

Qualitative validation of CAD-based simulations of NBI-induced prompt fast-ion losses against IRTV measurements in KSTAR

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1 Background & motivation

- Ports, cooling channels and diagnostics make real PFC geometry **non-axisymmetric**: NBI heat loads peak at **leading edges and limiters**, beyond toroidally symmetric models
- CAD-to-simulation tools (SMARDDA [1], HEAT [2]) are entering AI-augmented digital twins [3, 4], but experimental validation of their **3D heat-load footprints** is scarce [6]

This work

Qualitative validation of NBI-induced **prompt fast-ion loss** (bad-orbit loss) heat-flux predictions of the CAD-based code **NuBDeC** [5] against **IRTV** on the KSTAR lower PFCs

- Dedicated session, Nov. 19, 2025: scan of I_p , B_T and beam source; first benchmark that **isolates NBI prompt loss** from thermal-ion and ELM signals

2 NuBDeC and prompt (bad-orbit) loss

- Monte Carlo orbit following** with fast-ion–wall **collision detection** on CAD-derived unstructured meshes; per-face heat flux on the **3D PFC surface**, each face linked to its component (divertor, limiter, passive stabilizer)
- Inputs per shot: EFIT equilibrium, fitted n_e , T_e (Thomson), beam geometry / energy / power
- Prompt loss (bad-orbit loss)**: first-orbit loss of beam ions born on loss orbits, deposited on PFCs within one poloidal transit
- Toroidal (curvature / ∇B) drift $\Rightarrow$ wider loss orbits; drift in circular geometry [5, App. B], [9]:

$$V_D \simeq \frac{m}{eB_0R_0} \left(v_{\parallel}^2 + \frac{v_{\perp}^2}{2} \right), \quad T = \frac{2\pi qR}{v_{\parallel}}$$
$$D = \frac{V_D T}{2\pi} \simeq \frac{m q R}{e B_0 R_0} \frac{v_{\parallel}^2 + v_{\perp}^2/2}{v_{\parallel}} \xrightarrow{v_{\perp} \ll v_{\parallel}} q \rho_{\parallel} = \frac{r}{R} \frac{m v_{\parallel}}{e B_p}$$

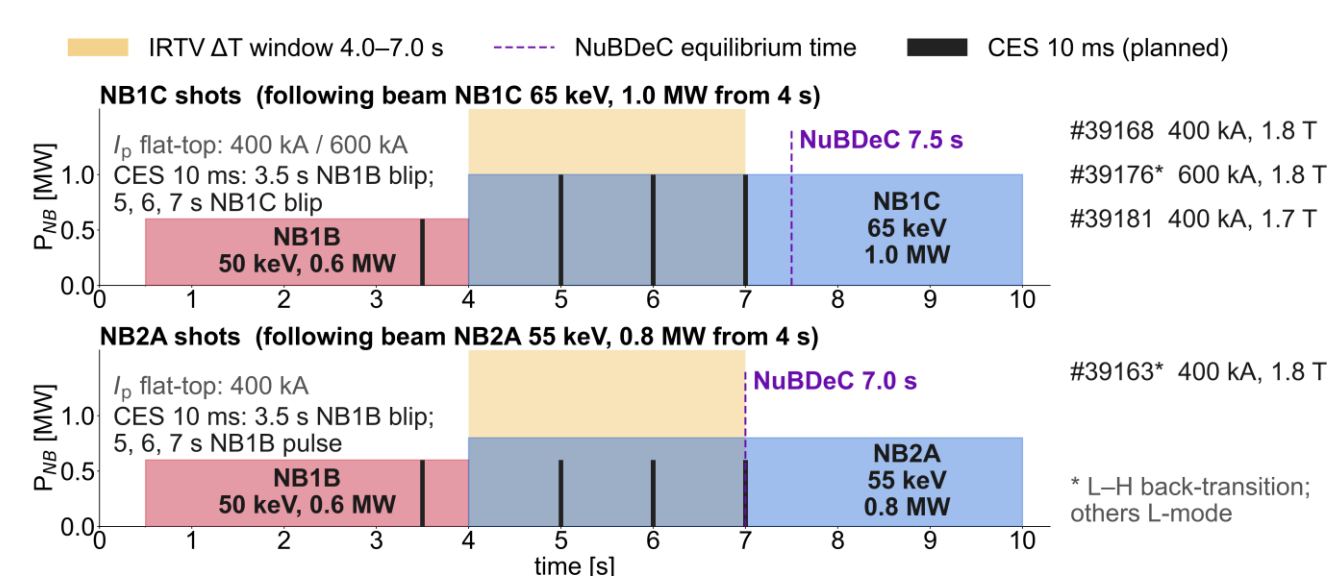
- $D \uparrow$ for $I_p \downarrow$ ($B_p \downarrow$, $q \uparrow$; $D \propto 1/I_p$) and for smaller $v_{\parallel}$ at fixed E_b (smaller tangency radius); B_T nearly cancels ($q \propto B_T$, $\rho_{\parallel} \propto 1/B_T$)

