NSTX

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Scrape-Off Layer and Boundary Physics Research on NSTX with an Introduction to LTX

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and the NSTX and LTX Research Teams

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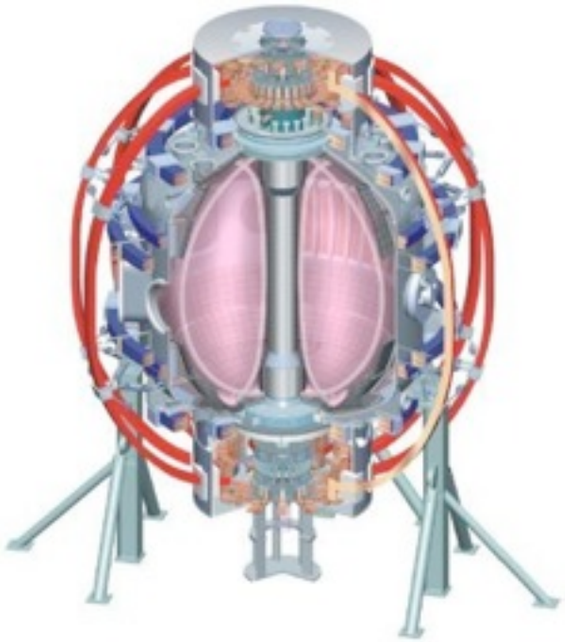
ORNL Experimental Plasma Physics Seminar
January 18, 2012



Outline

- SOL width and scaling (inter-ELM)
  - Summary of 2010 Joint Research Milestone Results
  - Comparison of D3D, CMOD and NSTX data + scaling
- Effects of Lithium on SOL width, heat flux and power accounting

- Introduction to the Lithium Tokamak Experiment (LTX)
  - Overview and Status of LTX (and why LTX is potentially exciting)
  - ORNL diagnostics on LTX
    - and what physics we hope to observe!
  - Results with and without evaporative lithium coating
  - Preliminary passive "CHERS" measurements
- LTX Experimental plans

NSTX-U will have Divertor Heat Flux Similar to ITER's

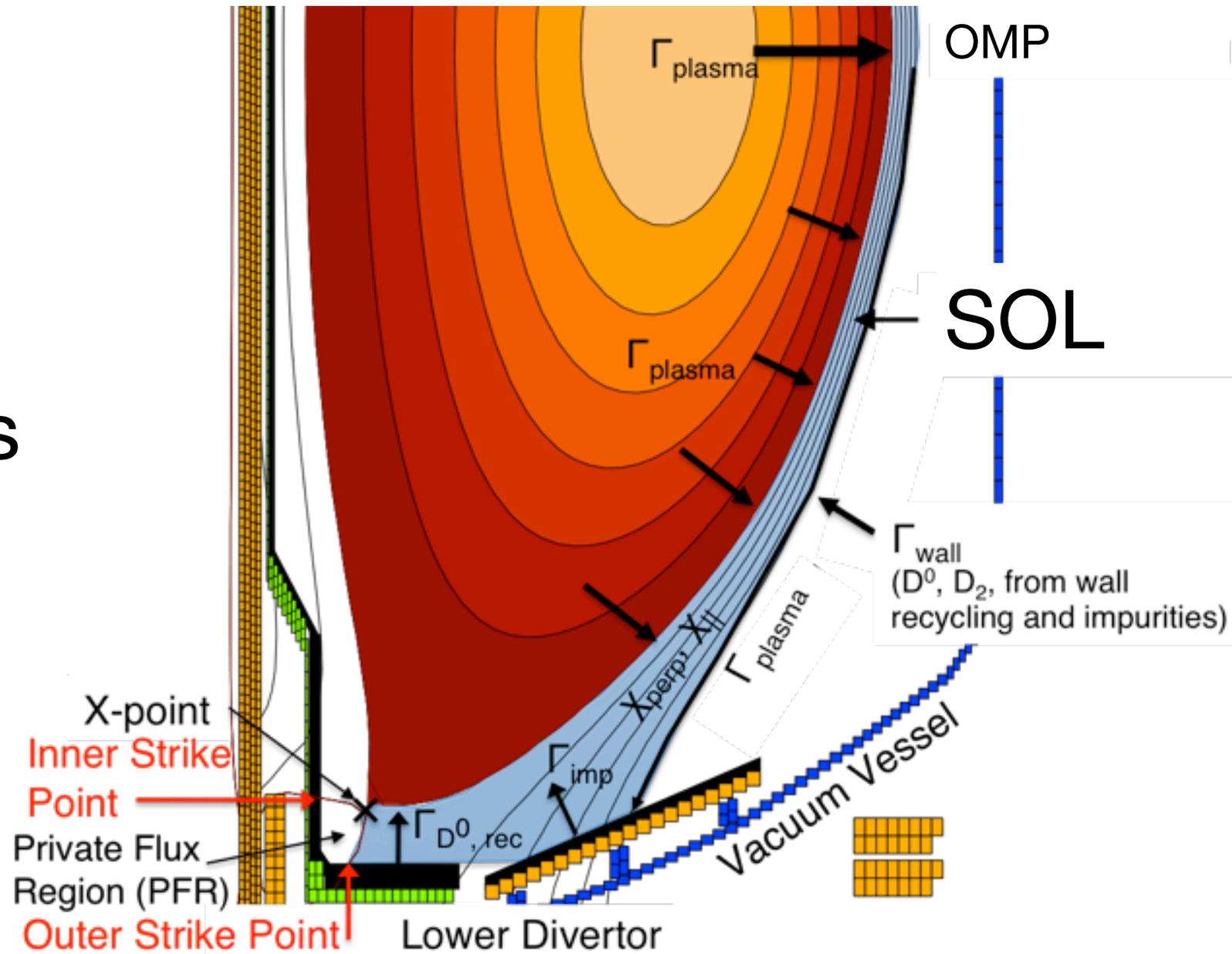
- NSTX-U is scheduled to be online in April 2014
  - Well ahead of ITER
  - Can provide a testbed for divertor physics and plasma-material interactions

- Understanding how heat flux and SOL width, λ_q scale with engineering parameters is required

- Heat flux mitigation and control of divertor conditions will be required for NSTX-U
  - NSTX-U: I_p = 2 MA, P_{NBI} = 10 MW → $q_{dep,\ pk}$ ~ 24 MW/m^2
    - Assumes a balanced double null (DN) operation with f_{exp} ~ 30

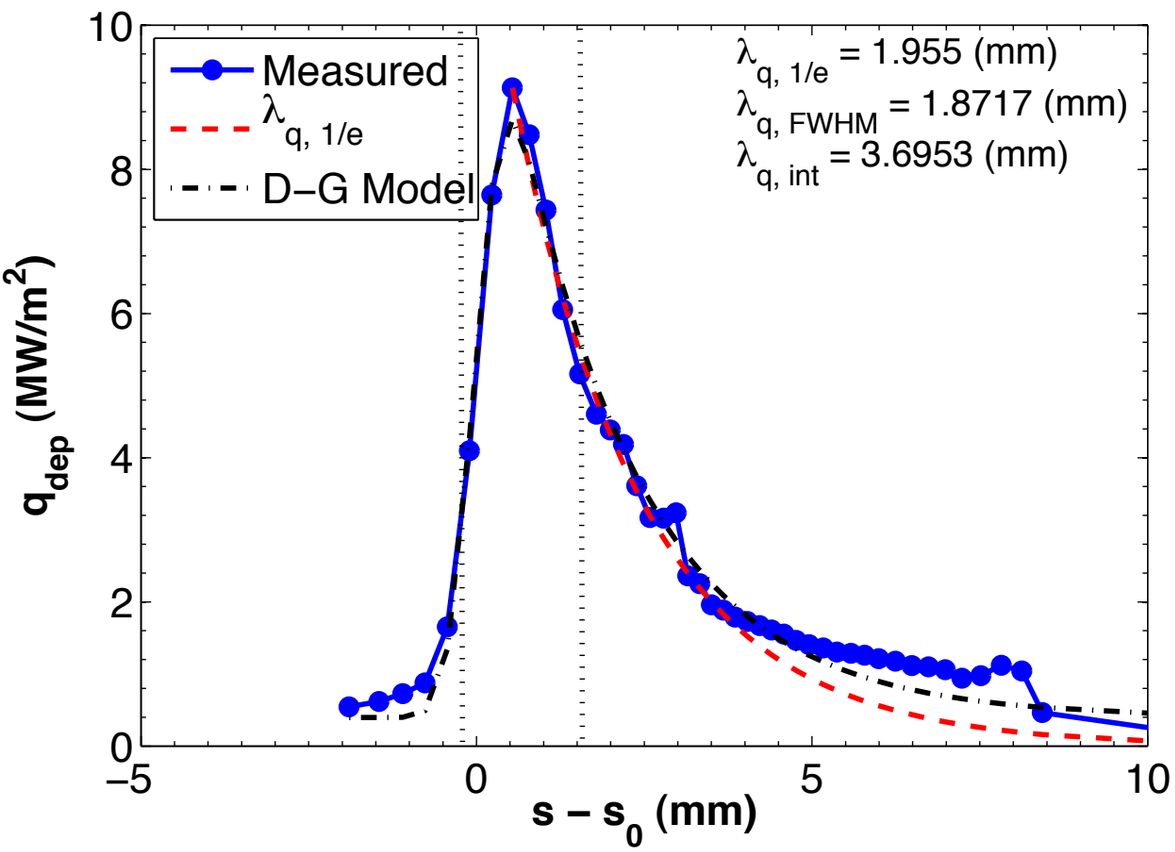
Scrape-Off Layer (SOL) Physics

- Scrape-off Layer width, λ_q is set by parallel and perpendicular χ's
- Competing, complex processes in the divertor
  - Source plasma particle and energy
  - Recycling
  - Impurity generation and transport
  - Radiation



There are numerous definitions for the SOL width, λ_q

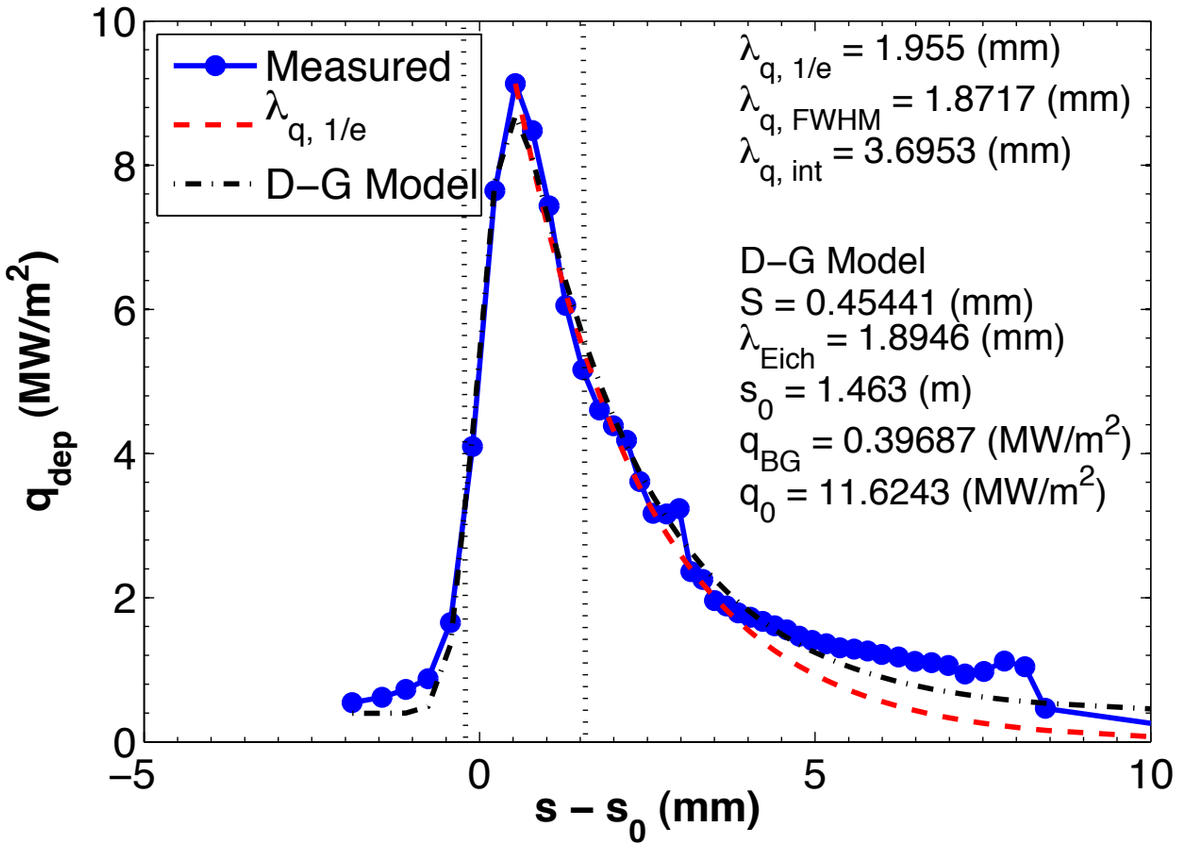
Deposited Heat Flux profile
magnetically mapped to the midplane



- Exponential: $\lambda_{q,\ 1/e}$
  - Fit to the near-SOL region
- Full-Width, Half Max: $\lambda_{q,\ FWHM}$
- Integral: $\lambda_{q,\ int}$
  - Introduced by A. Loarte, et al. *J. Nucl. Mater.* **366-269** (1999) 587
  - Numerical integration of radial heat flux profile

$$\lambda_{q,int} = \frac{\int \left(q(s) - q_{\mathrm{BG}}\right) ds}{q_{\max}}$$

There are numerous definitions for the SOL width, λ_q



s = radial coordinate

s_0 = Strike Point Location

$\bar{s} = s - s_0$

q_0 = peak heat flux

q_{BG} = background heat flux

λ_q ($\lambda_{q,\ Eich}$) = e-folding length of q in SOL

S = Gaussian diffusion parameter

- Diffusive-Gaussian (D-G) Model
  - Introduced in T. Eich, et al. *Phys. Rev. Lett.* accepted for publication (2012)
  - Simple semi-empirical model
  - Assumes λ_q is an exponential in the SOL before entering the divertor

$$q(\bar{s}) = q_0 \exp\left(-\frac{\bar{s}}{\lambda_q f_{exp}}\right)$$

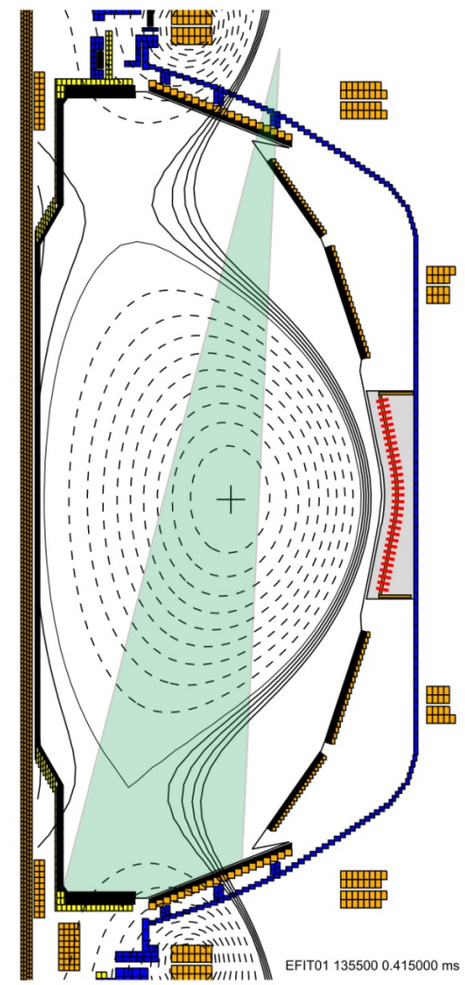
  - The exponential "diffuses" into the private flux region as it enters the divertor
  - No mechanism for this diffusion is put forth
    - But is clearly observed in all divertor footprints
  - 5 free parameters which require nonlinear least squares fitting to determine

$$q(\bar{s}) = \frac{1}{2} q_0 \exp\left(\left(\frac{S}{2\lambda_q f_{exp}}\right)^2 - \frac{\bar{s}}{\lambda_q f_{exp}}\right) \mathrm{erfc}\left(\frac{S}{2\lambda_q f_{exp}} - \frac{\bar{s}}{S}\right) + q_{BG}$$

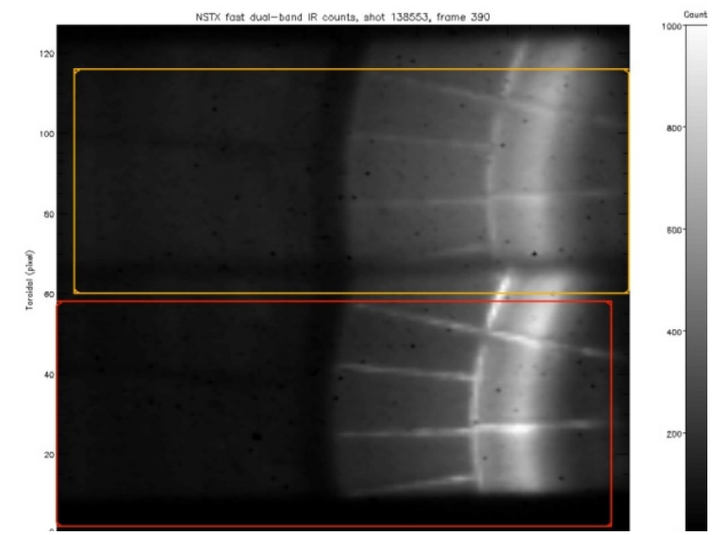
The Dual-Band IR Camera Allows Measurement of Divertor Surface Temperature with Variable Surface Emissivity

- The addition of lithium complicates the measurement of divertor surface temperature, T_{surf}
  - Li emissivity (clean) ~ 0.1
  - Graphite ~ 0.8
  - Lithium and Carbon are eroded and redeposited constantly through out the discharge
- 2 different IR wavelength bands are imaged simultaneously
  - MWIR: 7 - 10 μm
  - LWIR: 10 - 13 μm
- The ratio of the 2 bands yields temperature
  - Assumes the surface emissivity is similar across both wavelength bands
  - Not a bad assumption for a diffuse, grey body emitter
- Once T_{surf} is known, heat flux can be calculated
  - 2D finite difference calculation (THEODOR)

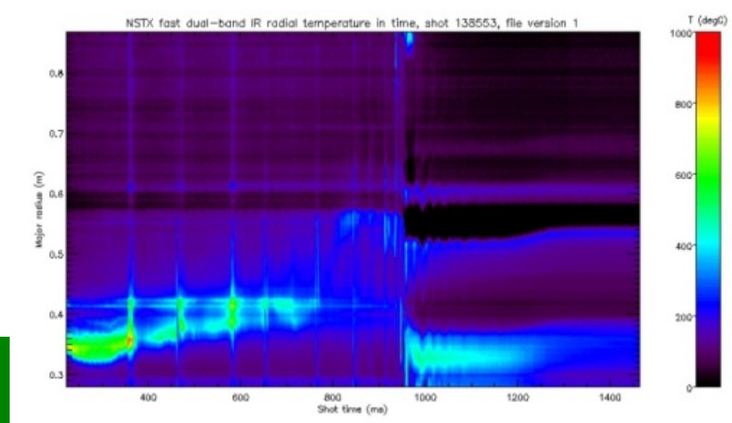
NSTX fast IR camera field of view

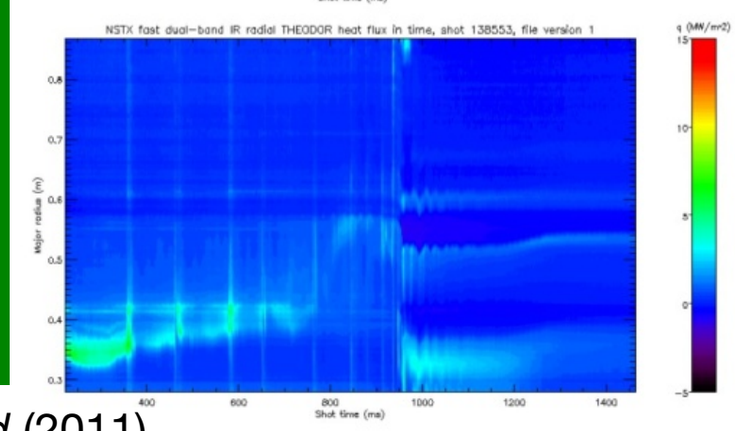


Raw dual-band data



T(R,t), q(R,t)





Fast IR Camera
Santa Barbara Focal Plane
128x128 pixels
LN cooled
frame rate ≤ 16 kHz
Typical operation at 1.6 kHz

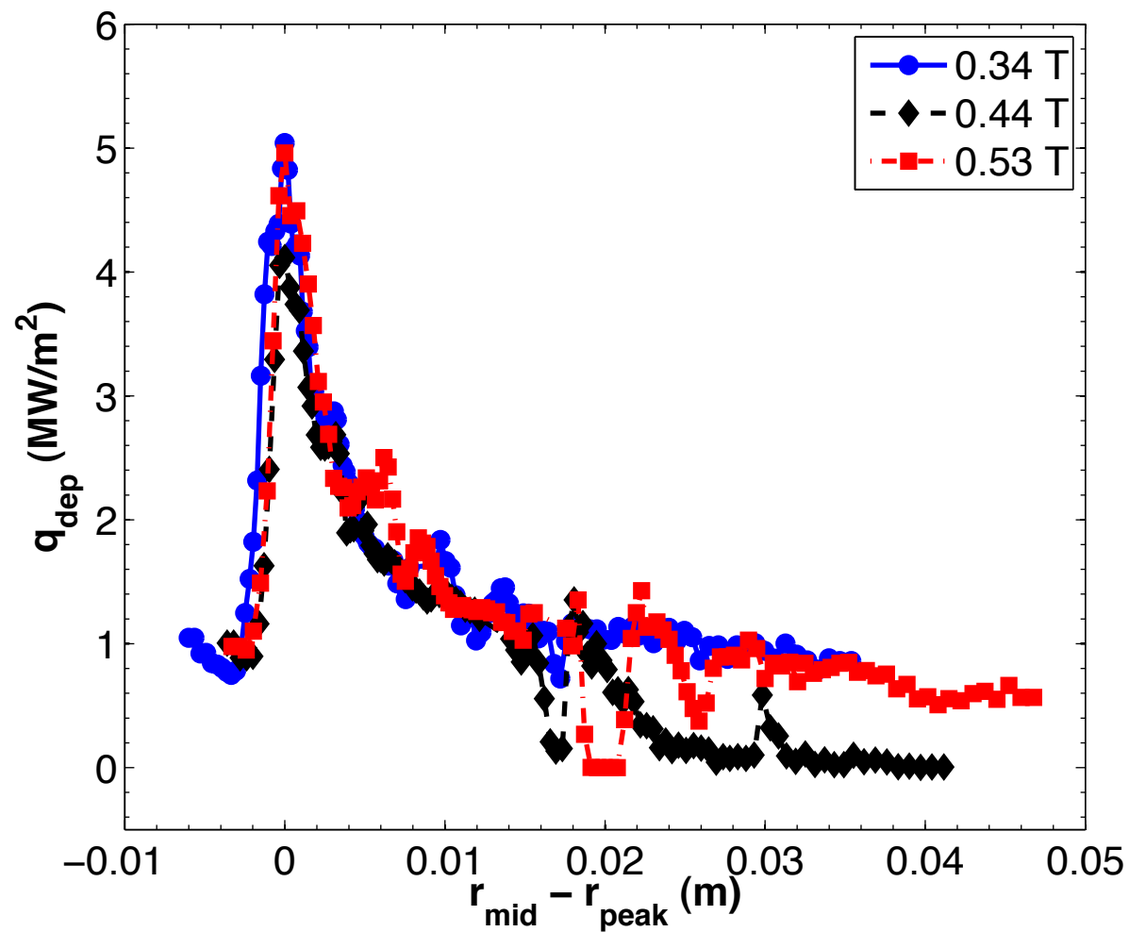
AG Mclean, RSI. *Submitted* (2011)

No Change is Observed in Heat Flux Profiles for Increasing B_t

- Have to be careful to compare profiles at similar times due to secular density rise in NSTX

