



Research in Versatile Experiment Spherical Torus (VEST) for the Development of Compact Fusion Reactor

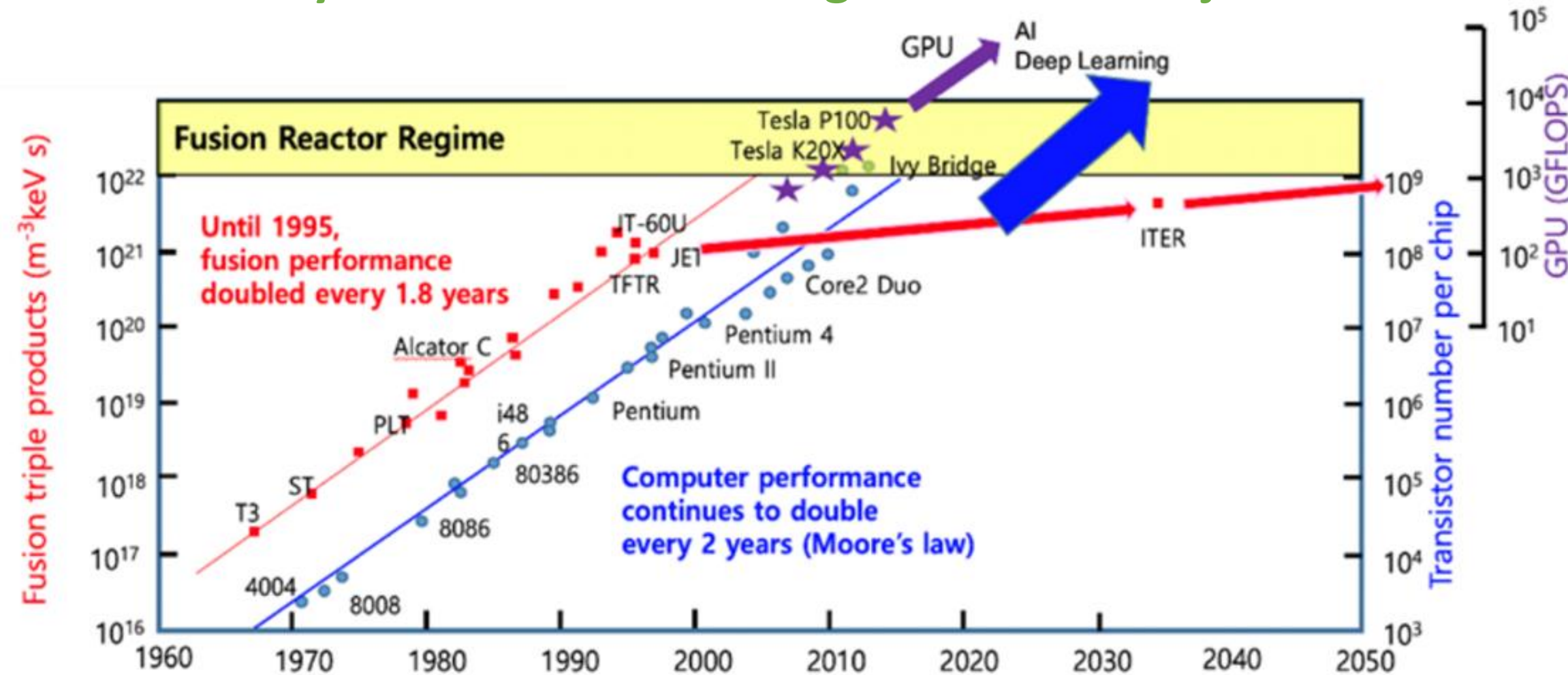
Yong-Seok Hwang and VEST team

Seoul National University

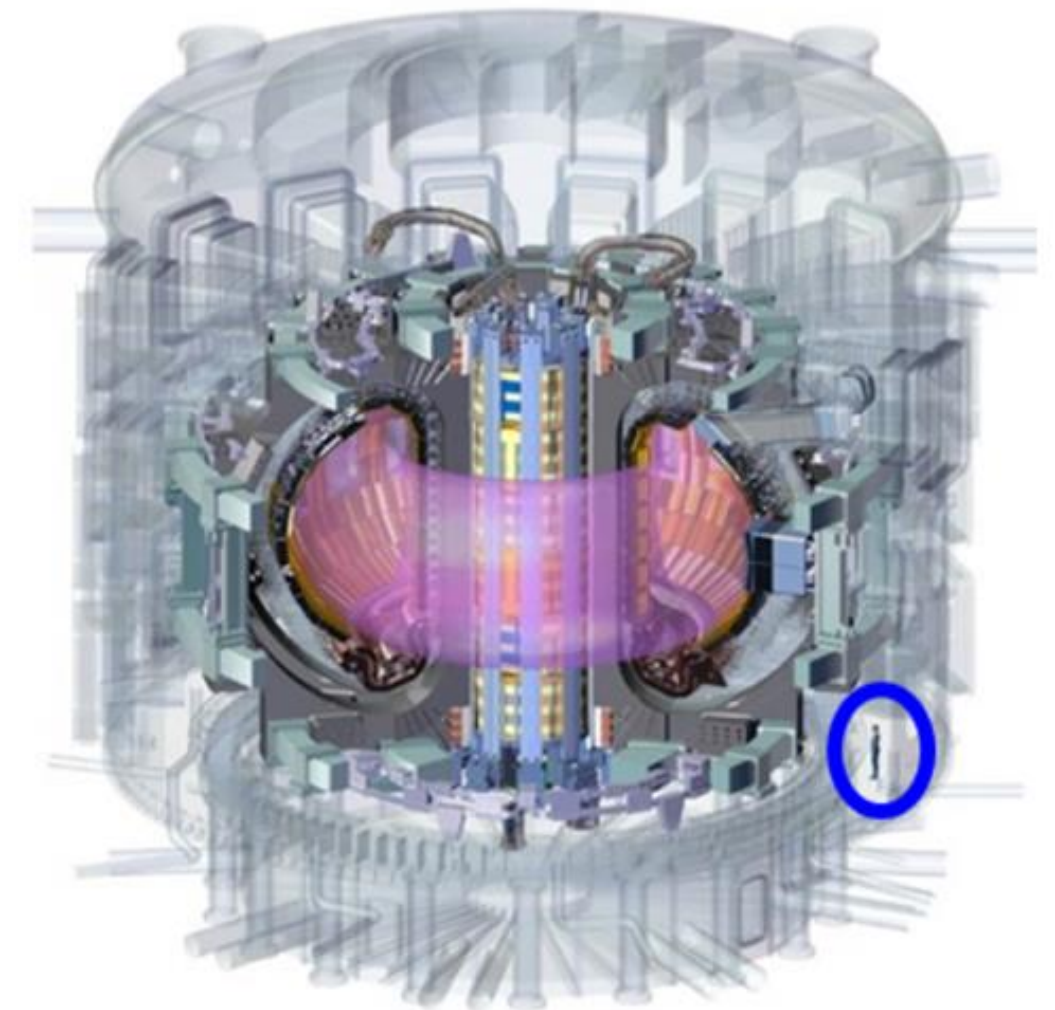
- **Spherical Torus as a Compact Fusion Reactor for Net Zero 2050**
- **Center for ST Fusion Metaware Research**
- **Versatile Experiment Spherical Torus (VEST)**
- **Research Activities and Plans for Compact Fusion Reactor**

How about Fusion Energy for Net Zero 2050?

History of Tokamak R&D Progress and its Projection



A massive fusion R&D project ITER



Fusion science has been developed as fast as IT technology until 2000, but significantly slowed down since the huge ITER project to verify fusion energy feasibility.

WHY? Size-dependent empirical approach for fusion performance

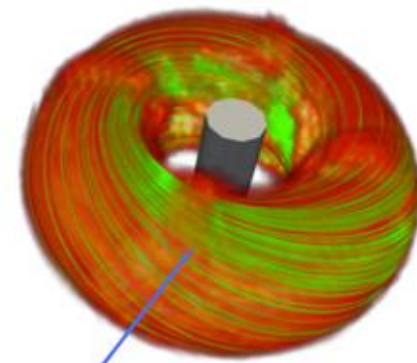
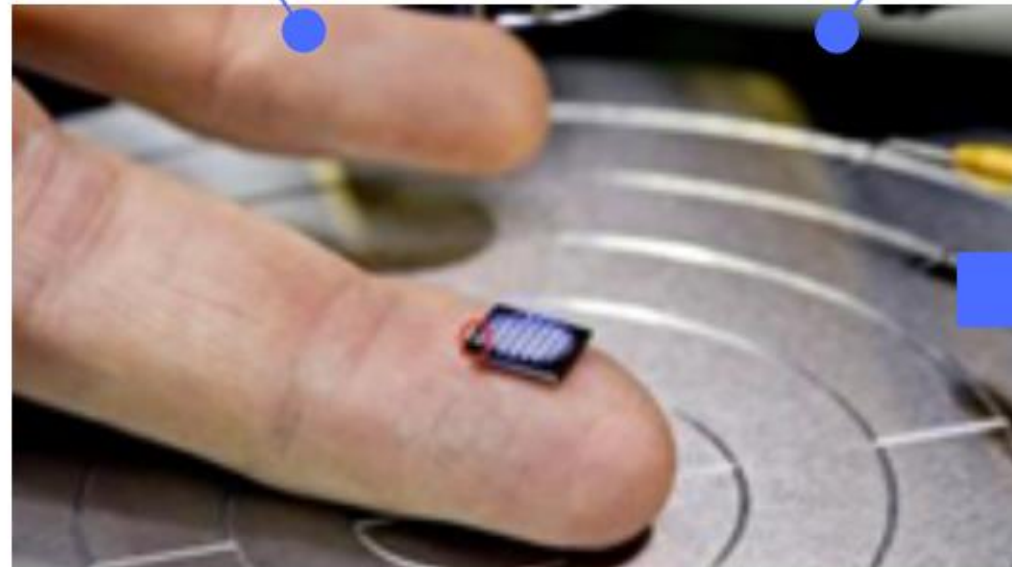
- Increased size of experimental devices such as ITER
- Long construction time and huge cost delay progress
- Scientific challenge to expedite fusion energy development **needs Paradigm Shift !!**

How to Realize Compact ST Fusion Reactor ?

Spherical Torus, ST + Virtual Fusion Reactor

→ Center for ST Fusion Metaware Research

2021. 7. 1 – 2025. 12. 31



Solution (by 2025)
Virtual Reactor on Chip

Objective:
Solving the ST Fusion
Plasma Challenges

- Stability
- Confinement

Expected Outcomes
(2050)

1,000 fusion
power plants

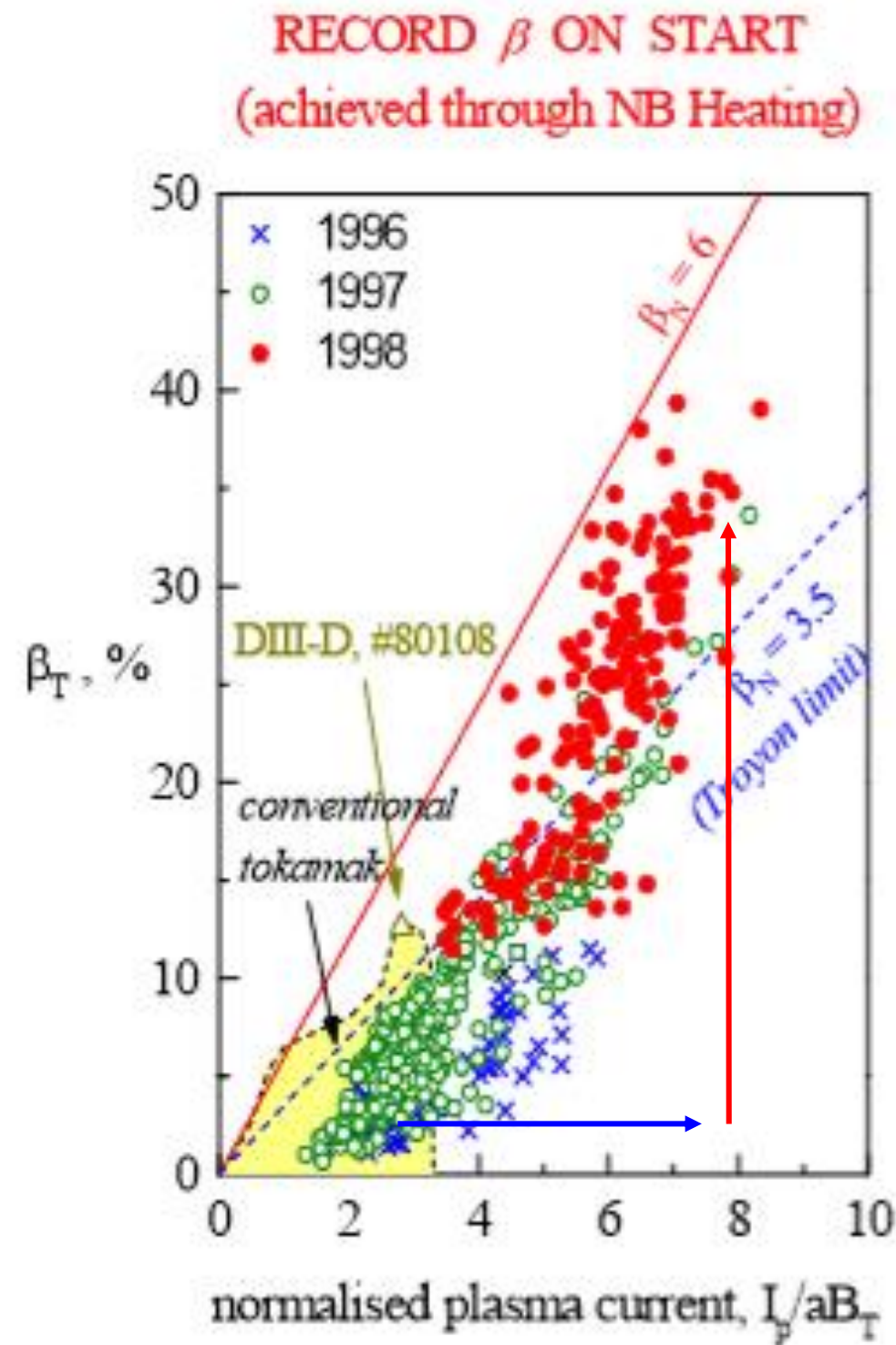


Apply virtual ST fusion reactor
to the design and optimization of compact ST fusion reactor
(Minimize repetitive building of huge experimental devices)

