P1.020: Using Doppler spectroscopy of Li ions to characterize plasma dynamics in LTX

Presented to
Workshop on Exploratory Topics in Plasma and Fusion Research (EPR2013)

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U.S. DEPARTMENT OF ENERGY · PRINCETON UNIVERSITY · PPPL

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Abstract

LTX

There has been a long-standing collaboration between ORNL and PPPL in the area of edge and boundary layer plasma physics. As part of this collaboration, ORNL has a large role in the instrumentation and interpretation of the edge physics in the Lithium Tokamak Experiment (LTX) In particular, a high-resolution spectroscopy diagnostic has been designed and is undergoing staged implementation on LTX. Here we present initial results (from 2012) of passively measured lithium charge exchange emission at 5166.89 Å in LTX, and show the expected measurement improvement from a recently completed upgrade to the diagnostic (to be utilized in 2013). Preliminary measurements have been made in transient LTX plasmas with plasma current, I_p = 40 – 65 kA, ohmic heating power, P_{oh} ~ 0.3 MW and discharge lifetimes of 10 – 30 ms. Doppler spectroscopy measurements are made with a short focal length spectrometer and optics similar to the Edge Rotation Diagnostic (ERD) on NSTX. The diagnostic is being upgraded to 17 toroidal sightlines (from 6) and 6 to 9 up-down symmetric poloidal sightline pairs (from 5 pairs). Radial coverage of the poloidal array will extend between $0.2<r/a<0.95$, while the toroidal array will cover $0<r/a<0.7$. Simulations suggest that line-of-sight measurements from the upgraded diagnostic can be inverted to yield local profile values of T_i, v_φ, v_θ and n_{Li}. Inversions rely on accurate equilibrium reconstructions, which are expected from recently completed repair/upgrade to magnetic diagnostics and due to the adaptation of the LRDFIT code to LTX. With the equilibrium magnetic field reconstructions and the estimation of local plasma parameters from this diagnostic, under the assumption of force balance the radial electric field profile, E_r, can be calculated. The effect of lithium on the E_r profile, as well as the fundamental plasma parameters, is a major topic of interest for LTX and the plasma physics community. Preliminary results will be presented, and a general summary of the status of ORNL collaborations with LTX will be given.

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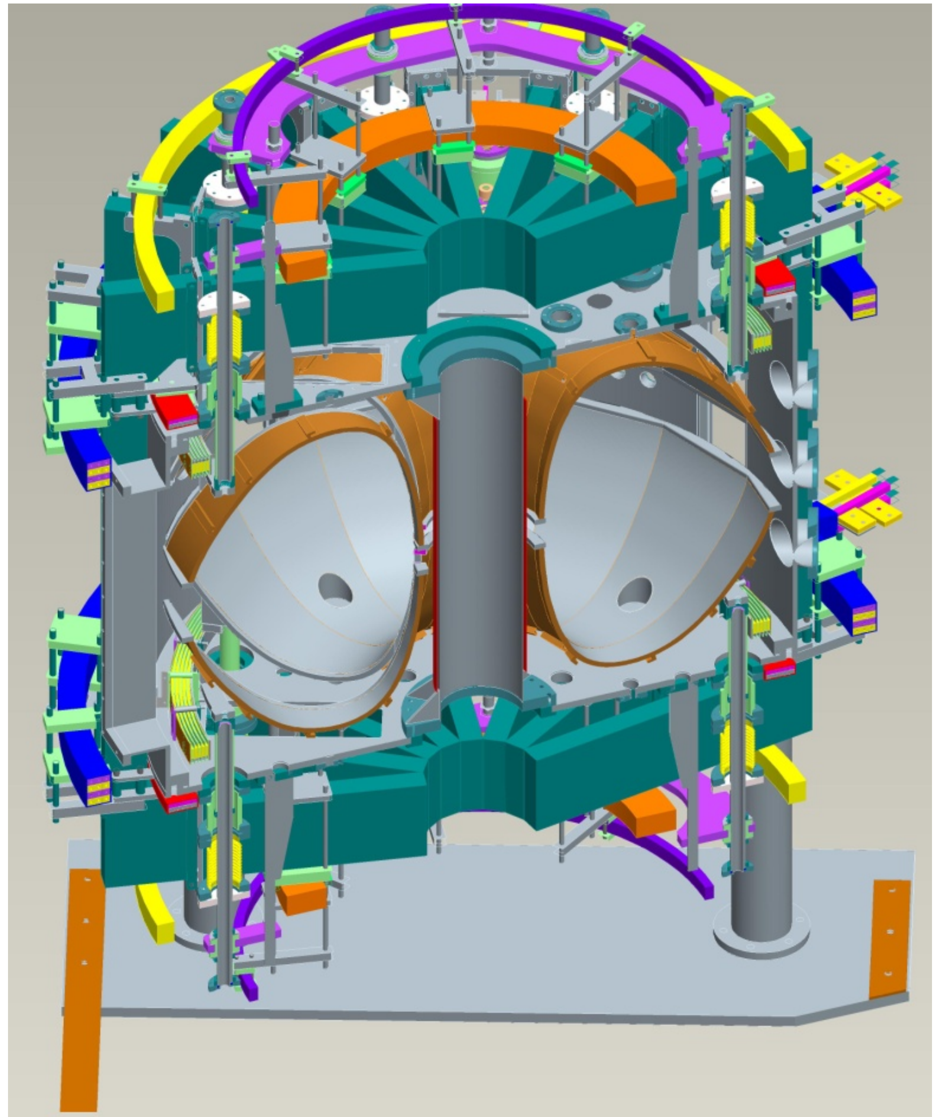
Lithium Tokamak Experiment (LTX)

- Small Spherical Tokamak
  - R=40cm, a=26cm, B_T=0.3 T
- 4 internal shell sections surround plasma
  - Toroidal & poloidal gaps
  - 3/8" copper +1/16" SS liner
  - Can be heated to 500°C (300°C so far)
- Lithium Technology Development
  - Li evaporation into He gas for ~micron coatings (so far mostly solid)
  - Liquid surface exposure probe
  - *In-situ* surface chemistry with Material Analysis Particle Probe (MAPP)
  - Injectors for liquid pools in bottom shells



For more details see P1.002 D. Majeski at this meeting.

ASTRA-ESC Reference Transport Model (RTM) predicts high performance with low recycling walls

LTX

Parameter	Achieved (Ohmic)	Projected (Ohmic)	Projected (NBI)
Plasma Current	65 kA	300 kA	400 kA
Current Flattop	20 ms	50 ms	
Central T_e	0.1-0.3 keV ?	1.4 keV	1.3 keV
Central T_i	?	0.2 keV	1.6 keV
Confinement τ_E	?	25 ms	59 ms

- **Physics goals of LTX: Study plasma physics with low-recycling lithium walls and the effects on:**
  - **Confinement and transport of particles, energy, and momentum**
  - **Instabilities and turbulence**
  - **Lithium impurities and other impurities**

ORNL-LTX Collaboration Overview

LTX

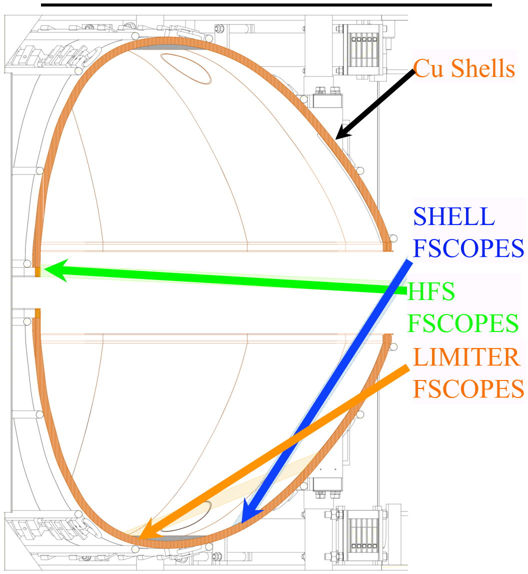
- ORNL and PPPL have had a longstanding collaboration on boundary plasma physics topics.
- This (3 year) proposal has been funded to address on LTX:
  - Implementation of a ChERS diagnostic
    - Main topic of this poster: T_i, v_{tor}, v_{pol}, n_{Li} from Li III 516.7 nm
    - Drived quantity: $E_r = -(vxB)_r + p_{Li}' / Zen_{Li} = v_{tor} B_{pol} - v_{pol} B_{tor} + p_{Li}' / Zen_{Li}$
  - Filterscopes and Compact Spectrometer Array (CSA) for plasma edge interaction
    - See T.K. Gray P1.019 poster at this meeting
  - SOLPS Modeling of neutral drag on NBI driven plasmas
    - See T.K. Gray P1.019 poster at this meeting

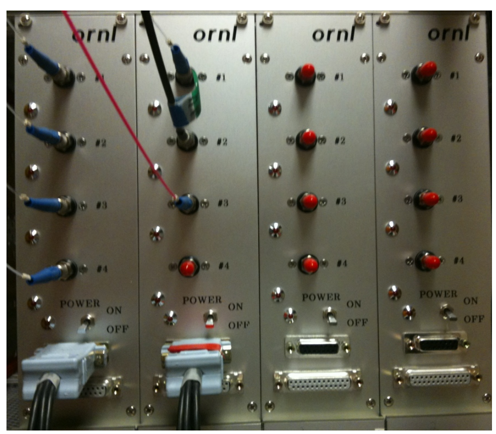
Erosion and PMI Diagnostics on LTX

- **LTX is equipped with several filterscope modules and minispectrometers to monitor edge impurities**
- **3 views:**
  - **High Field Side (HFS)**
  - **Lower Shell**
  - **Molybdenum Lower Limiter**

- Filterscope modules use very sensitive photomultiplier tubes to detect low light levels
  - PMTs are filtered with narrow bandpass filters to measure individual lines
  - Up to 100 kHz bandwidth

