Paper Rehearsal:

Validation of a synthetic fast ion loss detector model for Wendelstein 7-X

Nucl. Fusion

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Abstract

We present the first validated synthetic diagnostic for fast ion loss detectors (FILDs) in the Wendelstein 7-X (W7-X) stellarator. This model has been developed on, and validated against experimental data from, a FILD provided by the National Institute for Fusion Science (NIFS-FILD), with potential future applicability to the existing Faraday Cup FILD (FC-FILD) on W7-X as well as the scintillating FILD (S-FILD) currently under development. A workflow combining Monte Carlo codes BEAMS3D and ASCOT5 is used to track fast ions produced by neutral beam injection from the moment of ionization until they are thermalized or lost from the last closed flux surface, and from there to a virtual plane which serves as a projection of the entrance aperture to the FILD. Simulations in ASCOT5 are analyzed via a geometric method to determine the probability of transmission through the FILD aperture and onto the detector as a function of normalized momentum, pitch angle, gyrophase, and position at the virtual plane. This probability is then applied to the simulated ions arriving from the plasma, producing a simulated signal from a computationally tractable number of simulated fast ions. Simulated signals are presented for two W7-X experiments with neutral beam injection and quantitatively compared with experimental measurements from the NIFS-FILD diagnostic.

Background

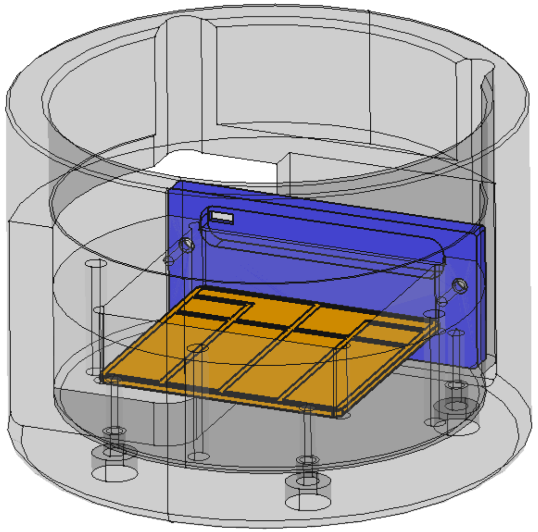
- **Fast ion confinement is an important optimization target of W7-X**
- **Measurement of lost fast ions helps to determine the success of optimization**
- **Need to be able to compare measured losses to our predicted losses, but fast ion loss detectors (FILDs) only make a local measurement of a very small fraction of the lost ions**
- **Have to develop methods to get from simulations of overall fast ion losses to simulated FILD signals that can be compared to experiment**
- **Often use codes like FILDSIM* to find an "instrument function" to convert between fast ions at the FILD pinhole to signal on the detector**
- **BUT the pinhole is so small that we often have to use tricks like considering all the fast ions that hit anywhere near it**

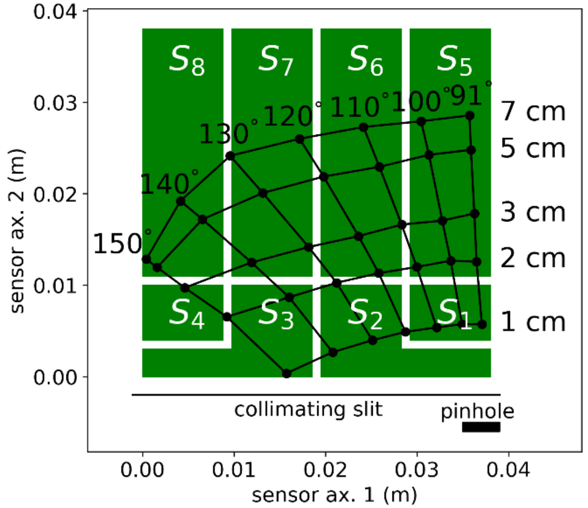
*Galdon-Quiroga J. *et al.* "Velocity-space sensitivity and tomography of scintillator-based fast-ion loss detectors." *Plasma Phys. Control. Fusion* **60** (2018), 105005. 10.1088/1361-6587/aad76e.

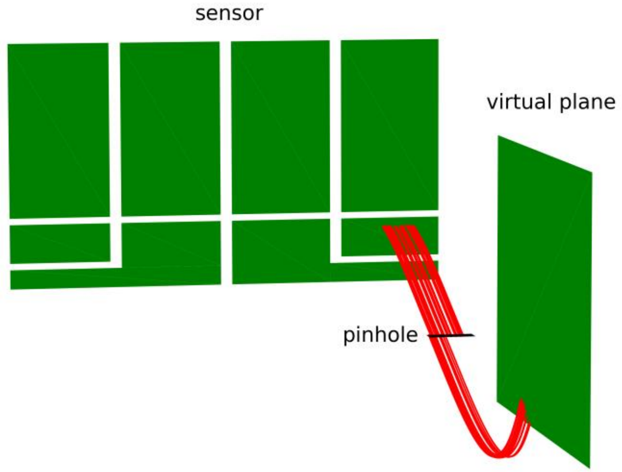
Schmidt B. S. *et al.* "A new FILDSIM model for improved velocity-space sensitivity modelling and reconstructions." *Plasma Phys. Control. Fusion* **66** (2024), 045004. 10.1088/1361-6587/ad268f.

Simulations of signal to sensors on NIFS-FILD*

- 8-channel Faraday Cup FILD, measures flux of fast ions as a current
- Pinhole and collimating structure spread strikes out by gyroradius (energy) and pitch, so the sensor hit can give you information on these quantities
- Mounted on the MPM for experiments in both OP1.2b and OP2.1
- Difficulty in simulating signals is that the pinhole is very small compared to LCFS (ratio of areas is about 1:20 million)
- Virtual plane used as projection of the pinhole and target for simulations to reduce necessary number of simulated particles!







*Ogawa K. et al. "Energy-and-pitch-angle-resolved escaping beam ion measurements by Faraday-cup-based fast-ion loss detector in Wendelstein 7-X." *J. Inst.* **14** (2019), C09021. 10.1088/1748-0221/14/09/C09021.