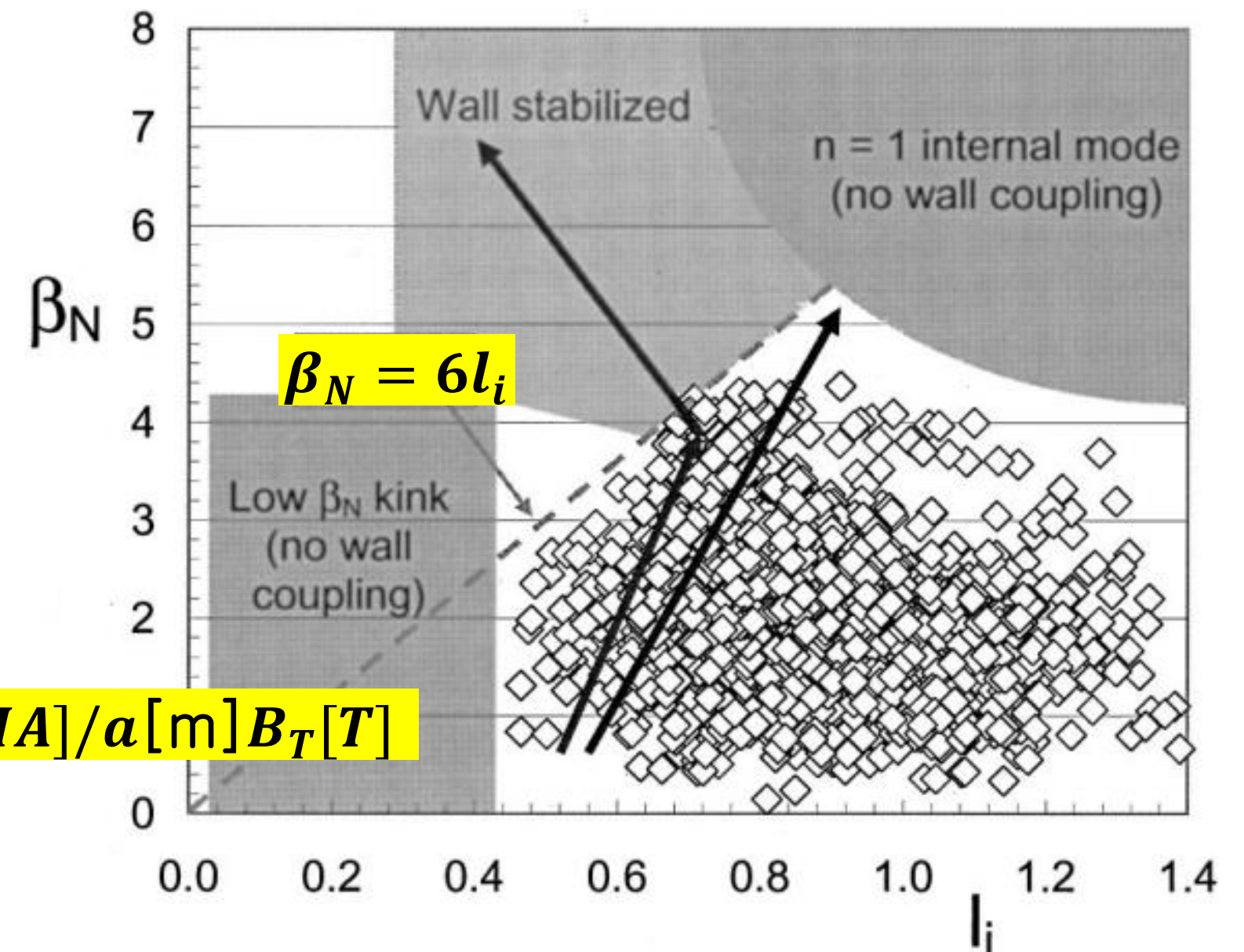
High-Beta Operation for Compact ST Fusion Reactor

MHD stability in ST : q_a , l_i and β_N

Low inductance with high bootstrap fraction in reactor



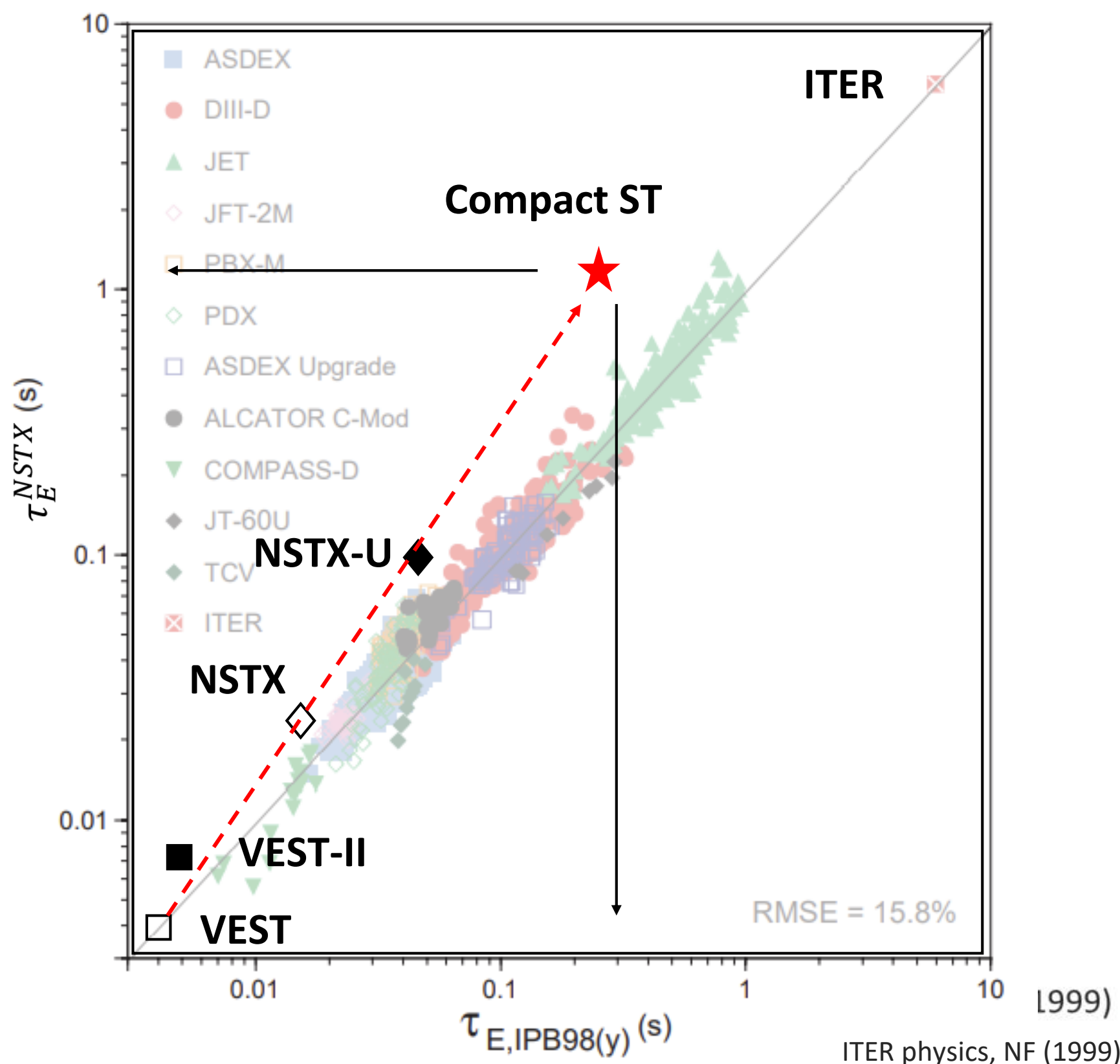
High β_N at low l_i
with wall stabilization



$$\beta[\%] = \beta_N I_P [MA] / a[m] B_T [T]$$

S.A. Sabbagh, et al., PoP (2002)

Good Confinement Operation for Compact ST Fusion Reactor



$$\tau_{E,th}^{ELMy} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} R^{1.39} a^{0.58} \kappa^{0.78} M^{0.19}$$

$$\tau_E^{NSTX} = 0.169 I^{0.57} B^{1.08} P^{-0.73} n^{0.44} R^{1.39} a^{1.69} \kappa^{0.78}$$

ITER



$R/a = 6.2\text{m}/2.0\text{m}$
 $B = 5.3\text{T}, I = 15\text{MA}$
 $Q = 10$ (500MW/50MW)

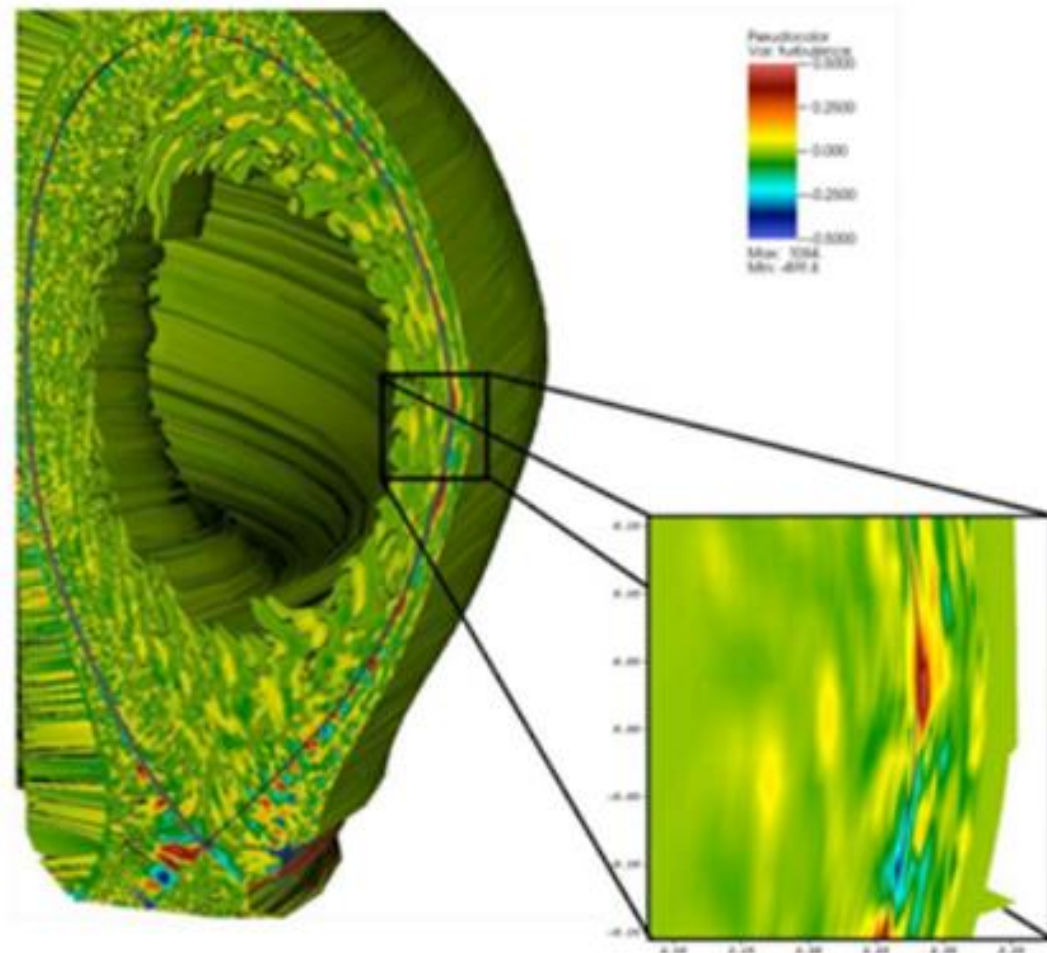
Compact ST



$R/a = 1.5\text{m}/1.0\text{m}$
 $B = 3\text{T}, I = 6\text{MA}$
 $Q = 7.5$ (70MW/10MW)

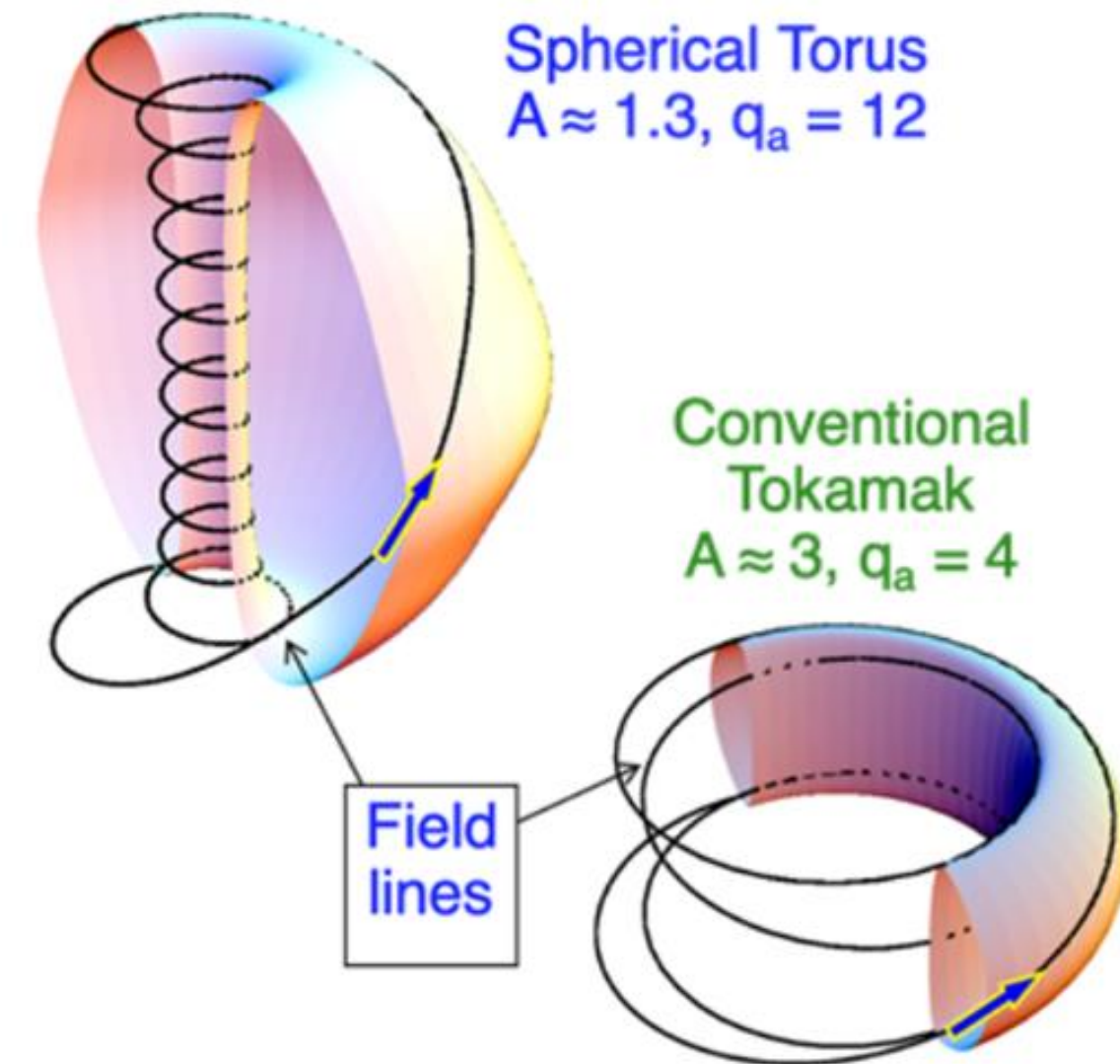
ST Theory Requires First-principle-based 6D Simulations

State-of-the-Art tokamak simulation: 5D Gyrokinetic (GK) simulation



Ku et al.,
Phys. Plasmas **25**,
056107 (2018).

- GK simulation: improving calculation speed via converting 6D to 5D calculations by averaging out the gyromotion.
- Tremendous computing time is normally required even with the world-best super computers even in the 5D calculation because of strong nonlinearity of fusion plasmas.

