Optimizing fast-ion confinement in NBI plasma for long-pulse operation of EAST

by

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Outline

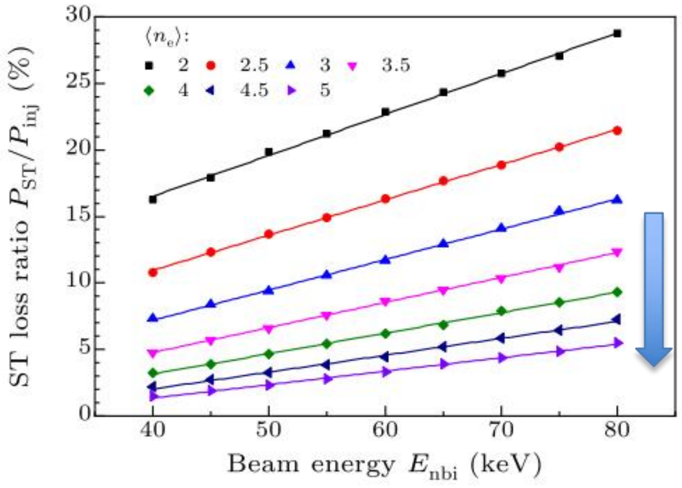
- Introduction of EAST NBI system
- Optimization of fast-ion confinement by adjusting plasma shape for long-pulse operation
- Upgrade of EAST NBI system for long-pulse operation
- Conclusion and discussion

Large shine-through loss requires the high density in LPO of NBI

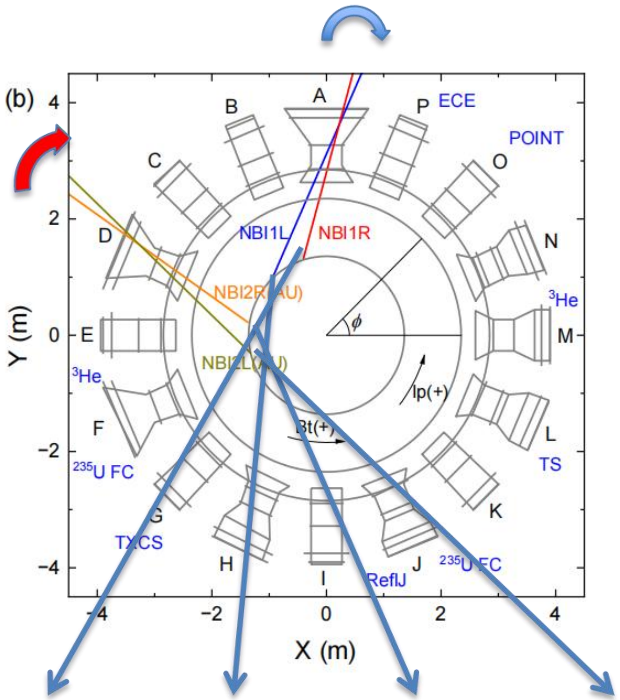
- The fully superconductivity and vertical injection port design of EAST leads to limitations of beam injection angles
(19.5/17 Deg.)

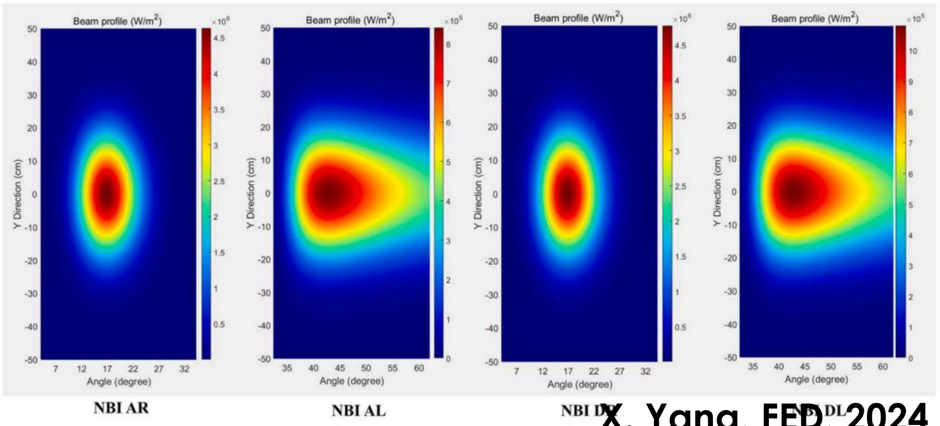
- A large number of shine-through loss particles will hit the first wall on the high-field side.

- **High-density plasmas are needed to avoid shine-through loss on EAST.**



J.F.Wang, CPL,2021





X. Yang, FED, 2024

Fig. 6. Heat load distribution cloud figure of Port A and Port D.

Large prompt loss limits long-pulse operation of NBI on EAST

- High density causes beam deposition profile to move outward.
- Moreover, this small injection angle results in a large number of trapped ions (f_{Trap}).
- **Large prompt loss limits long-pulse opeation of NBI on EAST in high density plasma.**

Ip=400kA， $f_{Gr}(n_e/n_G)$~0.65， E_{nbi}=55keV

NBI	NBI_AL	NBI_AR	NBI_DL	NBI_DR
f_{Trap}	15%	24%	18%	28%

$$\Delta_{\mathrm{pass}} \sim q r_L$$ **~ 3cm**

$$\Delta_{tr} \sim 2\left(\frac{2R}{r}\right)^{1/2} q r_L$$ **~ 15cm**

ASIPP

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- High density causes beam deposition profile to move outward.
- Moreover, this small injection angle results in a large number of trapped ions (f_{Trap}).
- **Large prompt loss limits long-pulse opeation of NBI on EAST in high density plasma.**
- **enlarging gapout --> Increase B_{start} --> redcued trapped ion fraction**
- **enlarging gapout --> drift the plasma inward--> move the deposition inward**

