MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Neutral beam experiments with upgraded power on Wendelstein 7-X Nuclear Fusion: IAEA FEC 2023

Samuel A. Lazerson
P. McNeely, N. Rust, O. Ford, M.N.A. Beurskens, S. Bozhenkov, I. Stepanov, D.Kulla, R. Lopez-Cansino, D.M. Kriete, E. Viezzer, V. Perseo, D. Hartmann, R.C. Wolf, and the W7-X Team

Paper Rehearsal

January 15, 2024

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Abstract

The neutral beam injection (NBI) system on Wendelstein 7-X was upgraded from two to four sources in the first high heat flux divertor campaign. This resulted in more than a doubling of the injected power as compared to the previous campaign, due to improvements in neutralization efficiency. The additional two sources were located in the complementary beam line of W7-X, allowing for some new diagnostic capabilities including coherence imaging charge exchange recombination spectroscopy. The high mirror, standard, low mirror, low iota, and low shear magnetic configurations were all explored with up to five seconds of neutral beam duration. In the standard magnetic configuration, stationary ion temperatures of 2 keV were achieved via neutral beam injection. Scaling from one to three NBI sources show a beneficial non-linear scaling in the stored energy and density. An initial line integrated density of at least 5×10^{10} m^{-2} was required for density peaking to occur. Reintroduction of electron cyclotron resonance heating (ECRH) into such discharges suggested that ECRH power and magnetic configuration play a strong role in the density pump-out and resulting changes in turbulence.

Introduction

- In the previous campaign W7-X was upgrade from two to four neutral beam sources
- Stellarator symmetric sources to those of previous campaign.
- Five seconds of heating achieved in many magnetic configurations.

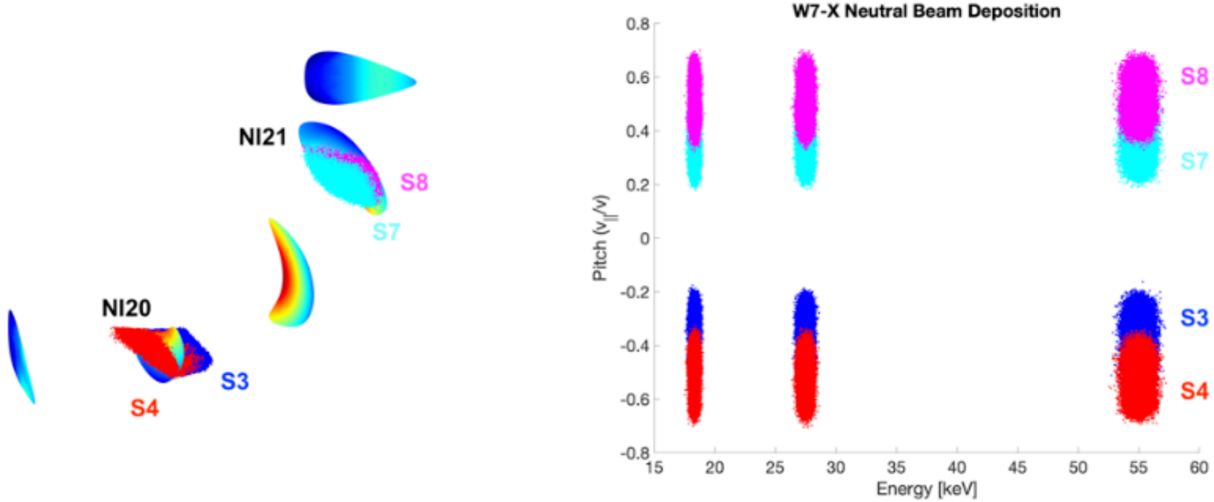


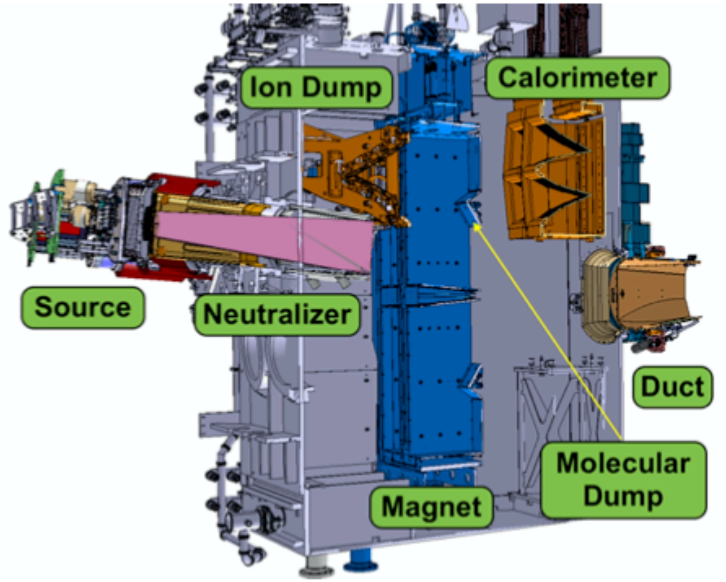
Figure 1. Neutral beam births in real space (left) and pitch energy space (right). The newly installed sources are S3 and S4 in the NI20 beam box. The equilibrium magnetic field strength is plotted for reference for various toroidal cuts. Data from BEAMS3D simulations[5].

