Sensitivity of Tokamak Transport Modeling to Atomic Physics Data: Some Examples

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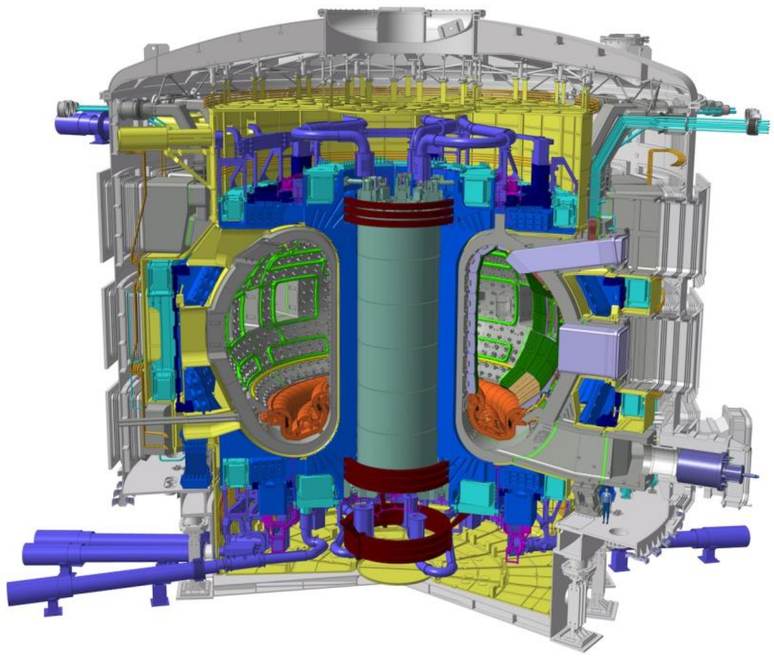
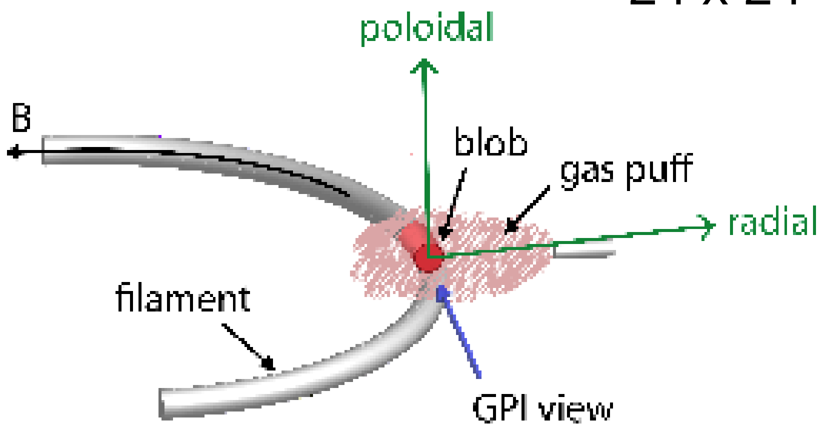
Accurate Atomic Physics Data Essential for Tokamak Modeling