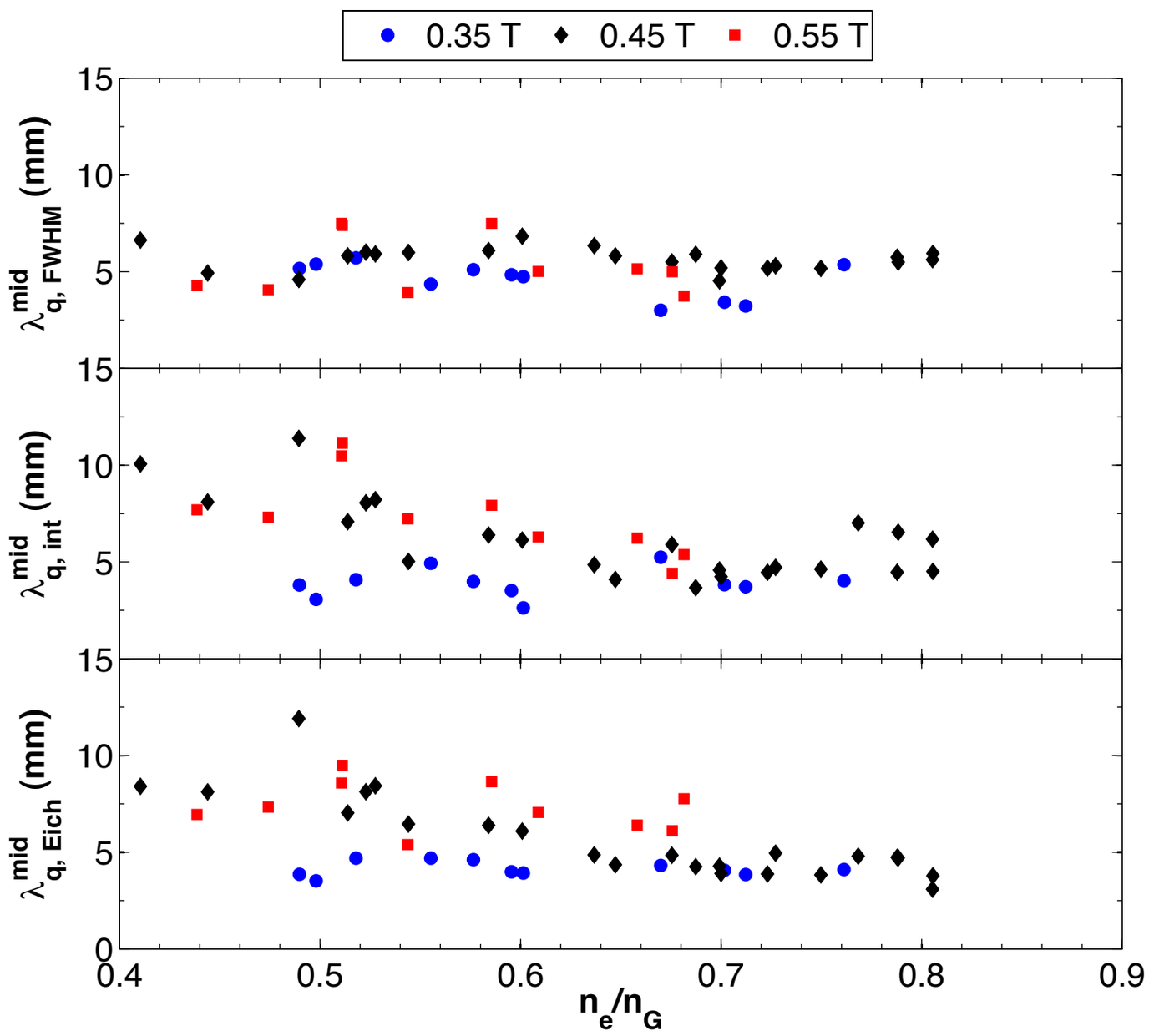
- No real change seen in heat flux profiles
  - $0.34 \leq B_t \leq 0.53$ T
  - $B_t \leq 1$ T for NSTX-U

- No dependence on B_t has been measured on other tokamaks either



$P_{NBI} = 4$ MW
$f_{exp} \sim 20$ (high δ)
150 mg Li evaporation
t ~ 0.3 sec

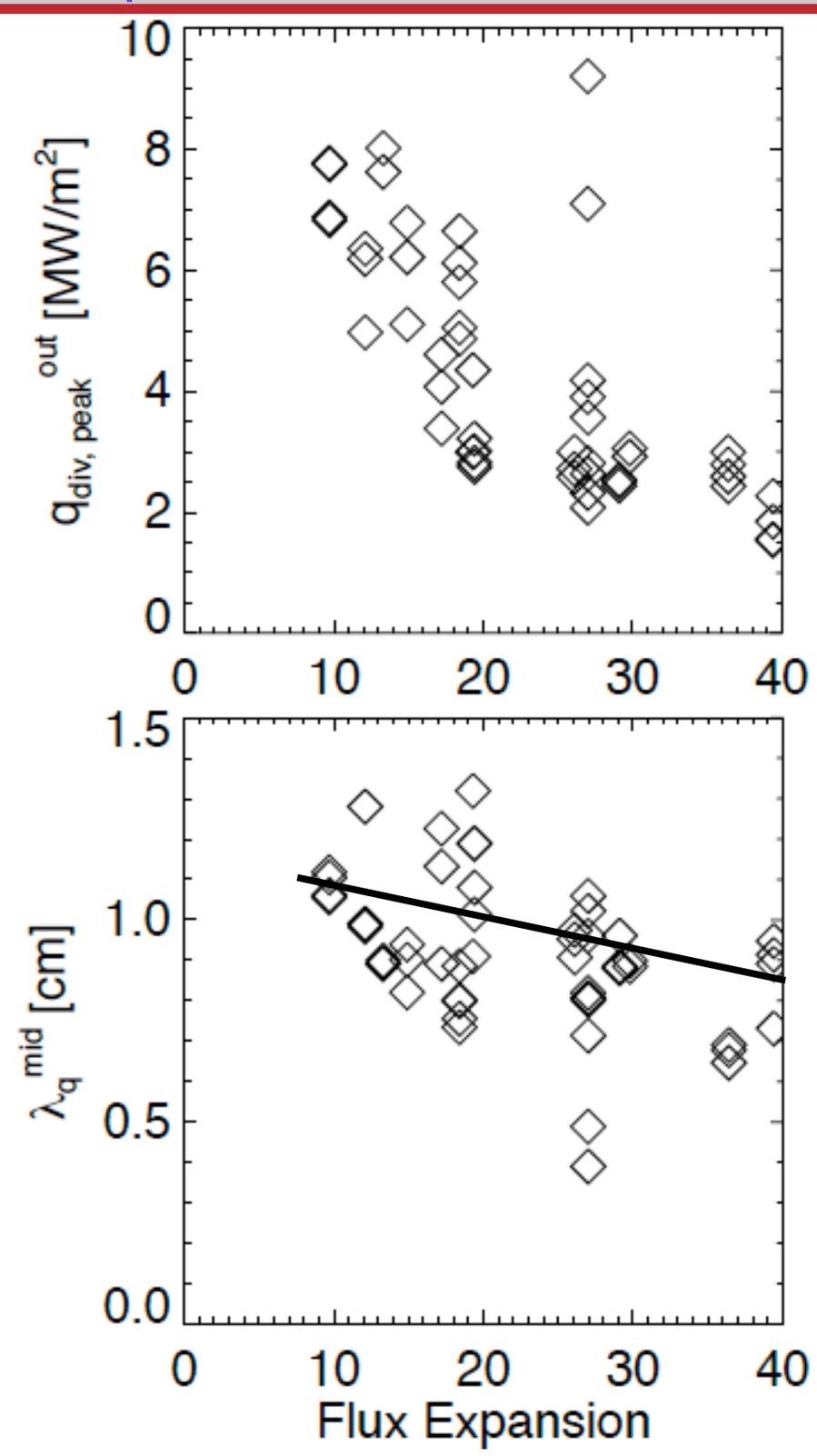
Secular Density Rise in NSTX Results in inter-ELM λ_q's that Contract Slightly as Density Increases



- Core density in NSTX rises during the discharge
  - Lack of cryo-pumping in boronized discharges
  - Carbon accumulation when Li is used
    - Li + SGI fueling has been shown to provide constant D density during discharge
- In general, inter-ELM λ_q's contract with density
  - $12 < \lambda_{q,\,int} < 3$ mm
  - $12 < \lambda_{q,\,Eich} < 3$ mm
  - FWHM $\lambda_q \sim$ constant
- Interestingly, $\lambda_q \sim$ constant for low B_t
  - lacking low density data at B_t = 0.35 T

Peak heat flux decreases inversely with flux expansion with roughly constant λ_q^{mid}

- Increased f_{exp} increases λ_q^{div} (not shown)
  - Increases the plasma wetted area
- $q_{div,peak}$ decreases as flux expansion increases
  - Flux expansion is a viable way to reduce divertor heat flux
- λ_q^{mid} stays approximately constant during the scan
  - Does decrease slightly from 1.1 → 0.9 cm

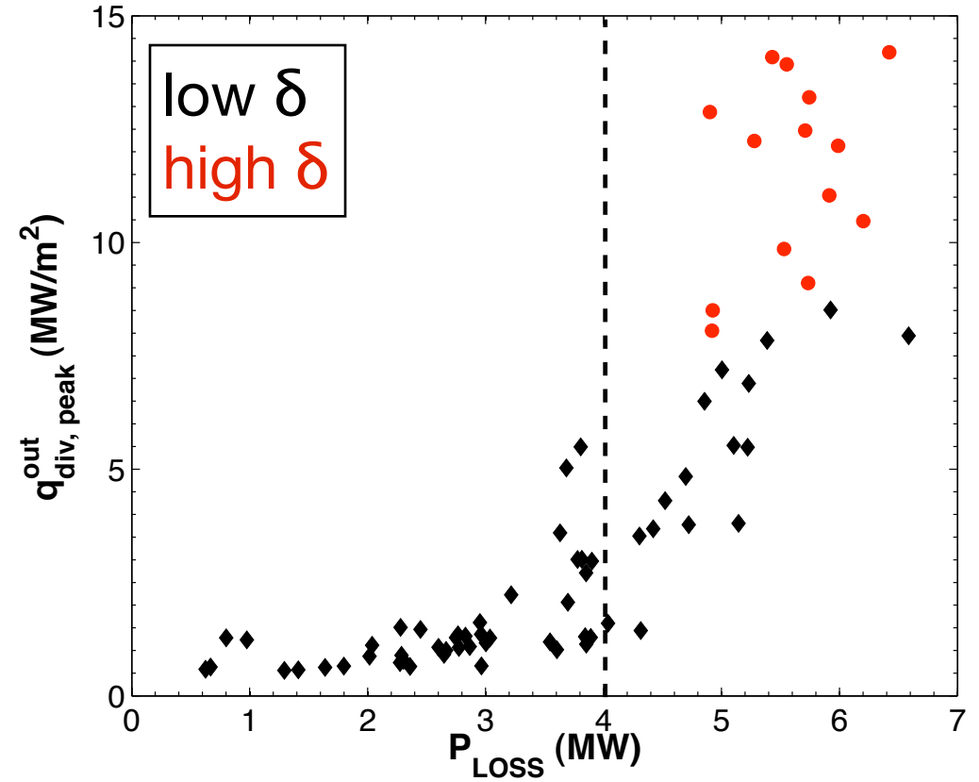


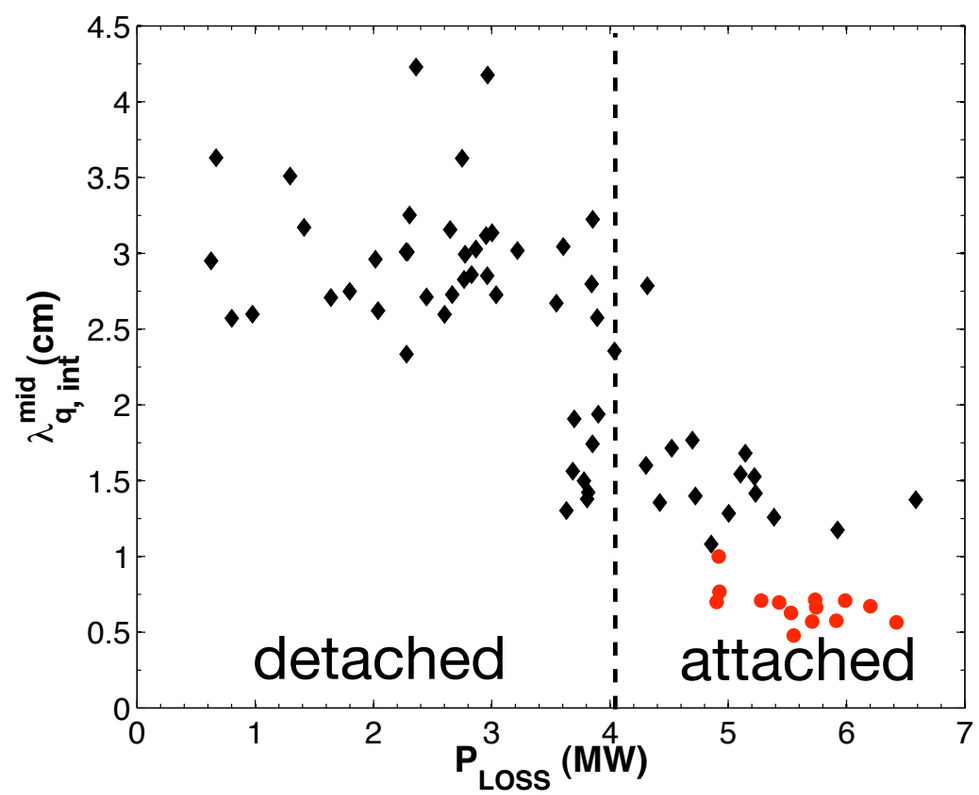
Heat flux width λ_q^{mid} largely independent of P_{loss} in attached plasmas

- Peak divertor heat flux increases with P_{loss}

$$P_{\mathrm{LOSS}} = P_{\mathrm{SOL}} = P_{\mathrm{OH}} + P_{\mathrm{NBI}} - \dot{W}_p - P_{\mathrm{rad}}^{\mathrm{core}}$$

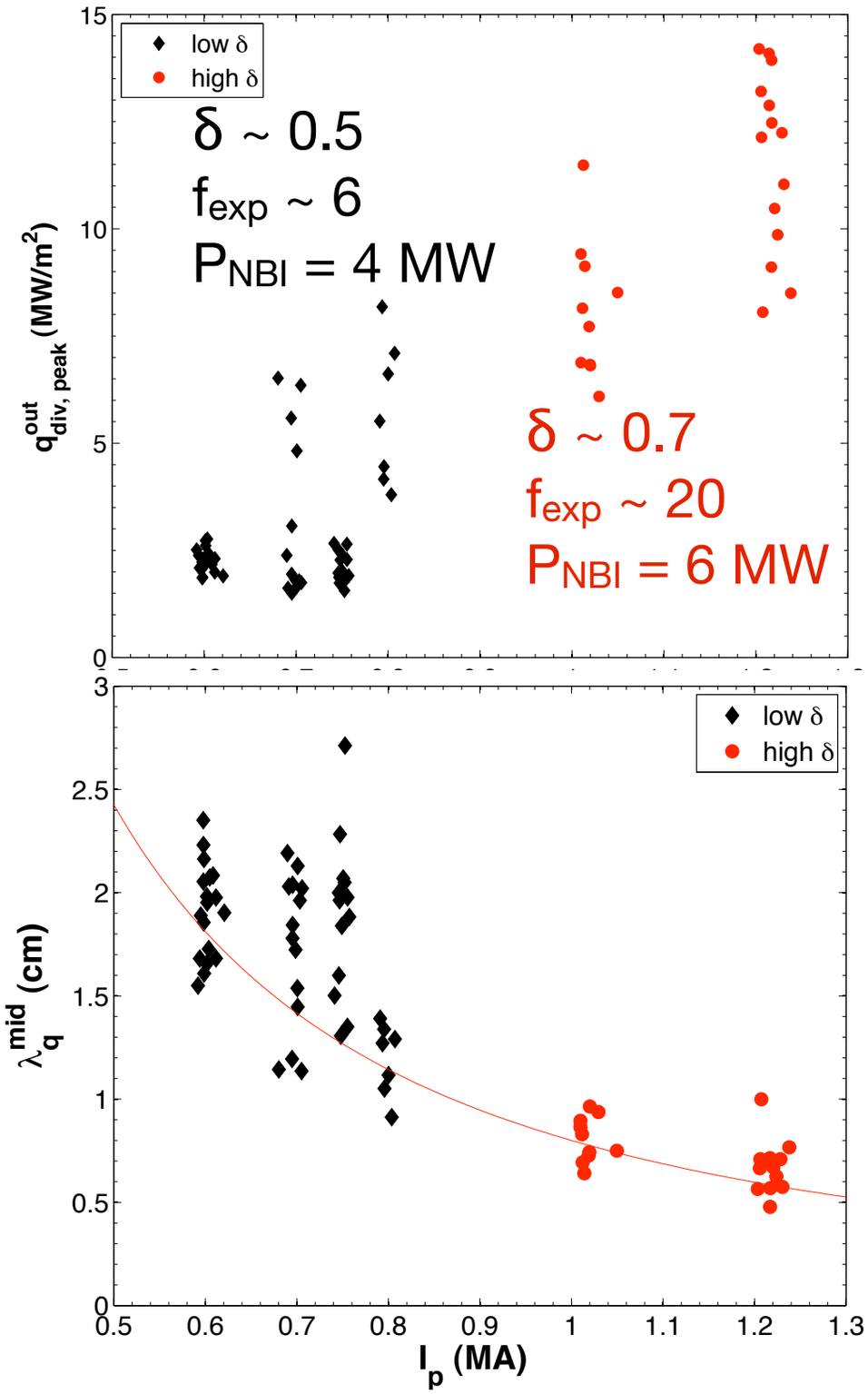
- Apparent change in slope near P_{loss} = 4 MW in these conditions
  - Divertor appears to transition from a radiative/ detached divertor to an attached divertor
  - Similar to previous experiments suggesting a radiative detached divertor at low P_{loss} [Paul 2005, Maingi 2007]
  - No rigorous determination of divertor attachment/detachment has been done
- λ_q^{mid} relatively independent of P_{loss} in high heat flux regime
  - P_{loss} > 4 MW
- Apparent I_p or q_{95} effect at higher triangularity
- λ_q^{mid} is reduced for higher δ, higher I_p discharges





Heat flux width, $\lambda_{q,\,int}^{mid}$ contracts with I_p

- Combined data from dedicated I_p scans in low δ and high δ discharges (boronized)
  - Different P_{NBI} and f_{exp}, but previous slides shows no P_{loss} or f_{exp} effect on $\lambda_{q,\,int}^{mid}$
  - q_{95}, $\lambda_{||}$ different
- λ_q^{mid} found to scale accordingly: $\lambda_{\mathrm{q,\ int}}^{\mathrm{mid}} \propto I_p^{\alpha}$
  - α = -1.6 for NSTX
  - α = -1 for D3D, C-MOD and JET



Projections for NSTX-U Heat Flux Suggests Several Challenges

- For anticipated NSTX-U Parameters:
  - I_p = 2 MA, B_t = 1 T
  - P_{LOSS} ~ 10 MW
  - f_{exp} ~ 30
  - δ ~ 0.7
  - $0.5 \leq n/n_G \leq 1.0$
- Assume $\lambda_q \sim I_p^{-1.6}$ from experiment
- Peak heat flux can be estimated:

$$q_{div,peak}^{out} = f_{div} P_{loss} \Big/ \left(2\pi R_{div,peak}^{out} f_{\exp} \lambda_q^{mid}\right) \text{ with } \lambda_q^{mid} = f(I_p, P_{loss}, B_t, f_{\exp}) \approx f(I_p)$$

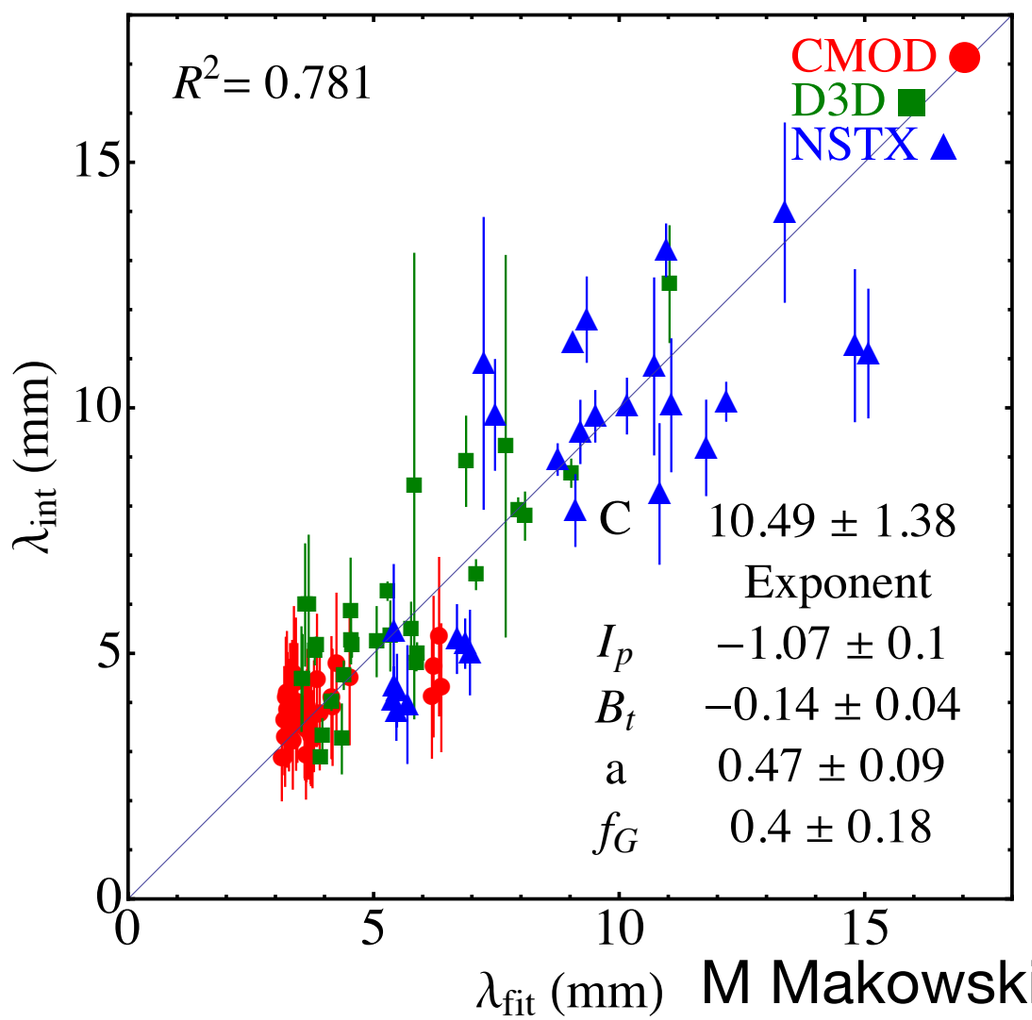
- q_{peak} ~ 24 MW/m^2!
  - f_{div} ~ 0.5 (double null operation)
- Some form of heat flux mitigation will be necessary for the upgrade
  - Snowflake (high flux expansion), divertor gas puffing
  - Lithium might help, but the mechanism is still not understood
    - Will discuss in more detail in a few slides

US Multi-Machine Scaling found $\lambda_q \propto I_p^{-1}$

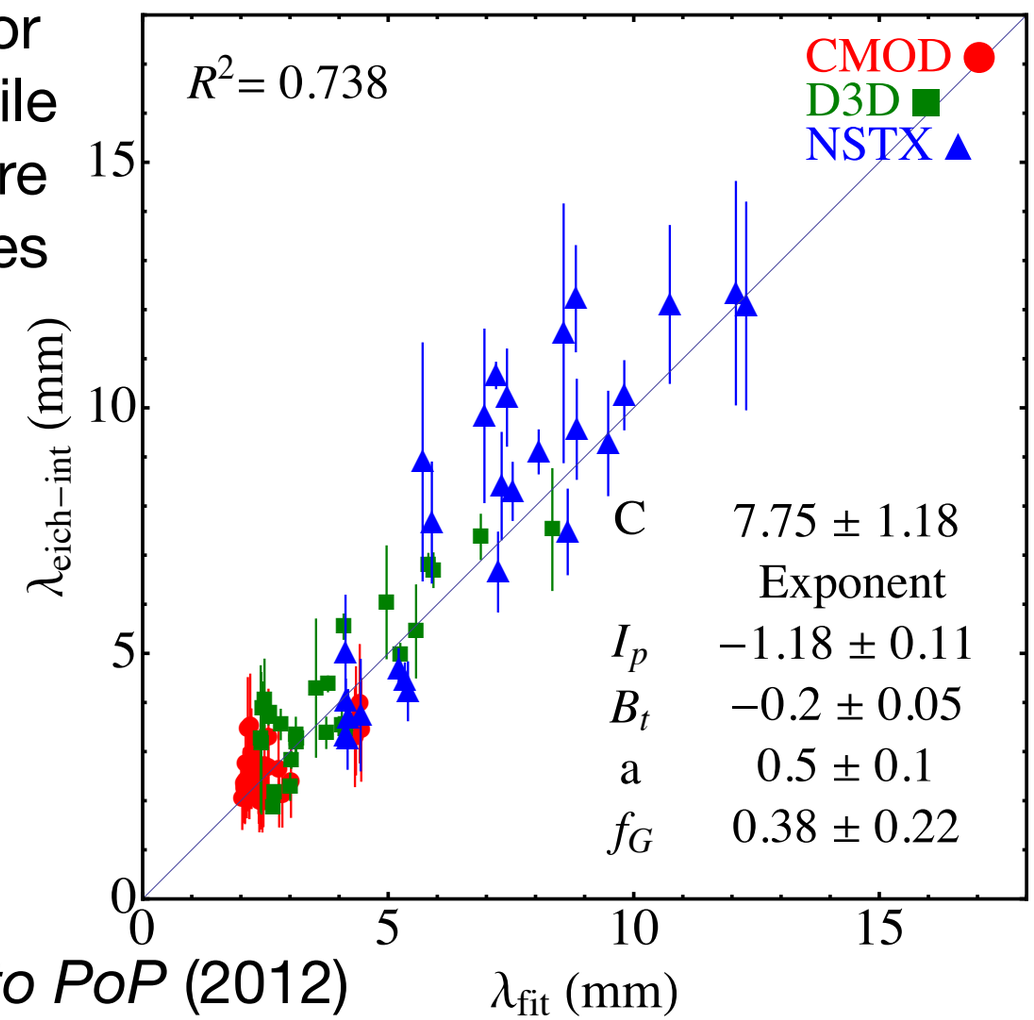
- Found a weak dependence on B_t
- Square-root dependence on minor radius (a)
- Similar dependence on Greenwald density (f_G)
  - Though with ~ 50% uncertainty