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$$\sin\varsigma_0 \begin{cases} < (B_{start}/B_{max})^{1/2} & \text{passing ion} \\ > (B_{start}/B_{max})^{1/2} & \text{trapped ion} \end{cases}$$

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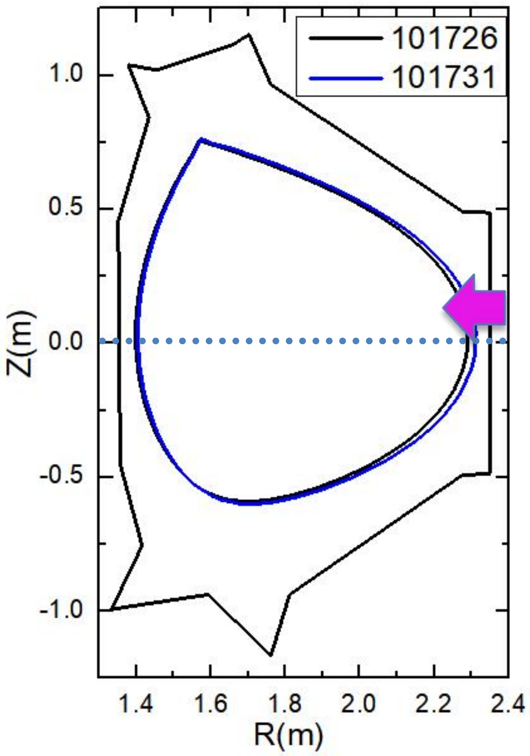
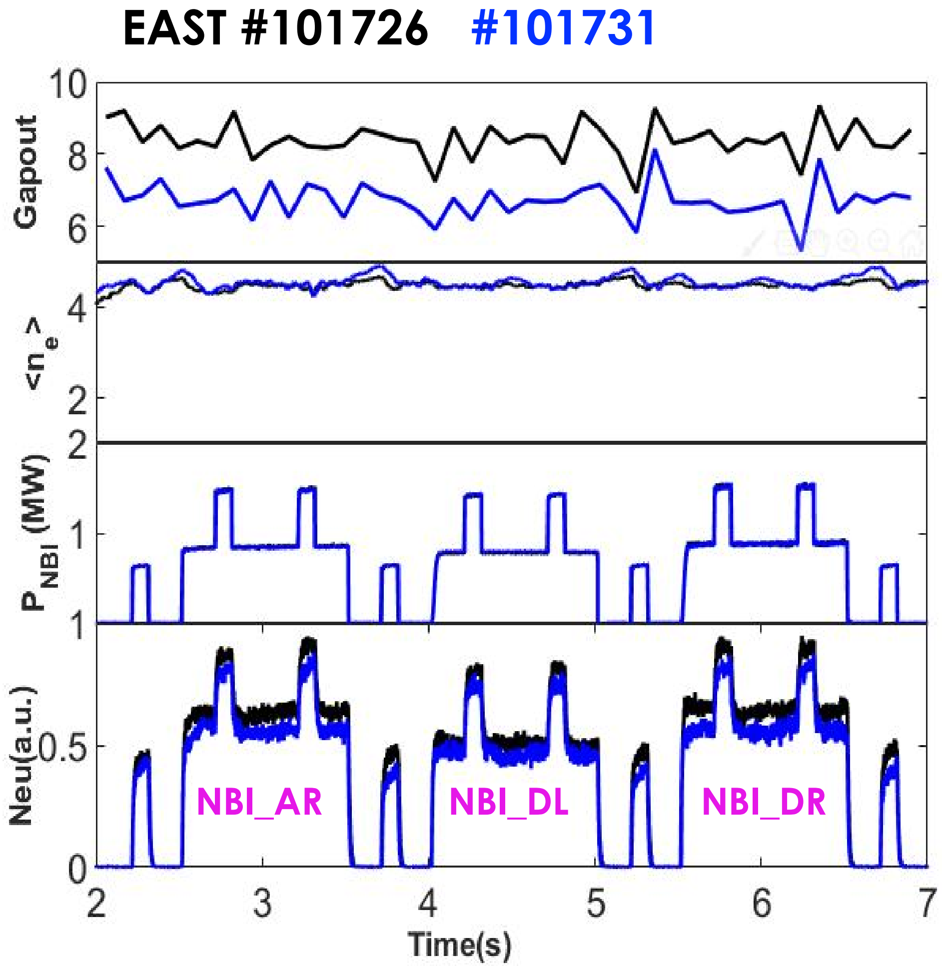
Enlarging gapout to improve beam heating in high density plasma

- gapout: the distance between the last closed flux surface (LCFS) and the limiter at the outboard mid-plane.
- high density $\mathbf{f_{Gr}\sim 0.65}$, Ip~400kA, Enbi~55keV,
- Beam heating increases with the gapout according to the neutron intensity.





Enlarging gapout to reduce impurity and radiation

- gapout: the distance between the last closed flux surface (LCFS) and the limiter at the outboard mid-plane.

