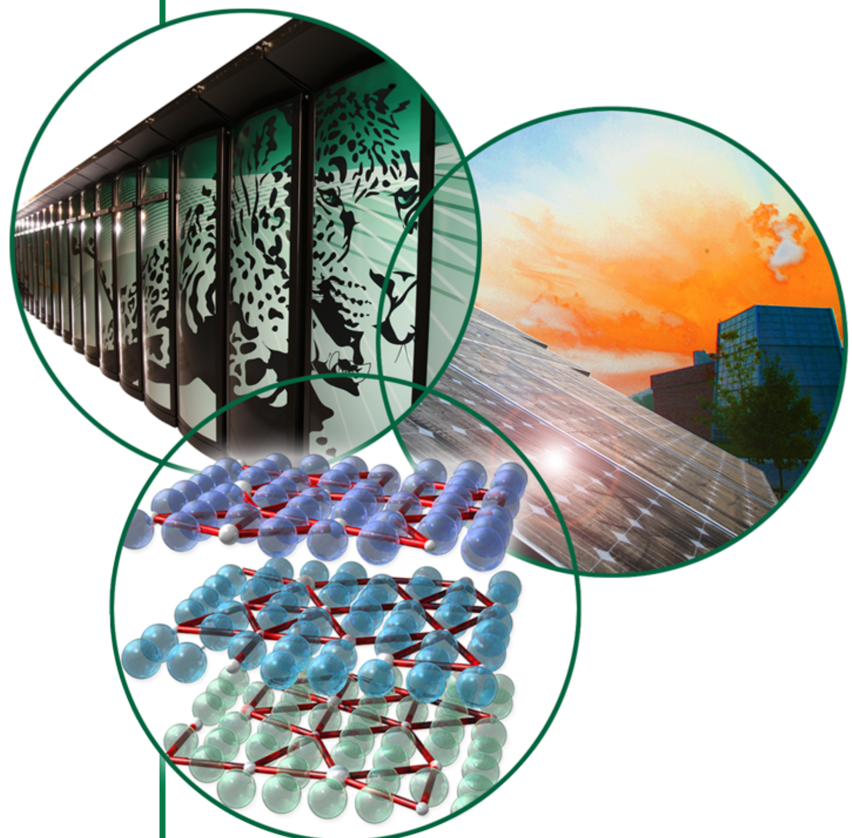
Beam Loss due to Foil Scattering in the SNS Accumulator Ring

