Acceleration of MHD rotation due to torques driven by NBI fast ion losses in LTX-β

Paul E. Hughes

in collaboration with

W. Capecchi, D.E. Elliott, L.E. Zakharov, R.E. Bell, C. Hansen, D.P. Boyle, S.N. Gorelenkov, R. Majeski, R. Kaita

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Key Points

- LTX-β toroidal Mirnov array for stability studies
- Co-I_P NBI added to provide core heating and fueling
- NBI-independent n=1 mode observed on toroidal array
  - Accelerated in counter-beam direction during injection
  - Indicates prompt loss of NBI ions
- Ion loss and resulting rotation dynamics modeled
  - Indicative of momentum and ion energy confinement times
- Based on March 2019 data

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- LTX-β magnetics upgrade
- NBI performance
- NBI discharge observations
  - Fueling
  - MHD rotation
- Modeling
  - Fast ion losses
  - Torque analysis
- Conclusions

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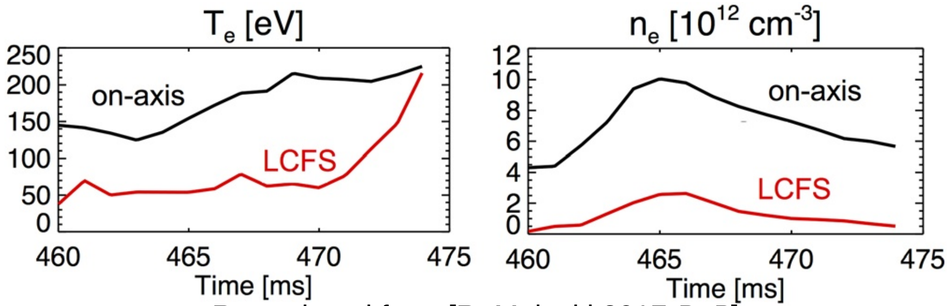
Lithium improves tokamak performance

- Lithium as a plasma-facing component (PFC) key to LTX
  - Coatings known to improve plasma performance
    - Benign impurity source: low *Z*, sputtering improves >200eV
    - Lithium retains hydrogenic ions (plasma chemistry?)
  - Potential for liquid/flowing PFC
- Predicted low-recycling / flat T_e regime [S.I. Krasheninnikov 2003 *PoP*]
  - Increased fusion volume in reactor
  - Reduced gradient-driven transport
  - Improved stability

Low-recycling regime observed in LTX

- "Isomak" flat T_e profile observed in LTX [R. Majeski 2017 *PoP*; D.P. Boyle 2017 *PRL*]
- However: edge fueling incompatible with low-*R* study
  - No fueling means n_e decays while T_e flattens
  - Transient state complicates analysis
  - Low n_e reduces TS fidelity: error bars $0.03T_e \rightarrow 0.25T_e$ at edge
- Need hot core fueling source: neutral beam injection (NBI)



Reproduced from [R. Majeski 2017 *PoP*]

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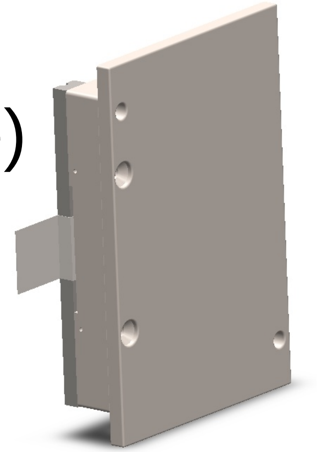
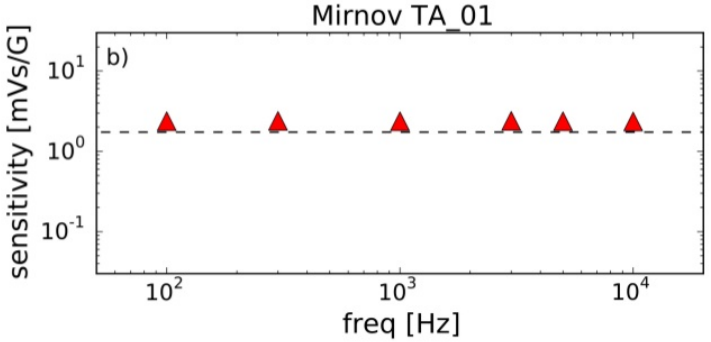
Toroidal Mirnov array for stability studies

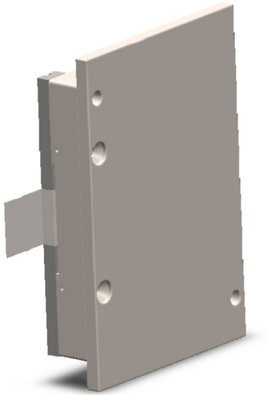
- MHD stability of LTX regime not empirically studied
  - No toroidal resolution in LTX: Mirnov array only at φ=0
- NBI heating and fueling should increase β (pressure)
  - 700kW beam heating >> Ohmic power (peak ~100kW)
- Developed new toroidal Mirnov array [P.E. Hughes 2018 *RSI*]
  - 10 spare 1-D Mirnov sensors from NSTX-U
  - Sensitivity benchtop calibrated to ~3%
    - 2.5% propagated from test jig calibration
  - <1% loss up to 10kHz

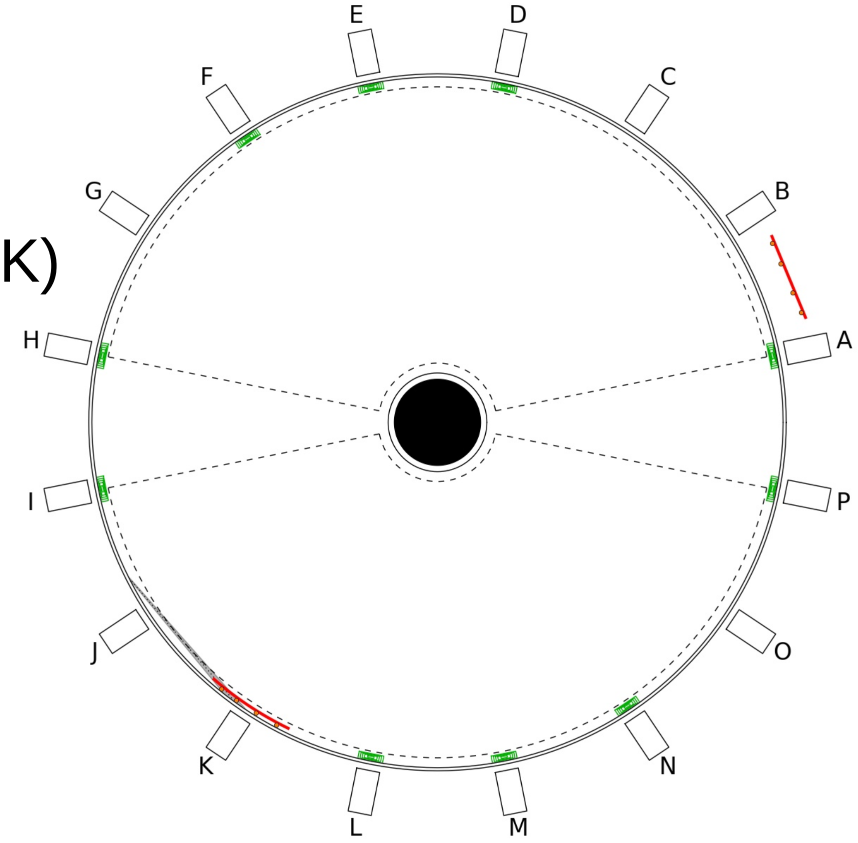




Toroidal Mirnov array implemented

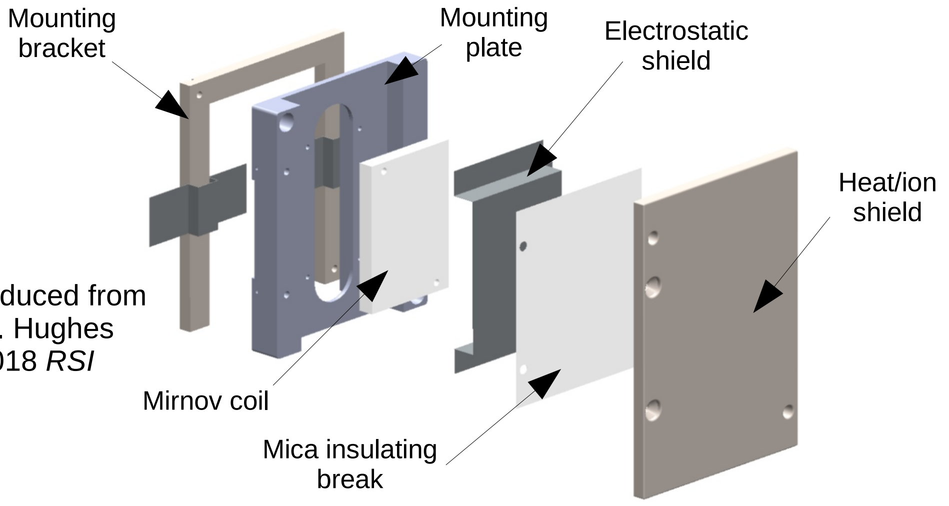
- Mounted to vessel wall
  - 10 locations → $n \leq 4$ sensitivity
- Some locations prohibited
  - e.g. AXUV view (J), beam dump (K)





