High Intensity Effects in the SNS Accumulator Ring

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HB 2008

August 27, 2008

Special Acknowledgments

- **Mike Plum for injection dump collaboration, information, and slides (Plum presentation on Wednesday @ 14:00).**
- **Sarah Cousineau and Slava Danilov for instability collaboration, information, and slides (Cousineau presentation on Tuesday @ 14:00).**
- **Andrei Shishlo for e-p results and collaboration on ORBIT Code.**

Understanding the Ring: Summary (from ASAC Review 01/2008)

- **We have measured the lattice parameters and found reasonable agreement with the model.**
- **We have measured and fixed cross-plane coupling in the ring.**
- **We have begun ORBIT benchmarks of ring beam distributions at low intensity. Results agree with experiment and explain the observed x-y coupling in the RTBT and at the target.**
- **We have begun to characterize the collimation system performance.**
- **We still don’t fully understand the injection chicane.**

SNS is at the Threshold of High Intensity

- **SNS production power is now 0.5 MW.**
- **This corresponds to ~0.6×10^{14} accumulated protons.**
- **Beam imperfections that are acceptable at lower power become unacceptable at high intensity.**
- **Collective effects add new sources of beam imperfection at high intensity.**
- **The main challenge of operating at high intensity is to achieve the exceptionally low beam loss required for high availability:**
  - **1.0×10^{-4} uncontrolled fractional beam loss**
  - **1.0×10^{-3} overall fractional beam loss**
- **The cause of beam loss is beam halo.**

Beam Halo

- **By halo, I mean beam falling outside of its intended range in 6D phase space.**
- **Halo in the SNS ring can have many causes:**
  - **Upstream problems, such as bad or partial chopping,**
  - **Foil scattering in the injection region,**
  - **Single particle effects, such as resonances and magnet alignment and field errors,**
  - **Collective effects from space charge and impedances,**
  - **Electron cloud effects.**
- **I will illustrate a number of these concerns in this presentation.**

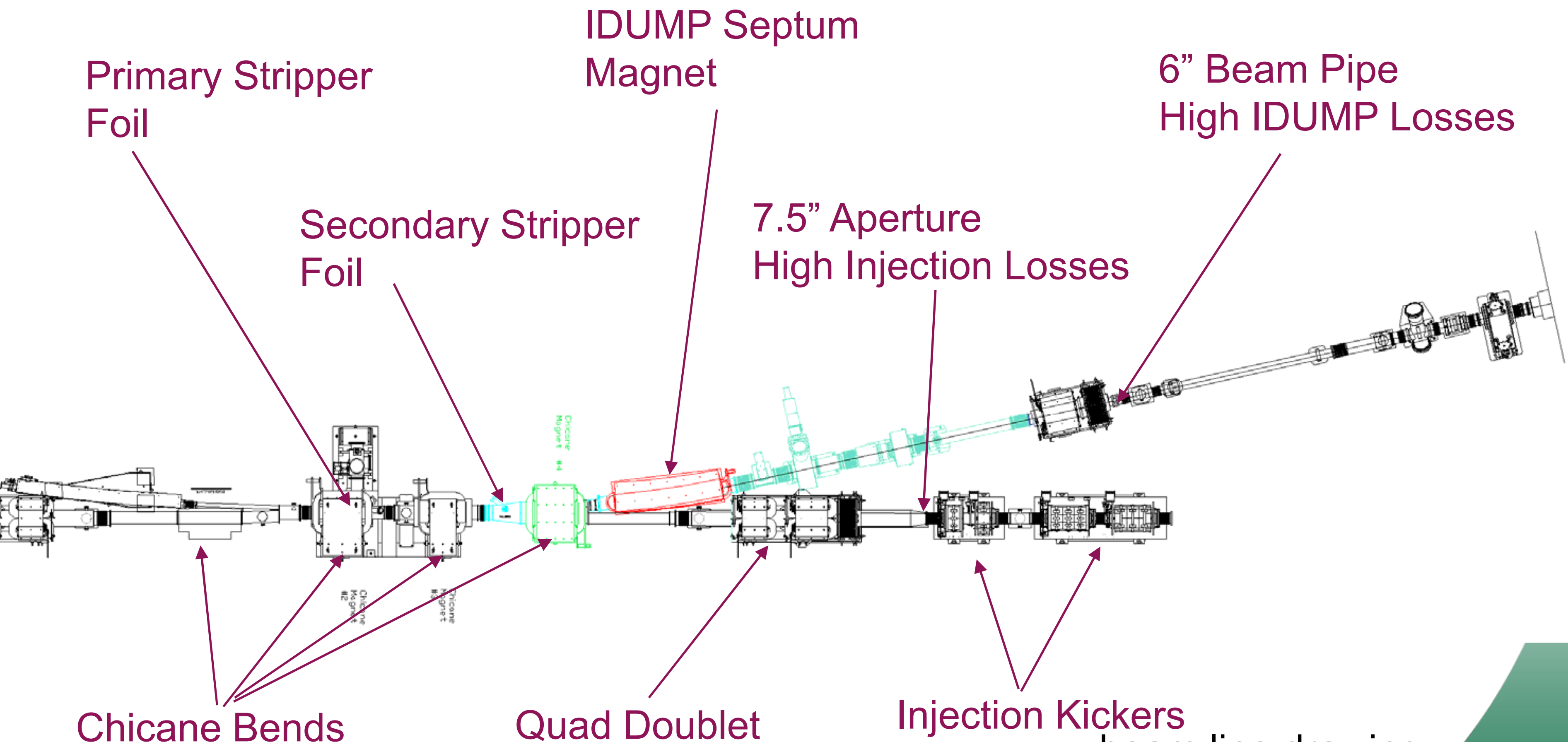
Chopping

- **Bad chopping can lead to beam-in-gap and, consequently, to high losses at extraction.**
- **Partial chopping increases the transverse emittance of the linac beam, thus increasing the quantity of H^- beam that misses the stripper foil and which must then undergo transport to the injection dump.**

Secondary Stripper Foil Scattering

- **Beam loss is high in the injection dump line.**
- **Much work has been done to mitigate this situation.**
- **Losses have moved downstream in the line.**
- **Scattering from the secondary stripper foil is probably a major contributor.**
- **The carbon secondary stripper foil is thick ~18 mg/cm^2.**
- **Compared losses with stripper foil to those with foil viewscreen (1 mm thickness of Al2O3) using**
  - **Simple analytic Rutherford scattering model,**
  - **ORBIT Code simulations,**
  - **Experimental measurements with foil and viewscreen.**

