Optimization of the beam heating and non-inductive current in NBI plasma for long-pulse operation of EAST

by

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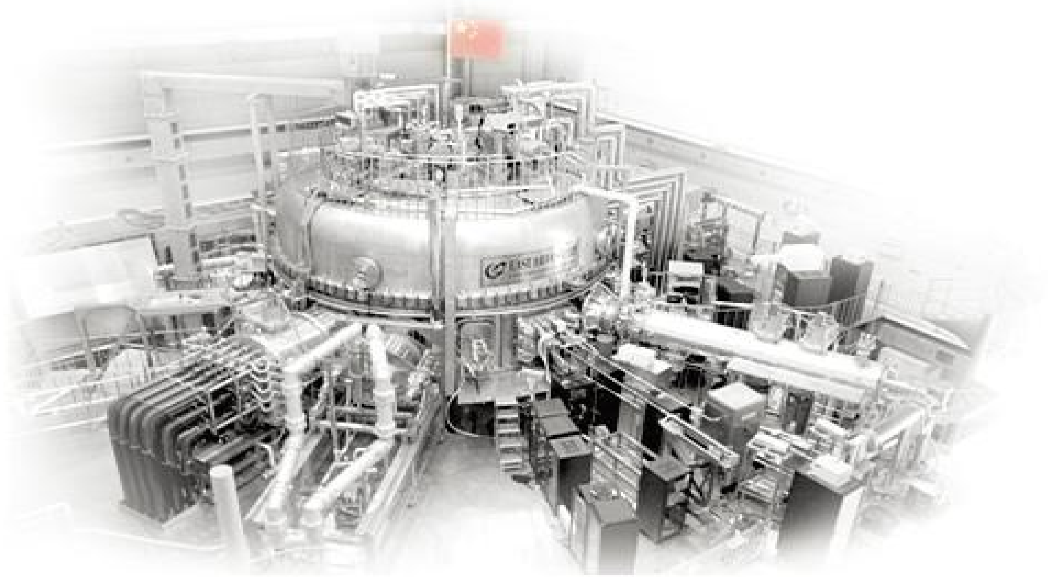

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Outline

- Progress of EAST NBI Engineering and experiments
- Optimization of the beam heating for high performancne plasma
- Optimization of the non-inductive current for long-pulse operation
- Conclusion and discussion

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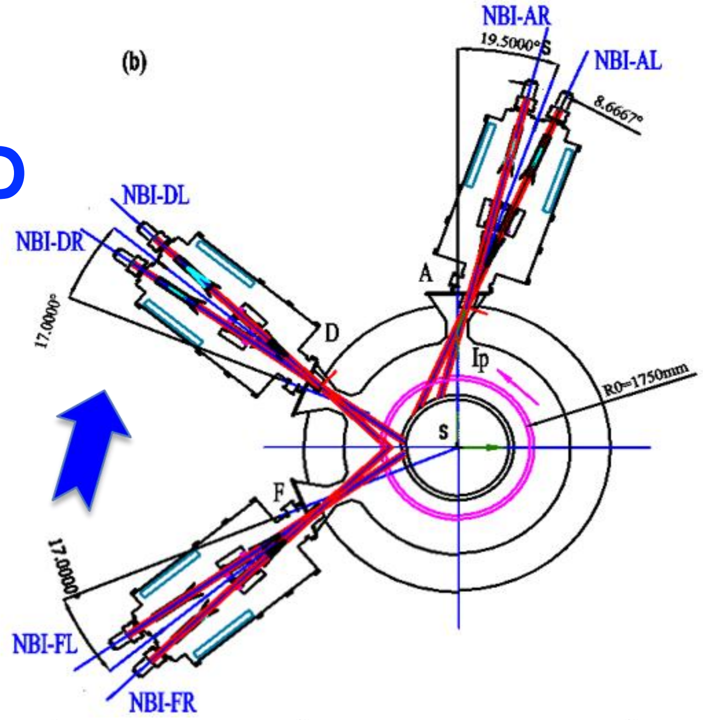
EAST NBI engineering upgrade for long pluse operation

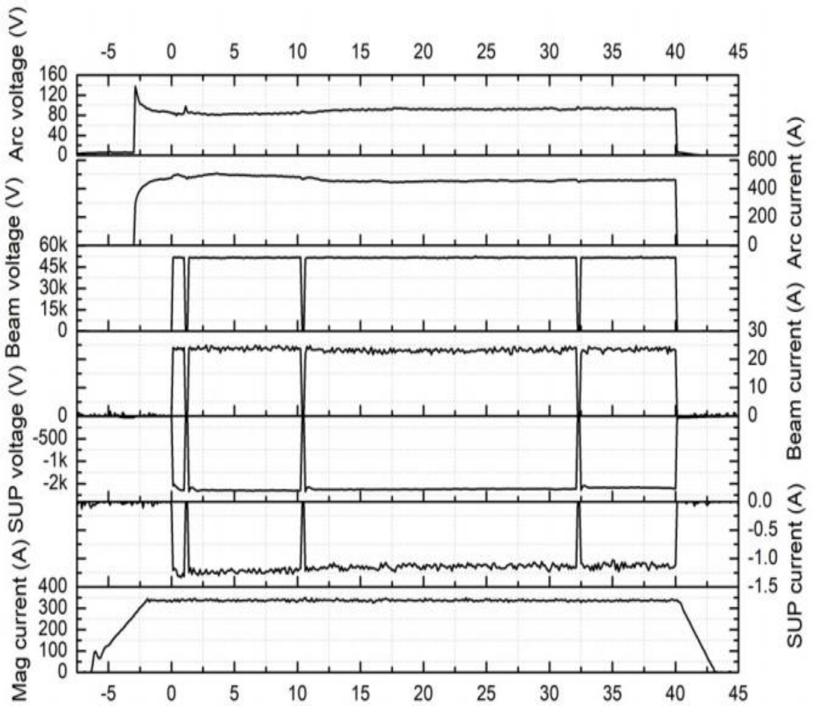
- **Shift of Counter-NBI (F- port) to Co-NBI (D-port)**
- **Development of beam re-turn on for long pulse operation**
- **Optimization of the feedback control system:Langmuir probe --> Arc power**

co-D

ctr-F



No.	Items	Specifications
1	Size of beam line	L:5800 mm W:2400 mm H:2400 mm
2	Ion source number	2
3	Type of ion source	Hot cathode
4	Beam cross section	100 mm × 480 mm
5	Beam species	deuterium
6	Beam energy	50-80 keV
7	Beam power	2-4 MW
8	Beam duration	10-100 s