Toroidal Mirnov array implemented

- Constructed w/ gap on -φ side
  - Protection from lithium
  - Heat shield for fast ions
  - Cable runs avoid shell gaps



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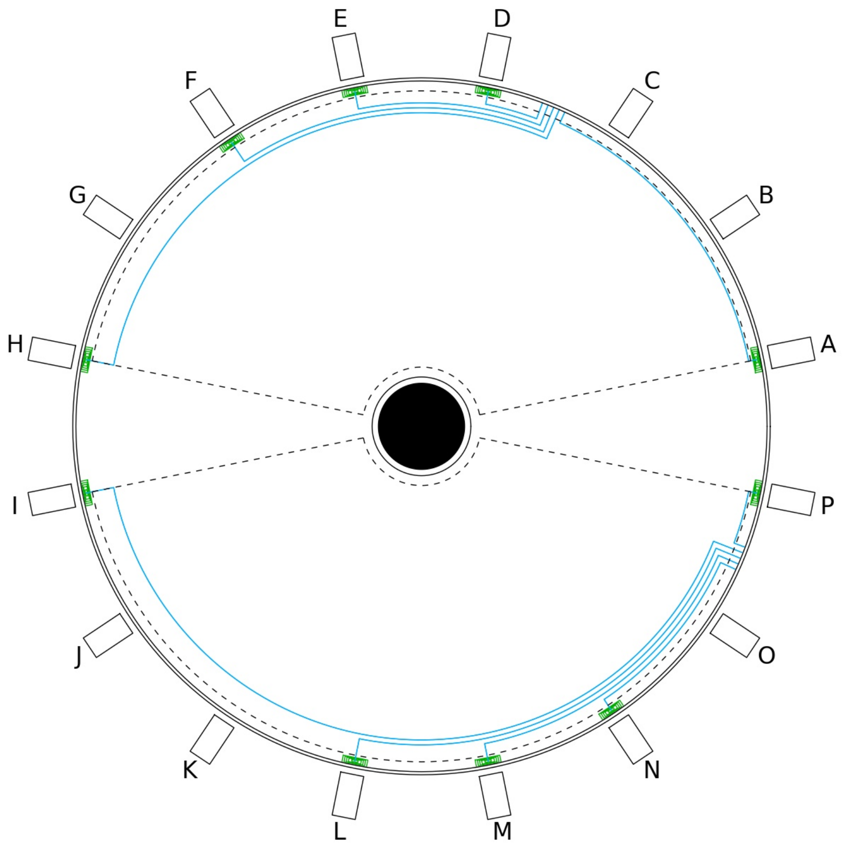
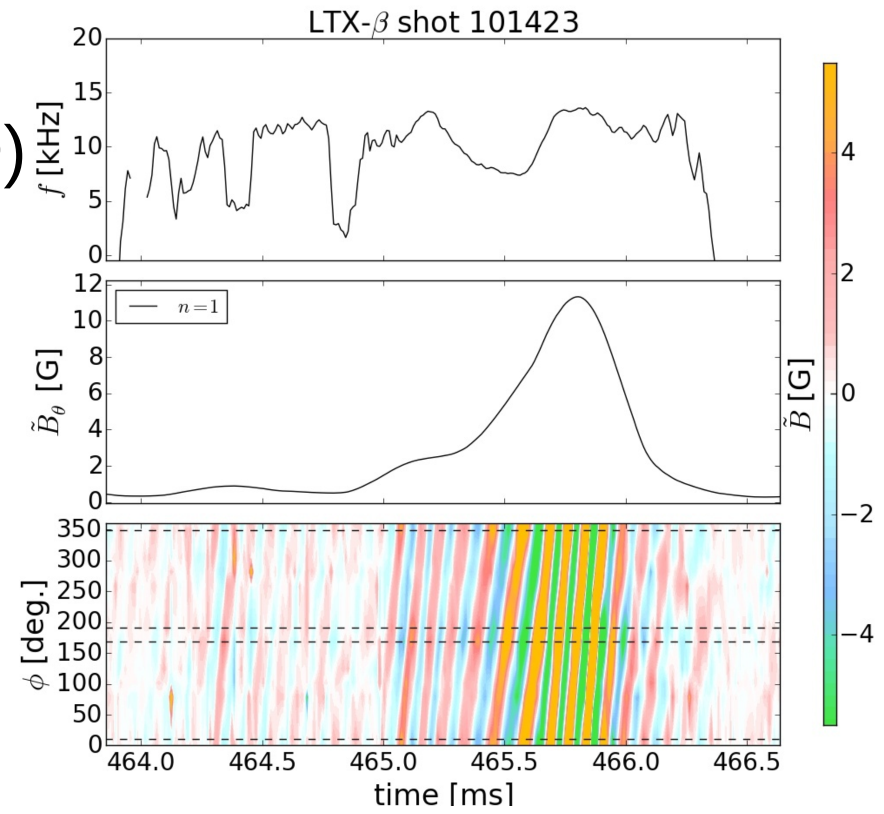


MHD spectroscopy tracks mode evolution

- Equilibrium subtraction
- Biorthogonal decomposition (SVD)
  - Form sensor x time signal matrix $\hat{S}$
  - SVD yields $\hat{U}\cdot\hat{\Sigma}\cdot\hat{V}^{*}=\hat{S}$
    - Spatial (U) and temporal (V) modes
  - BD mode = 2 matched SVD modes
    - Correlated sin&cos = rotating cos
- Track phases for frequency
  - Low amplitude → lost phase track



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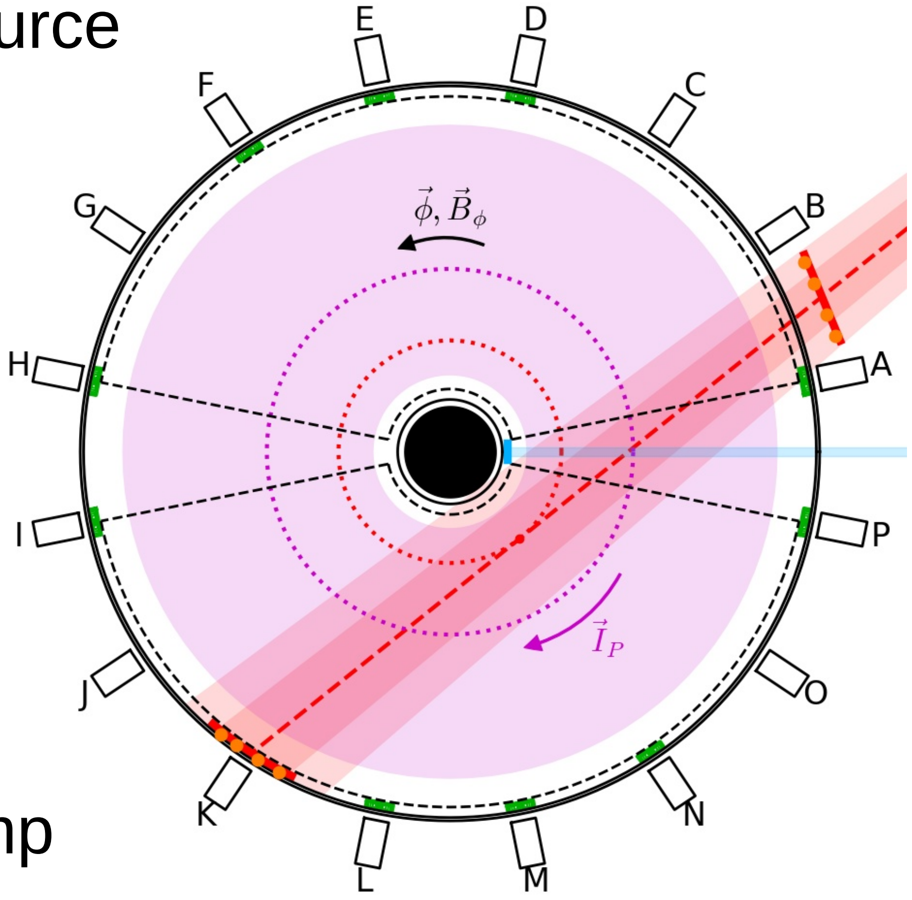
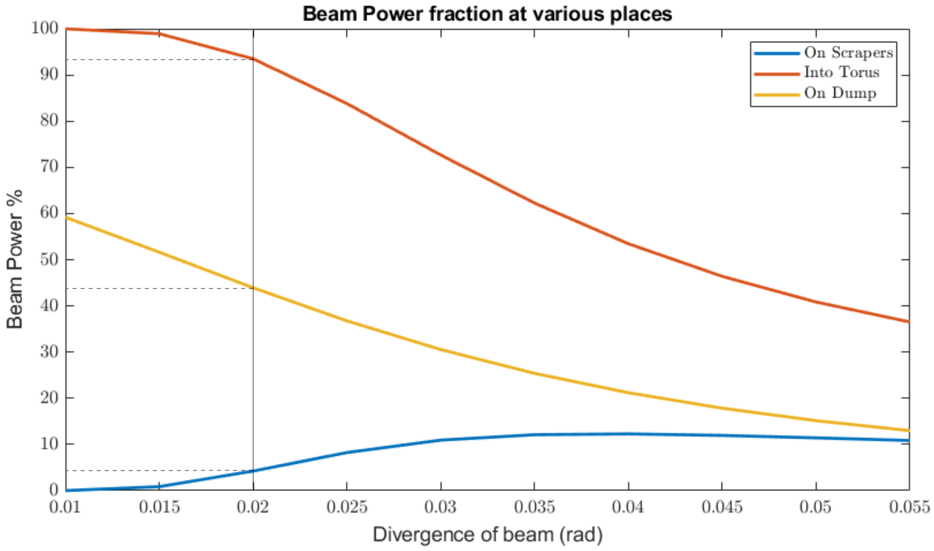
NBI added for hot core fueling

