Equilibrium Operational Space and Stability Limits in Early Operation of MAST-U

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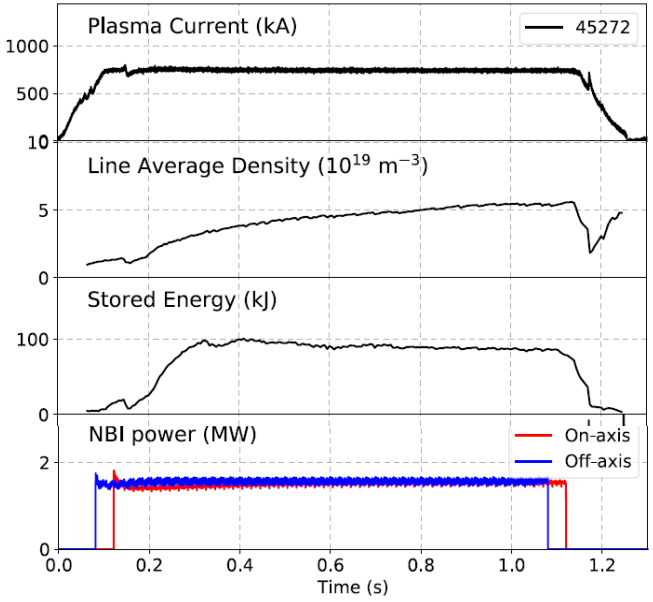
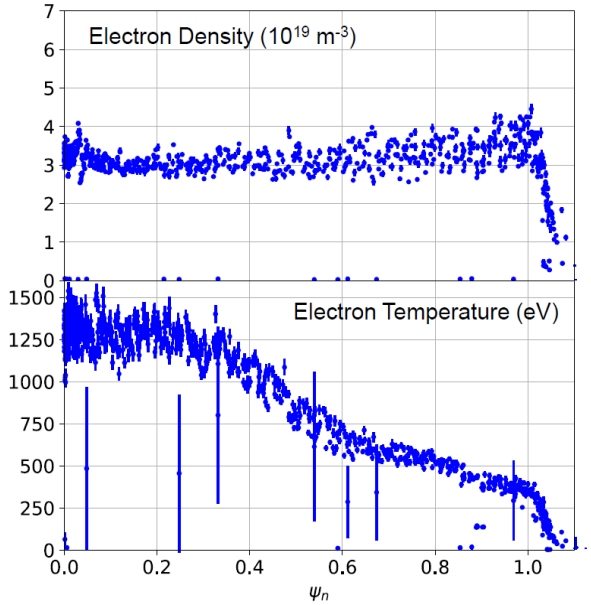
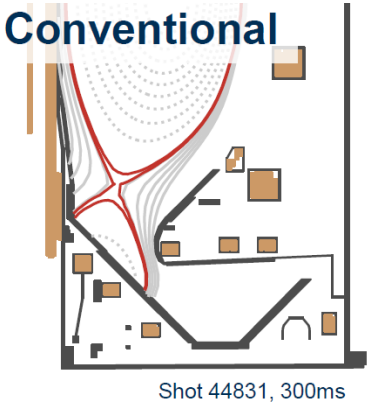
MAST-U achieved good physics results in its first campaign

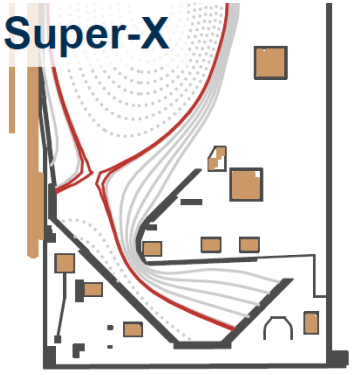
- 750kA plasmas with 1s flat-top
- Good pedestal performance
- Conventional and Super-X divertors







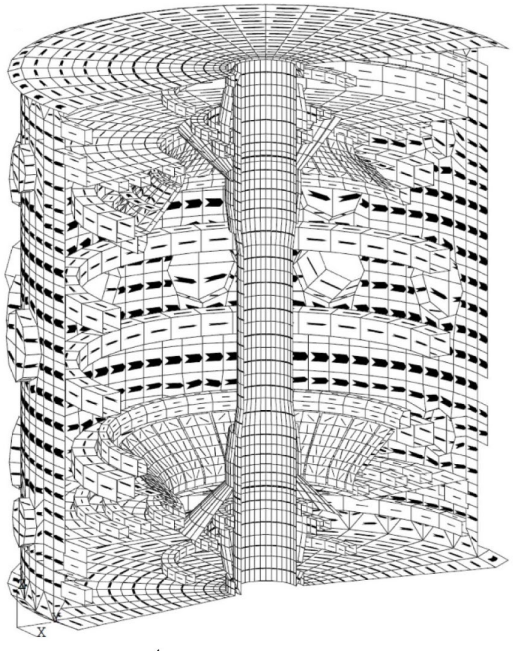
Shot 44831, 300ms

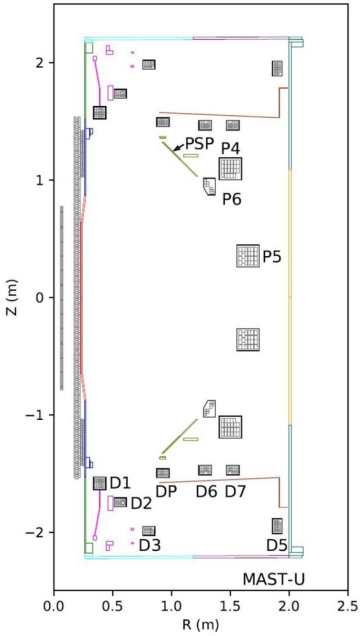


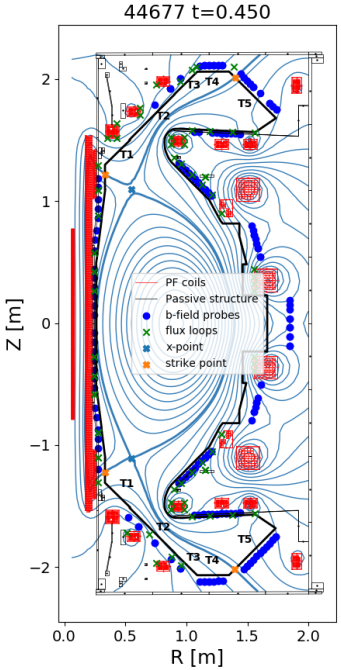
Shot 44314, 650ms

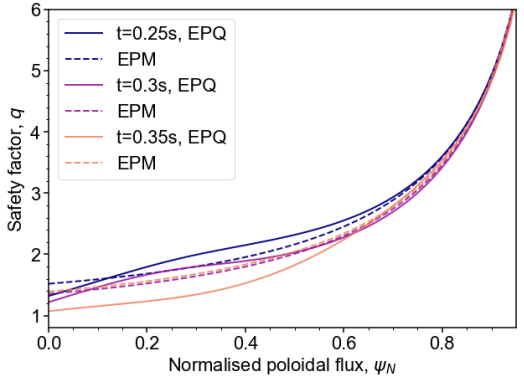
Equilibrium reconstruction techniques are progressing for MAST-U

3D VALEN model of surfaces to calibrate → 2D wall current model → Magnetic reconstructions → Plus motional Stark effect









- Kinetic reconstructions forthcoming

[J.W. Berkery, *et al.*, PPCF **63**, 055014 (2021)]

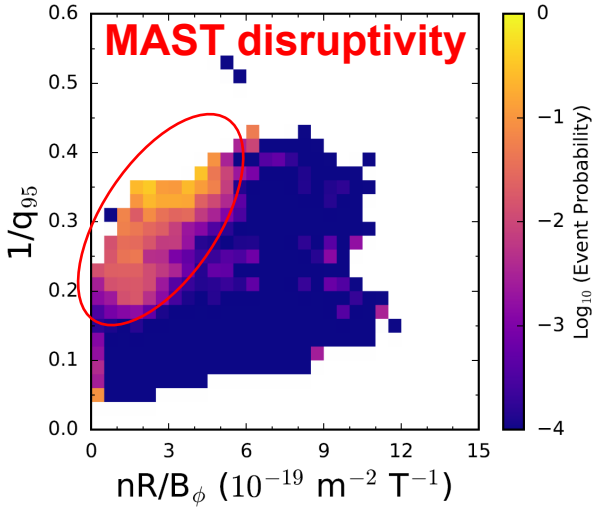
[L. Kogan, *et al.*, EPS (2022)]

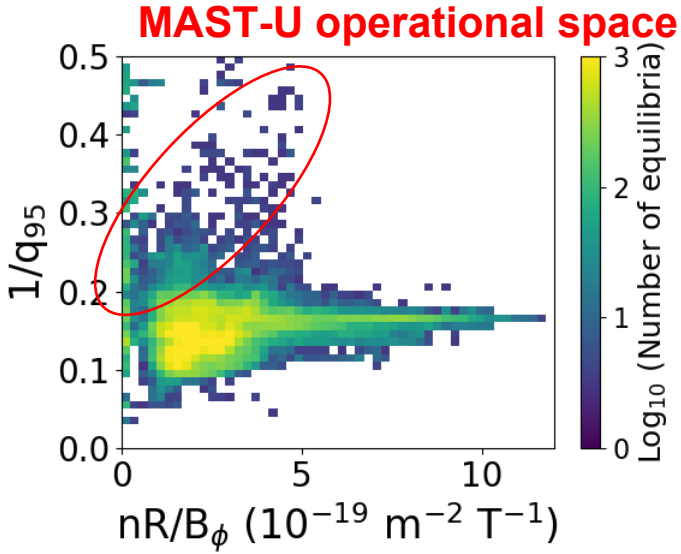
A large database of magnetics-only equilibrium reconstructions of MAST-U plasmas exists

- Database includes 855 discharges (June-Oct, 2021)
  - Not every discharge – need good flattop, good reconstruction
  - Flattop split in 5ms intervals – 108,826 total equilibria
- MAST-U discharges were categorized in discrete allowed scenarios
  - Plasma current level: 400-450 kA, 600 kA, 700-750 kA
  - Neutral beam heating: Ohmic (OH), one beam (SW or SS), two beam (2B)
  - Divertor shape: conventional (CD), SuperX (SX), or unlabelled (UN)

I_p (kA)	Divertor	Ohmic	SW	SS	2B
400	CD	148		12	
	SX	64			
	UN	44			
600	CD	39	9	25	7
	SX	56	12		8
	UN	16		6	
700	CD	53	77	31	108
	SX	68			
	UN	30	31	3	9

Hugill diagram shows that MAST-U has yet to access low density, low q disruptive space

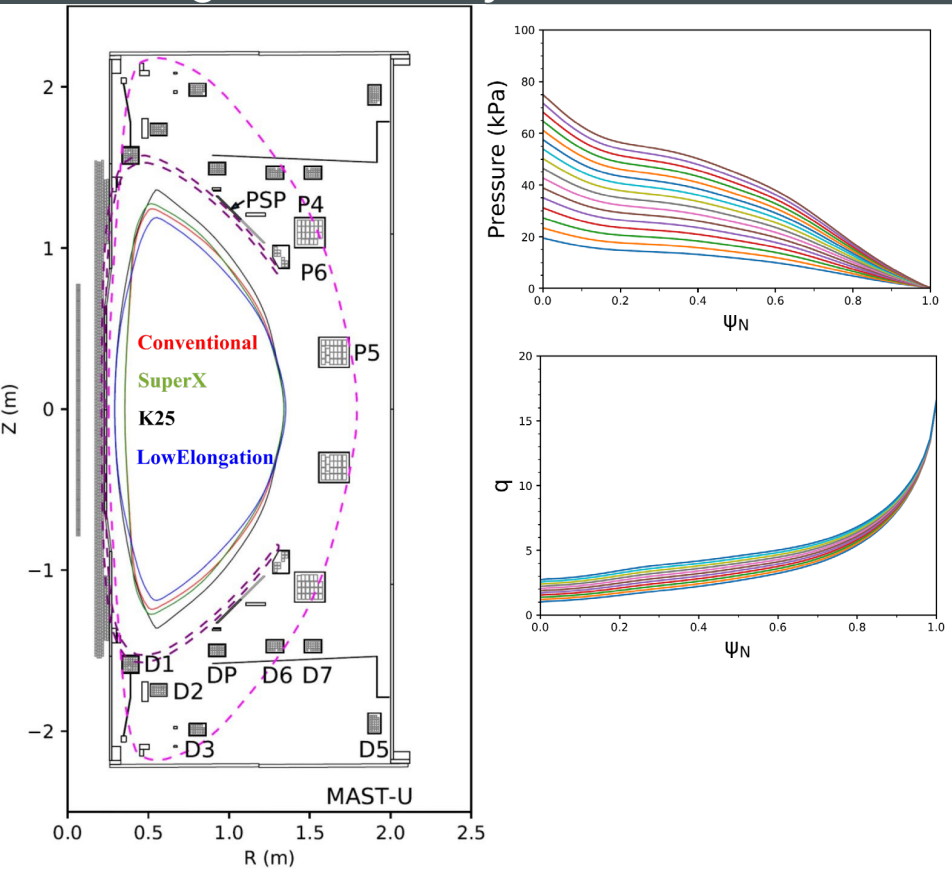




Squares with ≥ 3 equilibria plotted

- Disruption Event Characterization and Forecasting (DECAF) code used
  - Produces disruptivity or operational space plots – here 50x50 grids
- Hugill diagram showed high disruptivity for MAST at low density, low q_{95}
  - MAST-U has yet to really access this region of operational space much

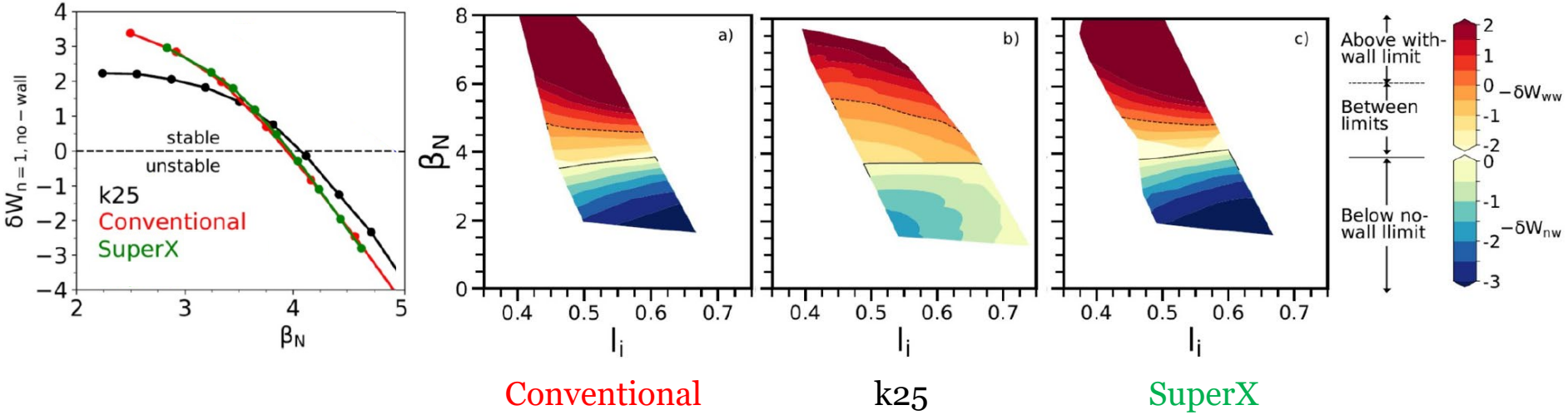
Before operation, MAST-U projected equilibria pressure and q_0 were scanned to find global stability limits



- Not all these p and q profile combinations are realizable in MASTU
  - They serve to explore the parameter space

[J.W. Berkery, *et al.*, PPCF **62**, 085007 (2020)]

Stability maps in parameter space are generated by DCON

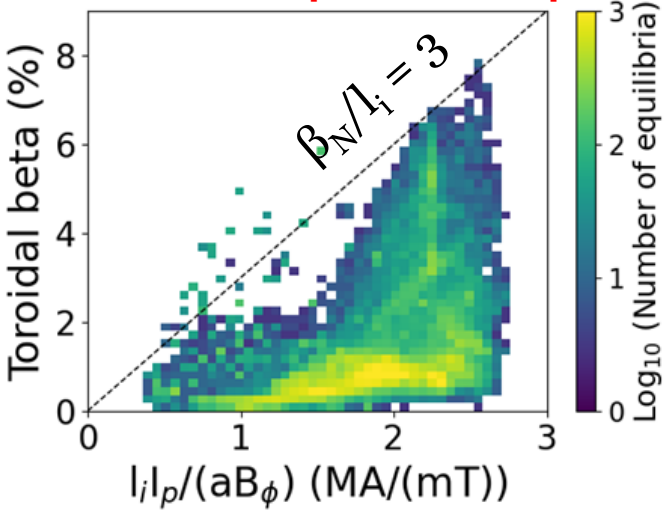


- Contours of $-\delta W$: red above the no-wall limit and blue below
- In each case, $\beta_N^{\text{no-wall}}$ increases slightly with internal inductance
  - $\beta_N^{\text{no-wall}} \sim 4$

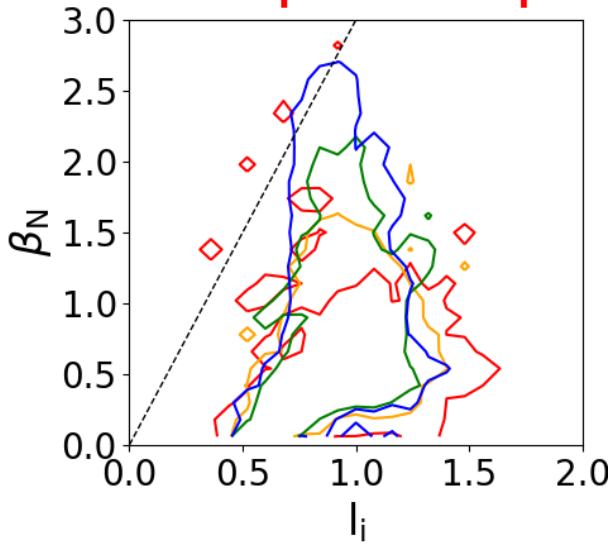
[J.W. Berkery, *et al.*, PPCF **62**, 085007 (2020)]

MAST-U has reached max β_N of 3.5 and β_N/l_i of 3.4, both below stability limits

MAST-U operational space



MAST-U operational space



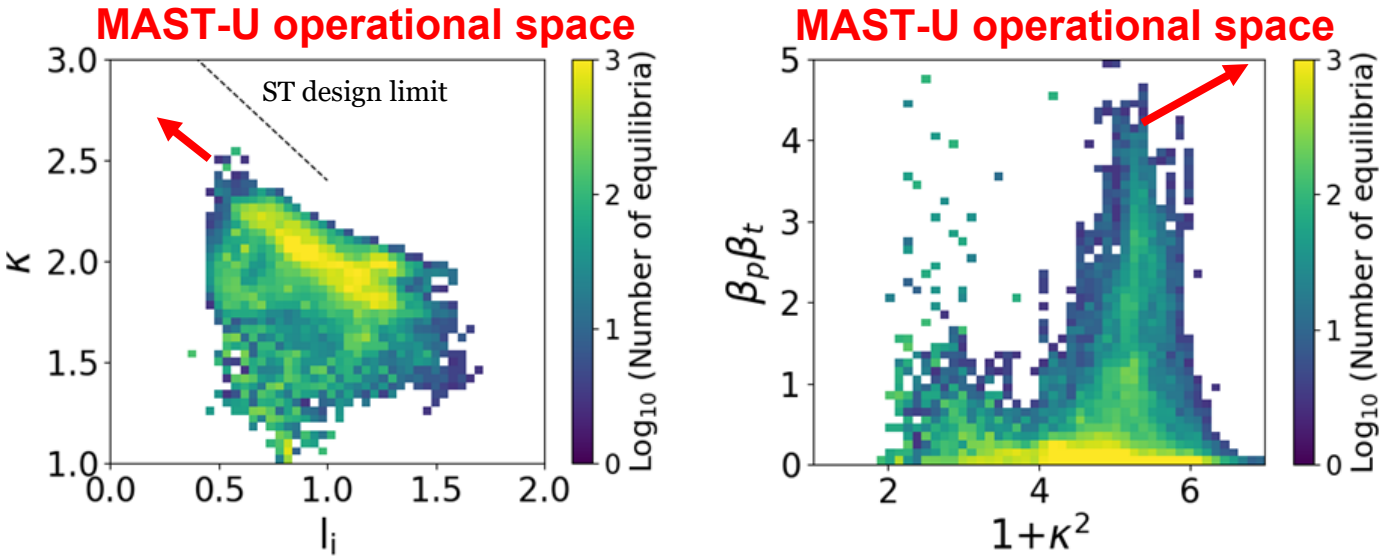
Contours contain ≥ 30 equilibria

Two beam
One beam, on axis
One beam, off axis
Ohmic

- Not surprisingly, two beam injection gives the highest β_N
  - The SS beam is oriented to deposit energy on-axis, so can generally lead to higher β_N plasmas than the off-axis SW beam
- Projected MAST-U no-wall limit: $\beta_N \sim 4$ and $\beta_N/l_i \sim 7$

[J.W. Berkery, *et al.*, PPCF **62**, 085007 (2020)]

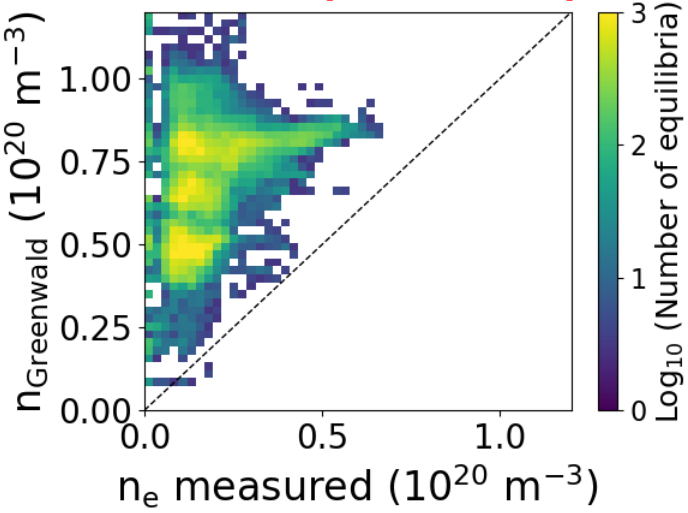
Plasma performance benefits from plasma shaping



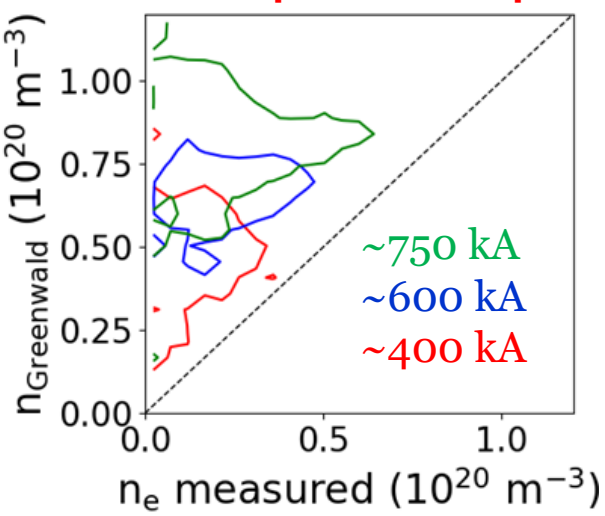
- With the exception of vertical stability, increased elongation in STs tends to increase the stability of the plasmas
  - κ increases both β_t for fusion gain and $f_{bs} \sim \beta_p$ for pulse length, sustainment
- Increased elongation is a focus of the second campaign

MAST-U has generally stayed well under the Greenwald limit in the flattop to this point