Upgrades to the NBI on W7-X expanded capabilities

- Improvements to calorimetry
- Heat shield thermography system implemented
- Second box expanded system capabilities
  - Doubling of nominal heating power
  - Passive subtraction of active FIDA now possible
  - CICERS system views second beam line
  - Balanced beam injection now possible

Calorimetry was improved from previous campaigns

- Inclusion of low pressure water cooled components allows for complete calorimetry
- Slow time rise requires curve fit temperature rise (over 90 seconds)
- Allows for 95% energy inventory of the neural beam box
- Tuning of neutralizer gas flow resulted in higher beam power 1.8MW -> 2.2 MW



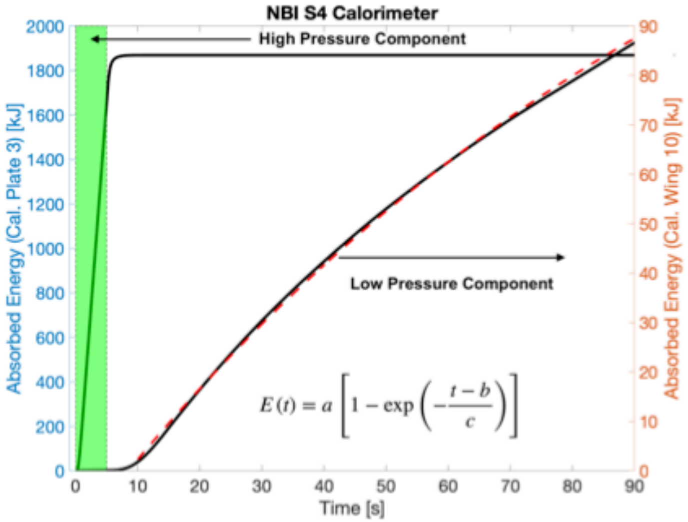


Figure 2. Cutaway view of a neutral beam box (right) and calorimetric plot for two component of the calorimeter (left). The calorimetric shows the energy integral for a component cooled by high pressure water and low pressure water. Red dashed line shows the fit curve and green shaded region shows neutral beam extraction.

Clear evidence of W7-X main field shifting neutral beam

- Calorimetry of both the calorimeter and ion dump plates confirms an upward shift
- Present in spectroscopic data as well
- Modeling of source is a Ph.D. topic of Lucas van Ham.

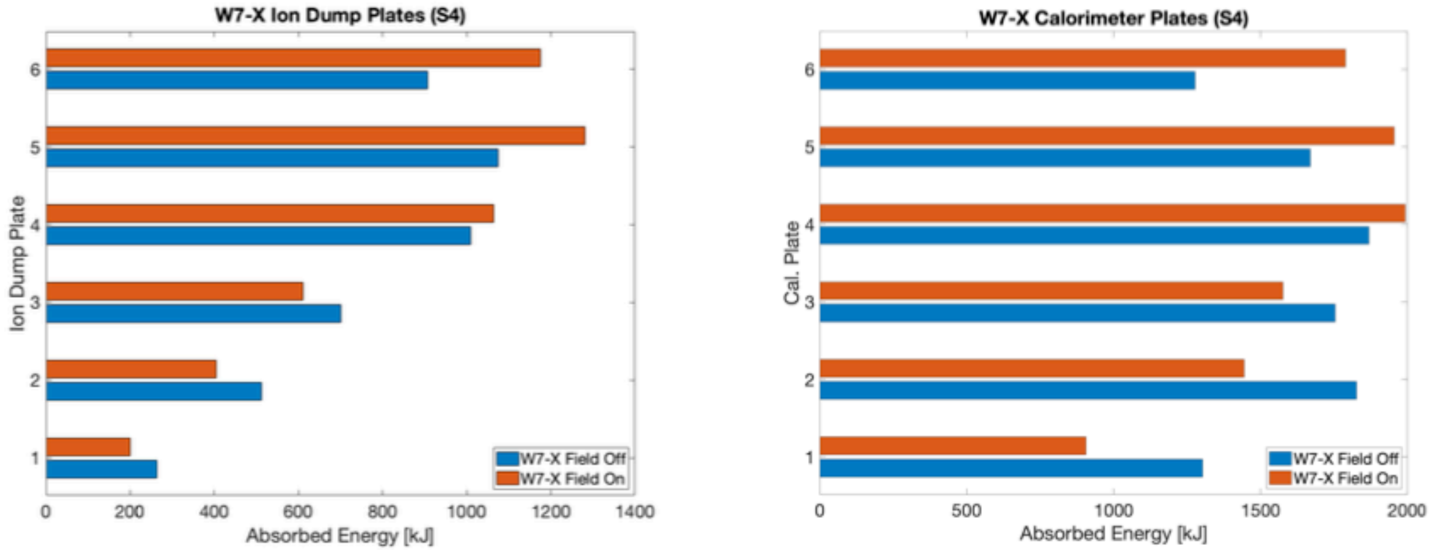


Figure 3. Calorimetry of ion dump plates (left) and calorimeter plates (right) for cases with and without the W7-X magnetic field turned on. Vertical axis is in order of vertical position with 6 being the top and 1 being the bottom plates.

