Understanding Beam Losses in High-Intensity Proton Accumulator Rings

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Special thanks to the many colleagues who contributed over the years

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Outline

- **Introduction: Example - the Los Alamos Proton Storage Ring (PSR)**
- **Measuring beam losses at PSR**
  - Beam loss data (typical ~0.0025 fractional loss) and activation MAP at PSR
- **Significant Beam Loss Mechanisms in PSR**
  - Nuclear and large angle Coulomb scattering in the injection stripper foil (~60-75% of total loss)
  - H0(n) excited states from stripper foil that Lorentz strip in downstream magnets (~15-25% of total loss)
  - Extraction losses (<10% of total loss)
  - Space charge emittance growth (not significant at routine operating currents)
  - Betatron Resonance crossing, can be avoided by suitable operating point
  - Beam instabilities, in particular, the two-stream e-p instability (generally avoided)
- **Modeling beam losses at PSR: MAD8/ORBIT, G4Beamline**
- **Conclusions and prospects for the future**

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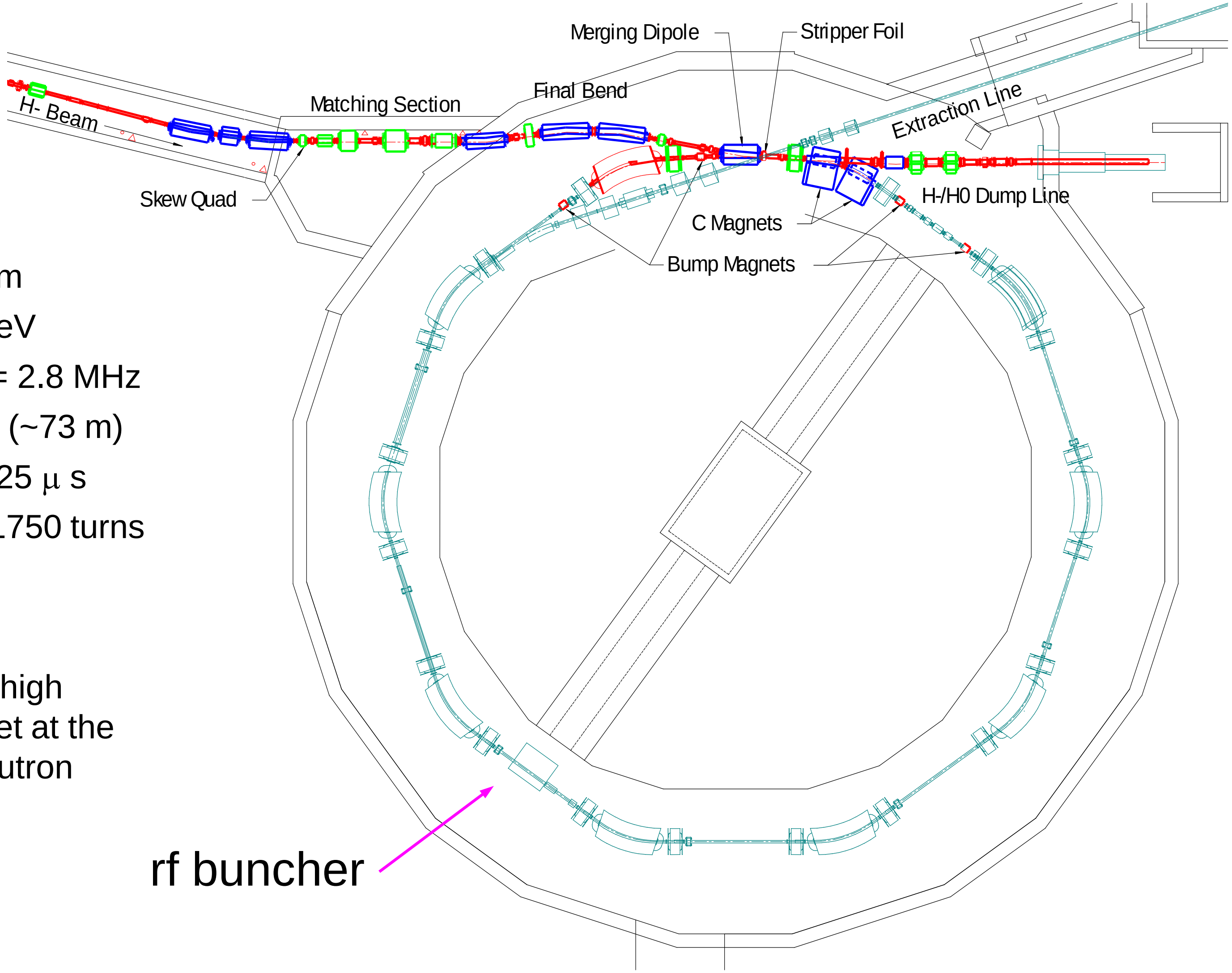
PSR Layout today



Circumference = 90.2 m

Beam energy = 798 MeV

Revolution frequency = 2.8 MHz

Bunch length ~ 290 ns (~73 m)

Accumulation time ~ 625 μ s

~1750 turns

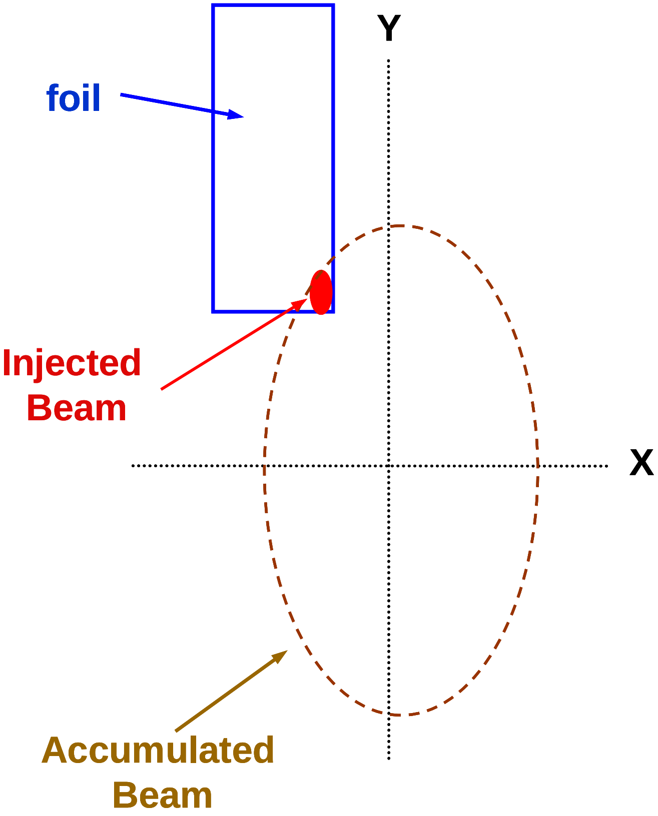
H- injection
Single-turn extraction

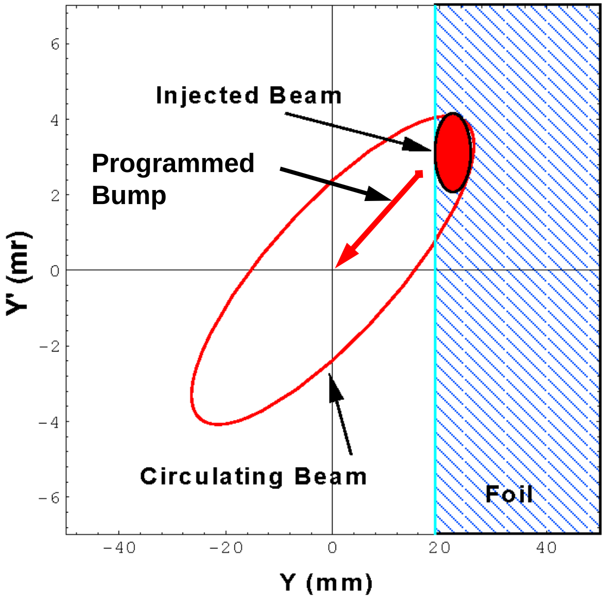
Main use is to provide high intensity beam on target at the LANSCE spallation neutron source

