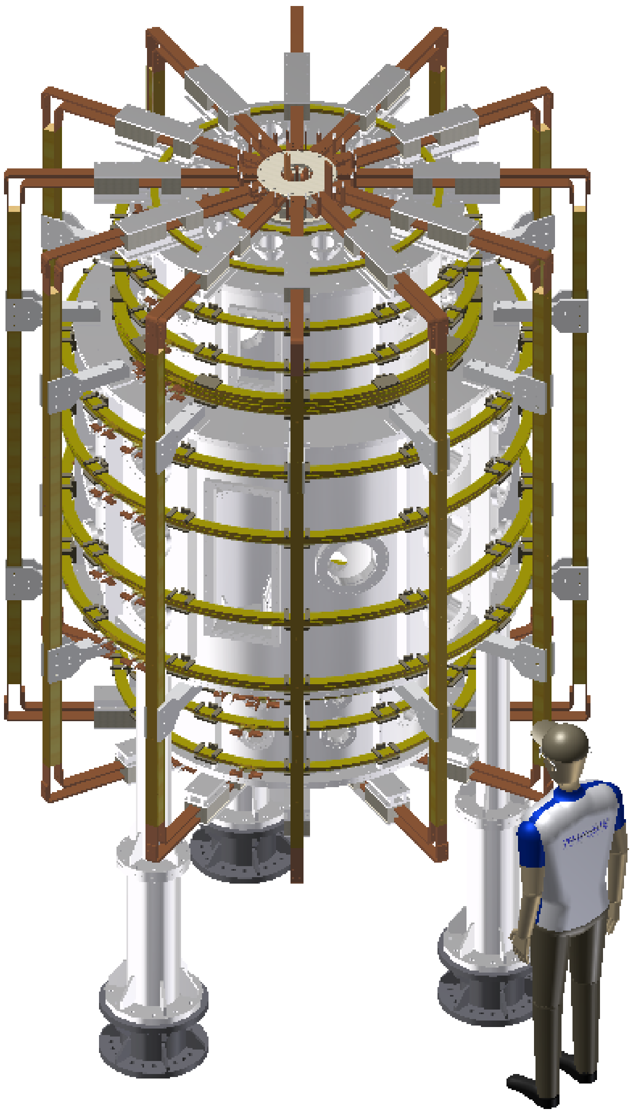
Outline

- **VEST device and Machine status**
- **Start-up experiments**
  - ECH/EBW heating as pre-ionization
  - Low loop voltage start-up using trapped particle configuration
  - DC helicity injection
- **Studies for Advanced Tokamak**
  - Research directions for high-beta and high-bootstrap STs
  - Preparation of profile diagnostics
  - Preparation for heating and current drive systems
  - Discharge performance upgrade
- **Summary**



VEST device and Machine status

VEST (Versatile Experiment Spherical Torus)



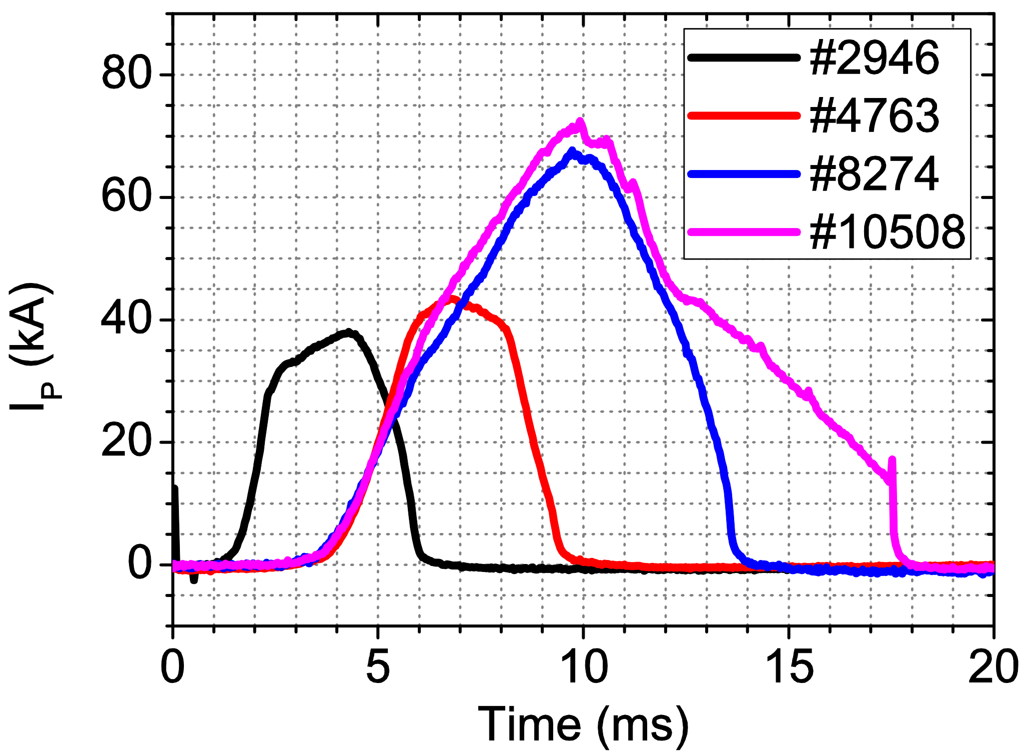
- **Objectives**
  - Basic research on a compact, high-β ST (Spherical Torus) **with elongated chamber in partial solenoid configuration**
  - Study on **innovative start-up, non-inductive H&CD, high β and innovative divertor concept, etc**

- **Specifications**

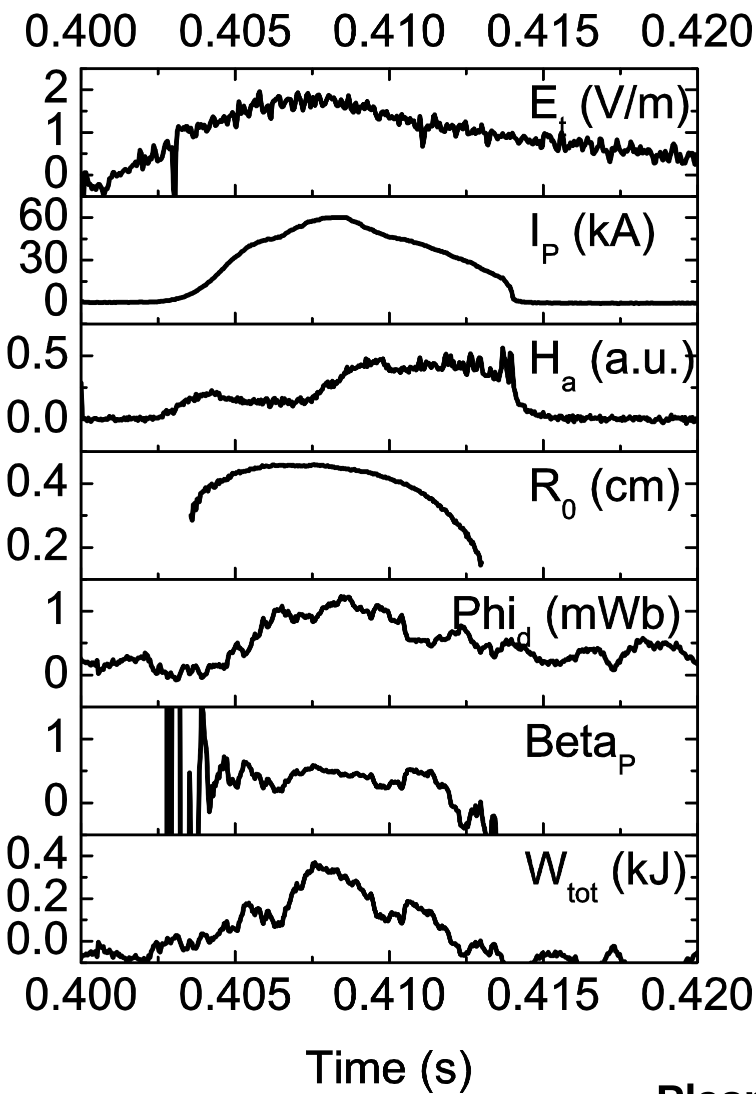
	Present	Future
Chamber Radius [m]	0.8 : Main Chamber 0.6 : Upper & Lower Chambers	
Chamber Height [m]	2.4	
Toroidal B Field [T]	**0.1**	0.3
Major Radius [m]	**0.43**	0.4
Minor Radius [m]	**0.33**	0.3
Aspect Ratio	**>1.3**	>1.3
Plasma Current [kA]	**~70 kA**	200
Elongation	**~1.6**	>2
Safety factor, q_a	**~3.5**	~4

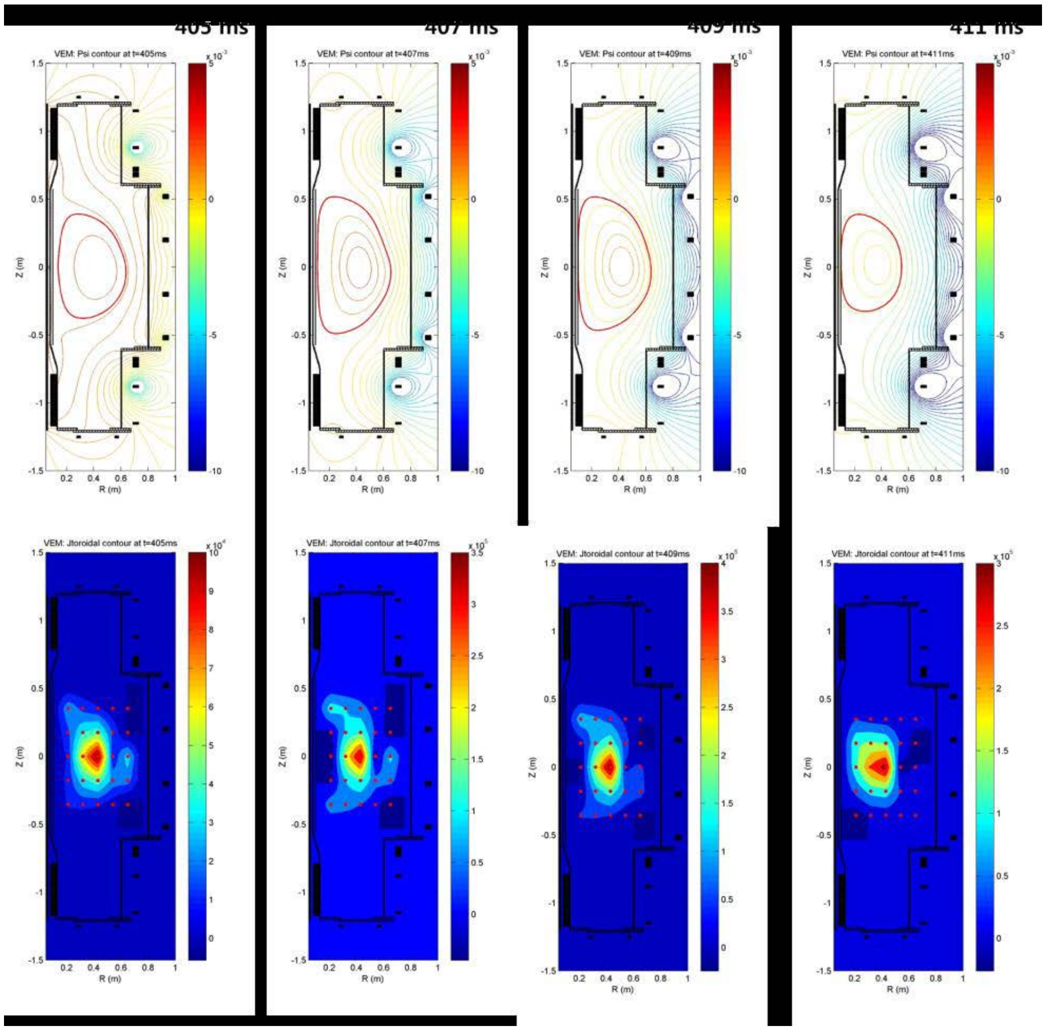
History of VEST discharges

- **First plasma: 13.1.21 [#2946]**
- **CS upgraded: 13.8.16 [#4763]**
- **Inboard W limiter: 13.10.17 [#8274]**
- **H_2 GDC: 14.11.14 [#10508]:** Maximum I_p of **~70 kA** with pulse duration of **~10 ms**
- **Inboard W limiter is covered with Graphite plate**



VEST discharge status



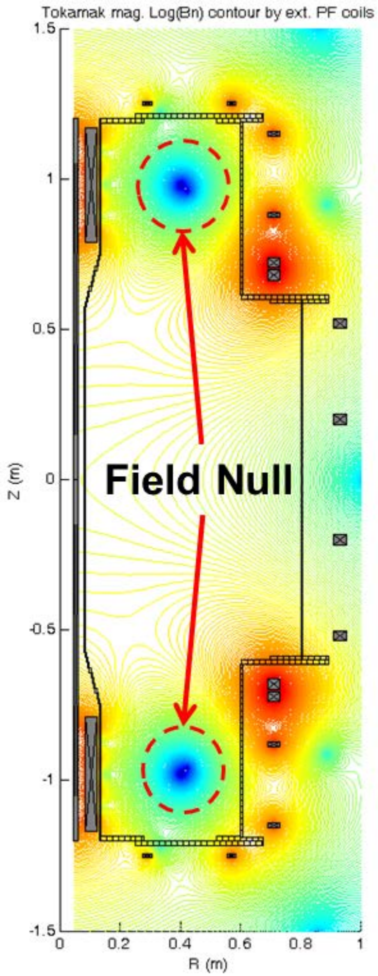


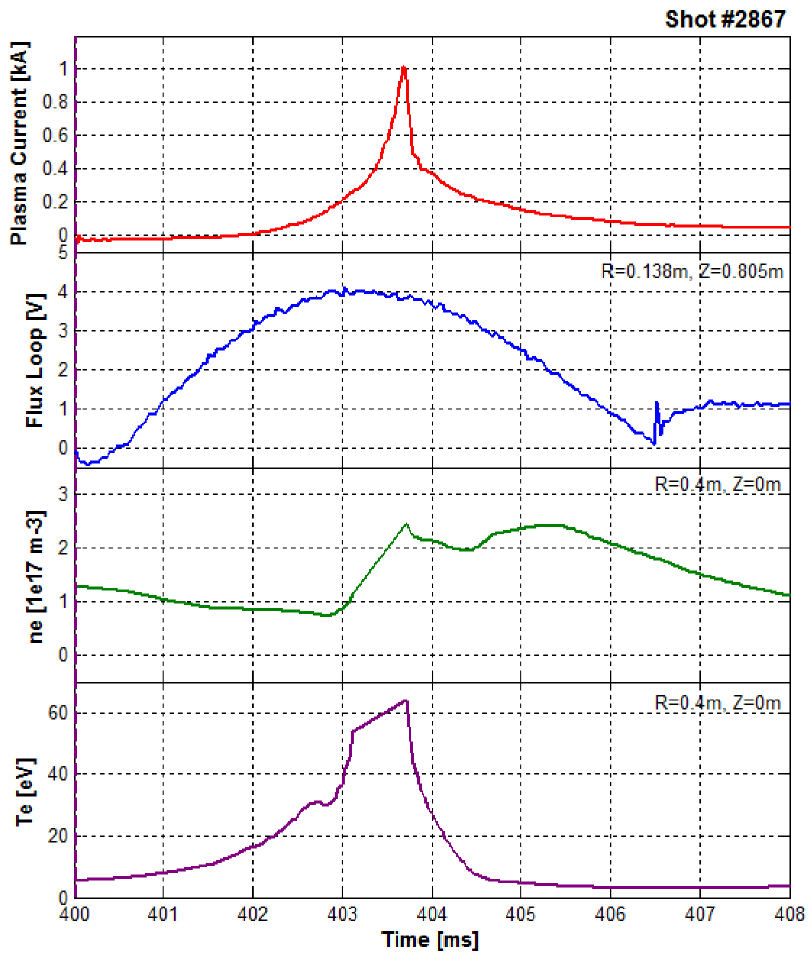
Plasma elongation κ ~1.6 with edge safety factor q_a ~ 3.7

Start-up Experiments

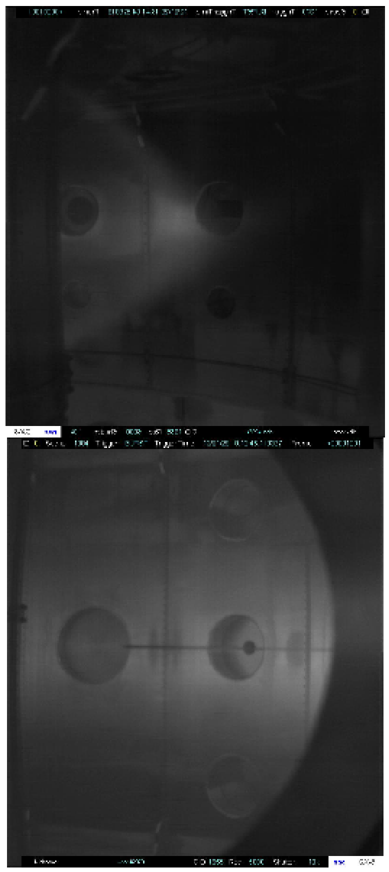
Double null merging start-up?

Double null merging start-up? Not successful !





