High Intensity Proton Accumulators

(R. Macek,7/3/01, Snowmass)

- Introduction
- Beam losses and their mitigation
  - Foil scattering
  - Excited states of H^0
  - Collimation
- Foil technology issues
- Transverse space charge effects
- 2-stream e-p instability
- Inductive inserts
- Conclusions

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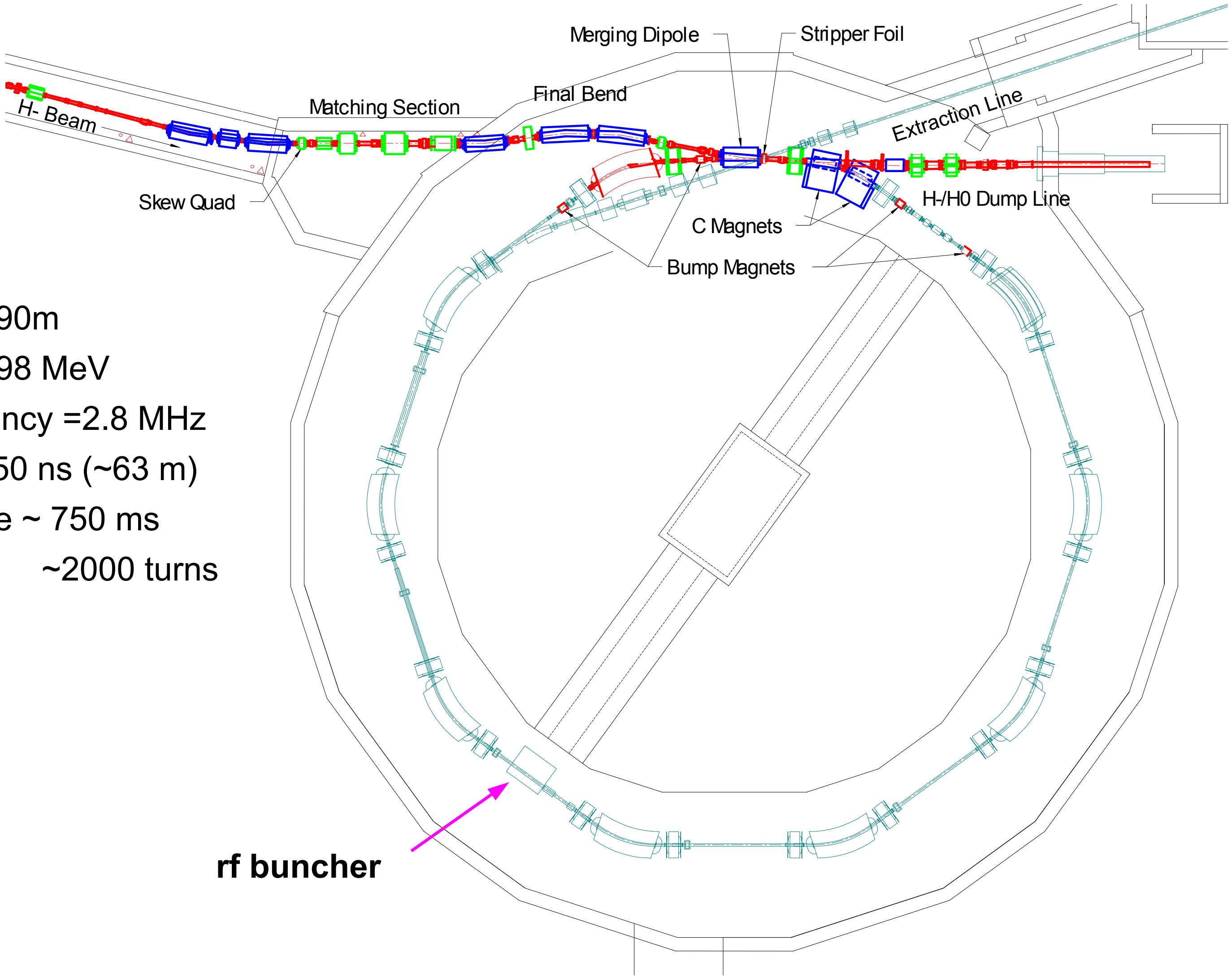
Introduction to DC Accumulator Rings (PSR,SNS,ESS)

- **Mission: highly reliable, high-intensity proton driver for short-pulse spallation neutron source**

- **Distinguishing characteristics**
  - **≥ 1000 turns of injection via H^- stripping**
  - **$E_{inj} = E_{final}$**
  - **High intensity (0.1- 2 mA throughput)**
    - **(0.3 – 2×10^{14}) single bunch, 0.25-1.0 μs long @ 10 – 60 Hz rep rate**

- **3 examples**
  - **PSR (LANL) operating since 1986 and providing numerous lessons for the next machines**
    - 3×10^{13} ppp @ 20 Hz, 0.8 GeV, 80 kW
  - **SNS under construction**
    - 1.7×10^{14} ppp @60 Hz, 1.0 GeV, 2 MW
  - **ESS conceptual design for 2 rings**
    - 2.3×10^{14} ppp @50 Hz, 1.33 GeV, 5 MW

PSR Layout



Circumference = 90m

Beam energy = 798 MeV

Revolution frequency =2.8 MHz

Bunch length ~ 250 ns (~63 m)

Accumulation time ~ 750 ms

~2000 turns

rf buncher

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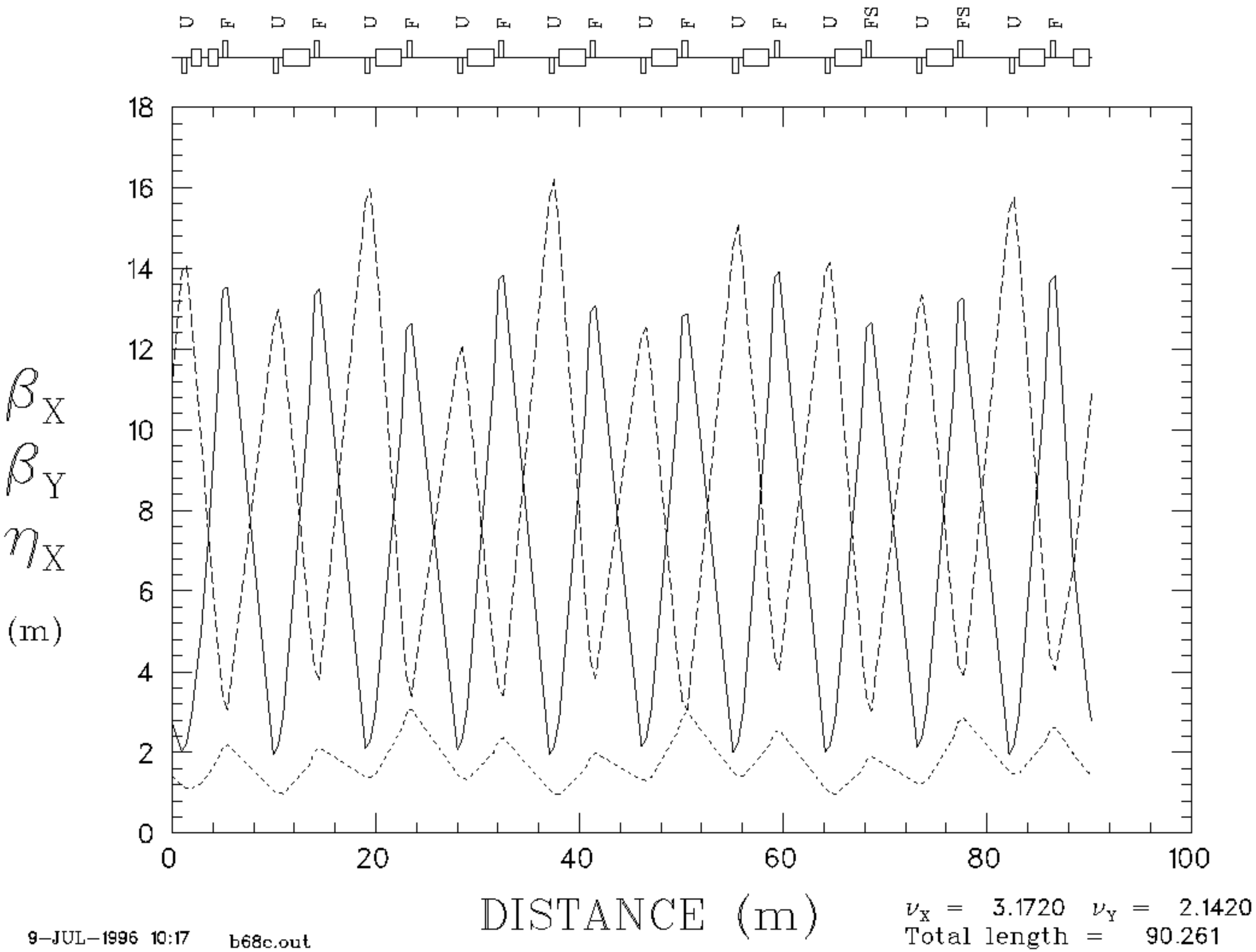
PSR Lattice functions (1998)