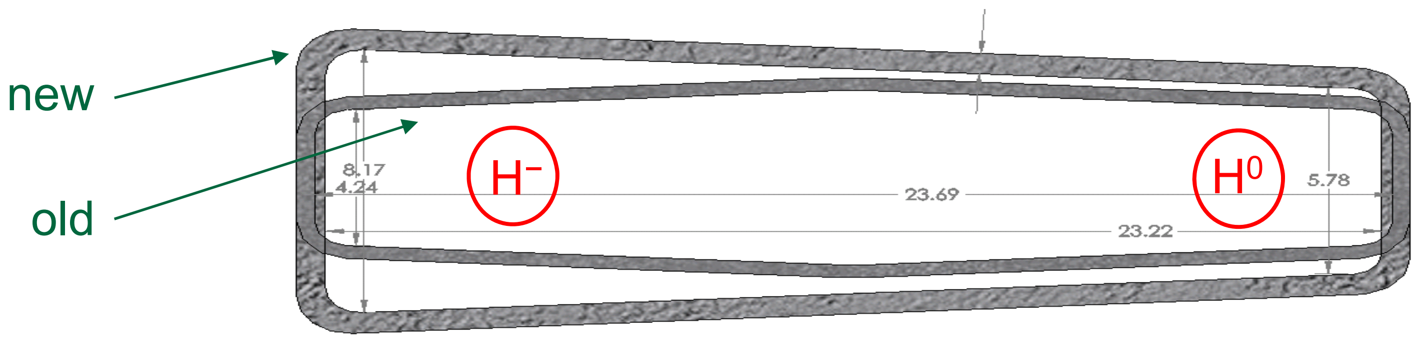
Injection Chicane and Dump Line



beam line drawing
from J. Error

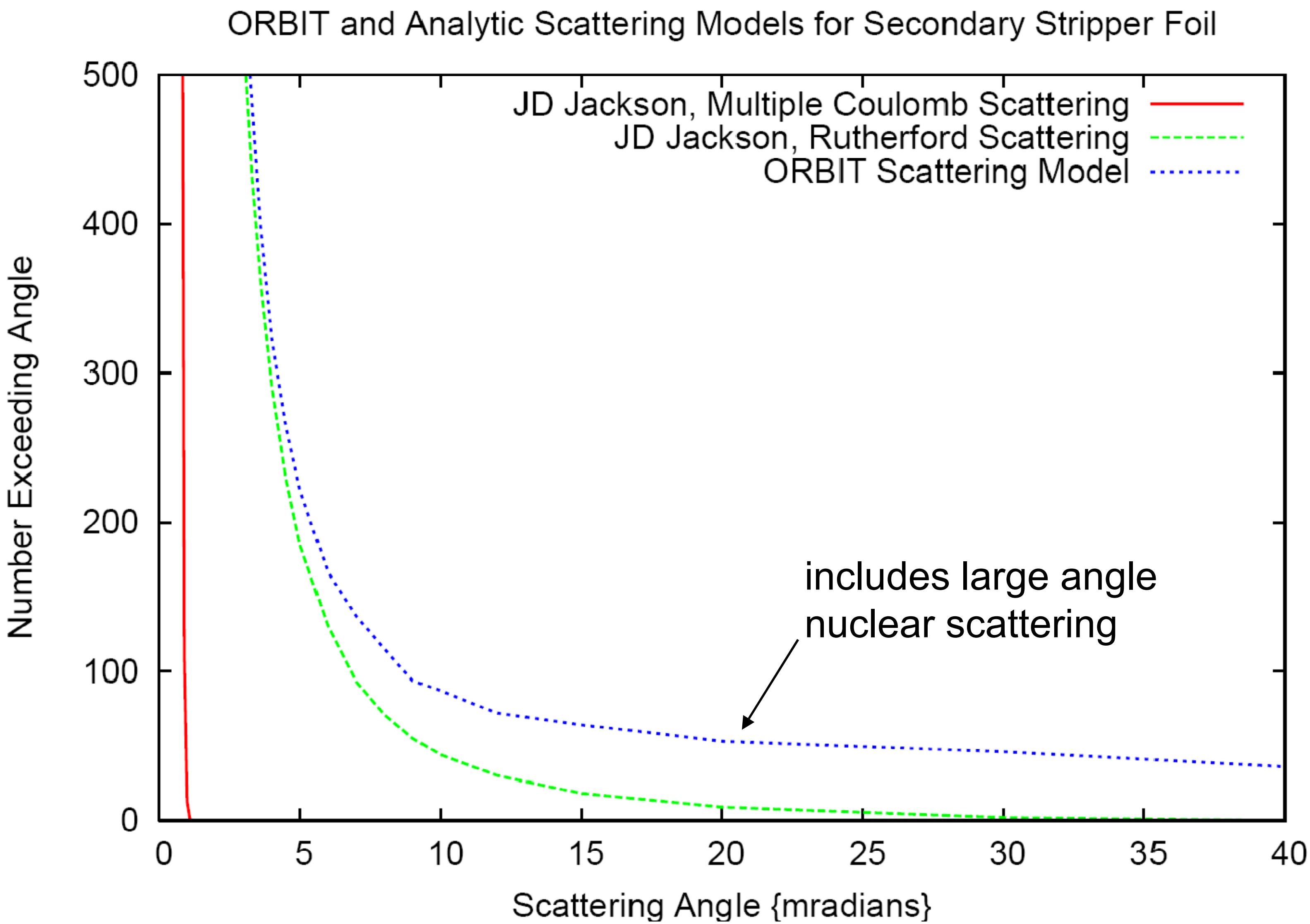
Beam in IDUMP due to Secondary Foil Scattering

- **Geometric prediction is that H^0 waste beam scattered by more than 8.2 mr and H^- waste beam scattered by more than 9.8 mr will be lost in septum.**
- **Some of the beam that survives the septum will be lost at the 6" beam pipe restriction.**



drawing from design team

Beam loss due to stripper foil scattering



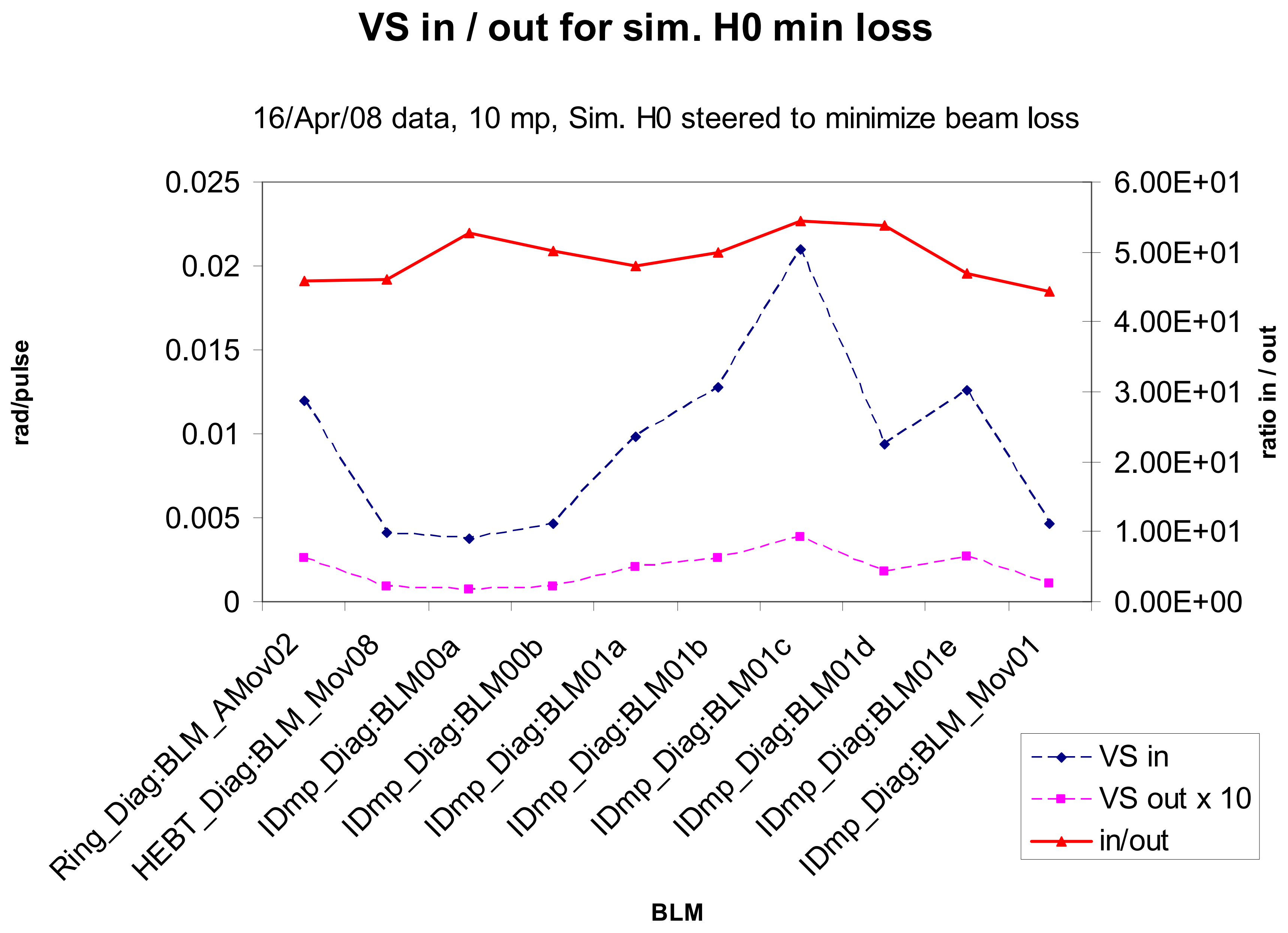
(10^6 particles launched,
18 mg/cm^2 carbon foil)