HB2012, Beijing
September 18, 2012

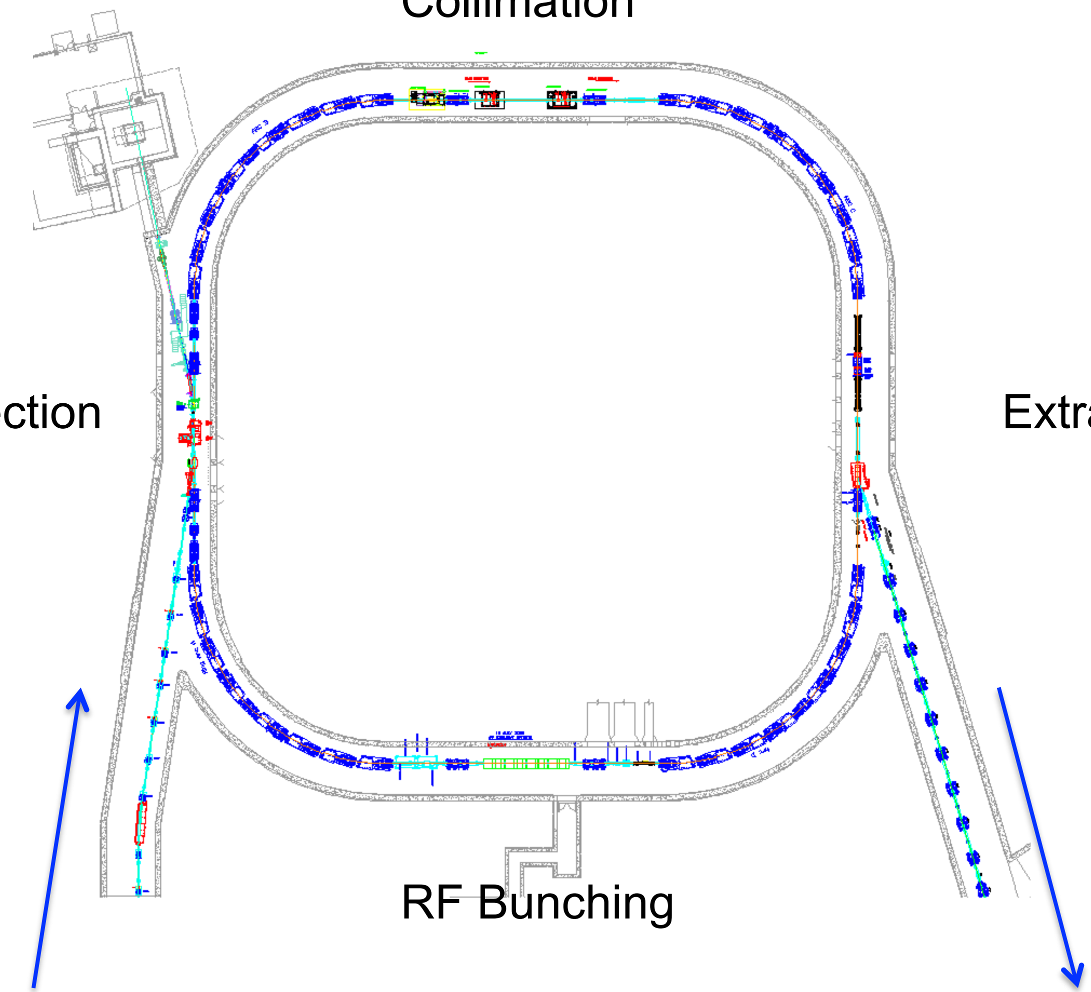
J. Holmes and M. Plum



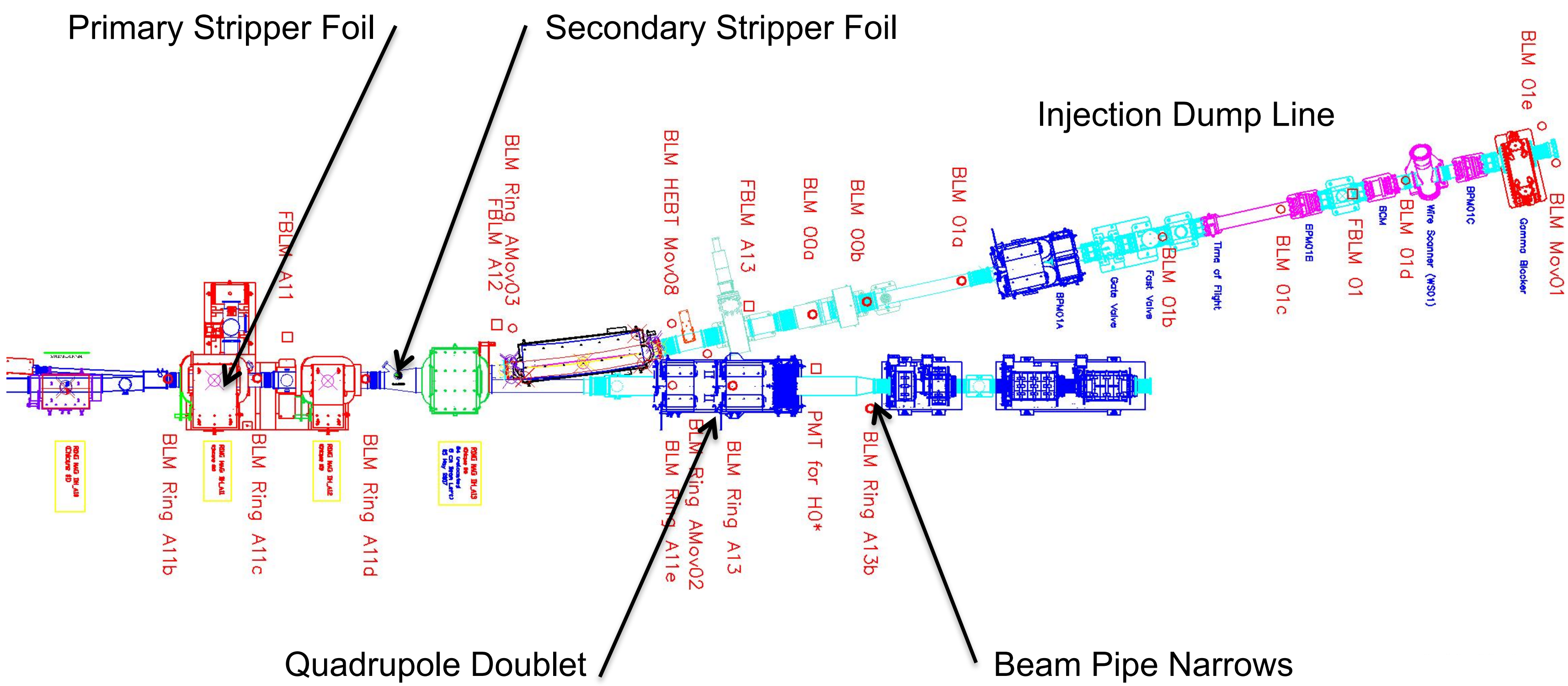
U.S. DEPARTMENT OF ENERGY

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

SNS Accumulator Ring (C=248 m)



Downstream from Injection



The Calculation

- **Use ORBIT Code with full SNS ring lattice and apertures**
- **Inject distribution of macroparticles and track for 1 turn**
  - Symplectic single particle tracking
  - Ignore collective effects
  - Assume apertures absorb all impacting particles
- **Tabulate fraction and distribution of beam loss for different (carbon) foil scattering models and thicknesses**
  - Two foil thicknesses:
    - 390 μg/cm^2 with 2×10^8 macroparticles
    - 18000 μg/cm^2 with 10^7 macroparticles
  - Three scattering models
    - No scattering
    - Small angle Coulomb scattering only
    - Full scattering model: Small angle Coulomb scattering + Rutherford scattering + nuclear elastic scattering + nuclear inelastic scattering
- **Compare with experimental activation and loss distributions**

Injection Parameters

- Injected beam energy = 925 MeV
- Injected beam – use linac distribution
  - Gaussian distribution
  - RMS emittances: $\varepsilon_x = \varepsilon_y = 0.221$ mm-mradian
  - Twiss parameters at foil:
    - $\beta_x = 10.221$ m , $\alpha_x = 0.065$, $\beta_y = 10.763$ m, $\alpha_y = 0.062$
- Assume foil is sufficiently wide and tall that all injected beam strikes foil
  - Actual foil strike distribution differs from linac distribution, due to circulating beam
  - We ignore this difference, which is at most a few millimeters and a fraction of a milliradian