Virtual plane as a target for simulations

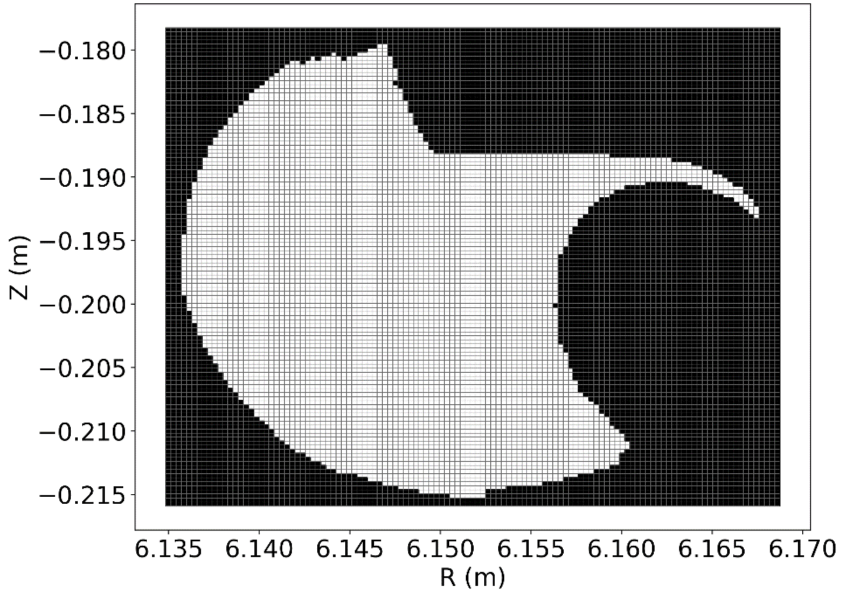
- Markers representing fast ions followed from injection to LCFS with BEAMS3D*, from LCFS to wall with ASCOT5
- As markers pass through the virtual plane at constant φ, they are saved, but not stopped
- Markers at the plane are separated into bins in R, Z, pitch angle, gyrophase, and a gyroradius-like quantity (same as gyroradius except it uses the full velocity instead of perpendicular velocity)
- Separate simulations are done to calculate, for each bin, the probability that a particle within will pass through the pinhole and onto one of the sensors

Definition of bin quantities:

$$\rho_L = \frac{mv}{|q|B} = \frac{v}{v_\perp} r_{gyro}$$

$$\chi = \cos^{-1}\left(\frac{v_{||}}{v}\right)$$

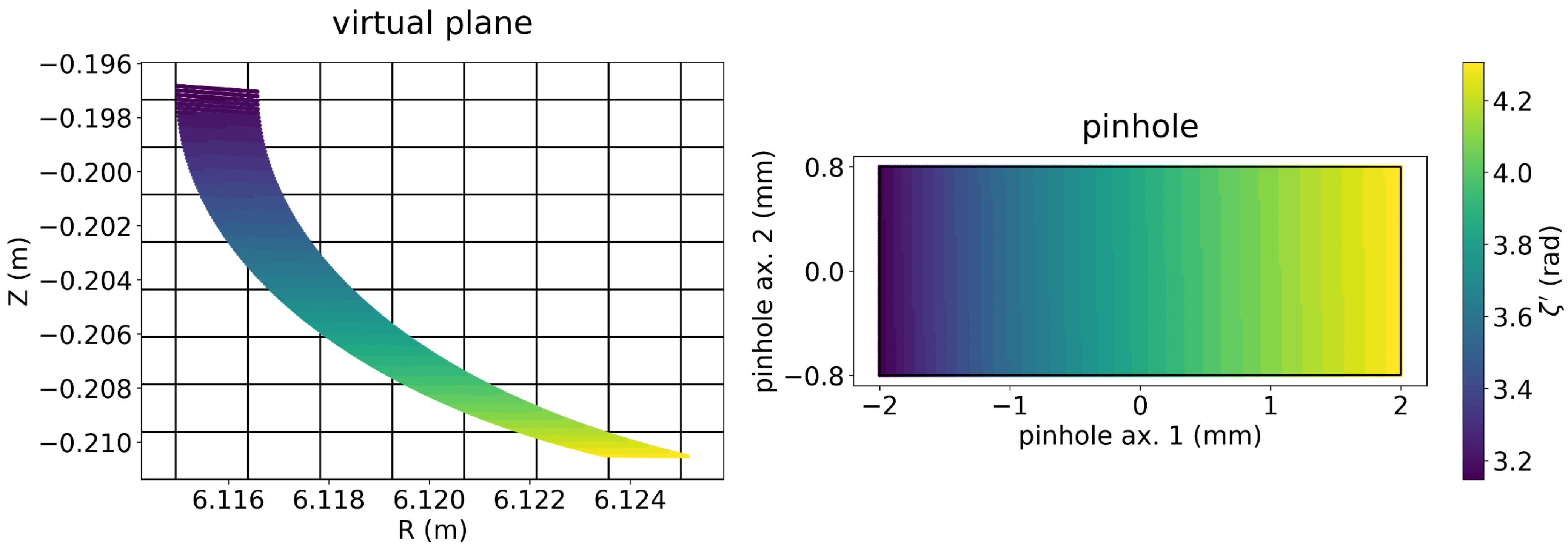
$$\zeta = \tan^{-1}\left(\frac{-\hat{v}_\perp \cdot (\hat{b} \times \hat{z})}{\hat{v}_\perp \cdot \hat{z}}\right)$$



*McMillan M. and Lazerson S. A. “BEAMS3D Neutral Beam Injection Model.” *Plasma Phys. Control. Fusion* **56** (2014), 095019. 10.1088/0741-3335/56/ 9/095019.

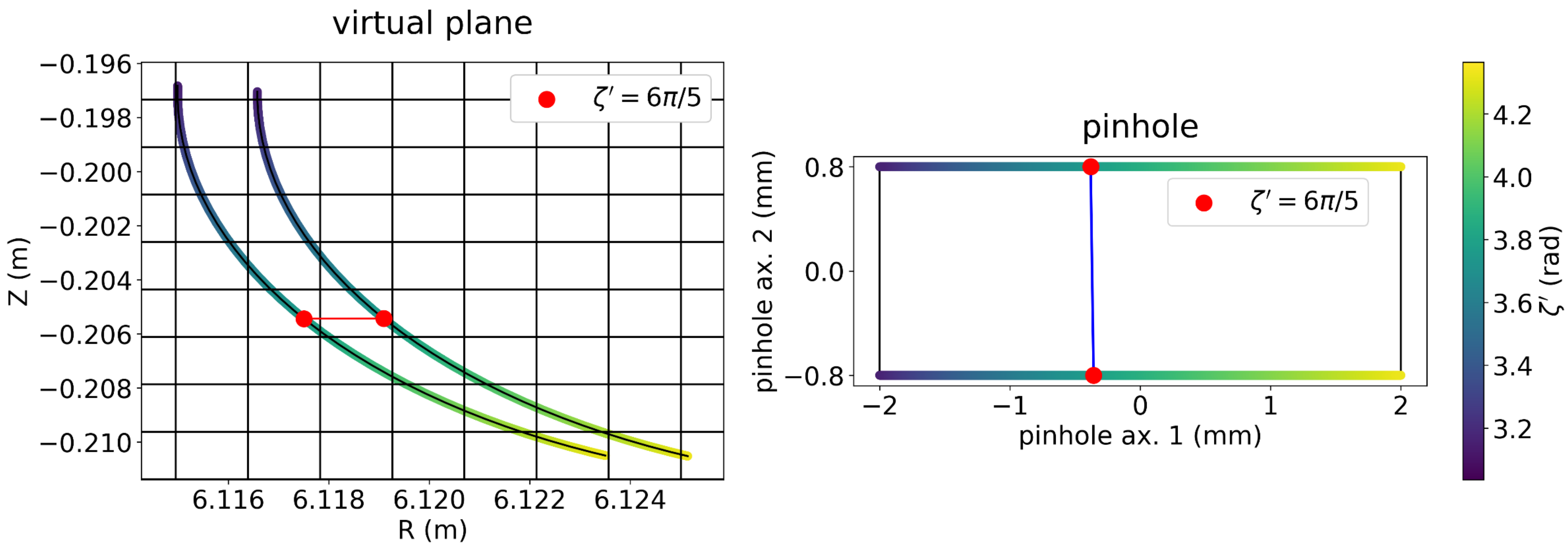
Calculating the probability of transmission