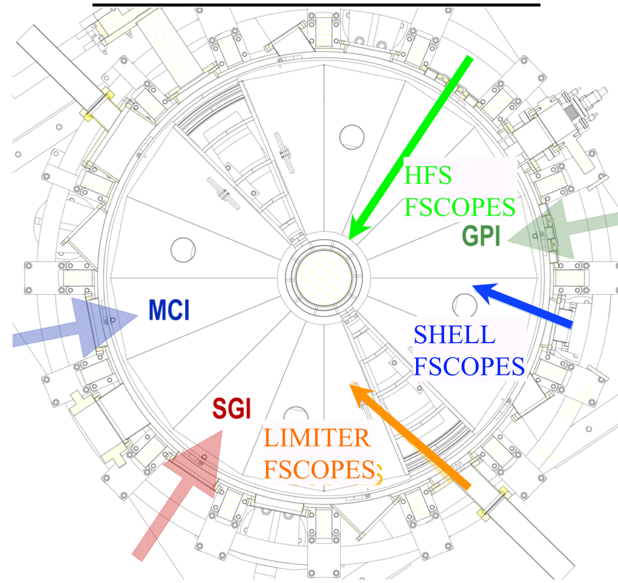
Poloidal Cross-section





Filterscope (FSCOPE) Hardware on LTX

Toroidal Cross-section

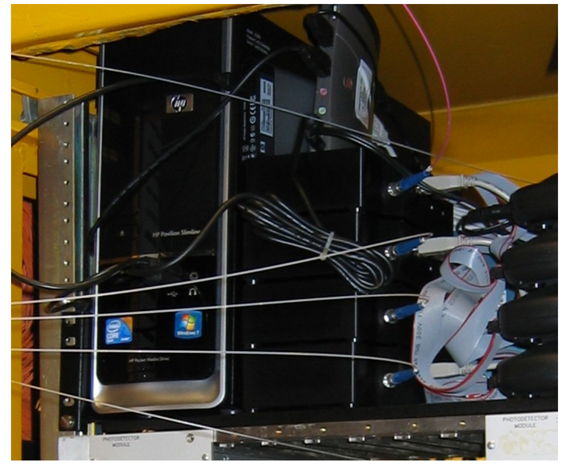


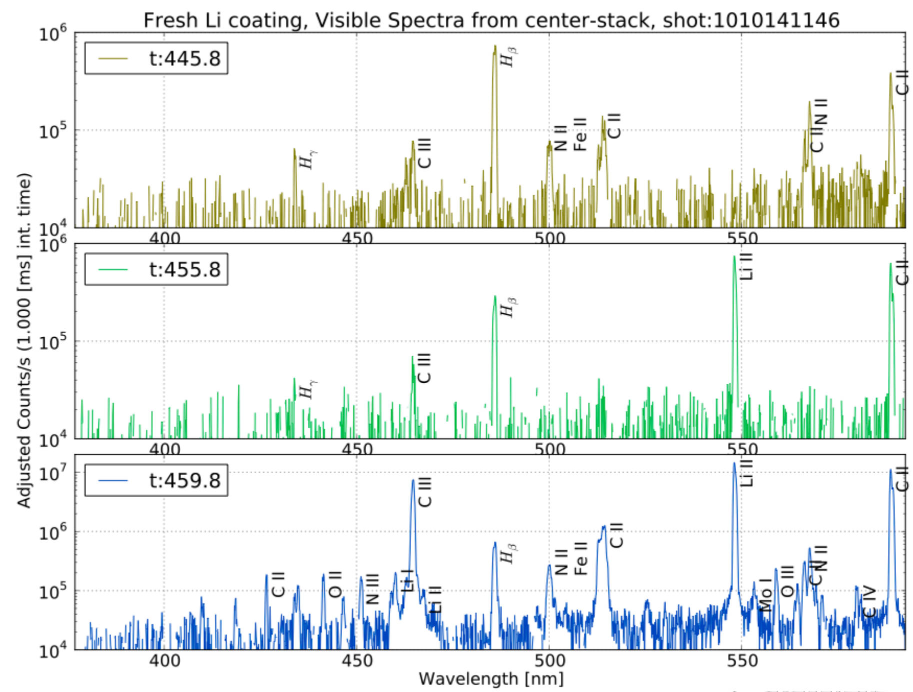
For more details see P1.019 T. Gray at this meeting.

Compact Spectrometer Array (CSA) for broadband measurement of visible spectrum from PFCs

LTX

- Using off-the-shelf compact visible spectrometers
  - Ocean Optics HR2000+
  - Operated at ~ 500 Hz
  - USB controlled and externally triggered
  - Shares sightlines with filterscopes (HFS, Shell and Limiter views)
- Good for measuring line radiation due to impurities from the PFCs
  - Due to high dispersion, not suitable for more extensive analysis (eg - stark and/ or doppler broadening)
- Dominate impurities are C, Fe, N, O in addition to Li



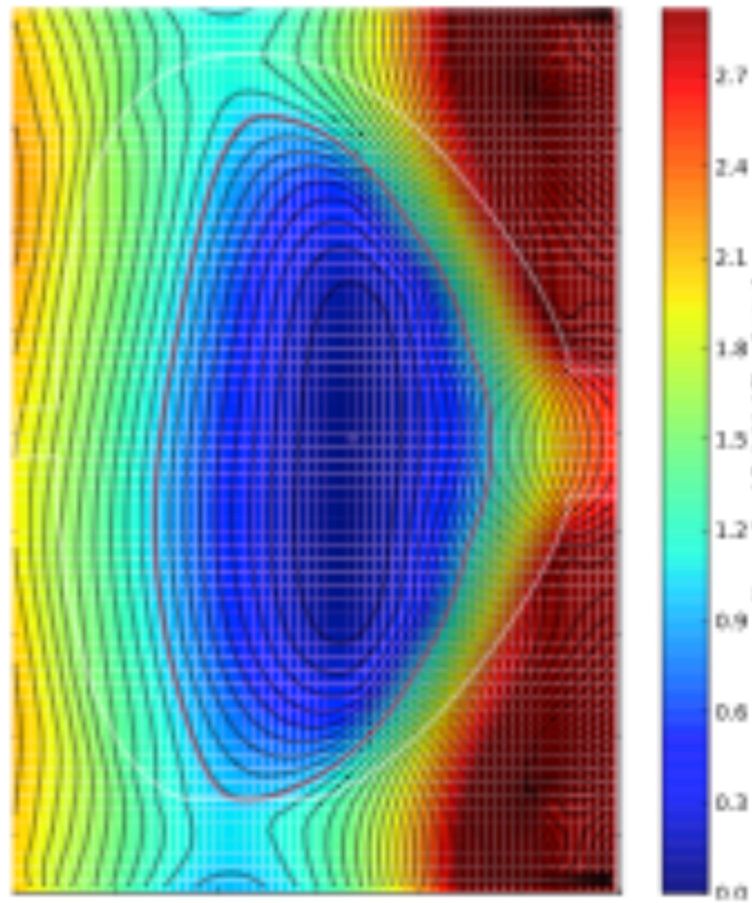


For more details see P1.019 T. Gray at this meeting.

Modeling of LTX Edge Plasmas is in the Initial stages

LTX

- Using a modified version of LRDFIT to calculate magnetic equilibria
  - Broken magnetics prohibit more accurate reconstructions
- SOLPS to estimate edge transport changes with changes in PFC recycling
  - Study momentum transport once the neutral beam is installed
  - Routine midplane n_e, T_e, T_i and v_t are necessary for these simulations



For more details see P1.019 T. Gray at this meeting.

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"CHERS" Staged Implementation Strategy

LTX

- Proposal awarded for 3 years of effort
- FY2011: Passive Spectroscopy
  – Install temporary optics and utilize available equipment to make preliminary measurements
- ~~FY2012: Active Spectroscopy~~
  – ~~Design and install optics in conjunction with the installation of the neutral beam injection (NBI) system~~
- FY2012 (revised): Continue Passive Spectroscopy
- FY2013: Optimization and Physics Exploration
  – Purchase and install dedicated hardware for an LTX-optimized ~~ChERS~~ "ChERS" diagnostic

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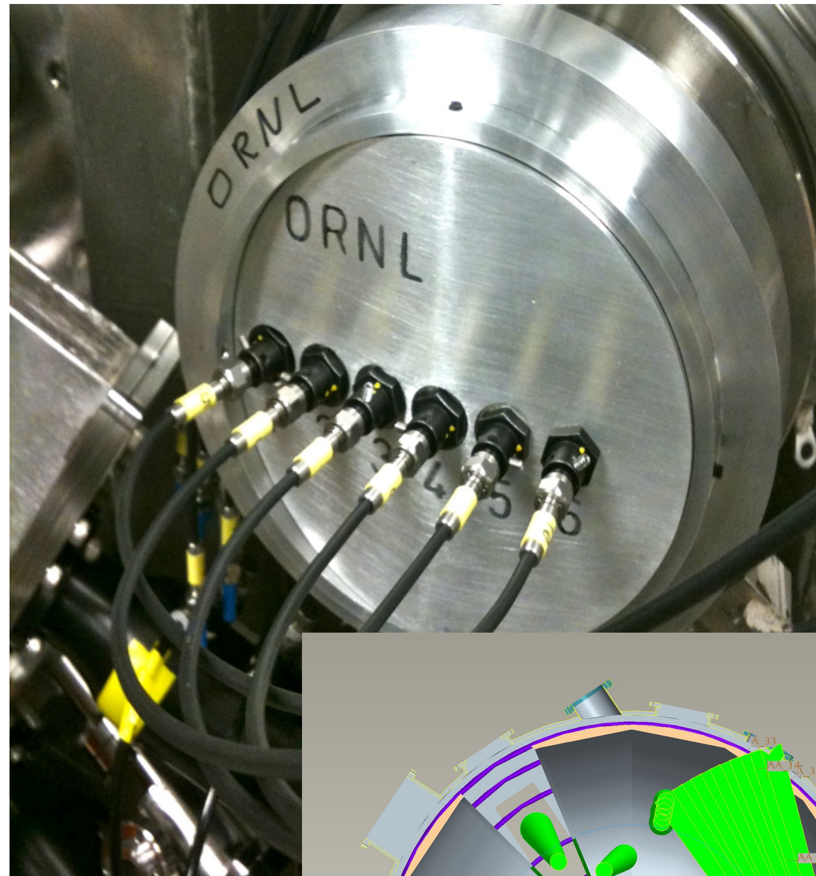
Spectrometer & Detector

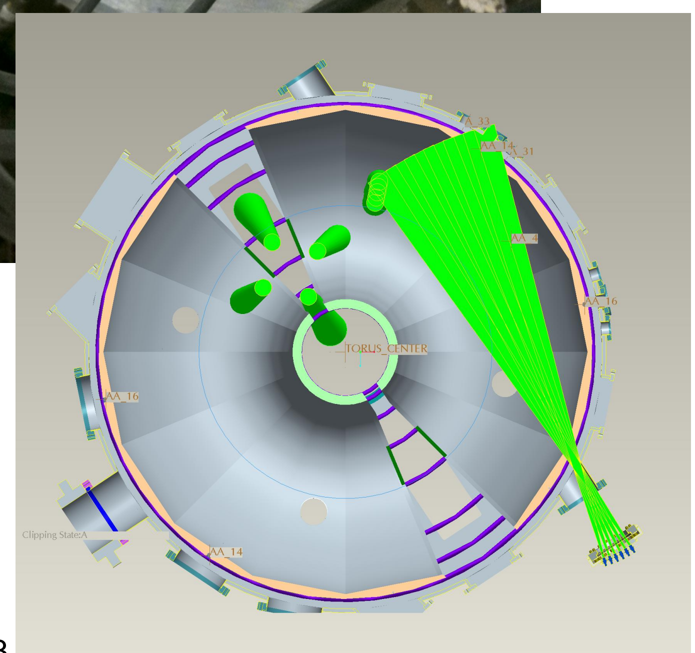
- Kaiser Optical Holospec f/1.8
  - Fixed “High Dispersion” grating
  - Curved entrance slits
- Fiberbundle: 17 channel SMA bundle for HD
  - 600 μm PCS (100 °C), 7 m
- Configuration with above:
  - 10 views: 85 mm exit lens
  - 15 views: 58 mm exit lens
  - 17 views: 50 mm exit lens
  - More views = lower resolution
- BP filter and new bundle can 2x or 3x views (at ½ or 1/3 of the wavelength coverage) w/ the addition of a new fiberbundle
- EMCCD fast framing camera: Princeton Instruments Pro-EM 512B
  - 16x16 μm pixels
  - On-chip binning allow ~1.5 ms frame rate

Ref: R.E. Bell, Rev. Sci. Inst. **75**(10): 4 (2004).