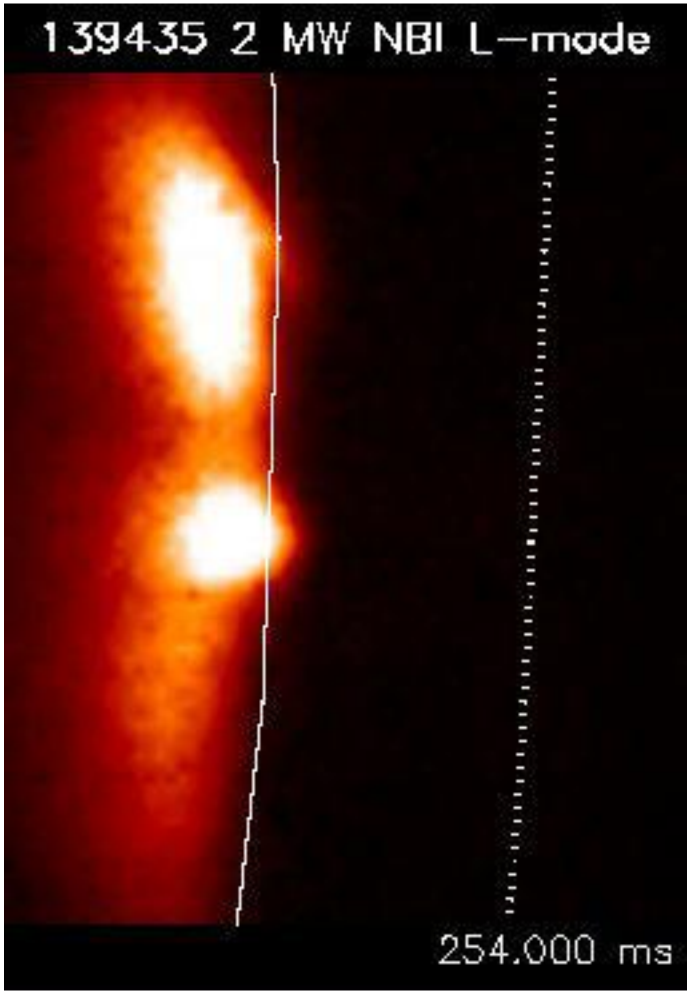
- Tokamak modeling critical for fusion energy because can't build a "small" reactor,
  - All represent extrapolation of knowledge,
  - Only approach is via 1st principles model.
  - Such models rely on atomic physics data.
  - Atomic data also needed for model validation,
    - E.g., in experimental diagnostics.
- Will show some examples:
  - Gas Puff Imaging:
    - Turbulence diagnostic,
    - Excellent opportunity for neutral transport validation.
  - High-Z impurity transport in tokamak plasmas,
    - Three examples.
  - "Closest to 1st principles" codes are kinetic,
    - Need more detailed data.