- Markers, in groups with constant (χ,ρ_L,ζ) at the pinhole, are traced forward (to the sensors) and backwards (to the plane) from the pinhole
- Assume (χ,ρ_L) don't change between plane and pinhole
- Want to get probability in terms of gyrophase at the plane (ζ'): we see that contours of constant ζ' are straight lines at plane and in pinhole, and strike pattern is defined by long edges of pinhole



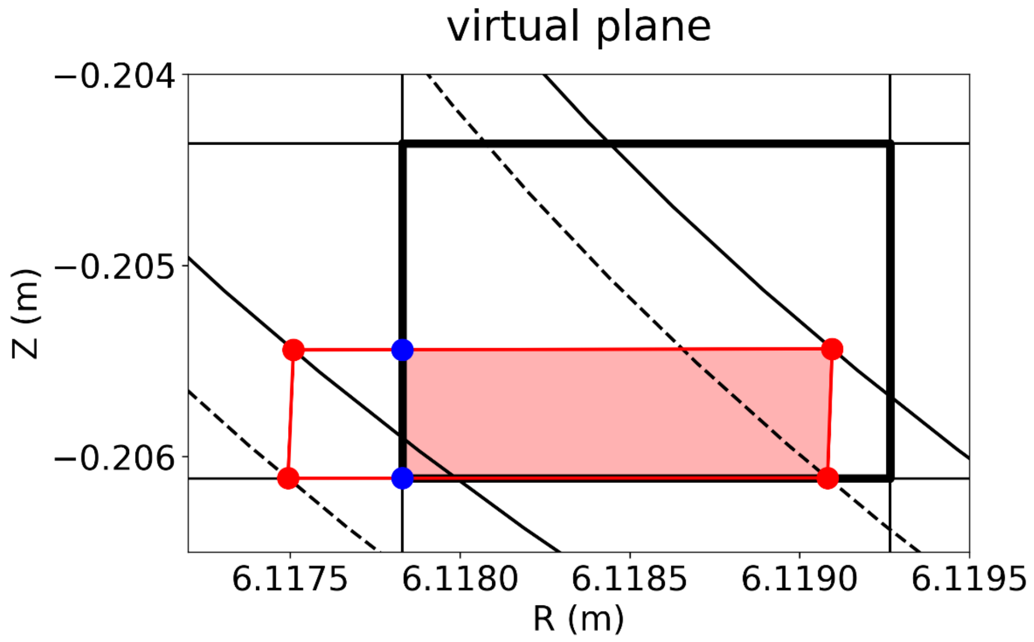
Backwards simulations only need markers from long edges

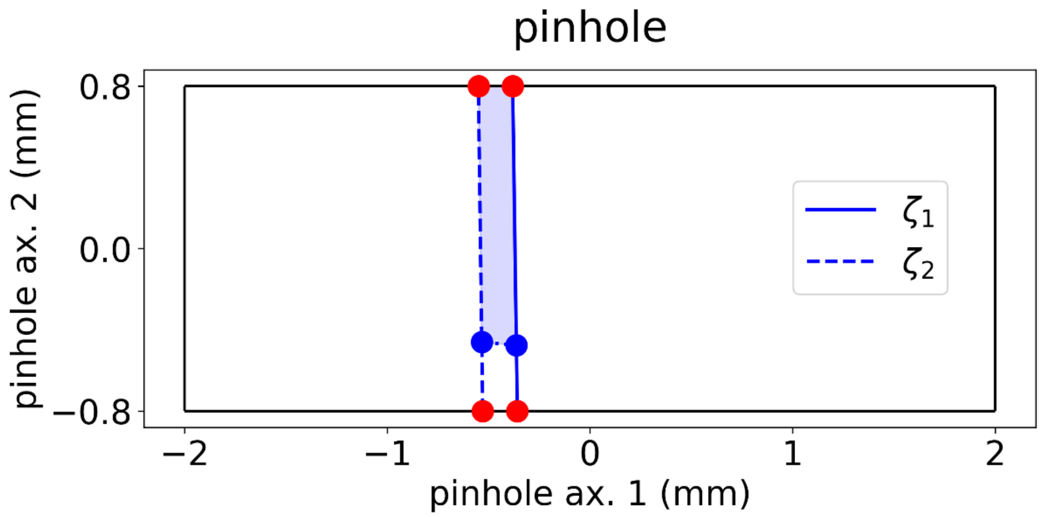
- Significant reduction in the size of the required simulations!
- To go from ζ at pinhole to ζ’ at plane: find the points at each edge of pinhole that correspond to a given ζ’ at plane



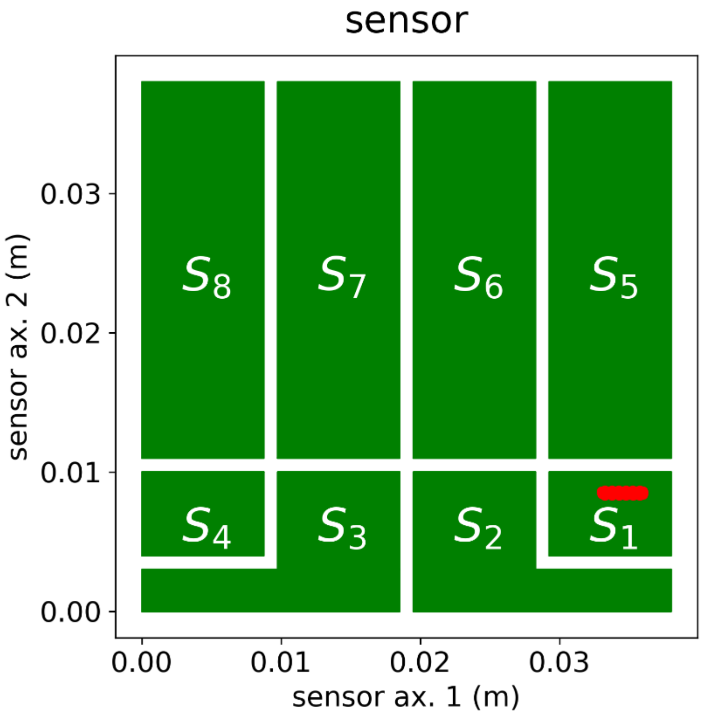
Use a second set of markers to transform to ζ' at the plane