Toroidal Lines of Sight (old)

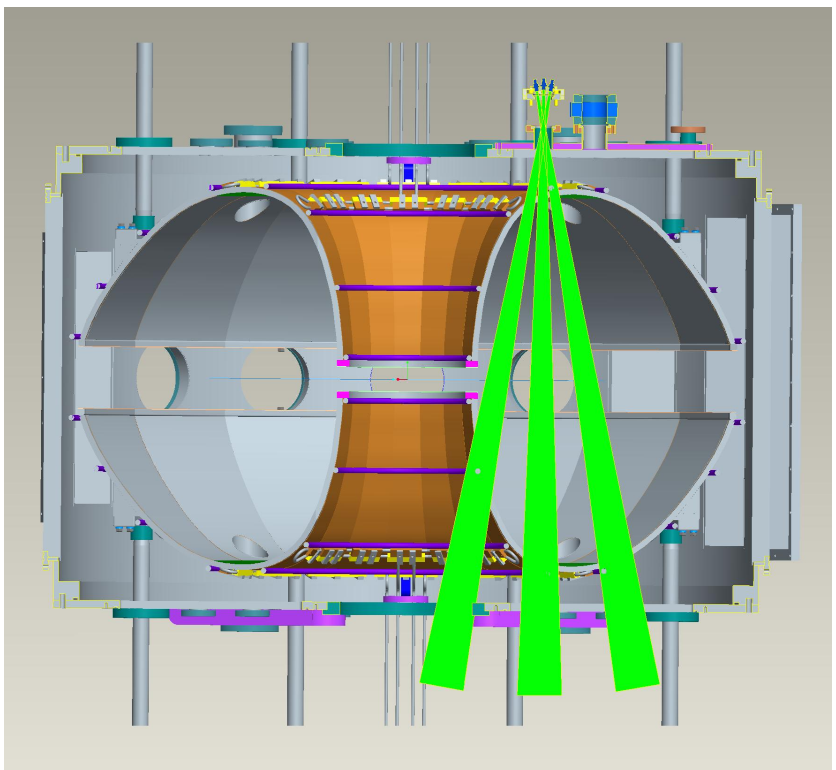
- **6 lines of sight with compact, modular collection optics.**
  - r/a: -0.11, 0, 0.11, 0.27, 0.37, 0.48
- **Collimating fused silica lens: Ocean Optics 74-ACR**
  - 5 mm diameter, f=10mm, f/2
  - Installed in "pucks" mounted on windows behind gate valve
- **Outboard range constrained by port geometry.**

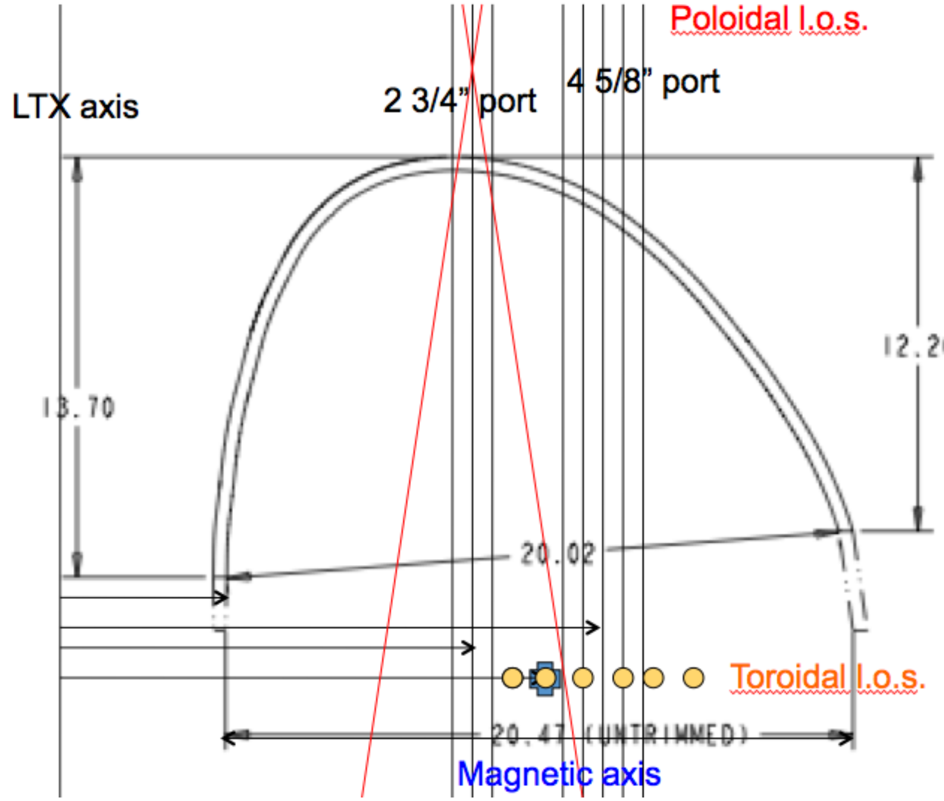




Poloidal Lines of Sight (old)

- 3 poloidal sightline pairs
  - r/a: ~0, -0.22, ~-0.46
- 5 poloidal sightline pairs
  - r/a: 0.06, 0.12, 0.17, 0.23, 0.29

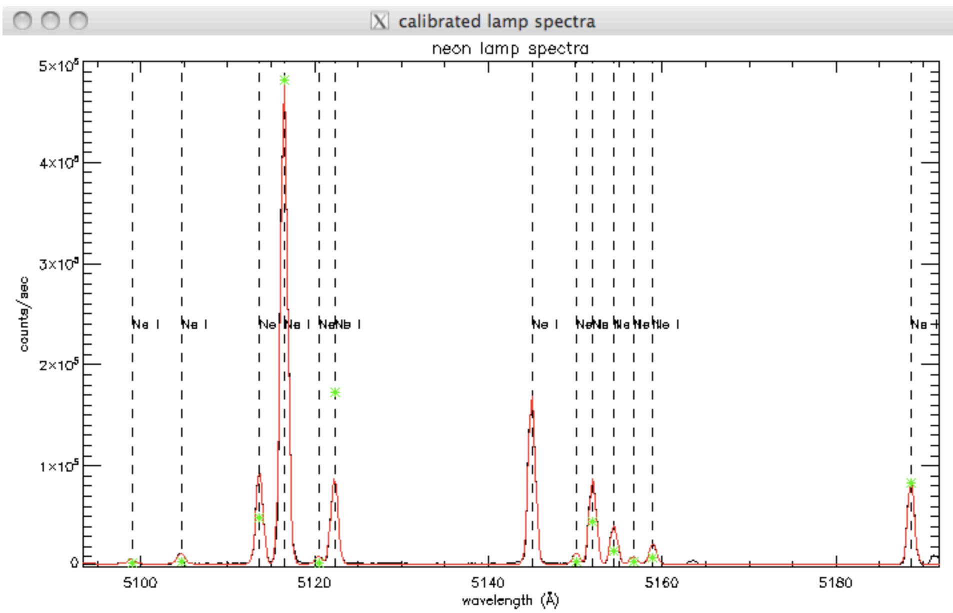


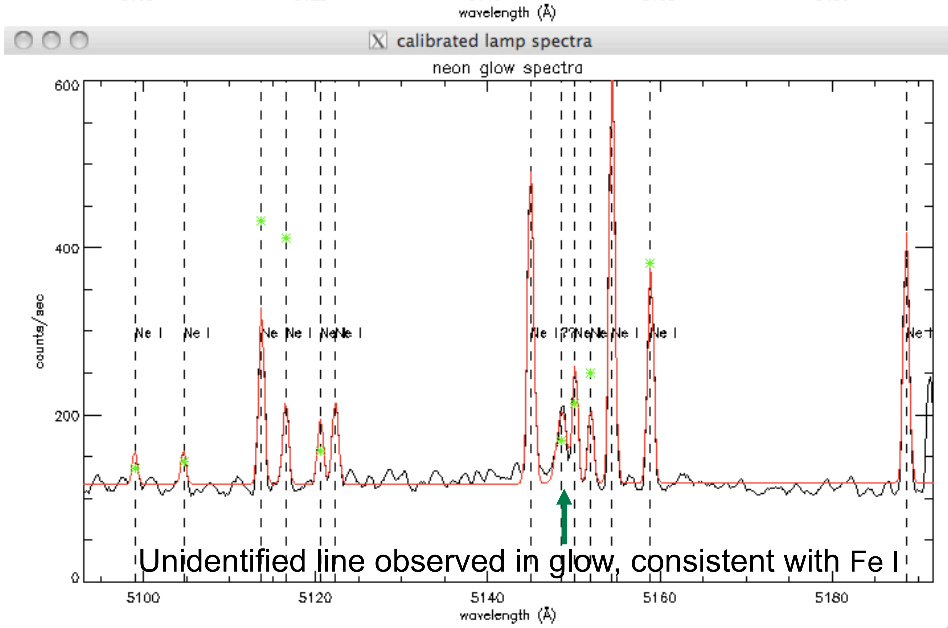


- Toroidal and Poloidal coverage from 0<|r/a|<0.5
  - Sufficient to estimate light levels.
  - Can we also get some physics data?
    - Depends on $n_{Li\ 2+}$ profile (see following slides)

