Accelerator Physics Challenges in the Spallation Neutron Source Accumulator Ring

Sarah Cousineau
Accelerator Physicist, SNS
Oak Ridge National Laboratory, USA

Argonne National Laboratory
October 28, 2005

Machine Overview: SNS Basics

What is it?

Project to build the most intense source pulsed source of neutrons in the world.

How much does it cost?

$1.4 billion

Where is it?

The SNS is being built on Chestnut Ridge, in Oak Ridge Tennessee.

Who is building it?

The SNS is a collaboration between six national laboratories: Oak Ridge National Laboratory, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Argonne National Laboratory, and Brookhaven National Laboratory, and Jefferson National Laboratory.

When will it be finished?

The SNS is scheduled for completion in the year 2006.

Machine Overview: The SNS Site Layout

- The SNS is a short-pulse neutron source with a single-purpose mission of neutron science.
- The peak neutron flux will be ~20–100 current neutron sources.
- It will be a short drive from HFIR, a reactor source with a flux comparable to the ILL

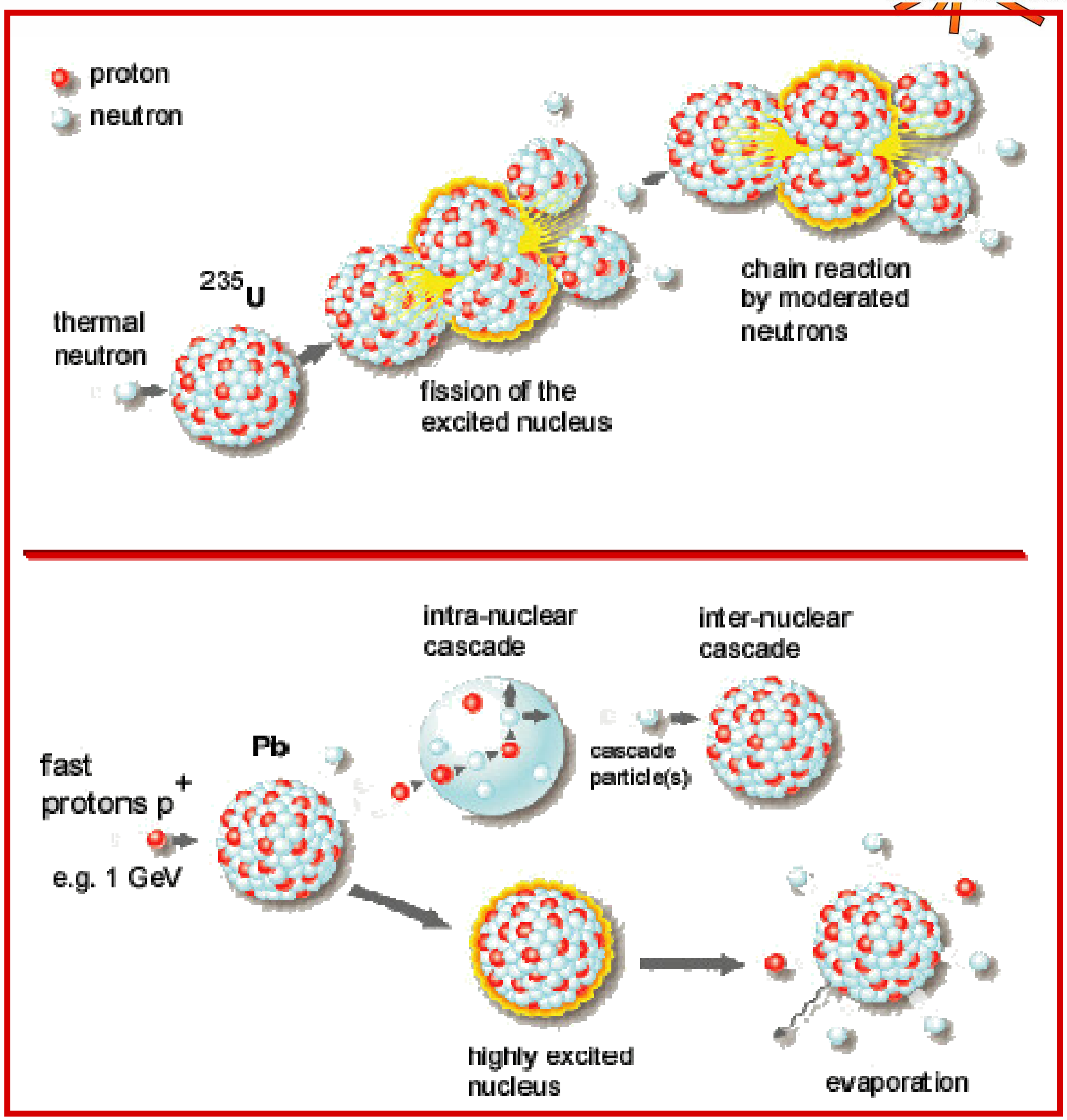
Machine Overview: Getting Neutrons by Spallation