MAST-U operational space



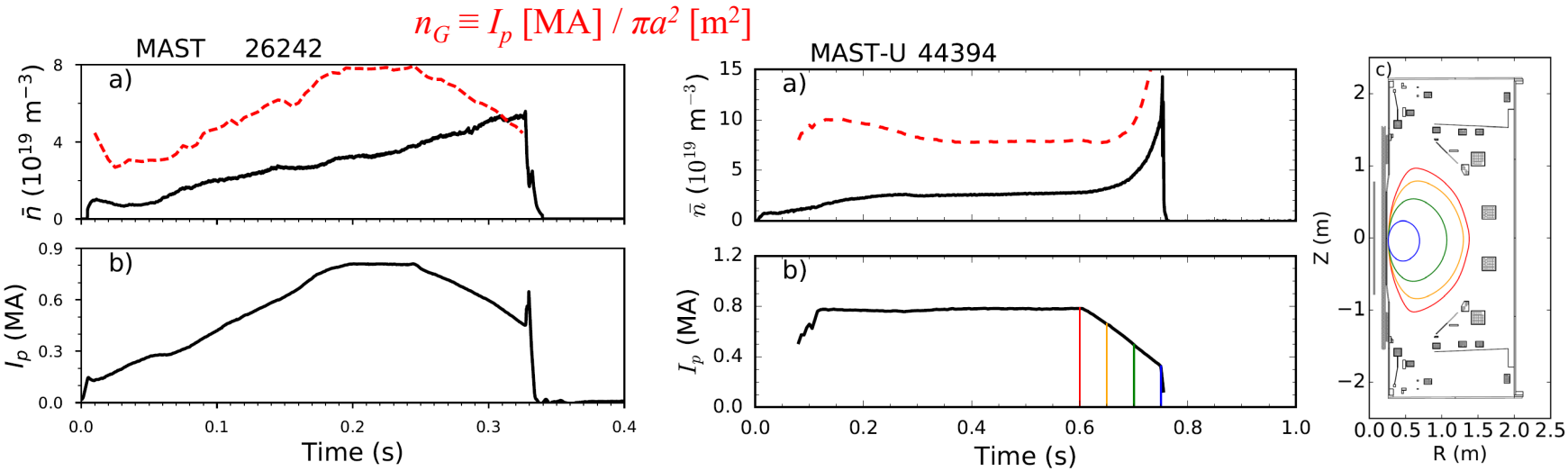
MAST-U operational space



Contours contain ≥ 30 equilibria

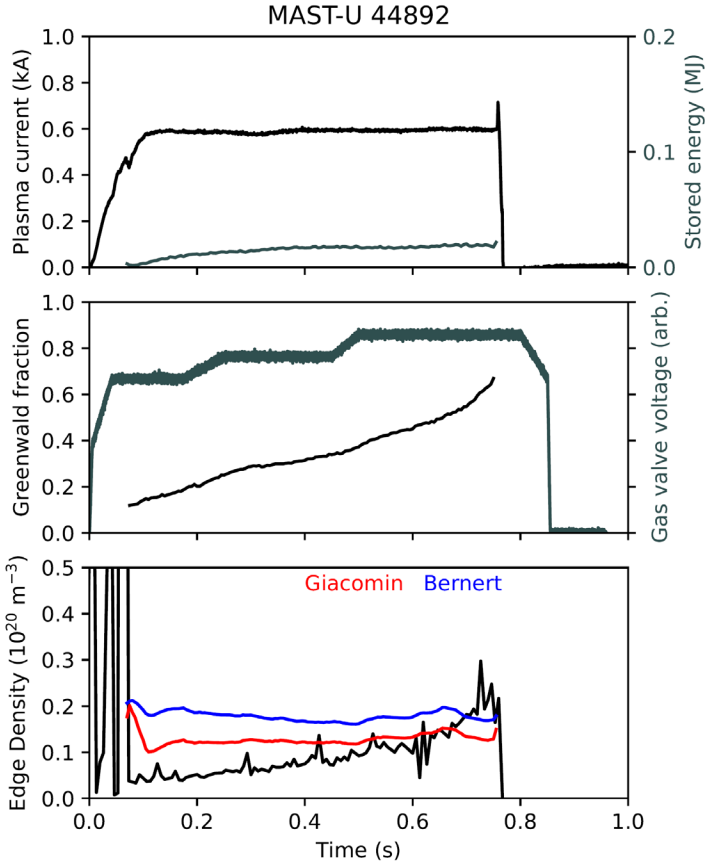
- There were occasional cases of flattop plasmas approaching the Greenwald limit
  - Experiments in the second campaign will push to establish density limits
- Lower plasma current shots need to maintain lower density

In MAST-U plasmas the Greenwald limit can be avoided by quickly shrinking the plasma



- MAST rampdown Greenwald density limits happened often
  - Reducing I_p brought the limit down while the density was still rising
- In some MAST-U cases, the limit rises in the rampdown
  - The plasma's minor radius is rapidly decreasing

Edge density limits can be reached before the Greenwald limit, potentially giving an early warning



- GWL low, but edge high -> disruption
- Not <u>stringent</u> criteria
  - In DECAF code could be one of multiple warnings

Giacomin **Bernert**

$$n_{\mathrm{lim}} = \alpha A^{1/6} a^{3/14} P_{\mathrm{SOL}}^{10/21} R_0^{-43/42} q^{-22/21} (1+\kappa^2)^{-1/3} B_T^{2/3}$$

$$\overline{n}_{e,H5,\mathrm{regr.}} = 0.506 \pm 0.192 \frac{P_{\mathrm{heat}}^{0.396\pm0.13}\, I_{\mathrm{p}}^{0.265\pm0.14}}{q_{95}^{0.323\pm0.14}},$$

The first physics campaign of MAST-U made great progress in exploring operational spaces

- Various plasma scenarios achieved:
  - Ohmic, one, or two neutral beams, 400-750kA, CD or SX
- Magnetics-only equilibria produced and used by DECAF for operational space diagrams
- Generally, MAST-U still has margin to increase performance without encountering stability limits
  - Beta, towards projected global stability limits
  - Elongation, towards vertical stability limits
  - Density, towards Greenwald limit