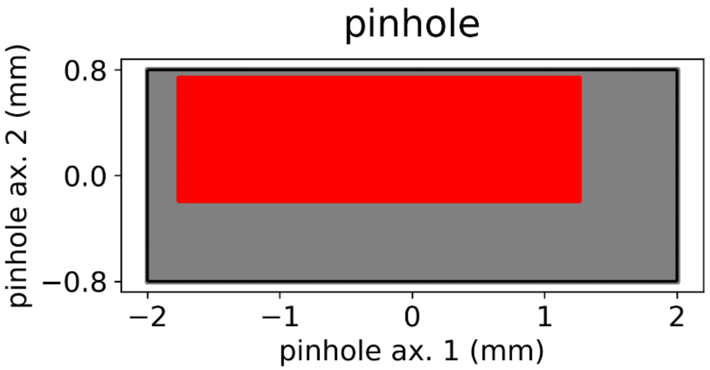
- Do the same for a second set of markers, with different ζ at pinhole, and connect the two sets of points
- Red lines designate area within which ions at the plane with single gyrophase ζ' can reach the pinhole with gyrophase in the range (ζ_1-ζ_2)
- Red area: intersection of that box with the bold bin in R,Z
- Probability of marker in (R,Z) box making it to pinhole: red area / area of bold box
- Blue area: the area of the pinhole seen by those markers coming from the plane



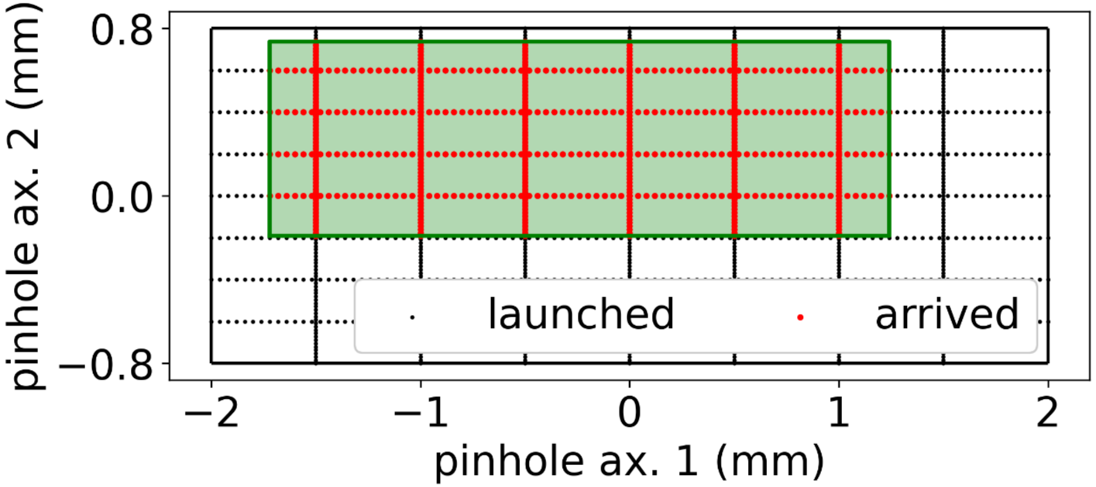


Trace markers forward from pinhole to sensor





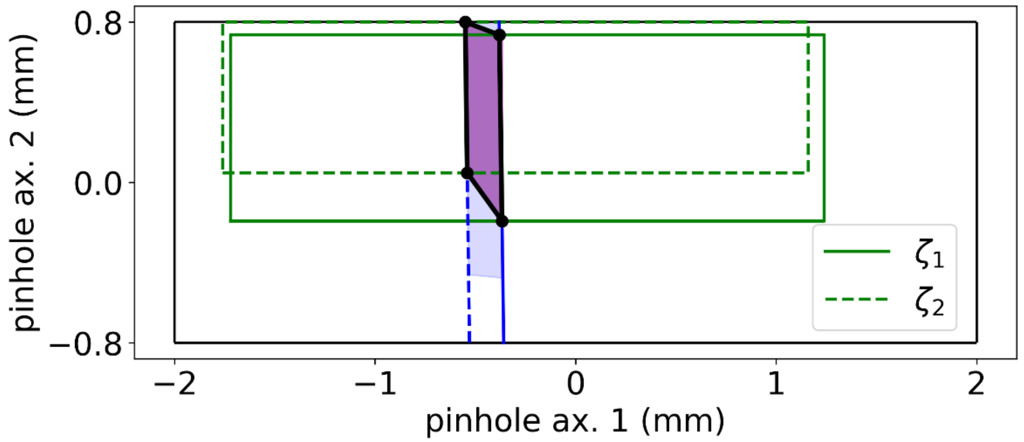
- Again, we have a set of markers with constant (χ,ρ$_L$,ζ) launched evenly within the pinhole (left)
- Those which reach the sensor S1 make up a continuous area within the pinhole
- Can find the extent by launching them in a cross-hatch pattern (below), instead of filling the pinhole
- Green area (below) same as red area (left), but found simulating fewer particles
- Probability of going from pinhole to sensor: green area / pinhole area



Combine the forward and backward simulations geometrically to get the full probability

- **Repeat the forward simulation for the second set of markers with different ζ at pinhole, same as backwards**
- **For every value of ζ, the markers which:**
  - can travel forward onto the sensor
  - can travel backwards into the bold (R,Z) bin shown on a previous slide
  - will have the single gyrophase ζ' when they reach that bin

  form a line in the pinhole (shown in black): the intersection between each blue line and the corresponding green box
- **The probability of markers in this set contributing to the signal is: purple area / blue area**