- high density **f_{Gr}~0.65**, Ip~400kA, Enbi~55keV

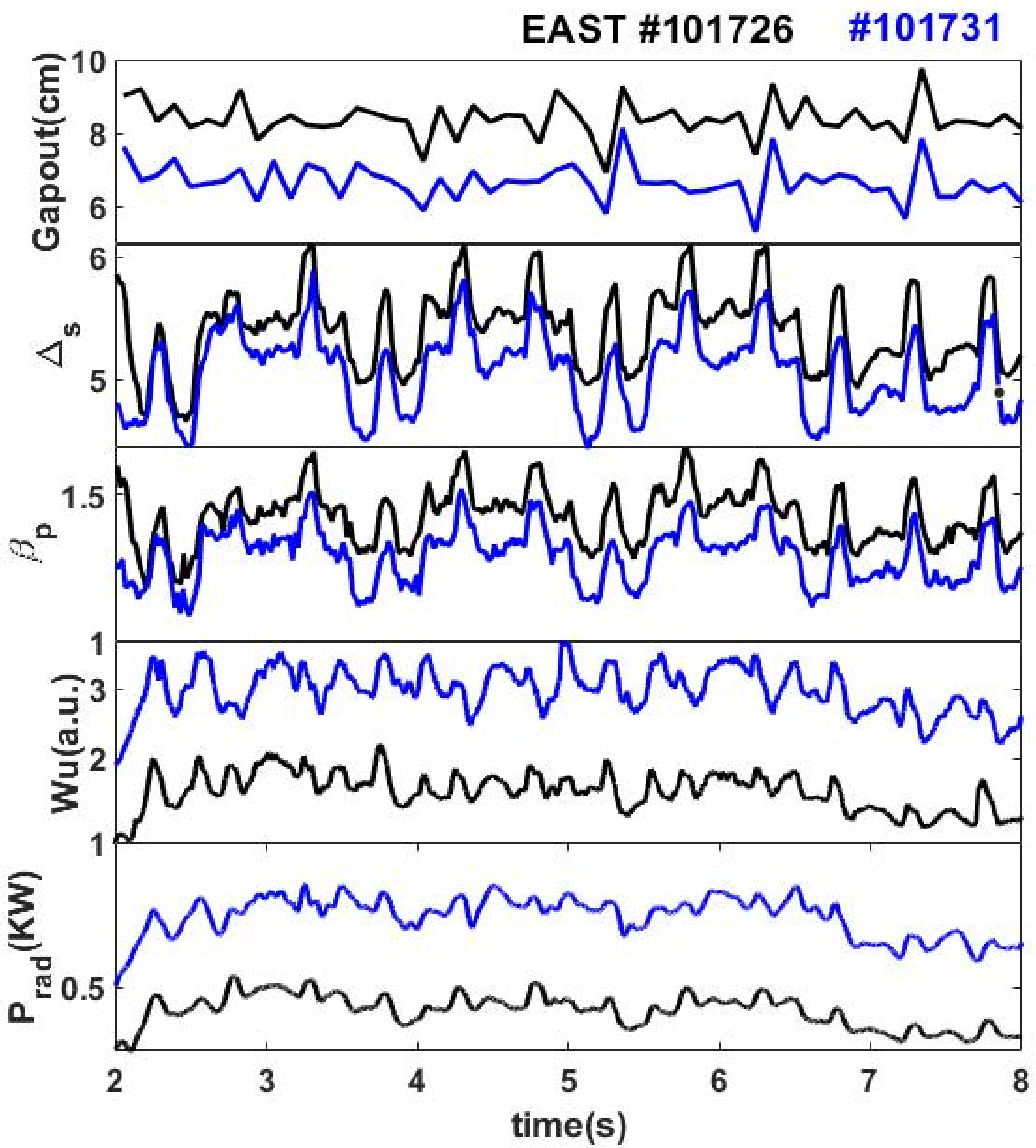
- **Larger gapout --> bigger Shafranov shift Δs**

  --> higher β_p

  --> lower tungsten impurity

  --> lower radiation power

which are benefit for long-pulse operation.



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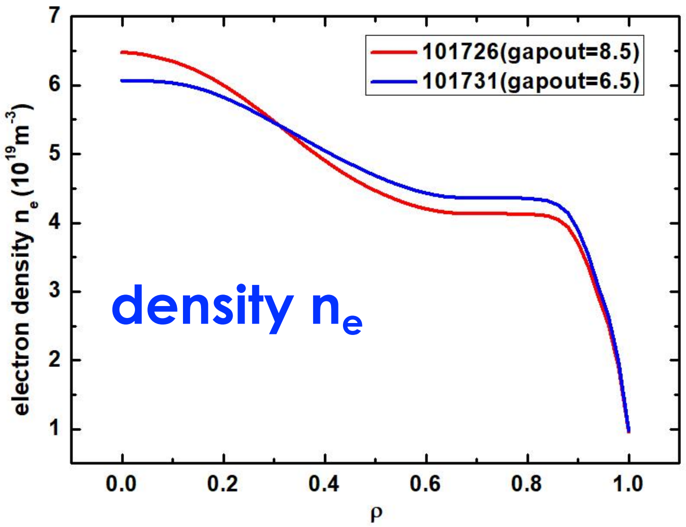
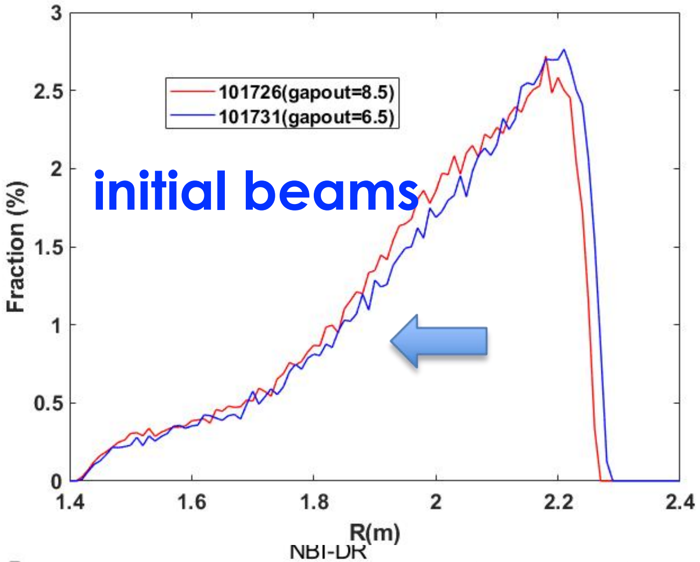
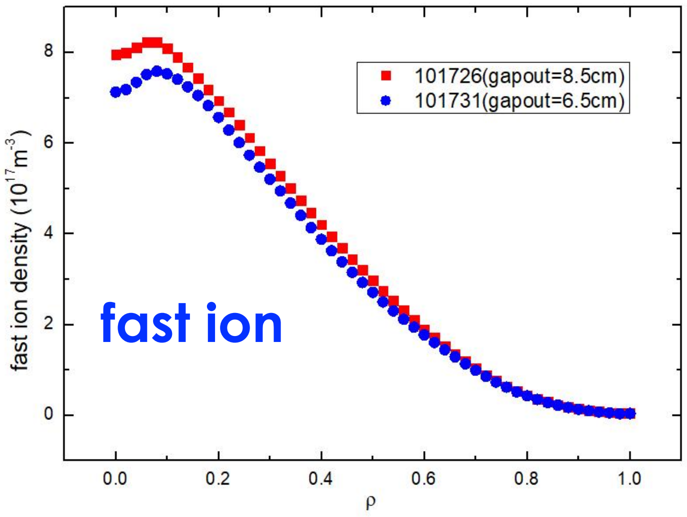
Enlarging gapout to reduce beam loss