- In agreement with EU work on AUG and JET
  - Predicts ITER λ_q ~ 1-2 mm (T. Eich's APS 2011 talk)

$$\lambda_{\mathrm{q,\ int}}^{\mathrm{mid}} = \mathrm{C}\ I_p^{\alpha}\ B_t^{\beta}\ a^{\gamma}\ f_G^{\delta}$$



C-MOD data is for EDA H-mode, while D3D and NSTX are for ELMy H-modes

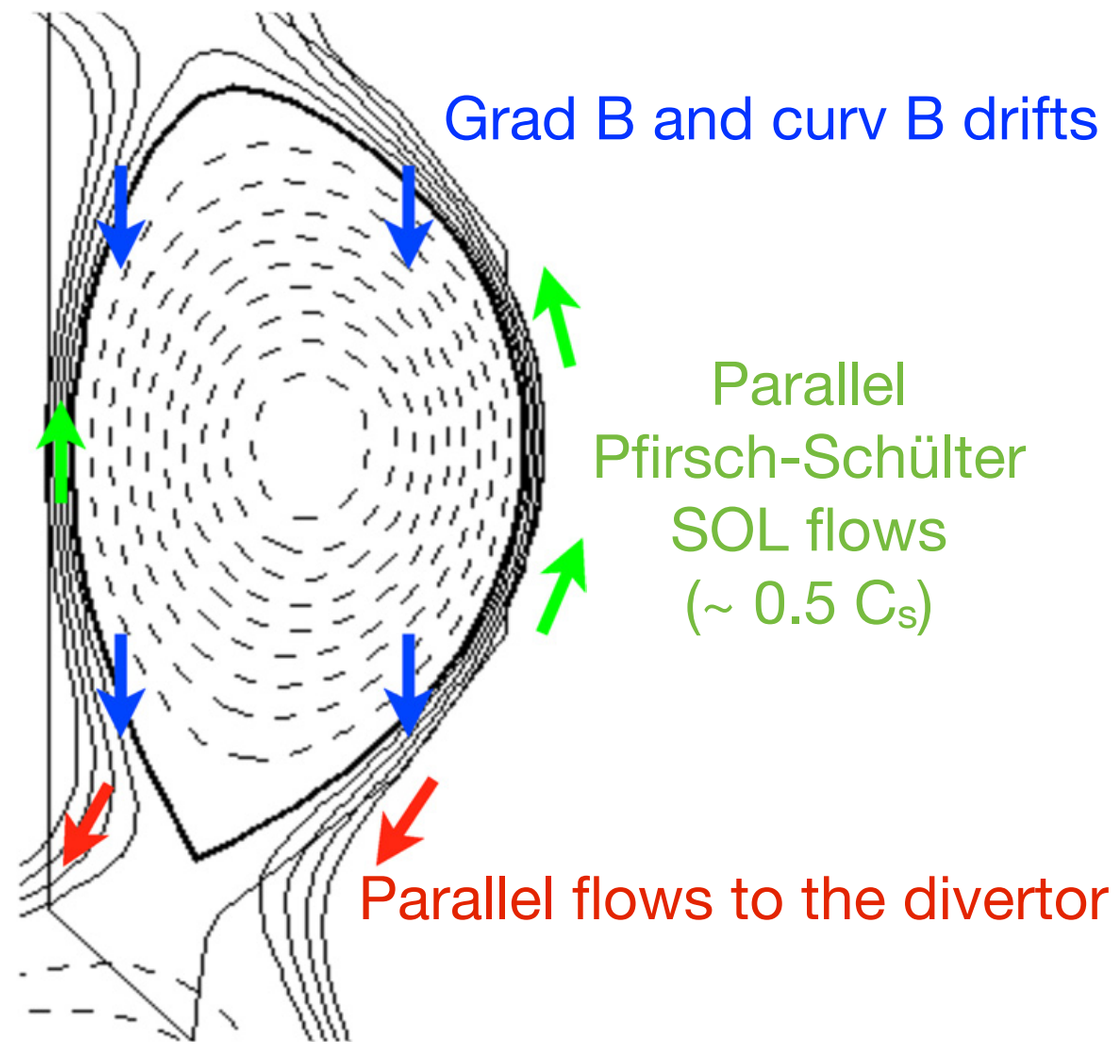


M Makowski, et al. *submitted to PoP* (2012)

The Heuristic Drift based Model Provides an Analytic Solution for the Power SOL width

- ∇B and curv B drifts carry ions across the LCFS
  - $\langle v_{\nabla B + \text{curv } B} \rangle = 2T/eZBR$
- These drifts are balanced by parallel flows
  - Flows that connect the top-bottom of the plasma (Pfirsch-Schülter flows)
  - also parallel flows that leave the plasma towards the divertors
- Results an analytic solution of the power SOL width, λ_q approximately equal to the poloidal ion gyro-radius
- Assumptions:
  - Parallel flow to the divertor ~ P-S flows
  - Anomalous $D_{\perp,e}$ is adequate to 'fill' SOL flux tubes as defined by the SOL flows
  - Low gas puff, attached divertor plasmas

RJ Goldston, NF. **52** (2012) 013009

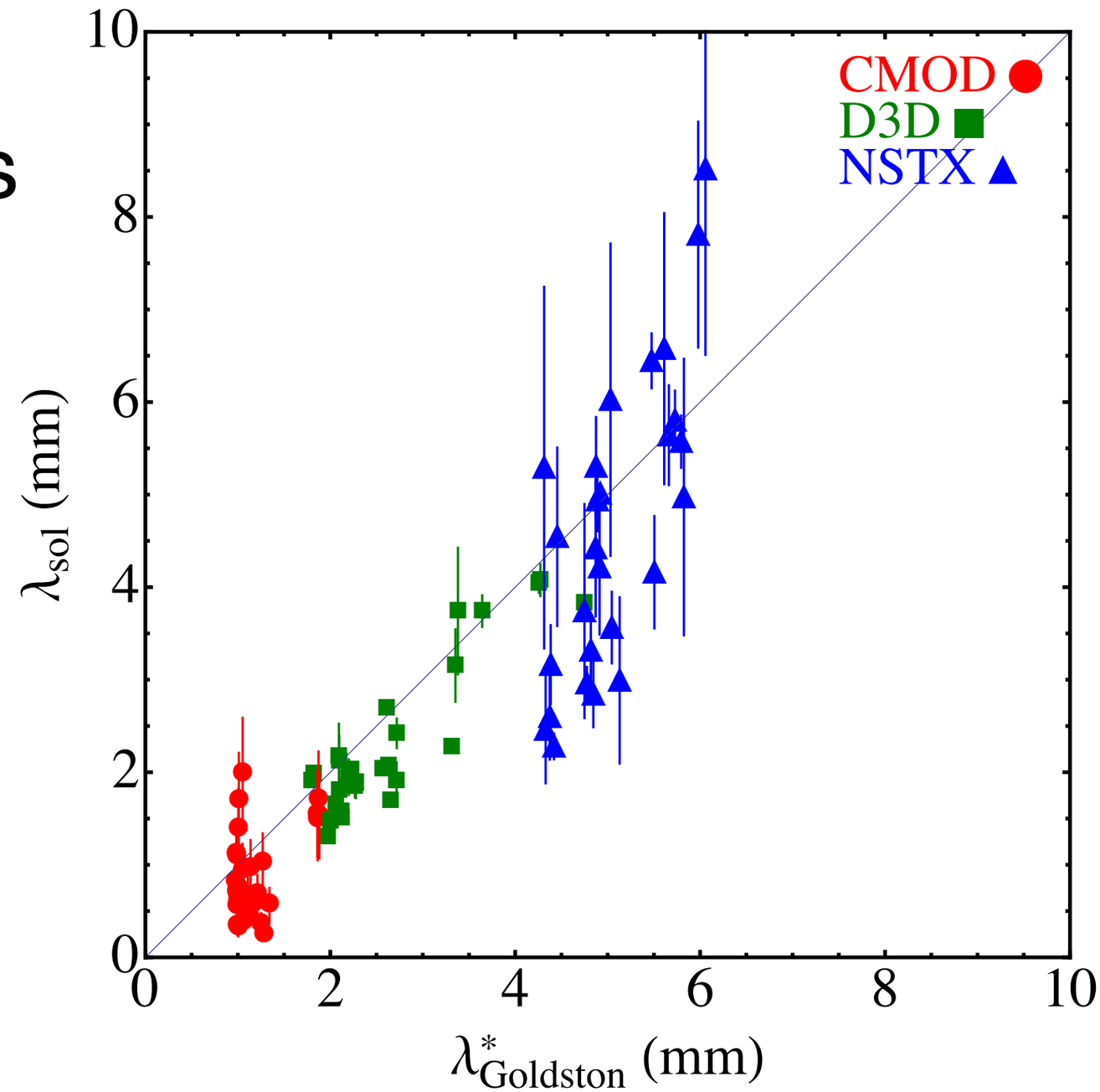


$$\lambda_q = \frac{4a}{eB_pR}\left(\frac{\bar{A}m_pT_{sep}}{(1+\bar{Z})}\right)^{1/2} \approx \frac{2a}{R}\rho_p$$

electron drift

Comparison with the Heuristic Drift based λ_q Model Shows Promise but not Fully Understood Yet

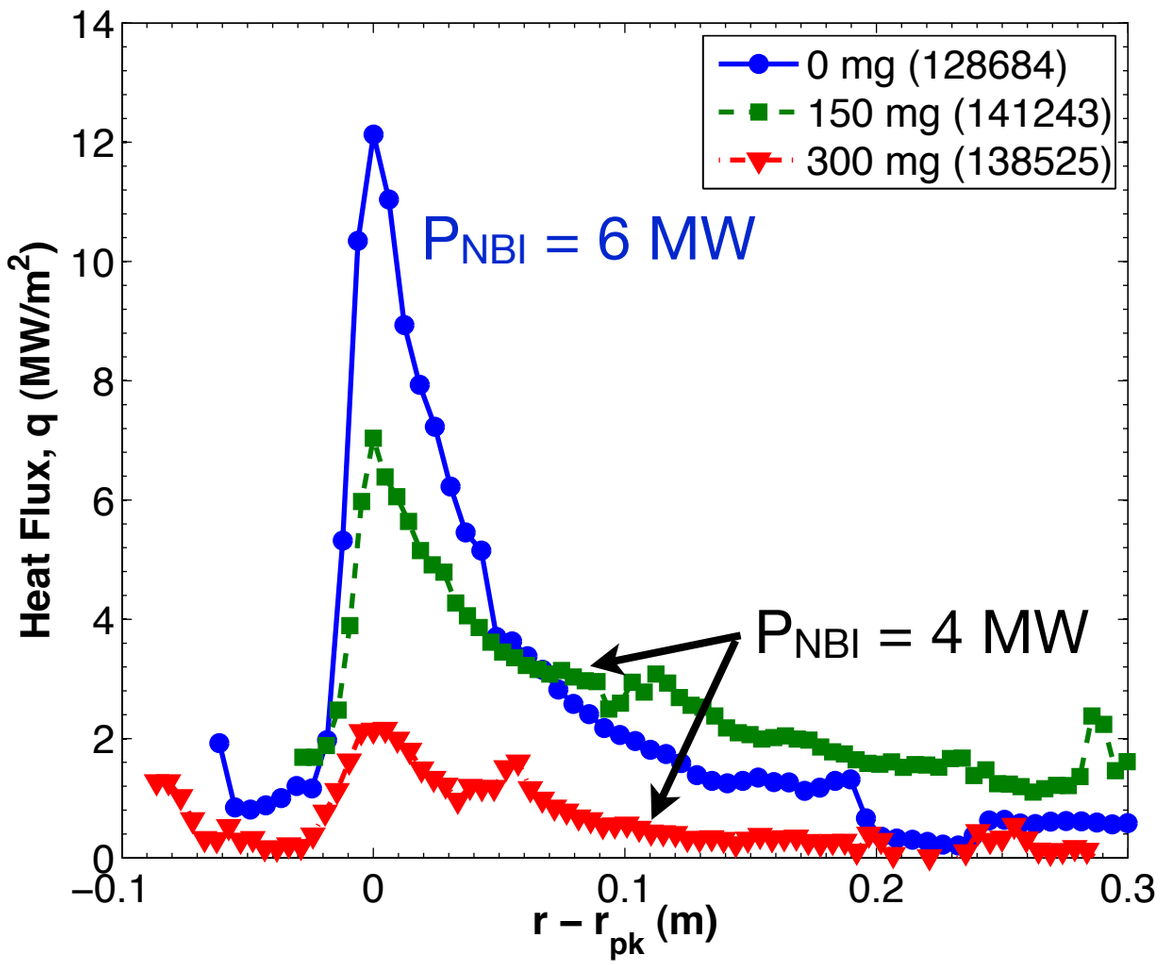
- Multi-machine comparison with Goldston's model works surprisingly well
  - JET and AUG data are also in good agreement
    - Goldston's APS 2011 Poster
- Some tendency for the Heuristic Drift model to slightly over-predict λ_q
  - Of order few mm



M Makowski, et al. *submitted to PoP* (2012)

Lithium Evaporation is shown to Reduce λ_q and Peak Heat Flux

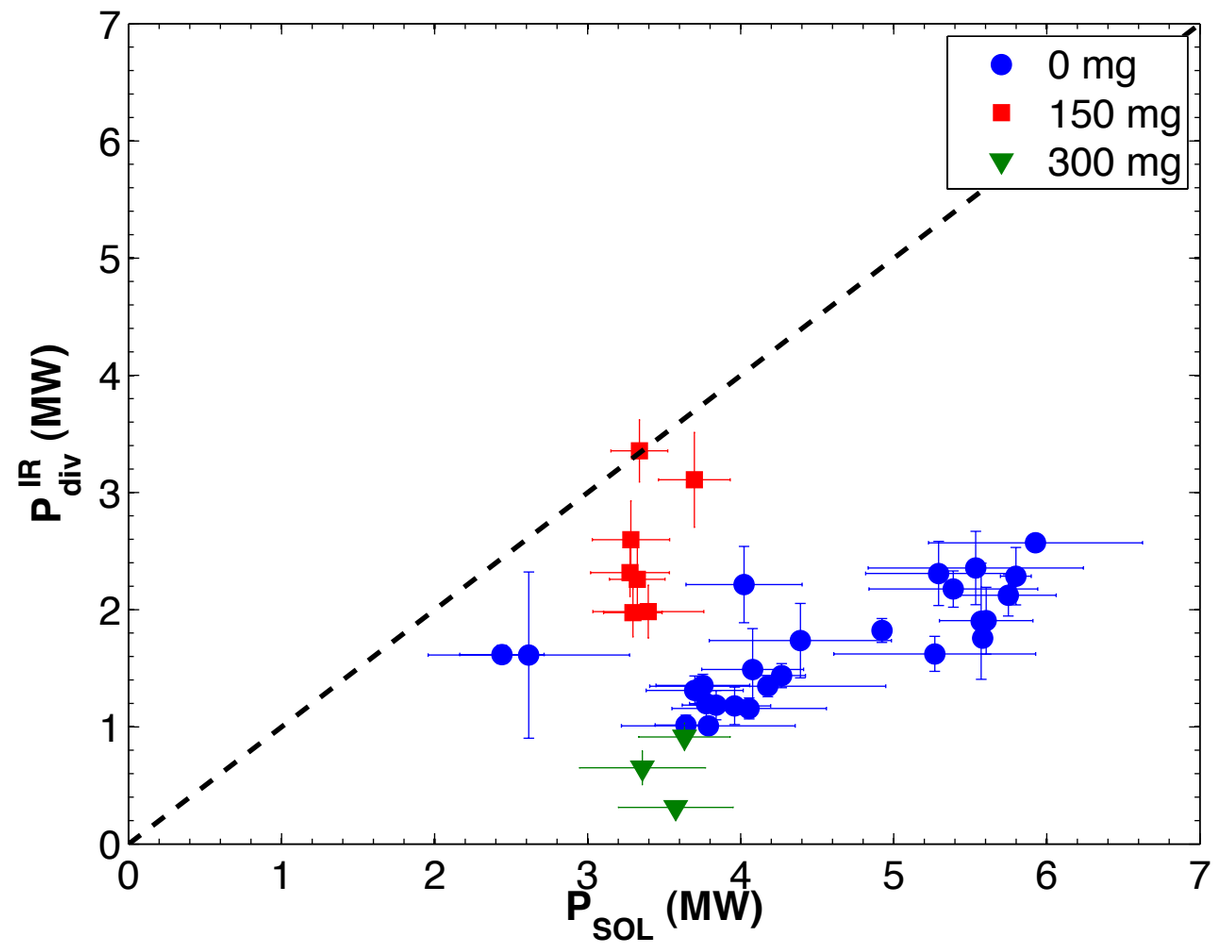
- Difficult to make direct comparisons with boronized dataset
  - Data is all before 2010
  - Mix of plasma shapes, P_{NBI}, etc
    - e.g. - no high δ, low I_p boronized data
- λ_q contracts with addition of lithium
- With sufficient Li, heat flux also appears reduced
  - Measurements made with DBIR camera
  - DBIR data is averaged to 50 frames ~ 30 Hz



t ~ 0.4 sec, inter-ELM
1.2 MA, 4 and 6 MW (0 mg)
high δ, f_{exp} ~ 20

Divertor Power Accounting with Heavy Lithium Evaporation is Reduced

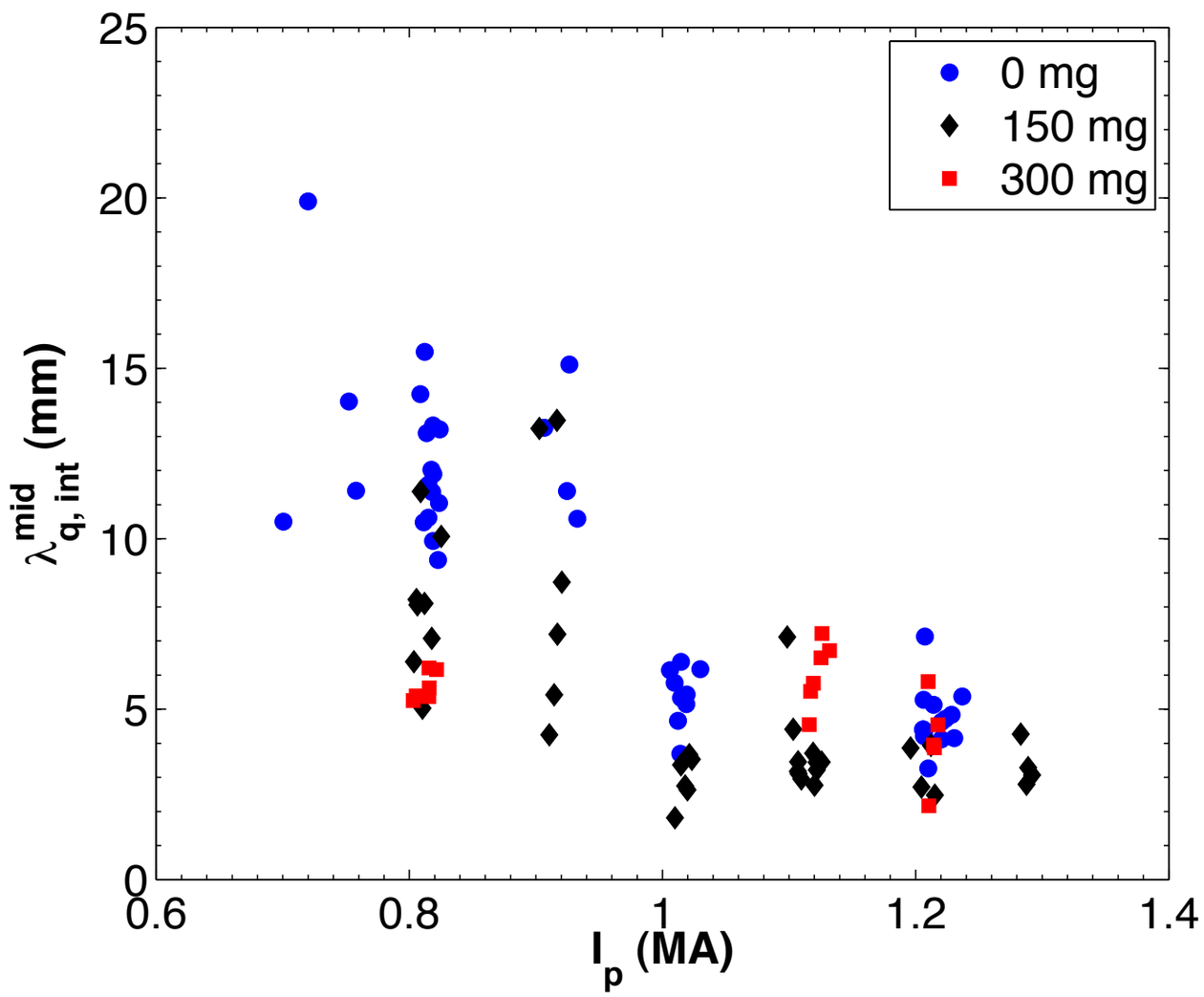
- If λ_q contracts, you'd expect heat flux to increase for similar P_{SOL} to conserve power
- P_{div}/P_{SOL} is similar for 0 and 150 mg of Li
- However, measured heat flux is reduced for 300 mg Li
  - Results in P_{div}/P_{SOL} dropping to ~ 12-20%
  - Wider range of P_{SOL} shots still to be analyzed for 300 mg



Data are shot averaged for ne/nG ≤ 0.6

Integral λ_q contracts with increasing Li deposition at low I_p

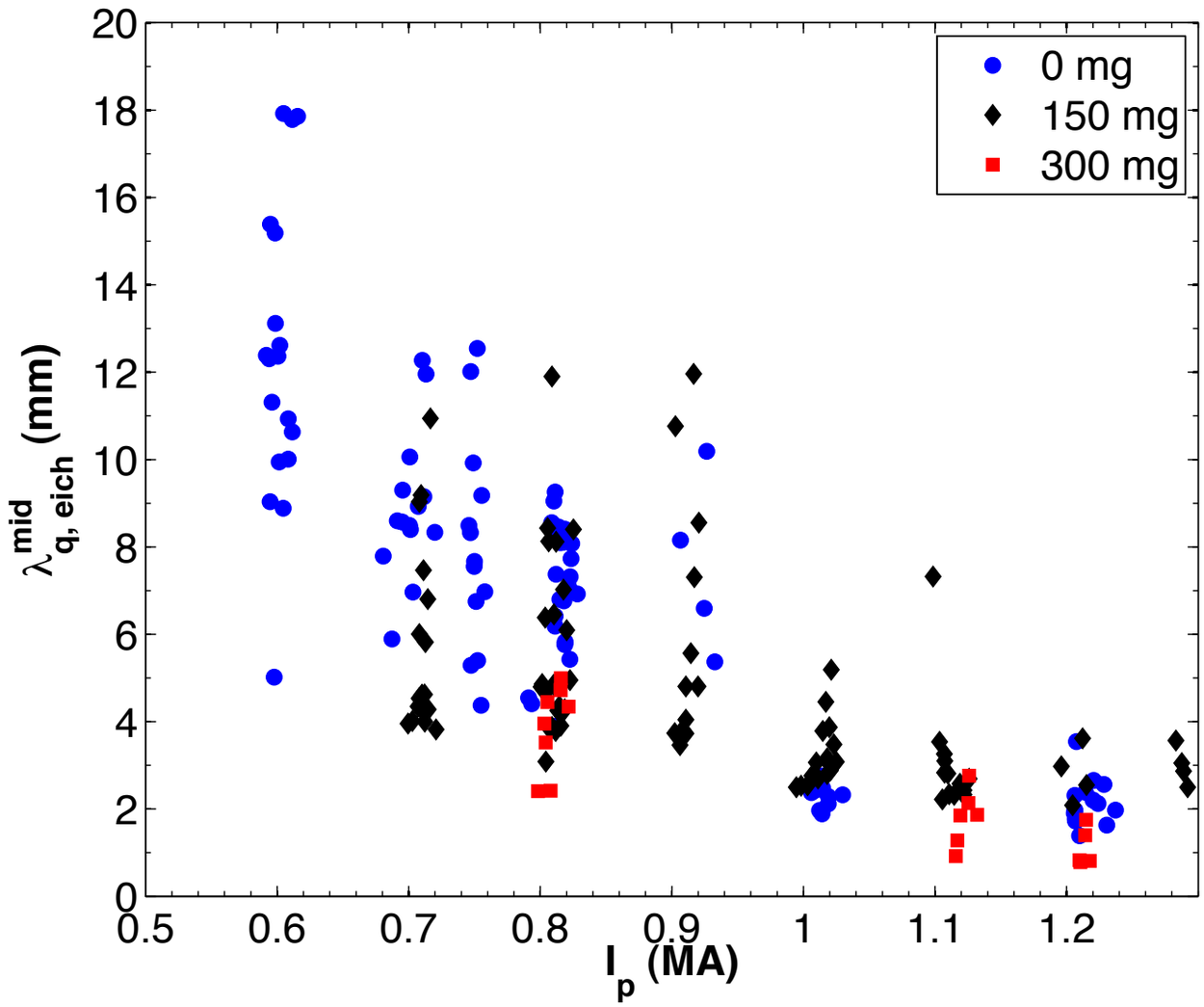
- $\lambda_{q,\,int}$ contracts between 0 and 150 mg of Li at low I_p
  - A lot of spread in the data due to density variations
- 300 mg data tends to have much less variation
- $\lambda_{q,\,int}$ at $I_p > 1$ MA very similar regardless of lithium amount
  - Results in a shallower $\lambda_{q,\,int} \sim I_p^{\alpha}$ scaling



