Fast ion physics at Wendelstein 7-X

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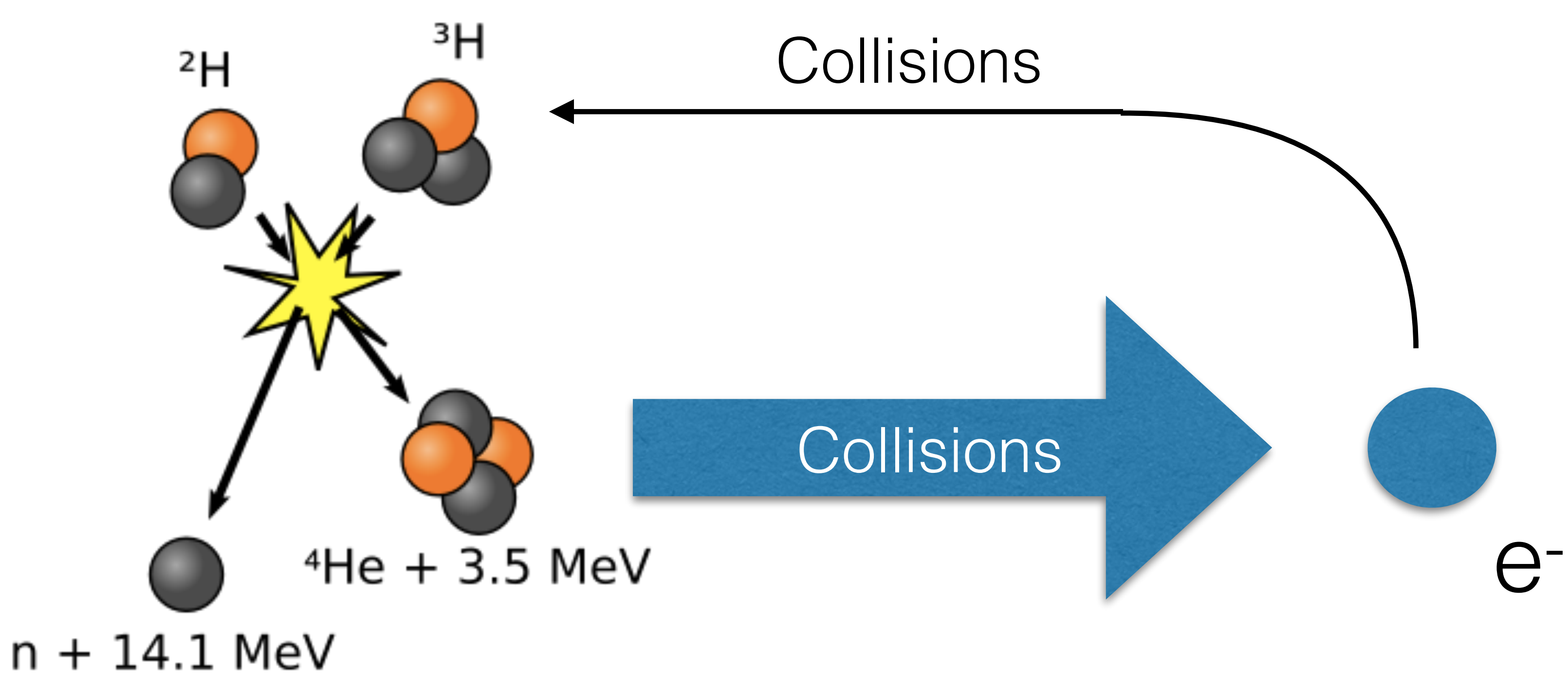
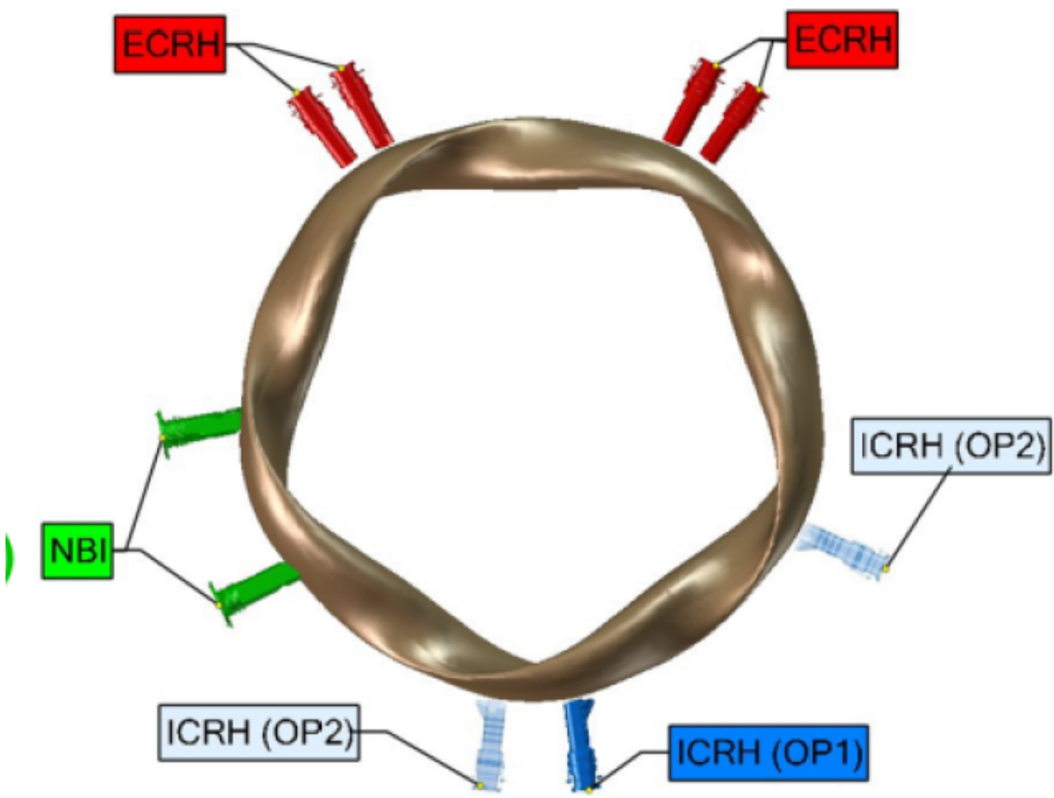
Why do we care about fast-ions in stellarators?

- Stellarators provide a transient free, disruption free, steady-state path to a fusion reactor.
- Deuterium-Tritium fusion produces 3.5 MeV He particles.
- These particles must slow down on the background plasma, thus heating it.
- If the particles aren't confined long enough to heat the plasma we cannot reach a burning plasma scenario.



What does Wendelstein 7-X offer as a facility?

- A neoclassical optimized, finite beta, long pulse stellarator
- Fast-ion generation systems
  - Two 55 keV neutral beams (~7 MW of heating)
  - ICRH system (~2 MW of heating)
- Flexible coil set
  - Seven superconducting shaping coils (iota, position, magnetic mirror)
  - Ten copper steady state RMP coils
  - Five copper steady state Trim Coils
- A large set of physics characteristics
  - Plasma densities from 5E18 to 2E20
  - Mode control with ECCD
  - Pulse lengths up to 1800s



The goal is to demonstrate optimization of stellarators for energetic particle confinement

- STELLOPT: Physics based tool for stellarator design
- BEAMS3D: Energetic particle code for stellarators
- STELLGAP: Tool for Alfvén continuum in stellarators

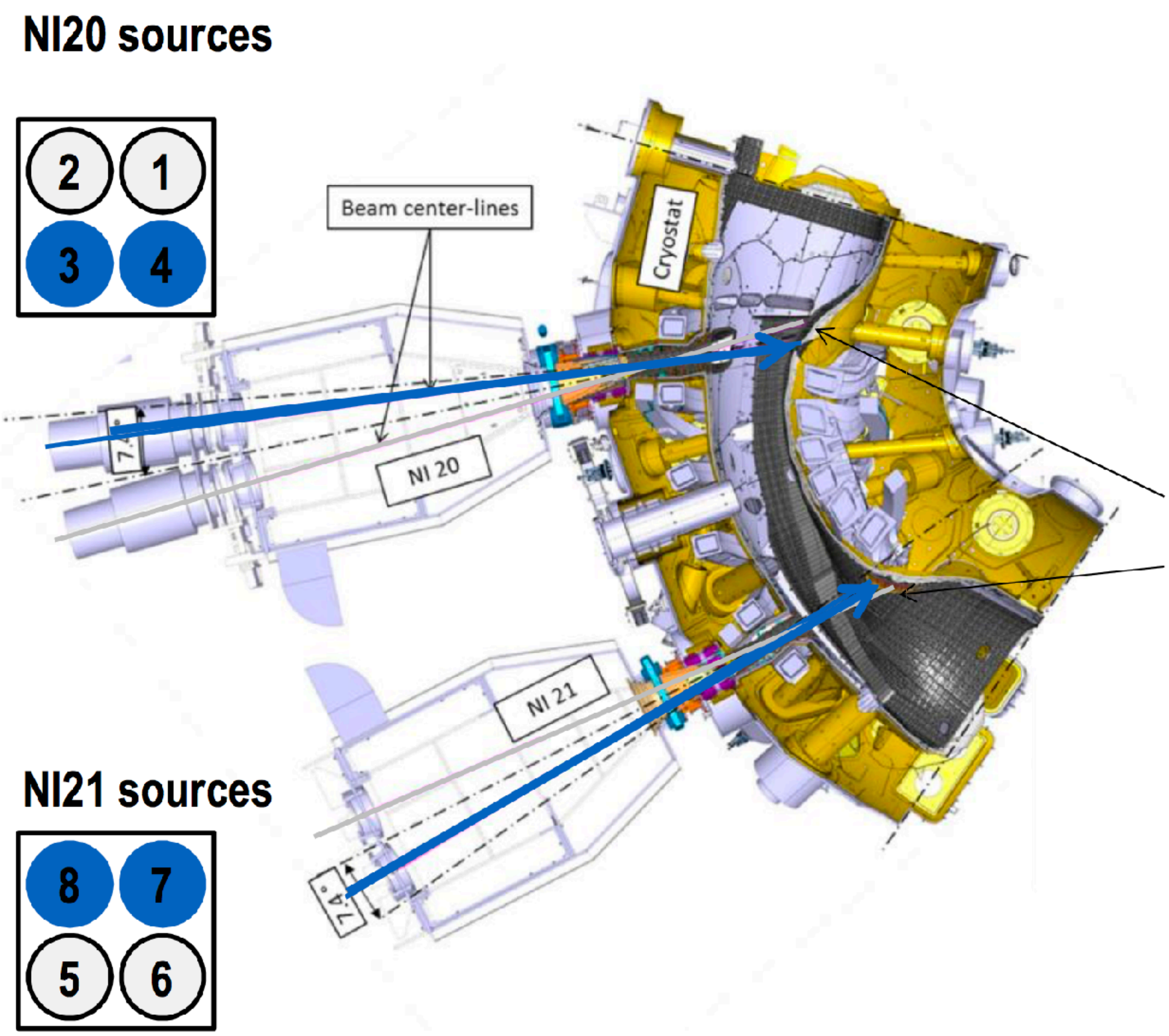
The Plan

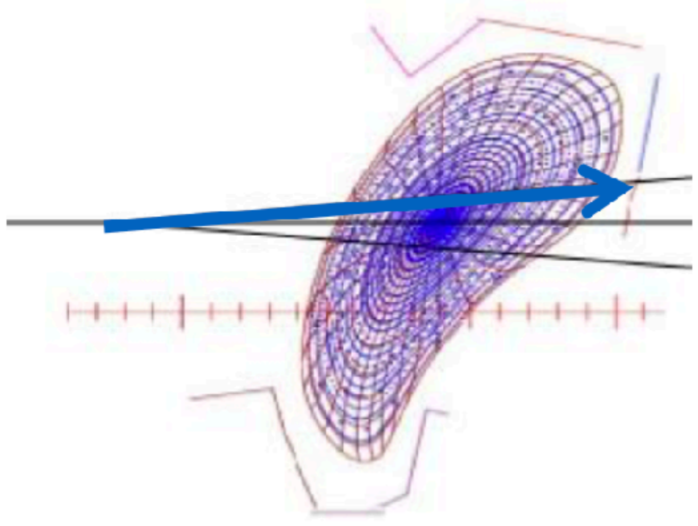
1. Validate the NBI deposition and loss estimates of BEAMS3D using W7-X data
   - Reconstructed Equilibria (from STELLOPT)
   - Measurements of beam deposition (from spectrocopy)
   - Measurements of wall losses (from IR cameras, fast ion loss detectors)
2. Validate the STELLGAP code using W7-X data
   - Reconstructed Equilibria (from STELLOPT / WAPID_FIT)
   - Measurements of mode activity (from Phase Contrast Imaging, Rogowski coils)
3. Validate an optimization capability for fast ions using W7-X.
   - Couple BEAMS3D to STELLOPT
   - Couple STELLGAP to STELLOPT
   - Create magnetic configurations with improved and degraded confinement