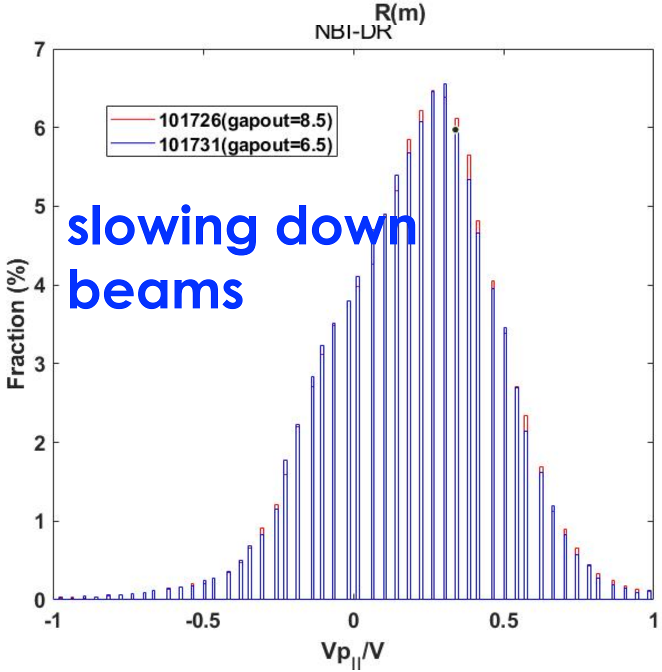
Simulations results:
(NUBEAM,TRANSP, ORBIT)

- **Larger gapout leads initial beams to deposite inward.**
- **Prompt loss (2%) and ripple loss (~2%) decrease with gapout.**
- **Fast ion density increases with gapout.**
- **The slowing down beams show the fraction of pitch angle >0 increases with gapout.**









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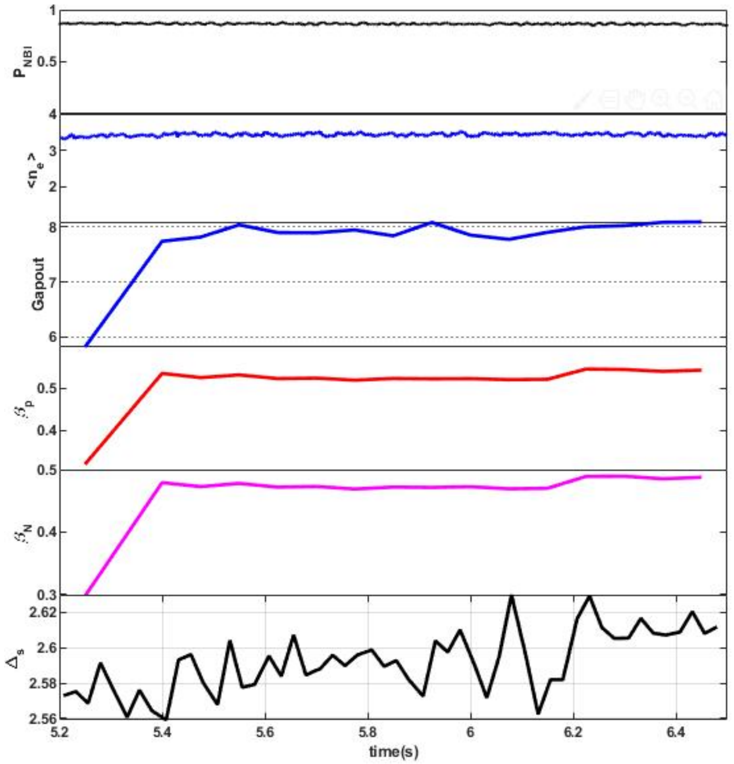
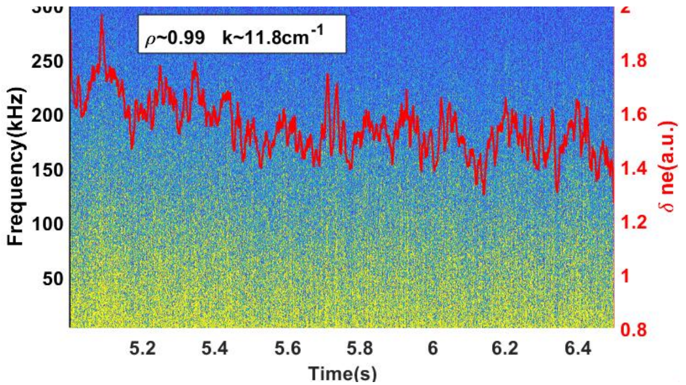
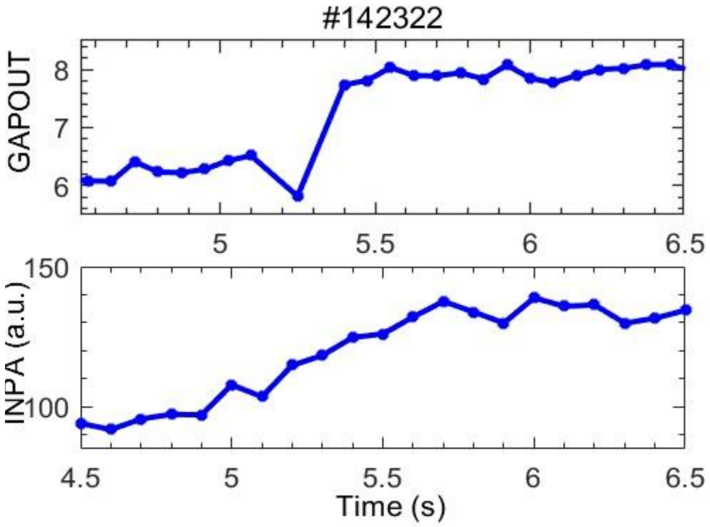
Larger gapout leads to more fast ions and lower turbulence intensity

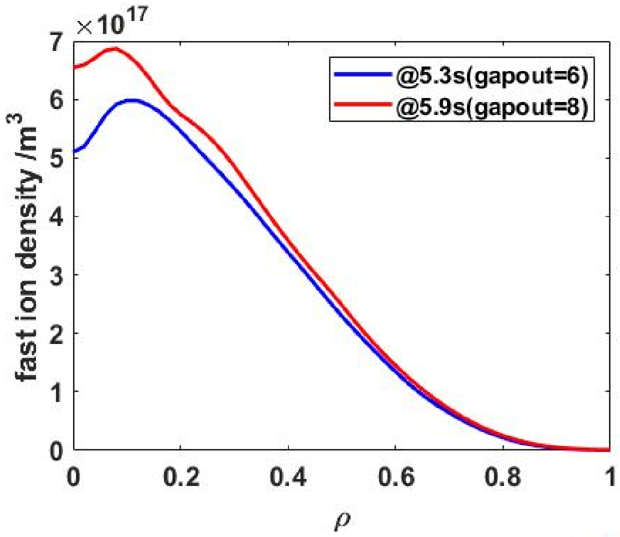
- When Ip=400kA, Bt=-2.4T, $f_{Gr}(n_e/n_G)$~0.54, with only NBI (E_{NBI}=55keV, P_{NBI}=0.85MW)
- **INPA diagnostic data shows that fast ion strength increases with gapout, which is consistent with the results of numerical simulations (NUBEAM/TRANSP).**
- **DBS diagnosis data shows that at ρ~0.99, the intensity of turbulence (k~11.8cm⁻¹) decreased with increasing gapout.**

EAST shot #142322，Ip=400kA









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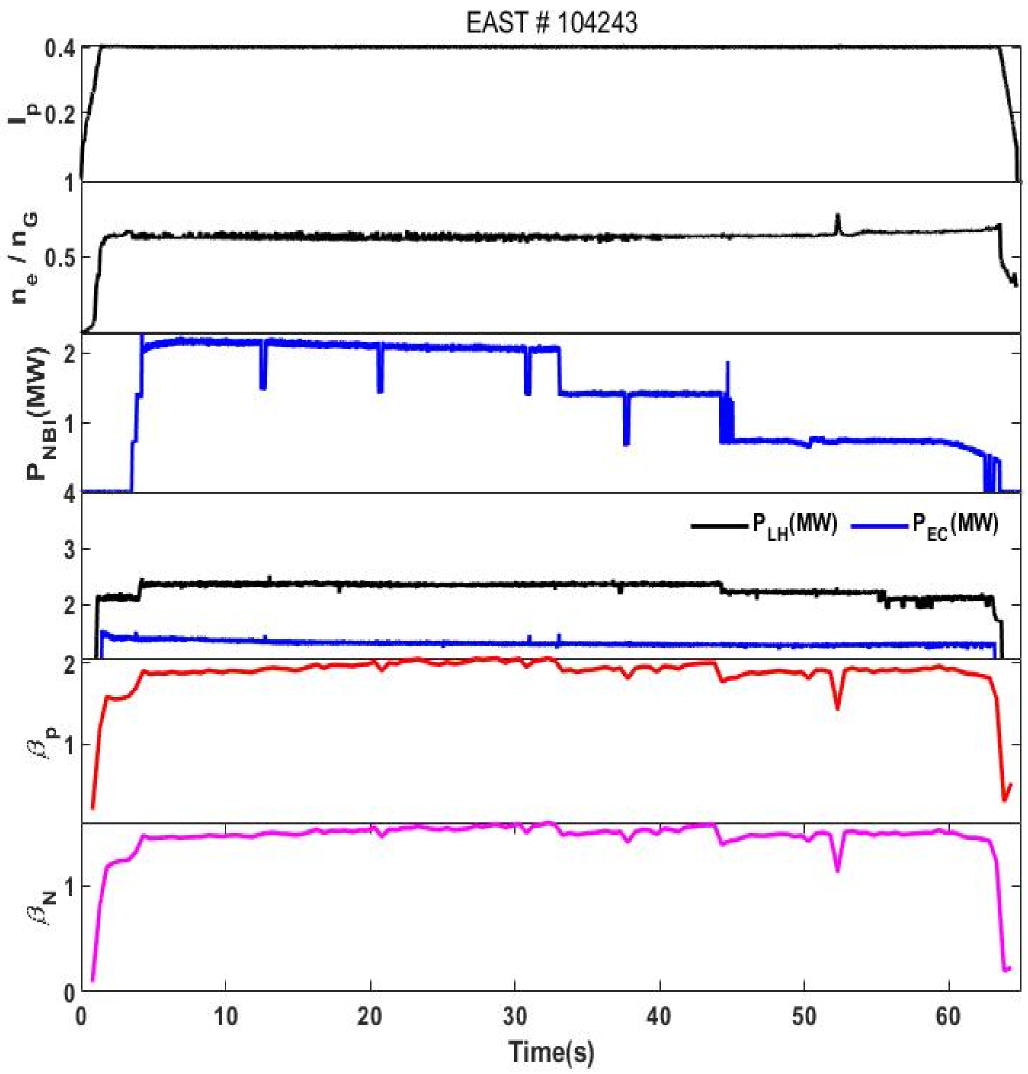
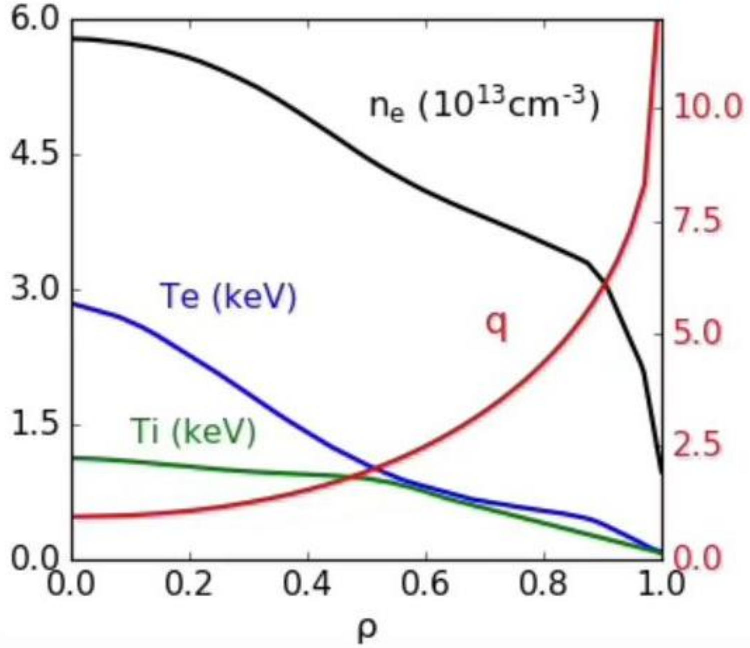
Duration of ~60s High-β_P Plasma Achieved with NBI+RF on EAST