A new heat shield thermography system was commissioned

- Two color pyrometers provide temperature measurements for each beam footprint on wall.
- Thermocouple data shows slow temperature rise after discharge.
- Source 6 thermocouple shows a possible upward shift of beam

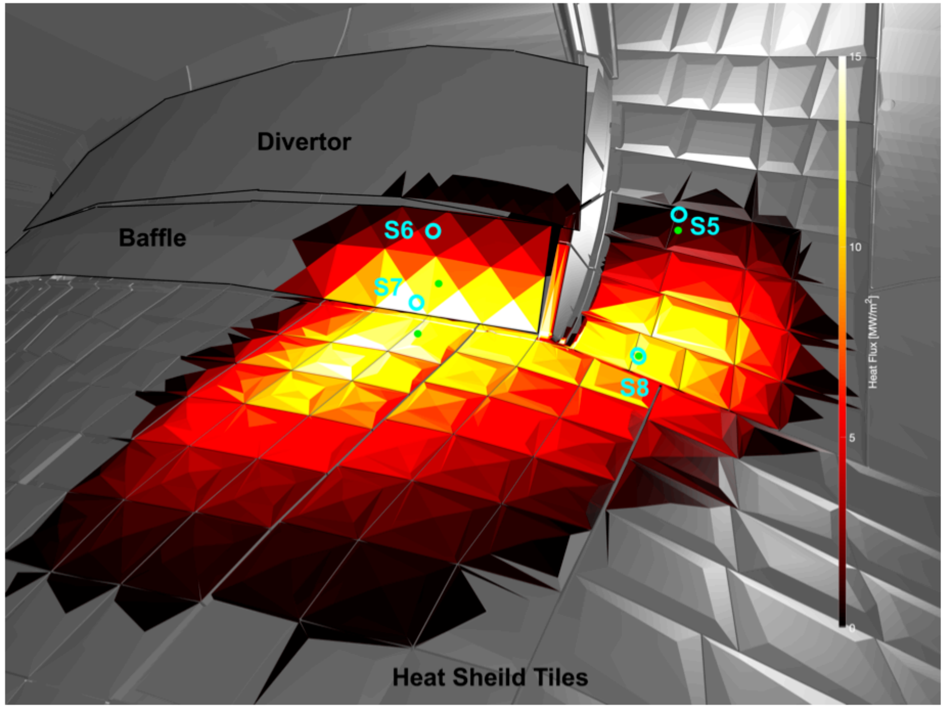


Figure 4. Geometry of the heat shield thermography system for the W7-X beam line system. Blue circles indicate approximate viewing region of the pyrometers, green dots indicate approximate positions of thermocouples. Heat loads shown for source 7 and 8 only.

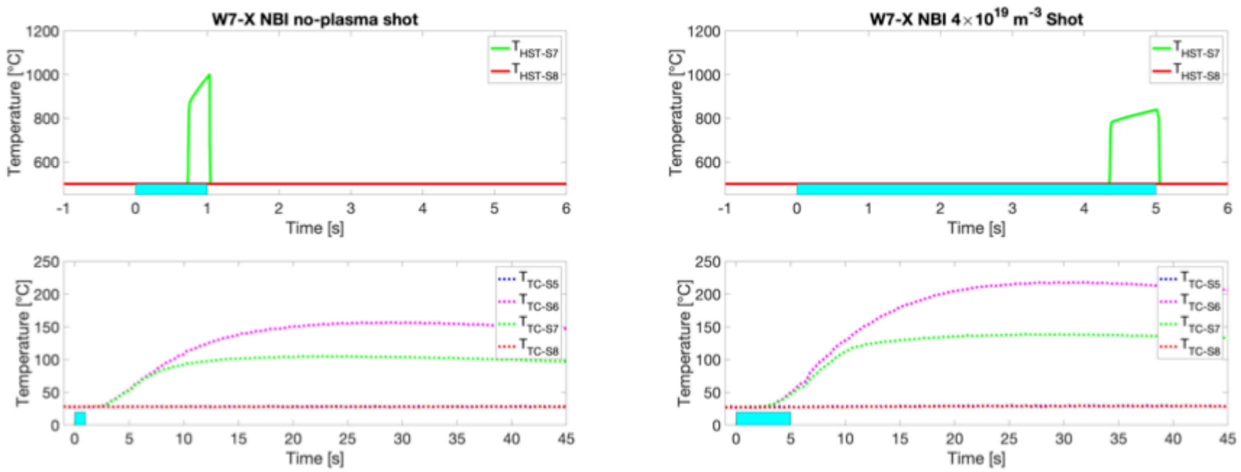
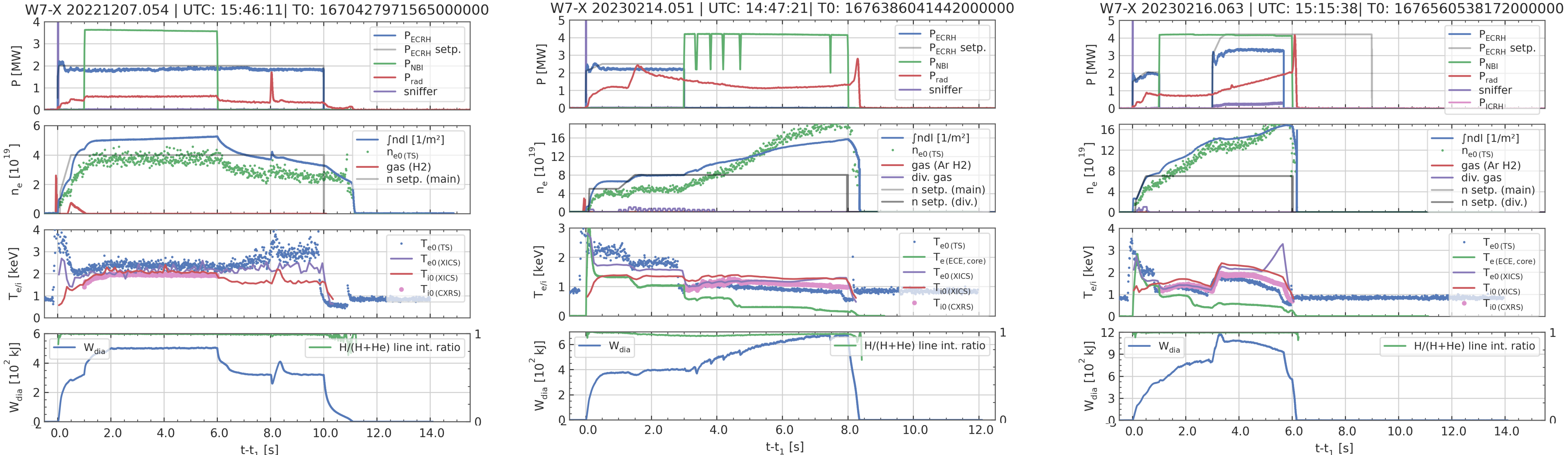