W7-X commissioned two NBI sources in OP1.2b

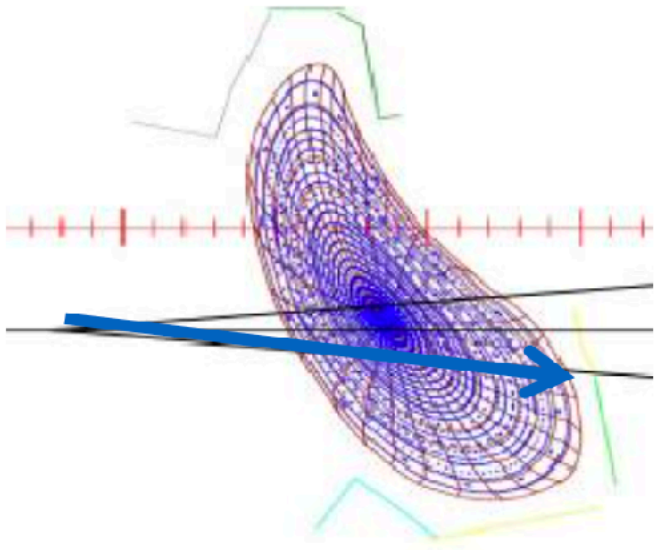
- One of two NBI boxes brought online in OP1.2b
  - Two Hydrogen ~1.8 MW sources at 55 keV
  - Co-injection geometry
- Fast Ion Highlights
  - No ion cyclotron emissions detected
  - Alfvén Eigenmodes appear in isolated discharges
  - 1200 ms of ECRH+NBI operation in High Mirror
  - 5000 ms of NBI heating in High Mirror
  - Attempts for OXB heating not successful
- MPM mounted NIFS-FILD system under analysis
- ICRH not yet ready (expect in 2021)

Neutral Beam Injection on W7-X

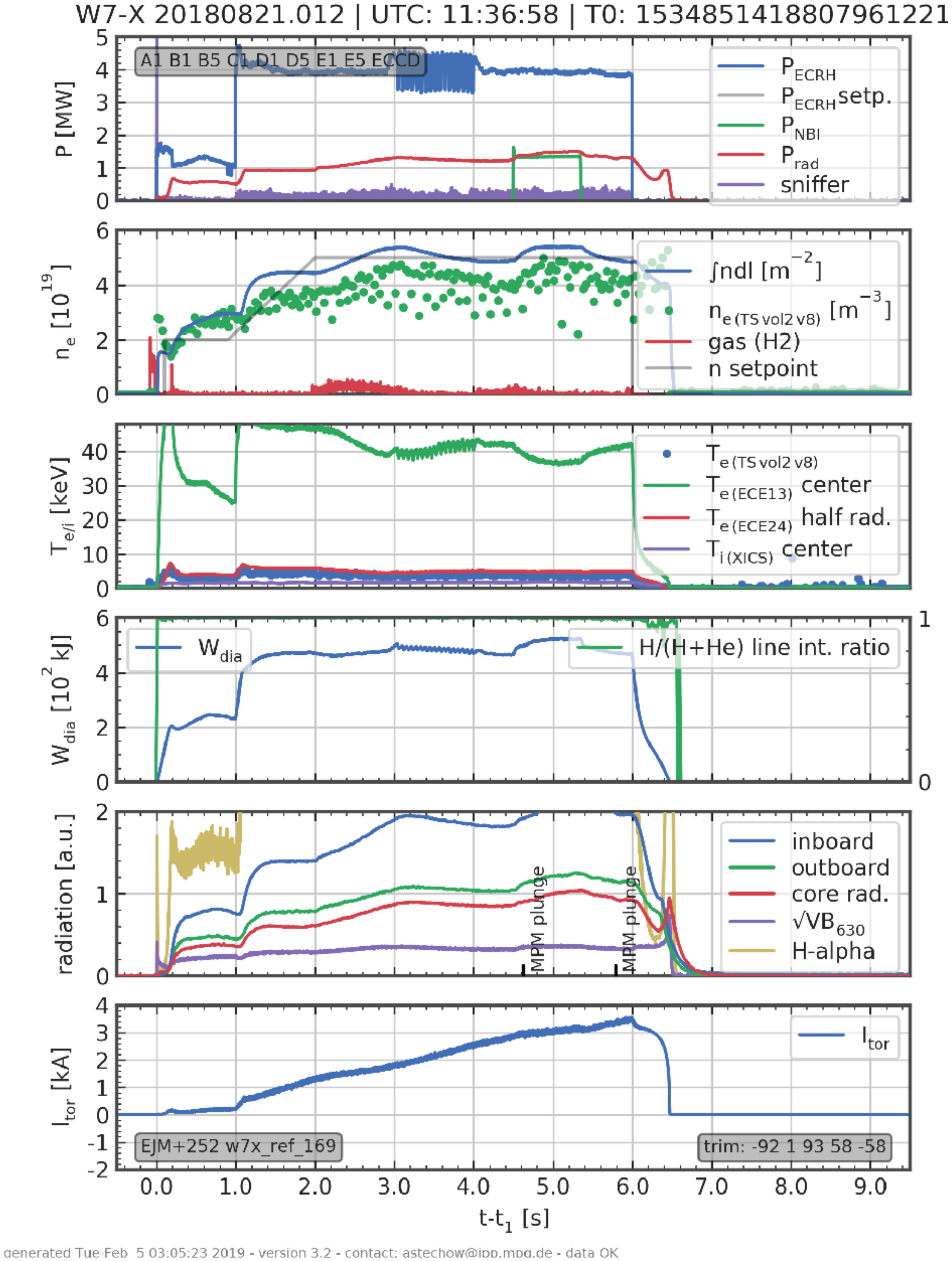




Beam dump area:
All areas are covered with actively cooled structures

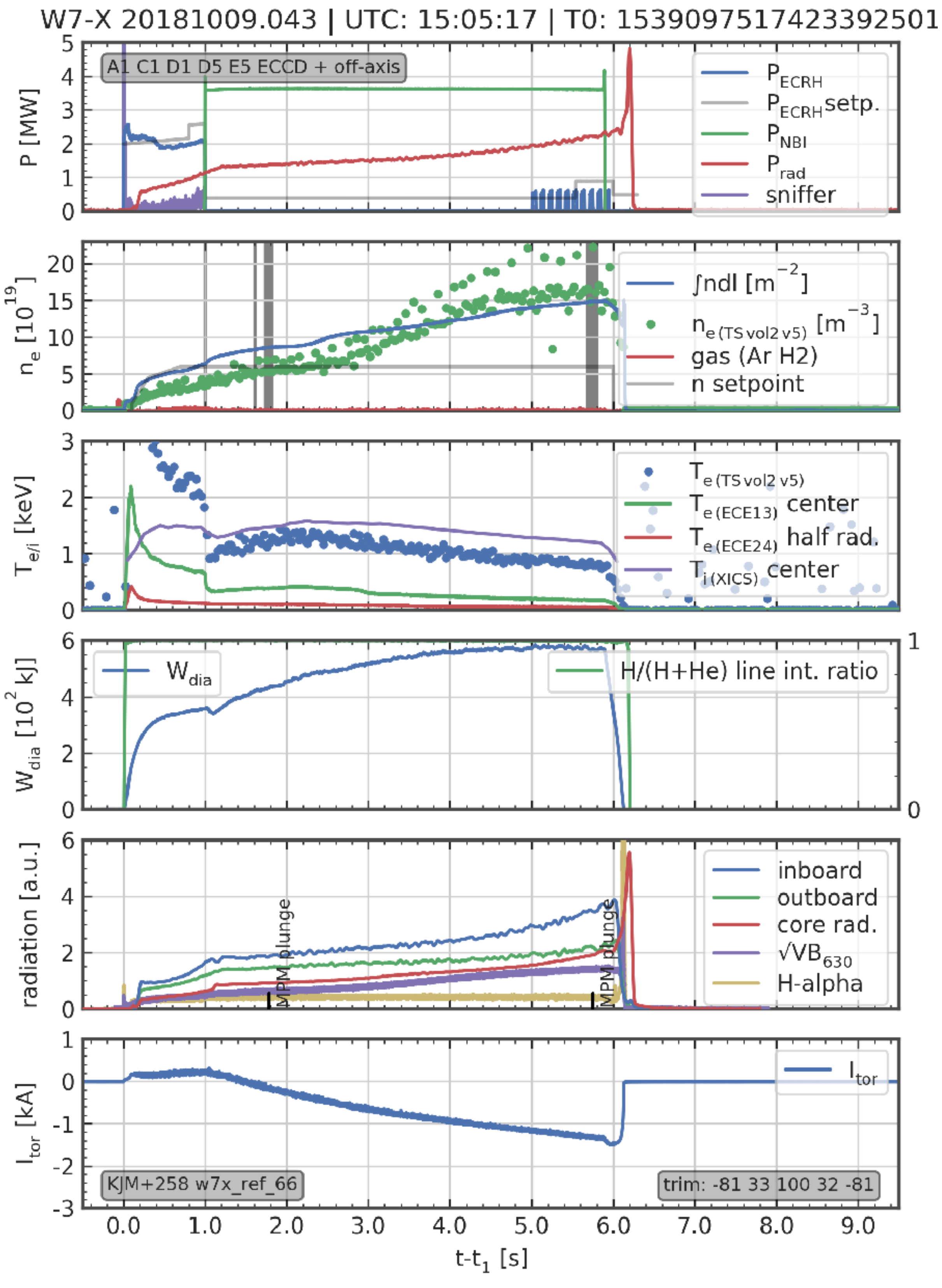


W7-X ECRH+NBI Discharge



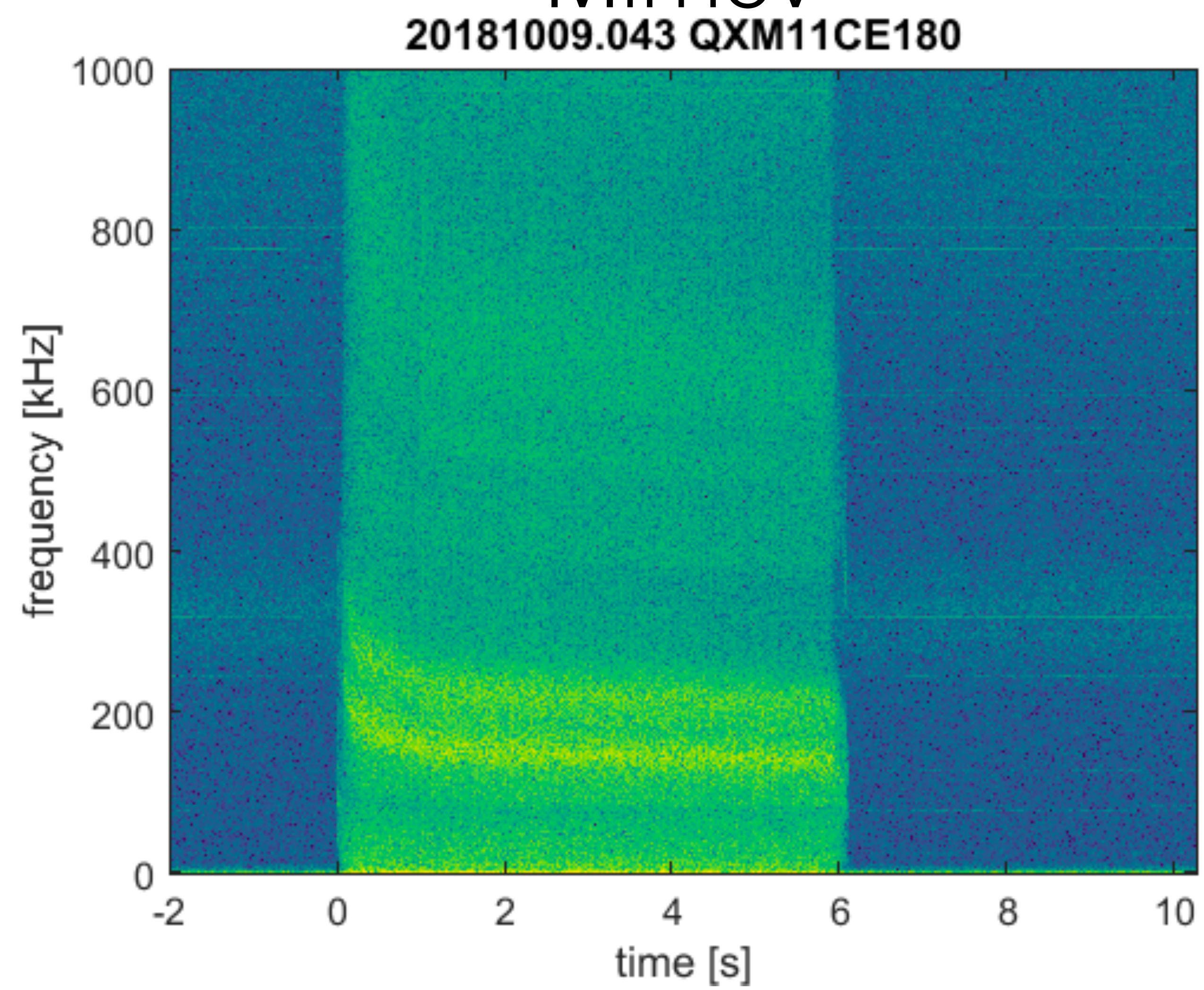
- Density asymptotes
- Ion Heating Modest
- Modest stored energy increase