Fission

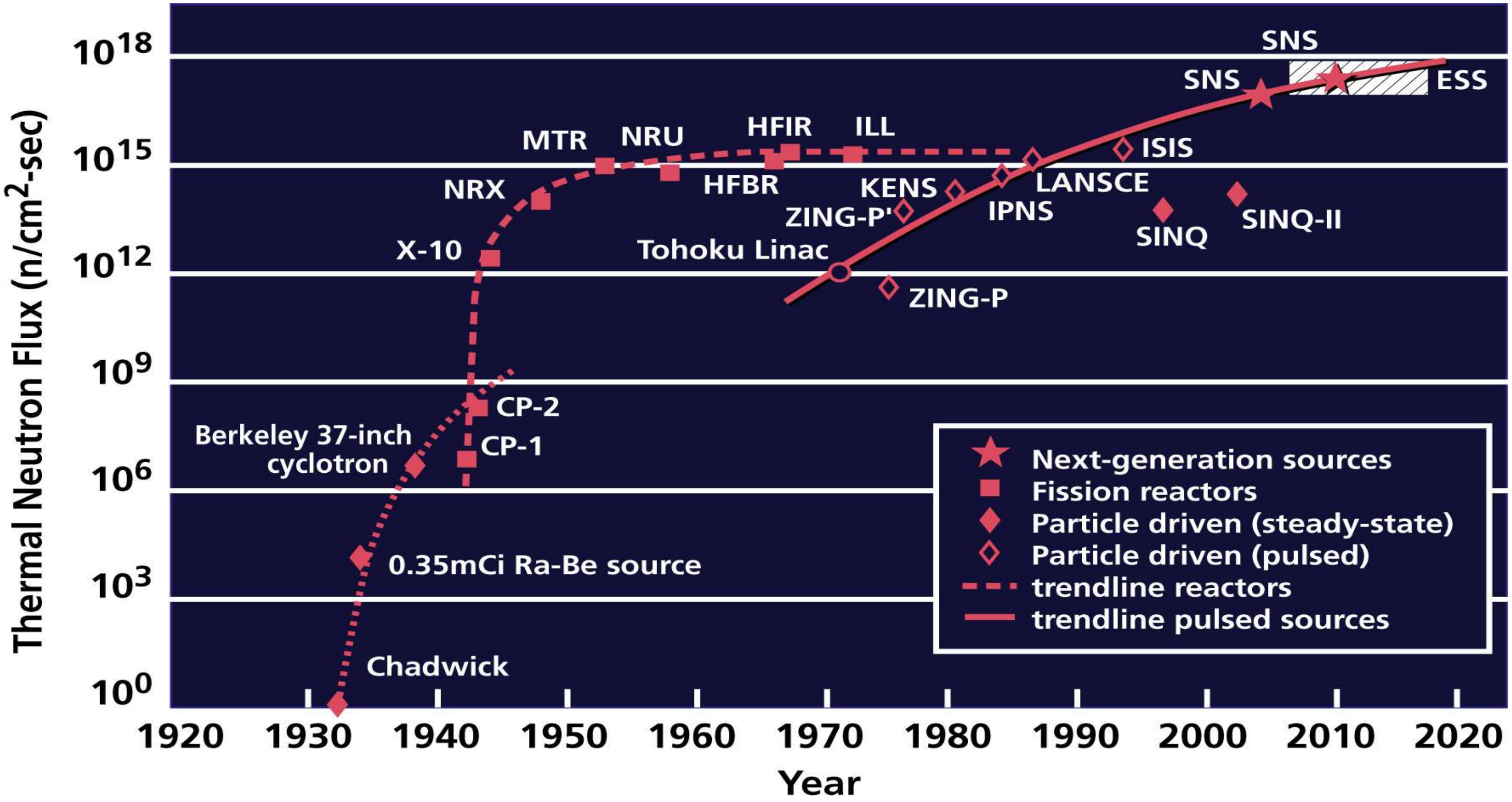
- chain reaction
- continuous flow
- 1 neutron/fission
- 180 MeV/neutron
- Higher average neutron density.