Figure 5. Experimental plots of measured wall component temperature for unmitigated source 7 shine through (left) and with a plasma at $4 \times 10^{19}\ m^{-3}$ density (right). Upper plots show temperatures measured by the HST pyrometer while lower plots are from thermocouples embedded in tiles. The shaded region indicates beam duration.

Experiments with NBI fall into three categories

- NBI into ECRH plasmas
  - 2 MW of ECRH + NBI (used for pulse length extensions)
- Pure NBI discharges
  - ECRH startup followed by switch to NBI
- ECRH reintroduction discharges
  - Pure NBI discharges where ECRH is brought back in



Neutral beam injection was performed into a variety of magnetic configurations

- **Standard configurations shows the greatest rise in diamagnetic energy for minimal density rise.**
- **Loss of density control in Low shear, and high mirror configurations (2 MW of ECRH)**

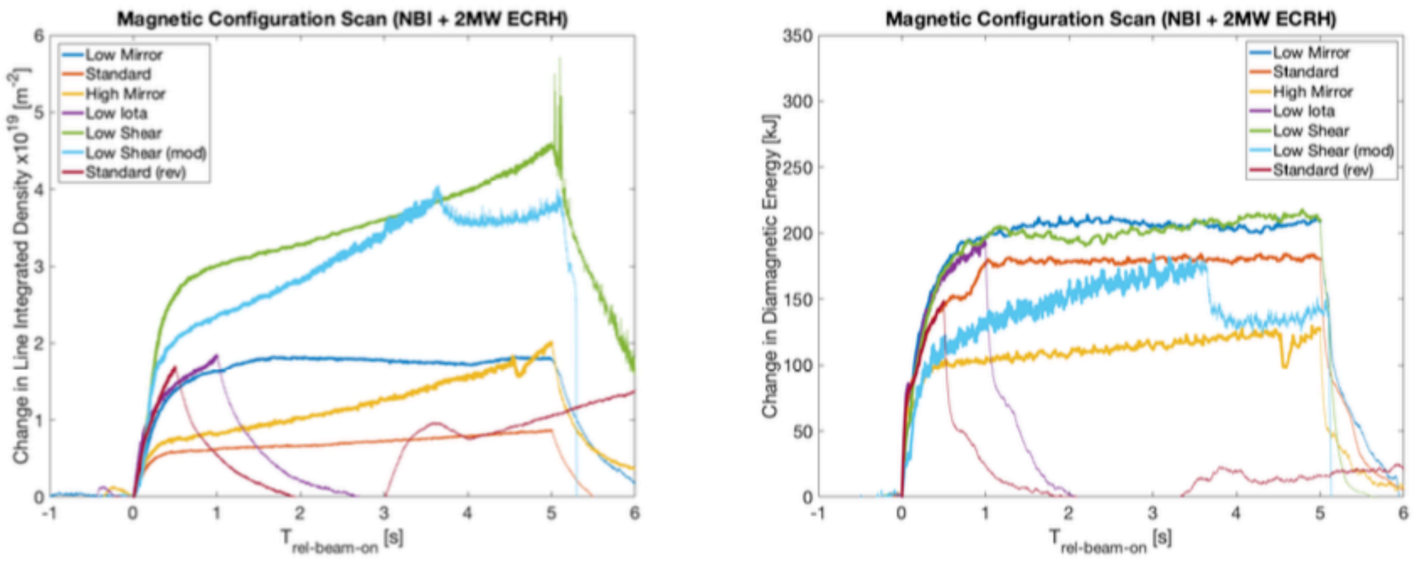


Figure 6. Change in line integrated density (left) and stored energy (right) scanning magnetic configuration. These discharges had 2 NBI sources, 2MW of ECRH and similar initial densities. Density and stored energy are scaled by subtracting the initial value before the NBI fired. Shot numbers: 20230216.28, 20221207.54, 20221201.36, 20230126.58, 20230307.24, 20230307.56, 20230118.16