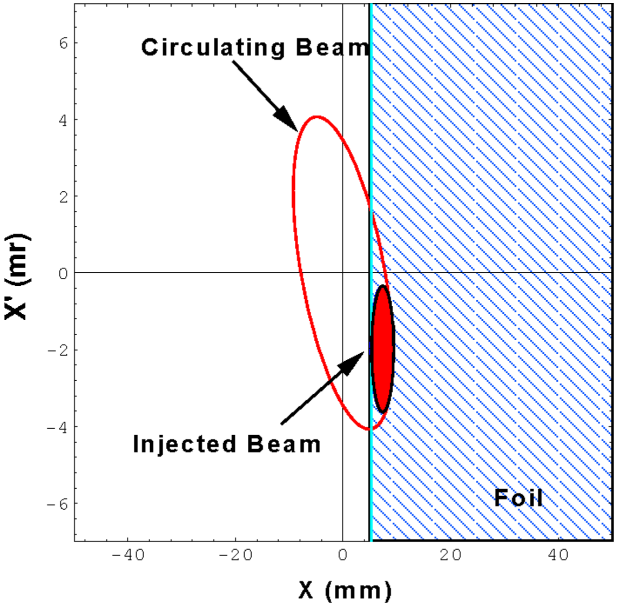
rf buncher

Injection painting

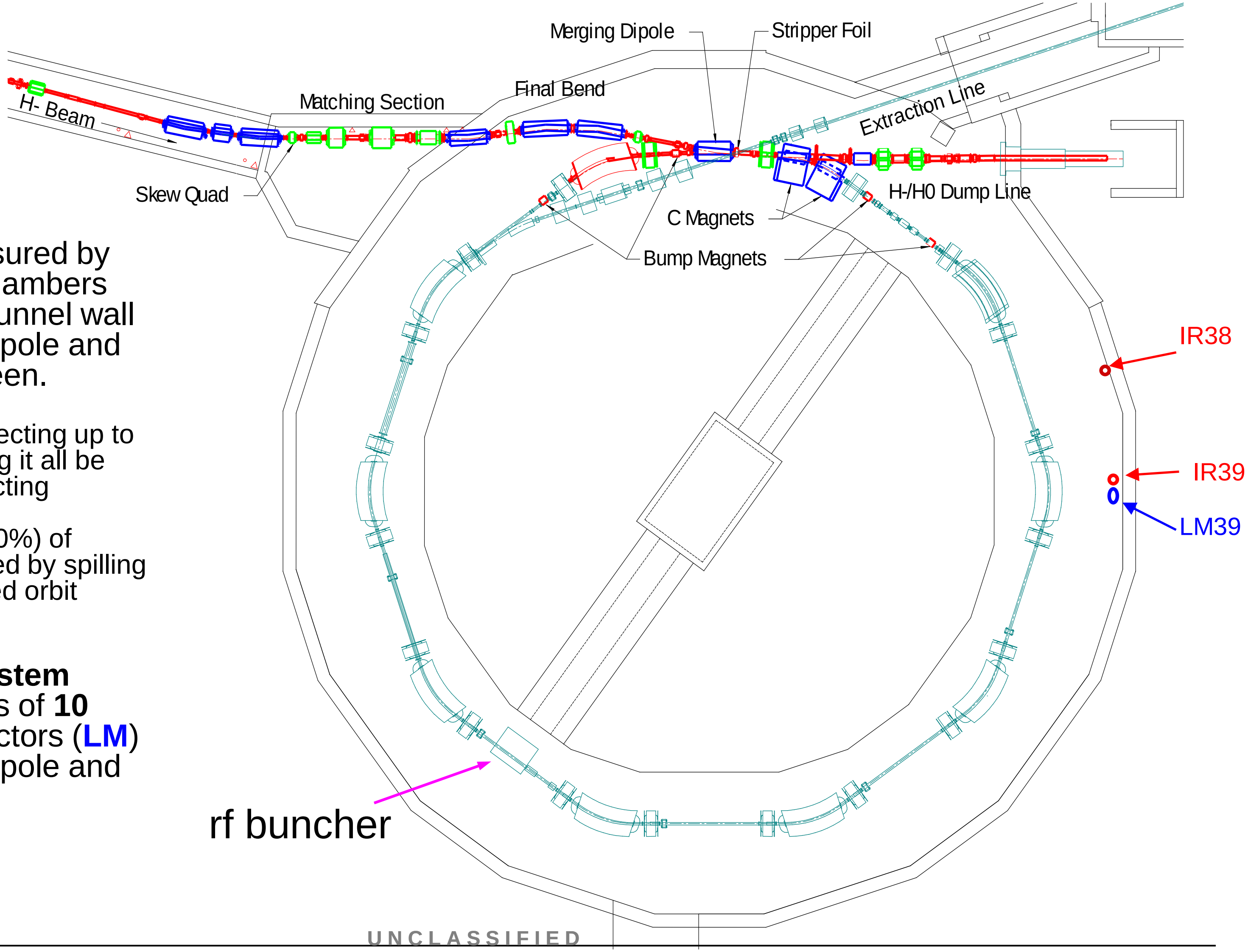
New foil







Beam loss monitoring at PSR



Total losses measured by sum of **19** ion chambers (**IR**) located on tunnel wall opposite each dipole and halfway in between.

- Calibrated by injecting up to 0.4 μC and letting it all be lost by not extracting
- Uniformity (15-30%) of response checked by spilling locally with closed orbit bumps

Fast response system (~10 ns) consists of **10** scintillation detectors (**LM**) opposite each dipole and next to **IRn9**

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Typical Beam Loss and Activation Map for PSR

Typical beam for operations
 ~110 μA

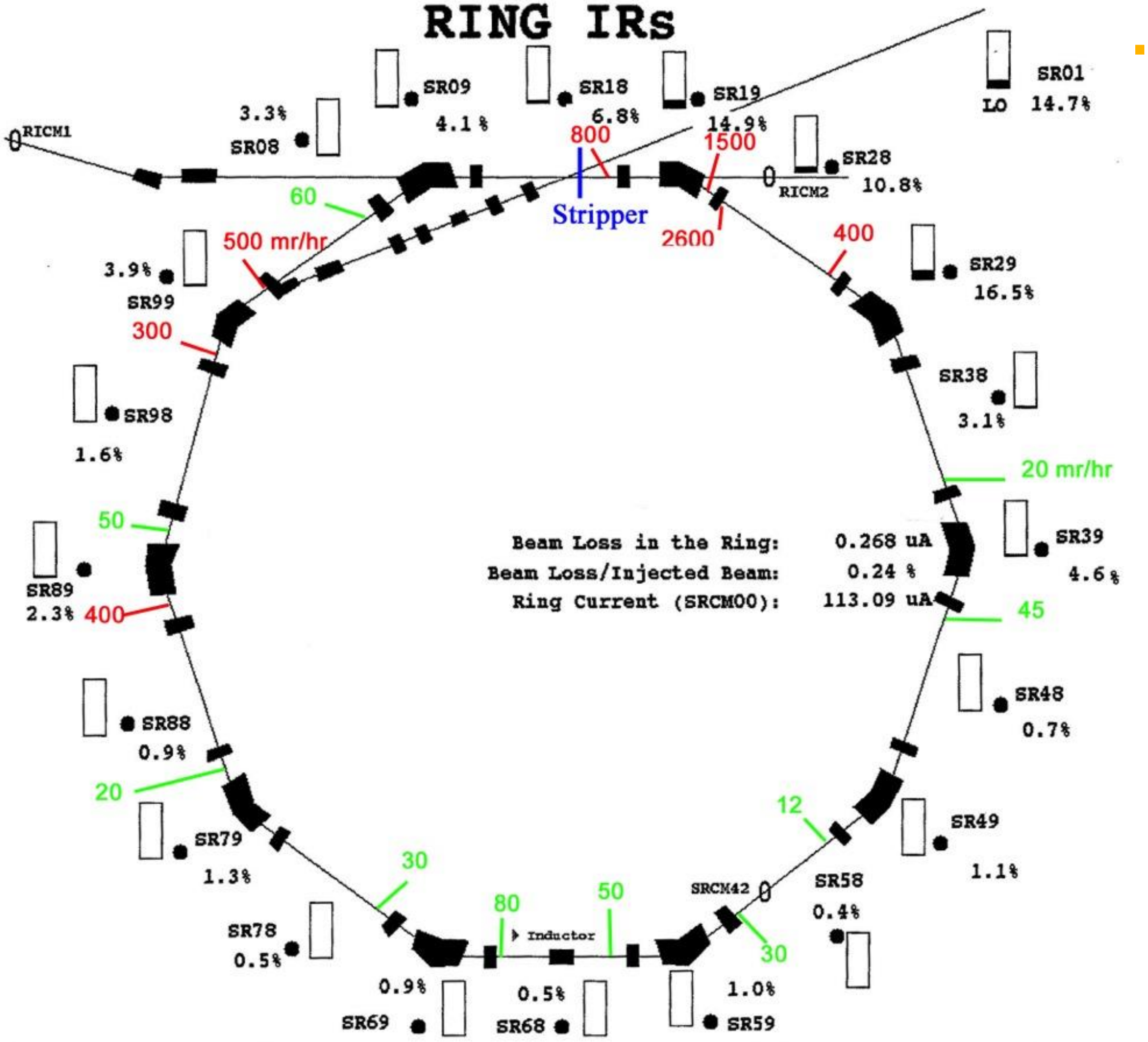
Typical beam loss ~0.0025
 (0.28 uA, 225W)

Compare to SNS (1mA,
 ~2x10^{-4} loss)

Losses measured from sum of Ion Chamber (IR) readings and a calibration constant

Activation data **(shown in color)** are from a survey taken after a day of cool down, measurements are at 30cm from beam pipe

Activation has a reasonable correlation with the time averaged loss monitor data



Beam Loss in the Ring: 0.268 uA
Beam Loss/Injected Beam: 0.24 %
Ring Current (SRCM00): 113.09 uA

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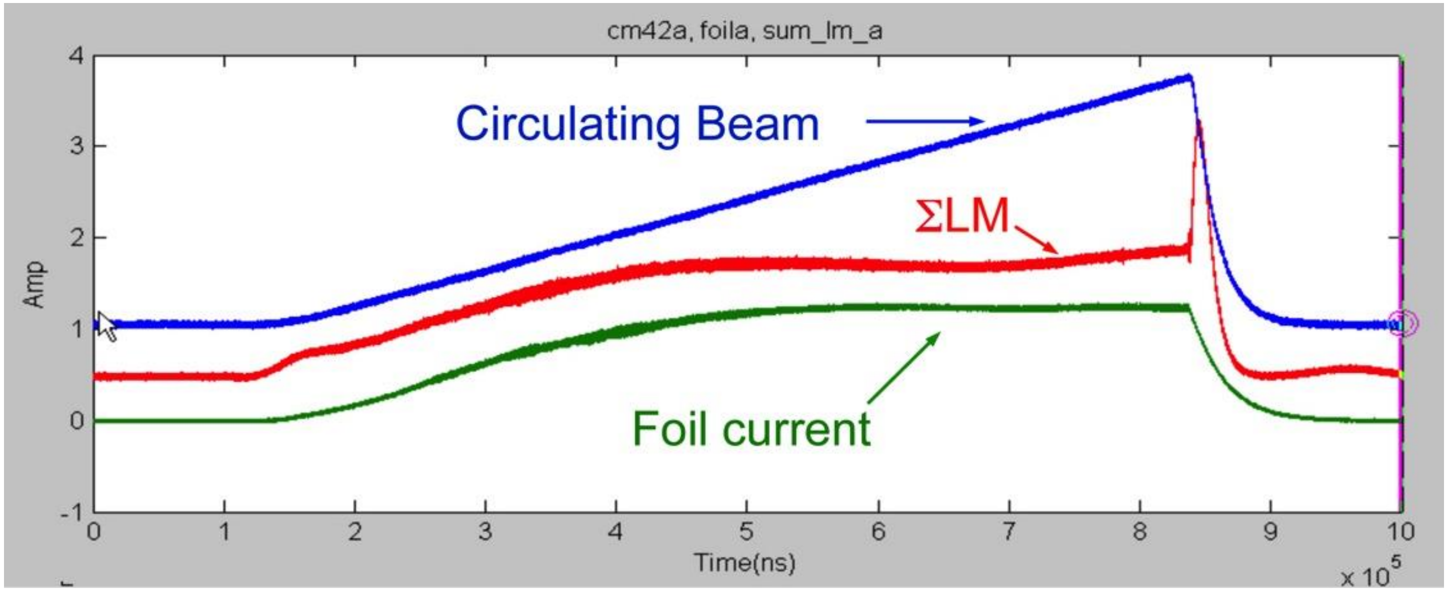
Losses from scattering in the injection stripper foil

- **Nuclear and large angle Coulomb scattering (65-75% of total loss)**
  - Well known cross-sections
  - Depends on number of foil hits by stored beam, typically **~100-150** for average beam proton in "production" beam use for spallation neutron source
    - Obtained from ACCSIM or **ORBIT simulations** and/or from **calibrated foil current measurements** (need to measure SEY as well)
    - Graph below from 1/17/03 data for 115 μA production beam; foil current and SEY of 1.06% (measured 6/13/02) imply **~70 foil hits/proton**



Simple estimate of Coulomb scattering losses

- **For large angle Coulomb scattering use a simple model of on-axis, pencil beam hitting the foil and limiting acceptance angles, θ_{xl} or θ_{yl} , obtained from limiting apertures, X_A and Y_A**

$$\theta_{xl}^2 = \frac{X_A^2}{b_{fx} b_{xA}} \quad \text{and} \quad \theta_{yl}^2 = \frac{Y_A^2}{b_{fy} b_{yA}}$$