Spallation

- no chain reaction
- pulsed operation
- 30 neutrons/proton
- 30 Mev/neutron
- Higher peak neutron density.



Machine Overview: SNS's Position in the World of Neutron Sources



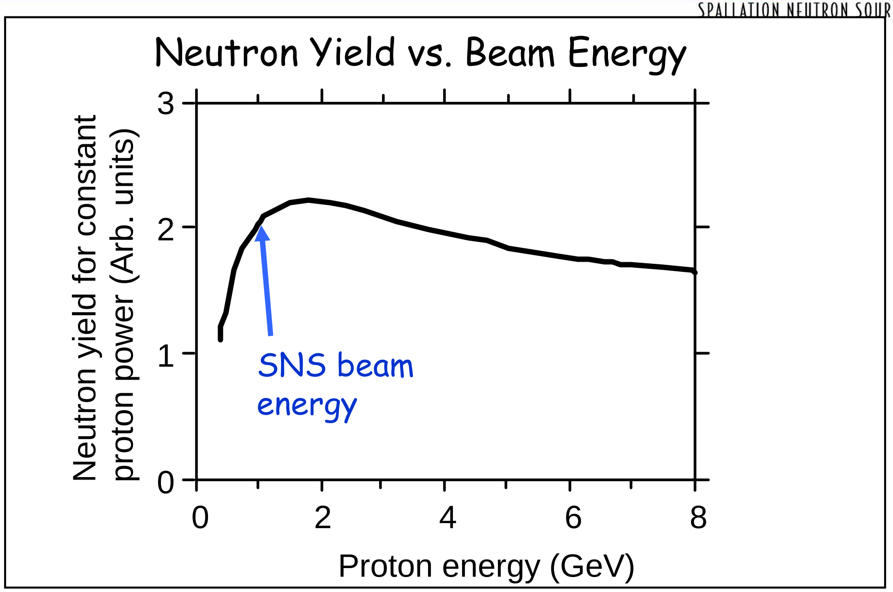
(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Machine Overview: Accelerator System Requirements

To get a high neutron flux...

Neutron flux scales directly with beam intensity → Need high beam intensity.

Neutron yield fairly flat past ~1 GeV for constant beam power.