Ti clamping broke in standard configuration

- **Thomson density consistent with line integrated density**
- **CXRS shows 600 eV enhancement of ion temperature for 4 seconds.**

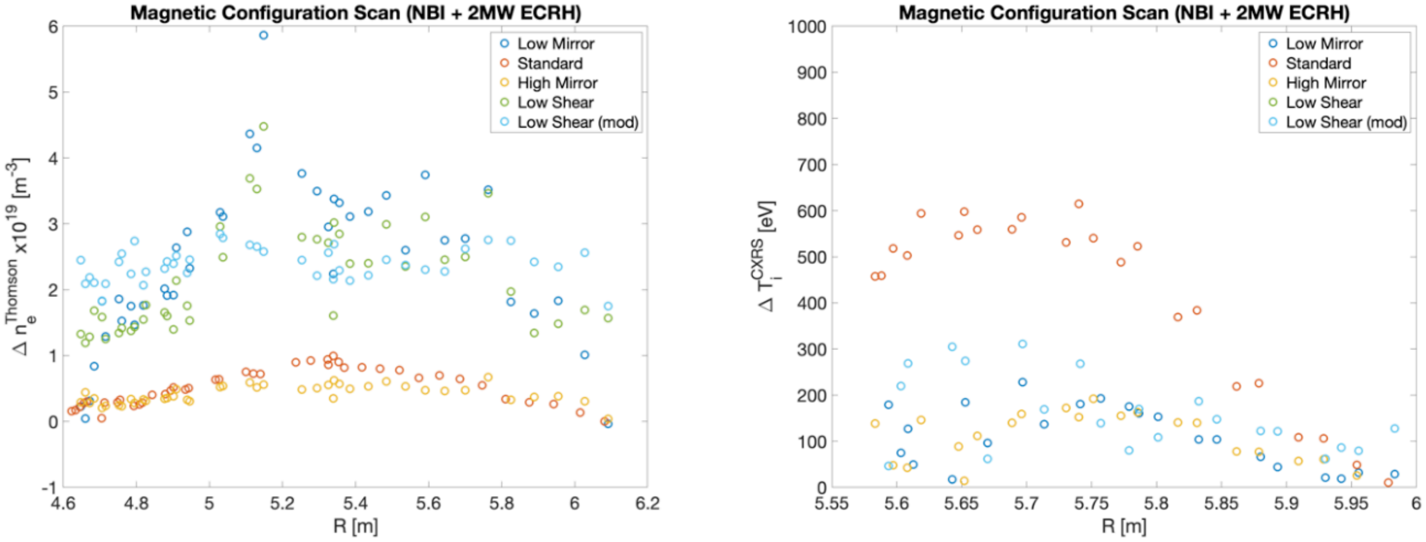


Figure 7. Change in electron density (left Thomson) and ion temperature (right CXRS) profiles when NBI is injected into various magnetic configurations. Configurations have been down selected to those achieving steady-state conditions between 2 and 3 seconds into the NBI phase. Electron temperature suggests about a 200 eV core temperature rise.

Scaling of NBI heating power shows a positive trend

- Density rise shows a strongly non-linear behavior with number of NBI sources
- Stored energy shows a continual doubling (non-linear)
- Possible confinement transition present