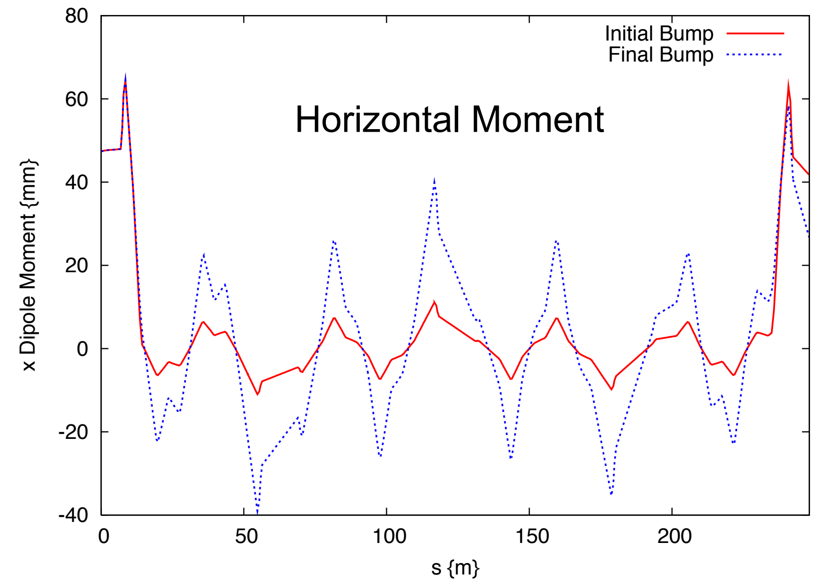
Beam-Foil Interaction Model Options

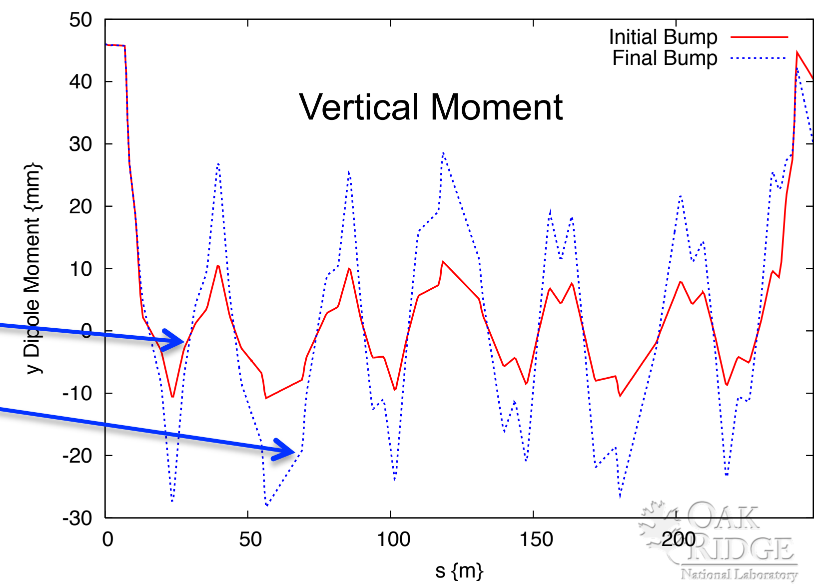
- Options:
  - 1) No interaction
  - 2) Small angle Coulomb scattering only (ACCSIM)
  - 3) Full foil scattering model implements ORBIT collimation model (Cousineau PhD Thesis)
    - Small angle Coulomb scattering (Jackson textbook): this differs from option 2 model
    - Rutherford Scattering (Jackson textbook)
    - Nuclear elastic scattering (Cousineau PhD Thesis - adapted K2 and MCNPX data)
    - Nuclear inelastic scattering (Cousineau PhD Thesis - adapted K2 and MCNPX data)

1st Turn Beam Orbit Depends on Time

Typical injection kicker waveform

Begin injection
End injection
Painting moves the closed orbit away from the foil as injection progresses.
We do calculations for initial and final bumps.





Fractional Loss Results ($\times 10^{-7}$)

Case	Initial Bump		Final Bump	
	Nuclear Elastic	Total	Nuclear Elastic	Total
390/18000 μg/cm^2:				
No scattering	0/0	0/0	0/0	0/0
Small angle Coulomb	0/0	36.6/1419	0/0	33.9/1342
Full scattering model	25.4/1173	69.8/3243	23.1/1089	61.3/3026

- All the loss mechanisms have low probability
- Total losses should scale linearly with the foil thickness
- Normalize losses: divide losses by foil thickness

Fractional Losses ($\times 10^{-7}$) Normalized to 1000 μg/cm^2 Foil Thickness

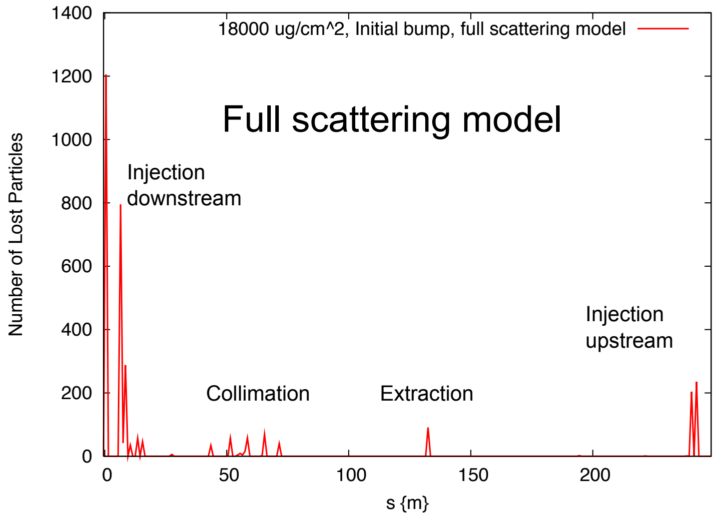
Case	Initial Bump		Final Bump	
	Nuclear Elastic	Total	Nuclear Elastic	Total
390/18000 μg/cm^2:				
No scattering	0/0	0/0	0/0	0/0
Small angle Coulomb	0/0	93.8/78.8	0/0	86.9/74.6
Full scattering model	65.1/65.2	179.0/180.2	59.2/60.5	157.2/168.1

