NBI performance for long pulse operation in KSTAR

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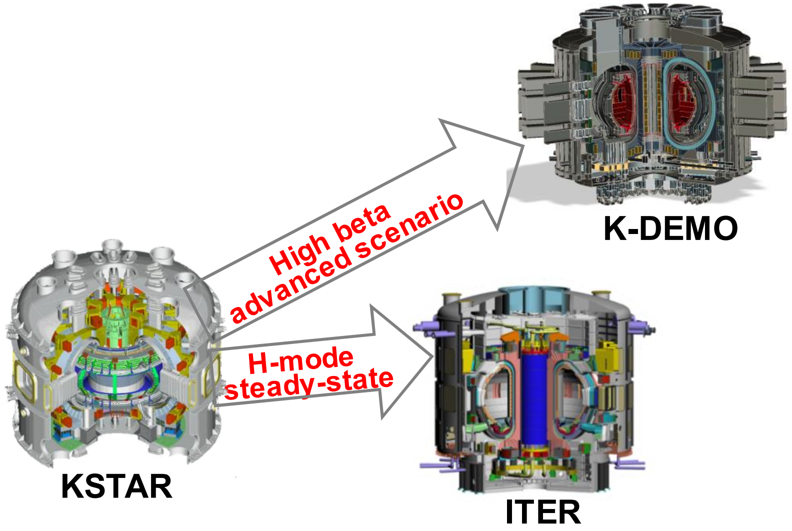
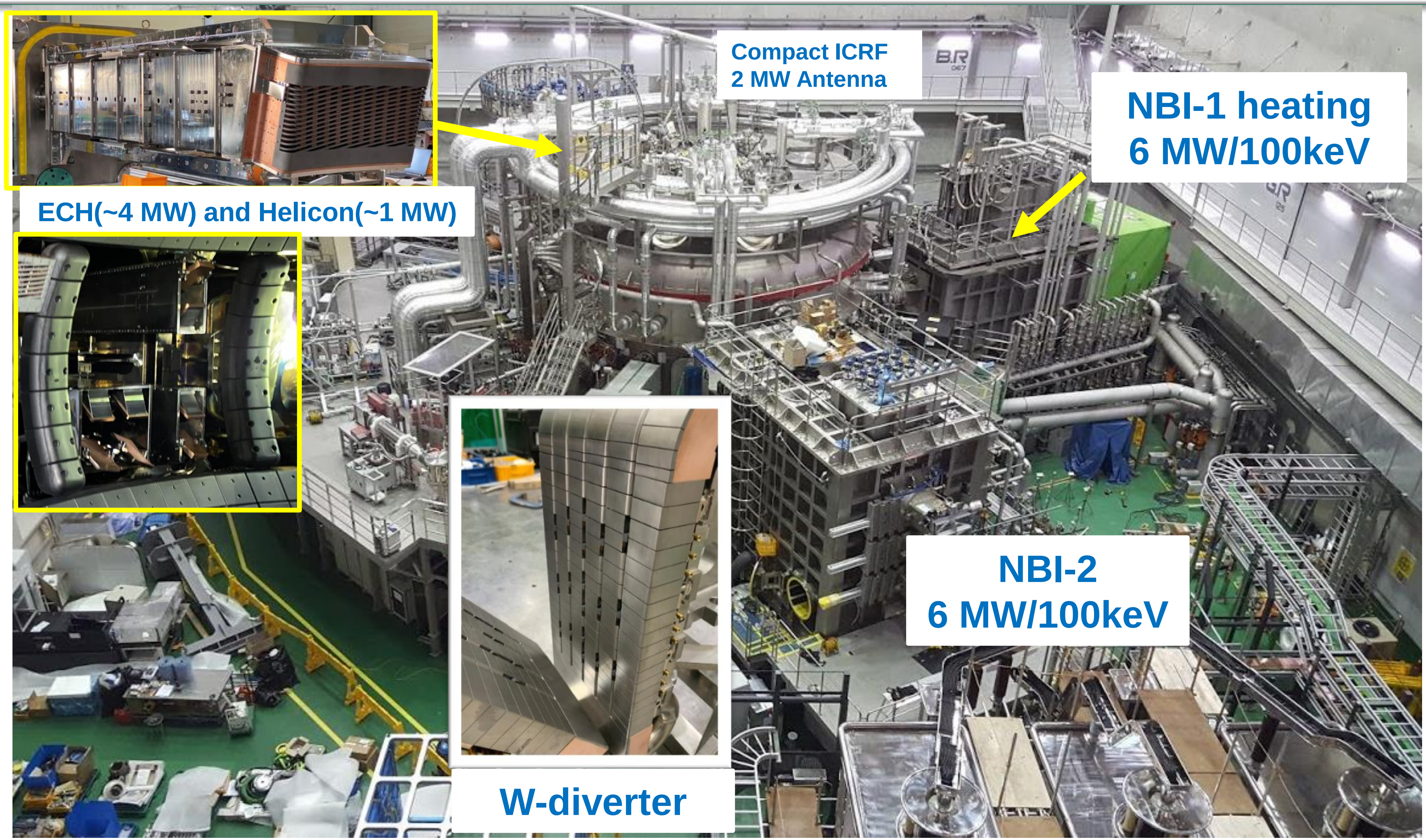