Testable predictions

- $I_p \downarrow$ (600 $\rightarrow$ 400 kA): loss $\uparrow$
- B_T (1.8 $\rightarrow$ 1.7 T): weak change
- NB1C ($R_{\text{tan}} = 1.245$ m) vs NB2A (1.56 m): smaller $v_{\parallel}/v$ at birth $\Rightarrow$ NB1C loses more
- Peaks at **leading edges** and the **poloidal limiter**

3 Experiment

- LSN L-mode held **below the L–H transition** (no ELM loss); LSN steers lost ions into the IRTV view, away from the thermal-ion footprint. Tangential IRTV (100 Hz), Thomson, CES



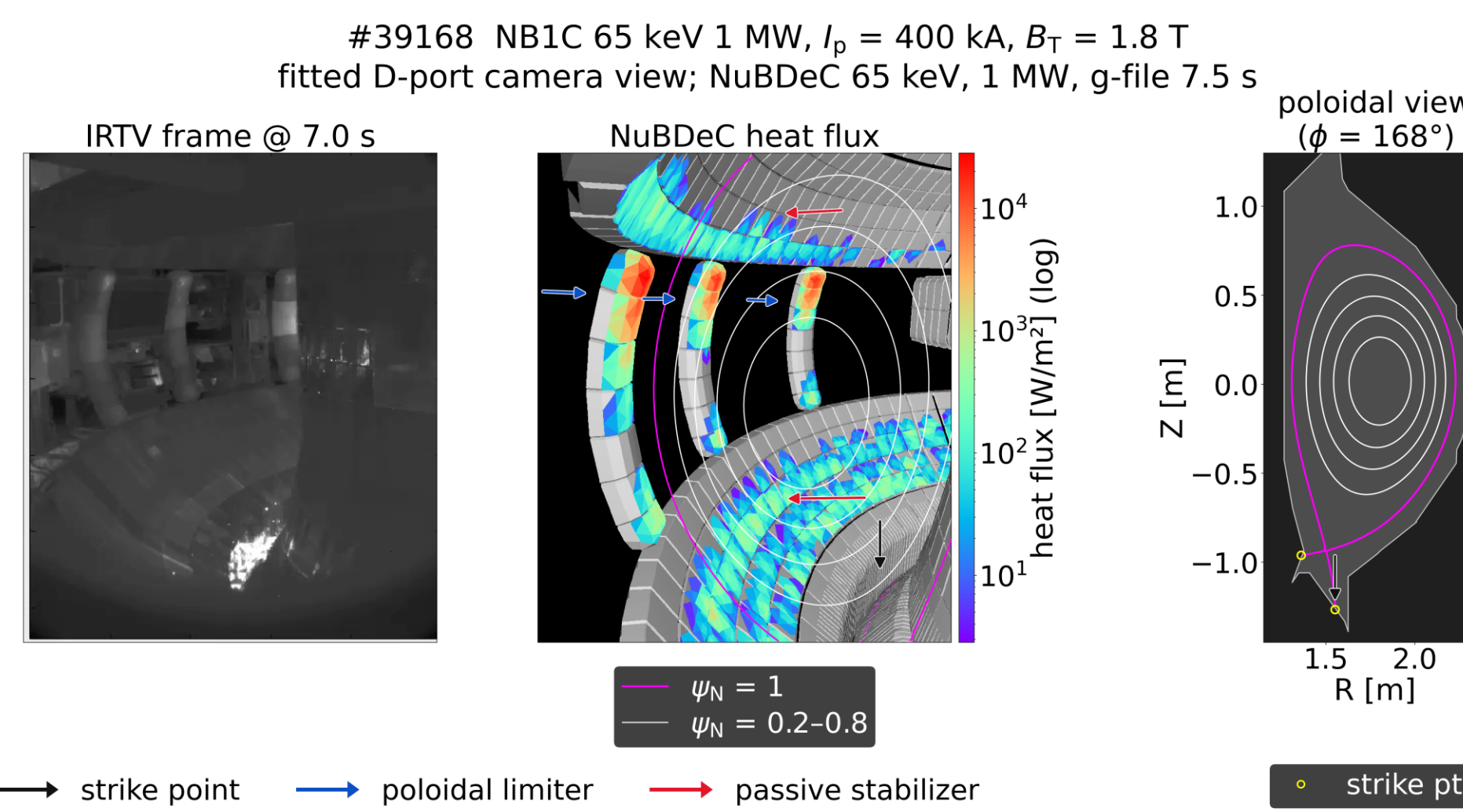
Baseline NB1B (0.5–4 s), beam under test from 4 s. IRTV ΔT window **4.0–7.0 s**; NuBDeC equilibrium at 7.5 s (NB1C) / 7.0 s (NB2A).