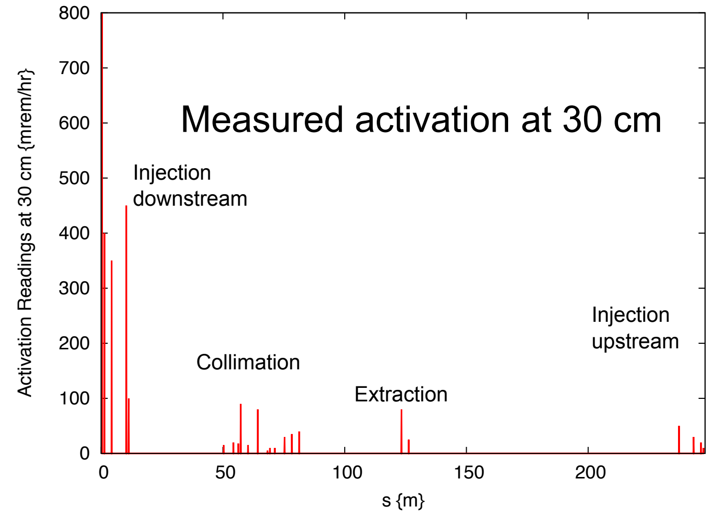
- Divided by 0.39 for the 390 μg/cm^2 cases and by 18.0 for the 18000 μg/cm^2 cases
- Good agreement, within statistical error
- Confirms linear dependence of the losses on foil thickness