- **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%

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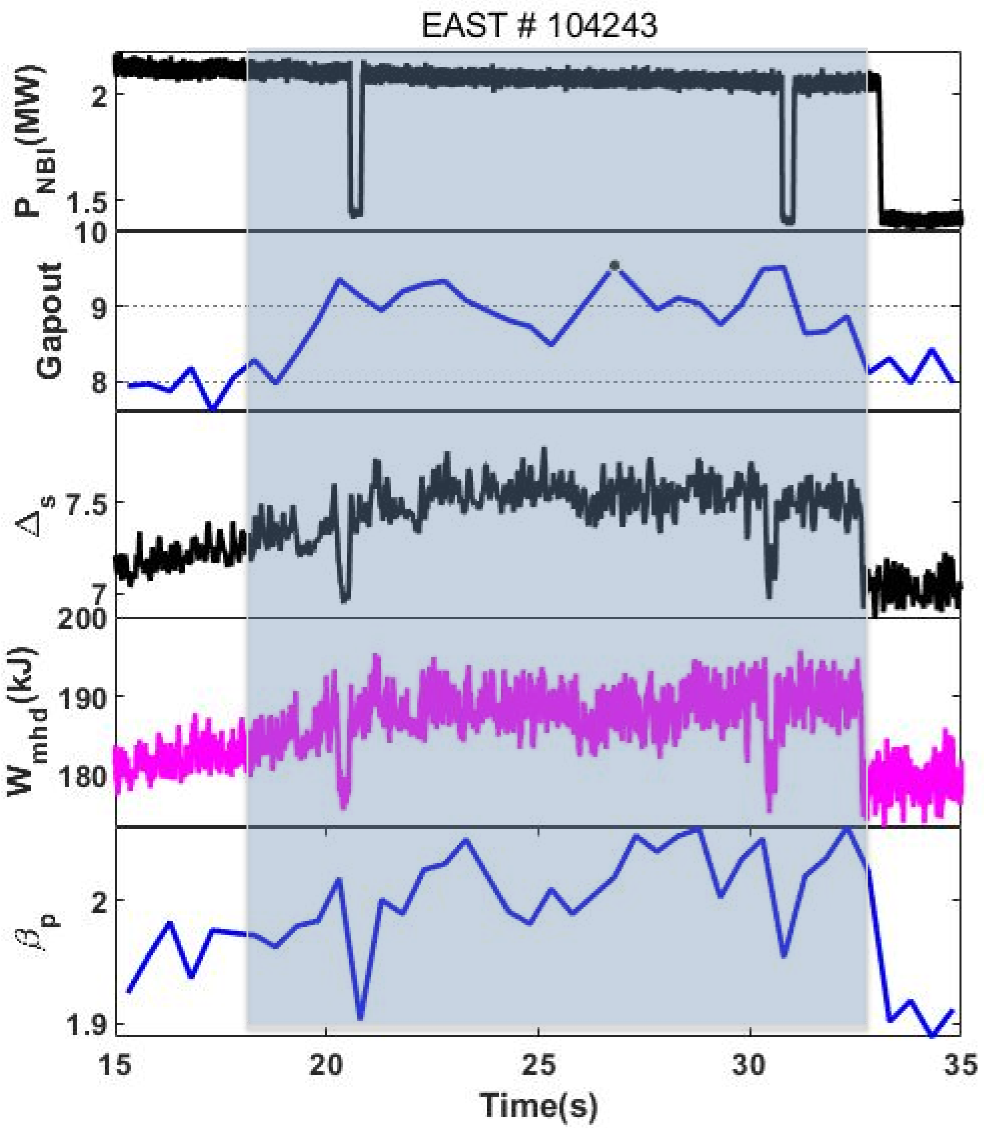
Enlarging gapout leads to long pulse High-β_P Scenarios in high density plasma

- For $f_{Gr}(n_e/n_G)$~0.65, when gapout increases about 1cm, increased thermal ion and fast ion gradient lead the plasma inner shifts about 0.5cm.

- **Higher β_p and total stored energy W_{mhd} (15kJ) have been achieved due to larger gapout and shafranov shift Δs.**



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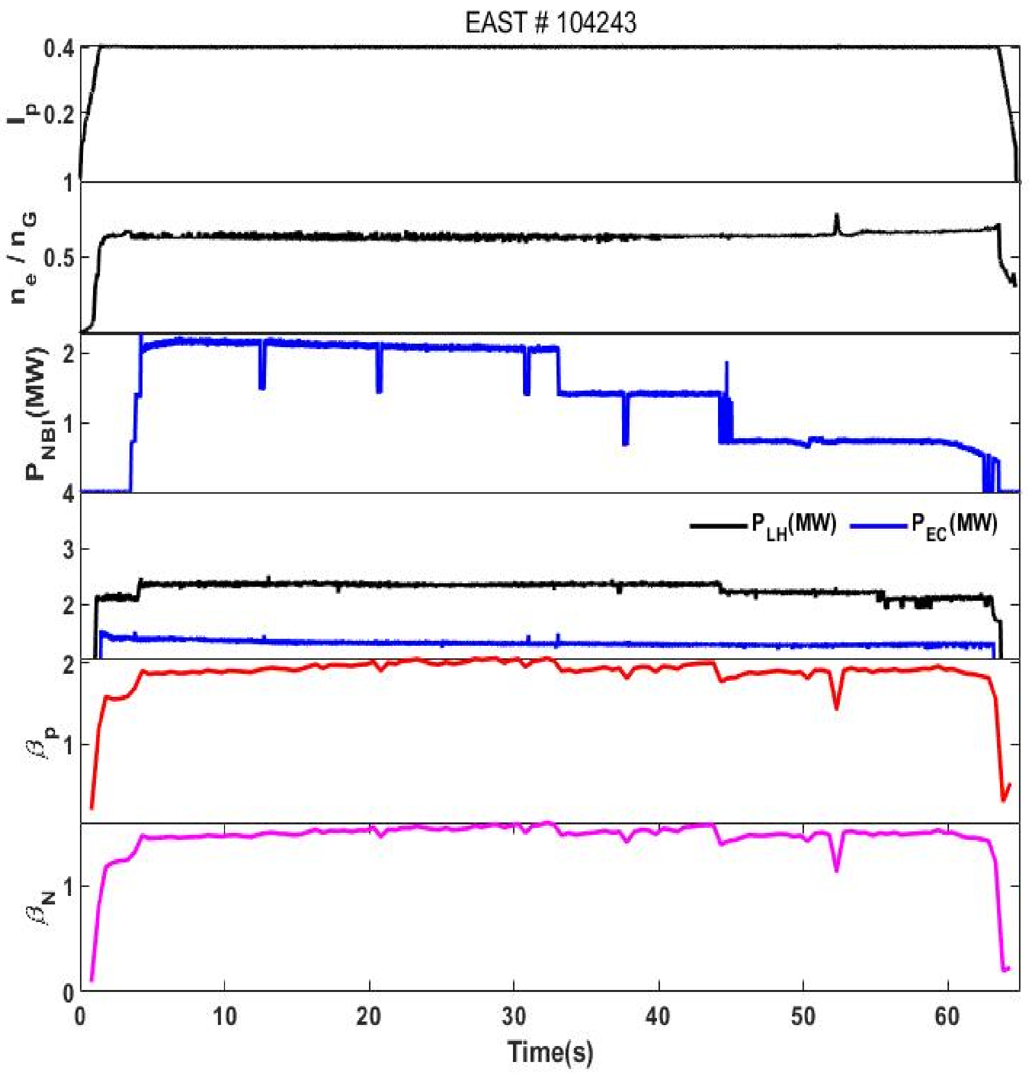
Beam self-adjusting method for long pulse NBI operation

- **Beam self- adjusting method based on beam re-turn on**

- **Ion source is easy to breakdown (BD) when operated in long pulse operaion with NBI. After the high-voltage power supply was shut down, the NBI control system will re-turn on the high-voltage power supply in about 90 ms to keep on extract the beam and ensure the long pulse operation on EAST.**



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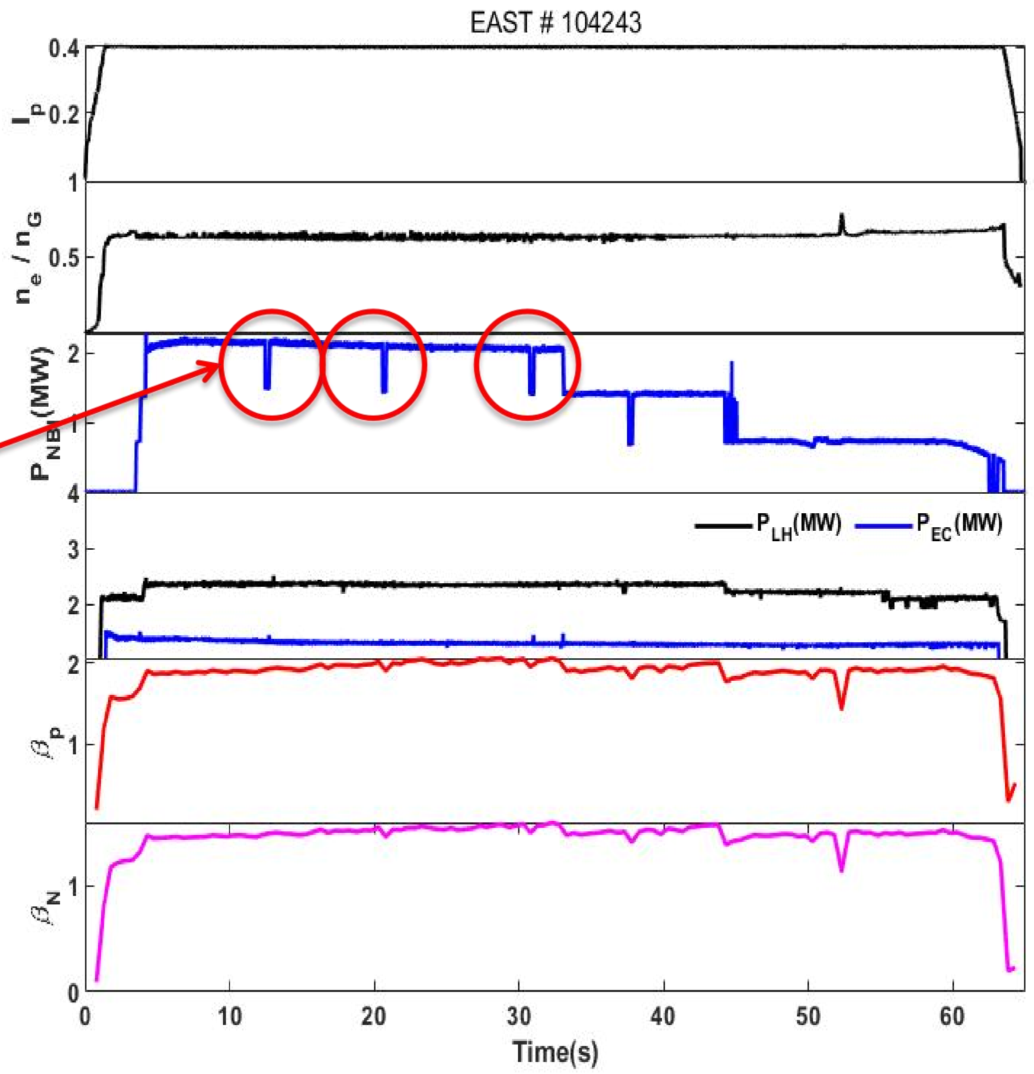
Beam self-adjusting method for long pulse NBI operation

- **Beam self- adjusting method based on beam re-turn on**
- **Ion source is easy to breakdown (BD) when operated in long pulse operaion with NBI.**
- **Beam re-turn on 90ms later**
- **Beam self-adjusting method has been applied in above Long pulse NBI operation.**

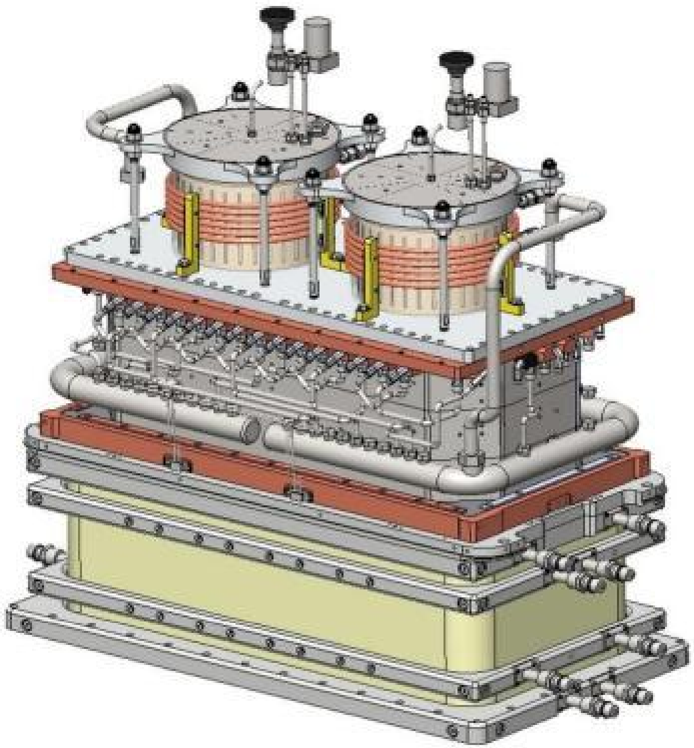


Upgrade ion source to radio frequency source for LPO

- **No filaments and maintenance free; simple structure; low cost and high reliability**
- **Promising candidate of next generation of NBI;**

Design of RF ion source for EAST	
Gas pressure	H2/D2, <0.6Pa
RF power	2×50kW
RF frequency	1 MHz
Antenna type	External antenna
Dimensions of driver	D=210mm; H=120mm
Bucket chamber and accelerator are similar with current arc source	

Yahong Xie et al. PPC-SOFE,, 2021



Conclusion and discussion

- **Simulations and experiments have proved that the plasma shape with larger gapout facilitates beam heating by depositing the initial beam ions inwards，decreasing prompt loss and ripple loss.**

- **Enlarging gapout reduces turbulence intensity and improves plasma confinement in high density NBI plasma.**

- **Although larger gapout is beneficial to beam heating, it needs to be considered comprehensively due to the gapout effect on RF heating，when many auxiliary heating methods are applied simultaneously.**

- **Self- adjusting method and RF sources in NBI engineering will be applied for long-pulse operation with NBI on EAST.**

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Thanks for your attention!