Long pulse of 40-s beam injection with beam re-turn on method on EAST

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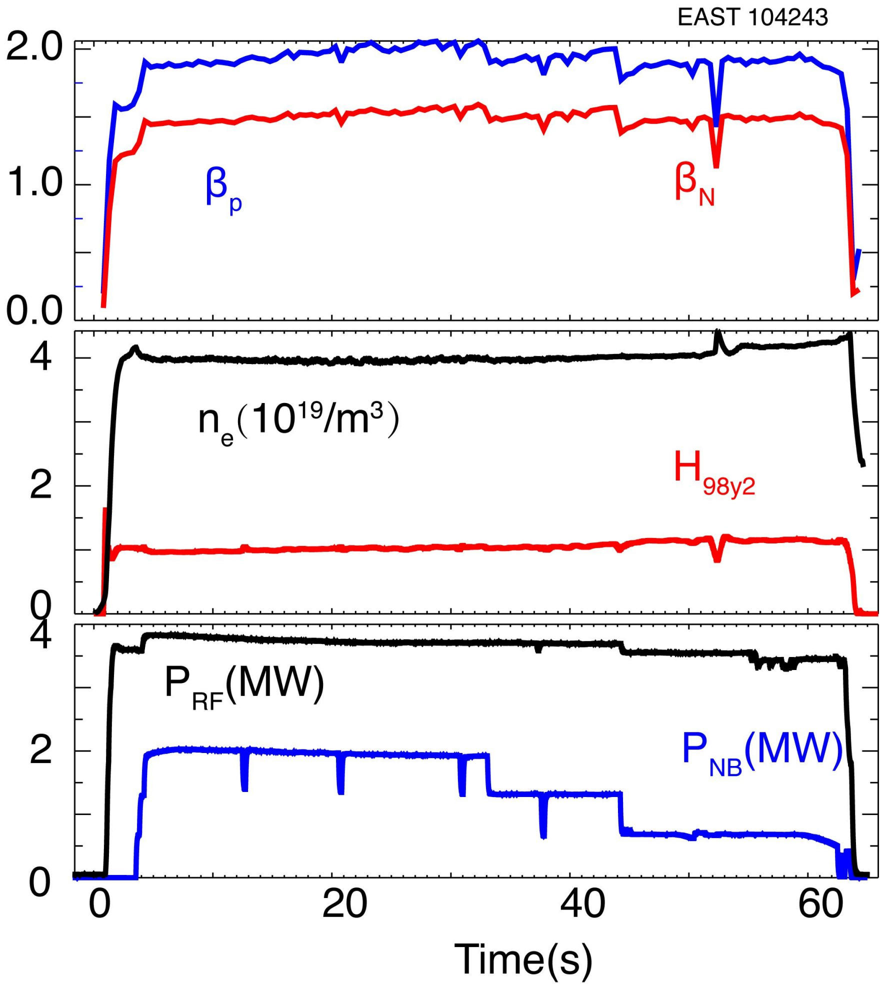
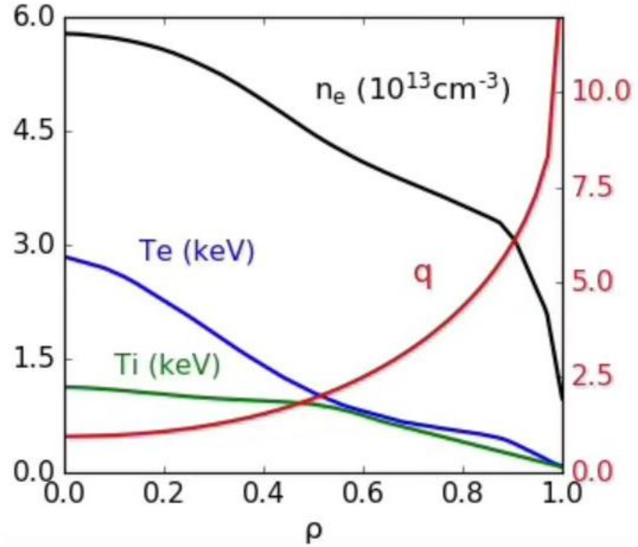
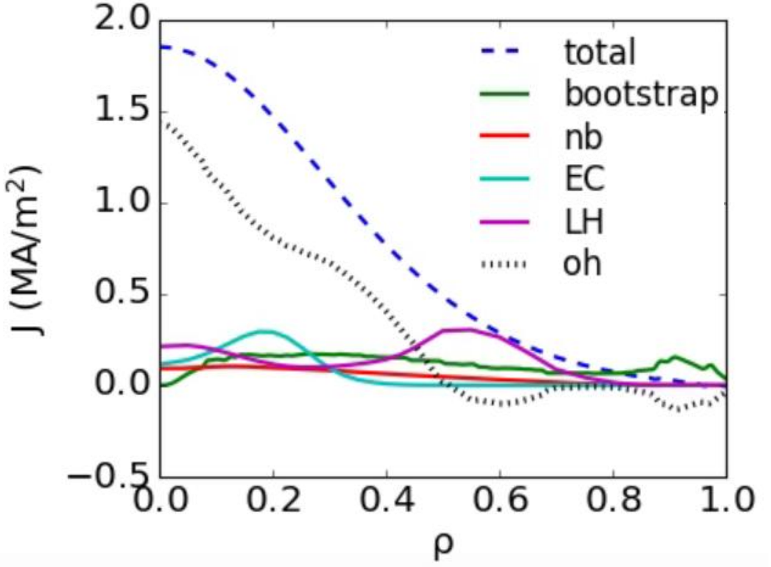
Duration of ~60s High Performance Plasma Achieved with NBI+RF on EAST due to Beam Re-Turn on method







- **High performance plasma with RF and NBI**
  - RF+NBI: P_{RF}~3.7MW, P_{NBI}~2.1MW
  - H_{98y2} >1.0, $f_{Gr}(n_e/n_G)$~0.65,
  - **β_P~2.0**, β_N ~1.6, f_{bs}~30%

Outline

- Progress of EAST NBI Engineering and experiments
- Optimization of the beam heating for high performance plasma
  - Shifting beam direction to reduce beam loss
  - Increasing beam power for high performance plasma
  - Enlarging gapout to decrease beam loss in high collisional plasma