Gas Puff Imaging Allows Us to “See” & Characterize Edge Plasma Turbulence

Camera view:
~24 x 24 cm

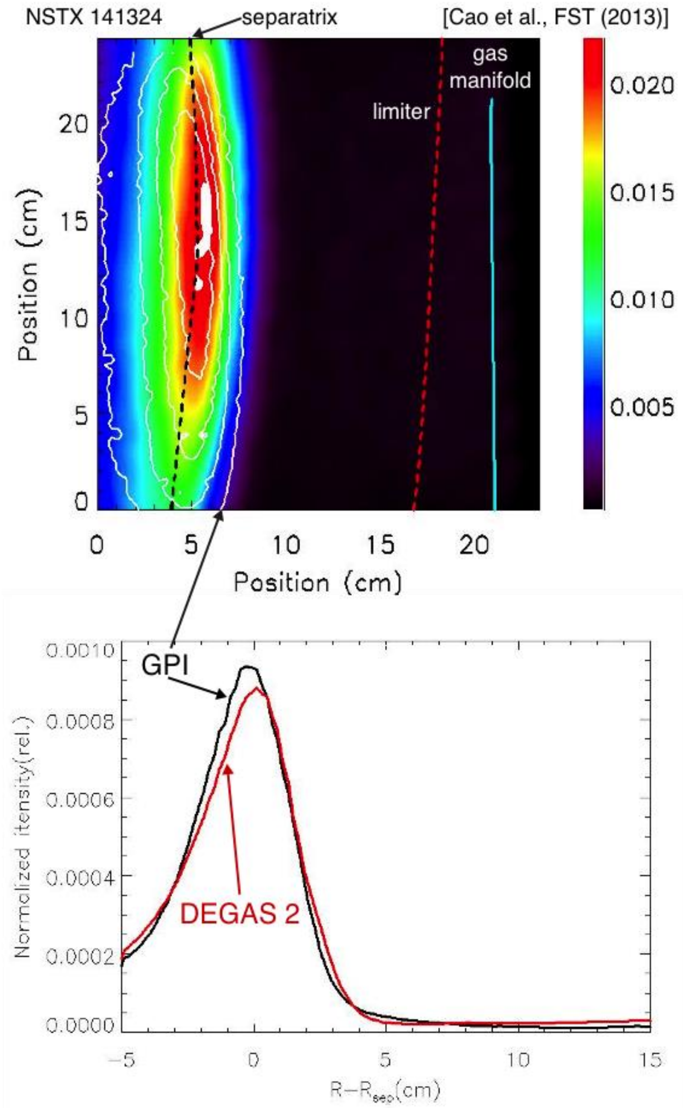




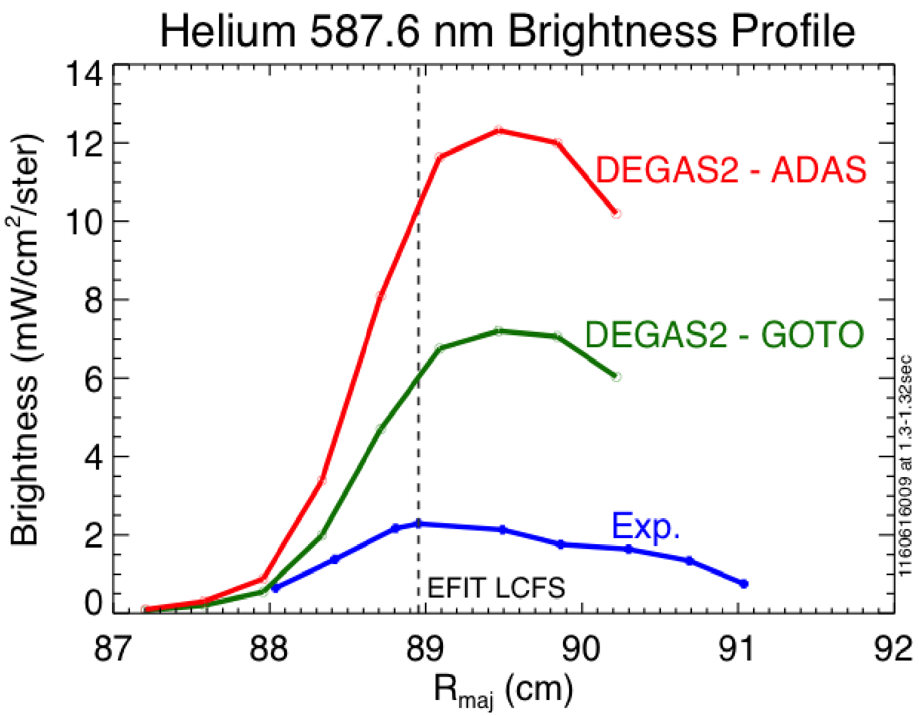
http://w3.pppl.gov/~szweben/
[Zweben et al., PPCF (2016)]

GPI Provides Nearly Ideal Opportunity for Validating Neutral Transport Codes

- And atomic physics data!
  - ⇒ Identify sensitivities & minimize uncertainties.
- Is "ideal" because:
  - Source & plasma well characterized,
  - Plasma-material interaction effects minimal,
  - Results can be directly compared with experiment.
- But, not completely:
  - Complex geometry,
  - Light emission nonlinear function ⇒ $\langle S(n) \rangle \neq S(\langle n \rangle)$.
  - Turbulence complicates n_e, T_e measurement.
- NSTX D_2 validation:
  - Observed: 1/89 D_α photons / atom ± 34%,
  - Simulated: 1/75 ± 18%.
- Doesn't include atomic physics uncertainty!
  - Subsequent update to n = 1 → 3, 4, 5 ⇒ ~10% change in emission.
    - How uncertain are these data?
  - D_2 dissociation contributes ~30% of D_α at peak & is more uncertain.



Simulated He GPI Emission in Alcator C-Mod Way Too Large!