Shot	I_p [kA]	B_T [T]	Beam under test	Role
39168	400	1.8	NB1C 65 keV, 1.0 MW	reference
39176	600	1.8	NB1C 65 keV, 1.0 MW	I_p scan
39181	400	1.7	NB1C 65 keV, 1.0 MW	B_T scan
39163	400	1.8	NB2A 55 keV, 0.8 MW	beam source

- Qualitative** comparison: footprint location and trend (IRTV a.u. vs W/m^2); thermal-ion loss stays on the divertor; 2 / 23 discharges excluded

4 Analysis method

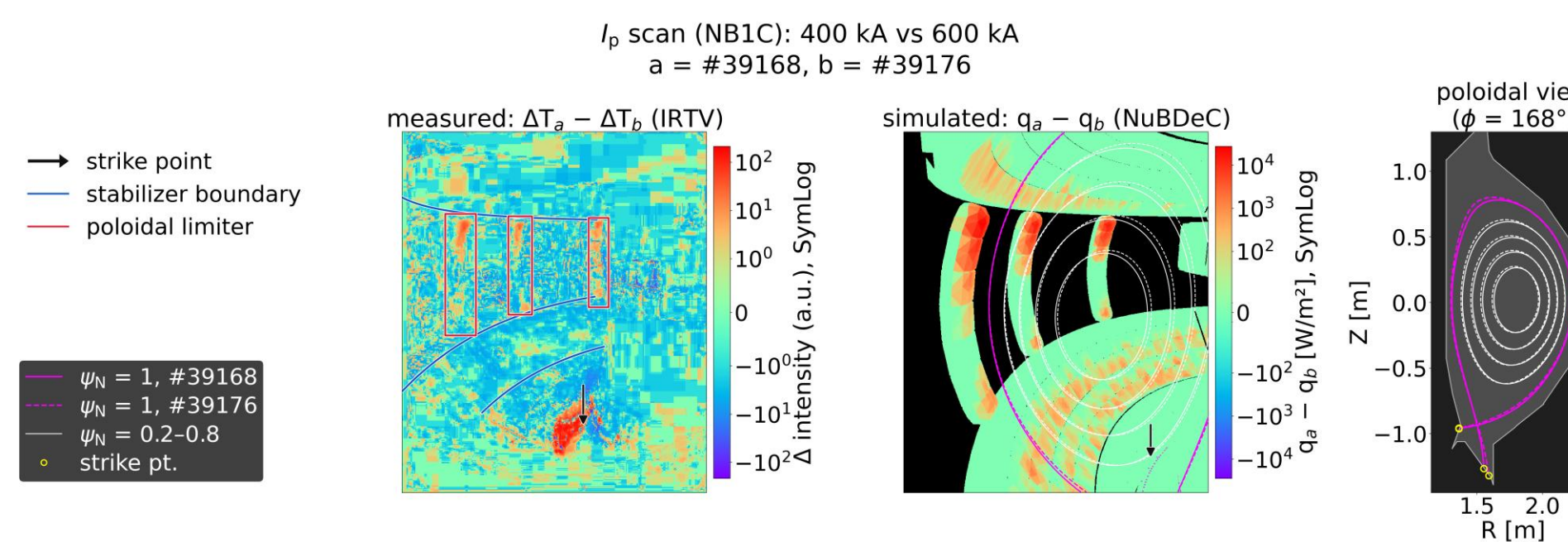
- $\Delta T = I(7.0 \text{ s}) - I(4.0 \text{ s})$: IRTV accumulated over **4–7 s**; the **shot-to-shot difference** $\Delta_a - \Delta_b$ isolates the scanned parameter and cancels common backgrounds
- NuBDeC heat flux rendered at the **fitted D-port camera view**, with the **$\psi_N = 1$ strike line** on the wall and $\psi_N = 0.2\text{--}0.8$ + LCFS on the poloidal plane $\phi = 168^\circ$
- Profile input: Thomson mtanh fit used as the **outward-remapped ($\rho \rightarrow \rho^2$) sensitivity profile**, $n_e^{\text{rm}}(\rho) = n_e^{\text{fit}}(\rho^2)$ (axis and separatrix fixed, outward shift $\Delta\rho = \rho(1 - \rho)$); identical to evaluating the ρ_{pol} fit at ψ_N



→ strike point → poloidal limiter → passive stabilizer
#39168: IRTV frame | NuBDeC heat flux at the same view | poloidal view of the drawn contours.