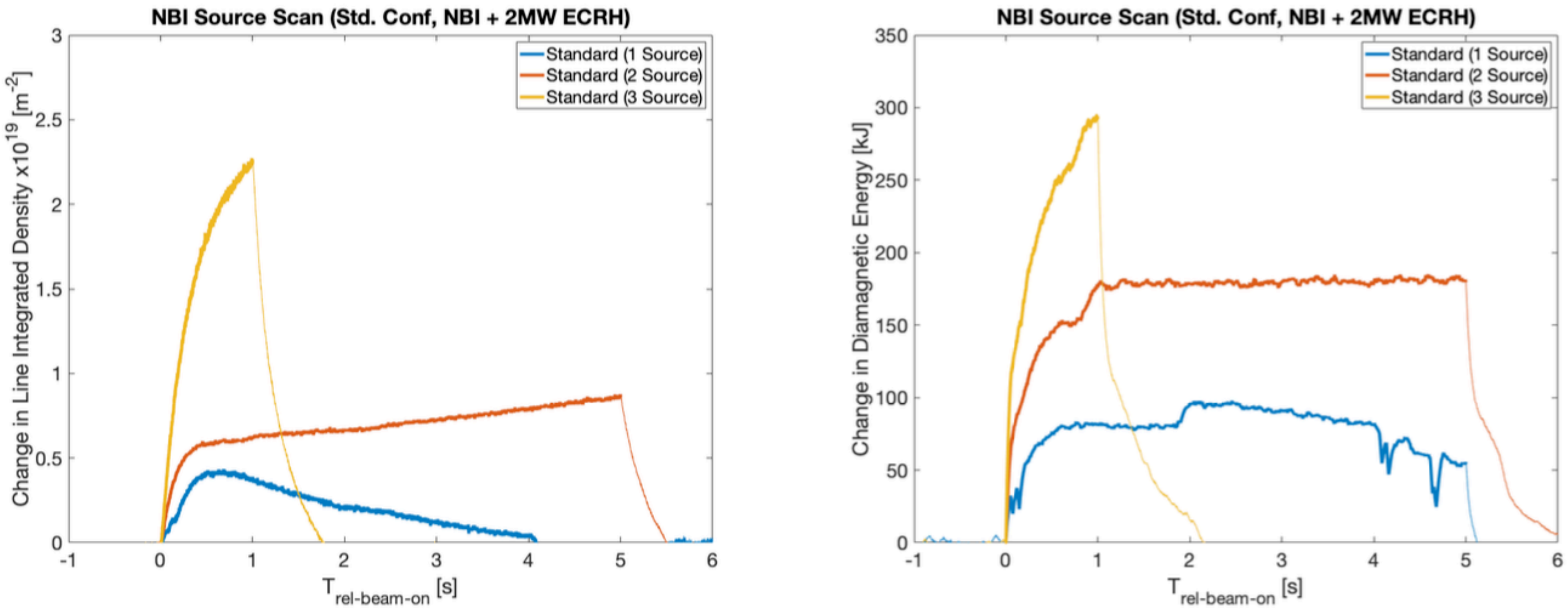


Figure 8. Change in line integrated density (left) and stored energy (right) scanning number of sources. These discharges had 2MW of ECRH and similar initial densities. Density and stored energy are scaled by subtracting initial value before the NBI fired. Shot numbers: 20230215.23 20221207.54, 20120215.19

In pure NBI discharges the initial density plays a role

- Below 5x10^{19} m^{-2} no strong density peaking is seen
- Core peaking appears when density rises above 9x10^{19} m^{-2}

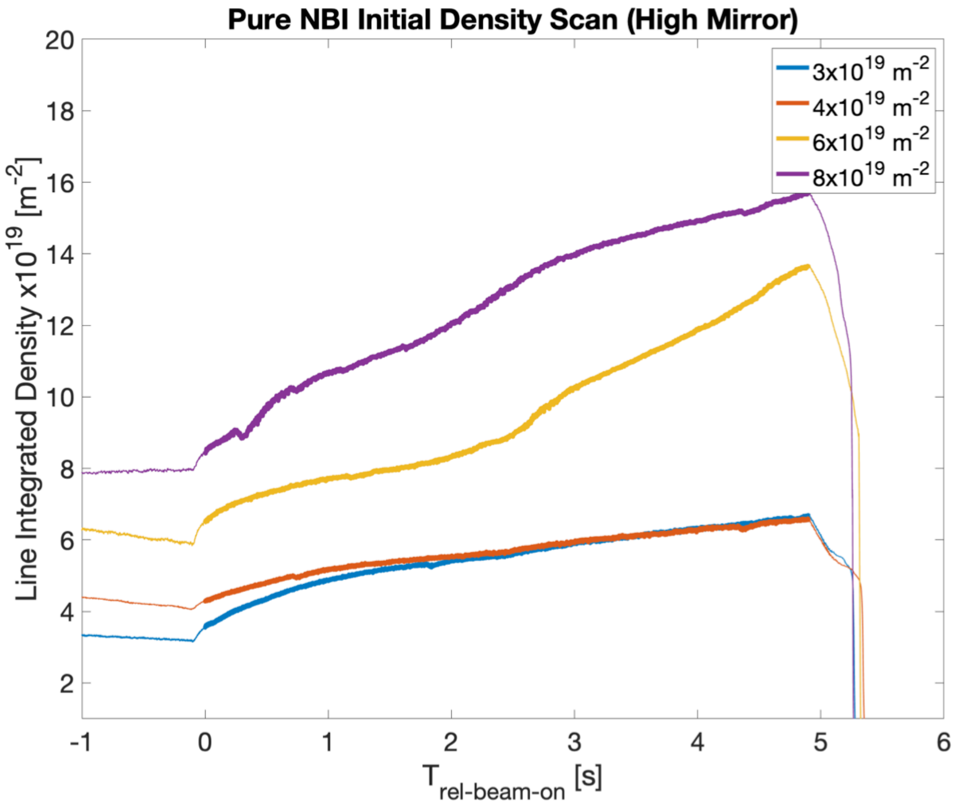


Figure 10. Effect of initial plasma density on pure-NBI discharge evolution. Shot numbers: 20230214.37, 20230214.41 20230214.47, 20230214.51

Pure NBI discharges show a strong dependence on magnetic configuration

- Limiter shows strongest density rise and largest diamagnetic energy
- Low mirror shows multiple changes in slope of density (peaking changes?)