Vessel-Filling Neon Glow Calibration

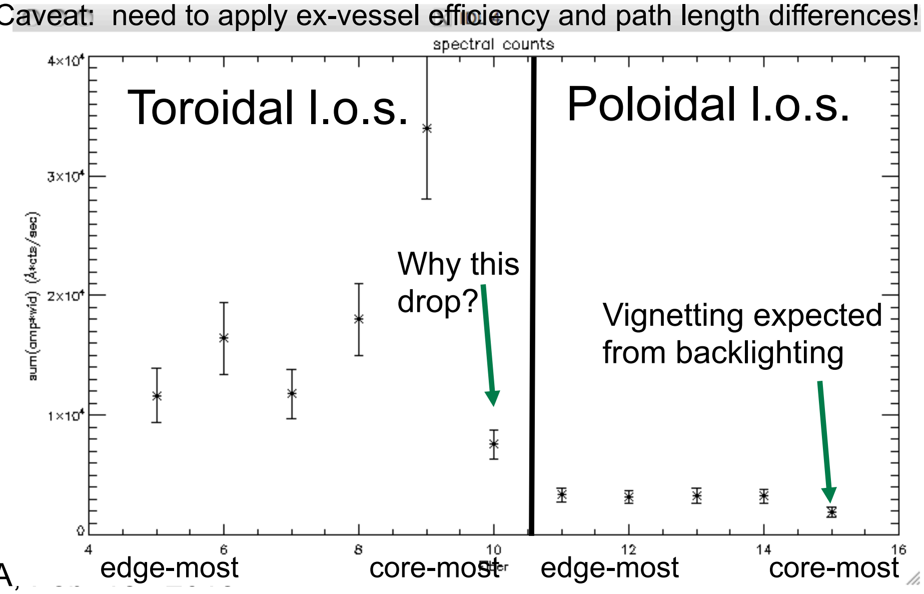
LTX



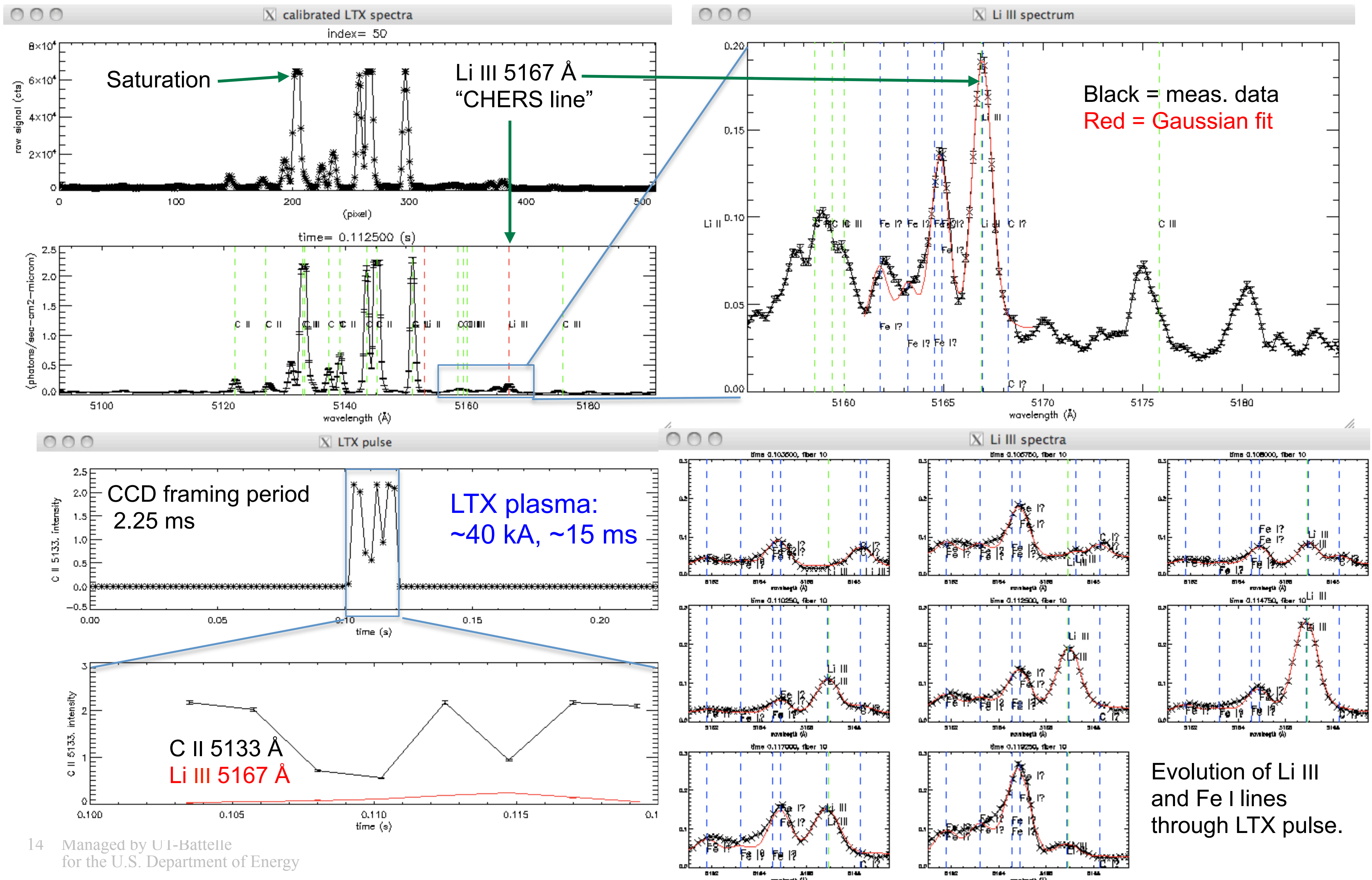


- Wavelength calibration well preserved (2 months later)
- Relative intensities of Ne lines differ between lamp, glow, & NIST
- Transmission variation of vacuum window and/or obstructions (assuming uniform glow).
  - resolve prior to data inversions!

Caveat: need to apply ex-vessel efficiency and path length differences!



Preliminary Data from LTX Pulses



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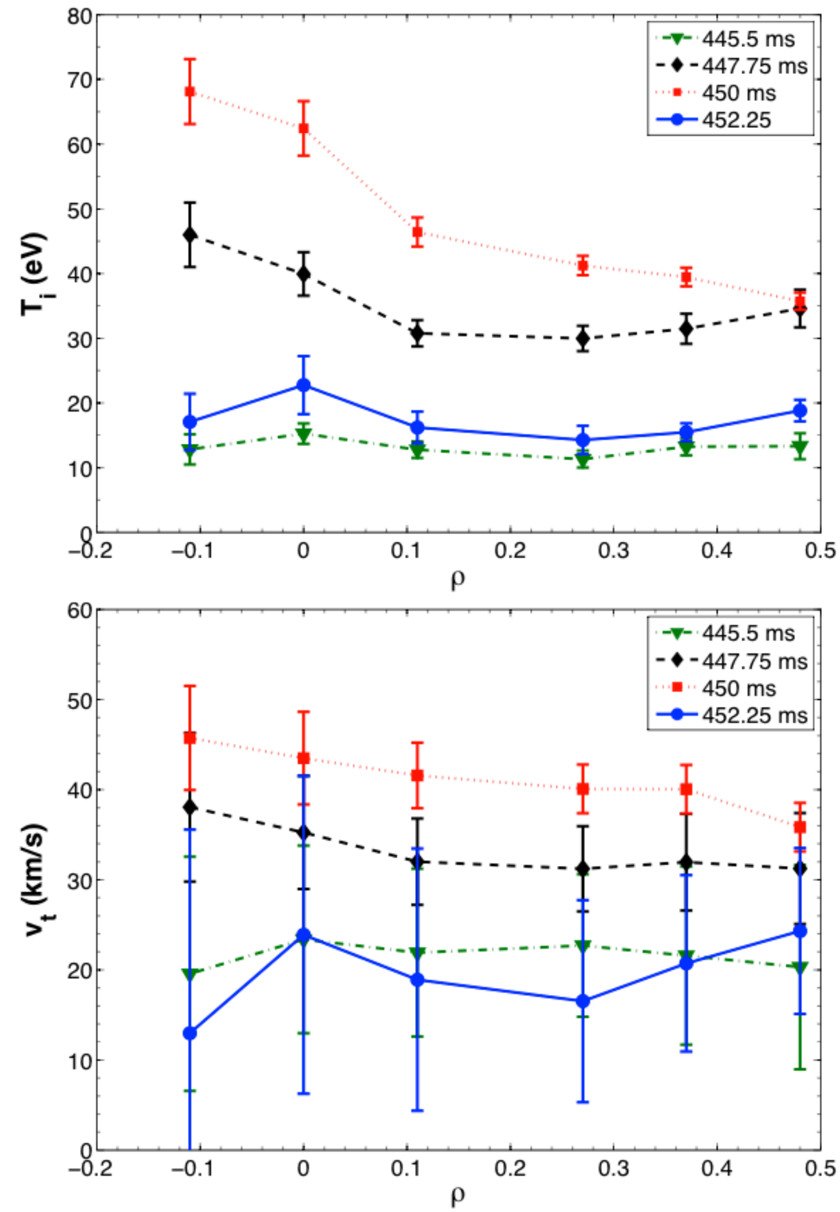
Line-integrated LTX Li III profiles

- T_i appears flat through out a discharge except at peak emission at 450~ms
  - Peaking close to 70 eV 10 ms into the discharge
- v_t also appears relatively flat through out the discharge
  - Peak v_t ~ 45 km/s
  - reached at the same time as the peak T_i
- Both T_i and v_t decrease due to the end of the discharge @ 452.25 ms



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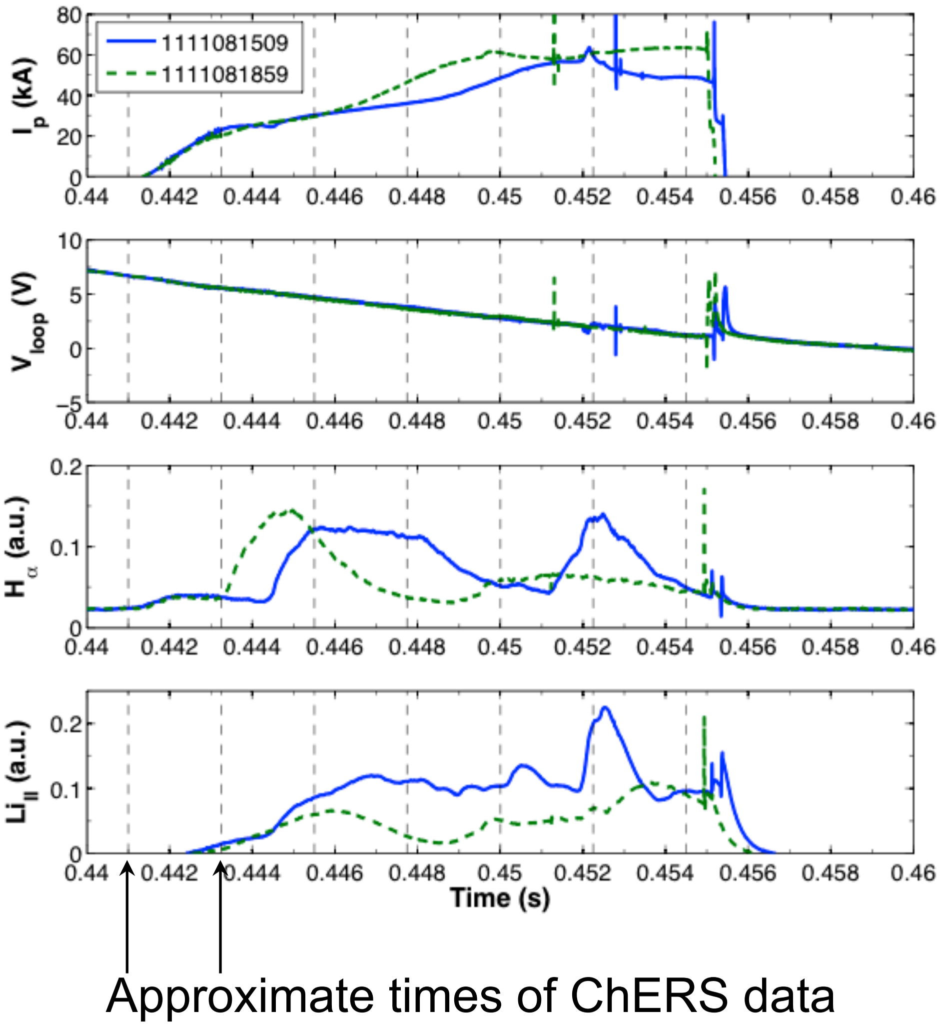
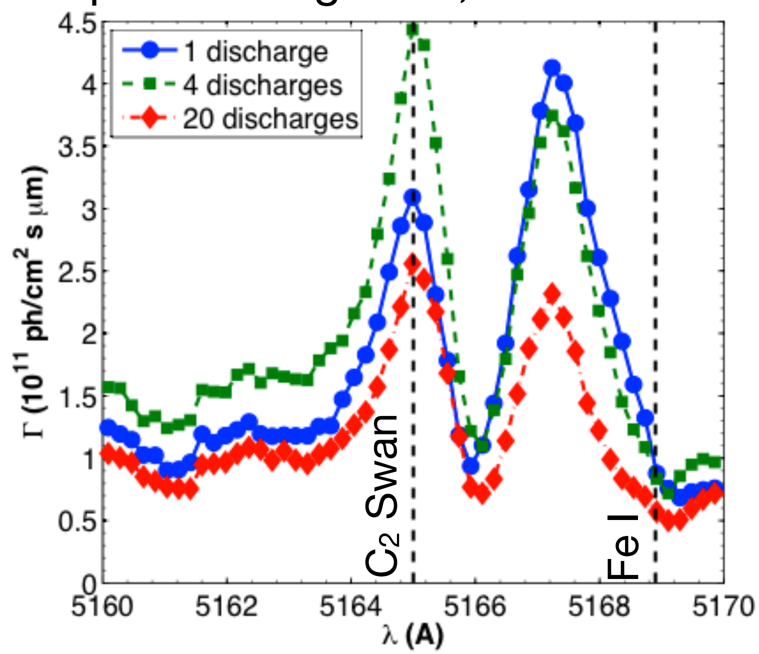
Series of discharges after evaporation as the lithium passivates



- **All shots are nearly identical**
  - **$50 \leq I_p \leq 65$ kA**
  - **some differences in fueling**
    - **Gas puffing vs Molecular Cluster Injector [5]**
  - **Discharge lifetime ~ 15 ms**

ρ = 0.11 sightline, t = 0.45 ms



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Passive Spectroscopy Simulations

LTX

- Code written to simulate (for a given set of Li^{2+} n_i, T_i, v_T profiles), what the measured passive spectra for this spectrometer/camera should look like.
- Additional code fits Gaussian distributions to this "data" to give l.o.s. estimations of the Li n_i, T_i, v_T profiles.
- These "measurements" are inverted to yield local values of Li n_i, T_i, v_T (which can be compared to the given profiles.)
  - R.E. Bell, Rev. Sci. Instrum. 68 (2) 1997, p. 1273.