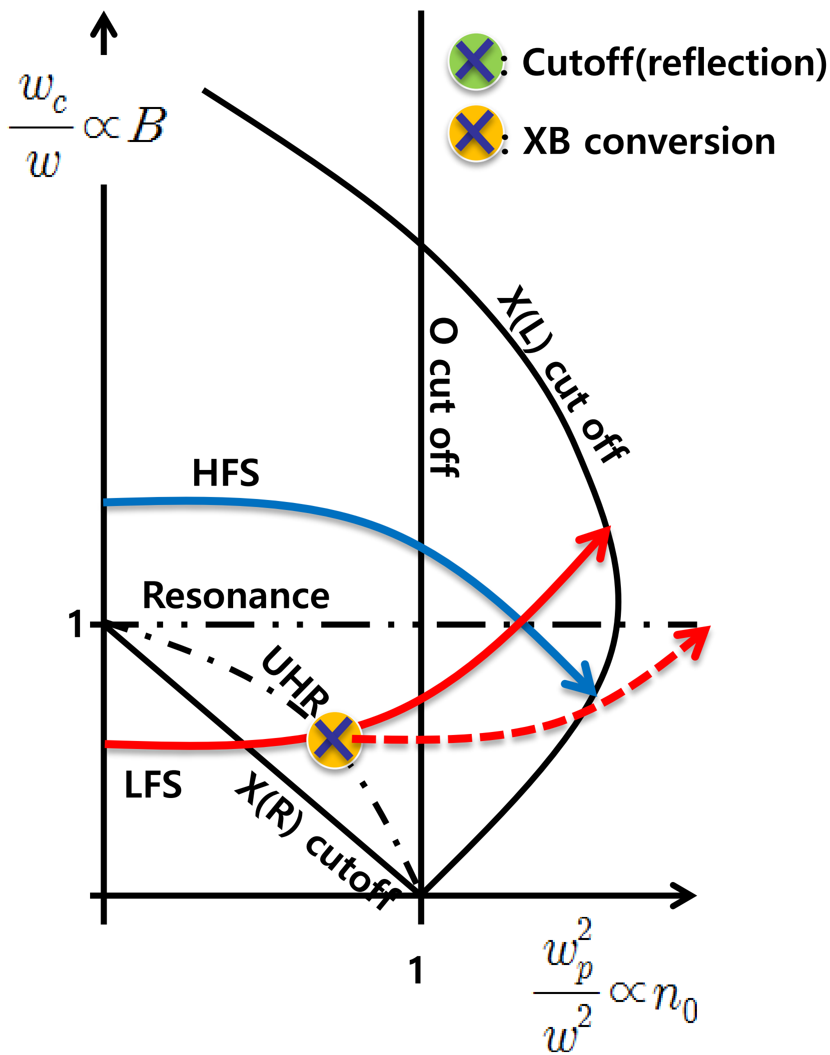
Upper Chamber (t=400ms) #2874

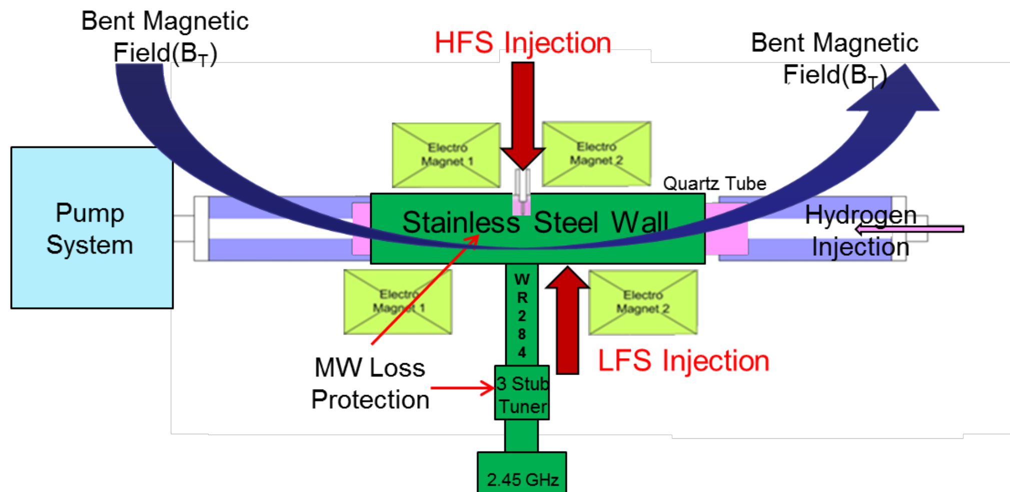


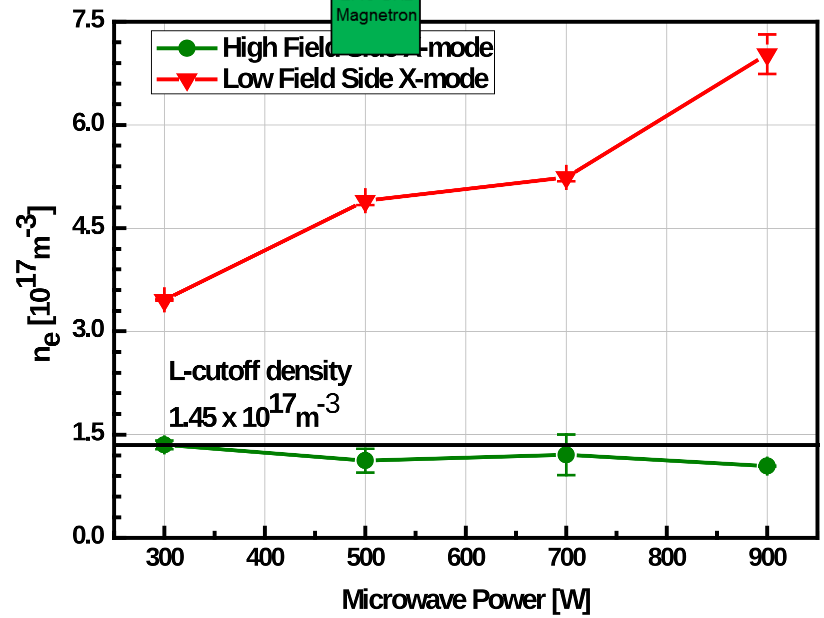
Main Chamber (t=400ms) #2879

Field null formation under severe eddy currents !

Over-dense plasmas with LFS XB mode conversion



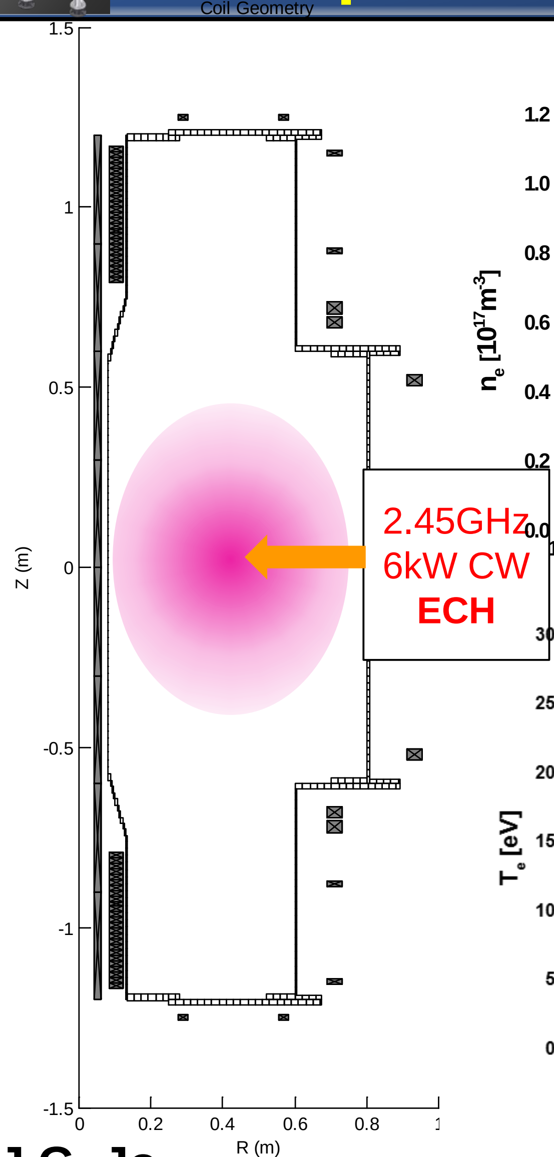


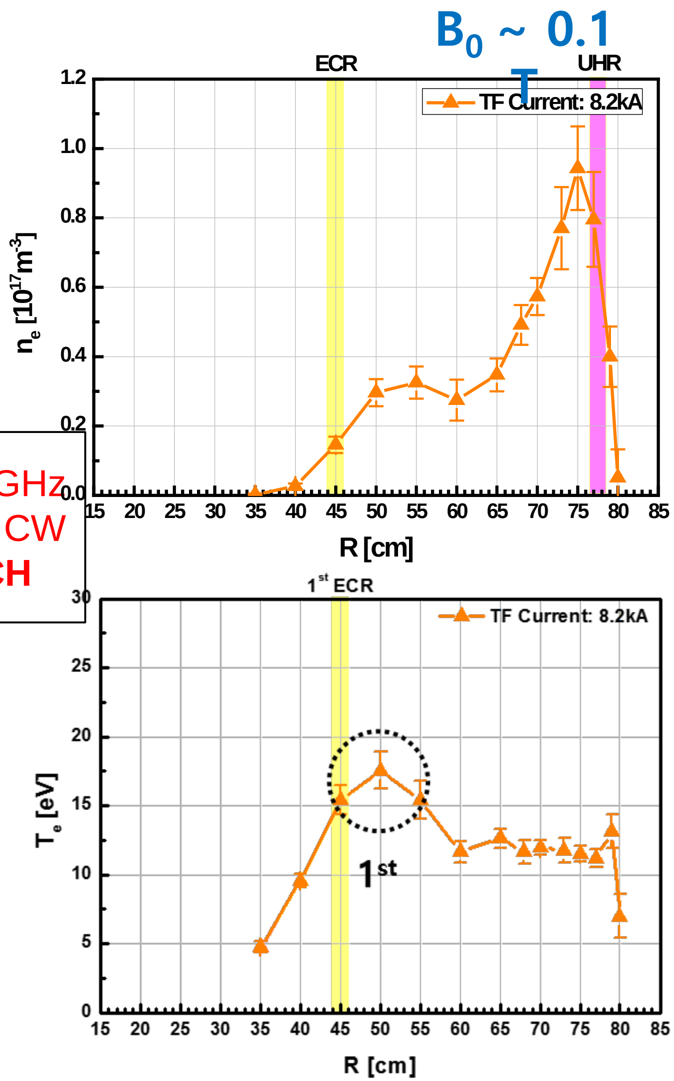


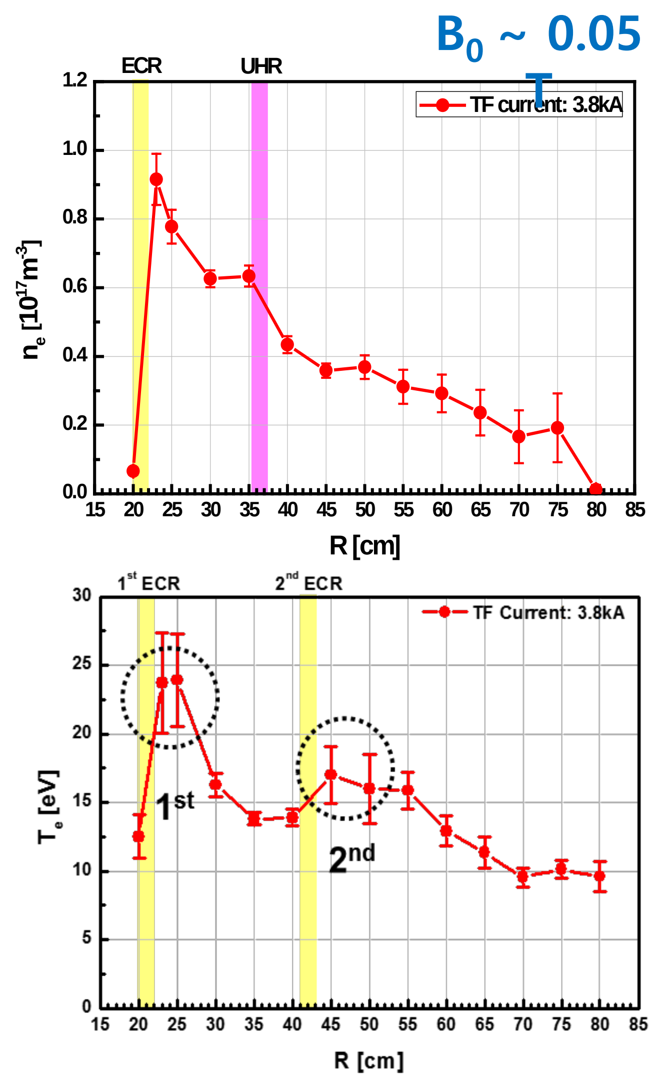
H.Y. Lee

Low field side (LFS) X mode launching is preferable !

VEST pre-ionization with LFS XB mode conversion





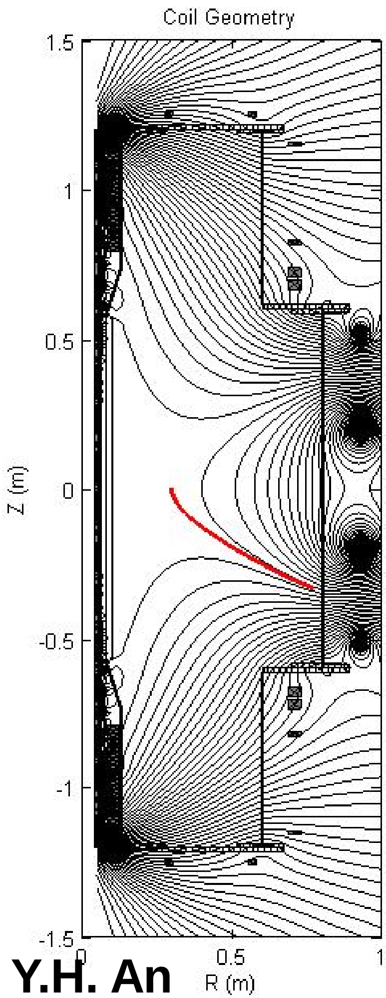


J.G. Jo

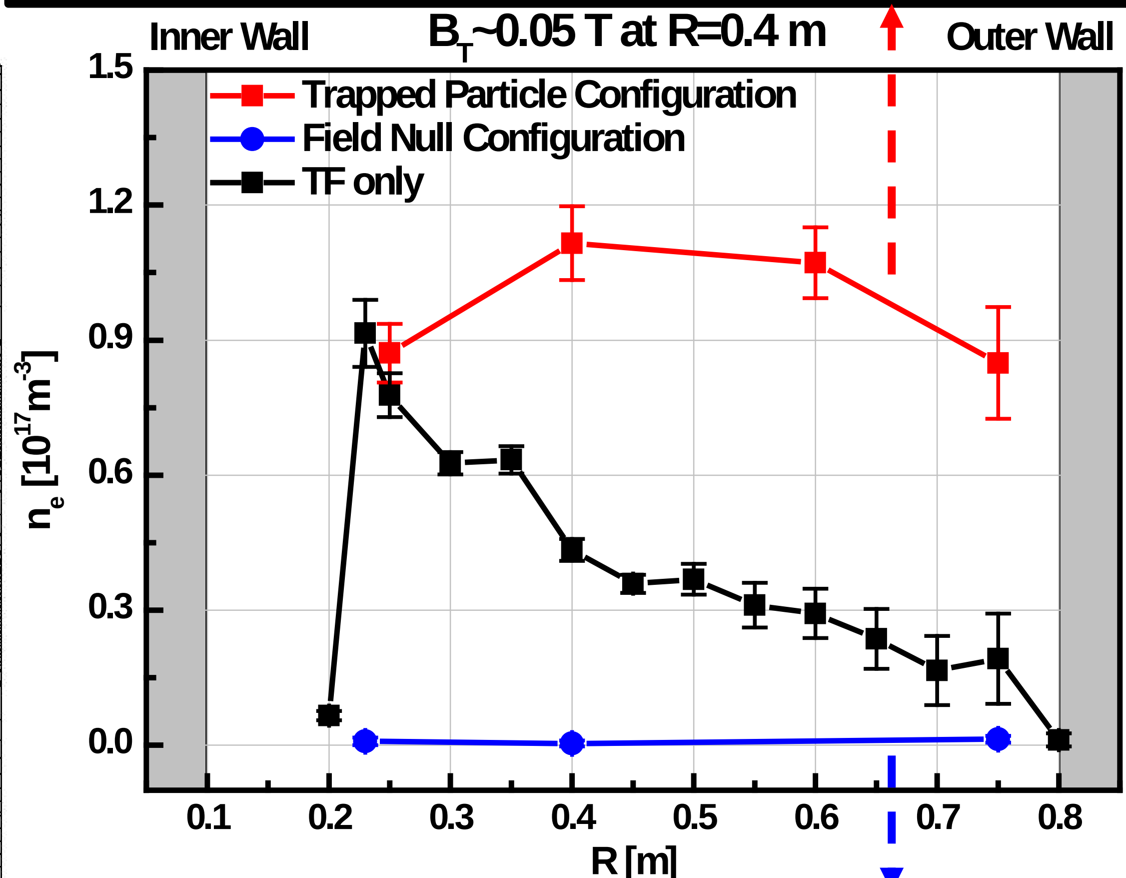
Slightly less than L cut-off density !