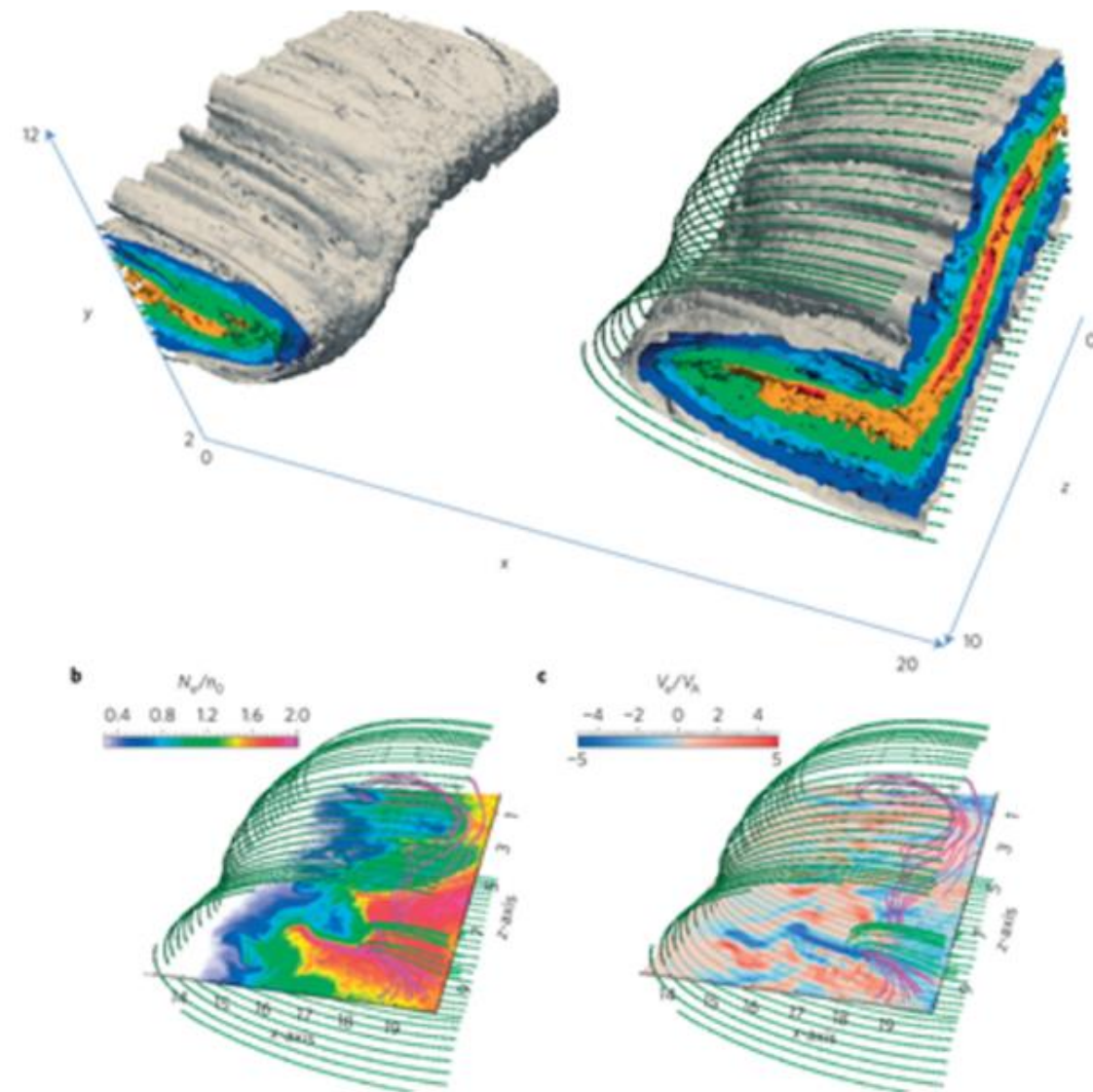


ST has **stronger nonlinearity and more complex particle orbits** than the conventional device

Current theoretical models (3-D MHD, 5-D Gyrokinetic) have limitations

First-principle-based 6D (3D+3V) full PIC simulation is necessary

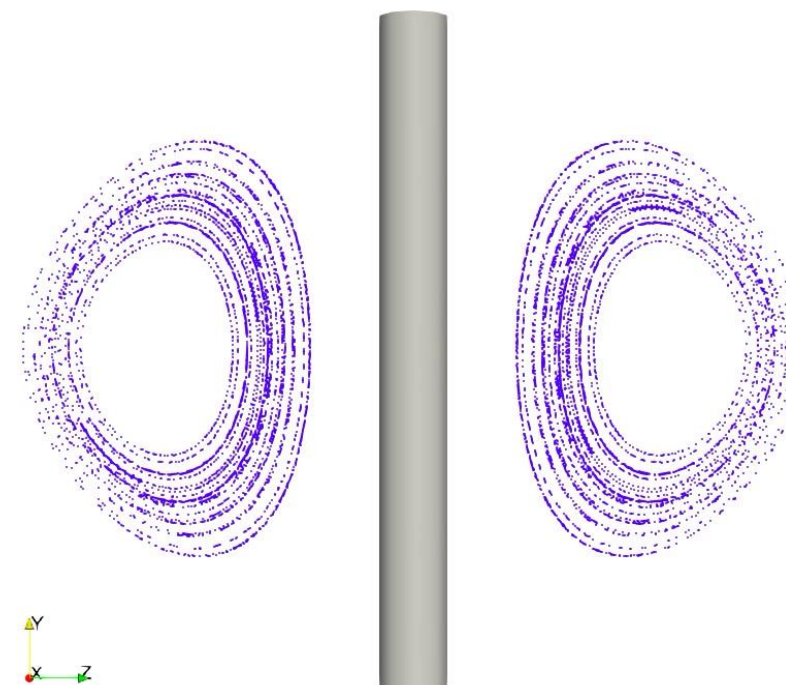
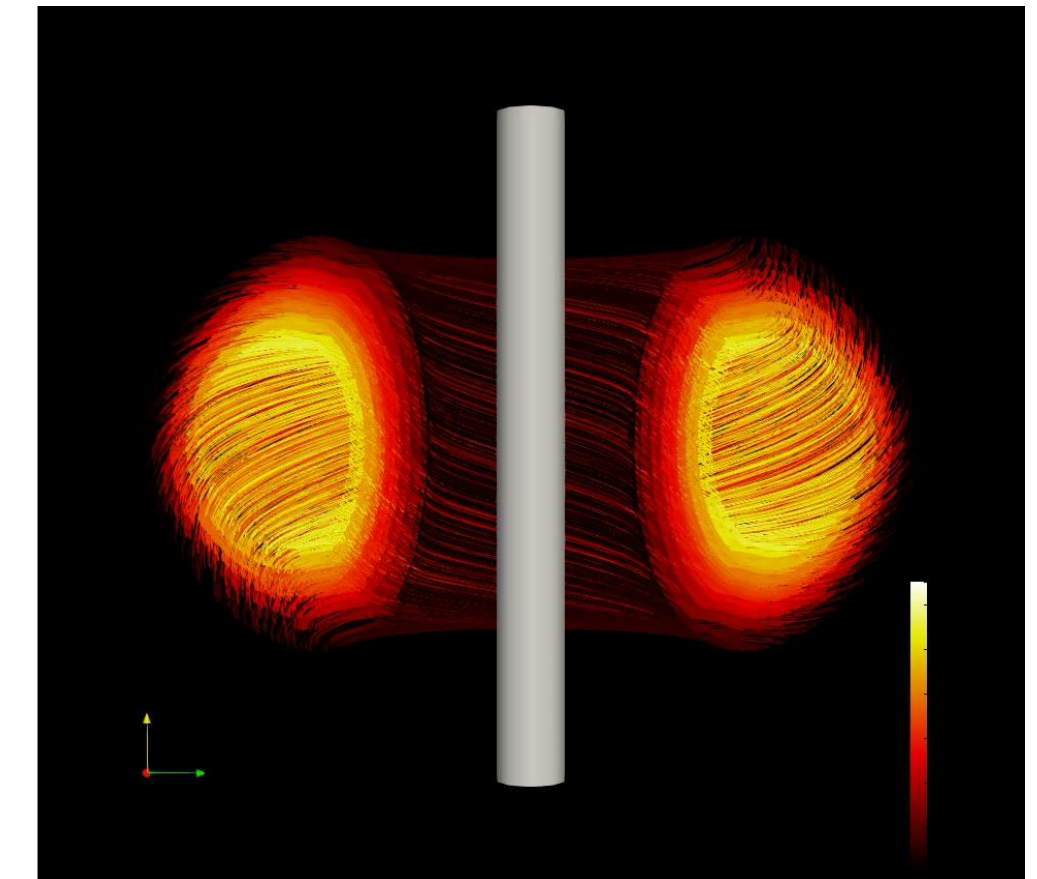
Preliminary Results with 6D Full PIC Code



G. Lapenta, et. al., Nat. Phys. 11, 690-695 (2015).

Magnetic reconnection
in space plasmas are
well addressed by ECsim code

Simulation Results in conventional tokamak (Simulation on magnetic surfaces)



J.Y. Park

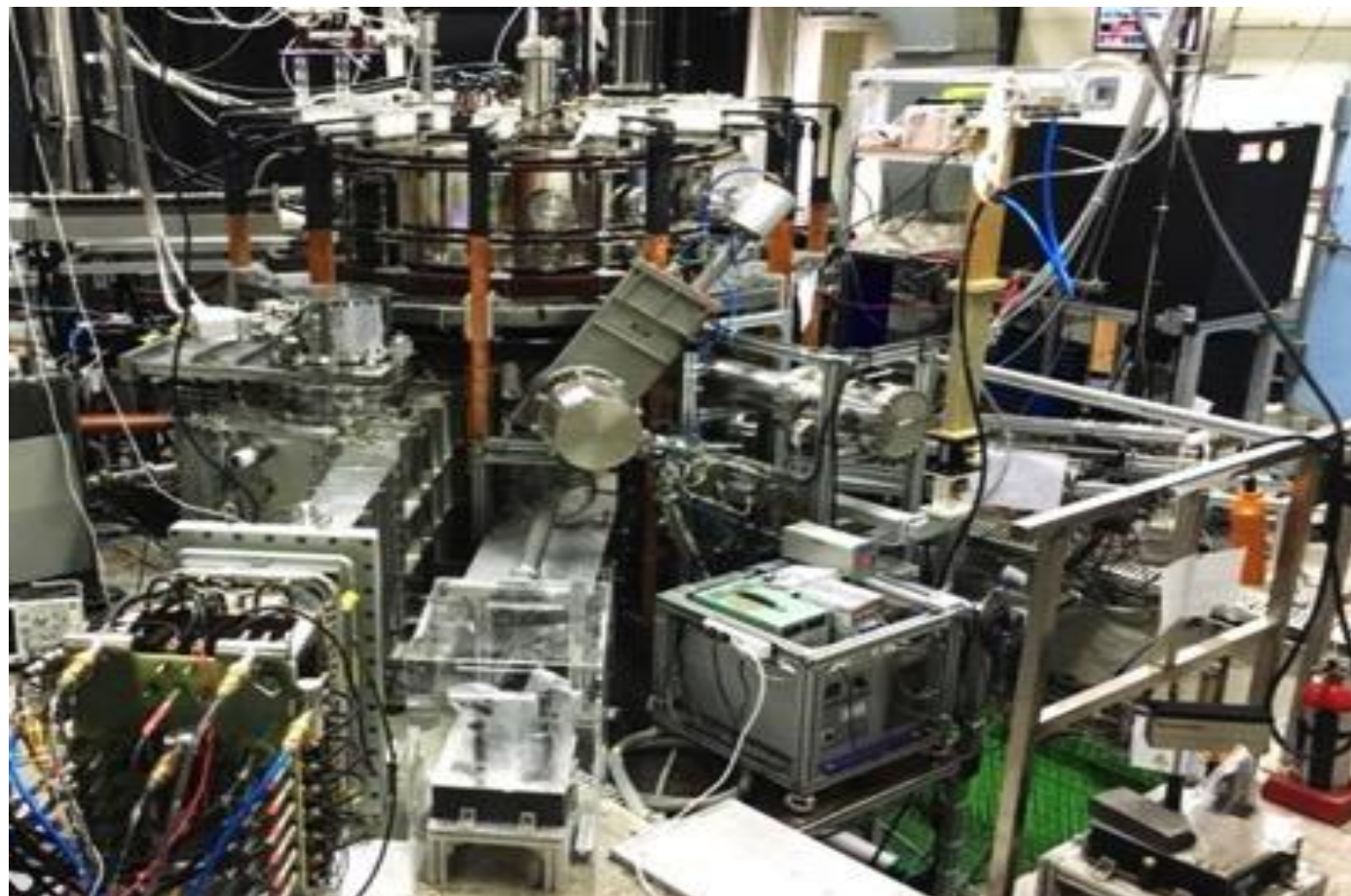
The result of 6D full PIC simulation on the conventional tokamaks
- Successful in the observation of tearing modes, a typical instability
in tokamaks → **Feasibility of full PIC simulation for tokamak is shown !**

- Increase of the simulation speed with GPU will make the code operational with 1 trillion particles
- 6D full PIC Code is under development

Real-Virtual ST Integrated System

[Hardware-VEST] ST experiments

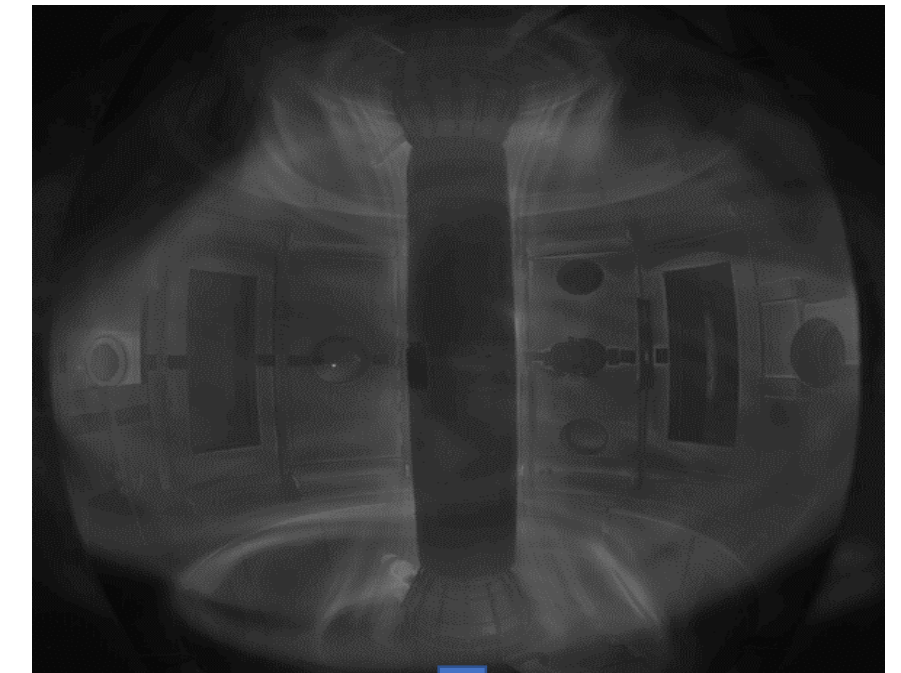
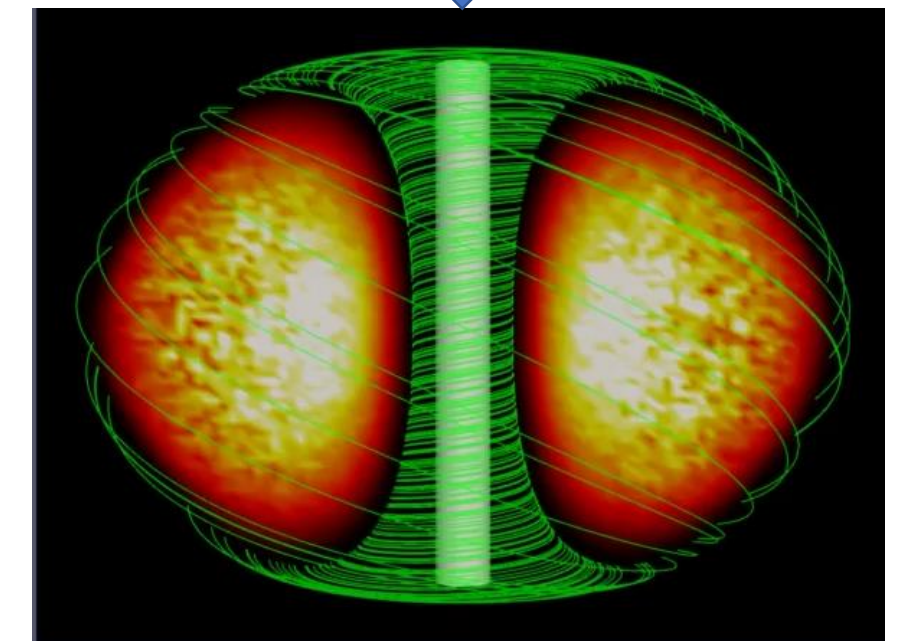
- ✓ Data generation for compact high beta ST
- ✓ **Device upgrade for simulation-oriented experiments**