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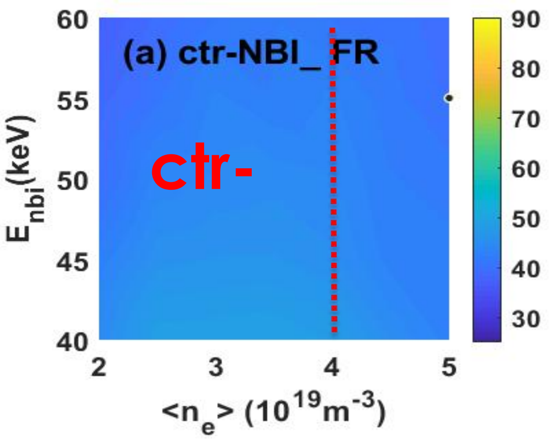
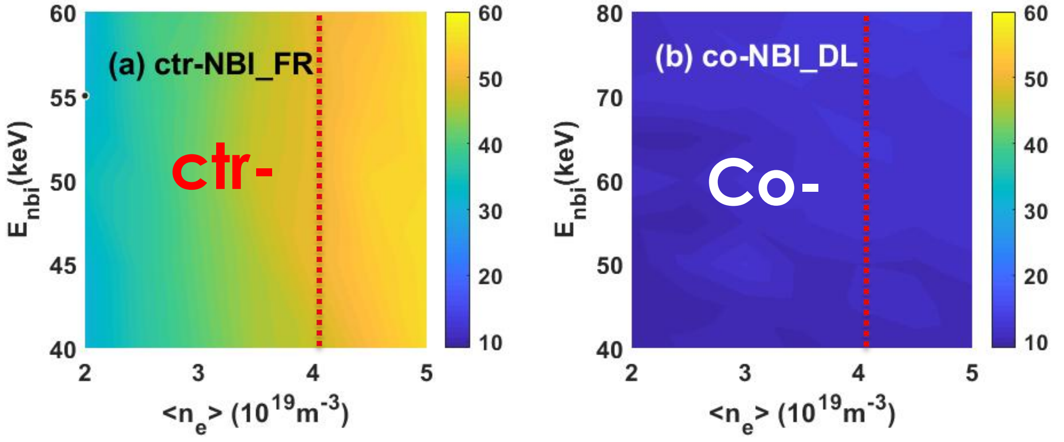
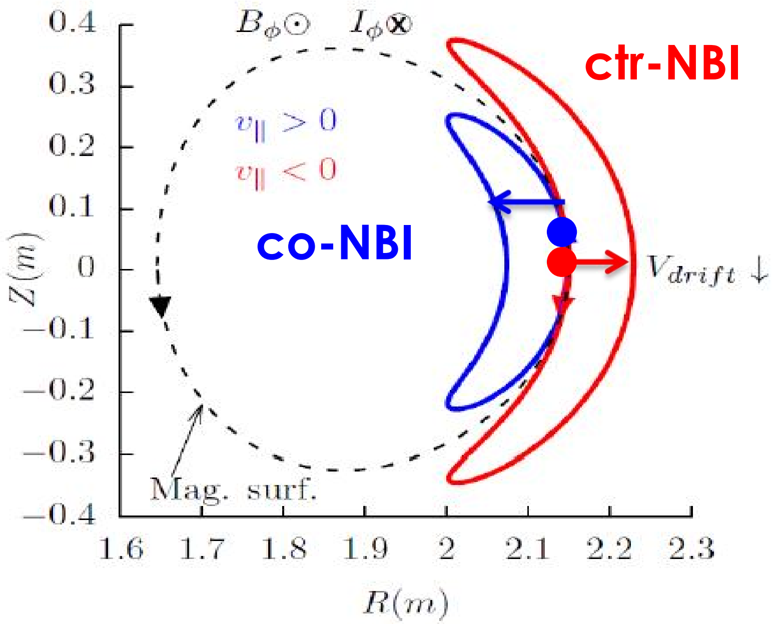
Shift ctr-NBI to co-NBI to greatly reduce prompt loss

Beam absorption ratio



Prompt loss ratio ~50%(ctr-) → ~10%(co-)





- **Optimizing beam direction to reduce beam loss**
  - Maximum absorption ratio: 90% (co-) and **50% (ctr-)**
  - Vary ctr-NBI_FR to co-NBI_DL, Prompt loss reduced **40%** (drift orbit direction, $n_e \sim 4 \times 10^{19} m^{-3}$, $E_{nbi} \sim 60$keV)
  - Also, beam heating about double （ctr- to co-）