J. Holmes, 27/May/08

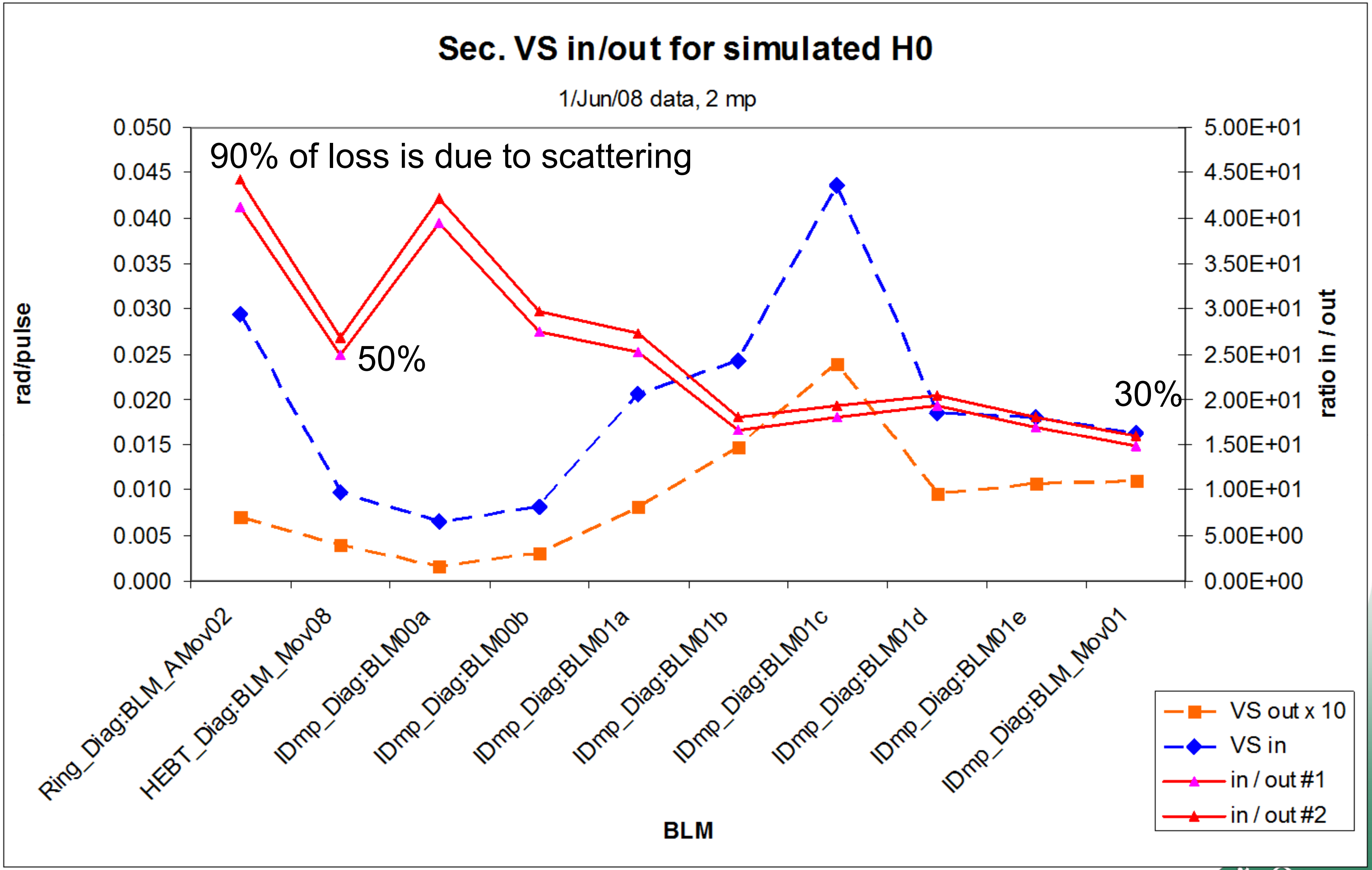
Foil vs. view screen scattering

- **Increase in scattering due to secondary view screen**
  - **34 - 38 times more scattering**
    - **38x more scattering according to hand calculation**
    - **30 - 40x more scattering from ORBIT calculation (using scattering routine between 6 and 10 mrad)**
  - **total loss = a x (scattering) + b x (base loss)**
    - **Example: if the sec. foil increase scattering 35 x,**
    - **and if we observe a loss increase by a factor of n,**
    - **then the base loss = (35-n)/34 x total loss**
    - **If beam loss goes up 35x, loss is entirely due to secondary foil scattering**
    - **If beam loss goes up 18x, half of the loss is due to scattering.**

Single beam species tuned to minimize beam loss



Beam loss for simulated H^0 beam



Conclusions from beam loss measurements

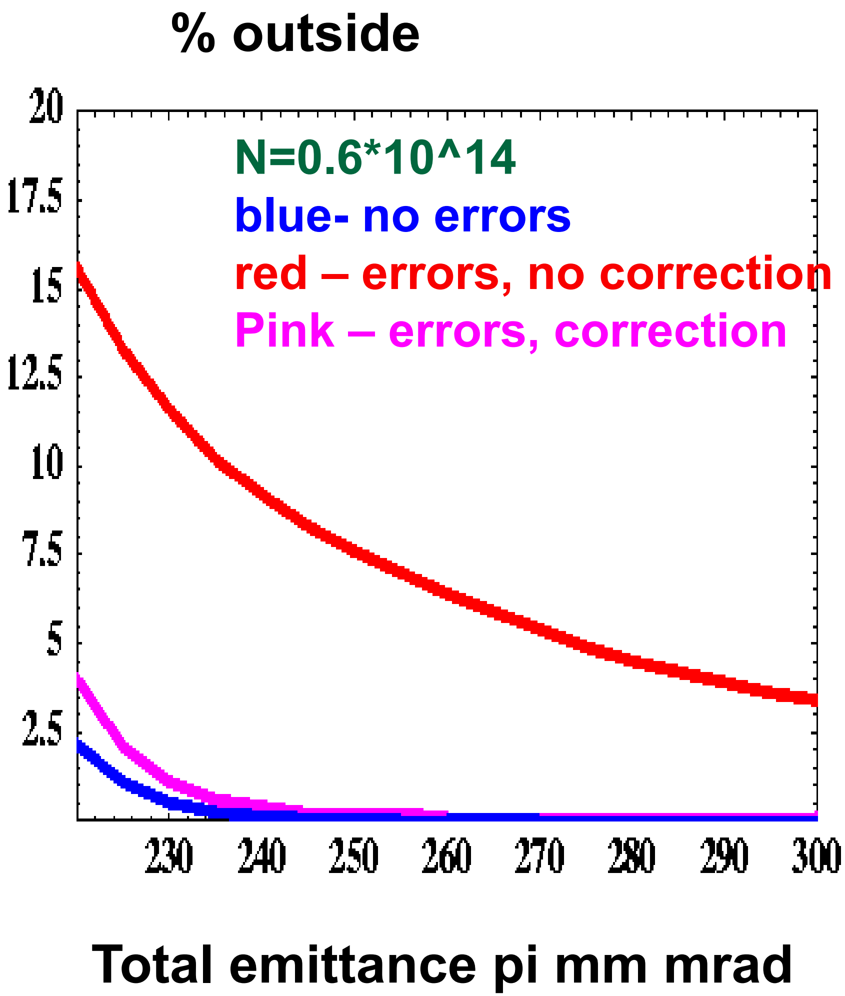
- **For a simulated H^0 beam tuned for lowest beam loss, ~100% of the observed loss is due to scattering in the secondary foil.**
- **The secondary view screen increases the loss due to scattering by 50x (theoretical estimate was ~35x).**
  - **base loss = (50-n)/49 x total loss**
- **For simulated H^0 beam, 30 – 90% of loss is due to scattering.**
- **Can't use this method for simulated H^- or production beam because the view screen is not wide enough to intercept these beams, but probably 30 – 90% of loss is due to scattering.**
- **We believe that beam loss that is not due to scattering is primarily due to beam tails (halo).**
- **We have just installed and are now using a new and thinner (~3.2 mg/cm^2) secondary stripper foil.**