KSTAR

KSTAR is to Address Key Physics and Technical Issues for ITER and DEMO



Developing Advanced CD is Another Key Issue in a long Term

First NBI (NBI-1) has been a work horse for KSTAR

❖ **Main mission of NBI-1**

- Core heating & on-axis CD by tangential co-injection

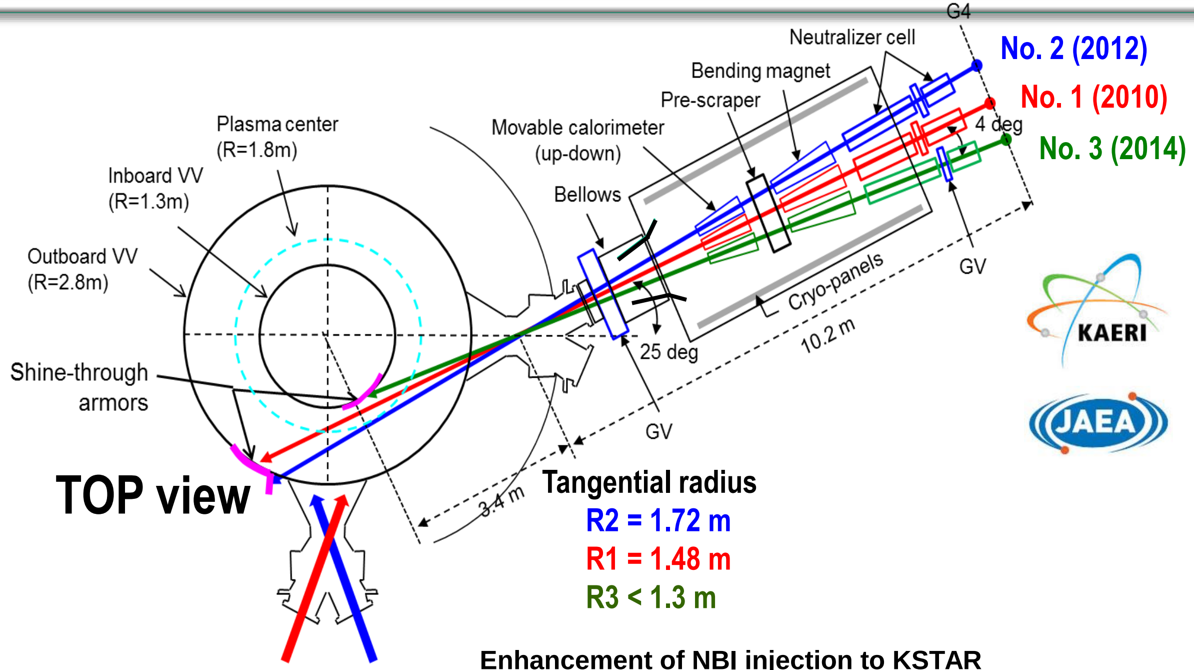
❖ **Specifications**

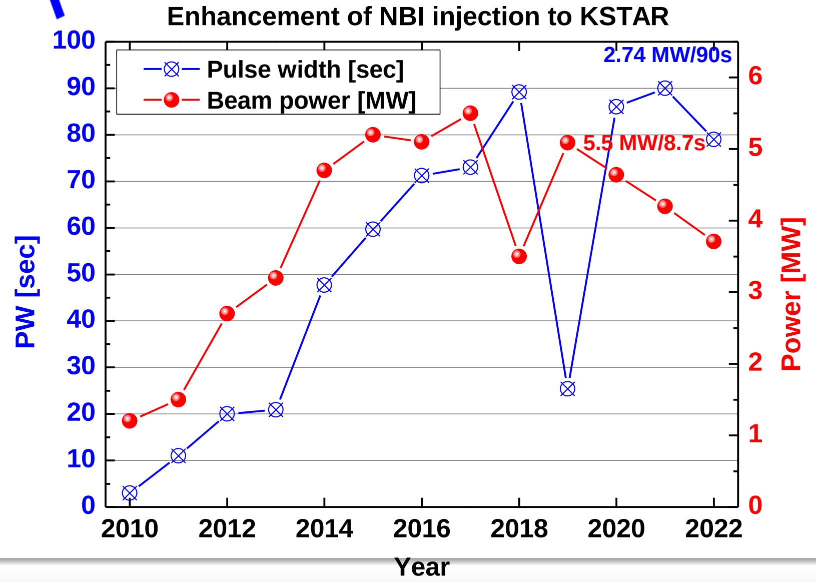
- 3 Ion source arranged in horizontally (placed in mid-plane)
- Max. power of 5.5MW using 100 kV D+ beam with arc discharge

❖ **Year-by-year enhanced the performance of NBI1**

- Maximum power of 5.5MW during 8.7sec using three ion sources
- 89.1 sec with 2.8 MW using two IS (at 85/90kV)

* Longest record pulse (~100s, #34705) with 3.9 MW (NB1(2,7MW)+NB2(1.2MW)))





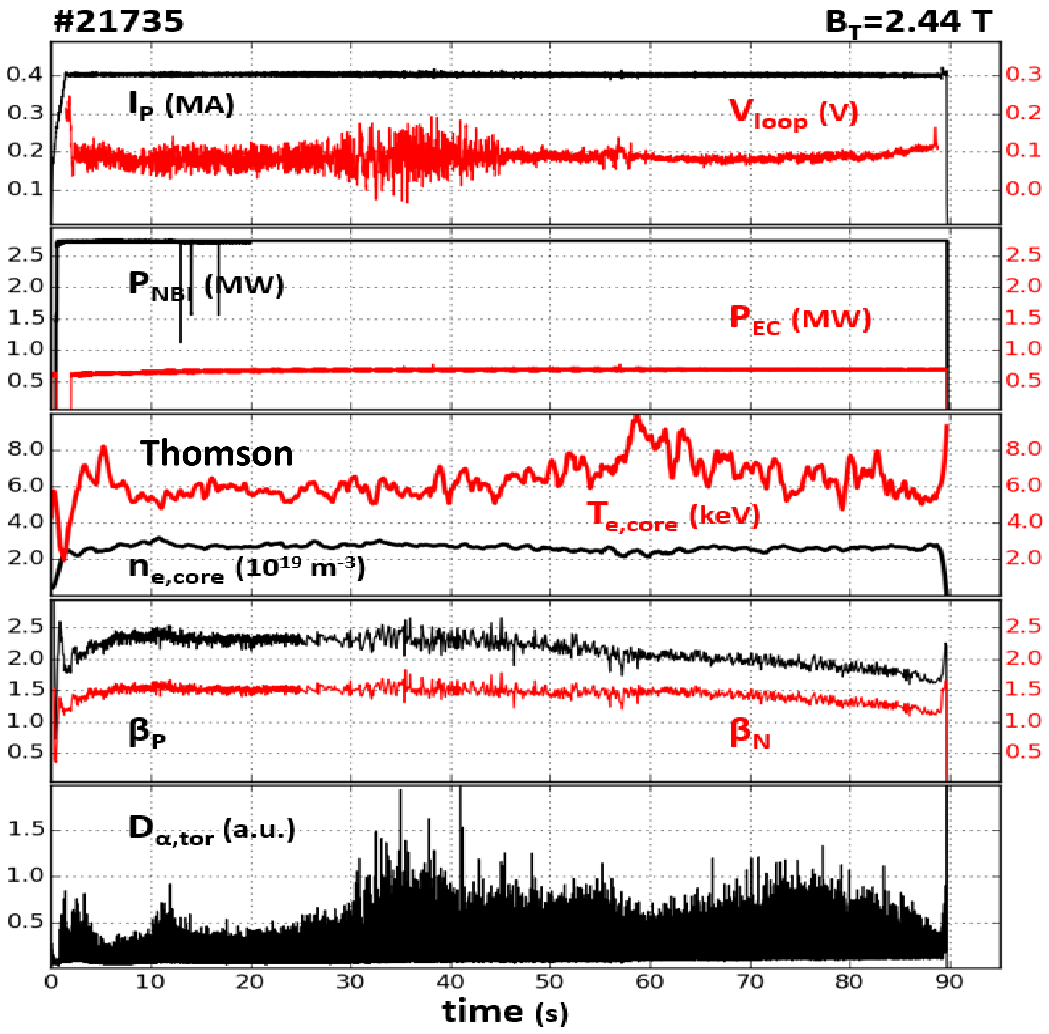
Introduction

- KSTAR is superconducting magnet machine aiming at long pulse operation and has showed the excellent results such as high Ti, high beta-p scenario etc. up to tens of seconds.

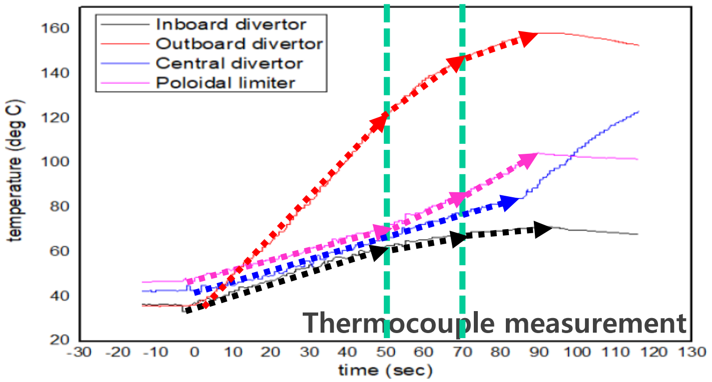
- As one of heating and CD mixtures, NBI contributed to the dominant non-inductive current source for the steady state operation as well as main heating in KSTAR
- Compared with the short pulse operation(~ a few s), there are a lot of technical issues in NB arising at tokamak operation during many year long pulse experiences.

- In particular, the plasma performance degradation observed in high performance long pulse plasma operation.
- Power degradation is one of issues in evaluating long pulse plasma performance
- Based on many year experiences, some lessons for long pulse NB operation are shown.