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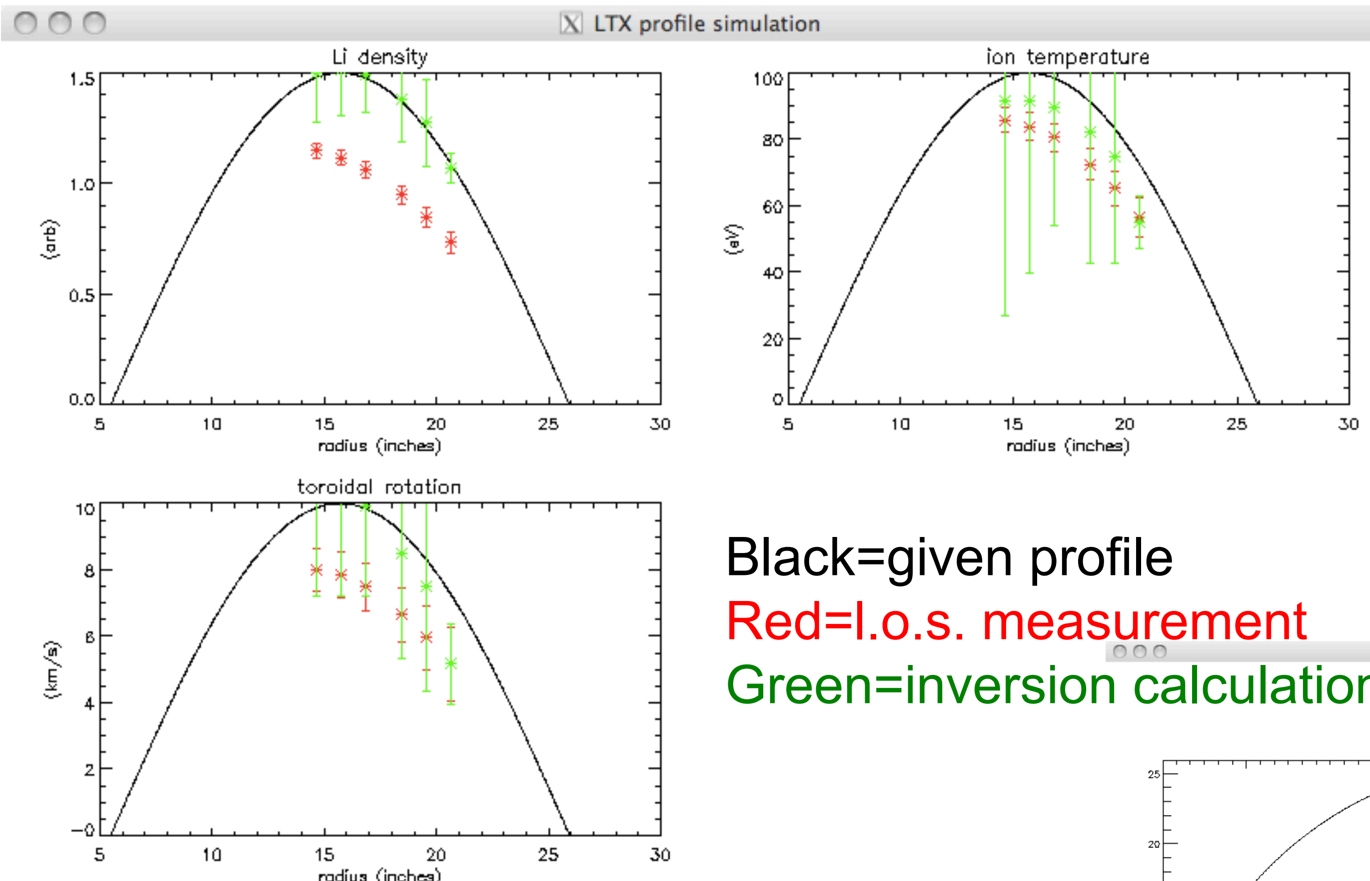
“As Built” Array with Peaked n_{Li} Profile



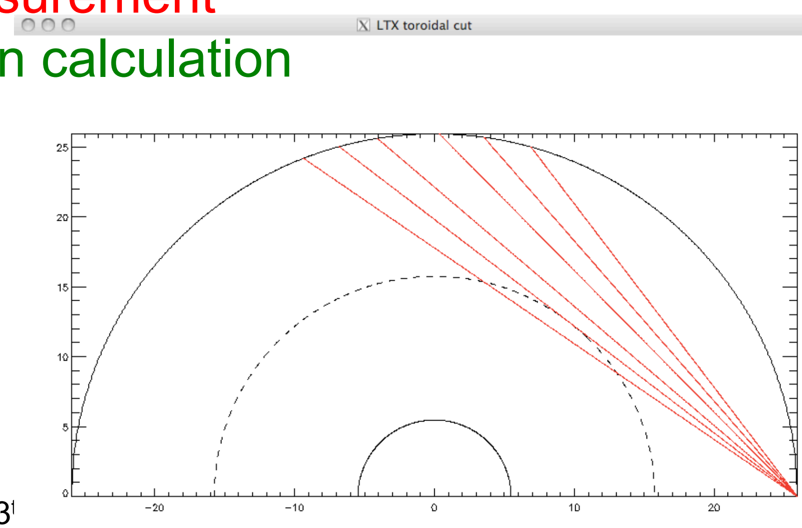
Lack of edge data leads to large error bar and inaccuracy on outer-most chord.

(75 micron instrument function)

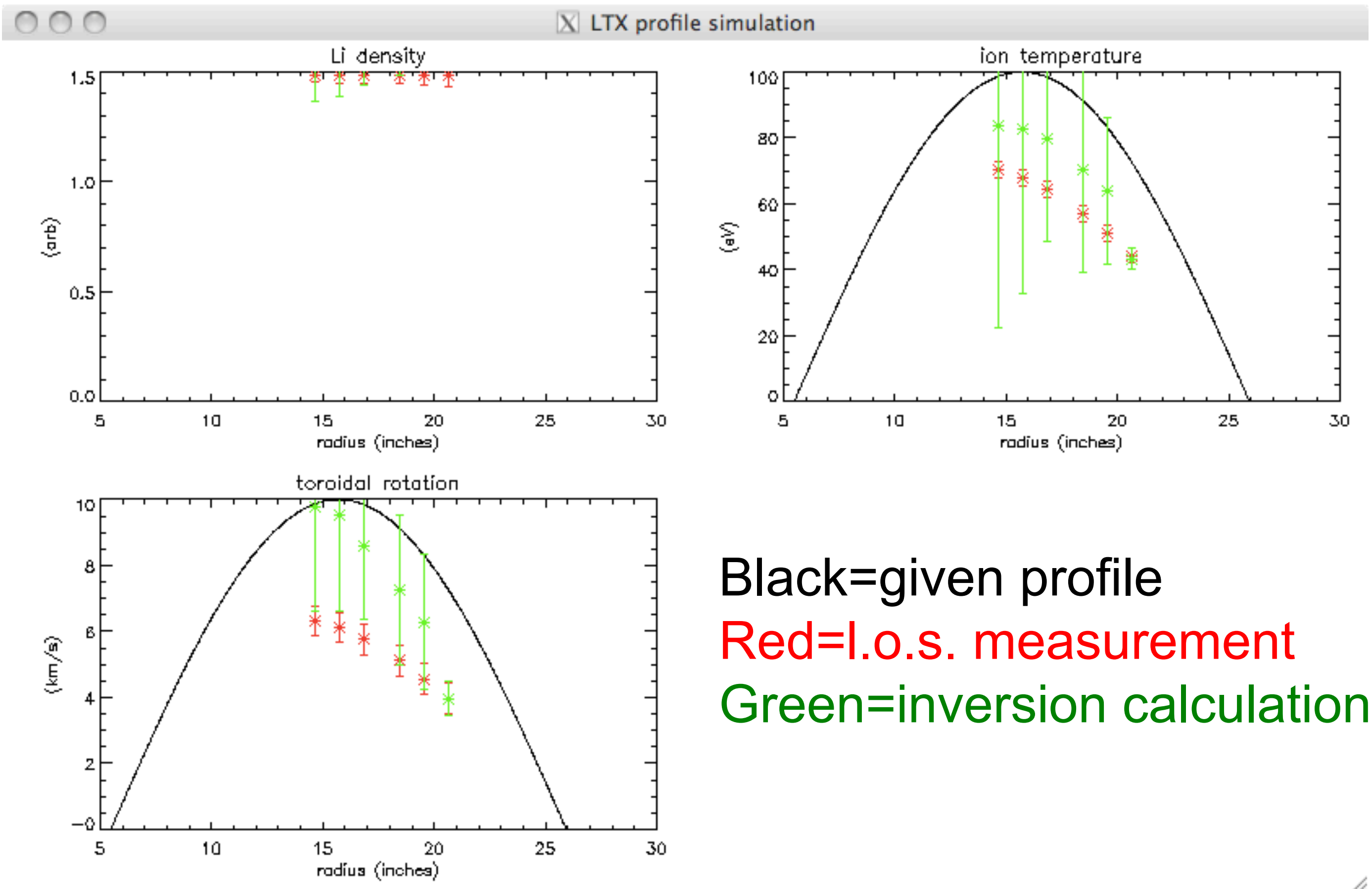
Black=given profile

Red=l.o.s. measurement

Green=inversion calculation



"As Built" Array with Flat n_{Li} Profile



Black=given profile
Red=l.o.s. measurement
Green=inversion calculation

Lack of edge data leads to large error bar and inaccuracy on outer-most chord.

Flat n_i profile causes difficulty for inversion routine.