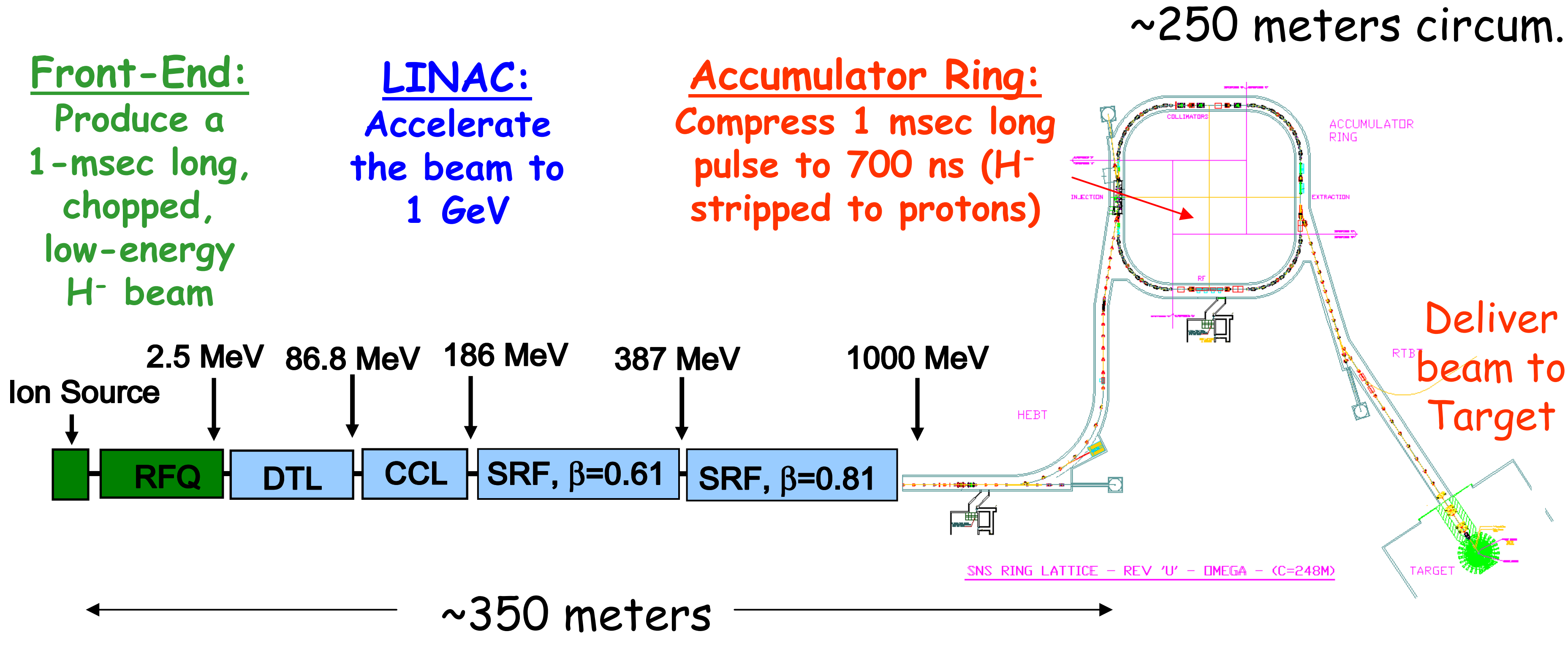


Accelerator system requirements:

- Pulse should be short (< 1 msec)
- Energy in 1 – 3 GeV range to maximize neutrons
- Repetition rate should be high (~60 Hz)
- High proton density on target – goal is 1.5×10^{14} protons per pulse!
- Project cost: $1.4 Billion

Machine Overview: SNS Accelerator Design

SPALLATION NEUTRON SOURCE



~250 meters circum.

Front-End:
Produce a
1-msec long,
chopped,
low-energy
H^- beam

LINAC:
Accelerate
the beam to
1 GeV

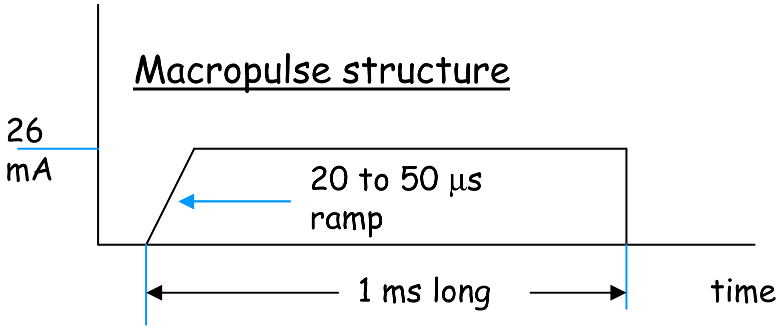
Accumulator Ring:
Compress 1 msec long
pulse to 700 ns (H^-
stripped to protons)

