Long-pulse Tokamak Operations
: a case study of full-superconducting magnet devices

Sang-hee Hahn
Korea Institute of Fusion Energy (KFE)
Daejeon 34133, South Korea
hahn76@kfe.re.kr

Group photo from 2010 IISS (UT Austin, US)

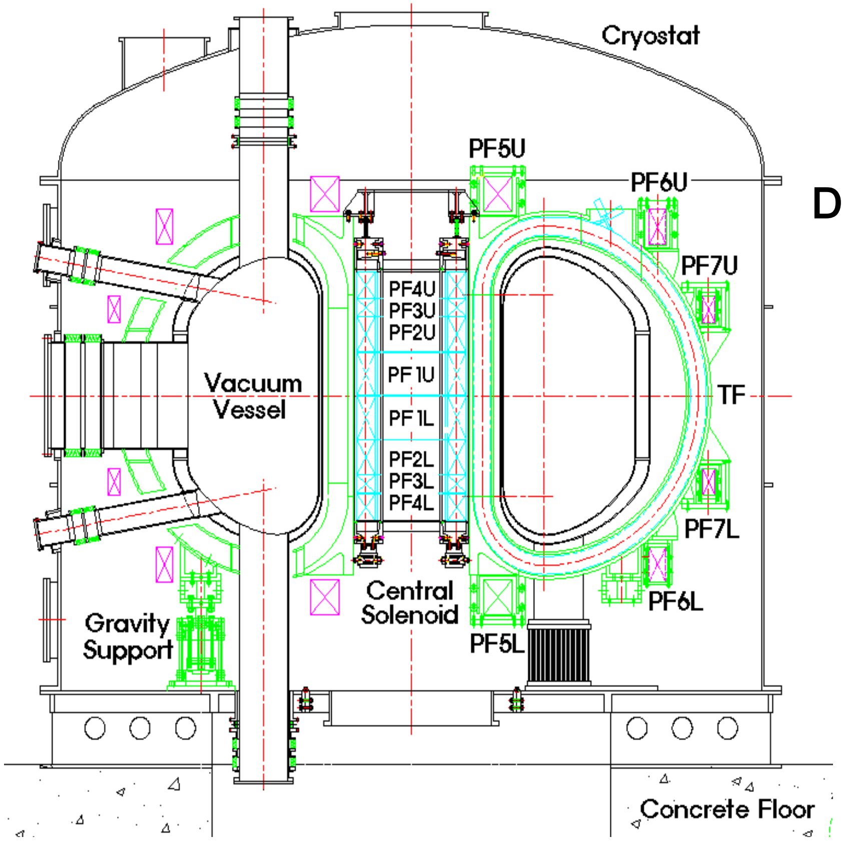
Introduction

- Extension of plasma pulse length is essential for economically meaningful fusion reactor
  - The longer the plant runs, the more electricity we can get per run

- The task is *not* equivalent to the mere physical extrapolations of known short pulses
  - Not every scenario can do the long pulse
  - The extension of the pulse strongly depends on machine specifics

- Scope of the lecture will be limited to
  - Tokamak operation (especially the superconducting devices)
  - Phenomena that the KSTAR encountered

KSTAR tokamak (2008-present)



Design value of KSTAR:

R_0= 1.8 m
a=0.5 m
I_P=2 MA
κ= 2.0
δ= 0.8
B_0= 3.5 T
t_{pulse}= 300 s

- Brief history (year-descriptions)

2008 - First plasma achieved

2010 – First diverted H-mode for SC devices

2011 – First ELM suppression at n=1 RMP

2016 – **Long pulse H-mode over 1 minute**

2017 – Long pulse 73s

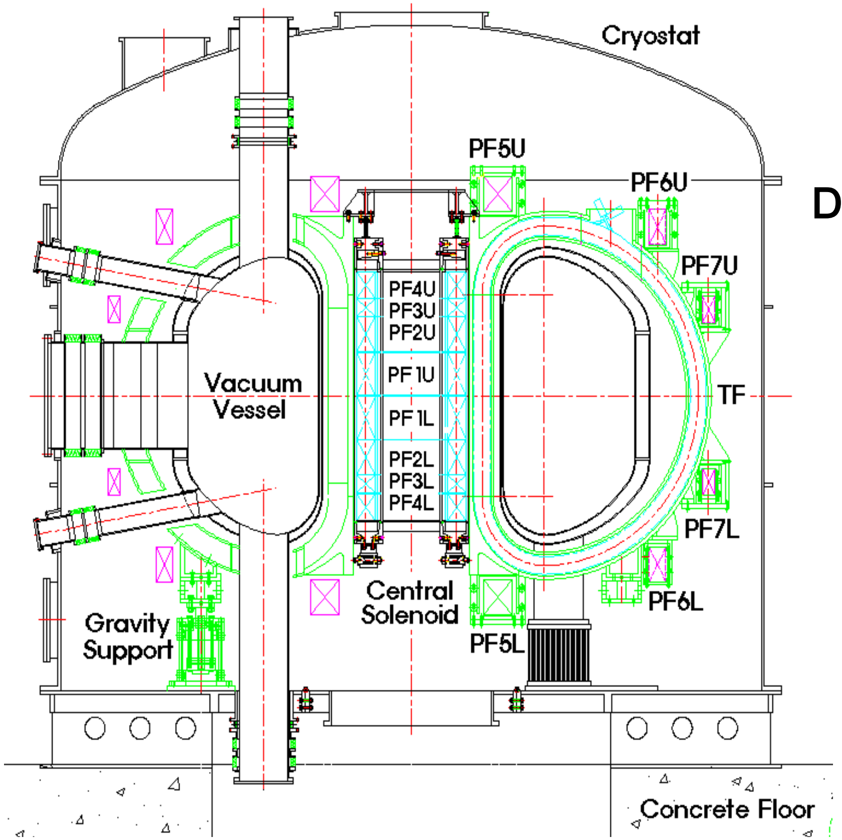
2018 – ELM suppression over 30s

2020 – Long pulse achieved to 91s

Reach to 1.1 MA / 15s with Wmhd ~ 0.8 GJ

2022 – **New device record for ELM suppression (>40s)**

KSTAR tokamak (2008-present)



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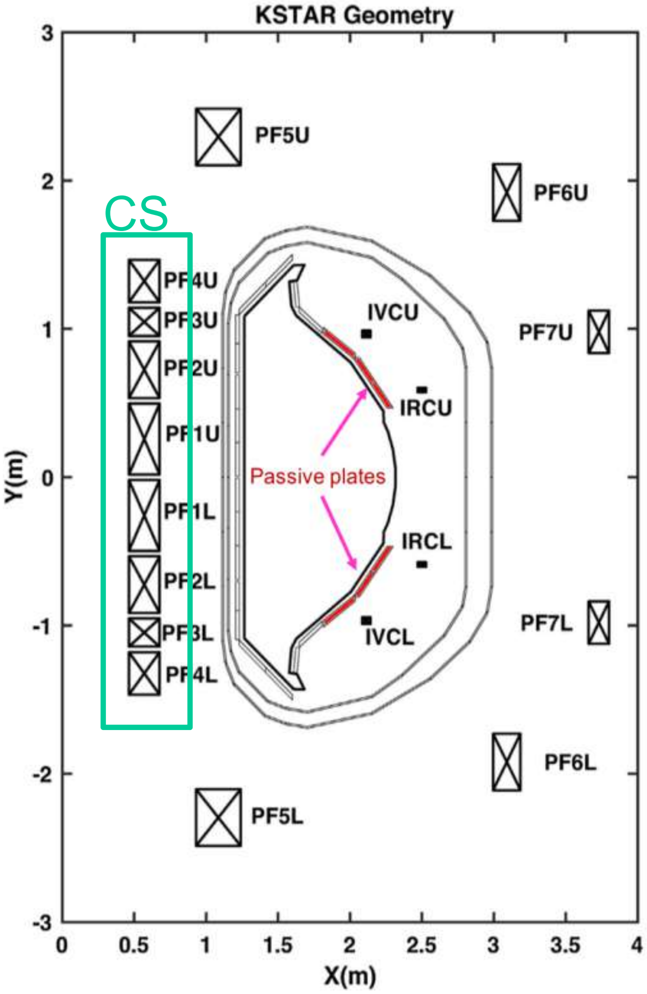


Figure 1. KSTAR geometry (2019)

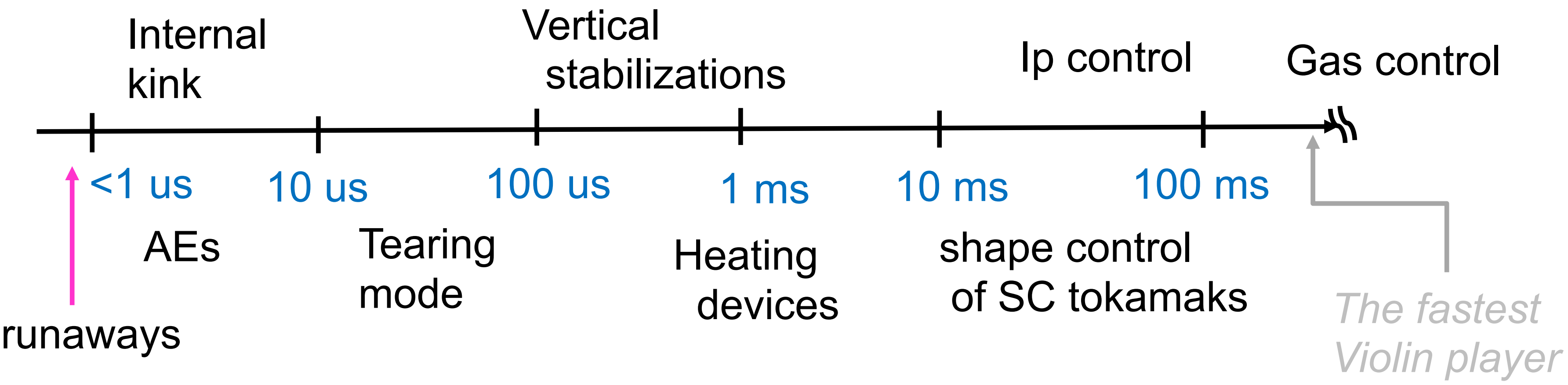
Outline

- Creating a long pulse

- Encountering challenges in control

- Concluding remarks

Time scale of the plasma discharge operation



The “fast” time scale:

* Most of plasma physics occur
* Human cannot react on time, automation needed
* Premeditated control setup & scheme
* requires “deterministic realtime” for control infra

Time scale of the plasma discharge operation

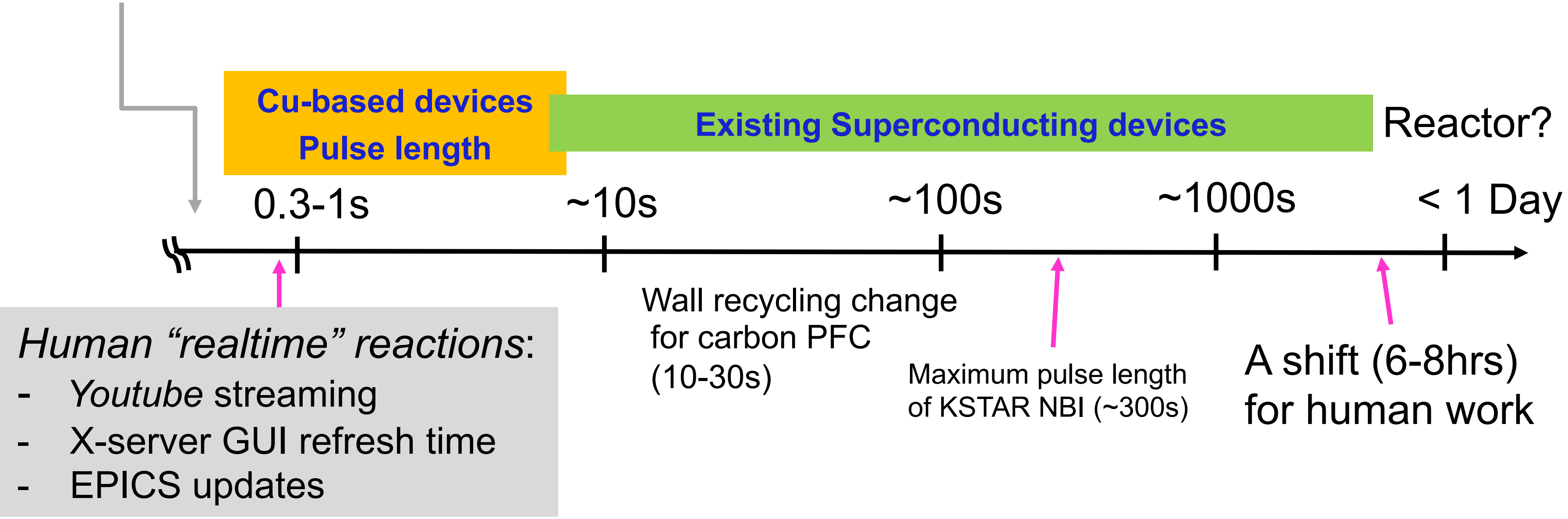
The fastest man
In the world

The "slow" time scale:

* Human can react based on visualization & audio & reflex

* Related diagnostics are slower
(KSTAR EPICS update : 1 sample/second)

* Macroscopic timescale phenomena can be consequences from accumulation of microscopic events



Cu-based devices Pulse length

Existing Superconducting devices

Reactor?