#21735, new record of pulse length (~90s) achieved in 2018 based on high beta-p discharge (~ 73s in 2017)

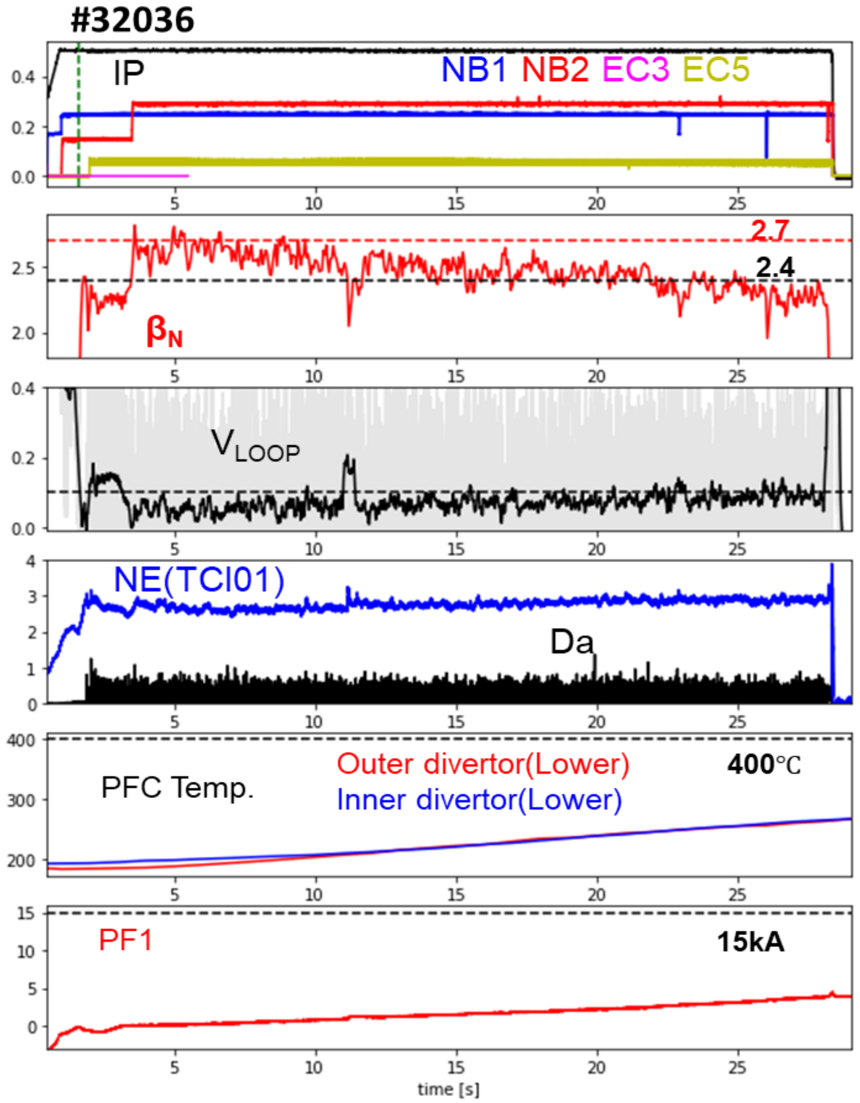


- I_P = 400 kA, B_T=2.44 T, P_{NBI}=2.8 MW, P_{EC}=0.7 MW
- V_{loop} ~ 0.1 V is kept during entire discharge.
- $β_P$ and $β_N$ are sustained to almost constant until ~45-50 sec.
- $β_P$ degradation for 50-60 sec comes from X-point changes to reduce a burden of PF3 and PF4.
- After 70 sec, $β_P$ degradation is accelerated.
- Finally, IVCC(In- Vessel Control Coil) temperature increase triggered interlock.
- It seems that high freq. and large amp. of IVC current results in increase of IVCC temperature, not radiation/fast ion loss.

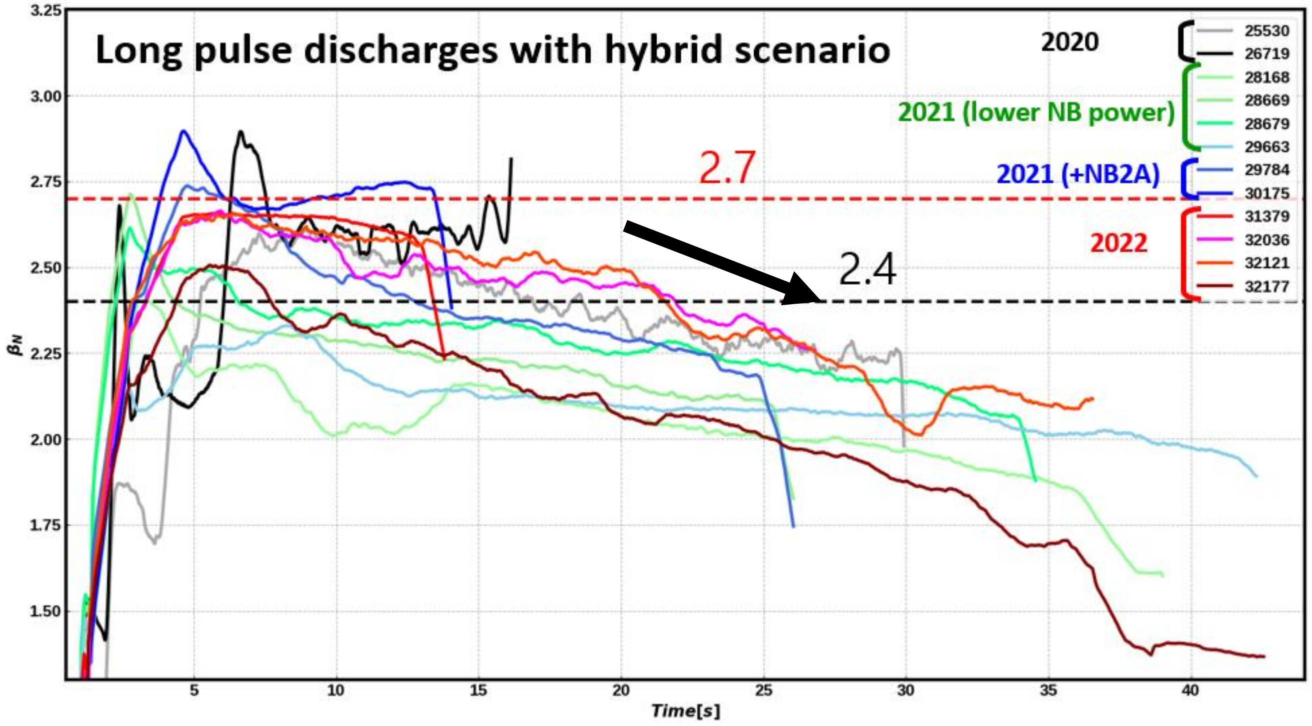


Need to identify the limitation toward long pulse operation

Quasi-steady state $\beta_N \geq 2.4$ operation for > 20 s
However, performance degrades as plasma beta is increased as well