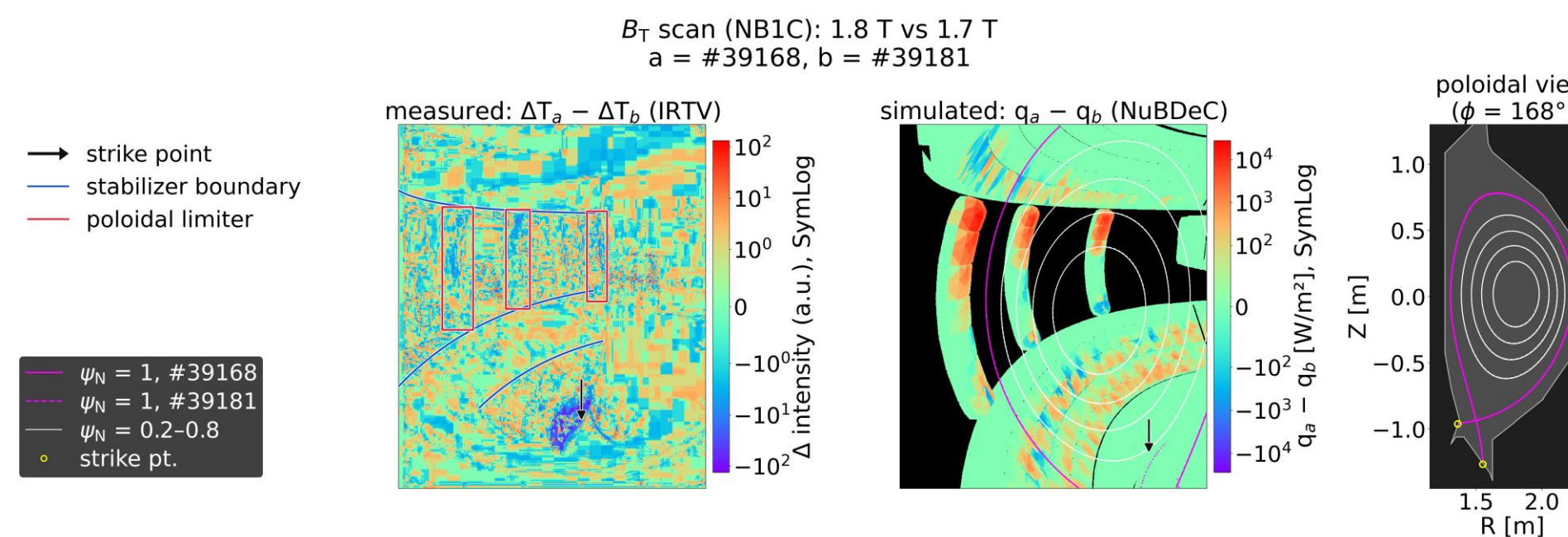
5 Results: parameter scans

NB1C · I_p scan: #39168 (400 kA) vs #39176 (600 kA)



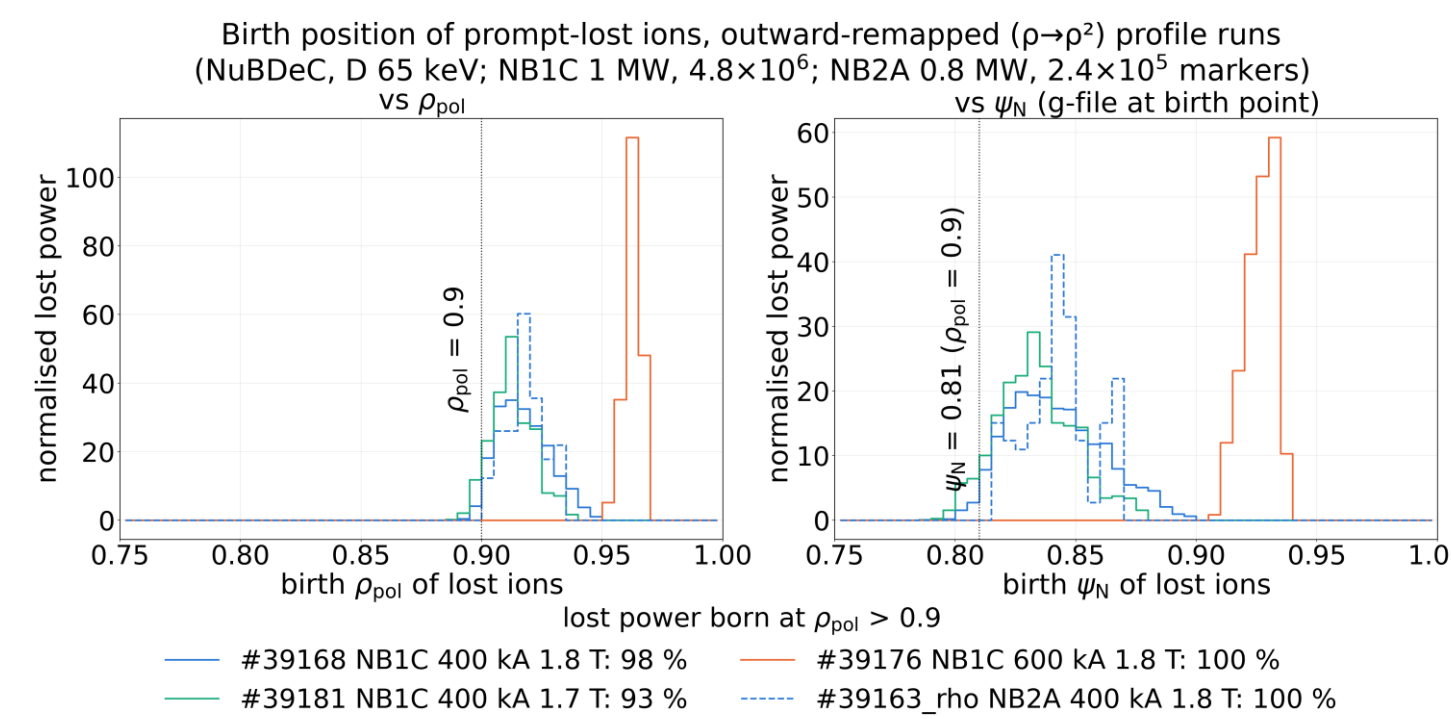
- Measured ΔT difference localized at the **predicted leading-edge and poloidal-limiter locations**; lower $I_p \Rightarrow$ larger ΔT (stronger drift)