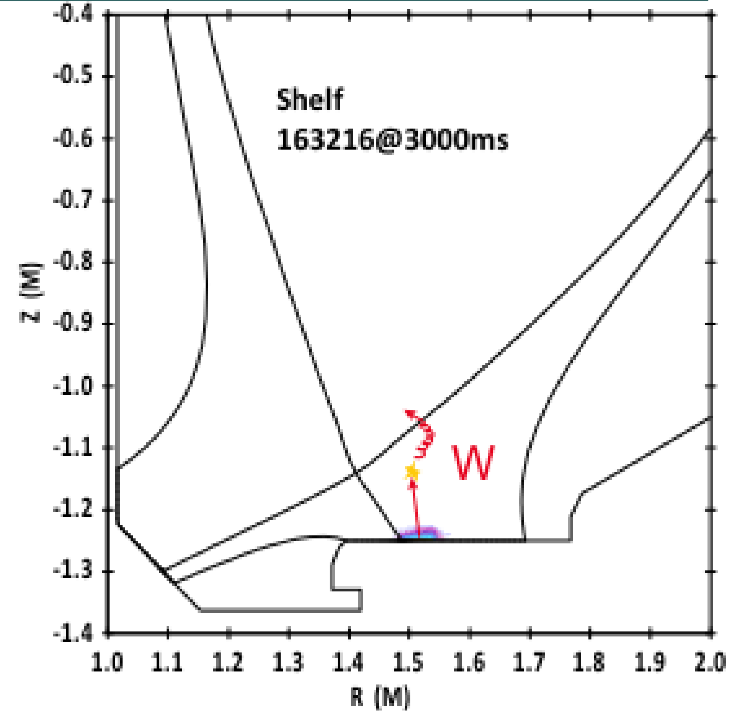


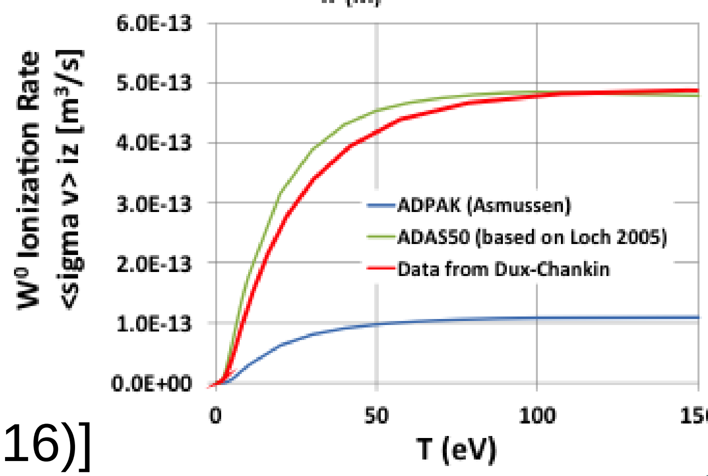
[S. Baek et al., APS-DPP (2016)]

- D_2 comparison similar to NSTX.
- Two He CR models:
  - M. Goto, JQSRT 76, 331 (2003),
  - S. Loch et al., PPCF 51, 105006 (2009).
- How accurate are these data?
- Alternative explanations dismissed:
  - Boundary conditions,
  - 4.1 T singlet-triplet mixing (Goto).
- Still to check:
  - Radiation trapping,
  - Turbulence effects.

Core Penetration Fraction Sensitive to W Ionization Rate

- Predictive OEDGE simulations of DIII-D W ring experiments.
- For “shelf” geometry:
  - ADAS50: 0.3% W reach core,
  - ADPAK: 16%!
  - Factor of 5 difference in ionization rate ⇒ factor of 50 difference in core penetration.
  - Similar results for “floor” geometry.
- Sensitivity enters via prompt redeposition model.
- Actual experiments will have WI data ⇒ can quantify source,
  - & core bolometry will give data on core concentration.
  - ⇒ may be able to reduce uncertainties.





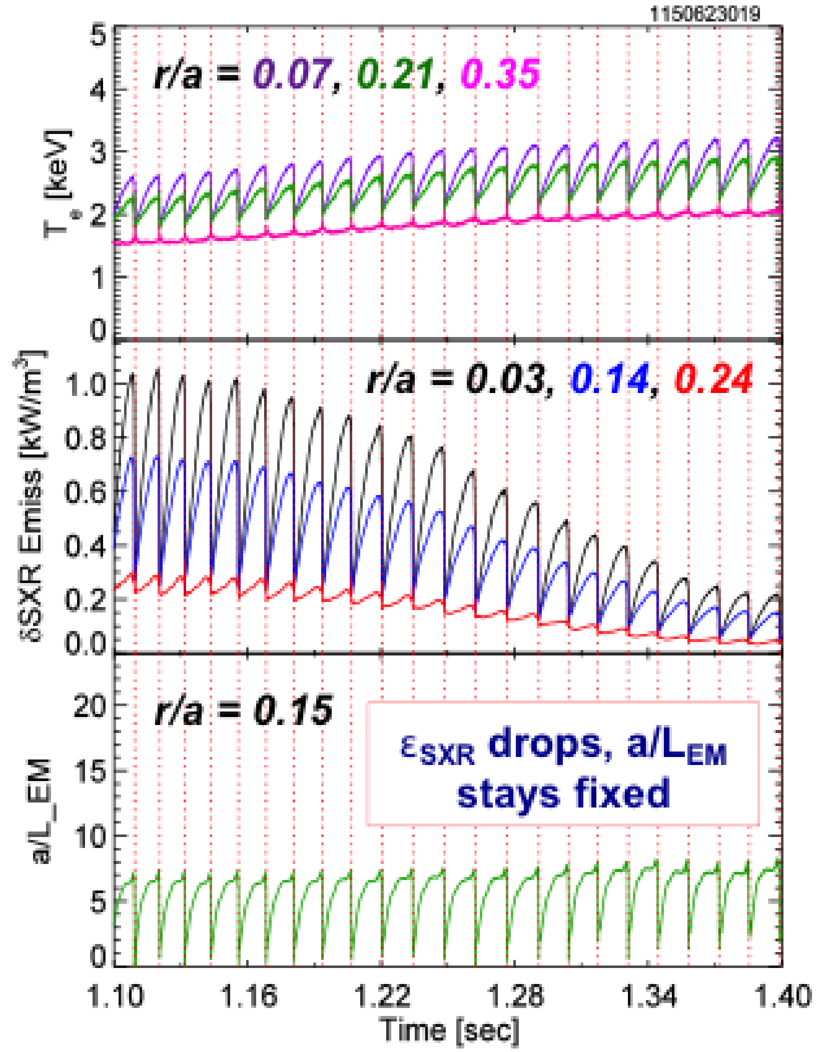
[J. D. Elder et al., PSI (2016)]