(75 micron instrument function)

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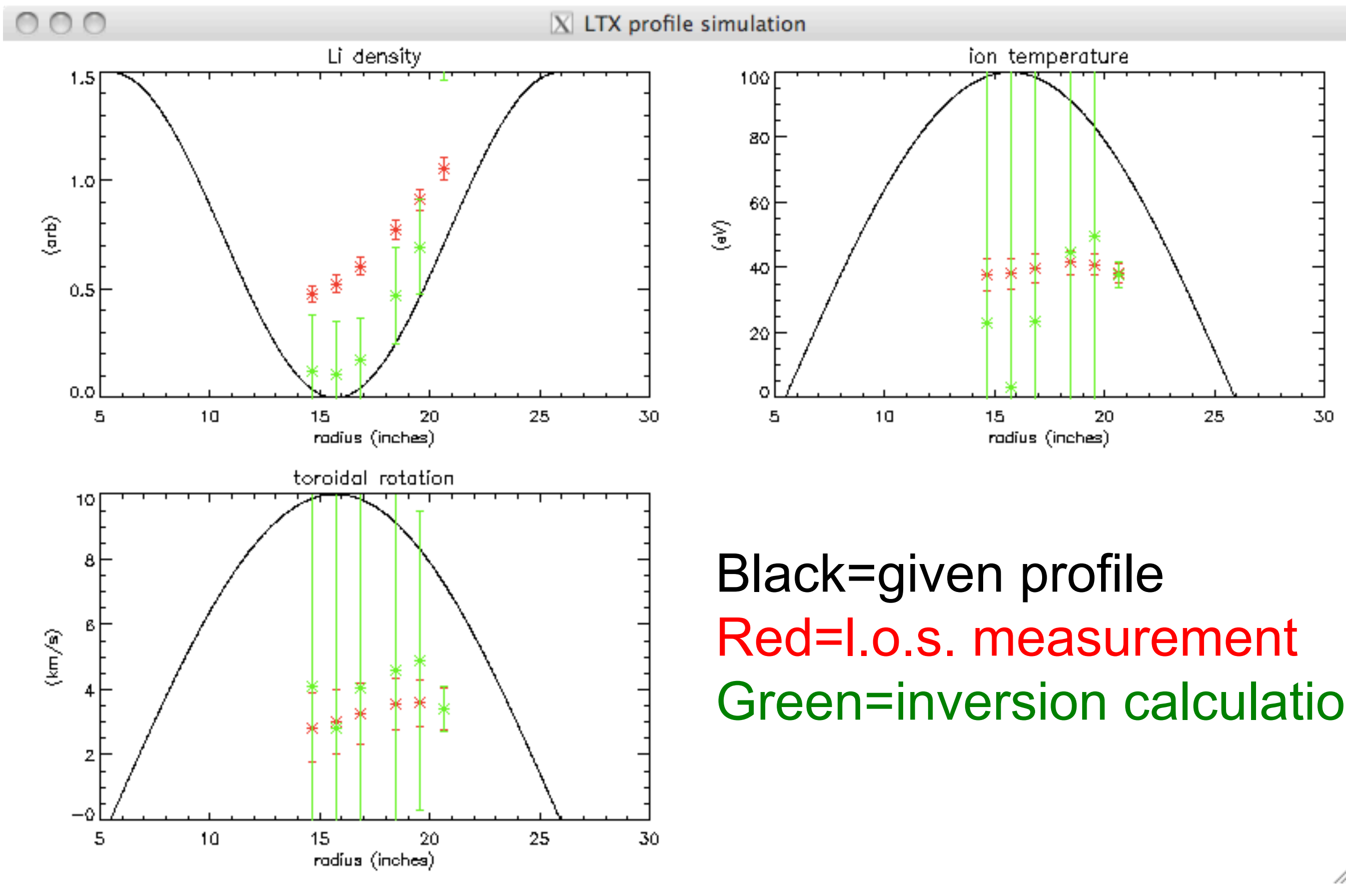
“As Built” Array with Hollow n_{Li} Profile LTX



Black=given profile

Red=l.o.s. measurement

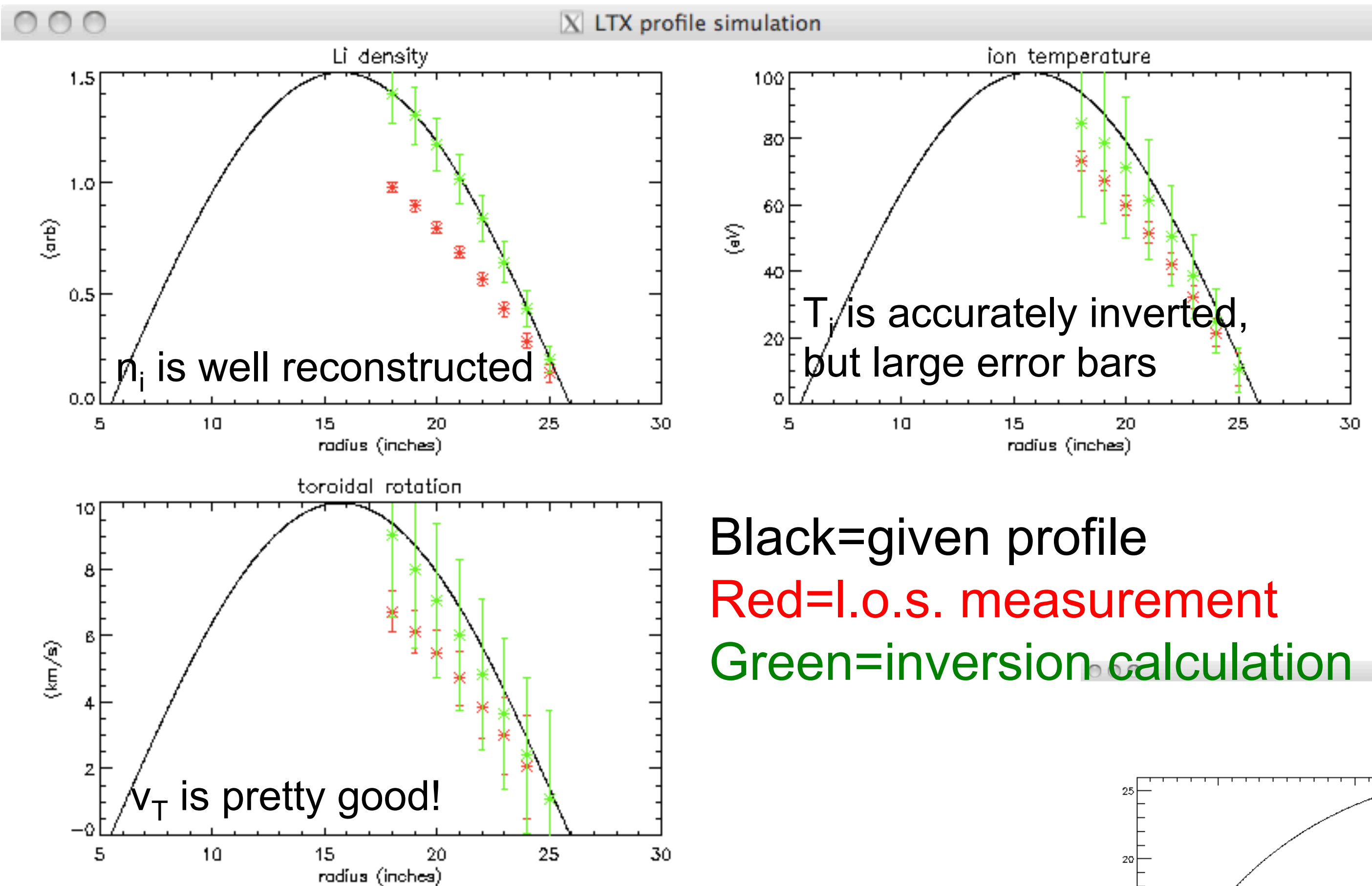
Green=inversion calculation

Lack of edge data leads to large error bar and inaccuracy on most chords.

Hollow n_i makes core T_i and v_T measurements problematic.

(75 micron instrument function)

Example 1" Resolution Array, 8 L.o.S.



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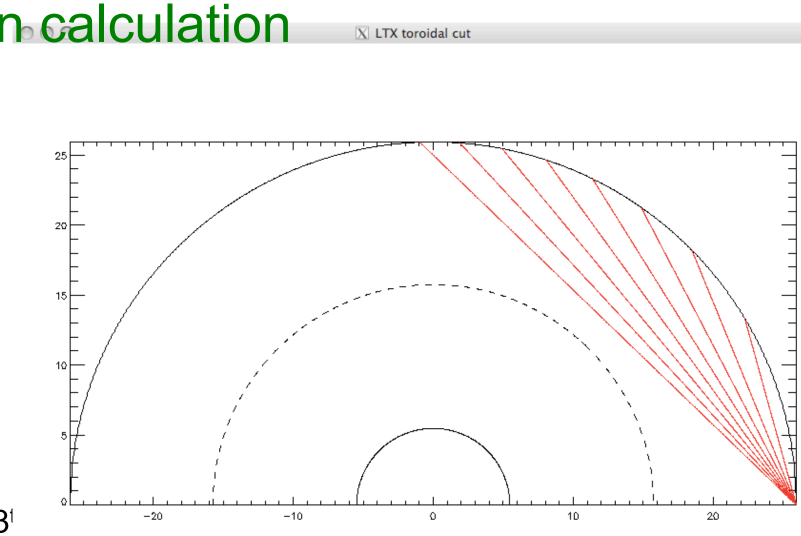
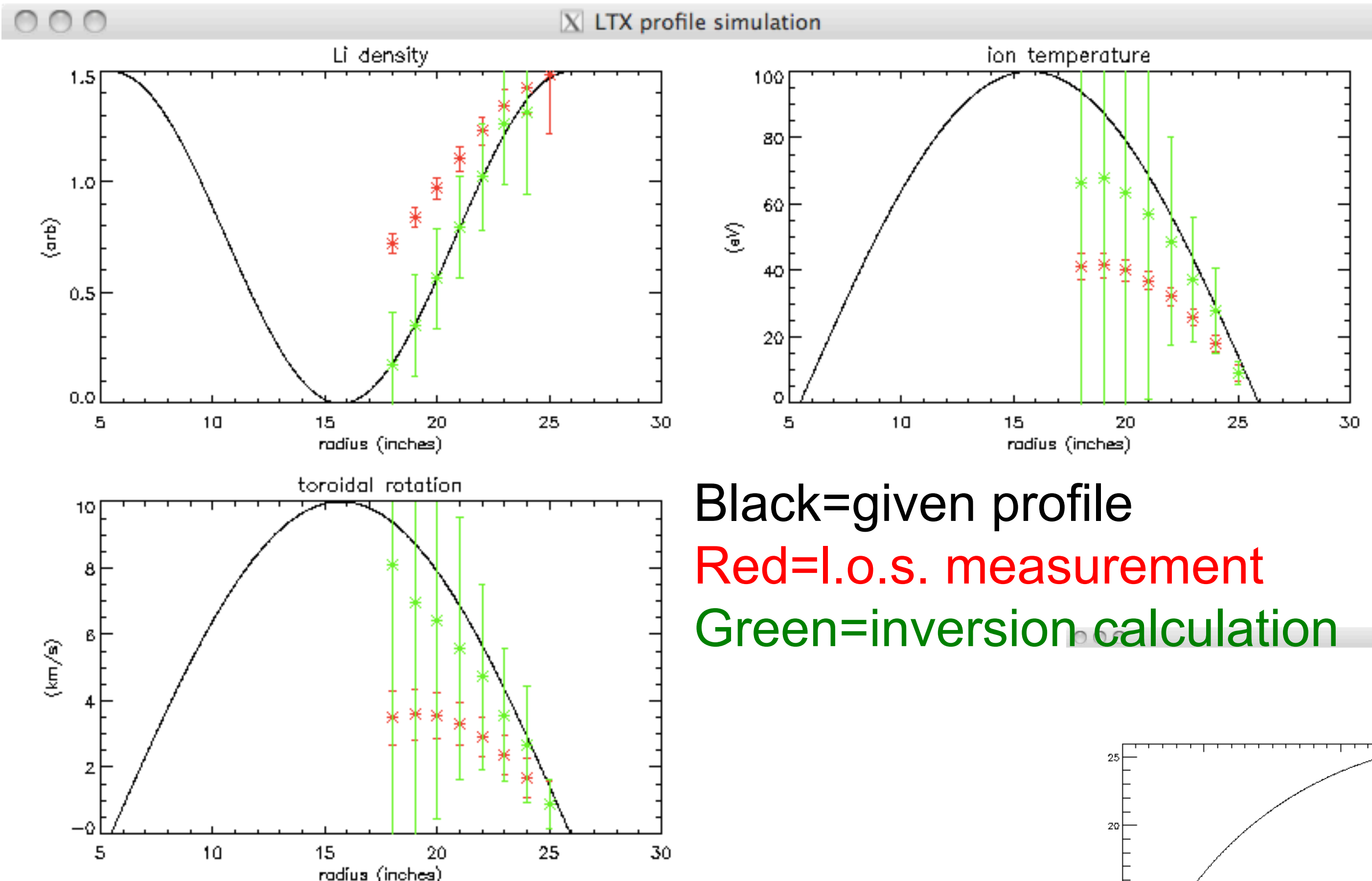
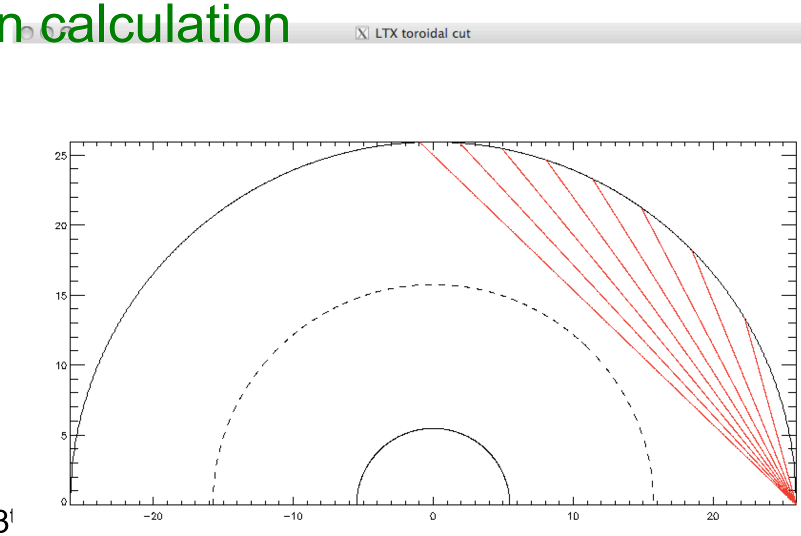