VEST (Versatile Experiment Spherical Torus)

**Digital Twins (DT)
Cyber-Physical System (CPS)**

Real experimental results



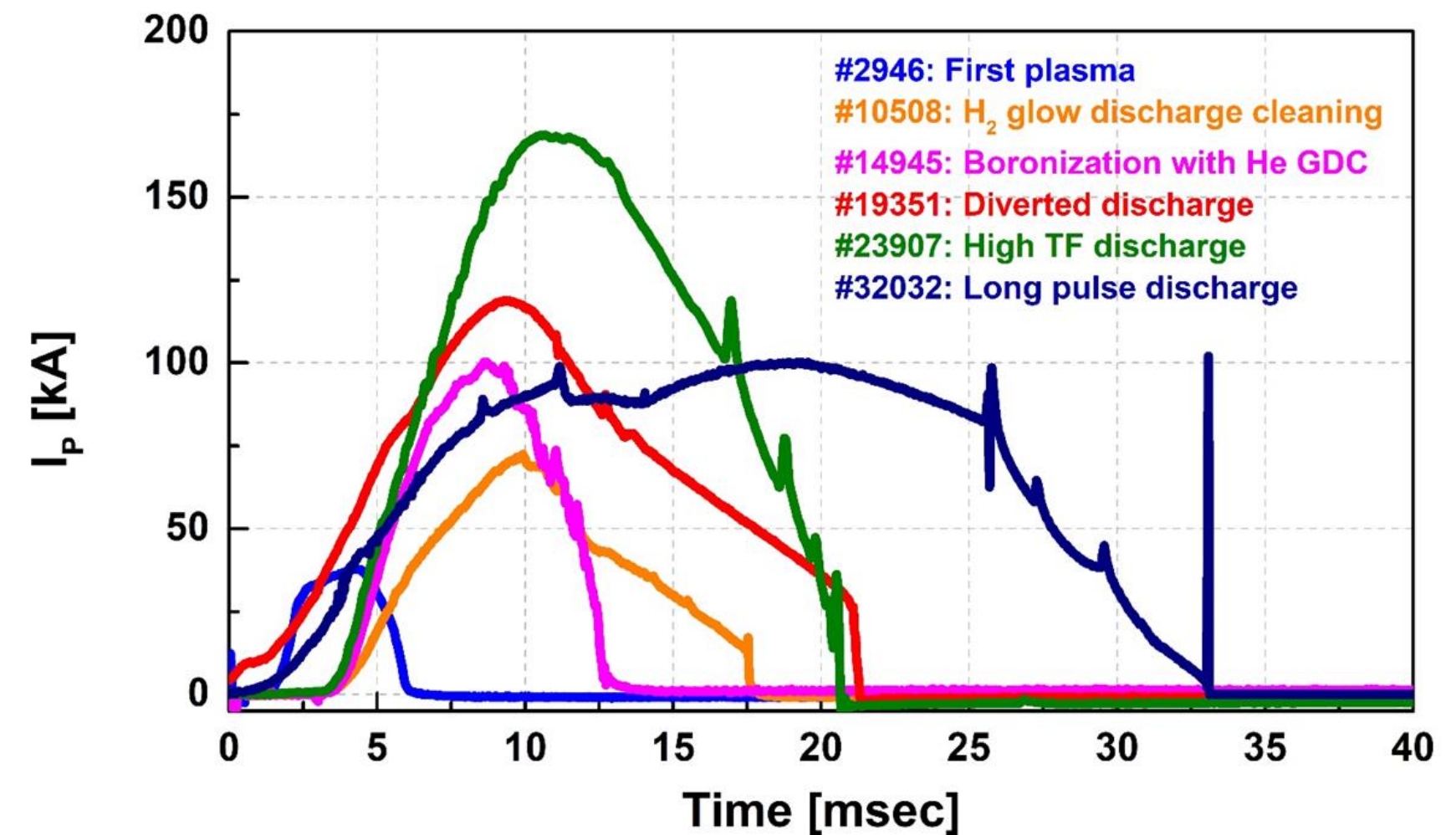
Virtual ST plasma model

[Software] First-principle-based 6D full PIC code

- ✓ 300 million particle simulation with CPU code
- ✓ **Billion particle simulation with GPU code** → **[MetaWare] Software and Hardware for DT/CPS**

VEST (Versatile Experiment Spherical Torus)

	Present	Upgrade
Toroidal B Field	0.1 – 0.18 T	< 0.3 T
Major Radius	0.4 m	0.4 m
Minor Radius	0.3 m	0.3 m
Aspect Ratio	> 1.33	> 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/5GHz, 30kW) NBI (20keV, 1.2MW) LHFW (500MHz, 200kW)



● History of VEST Ohmic Discharges

- #2946: First plasma (Jan. 2013)
- #10508: Hydrogen glow discharge cleaning (Nov. 2014) I_p of ~70 kA with ~10 ms
- #14945: Boronization with He GDC (Mar. 2016) Max. I_p of ~100 kA
- #19351: Slower ramp-up and diverted plasma (May. 2018) Max. I_p of ~120 kA with ~20ms
- #23907: Higher TF of 0.18T (Oct. 2019) Max. I_p of ~170 kA
- #32032 : Slower ramp-up, pulse length of ~30ms with the I_p of ~100 kA (April 2021)

● Major upgrade plans for VEST : Doubling of Ohmic and NBI heating capacities

High normalized plasma current and high beta

VEST Power Upgrade Plan : Ohmic Heating (OH) Phase

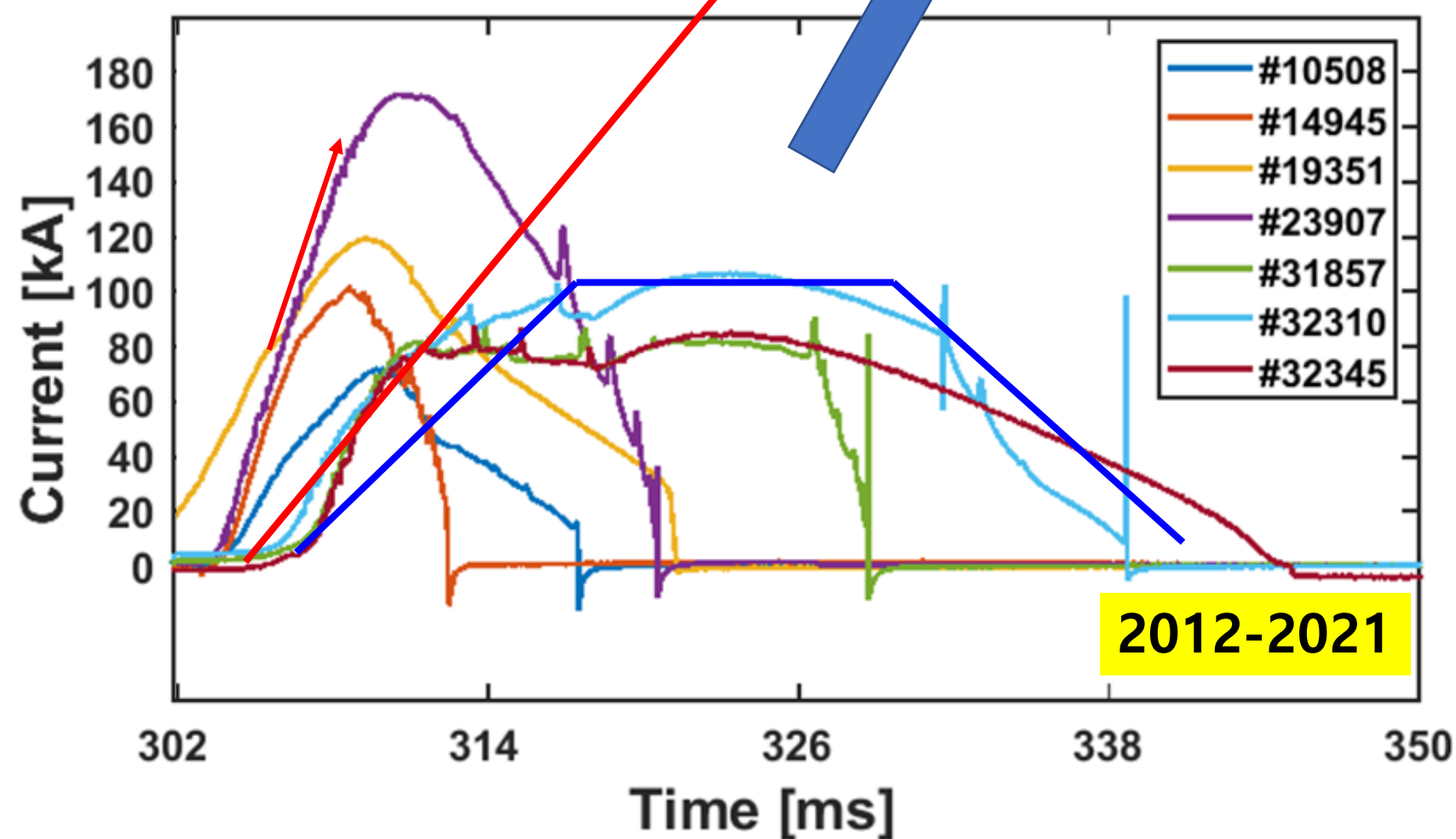
- OH plasma currents of up to 300kA → Start-up simulation High current (low q_a), long pulse

Normalized current from 3 to >5

OH/EF power upgrade
Vacuum and wall conditioning

$B_{TF} < 0.2T$, $I_p > 300kA$, $t_{flat\ top} > 10ms$

$R=0.4m/a=0.3m$, $\kappa=2$



- Double PF1 volt-second

✓ 10kA → -10kA swing ~50mVsec

✓ 20kA → -20kA swing ~100mVsec

$B_{TF} = 0.1T$, $I_p < 100kA$

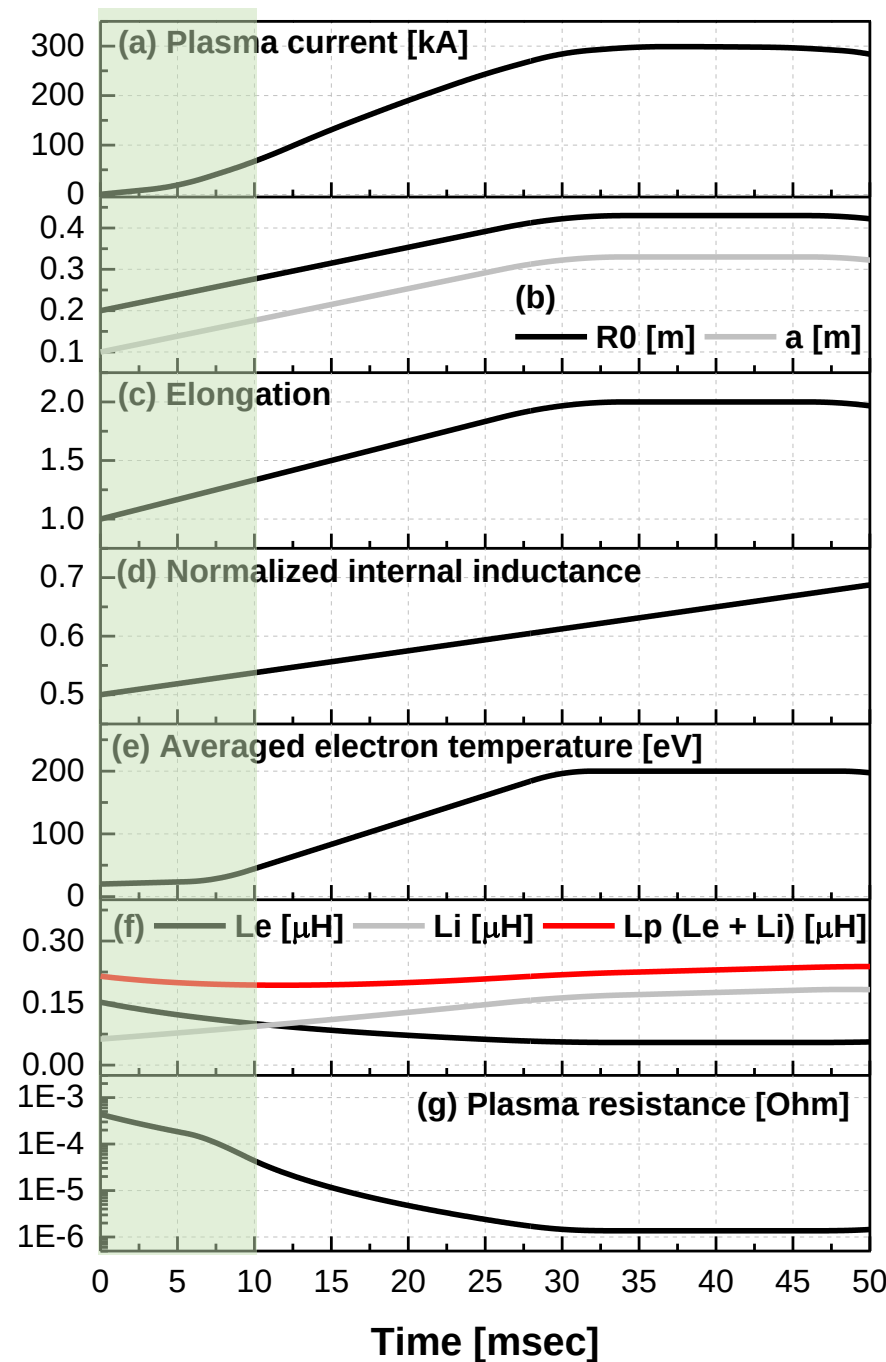
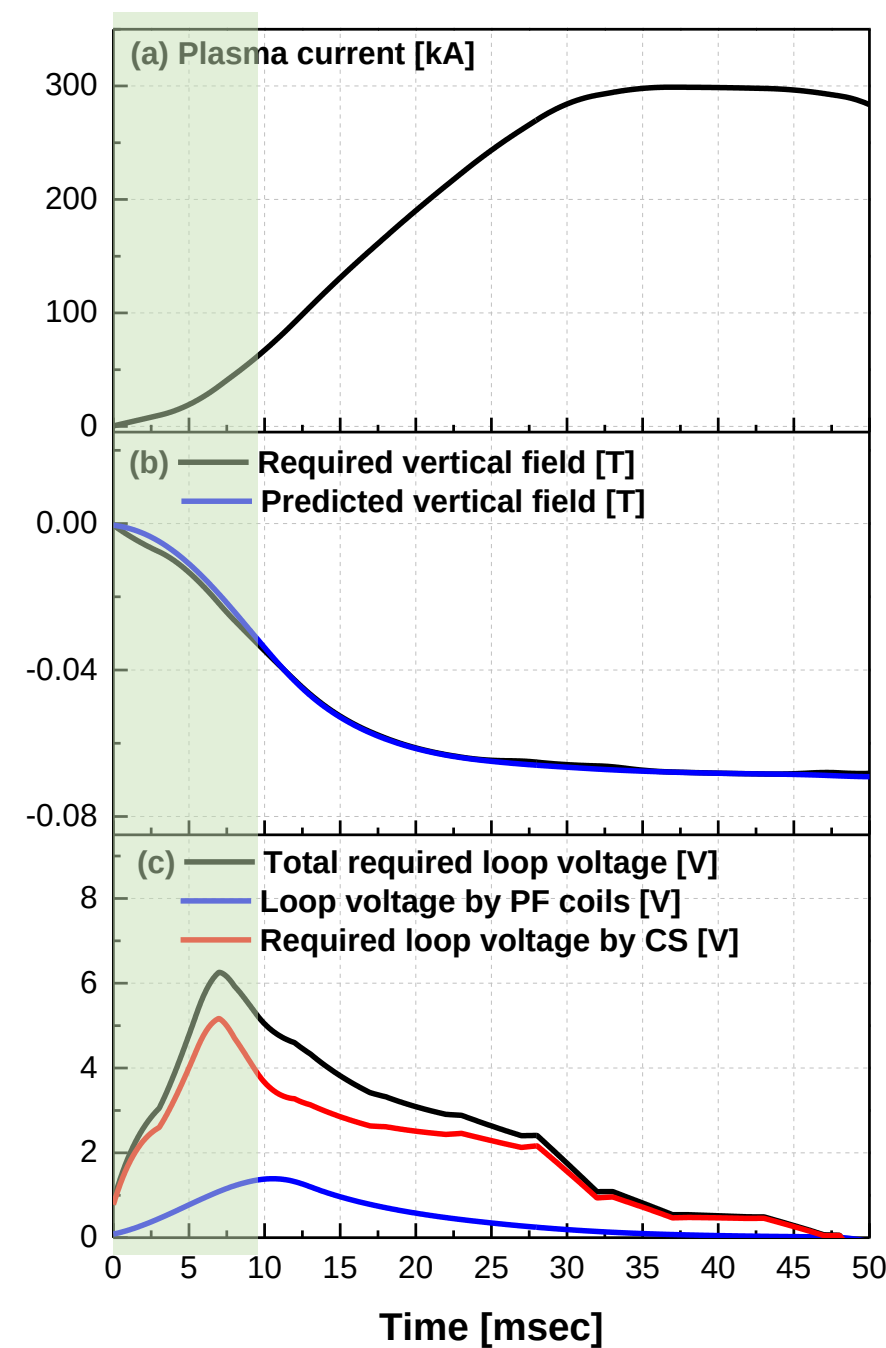
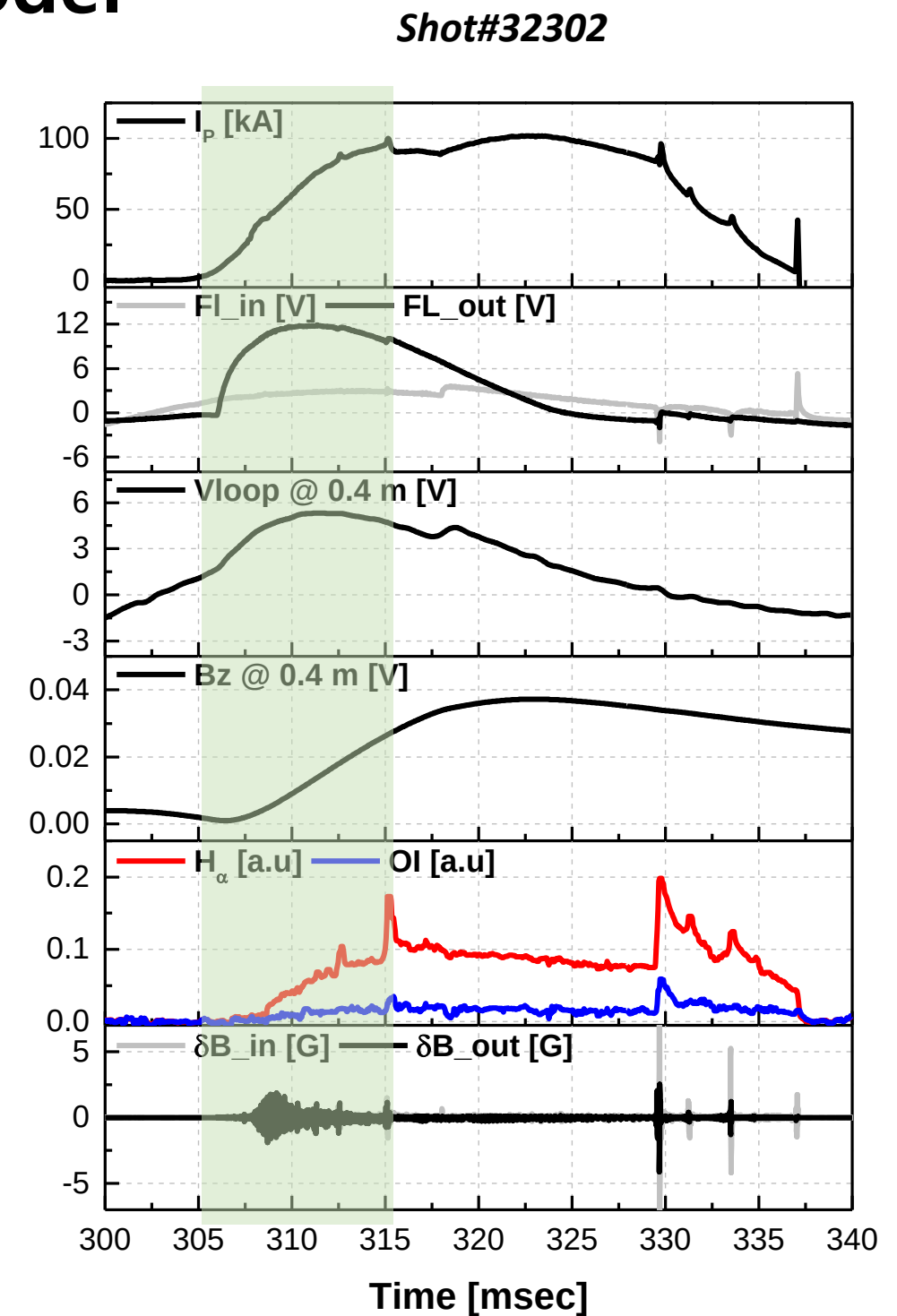
$B_{TF} = 0.18T$, $I_p < 170kA$