Optimization of Fusion Operating Scenarios Benefits from Accurate $L(T_e)$

- Optimize n_i & T_i profiles to maximize pressure (→ P_{fus}) & high J_{boot} (↓ recirculating power),
  - High-Z content must be controlled to do this.
- C-Mod experiments targeted at validation those control mechanisms:
  - Neoclassical transport,
  - Radio-frequency heating effects.
- Assess W transport via sawteeth!
  - How much peaking due to n_W?
  - How much to T_e?
  - Peaking ↔□ gradients ⇒ need dL/dT_e!

$$n_W = \frac{\varepsilon_{SXR}(r)}{n_e L_Z(T_e)}$$

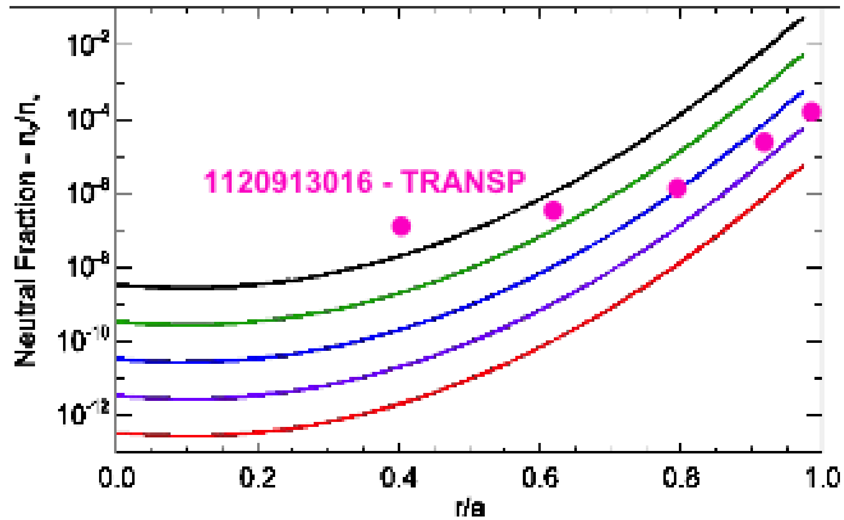
$$\frac{\nabla n_W}{n_W} = \frac{\nabla \varepsilon_{SXR}}{\varepsilon_{SXR}} - \frac{T_e}{L_Z}\left(\partial L_Z / \partial T_e\right)\frac{\nabla T_e}{T_e} - \frac{\nabla n_e}{n_e}$$

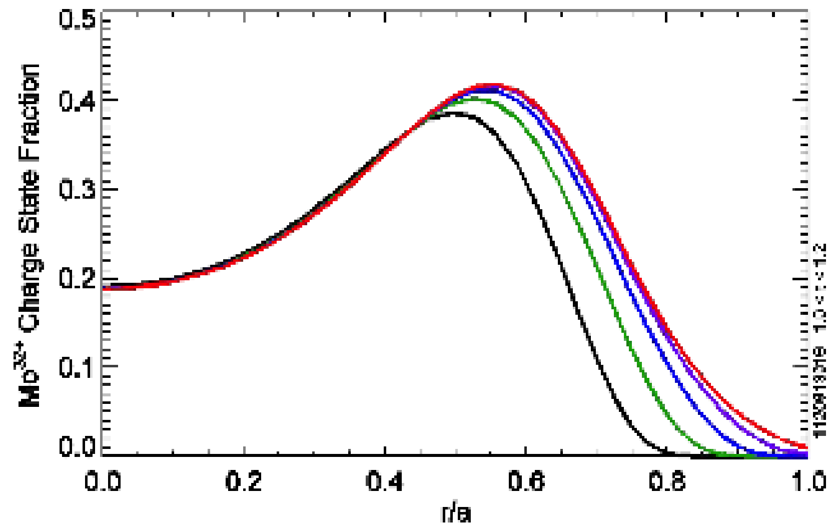


[Reinke et al., IAEA FEC (2016), Loarte et al., PoP (2015)]