NB1C · B_T scan: #39168 (1.8 T) vs #39181 (1.7 T)



- Measured: **stronger heating at 1.7 T** on the limiters and passive stabilizer ($\Delta_a - \Delta_b < 0$)
- NuBDeC: lost power 0.53 % (1.8 T) vs 0.17 % (1.7 T) $\Rightarrow$ **open discrepancy**, set by the edge input profile

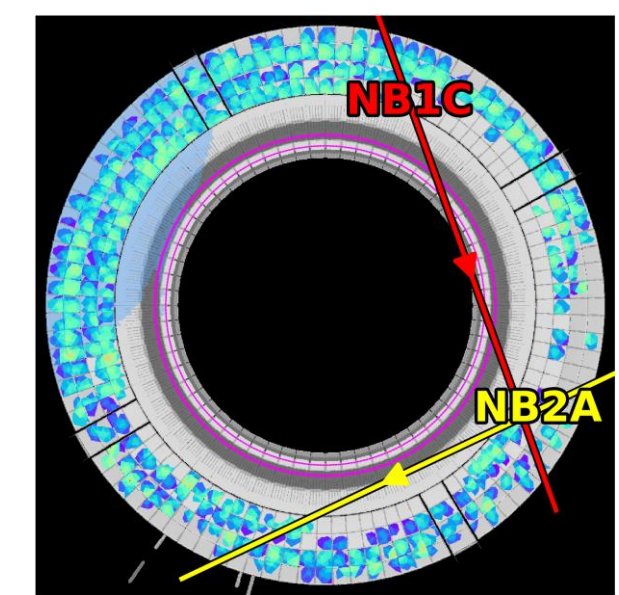
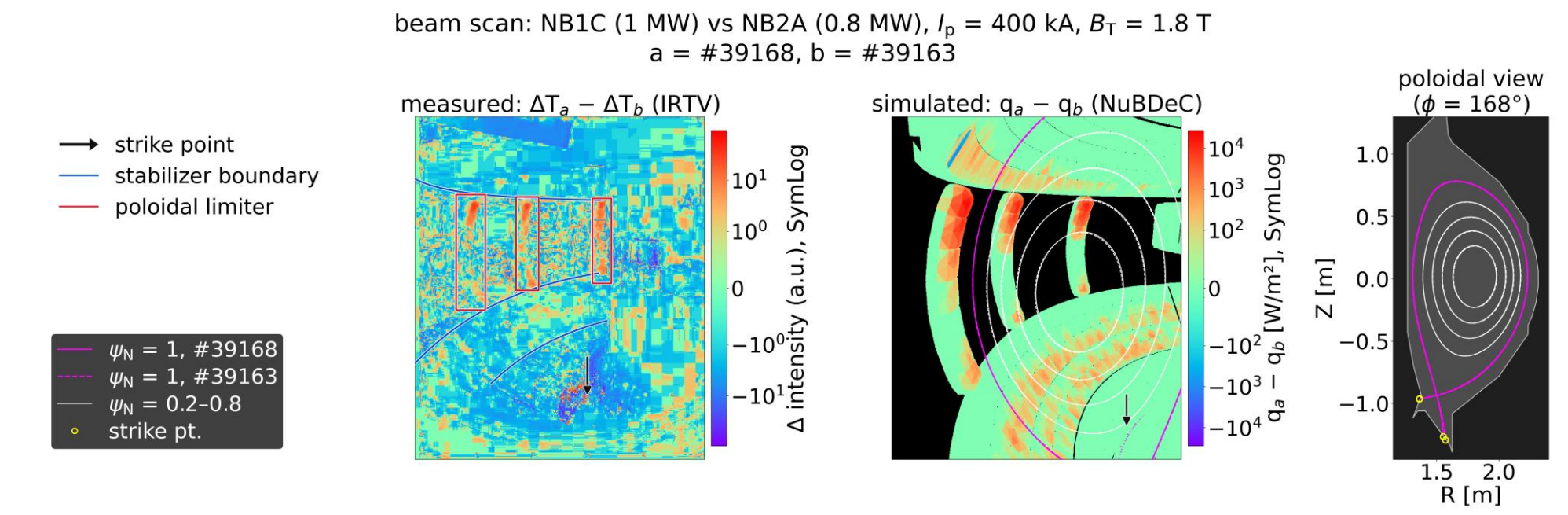
B_T scan: prompt-lost ions are born at the edge