- Budker Institute neutral beam source rated for 20kV, 35A (700kW)
  - Auxiliary heating ~1 MW/m3
  - Maximum fueling ~5%/ms
  - CHERS for T_i *and* v_φ profiles
  - Injects co-I_P (-φ) into vessel
  - R_{tan} ~ 21cm
- Injection period ~5ms
- Calorimetry on scrapers and dump



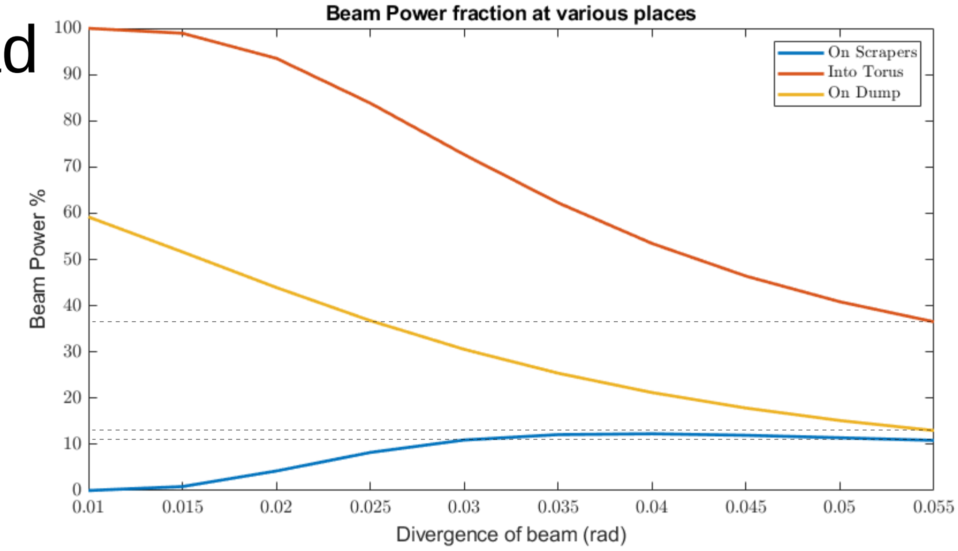
Nominal NBI performance

- 700kW optimal power at source
- Full/half/third energy fractions
  - ~82%/15%/3%
- ~90% max neutralization rate
- Divergence 20mrad
  - ~95% injection fraction
- Total injected beam:
  - 550kW



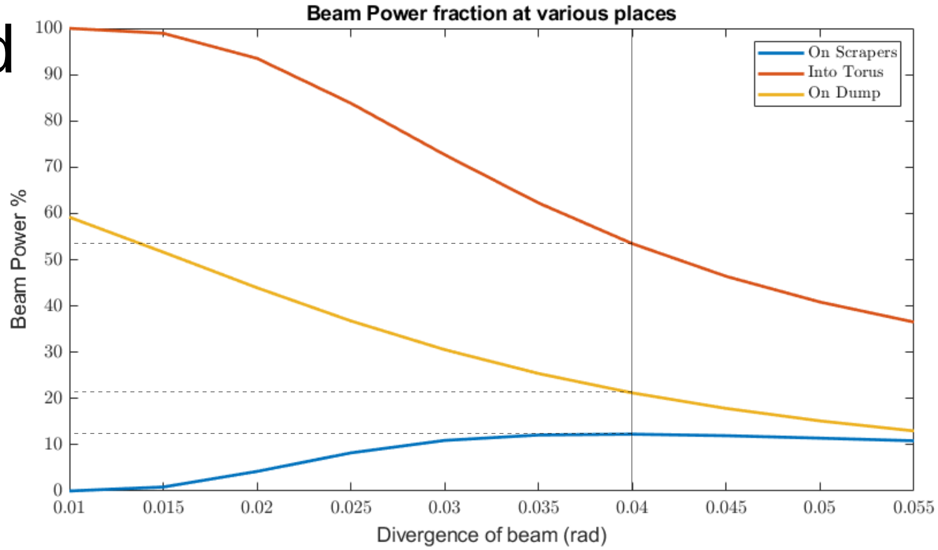
NBI observations: beam diagnostics

- Max E_{DP}/E_{beam}~13% → d~55mrad



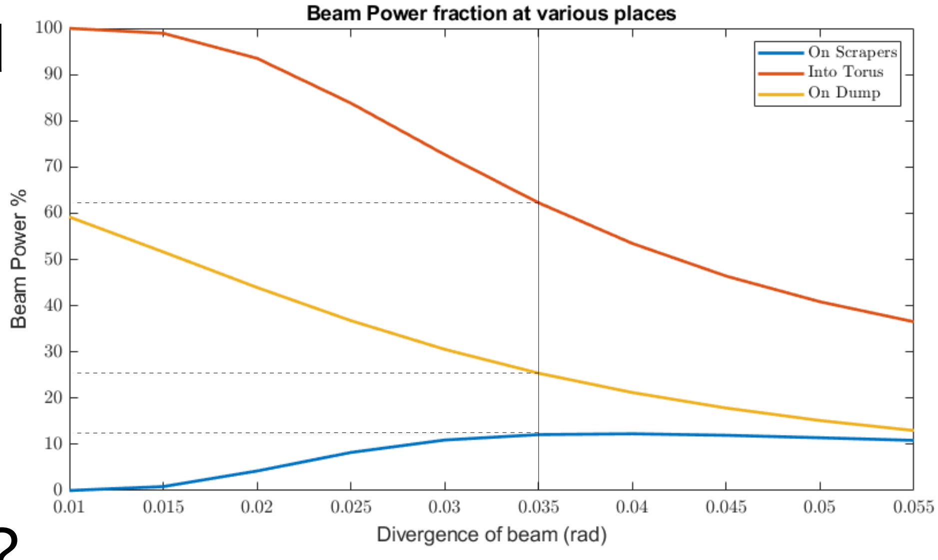
NBI observations: beam diagnostics

- Max E_{DP}/E_{beam}~13% → d~55mrad
- Max E_{DP}/E_{Scr}~2 → d~40mrad



NBI observations: beam diagnostics

- Max E_{DP}/E_{beam}~13% → *d*~55mrad
- Max E_{DP}/E_{Scr}~2 → *d*~40mrad
  - Spectroscopy → *d*~35mrad
    - Only 2 frames during NBI
- Discrepancy not yet explained
  - Complications to beam optics?
  - Flaws in calorimetry diagnostics?
- For d=35mrad, ~68% injection into torus
  - Alternative models show 63-73% injection