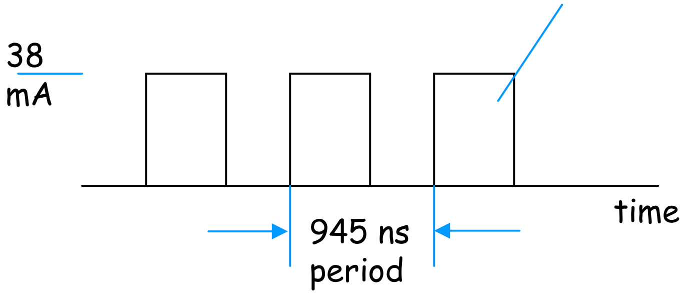
Deliver
beam to
Target

~350 meters

Machine Overview: SNS Design Parameters

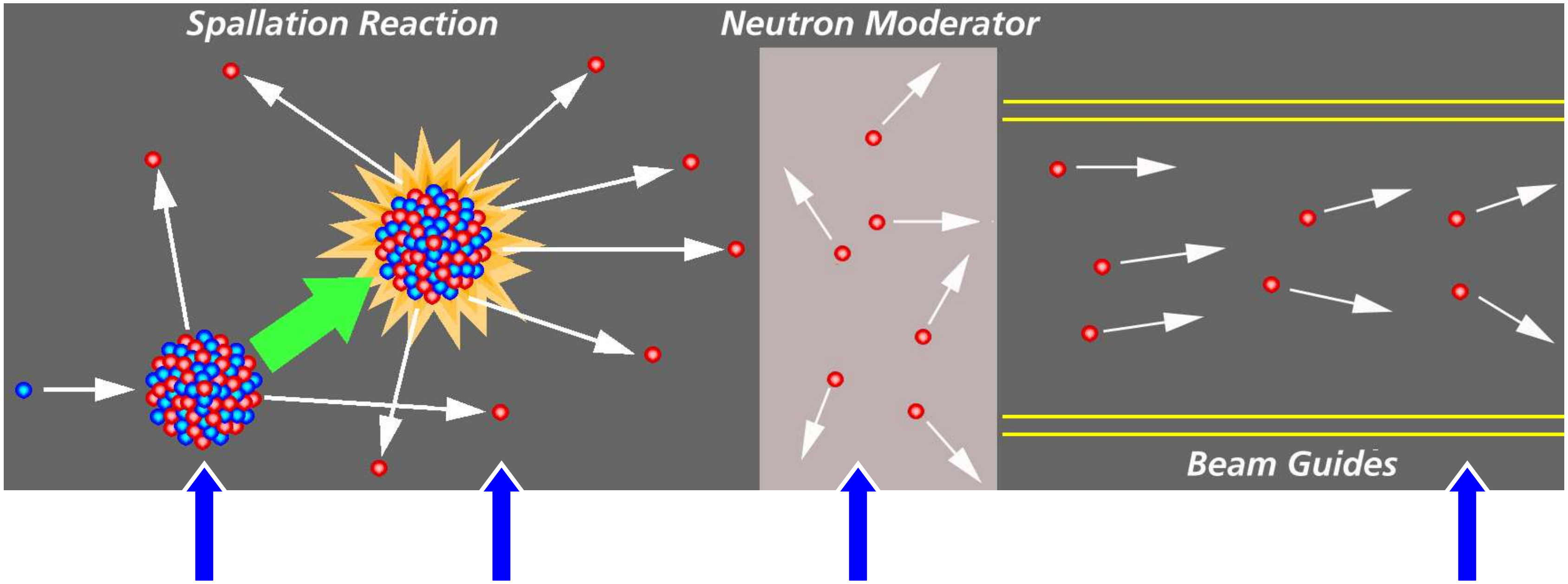
- Average proton power on target: 1.44 MW
- Beam energy: 1 GeV
- Pulse parameters: 1-ms pulse, 60 Hz repetition rate (6% duty)
- Beam current:
  - 26 mA average macropulse current
  - 38 mA peak H^- current
  - 1.6 mA average linac beam current
- Ring accumulation: 1 ms pulse compressed to 695 ns in 1060 injected turns
- Ring intensity: $1.5\text{x}10^{14}$ protons