Limited by magnetic/particle control !
Still more room for stability (reduce q_a) !

VEST Power Upgrade Plan – Startup Simulation

● Required PF1 coil currents from tokamak start-up model

S.C. Kim (Friday)



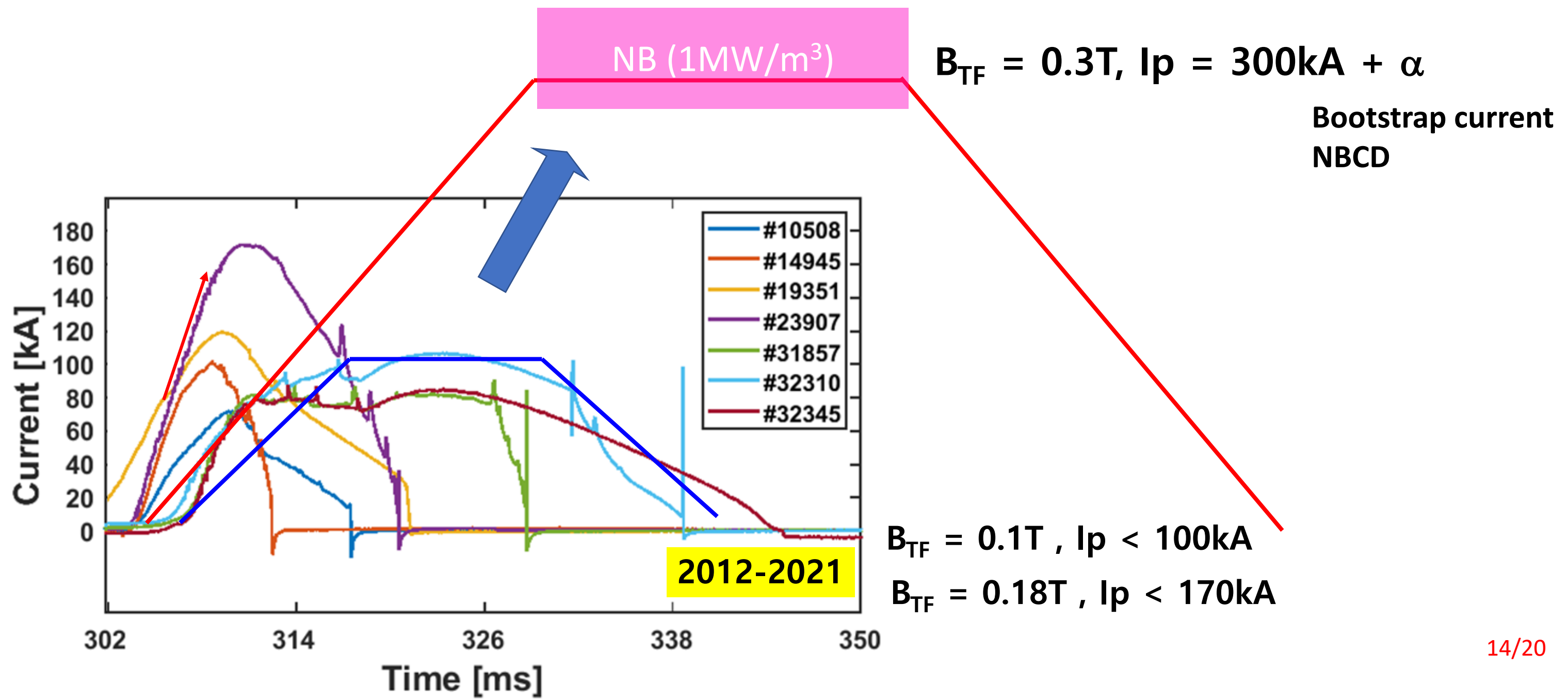
- Startup model (updated DYON) is confirmed with experimental data
- Shot plan for >300kA is simulated with the model for upgraded PF power systems

13/20

- VEST Upgrade **(Final goal: High beta, collisionless reactor-relevant regime)**

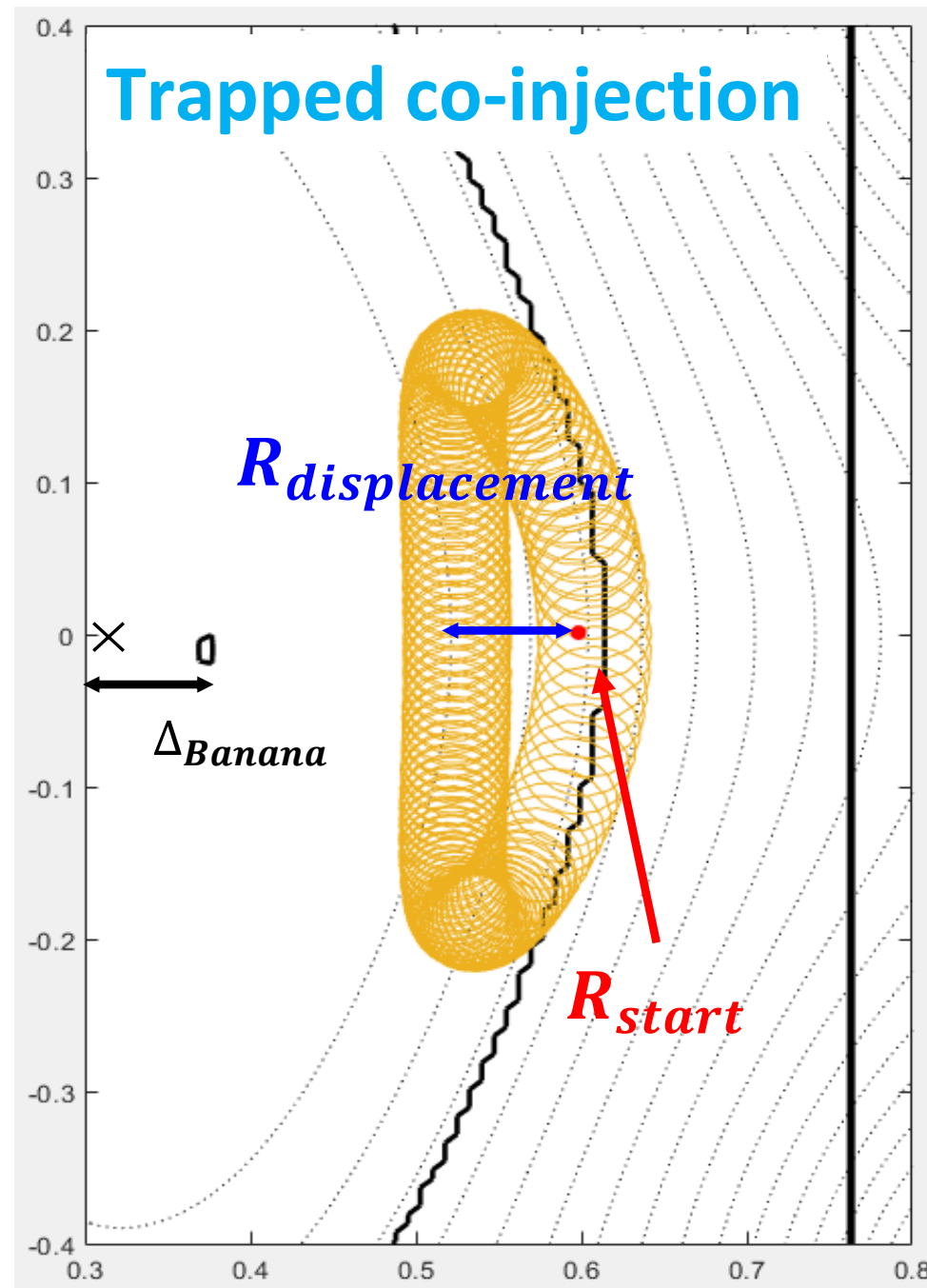
- OH Plasma ($I_p > 300\text{kA}$ at $B_{TF} = 0.2\text{T}$) → Start-up simulation **High current, long pulse**

- NBI-Heated Plasma ($P_{NBI} = 1\text{MW}$) → Integrated transport simulation **High beta, collisionless**

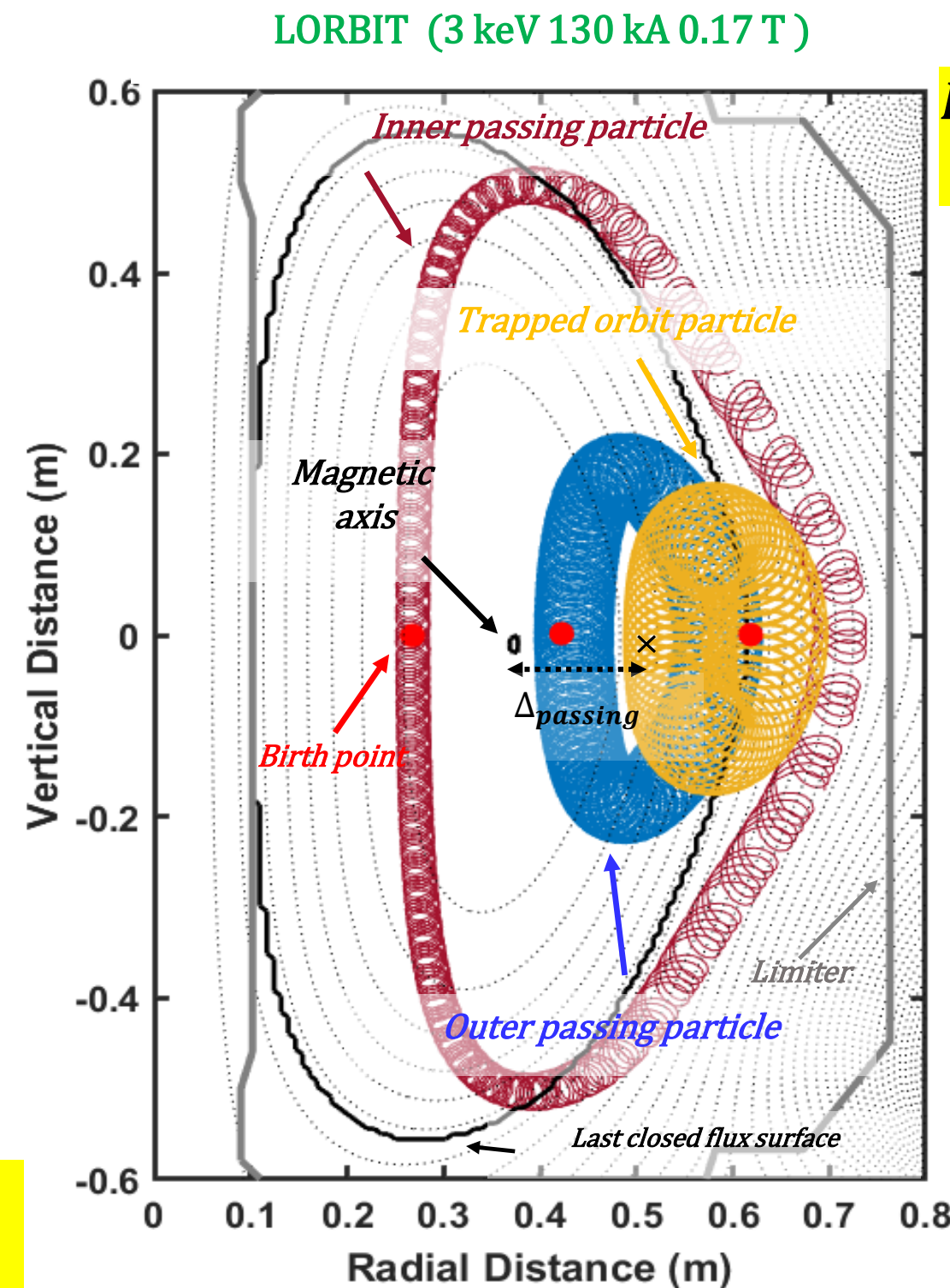


Confinement Condition of Fast Ions in ST

- Trapped particles are confined mostly in co-injection → High B_t is enough
- Passing particles are not because of passing particle orbit shift, especially in ST! → High I_p (B_p) getting important



$$R_{outwall} - R_{start} > R_{gyro} = \frac{mv_{\perp}}{|q|B_t}$$



$$R_{start} + R_{displacement} + R_{gyro} < R_{outwall} \rightarrow \text{Confined}$$