Long-pulse with β_N > 2.4 for > 20 s

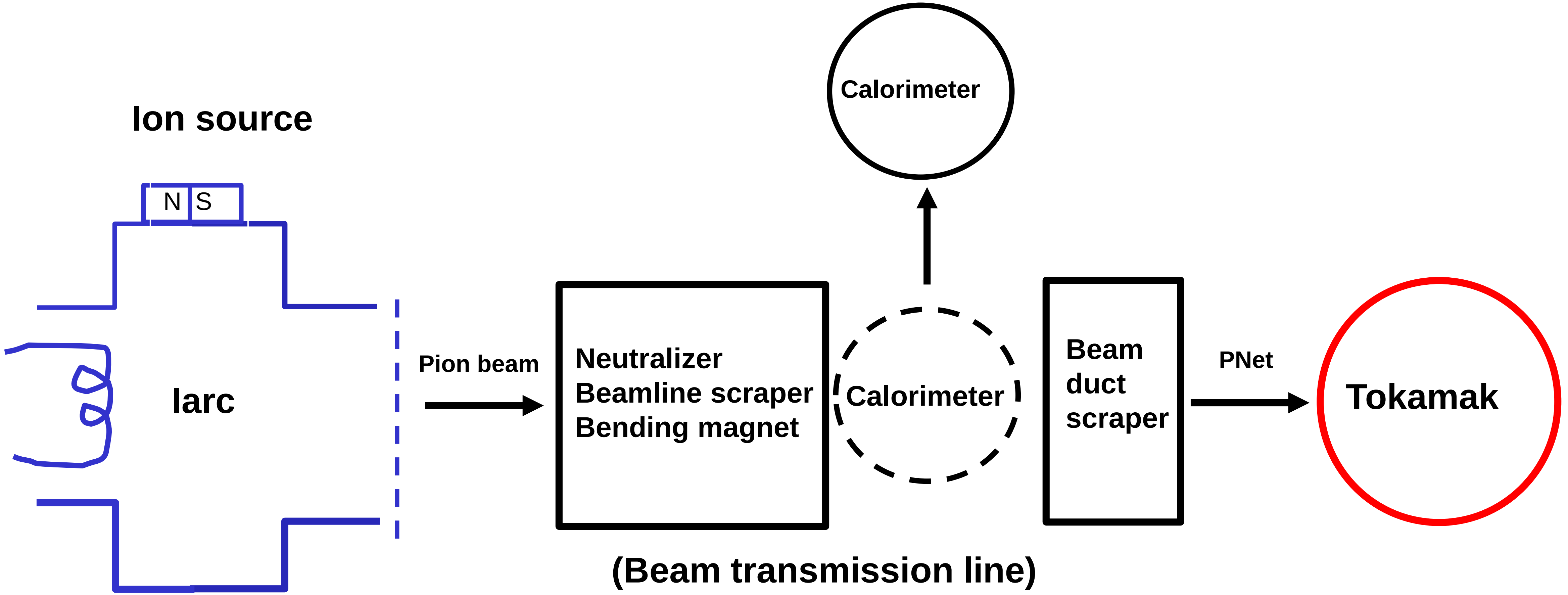


- **Discharge lasted up to 40 s but performance degrades a few percent.**
- **The more severe the degradation, the higher the performance.**

OUTLINE

- ***Introduction***
- ***NB beam power stability in long pulse operation***
- ***Arc power, PF field(tokamak operation)***
- ***Divergence by beam species***
- ***Engineering effort in high power beam line components***
- ***Summary***

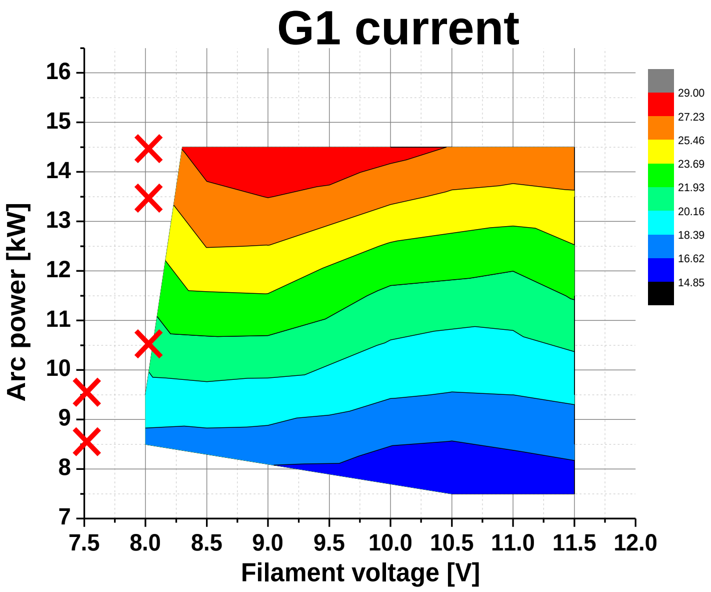
Neutral beam power transfer to tokamak



Pnet ~ f(Iarc, Ibeam, Pressure of gas, beam loss at transmission line…)

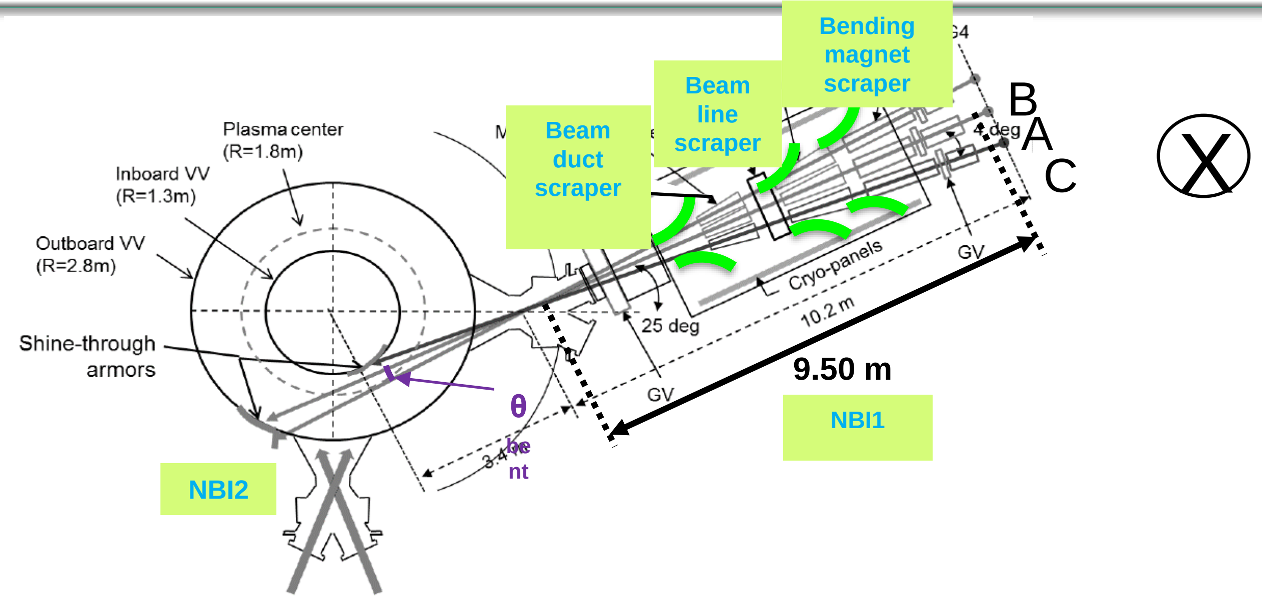
Ion beam current variations in filament arc ion source

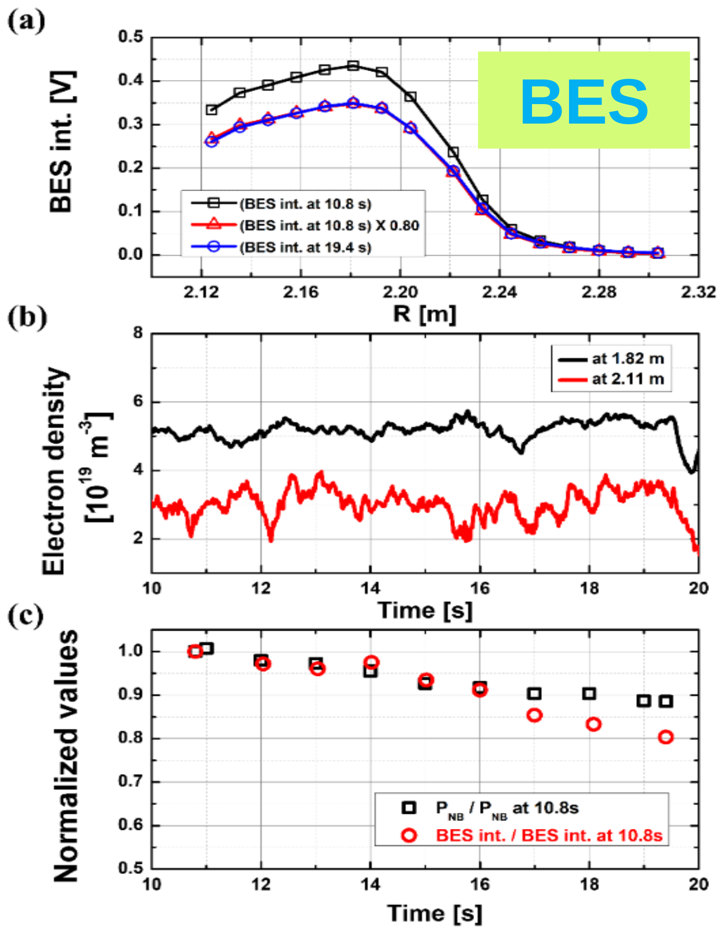
- **Beam current firstly depends on the arc current in power control mode**
  - Arc current depends on the fuel gas pressure and the cusp magnetic field configuration
  - **The beam current decrease is less than a few percent for more than 40s discharges**



Year	Shot #	Pulse width	IA-ARC (A) / variation	IA-beam(A) /variation	IB-ARC (A) /variation	IB-beam (A) /variation
14	11664	47	688/+20	38/-1	511/+20	42/0
15	14003	40	678/+10	40/1	343/17	42/0
17	18437	73	650/31	36/1.7	279/10	32/0.5
19	22528	43	662/28	36.8/1.5	374/30	38/0.7
20	27031	86	560/25	32.6/1.5	393/55	39.4/3
22	31536	71			445/73	36.2/-4

Neutral beam power stability in time





#28679 [MW]	Ion Beam power	Neutrali-zer	Bending magnet	Ion dump	BL scraper	Beam duct	Net Neutral beam power
Start(20s)	6.8	0.70	0.35	2.31	0.1	0.09	3.25
End(36s)	6.7	0.78	0.38	2.31	0.12	0.1	3.01
∆P/P(%)	0	11	8.5	0	10	11	**-8.8**

- **Calorimetric method shows the neutral beam loss at beam line in long pulse operation**
- **BES also shows the neutral beam power loss**
- **KSTAR Stray PF field may influence beam power to the plasma(~a few %)**

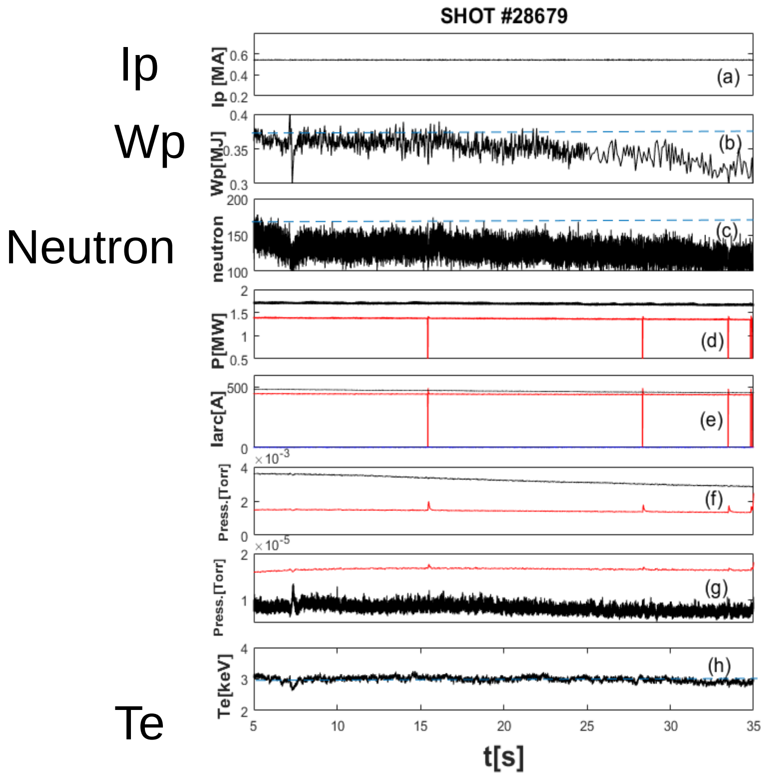
Neutron is the key measure to judge whether plasma performance degradation is from NB power degradation in addition to water flow calorimetric method

- **Neutron emission is used to judge NB power effect on plasma performance degradation**
- **Neutron emission is proportional to NB power and Te in beam target plasma reaction**

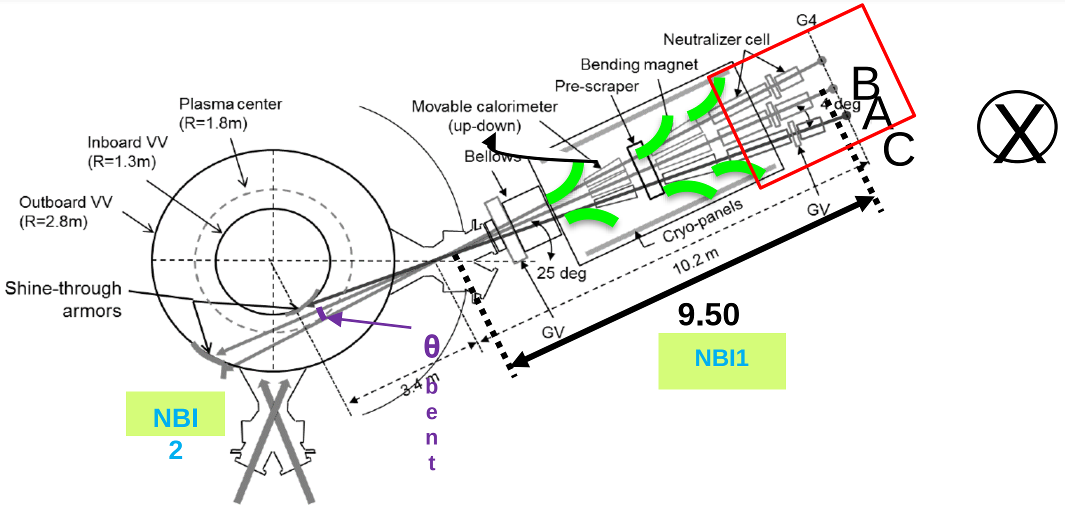
$$Neutron = \int n_b n_i < \sigma v > dV \;\propto [Pnbi\ \tau_s\ ]n_i \;\propto \boldsymbol{P_{nbi}\, T_e^{3/2}}$$

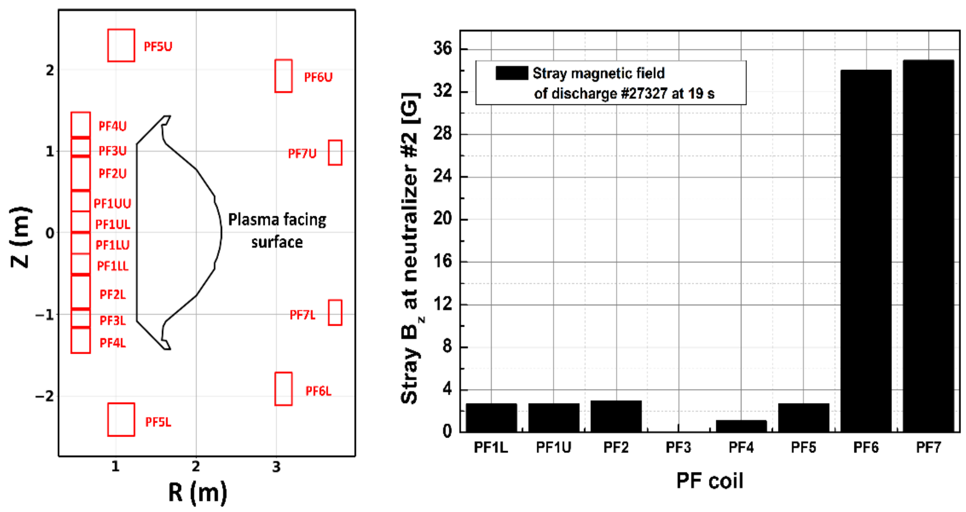
- **Cooling water flow calorimetric calculation shows the beam power loss on the beam component in long pulse operation**

	27327	28679	29663	34705
Scenario	High Ip	Hybrid	Hybrid	Long pulse
Plasma performance	down	down	down	down
Neutron	down	down	no	no
Te	no	no	down	no
NB power effect	Yes	yes	no	no

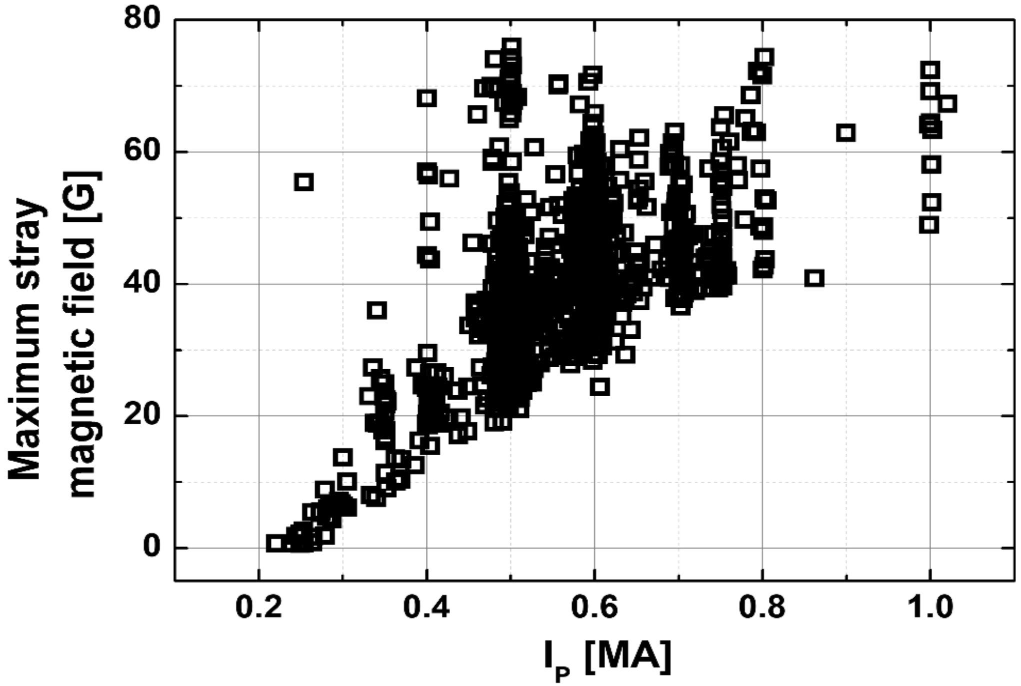


KSTAR stray magnetic field may influence neutral beam loss at the beam chamber and results in neutral beam power loss to the tokamak



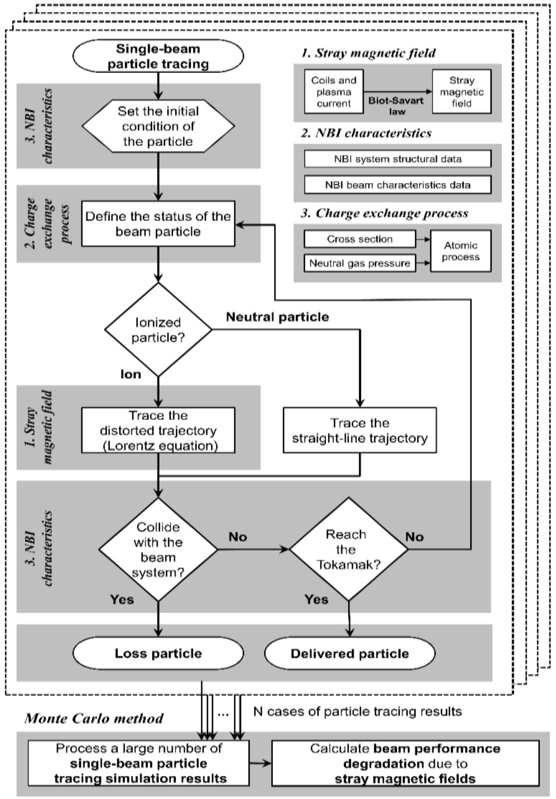


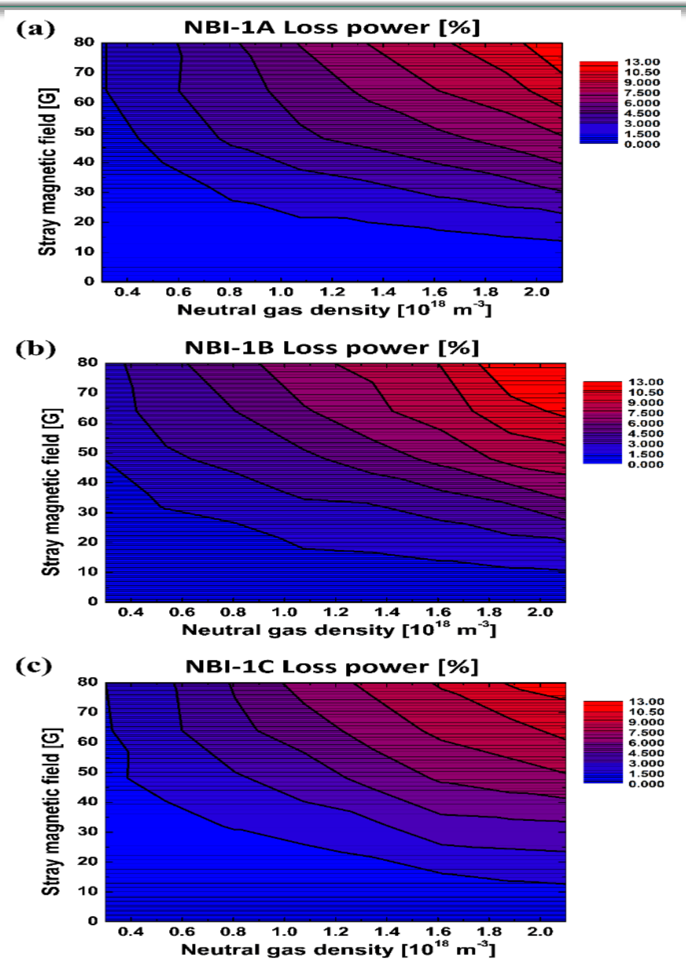
The stray magnetic fields generated by each PF coil of discharge #27327 at 19 s.
The PF 6 and 7 coils contribute significantly to the large stray magnetic field.



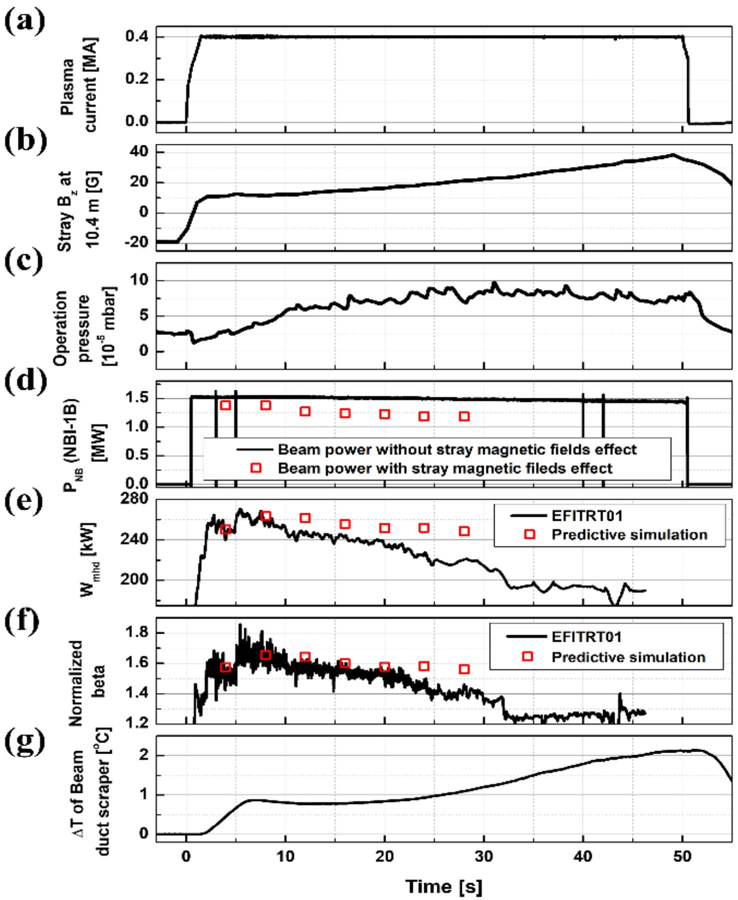
The maximum stray magnetic field at the end of the neutralizer in the 2022 KSTAR campaign. The stray magnetic fields increase as the plasma current (I_P) increases. **Variations in the pulse length** cause a difference in the maximum stray magnetic field within a specific I_P.

Monte-Carlo calculation is used for power loss to the tokamak and the predictive simulation confirmed the stray magnetic field effect





Beam loss vs. the **stray magnetic field** and **gas pressure**



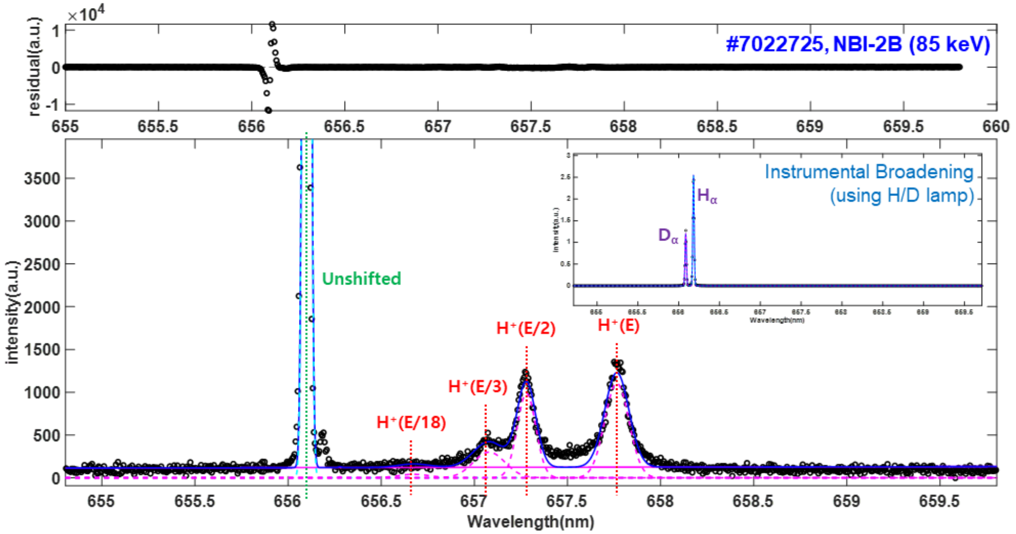
The predictive simulation showed that the beam performance degradation due to stray magnetic fields impacts the plasma performance degradation.

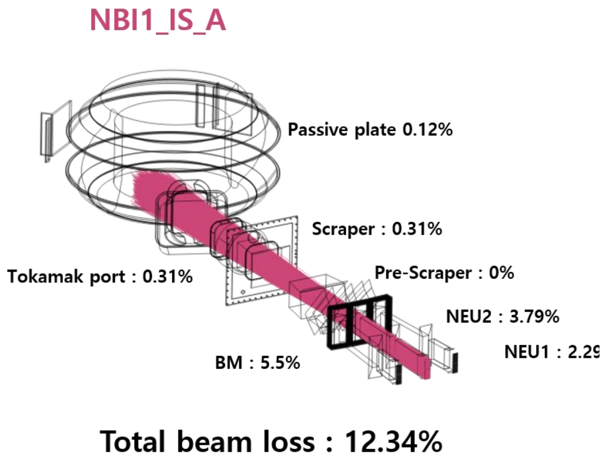
- **Active compensation against the stray magnetic field may be needed in KSTAR**

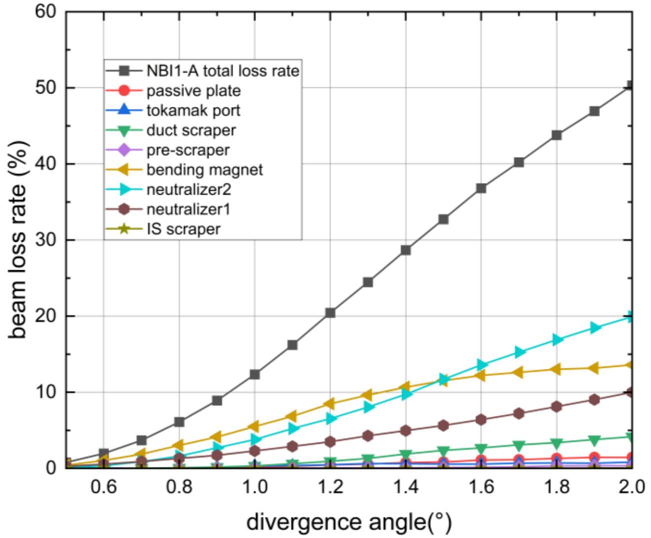
Need for real time monitoring beam species and divergence angle for long pulse operation as well as active magnetic field compensation

- **Beam species is different at NB1 and NB2**.
  - The divergence angle may be changed during the shot
  - The lower energy beam, the higher divergence angle