W7-X Pure NBI Discharge

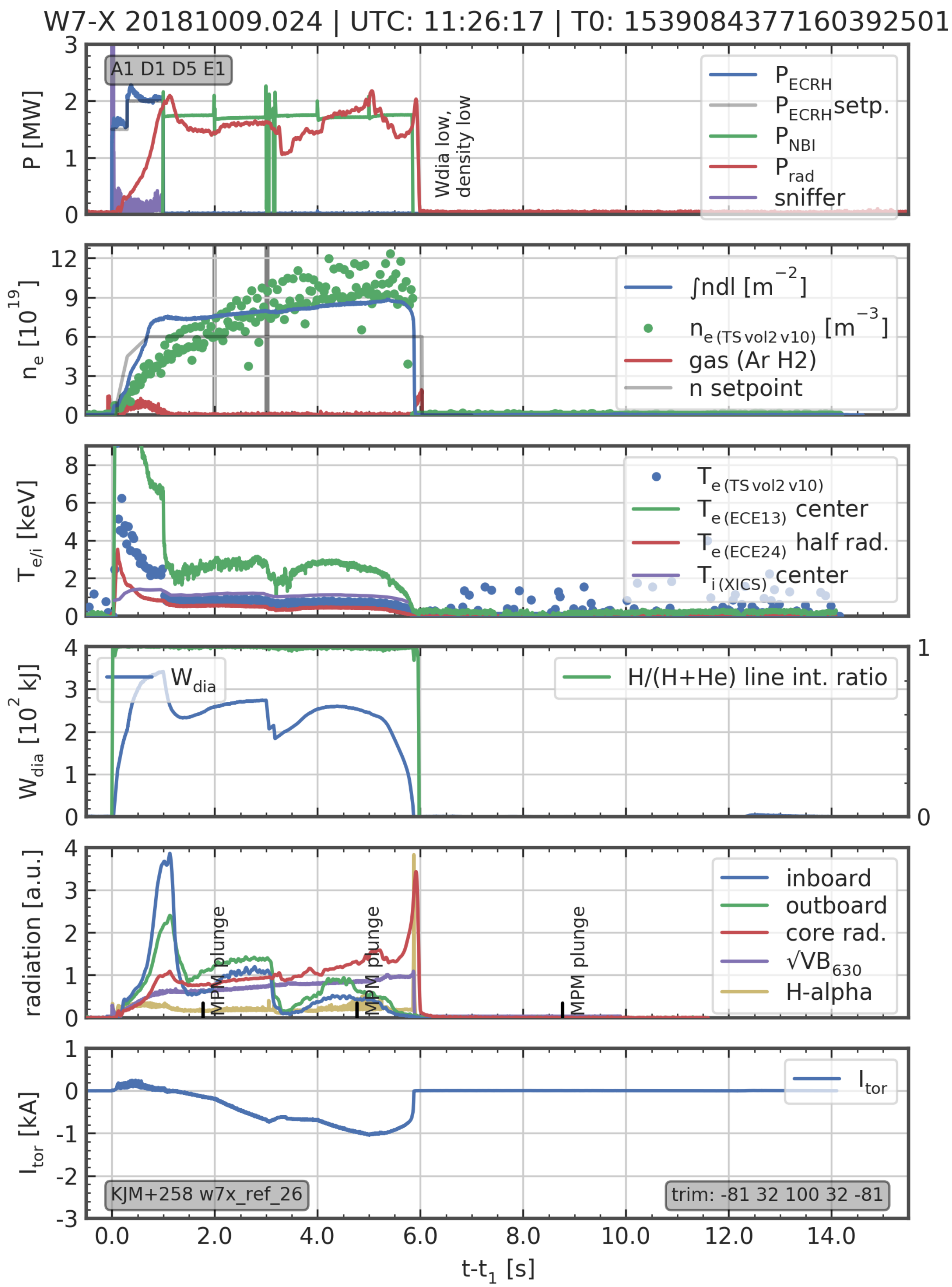


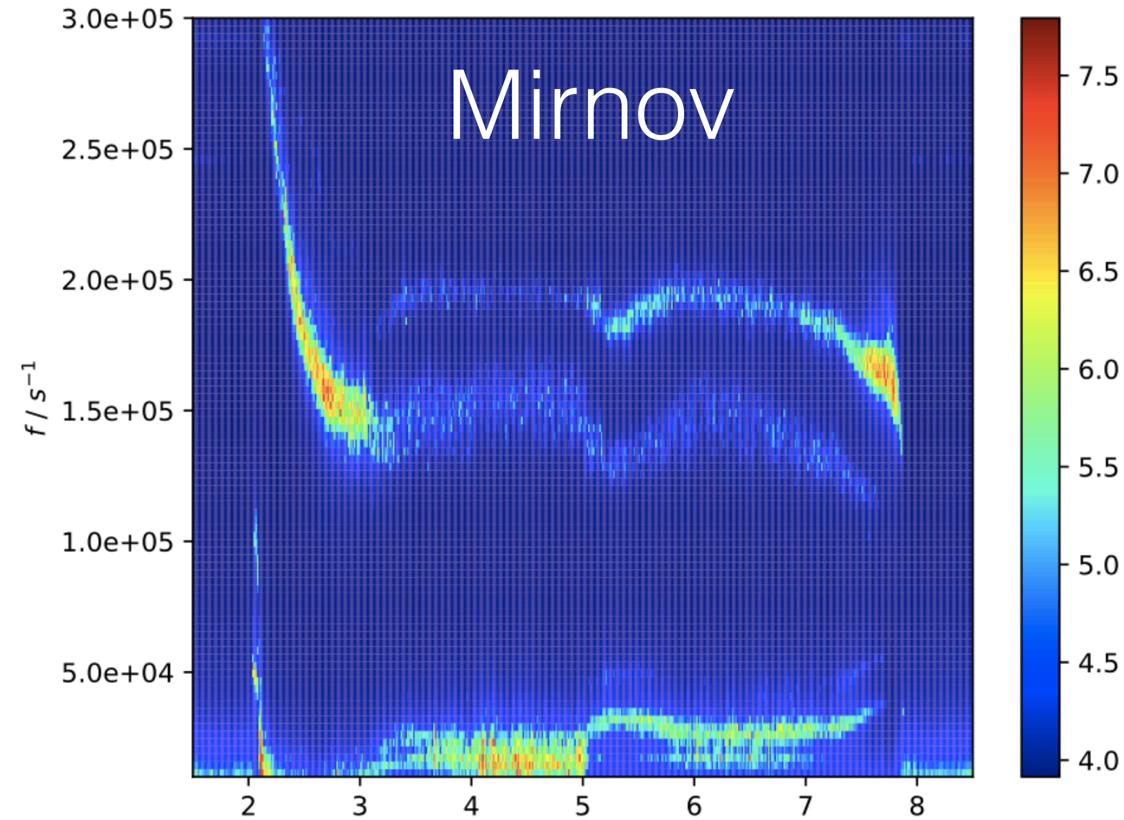
- Strong fueling
- Ion Heating Modest
- Store energy asymptotes
- Electron temperature falls

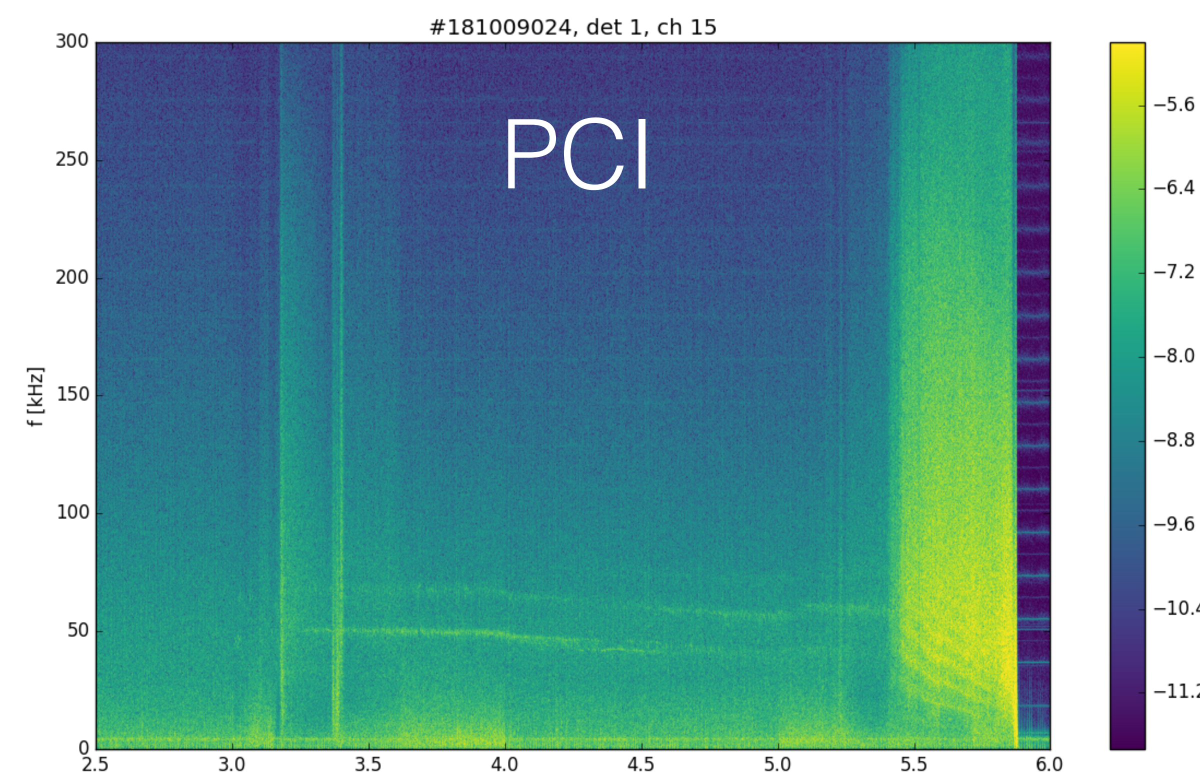
Mirnov



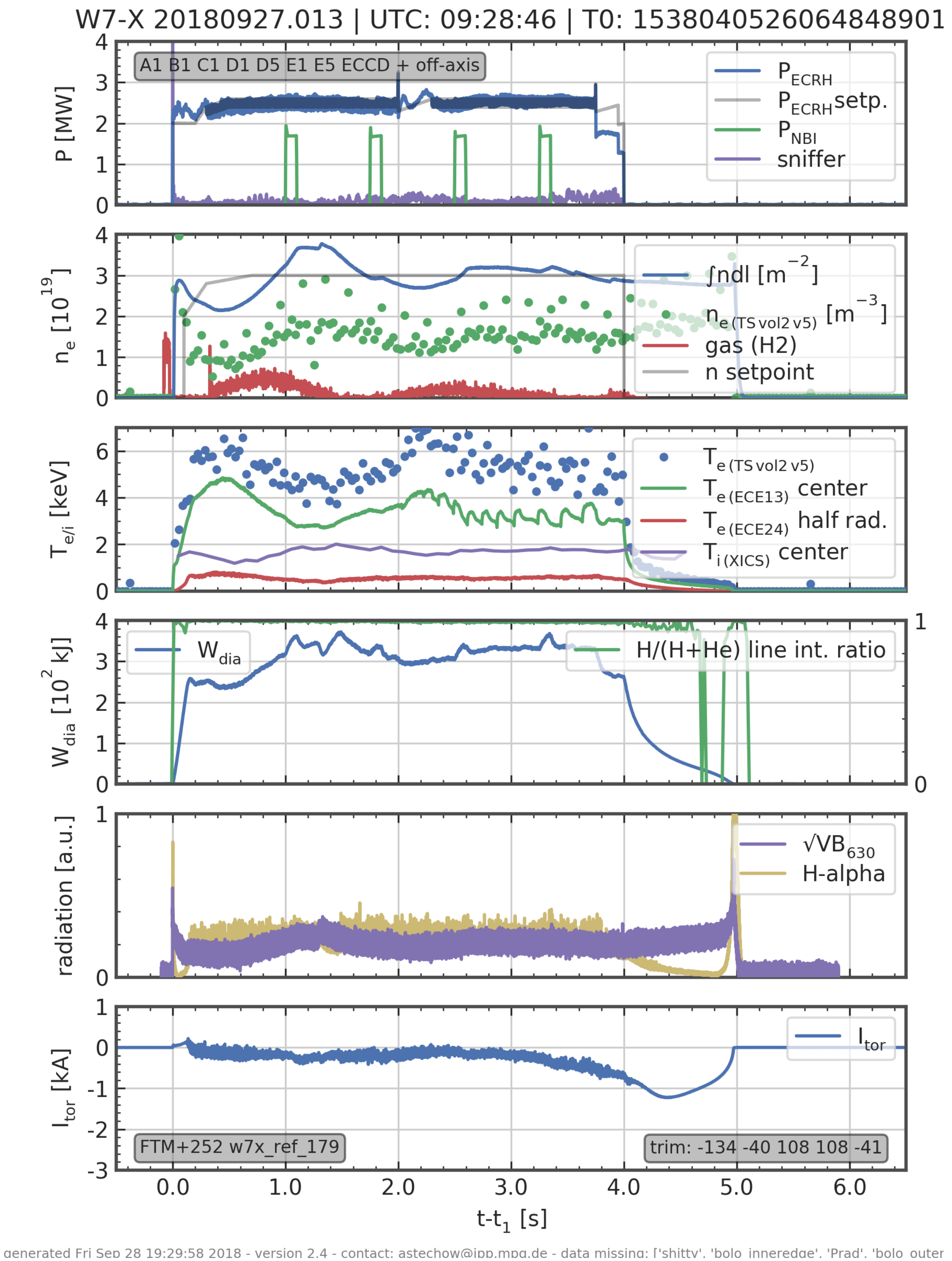
Presence of Alfvénic activity is infrequent