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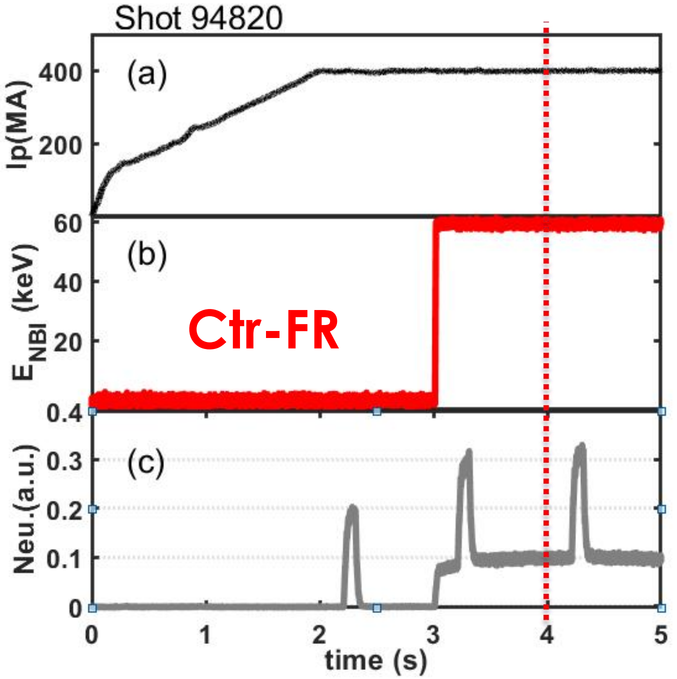
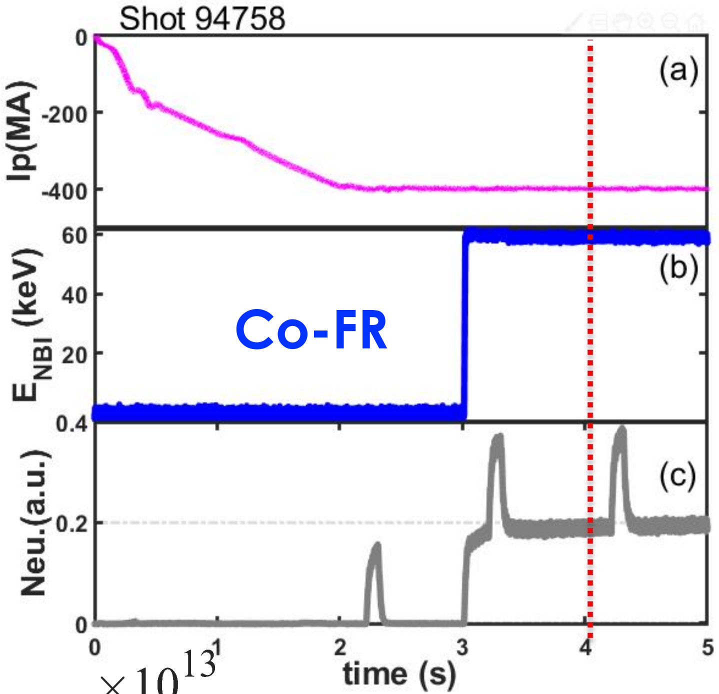
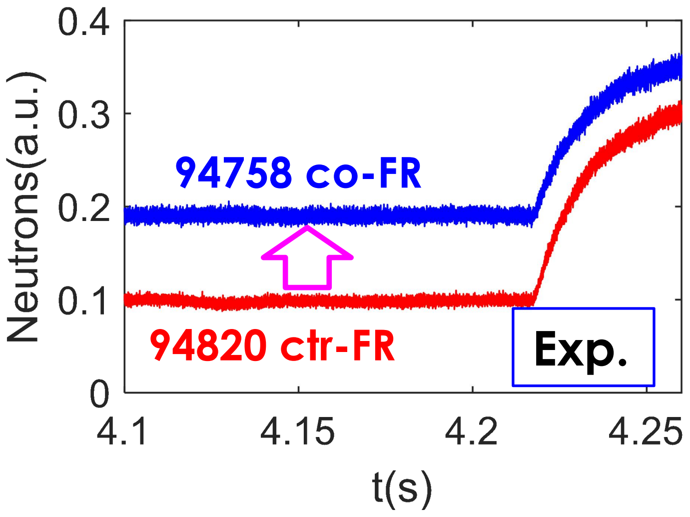
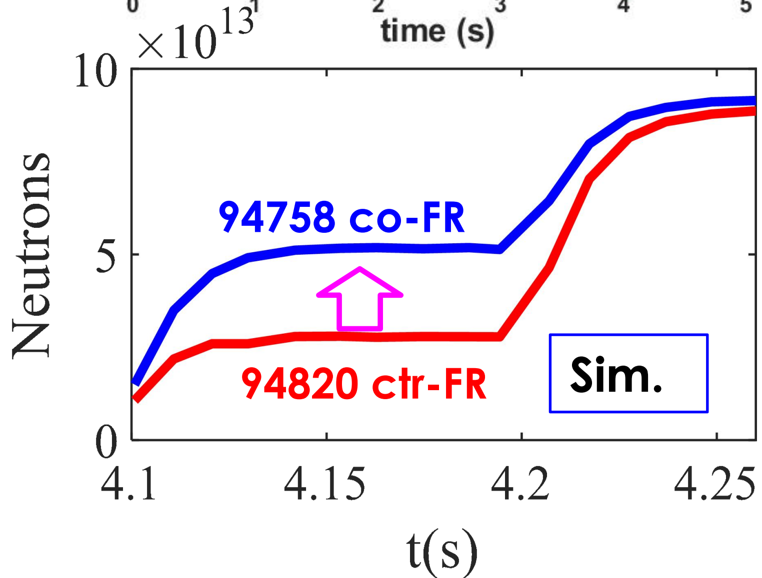
Experiments verify Heating improvement and loss reduction by optimizing beam injection