Example 1" Resolution Array is OK Even if n_{Li} is Hollow.



Black=given profile
Red=l.o.s. measurement
Green=inversion calculation



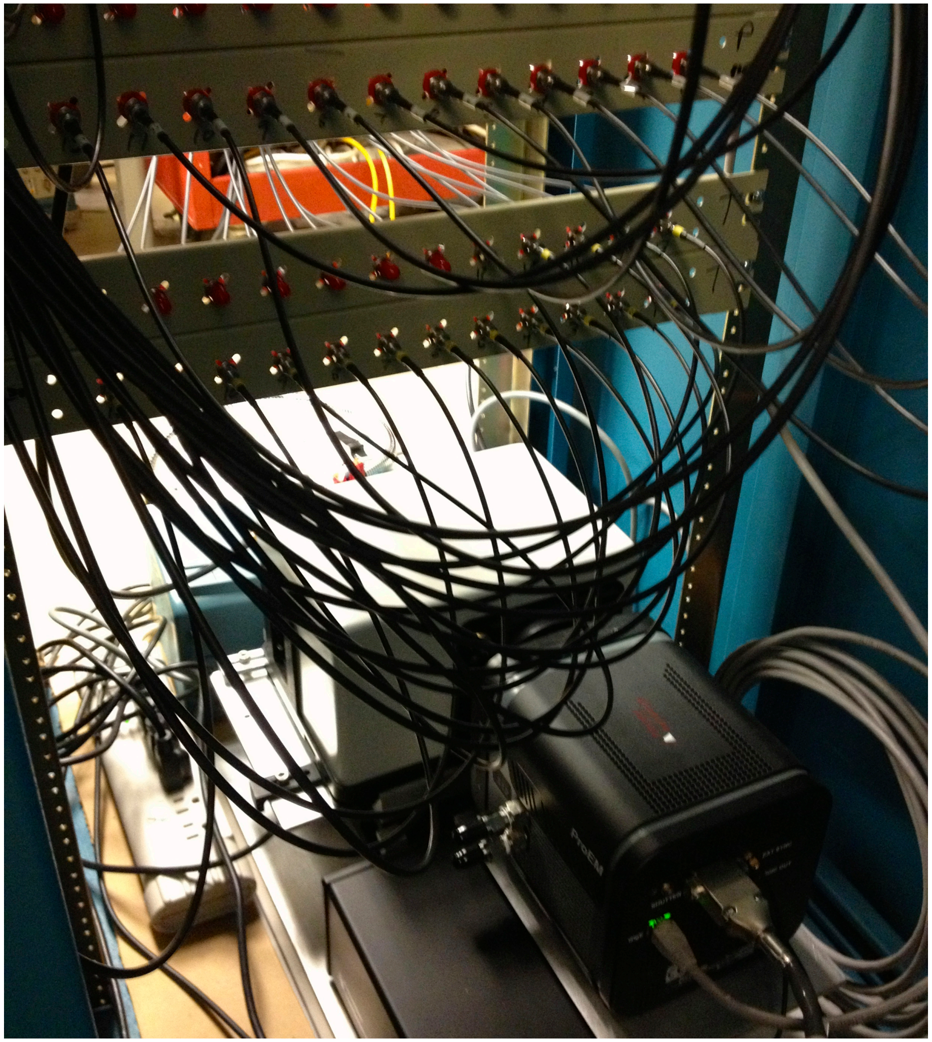
Passive Spectroscopy Simulation Summary

LTX

- Simulations of the "as built" toroidal array suggest that the inversion of line-of-sight passive spectroscopy data can be accomplished to yield local values of Li III emissivity, T_i, and v_T.
  - Greatest accuracy of the inversion is achieved when the brightness of Li III emission is centrally peaked.
  - Hollow Li III emission can not easily be inverted for the "as built" array.
  - Qualitative information about the Li III brightness profile shape can be inferred.
- Increasing the number of lines-of-sight improves the inversion accuracy, especially with the addition of edge chords.
- Since the installation of the Neutral Beam Injector (NBI) is greatly delayed, a more comprehensive passive spectroscopy array is justified.

“CHERS” upgrade recently completed LTX

- **Spectrometer/CCD moved from LTX machine area to diagnostic hall.**
  - Reduced noise
  - Improved light environment
- **“Transfer” fiber bundles bridge from diagnostic hall to LTX collection optics.**
- **Fiber-optic patch panel allows for view-swapping without machine access.**



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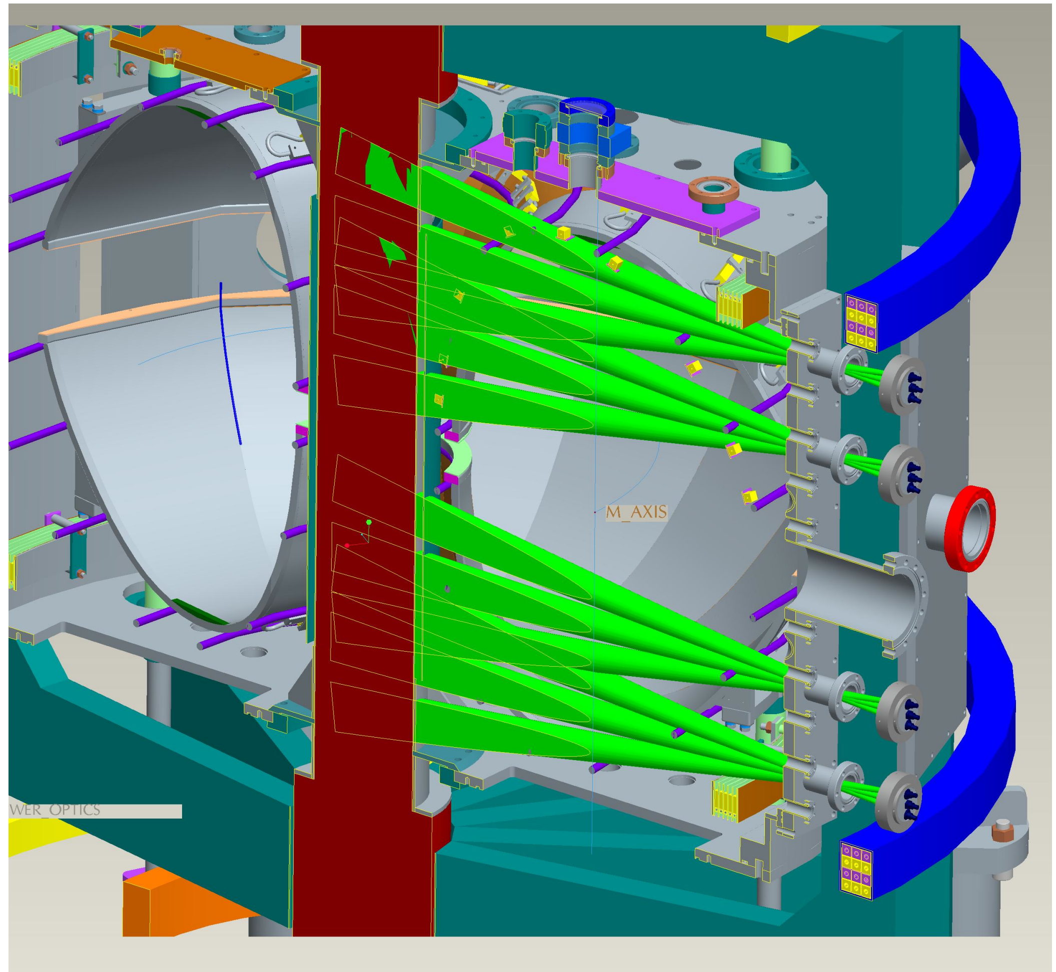
Poloidal Lines of Sight (new)

LTX

- Vertical line-of-sight arrays were replaced with horizontal arrays.
- “Matched pairs” of views above and below the nominal symmetry midplane.
- The assumption of up-down symmetry may not be accurate.
- Measurements from this array could shed some light on this issue.



