Initial performance of neutral beam driven plasmas in the LTX-β with fully coated solid and liquid lithium plasma facing components

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Presented at Magnetic Fusion Science Meeting on Monday, June 1

Outline

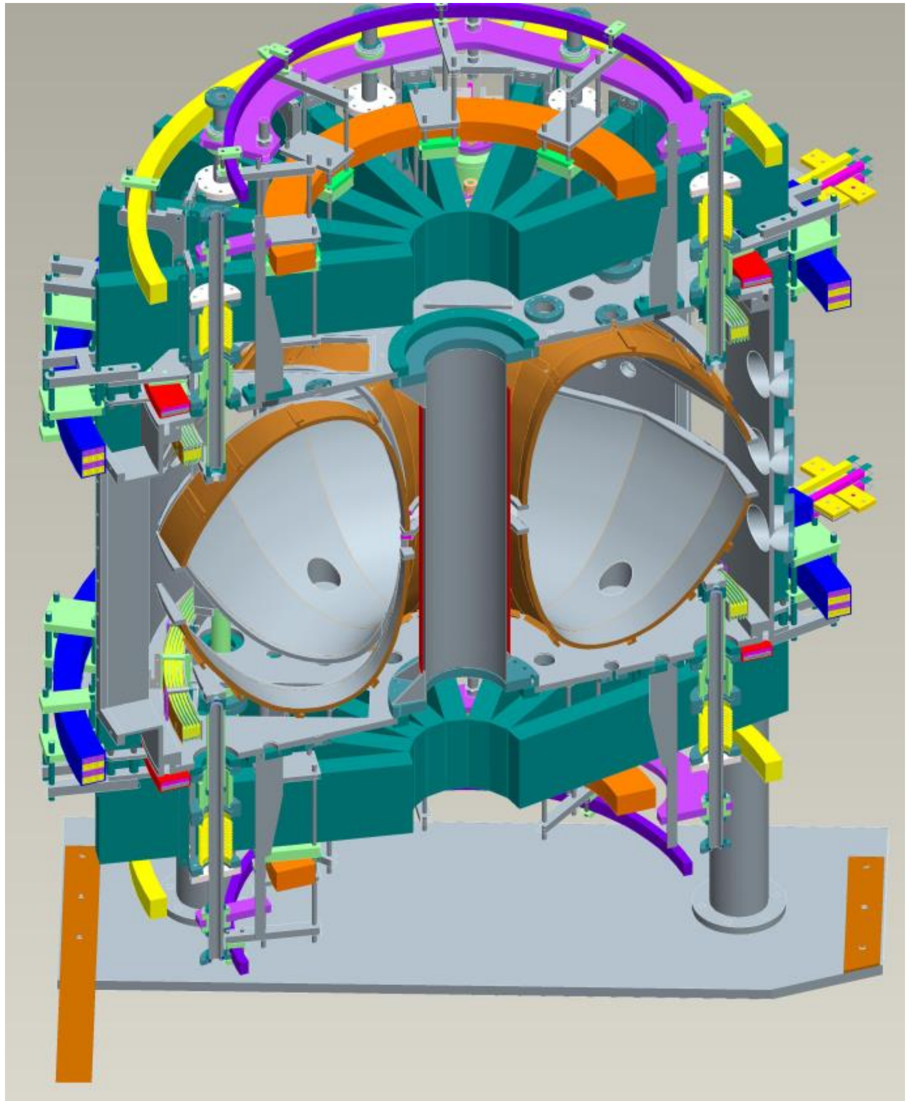
- LTX-β background
- Upgrade to LTX-β
- Notable Outcome results
- Future work

Outline

- **LTX-β background**
  - **Experiment description**
  - **Low recycling regime**
- Upgrade to LTX-β
- Notable Outcome results
- Future work

The Lithium Tokamak eXperiment-β, overview

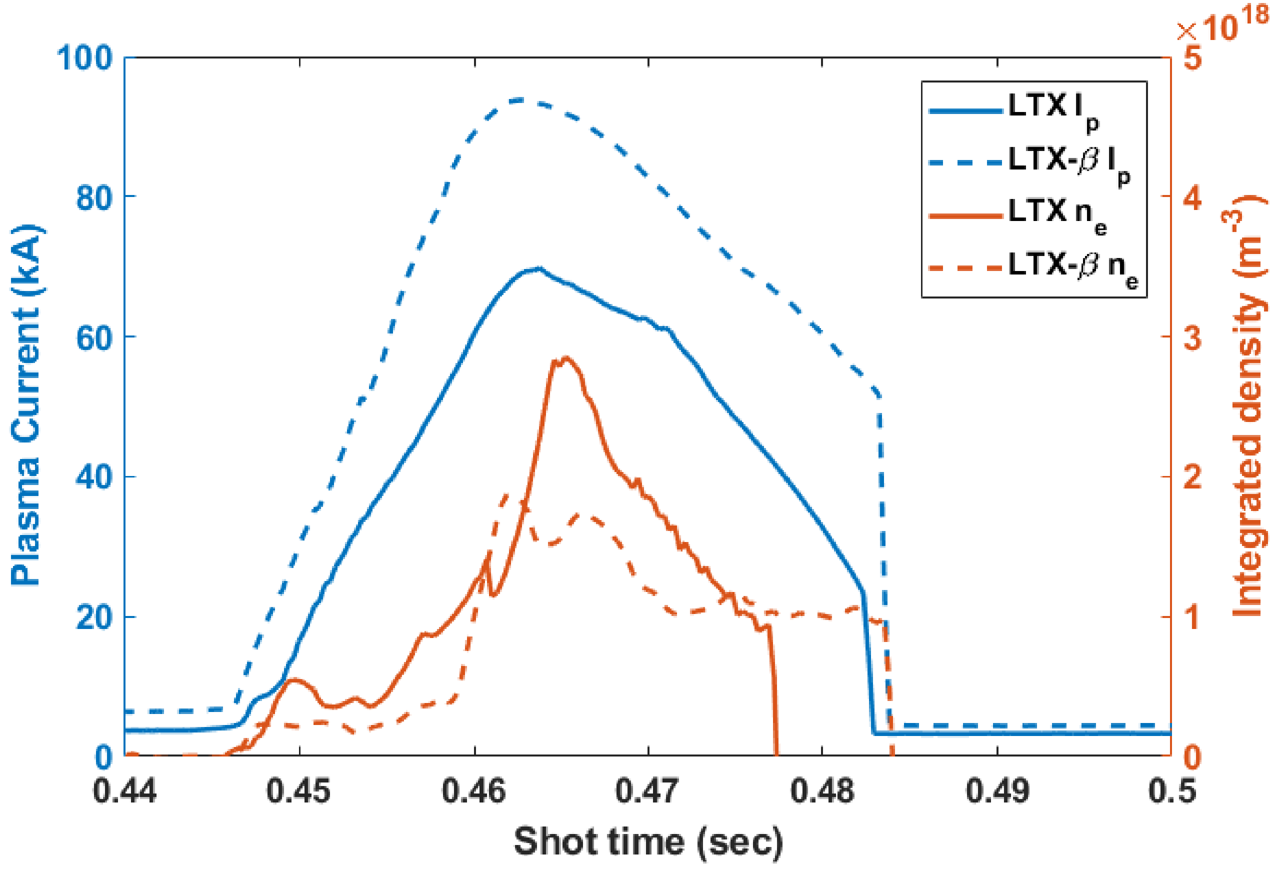
- Modest size
  - R=36-40 cm
  - a=20-26 cm
- $I_p = 75 - 100\ kA$ (150+ kA goal)
- $B_T = 0.3\ T$
- $T_e = 150 - 300\ eV$
- $n_e = 1 \times 10^{18} - 2 \times 10^{19}\ m^{-3}$
- Copper shells for heating, Li deposition, and limiting
- HFS limited



LTX-β

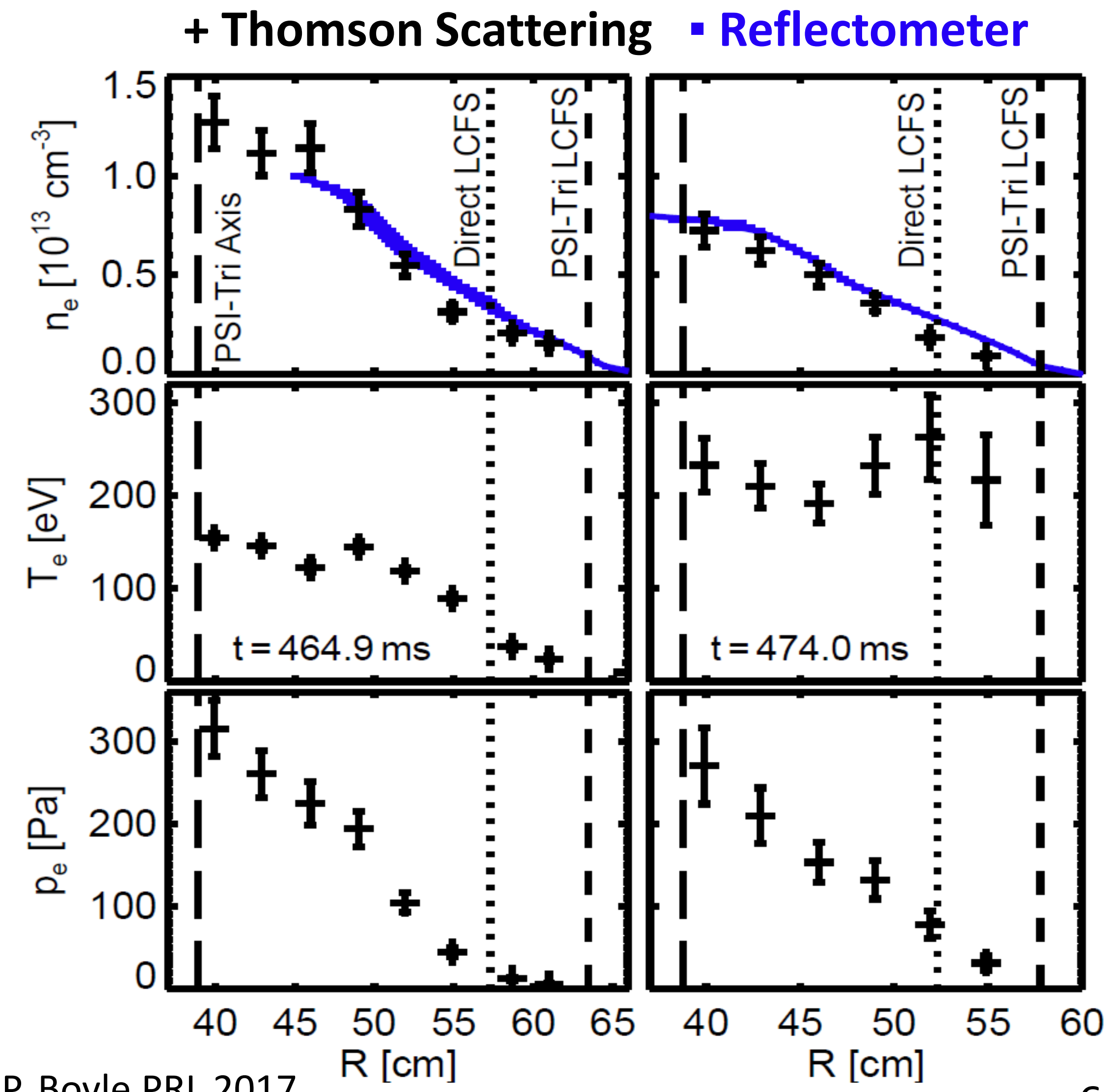
LTX-β shot style

- Feed forward programming
- Profile evolution occurs throughout the shot
- Pulse: ~35+ ms
- For comparable densities the plasma current of LTX-β is significantly higher than that of LTX



Low recycling regime (from LTX)

- Brought on by Lithium retaining hydrogen in the walls
- Retention results in rarified SOL
- Results in a “flattened”, elevated temperature
- **Hot core fueling is required to sustain**
  - That means NBI is needed
  - Without NBI this is intrinsically short lived
- May lead to interesting new physics
  - Low neutral drag
  - Very High ion temps.