$n_e/n_G \leq 0.6$

Eich λ_q Contracts mainly for discharges with 300 mg of Li deposition

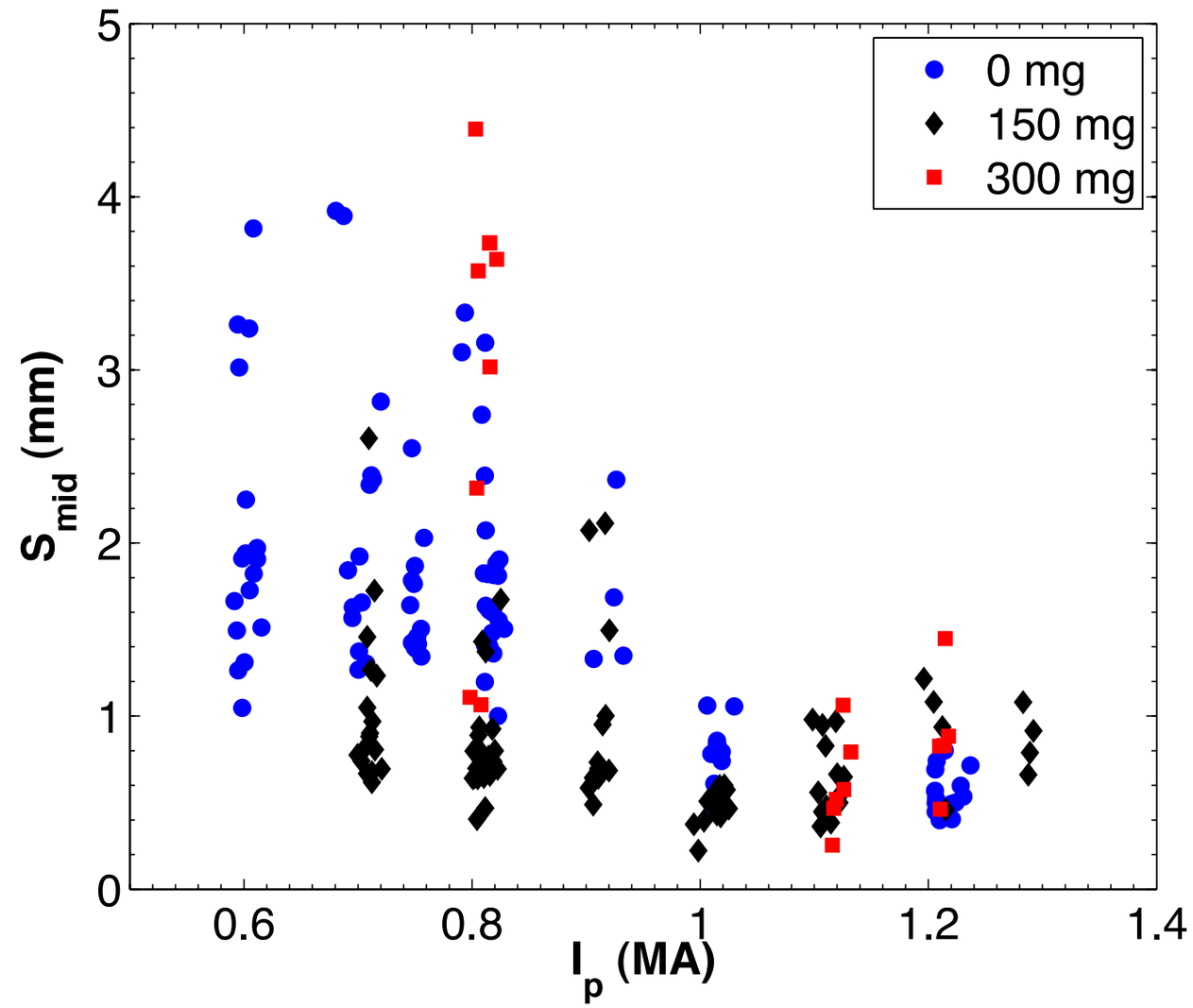
- Diffusive-Gaussian analysis shows similar trends for 0 and 150 mg data
  - Suggests SOL width is the same between 0 and 150 mg data
  - λ_q is broadened in the divertor in boronized discharges
- 300 mg data is still contracted



$$q(\bar{s}) = \frac{1}{2} q_0 \exp\left(\left(\frac{\mathrm{S}}{2\lambda_q f_{exp}}\right)^2 - \frac{\bar{s}}{\lambda_q f_{exp}}\right) \mathrm{erfc}\left(\frac{\mathrm{S}}{2\lambda_q f_{exp}} - \frac{\bar{s}}{\mathrm{S}}\right) + q_{\mathrm{BG}}$$

Similar level of diffusion into the PFR for 0 and 300 mg data, but not 150 mg of Li

- There appears to be less diffusion for the 150 mg data compared to 0 mg
  - Confirms $\lambda_{q,\,Eich}$ analysis
- However, S for the 300 mg data is comparable to the 0 mg dataset at low I_p
- Interesting that S is reduced for 150, but not 300 mg
  - Though, at high I_p S's are all similar
  - Possibly higher with 300 mg Li, but limited data

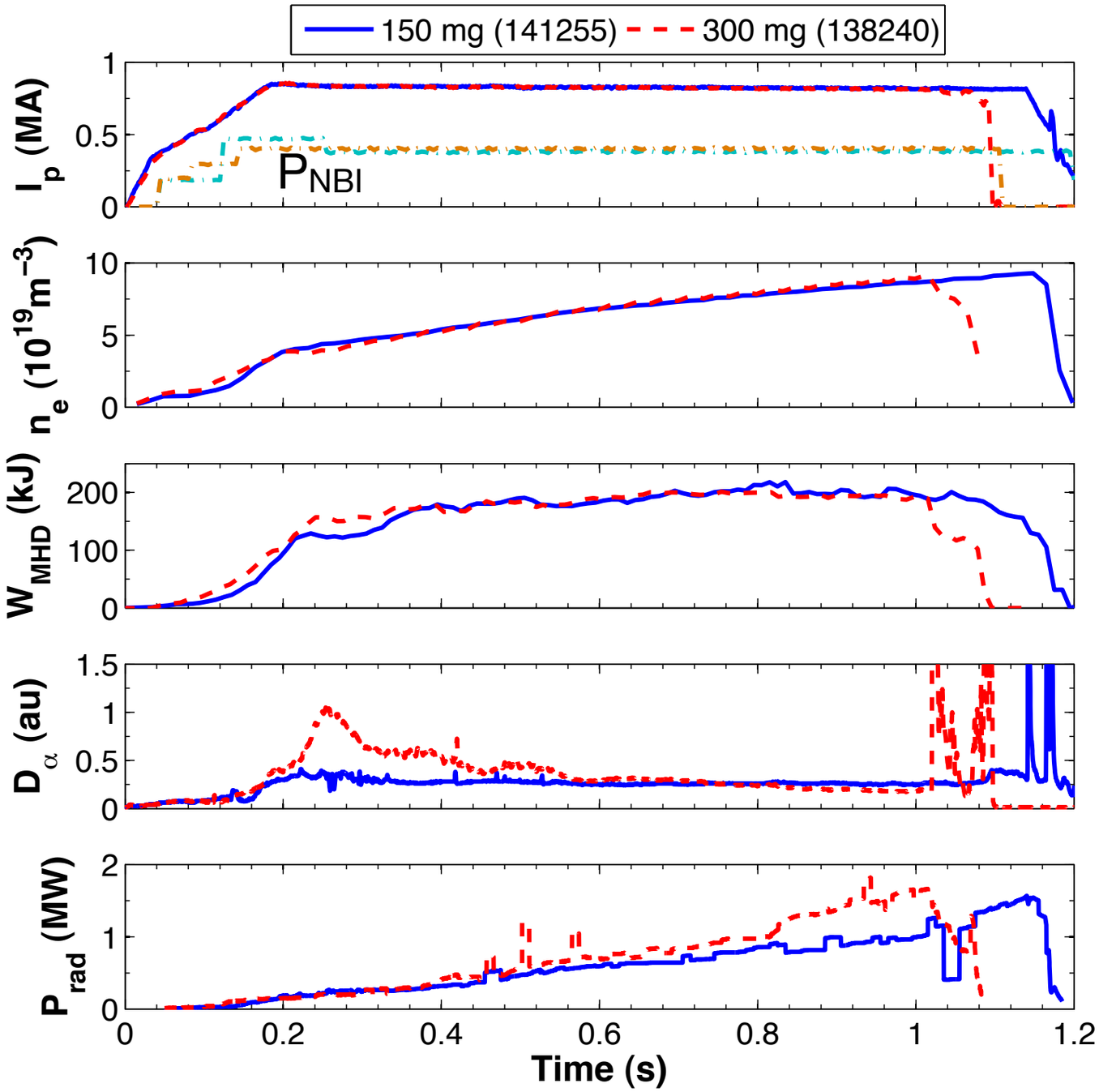


S is the Gaussian width parameter from D-G model
- Represents diffusion into the PFR

$$q(\bar{s}) = \frac{1}{2} q_0 \exp\left(\left(\frac{S}{2\lambda_q f_{exp}}\right)^2 - \frac{\bar{s}}{\lambda_q f_{exp}}\right) \mathrm{erfc}\left(\frac{S}{2\lambda_q f_{exp}} - \frac{\bar{s}}{S}\right) + q_{BG}$$

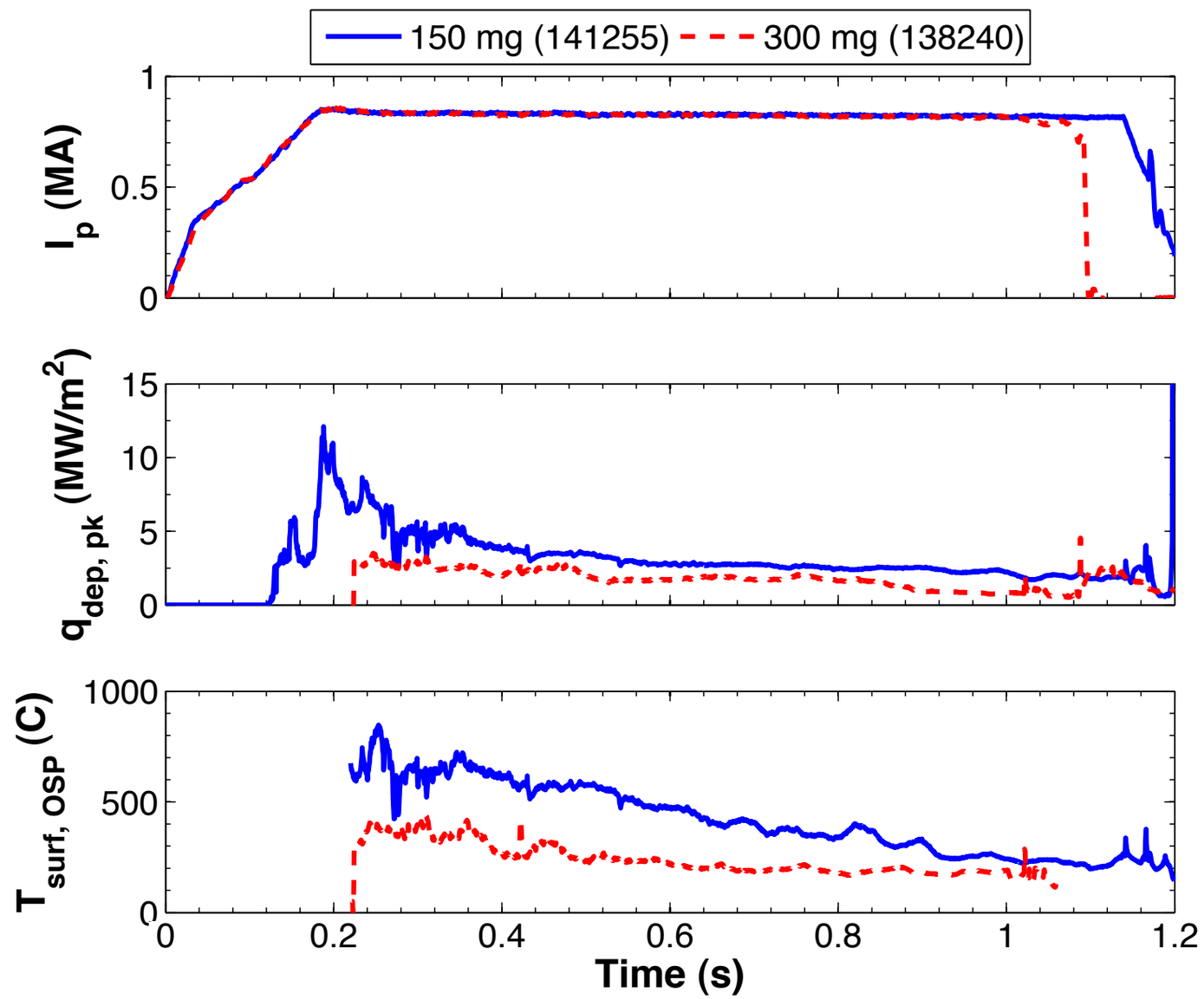
Comparing shots that are identical, other than lithium coverage, provides a means to study the lithium effects

- 2 identical shots
  - I_p = 0.8 MA
    - No ELMs
  - P_{nbi} ~ 4 MW
    - Some pre-heating used in 141255
  - high δ, f_{exp} ~ 20
- Not including 0 mg data since there's no <u>directly</u> comparable shot



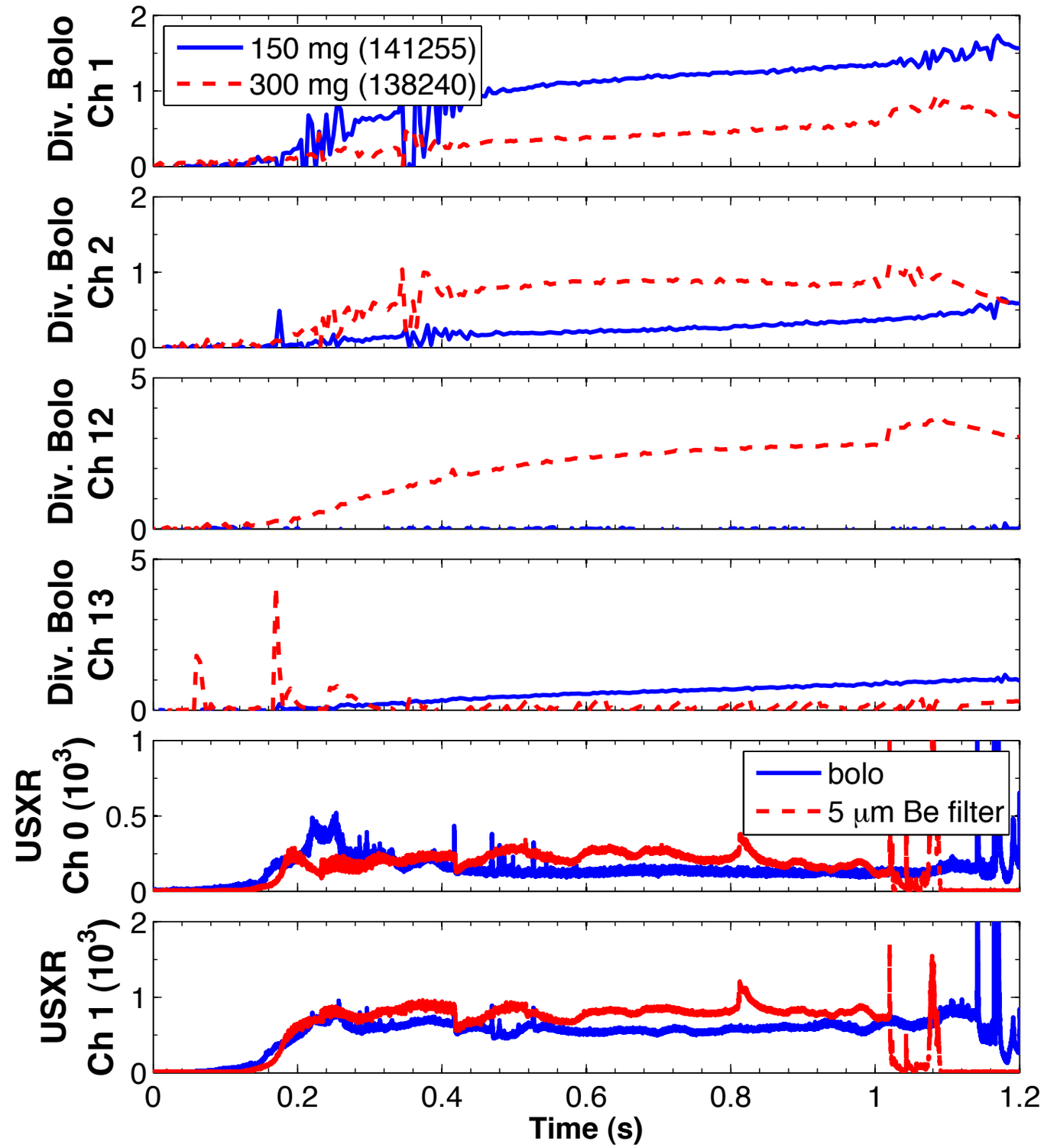
Clear reduction in divertor surface temperature and heat flux with increased lithium evaporation

- No ELMs in either discharge
- T_{surf} at the outer strike point stays below 400 C for 300 mg of Li
  - Peaks around 800 C for 150 mg
- Results in a heat flux that never peaks above 3 MW/m^2 with heavy lithium evaporation



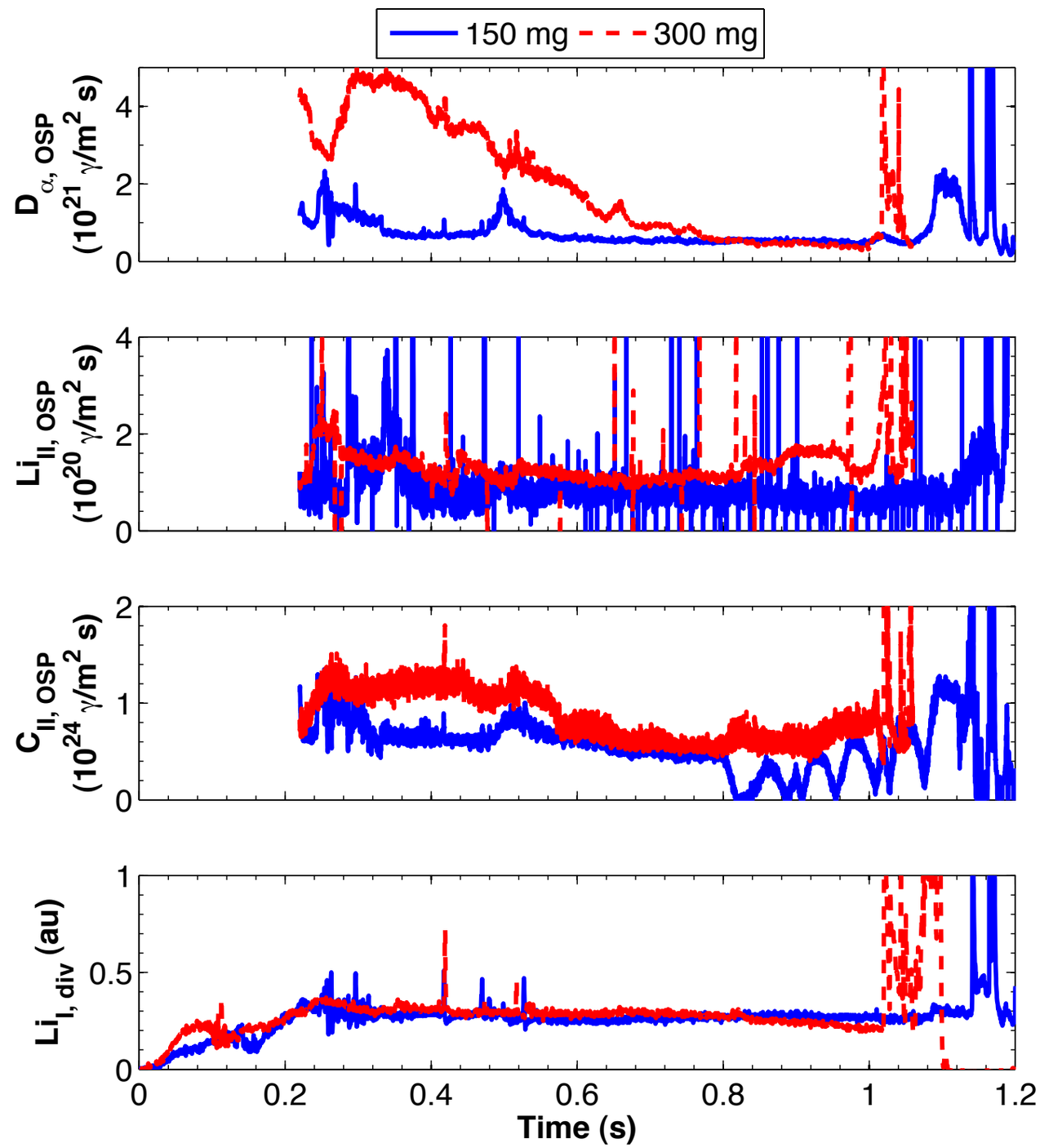
Divertor Bolometers provide a complicated picture of divertor radiation profile

- Not all divertor bolometer channels work from shot to shot
  - USXR had varying filters and apertures
  - Difficult to make direct comparisons shot-to-shot
- Ch 1 shows an increase in div. radiation with less lithium
  - Could be due to ISP reattaching with lithium [Scotti, PSI 2010]
  - Radiation is shifting downwards?
- If we compare Ch. 12 and 13, 300mg lithium has much higher radiation
  - Ch 12 wasn't working for 141255
  - Ch 13 wasn't working for 138240
- Modeling is necessary to sort out the divertor radiation



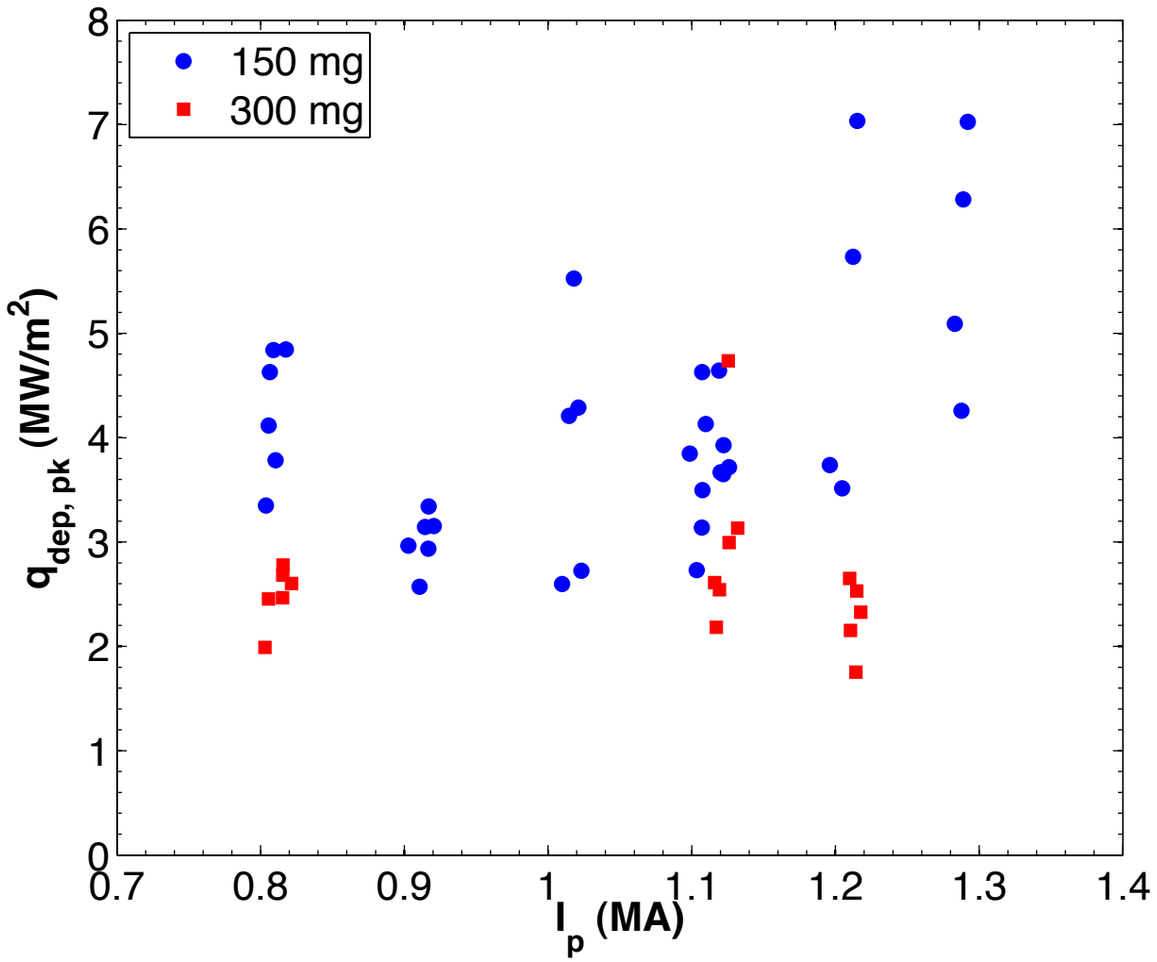
Increase in D_α and C II radiation at OSP with higher Li evaporation