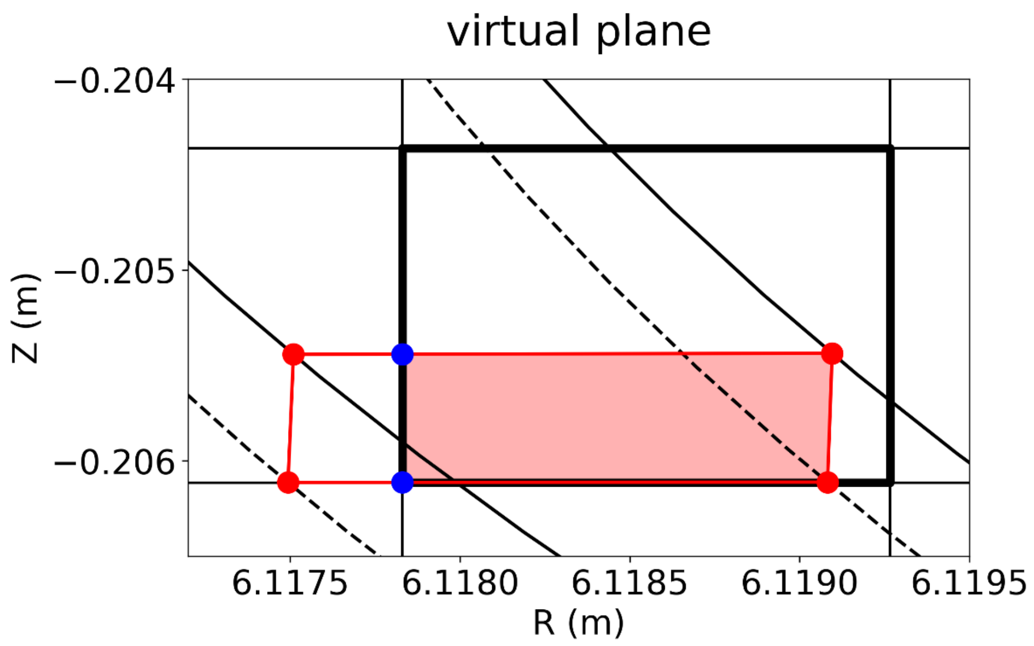


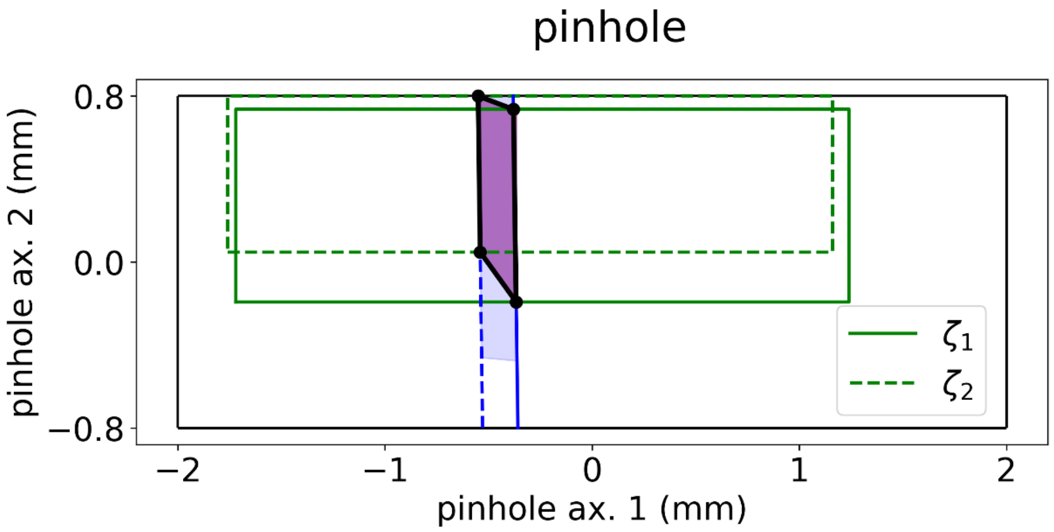
Combine the forward and backward simulations geometrically to get the full probability

- **Total probability that a marker, coming from anywhere in the bold (R,Z) box on plane, with velocity vector (χ,ρ_L,ζ'), will:**
  - **pass through the pinhole onto the sensor**
  - **have a gyrophase between (ζ_1-ζ_2) at the moment it passes through the pinhole**

is calculated as:

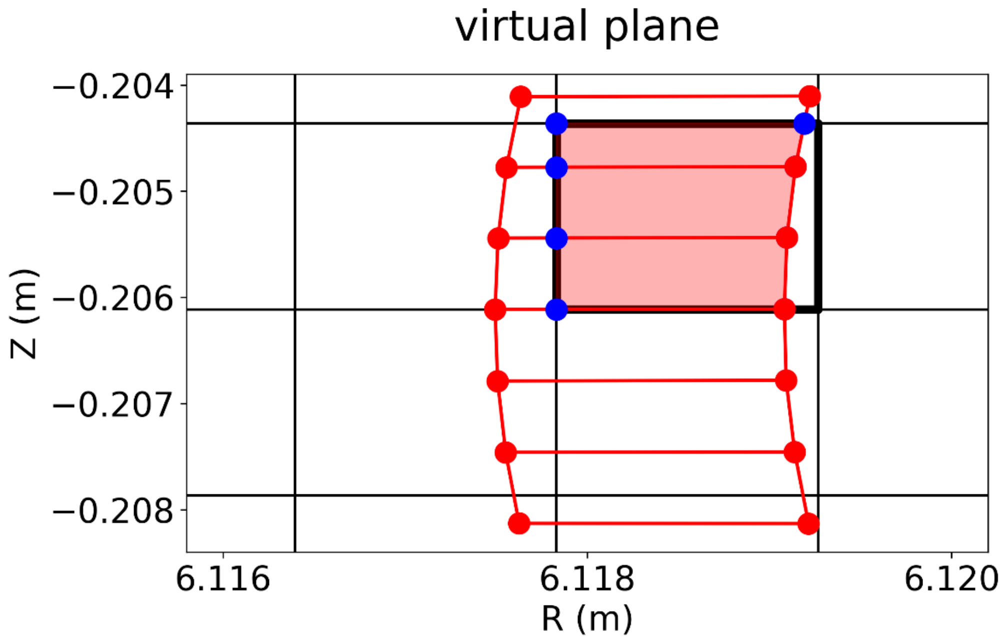
(red area) / (area of bold box) * (purple area) / (blue area)