Higher Order Lattice Resonances with Space Charge and Their Correction

- **Fedotov, Parzen, and coworkers at BNL studied computationally the effect of sextupole and octupole lattice imperfections and their correction using the ring sextupole and octupole correctors for high intensity beams in the presence of space charge. They found:**
  - **The resonances occur when collective, not individual particle, modes of oscillation are excited by lattice imperfections.**
  - **The resonances lead to a significant enhancement of the beam tail.**
  - **Magnetic correction of the driving terms ignoring space charge is sufficient to correct the resonances with space charge present.**
- **Their calculations were for working points in the vicinity of $(Q_x,Q_y) = (6.40,6.30)$.**
- **We operate in the vicinity $(Q_x,Q_y) = (6.23,6.20)$, away from sextupole and octupole resonances.**

w.p. (6.4,6.3) - Correction of sum coupling resonance Qx+2Qy=19 and 3Qx=19 resonance
(Fedotov, G. Parzen et al.)

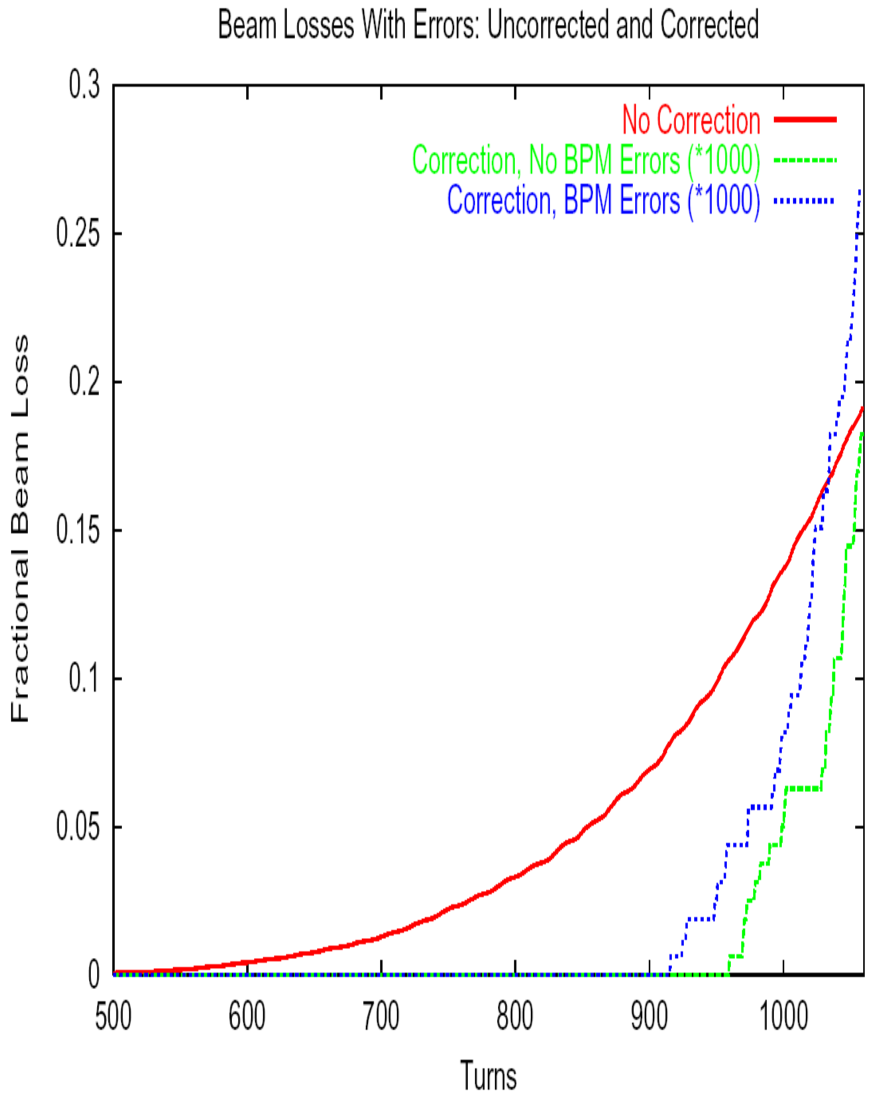
- Experimentally, one can directly measure width of nonlinear islands by measuring tune vs amplitude, or by measuring portion of the beam locked into a resonance with good accuracy.
- We correct the islands – the best we can do in practice, and then study resonance crossing with the space charge, although correction via stopband was done also and was compared to the correction scheme via islands.
- Studies were done using DYNA and UAL codes.



Calculations With Magnet Alignment and Field Errors: Beam Losses

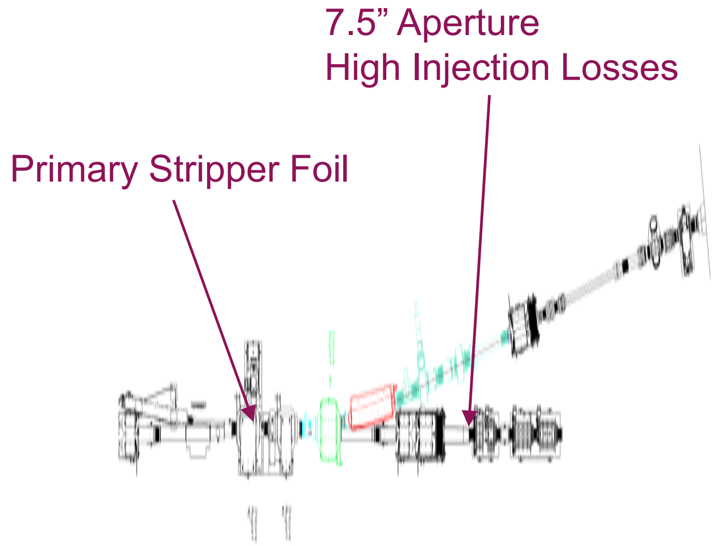
- High intensity injection was calculated using ORBIT with magnet alignment and field errors for many cases, including this one:
  - Without correction, about 20% the beam was lost
  - With correction assuming exact BPM signals, < $2*10^{-4}$ was lost
  - With correction assuming BPM signal errors, < $3*10^{-4}$ was lost