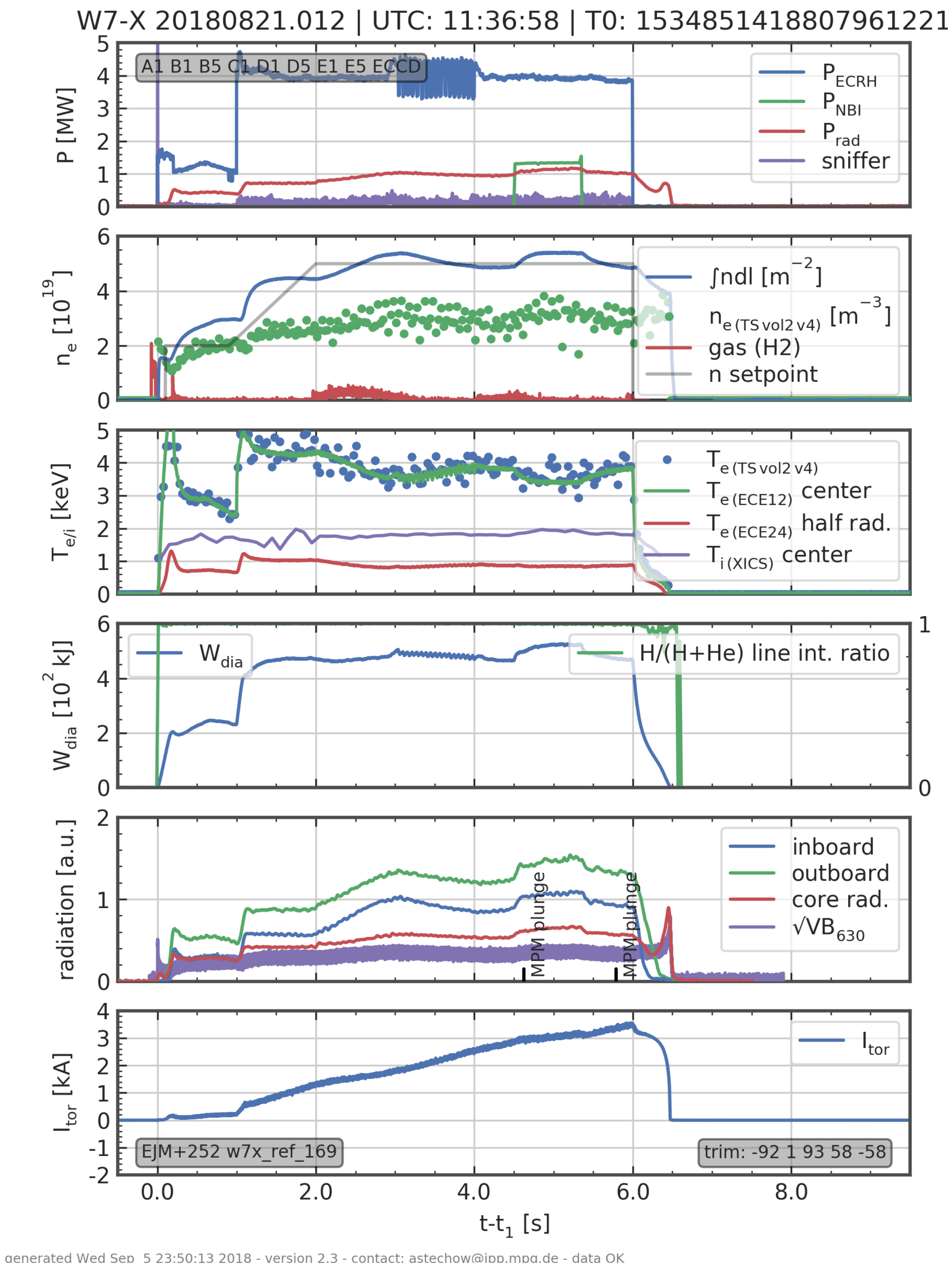


Effect of sawteeth under evaluation



- ECCD from t=2 s triggers sawtooth
- Seen clearly in ECE core channel
- Iota ~ 1 on axis

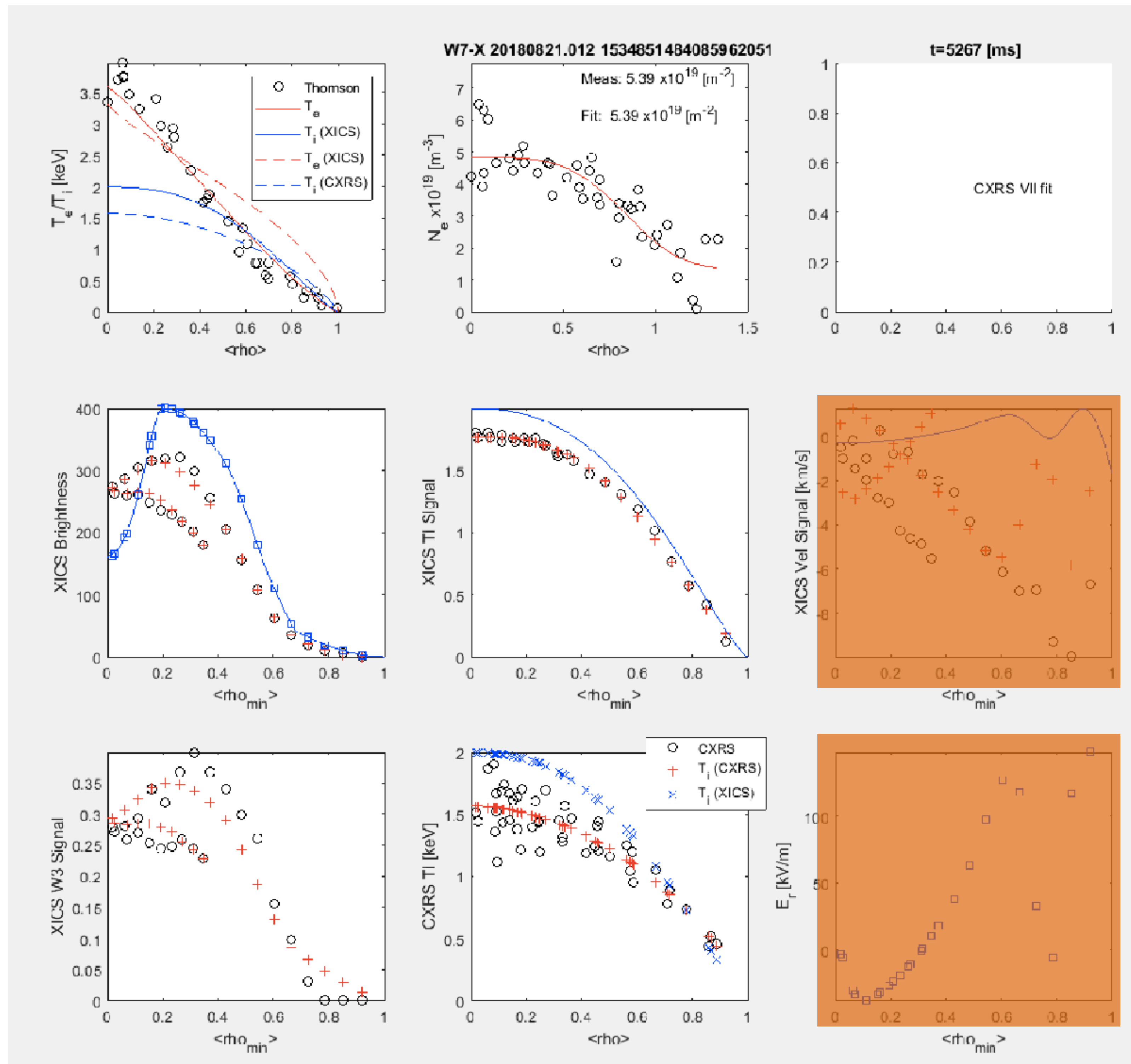
Code validation discharges identified



- Scan of density in Standard configuration
  - 2E19
  - 5E19
  - 7E19
- Scan of rotational transform
  - 5/4
  - 5/5
  - 5/6 (low iota TBD)
- Scan of mirror term
  - Standard
  - High Mirror

Validation begins with profile reconstruction

- WAPID_FIT
    - Fast Inversion
    - Vacuum LCFS
    - VMEC ß=0
    - Thomson (Te, ne)
    - XICS (Ti,Te,Er)
    - CXRS (Ti)
- STELLOPT
    - Eq. Recon.
    - Magnetics (DIAGNO)
    - ECE (TRAVIS)
    - Thomson (Te, ne)
    - Inteferrometry
    - XICS (Ti, Te, Er)
    - CXRS (Ti)



STELLOPT Reconstructions are more intensive

- Self-consistent equilibria (pressure, current, fixed/free boundary)

Fit parameters

Equilibrium
- Ne (gauss_trunc)
- Te (8 knot spline)
- Ti (8 knot spline)
- dI/ds (power_series)
- Total Toroidal Current
- Total Toroidal Flux

Additional
- XICS W emissivity (8 knot spline)
- Phi (power_series)

Reconstructed Signals

STELLOPT
- Thomson Ne (Ne)
- Thomson Te (Te)
- XICS W Brightness (W emis.)
- XICS Ti (Ti, W emis.)
- XICS W3 (Te, W emis.)
- XICS vel (Phi)
- CXRS (Ti)

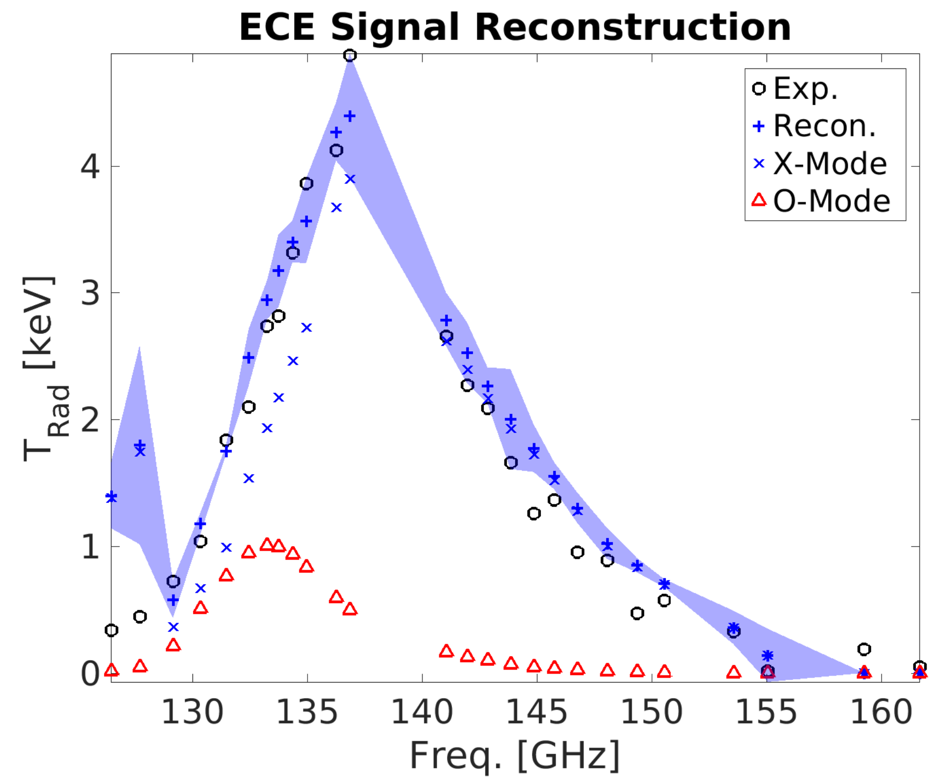
DIAGNO
- Flux loops (p, j, Flux)
- Rogowski coils (p, j, Flux)

TRAVIS
- ECE (Te, Ne, Flux)

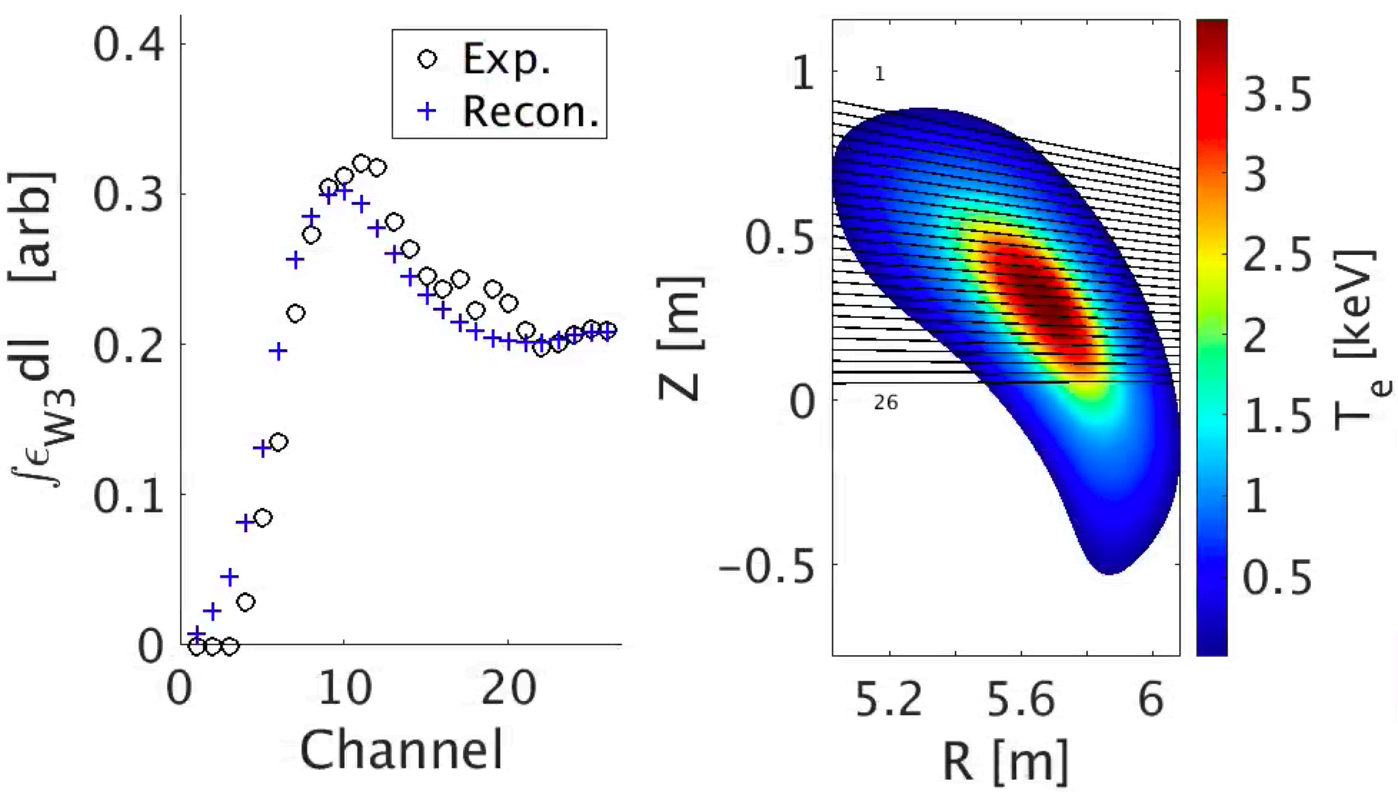
- Single time slice: 10 hrs, 2176 procs. Cori KNL