0.3-1s ~10s ~100s ~1000s < 1 Day

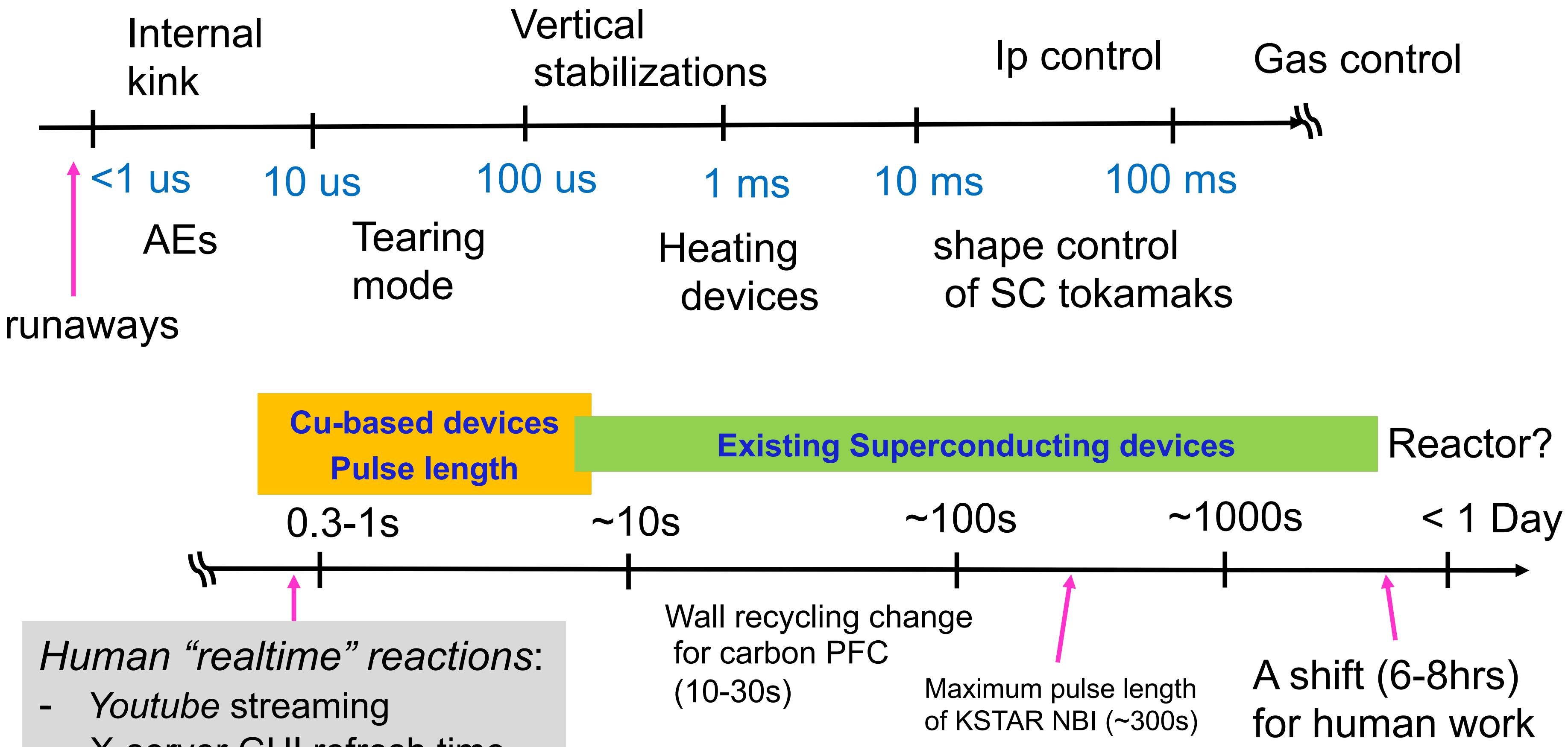
Human "realtime" reactions:
- *Youtube* streaming
- X-server GUI refresh time
- EPICS updates

Wall recycling change for carbon PFC (10-30s)

Maximum pulse length of KSTAR NBI (~300s)

A shift (6-8hrs) for human work

Time scale of the plasma discharge operation


Internal kink

Vertical stabilizations

Ip control

Gas control

<1 us

10 us

100 us

1 ms

10 ms

100 ms

AEs

Tearing mode

Heating devices

shape control of SC tokamaks

runaways

Cu-based devices Pulse length

Existing Superconducting devices

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~10s

~100s

~1000s

< 1 Day

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Creation of a long pulse : two aspects to consider

- Only a few scenarios with high fraction of non-inductive current drive (NICD) can sustain the pulse over the inductive flux consumption limit

- The long pulse discharges interacts with the surrounding hardware, changing the known engineering constraints during the discharge

Creation of a long pulse : two aspects to consider

- Only a few scenarios with high fraction of non-inductive current drive (NICD) can sustain the pulse over the inductive flux consumption limit
  - Amount of current drive is determined by the scenario
  - Choice of scenario in the operating space

- The long pulse discharges interacts with the surrounding hardware, changing the known engineering constraints during the discharge

Creating & sustaining plasma current in a tokamak : methods of current drive (CD)

$$I_p = \boxed{\frac{V_{loop}}{R_{plasma}}} + \boxed{NBCD + ECCD + I_{BS}}$$

Inductive CD

Vloop : “loop voltage”

Rplasma : Resistance of plasma

Non-Inductive CDs

NBCD : current drive by Neutral Beam

ECCD : current drive by EC resonance

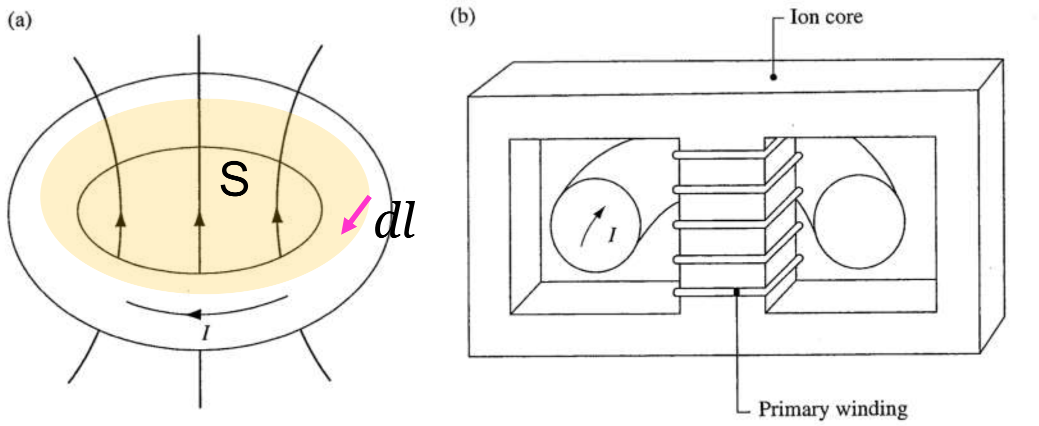
I_{BS} : the “Bootstrap current” induced by the density gradient

Creating & sustaining plasma current in a tokamak

$$I_p = \boxed{\frac{V_{loop}}{R_{plasma}}} + NBCD + ECCD + I_{BS}$$

Inductive CD

- Inductive method creates plasma current by Faraday’s law of induction
  - The amount of current is determined by plasma resistance



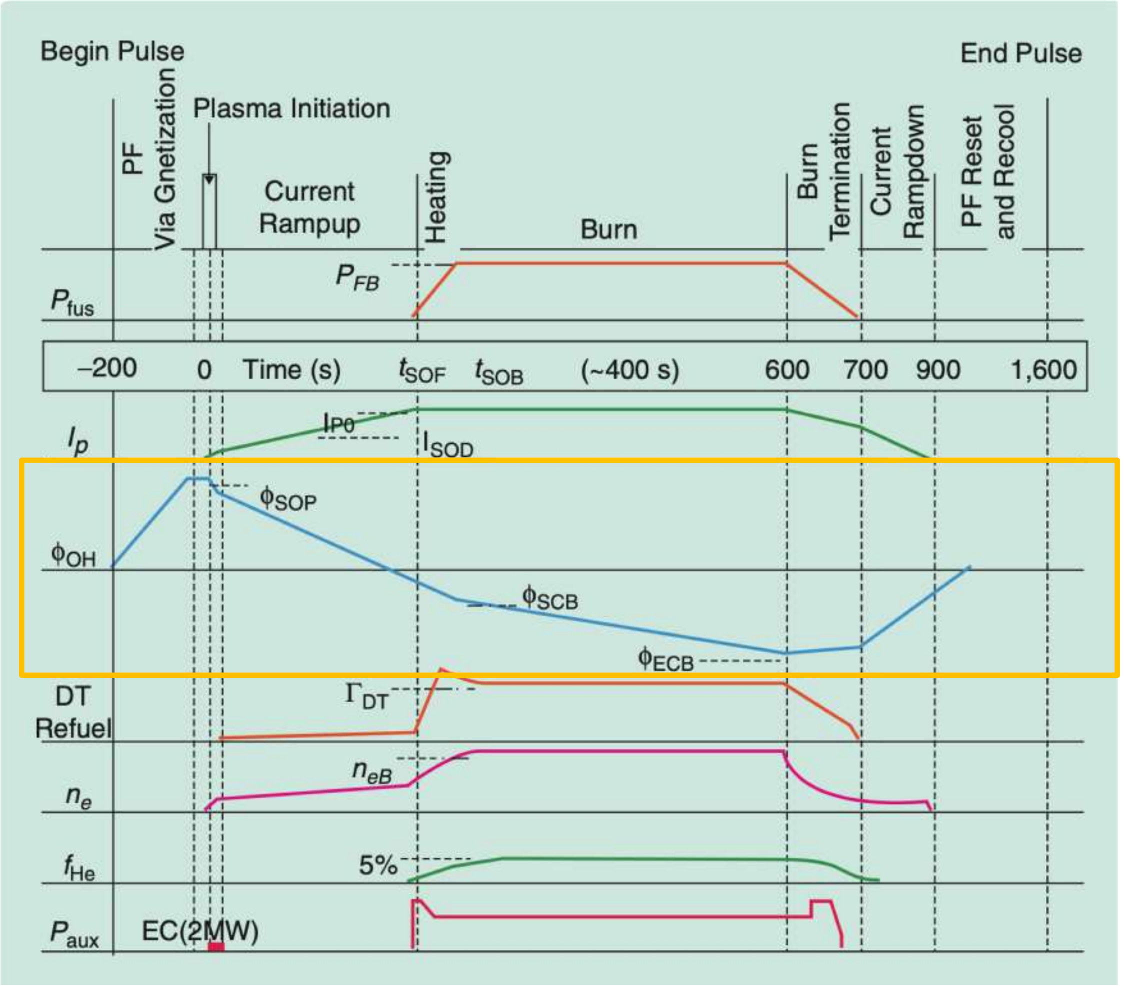
$$V_{loop} = \int_0^{2\pi a} E dl$$

$$E = -\frac{d\Phi_{pol}}{dt}$$

Wesson, “Tokamaks” 4th ed, p14 (2004)

Creating & sustaining plasma current in a tokamak : inductively sustained pulse length is limited

The inductive operation scenario of ITER



Y. Gribov, J.B. Lister, and A. Portone, IEEE Control Systems Magazine **26**, 79 (2006).

- Amount of flux consumption (Φ_{OH}) is limited by the max flux provided by the central solenoid (CS) coil
  - The derivative of the flux consumption corresponds to the loop voltage (Vloop)
- Note that it is a machine constraint:
  - Large current power supply is expensive
  - The amount of the Vloop is often limited by the SC coils' AC coupling loss limitations
  - The plasma resistance is difficult to determine

Sustaining of plasma current by non-inductive current drive (NICD) methods

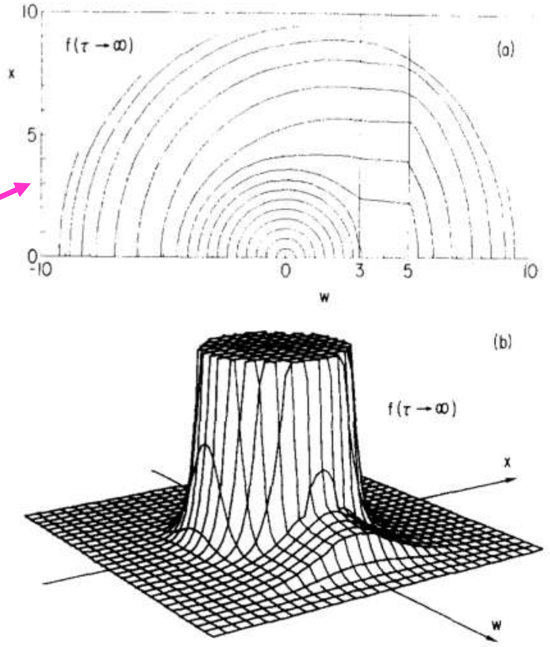
$$I_p = \frac{V_{loop}}{R_{plasma}} + \boxed{NBCD + ECCD + I_{BS}}$$

Non-Inductive CDs

NBCD : current drive by Neutral Beam
by collisional slowing down or charge-exchange of fast ion

ECCD : current drive by EC resonance
formation of nonisotropic velocity space

I_{BS} : the "Bootstrap current" induced
by the density gradient in the plasma edge



C.F.F. Karney, and N.J. Fisch,
Physics of Fluids **22**, 1817 (1979)

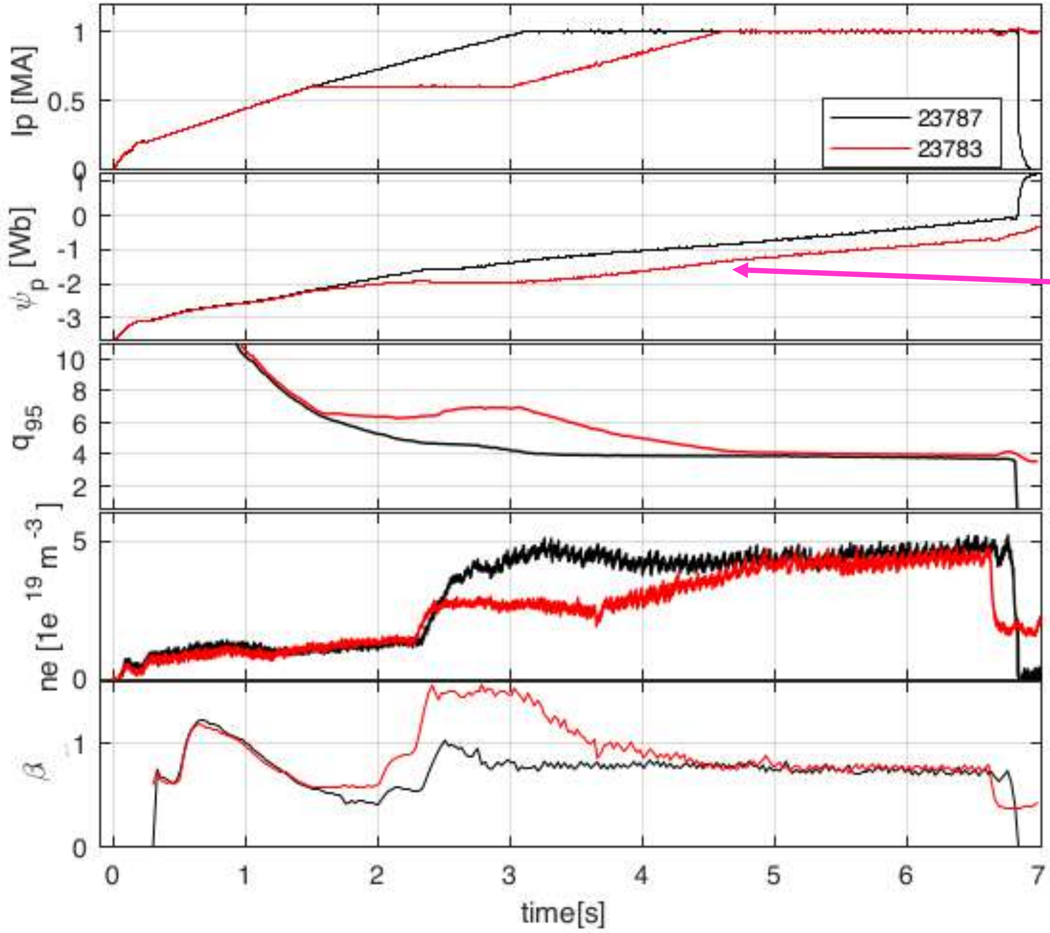
All highly nonlinear and
need modeling to predict (See talk by F. Poli)

Earlier L-H by creating short Ip flattop can save the flux consumption during the rest of pulse

Poloidal Flux (FL23)

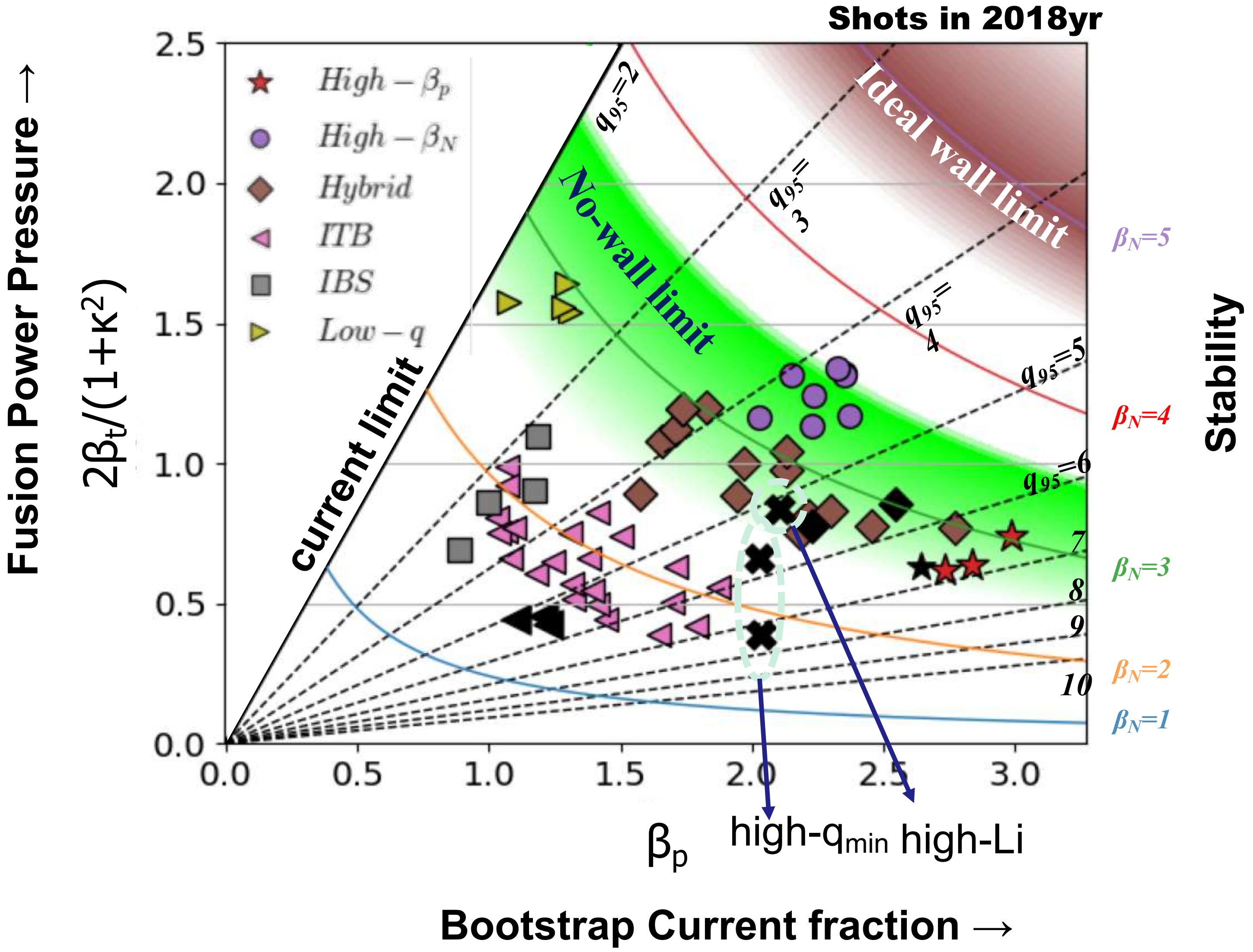
Electron density

Poloidal Beta

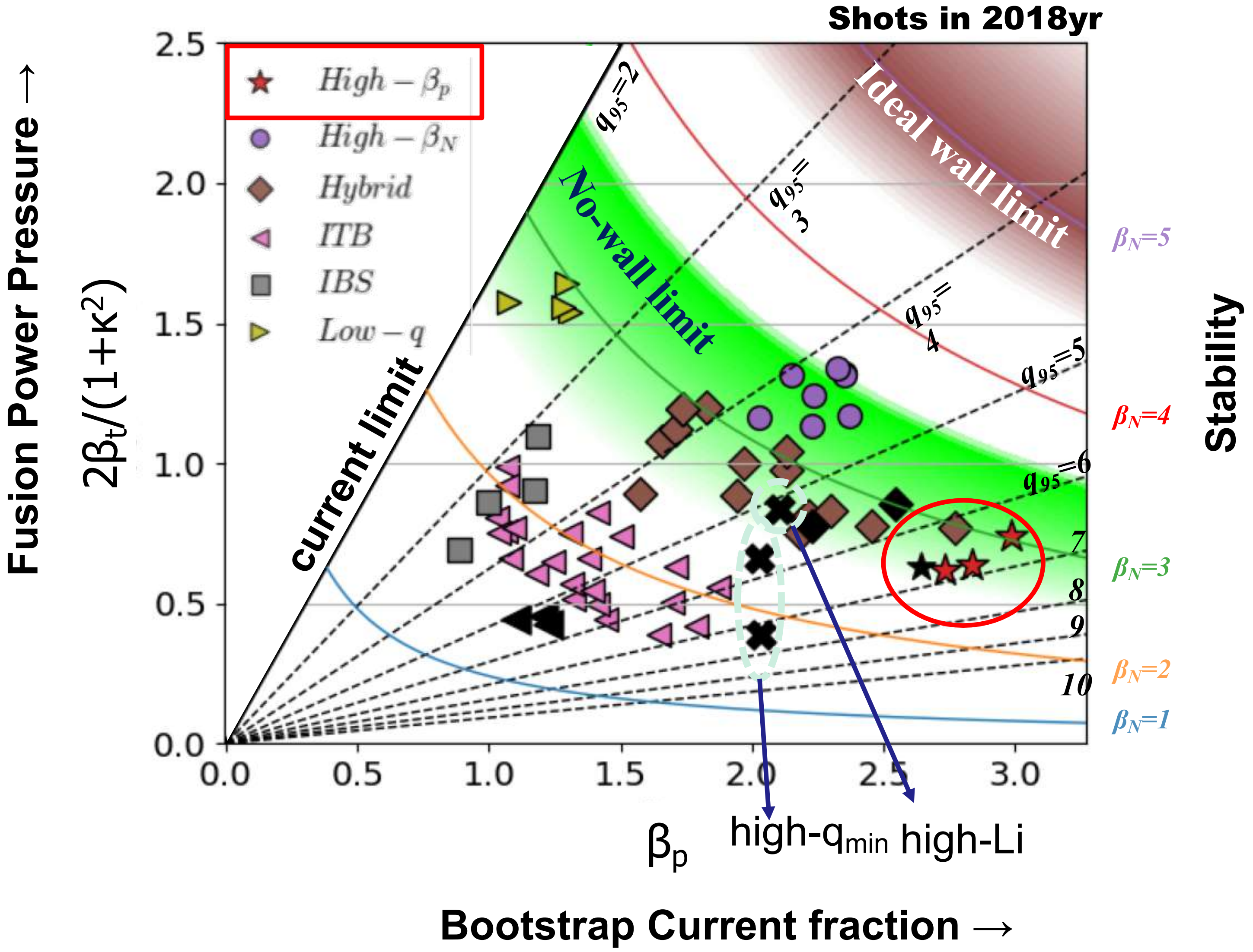


Flux saving
By earlier L-H
→ Increase of
bootstrap current

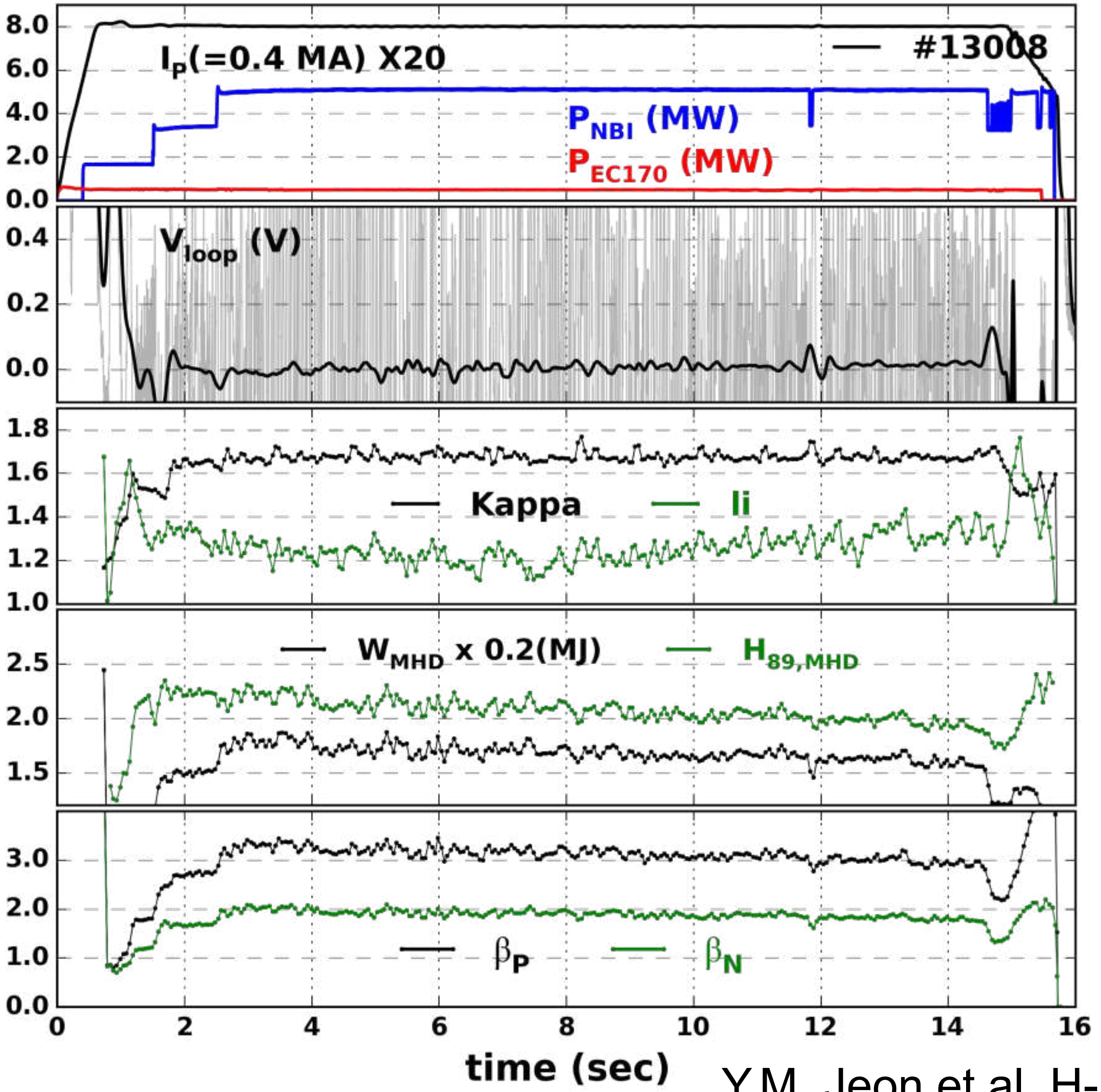
Various Scenarios exist in a range of operating space



Various Scenarios exist in a range of operating space
: Scenarios with high f_{BS} chosen for the long pulse



100% non-inductive CD high β_P scenario found at high B_T

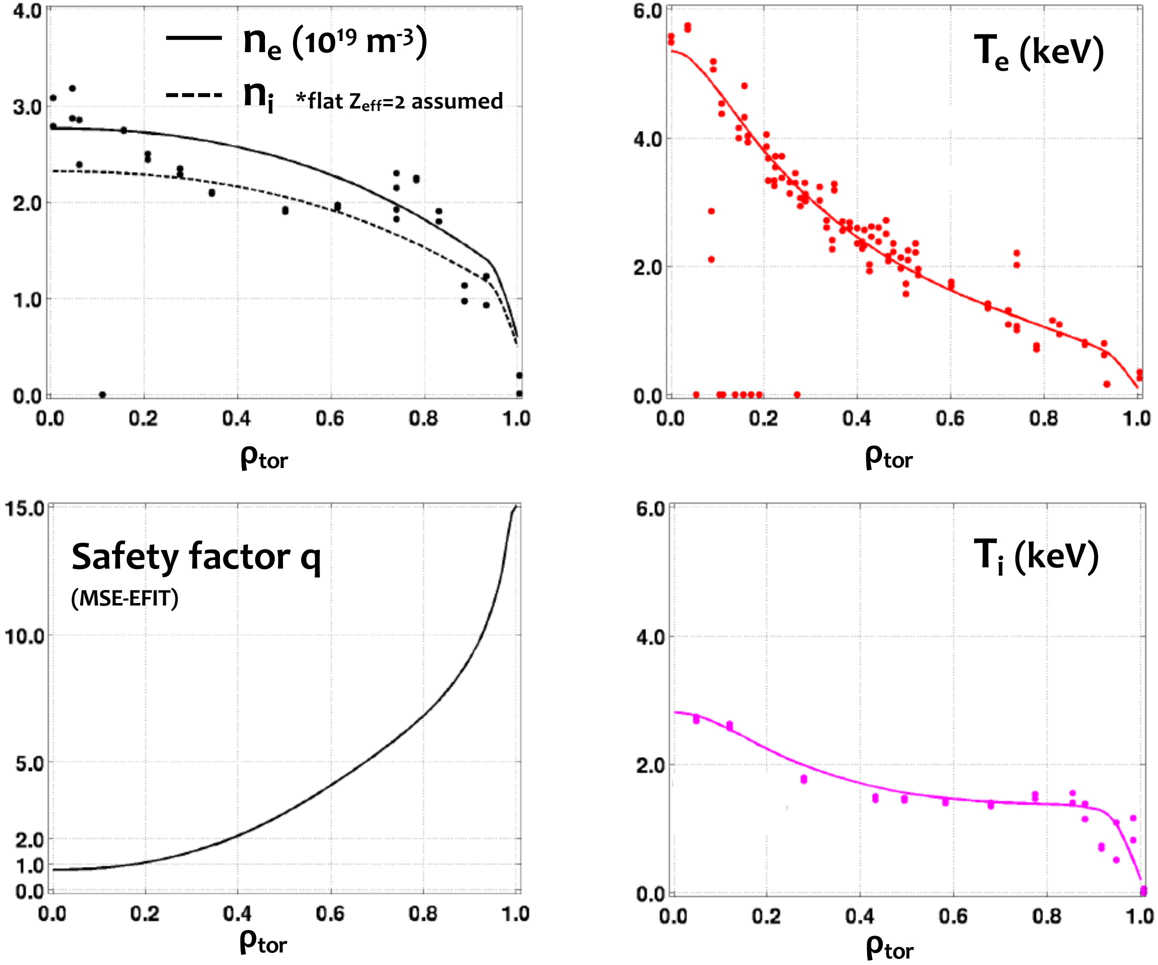


- **f_{NI}~1.0 high β_P** achieved
  - V_{loop} ~ 0.0 with NBI+ECH = 5.5MW
  - **β_P > 3.0**, β_N ~ 2.0
  - **Central ECCD is essential**
    - At B_T= 2.9 T
    - EC 170GHz at the plasma center
  - Similar characteristics as "high li" mode[**]
    - elongation~1.7, q_{95} ~ 11
  - **Pulse terminated by PFC overheat due to fast ion losses**

Y.M. Jeon et al, H-mode WS (2017)

Non-inductive CD and bootstrap fraction estimates of high β_P scenarios

Profile Measurement for #17355



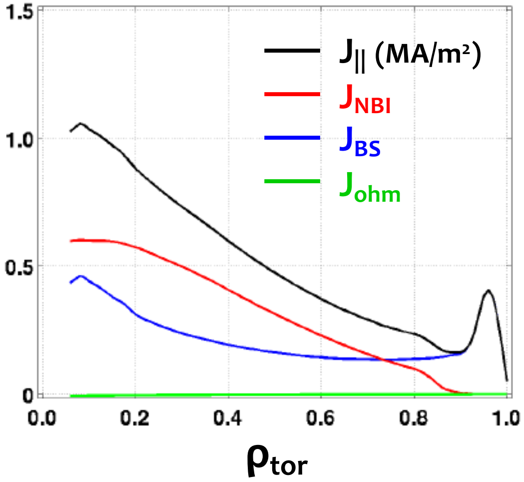
CRONOS estimates for f_{NI} :

I_{total} = 0.40 MA

I_{NBI} = 0.21 MA (f_{NBI}=0.52)

I_{BS} = 0.19 MA (f_{BS}=0.48)

f_{NI} ~ 1.0, $H_{98(y,2)}$~1.4

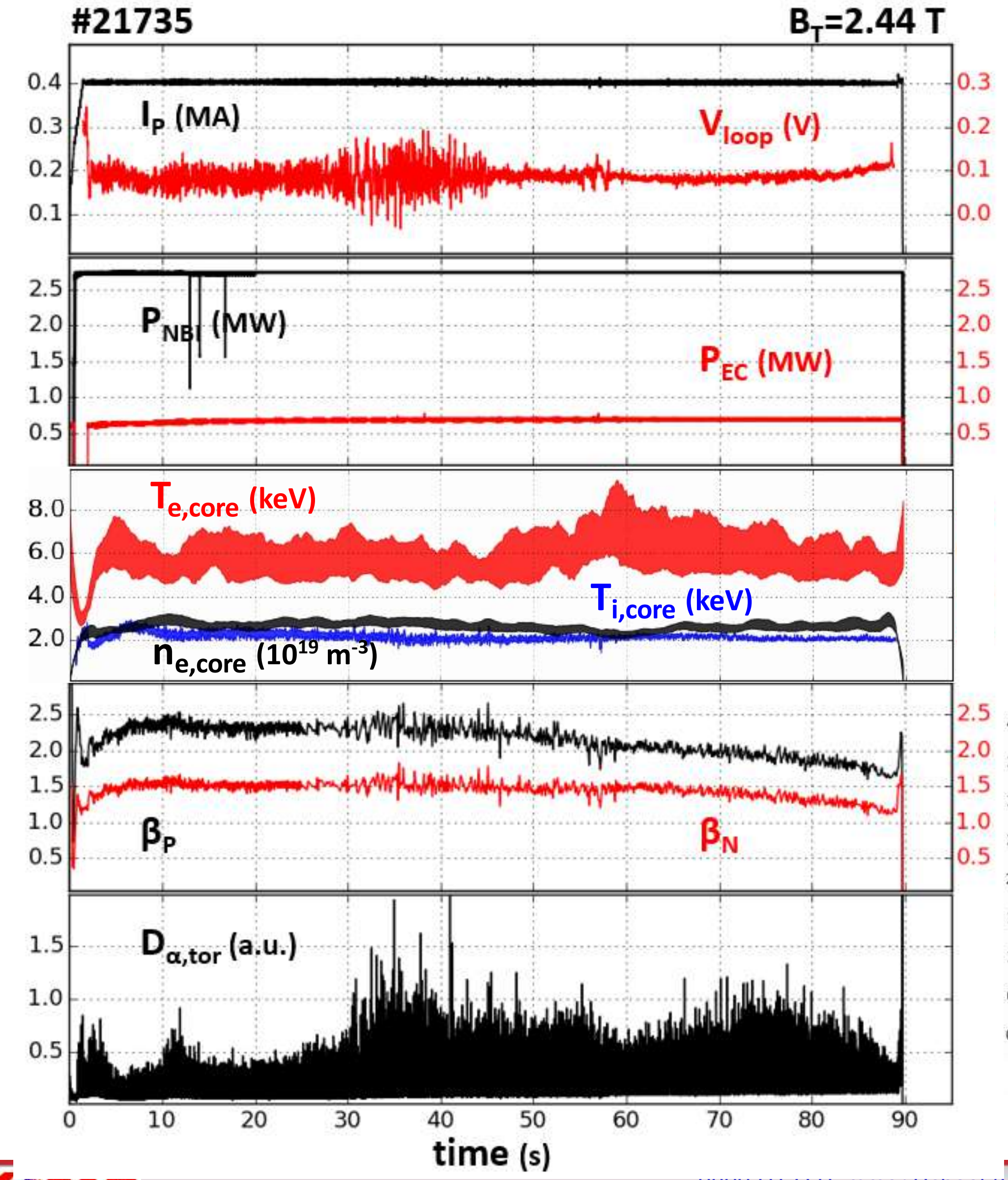


(No ECH modeling included)

S. Hahn et al, 2017 IAEA-TM-SSO

The longest pulse (~90s H-mode) @ KSTAR achieved using high βp state

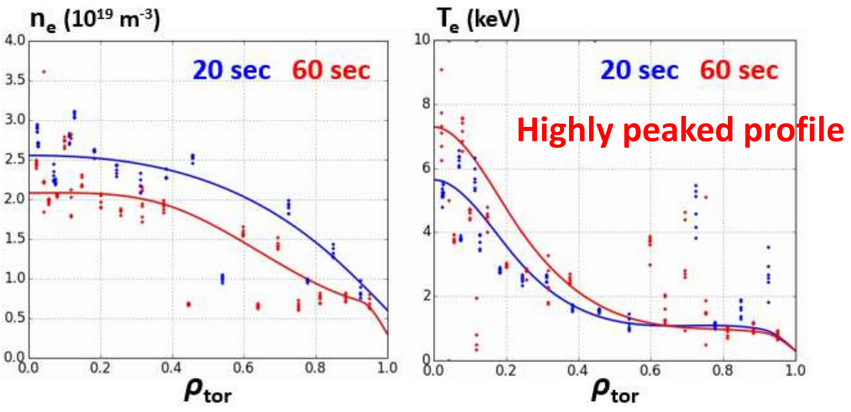
H.S. Kim et al., IAEA FEC 2020. EX/P2-02



- **Operation Condition :**

  I_P=400 kA, B_T=2.44 T, P_{NBI}=2.8 MW, P_{EC}=0.7 MW

  - **Optimized application of EC injection is a KEY that discharge was in the High $β_P$ state**
- **V_{loop}~0.1 V was kept constant for whole discharge**
- **$n_{e,core}$ ≤ 2.5 x10^{19} m^{-3}, $T_{e,core}$ ≥ 5.0 keV, $T_{i,core}$~2.0 keV**
- **$β_P$~2.4 ($β_N$~1.5) was kept constant for ~45-50 sec**
  - **Gradually decrease of plasmas performance should be resolved**



Highly peaked profile

Creation of a long pulse : two aspects to consider

- Only a few scenarios with high fraction of non-inductive current drive (NICD) can sustain the pulse over the inductive flux consumption limit

- The long pulse discharges interacts with the surrounding hardware, changing the known engineering constraints during the discharge

  1) vacuum vessel chamber conditions

     – additional constraint applies

     - conditions vary during the pulse

  2) auxiliary heating devices – the CD efficiency can drop

  3) diagnostics – basic diagnostics can change

  4) control magnets – inductive/NI portion varies

Switching to SC device has both advantages / disadvantages

	Pro	**Con**
Toroidal field	Can maintain the field larger & longer under lower cost	Conventional between-shot GDC is practically impossible
Poloidal field	Lower power supply requirements for larger magnet & higher current sustain	Coils are far away // Need to avoid AC loss accumulation // flux swing is rather limited
Vacuum vessel	Larger volume can be made under high BT	Opening is rather limited // baking takes more time

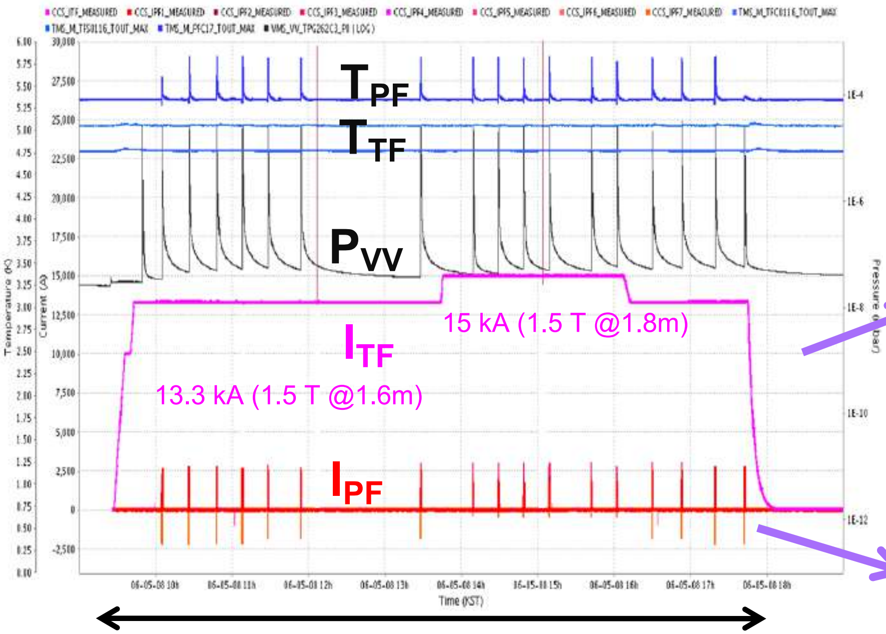
* Magnetic energy stored on the full-charged TF @ KSTAR ~ 0.5 GJ

Y.-K. Oh, et al., Fus. Eng. Des. 84 (2009) 344–350.

Operational sequence design

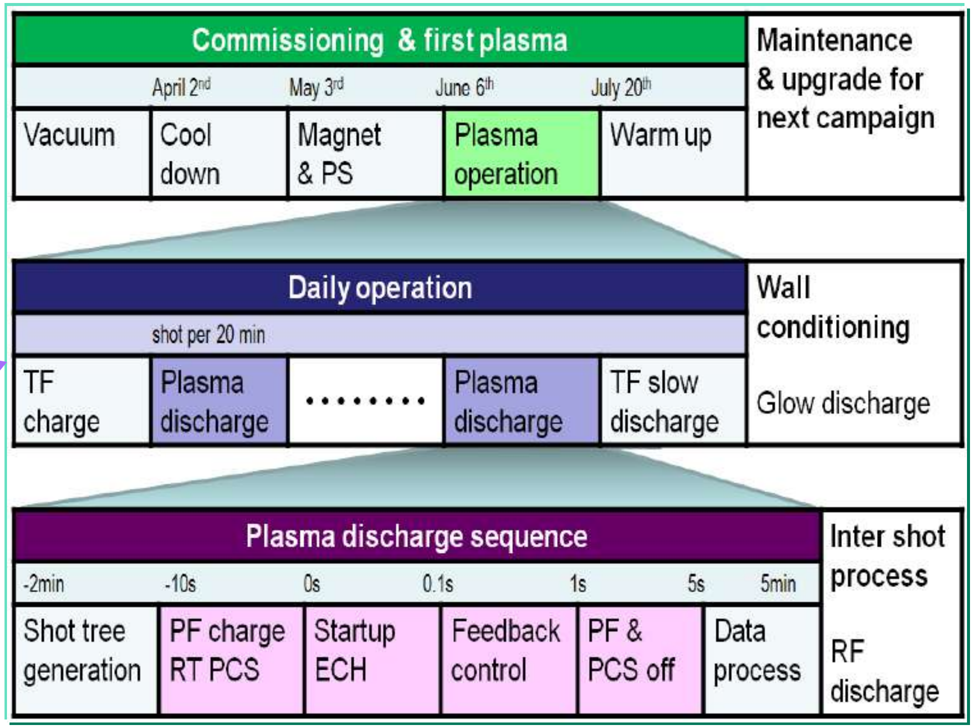
- **TF field is on over 10 hours per day**
  - **Glow discharge applied only when before/after the daily operation**
  - RF discharge cleaning applied for between-shot cleaning by the request of session leader
- Pulse operation controls are involved for magnet, gas, heating, and plasma discharge
- Each plasma discharge (shot) per 10~15 minutes
  - depending on the magnet temperature conditions
  - Creates shot-based data

Daily operation results



~10 hours for typical one day

Operational sequence



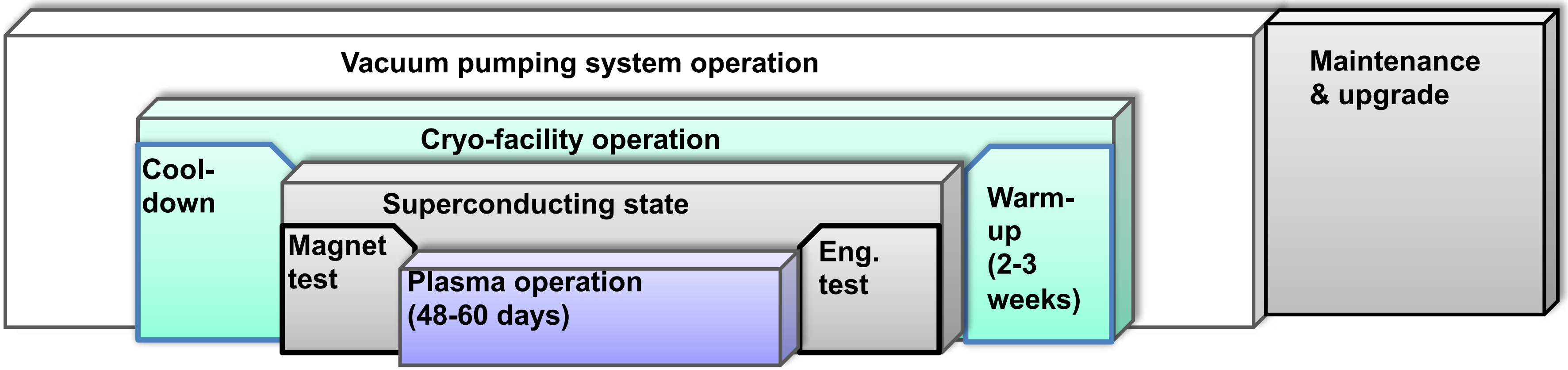
Commissioning & first plasma					Maintenance & upgrade for next campaign
	April 2nd	May 3rd	June 6th	July 20th	
Vacuum	Cool down	Magnet & PS	Plasma operation	Warm up	

Daily operation					Wall conditioning
shot per 20 min					
TF charge	Plasma discharge	………	Plasma discharge	TF slow discharge	Glow discharge

Plasma discharge sequence						Inter shot process
-2min	-10s	0s 0.1s	1s	5s	5min	
Shot tree generation	PF charge RT PCS	Startup ECH	Feedback control	PF & PCS off	Data process	RF discharge

Operation Phases of a full superconducting tokamak: Example of KSTAR

4-step procedures for SC tokamak operations



Vacuum conditioning (3 weeks)

- Vacuum vessel pumping
- Cryostat pumping
- Leak detection
- Baking
- Discharge cleaning

Cool-down (3 weeks)

- Refrigerator cool-down
- Distribution cool-down
- SC magnet purging
- Step 1 (300 K → 80 K)
- Step 2 (80 K → 20 K)
- Step 3 (20 K → 4.5 K)
- SC phase transition

SC magnet test (1-2 weeks)

- Joint resistance check
- Insulation test
- TF power supply test
- PF power supply test
- Field measurement
- AC loss measurement

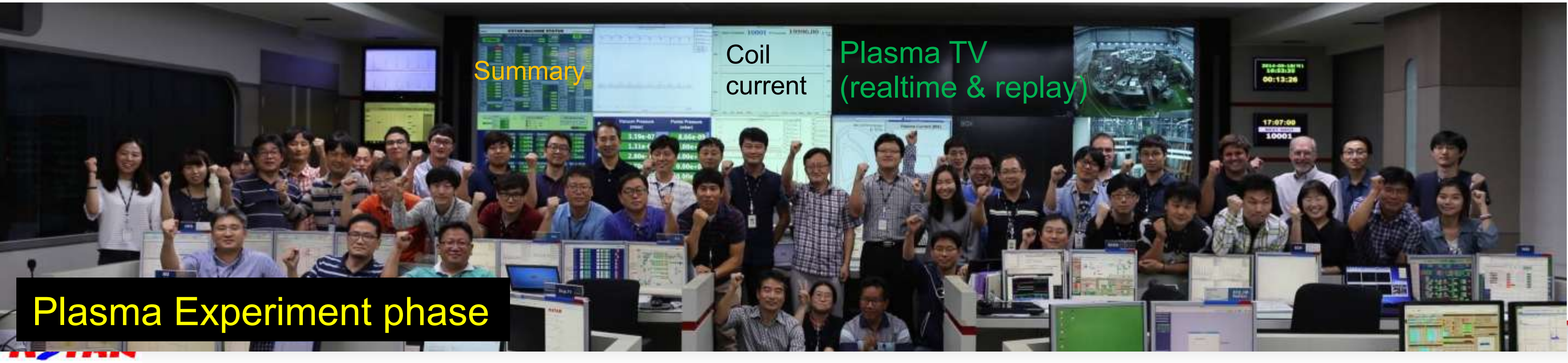
Plasma operation (3 months)

- Field null formation
- Blip operation
- ECH pre-ionization
- Gas control
- Diagnostics calibrations
- Discharge cleaning
- Feedback control

Different physical quantities monitored at different operation phases

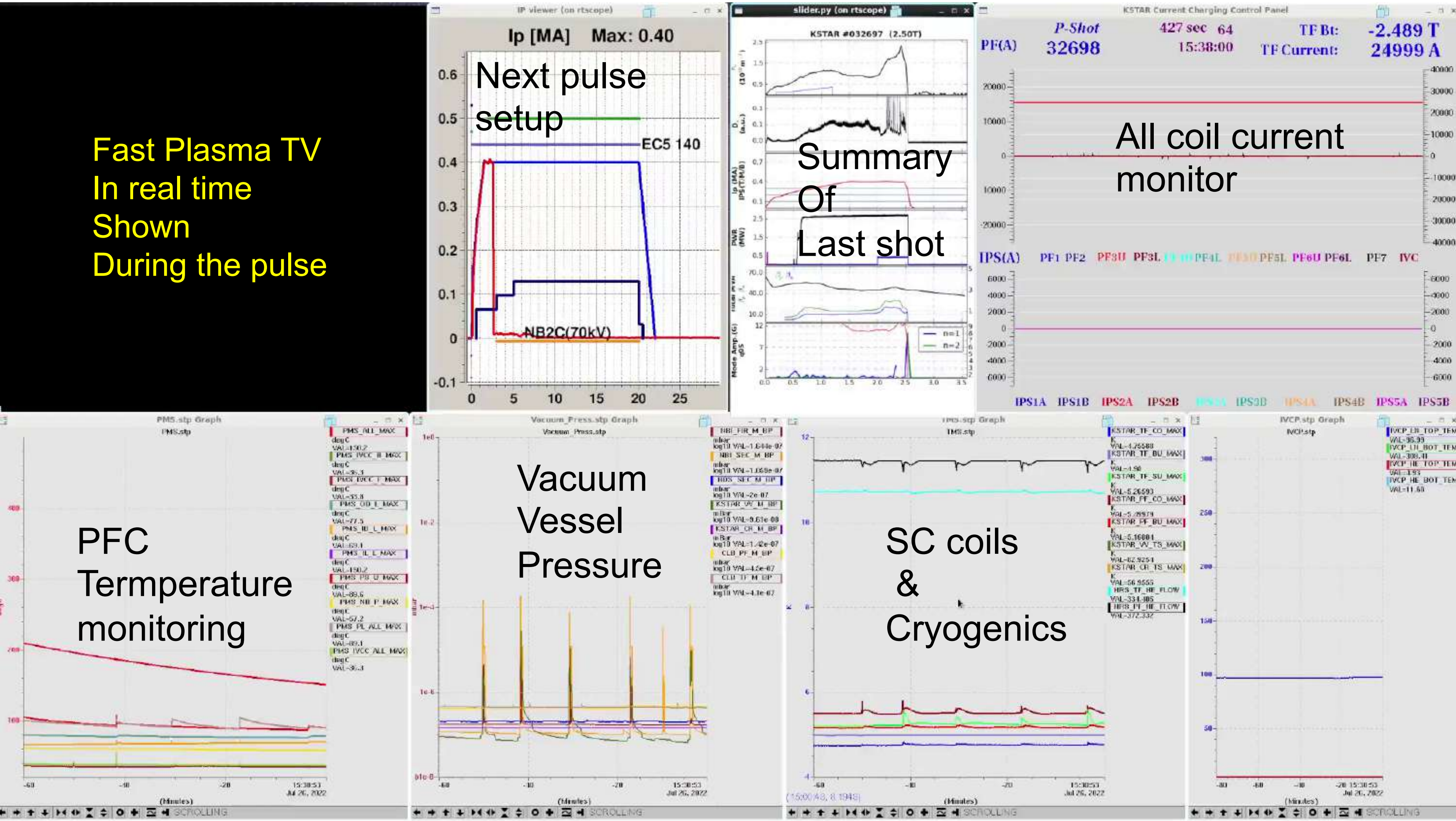
Cooldown phase

Magnet Commissioning (Charge-up) phase



Plasma Experiment phase

Components monitored for plasma operation (2022.Jul)



Fast Plasma TV
In real time
Shown
During the pulse

Next pulse setup

Summary
Of
Last shot

All coil current monitor

PFC
Termperature
monitoring

Vacuum
Vessel
Pressure

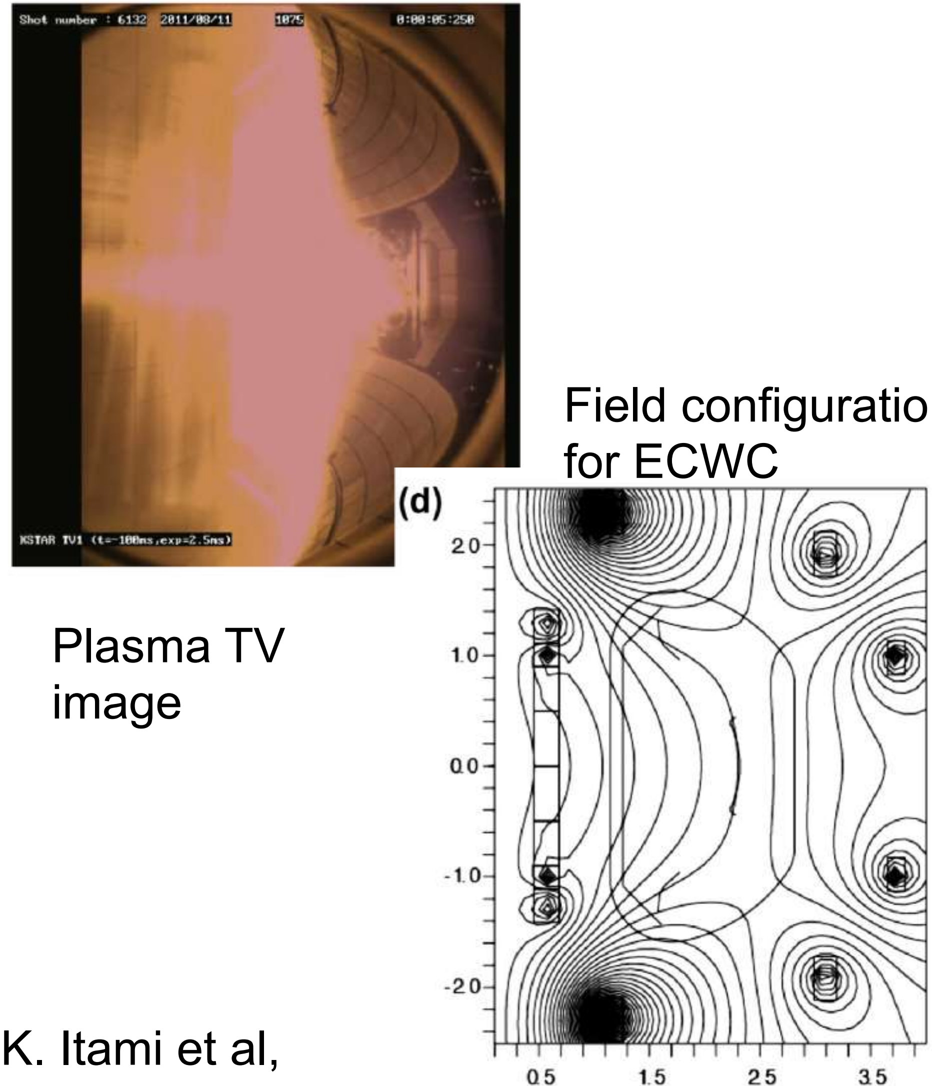
SC coils
&
Cryogenics

RF cleaning (ECWC) has been adapted as the auxiliary wall conditioning for startup recovery

- Fundamental EC + He cleaning tested first
- PF coils charged to distribute the high-density part spread from resonant layer to both radial sides

- The present version uses X2 ECRF instead (just for BT operation conveniences)

- The main effect is believed as easier burn-through
- Reduction of retention is questionable



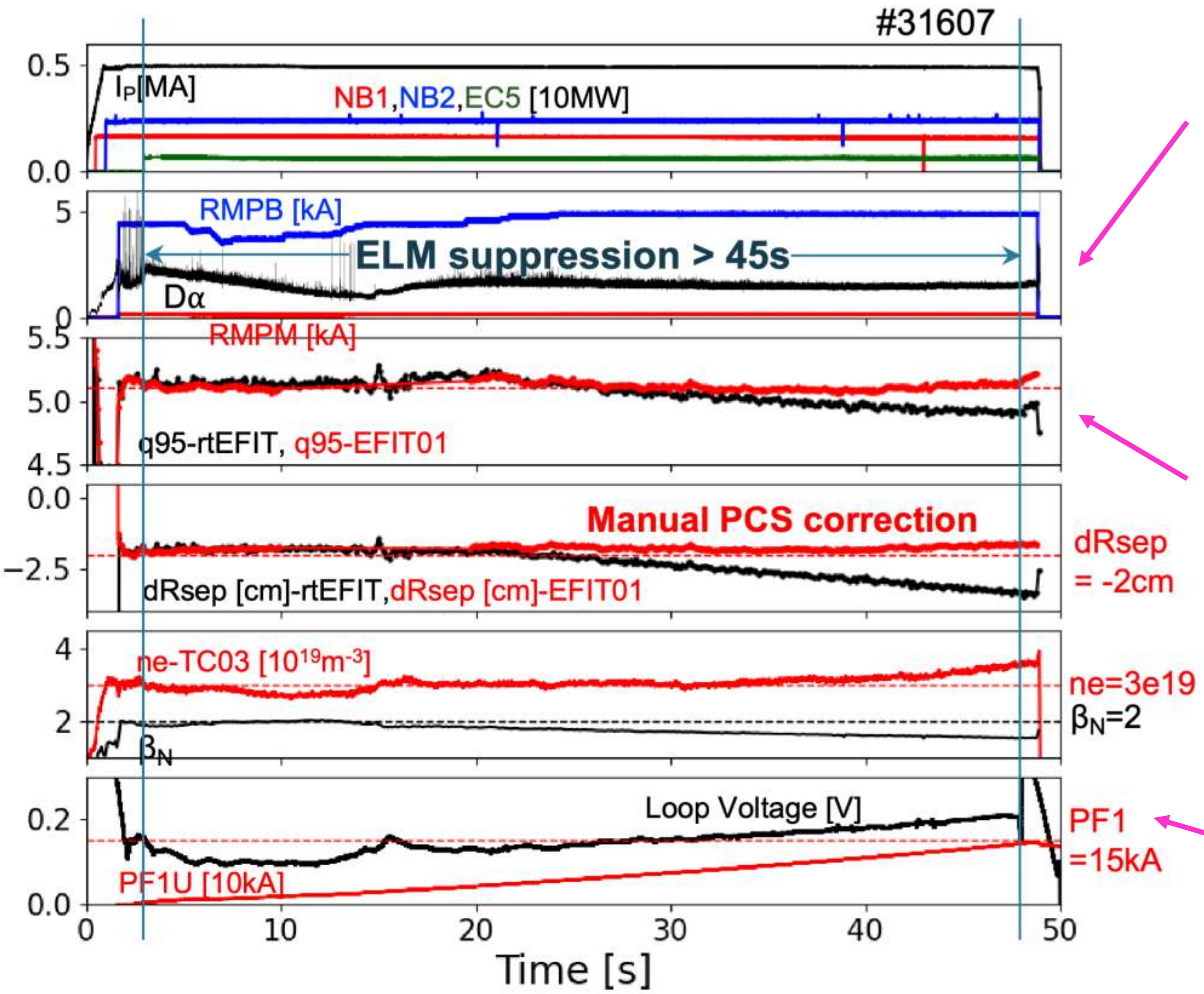
Field configuration for ECWC

Plasma TV image

K. Itami et al,
JNM 438 (2013) S930–S935

ELM suppression attempt in a long pulse (~45s) reveals what's changing during the pulse

Courtesy by J.K. Park (PPPL)

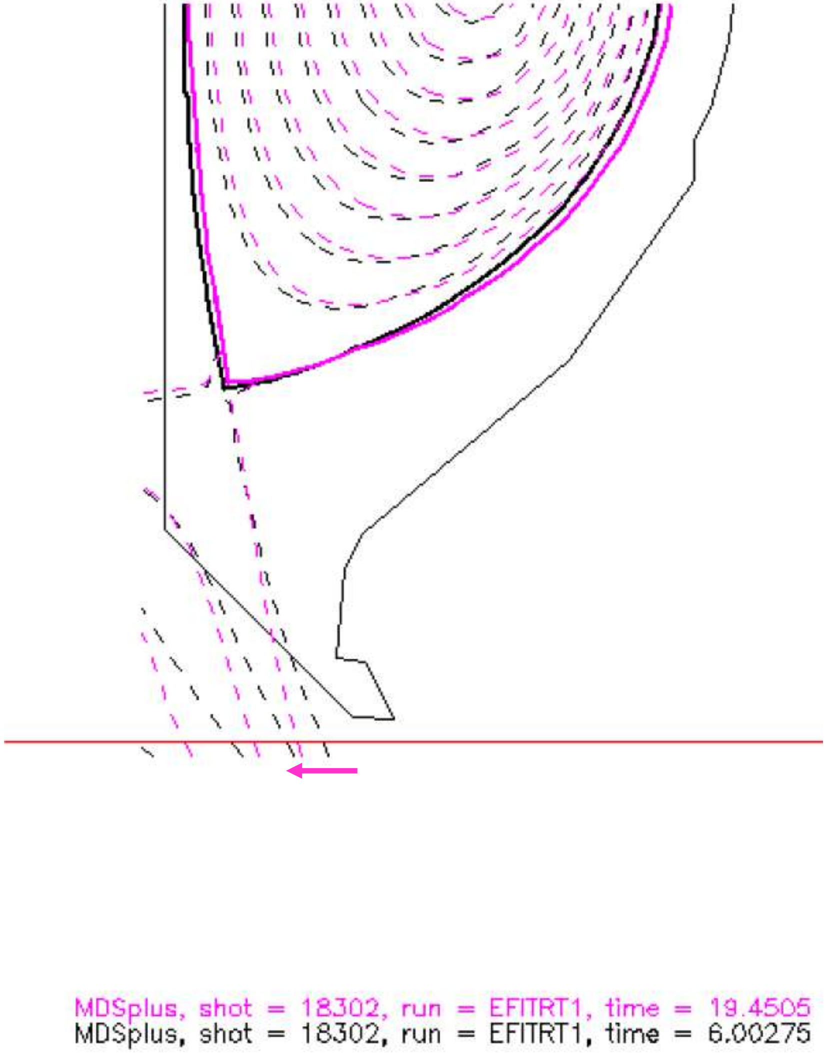


The Da baseline changes
: indicates the neutrals
surrounding the plasma
change with time

The equilibrium varies
due to
1. Diagnostics change
   - heat on PFCs
   - integrator drifts
2. Kinetic changes on beta,
   ne, and recycling

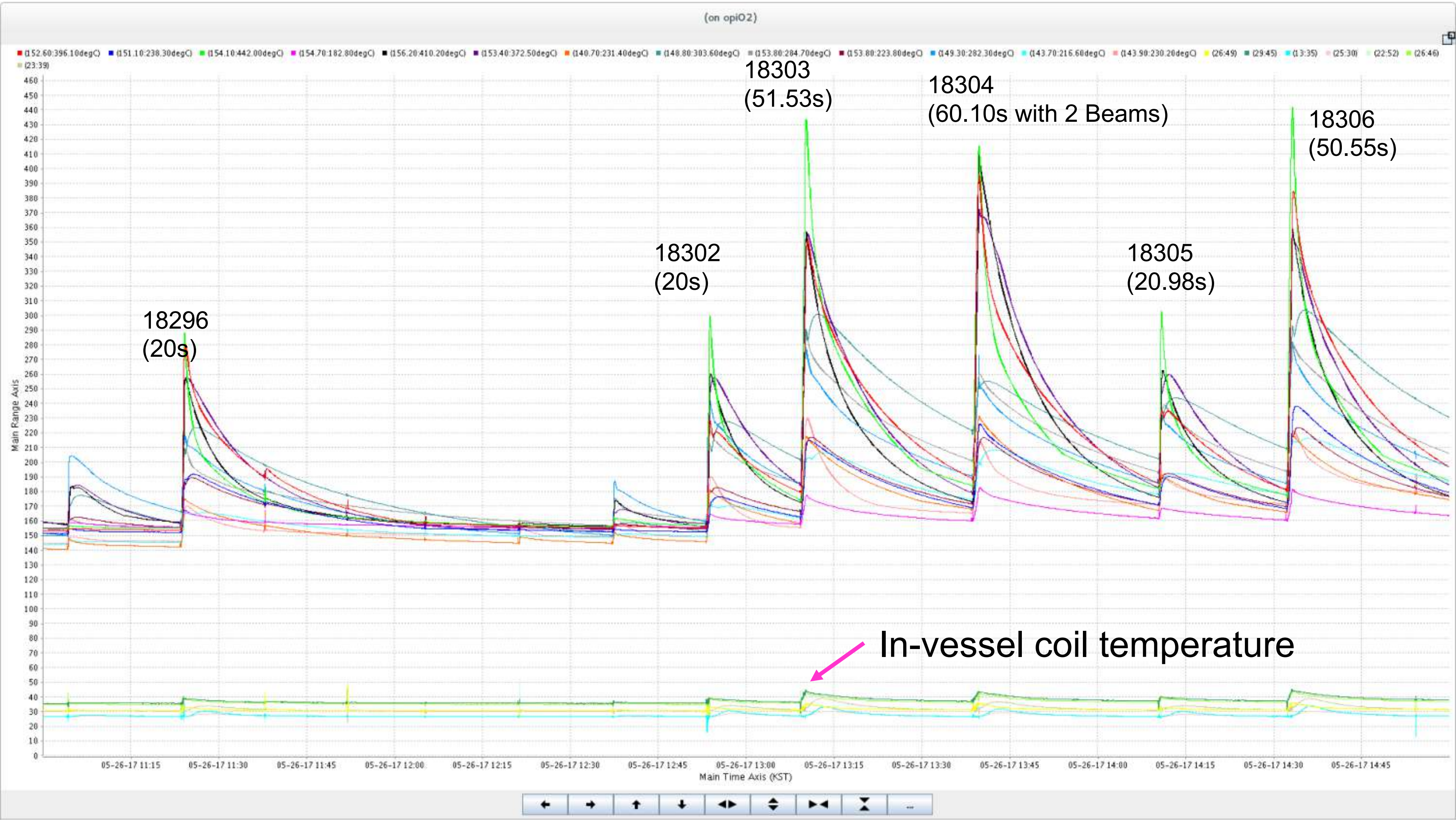
Discharge terminated
by limit of electricity
+ increase of Vloop

Magnetic equilibrium subject to change during the long pulse



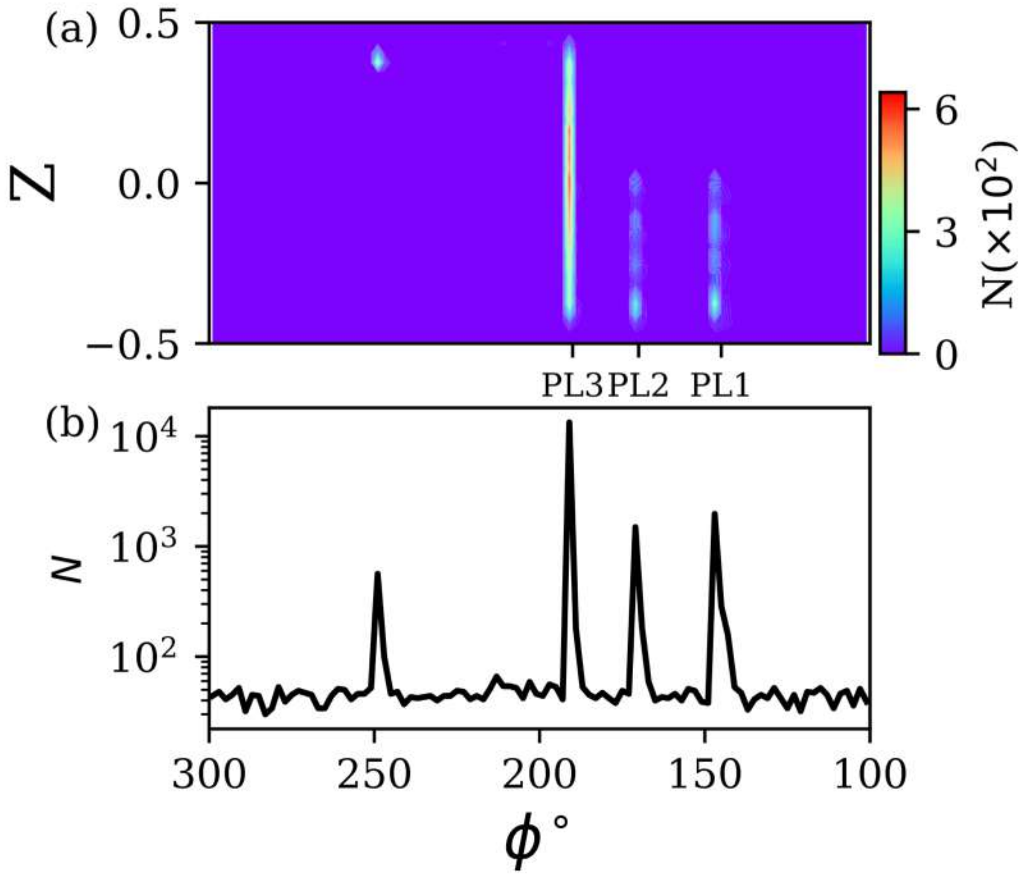
- By comparing rtEFIT & divertor IR measurement at #18302, inward **movement of the outboard striking point** is confirmed as real
  - Possible reasons:
    - Magnetics sensor drift & thermal effect on the pickup coils
    - The kinetic property change (βp drop, ne increase) can vary the squareness
- Later in 2022 we found that the choice of shape control can reduce/increase such changes
  - Switching from RX to Rstk (radial position of outboard striking point) feedback reduced the moving issue

PFC temperature rise is related to the pulse length but no strict relations

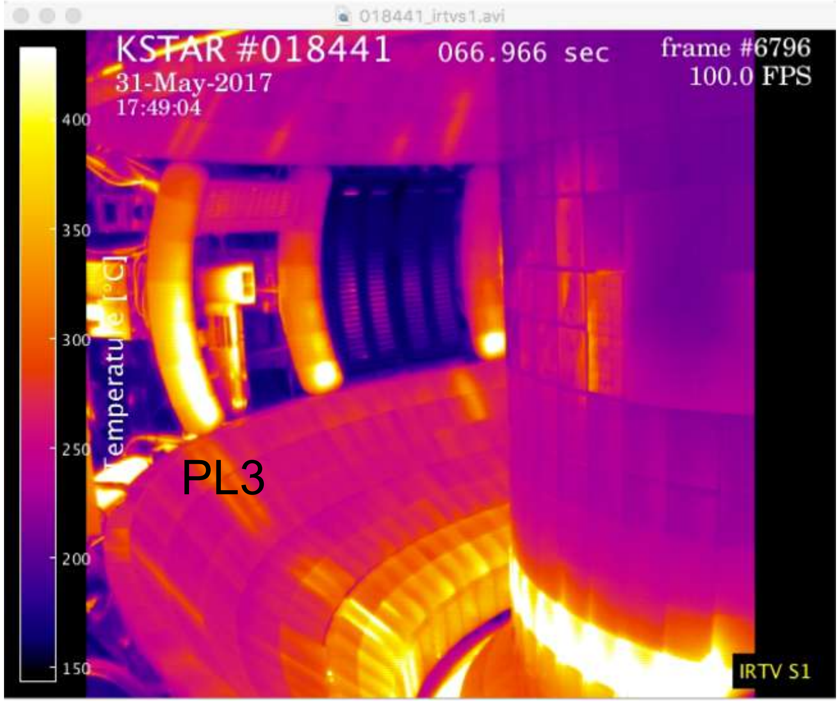


Beam prompt loss control important for avoiding PFC overheat / hotspots

- The guiding-center orbit code accounts for the PFC hotspots by NB prompt loss in the outboard poloidal limiters



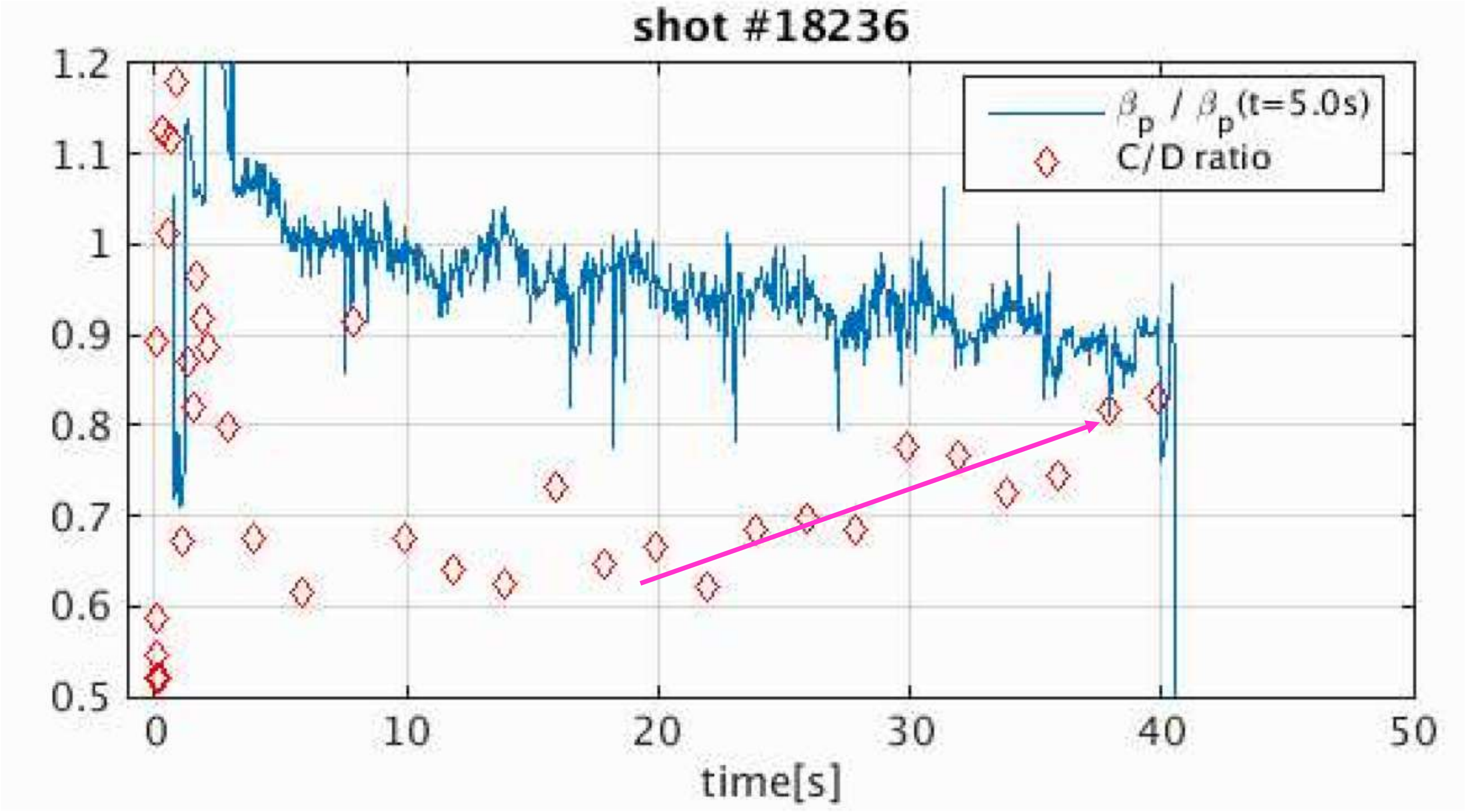
T. Rhee, K. Shinohara, H.-s. Kim et al.,
Physics of Plasmas 1 (2019).



IRTV S1 / Courtesy by
D.C. Seo (KSTAR)

C(III)/D ratio evolution during the long pulse

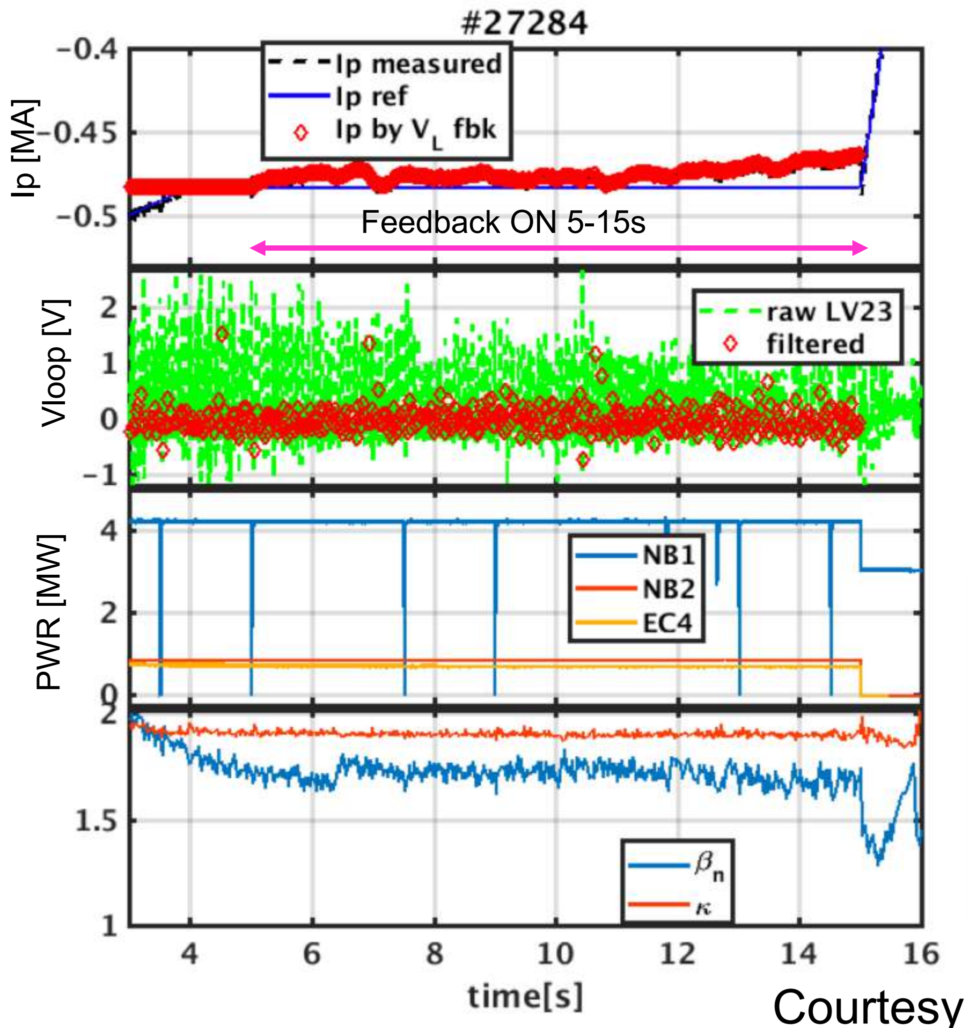
C/D ratio from visible spectroscopy starts increasing at t > 20s



Visible spectrometer KSTAR / Courtesy by SooHyun Son (KSTAR)

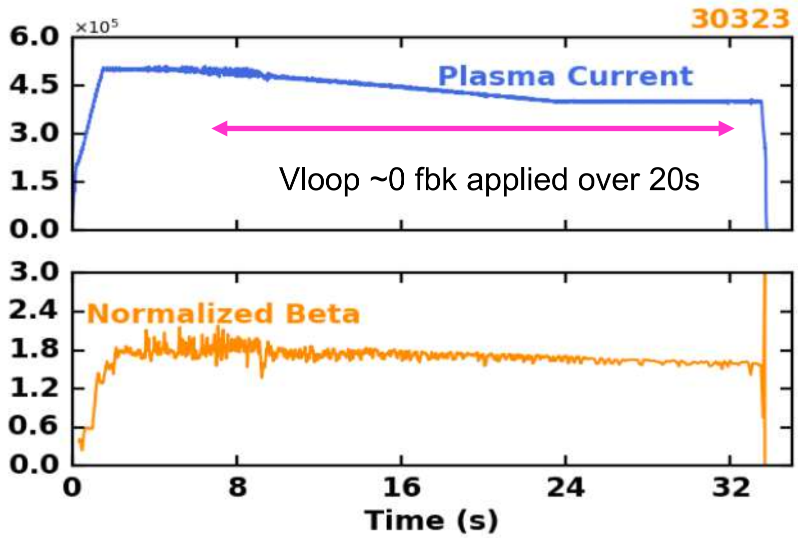
Loop voltage feedback control on Vloop ~0 target demonstrated the NICD varies over time

- Ip target regulation for Vloop ~0 target (part of the profile control @ PCS)



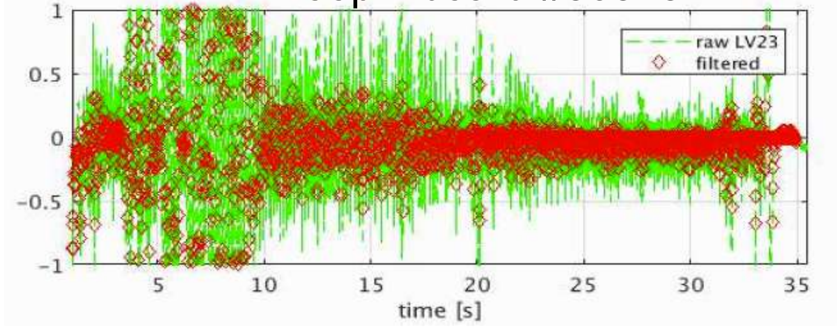
Feedback ON 5-15s

Vloop~0 + long pulse



Vloop ~0 fbk applied over 20s

Vloop inboard #30323

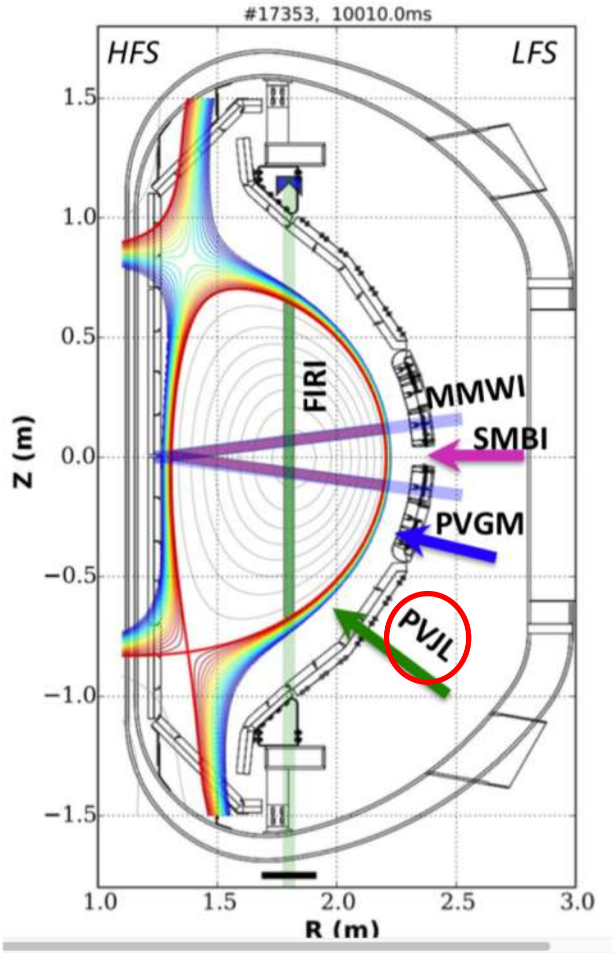


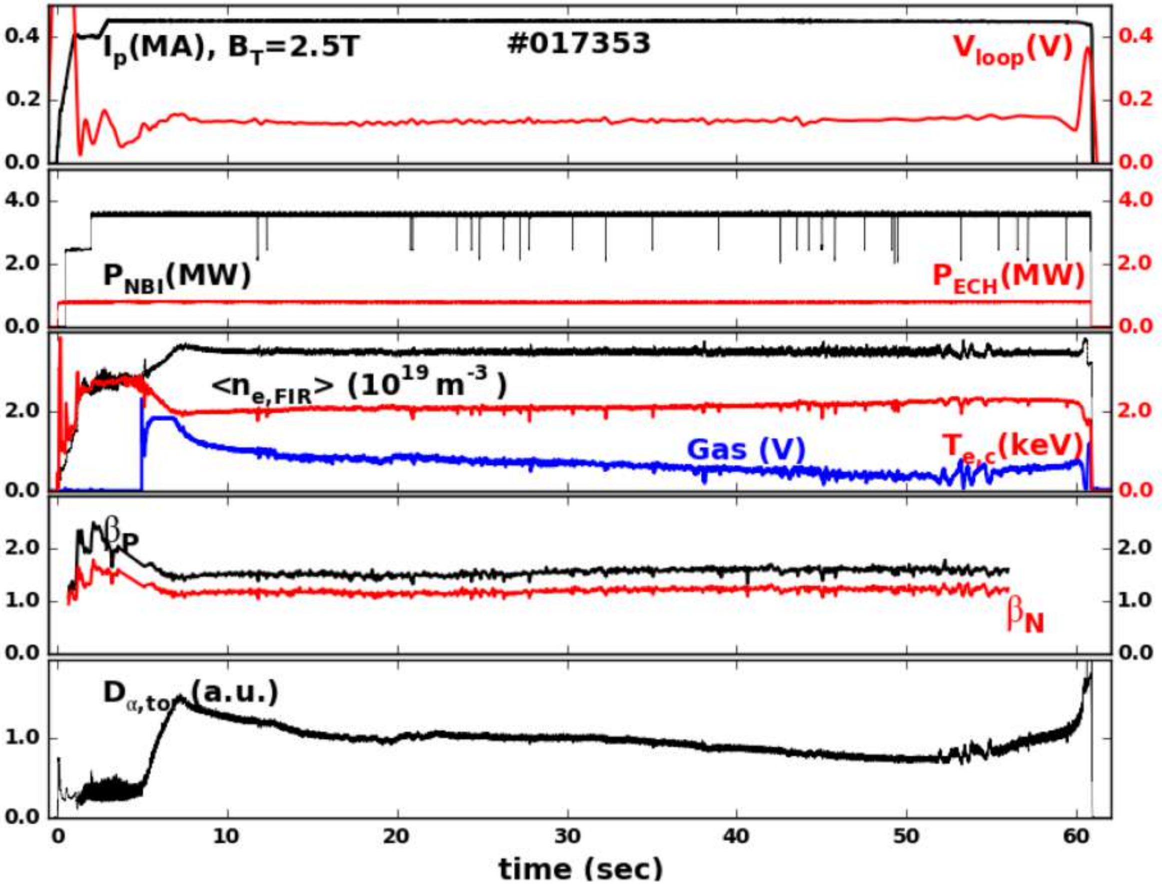
Courtesy by W. Wehner (GA) / J. Kang (KFE)