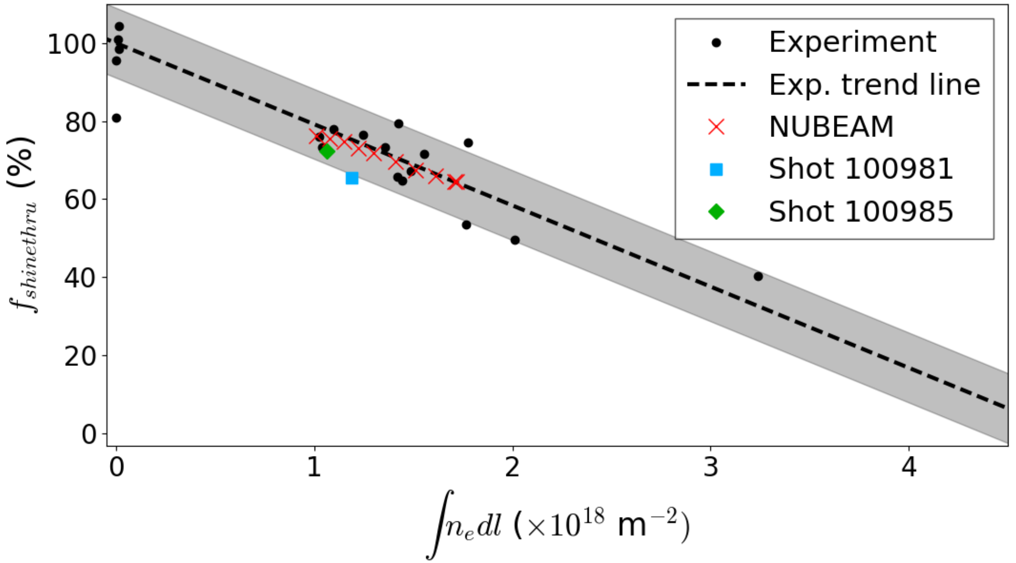
Optimal NBI Power and Torque Injection

- NUBEAM agrees well with preliminary NBI discharges
  - ~70% shine-through in target discharge
- Accounting for injection, neutralization, and shine-through, with full fast ion confinement:

$$P_{NBI} \sim 120\,\mathrm{kW}\ \left(P_{OH} \sim 100\,\mathrm{kW}\right)$$
$$\Gamma_{NBI} \sim 4\times10^{19}\,\mathrm{s}^{-1}\left(N_e \sim 2.5\times10^{18}\right)$$
$$\vec{\tau}_{NBI} \sim -10\,\hat{z}\,\mathrm{mN{\cdot}m}$$
$$\Delta N_e / N_e \sim 8\,\%$$

  - Calculating slowing down time

$$\tau_s = 6.28\times10^8 \frac{T_e^{2/3}}{n_e \ln\Lambda} \sim 10\,\mathrm{ms}$$
$$\Delta f_\phi \sim -1.5\,\mathrm{kHz}\ \ \text{during NBI}$$



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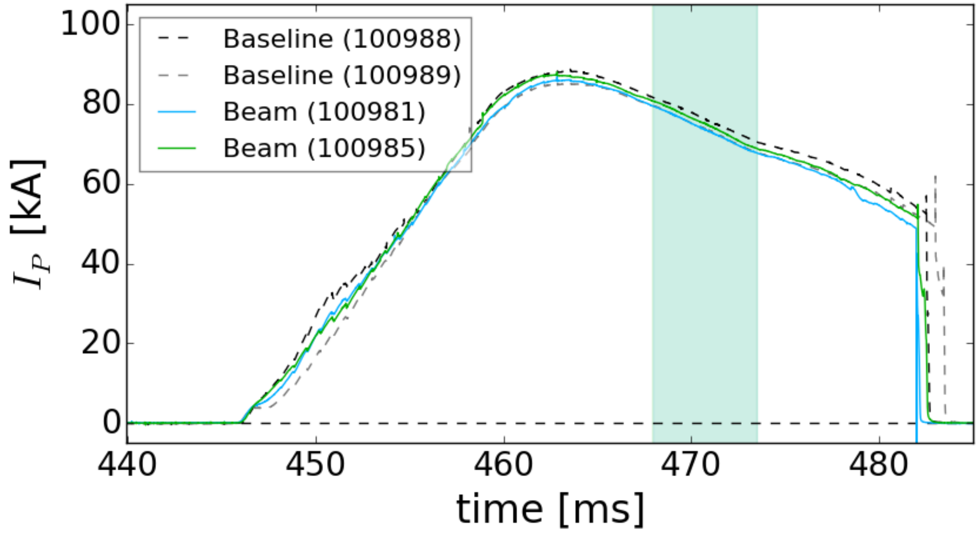
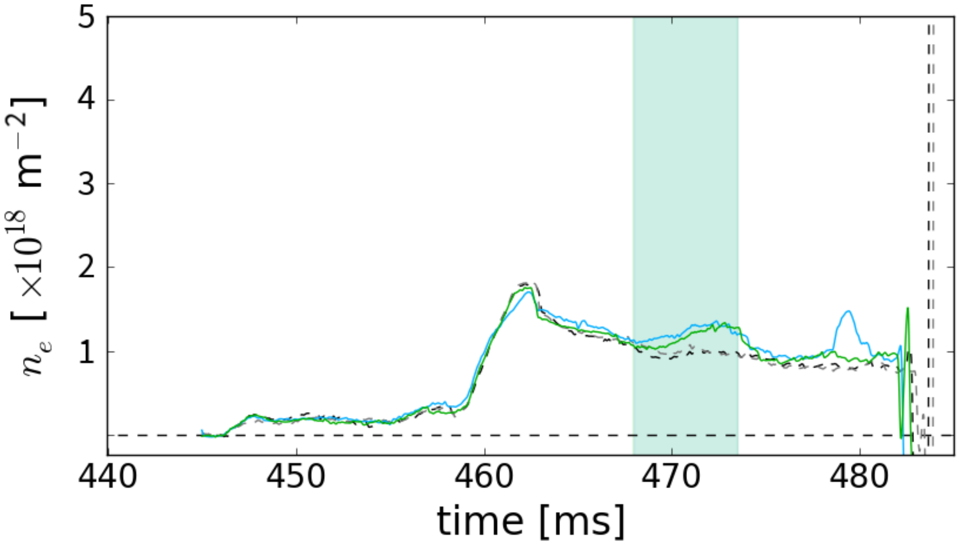
NBI and Non-NBI Discharge Styles

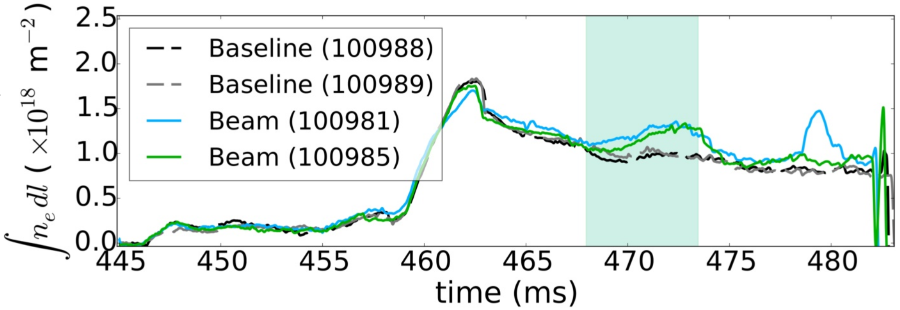
- Target discharge style: initial beam-into-plasma series
- Peak I_P ~85kA, I_P during NBI 67-80kA
- Before NBI, $\int n_e dl \approx 1 \times 10^{18}\,\mathrm{m}^{-2}$





Plasma Response: Fueling

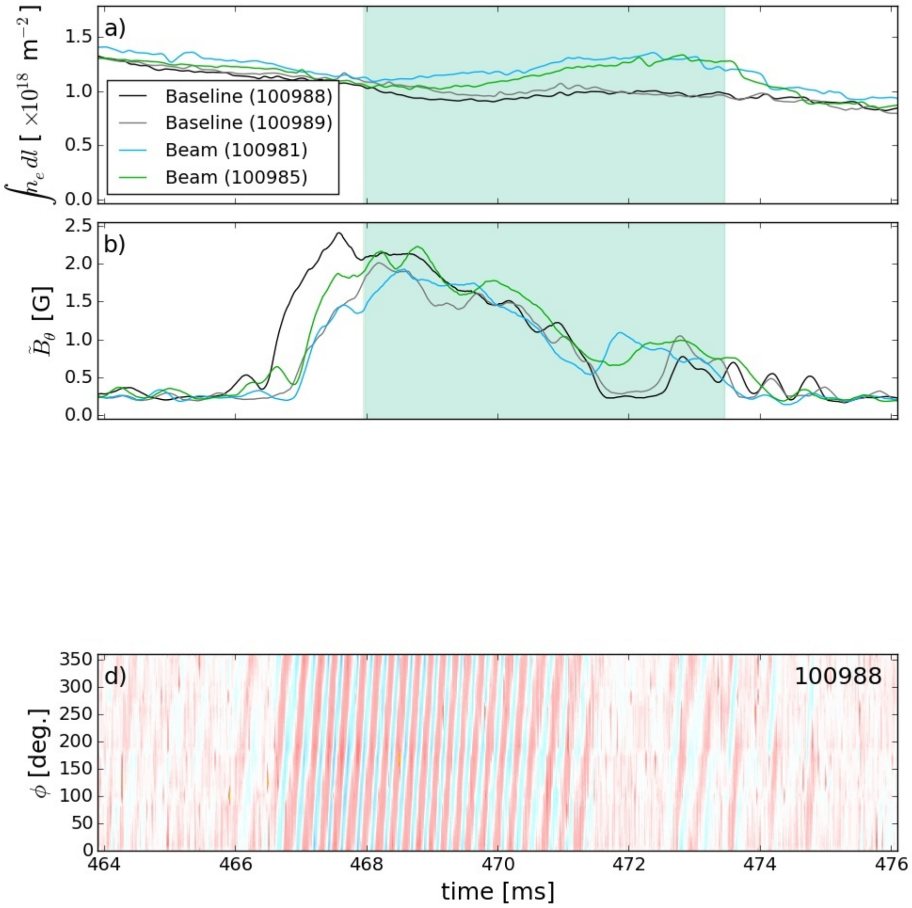
- $\Delta \int n_e dl \approx 33\% \int n_e dl$
  - ~ injected beam fluence
- Diamagnetics → Δp ~ 0