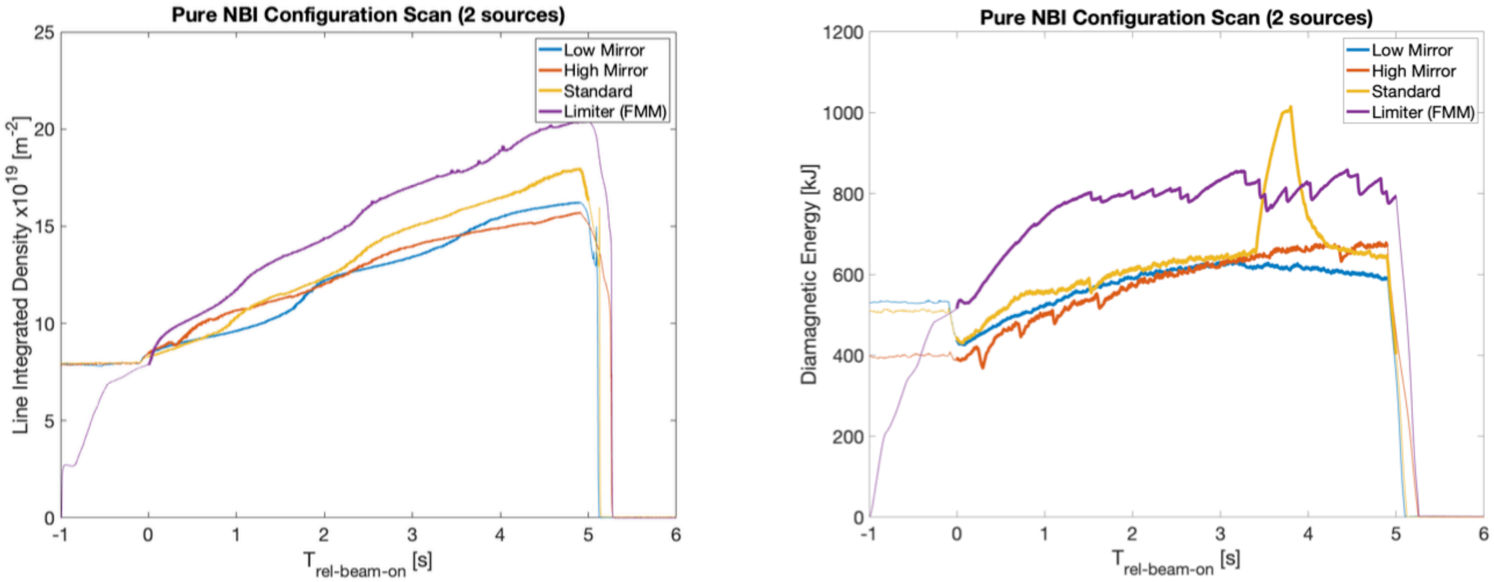


Figure 11. Line integrated dnesity (left) and diamagnetic energy (right) scanning magnetic configurations for pure NBI discharges. All experiments performed with 2MW ECRH startup and switched over to two source NBI heating. Standard configuration has a blip of 4 MW of ECRH at 3.5s. Shot numbers: 20230323.61, 20230214.51,20230323.42, 20230216.61

Impact of ECRH on pure NBI discharges was investigated in detail

- **Between 1.5 and 2 MW of ECRH density pump out begins**
- **Feedback of ECRH power on density could be a path to steady-state high performance.**