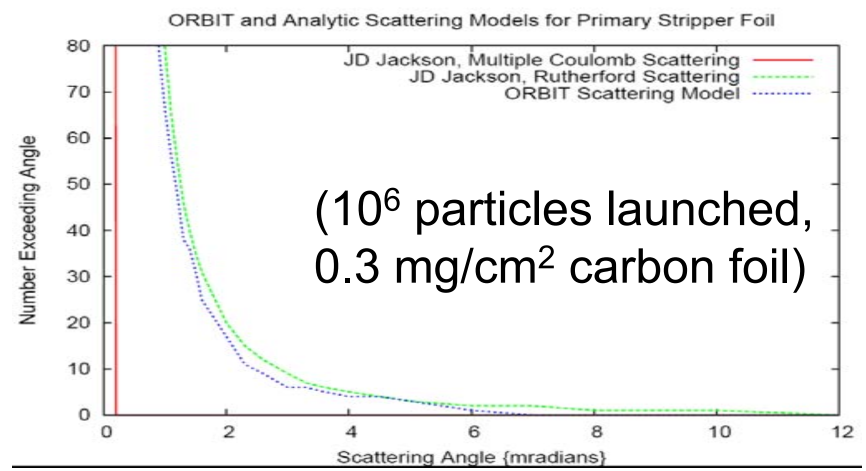
- ORBIT simulations conclude that the SNS ring orbit correction system using BPM signals to optimize dipole corrector and quadrupole family strengths is adequate to correct orbit deviations, phase advances, and losses for alignment and field errors at the anticipated levels.



Injection Losses: Primary Stripper Foil Scattering

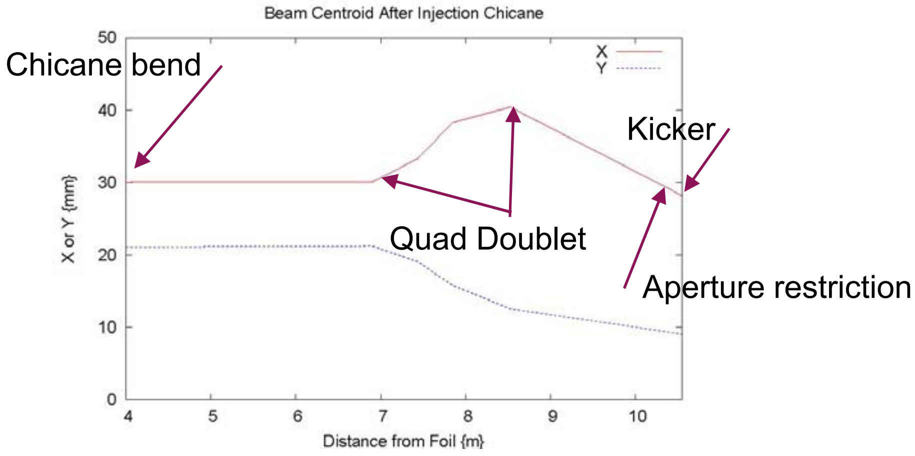
- **Beam losses are high in the downstream side of the injection region.**
  - **The beam pipe narrows.**
  - **The beam is off center.**
  - **Primary foil scattering is suspected.**
- **Primary foil thickness ~300 μg/cm^2.**
- **Inelastic nuclear scattering loss ~2×10^{-6} per foil hit. Expect between 6 and 15 foil hits per proton, depending on painting scheme.**
- **ORBIT simulation:**
  - **4.0×10^{-3} total loss**
  - **15.2 foil hits / proton**
  - **0.4×10^{-4} nuclear inelastic loss**
  - **1.3×10^{-3} total scattering loss**
  - **1.3×10^{-4} injection region loss**
  - **0.8×10^{-4} injection region scattering loss**

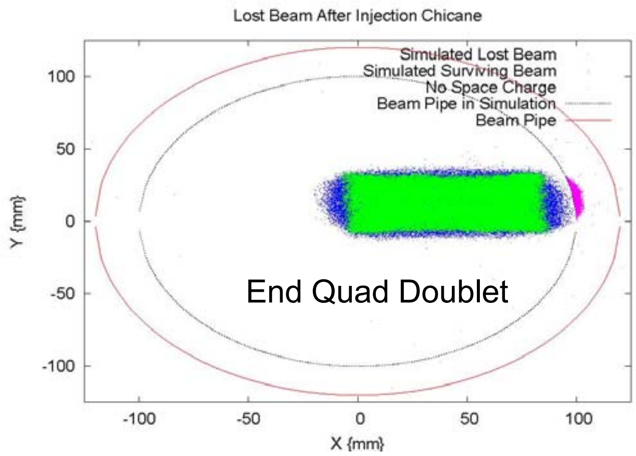


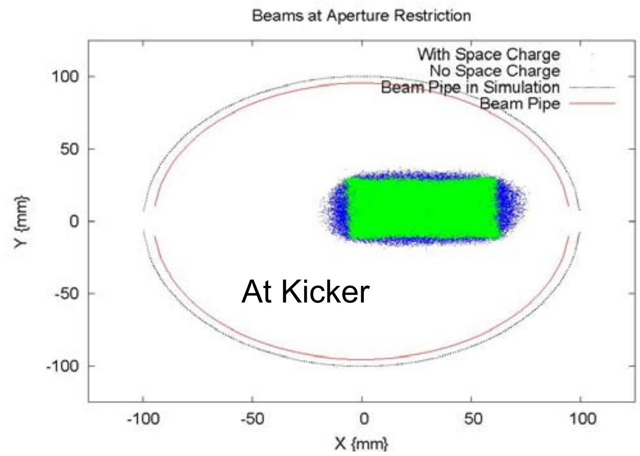


Injection Losses: Space Charge

- **Space charge losses:**
  - **2.7×10^{-3} total**
  - **0.5×10^{-4} injection region**



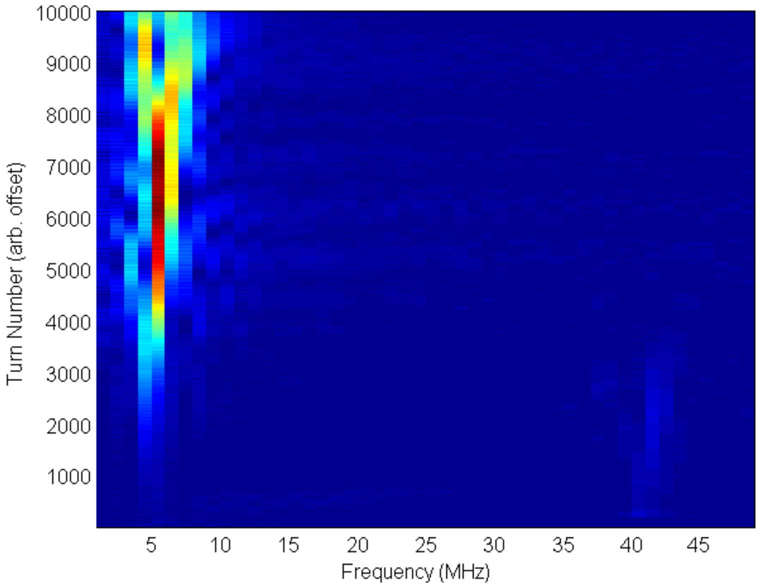




Extraction Kicker Instability

- ***Observed Experimentally***
  - **1.3×10^{14} protons accumulated without instability.**
  - **Tune settings $(Q_x, Q_y) = (6.23, 6.21)$.**
  - **To induce instabilities, the ring RF cavities were turned off to provide coasting beams.**
  - **Observed transverse instability in the vertical direction for a stored coasting beam.**
    - **Dominant harmonic at 6 MHz and noticeable excitation in the 4→10 MHz range.**
    - **“Slow” mode → harmonic n = 12, and excitation in the range $10 \leq n \leq 16$.**
    - **Measured at 7.5×10^{13} protons and corrected (zero) chromaticity.**

Turn-by-turn frequency spectrum of the coasting beam extraction-kicker-induced Instability seen in SNS.