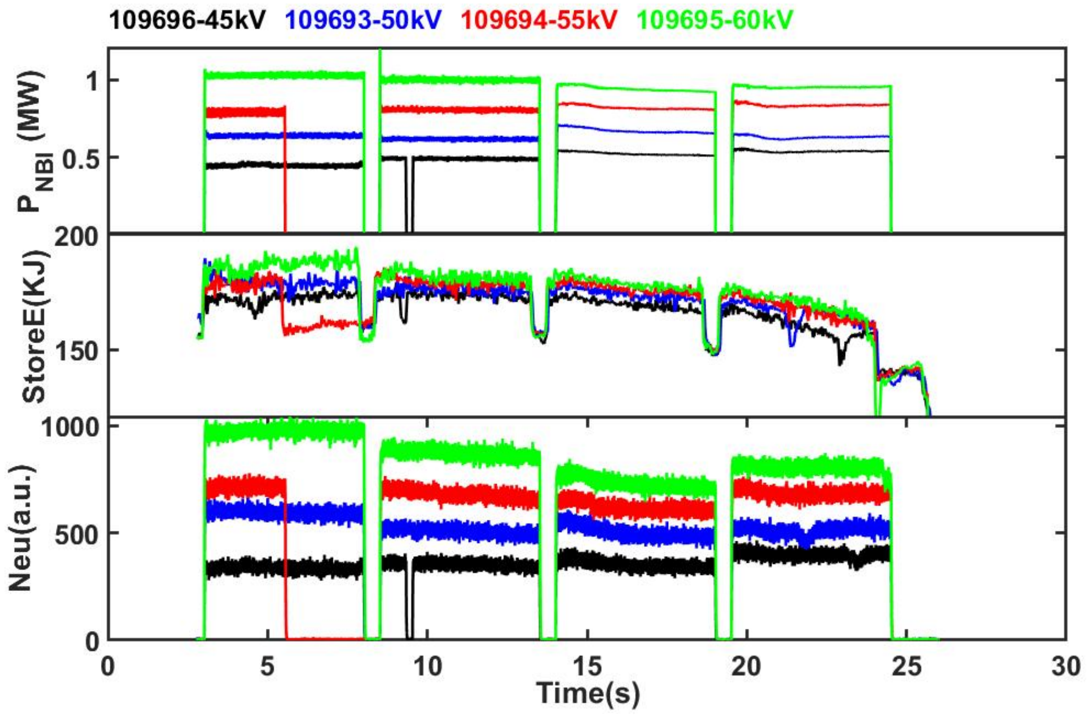


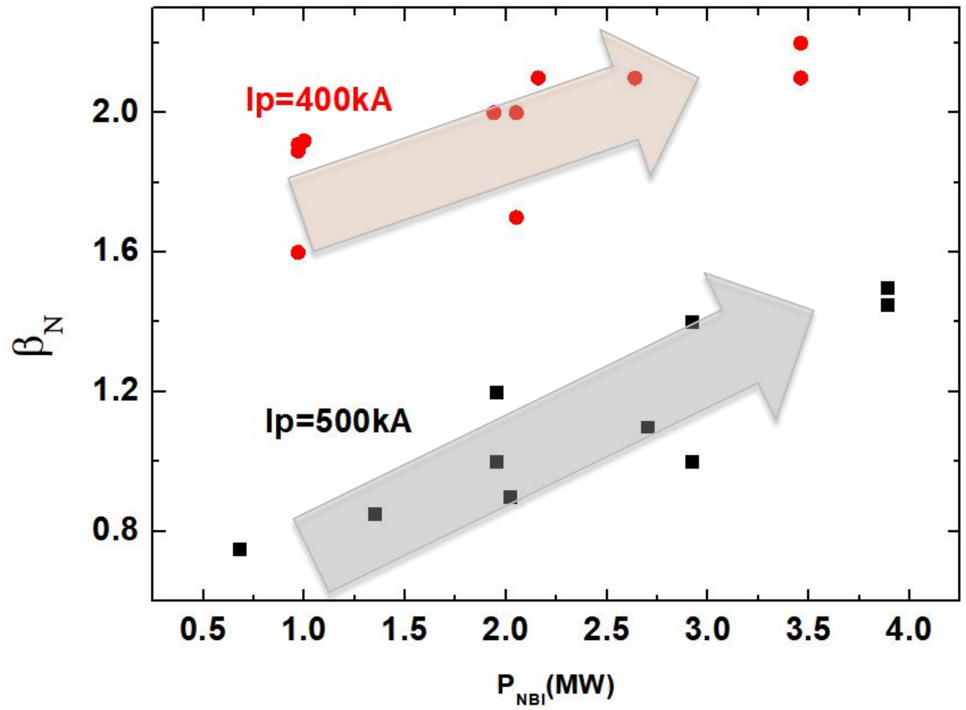
- **Shot 94820 with CC-Ip (Counter-Clockwise) :**
  - n_e~$4\times10^{19}m^{-3}$, gapout~3.6cm, P_{RF}~3.2MW, NBIAL~blips; **ctr-FR** with E_{nbi}~60keV

    Neu. (a.u.)~0.1
- **Shot 94758 with C-Ip (Clockwise) :**
  - n_e~$4\times10^{19}m^{-3}$, gapout~6.2cm, P_{RF}~3.2MW, NBIAL~blips; **co-FR** with E_{nbi}~60keV

    Neu. (a.u.)~0.2
- Simulated neutron rate rises from $2.7*10^{13}$n/s to $5.2*10^{13}$n/s

Increasing beam energy and power for high beam heating and β_N





- Discharges with different beam energy and power:

  I_p=500kA, n_e~4.1x10^{19}m^{-3}, q_{95}~6.0, P_{LHCD}~1.7MW, P_{EC}~1MW
- Neutron intensities show beam heating increases as beam power

- Ip=400kA discharges: B_T=-2.4T
  - n_e~4.3x10^{19}m^{-3}, P_{RF}~5MW
- Ip=500kA discharges: B_T=-2.4T
  - n_e ~4x10^{19}m^{-3}, P_{RF}~1.5MW
- β_N increases linearly with beam power (higher absorpted power)

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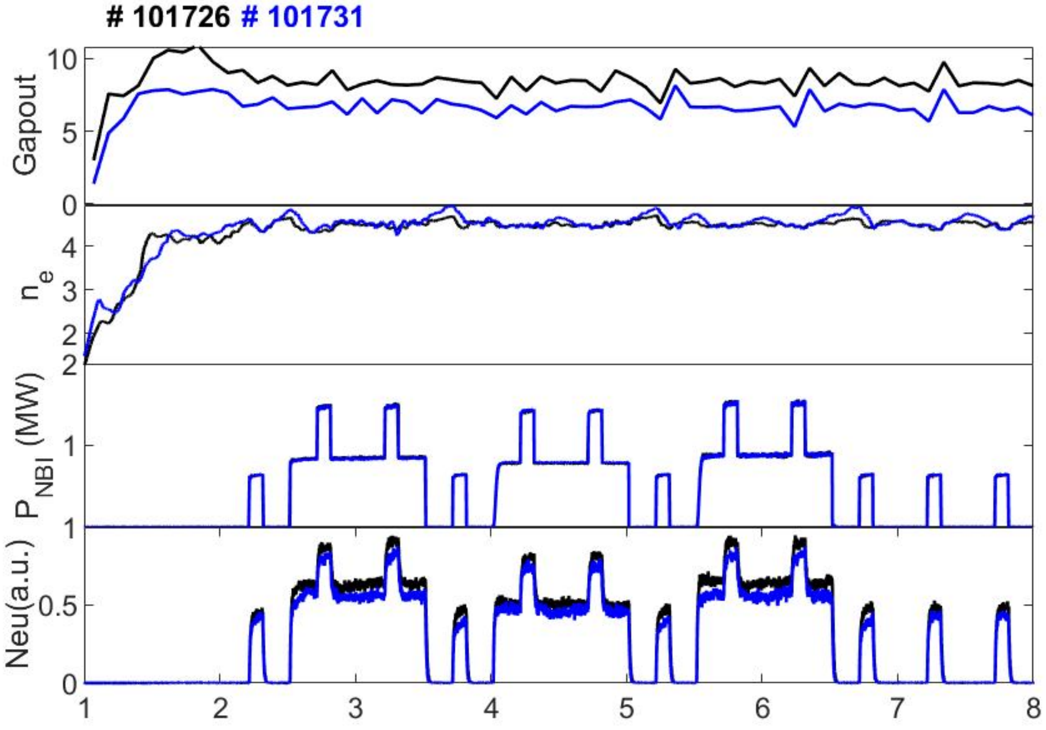
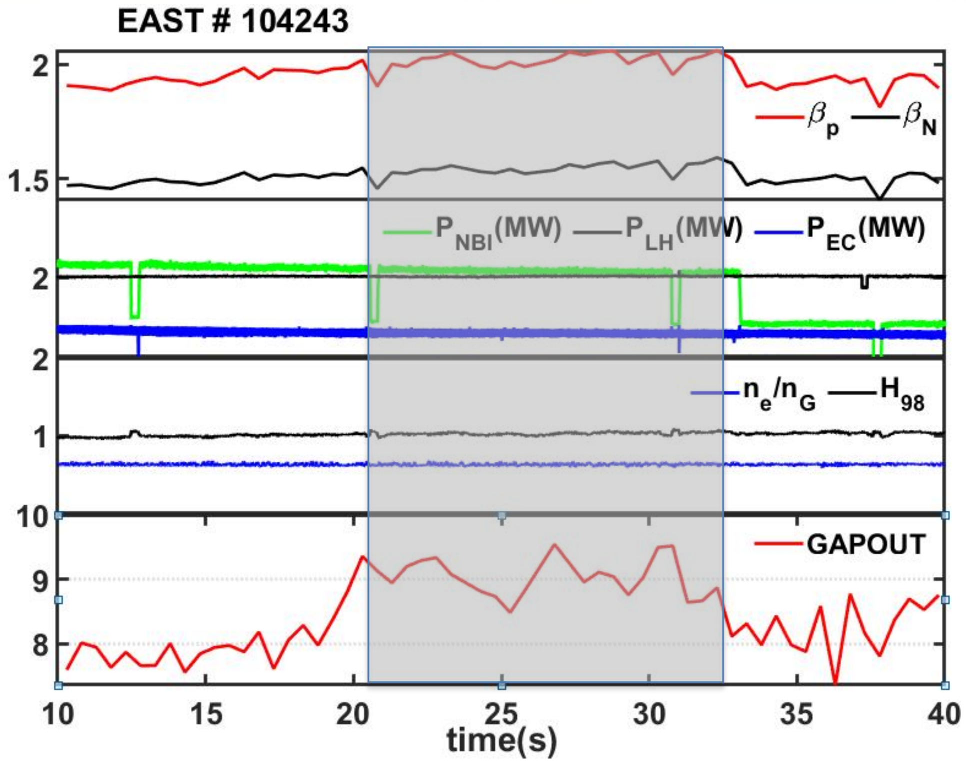
Enlarging gapout for Long Pulse High-β_P Scenarios with NBI in high collisional plasma