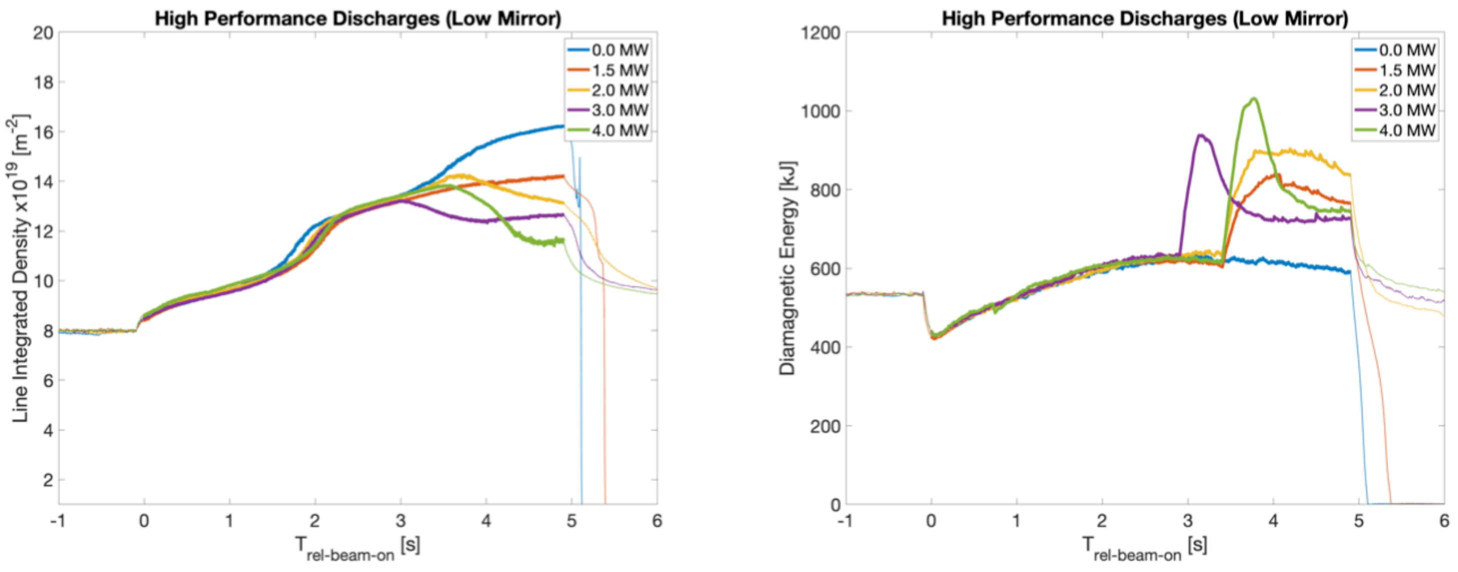


Figure 13. Line integrated density (left) and diamagnetic energy (right) scanning reintroduced ECRH power. All experiments performed with 2MW ECRH startup and switched over to two source NBI heating. Reintroduced ECRH is in the O2 polarization. Shot numbers: 20230316.61, 20230316.69, 20230316.66, 20230316.64, 20230316.76

Reintroduction of ECRH is a strong function of magnetic configuration

- **FMM limiter configuration achieves very high performance.**
- **ECRH threshold for density pump out appears configuration dependent**

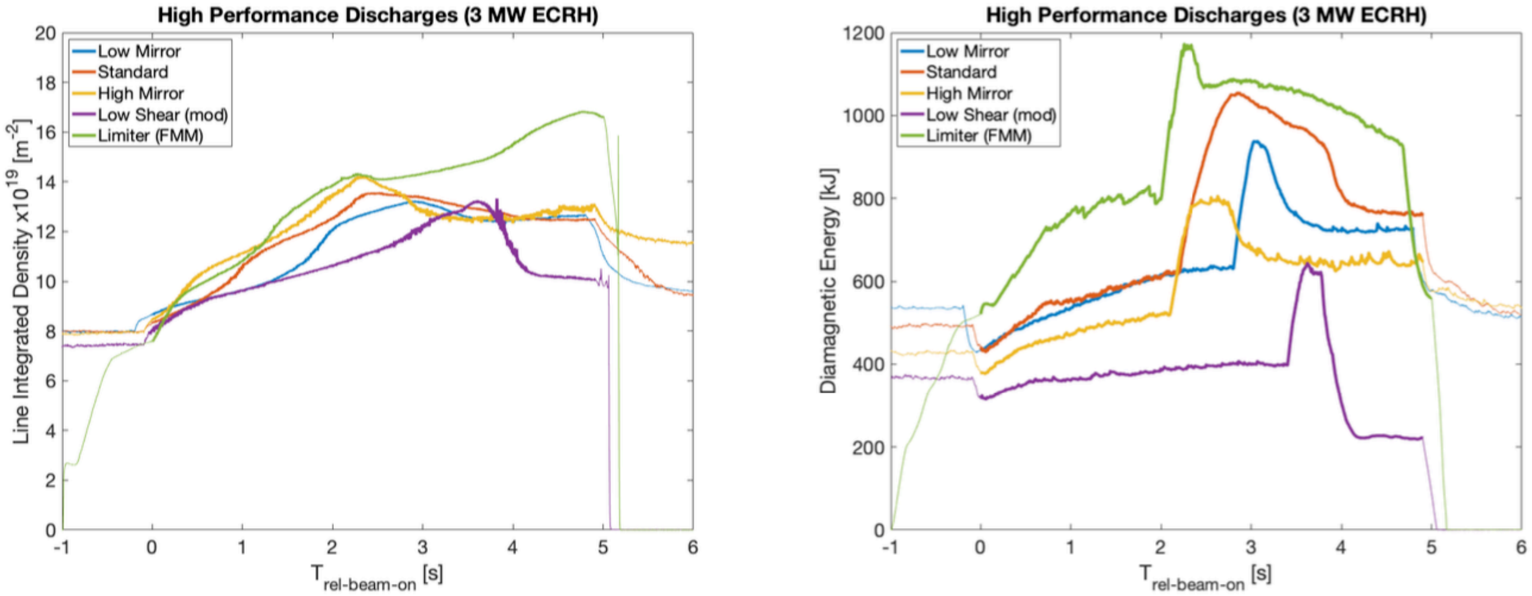


Figure 12. Line integrated dnesity (left) and diamagnetic energy (right) scanning magnetic configurations where ECRH is reintroduced into pure NBI discharges. All experiments performed with 2MW ECRH startup and switched over to two source NBI heating. Reintroduced ECRH is in the O2 polarization and 3MW. Shot numbers: 20230316.64, 20230323.34, 20230223.38, 20230307.66, 20230216.63

Conclusions and outlook

- In OP2.1 a second neutral beam line was brought online, significantly extending the heating power and capabilities of W7-X.
- Improvements to calorimetry confirmed an increase in neutralized power to 2.2 MW
- An upward shift of the beams linked to the main field of W7-X was measured
- A heat shield thermography system was demonstrated and commissioned
- Experiments with up to three sources were performed
  - Ti > 2 keV was achieved in the standard configuration
  - Experiments with three sources show a positive scaling with source number
  - Pure-NBI discharges showed a strong sensitivity to initial plasma conditions
  - ECRH reintroduction experiments show a subtle sensitivity to ECRH power
- Future experiments will explore high density operation