- **Ion beam loss increase ~20% at 10% divergence angle changes**

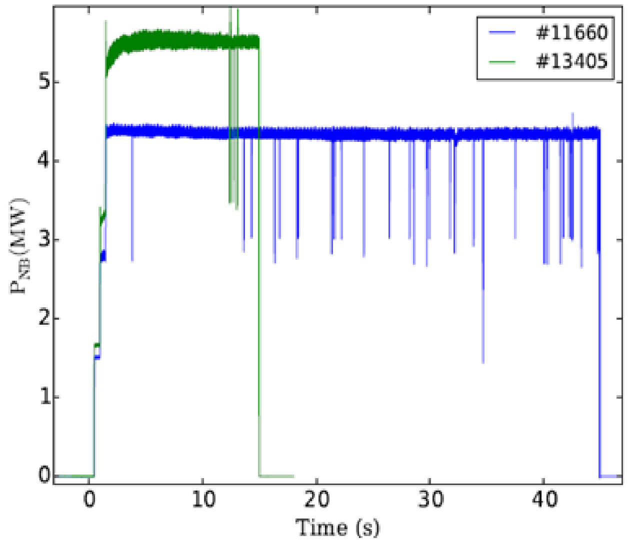


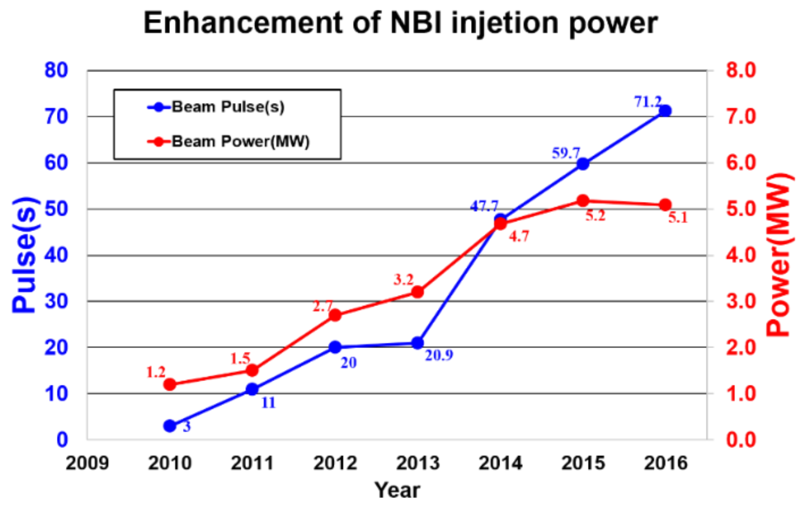


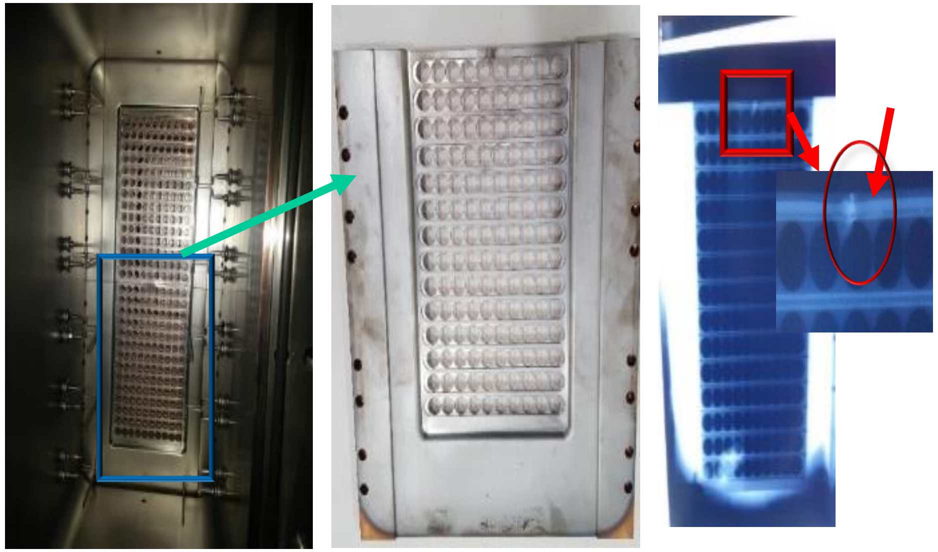


⇒ $f_{H^+} : f_{H_2^+} : f_{H_3^+}$ = 65.02 : 24.28 : 10.70 θ_{H^+} = 0.902º, $\theta_{H_2^+}$ = 0.974º, $\theta_{H_3^+}$ = 2.0177º

Reliable technology of high power Long Pulse NBI has been developing (confirmed to 60s until 2015)







- To test the high power beam of NB1, tokamak dummy plasma is required. (NB1 calorimeter can operate in less than 10s)
- 5.5MW(12s) and 4.2MW(55s) at tokamak operation
- After campaign, some damage part(clogged pipe) at the grid of ion source was found

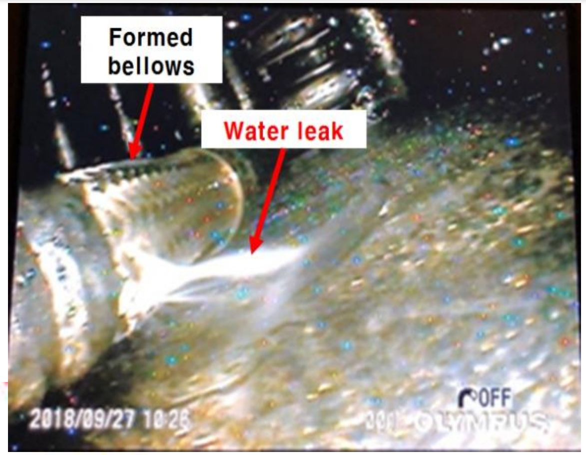
In 2016 SOFT, we reported the damage of ion source grid at long pulse operation and planned a need for the comprehensive study for ion dump and calorimeter

Several accidents occurred during 2018~22 campaign

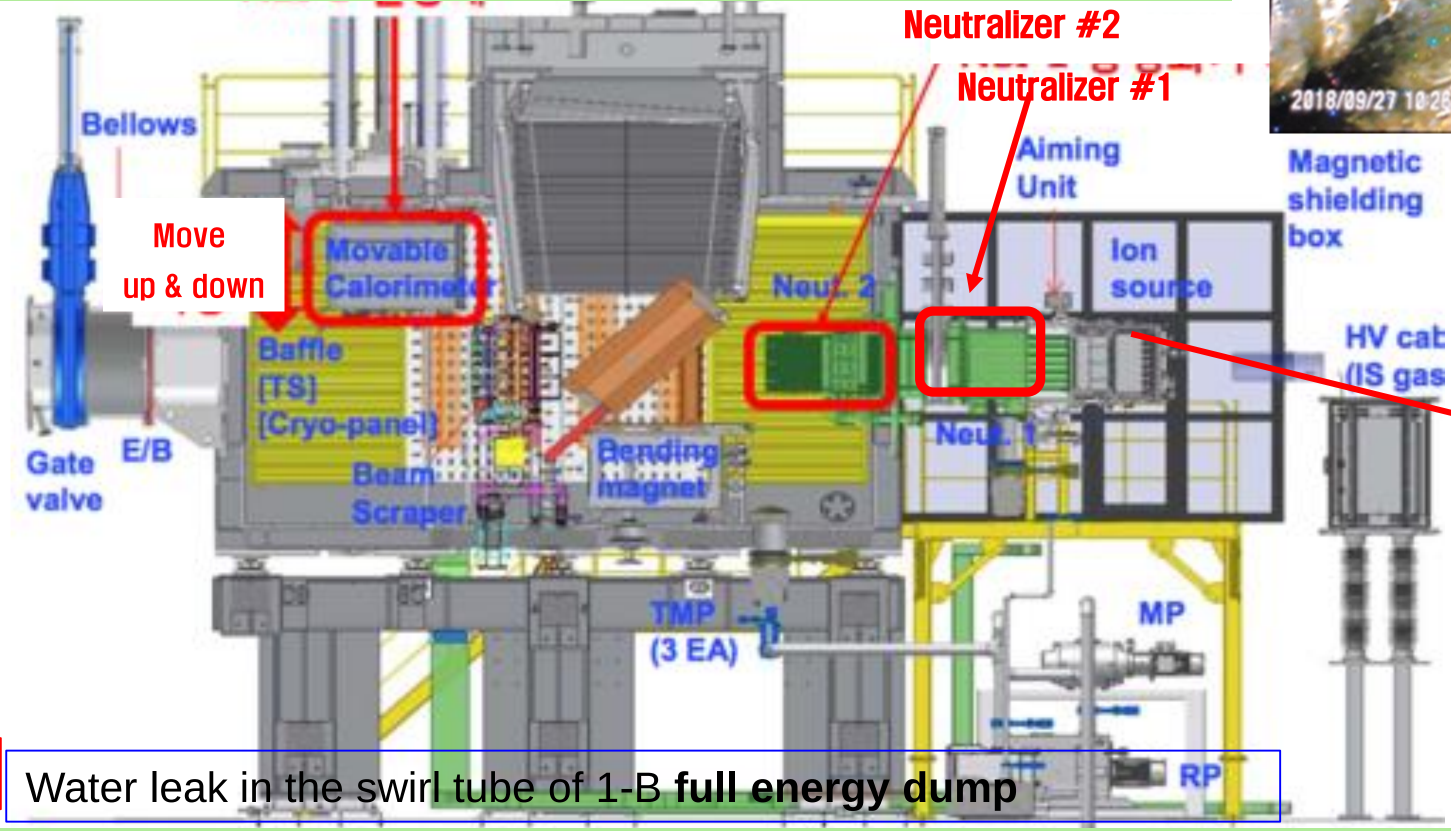
KSTAR

2018,2022

Vacuum and H2O partial pressure increase inside the beam chamber during the experiments.
Replaced formed **bellows** with stainless steel pipe



- ✓ **All cooling line bellows in calorimeter, neutralizer were replaced by flexible or rigid tube in 2022**



2018,2022

Grid damage Replace with spare grid

2021

Water leak in the swirl tube of 1-B **full energy dump**

- ✓ **Ion dump at new NBI(NBI2) used hypervapotron rather than swirl tube**

Summary

- NBI has contributed to KSTAR's aim for long pulse steady state operation by CD as well as the main heating in KSTAR
- Several features are shown at many year long pulse operation, which was not shown in short pulse operation
- Plasma performance degradation in time is explained by NBI performance change
- Net NBI power to tokamak is decreased due to PF field
  (Beam species may change during the shot and results in beam divergence.)
- Engineering efforts are also shown for reliable long pulse operation in beam line components
- For the final goal of KSTAR, real time monitoring of beam characteristics as well as active PF field compensation may be needed for the reliable and prec ise control of beam power.

Your comments and guidance is very much appreciated