CX Recombination Affects Ionization Balance & Diagnostic Interpretation

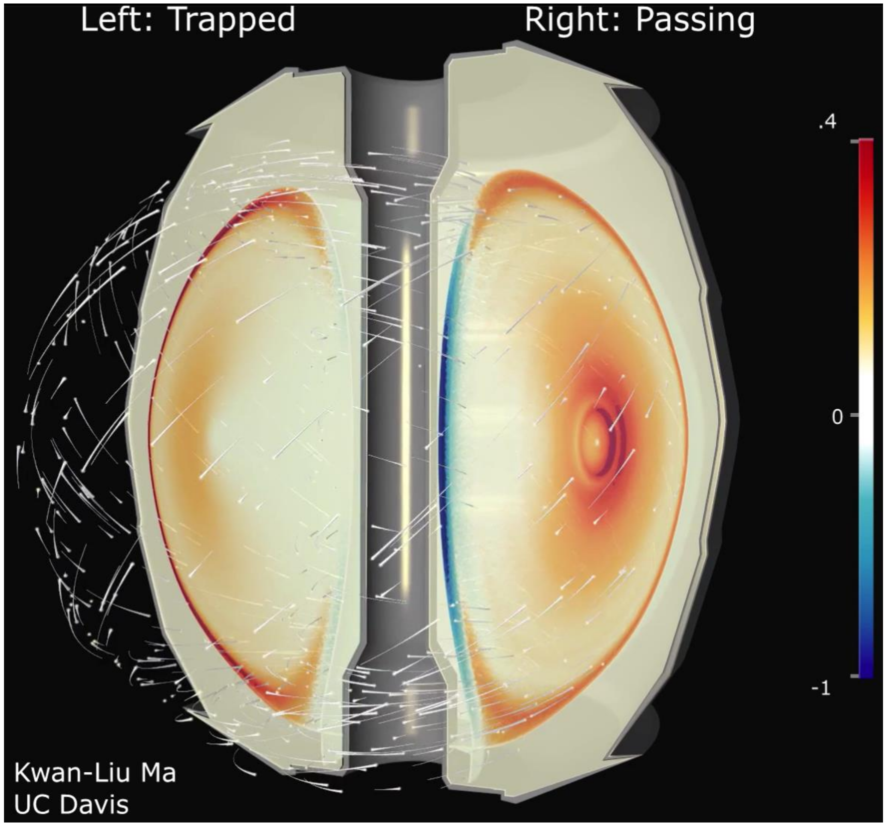
- Assume n_0/n_e profiles & calculate Mo^{32+} distributions:
  - Net effect of CX recombination equivalent to $\Delta r \sim 0.1$ a!
- Impacts transport model based on Mo^{32+} diagnostic,
  - E.g., ignoring CX would require pinch to match observed Mo^{32+}.
- Relevant for diagnostic analysis, e.g., C-Mod XICS [Reinke, RSI (2012)].
- More important in devices with NBI!
- But, CX recombination data hard to find for W, Ca, …
  - Can rough estimates be made without much effort?





Kinetic Codes Will Need More Detailed Data

- 6-D codes track velocities of all reactants & products.
- E.g., [Tskhakaya CPP (2016):
  - H^+ + e radiative recombination from photoionization,
  - 3-body recombination from ionization.
- Large scale gyrokinetic / drift kinetic codes are 5-D.
  - Focus is on ion distribution.
  - & electrons in atomic processes treated heuristically.
  - But, want correct electron energetics.



Bootstrap current calculation with XGCa [Hager PoP (2016)]

Conclusions

- From Gas Puff Imaging:
  - D collisional radiative model in good shape,
    - Molecular contributions more uncertain.
  - Are there problems with He model?
- High- Z Impurity Transport:
  - W first ionization critical,
  - Knowing dL/dT_e accurately would be useful,
  - Data for CX recombination of closed shell ions needed for diagnostic interpretation.
- 1st principles kinetic codes need velocity data for all reactants & products.