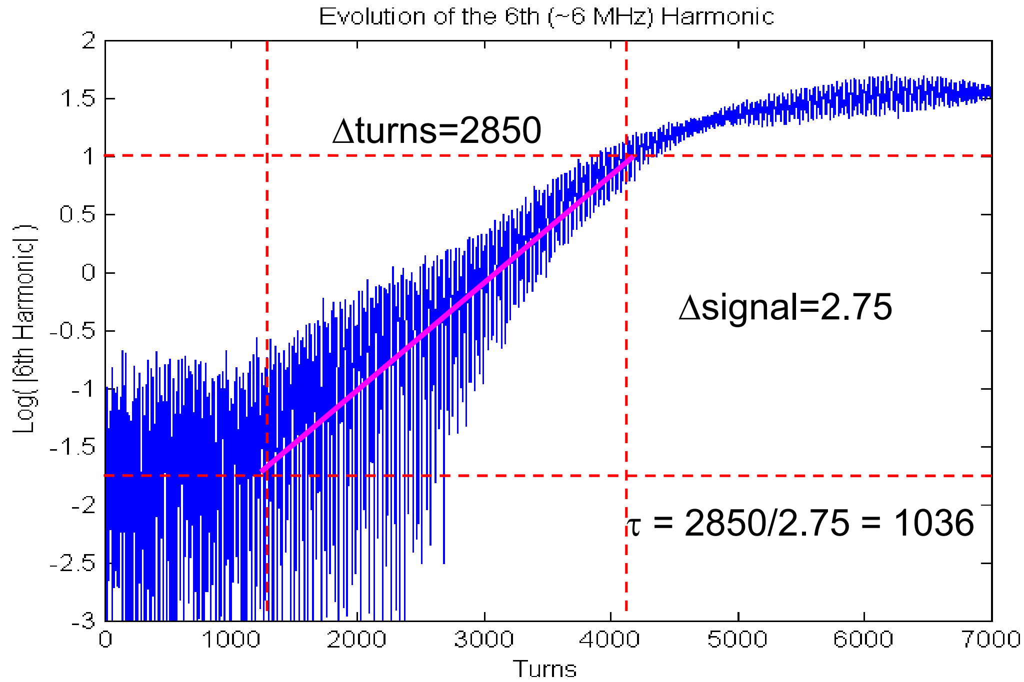


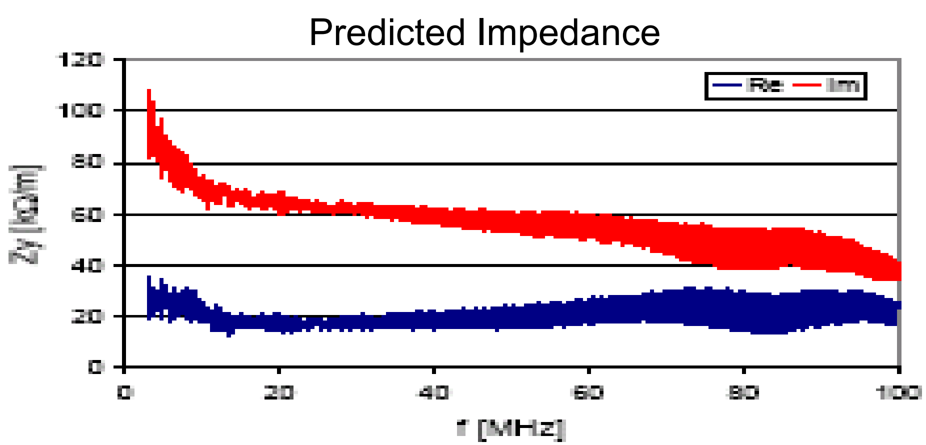
Estimation of Extraction Kicker Impedance

Can derive impedance from experiment using formula:

$$\mathrm{Re}(Z) = \frac{2\gamma\beta^2 E_o}{\tau \beta_{twiss} I_{ave}}$$

Experimentally-measured impedance: Z ≅ 28 KΩ/m



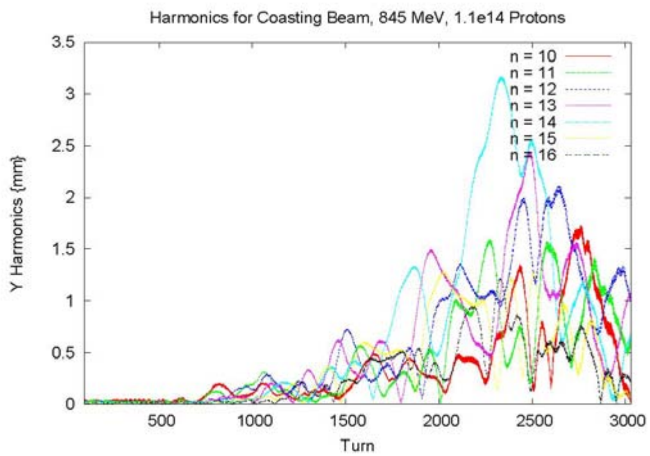


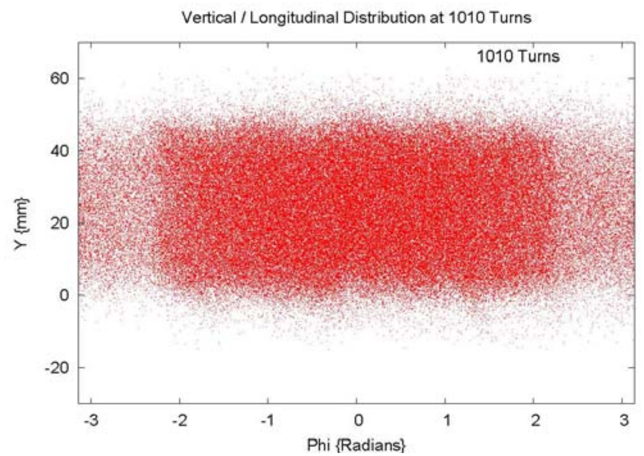
Lab-measured impedance: Z ≅ 25 KΩ/m

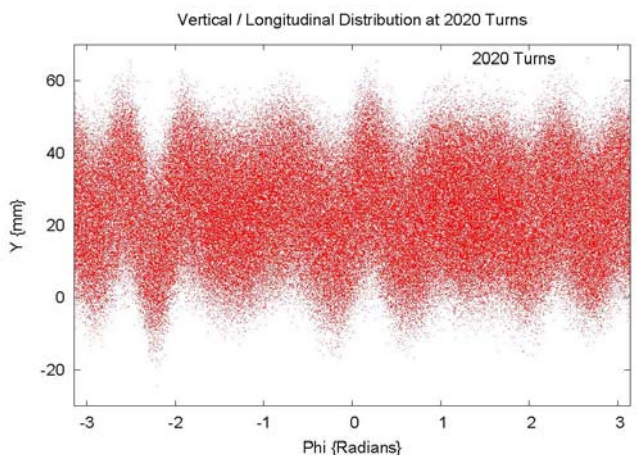
*H. Hahn, PRSTAB, **7**, 103501*

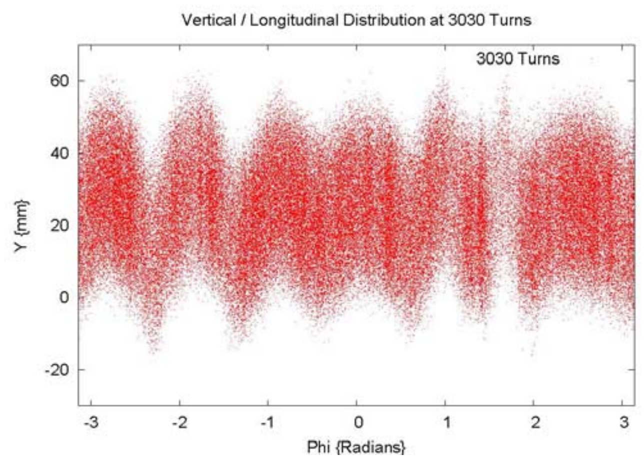
Extraction Kicker Instability

Simulated using ORBIT with extraction kicker impedance, 3D space charge, and 1.1×10^{14} protons and natural chromaticity.