Birth position of the lost ions (NuBDeC, 4.8×10^6 markers).

- 93–100 % of the lost power is born at **$\rho_{\text{pol}} > 0.9$** ($\psi_N > 0.81$), where T_e is too low to ionize the beam neutrals $\Rightarrow$ the **edge n_e , T_e input** sets the loss
- #39181 7.5 s input: edge n_e ($\rho_{\text{pol}} 0.90\text{--}0.95$) 20 % below the 4–7 s Thomson mean. Lost power (4.8×10^5 markers): 0.195 % (7.5 s), 0.250 % (4–7 s avg.), 0.518 % (6.30 s, highest edge)
- With the 6.30 s profile the limiter power is $1.18 \times \#39168 \Rightarrow$ **measured sign reproduced**

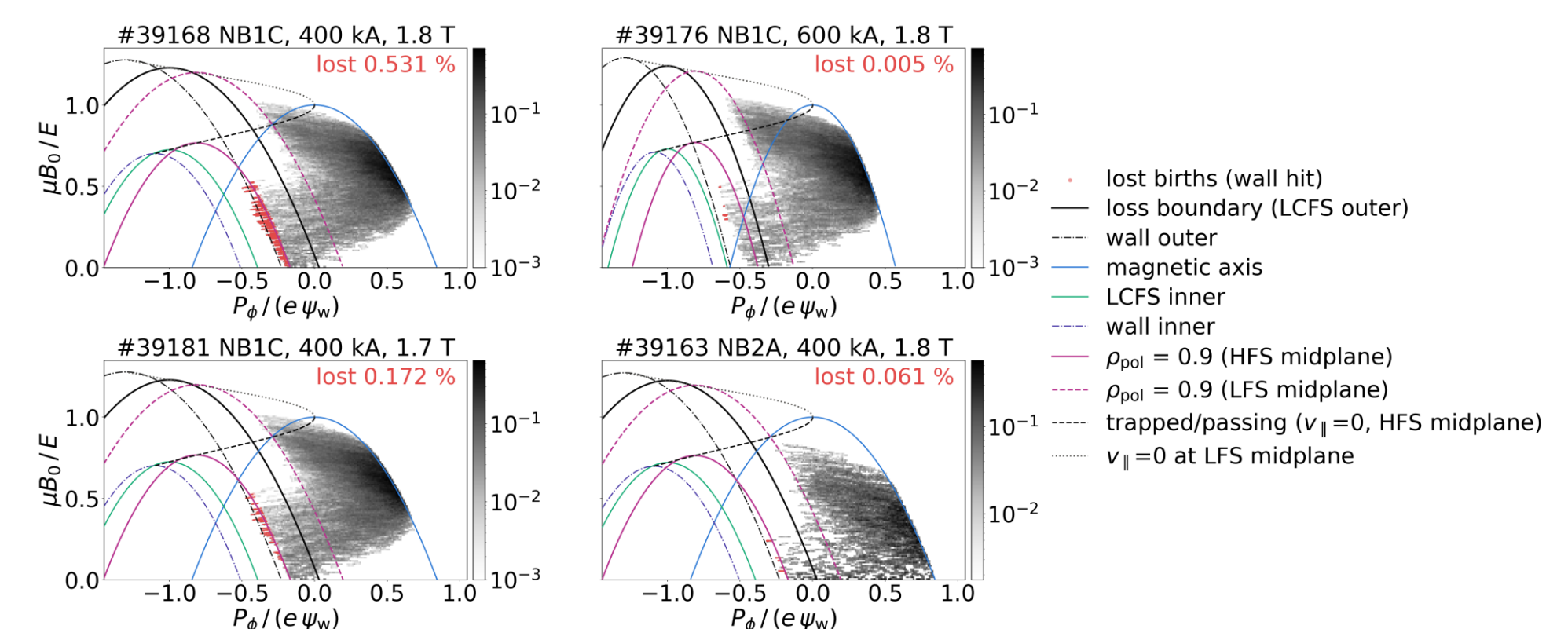
Beam source · NB1C #39168 vs NB2A #39163 (400 kA, 1.8 T)



Top view (NuBDeC): NB1C (red) and NB2A (yellow) beam axes [10], $\psi_N = 1$ strike lines (magenta).

- NB1C tangency radius **1.245 m**, smaller than NB2A 1.56 m (NB1A 1.486 m) $\Rightarrow$ smaller $v_{\parallel}/v$ at birth $\Rightarrow$ larger drift D
- Measured and simulated: **more limiter heating with NB1C** (1 MW vs 0.8 MW, no power normalization); NuBDeC NB2A/NB1C wall power 0.10
- #39163: remapped profile, only 2.4×10^5 markers: noisy, boundaries resolved

6 Birth phase space of lost ions



7 Conclusions & outlook

First qualitative benchmark of CAD-based prompt-loss prediction on KSTAR

- ΔT appears at the **predicted leading-edge and limiter locations**
- Measured I_p trend (NB1C) and source trend (NB1C > NB2A at 400 kA) follow NuBDeC; **toroidal drift** is the main driver
- B_T scan: a weak knob; the simulated loss follows the beam births at the edge ($\rho_{\text{pol}} > 0.9$), i.e. the edge T_e / n_e input. With the highest-edge (6.30 s) #39181 profile the **measured sign on the limiters is reproduced**; next: slice-resolved 4–7 s runs

Outlook: toward an AI-native treatment of engineering detail

- Quantitative predictive model; **surrogate model** predicting prompt-loss heat flux directly on the unstructured PFC mesh
- Enables:
 - exhaustive NBI parameter scans during the **conceptual design** of future devices (ITER, CPD, DEMO)
 - between-shot heat-load guidance**: avoid wasted discharges, fine-tune heating to each experiment's mission
 - integration into the KFE **digital twin platform**

References

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 - [3] W. Tang et al., arXiv:2409.03112 (2024) [4] N. Bhatia et al., AIP Adv. 15 (2025) 045018
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