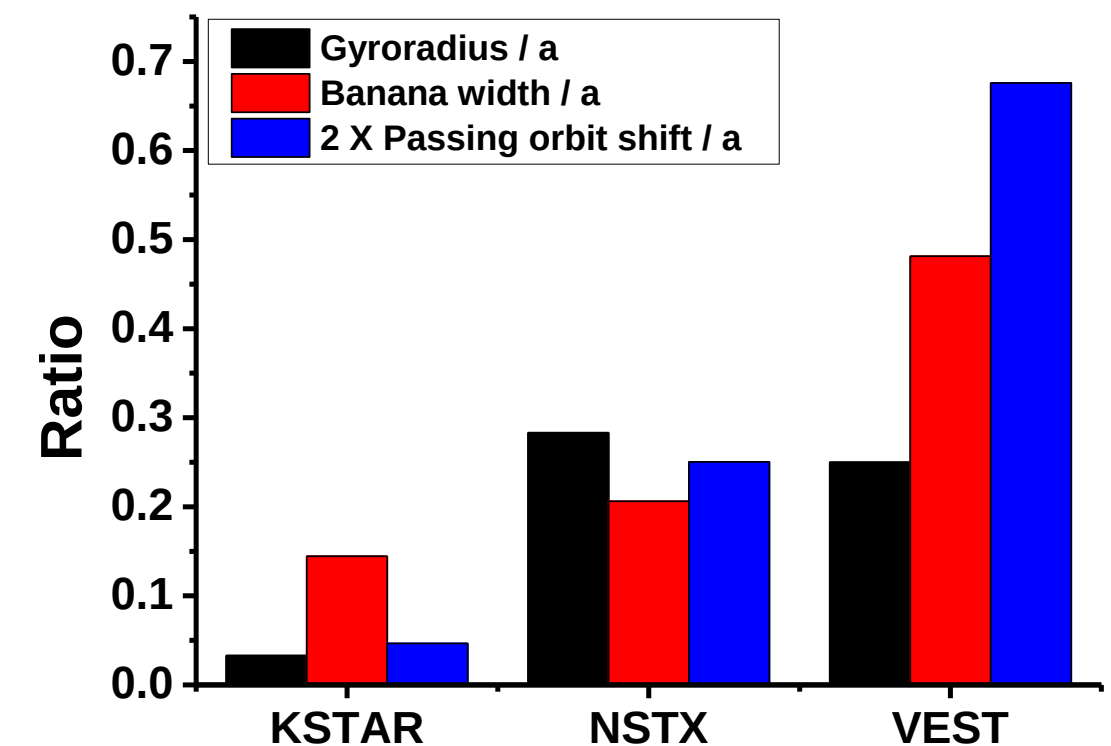
$$\frac{m_i v_{\perp}}{|q| B_t}$$

$$\frac{m_i v_{\parallel}}{e B_{\theta}}$$

Banana width

$$\frac{r}{R_{start}} \frac{m_i v_{\parallel}}{e B_{\theta}}$$

Passing orbit shift



Initial Results of NBI Heating Experiments in VEST

G.H. Lee

Two almost identical shots with different B_p

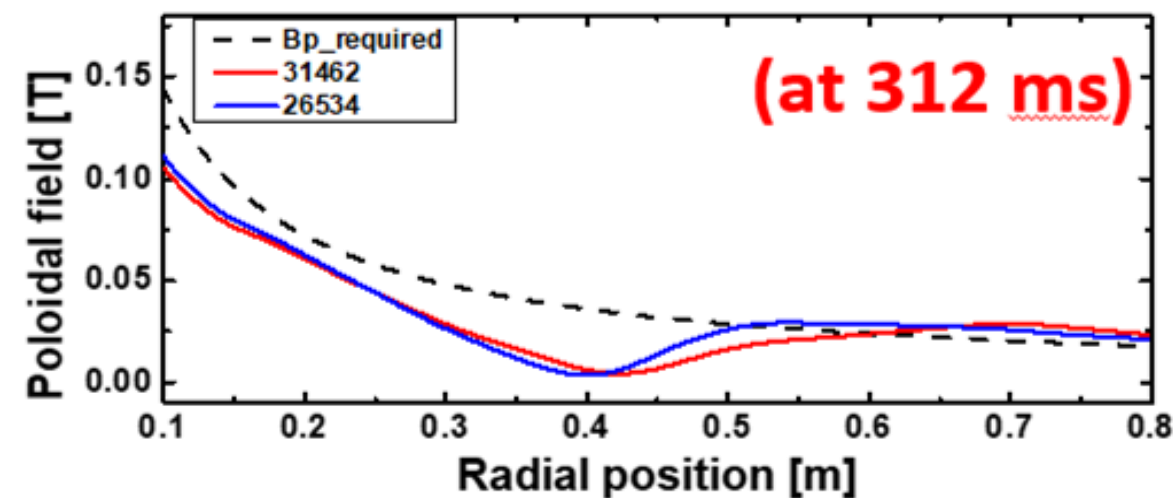
Shot Number : #26534, #31462

Base pressure : 1.5E-6 Torr

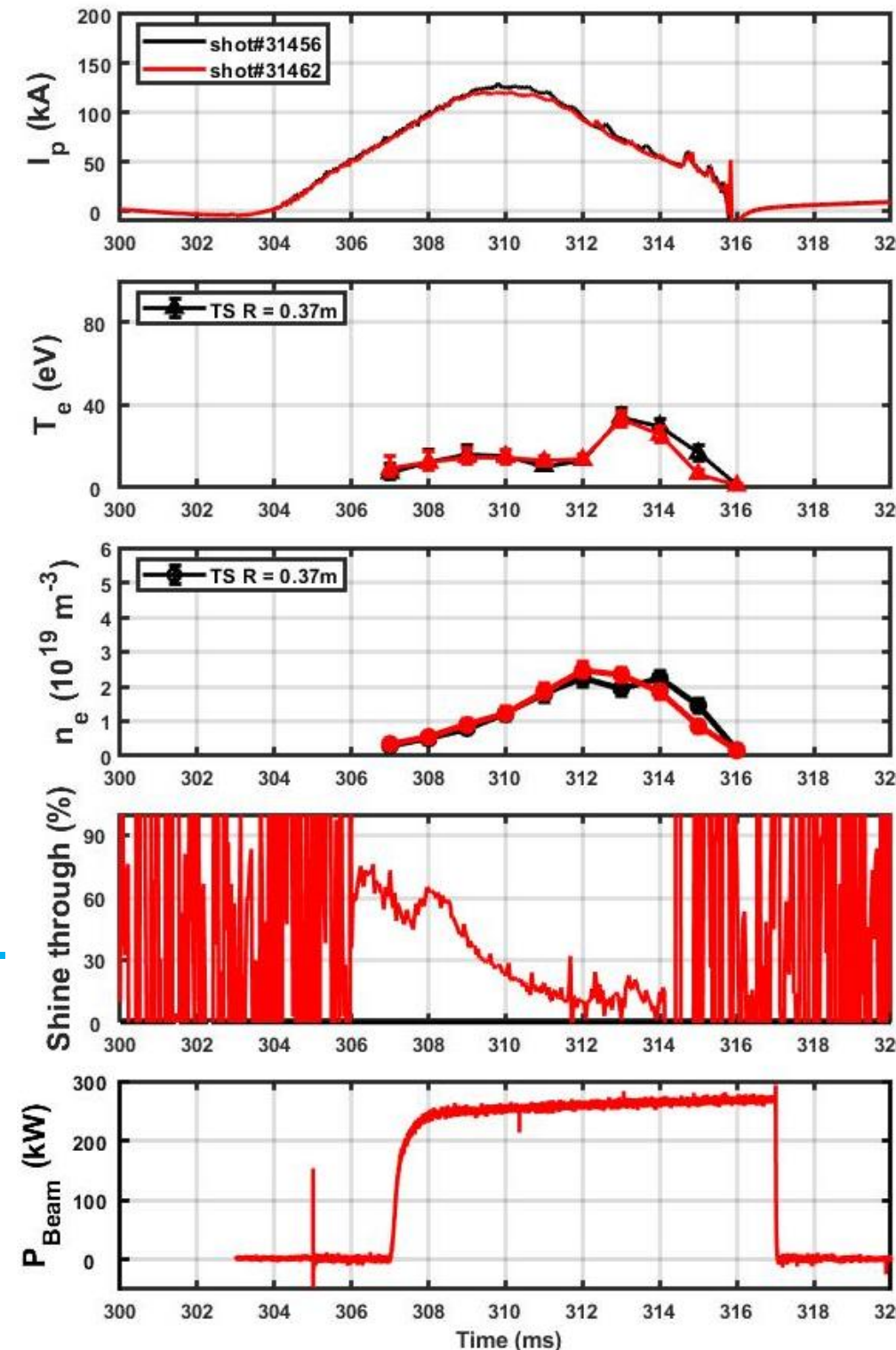
Wall conditioning : GDC(1 hr), Boronization(0.5 hr)

Bt : 0.175 T at R = 0.4 m

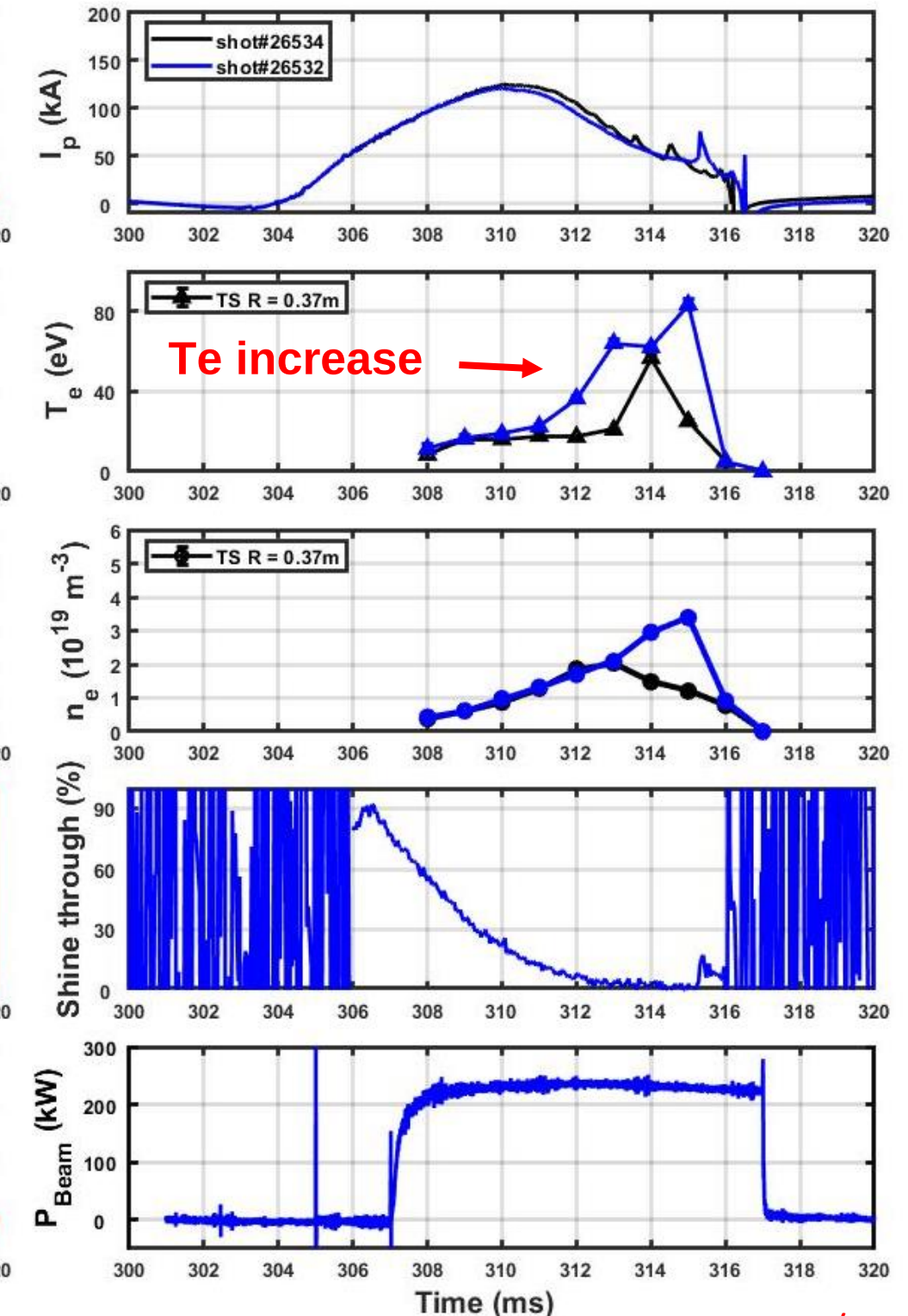
I_p : 128 kA, 131 kA (at peak)



Low B_p near the axis case (#31456)



High B_p near the axis case (#26534)



- Improvement NB heating efficiency by increasing the poloidal field near the magnetic axis is clearly confirmed.
- In both cases, the changes in plasma current was not significant, and the shine-through loss is similar in both cases.
- the increase in electron temperature due to beam injection appears only in the high B_p case.
- Heating efficiency is ~20 %