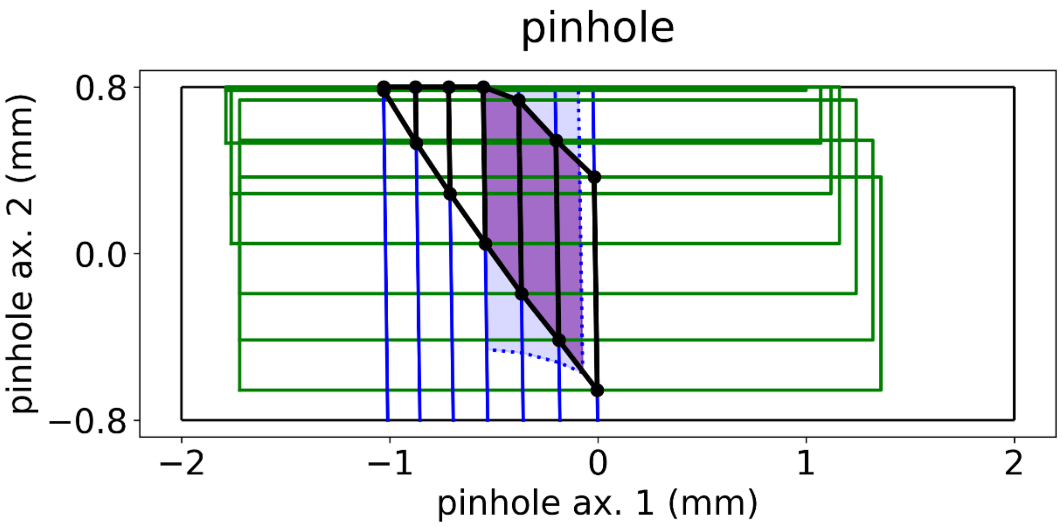




Sum over gyrophase bins at the pinhole to get the total probability

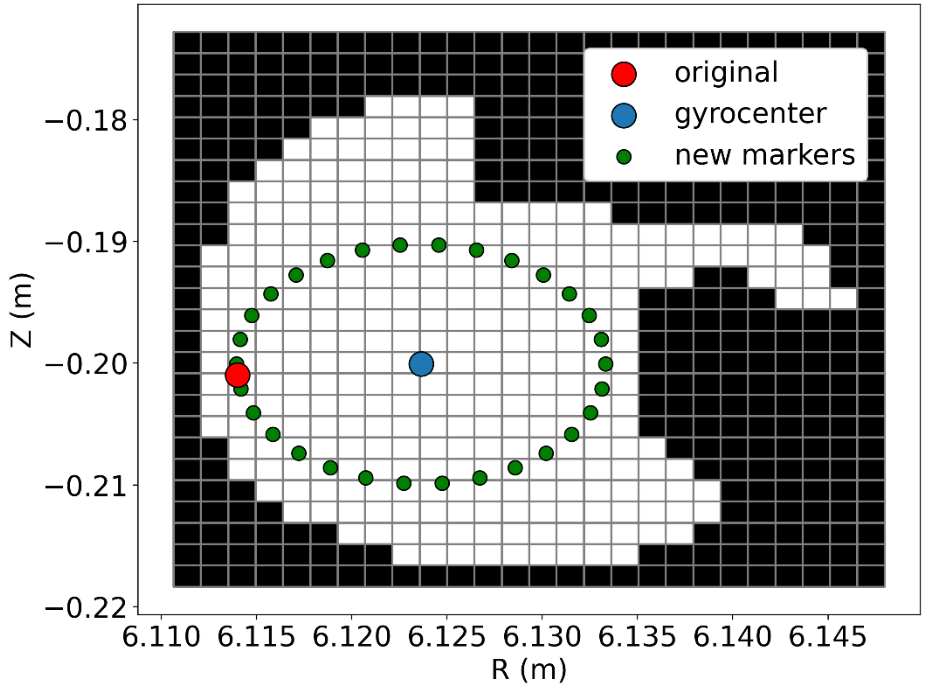
- We don't care what ζ is at the pinhole, so: sum up the probability defined in the previous slide over every ζ bin at the pinhole to get the total probability of transmission through the pinhole!
- Now we have a probability of contributing to the signal for a bin in (R,Z) at the virtual plane, and a single velocity vector defined by (χ,ρ_L,ζ')
- To get bins in (χ,ρ_L,ζ'), repeat this process for several values of each quantity and average the probabilities together: result is a 6D probability matrix (6^{th} dimension is the sensor)





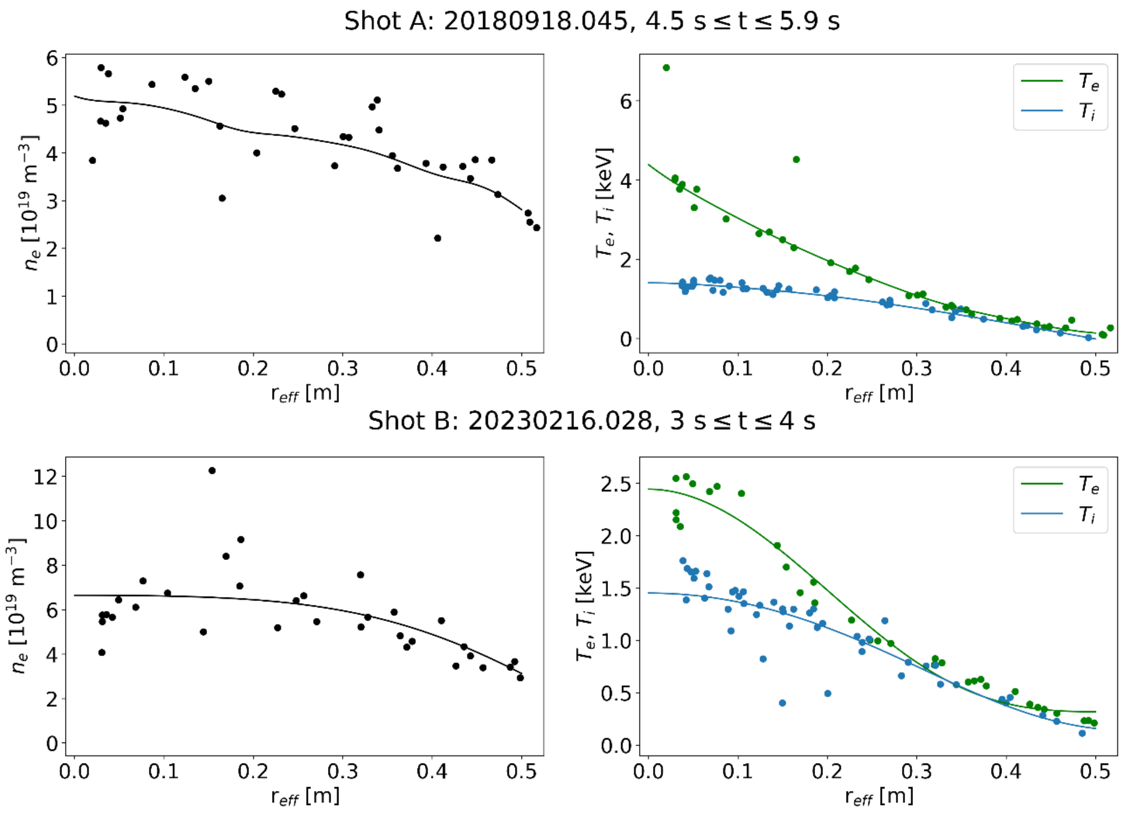
Markers at plane are expanded around the guiding center

- Still need more markers to have sufficient statistics:
- For each marker that passes through the plane, find the guiding center and expand around it, making many (~1000) new markers with evenly spaced gyrophases
- Trace the new markers backwards and remove any which hit the side of the probe head; these are not viable
- Split the weight of the original marker between the remaining new markers
- Apply the probability matrix to each new marker!
- Do a boxcar sum over all markers, from their time of arrival to the end of the NBI, to find the total signal



Using this method to simulate NIFS-FILD results from experiments!