- $\Delta n_e >> \Delta p$ implies fueling during NBI is *cold* gas
  - Not seen with beam *gas* alone, only full NBI
  - Liberated from lithiated wall?
  - Jan. 2020: moderate T_e peaking during NBI
- Observations are all consistent with prompt fast ion losses

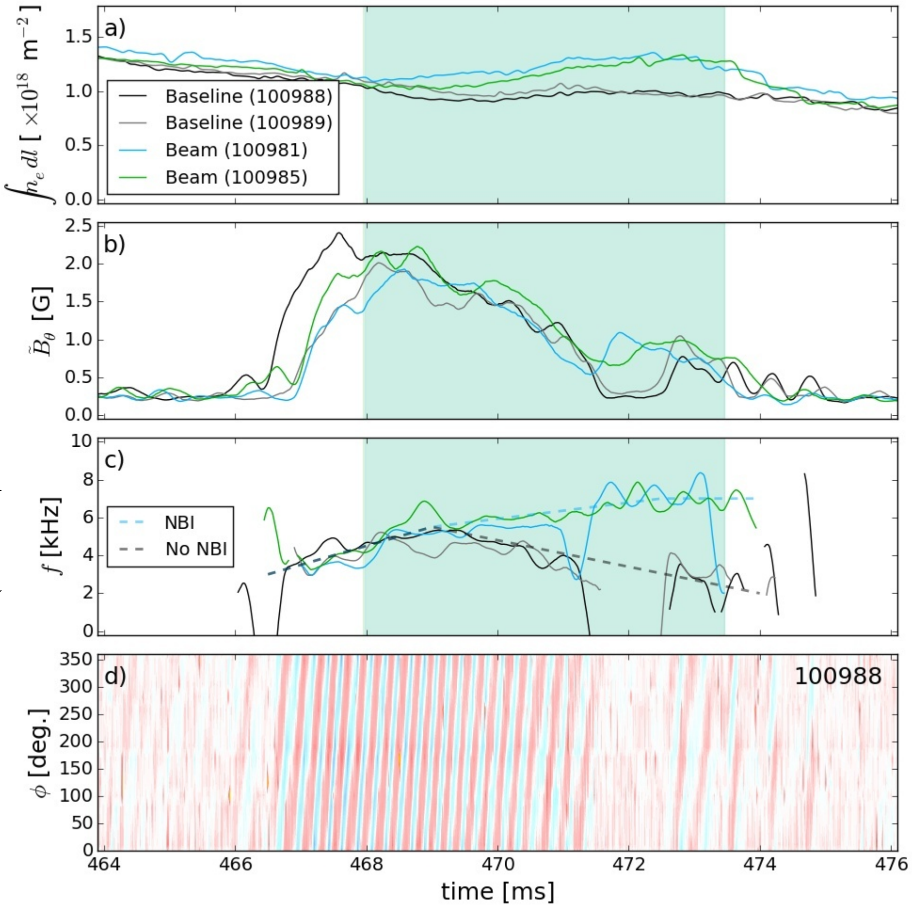
NBI Observations: Plasma Response

- MHD also consistent w/ Δp~0
  - n=1 mode amplitudes
  - Similar w/ and w/o NBI



NBI Observations: Plasma Response

- MHD also consistent w/ Δp~0
  - n=1 mode amplitudes
  - Similar w/ and w/o NBI
- NBI affects MHD *rotation*
  - $\Delta f_\phi^{spont} \sim -3.5\,\mathrm{kHz}$
  - $\Delta f_\phi^{NBI-opt} \sim -1.5\,\mathrm{kHz}$
  - $\Delta f_\phi = \Delta f_\phi^{NBI-obs} + \Delta f_\phi^{spont} \sim 1.5\,\mathrm{kHz}$
- *Counter*-NBI (+φ) torque
  - Consistent with fast ion loss



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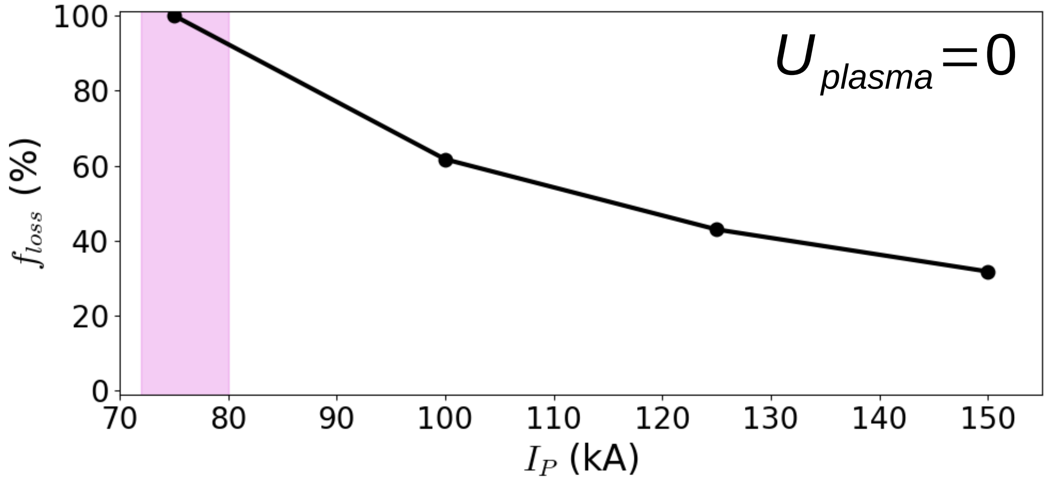
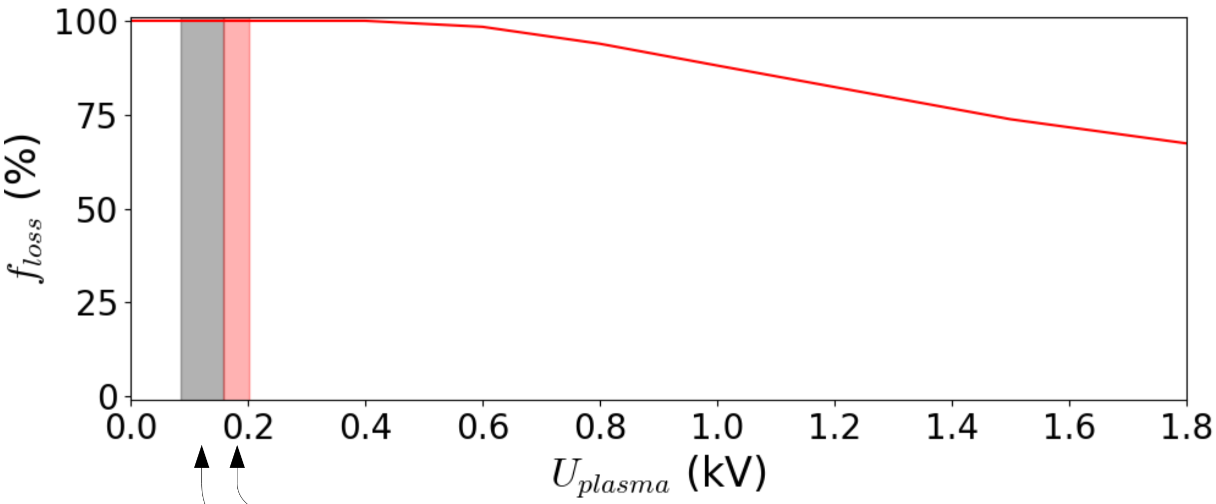
3Dorb models fast ion losses