- Minimal if any increase in lithium emission with increased Li evaporation
- Factor of 4-5 increase in D_α
- Roughly 30% increase in C II emission at OSP
- Analysis of divertor Langmuir probes is still underway
  - Only 1 probe near OSP in high δ shape
  - Preliminary analysis doesn't show much difference with increased Li



The result is a Decrease in Peak Divertor Heat Flux when 300 mg of Li Evaporation is Used

- Limited set of 300 mg DBIR measurements
  - Currently working to add to the dataset
  - Signal to Noise Ratio increases as surface emissivity is reduced
- Challenging picture when the divertor bolometers and visible measurements are considered
- SOLPS modeling is needed to fully understand what's going on



$n_e/n_G \leq 0.6$

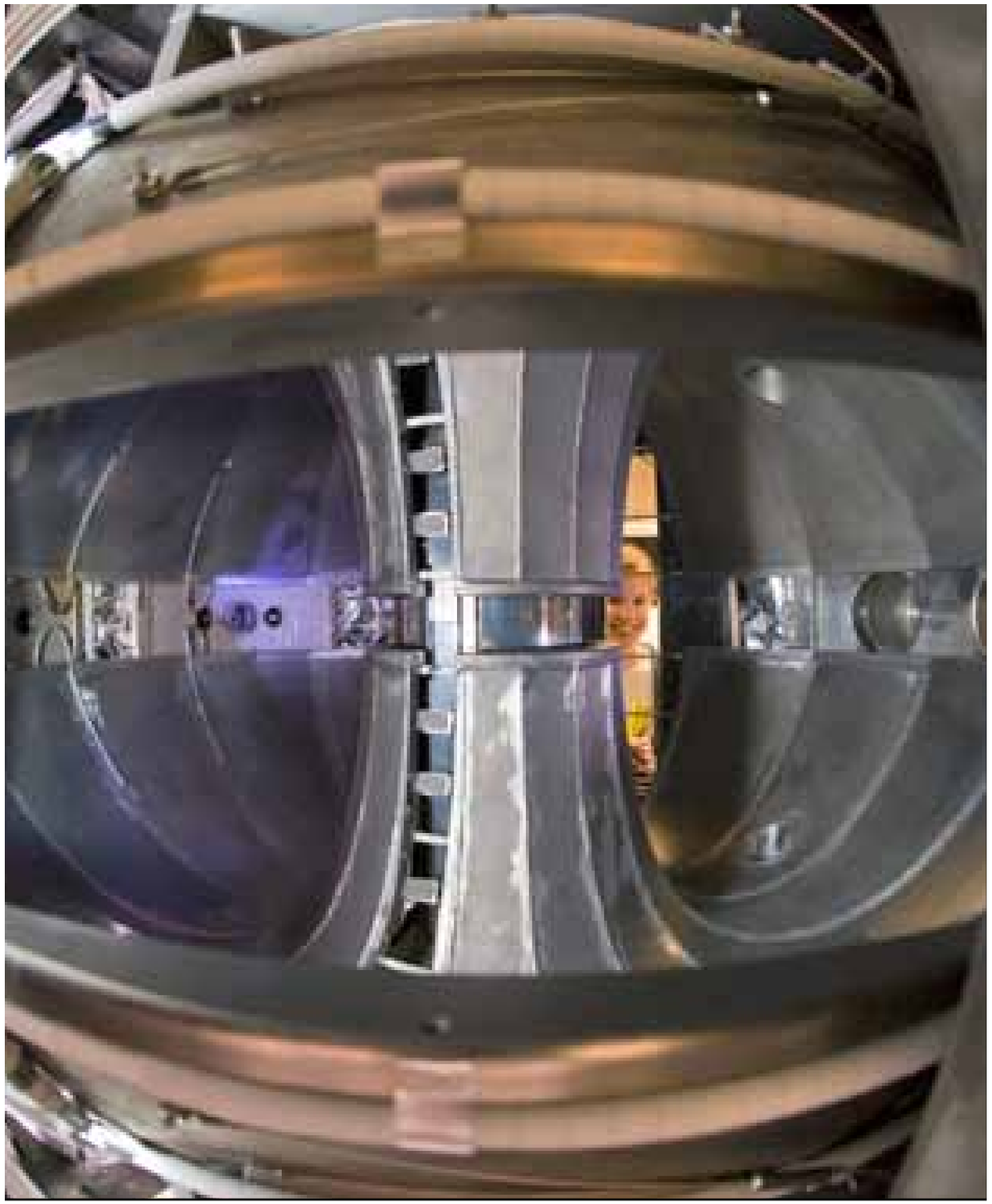
Summary of NSTX SOL/Boundary Physics

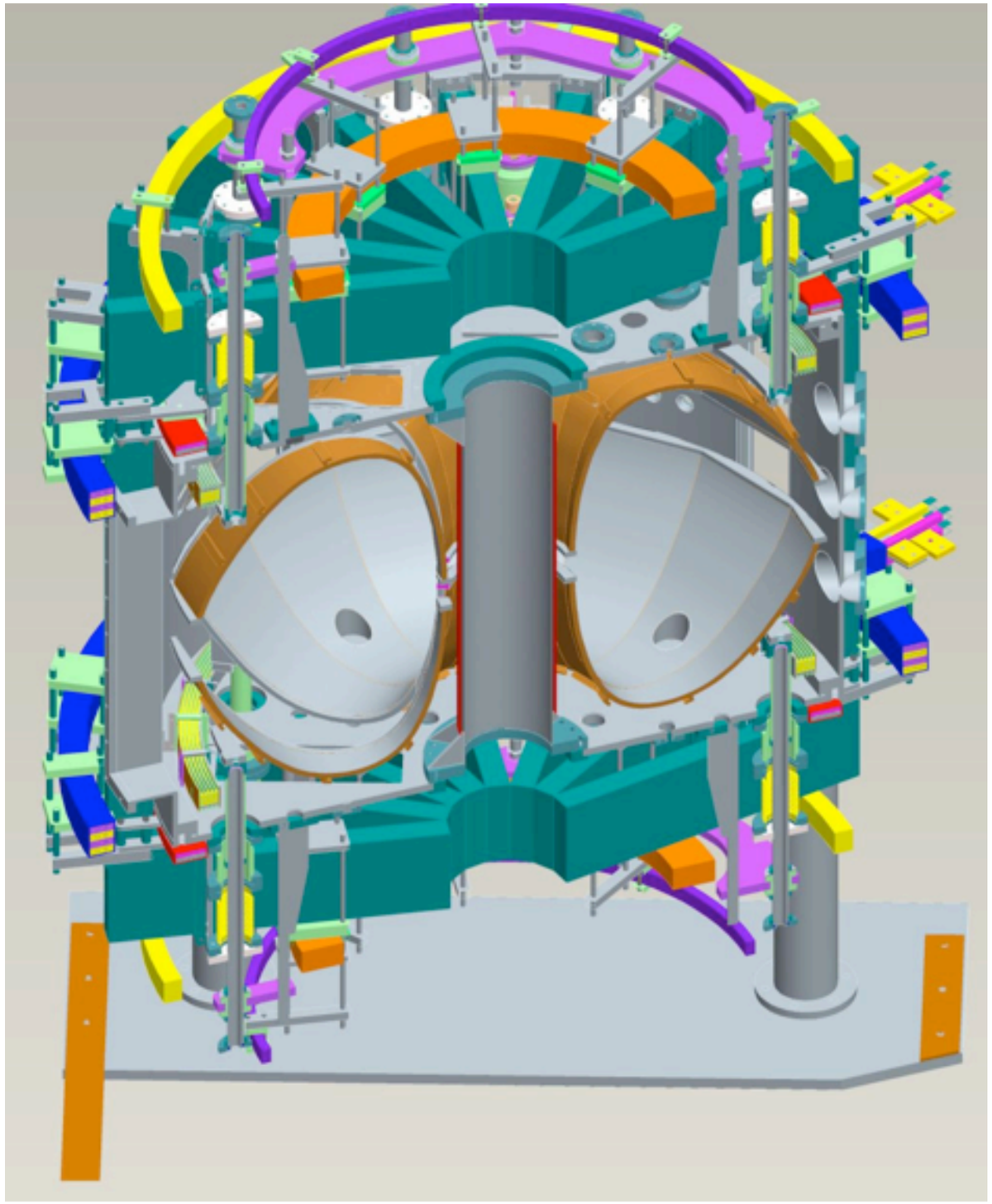
- Find $\lambda_{q,\,int} \sim I_p^{\alpha}$ for boronized discharges
  - This trend is shallower with lithium
- Heat flux in NSTX-U ~ 24 MW/m^2
  - Require some kind of method to mitigate the heat flux
  - Flux expansion, DN operation, maybe Li
- Lithium causes a contraction in λ_q at low I_p
  - λ_q's are similar at high I_p regardless of lithium
  - Appears to be due to increased diffusion into the PFR for 0 mg compared to 150 mg
  - However, at 300 mg of Li, there is a similar amount of diffusion in the divertor as for boronized discharges
- Reduced heat flux when heavy Li evaporation is used
  - Heat flux at 0 and 150 mg is similar
  - Need modeling to fully understand the divertor physics

NSTX-U Plans

- Implement Dual Band technique on all IR cameras
  - Fast, Lower Divertor (wide angle), Upper Divertor and CS
  - Will be challenging since the DBIR analysis is very time intensive
- Install fast eroding thermocouples on the upper and lower divertors
  - Diagnostic already implemented on C-MOD
  - Real-time divertor T_{surf} measurements
  - Control magnetic balance to maintain double null configuration
  - Real-time heat flux mitigation (gas puffing, etc)
- Try to determine why increasing Li coverage leads to better performance (UTK proposal)
  - Upper divertor spectroscopy coverage for DN operation
- Possibility of pellet injection for fueling and ELM pacing???

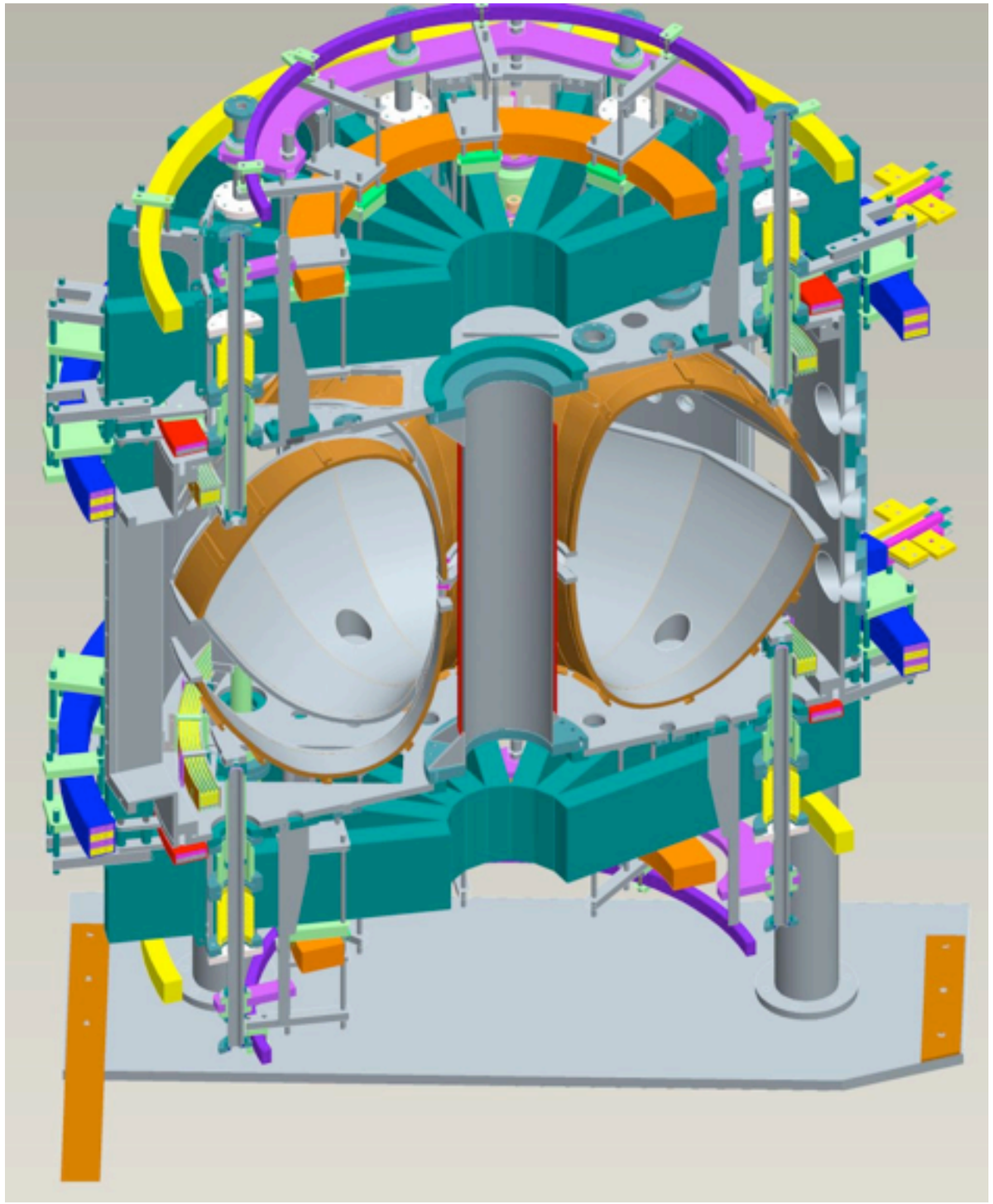
Introduction to the Lithium Tokamak Experiment (LTX)





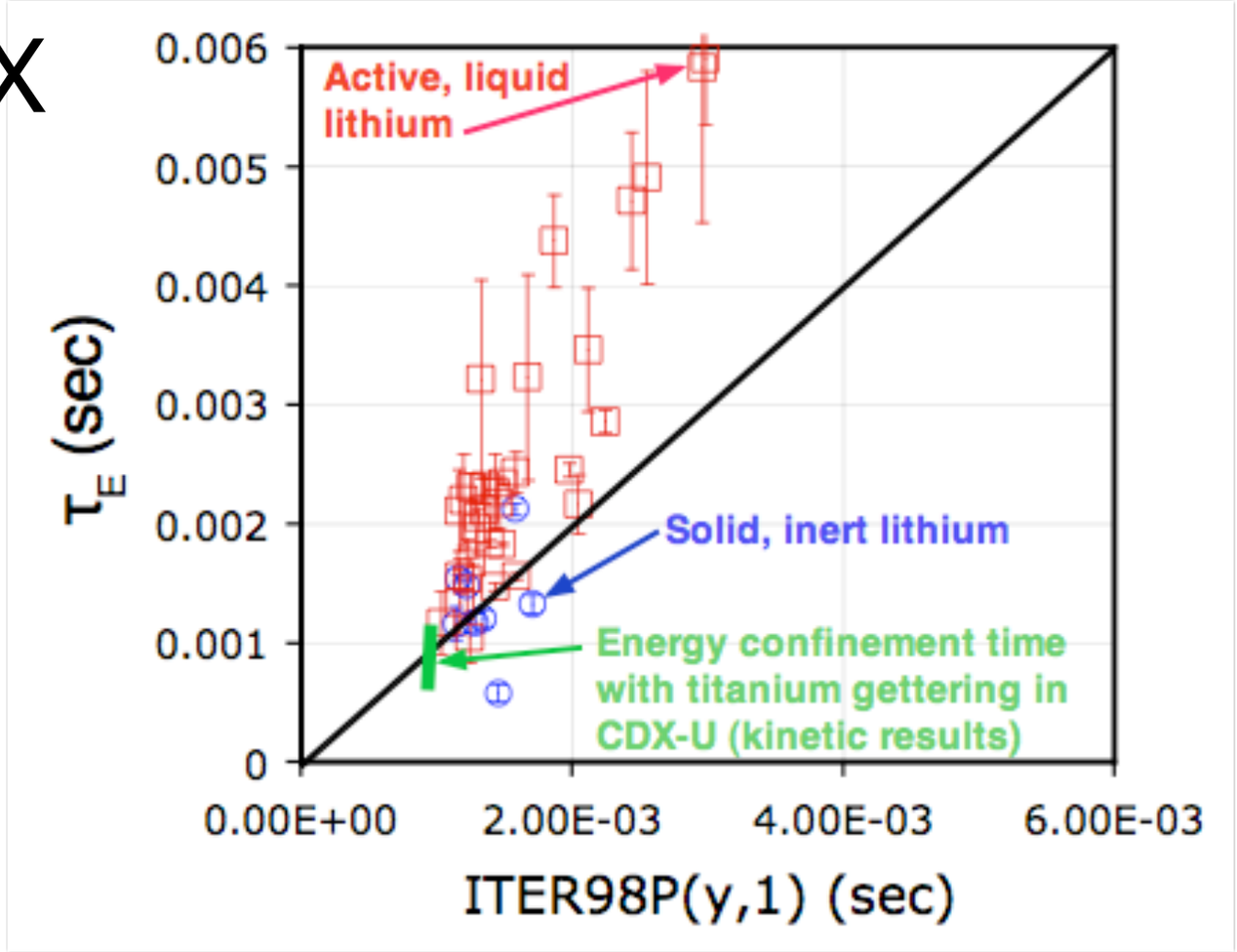
Lithium Tokamak Experiment (LTX) is intended to explore the physics of plasmas with an ultra low recycling boundary

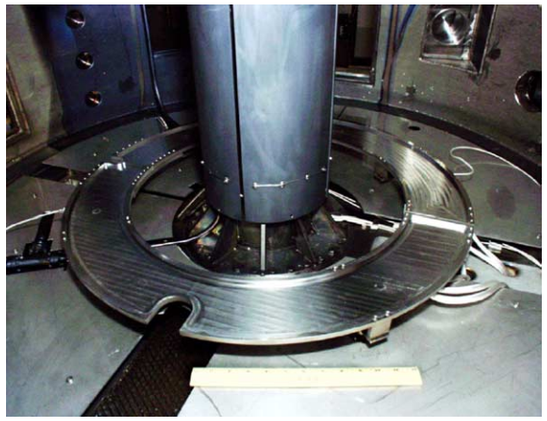
- Small, short pulse, limited spherical torus
  - Upgrade of the CDX-U experiment
- PFC surface area ~ 90% liquid lithium
  - No Carbon PFC's
  - Using 3/8" thick copper shells
    - SS explosively bonded to prevent Li from attacking the copper
- ORNL has the lead in investigating edge physics on LTX



Operation of CDX-U with Liquid Lithium PFC's resulted in record confinement times for L-Mode Tokamaks

- CDX-U was similar to LTX
  - Lithium was confined to a toroidal tray
    - Would operate tray hot to evaporate lithium
  - $I_p < 70$ kA
  - 15 ms discharge lifetime
  - $P_{aux} < 0.3$ MW
- With liquid tray + lithium evaporation, $\tau_E \sim 6$ ms
- Well above ITER98P scaling for L-mode
  - Factor of 2!





R. Majeski, et al., PRL **97**(7) (2006) 075002

LTX was Designed to Further Explore Fusion Plasmas with Near Zero Recycling Boundaries

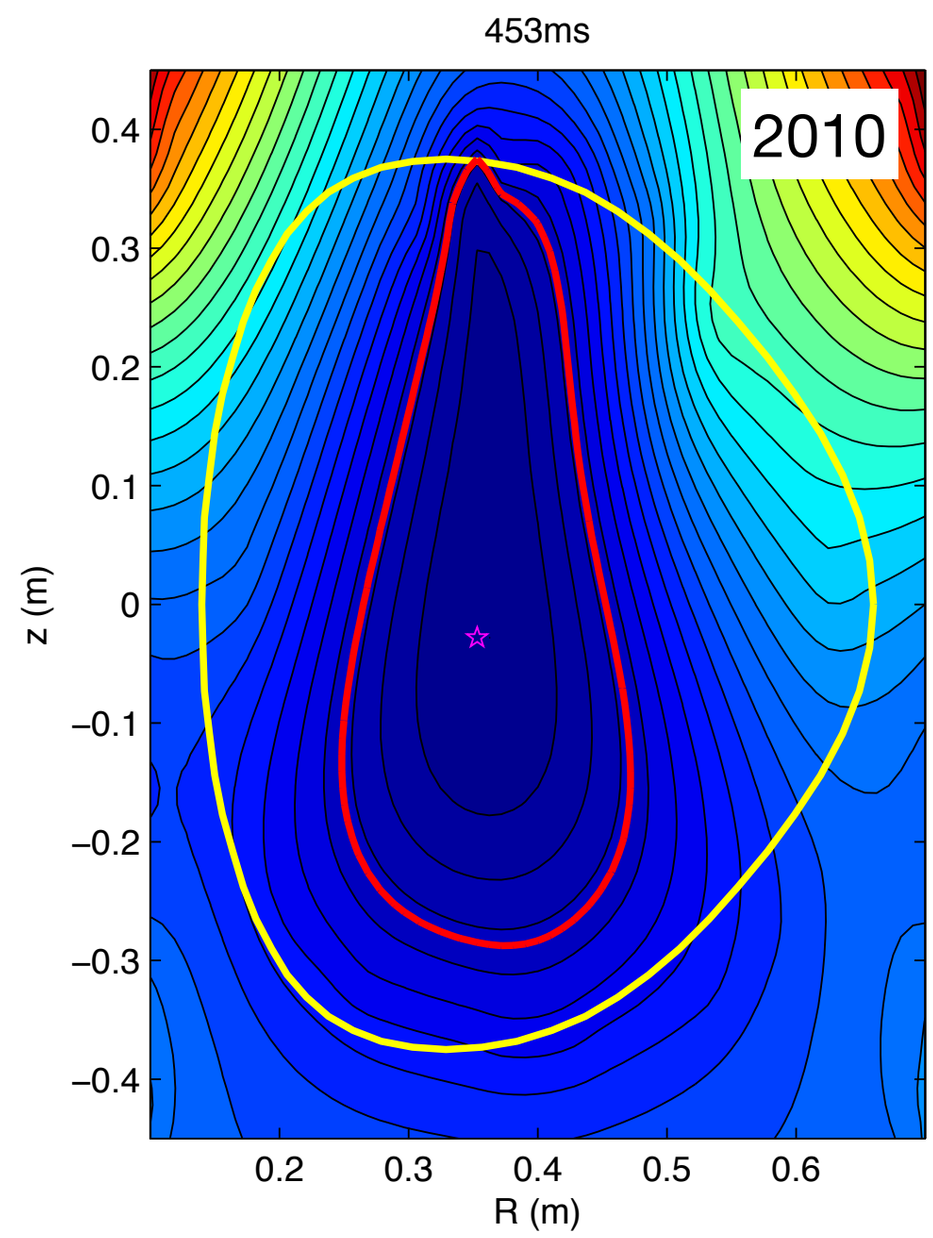
- ORNL Diagnostics include:
  - Filterscopes (16 channels)
  - Visible spectroscopy
  - VUV spectroscopy
  - Charge Exchange Recombination Spectroscopy (ChERS) system
- Eventual SOLPS modeling of LTX plasmas

- LTX upgrades to CDX-U include:
  - Shells to allow for 90% of the surface area to be liquid lithium
  - Improved IGBT based Ohmic and TF power supplies to increase the pulse length
  - Eventually, a diagnostic neutral beam for auxiliary heating (20 kV, 5 A)

LTX Parameters	achieved (designed)
Major Radius, R	0.4 m
Minor Radius, a	0.26 m
Toroidal Magnetic Field, B_ϕ	1.8 kG
Duration	~ 15 ms (100 ms)
Plasma Current, I_p	67 kA (100 kA)
core density, n_e	~ $8(10)^{18}$ /m^3
core Electron Temperature, T_e	100 — 150 eV