Enhanced pre-ionization in TPC

Field Null Configuration

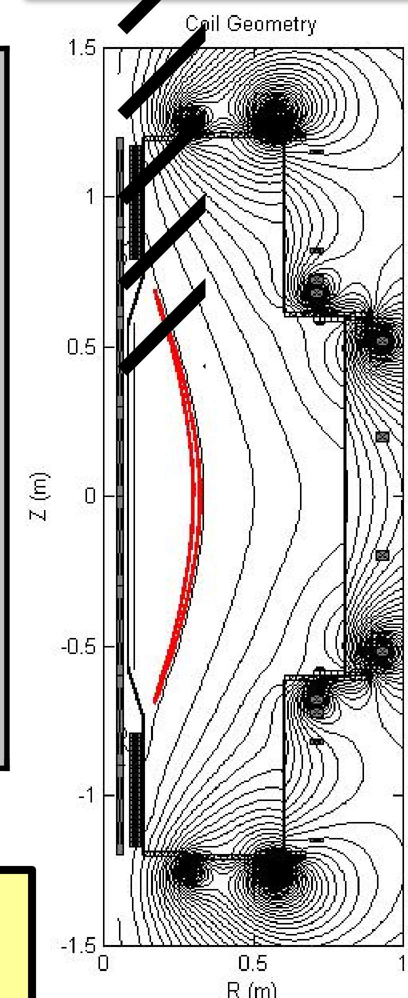


Significant enhancement of pre-ionization under TPC (Trapped Particle Configuration)

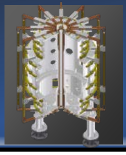


Severe degradation of pre-ionization under field null

Trapped Particle Configuration



Y.H. An

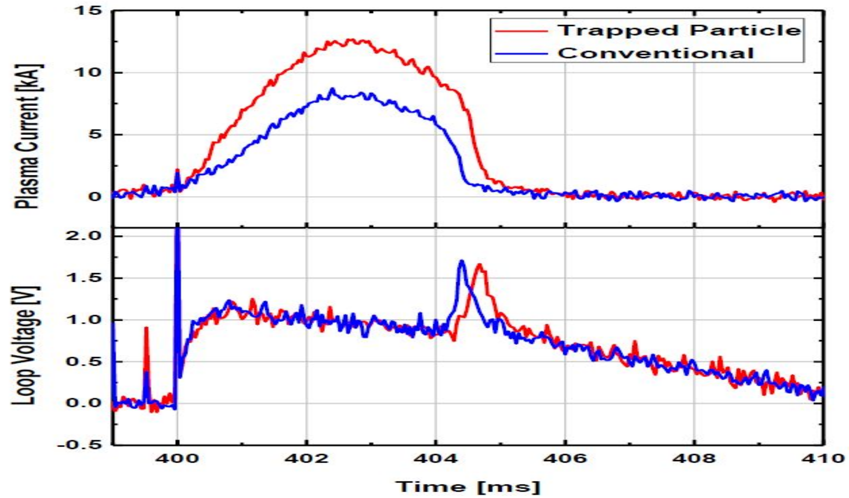


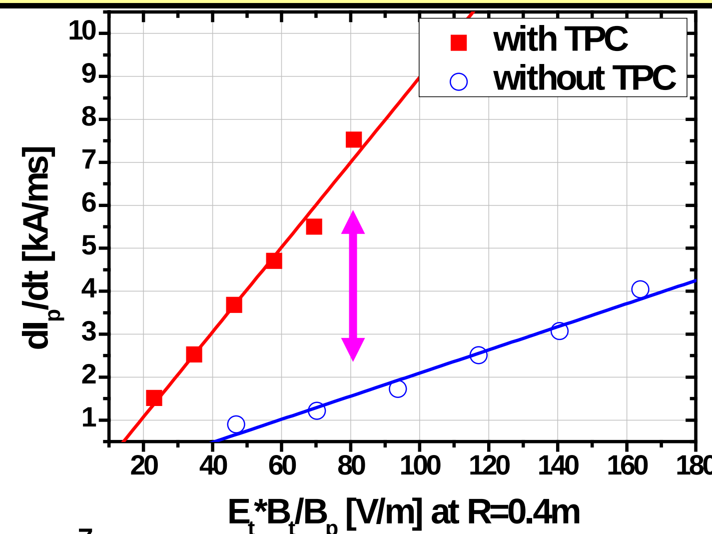
Ohmic Start-up with ECH Pre-ionization

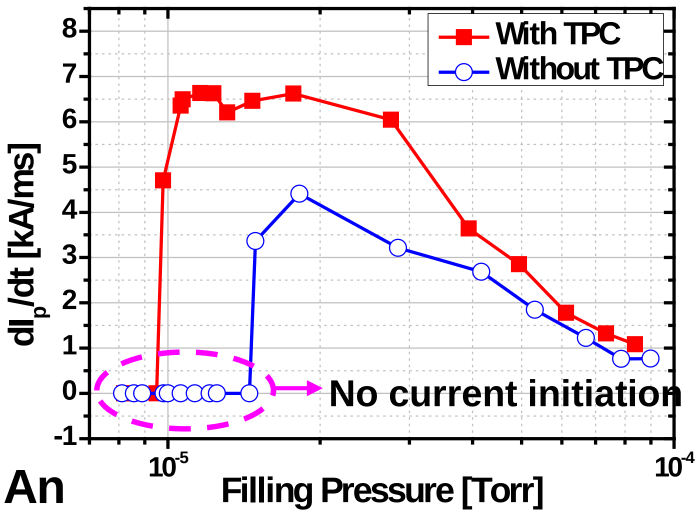
Higher dI_p/dt and Wider Operation Regimes with TPC

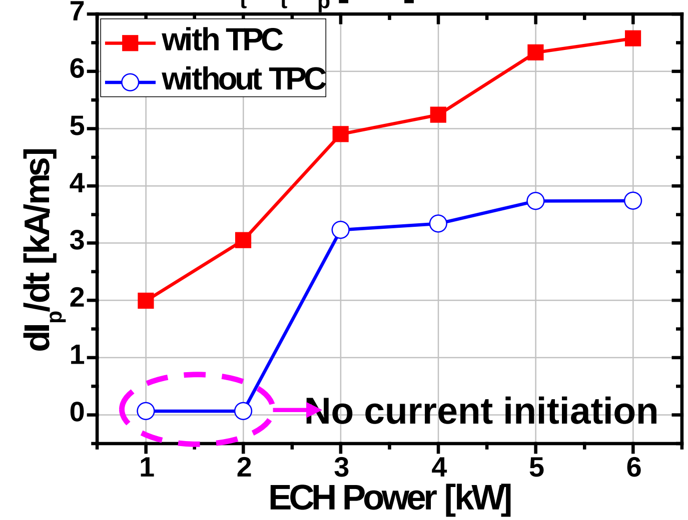
Higher dI_p/dt under TPC with identical V_{loop} and E_tB_t/B_p

Wider operating windows for gas pressure and ECH power









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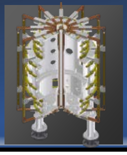
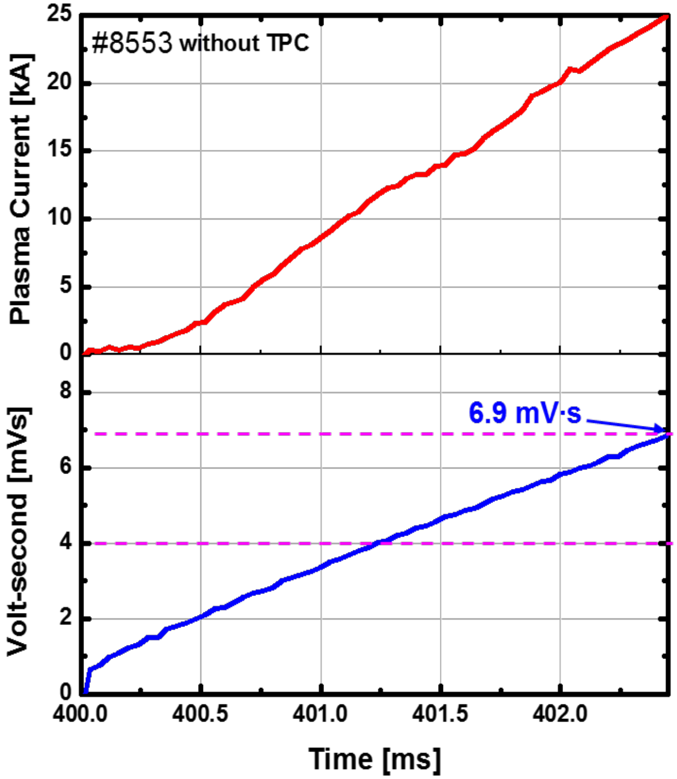
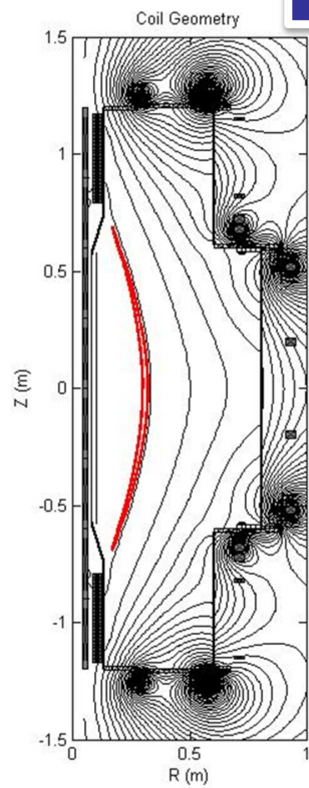


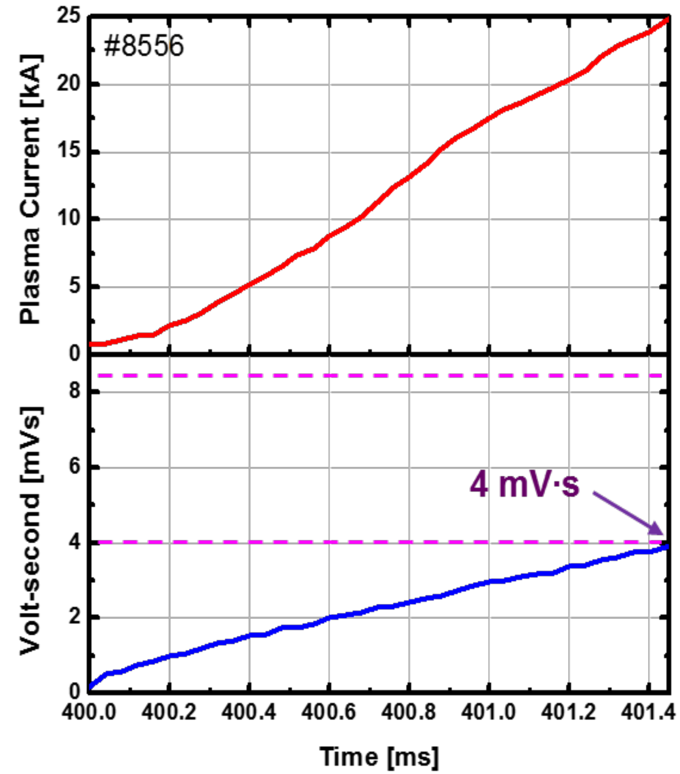
Ohmic Start-up with ECH Pre-ionization

Prompt I_p initiation in TPC with volt-sec saving

TPC







- TPC intrinsically forms equilibrium field that can provide stable B_v even at the low I_p and stable decay index in all times enabling prompt I_p initiation.
- Volt-sec saving of about 40% with TPC compared to the case without TPC

Y.H. An

TPC as an Efficient Start-up Method

Trapped Particle Configuration

Enhanced pre-ionization
by increase of particle confinement

↓

Start-up with low loop voltage, low volt-second consumption, low ECH power and wider pressure window.

↓

- **Low loop voltage start-up of super-conducting tokamaks such as ITER**
- **The efficient start-up of spherical tori with limited volt-second by reduced V·s consumption**

Prompt I_p initiation
due to the intrinsic stable B_p configuration

↓

Start-up without waste of volt-second by enabling prompt I_p initiation

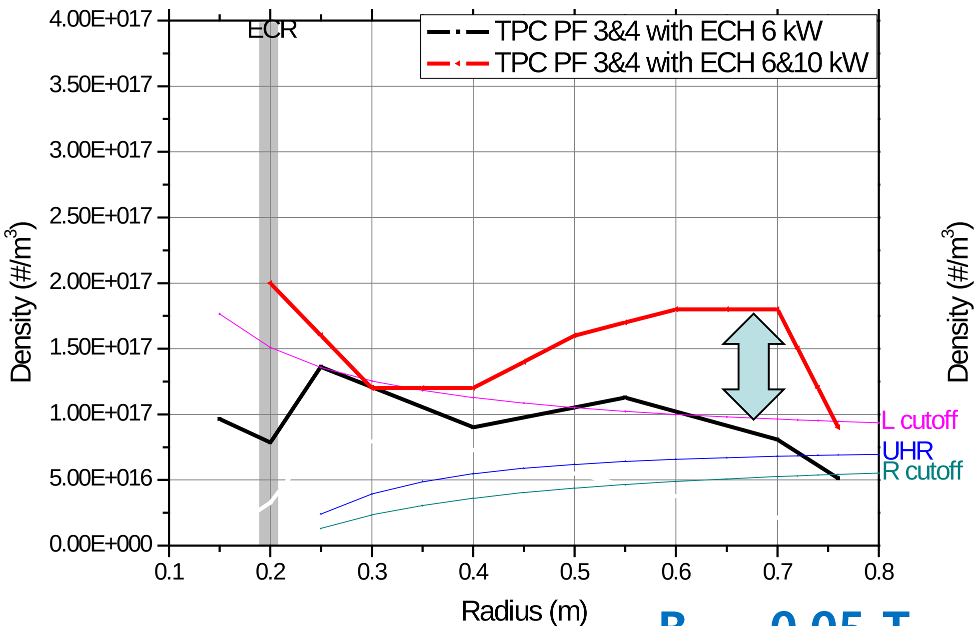
↓

- **Reduced V·s consumption and extended discharge duration by prompt I_p initiation particularly for super-conducting tokamaks with the limited current slew-rate of super-conducting PF coil***

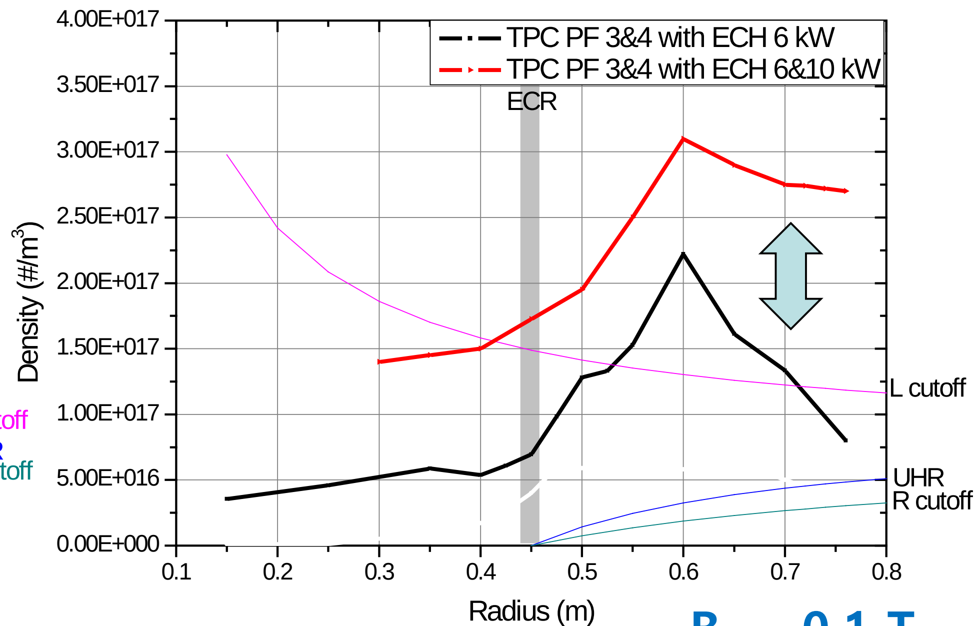
- **TPC can be an alternative to the widely used field null configuration for more efficient ECH-assisted start-up.**

* In super-conducting tokamaks, the use of field null requires transition of the B_p structure to the equilibrium field which takes considerable time limiting I_p ramp-up rate

Over-dense Plasma Formation with EBW heating in TPC



$B_0 \sim 0.05$ T

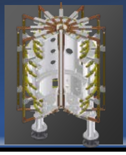


$B_0 \sim 0.1$ T

- **Mode conversion efficiency is calculated with 1-d full wave simulation**
- **EC/EBW heating with 6kW CW ECH**
  - **Bo~0.05T : Broad density profile makes low MC conversion efficiency (0.0105)**
  - **Bo~0.1T : Steep density gradient near UHR and relatively high MC efficiency (0.2625)**
- **EC/EBW heating with additional 10 kW pulsed ECH power**
  - **Clear over-dense plasma formation with EBW mode conversion near UHR**
  - **Bo~0.05T: low MC efficiency (0.0105→0.4819), Bo~0.1T: high MC efficiency (0.2526→0.756)**

H.Y. Lee

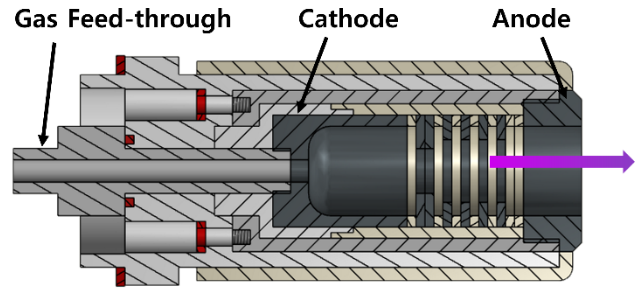
More than L cut-off density !



