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Improvement of neutral beam heating efficiency by reducing the first orbit loss in Versatile Experimental Spherical Torus

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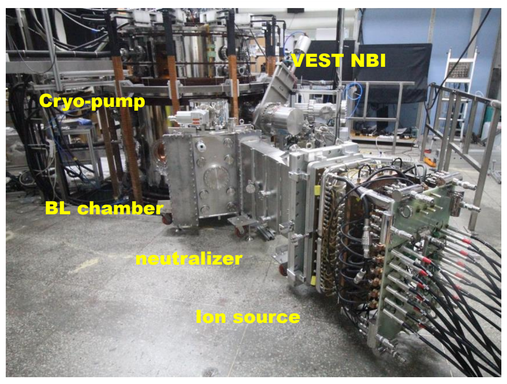
I. Introduction & Motivation

NBI system of VEST



- A Spherical torus (ST) with small aspect ratio has been considered as fusion reactor due to its compact size and high beta characteristics. However, Because of intrinsic characteristics such as small size and low Bt, efficient NB heating is limited.
- In particular, since the orbit loss is determined by the relative size of the fast ion orbit and the device, the orbit loss is very large in ST smaller than the conventional tokamak.
- In this presentation, we present the results of the first neutral beam heating experiment in VEST, and suggest that heating efficiency can be increased by increasing the distance between the magnetic axis and the outboard wall through simple confinement condition analysis based on orbit calculation. And we also present the experimental results applying this method.

II. Analysis of the first orbit loss

Confinement condition of fast ion

General orbit confinement condition

$$R_{max} = R_{g.c.max} + R_{gyro} < R_{wall}$$

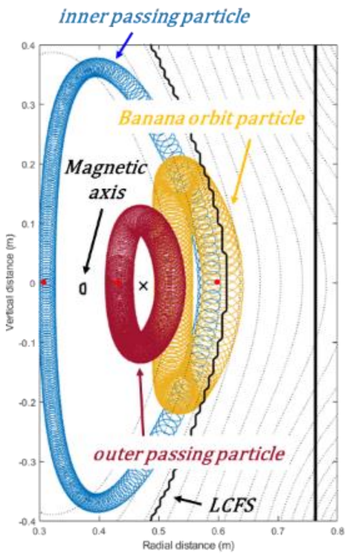
For co-injection case,

$$\Delta_{passing} \simeq -\frac{r}{R_{birth}}\frac{m_i v_{\parallel}}{eB_\theta}$$ Orbit axis shift by grad B drift

$$R_{passing\_axis} = R_{axis} + \frac{r}{R_{birth}}\frac{m_i v_{\parallel}}{eB_\theta}$$

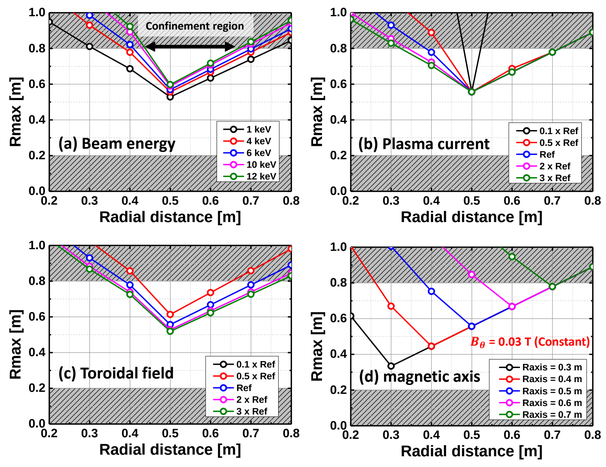
$$R_{birth} + \frac{m_i v_{\perp}}{eB_T} < R_{wall} \text{ (when } R_{birth} > R_{passing\_axis})$$

$$2R_{axis} + 2\frac{r}{R_{birth}}\frac{m_i v_{\parallel}}{eB_\theta} - R_{birth} + \frac{m_i v_{\perp}}{eB_T} < R_{wall} \text{ (when } R_{birth} < R_{passing\_axis})$$