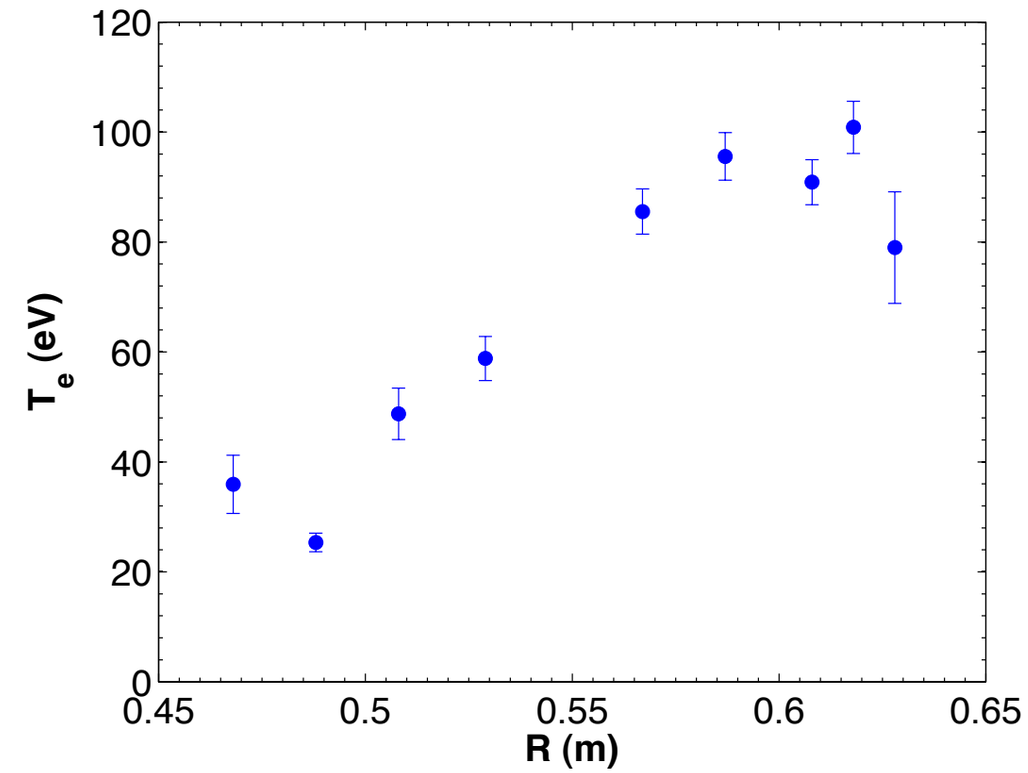
Equilibrium Reconstructions are not yet Routine or Reliable

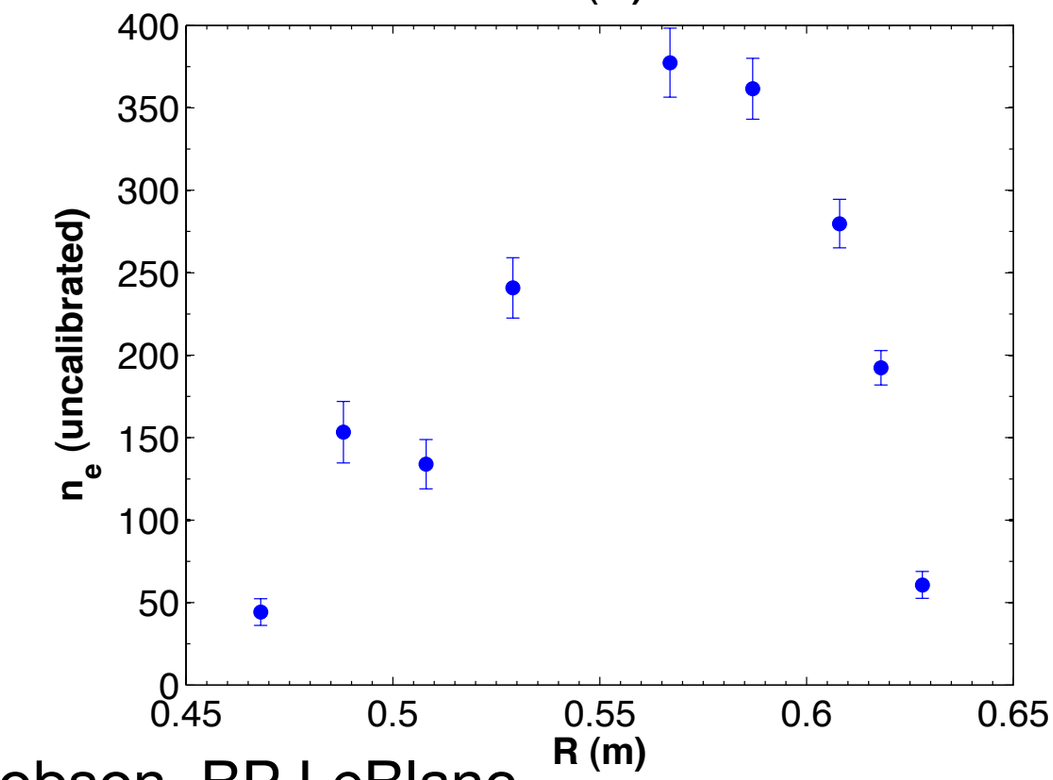
- Most recent (2010) equilibrium reconstructions use a modified LRDFIT
  - Issues with convergence in G-S solver
  - Doesn't model shell eddy currents
- 2011 plasmas appear to have better plasma shaping -- but no reconstructions yet
  - New post-doc hired to focus on equilibrium reconstruction
- Better model effects of eddy currents and inductive pick-up on the magnetic diagnostics
  - Possibly use L. Zakarov's code



Thomson Scattering Measurements Show Outboard Peaked Profiles

- MPTS measurements aren't routine yet
  - Using a 30 Hz, CO_2 laser
  - Limited to 1 profile per shot
- MPTS shows T_e and n_e peaked outboard on the low field side
  - 2011 data show higher T_e ~ 200 eV, still outboard peaked
- Additional edge TS channels coming online later this year

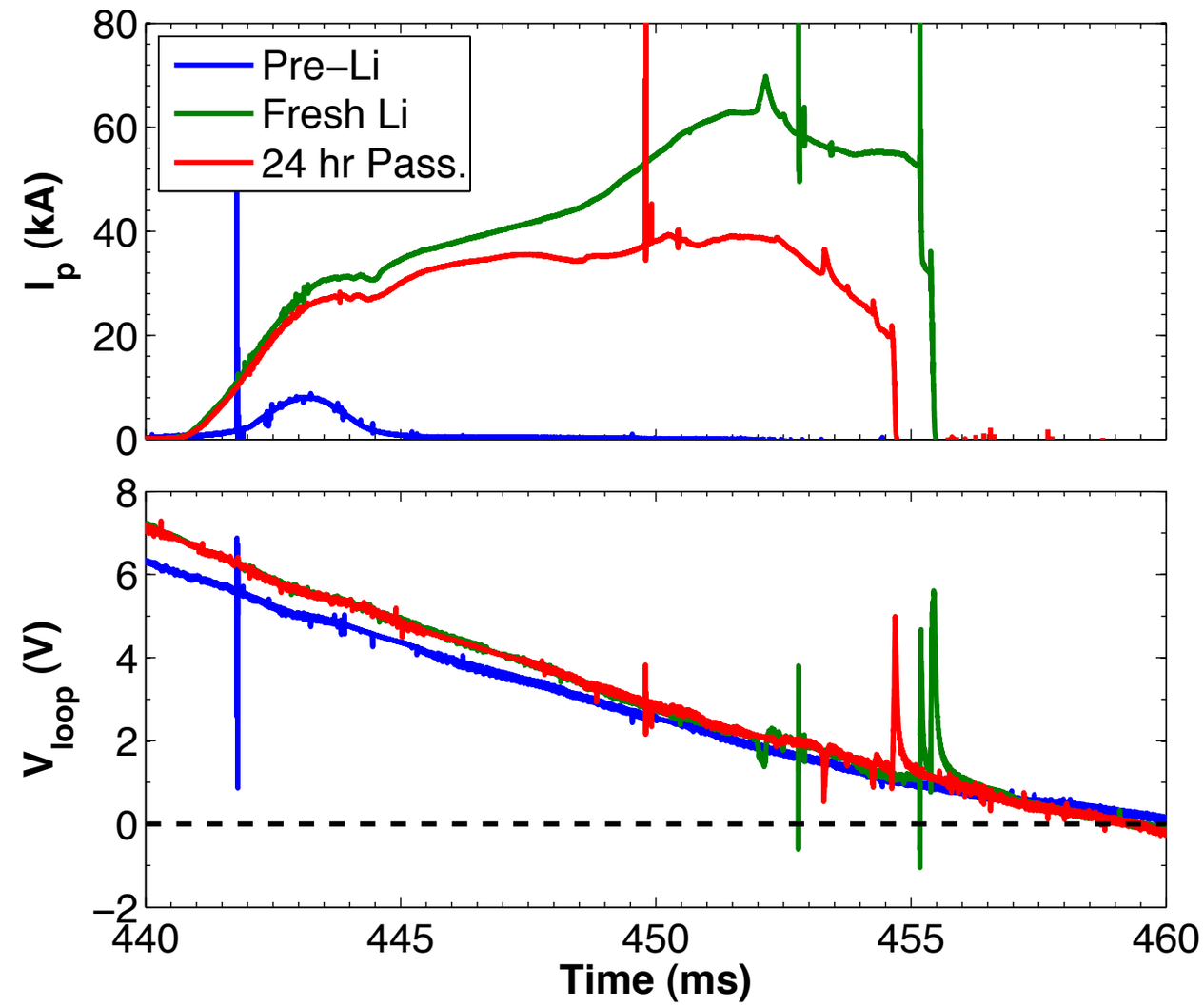




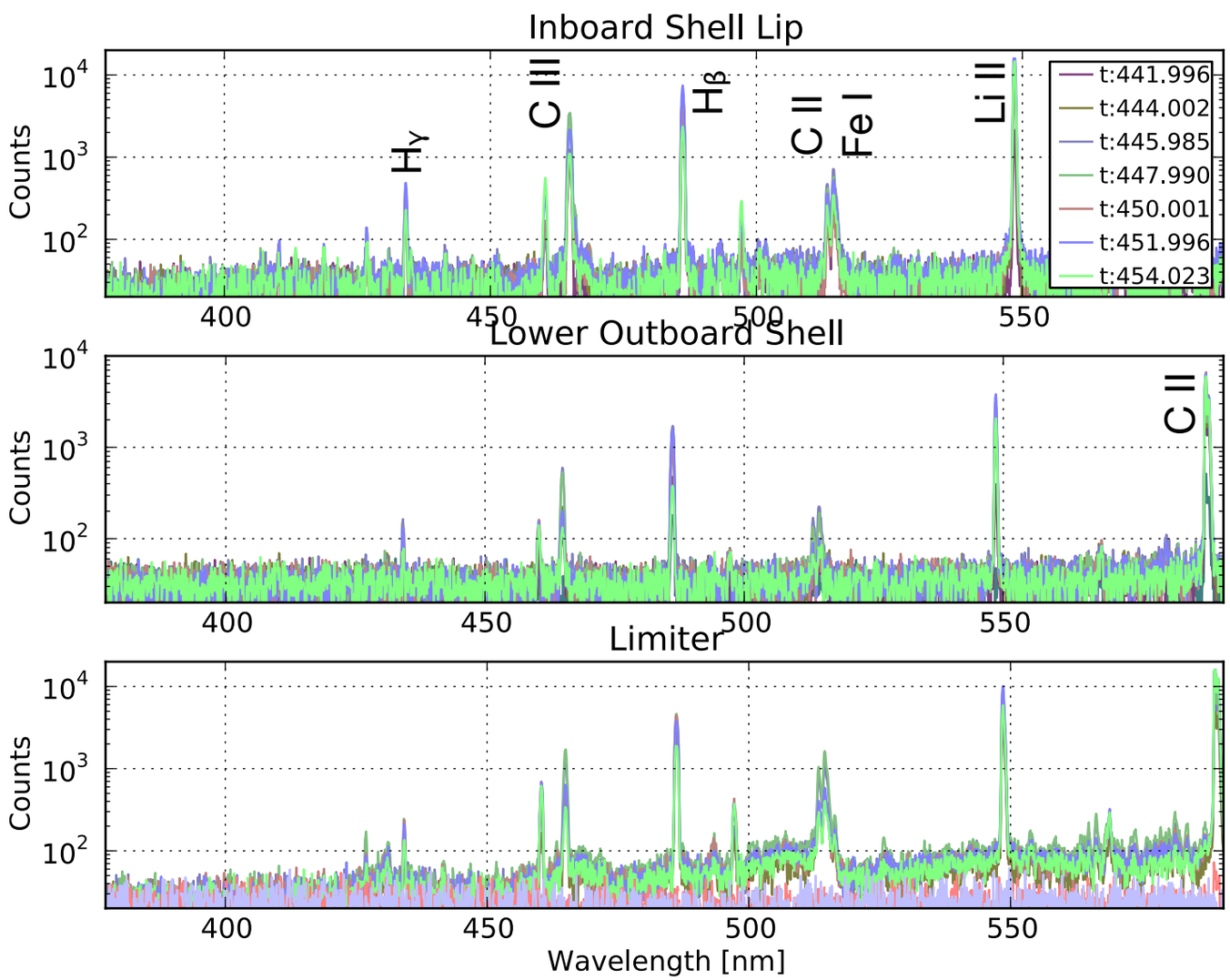
CJ Jacobson, BP LeBlanc

Application of lithium greatly improves I_p and discharge lifetime

- Operation on a bare SS shell results in meager discharges
  - 5-8 kA
  - discharges last < 5 ms
- With Li evaporation into He gas:
  - To achieve more uniform lithium coverage
  - I_p > 50 kA (up to 67 kA)
  - Discharges extended out to ~ 15 ms
- Lithium coating passivates and discharge quality subsequently suffers



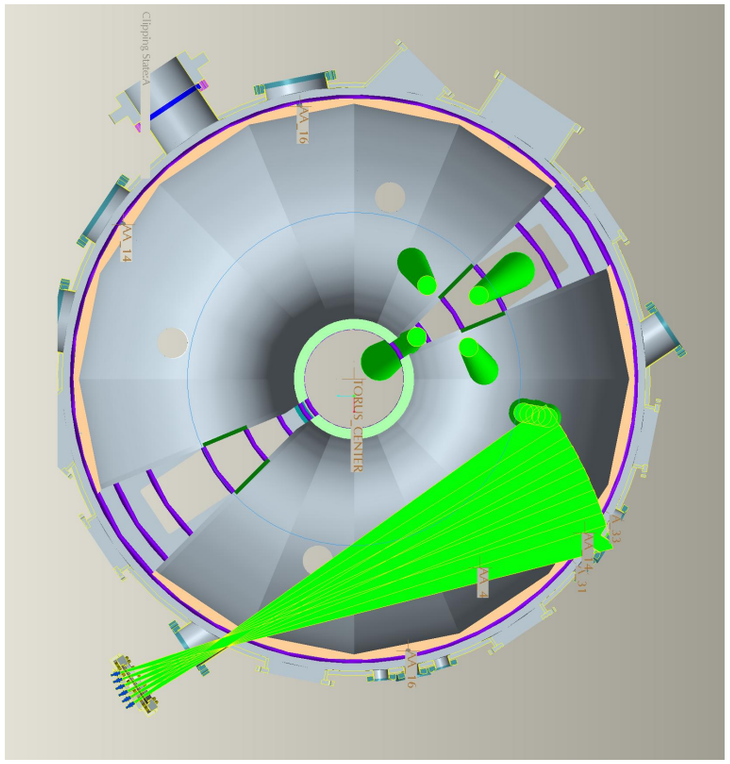
Visible Spectroscopy Shows Presence of Carbon Impurities



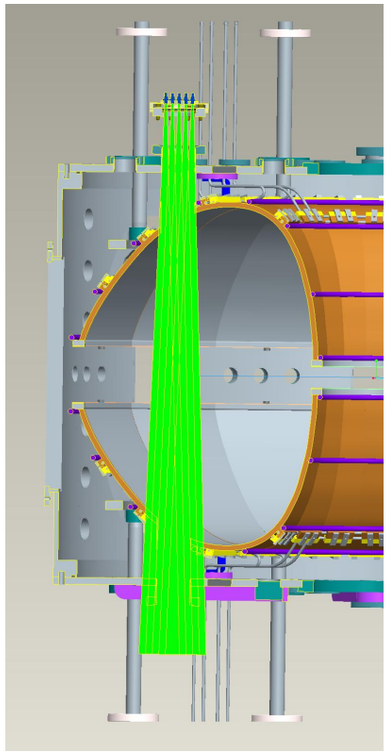
- Ocean Optics Visible Spectrometers
  - Same set-up as on NSTX
  - 380 - 590 nm
  - ~ 1.5 nm resolution
  - 3 views: Inboard and Outboard shells and Mo limiter
- Carbon is the dominate impurity
  - Source is possibly from shells or a persistent vacuum leak
    - Base vacuum is limited to $5(10)^{-7}$ T
- Iron is also present
  - Suggests insufficient Li coverage of shells
- No Mo outflux measured on spectrometers or filterscopes

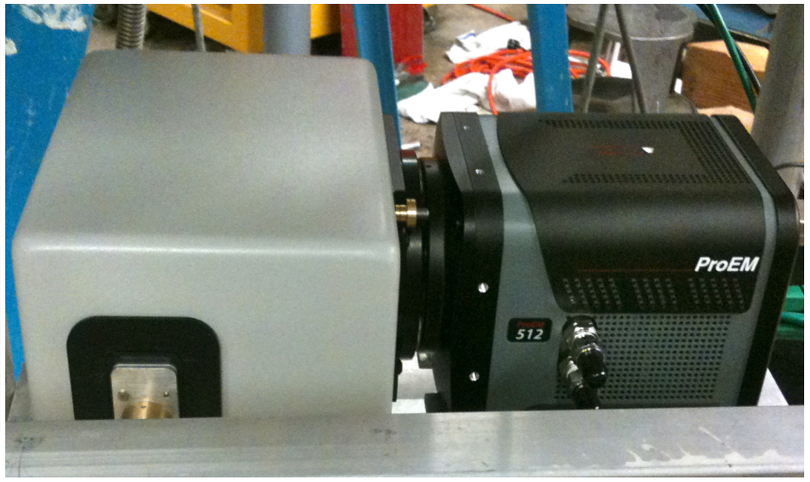
Preliminary CHERS set-up on LTX was designed to Passively Measure Available Li III CER Light

Toroidal



Poloidal

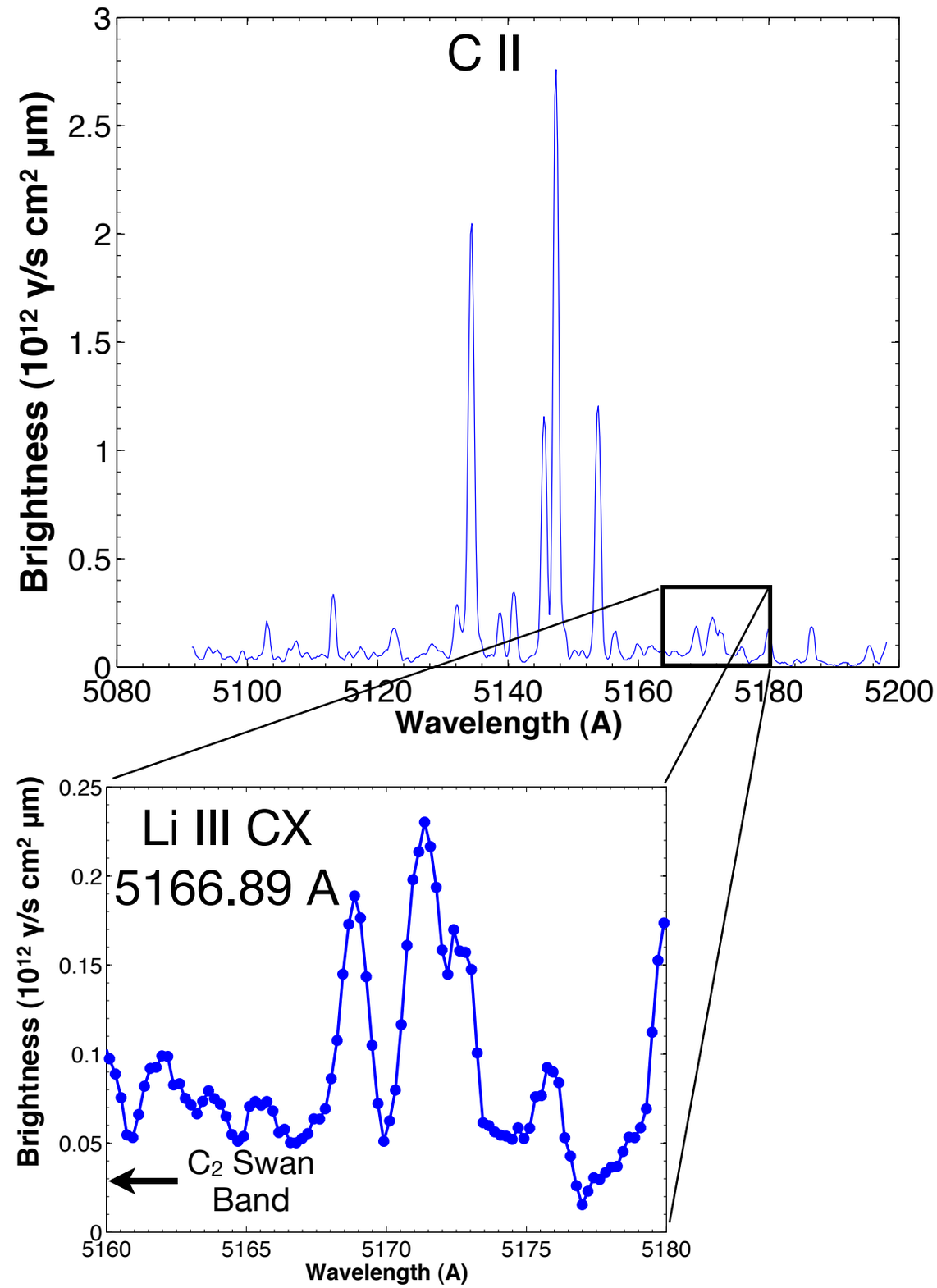




- Sightlines:
  - using optical "pucks" similar to those used on the test stand
  - 6 toroidal
  - 5, up/down symmetric poloidal
  - 3, up/down symmetric poloidal (partially obstructed by magnetics)
- Short focal length Spectrometer
  - 5090 - 5200 Angstrom
  - Coupled to 512x512 ProEM CCD camera
  - On loan from ORNL
  - Grating is borrowed from R. Bell

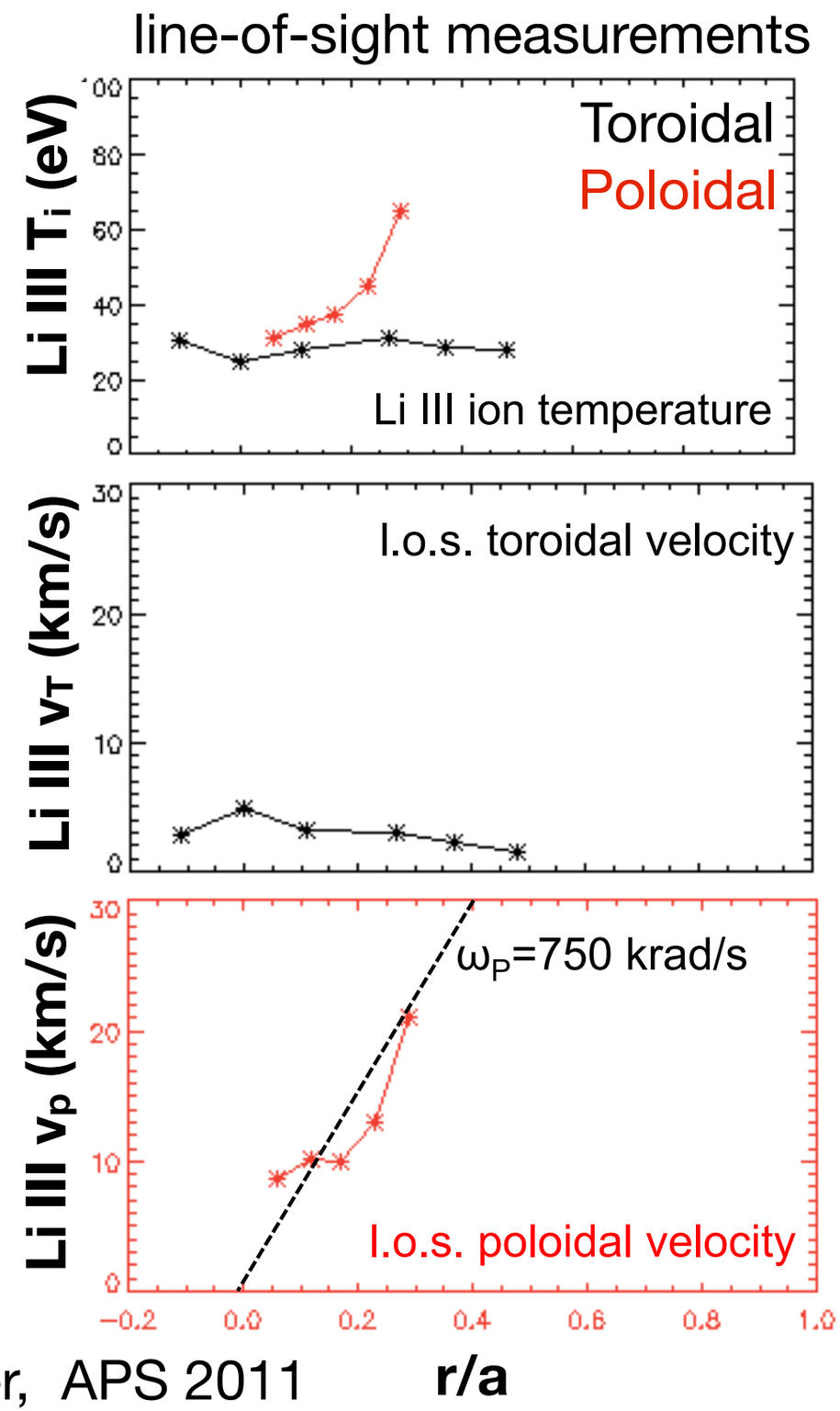
Preliminary Passive Measurements Show Spectra Dominated by C but with Measurable Li CX light