VEST Upgrade Plan for Effective NBI Heating

➤ NBI Heating with 1MW/20keV system

Effective NBI coupling

High beta, collisionless regime

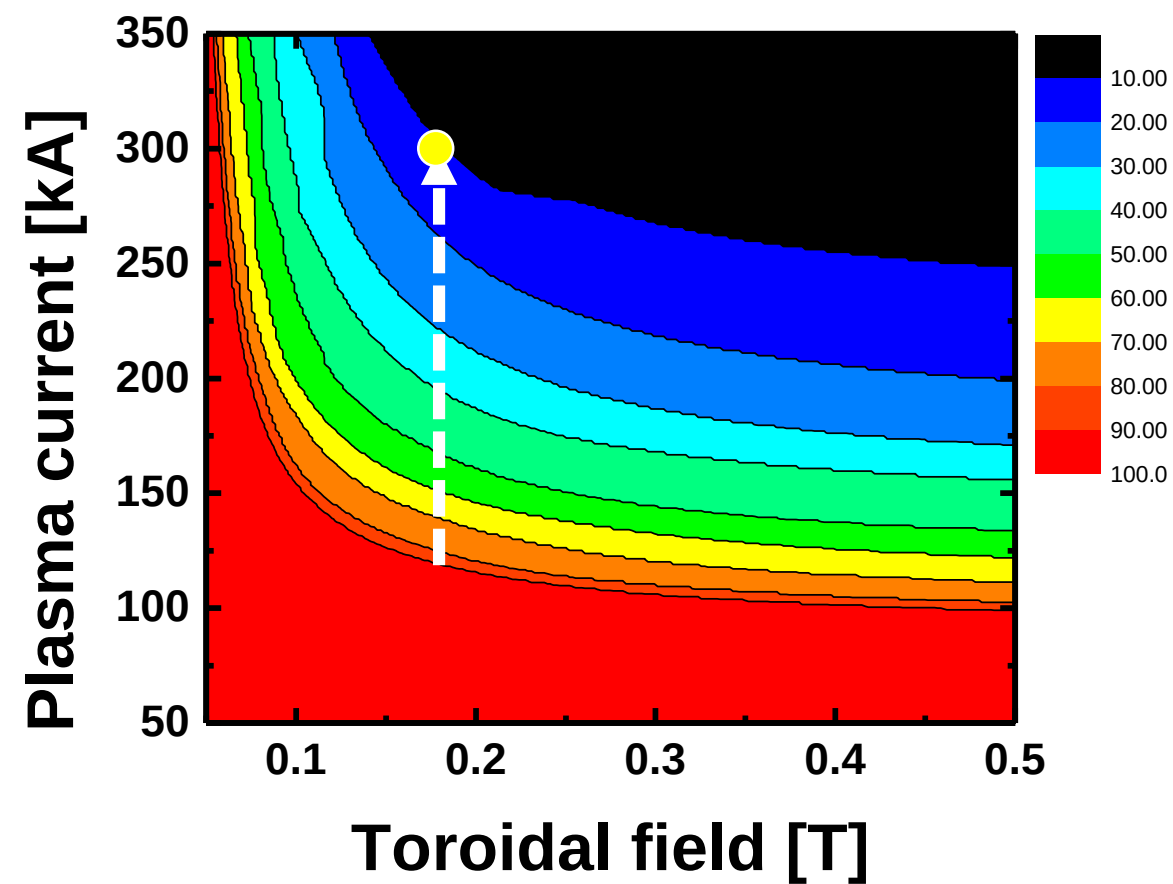
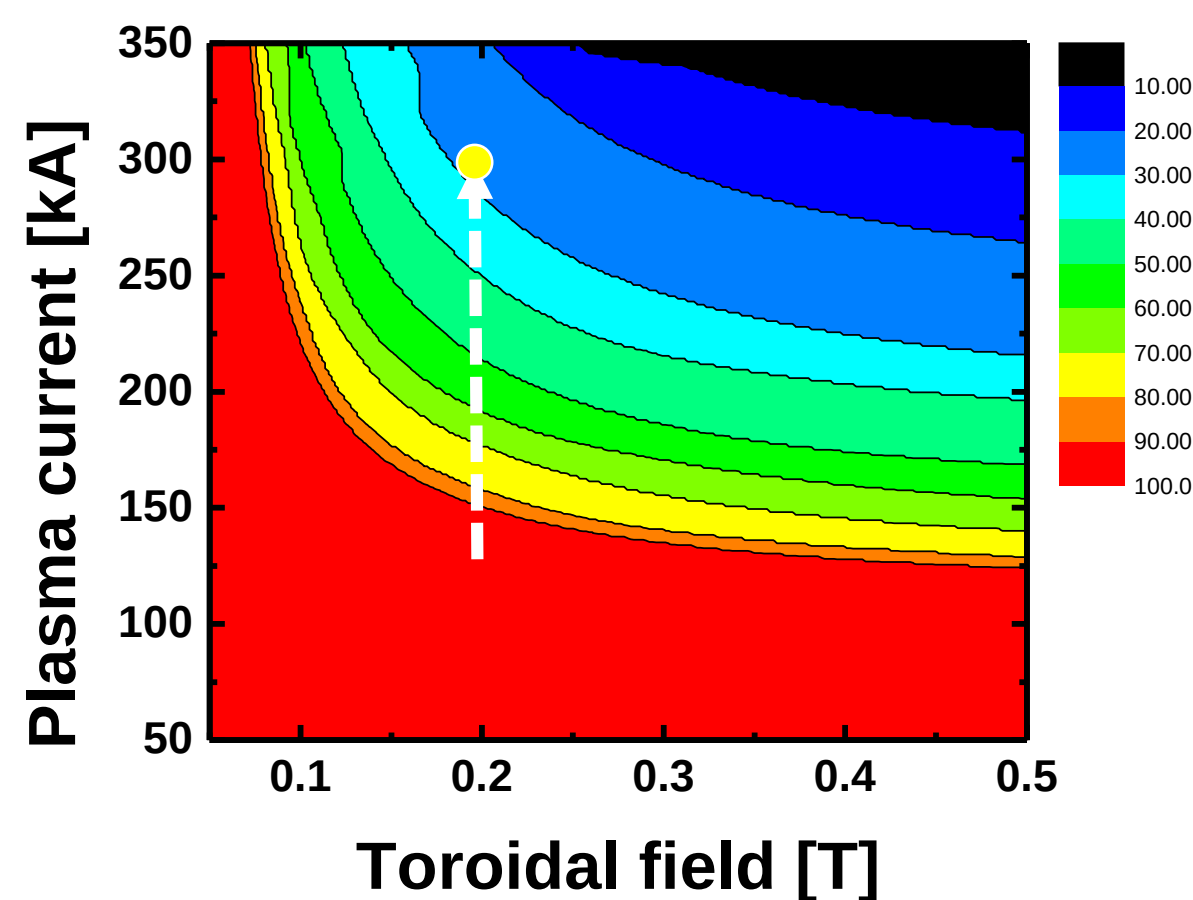
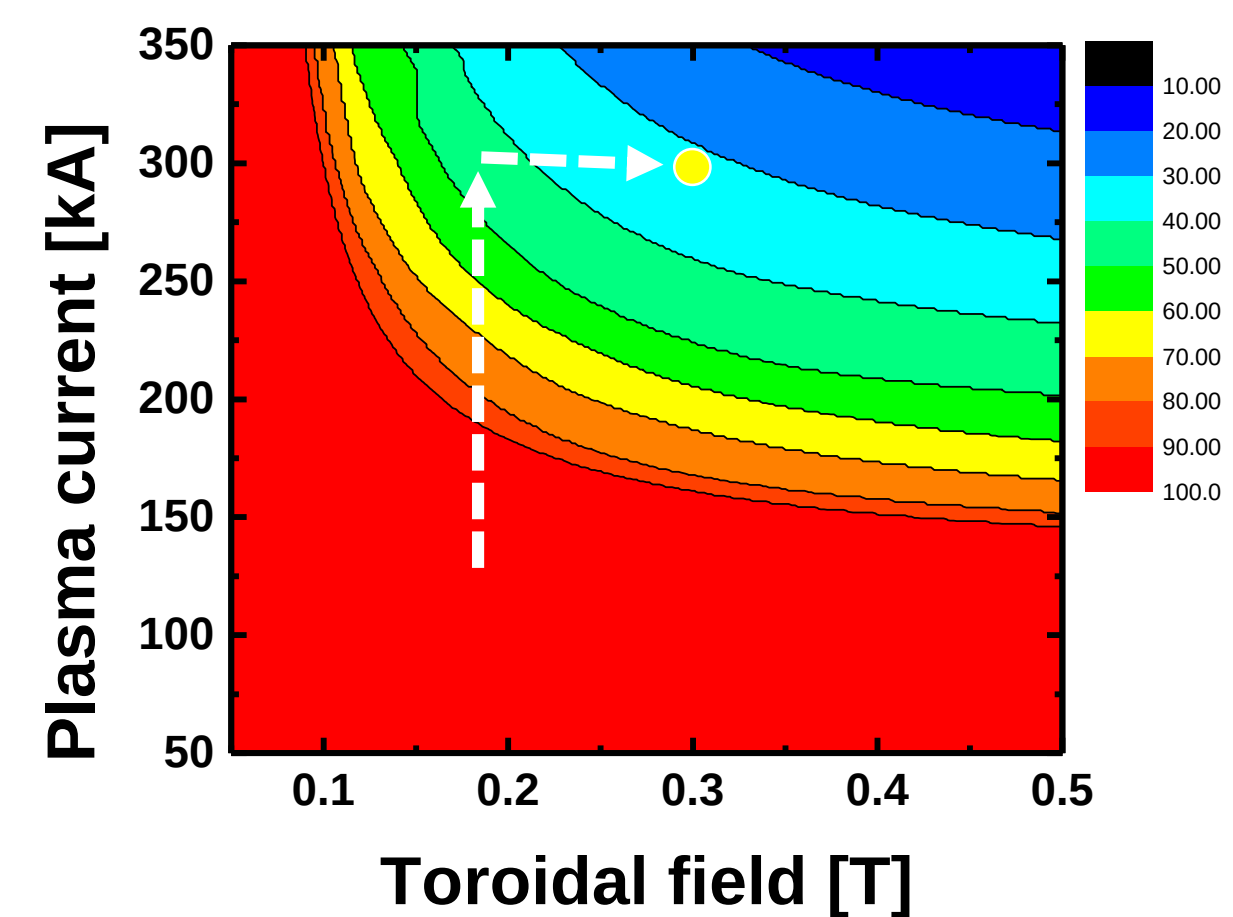
Simple model of fast particle orbit loss as a function of plasma current & toroidal field strength

- Plasma density (peak) : $2E19/m^3$ (shine through loss 17% at 10keV, 27% at 20keV)
- Reference value : I_p (120 kA), B_t (0.175 T), # 26534_310 ms

Beam energy : 10 keV (<300kW)

Beam energy : 15 keV (<600kW)

Beam energy : 20 keV (<1.2MW)

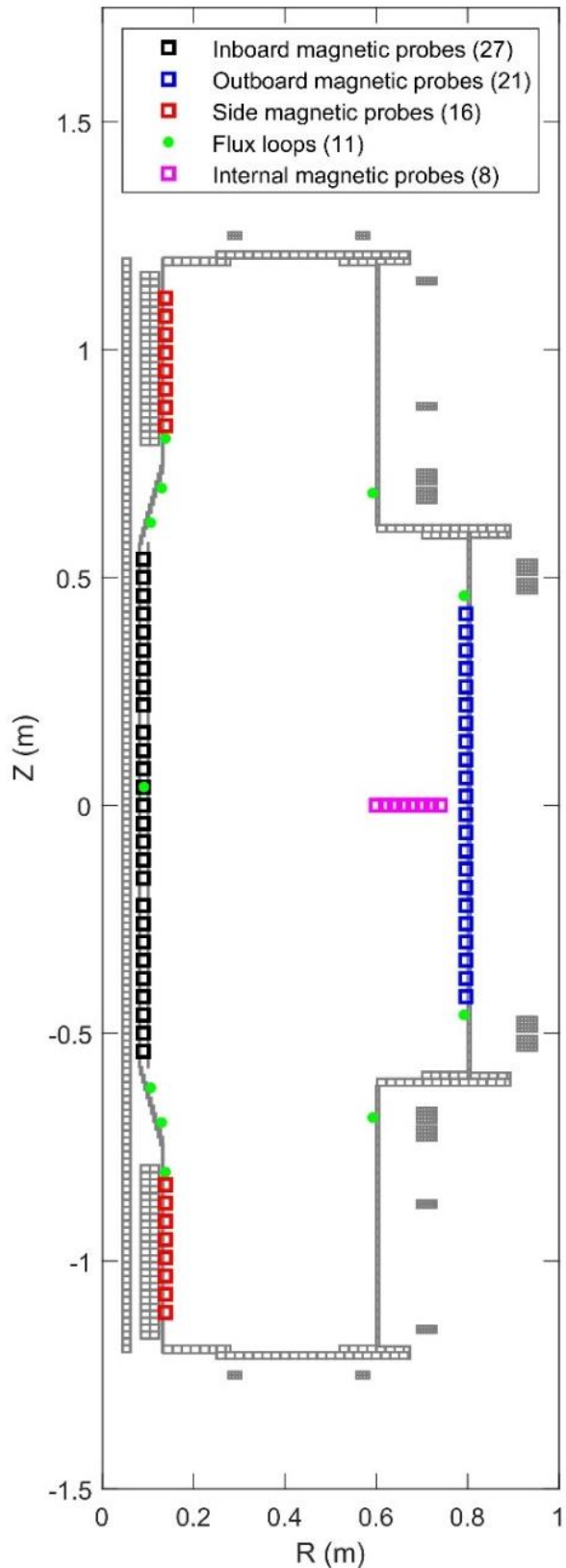


Increasing plasma current up to 300kA at 0.18T
→ Reduce orbit loss from 90% to 10%

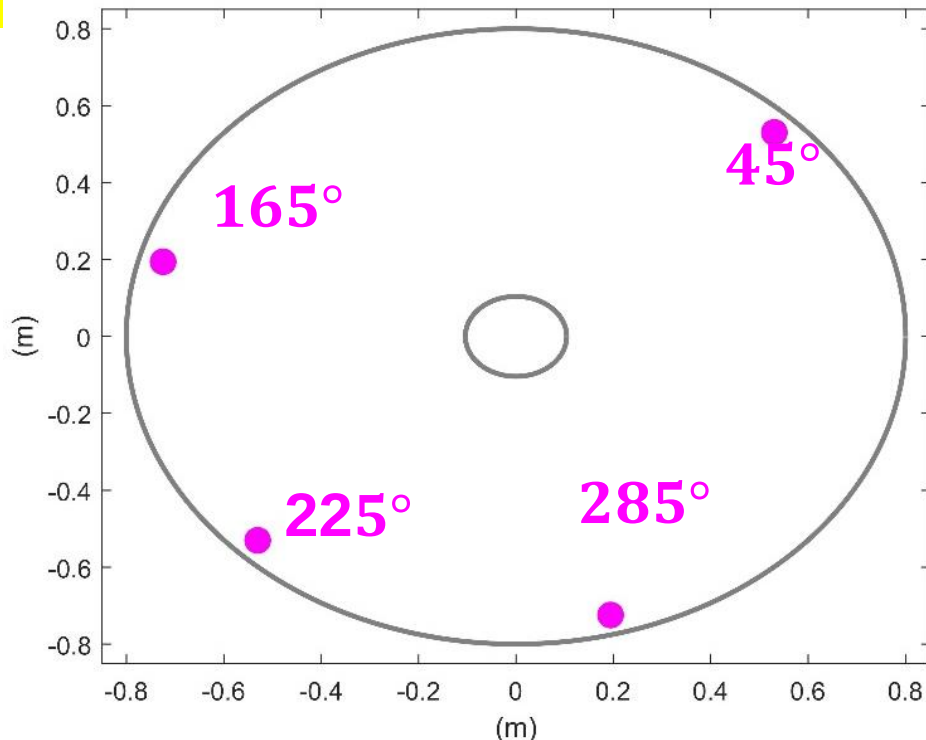
→ Reduce orbit loss to 30%

→ Reduce orbit loss to 50%
→ to 30% (at 0.3T)