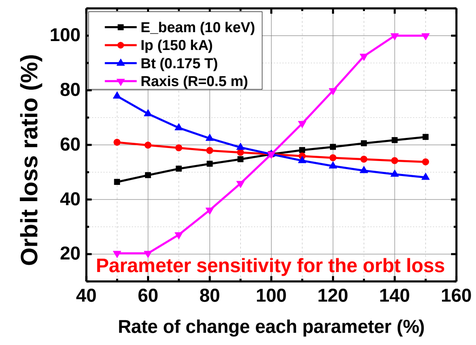


The first orbit loss calculation

Parameter scan for the first orbit loss



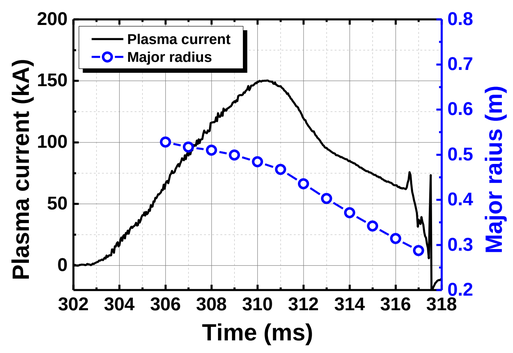
Parameters	Reference values
Outboard wall position (R_{wall})	R = 0.8 m
Magnetic axis position (R_{axis})	R = 0.5 m
Toroidal field (B_T at R = 0.4 m)	0.175 T
Plasma current (I_p at peak)	150 kA
Beam energy (E_{beam})	4 keV
Pitch angle ($v_{\parallel}/v_{\perp}$)	0.5

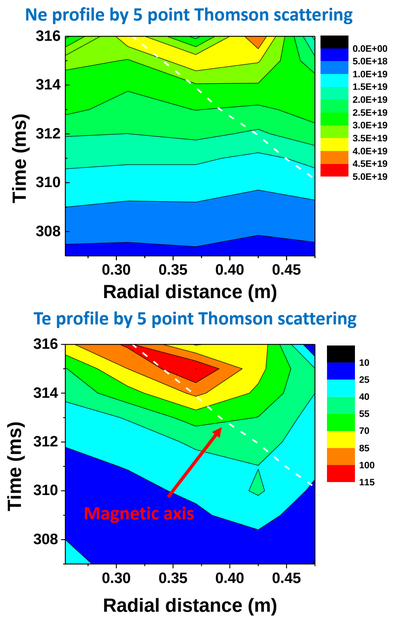


III. First NB heating results

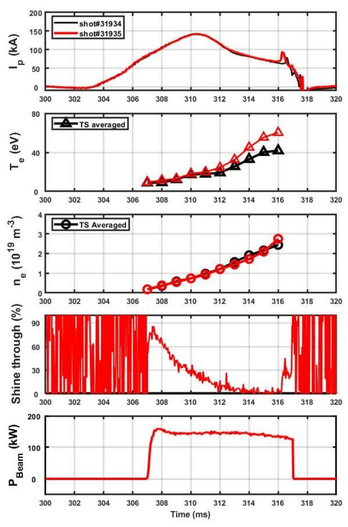
Target ohmic plasma

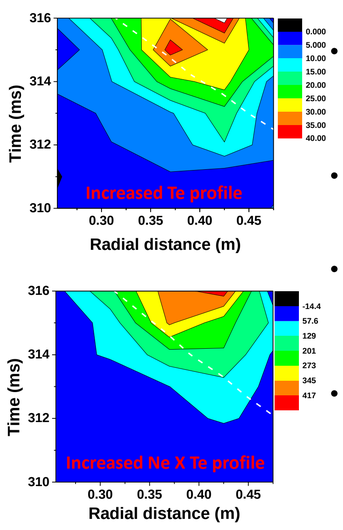
Base pressure : 1.5E-6 Torr
Wall conditioning : GDC(1 hr), Boronization(0.5 hr)
Bt : 0.175 T at R = 0.4 m
Ip : 148kA, (=310 ms, peak), 14 ms
Raxis = 0.5 m at 311 ms, outboard wall limited





NB heating results





- The electron temperature increase is observed without significant plasma density change.
- The average value data for the 5 point Thompson measurement shows that the difference in electron temperature gradually increases to reach a 20 eV increase.
- Before 310 ms, any heating effect is not shown due to high shine-through loss
- The critical energy is calculated by 14.8 x Te. For VEST, it is less than 2kV. Therefore, most beam energy transfers to electron
- As the magnetic axis moves inward, the heating effect begins to appear further inward. On the other hand, since the outside of the magnetic axis is an region that is advantageous for confinement, heating continues regardless of the change in the axis position.

0D power balance analysis

$$P_{absorption} = \frac{3}{2}\frac{d(n_e T_e)}{dt}$$

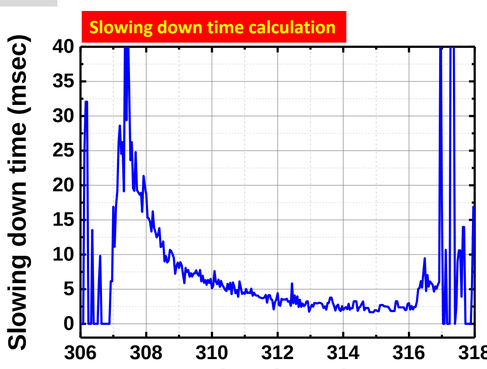
$$P_{fast} = \varepsilon_n P_{Extraction} - P_{shine-through} - P_{orbit}$$

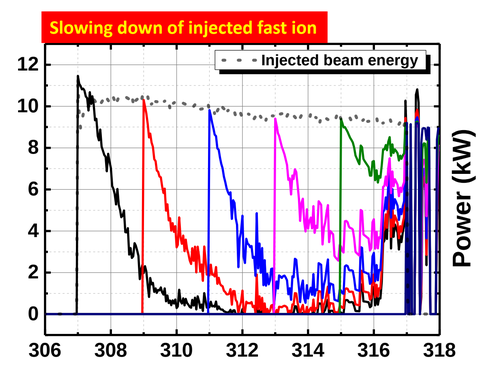
$$P_e = \frac{m_i v_i^2}{\tau_{se}} = \frac{2E_{fast}}{\tau_{se}} = \frac{2}{\tau_{se}}(P_{fast} \times dt)$$

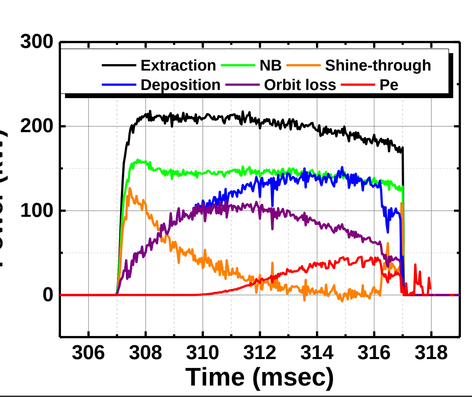
$$\tau_{se} = 6.27 \times 10^8 \frac{T_e^{3/2}}{n_e ln\Lambda}\frac{A}{Z^2}$$

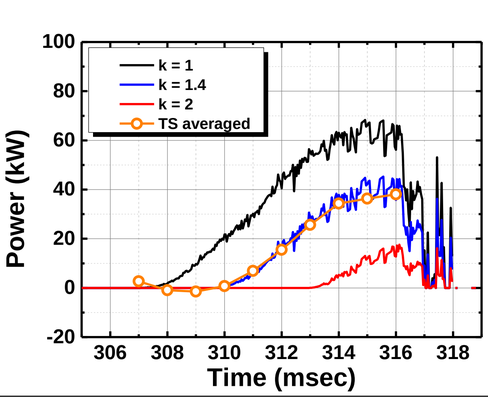
$$E_{fast} = E_{fast0}[e^{-\frac{3t}{\tau_{se}}} - \left(\frac{E_c}{E_{fast0}}\right)^{\frac{3}{2}}(1 - e^{-\frac{3t}{\tau_{se}}}]^{2/3}$$

$$P_{absorption}(t) = \sum_{n=beamstart}^{t} P_{e,n}(t)$$









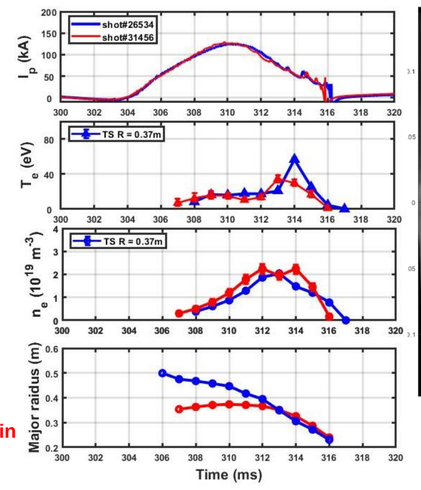
IV. Application of magnetic axis position effect

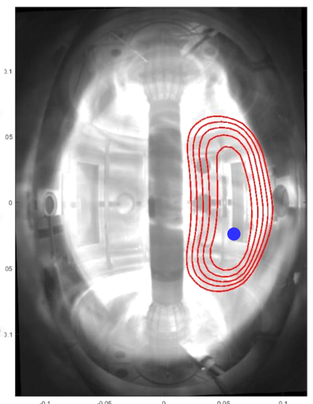
Target ohmic plasma

ShotNumber : #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
Ip : 128 kA, 131 kA (at peak time : 310 ms)
Raxis = 0.4 m, 0.47 m

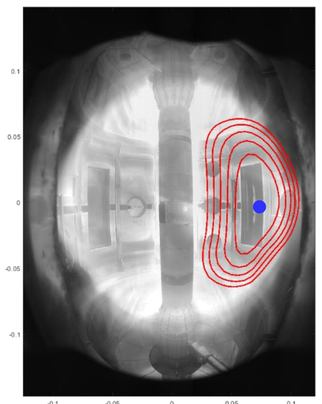
NB heating results

- Improvement NB heating efficiency by increasing a gap distance between magnetic axis and outer wall is clearly confirmed.
- In both cases, the changes in plasma current was not significant, and the shine-through loss is similar in the two case.
- the increase in electron temperature due to beam injection appeared only in the inboard axis case
- NB heating efficiency is calculated as 10 % by power balance model.

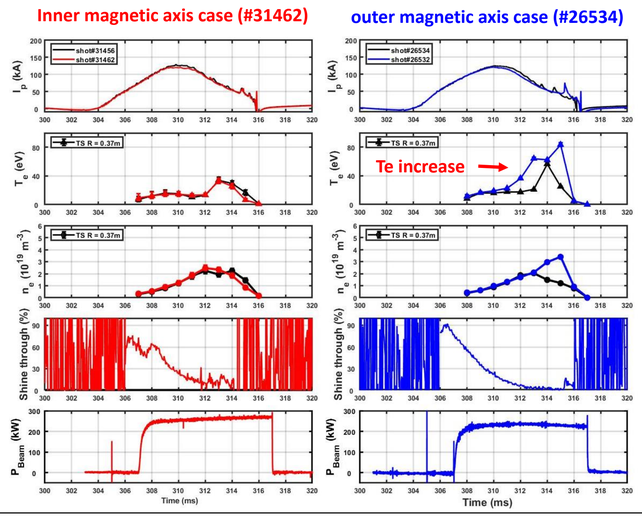




26534 (310 ms)



31456 (310 ms)



V. Conclusion & Future work

- The simple 0d power balance model with orbit loss estimation was constructed for neutral beam heating efficiency.
- From orbit loss calculation results, we predict that the position of the magnetic field axis can have a significant effect on the orbital loss.
- The first neutral beam heating experiment was successfully conducted by obtaining the results of the electron temperature rise.
- By evaluating the heating efficiency according to the discharge time, it was confirmed that the orbit loss decreased with time at the second half of the discharge. And this also seems to be the effect of the change of the magnetic axis position.
- The Neutral particle beam heating experiments were performed on two targets with the same plasma current, electron temperature, and density, but with different positions of the magnetic axis. From this, the effect of the magnetic axis was clearly confirmed.
- In the future, the study on the cooling effect due to beam loss will be conducted through the beam blip experiment. In addition, charge exchange loss will be investigated as a third step of the step-by-step study.