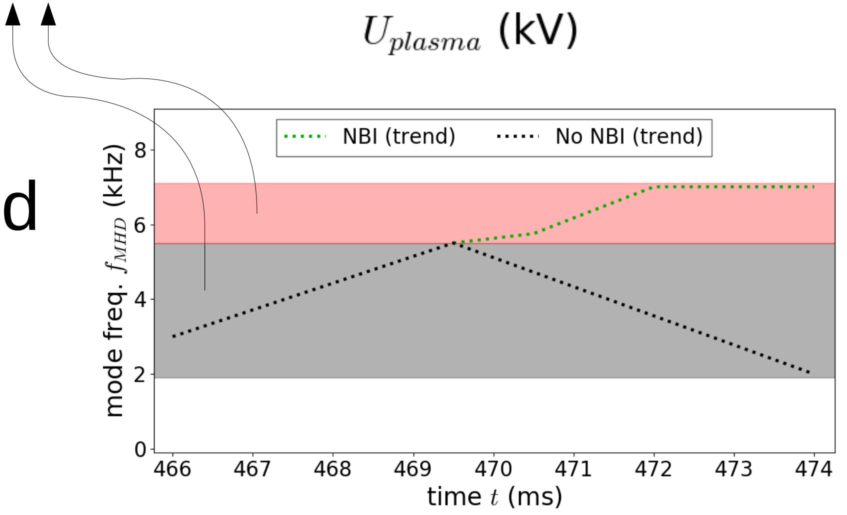
- 3Dorb: 3D particle tracker by Zakharov and Gorelenkov
  - Full orbit tracking
  - Axisymmetric wall model
  - Can include E_r effect on confinement of ions
- TRANSP+NUBEAM
  - Modeling in progress



3Dorb models f_{loss} vs U_{plasma}

- f_{loss} reduced by U_{plasma}
- Assuming $\vec{v}_{MHD} = \vec{v}_{\vec{E}_r \times \vec{B}_\theta}$
  - $U_{plasma} \sim v_{MHD} B_\theta r_a$
  - Shaded regions:
    - Black: Non-NBI
    - Red: NBI-accelerated
- Suggets neglecting E_r is valid for this discharge style





Torques estimated with analytic model

- Wesson-like n_e with $\int n_e dl$ from microwave interferometry
- Sum of torques...
  - Injected torque (-φ) $\vec{\tau}_{inj} = m_p \sum_\eta \sum_\epsilon \Gamma_\epsilon^\eta \bar{f}_{dep}^\eta (\vec{R}_{tan}^\eta \times \vec{v}_\epsilon)$
    - Fast beam ions damping against thermal population
  - JxB torque (+φ) $\vec{\tau}_{\vec{J}\times\vec{B}} = \langle \vec{R}_0 \times (\vec{J}_r \times \vec{B}_\theta) V_{\vec{J}} \rangle$
    - Lost ions → $+J_r$ with poor torque coupling
    - Ambipolarity → well coupled thermal ion $-J_r$
    - Poloidal & toroidal, but poloidal flow damped
  - Anomalous viscous Torque $\vec{\tau}_{anom} = m_p \langle n_e V_{\vec{J}} \rangle (\vec{R}_0 \times \vec{v}_\phi) / \tau_\phi$ [5]
    - τ_ϕ is the momentum confinement time
    - Torque damps acceleration, taken relative to spontaneous rotation

$$r_{dep} \equiv \int Q(r) dr / Q_{total}$$

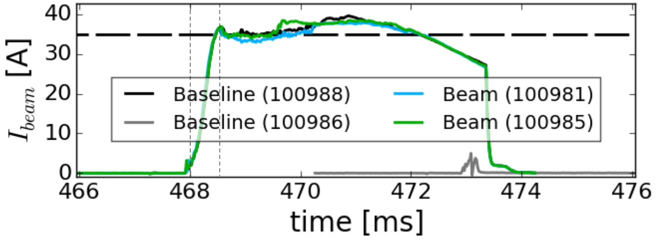
$$V_{\vec{J}} \equiv V_{plasma} (1 - r_{dep}^2 / a^2)$$

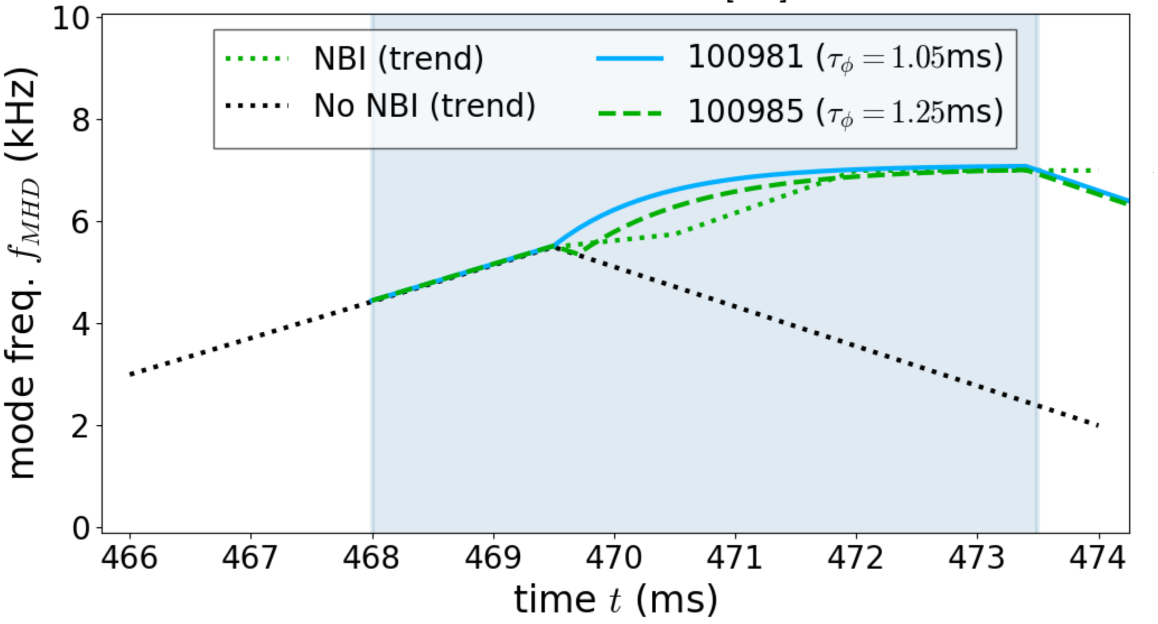
Rotation evolution reveals transport

- Torque balance: $\vec{\tau}_{tor} = \vec{\tau}_{inj} + \vec{\tau}_{\vec{J}\times\vec{B}} + \vec{\tau}_{anom}$
- NBI & No NBI trends from observations
- Torque modeling parameters:
  - Measured: I_{beam}, $\int n_e dl$
  - Estimated: $f_{shinethru}$, f_{lost}
  - Free parameter: τ_ϕ
- Best $\tau_\phi \approx 1.2\,\text{ms}$
  - Torque delayed

    $\tau_{delay} = \tau_\phi + \tau_{on}^{NBI} \approx 1.7\,\text{ms}$
  - $\tau_{E,i} \sim \tau_\phi$ [C.S. Chang 1999 *NF*]

$\tau_{on}^{NBI} \approx 0.5\,\text{ms}$





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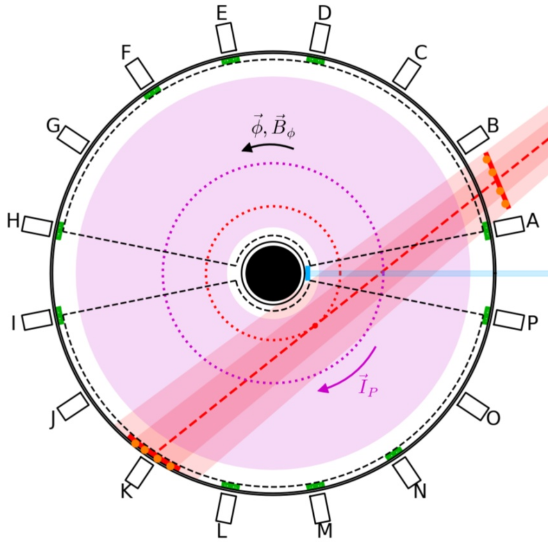
Conclusions

- NBI now standard in LTX-β operation
- Toroidal Mirnov array implemented for stability studies
- Pre-existing n=1 mode counter-accelerated by NBI
  - Suggests prompt loss of NBI ions
    - J_r generates counter-I_P $J \times B$ torque
- Analytic model suggests $\tau_{\phi}, \tau_{E,i} \sim 1.2\,\mathrm{ms}$
  - Compare $\tau_{E,e} \approx 1\,\mathrm{ms}$ (lower-I_P shots with TS)

Conclusions – Future Work

- NBI operation: improved beam divergence
  - Power supply renovation planned
    - Should also increase beam duration
- Plasma operation: higher I_P, reduced f_s, longer discharge
  - OH capacitor bank upgrade planned to double C_{OH}
- Diagnostics: density and temperature profiles
  - Thomson scattering adding HFS chords
  - T_e and v_φ profiles from CHERS (requires higher T_e)

Thank You



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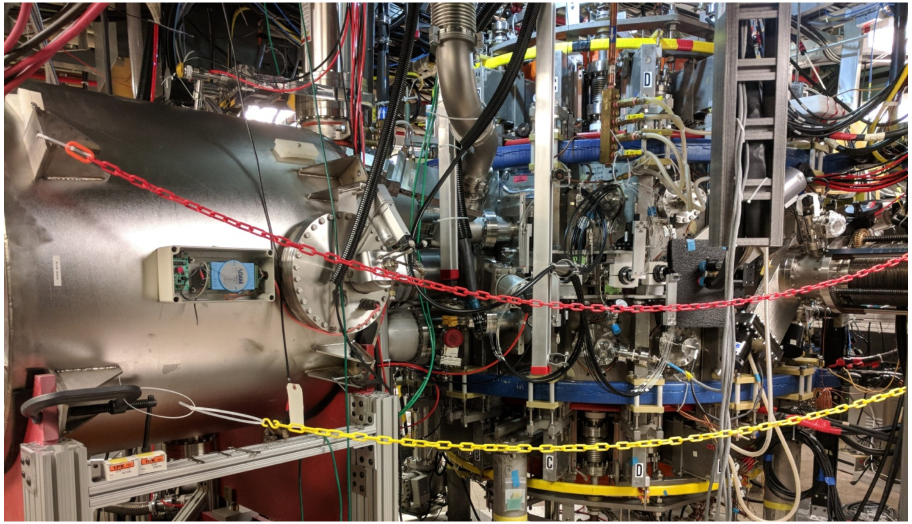
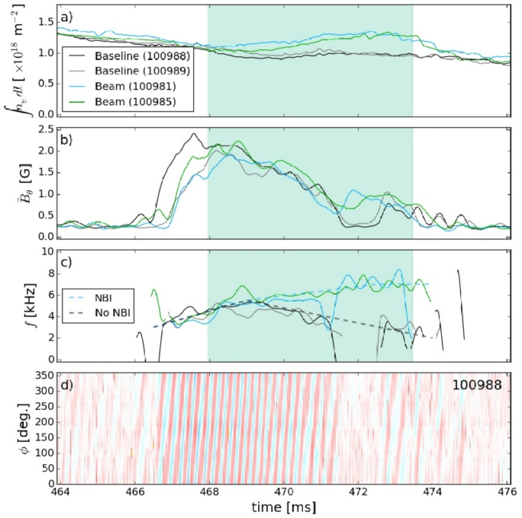
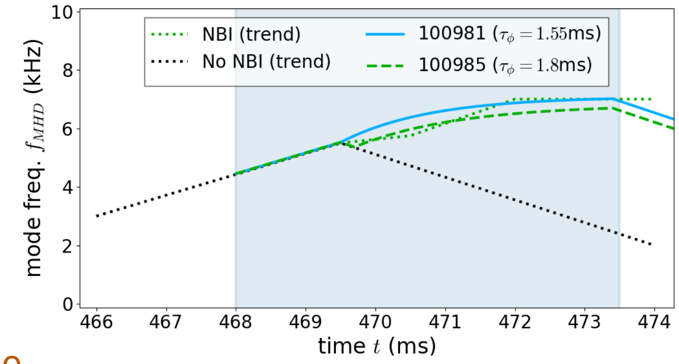




a)
Baseline (100988)
Baseline (100989)
Beam (100981)
Beam (100985)
b)
c)
NBI
No NBI
d)
100988
time [ms]



NBI (trend)
No NBI (trend)
100981 ($\tau_\phi = 1.55$ms)
100985 ($\tau_\phi = 1.8$ms)
mode freq. f_{MHD} (kHz)
time t (ms)

Extra slides: References

[1] On Lithium walls: S.I. Krasheninnikov 2003 *PoP*

[2] Flat T_e in LTX: D.P. Boyle 2017 *PRL*

[3] Lithium PFCs in LTX: R. Majeski 2017 *PoP*

[4] Magnetics in LTX environment: P.E. Hughes 2018 *RSI*

[5] Plasma rotation under J_r: C.S. Chang 1999 *NF*

[6] Momentum transport: J.E. Rice 2008 *J. Phys.: Conf. Ser.*

Extra Slides: Magnetics and lithium

- Lithium damages magnetics
  - Flows to coat surfaces
  - Infiltrates ceramics
  - Shorts windings
  - Corrodes copper wire
- Damaged past LTX sensors
  - Three in-shell poloidal arrays
  - ~2/3 of shell-edge poloidal array

Extra Slides: Mirnov analysis

- Equilibrium subtraction

  1) $n = 0$ component

  2) σ=167μs Gaussian-smoothed local signal

- Biorthogonal decomposition (SVD)
  - Normalize each signal $\bar{S}_i = S_i / \sigma_{S_i}$
  - SVD yields $\hat{U} \cdot \hat{\Sigma} \cdot \hat{V}^* = \hat{S}$
    - Spatial (U) and temporal (V) modes
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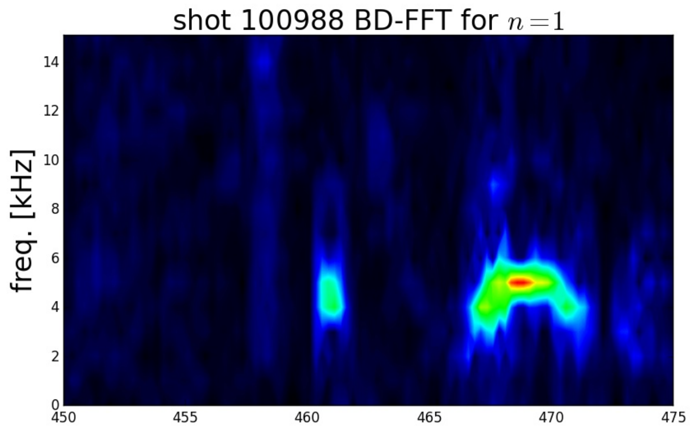

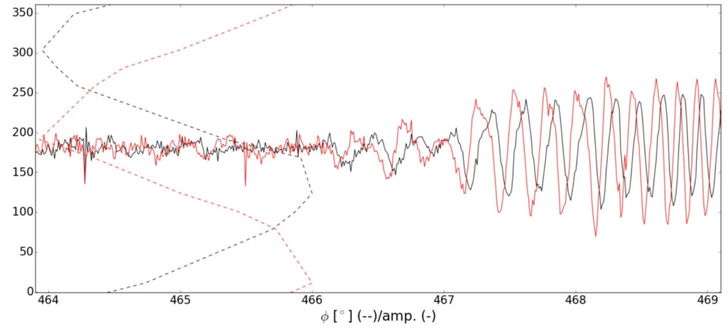

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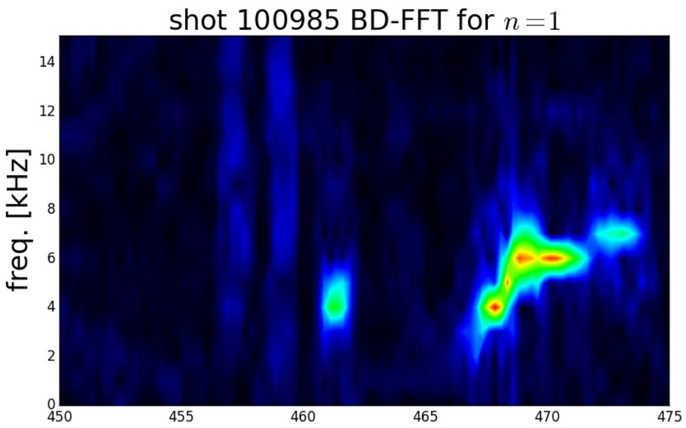
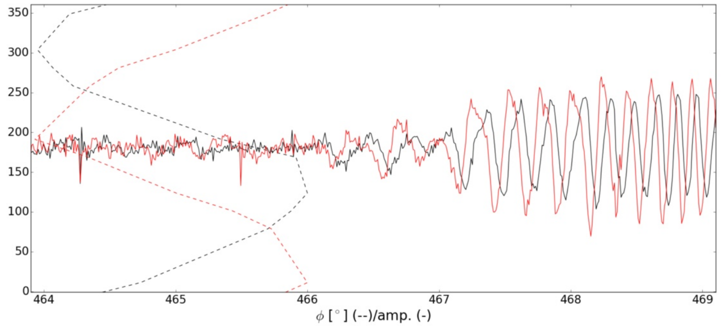
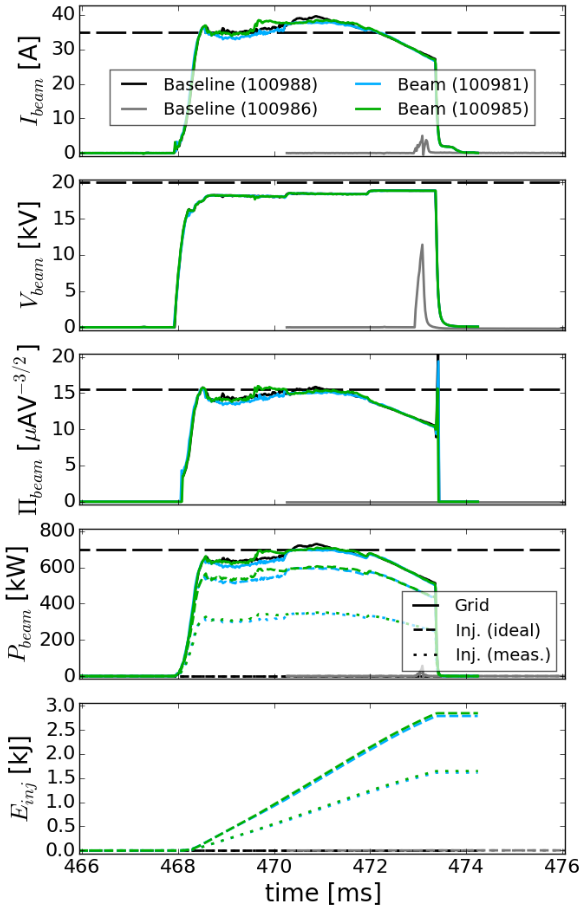