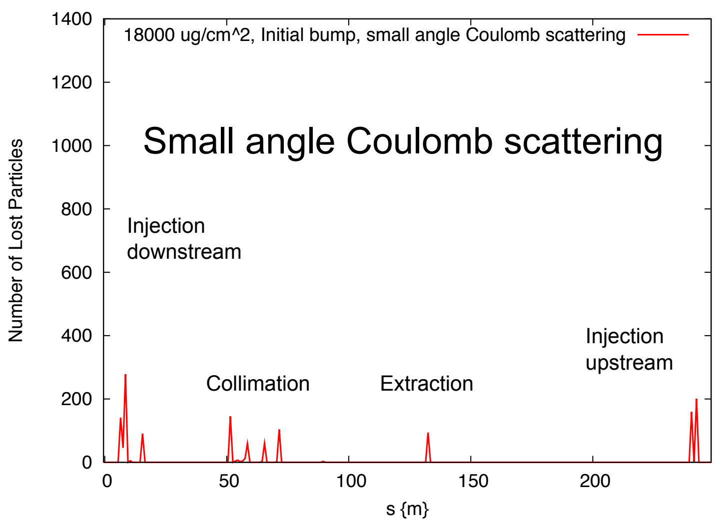
Summary of Results

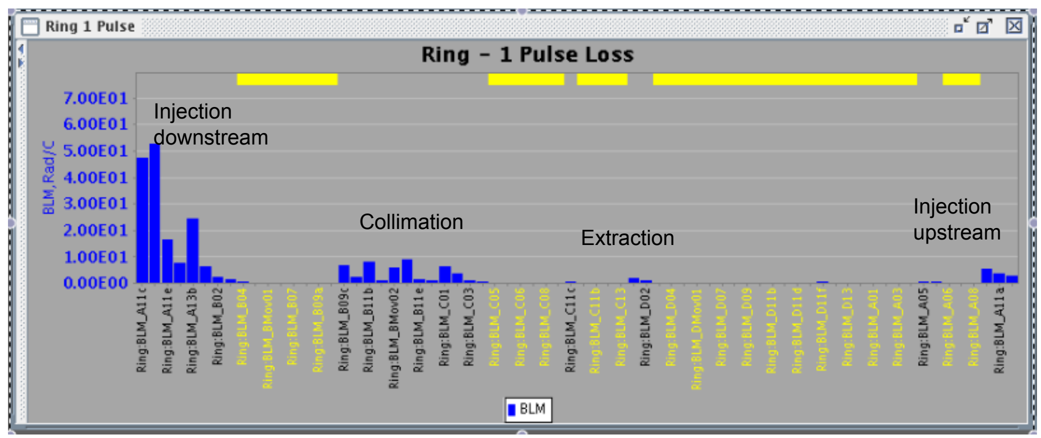
- Results:
  - 1) Slightly higher losses with initial bump than final bump – counterintuitive, but not significantly different
  - 2) No losses when foil scattering is neglected - observed losses caused by foil scattering
  - 3) Small angle Coulomb scattering responsible for slightly less than half of the total losses
  - 4) Nuclear inelastic scattering responsible for slightly more than one third of the total losses
  - 5) Remaining losses presumably due to Rutherford scattering and nuclear elastic scattering
- Fractional losses are $\sim 1.8\times10^{-8}\tau$, where τ is the foil thickness in $\mu g/cm^2$, during the first turn following foil scattering
- Of these small angle Coulomb scattering contributes $\sim 0.8\times10^{-8}\tau$ and $\sim 0.6\times10^{-8}\tau$ come from nuclear inelastic processes

Loss Distribution Around Ring



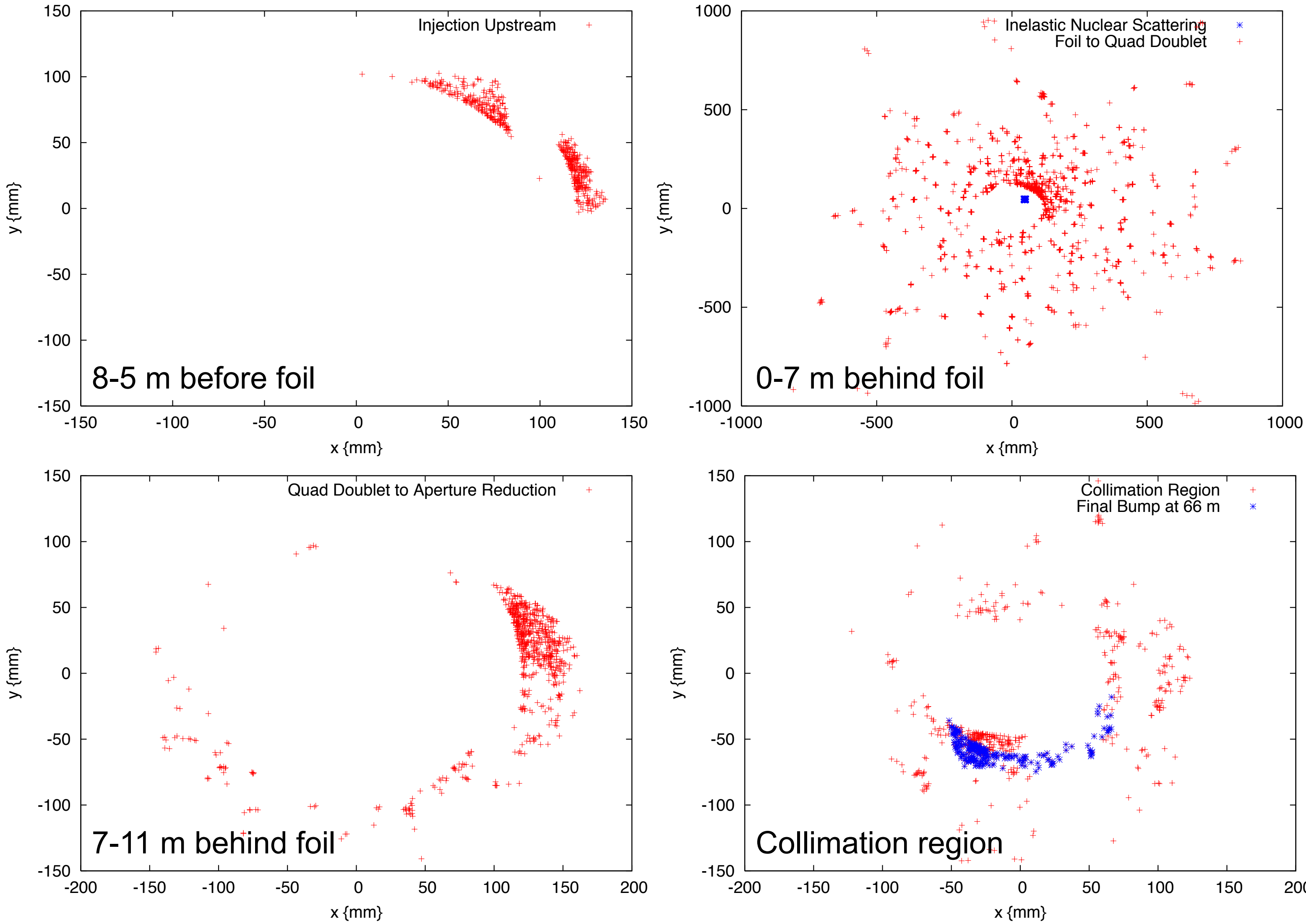






BLM Readings for Production Beam

Transverse Distribution of Losses



Observations

- Full foil scattering model, activations, and BLMs:
  - Most activity within the 20 meters after the foil
  - Losses further downstream:
    - Collimation section (~50-60 m in the plot)
    - Extraction section (~130 m)
    - Beginning of the injection chicane (~240 m).
- Full scattering model, activation measurements, and BLM readings very similar
- Inelastic nuclear scattering gives very first peak in ORBIT tabulation
- Nuclear losses and Rutherford scattering mostly in first 7 meters
- Most losses further downstream due to small angle Coulomb scattering
- Injection region losses concentrated toward outside (beam left) and above center, consistent with injection painting
- Collimation region losses are stronger below center
- We now attempt a more quantitative analysis of foil scattering and BLM results

Compare Calculated and BLM Losses

- Convert losses to the same units
- BLMs were previously calibrated using controlled beam spills
- Calibration allows a rough estimation of fractional beam loss. The above BLM plot was taken for a beam with
  - 18 µCoulombs
  - 910 MeV
- Computational results can also be used to predict the total beam loss and loss distribution due to foil scattering for any assumed number of foil hits per proton. We assume
  - 390 $\mu g/cm^2$
  - 6 foil hits/particle

Results

- BLM readings -> total fractional beam loss = 1.9×10^{-4}, with most occurring not far downstream of the foil
- ORBIT foil model assuming 6 foil hits -> fractional beam loss due to foil scattering = 4.3×10^{-5}, or about 23% of the BLM prediction
- ORBIT foil model would require 26.5 foil hits to 1.9×10^{-4}
  - This is almost certainly too many compared with the actual number, which is probably no higher than 10 foil hits per proton
- 10 foil hits per proton -> total fractional beam loss = 7.2×10^{-5}
- Both the number foil hits and BLM coefficients are only roughly known. Independent estimates of fractional ring loss are $\sim1\times10^{-4}$, between BLM and ORBIT results

Discussion

- Uncertainties in the comparison:
  - BLM calibration coefficients are not precisely known.
    - Difficult to control the exact locations for intentional beam spills.
    - Variations in the actual and intended locations can affect the BLM readings and, consequently, the calibration.
  - Number of foil hits per proton is uncertain.
    - Sensitive to the actual injection painting.
    - Although optimized ORBIT simulations predict about 6 foil hits/proton over the course of injection, the actual number could be higher.
  - Finally, about 5% of the injected beam either misses the primary stripper foil or is incompletely stripped.
    - Secondary stripper foil of thickness 1500-2000 $\mu g/cm^2$ these particles before they go to the injection dump.
    - ORBIT model predicts associated losses in the range $1.3\text{-}1.8\times10^{-6}$, a small contribution.
- Given the uncertainties, the level of agreement between ORBIT and the experiment for the fraction and distribution of beam loss is reasonable.

Next Steps

- Further studies will be pursued to enhance the understanding of beam loss in the SNS ring.
- Carry out ORBIT simulations of accumulation with variations on loss models and beam dynamics.
- Another future direction that we have begun to pursue is to model the injection region using the code G4beamline:
  - Physics models from the Geant4 code
  - Plus accelerator beam line elements.
  - With its sophisticated interaction models, including secondary particles, G4beamline will provide further elucidation of the contribution of foil scattering to ring losses.