Control of density can slow down performance degradation in L-mode long pulses

Long high heat flux to PFC → wall recycling increase →particle balance change

- With <u>active density feedback</u> by conventional gas puff, overall performance gets down but no degradation occurred during 60s

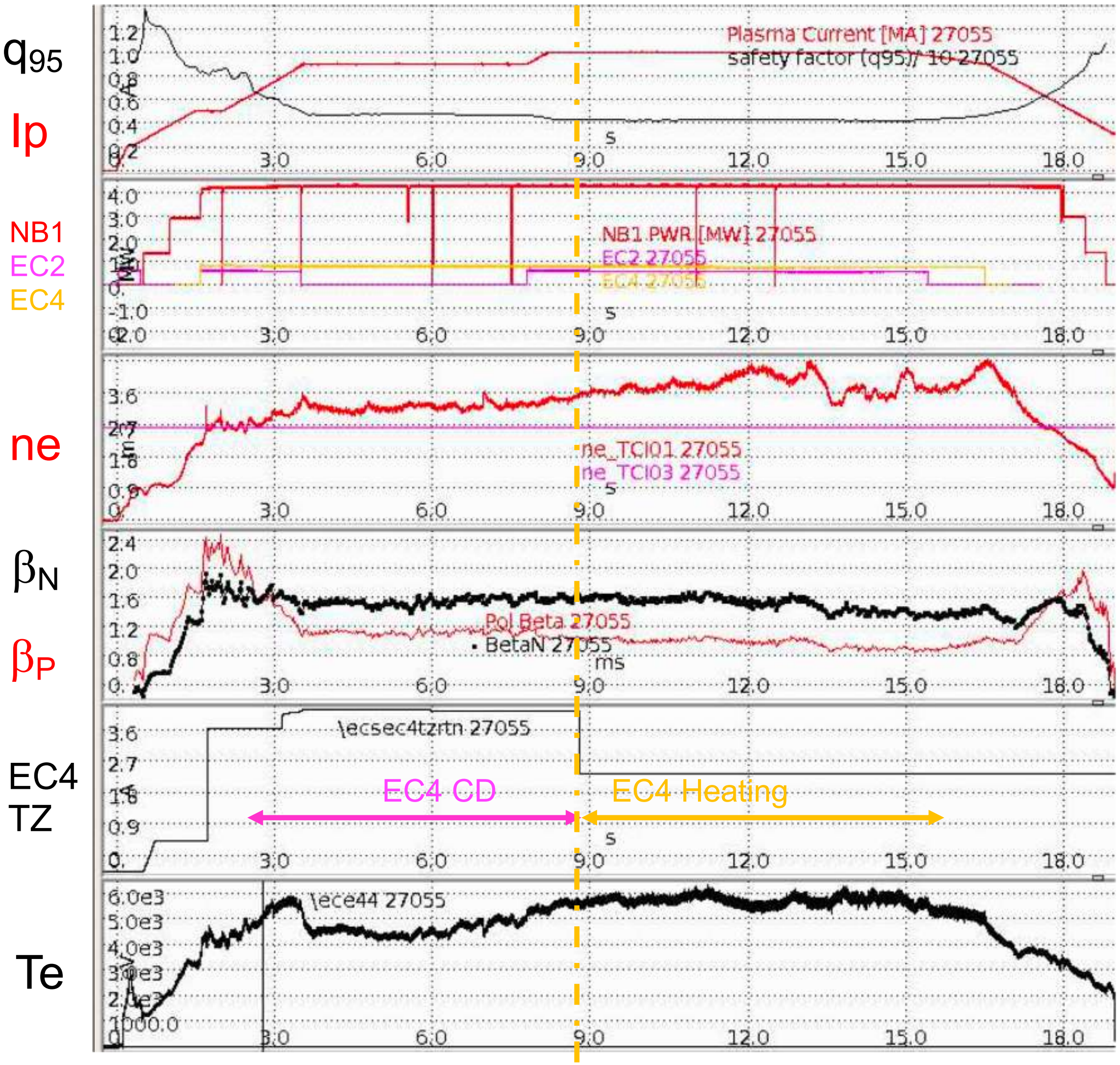




J.W. Juhn (KFE)

Real-time EC control, switching from ECCD to ECH, in order to avoid the reflection

#27055, 1.0MA, BT=26000A



Realtime EC mirror steering system [*] enables mirror beam angle changes during the pulse

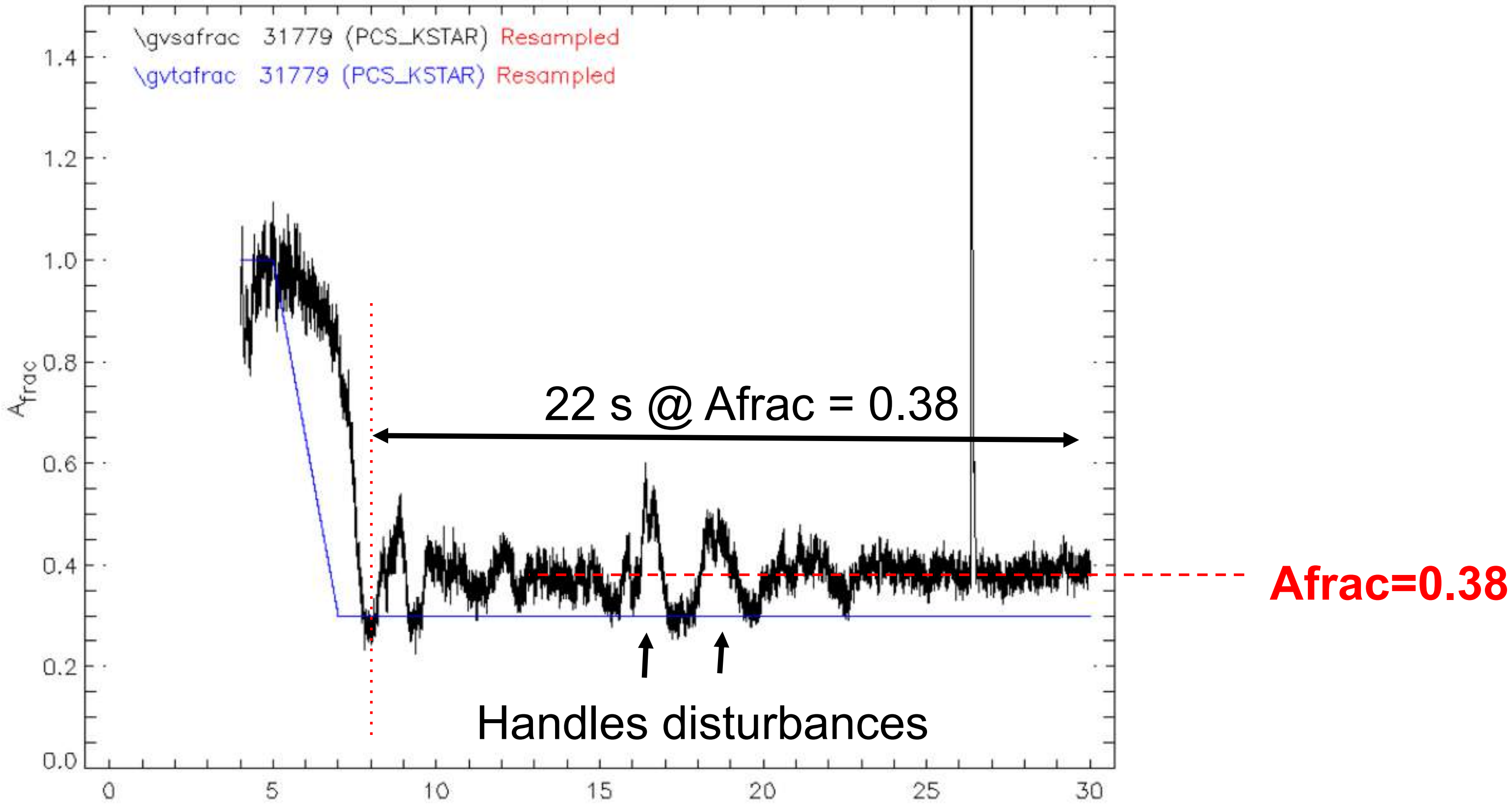
Under limited beam power
P_{NB} = 4.6 MW

EC4 Switched from ECCD to ECH in order to avoid reflection by high-ne plasma:
techniques used for 1.1 MA /15s achievements

[*] M. Joung, M. Woo, J. Han, et al., Fus. Eng. Des. 151 (2020) 111395.

N2-seeding Detachment control beyond the wall time

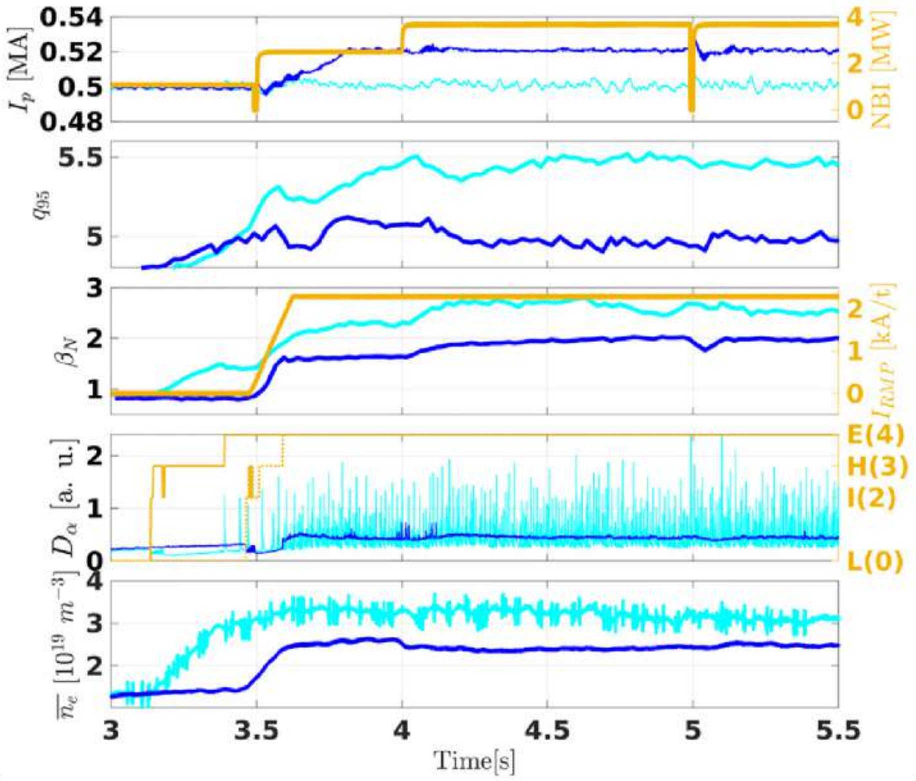
- The max PFC temperature remain under the safe regime (< 350 C) throughout the pulse
- See D. Eldon's talk for control details (also in *D. Eldon, PPCF* ***2022***)



Courtesy by D. Eldon (GA) / H.H. Lee (KFE)

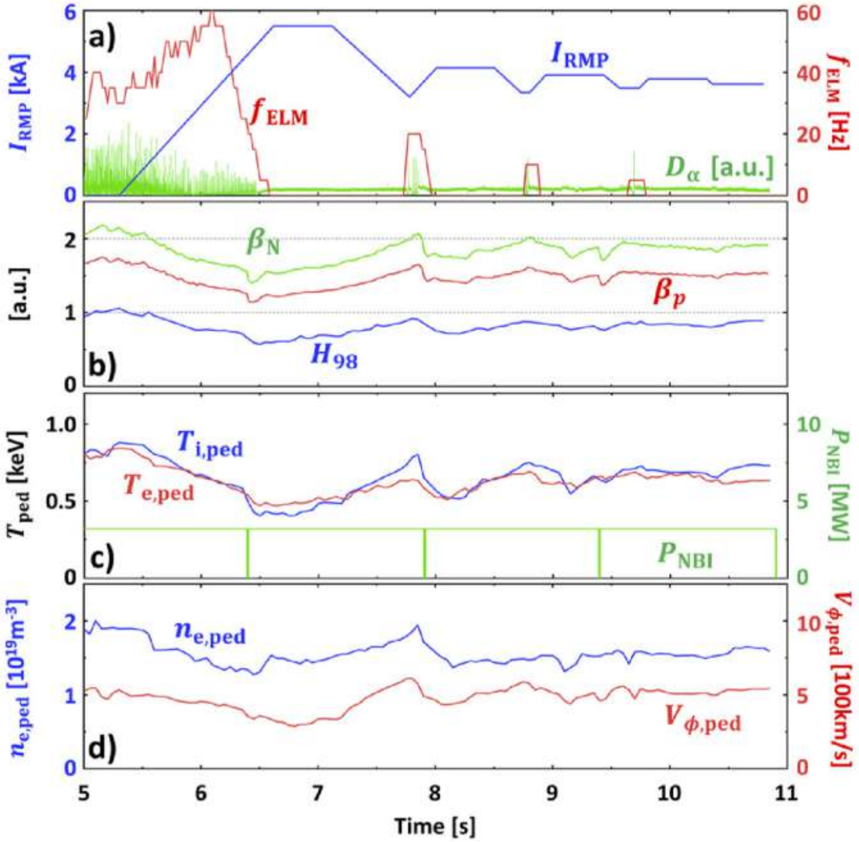
Various control techniques utilized to automate long-pulse n=1 ELM crash suppression

A pre-emptive RMP-ELM suppression based on the ML L-H detector



G.W. Shin et al., NF 2022

Adaptive ELM control that regulates the ELM frequency and amplitude



S. Kim, NF 2022

R. Shousha, PoP 2022

Concluding Remarks on designing long-pulse tokamak operations

- Think about the Operational Space & Limits
  - On tokamaks, inductive CD has a hardware limit and NICD also bounded to the heating/CD capacity
  - Model-based approach always helps
  - Choose the most probable one
- Interface matters, not only the fast part but also the slow/longterm part
  - Fast parts require **automation** that the human cannot react
  - Slow/longterm part may include human reaction interfaces (e.g. Emergency stop buttons)
- Integration & Orchestration important
  - It is not a mere plasma physics, but a whole integration of modern science & technology
  - Measurement should not be disregarded → good measurement makes everything work