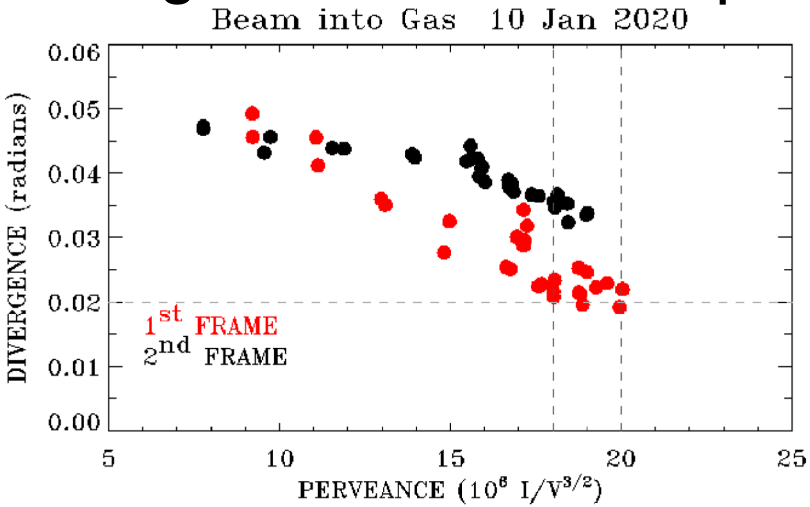
Extra Slides: Beam parameters

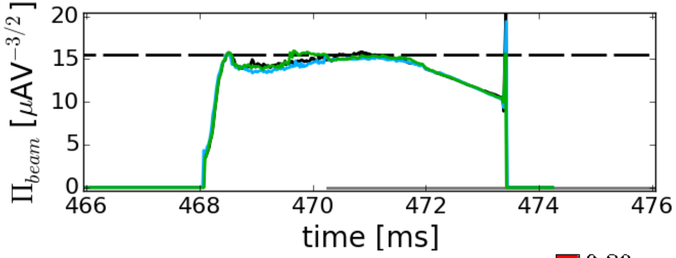
- Beam sourced by arc chamber
  - Gas feed at anode & cathode
  - Provides ions and electrons to grids
  - Biased relative to accel grid
- Accel grid at V_{beam}
  - Also electron decel grid & ground grid
- Perveance/divergence relationship
  - Fast variation complicates measurement
  - Nominal perveance ~15μA/V$^{3/2}$

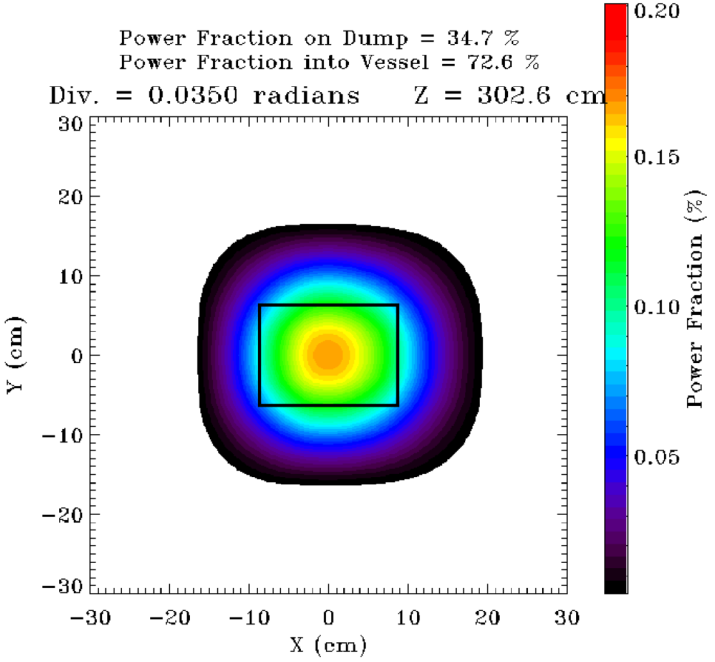


Extra Slides: Beam profile

- Beam divergence varies with perveance



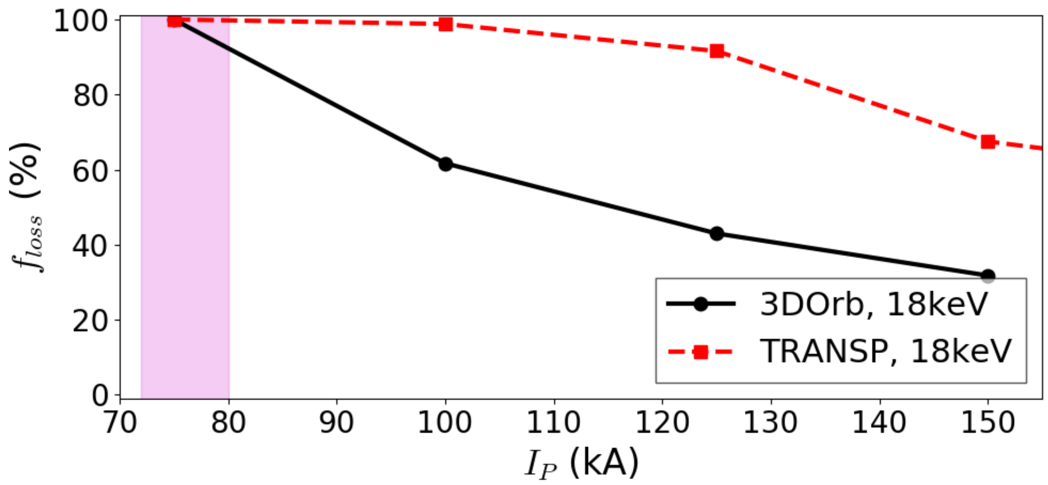




- Beam dump is far past beam waist
  - Small fractional solid angle
  - Shells above/below dump plate

Extra Slides: 3Dorb vs TRANSP

- Good agreement at low plasma current
- TRANSP results suspect
  - Equilibrium differences under investigation
  - Close to 3Dorb if ions are counted lost at LCFS



- Discrepancy to be resolved/understood for upcoming paper

Extra Slides: Poloidal flow damping

- Magnetic pumping can be conductive or viscous
- In target discharges, modestly noncollisional: $\tau_{ii} \approx 2 \times (q_a R_0)/v_{th}^i$
  - Implies intermediate damping timescale
  - $\tau_d^{cond} \sim \tau_{ii} \approx 90\,\text{ms}$
  - $\tau_d^{visc} \sim (q_a R_0 / v_{th}^i)^2 / \tau_{ii} \approx 20\,\text{ms}$
- Damping fast compared to beam: $\tau_d^{cond} \sim \tau_d^{visc} \ll \tau_{beam}$
  - Suggests poloidal motion is saturated
  - Measured acceleration dominantly toroidal

Extra Slides: Analytic approximations

LTX-β

- Beam width modeled as multiple rays
- Local deposition w_{dep} along ray scaled to ray-integrated n_e
  - Re-scaled to central ray-integrated density and shinethru
  - $dw_{dep} \approx \frac{n_e(r) f_s^0 A_{ray}\, ds}{\int n_e^0 ds}, \quad r \equiv r(s)$
- Integrated over all rays
  - Momentum deposition yields NBI torque
  - Charge deposition yields JxB torque
- Also yields weighted $r_{dep} \equiv \int Q(r)\, dr / Q_{total}$
- $V_{\vec{j}} \equiv V_{plasma}\left(1 - r_{dep}^2 / a^2\right)$