- Li III CX emission at 5166.89 Ang
- Able to run at 2.25 ms frame rate
  - 1.8 ms integration time
  - Given the short pulse duration, fast frame rate is important
- Presence of carbon and iron emission in passive measurements
  - Iron is likely from the shells
- Carbon may complicate analysis much like it does in NSTX
  - C_2 Swan Band from 5150 - 5165.25 A
  - C VI CX @ 5166.67 A
    - Probably not an issue for these passive measurements
    - Possible issue when the DNB is added



Preliminary Passive CHERS Measurements Show Promise

- Flat toroidal T_i and v_T
  - $T_i \sim 20 - 30$ eV
  - $V_T < 5$ km/s
- Outboard peaked poloidal T_i
  - T_i up to 70 eV
  - Not using up/down matched optics for these measurements
  - Further analysis is required
- Outboard peaked poloidal v_p as well
  - $V_p \sim 20$ km/s at the edge



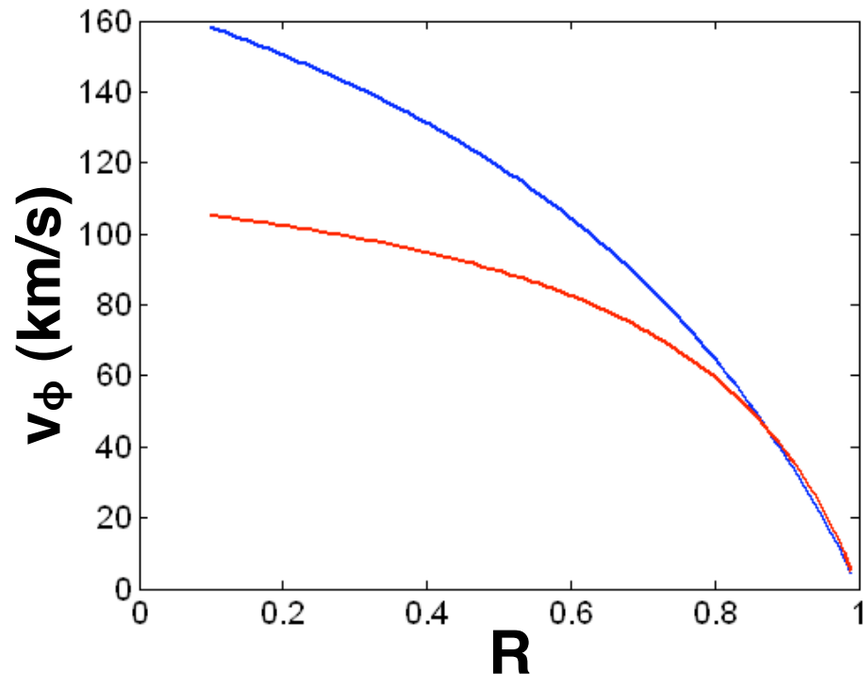
TM Biewer, APS 2011

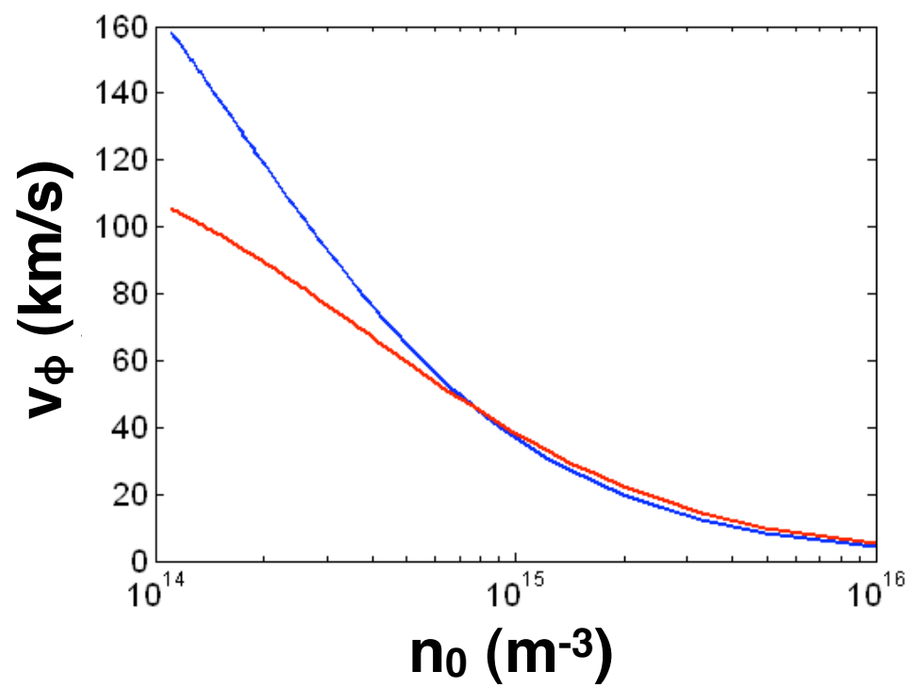
Theoretically, reduced recycling could substantially increase Toroidal Velocity

- From momentum balance:

$$mNR_0 \frac{\partial v_\phi}{\partial t} = T_{NBI} - \frac{mR_0 N v_\phi}{\tau_\phi} - \int mnR_0 v_\phi \nu_n dV$$

- If liquid lithium substantially reduces edge neutral density,
- ion-neutral friction will be reduced
- Resulting in increased toroidal velocity with reduced recycling



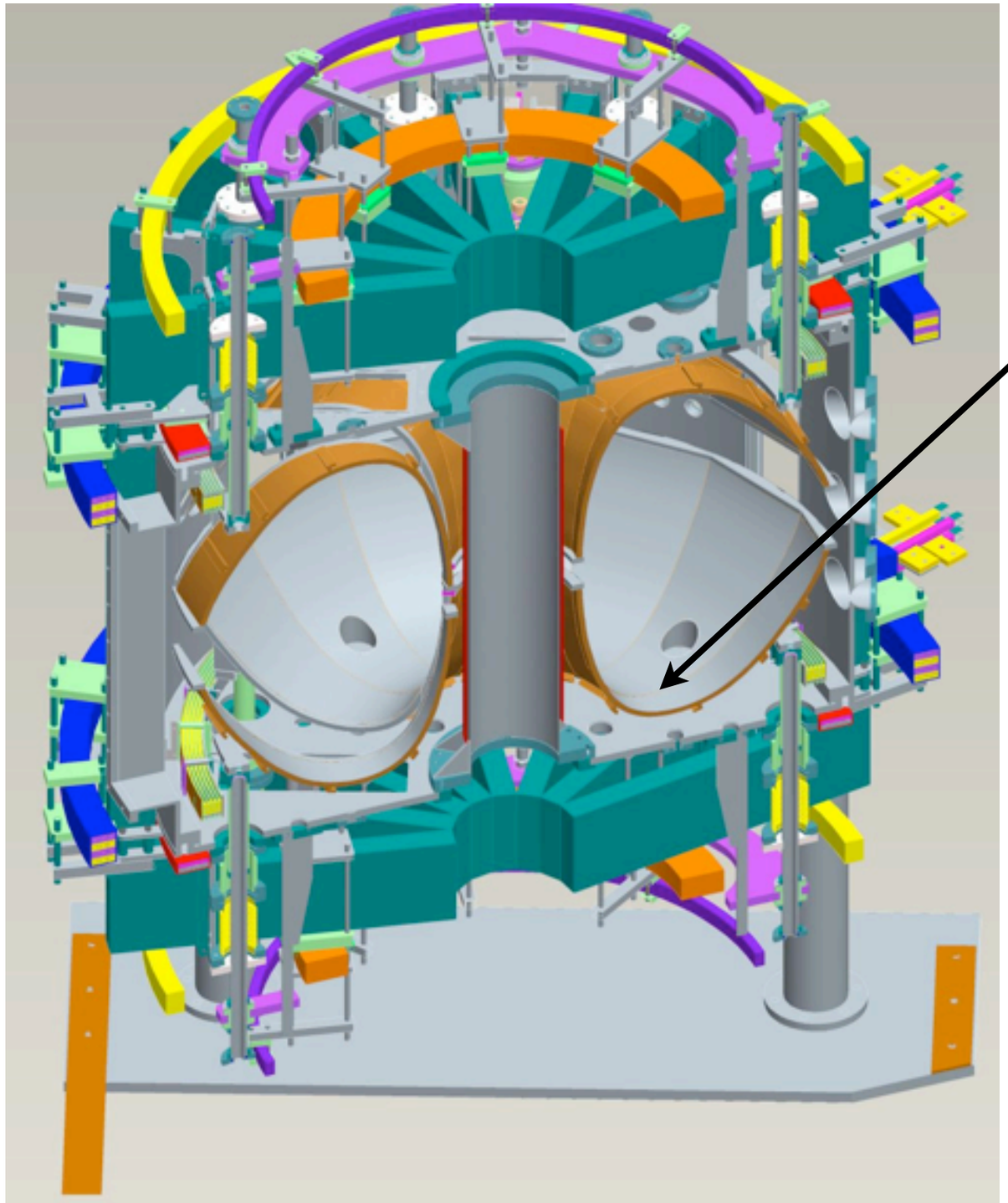


J. Canik

Summary of recent LTX results

- LTX is running after being down for almost a year
- Lithium evaporation increases I_p and discharge lifetime
- Measurements show the presence of many impurities
  - Carbon
    - Persistent vacuum leak
    - Impurities on the shells
  - Iron - likely from insufficient Li coverage of the shells
- Preliminary passive “CHERS” diagnostic is running reliably
- First results show poloidal T_i and velocity peaked on the LFS
  - These measurements aren’t using up/down symmetric viewing chords.
  - But are somewhat consistent with preliminary MPTS measurements

Upcoming LTX plans



- Optimize IGBT Ohmic PS to increase pulse length
- Localized Li evaporation
  - Similar to the tray of Li from CDX-U
- Liquid lithium “puddle”
  - Hot shells (T > 400 C) to increase Li coverage (plasma ops at lower T)
  - Increased Li Coverage
  - What happens to the C and Fe?
- Status of Diagnostic Neutral Beam
  - Currently tested up to 22 kV, 2.5 A for 500 ms
  - Requires modifications to the LTX pump duct for installation
  - 12 month timeline?
  - Nova Photonics was recently awarded a new Phase I SBIR to further develop the beam

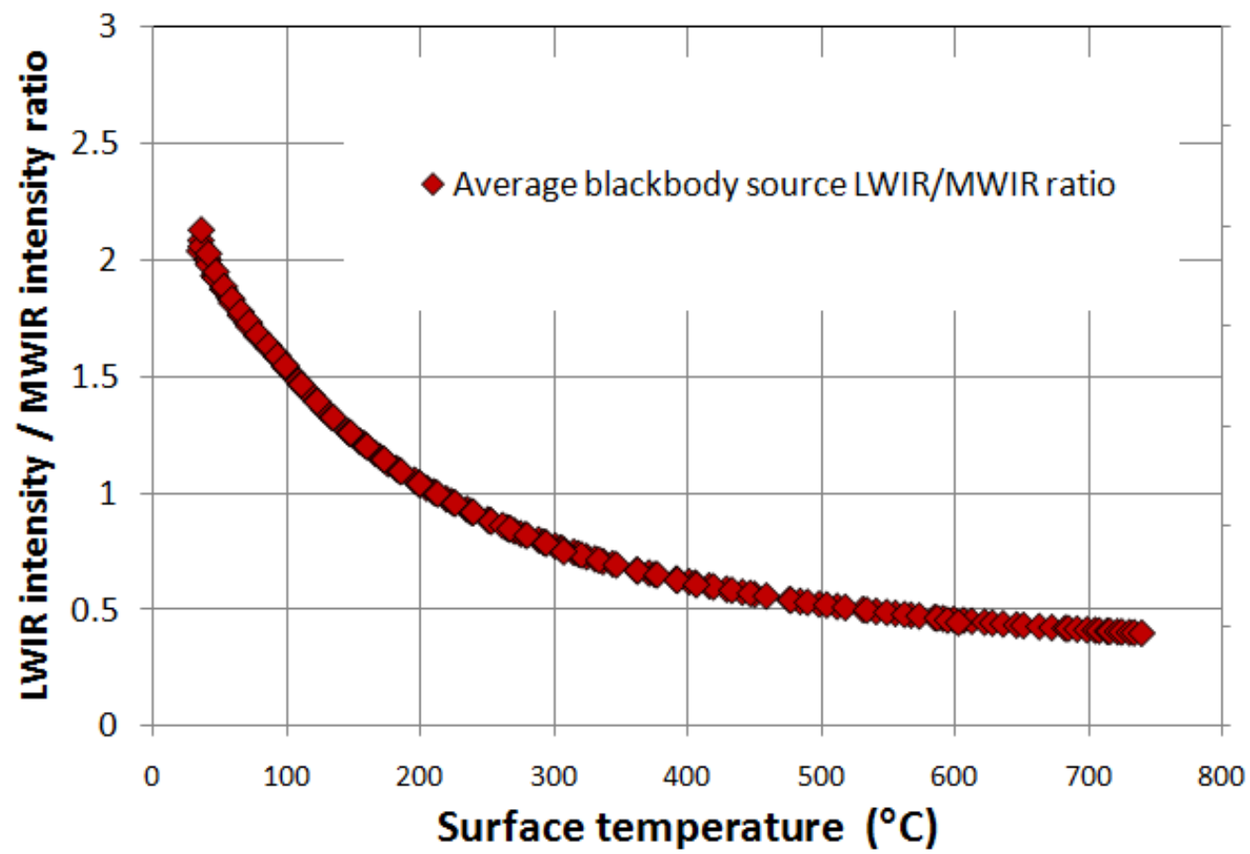
Lithium is AWESOME!!!!!!!!1

- Lithium has the possibility of providing large area pumping surfaces (near zero recycling) such as on LTX
  - Pro: Not localized like a cryo-pump
  - Con: not nearly as controllable as a cryo-pump
- Lithium has been shown to greatly improve confinement time, edge stability (ELMs), reduce $P_{L\rightarrow H}$, etc etc with little to no Li contamination in the core plasma on NSTX
  - Possibly reduce divertor heat flux
- Lithium's applicability to long pulse/steady state plasmas has not yet been demonstrated
  - Can Li provide a low recycling surface indefinitely in long pulse tokamaks?
  - Some promising early results from EAST
    - Using lithium dropper (from PPPL) to access long H-modes

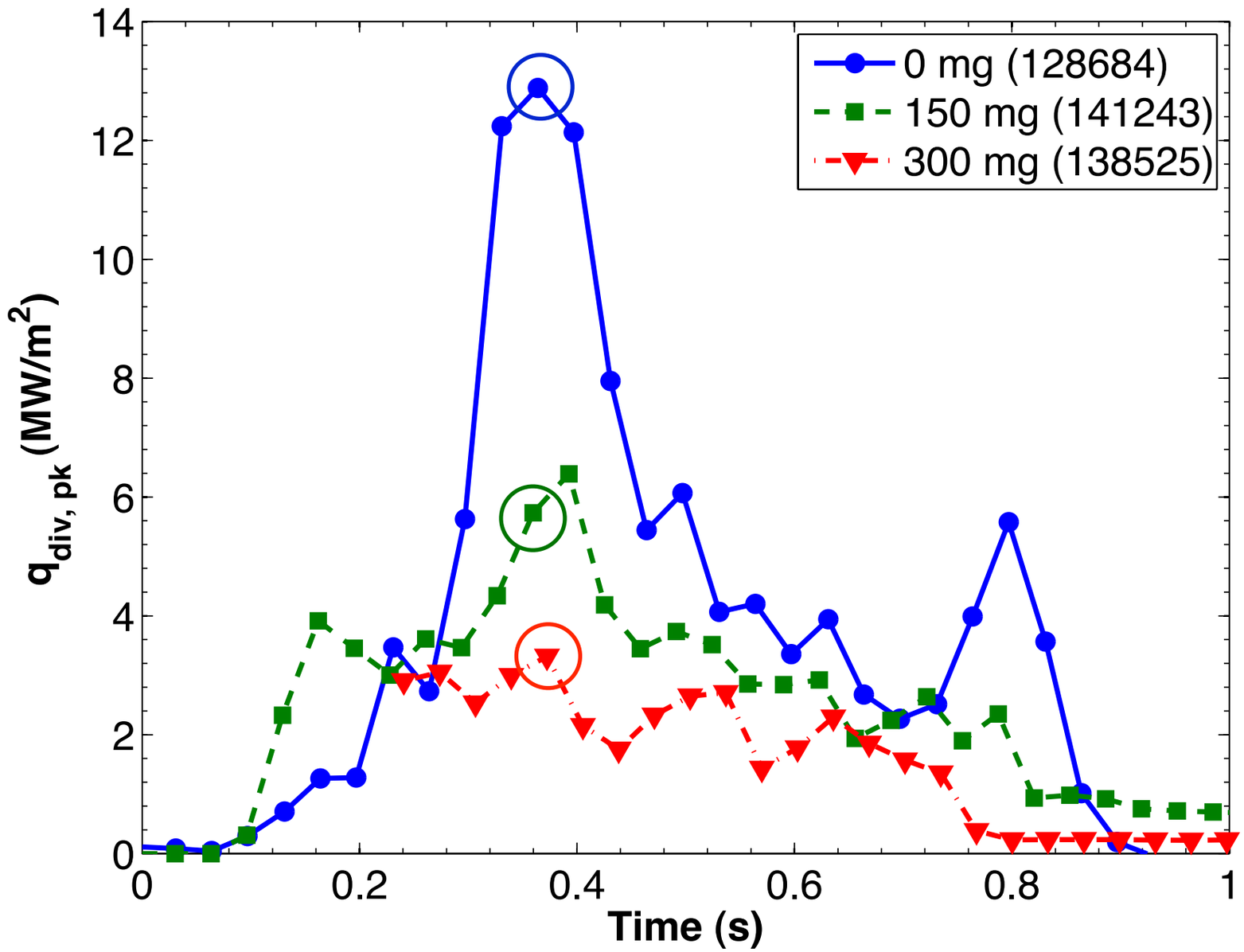
Back-up Slides

Calibration of DBIR is performed *ex-situ* and *in-situ*

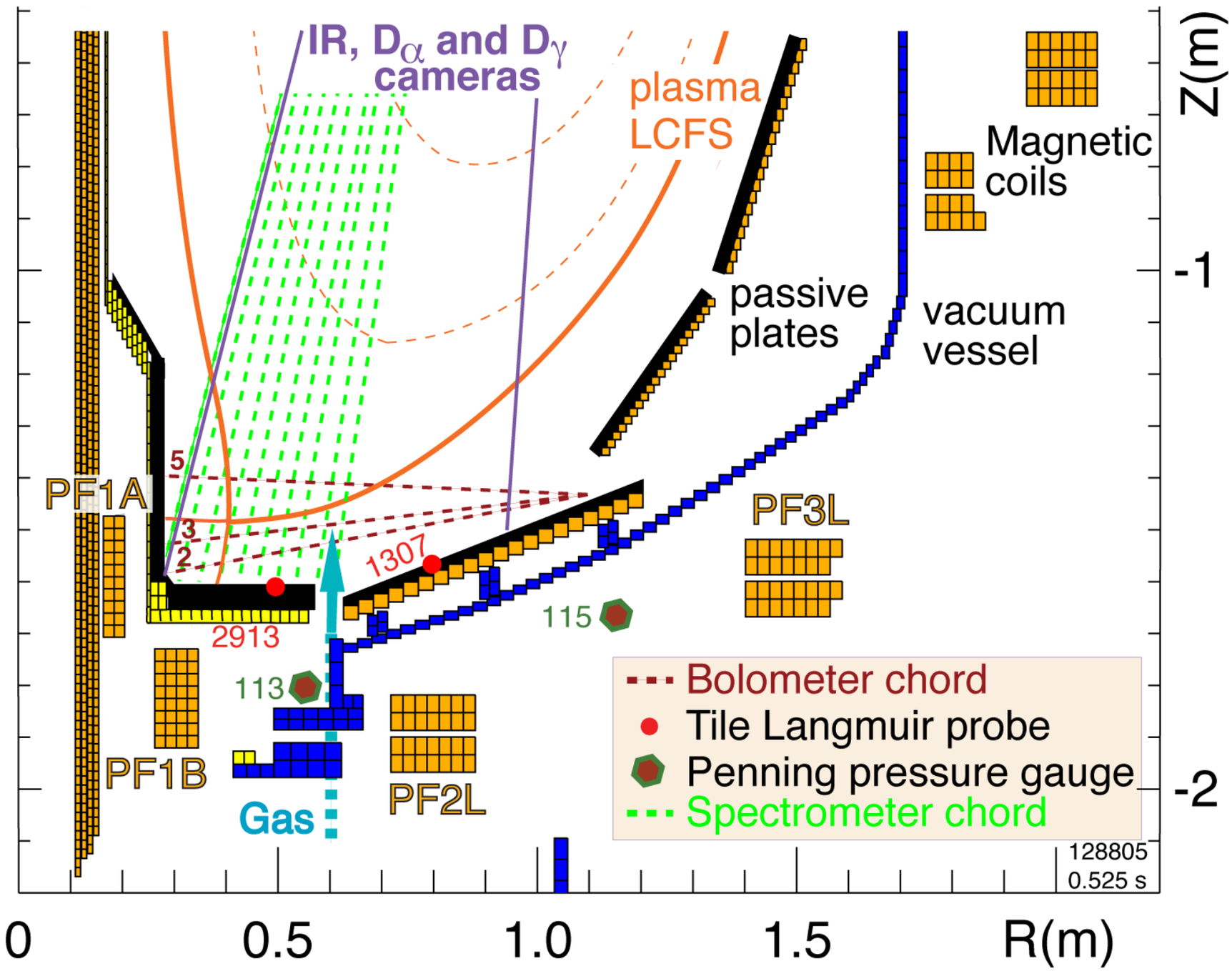
- *Ex-situ* with a calibrated black body light source
  - Up to 1200 C
- *In-situ* during:
  - NSTX bake out prior to run campaigns
  - LLD heating tests
    - With and without Li on the LLD
- Frame averaging is generally needed due to low Signal/Noise ratio



Time evolution of Divertor Heat Flux for 1.2 MA Discharges with varying Lithium amounts