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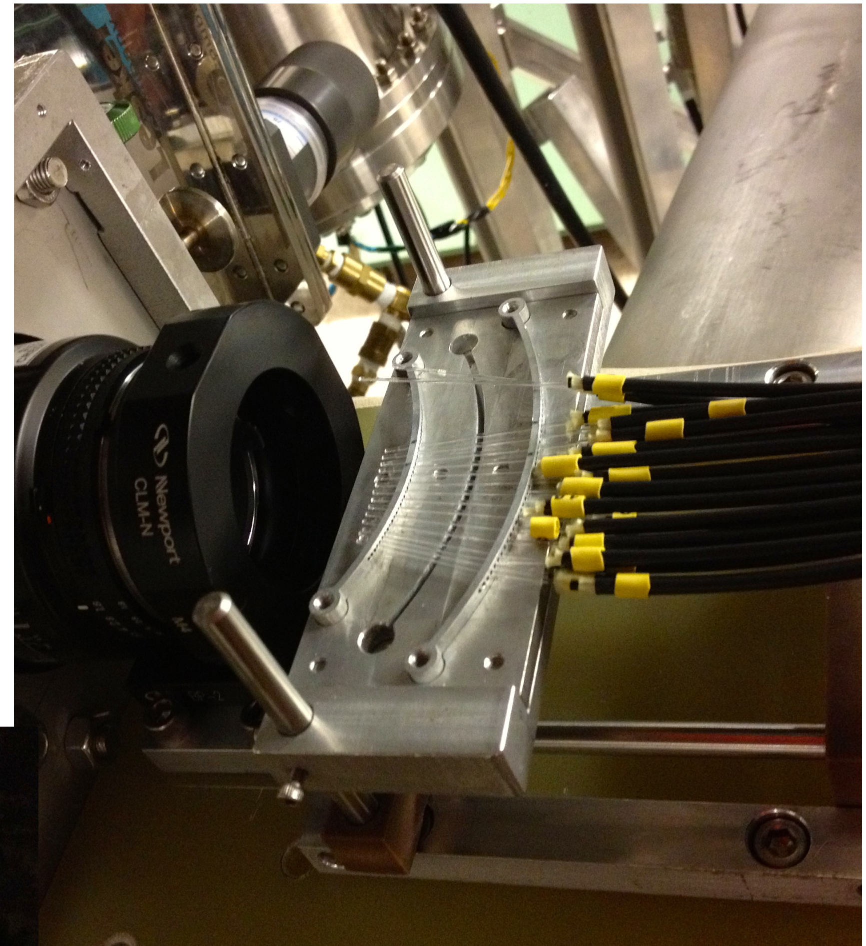
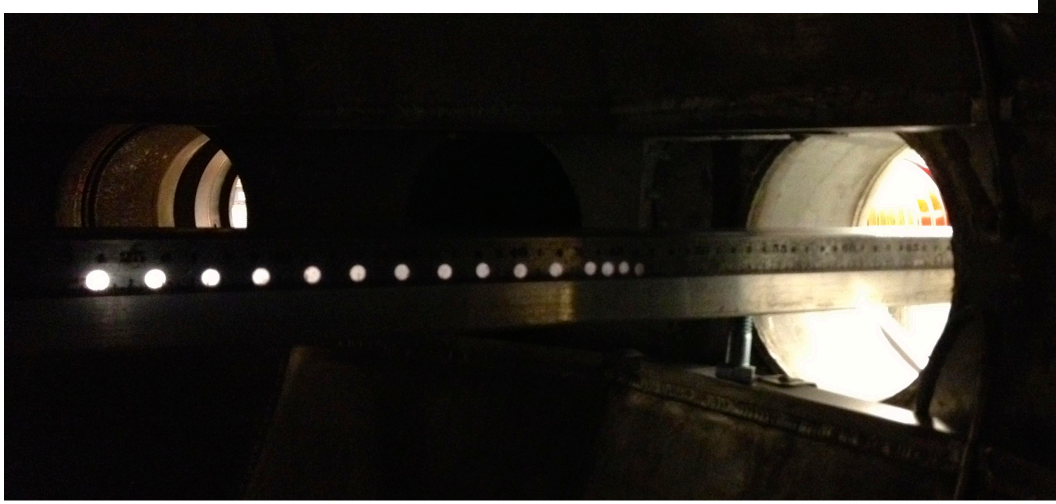
Toroidal line of sight array expanded

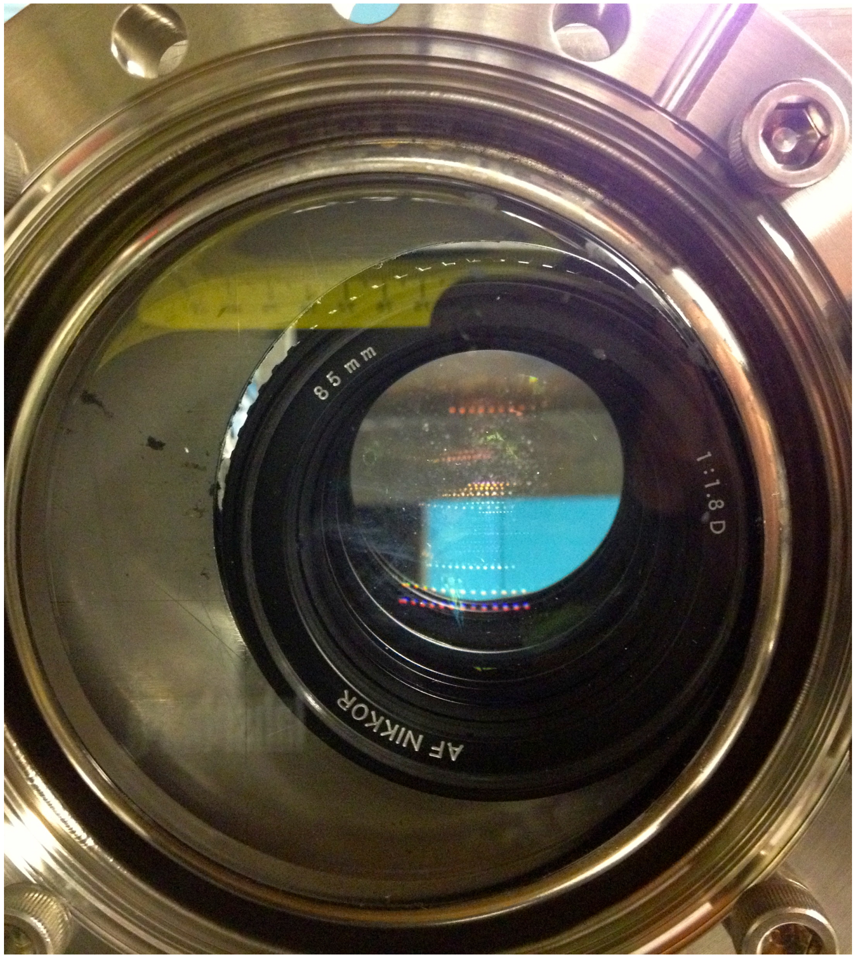
LTX

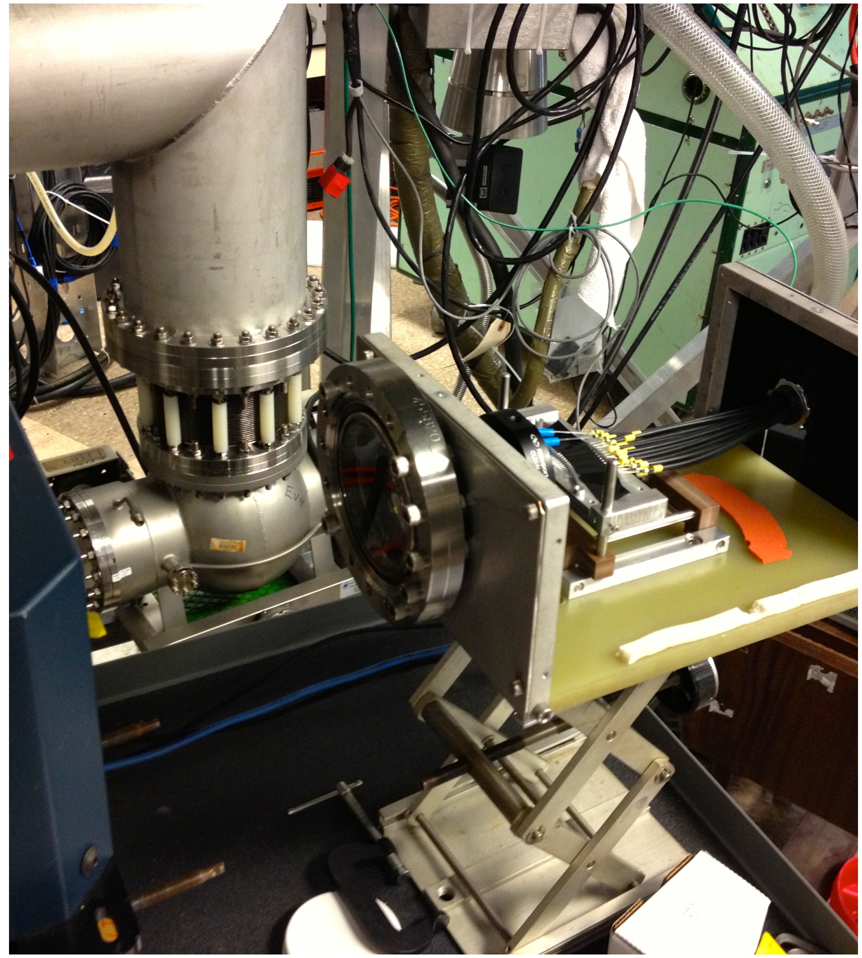
- Modular f=10mm, f/2 optics replaced with single f=85mm, f/1.8 lens
- 17 fiber line of sight replaces 6 modular sightlines





Intensity calibrations include entrance windows





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Future Plans

LTX

- NBI delays have constrained the measurements to "passive" spectroscopy for remainder of this Proposal.
- Have upgraded sightline arrays to enable inversion of line-of-sight integrated measurements.
  - Waiting for LTX operation (expected in March 2013).
- Grant renewal proposal to be prepared based on "passive spectroscopy" with aim to implement NBI and ChERS, along with continuation of CSA, filterscopes, and SOLPS modeling.
- ChERS design relies heavily on the amount of active emission of Li III in LTX, which depends on n_e, T_e, n_{Li}.
  - Have measured passive Li III emission in LTX
  - Need calculation to estimate active Li III emission at NBI ion energy (20 - 40 keV)
- Tailor existing "ChERS" hardware for active CHERS.

Summary and Conclusions

- ORNL-LTX collaboration has successfully installed and operated spectroscopy hardware for improved measurements on LTX.
- Staged implementation of "ChERS" diagnostic on LTX: initial passive spectroscopy measurements presented here.
- Hardware installed on LTX in September 2011.
  - Radial coverage from r/a < 0.5
  - 6 toroidal chords, 5-8 matched pair poloidal chords (vertical, up/down)
  - Time resolution ~2 ms (LTX pulse length ~>20 ms)
- Spectral simulations suggest an enhanced configuration is needed to distinguish qualitative line-integrated profile effects.
- Hardware installed on LTX in January 2013.
  - Radial coverage from r/a < 0.8
  - 17 toroidal chords, 6-9 matched pair poloidal chords (horizontal, above/below midplane)
  - Time resolution unchanged
- Passive spectroscopy with new arrays planned for 2013.
- Active spectroscopy (ChERS) to be proposal (renewal) for FY14-FY16.

Reprints

LTX

- Copies of this poster are available online:
  - http://sprott.physics.wisc.edu/biewer/EPR2013poster.pdf
- Or, write your name and email address below: