Laser Blow-Off Impurity Injection Experiments in the HSX Stellarator

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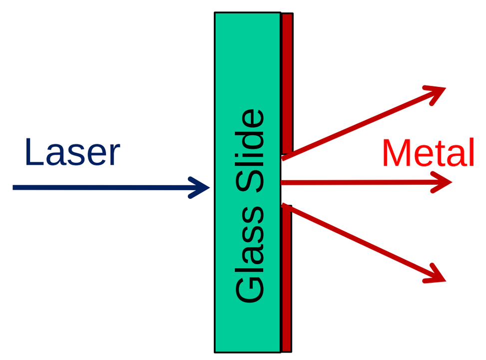
Overview and Motivation

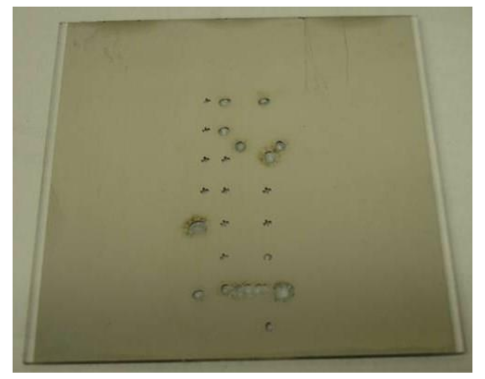
- Impurity control and effective helium exhaust are open areas of research for the stellarator reactor concept
  - The expected "Ion Root" operating point of a stellarator reactor is predicted to enhance impurity confinement
  - Some stellarators have seen unexpected, and unexplained increase in impurity transport under specific operating conditions
    - W7-AS had an "High Density H-mode"[Grigull, '01]
    - LHD has an impurity "hole" [Ida, '09]
  - No clear path exists to satisfactory impurity handling in a reactor scale stellarator
- We have undertaken an experimental program to measure the impurity transport properties of the HSX stellarator. Our goals are to:
  - Inject aluminum neutrals into HSX plasmas using a laser blow-off technique
  - Measure the resulting radiation using AXUV photodiode arrays
  - Determine the impurity diffusivity and convective velocity using the STRAHL code
  - Compare these findings with the neoclassical model using the PENTA code
- Progress has been made toward the experimental goals
  - Aluminum has been injected into HSX discharges
    - The injection was visible on a photodiode
    - The injection did not perturbing the background plasma parameters
  - Two photodiode pinhole cameras have been installed on HSX, and five more are under construction.

Laser Blow-Off

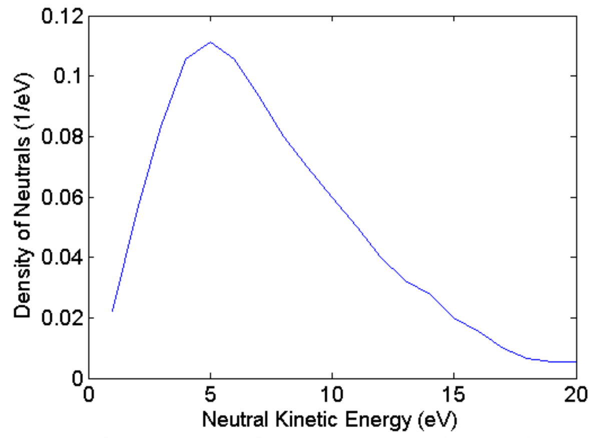
- A glass slide with a 0.5–2.0 μm thick layer of the selected material is back-illuminated with a laser
  - This creates short burst of neutrals, which ballistically enter the plasma
  - The energy spectrum of neutrals is a function of the laser energy density, film thickness, and material
  - The number of neutrals injected can be controlled with spot size and film thickness
- The laser blow-off properties of aluminum have been particularly well characterized by other researchers [Marmar, '75 & Breton, '80]



A schematic view of the laser blow-off process



A laser blow-off target that has been used on HSX

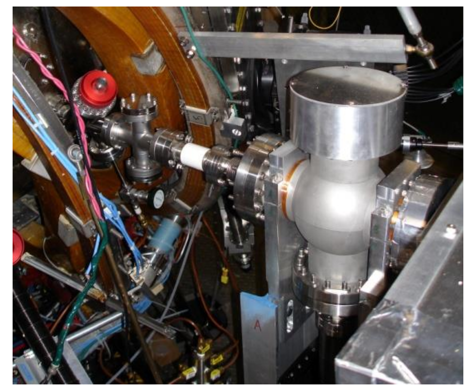


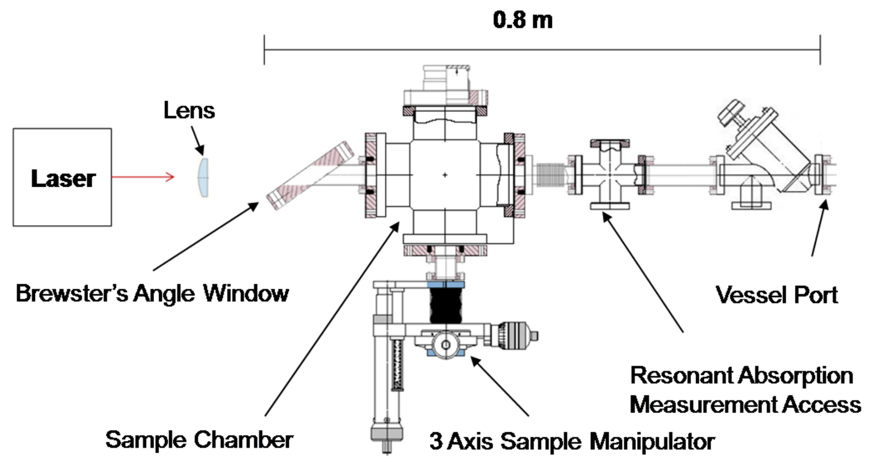
The neutral spectrum for a 2 μm aluminum film illuminated with a 7 J/cm² laser pulse [Breton '80]

The HSX Laser Blow-Off System

HSX Beam Line Details:

- Laser: 850 mJ YAG – Surelight III
  - Allows use of up to a 4 mm spot at 7 J/cm²
- Solid angle of injection: 3 x 10^{-3} sr
- Spot size adjustable by movable lens
- Projected to inject up to 10^{16} neutrals into the plasma per pulse

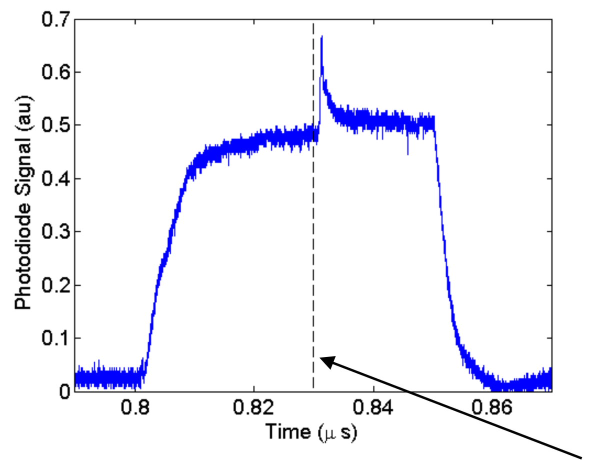




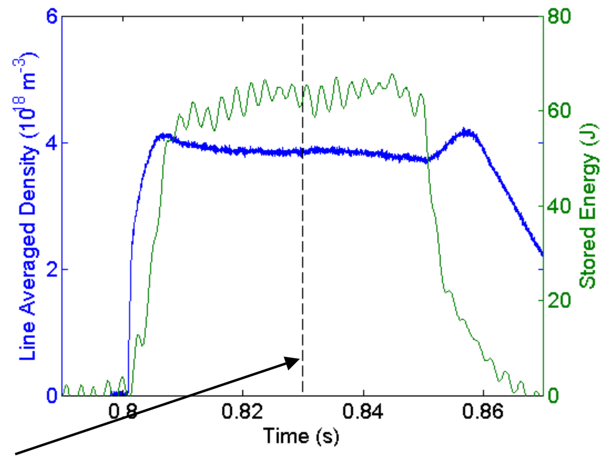
Initial Results:

- Test injections have been performed with:
  - 1 μm aluminum layer
  - Full laser power (850 mJ)
  - 1 mm diameter laser spot
- The injections were visible on photodiode
- They did not significantly impact the line-averaged density or stored energy

Bare Photodiode



Background Parameters



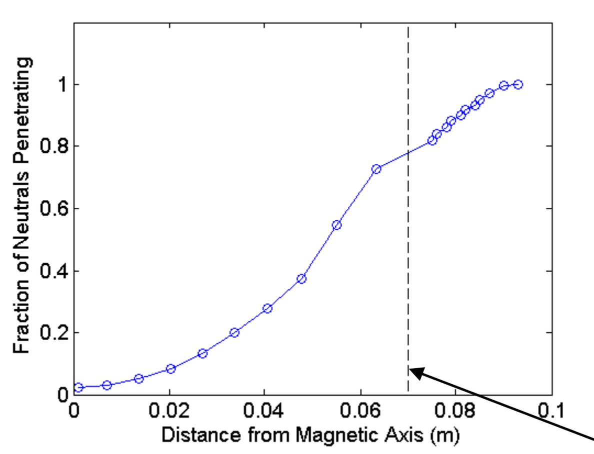
Laser Firing Time

Simulation of Laser Blow-Off

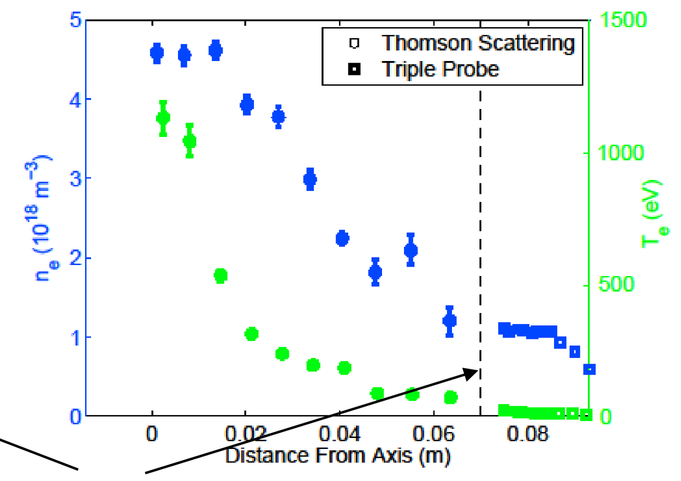
Simulation of Impurity Beam Penetration:

- Considers only electron impact ionization
  - Atomic data from ADAS
- Neutral spectrum taken from [Breton '80]
- Projects adequate deposition within the confinement volume

Neutral Penetration Prediction



Background Plasma Parameters

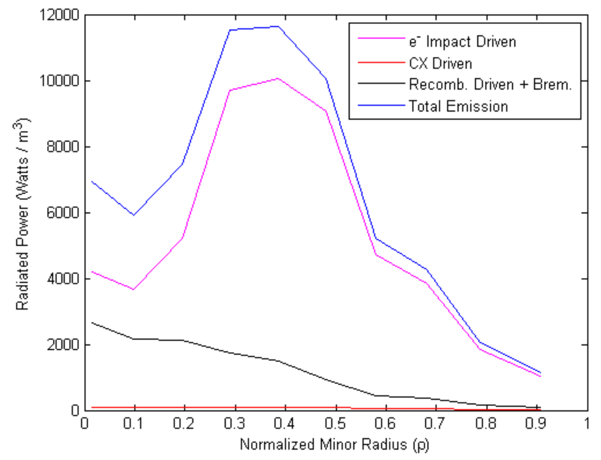


Last Closed Flux Surface

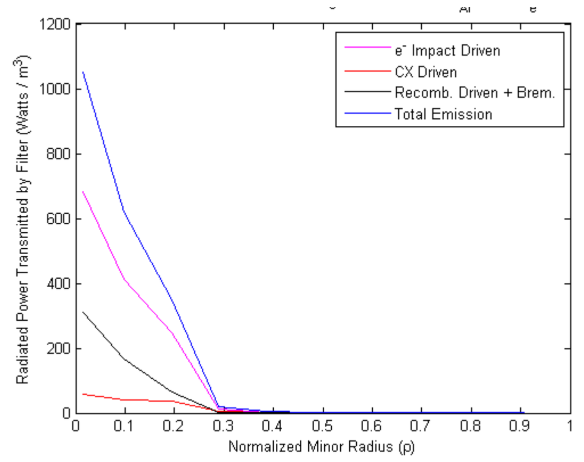
Simulation of Impurity Radiation Profiles:

- Assumes n_{Al} = 0.01 n_e
- Total emissivity was calculated with ADAS, using HSX plasma parameters
  - Integrated: P_{Tot} = 1.65 kW
- The portion of the radiation that would transmit through a 5 μm beryllium filter was also calculated
  - Integrated: P_{SXR} = 10 W
  - SXR data won't be useful in the outer two-thirds of the plasma