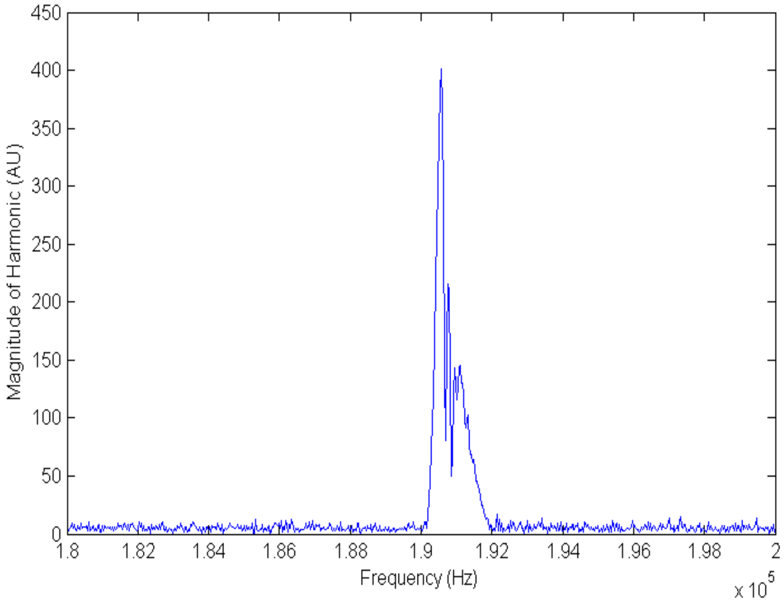






Resistive Wall Instability

Ring was tuned to below integer values of (5.795, 5.8), in order to produce instability in the regime of high impedance.



For resistive wall instability:

$$f_{instability} = f_{revolution}\,(n - Q)$$

For n=6, Q=5.8, $f_{instability} \cong 200$kHz

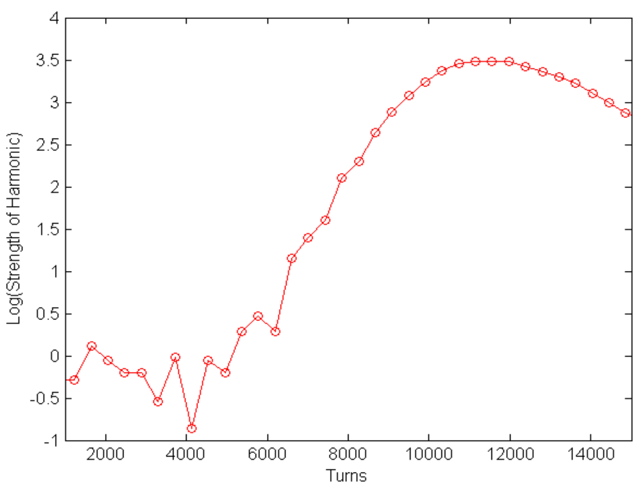
Instability observed at 191 kHz – probably because tunes were shifted to 5.81

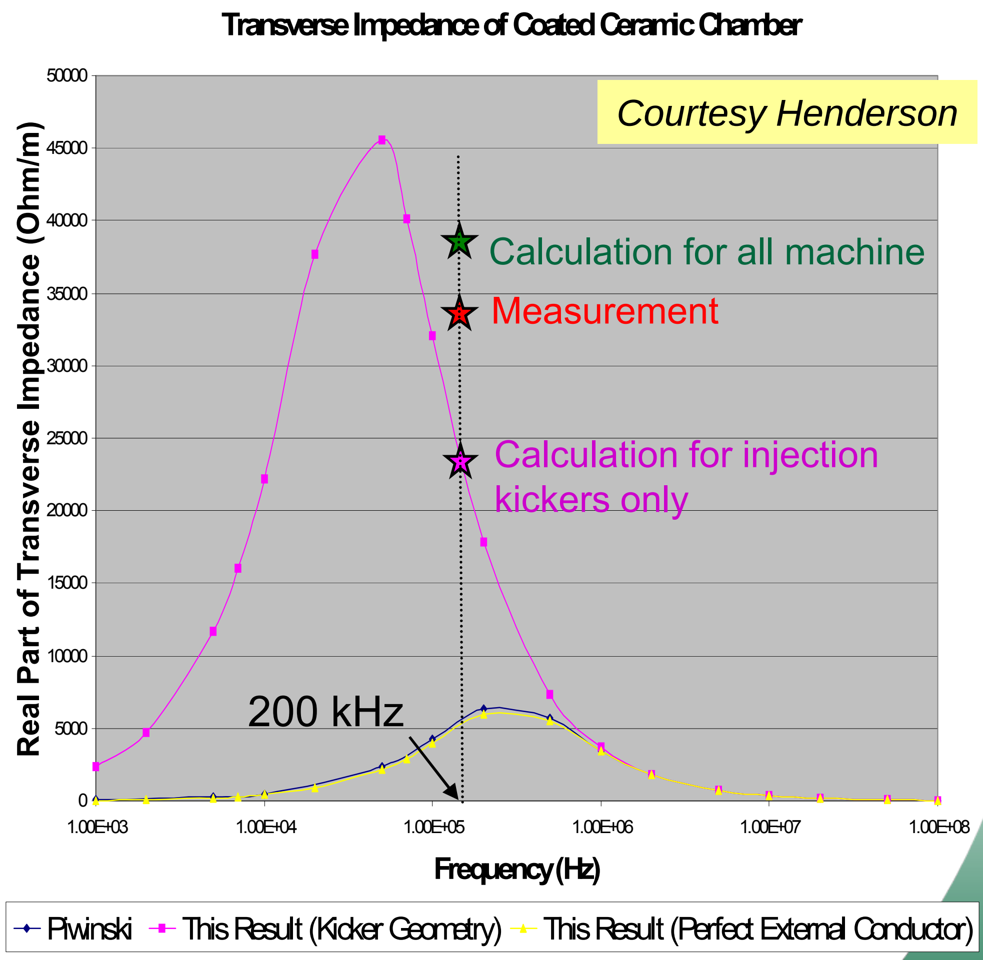
OAK RIDGE National Laboratory

Estimation of Resistive Wall Instability Impedance

Comparison with predictions (reference):

Logarithm of Evolution of 6th Harmonic

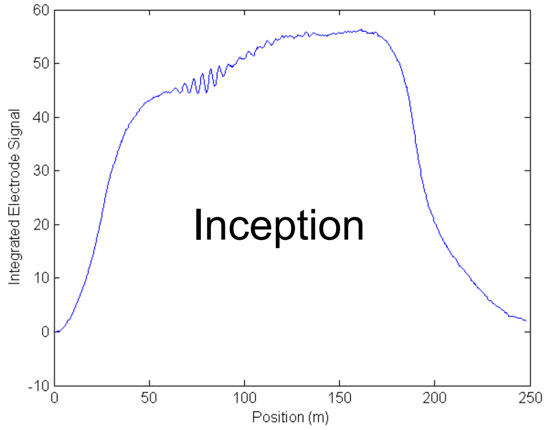


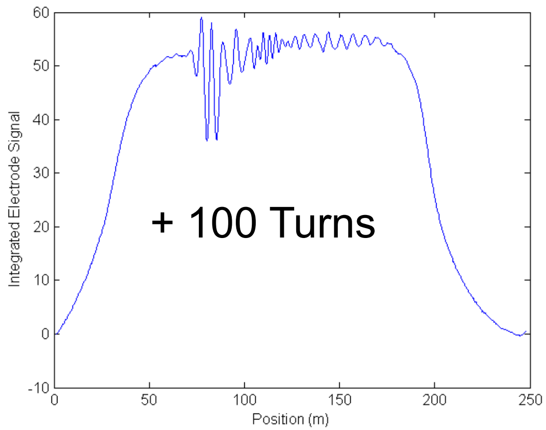


Impedance estimate from data: Re(Z)≅ 34 kΩ/m

E-P Instability

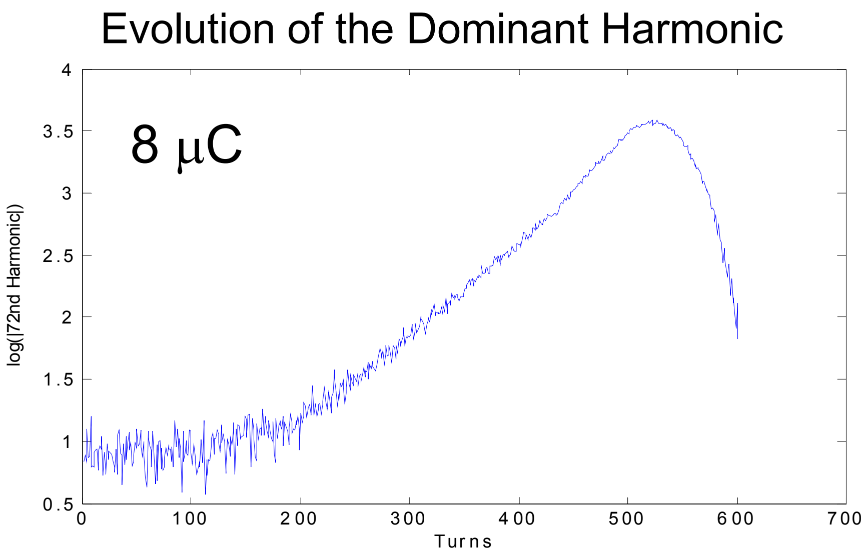
- **The electron cloud instability initially develops toward the first half of the proton beam and extends toward the rear as the instability grows.**
- **The figures show the e-p instability as seen in coasting beam current profile shortly after its inception (top) and 100 turns later (bottom).**
- **Analysis of experimental BPM data places the onsets of instability at 3.4×10^{13} protons in the horizontal plane and at 5.8×10^{13} protons vertically. However, higher intensities are obtained in the vertical direction.**





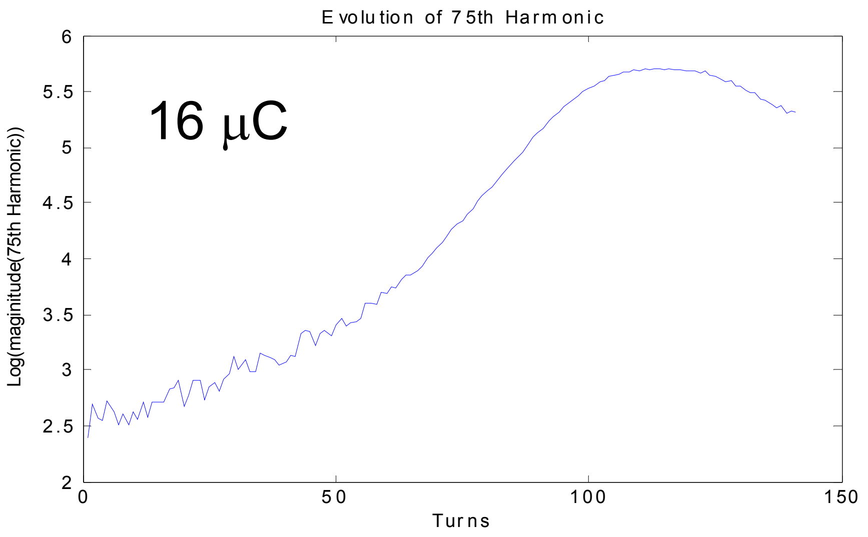
Calculation of Effective e-p Impedance

We can estimate the “effective impedance” of the electron cloud, at different intensities:



8 μC beam:

Re(Z)=168 KΩ/m



16 μC beam:

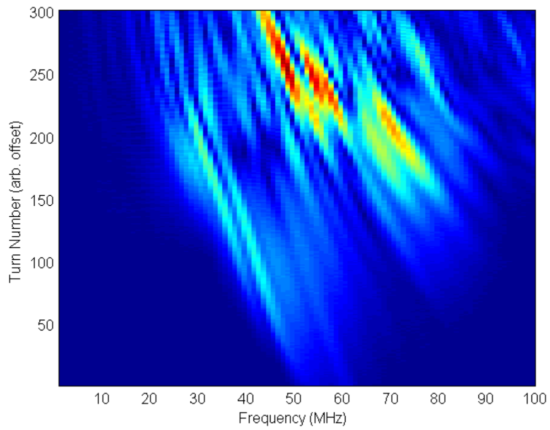
Re(Z)=1.9 MΩ/m

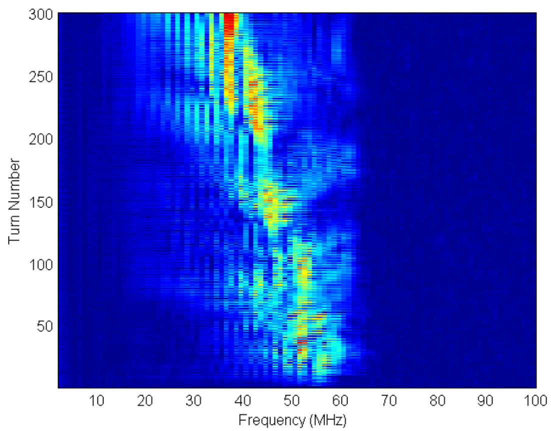
e-p is has the largest impedance observed thus far – by a large margin!

ORBIT Simulation of Observed E-P Instability

- **Use experimental operating parameters.**
- **The figures show the turn-by-turn vertical frequency spectrum of the coasting beam e-p instability in SNS. Top: measured results. Bottom: ORBIT simulation.**
- **Range and extent of the simulation frequency spectrum lower and smaller than observed experimentally.**
- **Both measured and simulated spectra drift toward lower frequencies as the instability evolves.**
- **Simulation agrees qualitatively with reality, but there are quantitative differences. These may be due to the position and localization of the electron cloud nodes in the simulations.**

Experiment





Simulation

Summary and Comparison of Observed Instabilities

Instability Type	Frequency	Measured Impedance	Predicted Impedance
Extraction Kicker	6 MHz	~28 KΩ/m	~25 KΩ/m
Resistive Wall	191 KHz	~34 KΩ/m	~40 KΩ/m
e-p	78 MHz (@ 16 μC)	~1.9 MΩ/m (@ 16 μC)	N/A

Conclusion

- **We have reached the threshold of high intensity in the SNS ring:**
  - **~0.6×10^{14} proton accumulation in production.**
  - **~1.3×10^{14} proton accumulation in dedicated studies.**
- **Main concern is beam loss caused by halo.**
- **We are studying and evaluating the causes and effects of halo-generating mechanisms including:**
  - **Foil scattering**
  - **Space charge**
  - **Collective instabilities**
    - **Extraction kicker**
    - **Resistive wall**
    - **E-P Instability**
- **We are just getting started.**