The Electron Gun and Power system

Plasma washer gun

- High electron current based on arc discharge
- Low impurity
- Washer stacks

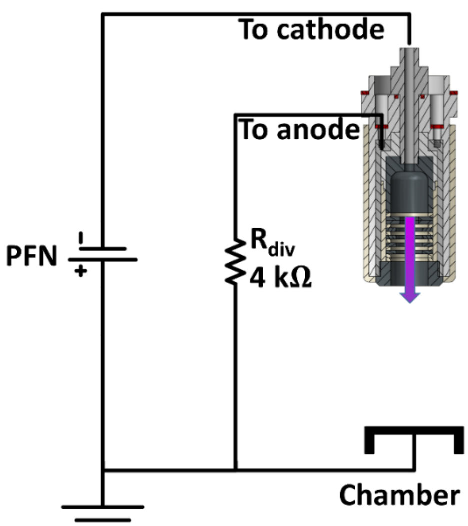


Power system configuration

- Single and Double power system
- PFN - Composed of circuits consist of C & L

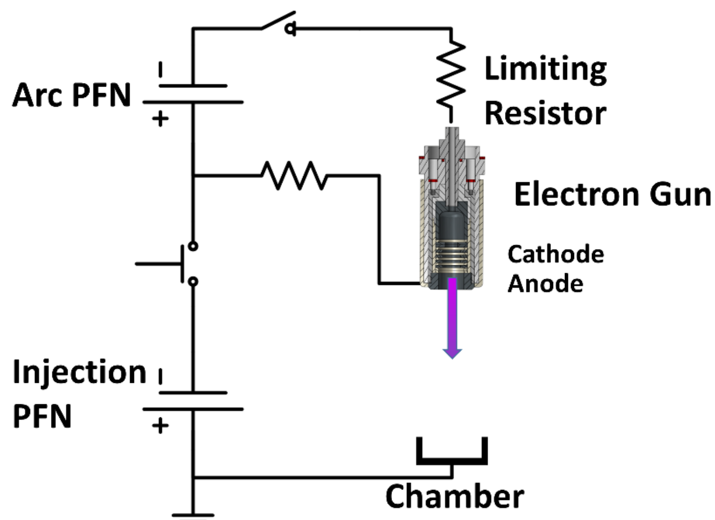
1. Single power system

- PFN for Arc discharge & injection



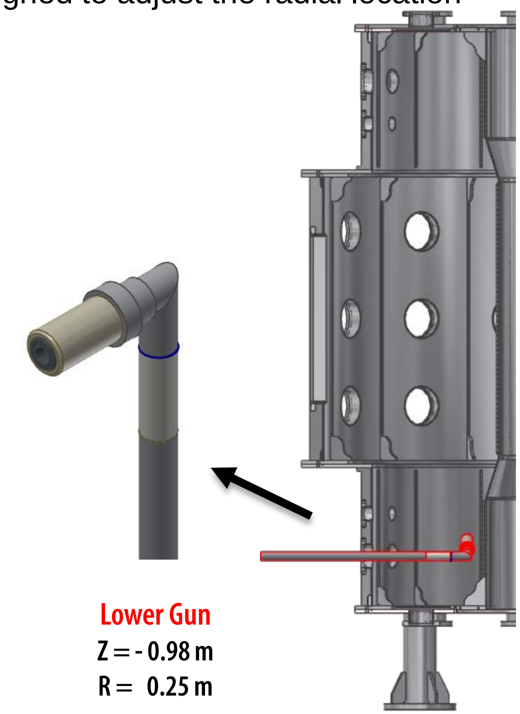
2. Double power system

-PFN for Arc discharge
-PFN for Injection voltage



The location of injector

- Assembled into a stainless steel pipe
  - Designed to adjust the radial location



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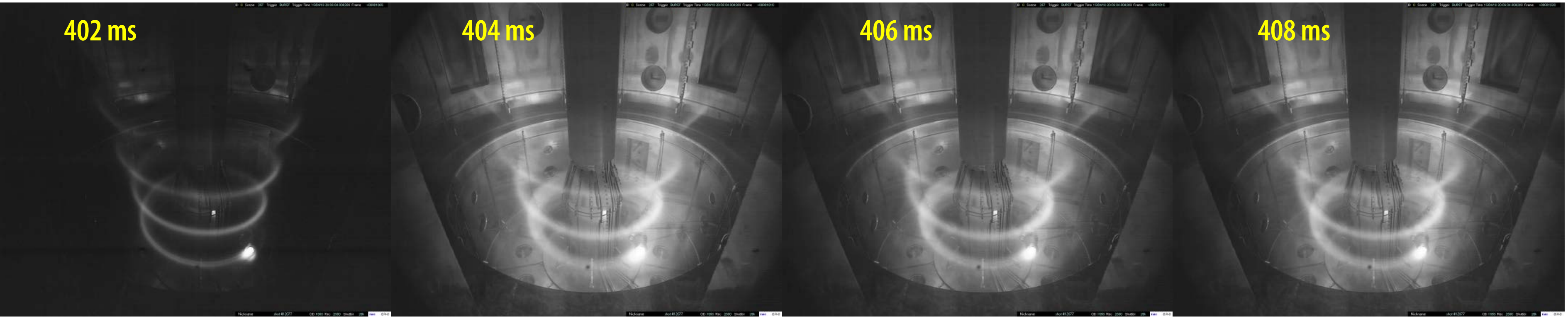
Visual evidence of reconnection from current stream

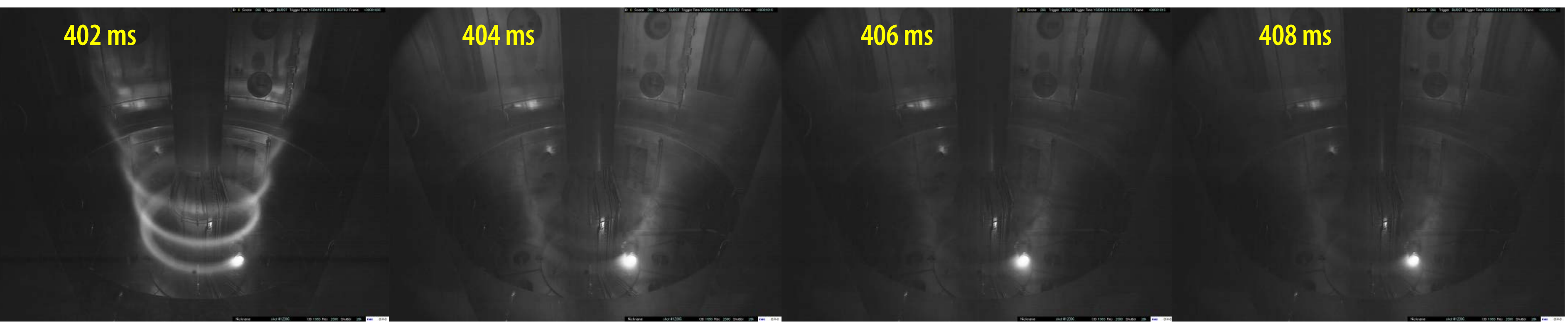
No reconnection
(Shot # 12077)

V_{inj} **~ 200V / I_{inj} 1.2kA / PFN Charging of 1.2 kV**
Current steam stacking defined by helical vacuum field



Reconnection
(Shot # 12086)

V_{inj} **~ 500V / I_{inj} 1.5kA / PFN Charging of 1.6 kV**
Multiplication factor more than stacking ratio



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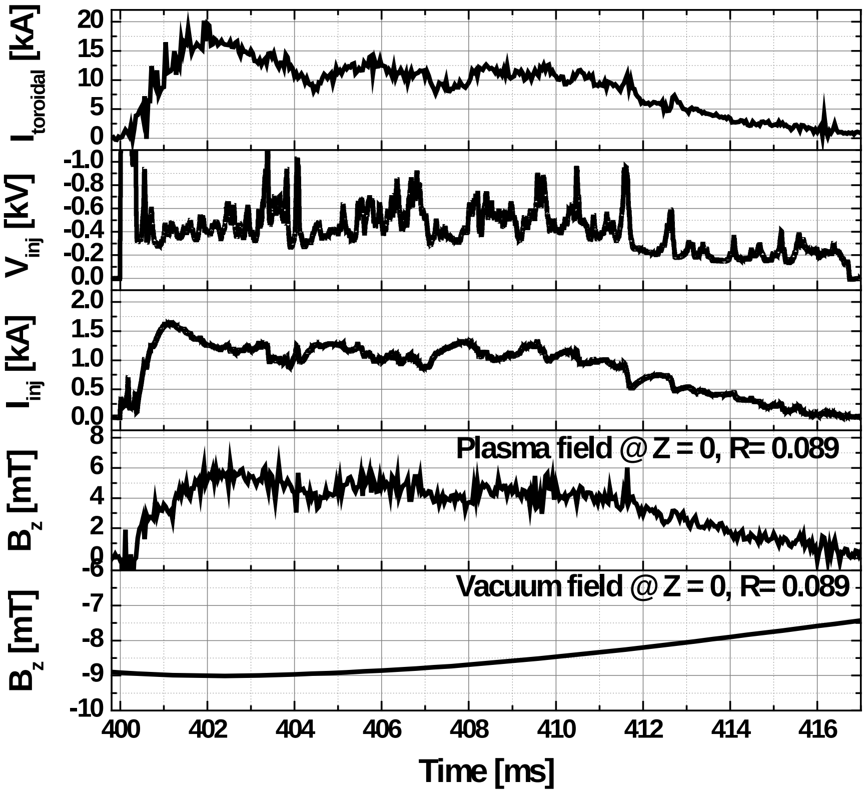
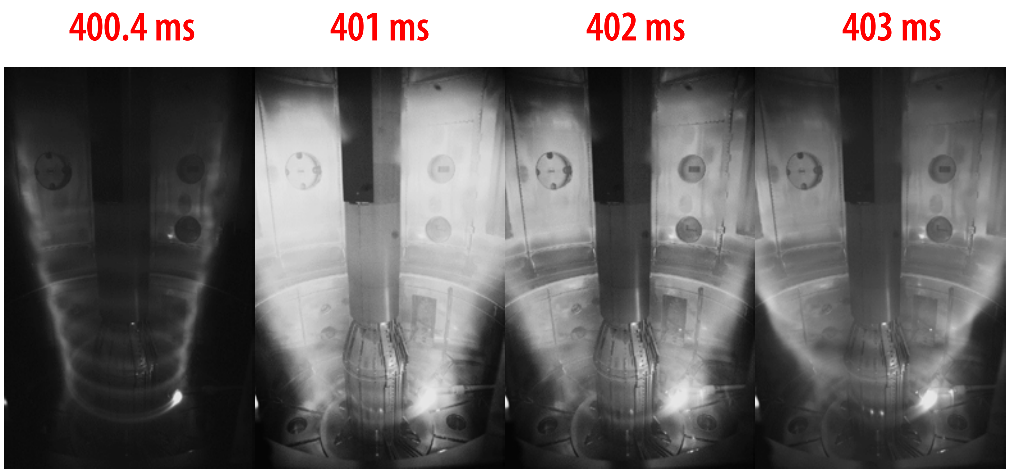
Current Sheet Formation





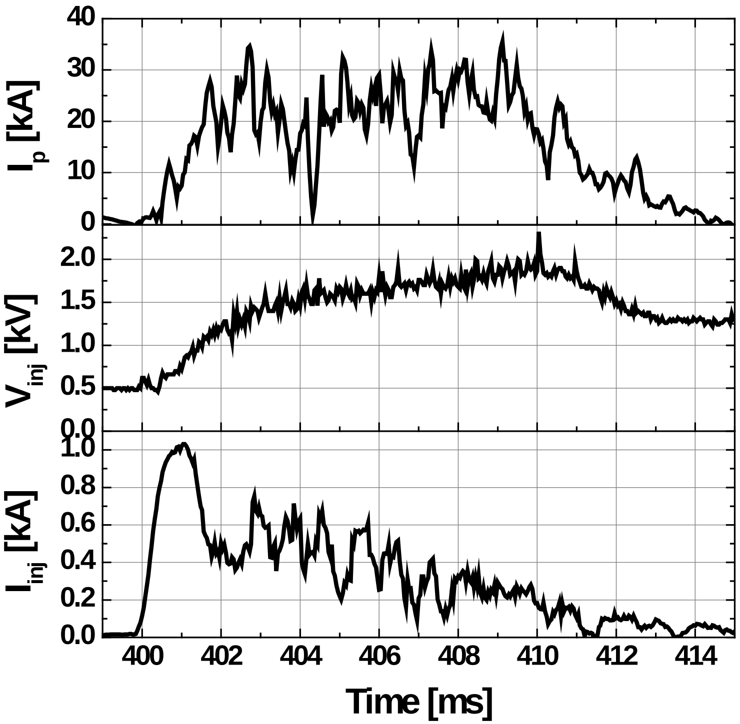
Lower Gun Location
R = 0.25 m
Z = - 0.804 m

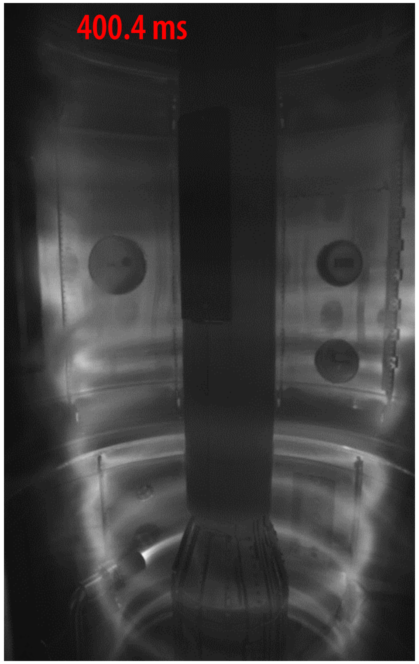
Magnetic Field Structure
Stacking ratio, G = 7 ~ 8
Multiplication, M = ~ 16

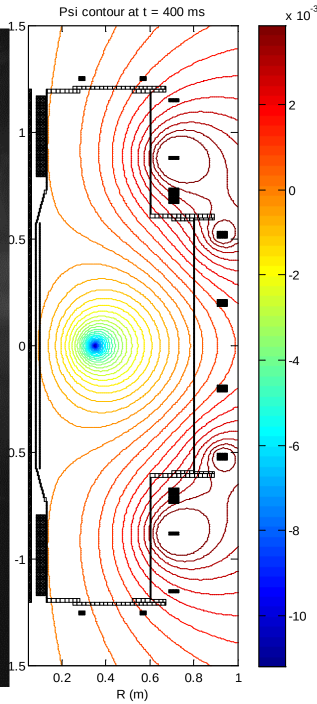
- **A toroidal current of up to ~20 kA has been generated by the electron gun.**
  - **Increased multiplication factor confirmed as current streams reconnected, but**
  - **Neither radial force balanced nor relaxed to tokamak like plasma.**
- **Very dynamic states of current sheet are observed.**
  - **Toroidal current is more sensitive to injection voltage than injection current.**
  - **V_{inj} and I_{inj} change with plasma states due to the PFN characteristics.**

J.Y. Park

Tokamak-like Plasma Formation







- A plasma current of up to ~30 kA has been generated with high V_{inj}
  - **Tokamak-like plasma formation confirmed !**
- Gradual decrease in injection currents keeps from further plasma current increases.

  → Injection power supply with current regulation under preparation

J.Y. Park

Studies for Advanced Tokamak

Experimental research direction for VEST

Fusion reactor requires

high beta (or Q) and high bootstrap current

Alpha heating (high Q)
→ Centrally peaked pressure profile

Hollow current density profile (low li)
→ Centrally peaked pressure profile

Stability and Confinement ?

Profile diagnostics

High power neutral beam heating

Current density profile control
Bootstrap/EBW/LHFW

Experimental research direction for VEST

Advanced Tokamak Scenario

- Simultaneous achievement of high beta and high bootstrap current is required for advanced tokamak scenario.

⇩

High bootstrap current fraction in reversed shear mode

+

High beta in spherical torus with low aspect ratio

⇩

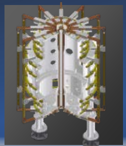
- **Spherical Torus with Reversed Shear**
  - Sufficient confinement from ITB formation by RS
  - Possible high beta even with low li in RS due to low aspect ratio

⬇ **High power NBI to center, forming RS in VEST!**

Advanced Tokamak Regime in VEST*

* Estimated by 0-D system code

- **Low toroidal field(0.1T) with high β_N(~7)< $\beta_{N,Menard}$(8.7) and I_p(0.08 MA).**
- **Fully non-inductive CD with 80% bootstrap fraction may be possible with ~500kW.**
- **High H factor(~1.2) needs to be attempted by forming ITB with MHD stability.**

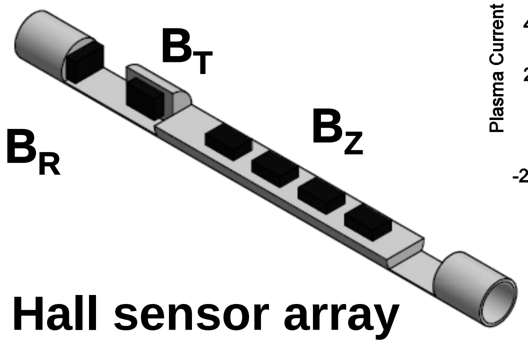


Diagnostic systems in VEST

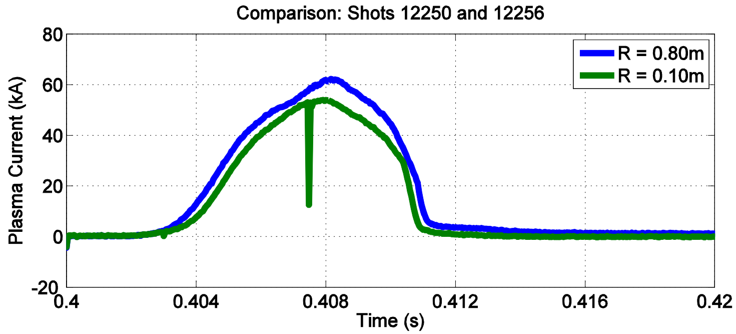
Diagnostic Method		Purpose	Remarks
Magnetic Diagnostics	Rogowski Coil	Plasma current & eddy current	3 out-vessel & in-vessel coils
	Pick-up Coil & Flux Loop	B_z, B_r & Loop voltage, flux	56 pick-up coils 9 loops
	Magnetic Probe Array	B_z, B_r measurement inside plasma	Movable single array
Probe	Electrostatic Probe	Radial profile of T_e, n_e	2 Triple Probes Mach probe
Optical Diagnostics	Fast CCD camera	Visible Image	20kHz
	H_α monitoring	H_α	H_α filter+ Photodiode
	Impurity monitoring	O & C lines	Spectrometer
	Interferometry	Line averaged n_e	94GHz, single channel
	Reflectometry	Radial profile of n_e	Edge density profile
	EBE radiometer	Core, edge T_e	BX mode conversion
	Charge Exchange Spectroscopy	Rotation and T_i	DNB
	Thomson Scattering	T_e, n_e profile	NdYAG laser

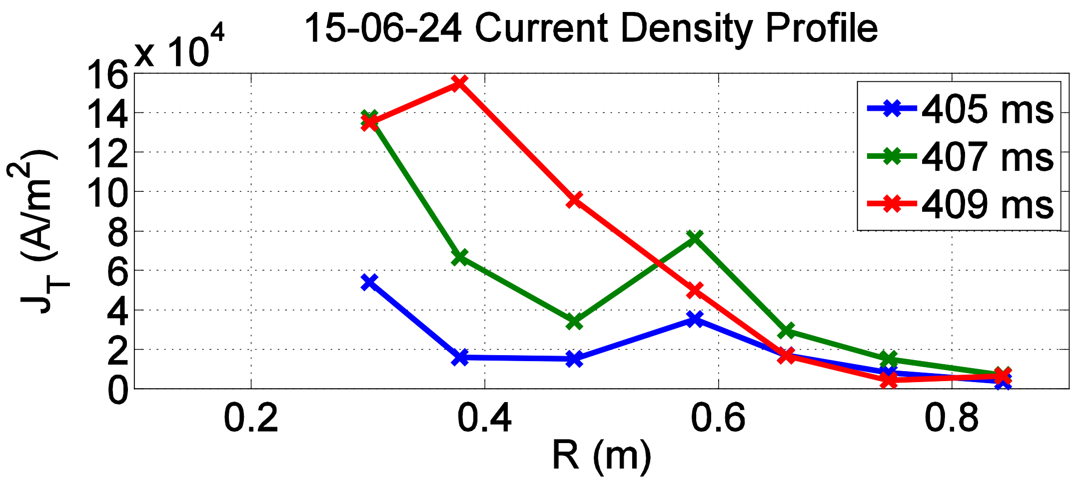
Diagnostic systems in VEST

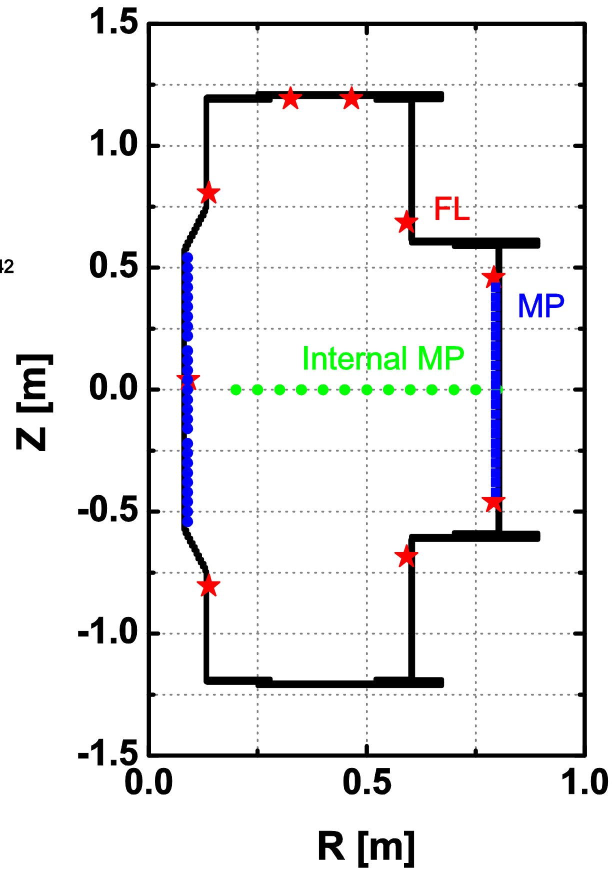
Direct Measurement of mid-plane Toroidal Current Density Profile



Hall sensor array





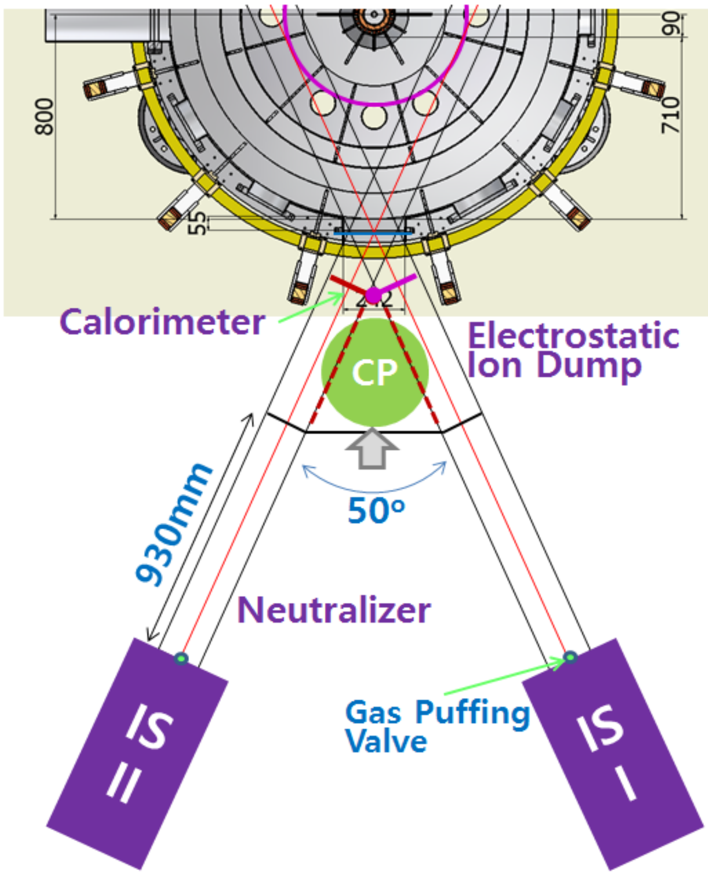


J.H. Yang

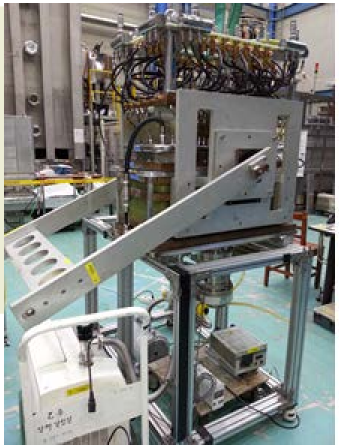
Full equilibrium reconstruction is under development

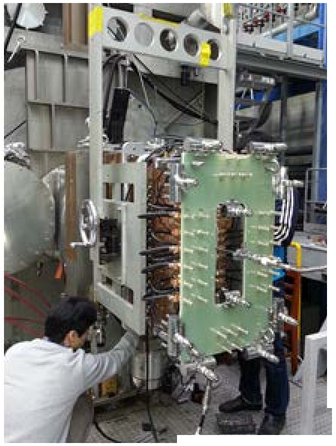
High power low energy NBI preparation

VEST NB BLs Design Detail

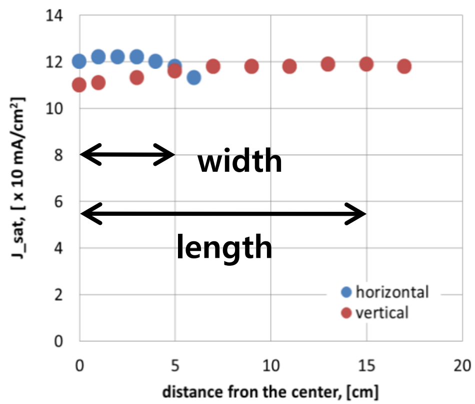


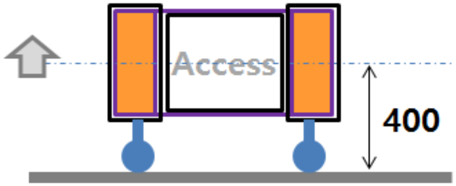
Ion source under test



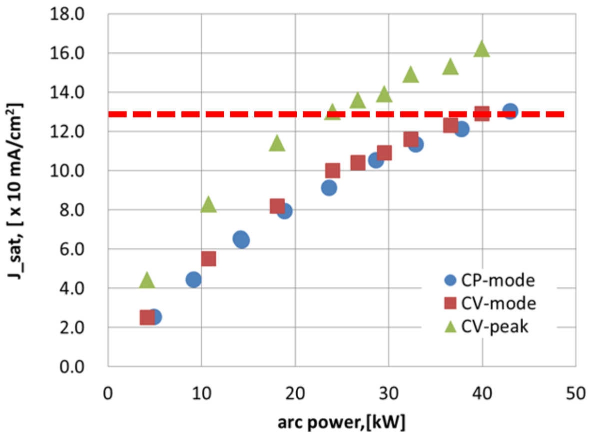


Ion saturation current density
40kW, 12V, 140sccm, 200ms





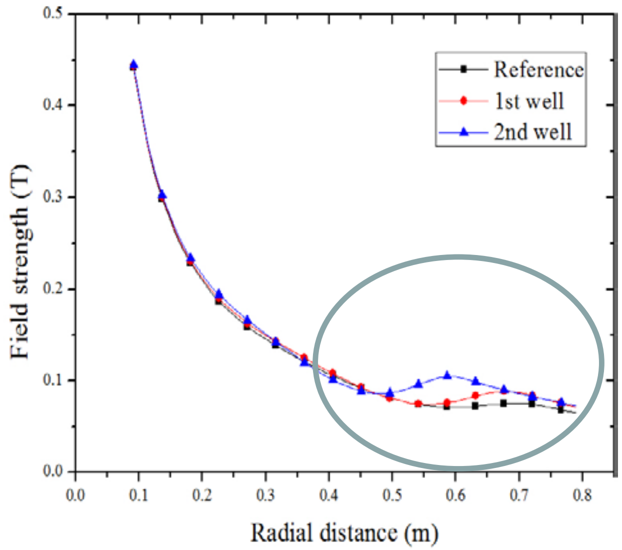
Ion saturation current density v.s Arc power
12V, 140sccm, 200ms



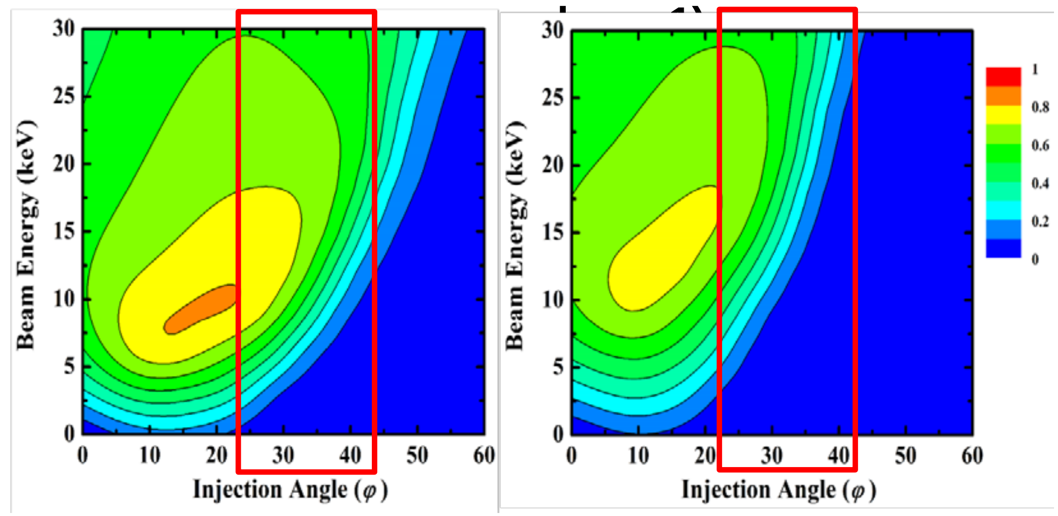
Two beams with 300kW each
First beam by FY2016-2017

S.H. Chung (KAERI)

Reduced beam loss with magnetic well formation



(Optimized injection condition for VEST with well)



	well shape 1	well shape 1	well shape 2	well shape 2
Beam energy (E_b)	20 keV	25 keV	20 keV	25 keV
I_p (kA)	80	80	80	80
n_0 ($10^{13}/cm^3$)	1	1	1	1
Injection angle (φ)	40°	45°	30°	35°
Shine through (R_s)	30 → 27%	35 → 37%	30%	38%
Orbit loss	30 → 16 %	60 → 12%	7%	6%
Total beam loss	66 → 43%	95 → 49%	37%	44%

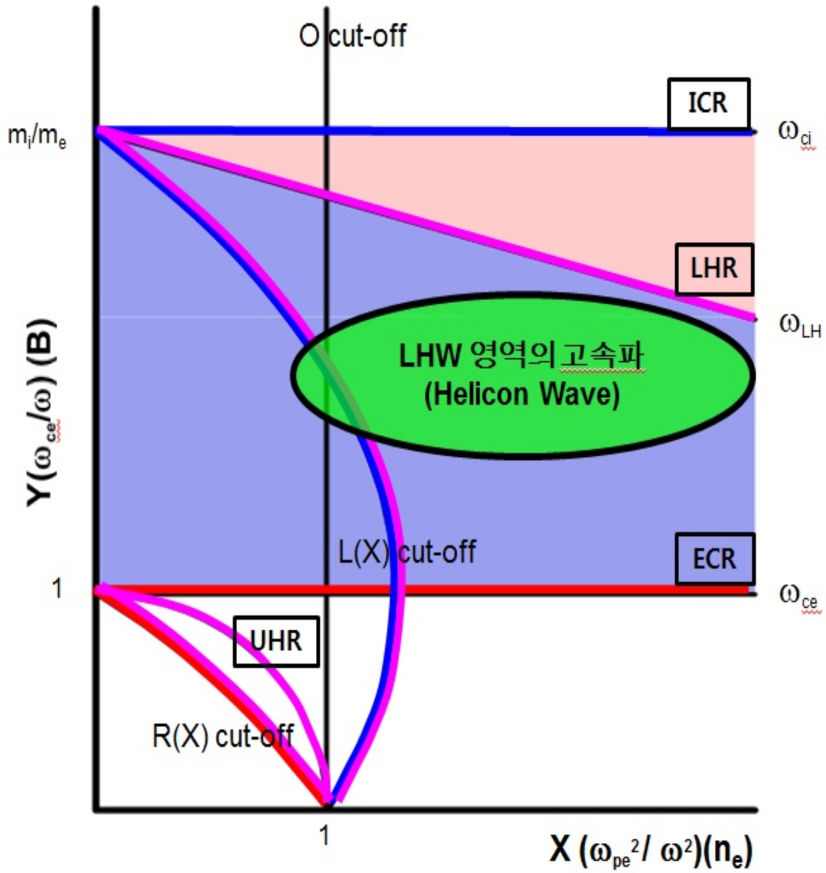
(NUBEAM, Optimized injection condition for VEST)

S.K. Kim

Core heating by LHFW

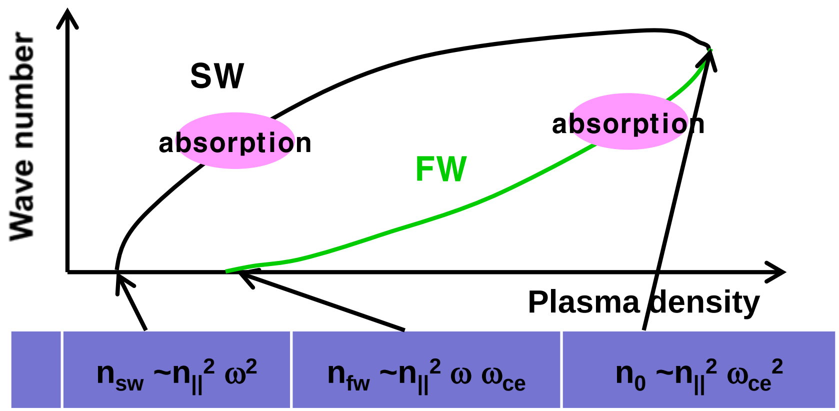
High Power NBI and fast Lower Hybrid systems from KAERI

< CMA diagram of Helicon Wave>



S.H. Kim (KAERI)

< Helicon Wave Dispersion Relation >

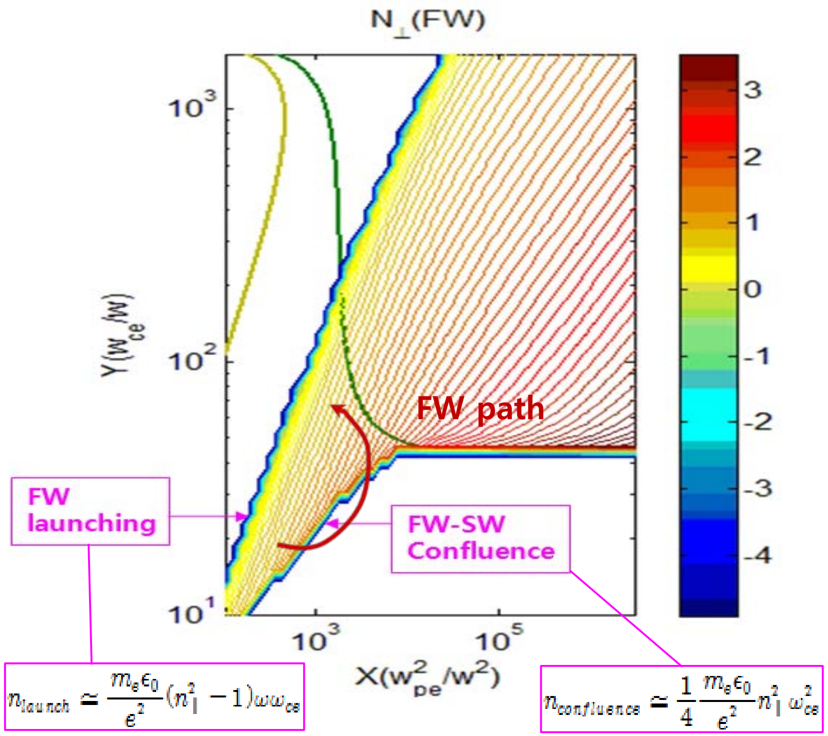


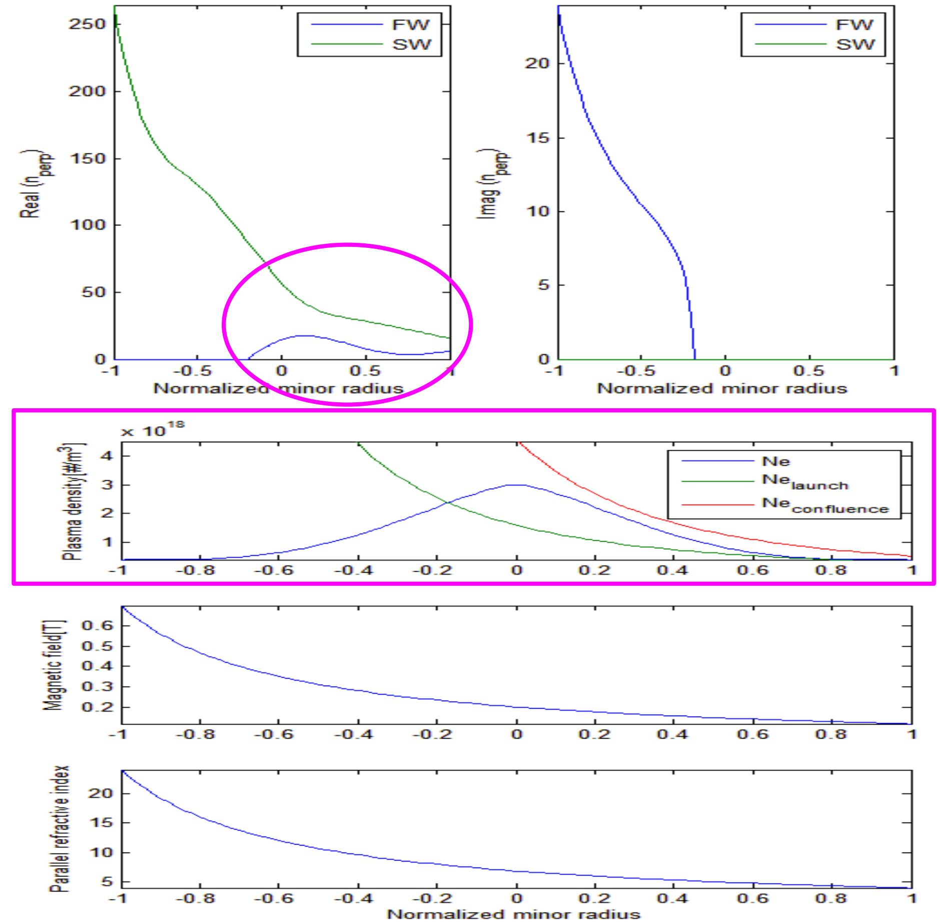
- **For high density plasma in fusion reactor**
  - Slow wave branch of LHW
    → Absorbed at the edge region
  - **Fast wave branch of LHW**
    → Possible absorption at the core region

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

LHFW accessibility

Accessibility for Lower Hybrid Fast Wave(LHFW)





- Possible propagation regime in CMA diagram
  - FW launching density ~ f($n_{||}$, w, w_{ce})
  - FW-SW confluence density ~ f($n_{||}$, w_{ce})

<f=500[MHz], n_0= 3x10[18][#/m[3]] B_0=0.2[T], $n_{||}$=4.0>

S.H. Kim (KAERI)

 # Accessibility condition is satisfied.

Ray Tracing Simulation with GENRAY

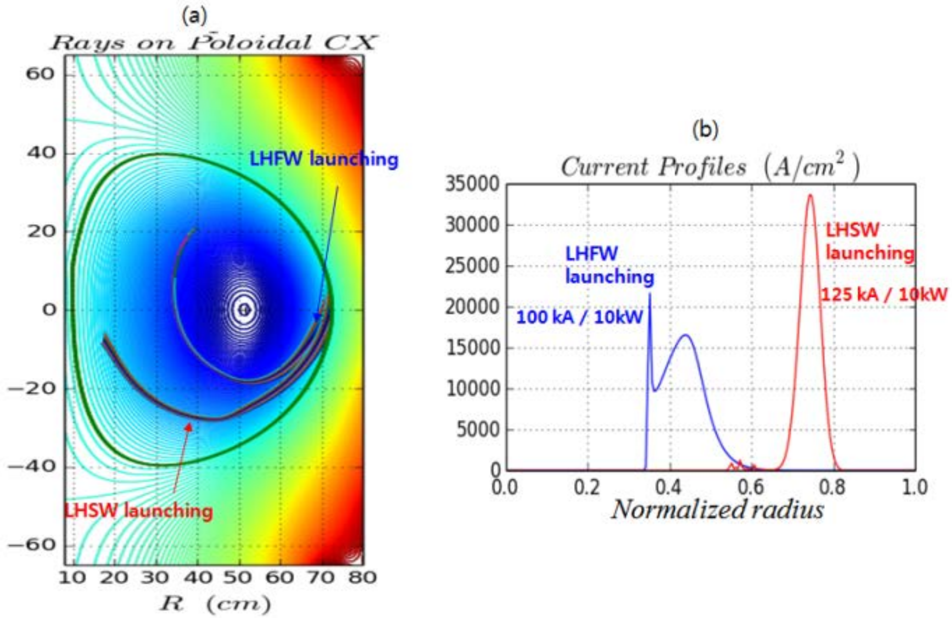
- **Ray tracing simulation**

✓ The parallel refractive is 4.0 which satisfies the accessibility condition for the given magnetic field and RF frequency.

✓ The propagations and driven currents are calculated with GENRAY code for LHFW and LHSW launching cases on VEST.

✓ **The LHFW can propagate into more central region and the driven current is comparable to that of LHSW.**

S.H. Kim (KAERI)



Ray tracing : (a) ray, (b) driven current profile

Parameters	Values
B_0	0.2 T
Frequency	500 MHz
$N_{\|\|}$	4.0
Core density	3×10^{18} #/m^3
Edge density	4×10^{17} #/m^3
Core temperature	3 keV
Edge temperature	0.2 keV

Parameters for ray tracing calculation on VEST

LHFW Components

▪ Klystron

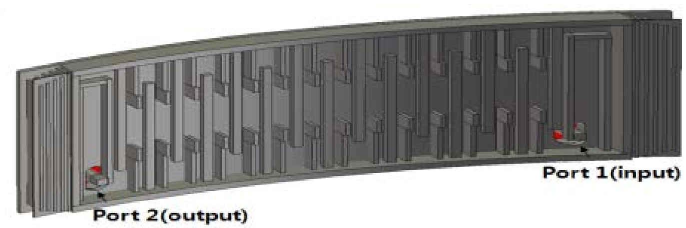
✓ The klystron is prepared by refurbishing an old UHF broadcasting system of Korea which has been hold by SNU..

Parameters	Values
Frequency	470~700 MHz
Output power	37.5 kW
Gain	48 dB
Beam voltage	19.5 kV
Beam current	5.4 A
Electrode voltage	19.5 kV
Heater voltage	7 V
Heater current	17 A
Body current	50 mA
Magnet voltage	145 V
Magnet current	32 A
Collector cooling	Water 2.0 gal/min
Body cooling	Water 1.5 gal/min
Magnet cooling	Water 2.0 gal/min
Gun cooling	Forced air 50 ft^3/min

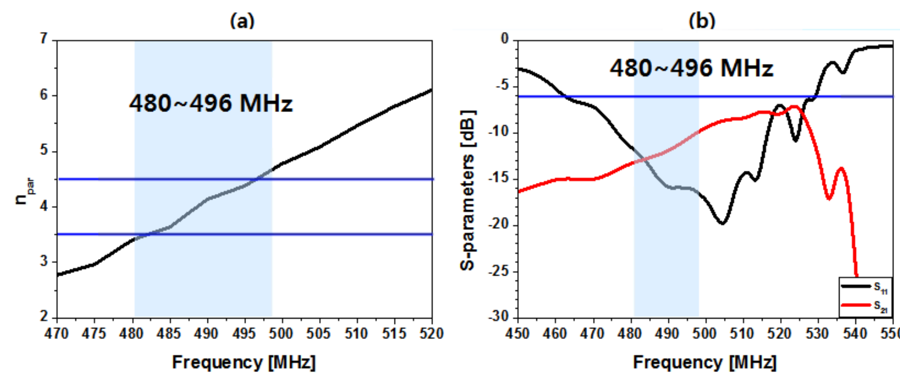
Specification of klystron

▪ Antenna

✓ In 480~496 MHz frequency range, the parallel refractive index is between 3.5 and 4.5 and the S-parameters S11 and S12 are less than -10 dB.



Curved antenna for LHFW RF system on VEST



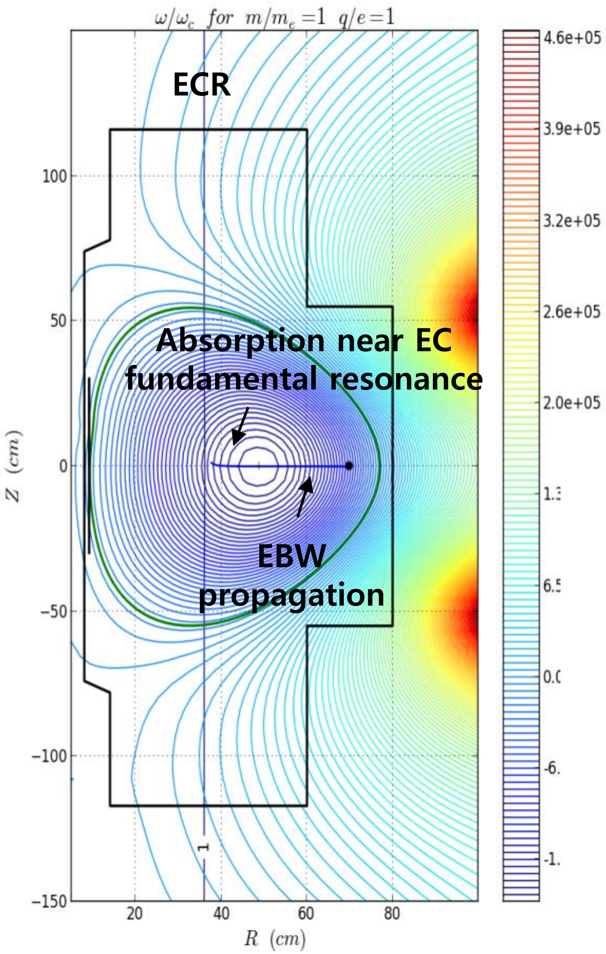
Parallel refractive index spectrum (a) and S-parameters (b) of curved inter-digital antenna designed.

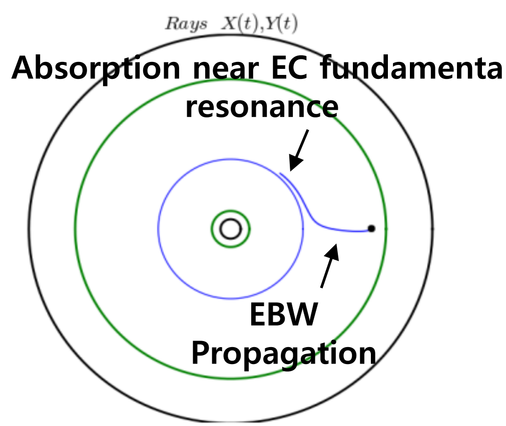
S.H. Kim (KAERI) and B.J. Lee (Kwangwoon Univ.)

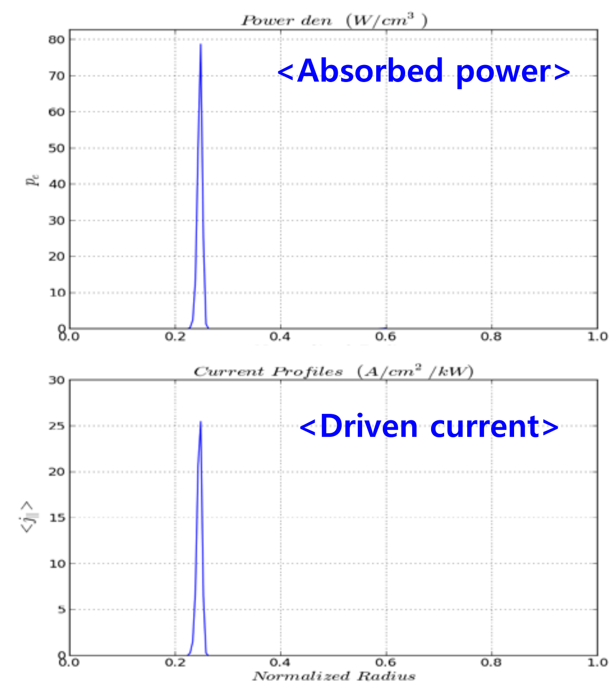
EBW heating with XB mode conversion

► Core heating and current drive with XB mode conversion

- GENRAY, CQL3D, mode conversion codes are used
- Perpendicular, LFS, X-mode injection
  - Short distance between R(X) cut-off and UHR
  - High XB mode conversion efficiency with low $n_{||}$
  - Good central heating and current drive expected





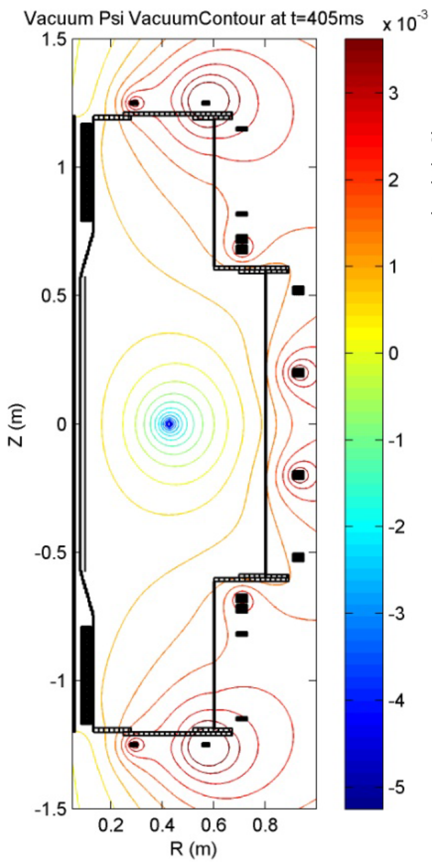


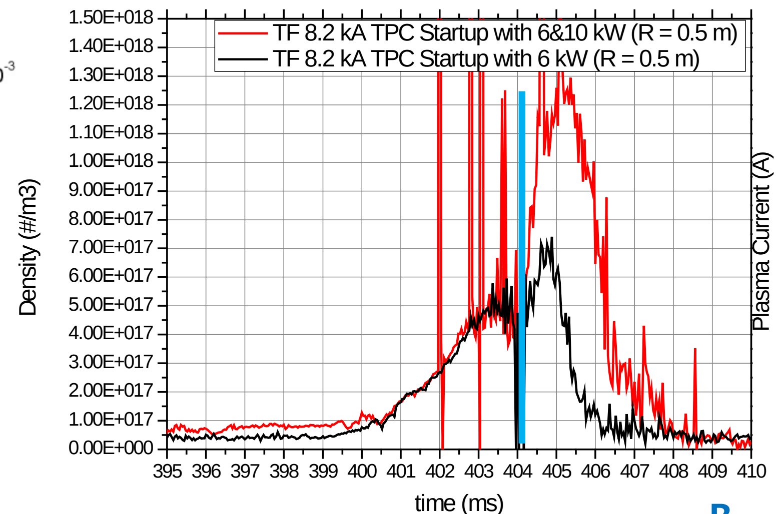
S.H. Kim (KAERI)

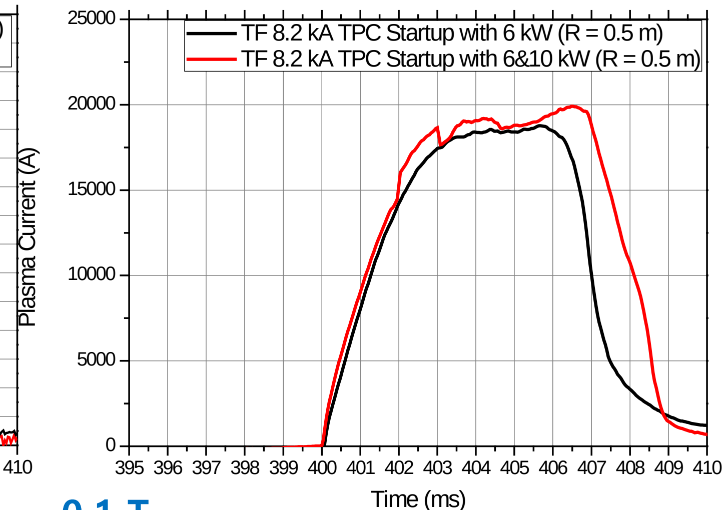
Current density profile control

EBW heating with XB mode conversion in VEST

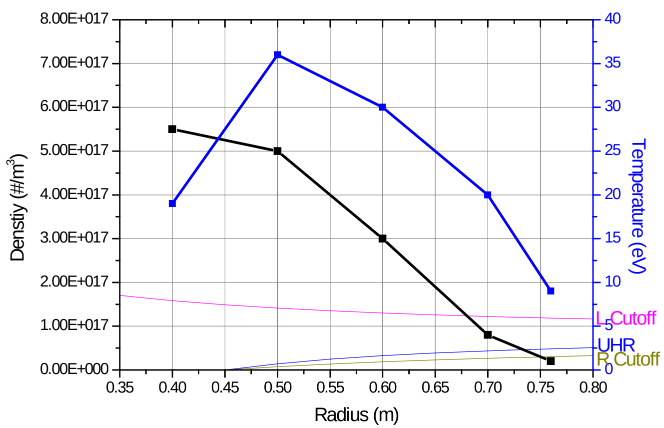
► EBW heating (6kW cw+10kW pulse) on Ohmic plasmas with TPC

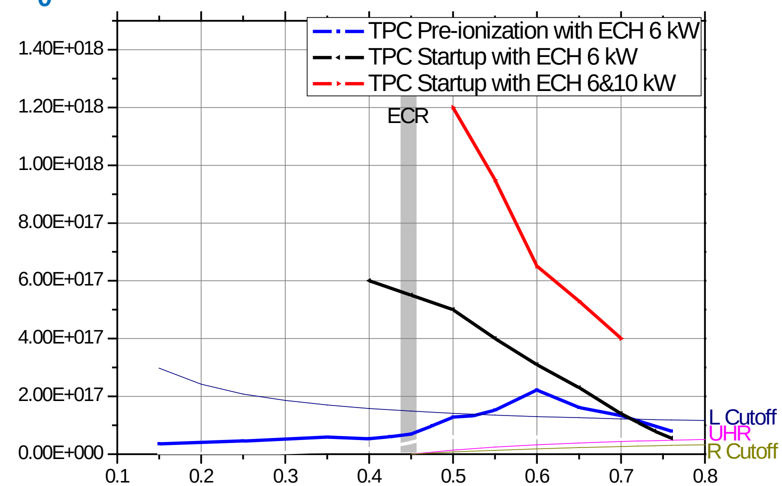






B_0 ~ 0.1 T



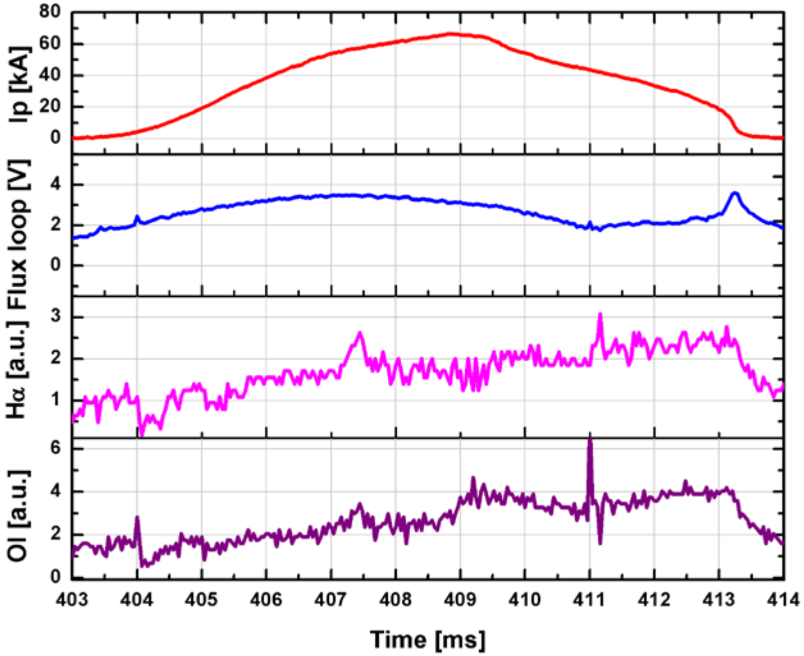


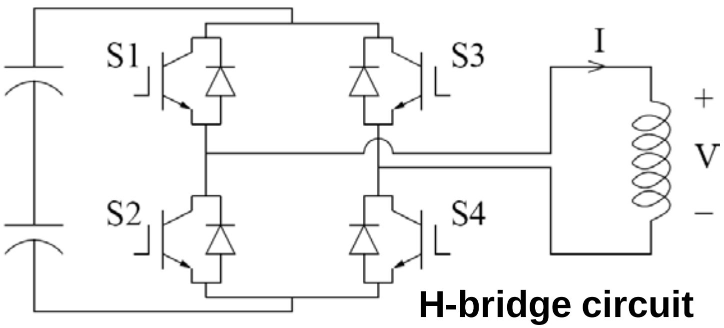
H.Y. Lee

404 ms

Preparation for High Density Target Plasmas

High density Ohmic plasmas with >80kA for >20ms

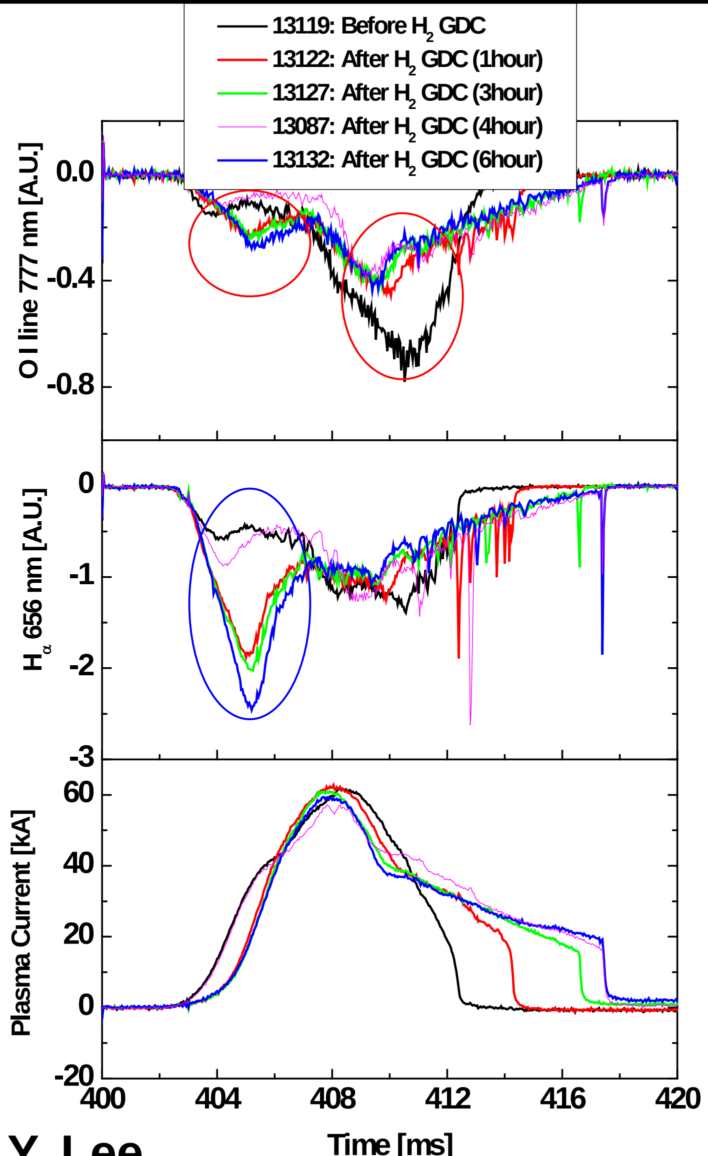




H-bridge circuit

- **Preparation for high density plasmas as NBI target**
  - Low shine through and good coupling
- **Target plasmas for VEST NBI**
  - R_0=0.4 m, a=0.3 m → **R_0=0.35 m, a=0.25 m**
  - I_p<70 kA for 10 ms with elongation < 1.6
    → **I_p>80 kA for >20 ms with elongation > 2**
- **Implementation**
  - Wall conditioning : GDC, **baking**
  - **TF & PF power system upgrade**
  - Feed-forward/back control system

Wall conditioning with hydrogen GDC

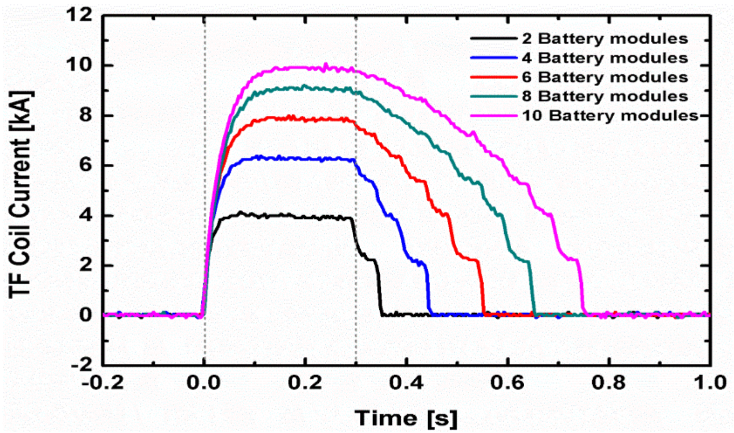


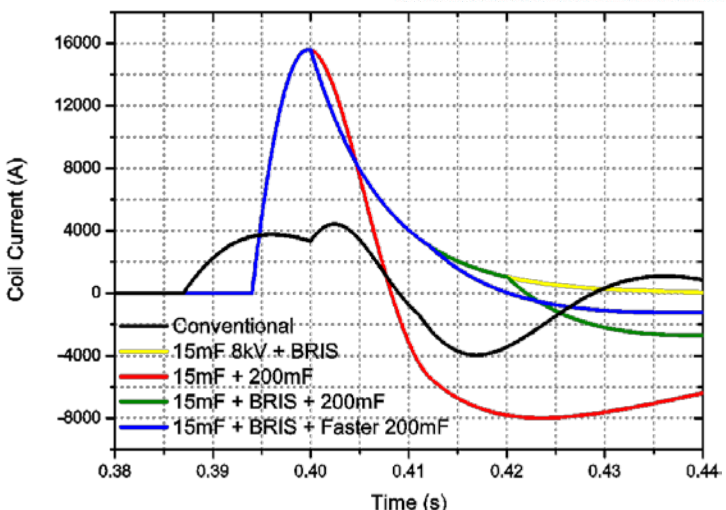
- Wall conditioning using H_2 GDC
  - Oxygen impurities are reduced significantly with GDC
  - Plasma pulse duration extended accordingly with reduced OI radiation
  - Inboard limiter considered as major oxygen impurity source
  - Increased H alpha radiation in the initial phase with increased treatment time
  - Strong hydrogen retention inboard limiter confirmed with hydrogen GDC
- H_2 GDC more than 4 hours is need to remove water for long pulse plasma discharge.
- Active cooling of inboard limiter is under preparation for baking

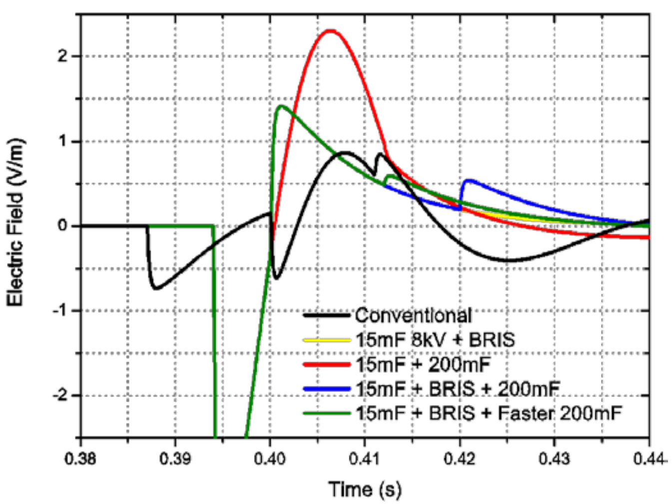
H.Y. Lee

Upgrade of TF and PF power supplies

- TF field will be increased by adding capacitors (0.1T → 0.2~0.3T)
- PF curret waveform will be modified for better loop voltage utilization







J.H. Yang

Summary

- **VEST has achieved successful ohmic operation with plasma currents of up to ~70 kA, elongation of ~ 1.6 and safety factor of ~3.5 with ECH pre-ionization.**

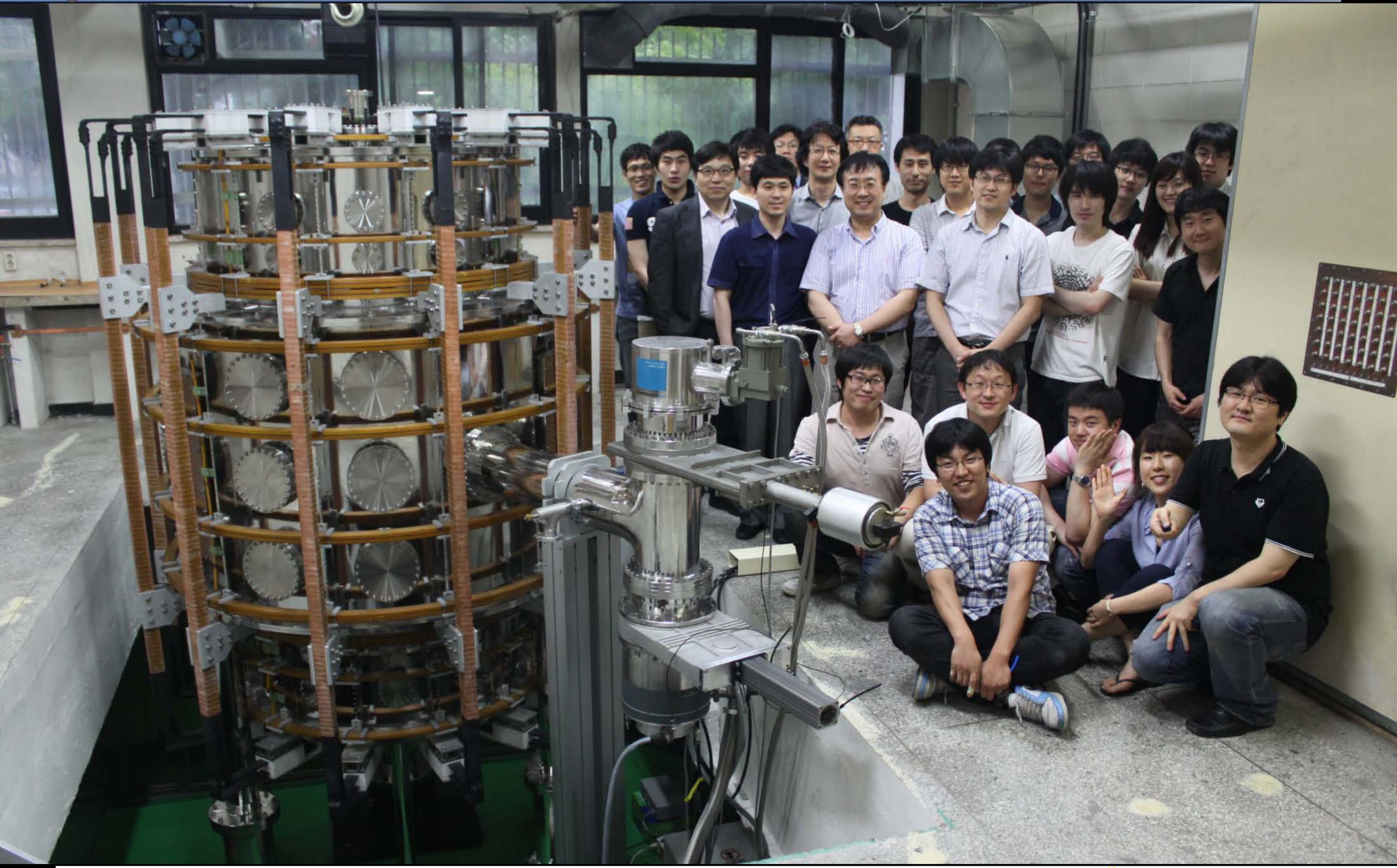
- **EBW heating with direct XB mode conversion from LFS launching by generating over-dense plasma in the pre-ionization phase with TPC structure as well as ohmic plasmas.**

- **TPC(Trapped particle configuration) is developed as an efficient ECH-assisted start-up method.**
  - Enhanced pre-ionization improves start-up with low loop voltage, low ECH power and wider pressure window.
  - Intrinsic stable magnetic structure leads volt-sec saving with prompt I_p initiation and smooth coil current change.