Electron temperature profile is well determined

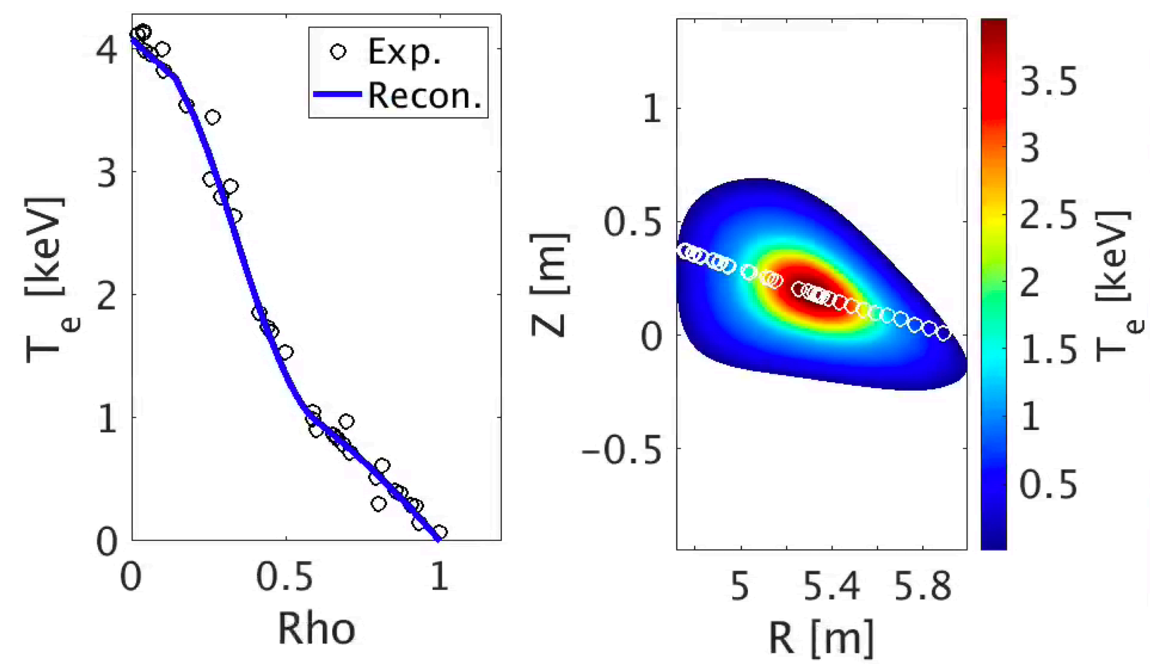
- Thomson provides HFS/LFS fit
- ECE reconstruction looks good
  - Sensitive to ne, Te, and PHIEDGE
  - Full TRAVIS model
- XICS W3 Factor also in good agreement



XICS

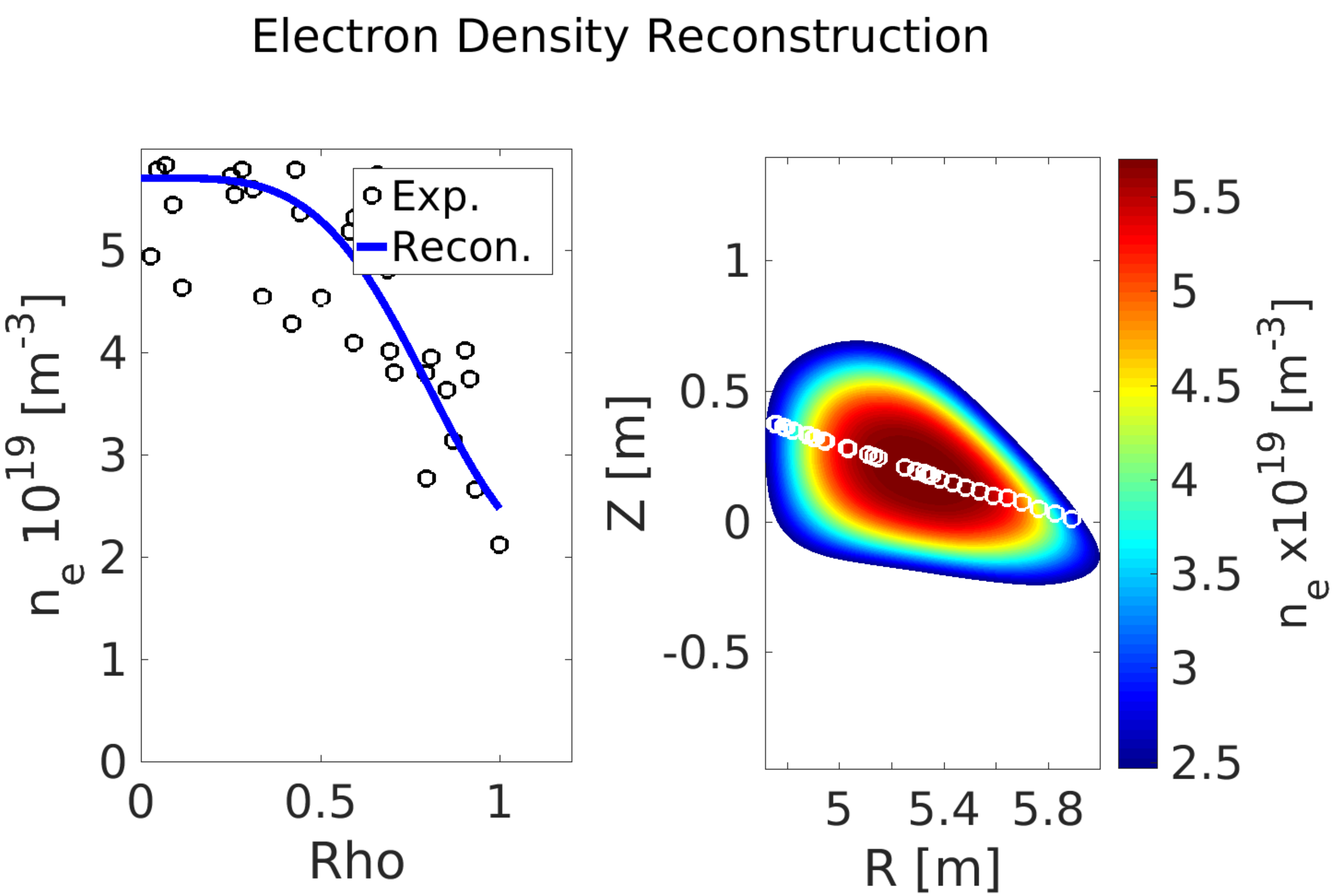


Thomson



Electron density?

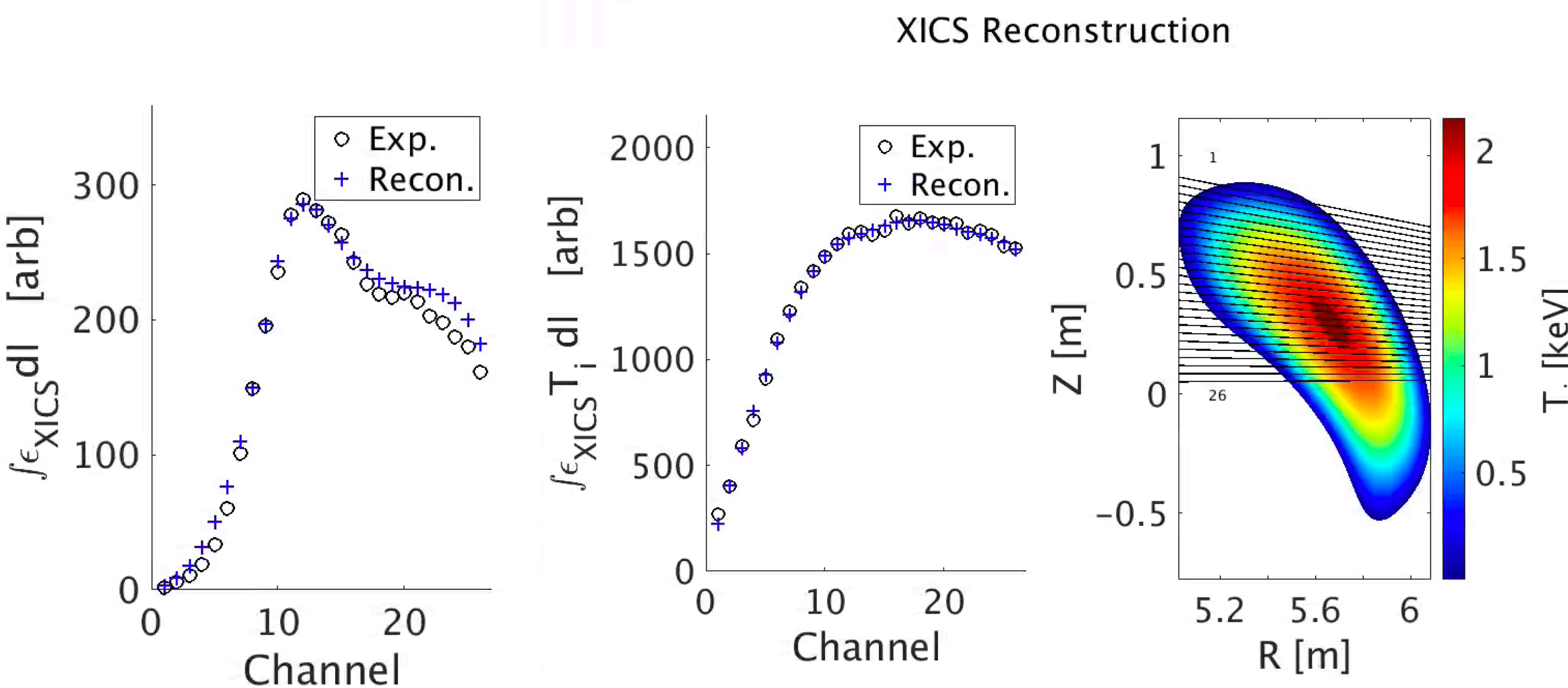
- Interferometer used to determine density amplitude
- Thomson normalized to force feedback on profile
- ECE provides information on Ne as well



Alkali Metal Beam could help

Ion temperature consistency improving

- Fit to XICS looks is good
- Consistence with CXRS under investigation

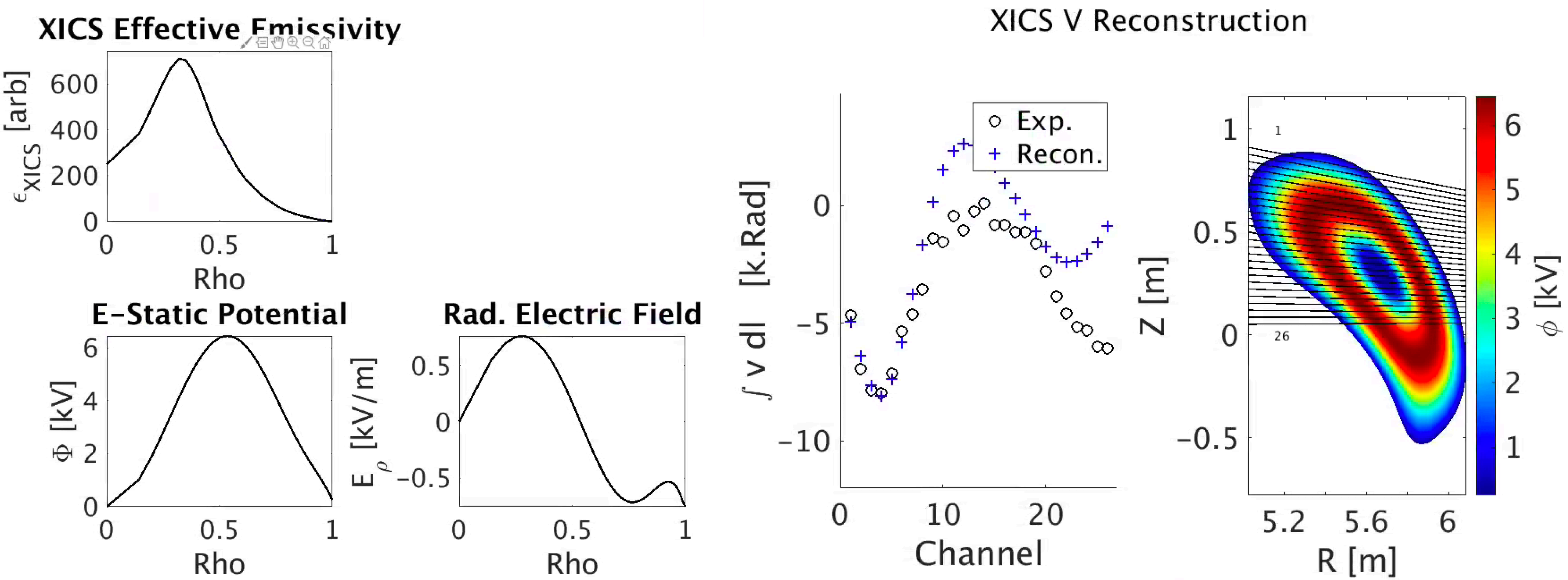


Works well for Ti Profile, need to verify with CXRS

XICS can also provide radial electric field

- STELLOPT varies electrostatic potential
  - Used to calculate poloidal velocity
- Fit's measured poloidal velocity

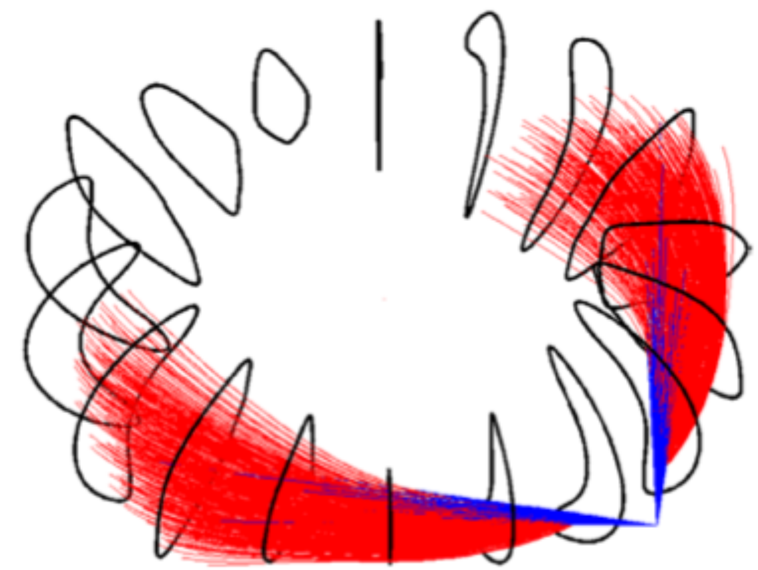
$$\frac{d\Phi}{d\rho} = \vec{u} \times \vec{B}$$



Still vetting reconstruction process

The BEAMS3D code follows non-interacting gyro particles and neutral trajectories. The magnetic field is represented on a cylindrical grid allowing trajectories to be followed across the the VMEC boundary (virtual casing). The code includes collisional processes such as ionization, slowing down, and pitch angle scattering.

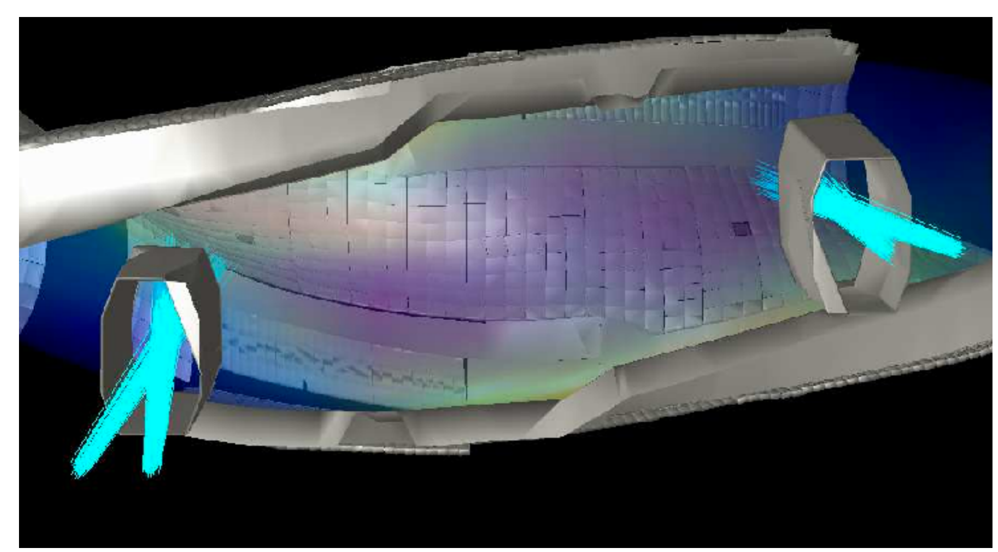
- Interfaced to VMEC
- Gyro-center orbits
- Neutral trajectories
- Physics Modules
    - Ionization (ADAS)
    - Slowing Down
    - Pitch Angle Scattering



Equations

$$\frac{d\vec{R}}{dr} = \frac{\hat{b}}{qB} \times \left(\mu \nabla B + \frac{m v_{\parallel}^2}{B} \left(\hat{b} \cdot \nabla \right) \vec{B} \right) + v_{\parallel} \hat{b}$$

$$\frac{dv_{\parallel}}{dt} = -\frac{\mu}{m} \hat{b} \cdot \left(\nabla B \right)$$



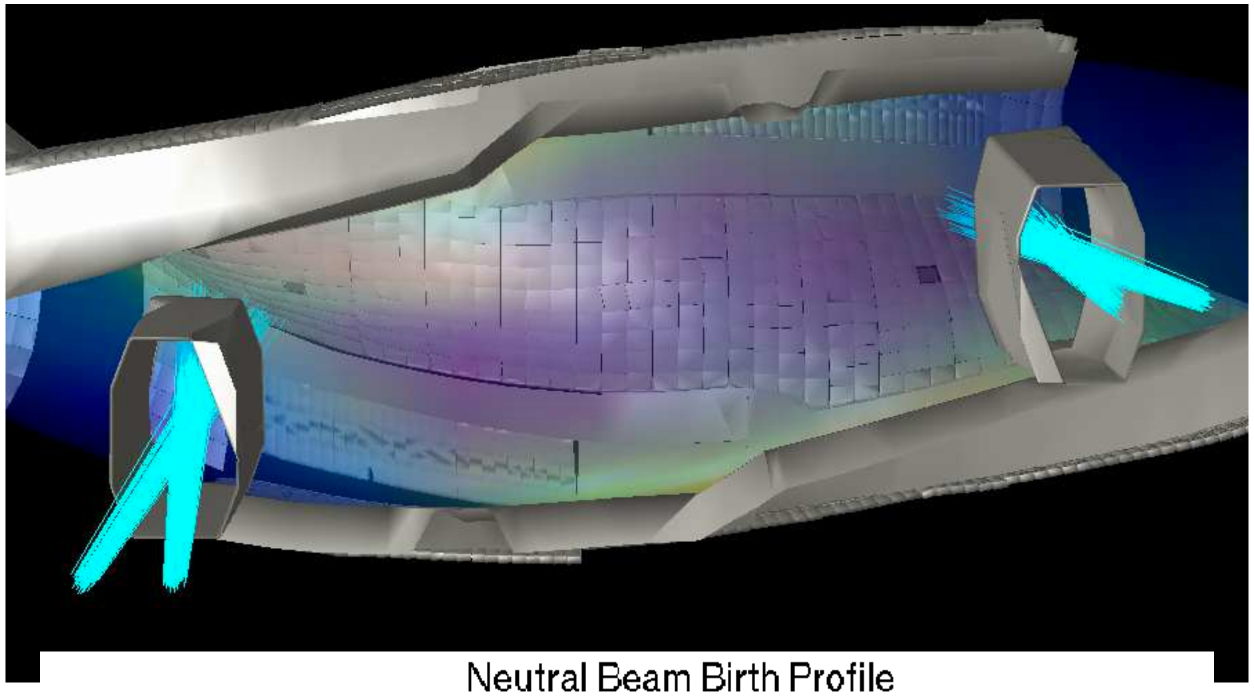
M. McMillan and S. A. Lazerson, "BEAMS3D neutral beam injection model", PPCF 2014 (https://doi.org/10.1088/0741-3335/56/9/095019)

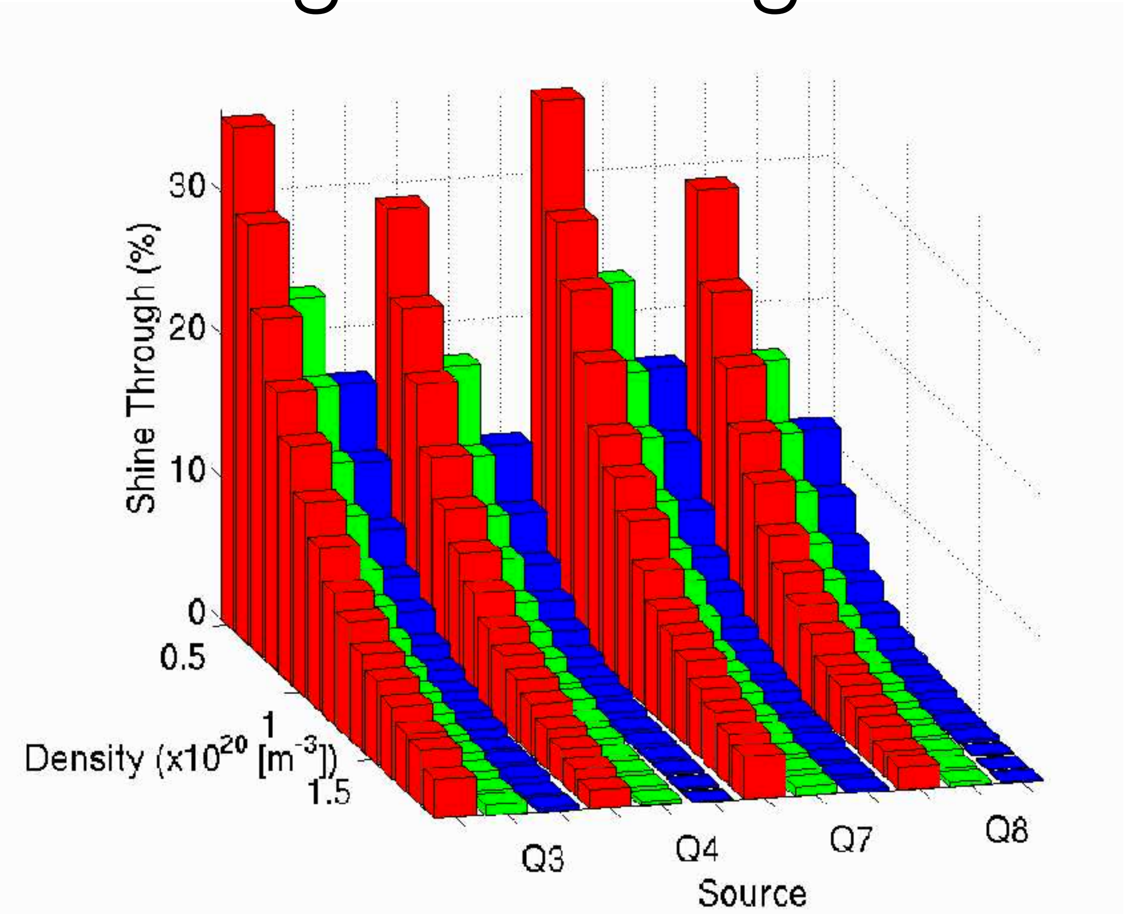
Preliminary modeling shows strong dependence on density profile

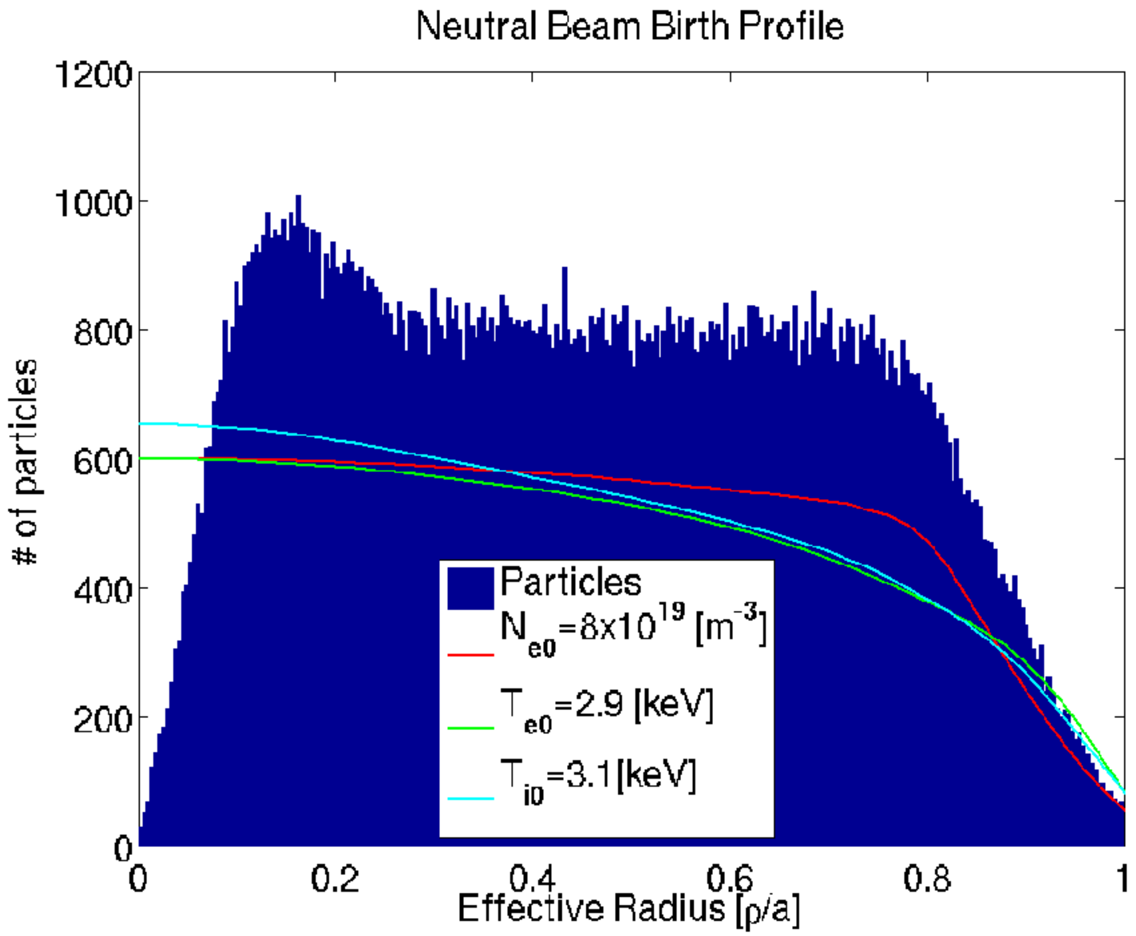
T_e, T_i, n_e, and Z_{eff} affect deposition

ADAS used for

- Electron Impact
- Ion Impact
- Charge Exchange

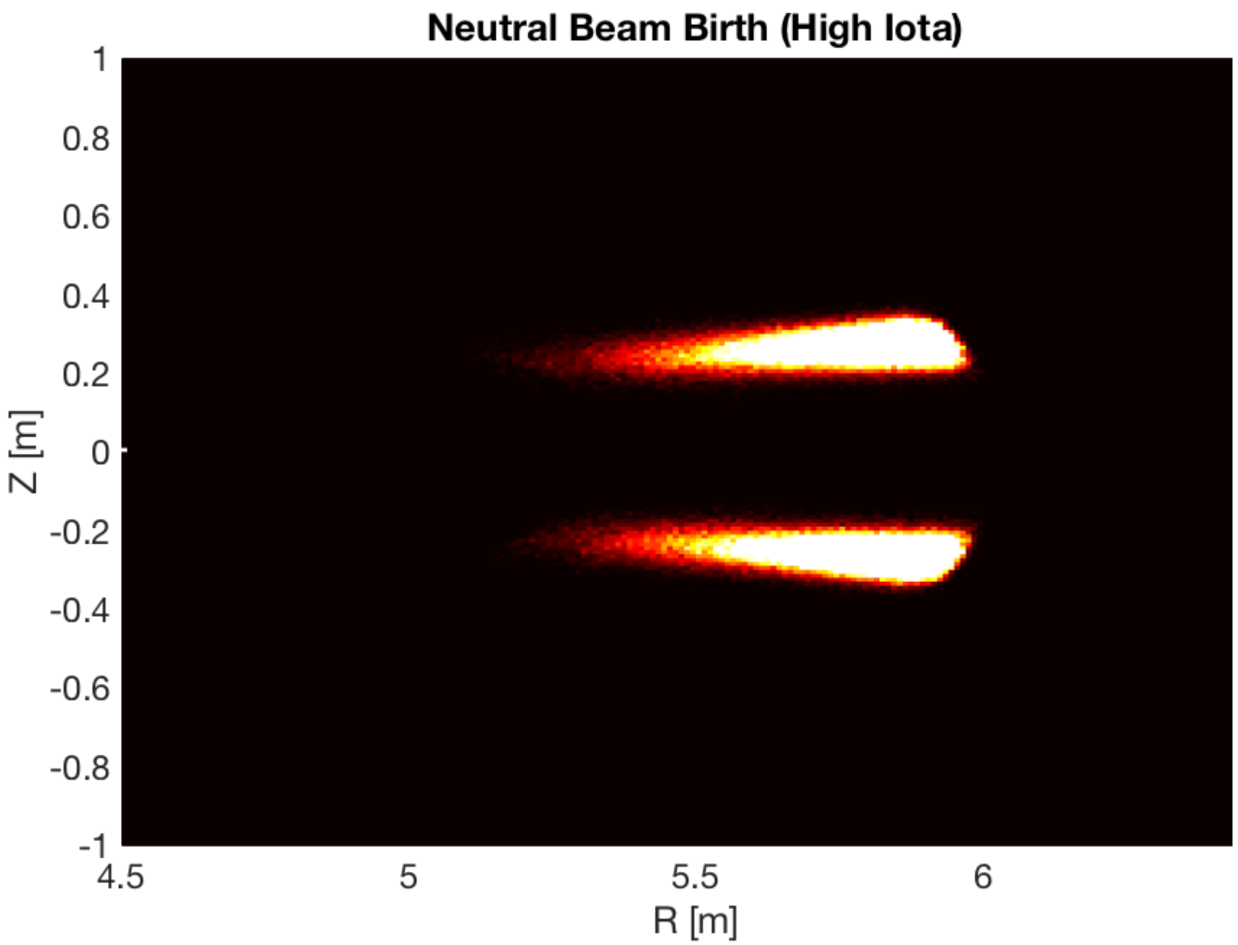


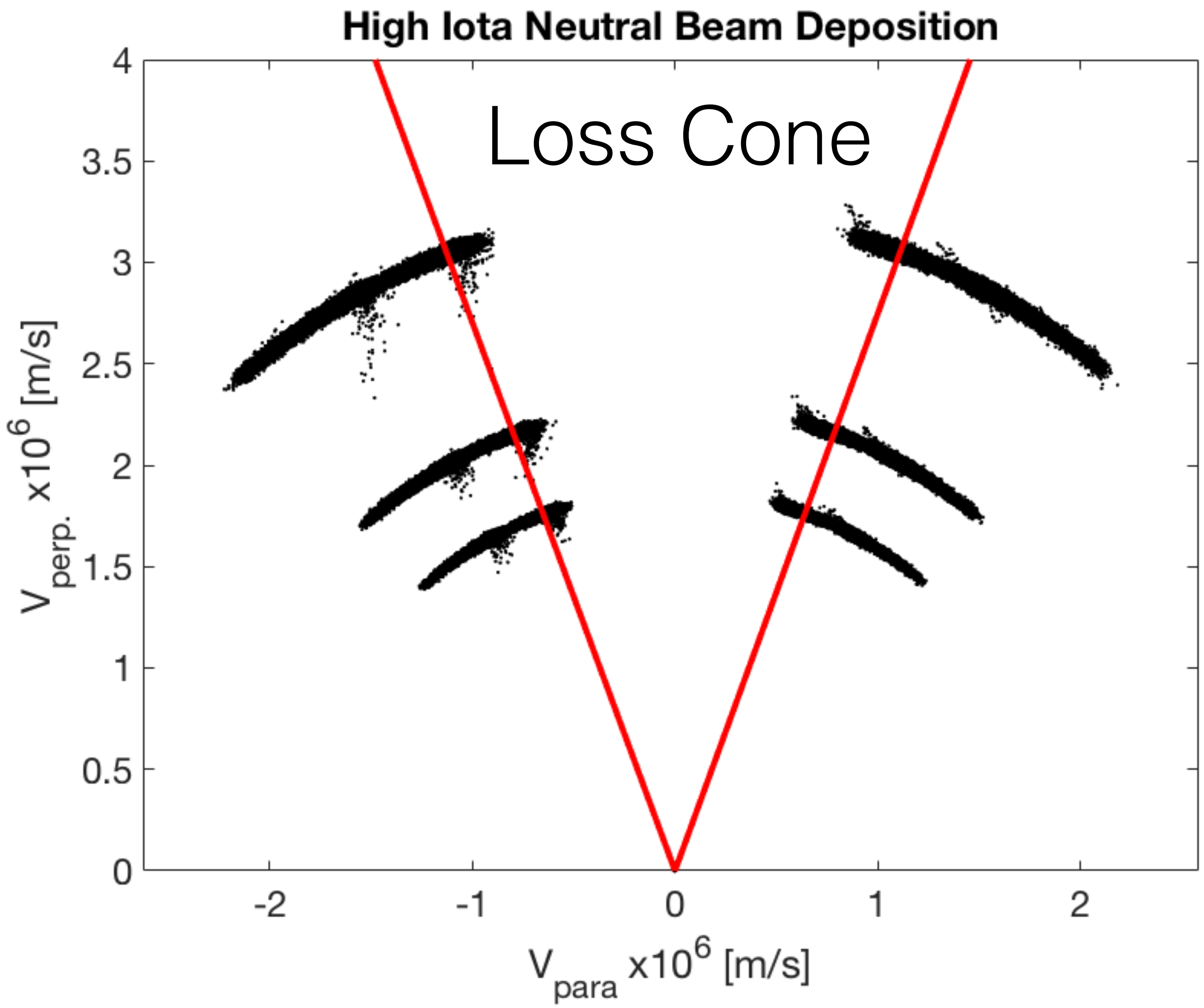




S. A. Lazerson et al., "Predictions of neutral beam deposition and energetic particle loss in W7-X", EPS 2016

Early deposition runs show injection outside loss cone





S. A. Lazerson et al., "Energetic particle loss estimates in W7-X", APS DPP 2017

The STELLGAP code calculates Alfvén Gap Structure in 3D systems

The STELLGAP code solves for the Alfvén Gap structure in 3D toroidal systems.

- Interfaced to VMEC
- Git Repo
  - https://github.com/ORNL-Fusion/Stellgap
- Validated against W7-AS and NSTX data
- Plan to implement in STELLOPT
- Can inform anomalous transport of fast ions

Equations

$$\mu_0 \rho \omega^2 \frac{|\nabla \psi|^2}{B^2} E_\phi + \vec{B} \cdot \nabla \{ \frac{|\nabla \psi|^2}{B^2} (\vec{B} \cdot \nabla) E_\psi \} = 0$$

No W7-X analysis performed yet

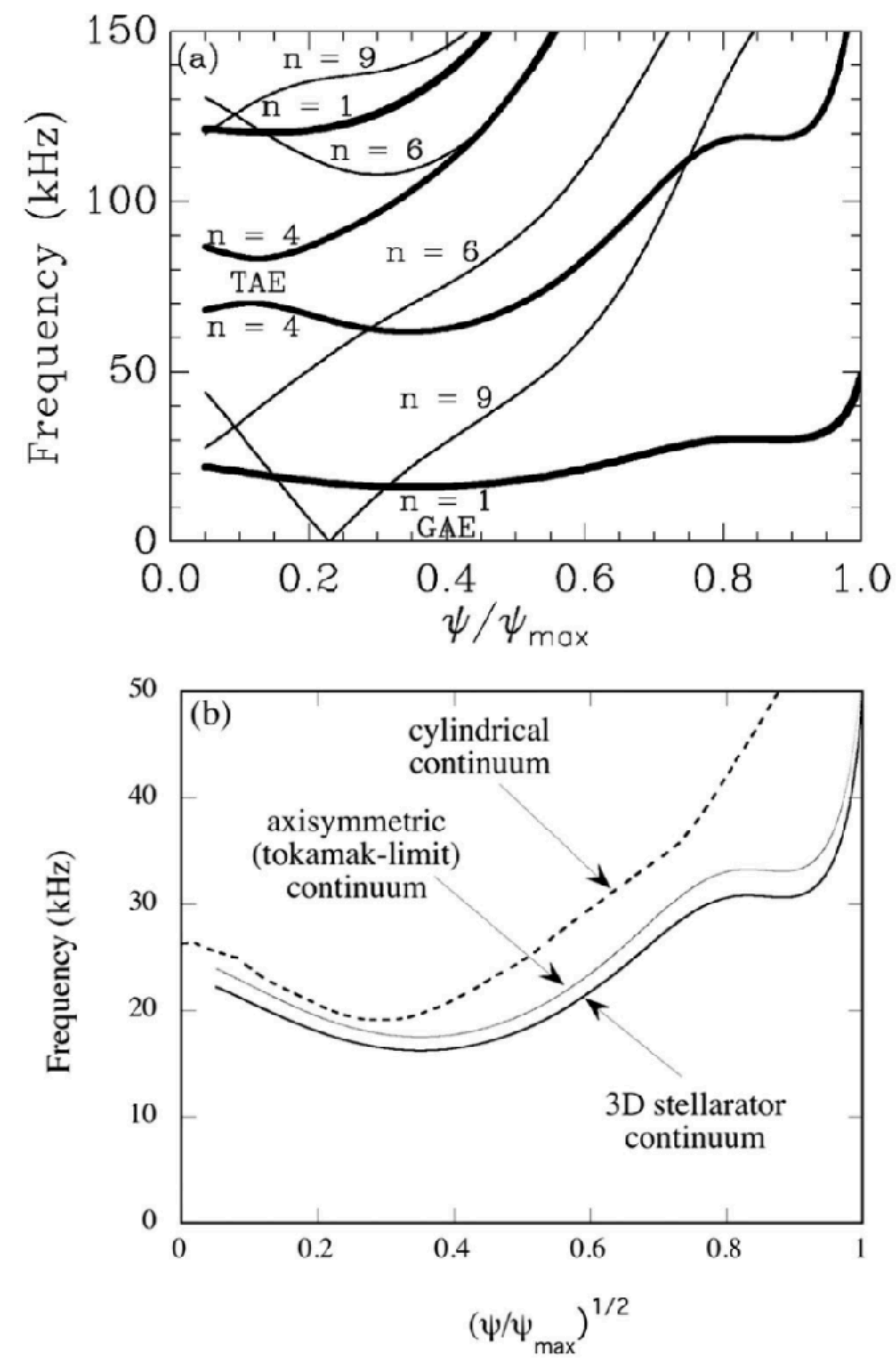


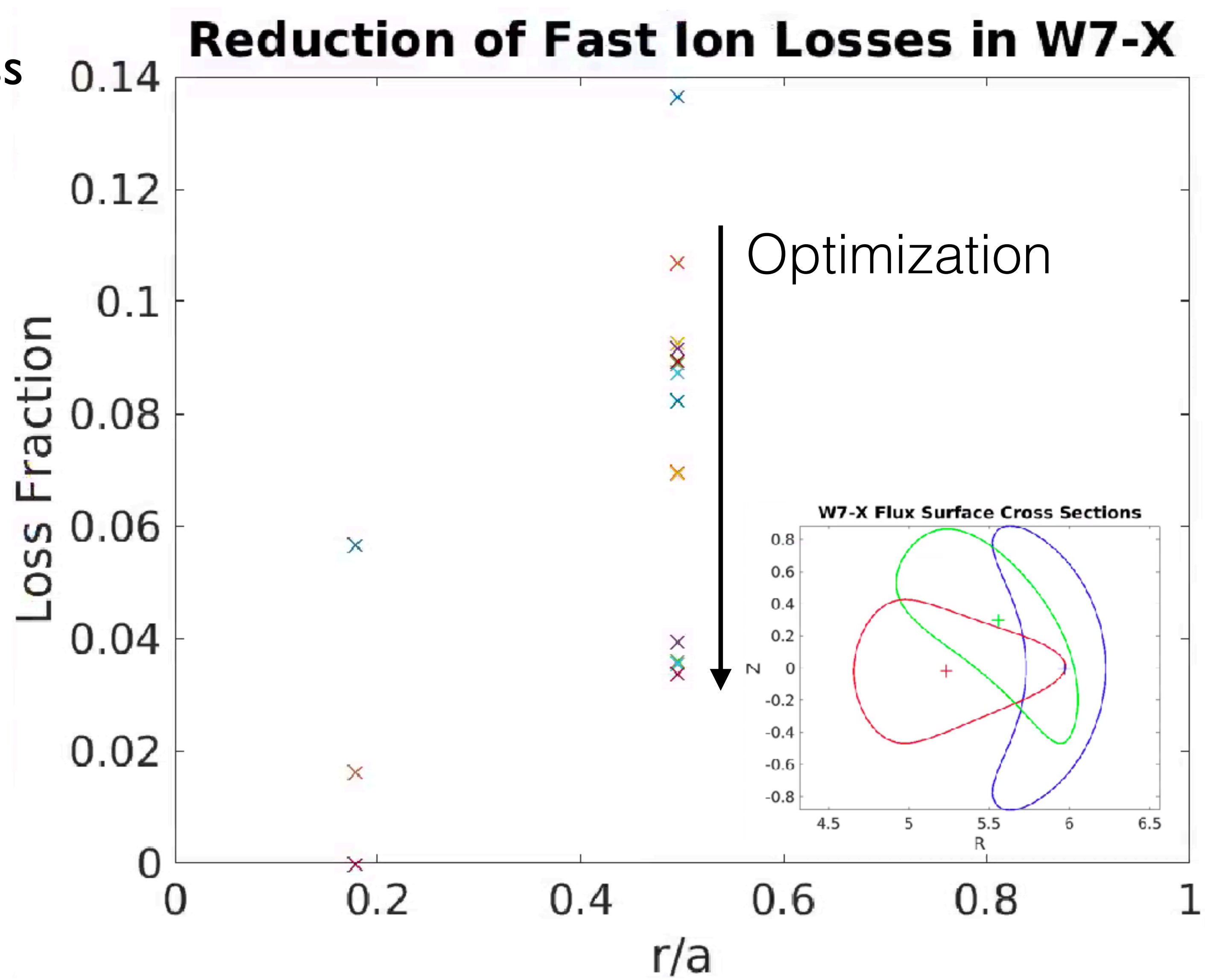
FIG. 2. (a) Continuum gap structure for W7-AS low shear case #40173, and (b) comparison of the lowest frequency $n=1$ continuum based on cylindrical, axisymmetric and stellarator equilibrium models.

D.A. Spong, R. Sanchez, and A. Weller, "Shear Alfvén continua in stellarators", POP 2003 (https://doi.org/10.1063/1.1590316)

Implementation of BEAMS3D in STELLOPT allows optimization of stellarator equilibrium for improved fast ion confinement. Requires large scale computations which are now available.

- Collisionless simulations up to VMEC boundary
- Free Boundary LM Optimization
  - Vars: Coil Currents, PHIEDGE
  - Targets: B0, Vac. Iota, Volume, NEO, EP Loss
- NERSC Cori
  - 4096 Processors
  - 40960 Particles
  - 200 ms particle simulation window

Coil	Current [kA]
I1	13.22
I2	13.12
I3	14.34
I4	13.82
I5	15.12
IA	-2.15
IB	1.06

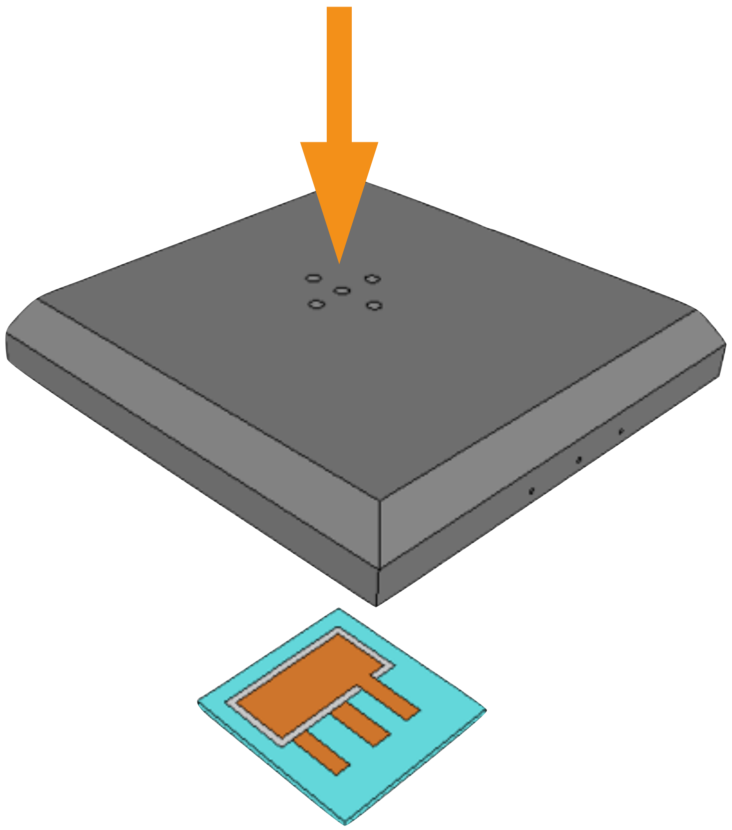


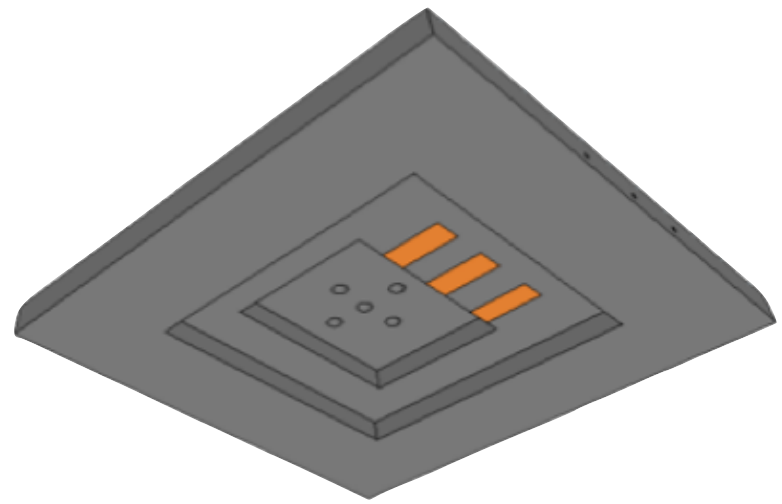
Novel Fast Ion Loss Detector Development

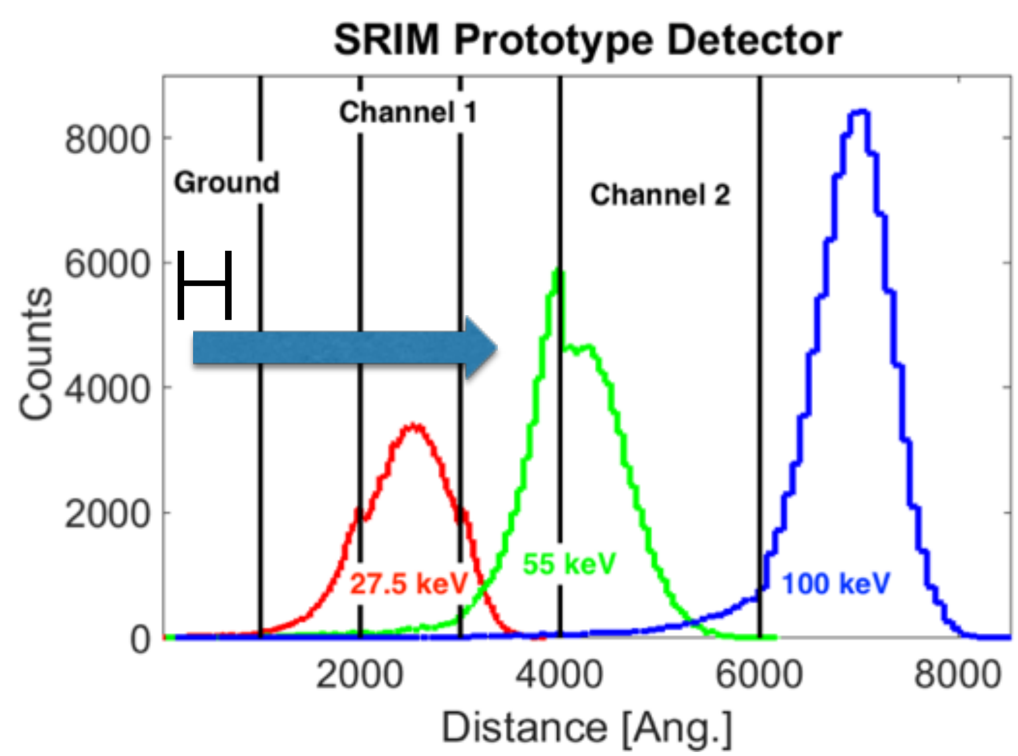
Package is a carbon tile with imbedded Faraday cup sensor.

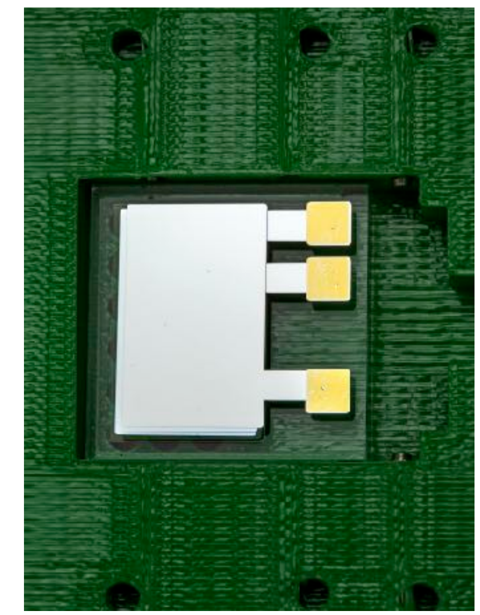
- 3 Channel prototype for testing (next week)

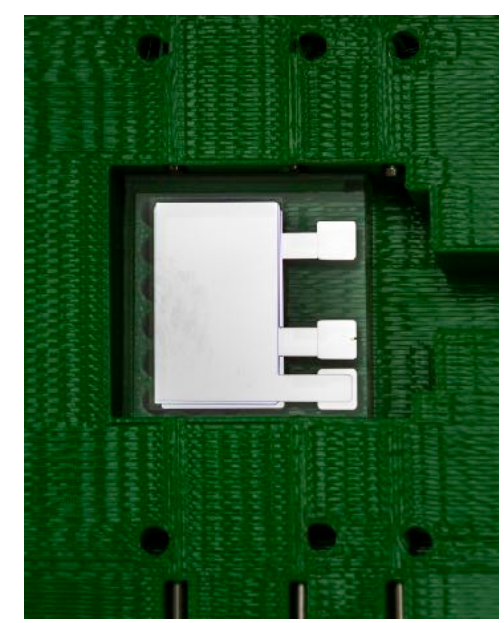
Particles











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Fast Ion Physics looking toward OP2

- Second NBI box will be brought online
  - Two 1.8 MW sources (of 4)
  - Up to 7.2 MW of total NBI heating
- ICRH system will be brought online
  - ~2 MW at up to 150 keV
  - Three ion scheme
- Progress of work
  - Reconstructions of discharges under way
  - Assessment of beam deposition under way
  - Prototype fast ion loss detector testing under way
  - STELLOPT/BEAMS3D coupling under assessment
- Next steps
  - Preliminary design for W7-X FILD array
  - Slowing down simulations using BEAMS3D