NBI_AR Beam heating and loss

gapout	ST(%)	Prompt loss (%)	Total heat (%)	Neutron rate (n/s)
8cm	9.98%	15.67%	76.38%	2.5E+13
6cm	9.4%	17.11%	75.24%	2.1E+13

- Larger gapout in high n_e (~$4.5 \times 10^{19} m^{-3}$) leads to less trapped particles, less prompt loss
- In the longest NBI H-mode discharge on EAST, higher β_N and β_p, **gapout 9cm. (normal 5~7cm)**

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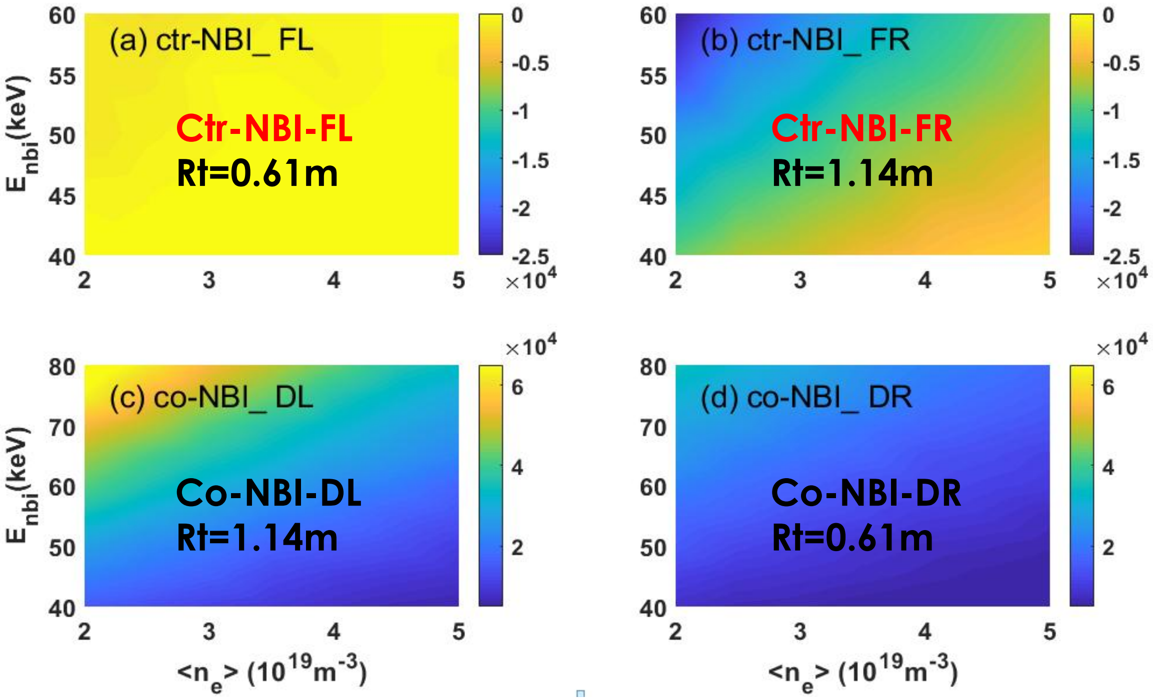
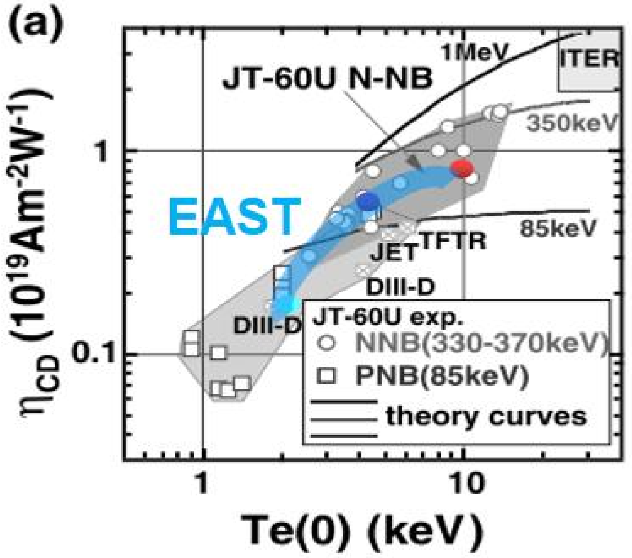
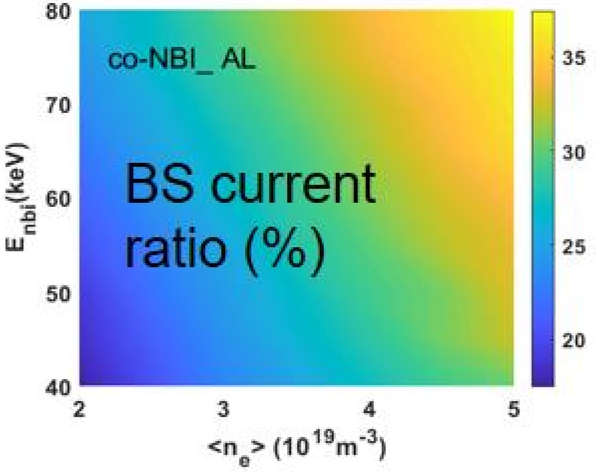
Optimizing beams and T_e for high NBCD and Bootstrap current

NBCD in different beams injections





$$\eta_{CD} \equiv \langle n_e \rangle R I_{NBCD} / P_{INJ}$$



- NBCD was greatly improved by shifting ctr-beams to co-beams.(less loss and higher I_{fast})
- For co-NBI-AL with E_{nbi}~80keV, η_{CD} **~0.2** (T_e~2keV); η_{CD} **~0.6** (T_e~4keV); η_{CD} **~0.77** (T_e~10keV), η_{CD} versus $T_e(0)$ has the similar trend with DIII-D NBI.
- BS current ratio (I_{BS}/I_p) increases with E_{nbi} and n_e.