D.P. Boyle PRL 2017

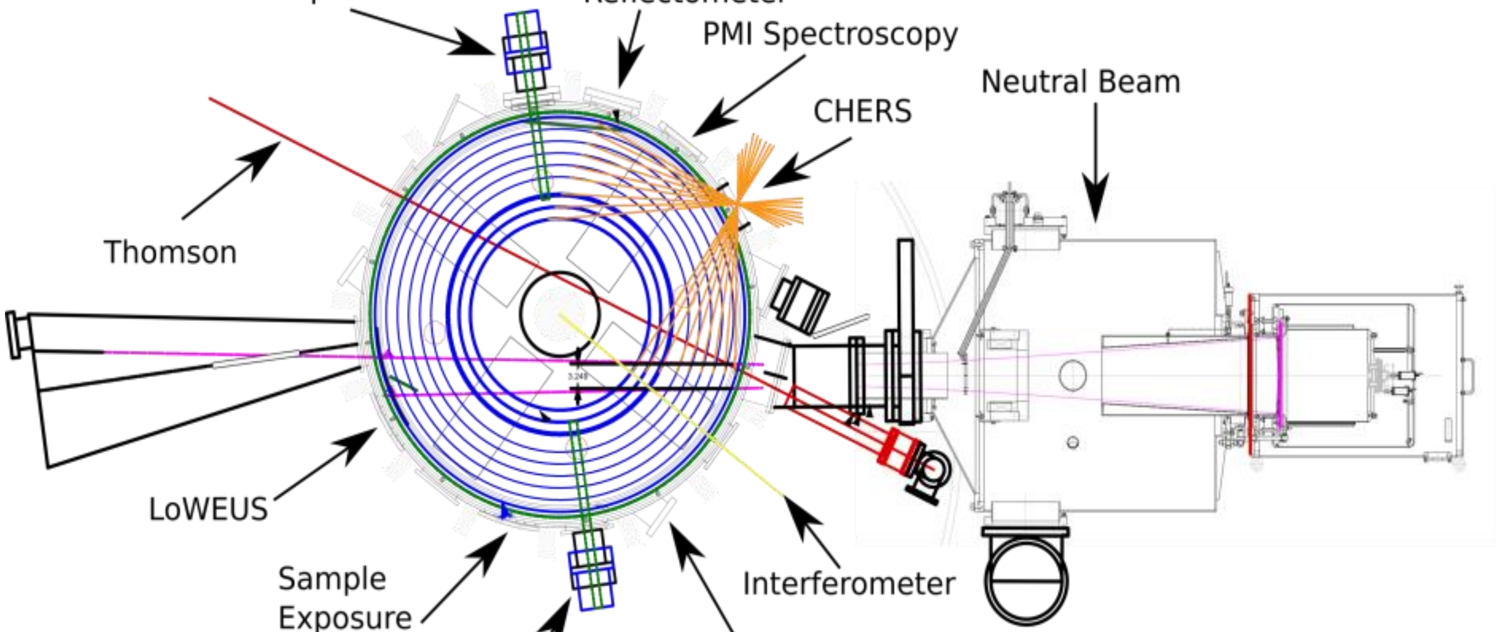
LTX-β

Outline

- LTX-β background
- **Upgrade to LTX-β**
  - **Lithium deposition**
  - **Diagnostic upgrade**
  - **Neutral Beam Injection (NBI)**
- Notable Outcome results
- Future work

LTX-β

Upgrade Overview



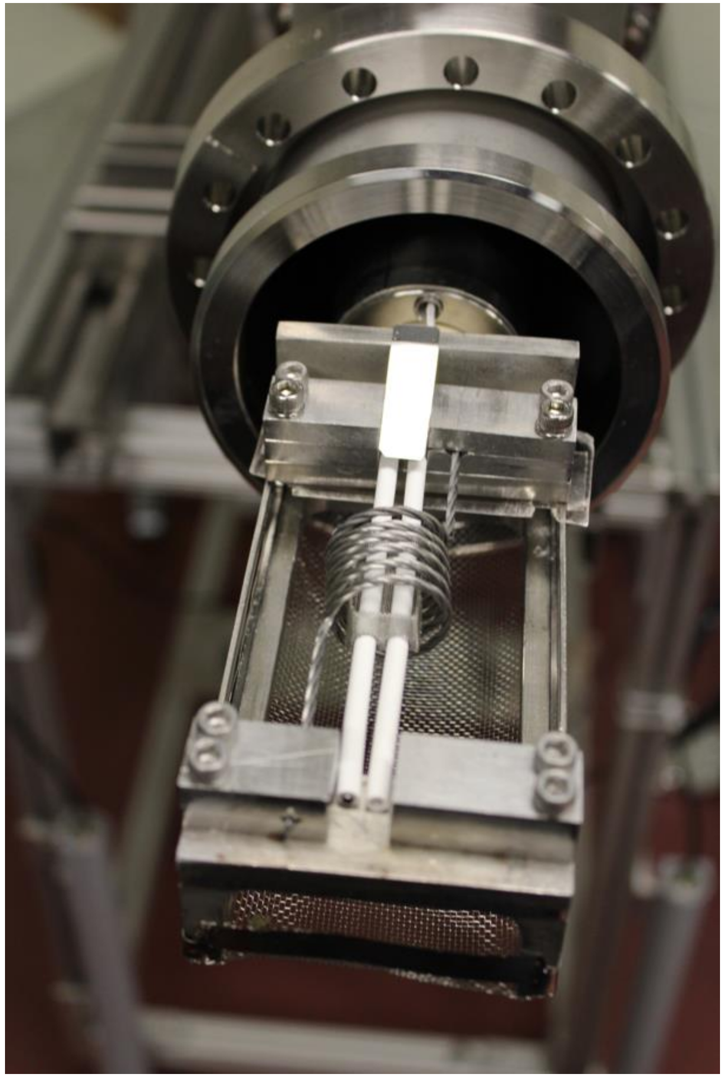
D. Elliott SOFE/IEEE 2019

- Thomson scattering: Improved camera, fibers, dump
- Magnetic sensor array for mode analysis
- Langmuir probes/RFEA for SOL ions
- CHERS, multiple visible spectrometers
- Sample Exposure Probe for PMI study
- Filtered fast cameras, XUV/UV spectrometers
- Interferometer & reflectometer enhanced for $\tilde{n}_e$

LTX-β

Lithium evaporators

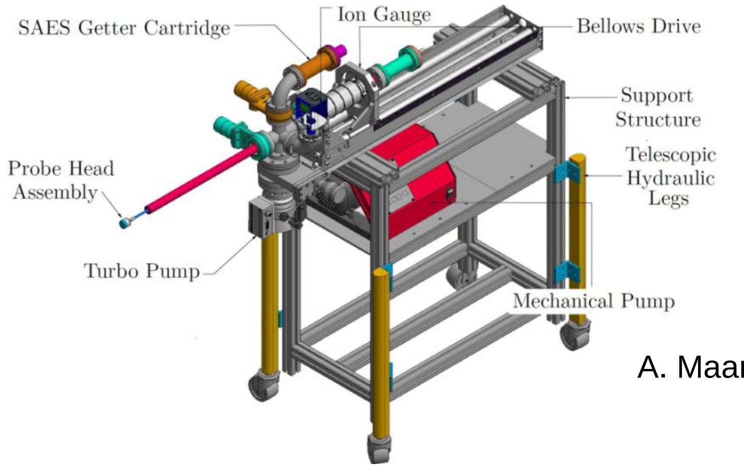
- Dual evaporators for greater coverage
- Smaller “heating element” for faster coverage
- Evaporating from midplane for more even coating
- Quartz Crystal Deposition system to monitor Li thickness
- Sample Exposure Probe (SEP) used for studying PMI



LTX-β

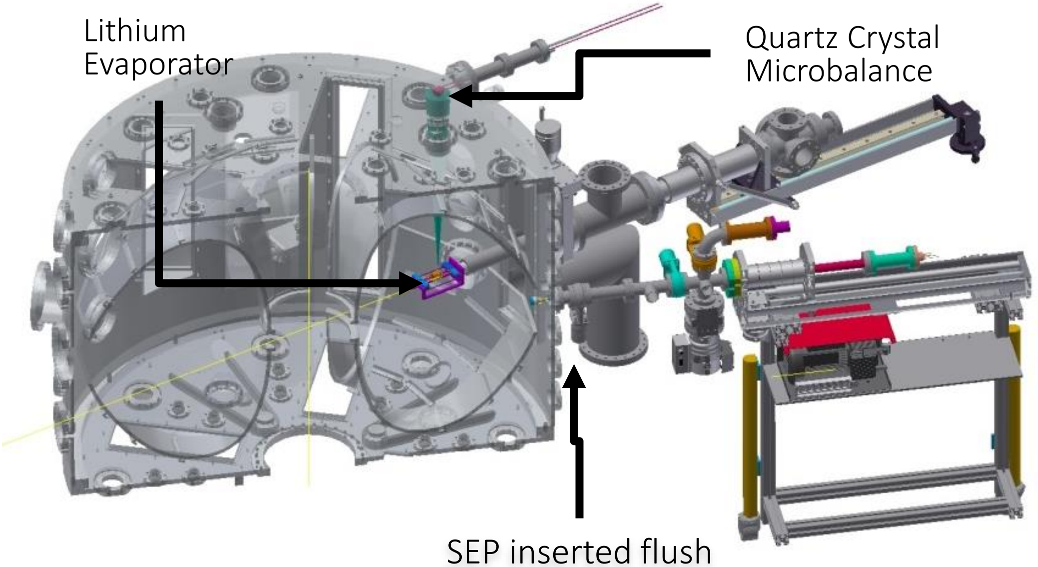
Sample Exposure Probe and PMI studies

- Interfaced with the surface science laboratory
- Can study lithium evolution over time
- Determines surface chemical make-up
  - Which compounds are present
  - In what abundances
  - At what thicknesses
  - Then related back to plasma performance



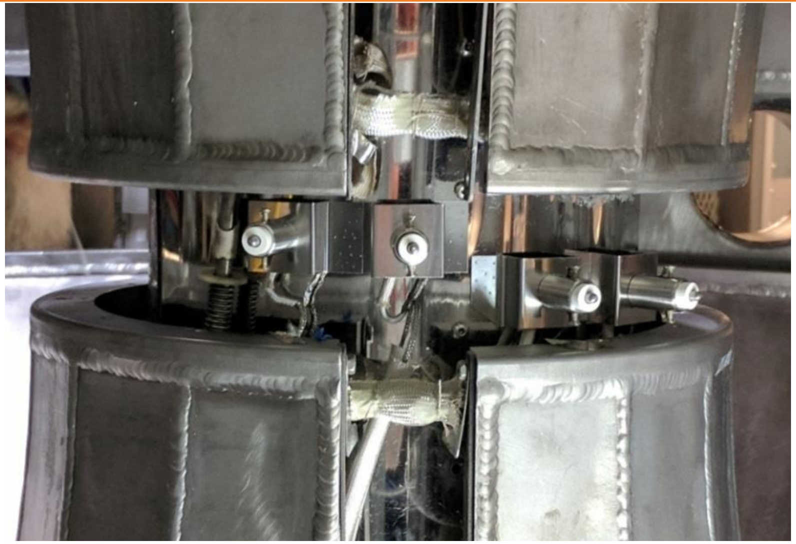
A. Maan RSI 2019; SOFE/IEEE 2019

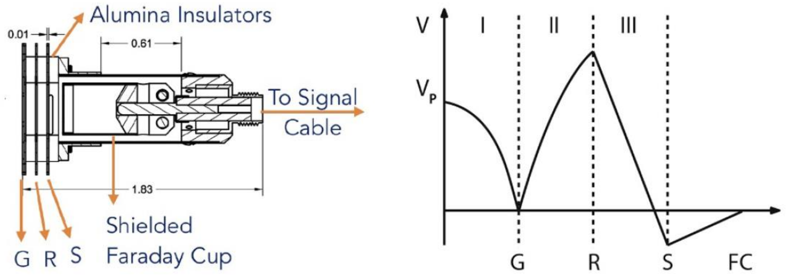
Mechanism for hydrogen retention in lithium PFCs explored on LTX-β with Sample Exposure Probe (SEP)



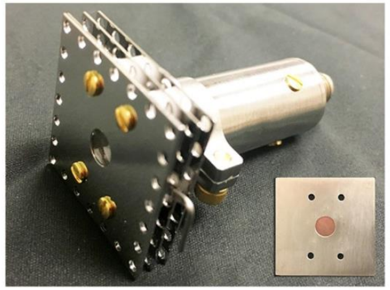
LTX-β

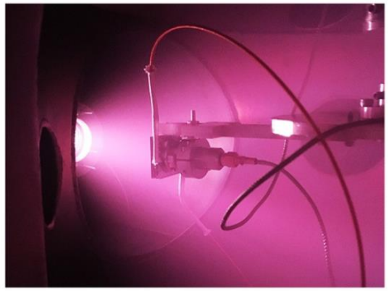
SOL diagnostics: Langmuir probes and RFEA





(a) (b)





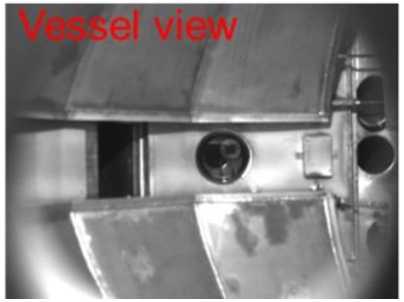
- SOL mirror confined
  - Electric fields not confined to sheaths
  - Loss rate determined by ion pitch angle scattering
  - Pastukhov potential $\varphi_p \sim 0.7\ T_e$ for LTX
  - SOL electric field should eject sputtered impurities
- 4x high field side single Langmuir probes
- Low field side single Langmuir probe
- Retarding field Energy Analyzer

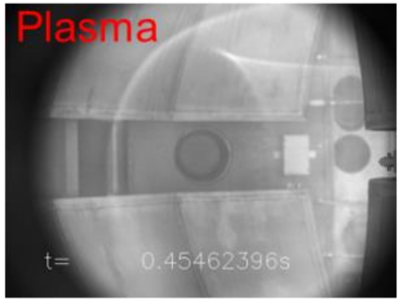
X. Zhang PSI/NME 2019

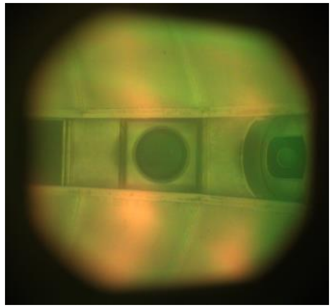
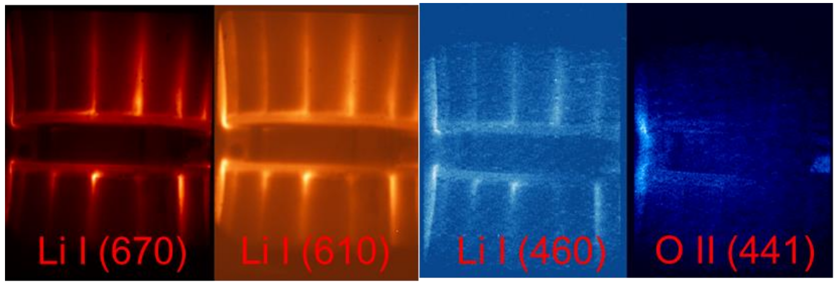
LTX-β