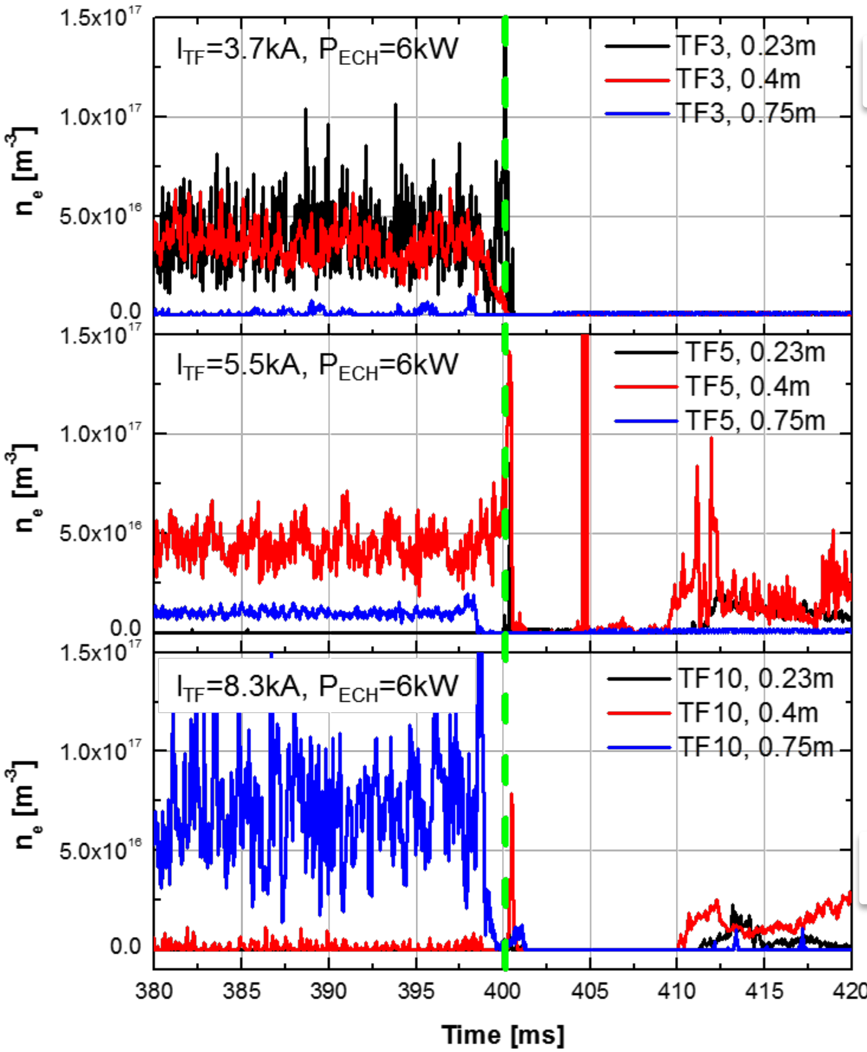
- **DC helicity injection startup experiments generate plasma current of ~20 kA with single power and ~30 kA with two power system, confirming tokamak-like plasmas.**

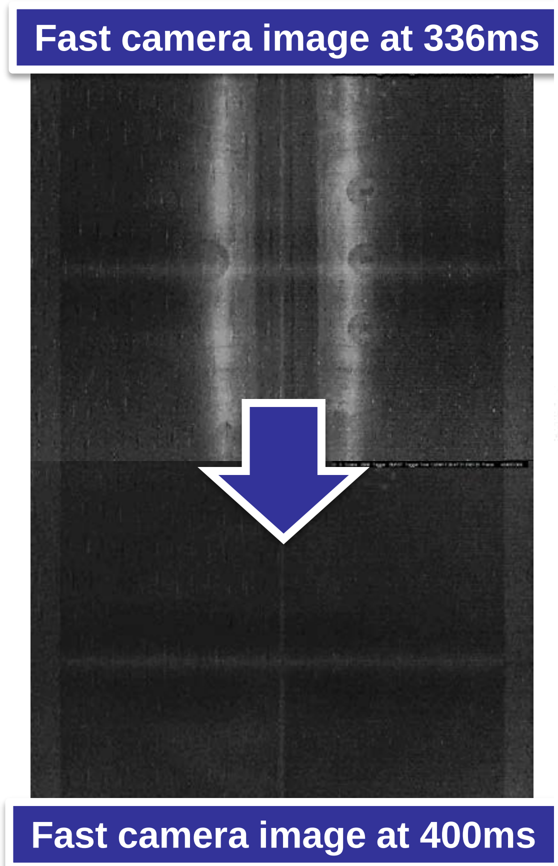
- **Experimental preparation for the study of advanced tokamak is progressing.**
  - Profile diagnostics are under preparation
  - High power NBI of ~ 500 kW and prototype NBI are under development.
  - EBW/LHFW heating and current drive experiments are under preparation by performing simulations and preparing hardware systems.

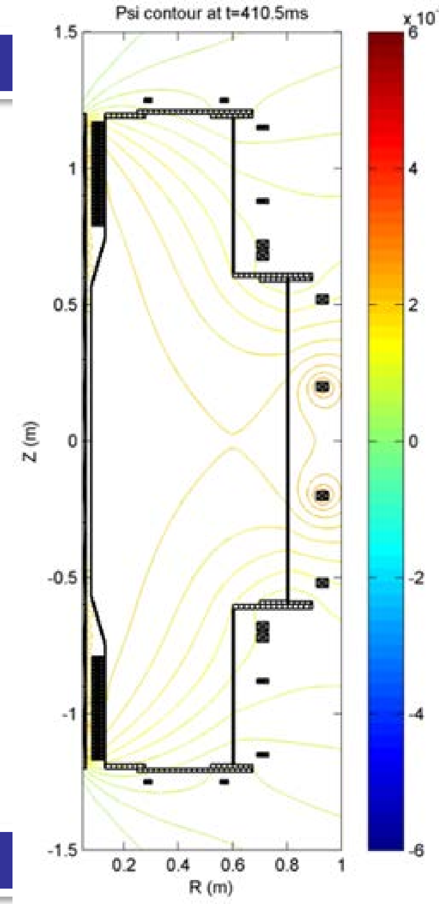
Thank you for your attention !

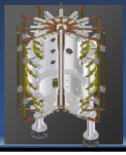


Low loop voltage start-up with ECH pre-ionization



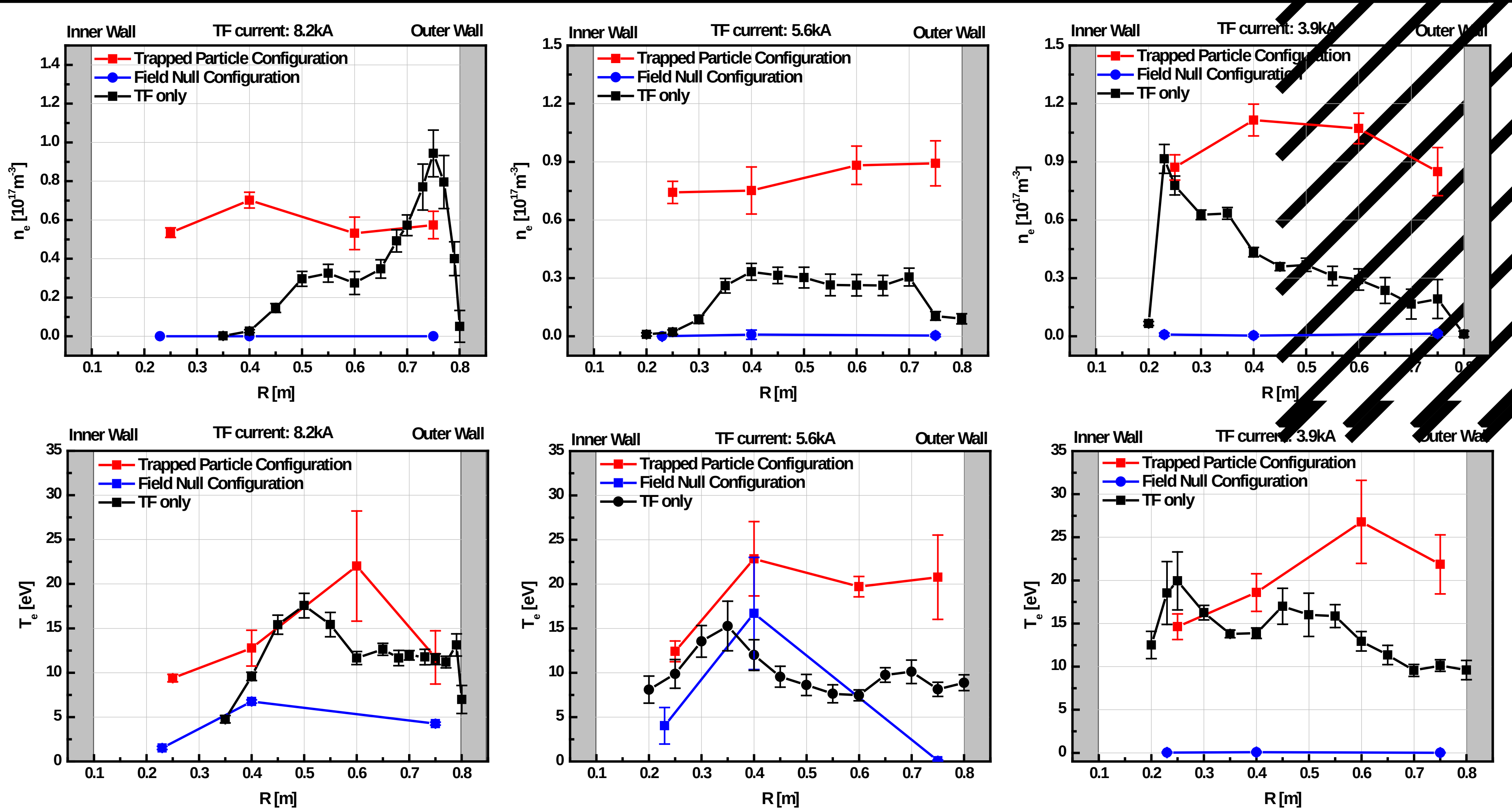






ECH/EBW pre-ionization

Significant enhancement of n_e & T_e under TPC

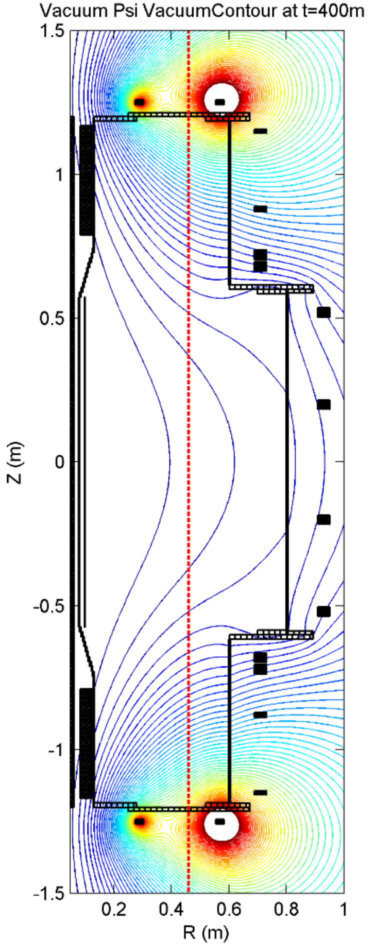


- Significant enhancement of pre-ionization plasma with trapped particle configuration
- Significant degradation of pre-ionization plasma with field null configuration
- Temperature peaks near ECR resonance

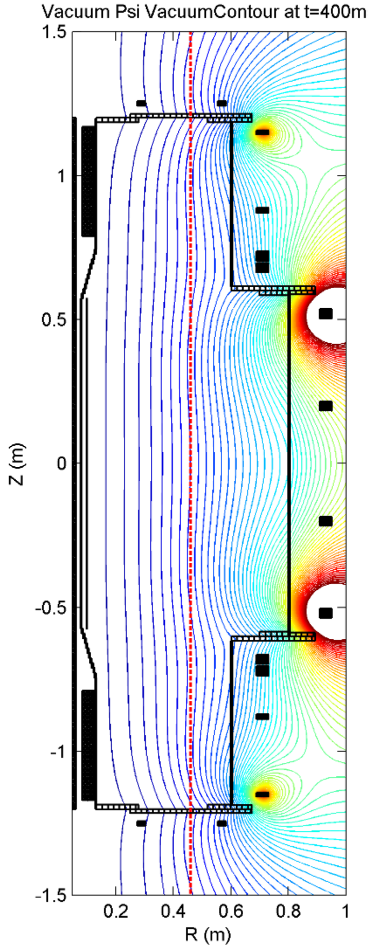
Enhanced pre-ionization with mirror trapping

Trapped Particle Configuration

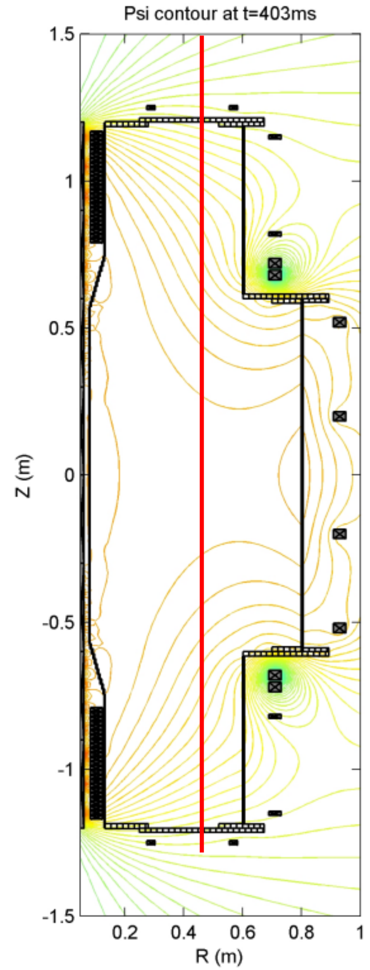
$R_m \sim 3$

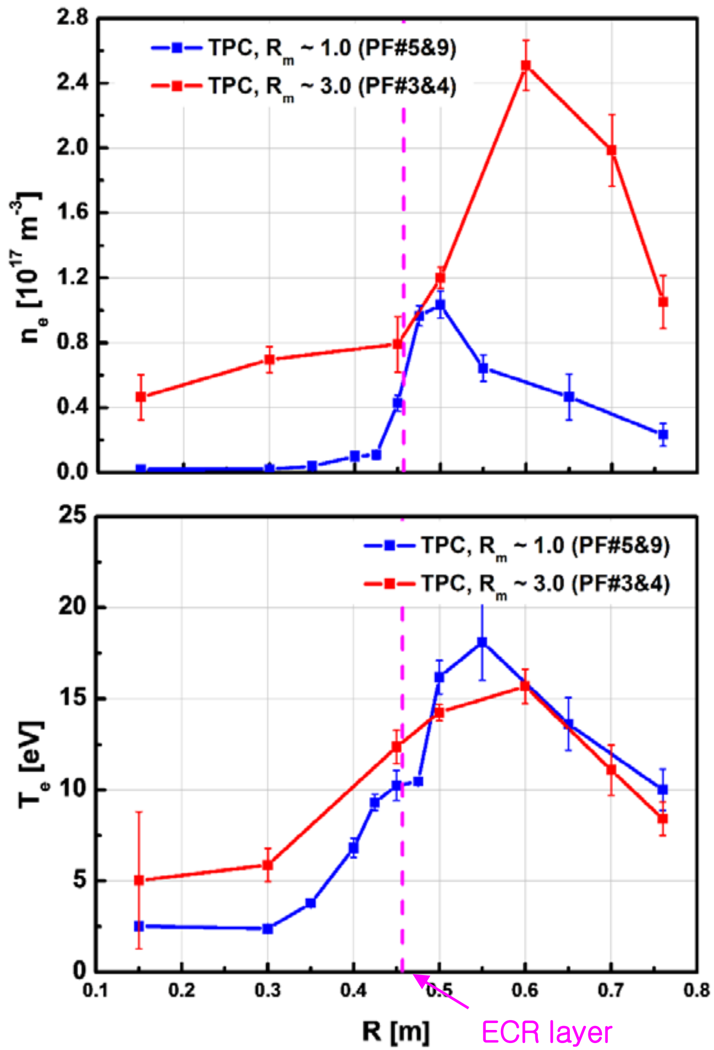


$R_m \sim 1$



Field Null Configuration





J.W. Lee

Advanced Tokamak Study with VEST

R_0(m)	0.4	0.4	**0.35**	0.35
a(m)	0.3	0.22	**0.25**	0.19
A	1.33	1.8	**1.4**	1.8
Kappa	2.227	1.922	**2.167**	1.922
β_N from β_T	7.351	12.317	**6.951**	9.238
f_{boot}	0.8	0.8	**0.8**	0.8
β_T	0.314	0.191	**0.220**	0.143
B_T(T)	0.09	0.21	**0.10**	0.20
I_p(MA)	0.11	0.07	**0.08**	0.06
n_{ave}(10^{20}m-3)	0.20	0.23	**0.21**	0.25
T_{e_ave}(keV)	0.10	0.29	**0.09**	0.19
P_{CD}(MW)	0.72	0.18	**0.51**	0.23
τ_{E_H98y2}(sec)	0.00206	0.00302	**0.00141**	0.00170
τ_E(sec)	0.00218	0.01368	**0.00171**	0.00494
HH	1.06	4.52	**1.21**	2.91

Reversed shear mode in ST

- RS may have sufficient confinement with ITB formation
- ST may have high β_N even with low li in RS
- High power NBI to center, forming RS! → Stable?

❑ VEST Advanced Tokamak Regime with system code

- ✓ Low toroidal field(0.1T) with high β_N(~7)< $\beta_{N,Menard}$(8.7) and I_p(0.08 MA).
- ✓ Fully non-inductive CD with 80% bootstrap fraction may be possible with ~500kW.
- ✓ High H factor(~1.2) needs to be attempted by forming ITB with MHD stability.