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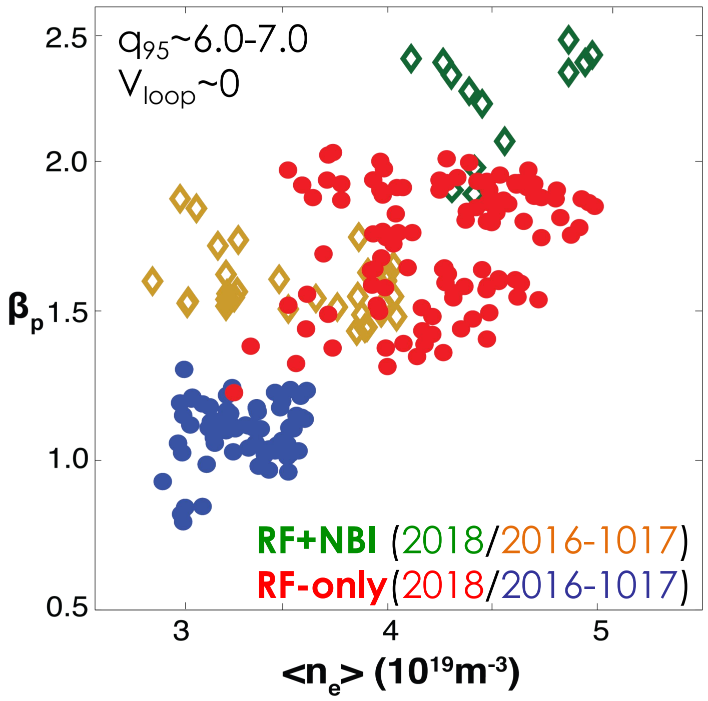
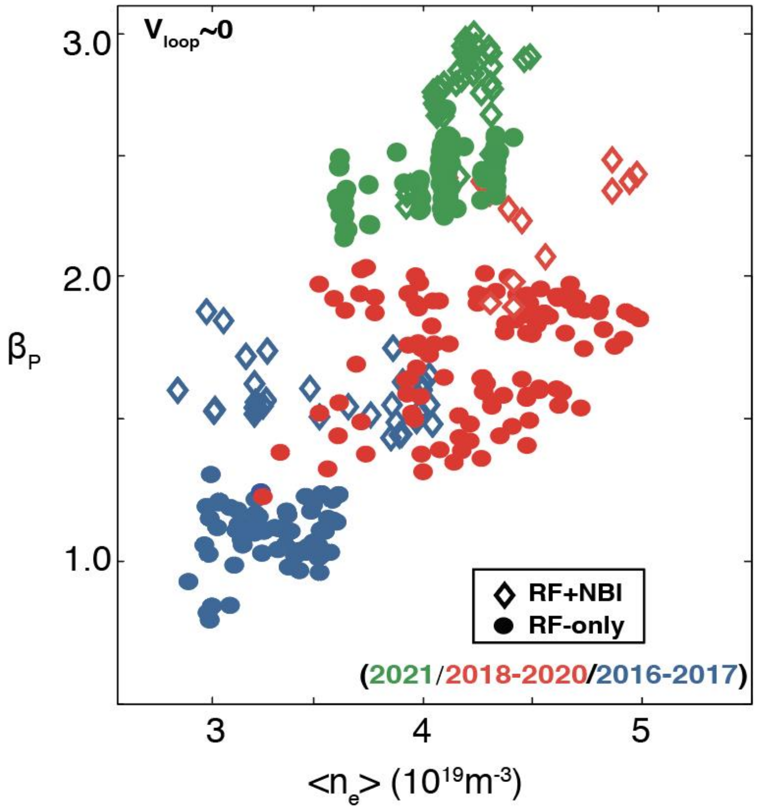
High NBCD and BS current expand Fully Non-inductive High-β_P Scenarios





- Before NBI upgrade (before 2020Y.) with RF and co-NBIA +ctr-NBIF : β_p~2.5
- After NBI upgrade (in 2021) with RF and co-NBIA +co-NBID: β_p~3.1