Total Emissivity Profile



Soft X-Ray Emissivity Profile

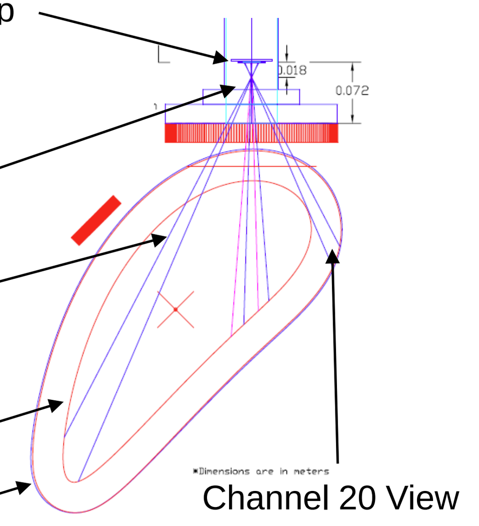


Reconstruction of Impurity Emissivity Profile

- Impurity radiation will be detected with AXUV photodiode arrays
  - Two have been installed on HSX
  - Five more are under construction
- The detectors view the plasma through a 1 mm pinhole to achieve spatial resolution
- A beryllium filter can be rotated over the pinhole on several of the detectors so that the photodiode detects only the soft X-ray emission

Determining the View of Each Detector:

- The volume around the paraxial ray is discretized
- The solid angle of the detector, as viewed from the center of each volume element, is calculated
  - This gives the relationship between the emission in each volume element and the signal at the detector
- Since each volume element is small, it is taken to be located at a single radial location
  - The volume elements can be binned into the appropriate portion of a matrix relating the 1D emissivity profile to the power incident on each detector

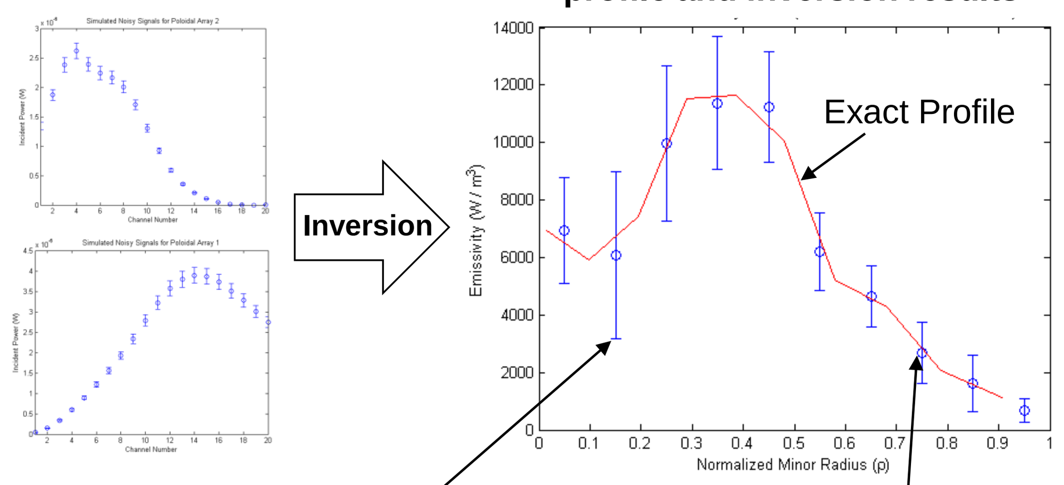


Synthetic Diagnostic with Noisy Data:

- Exact expected signals are calculated for each detector from the view information and the emissivity profile
- A Monte-Carlo code adds uncorrelated noise (5% std. dev.) to the exact signal predicted for each detector
  - At each iteration, a least-squares inversion is performed
- The mean and standard deviation of the inversion results are compared to the exact profile

Detector Signals With Noise Added

Comparison of exact emissivity profile and inversion results



Calculating Transport Coefficients with STRAHL

- The transport code STRAHL [Behringer, '87] is used to solve the 1-D continuity equation for each impurity charge state, including the source / sink term due to ionization / recombination from adjacent charge states

$$\frac{\partial n_{I,Z}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\left(D^* \frac{\partial n_{I,Z}}{\partial r} - v^* n_{I\ Z}\right) + Q_{I,Z}$$

- ADAS is used for atomic data calculations
- The background plasma parameters are assumed to be constant and are inputs to the code
- Temporal and spatial impurity source rates, diffusivities and convective velocities are inputs to the code
- The code outputs the time dependent emissivity profile
- When used in conjunction with a nonlinear optimization algorithm, STRAHL can be used to determine the impurity convective velocity and diffusivity from the time dependent emissivity

53rd Annual Meeting of the Division of Plasma Physics, November 13 – November 18, 2011, Salt Lake City, UT