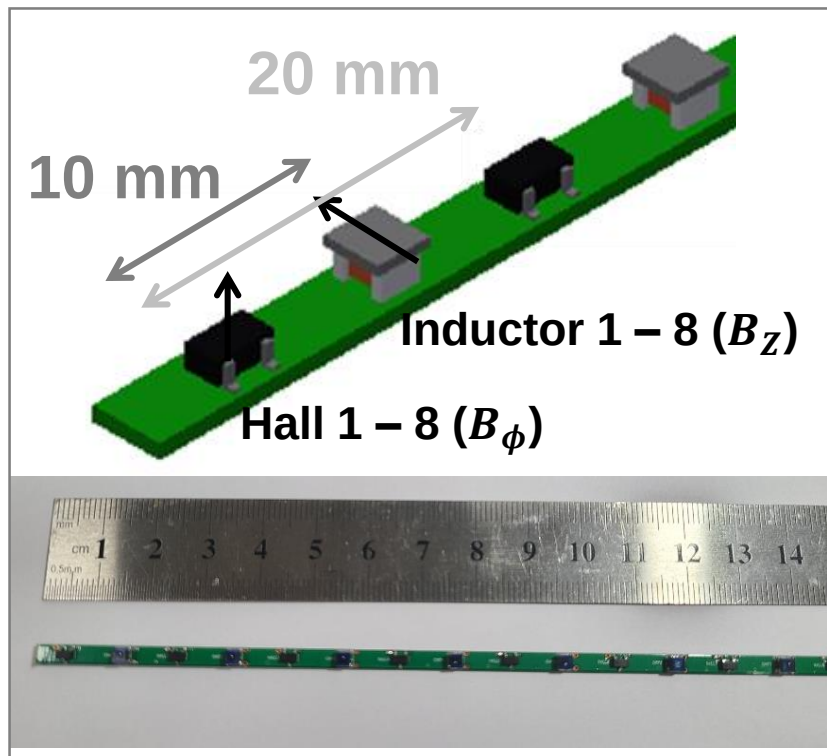
Magnetic diagnostics



Poloidal magnetic map



Location of toroidal mirnov coils



Internal magnetic probe arrays

Equilibrium Reconstruction

- External magnetics
 - Magnetic probes (63): B_z (vertical field)
 - Flux loops (7): ψ_p (poloidal flux)
 - Rogowski coil: I_p (plasma current)
 - Diamagnetic flux from TF current
- Internal magnetics: B_z (vertical field)
 - Located at mid-plane ($Z \sim 0$ m) & movable
 - 8-channel hall sensor arrays with 5 cm spatial resolution
- Thomson scattering: N_e, T_e (electron pressure)
 - 5-radial position
 - (0.475, 0.425, 0.37, 0.31, 0.255 m)
 - 10-time point measurement with 1ms time resolution in a discharge

Magnetic
FIT

Kinetic
FIT

External magnetic diagnostics, Diamagnetic flux from TF
Movable internal probe array, Thomson scattering

T.K. Kim (Friday)

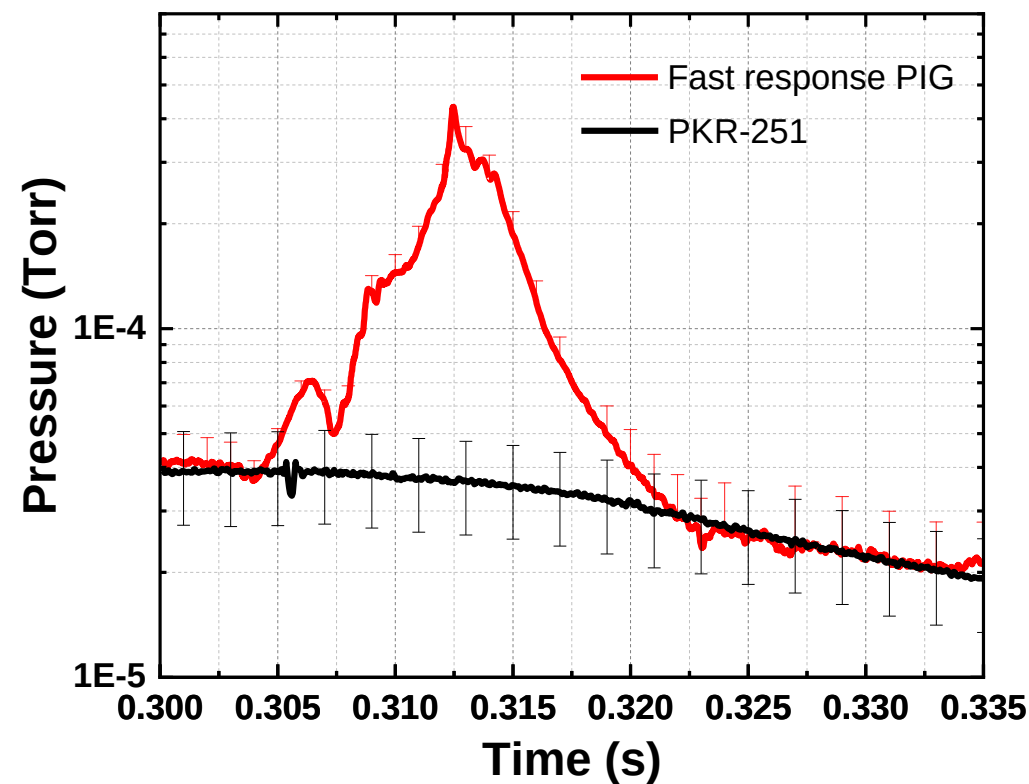
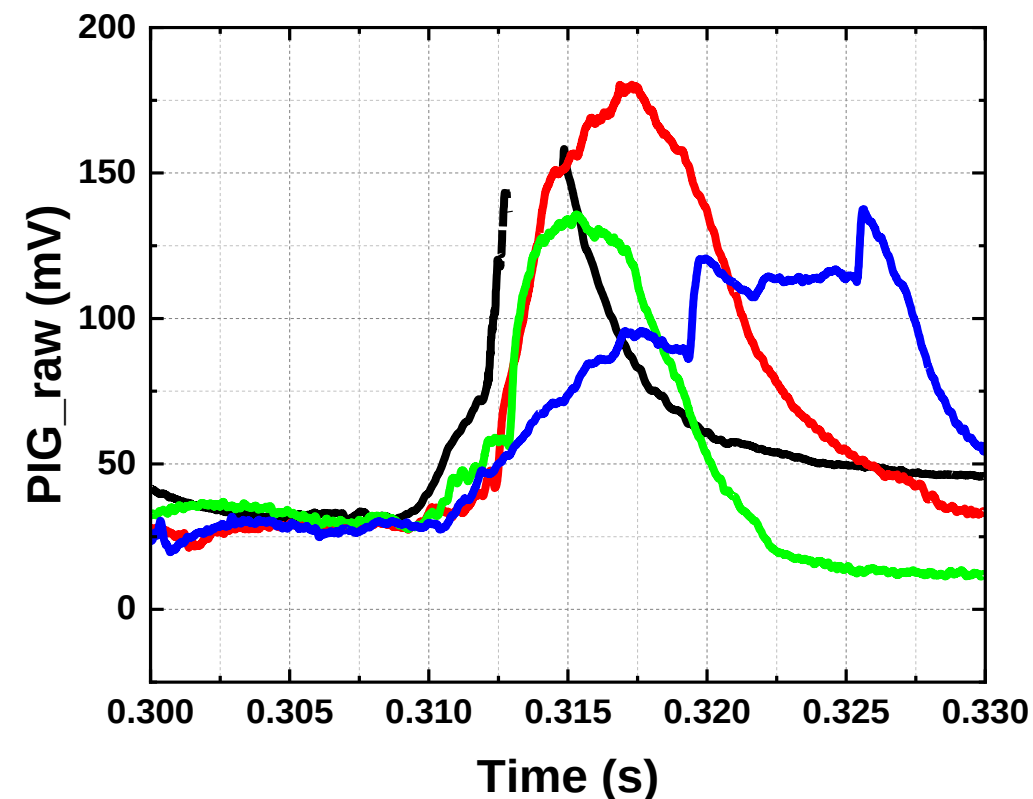
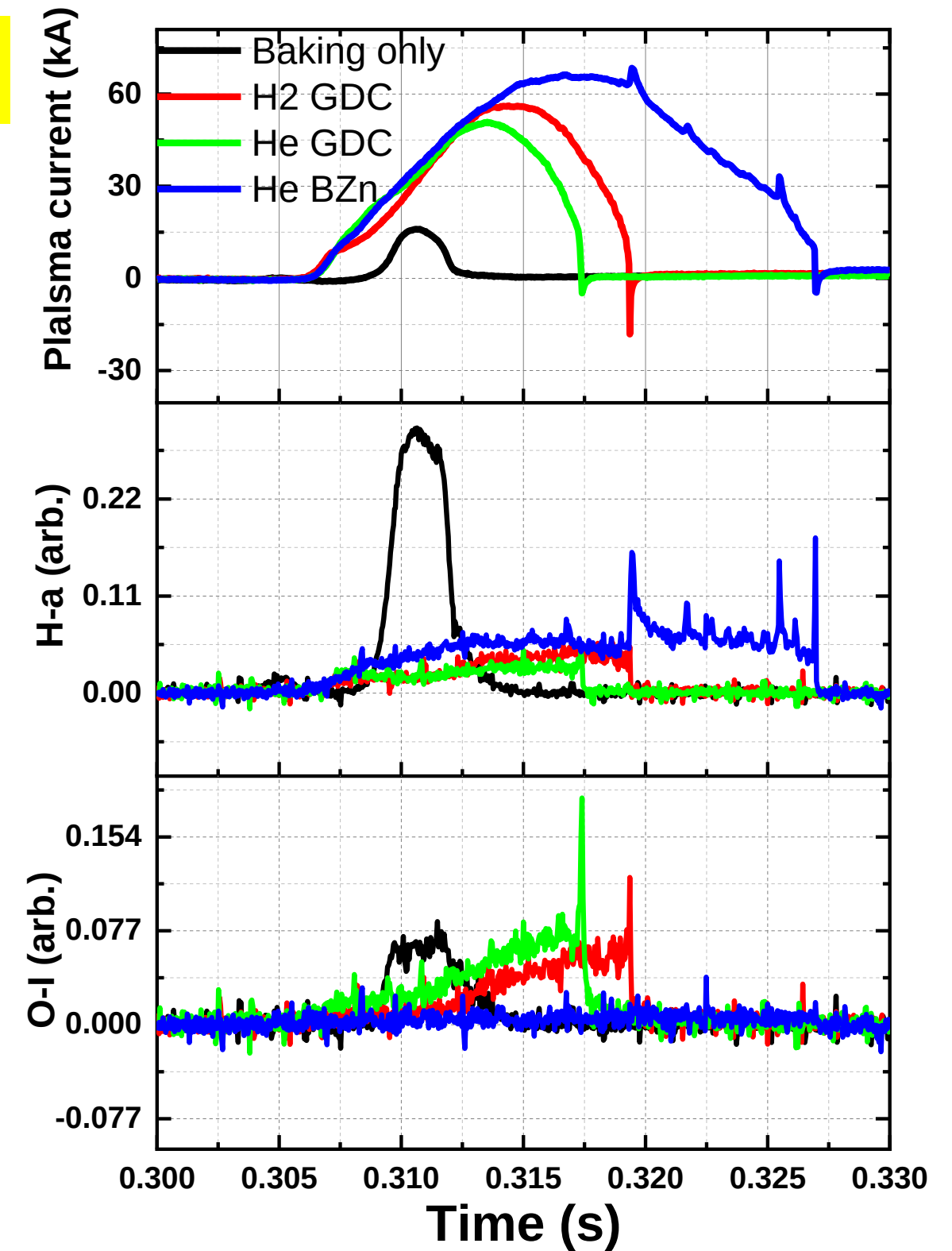
18/20

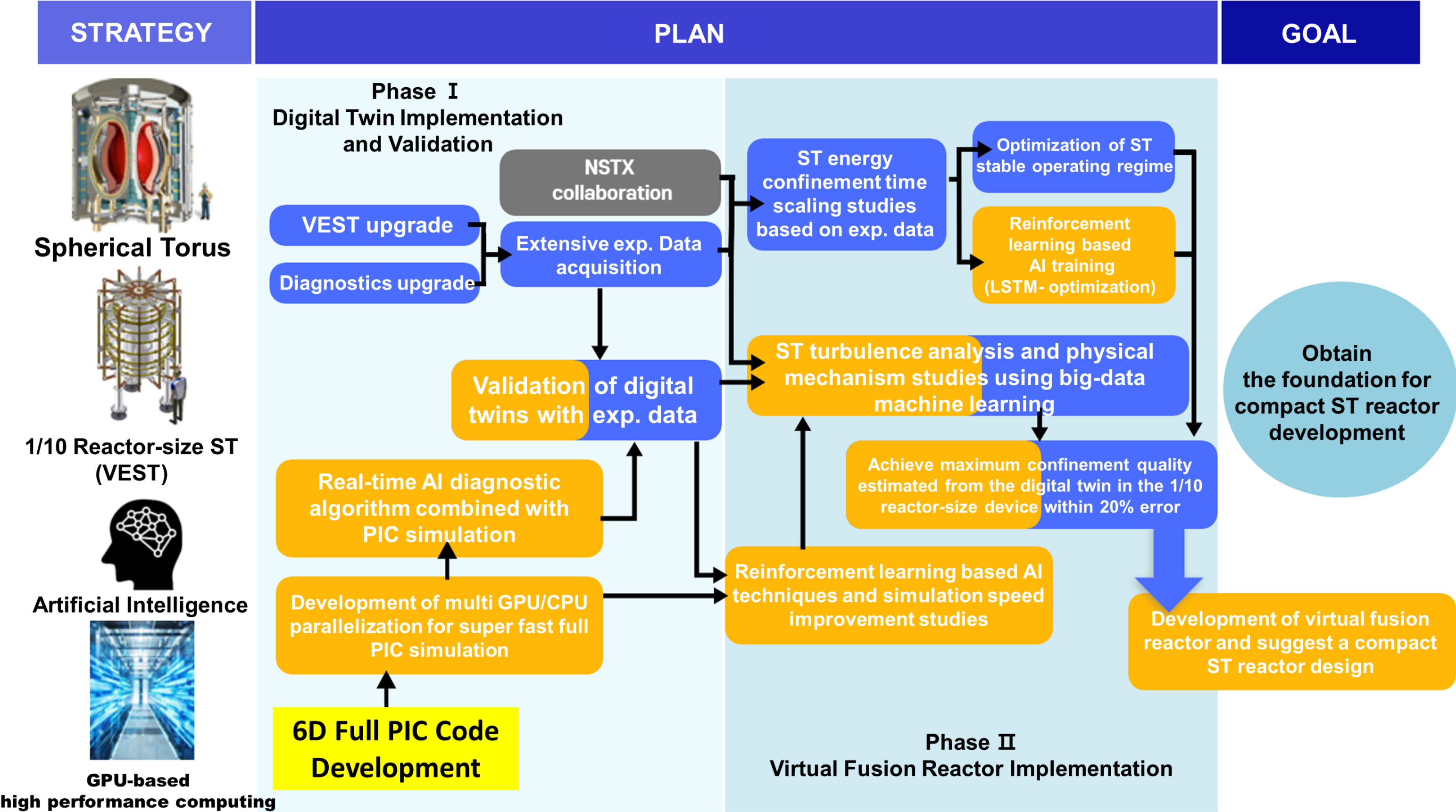
J.H. Kim (Wed.)

Activities for Simulation-Oriented Experiments

- Development of fast fueling system
- Improvement of vacuum and wall conditioning systems

- Vacuum (pumping) system improvements
- Real-time monitoring PIG gauge development
 - ✓ Plasma wall/limiter interaction assessment
 - ✓ Wall conditioning method comparison
- Limiters and wall conditioning method optimization





Dreaming Enertopia on Earth with Fusion

Thank you for your attention.

감사합니다. yhwang@snu.ac.kr