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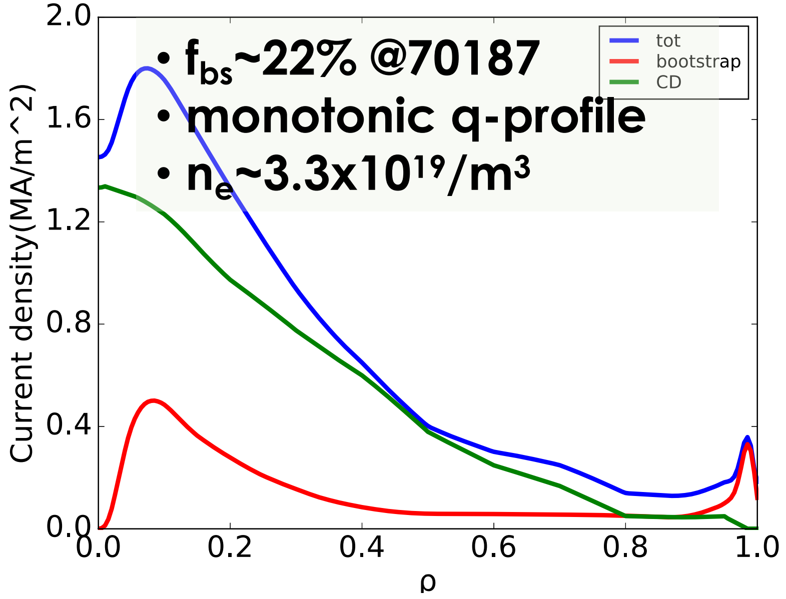
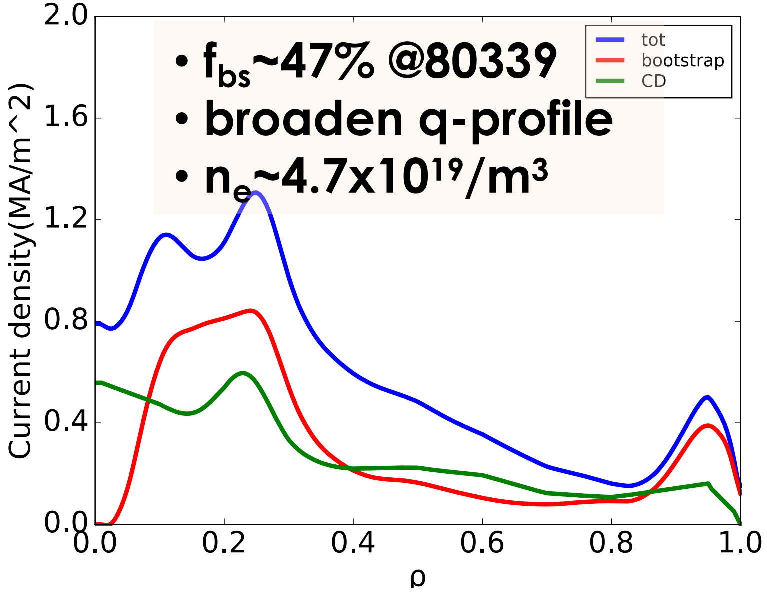
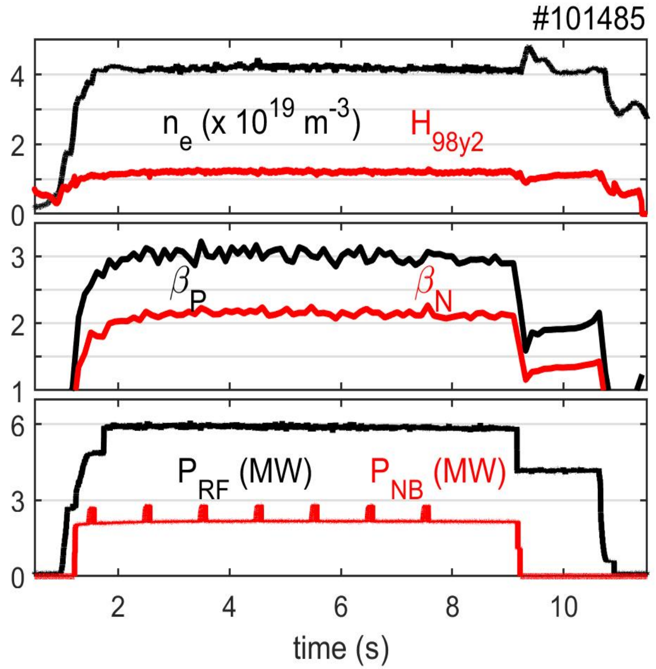
High NBCD and BS current expand Fully Non-inductive High-β_P Scenarios







- **Shot 70187 with β_p~2.0:**
  - $<n_e>$~3.3x10^{19}m^{-3}, q_{95}~6.7, H_{98y2}~1.25, P_{RF}~4.0MW, P_{NBI}~2.5MW/55keV, **f_{bs}~22%**.
- **Shot 80339 with β_p~2.5:**
  - $<n_e>$~4.7x10^{19}/m^3 (f_{Gr}~0.78), H_{98y2}~1.25, β_N~2.0, P_{RF}~4.0MW, P_{NBI}~3.2MW/60keV, **f_{bs}~47%**;
- **Shot 101485 in 2021 with β_p~3.1:**
  - $<n_e>$~4.3x10^{19}m^{-3}, H_{98y2}~1.2, β_N~2.1, P_{RF}~6MW, P_{NBI}~2.5MW/65keV, **f_{bs}>50%**;

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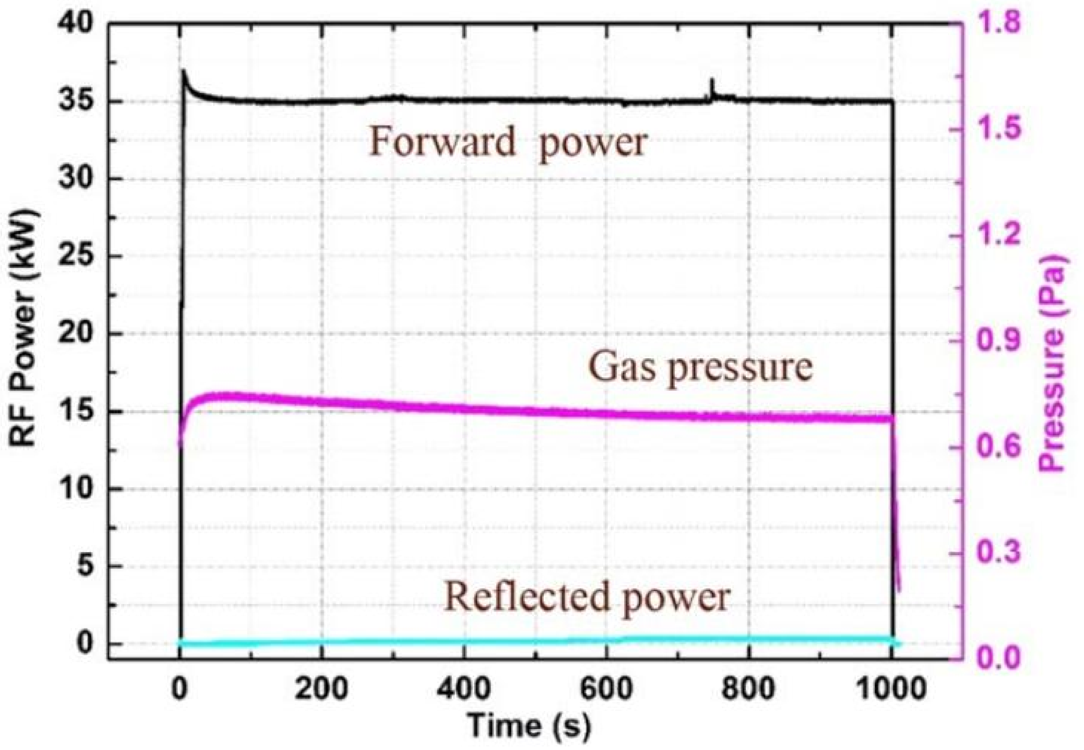
Conclusion and discussion

- Significant progress has been made in long-pulse operation with NBI on EAST (~60s).

- High β_N / β_p scenarios have been expanded by optimizing beam heating and non-inductive current.

- Although **gapout** is beneficial to NBI heating, it needs to be considered comprehensively due to its effect on RF heating.

- A **1000 s** plasma generation with RF source on the test bed has been obtained, which is beneficial for long-pulse operation with NBI on EAST.



Waveform of plasma generation with 1000 s duration

Hu C.D. PST 2019

Thanks for your attention !