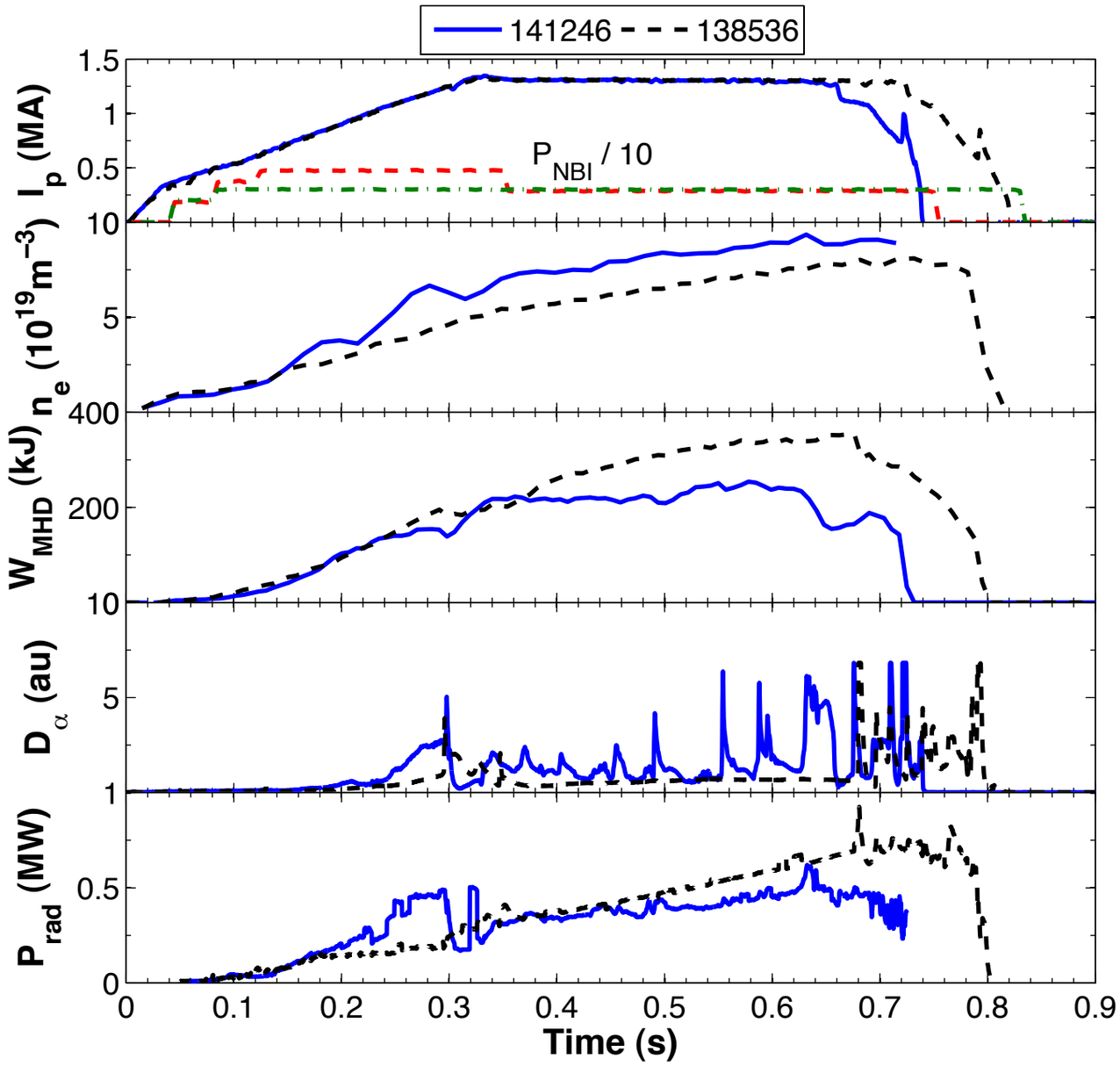


NSTX Divertor Diagnostics

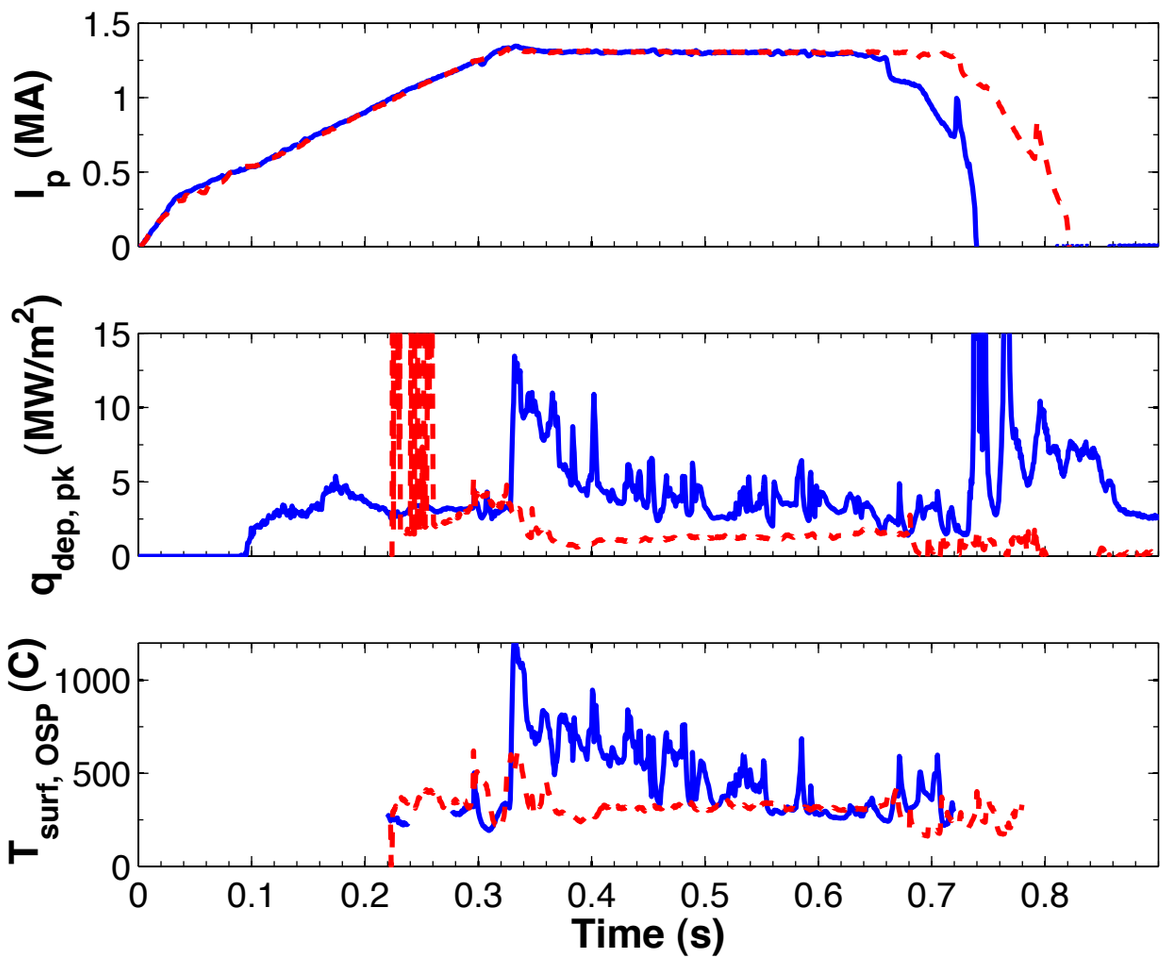


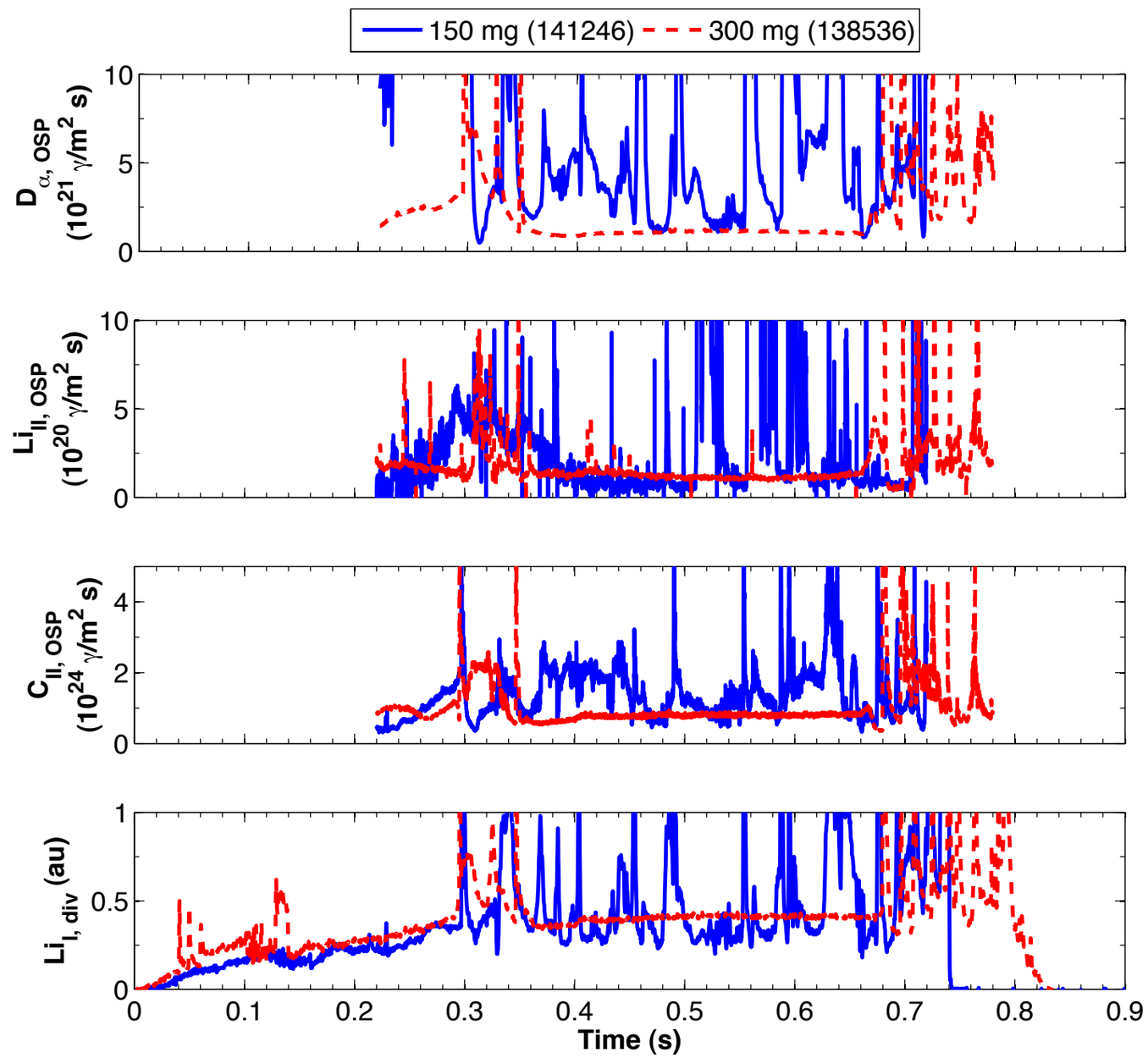
1.3 MA Comparison of the effects of Lithium

- Reemergence of ELMs for 150 mg data complicates analysis
- Again, 2 identical discharges
  - I_p = 1.3 MA
  - P_{NBI} = 3 MW
    - Some pre-heating for 141246
  - high δ, high f_{exp}



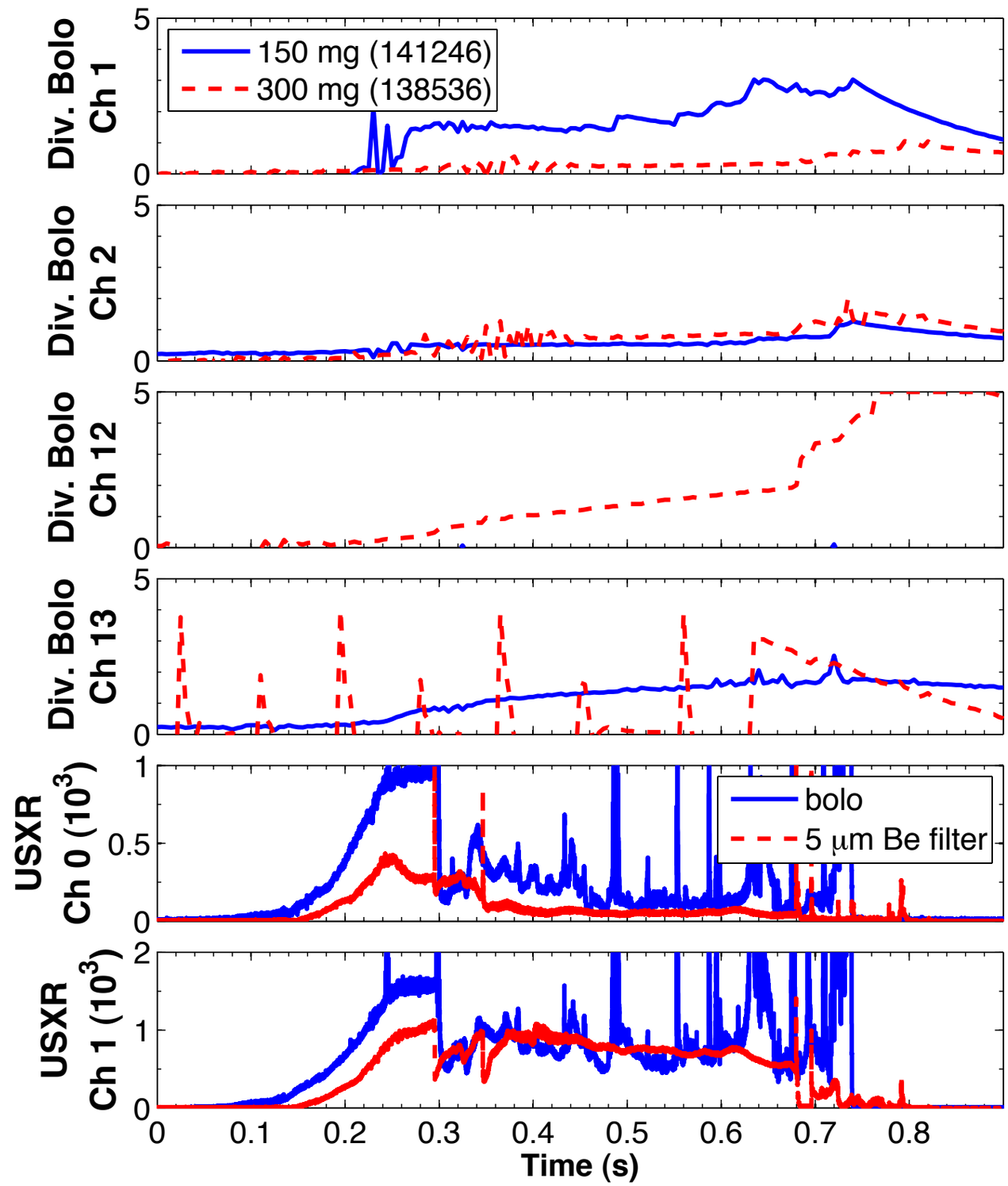
1.3 MA Heat Flux Divertor Visible Measurements





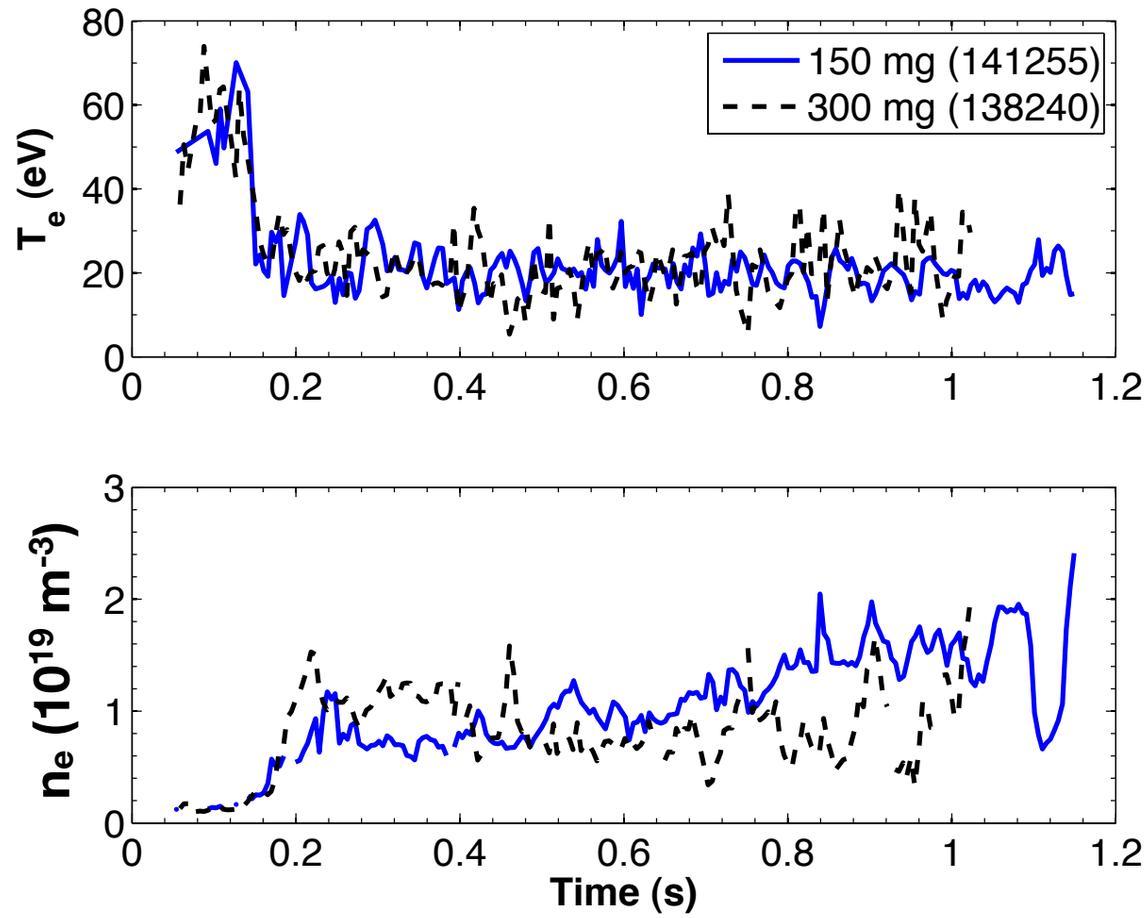
Possible quiescent windows for analysis:
~ 0.31, 0.47, 0.52 sec

Divertor Bolometry for 1.3 MA discharges



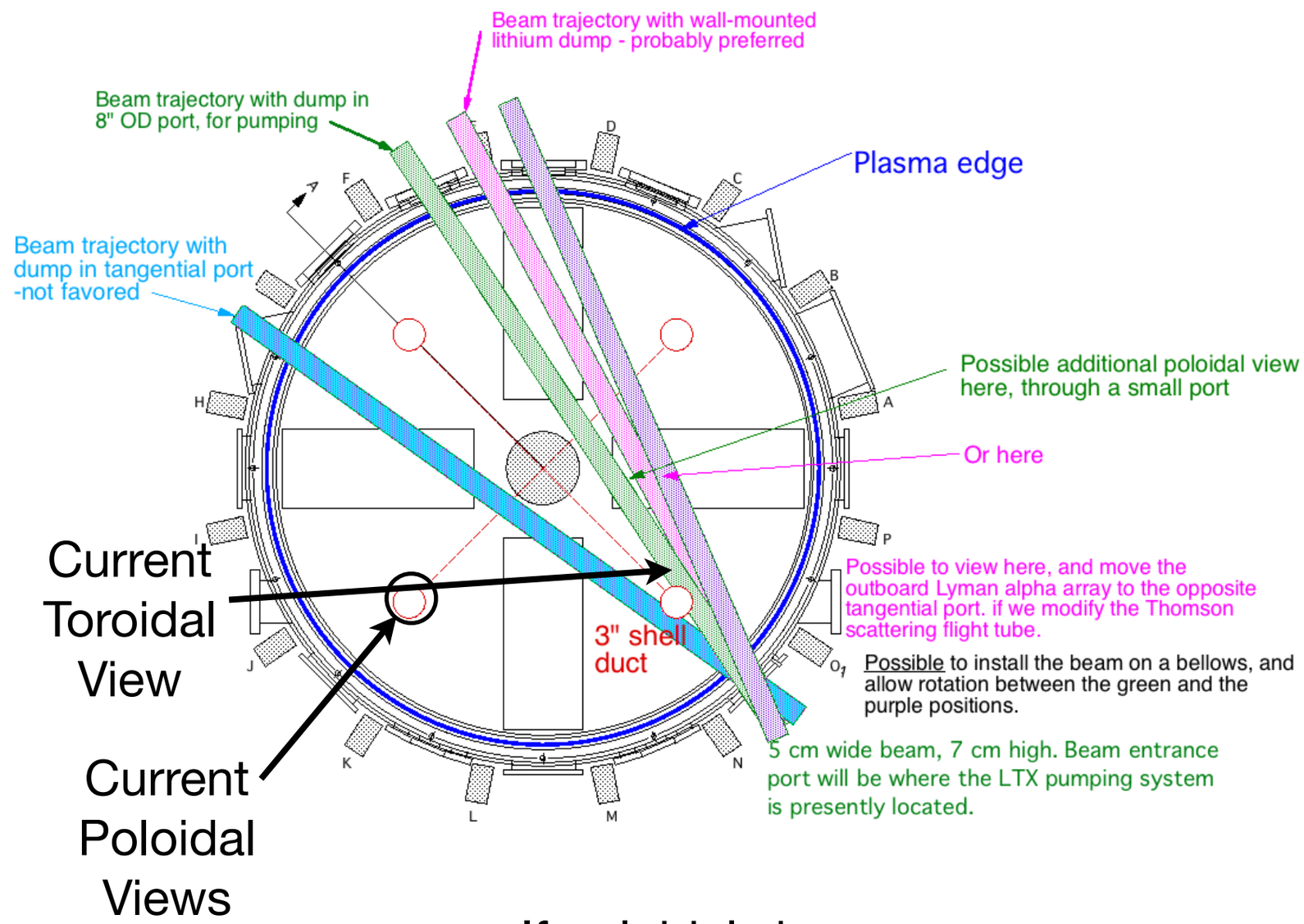
No Evidence of Divertor Detachment with Heavy Lithium Evaporation

- No difference in divertor n_e and T_e from Langmuir probe
  - Limited to 1 LP on the inboard divertor
- Current analysis uses a "classical" Langmuir probe interpretation of swept probes
  - Assumes Maxwellian distribution
  - Only utilizes data taken in ion saturation up to V_{float}
- Recent work (M. Jaworski, APS Invited 2011) that the electrons are Bi-Modal
  - $T_e \sim 5$ eV
  - May also be affected by lithium



LTX Diagnostic Neutral Beam

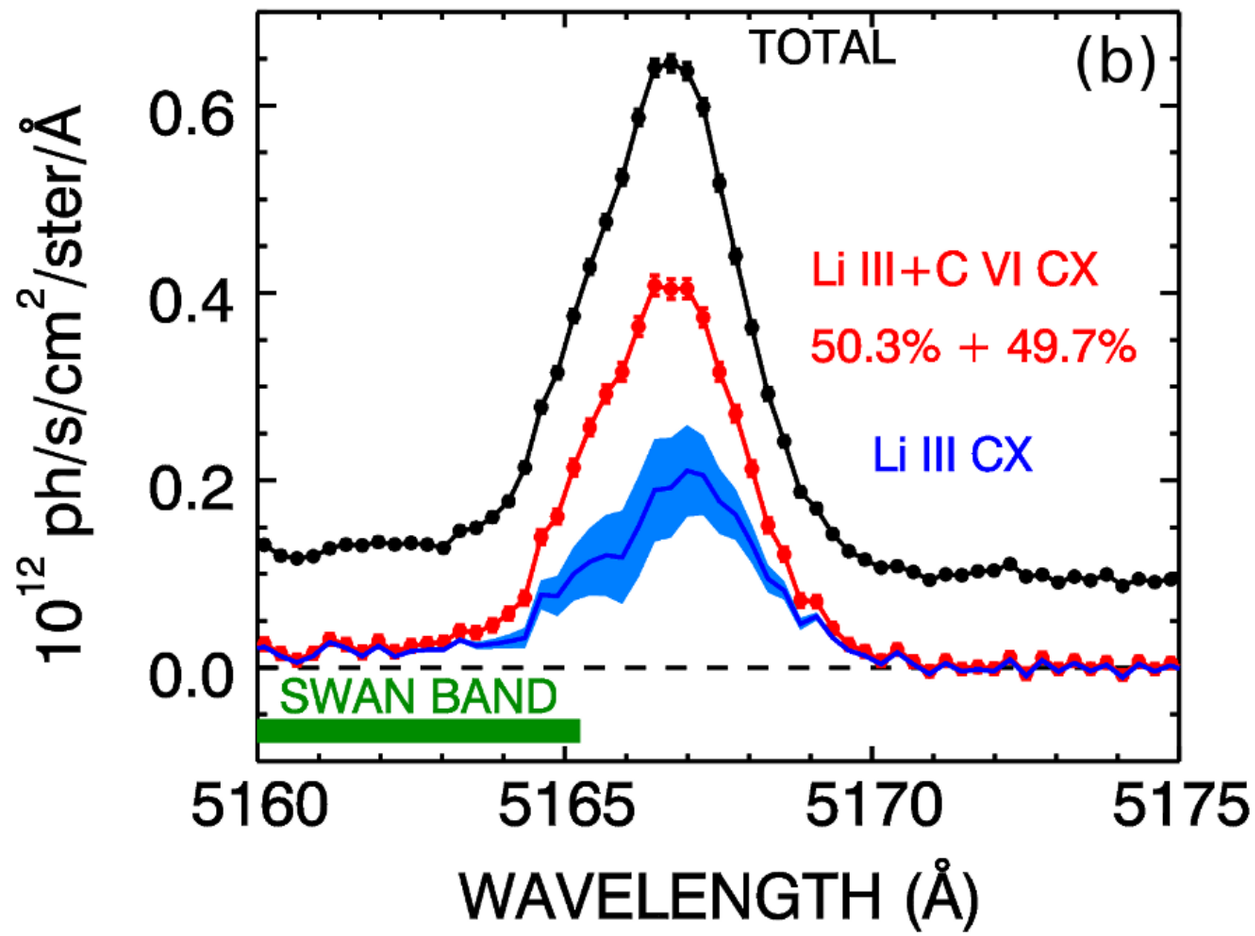
- Beam was developed by Nova Photonics
  - Originally for NCSX
  - 40 kV, 5 A DNB
  - 5cm x 7cm square
- Will be placed where the pump duct currently resides
  - Requires modification to the pump duct
  - Plus armor for shine through



If poloidal views are necessary, there aren't many ports on LTX available with a beam view

Contamination of Li III CX with Carbon is a possibility when the Neutral Beam comes online

- To estimate C VI CX line intensity,
  - NSTX used the carbon, poloidal CHERS system to estimate the density of the n = 7→5 state (5290 A)
  - collisional-radiative model to estimate the density of the n = 14 → 10 state (5166.67 A)
  - Benchmarked the CR model with TFTR data



M Podestà, *et al*. submitted to NF. (2012)