Fast filtered cameras, XUV/UV spectrometers

- For studying impurity radiation
- Also used for aiming and divergence estimates of NBI
- Also used for tracking plasma location and evolution



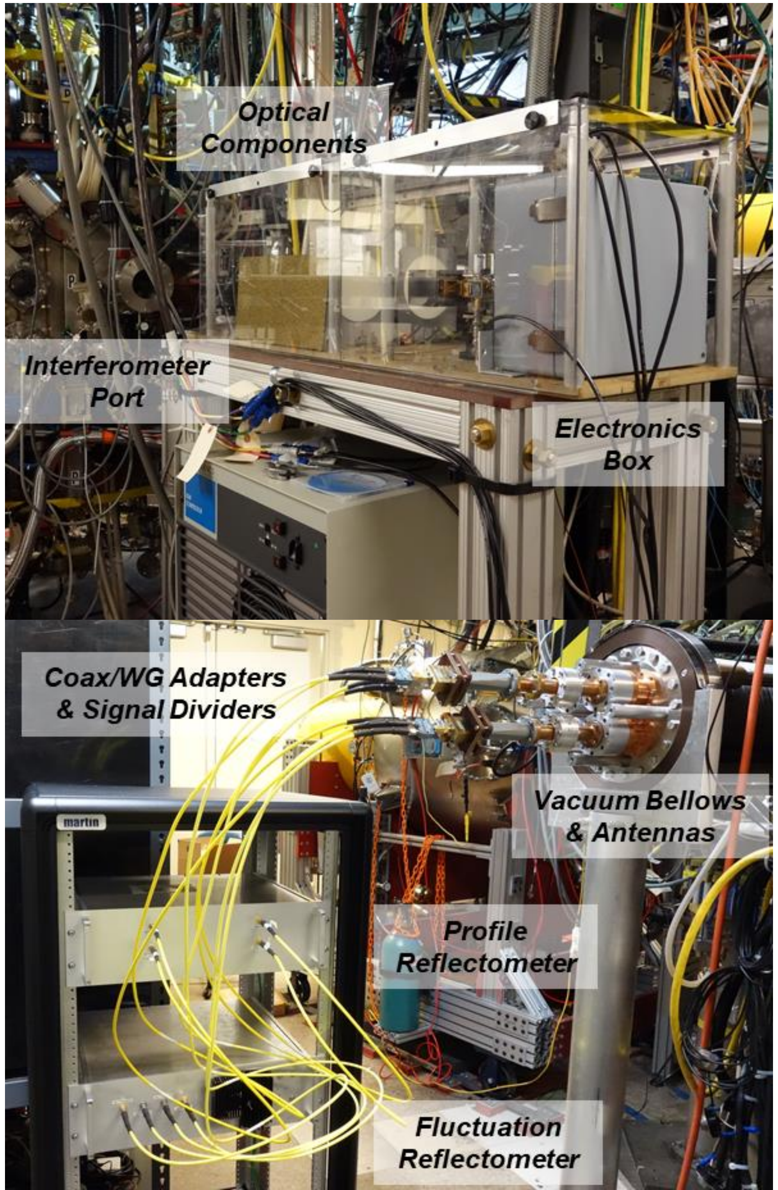


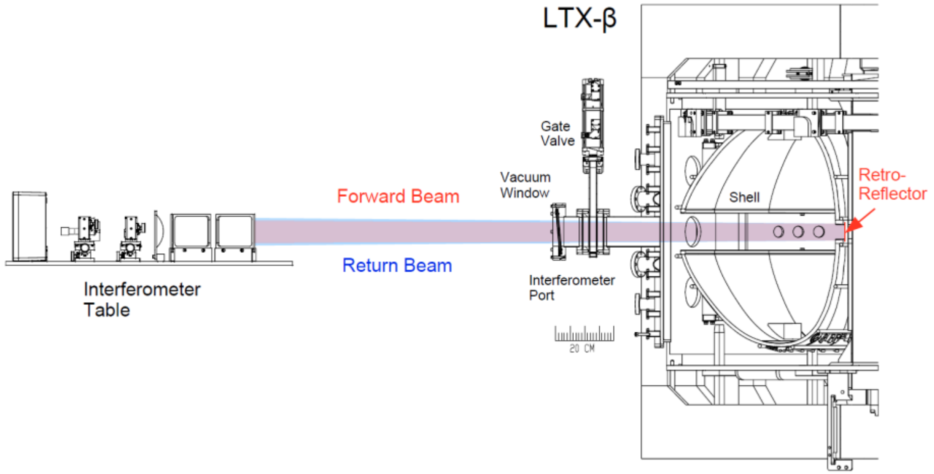



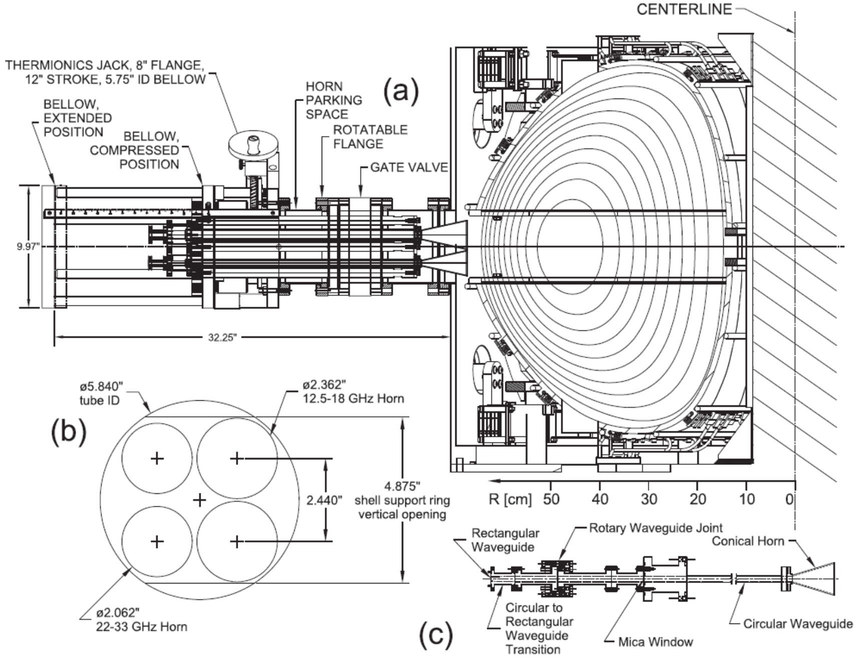

LTX-β

Fusion Energy Sciences

Microwave Interferometer & Reflectometer





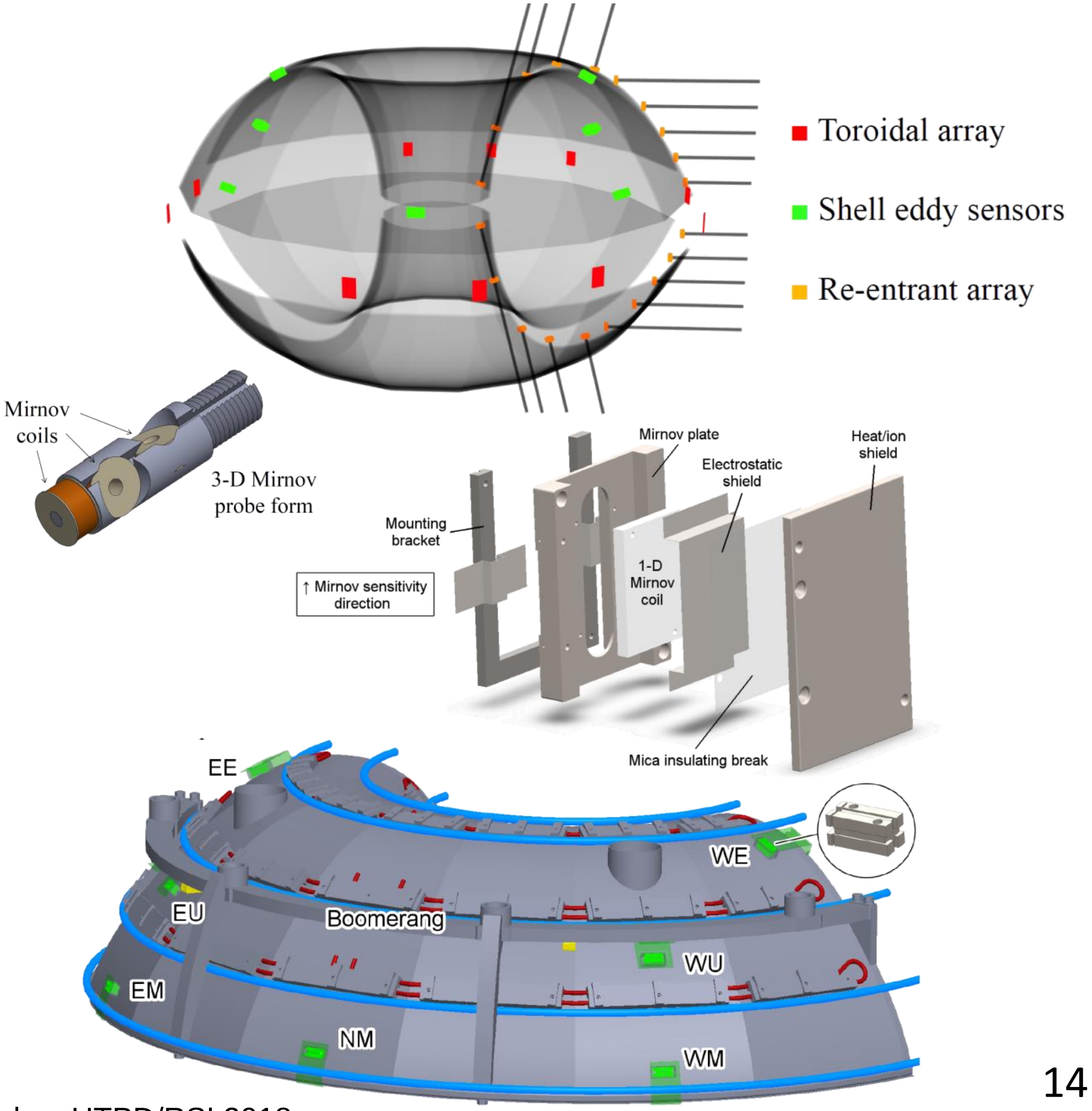


UCLA

LTX-β

Enhanced Magnetics for improved equilibria & 3-D eddy currents, perturbations, & instabilities

- Increase to have 28 re-entrant orthogonal 3-D Mirnov triplets (previously 18 triplets)
- Toroidal, axial, perpendicular
- 20 in plane centered in toroidal gap
- Sensitive to poloidal m < 6
- 8 off-center, off-radial in gap
- Top-Bottom/Left-Right/In-Out
- Add 10x 1-D Mirnovs
- Sensitive to n < 5 perturbations
- Mounted to vessel wall at midplane
- Add 7x 2-D Mirnov pairs
- East/West Edge, Upper, Midplane; North Midplane
- Perpendicular & tangential to shell
- Sensitive to eddy currents in shells

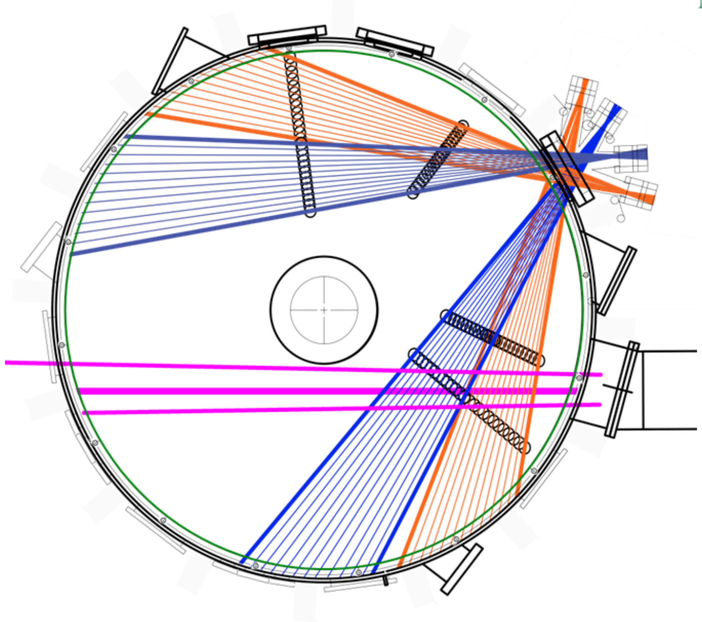


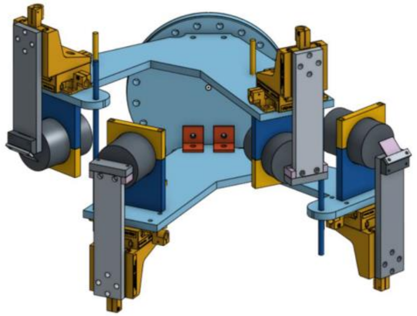
Hughes HTPD/RSI 2018

CHERS enables local T_i, v_{Tor}, n_{imp} profiles

- 2 sets of views to increase coverage
- 13 core views from 26-43.5 cm
- 13 edge views from 43-59 cm
- Symmetric passive views for background subtraction
- f/1.8, 75 mm commercial optics
- spacing/resolution: ~1.3 cm

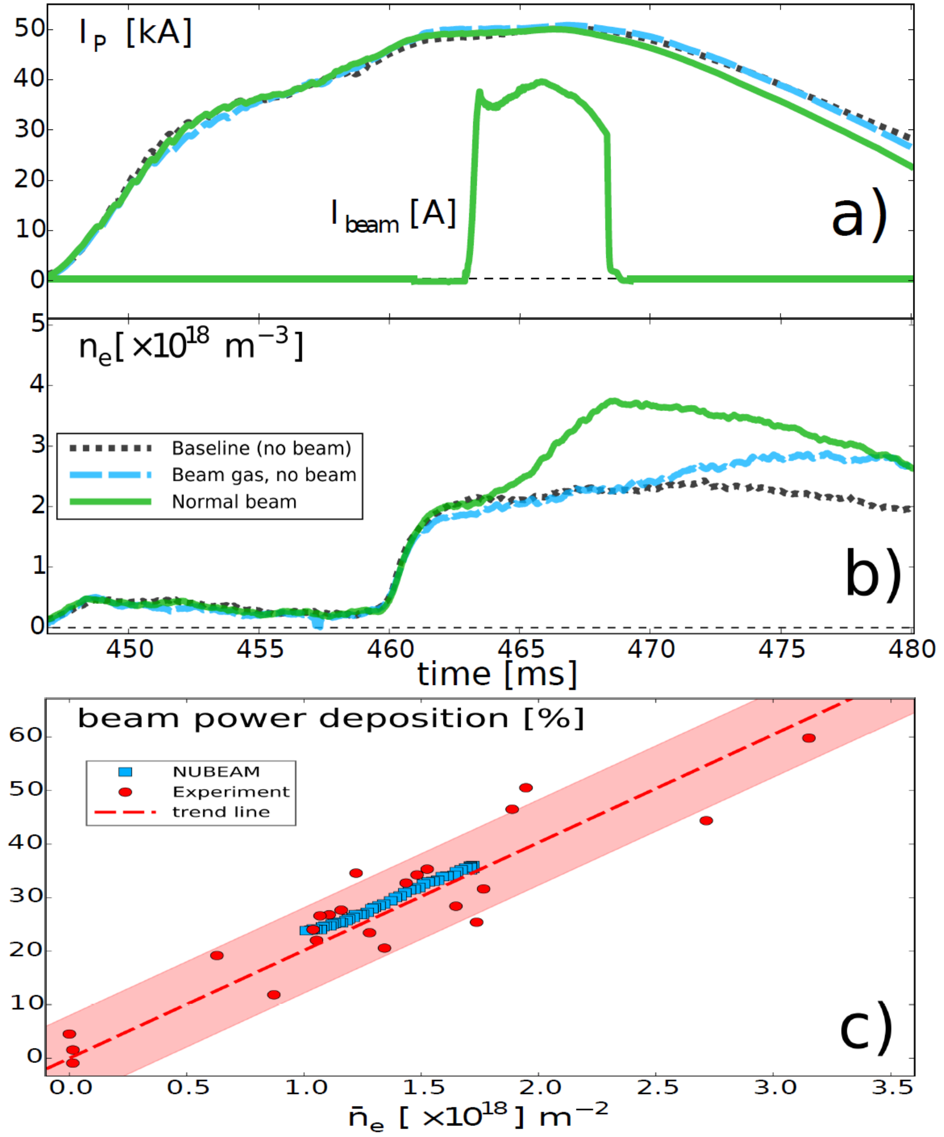
D. Elliott HTPD/RSI 2018





Initial NBI data

- Initially seemed to work great.
  - Fueling seems evident in interferometry case
  - Increase in stored energy indirectly measured
  - Matched trend from NUBEAM
- Seemed to only need increases in power and reliability



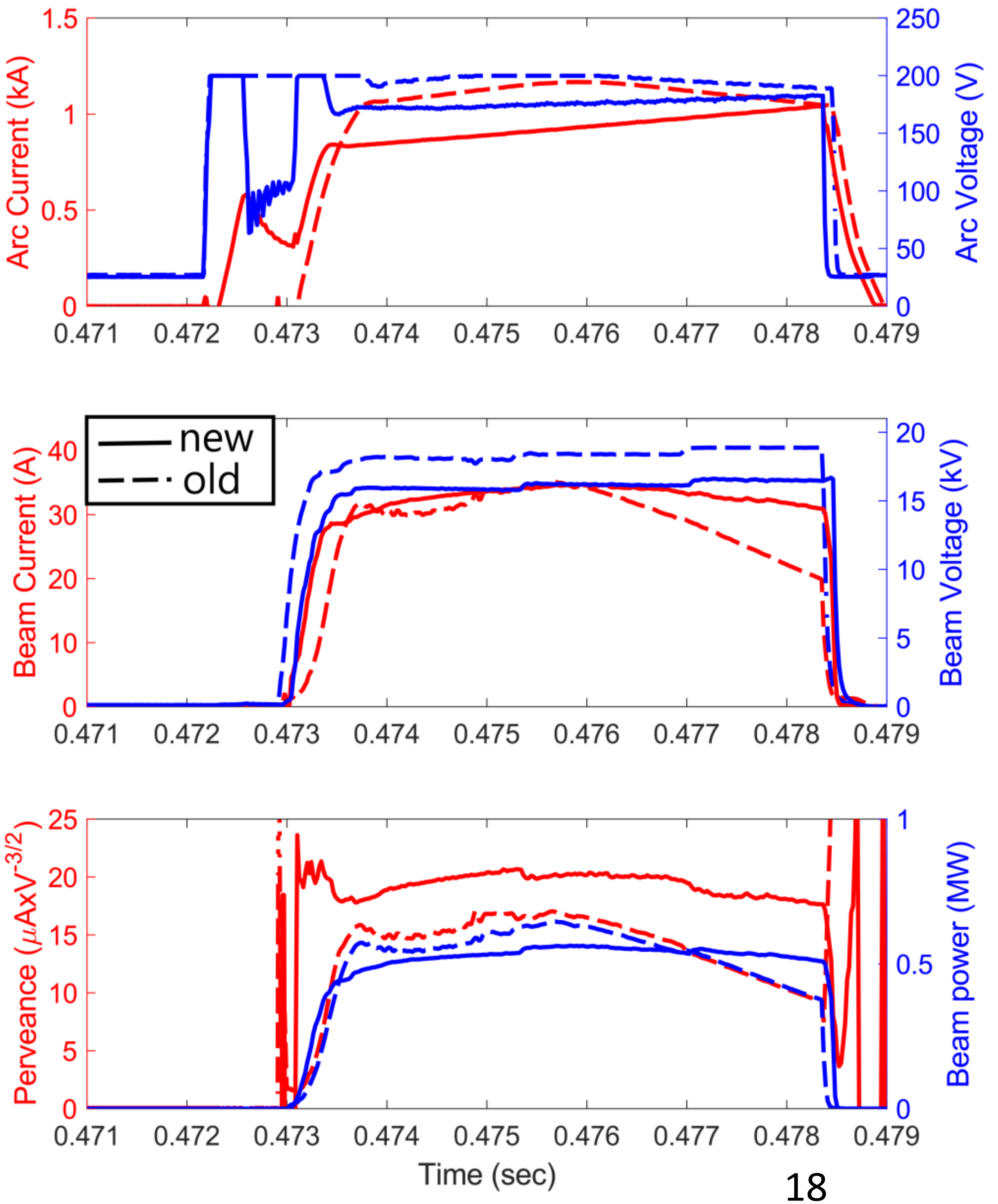
LTX-β

Outline

- LTX-β background
- Upgrade to LTX-β
- **Notable Outcome results**
  - **Better NBI**
  - **Compare liquid and solid lithium w/NBI**
- Future work

Beam Optimization

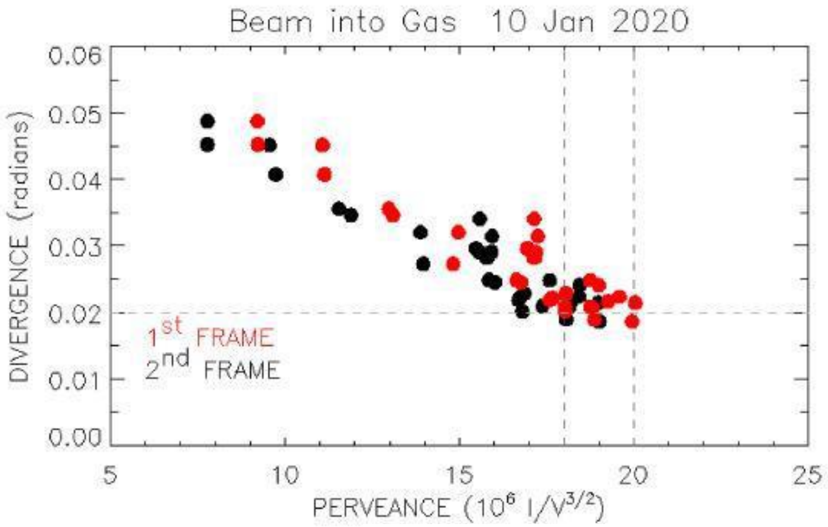
- Operational improvements to flatten all of the curves
  - New valves
  - Refreshed power supply
- **Increased perveance**
  - **For these results ~20 μP at 16.5 keV**
  - was ~15 μP at 18.5 keV
  - Accompanied reduction in divergence
    - Occurs well beyond spec, μP
    - Divergence may change with different beam voltage
- **Power supply 20 keV**
  - **15-20 keV nearly doubles CXS emission cross section**
  - Unclear if divergence will stay low
  - Currently testing

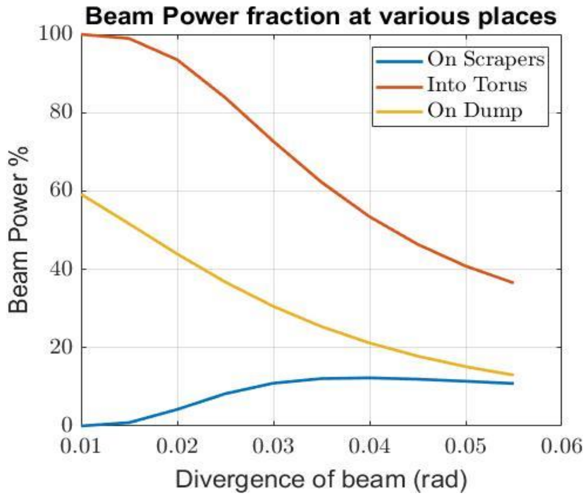


LTX-β

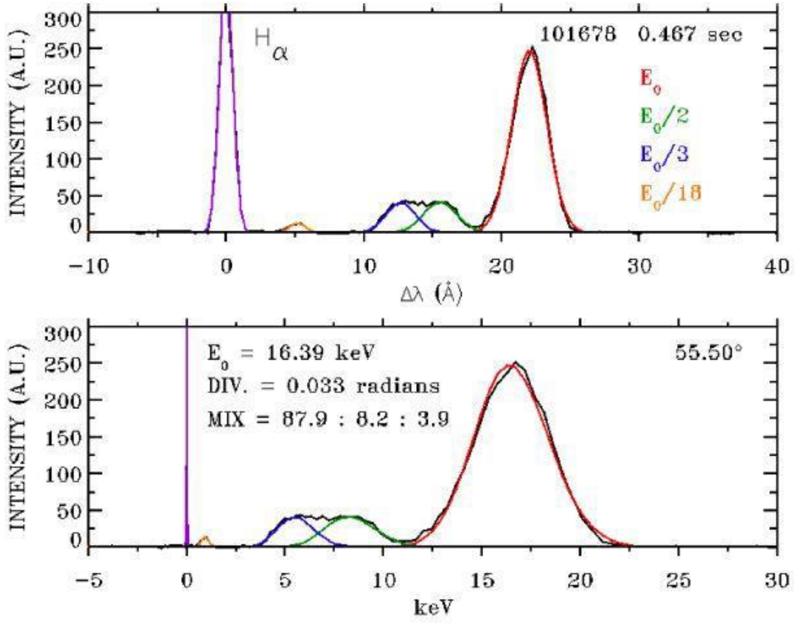
Beam Optimization

- Specifications
  - Divergence <0.02 rad
  - Perveance: <15 μP
- Measured optimal perveance 20 μP; operating at 16.5 keV
  - This was the minimized divergence
  - We need minimized divergence to get the beam into the plasma
  - This higher perveance means we need relatively higher current for a given voltage





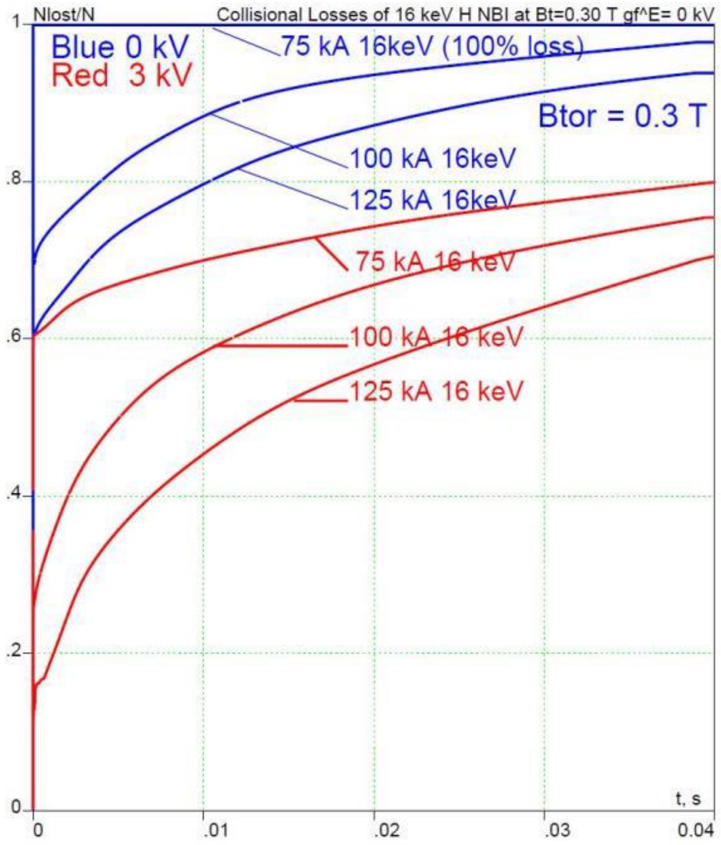
Courtesy of R. Bell & the HAL spectrometer



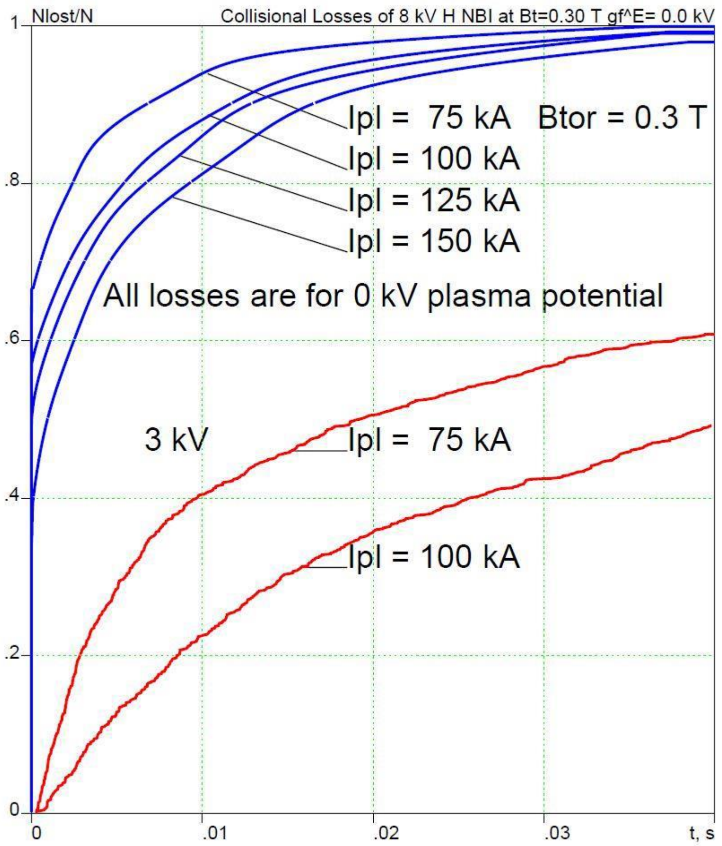
NBI modeling

- 3DOrb simulation is a 'worst-case scenario'
  - Excludes slowing down collisions
- Currently much of the NBI is lost in this model
- To reduce loss fraction:
  - Reduce beam energy
  - Increase plasma current
  - Ensure low recycling regime/high plasma potential

16 keV beam ions (full energy)

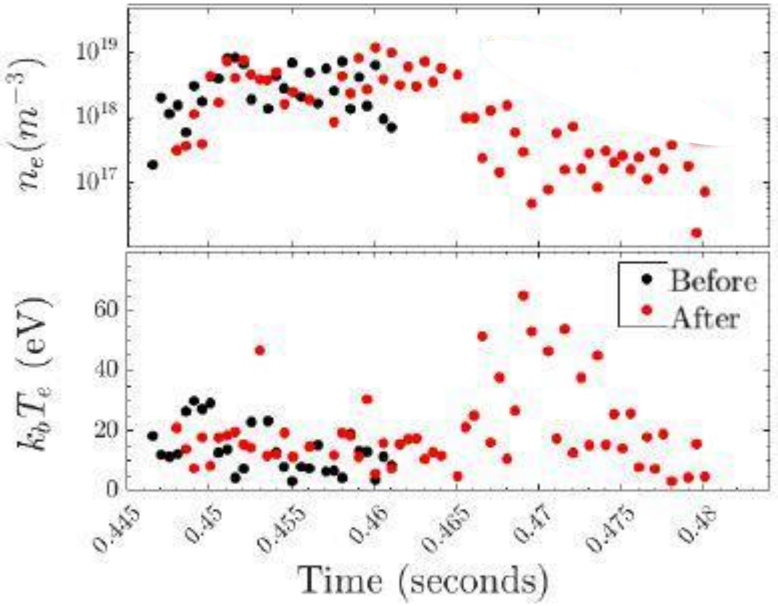


8 keV beam ions (half energy)

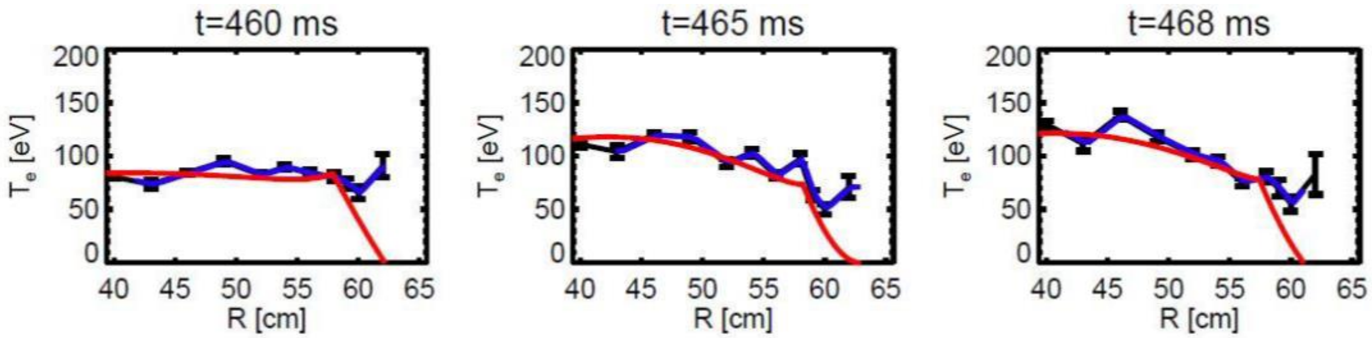


Evidence of low recycling regime

- Evidence of low recycling regime with LP
  - Fueling halted at 457 ms
  - Low edge density
  - High edge temperature
- TS from later shots show flat T_e
- Not enough data to be conclusive, but we are close



HFS LP data
Before and After
Li deposition

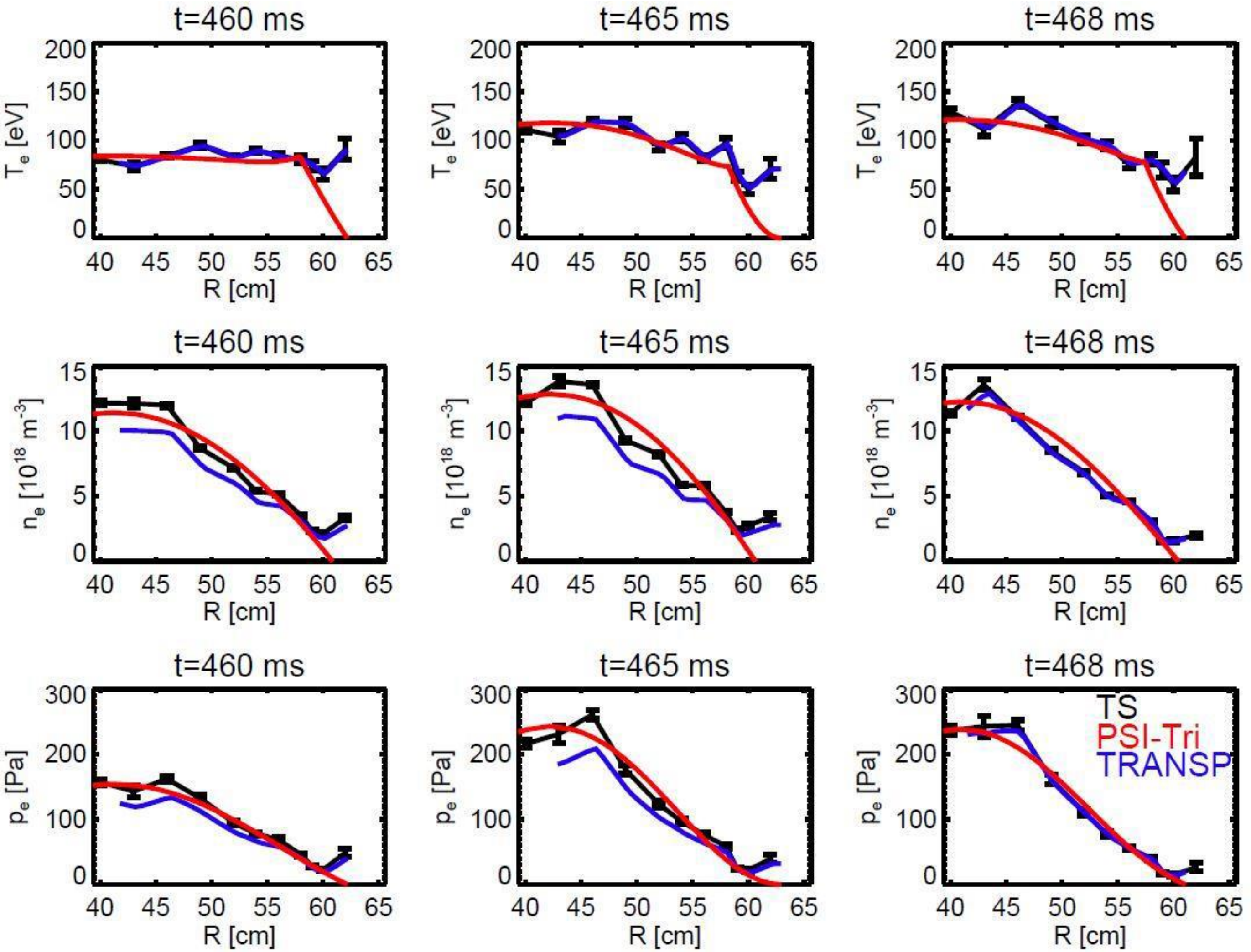


Measurements, TRANSP, Psi-TRI

LTX-β

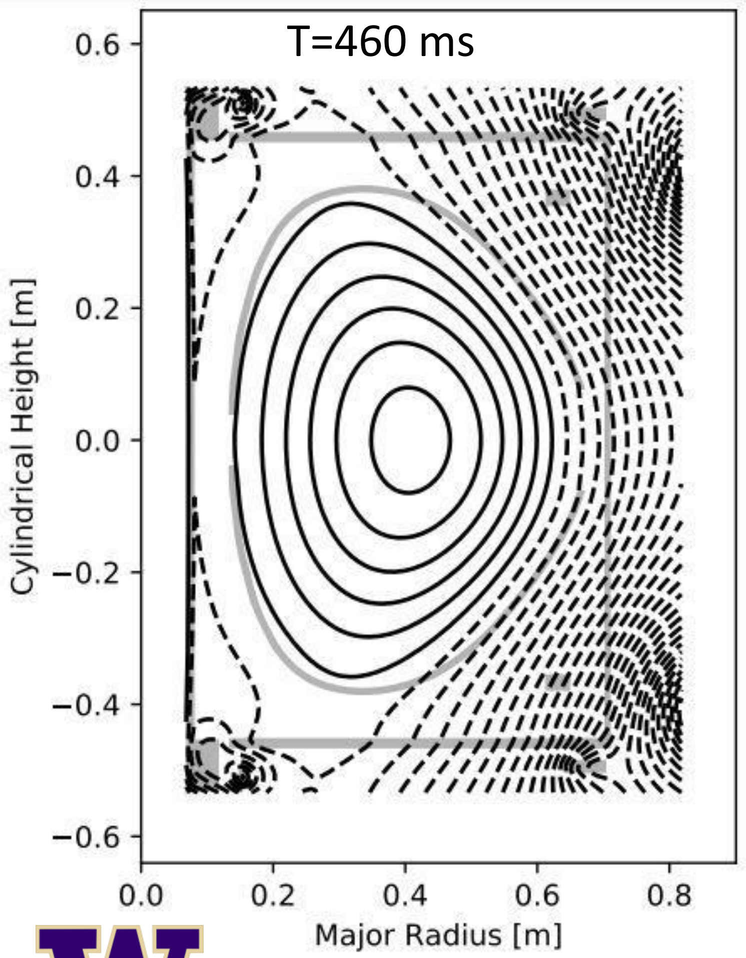
Performance of NBI with solid Li walls

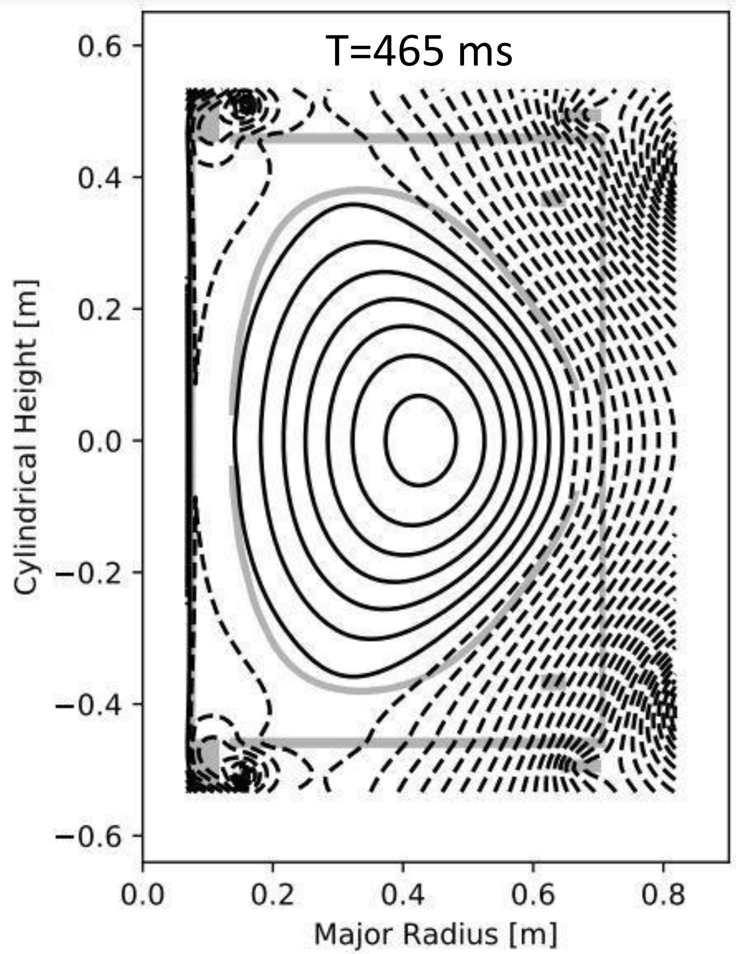
- NBI occurs from 463-468 ms, near peak current and density
- Increases in Temperature & Pressure
- Density not obviously effected
- Averaged over several shots
- I_p~75 kA, thus not ideal performance or confinement

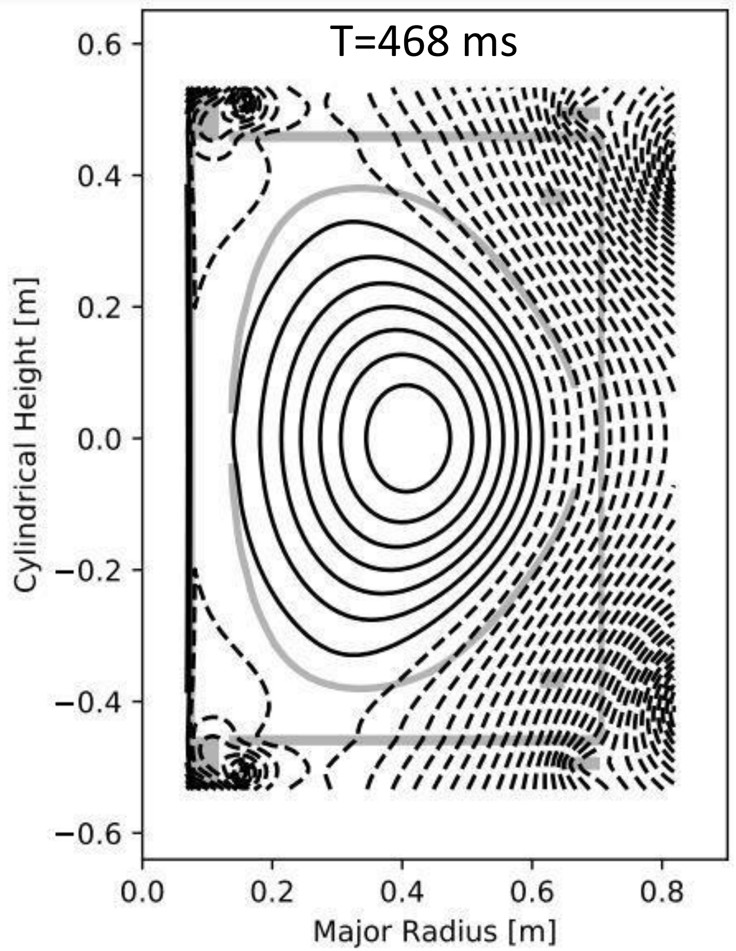


LTX-β

Psi-Tri Equilibria reconstructions (hot walls)



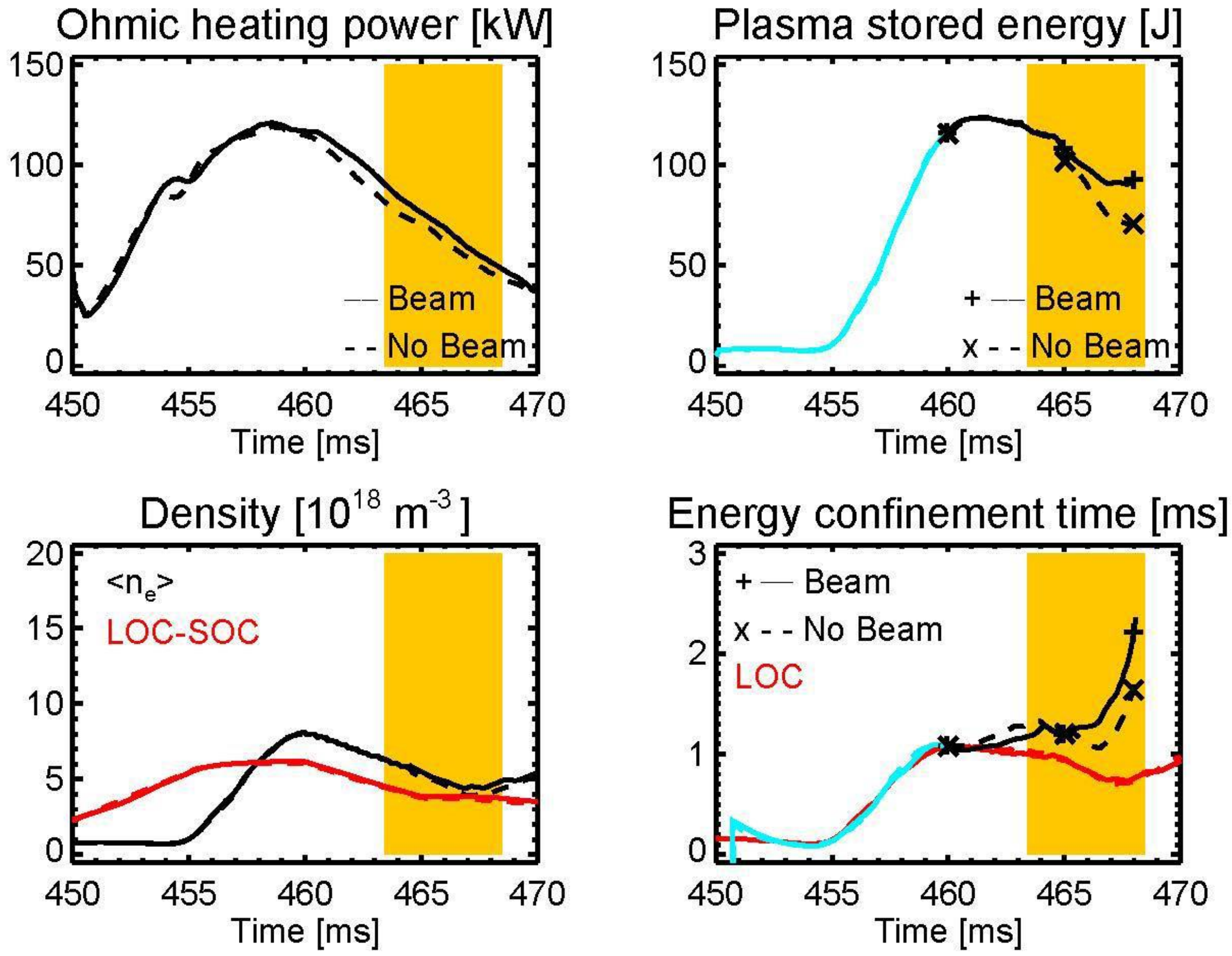




- Consistent plasma shape, moving slightly outward during NBI.
- Centroid near 40 cm, very near the limit of TS profile

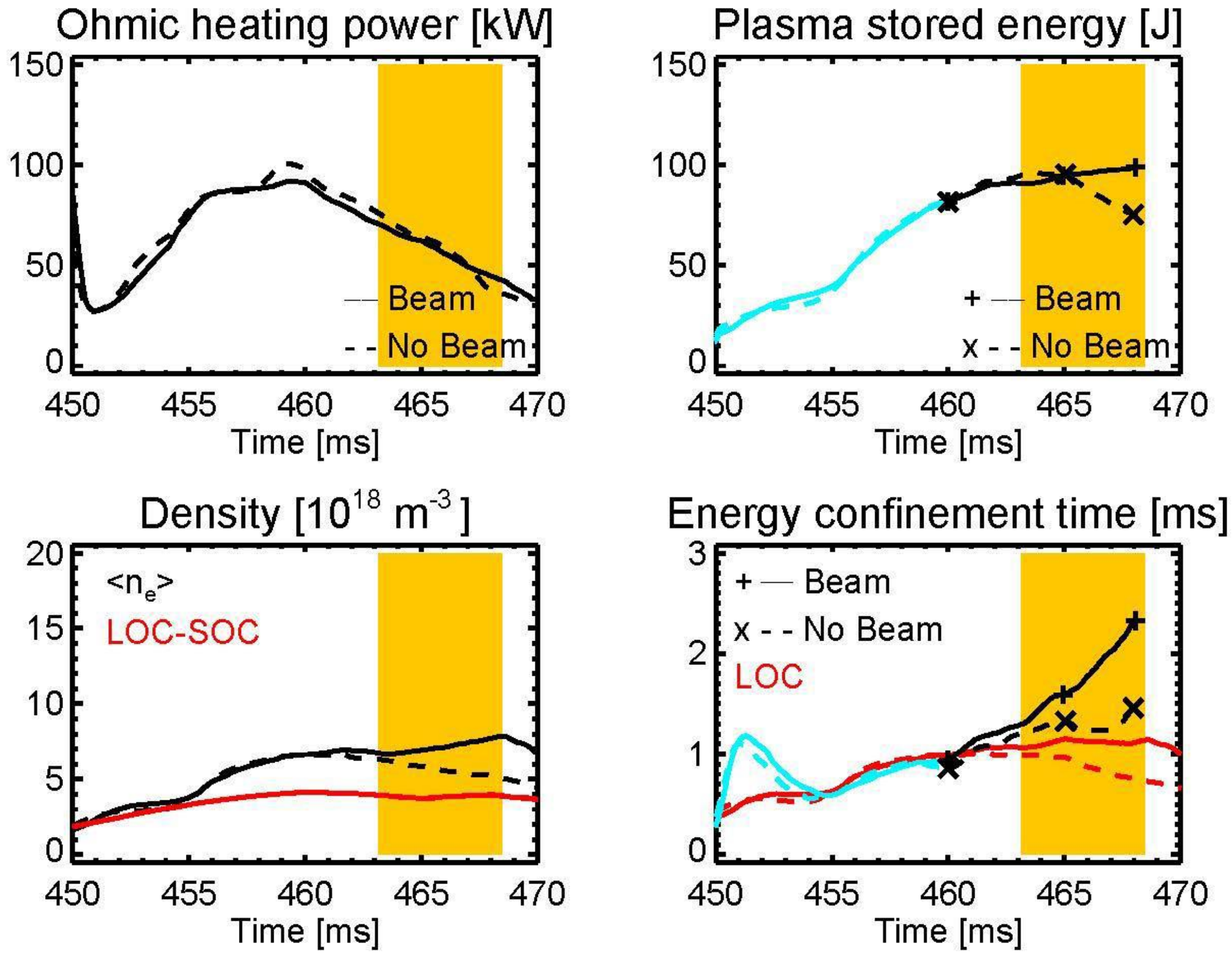
NBI performance in LTX-β with solid lithium

- Results from TRANSP and Thomson scattering
  - Stored energy increases with NBI
  - Density does not seem to change with TS
    - It does change with interferometry
  - Energy confinement also increases, but not as convincingly



NBI performance in LTX-β with liquid lithium

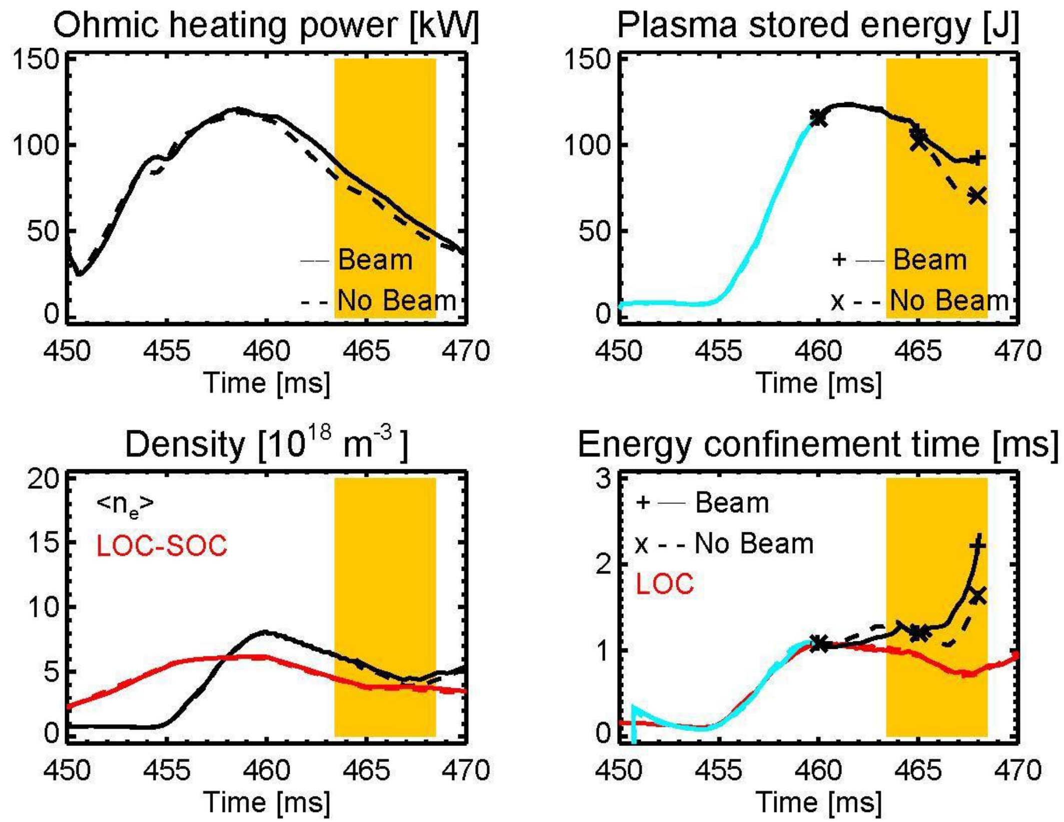
- Results from TRANSP and Thomson scattering
  - Density, stored energy, and energy confinement all increase
- **The data is not strong enough to conclude that NBI is more effective with hot walls**
  - Continued discharge development with both conditions is necessary to draw any final conclusions



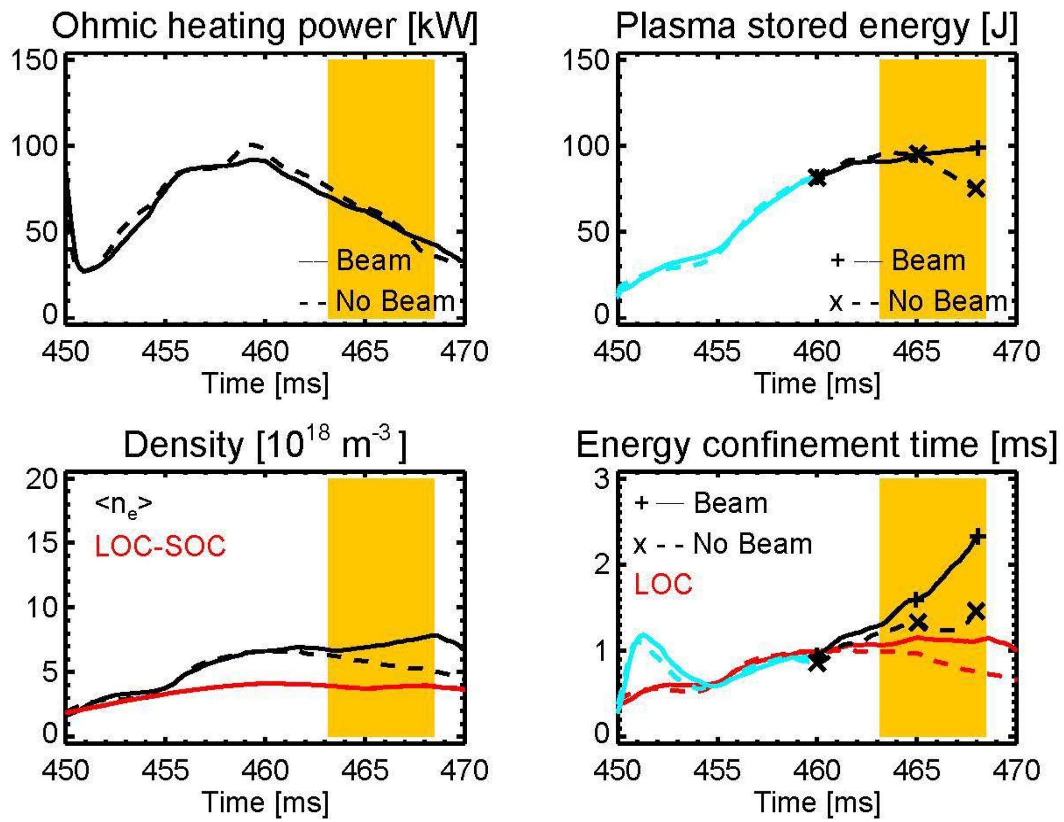
LTX-β

Comparison between solid and liquid lithium

Solid wall discharges



Hot wall discharges



There are some effects, especially on stored energy, but we need to improve coupling for both scenarios.

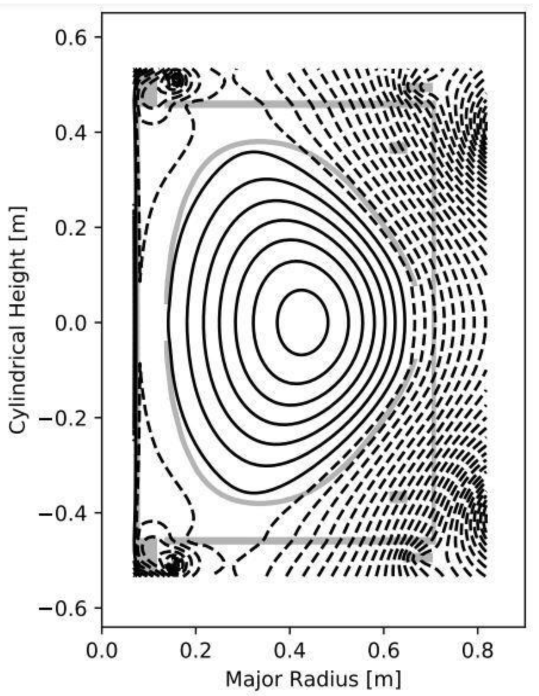
First light from Charge Exchange

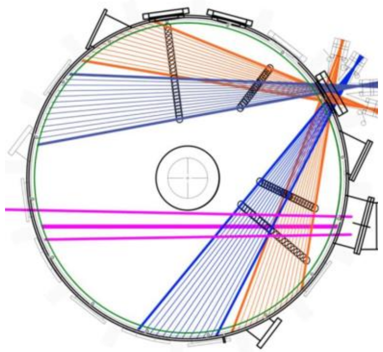
- Charge exchange light observed occasionally in the core (R=39 cm)

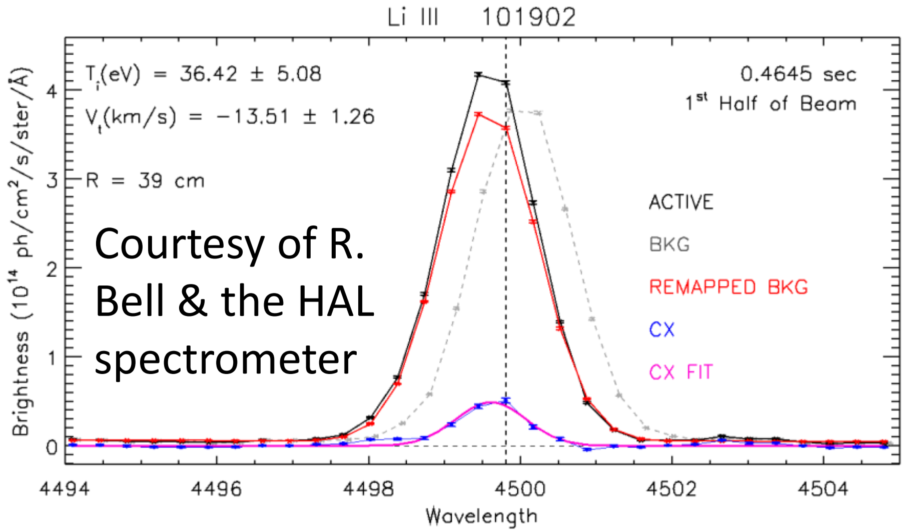
This data is preliminary

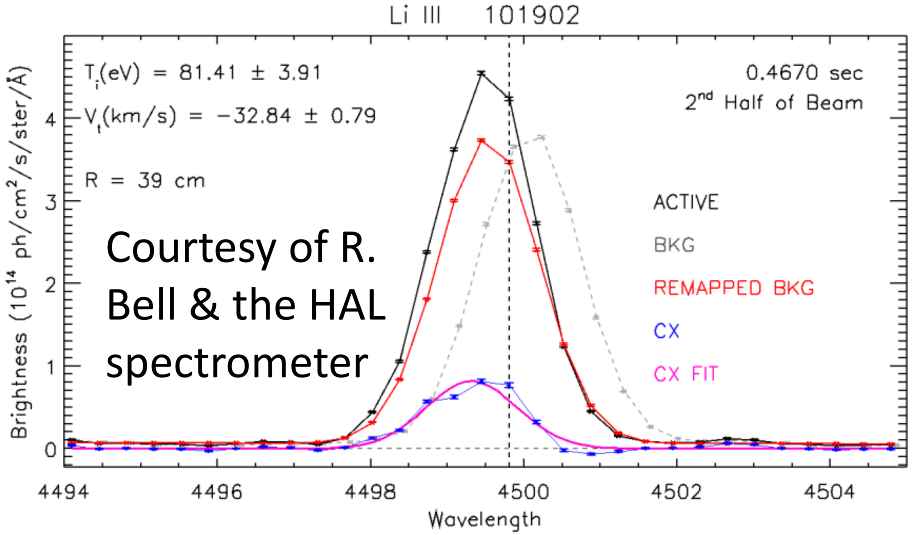
- With T_e~150 eV
  - Higher temps mean more source particles and less background
- NBI_V~16.5 kV
  - The CX cross section at 20 kV is nearly double that at 16.5 kV

Eq. Reconstruction at 465 ms









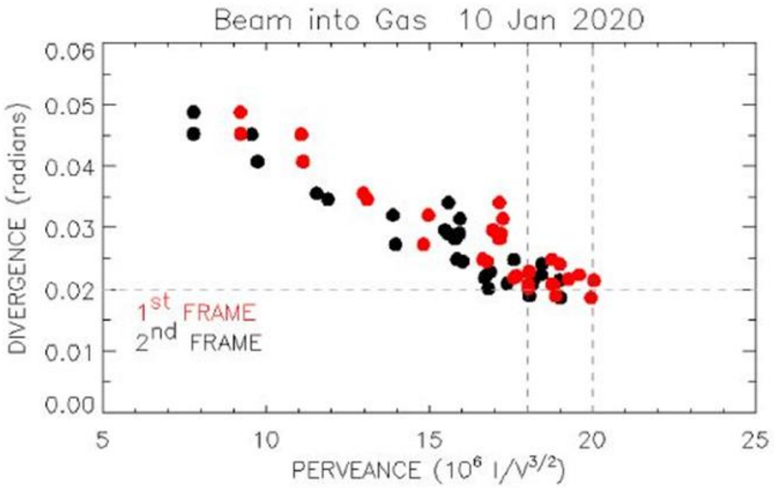
LTX-β

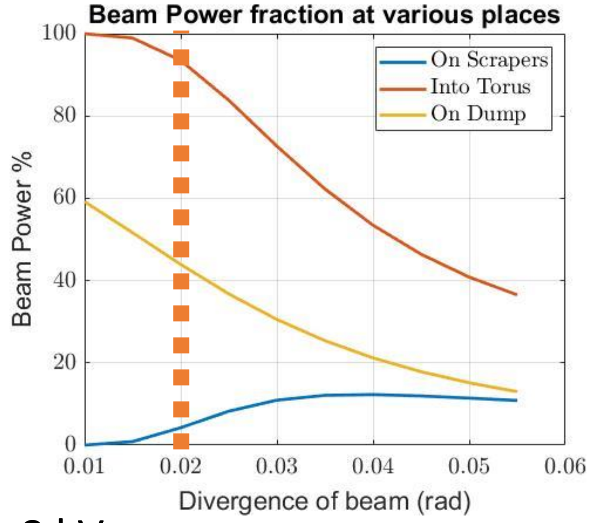
Outline

- LTX-β background
- Upgrade to LTX-β
- Notable Outcome results
- **Future work**
  - **Improve NBI**
  - **Broaden Thomson coverage**

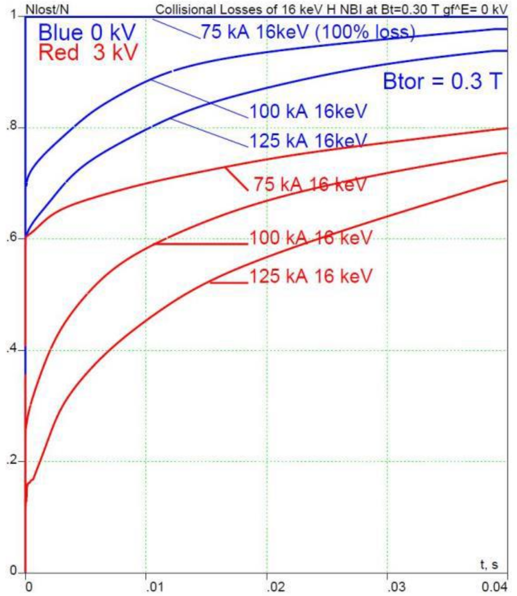
NBI future optimization for coupling

- Increase power coupled into the plasma
  - We can now operate at full spec energy (20 kV)
  - Keep divergence down/perveance up
  - Improve coupling fraction
    - Increase plasma current
    - Decrease beam voltage
      - Decreases total power
      - Improves coupling efficiency
      - Makes CX even harder
- More plasma current solves everything, but is a challenge

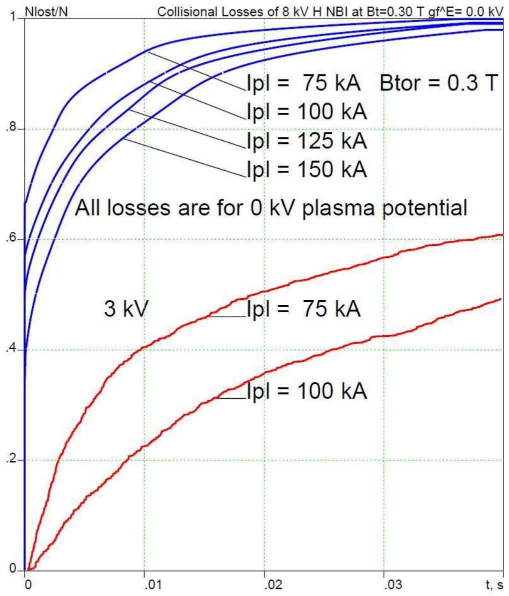




16 kV

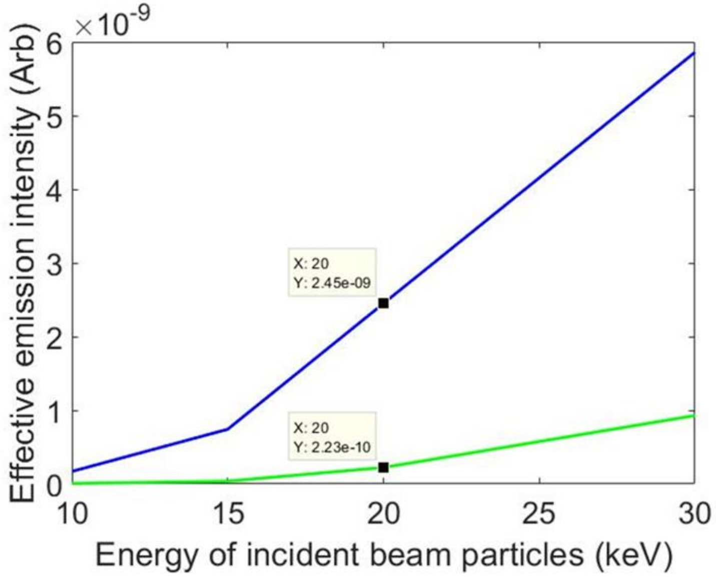


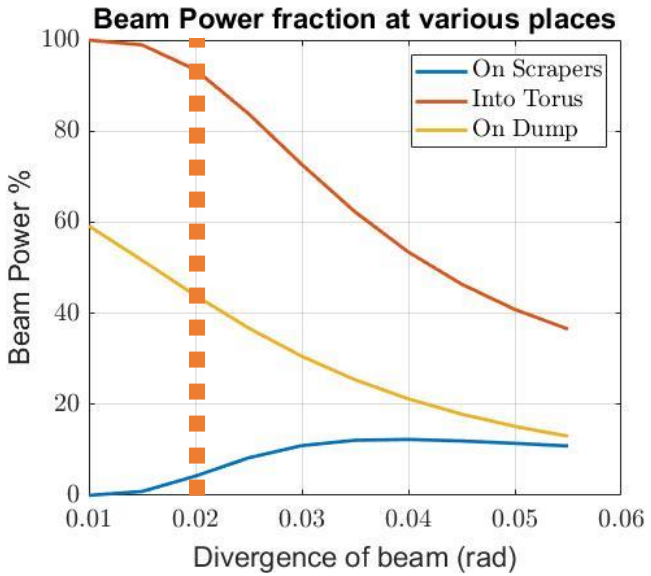
8 kV

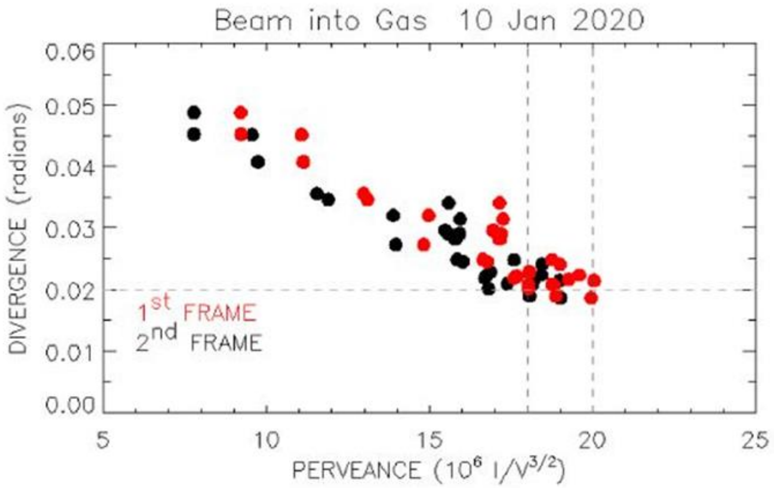


NBI future optimization for CX/measurements

- 20 kV improves CX by more than 2x
  - 20 kV will need 56 amps to maintain 20 μP (>1 MW/~150% spec)
  - May not require such high Perv. At 20 kV
- 20 keV will have high shine through
  - Good for CX, very bad for coupling
- Oscillating supply seems to be the best solution but will take time



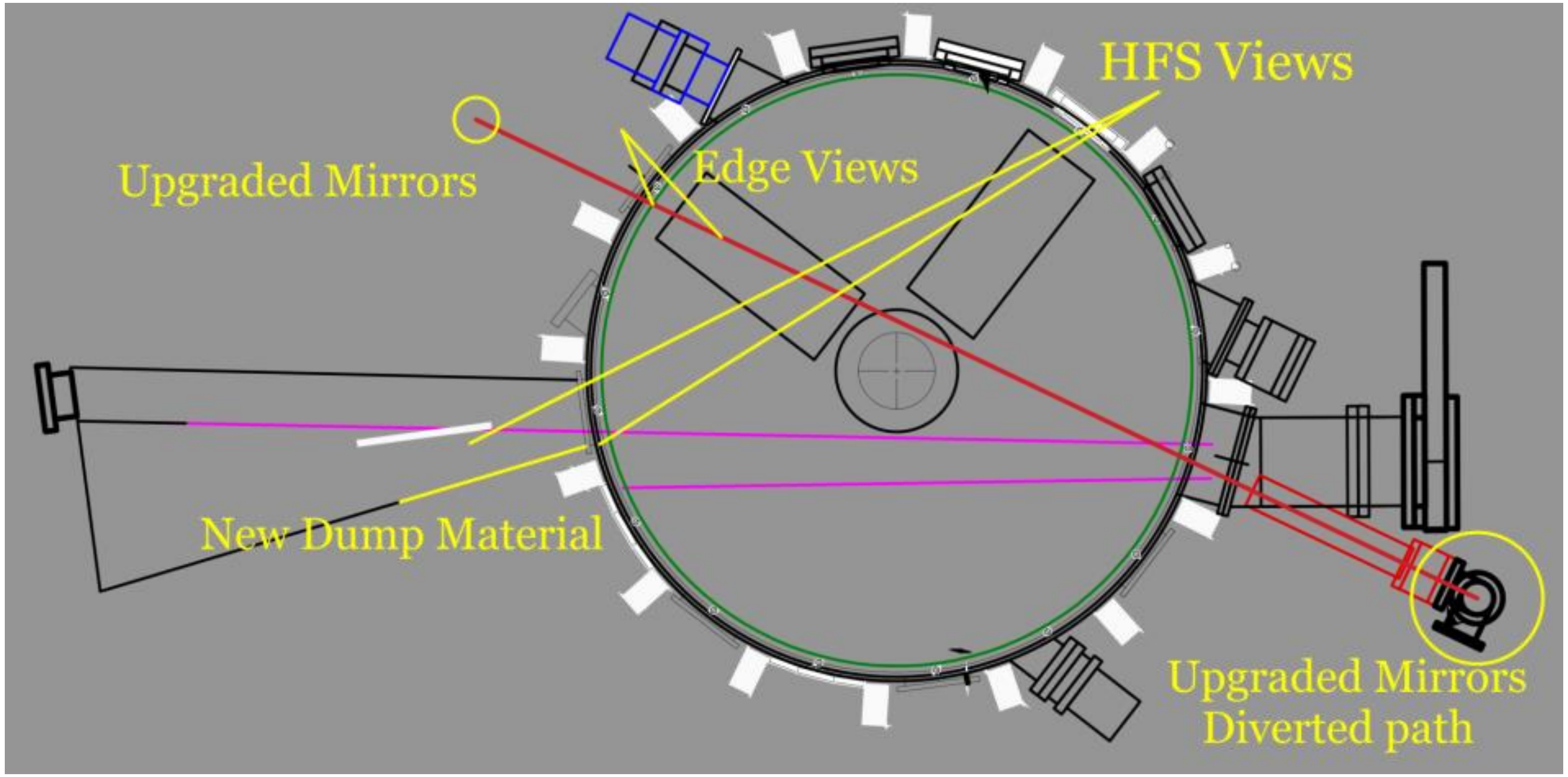




LTX-β

High field side Thomson views planned

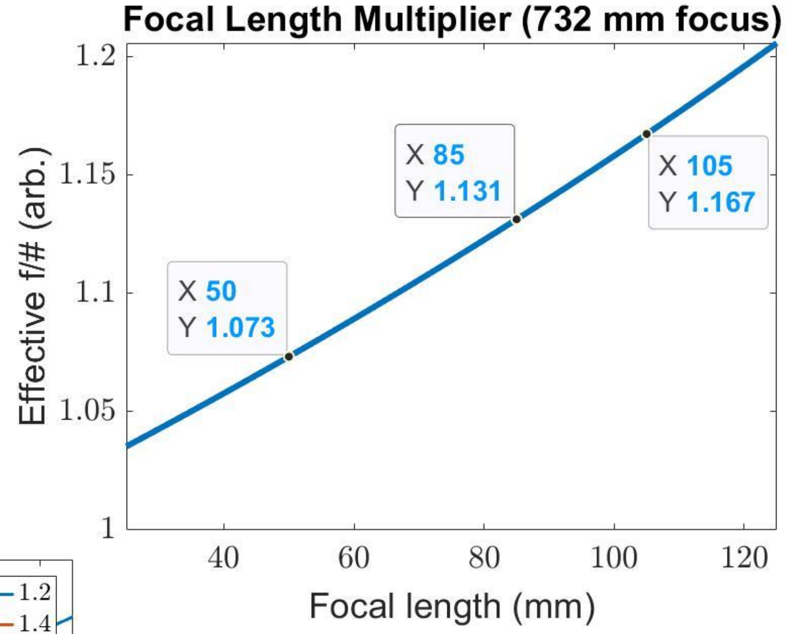
- Help constrain magnetic axis
- Give single shot profile

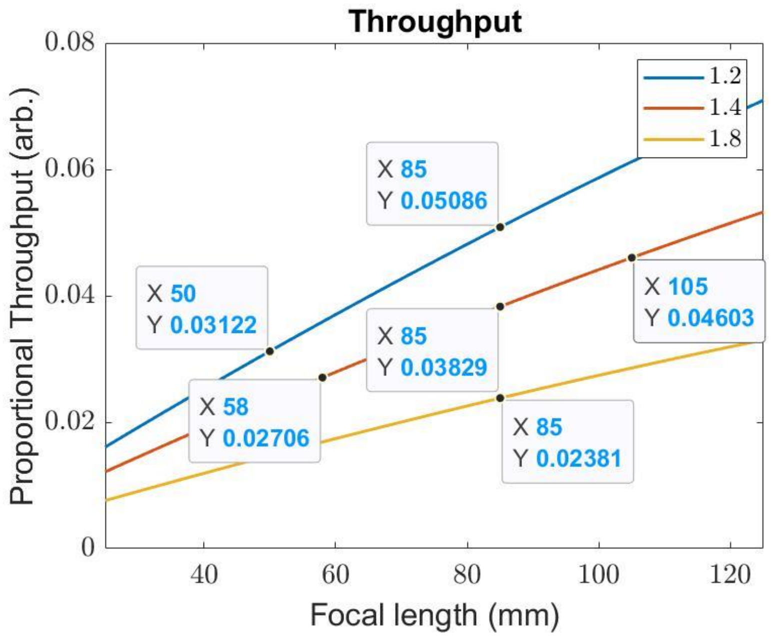


LTX-β

HFS TS optimization Criteria

- Coverage R=25-40 cm
  - To ID centroid
- Using polychromators
  - Higher temps
  - Fewer views
  - Maximize throughput
  - ~f/1
- Ideal fibers ~f/1.1
- Use commercial optics
  - Selecting f/# and fl
  - 85 mm f/1.2 works best





LTX-β

Current status, and review

- Upgraded diagnostics
  - Commissioned TS, CX, LP, PMI studies, Magnetics, visible spec., Improved Interferometry and reflectometry
  - Improving TS and probes for recycling
- NBI commissioned
  - Low voltage good for coupling
  - High voltage good for CX and max power
- Liquid and solid lithium performed similarly
  - Further shot development needed to confirm