- **For single Coulomb scattering use the Rutherford formula in small angle approximation (from Jackson, “Electrodynamics”, eqn. 13.92)**

$$\frac{d\sigma}{d\Omega} \cong \left(\frac{2Ze^2}{pv}\right)^2 \frac{1}{\theta^4} = \frac{C_0}{\theta^4} \qquad \theta^2 = \theta_x^2 + \theta_y^2 \qquad C_0 = \left(\frac{2Ze^2}{pv}\right)^2 = \left(\frac{2Zm_e r_e}{\gamma\beta^2 M}\right)^2$$

  - For typical PSR production beam θ_{xl} = 7 mr, θ_{yl} = 3.3 mr; integrating the differential cross-section over the region outside the ring acceptance from $|\theta_x| = \theta_{xl}$ to ∞ and $|\theta_y| = \theta_{yl}$ to ∞ gives

$$\sigma_{lost} = C_0 \left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2} \tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right) + \frac{1}{\theta_{yl}^2} \tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right) \right]$$

  - The probability (per foil traversal) of a single large angle scattering that leads to particle loss is $P = N\sigma_{lost}t$, where $N = N_0\rho/A$ is the number of atoms per unit volume; for PSR parameters (above) and a 400 μg/cm2 carbon foil **$P = 6.1\times10^{-6}$** per foil traversal or, for a typical 150 foil hits/proton, the fractional loss from large angle Coulomb scattering **is 0.00091**

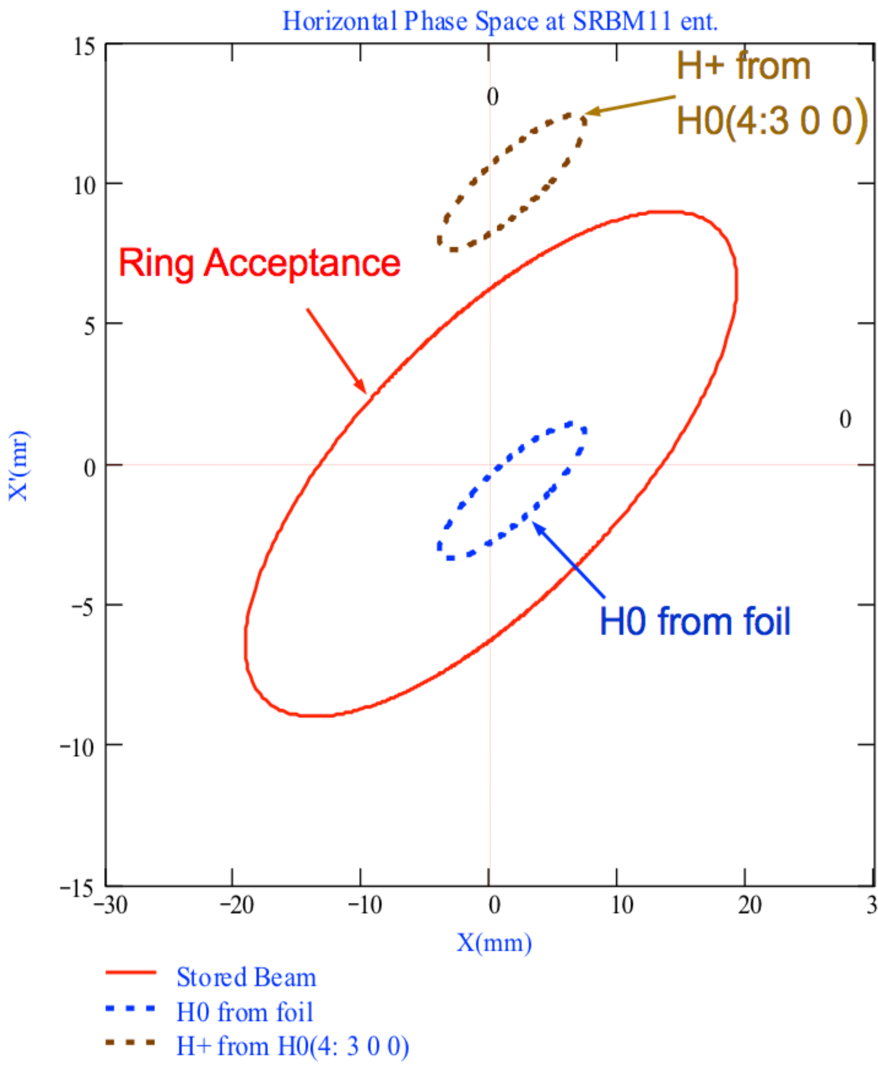
lost

Estimates of foil scattering losses cont'd

- **Nuclear scattering includes nuclear reactions plus elastic and quasi-elastic scattering**
  - Use published data (from PDG handbook) on nuclear collision lengths for carbon i.e., λ_T = 59.2 g cm^{-2}, thus the fractional loss from 150 foil traversals is **0.00102**, which is about the same as for large angle Coulomb scattering from previous slide
- **Thus, the foil scattering loss = sum of losses from large angle Coulomb loss + loss from nuclear scattering = 0.0019 (for 150 foil traversals per proton) as estimated by the simple model model above and previous slide**
  - Compare with typical total fractional loss of ~0.0025
- **Can also use ORBIT simulation/tracking code with nuclear and Coulomb foil scattering built in (more later); gives result for production beams in basic agreement with measurements and the simple model**

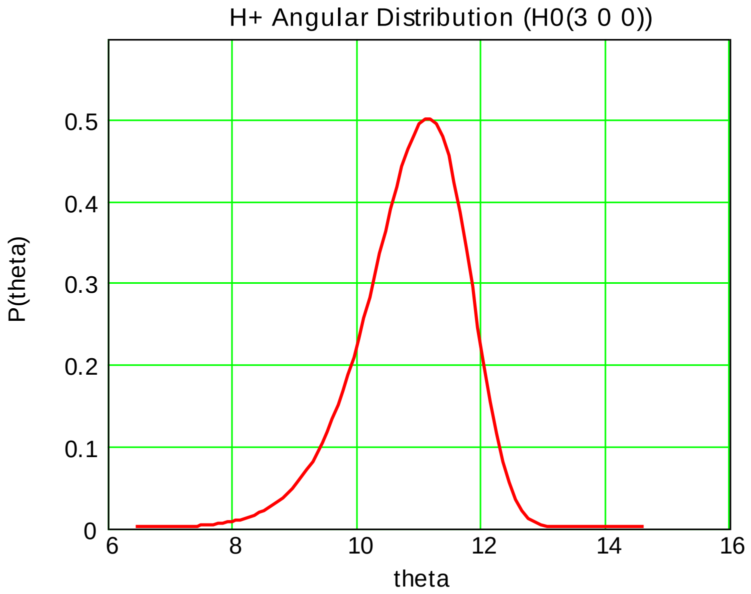
Example of loss from an excited state of H0

- **Plot showing horizontal beam phase space ellipses projected to entrance of first dipole (SRBM11) down stream of stripper foil**
  - n=4 Stark state:
    n1=3, n2=0, m=0
  - Strips part way into magnet and resulting H+ is bent ~ 11 mr less than protons from foil and falls outside acceptance of the ring
- **n=1 and 2 states are not stripped**
- **All of n=3, n=4, and n=5 Stark states are stripped and most are lost**
- **Higher Stark states strip easily and contribute to halo**



Estimating loss characteristics from H0(n>2)

- **Use formulas from Damburg and Kolosov* for line width of Stark states and from this obtain stripping probability as a function of magnetic field**
  - From these calculate Δθ for the H+ (and width of Δθ band for each Stark state) in fringe field of dipole to see if it falls outside the acceptance
  - Example below for n=4: 3 0 0 state

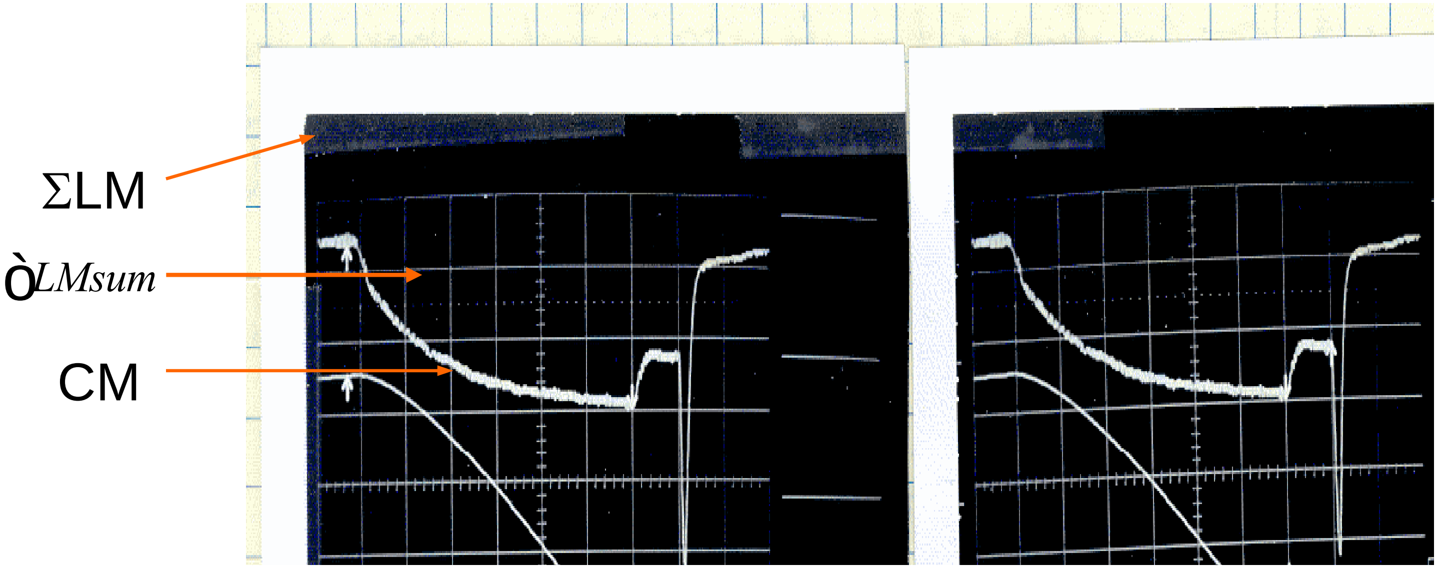


* "Rydberg States of Atoms and Molecules", Edited by R. F. Stebbings (Cambridge University Press, Cambridge 1986)

- **We use yield/cross-section data for excited states from LANL experiments (Gulley etal, Phys Rev A, vol 53 p3201 (1996)) to calculate yield of various excited states for foil in use.**
  - Observed sum of excited state losses (next slide) agree within a factor of ~2 with the yield from Gulley et al

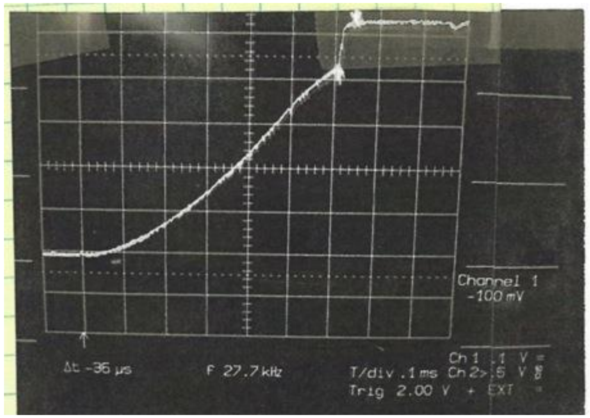
Measuring losses from excited states

- **Total losses during accumulation can also be monitored by a fast response system (~10 ns) of 10 Scintillation detectors (LM) opposite each ring dipole.**
- **“1st turn losses” (excited states) by storing for ~ 100 µs after end of accumulation and measuring LMsum signal “drop” at end of accumulation**
  - Example below from experiment 6/11/2002 with 4-layer carbon foils (~400 µg/cm2) of that era
  - Total fractional losses during accumulation were ~ 0.0047, and data from pictures below indicates that excited state losses were **44%** of total losses, somewhat higher than typical
  - Results for HBC foil in 2010 showed excited state loss were **18%** of the total loss



Extraction Losses at PSR

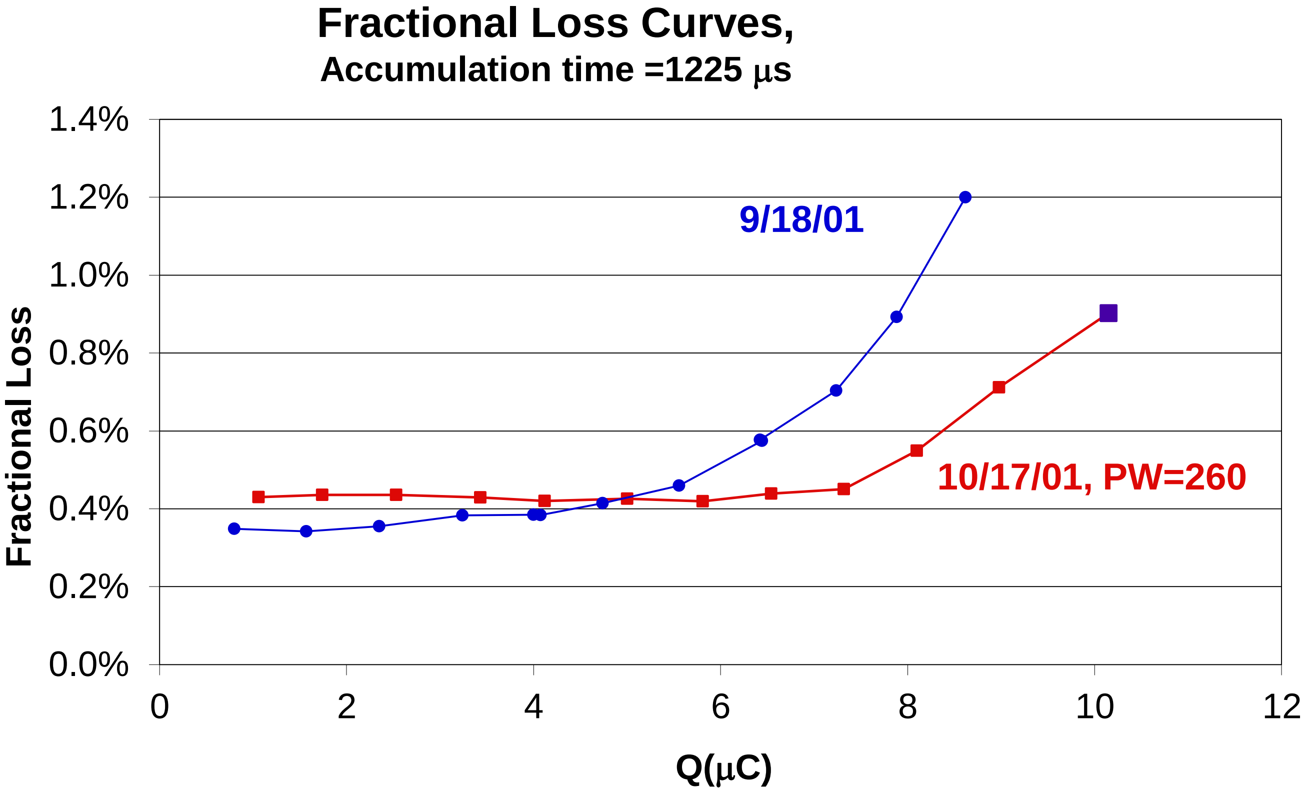
- **Measured by special fast detectors located on wall opposite dipoles in sections 8, 9, 0, 1 and 2**
  - Designed to avoid saturation on fast loss
  - SRLV are standard scintillation-based loss monitors with last 4 photo multiplier dynodes shorted to reduce gain
  - SRVE are plastic scintillator detectors using vacuum photodiodes which won’t saturate on extraction losses
    - Sample ΣSRVE signal (integrated) from a log book showing jump at extraction
    - The jump is proportional to the extraction loss
    - Calibrated by spilling (extraction septum magnets off) single beam pulse with known charge in 1-turn extraction
    - Calibration constant has factor of 2 or so uncertainty



- **Typical extraction loss per turn is ~1 nC (~5-10% of total loss)**
  - Roughly consistent with activation at extraction septum region

Effect of Space Charge on Measured Losses

- Studied in an experiment where beam was accumulated for 1225 μs with production injection offset and then vary intensity with jaws at front of linac
- 9/18/01 PW=280 ns, 10/17/01 PW=260 ns, last point at 10.15 μC had PW=285 ns
- Space charge does not significantly influence losses below 6 μC/pulse



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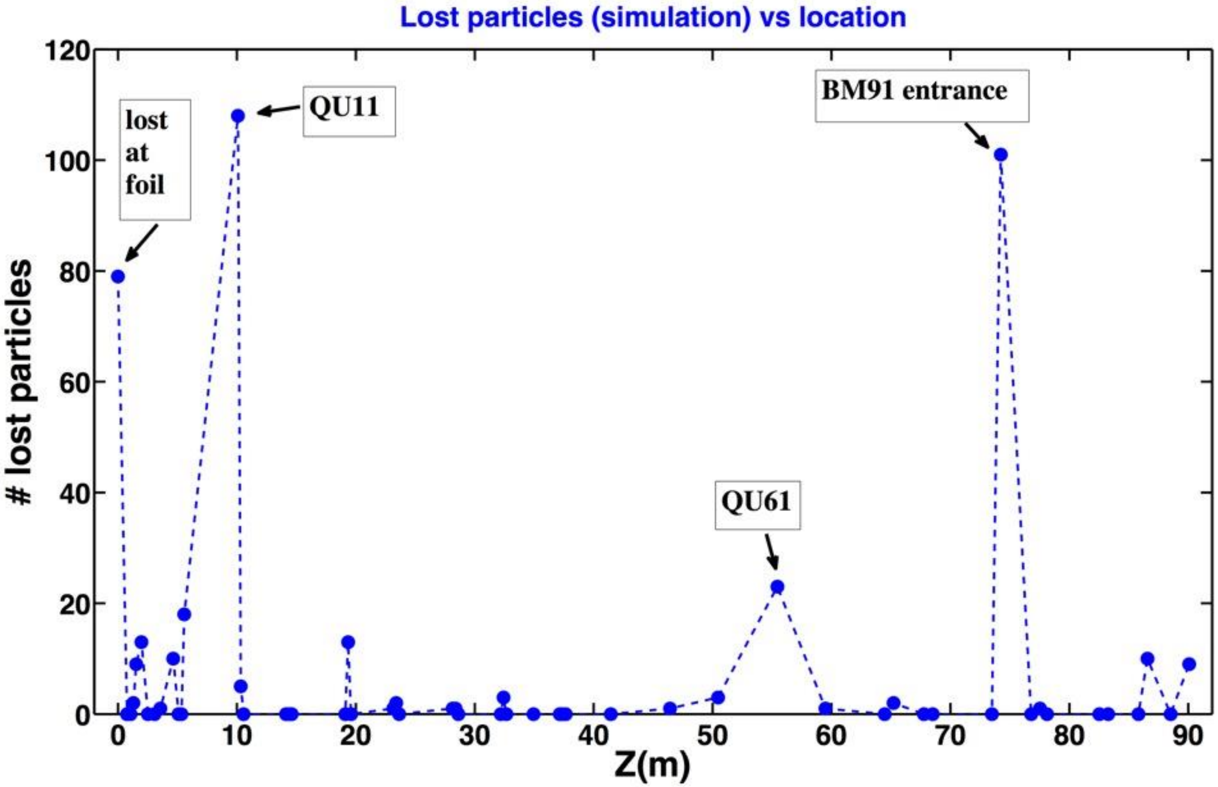
Modeling losses at PSR

- **Use ORBIT (J. Holmes et al, SNS) with MAD8 matrices for the ring lattice model**
- **ORBIT tracking includes nuclear and Coulomb scattering in the foil, space charge effects, painting with programed bump magnets but production and stripping of H0(n) excited states is not included**
  - Losses from H0(n≥3) simulated by manually introducing appropriate angular error for various stark states at entrance to first dipole (1.2 T field) after foil
    - Those for n=3 and most of n=4 lost in first ¼ turn after stripping
  - Use numerous "black" apertures in various magnets to obtain losses of proton beam
  - Use **G4beamline** code (T. Roberts, Muons, Inc.) to model energy deposited in loss monitors with proton loss local distribution from ORBIT as input
    - Energy deposited per lost proton consistent with ion chamber loss monitor calibration; (more detailed example in later slide on the new IR calibration)
- **Example: Model accumulation of 5 μC/macropulse production beam (2/3/14) with measured injection offset (with ~25% error) and measured injected beam phase space distribution (from 2010 experiment)**

ORBIT modeling of production beam losses cont’d

- **Model gave 0.0023 fractional losses (excited state and extraction losses not included) compared to 0.0024 measured total fractional loss (from IR loss monitoring system)**
  - Distribution of lost particles (from simulation) below



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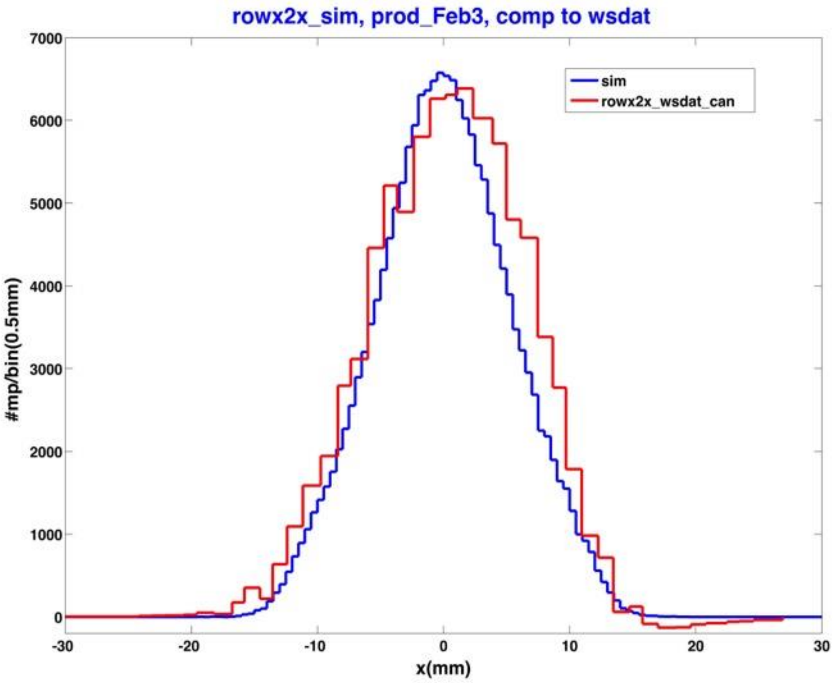
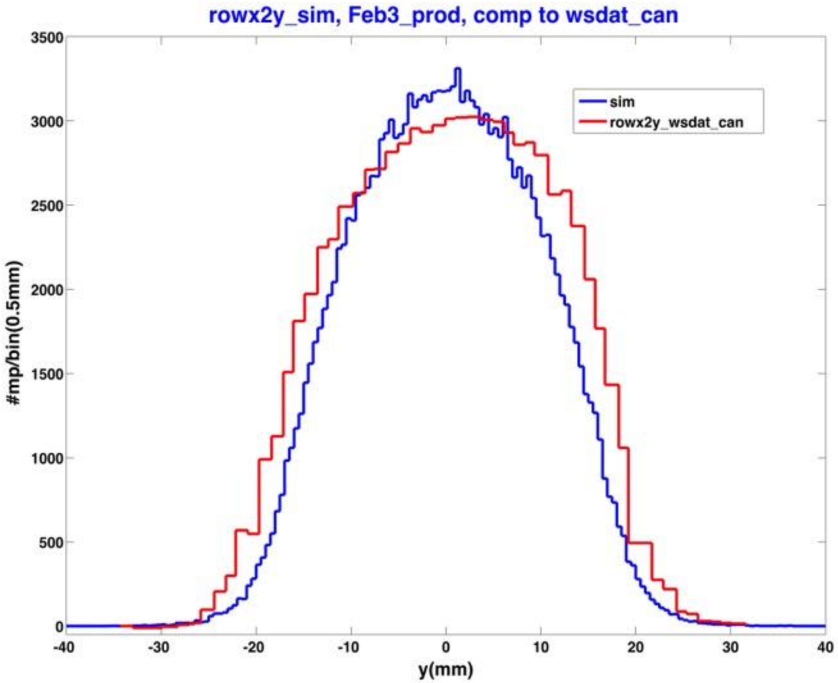
Compare data and simulated profiles at extraction wire scanners

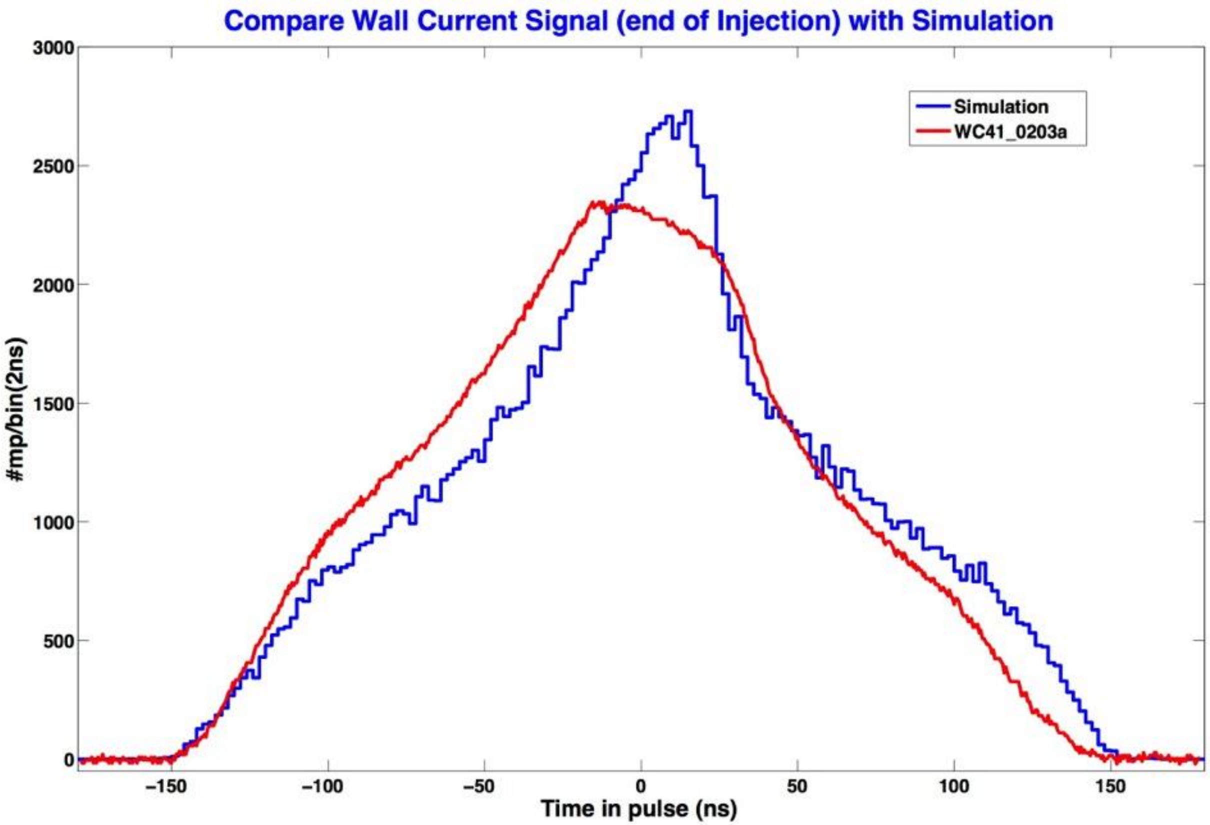
- **Production beam Feb 3, 2014; wire scanners rowx2x, rowx2y**
- **Data in red, simulation histogram blue**
- **Reasonable agreement between data and simulation, given noise in wire scanner position signal**


rowx2x_sim, prod_Feb3, comp to wsdat


rowx2y_sim, Feb3_prod, comp to wsdat_can

Compare simulation and data for longitudinal profile

- **Production beam Feb 3, 2014**
  - Signal (red) from wall current monitor at extraction
  - RF buncher phase shift improves centroid match but increases losses in simulation

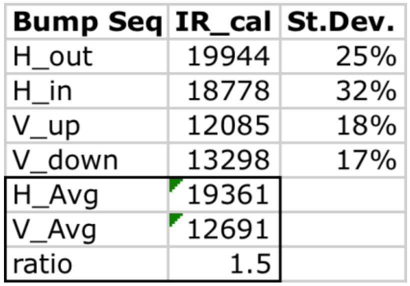


Revised IR monitor “calibration” and uniformity checks

- **Old method: used known intensity of coasting beam with no extraction**
  - Concern: even with various local bumps, losses appear mostly in just a few spots
- **New method: use standard bunched beam accumulation for 625 μs and a short store (100 μs) plus extraction but use large bumps to lose a large fraction (50% or more) of the beam**
  - Use a low intensity beam of ≤ 0.4 μA average current in order to limit activation of ring during the large fractional loss measurements
- **Get a decent measure of lost beam intensity using wall current monitor (SRCM42) signal difference for a low loss, well centered beam and the beam with losses from a large bump**
- **Losses are more localized at calculated bump locations and avoid the uncertainty of loss locations and shielding effects during the long store of the coasting beam calibration method**
  - ORBIT simulations with large bumps show most of the beam is lost in one quadrupole at the bump location

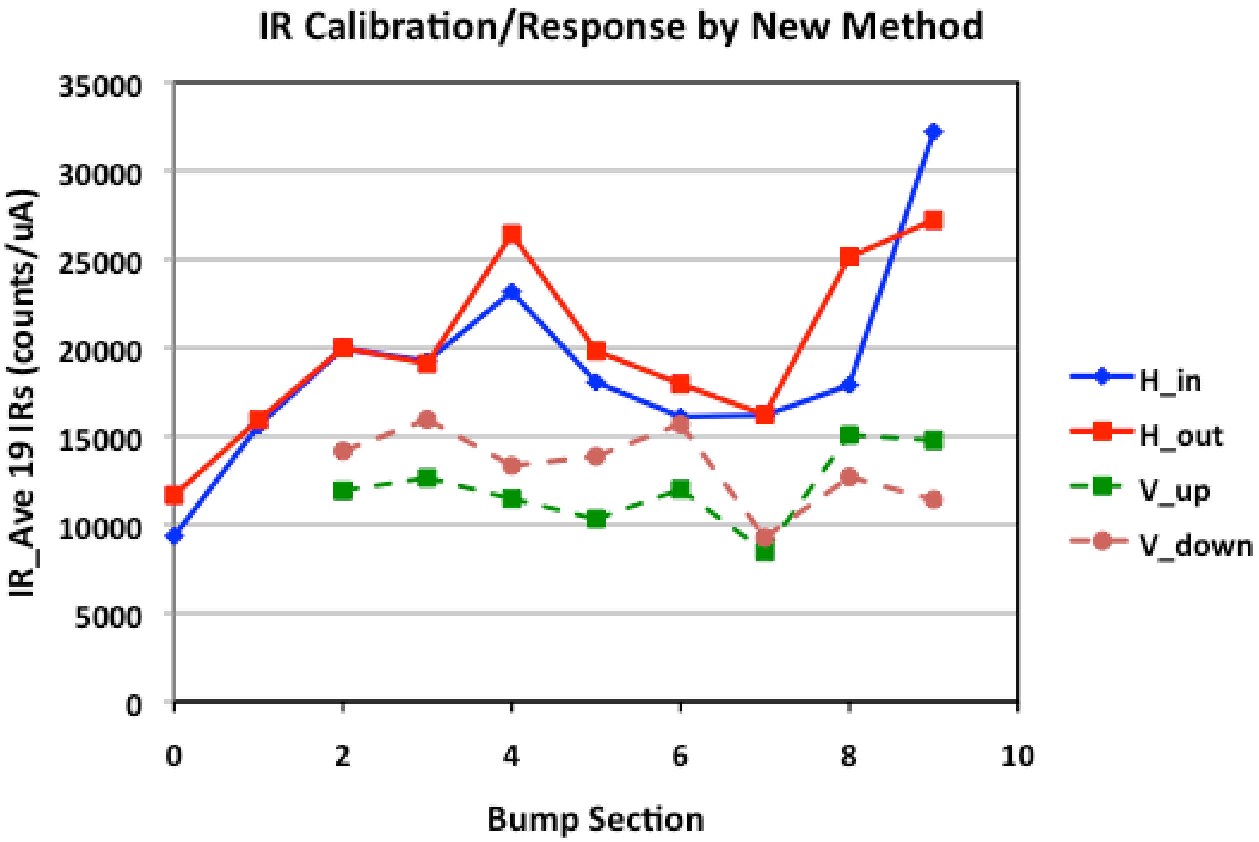
IR System Responses using new method, 10/31/12

- 625 μs, accum.,
  100 μs store
- IR28 excluded from average
- Losses for each bump are well localized for this method
- H_Avg/V_Avg = 1.5



Bump Seq	IR_cal	St.Dev.
H_out	19944	25%
H_in	18778	32%
V_up	12085	18%
V_down	13298	17%
H_Avg	19361	
V_Avg	12691	
ratio	1.5	

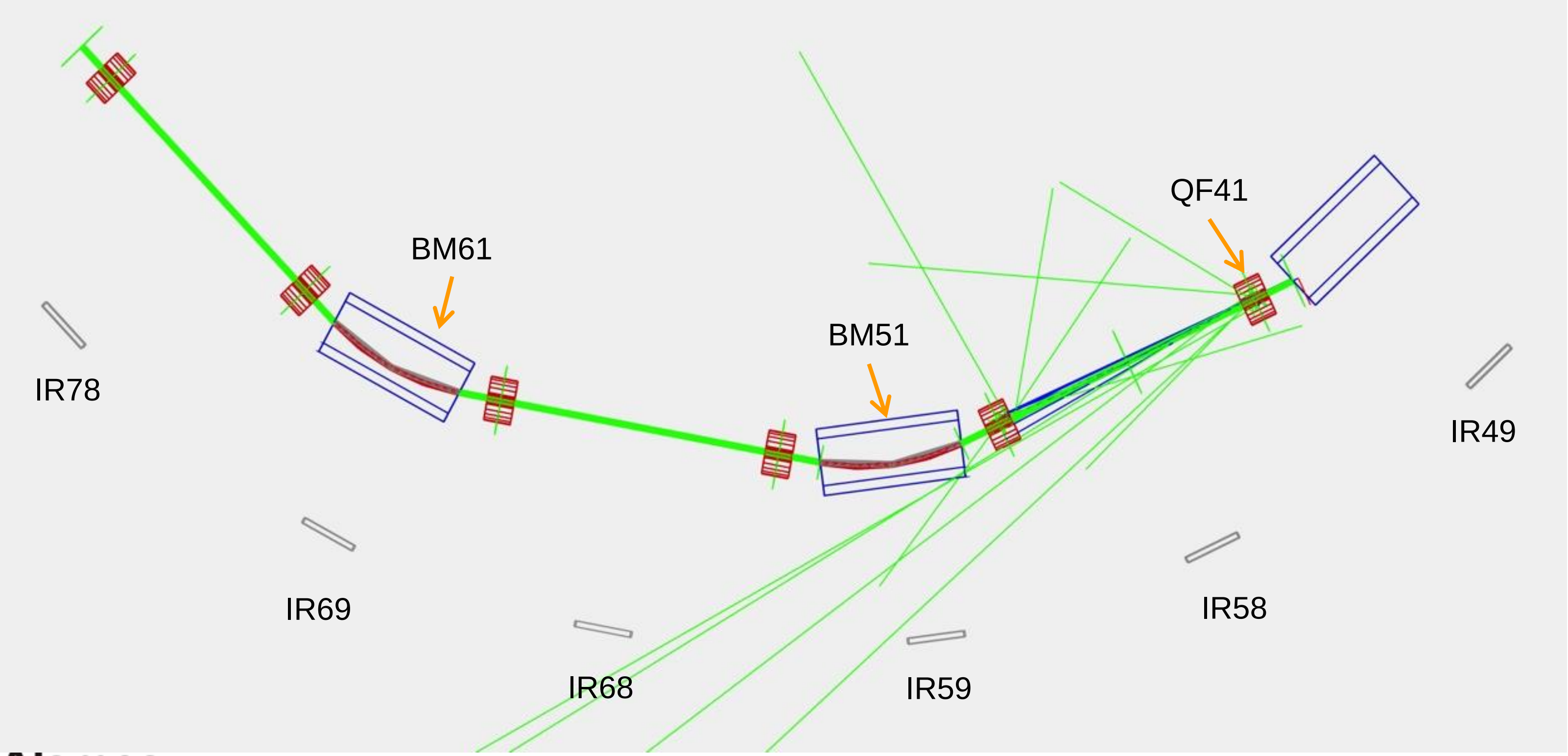
Aug 1998 cal. = 13,596 (counts/μA)



- **No need to change existing calibration from old method, but be aware of the new results on variability; the absolute loss will depend on the actual loss pattern, which does not change much for typical production beams**

G4beamline simulation of loss in SRQF41 for -43 mm H bump

- ORBIT losses in QF41 aperture extrapolated back to point 0.5 m in front of QF41
- Visualization picture shows tracking of 10 lost particles and their secondaries (positives:blue, neutrals:green, negatives:red)
- Energy deposited in various objects tallied in a table



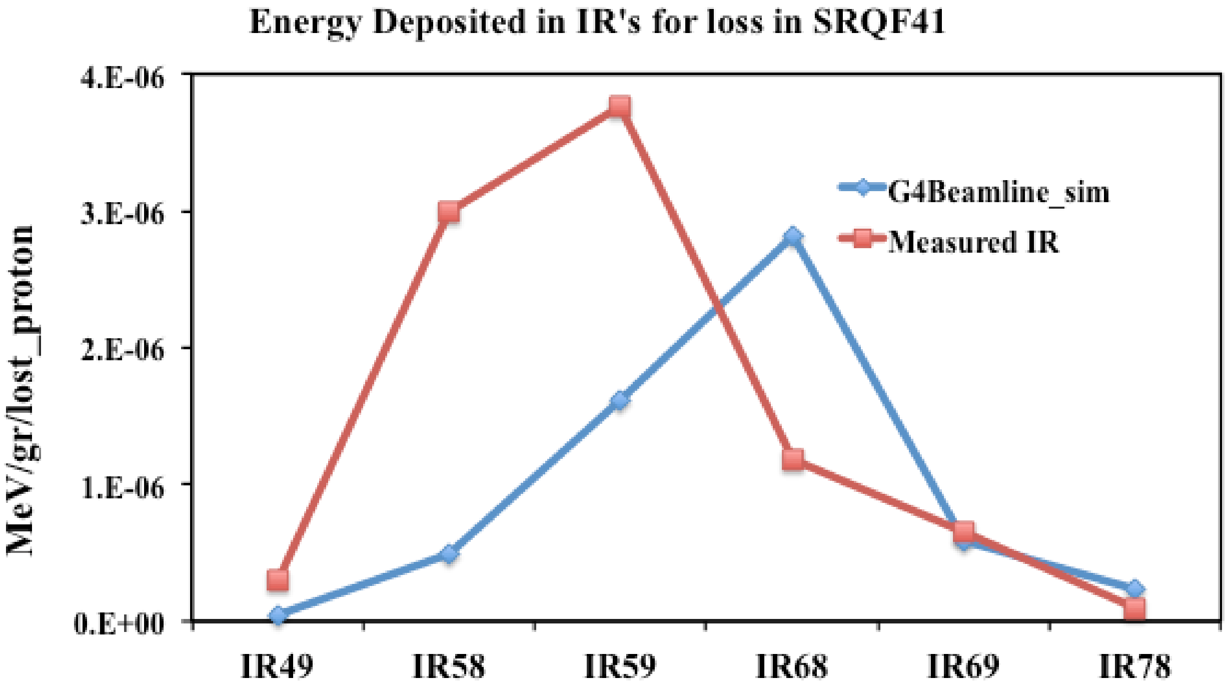
Energy deposited in IR's compared with calibration data

- **Example for -43 mm Horizontal bump in Section 4 (lost in SRQF41)**
  - G4beamline simulation gave **5.78×10^{-6}** MeV/gram/(lost proton) for the sum of 6 IR's (IR49 through IR78)
  - The sum of measured IR signals for this bump gives **8.98×10^{-6}** MeV/gram/(lost proton)
  - Ratio simulation/measured = 0.64

- **Compare distribution of energy deposited in IR's**

Simulation
maximum
shifted by ~1 IR
compared with data

Not too surprising
given the given the
approximations in
material layout



Summary and conclusions

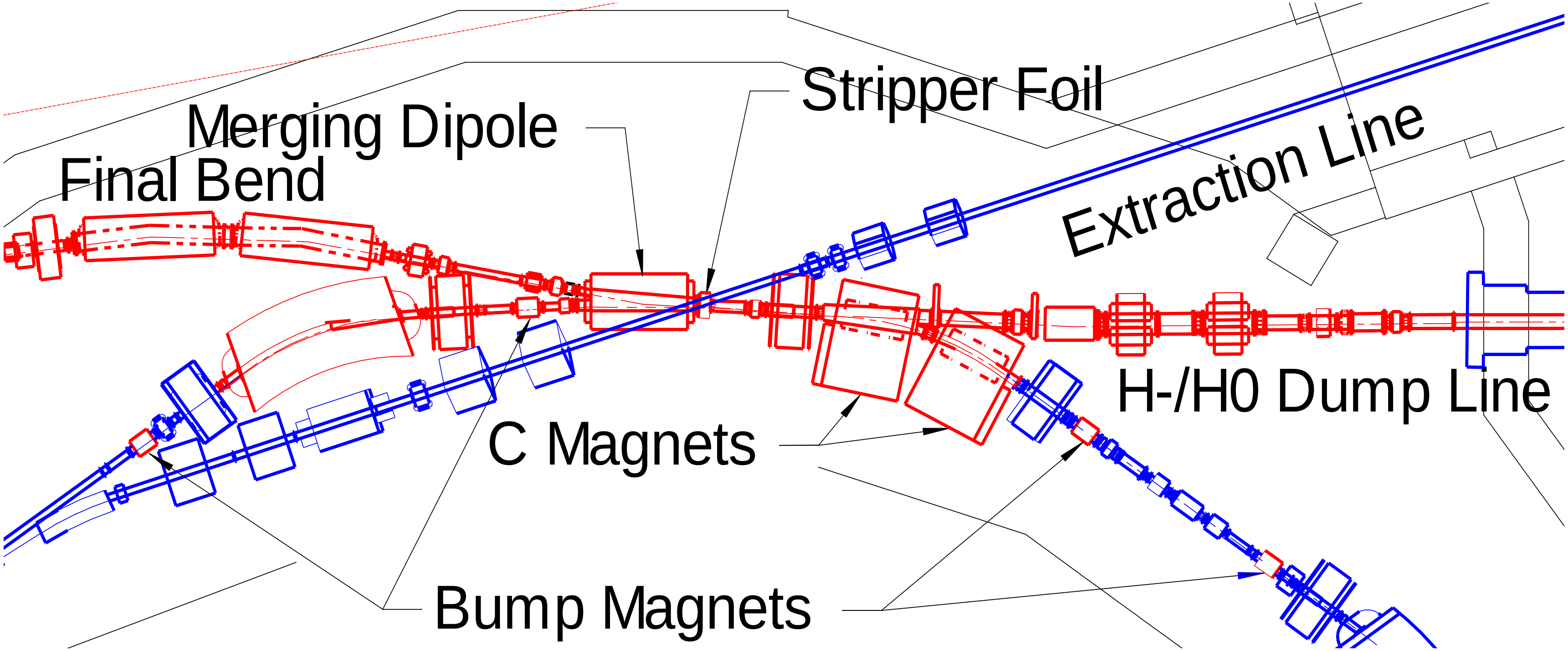
- **The main beam losses mechanisms for PSR have been studied extensively and are now well-understood**
- **Observed fractional beam loss at PSR is typically 0.0025 ± 0.0005 for production beams after empirical optimization by operators**
  - ~75 % of the loss is from foil scattering and the remainder from excited states of H0 and extraction losses
  - SNS has an order of magnitude lower fractional loss but for a factor of 12 higher beam power
- **The combination of ORBIT and G4Beamline are valuable tools for modeling both losses and the loss monitoring system (IRs) response**
  - Beside energy deposited in IR's, G4Beamline gives distribution of secondaries striking down stream chamber walls, which is needed for modeling electrons for the e-p instability

Future prospects

- **Various improvements to accumulators rings (more aperture, adequate space for separation of H0, H- and H+ beams, continued foil development, use of collimators and active damping of the e-p instability) along with careful attention to detail could lead to ~2-3MW beam power (at ~1GeV) for short pulse spallation sources using H- foil stripping injection.**
- **Injection by laser stripping of H- could solve the major problem of losses from beam interactions with foil, thus permitting even higher intensity.**
  - Proof of principle experiments at SNS are encouraging but many practical issues for reliable implementation in the demanding accelerator environment are likely to take much hands-on experience to identify and resolve
- **A key issue for a short-pulse spallation source at >2 MW beam power is target reliability and lifetime.**
  - 2MW may be the practical limit for short-pulse spallation neutron sources
- **ESS is a long-pulse spallation source designed for 5MW, is now under construction and is a promising future direction for high-power spallation neutron sources.**

Backups

PSR Injection Layout today



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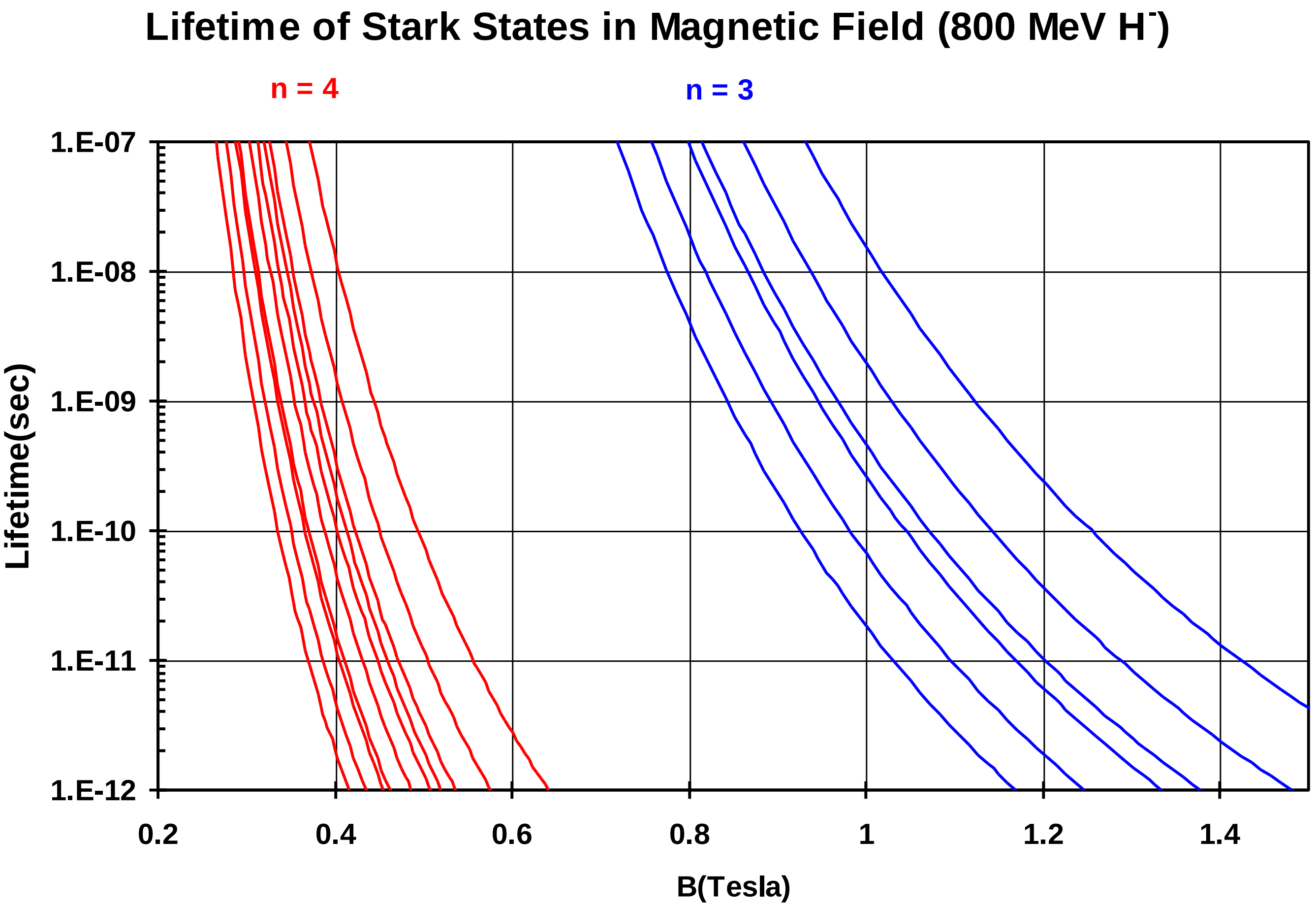
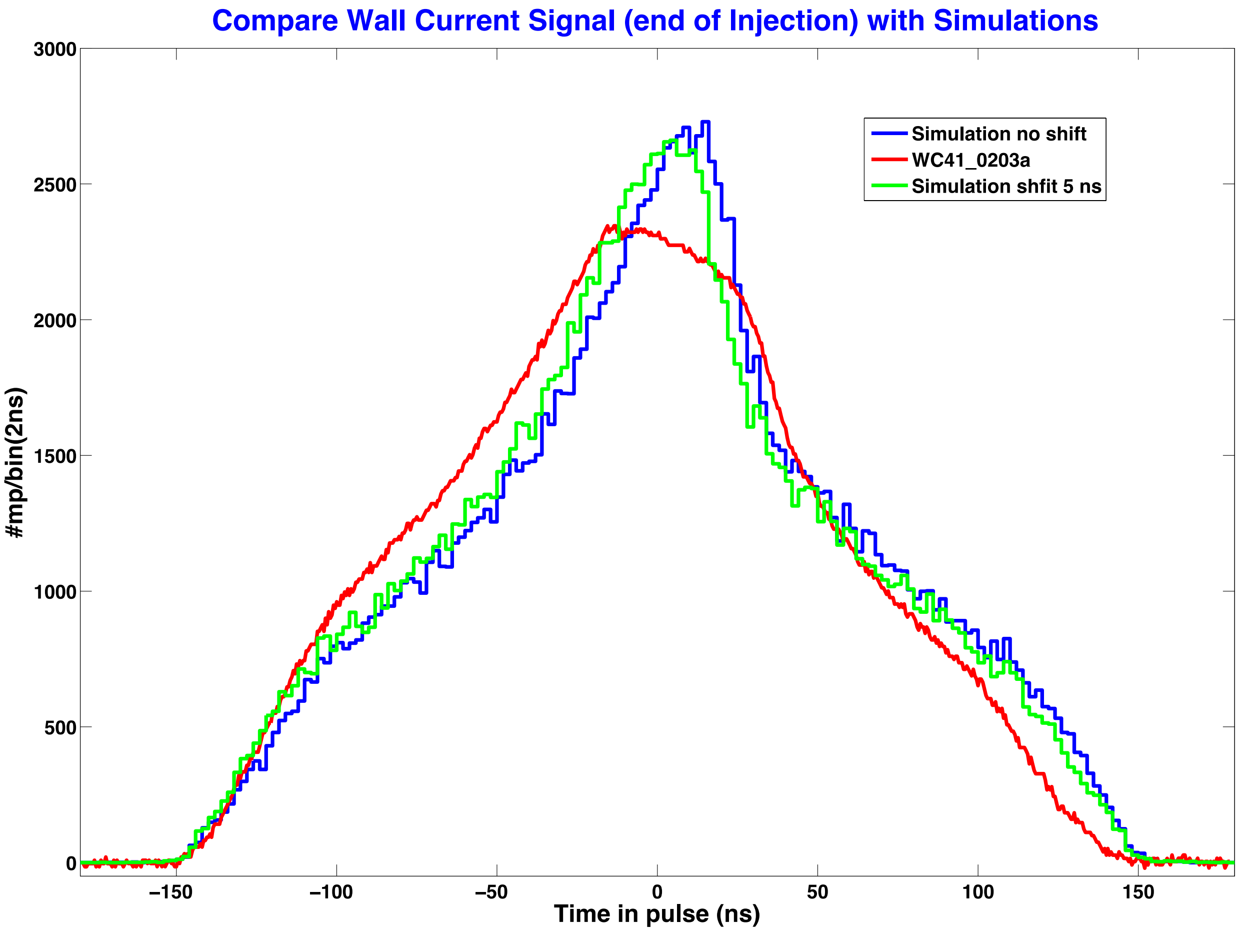
Lifetime of Stark States at PSR

From calculation using Damburg Kolosov formulas



Add result of changing buncher phase 5 deg in sim

- **Production Feb 3, 2014**



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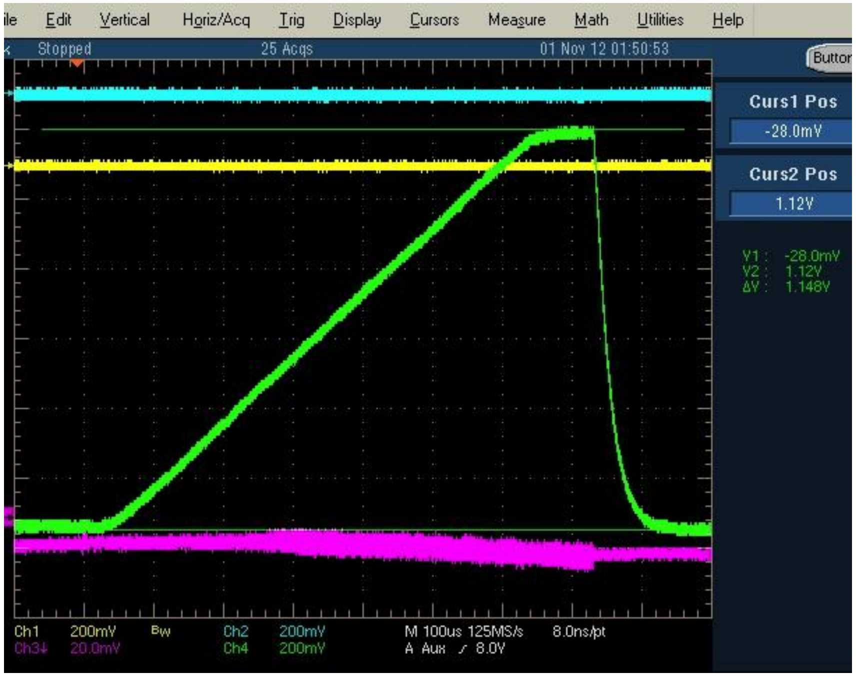
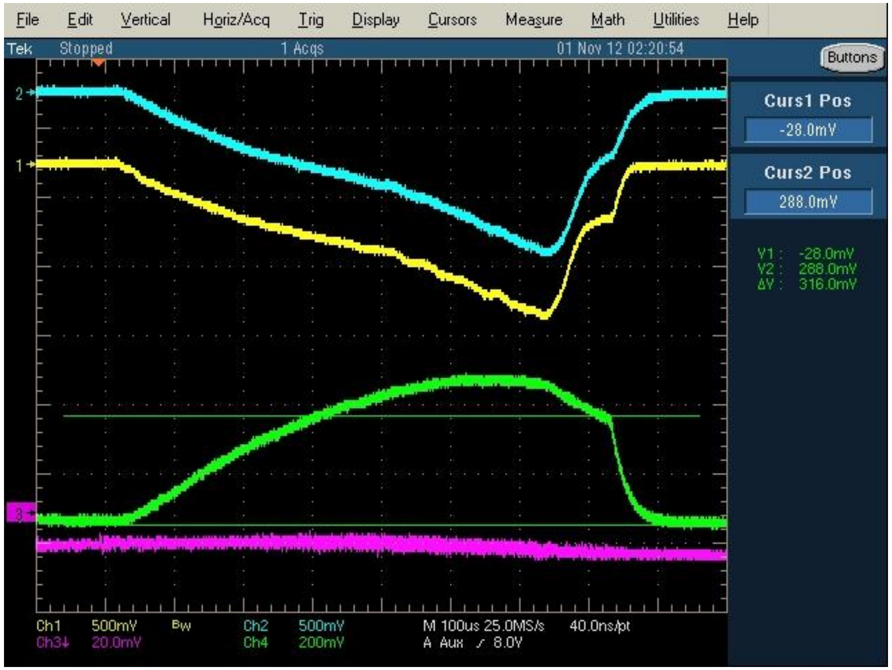
Measure lost current with SRCM42 (green trace)





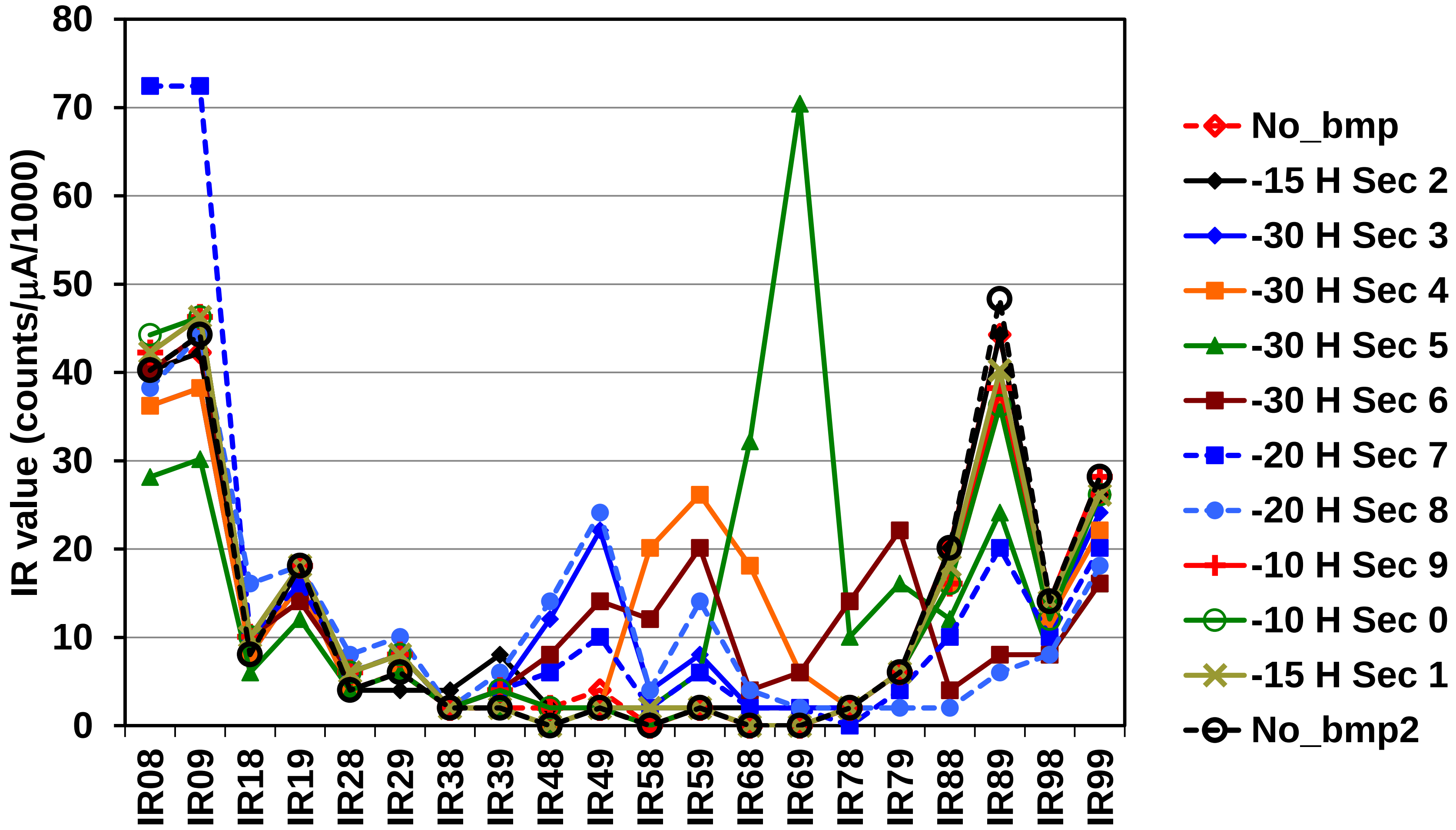
No bumps, standard accumulation, measure current at extraction

H bump out -45 mm sect 2, measure current at Extraction

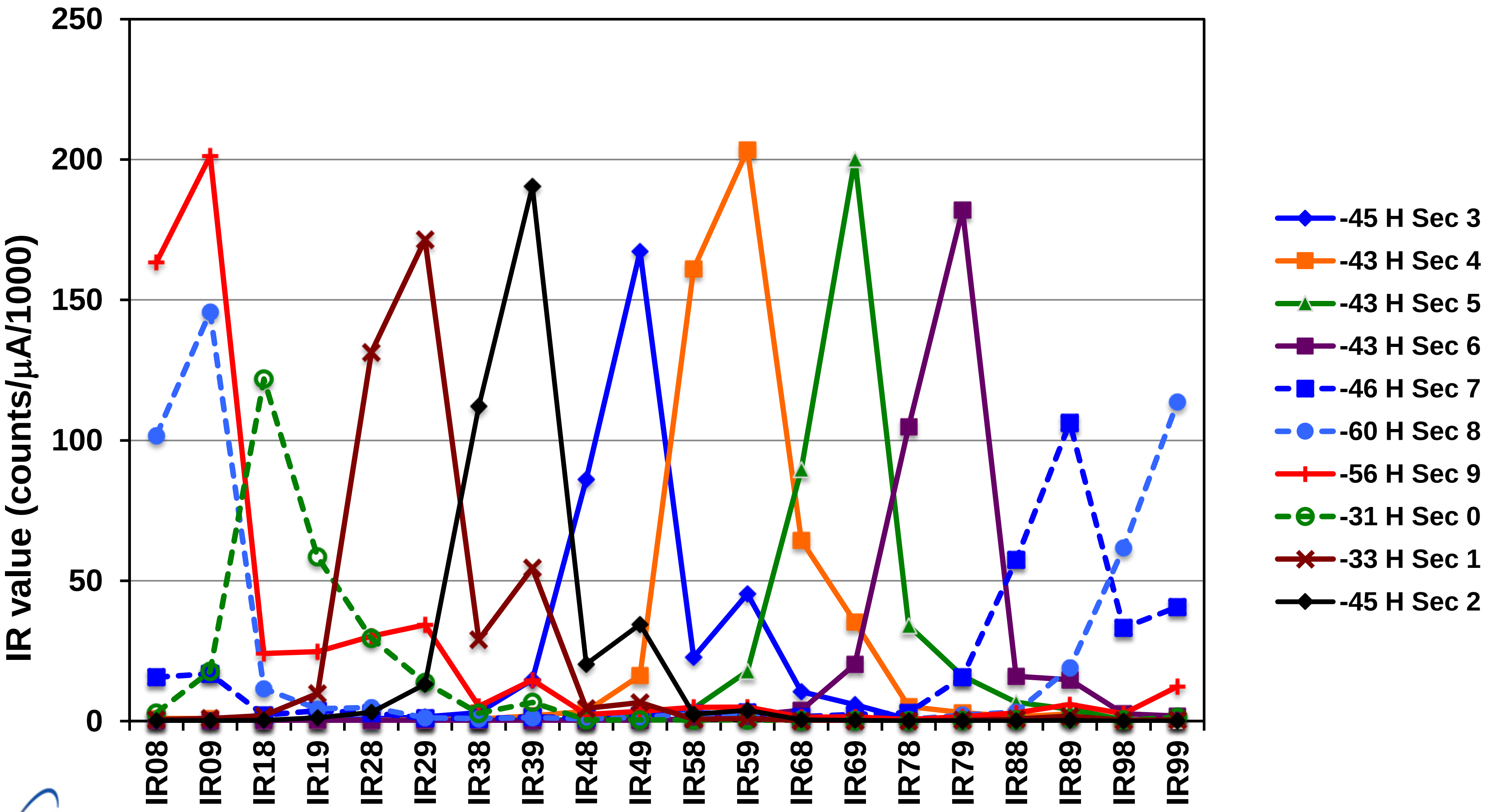
LMsum signal blue

LM39 signal yellow

IR Response Patterns for H “out” bumps for 1998 Calib.



IR patterns for H “out” bumps, new calibration method



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Control of the two-stream e-p instability at PSR

- **Principle Characteristics**
  - Transverse coherent beam motion driven by electron cloud
  - Main electron source: amplification of “seed electrons” (from beam losses etc) by trailing edge multipactor; with ejection from Quadrupoles by ExB into drift spaces
  - Amplitude growth times ~ 50-150μs (75μs typical)
  - Frequency 100-250 MHz (bounce frequency of electrons in beam potential)
- **Controlled mainly by Landau damping from the momentum spread generated by higher rf buncher voltage**
  - Threshold intensity a linear function of buncher voltage for fixed bunch width, fixed accumulation time and fixed injection offset
- **The higher momentum spread to control e-p means larger horizontal beam size and some extra beam loss in the ring and extraction line**
- **Inductive inserts largely compensate longitudinal space charge and keep beam out of the gap between bunch passages**
- **Active damping by transverse feedback was demonstrated at PSR**