- Simulated two shots, one from OP1.2b with NBI source 8 blipped, another from OP2.1 with sources 4 and 7 steady-state
- Used Thomson, XICS, and profile cooker to get profiles for simulations
- Ran density scan for shot B, varying density profile by +- 10%

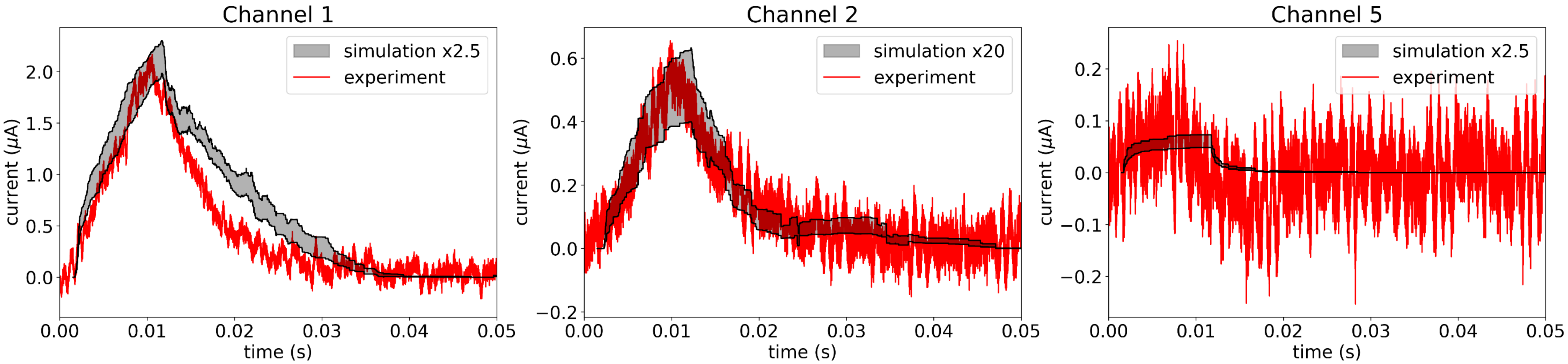


Losses by beam & simulation:

Simulation	Beam	Port	Shine.	Lost	Absorb.
Shot A	8	15.5%	17.4%	24.4%	42.7%
Shot B, n_e - 10%	4	15.3%	10.4%	27.7%	46.6%
Shot B, orig	4	15.3%	8.4%	28.4%	48.0%
Shot B, n_e + 10%	4	15.4%	6.7%	28.7%	49.3%
Shot B, n_e - 10%	7	7.9%	15.4%	41.1%	35.6%
Shot B, orig	7	7.9%	12.6%	42.7%	36.8%
Shot B, n_e + 10%	7	7.9%	10.5%	43.8%	37.7%

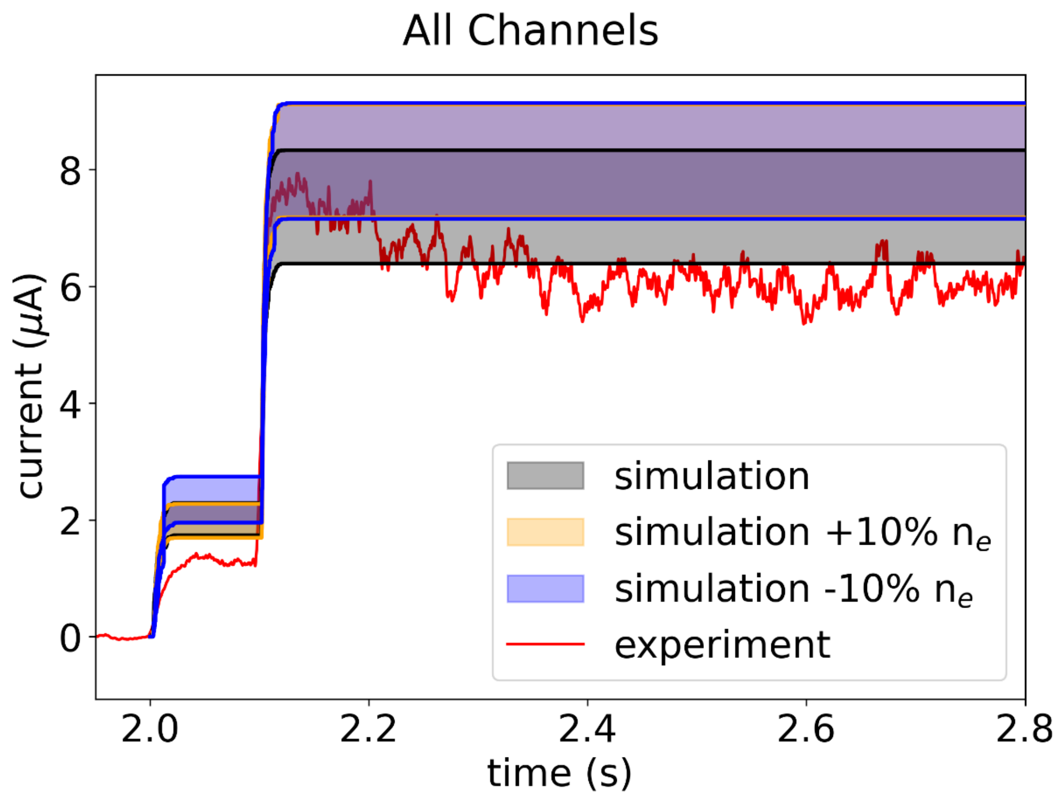
Shot A (20180918.045) results

- **Simulated signal scaled, shifted 1.5 ms forward in time**
- **Experimental signal noise filtered, averaged over 4 NBI blips**
- **Rise time of the signal matches experiment**
- **Signal underpredicted overall, much more in Channel 2 than Channels 1 and 5 (little to no signal in other channels)**
- **Some uncertainty from short duration of NBI**



Shot B (20230216.028) results

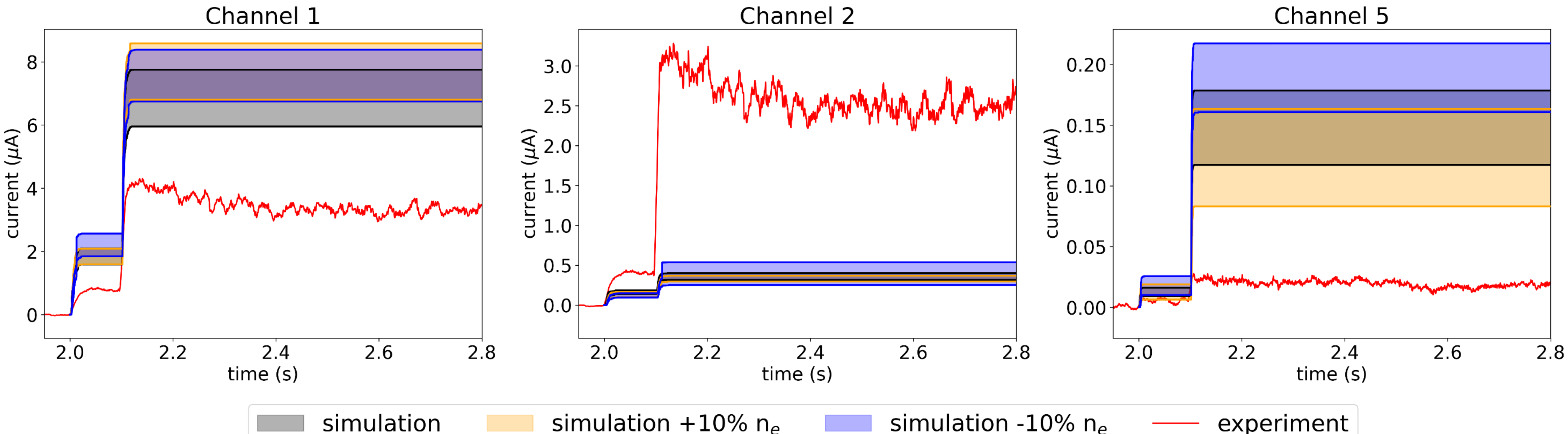
- Total simulated signal for all channels combined matches experiment closely without needing to be scaled
- Variation in signal from density less than uncertainty in signal from the method used (in particular, the choice of bin size when finding the probabilities)