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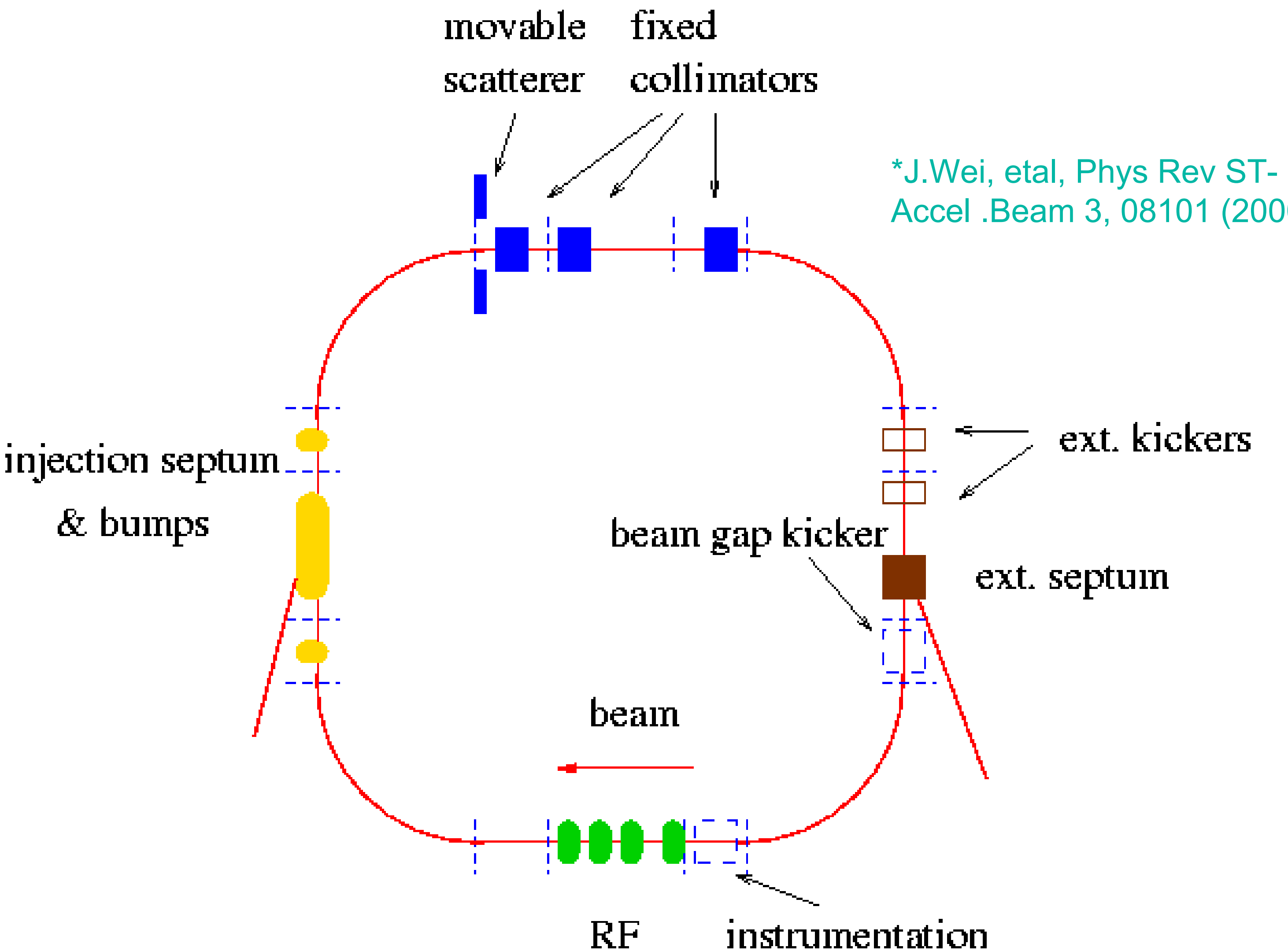
SNS Ring Layout*

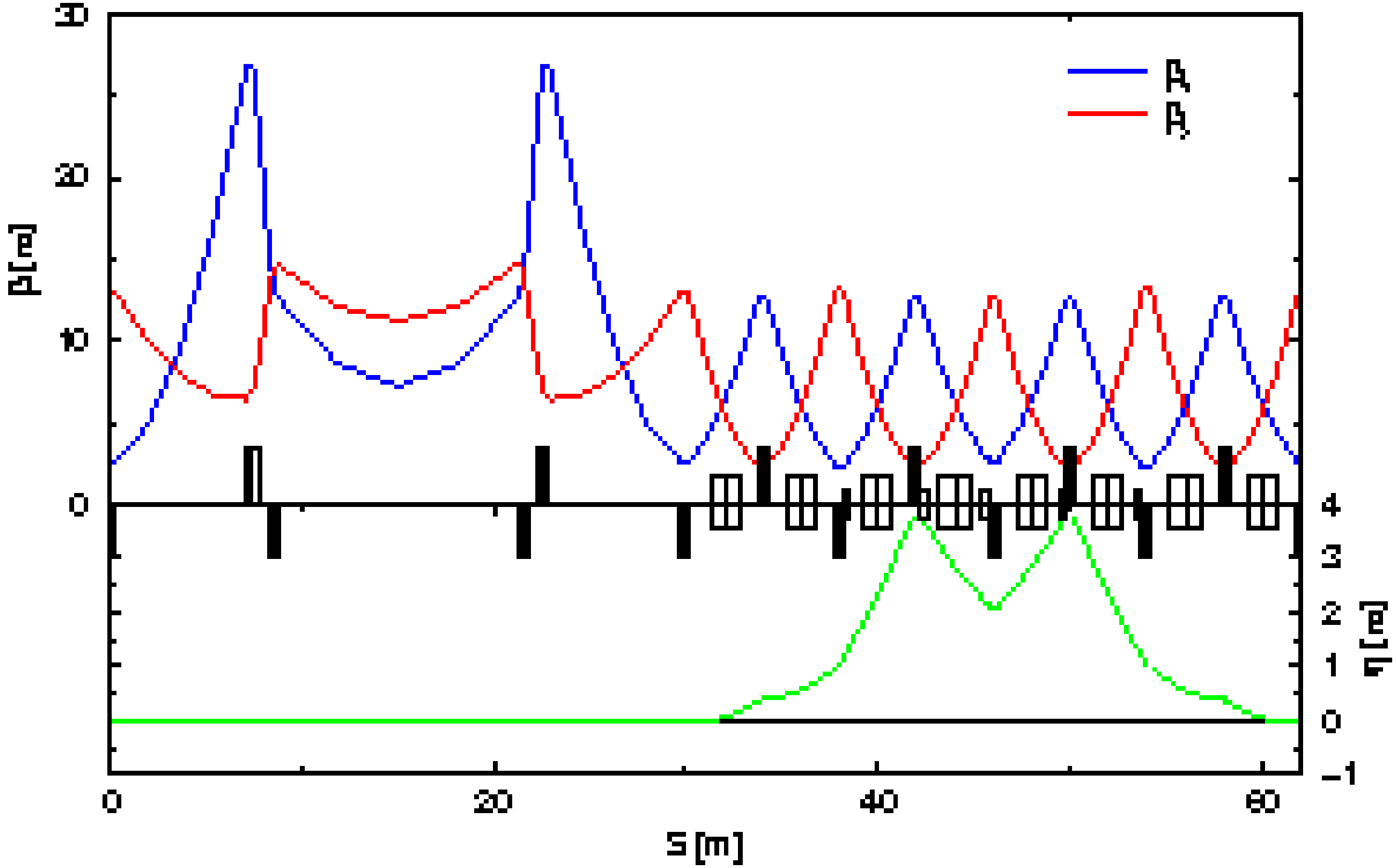
(courtesy Jie Wei)

*J.Wei, etal, Phys Rev ST-Accel .Beam 3, 08101 (2000)



SNS Lattice Functions

Working point (6.40,6.30)



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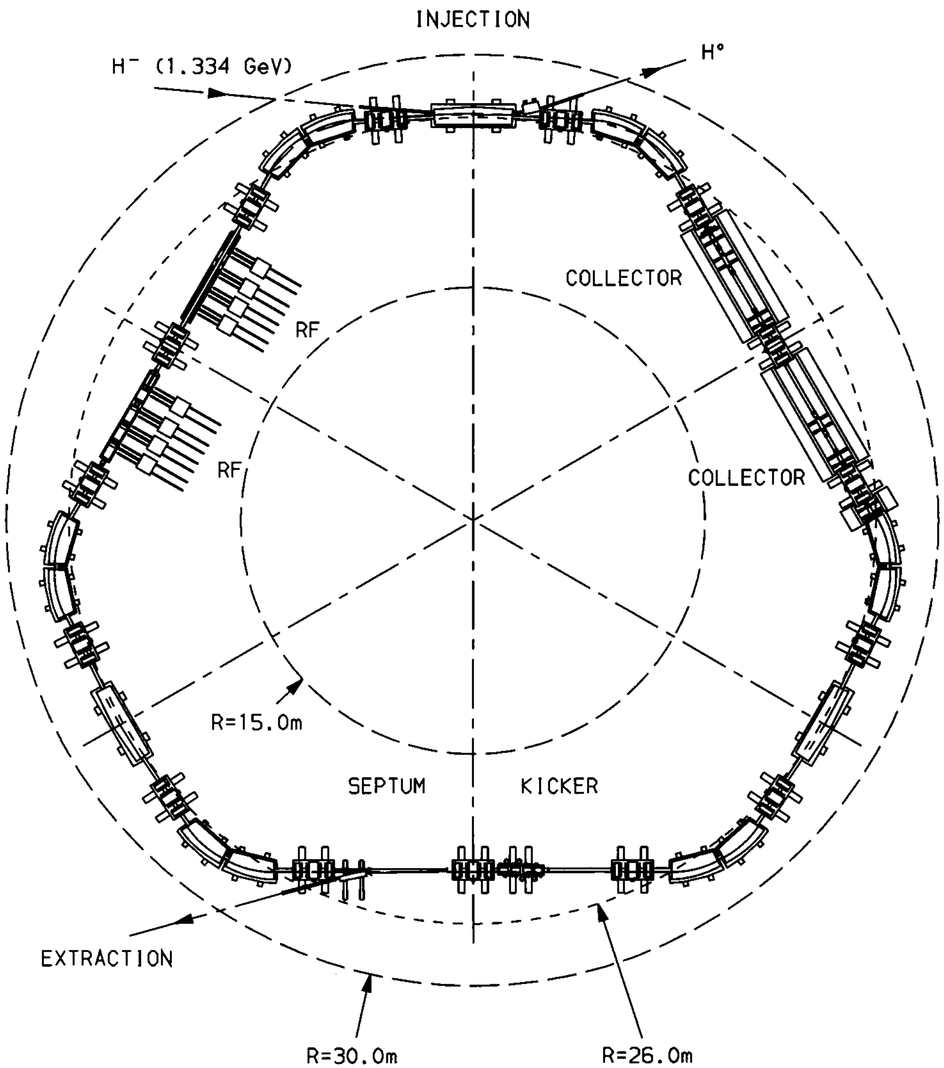
ESS Ring Layout



Uncontrolled beam losses

- Arguably the most challenging problem with these machines
  - ~300 nA (0.3%) uncontrolled losses at PSR mostly in 3 sections (~ 25 m) around injection and extraction
  - Up to 50 Rem/h hot spots, 1-5 Rem/h at 30 cm at injection section
- ~60% of uncontrolled loss at PSR from nuclear and large angle Coulomb scattering from foil
  - Keep beam off the foil as much as possible with optimized injection painting
    - ~ 50 hits/proton at PSR, 6-7 hits/proton in SNS and ESS designs
  - Large acceptance helps contain more of the Coulomb scattering
- Losses from excited states of $H^0(n)$
  - $H^0(n)$ field-strip part way into the down stream magnet
  - Yield $\propto n^{-3}$
  - 20 - 40% of losses at PSR
  - Reduce by using low magnetic field and placing foil in a field
- Losses from space charge emittance growth

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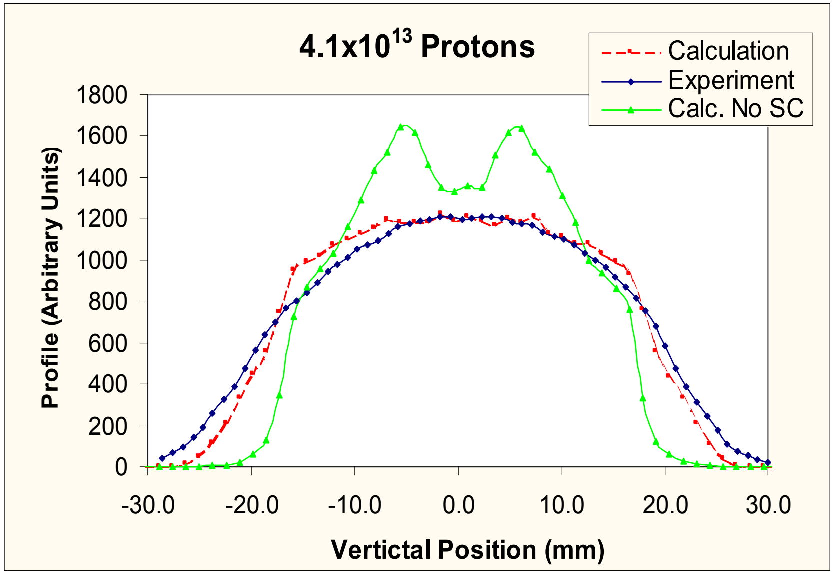
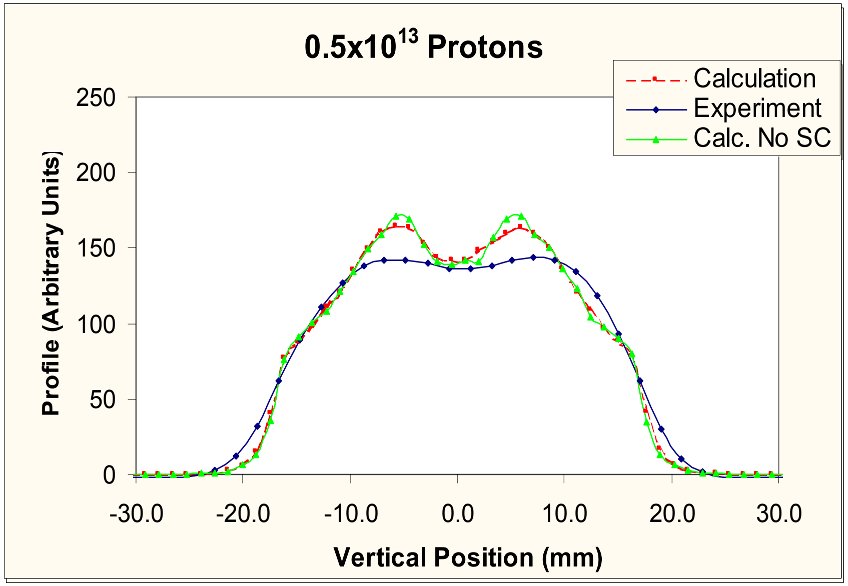
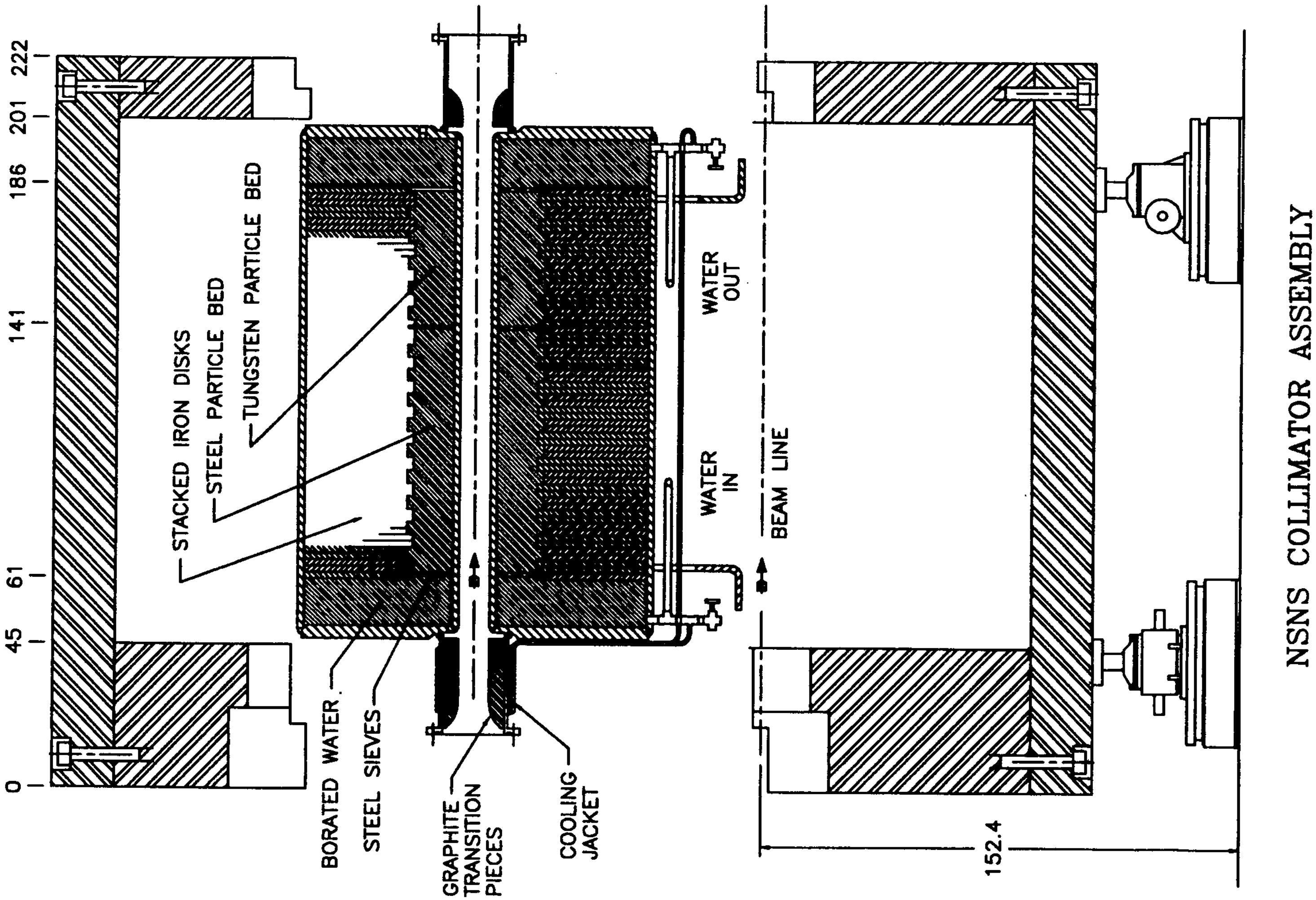
Emittance growth from Transverse Space charge

- **Vertical profiles from PSR compared to ORBIT simulations (courtesy J. Galambos & J. Holmes 1999)**





SNS Collimator



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Stripper Foils

New (4 layer)

Used (2 layer, 1997)

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e-p instability and electron cloud effects

- Strong, fast, transverse instability that limits peak intensity at PSR*
  - Growth time ~ 75 μs or ~200 turns
- Now seen at several machines but not ISIS
- Can be roughly understood in centroid model of coupled motion of electrons and protons (Zotter and Neuffer)
  - Unstable modes (n-Q) close to Q_e (ratio of electron bounce frequency to Ω_0)
  - Threshold condition with Landau damping in rough agreement with observation
  - For a bunched beam, Neuffer assumed trapping of e's by beam in the gap
- Source of electrons and electron density in the beam are the main remaining unknowns
  - Need ~ 1% neutralization to explain observed thresholds
  - Program of measurements underway at PSR using retarding field analyzers (RFA) and various collections plates

* See R. Macek, etal, PAC 2001, FOAB007

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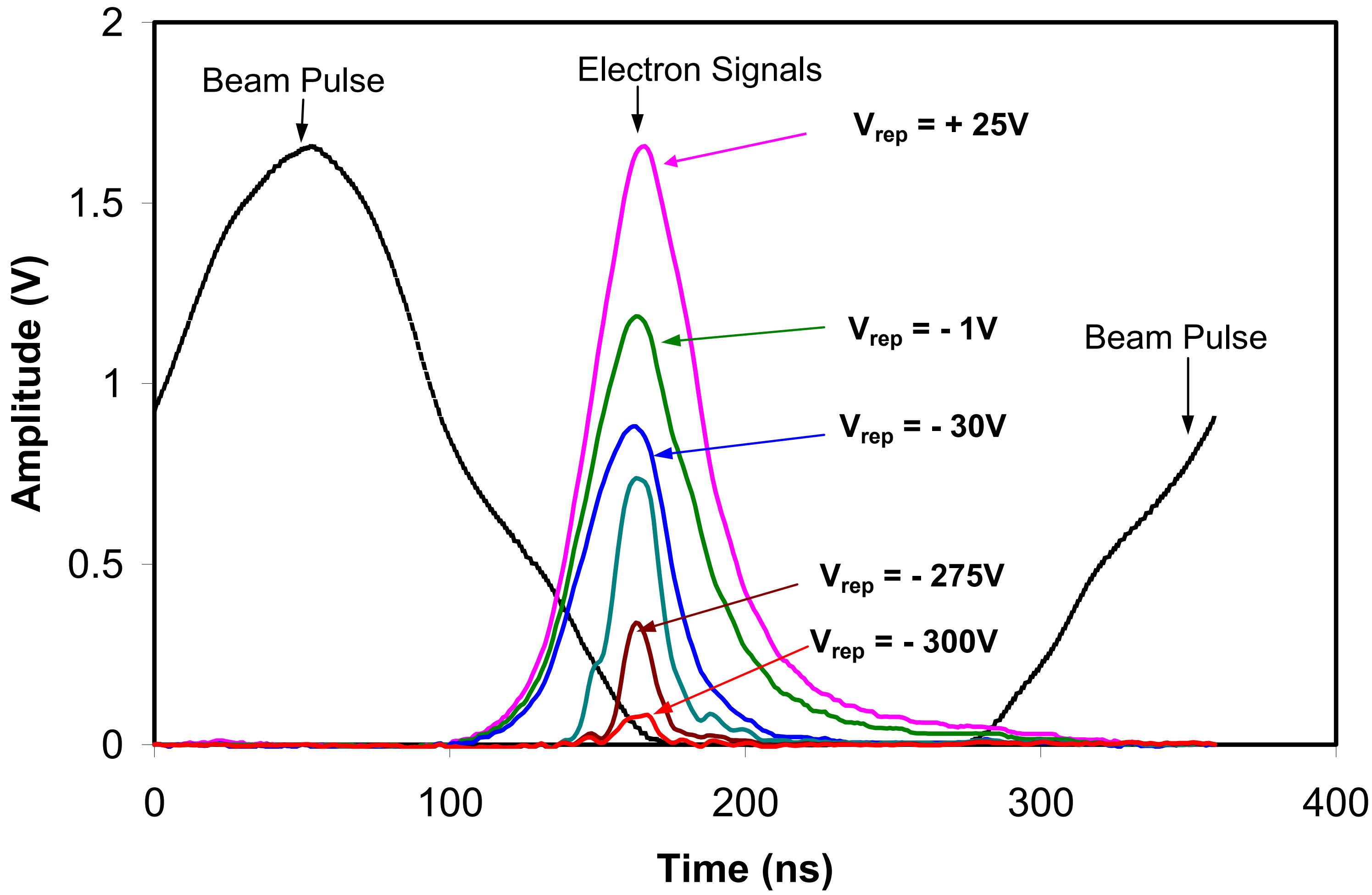
RFA Electron signals in a straight section



Summary of main electron cloud observations at PSR

- **Characteristics of the electron cloud**
  - Electrons strike the wall in pulse near the end of the beam pulse with energy spectrum that extends beyond 250 eV
  - High electron flux everywhere, including inside a dipole and a quadrupole
  - Higher flux for unstable beams
- **Measured dependence on location, beam intensity, beam pulse shape, local beam losses and vacuum pressure**
  - Electron flux increases with beam intensity, local beam losses and vacuum pressure
- **Electron cloud observed in the extraction line has same characteristics as in the ring**
- **Tested effect of TiN coating: factor of 100 or more suppression**
- **Other observations**
  - Vacuum pressure rise for high intensity pulses (8 μC/pulse)
  - Conditioning effect on instability threshold curves

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What do the observations mean for e-p?

- Great deal of data on the characteristics of the cloud and factors influencing it but lack a direct measure of what counts the most – the electron density in the beam
- Trailing edge multipactor mechanism can account for a good fraction of the flux striking the walls
  - Suppression by TiN
  - Single pass electron signal in extraction channel similar to the ring signals
- We expect the simulations of Furman and Pivi will be most helpful in interpreting the electron cloud data
- Some remaining puzzles
  - Instability threshold does not track the strong intensity dependence of the electron signal (I^6) seen in several locations
  - Instability threshold does not track the increase in electron signal from increases in vacuum pressure or beam losses
- Have built a new detector (electron sweeper) to measure electrons surviving the gap

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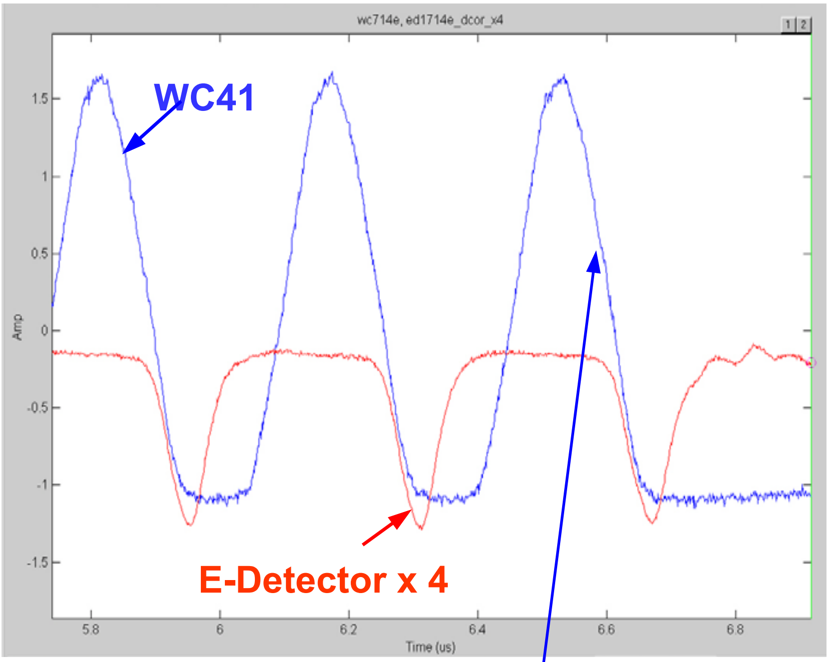
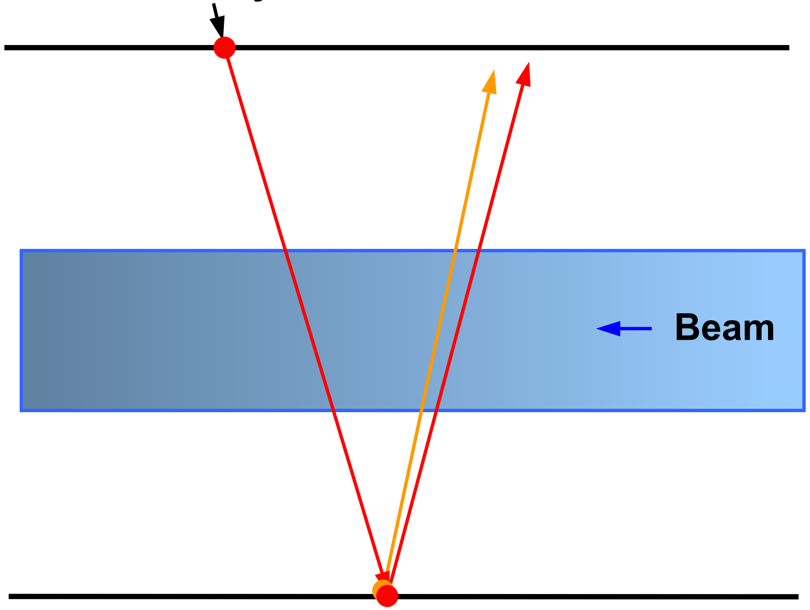
“trailing edge” multipactor



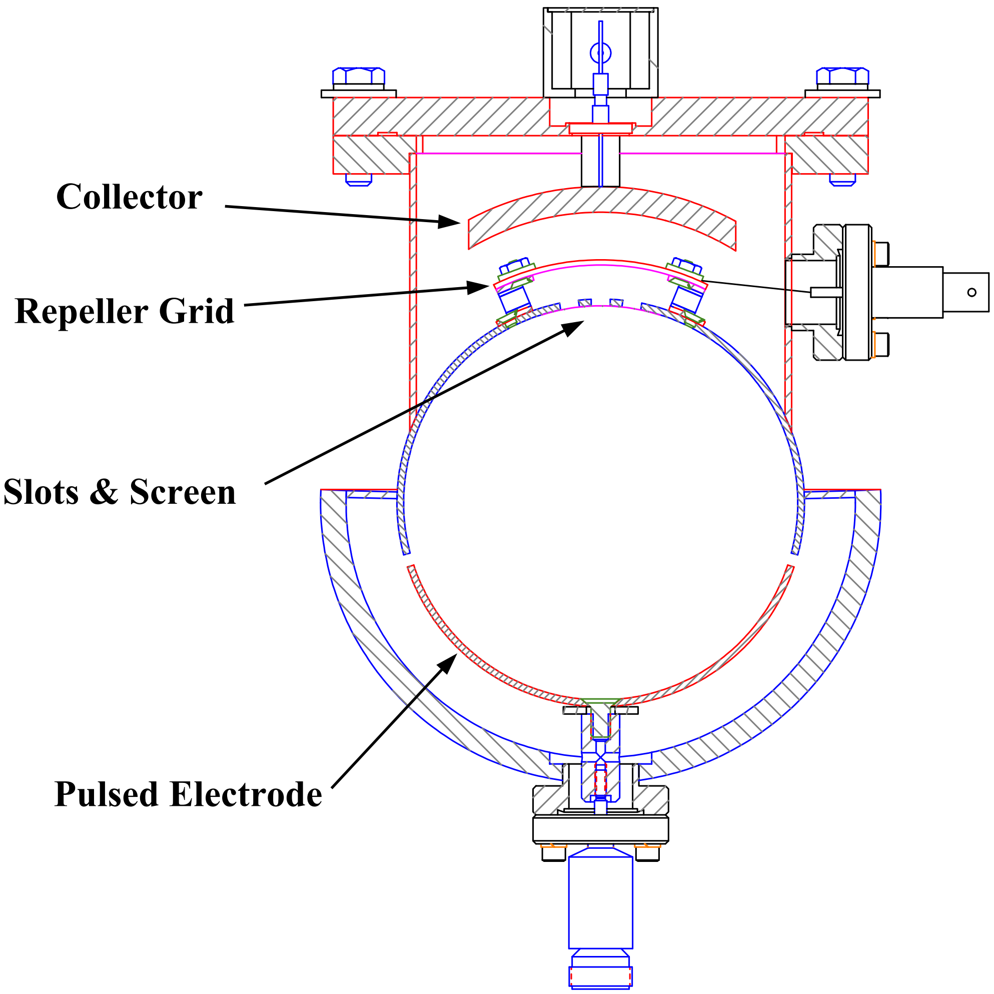
Energy gain is possible in wall-to-wall traversals on trailing part of beam pulse

Electron born at wall from say losses



Energy gain in one traversal is high enough for multiplication

Electron-sweeping detector

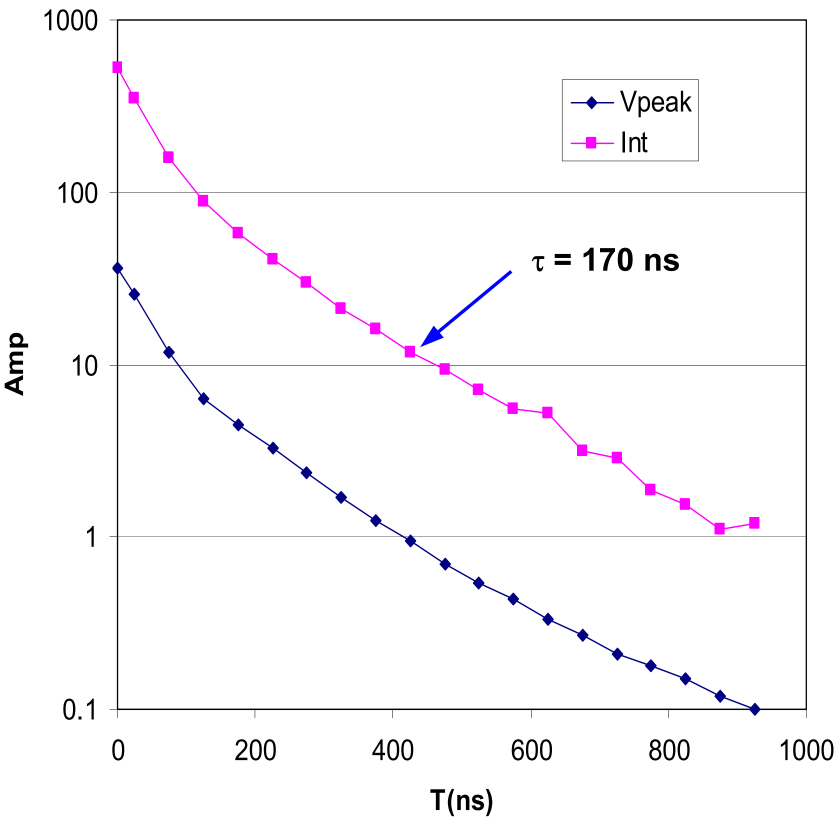


Signal

- **Xerox of log book**

Electrons in pipe vs time after end of beam pulse

- **Preliminary results** for 5 μC/pulse looking just after extraction
- Long exponential tail seen with 170 ns decay time
- Still see electrons after 1 μs
- Implies a high reflectivity for low energy electrons
- Implies neutralization lower limit of ~1.5% (to be refined)
- We look forward to studying the correlations with the “multipactor” electron signal and beam intensity, etc



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Known or conjectured remedies for e-p

- **Clean gap**
  - rf, inductive inserts
  - gap kicker
- **Landau damping from higher rf voltage (higher momentum spread), inductive inserts, multipoles, and XY coupling**
- **Suppress electron generation**
  - TiN coatings, solenoid windings
  - good vacuum, low losses
  - collect electrons from the foil
- **Wide-band active damping**

Use of Inductive Inserts for compensation of longitudinal space charge

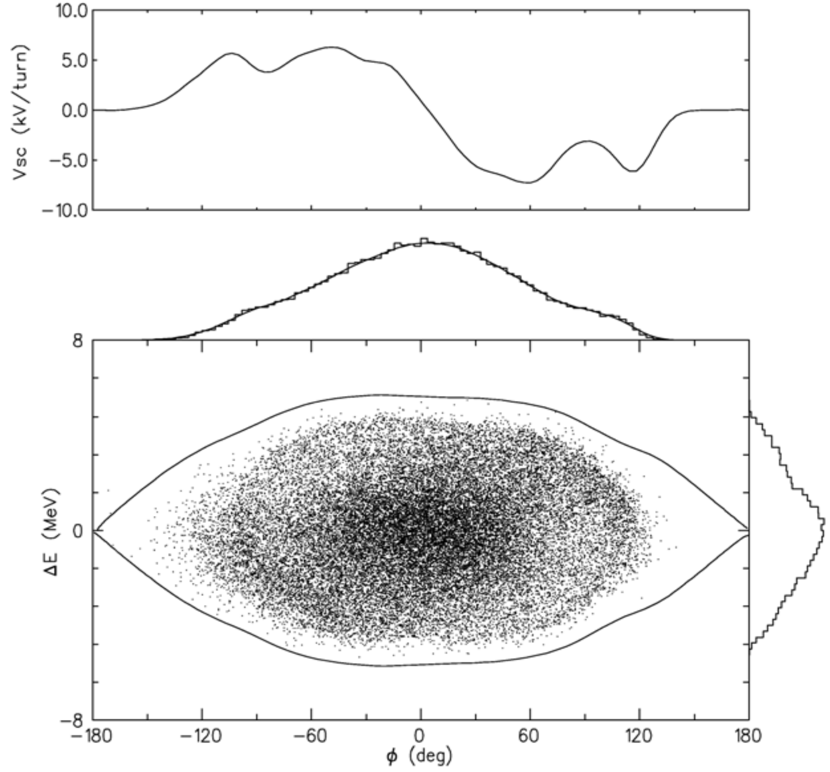
- **Being considered for the FNAL proton driver project**
- **Idea is to add ferrite to increase wall inductance to cancel longitudinal space charge voltage per turn**

$$V_s = \frac{\partial \lambda(s)}{\partial s}\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \Omega_0 L\right] e\beta c R$$

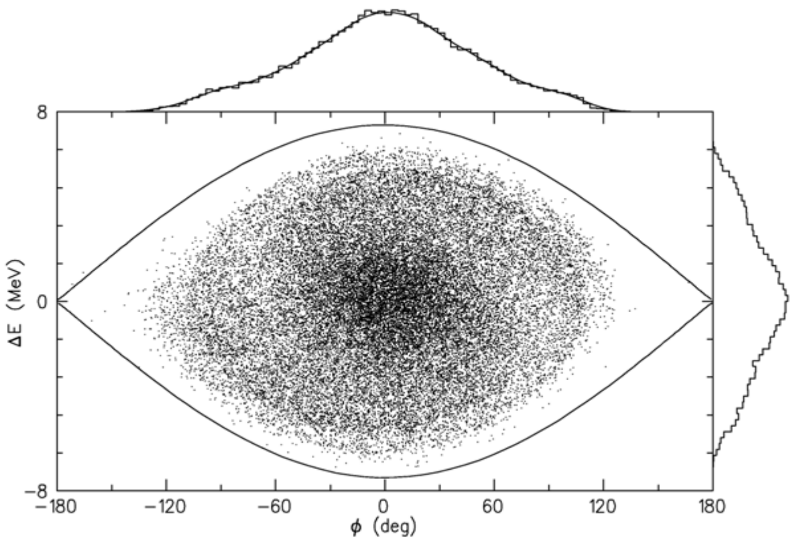
- **At PSR the motivation was to help control the e-p instability by preventing beam from leaking into the gap and increasing the momentum spread (more Landau damping)**
- **Ferrite inserts were effective at PSR after a longitudinal "instability" (resonance) was cured by heating the ferrite**
  - **Cleaner gap**
  - **Increased e-p instability threshold by ~30%**
  - **Allows operation with 15-20% longer bunch**

ACCSIM simulations with longitudinal space charge at PSR

No longitudinal space charge compensation (7.3 μC)



Space charge completely canceled (7.3 μC)

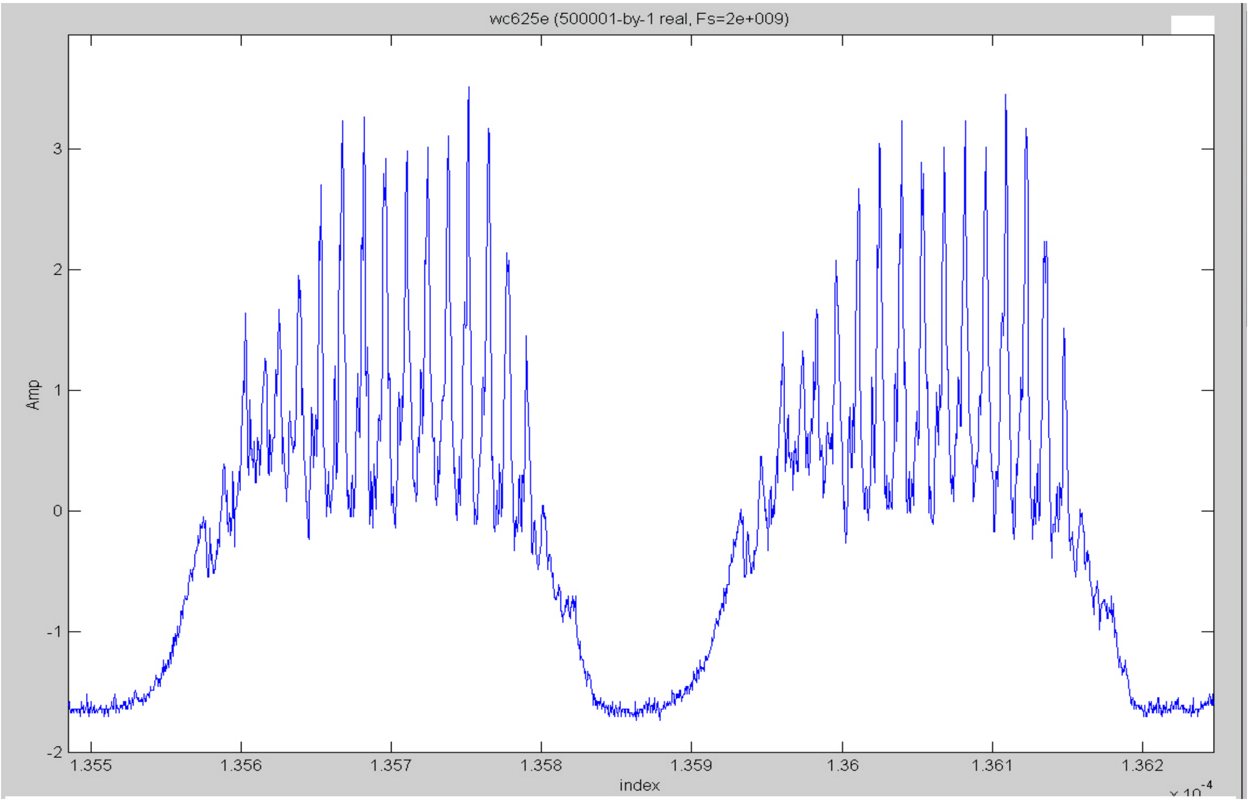


Spickermann 2/10/00

Longitudinal resonance with room temperature ferrites installed

Wall Current Monitor for two turns of coasting beam (RF off)

RF off, Injected PW = 250 ns, accumulate 125 μs, 500 μs store, Inductor Bias=0, 3 modules installed



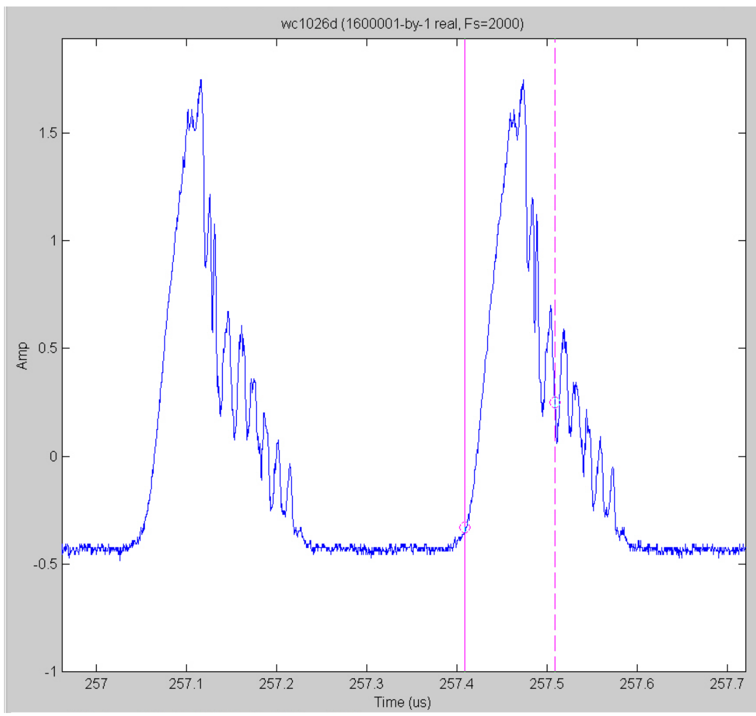
See longitudinal modulation at 72.7 MHz, close to the estimated beam-driven, ferrite-loaded cavity resonance (TM_{010} mode).

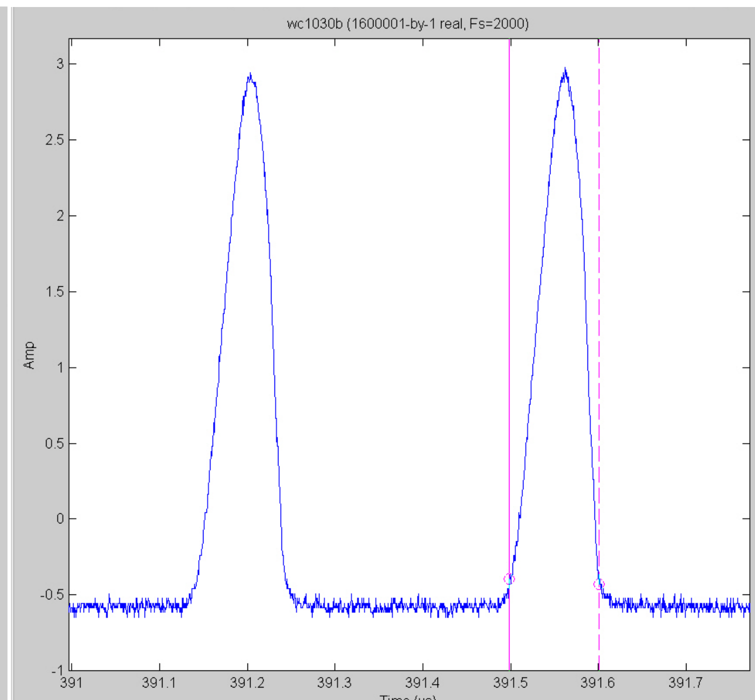
Effect of Heating the Inductor Ferrite

- Ferrite Inductor (2 modules) at room temperature
- 3.3 μC accumulated

- Ferrite at 130º C
- 3.3 μC accumulated
- Longitudinal signal at cavity resonance down 30db from room temperature case

Wall Current Monitor





Bk91, p150

Bk92, p10

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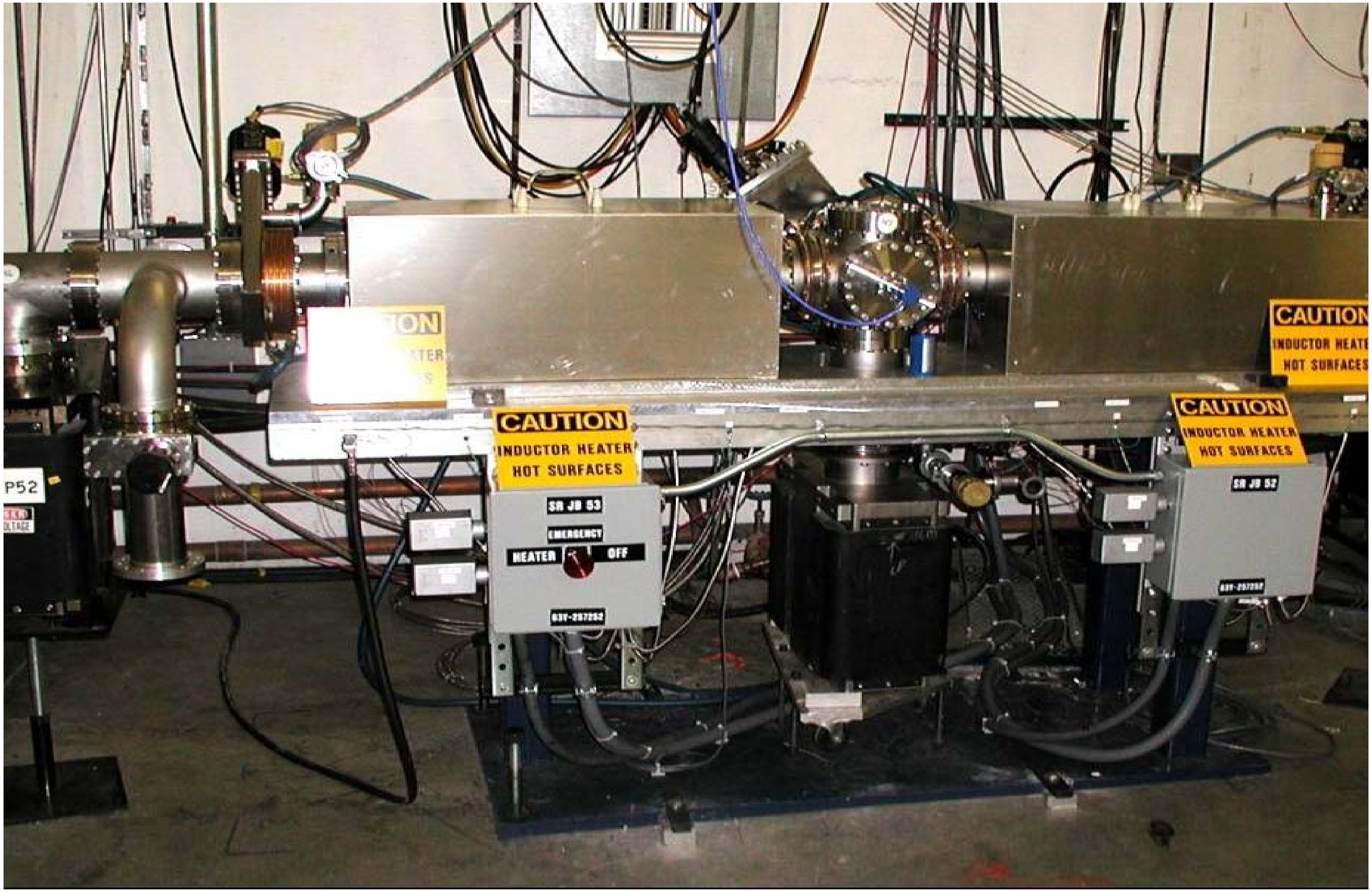
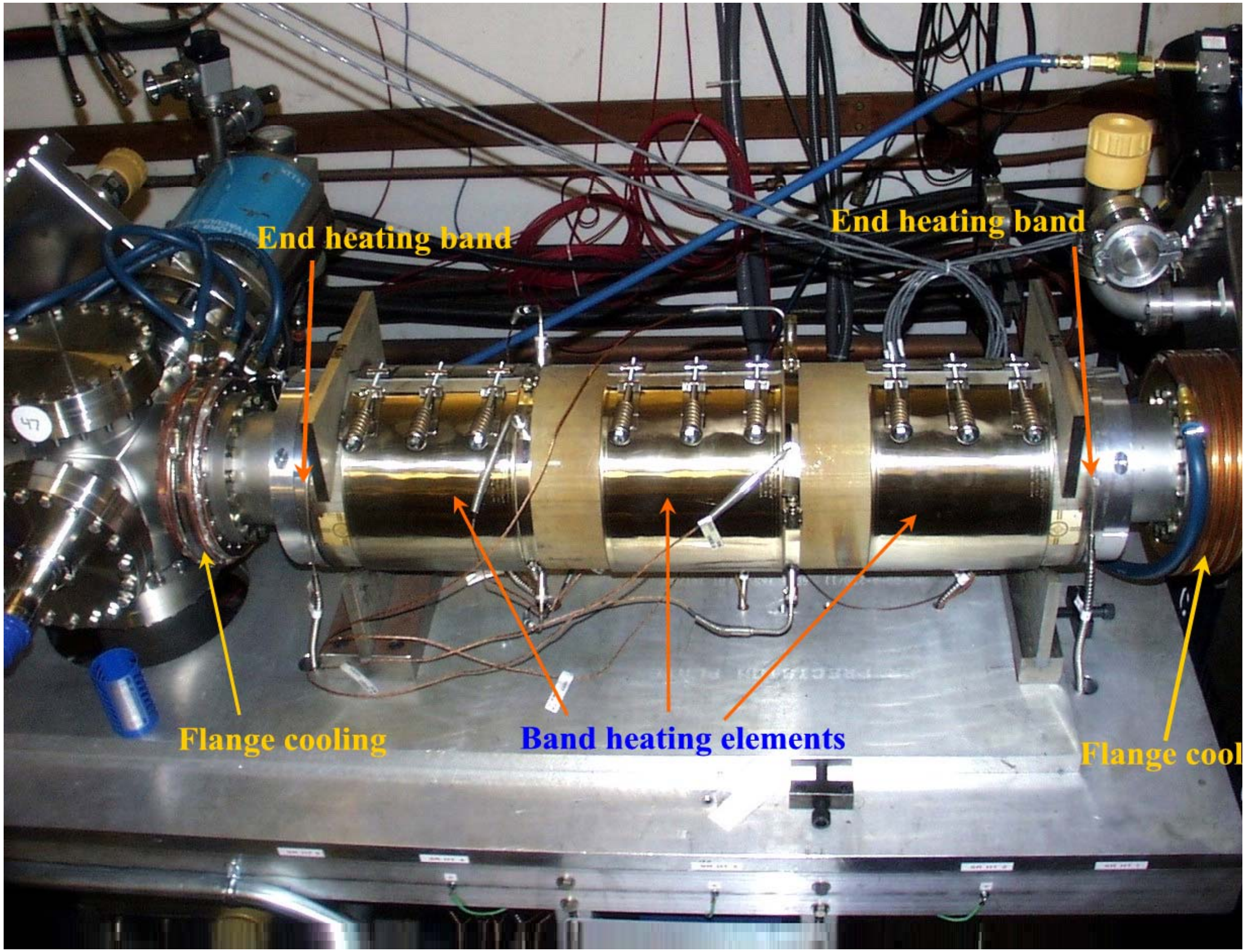
Final version of 2-module inductor installed in PSR



Layout of inductor heating elements



Summary of R&D needs

- **Numerous technology challenges**
  - Improved foils
    - Longer life, retain shape
    - Diamond foils may have merit
  - Diagnostics
  - Experimental verification of collimator designs
- **Electron cloud effect and e-p instability**
  - Detailed simulations of the electron cloud generation
  - Improved theory for bunched beams
  - Direct measure of electron density in the beam at PSR
  - Measure the impedance of the electron cloud
- **Longer Term: laser-aided injection to eliminate stripping foils**
  - Many technical challenges