Ratio of signal between channels not reproduced in simulations!

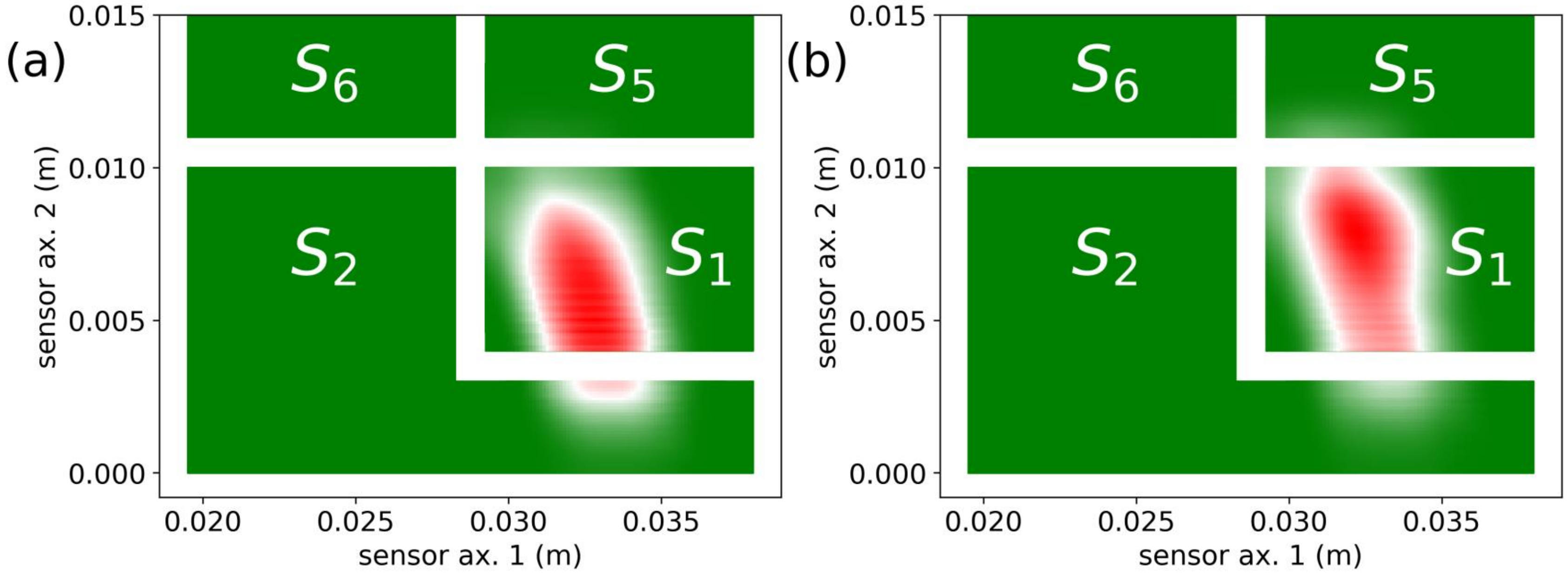
- **Ratio between simulation and experiment for each channel and beam showed in table below**
- **Just like for Shot A, ratio is higher for Channels 1 & 5 than Channel 2!**

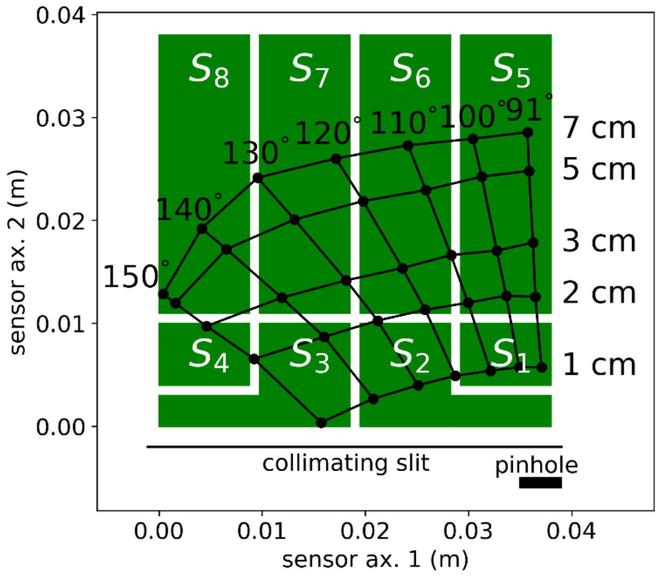
Beam	Channel 1	Channel 2	Channel 5
Source 4	2.4	0.39	2.0
Source 7	2.0	0.097	12.0
Combined	2.1	0.14	8.4



Strike patterns on sensors can give us more information

- **Below: strike pattern on sensors from beam sources 4 and 7 in Shot B**
- **Difference between Channels 1 & 5 and Channel 2 could be the result of strikes being shifted upward in the simulation as compared to experiment; would only need a shift on the order of mm to explain this**
- **Possible reasons:**
  - Actual measured ions have lower energies than those in the simulation (due to slowing down in SOL, for example)
  - Errors in CAD model of probe head and sensors, or insertion position





Conclusions

- A new, more detailed method of getting simulated FILD signals using fewer simulated fast ions was developed
- For steady-state NBI in W7-X, the combined signal to all channels agreed closely between simulation and experiment
- For NBI blips, the signal was under-predicted by simulation, but the rise time behavior was well matched
- Both simulations showed higher simulated signal in the sensors meant to measure higher-energy ions, which could be a result of not including slowing down in the SOL, or of issues with the FILD model used in the simulations
  - Could be uncertainties in the FILD head position, for instance from the dead-weight droop of the MPM arm
  - Future work will explore the impact of changes in the probe position and orientation on the signal