Macropulse structure


Chopping structure

Machine Overview: Beam on Target

Pulses of neutrons from the liquid mercury target will be slowed down in a moderator and guided through beam lines to areas containing special instruments such as neutron detectors .



neutrons being knocked off of mercury atoms

neutrons being boiled off of mercury atoms (10's of MeV)

neutrons being cooled in either water or 20 K liquid hydrogen (fractions of eV)

neutrons being guided to experimental facility

The High Intensity Challenge

- Many hadron machines push *beam energy*. SNS pushes *beam intensity*. We are in the class of "low energy, high intensity" accelerators.
- When complete, the SNS will be the highest intensity accelerator in the world.
- The high beam intensity presents many operational challenges. Main challenge is to minimize beam loss which causes radiation.

The SNS accumulator ring winds the beam from the linac up ~1000 times before sending it to the target for neutron spallation.

The SNS Ring Design

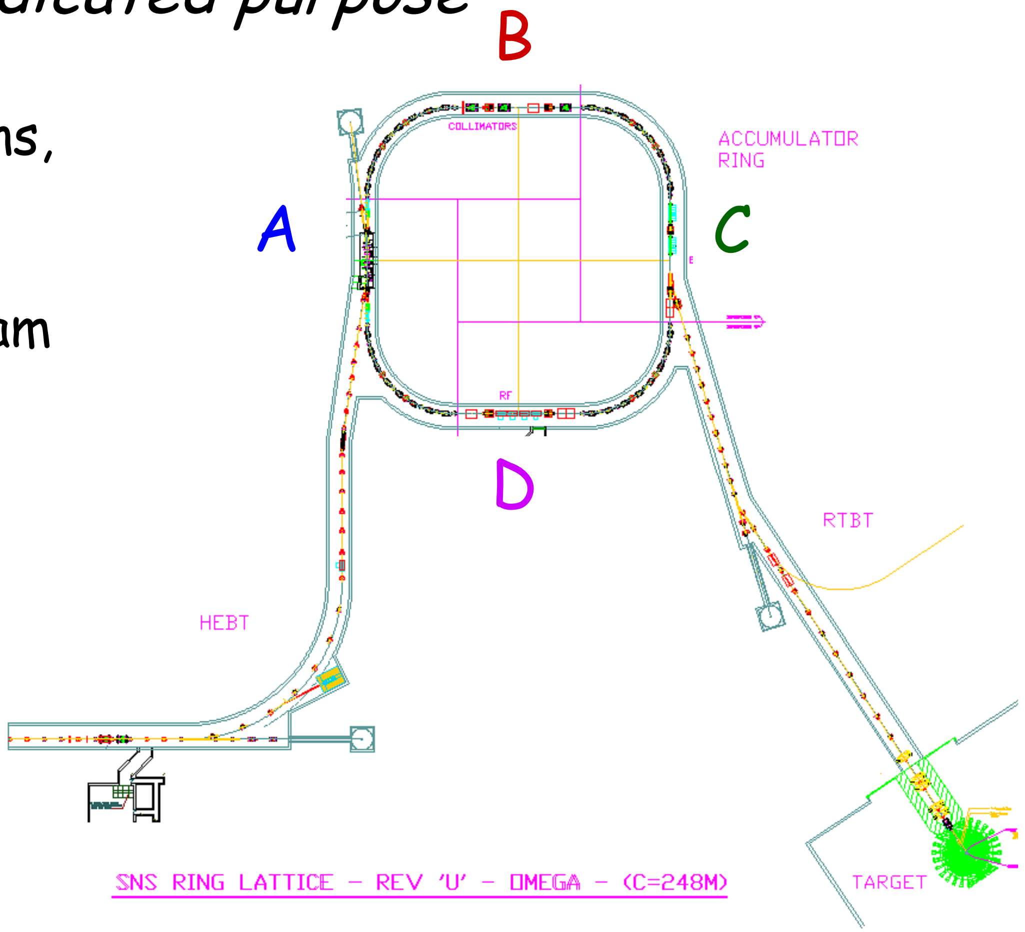
Each of the 4 sides has a dedicated purpose:

A – Injection: Strip H^- to protons, dispose of electrons.

B – Collimation: Clean up the beam halo.

C – Extraction: Single turn extraction to target.

D – RF Bunching: Keep beam bunched to 66% of ring.



SNS RING LATTICE – REV 'U' – OMEGA – (C=248M)

Collective Effects and Space Charge

Collective effects, i.e., the beam interacting with itself and its environment, are the primary cause of halo formation and emittance growth that cause beam loss in high intensity, low energy machines.

Emittance growth is a one way street in proton drivers… There is no damping mechanism.

To achieve the same radiation safety standards, SNS must operate with uncontrolled beam loss one order of magnitude lower than the lowest ever achieved:

Best beam loss achieved (PSR): 0.2% × I_{beam}
Required SNS beam loss: 0.01% × I_{beam}

Ring Low Loss Design Philosophy

Space charge in particular (Coulomb force interactions) anticipated to be most problematic collective effect.

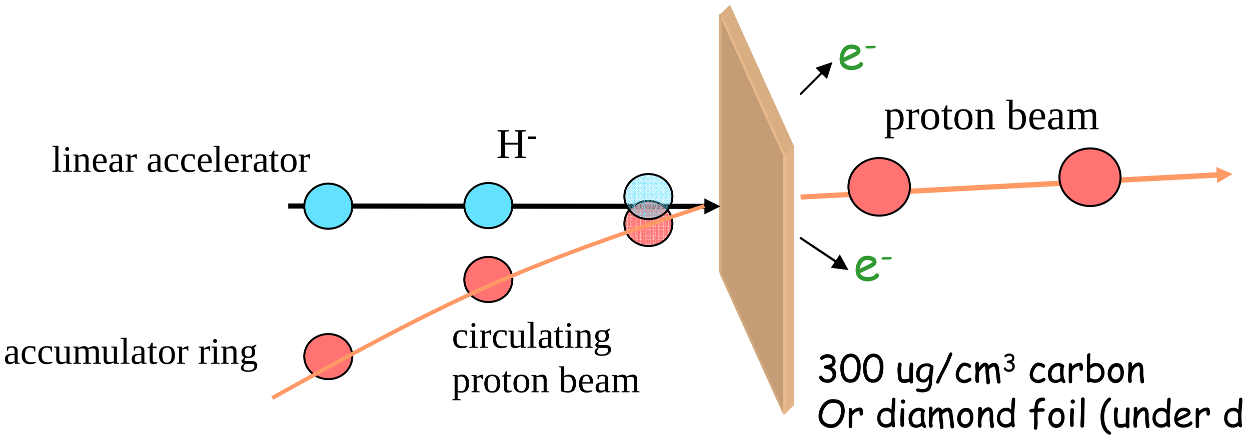
→ **We are always trying to minimize space charge effects.**

The SNS ring was designed with a low-loss philosophy:

- ✓ Optimization of injection region.
- ✓ Choice of tune working point, optics design.
- ✓ Installation of collimation system.
- ✓ Mitigation of electron cloud phenomenon.
- ✓ Minimization of impedances.

Getting Into the Ring: The Injection Region

Proton drivers accelerate H^-, strip to protons. This enables efficient merging of beam trajectories, minimizes emittance growth.



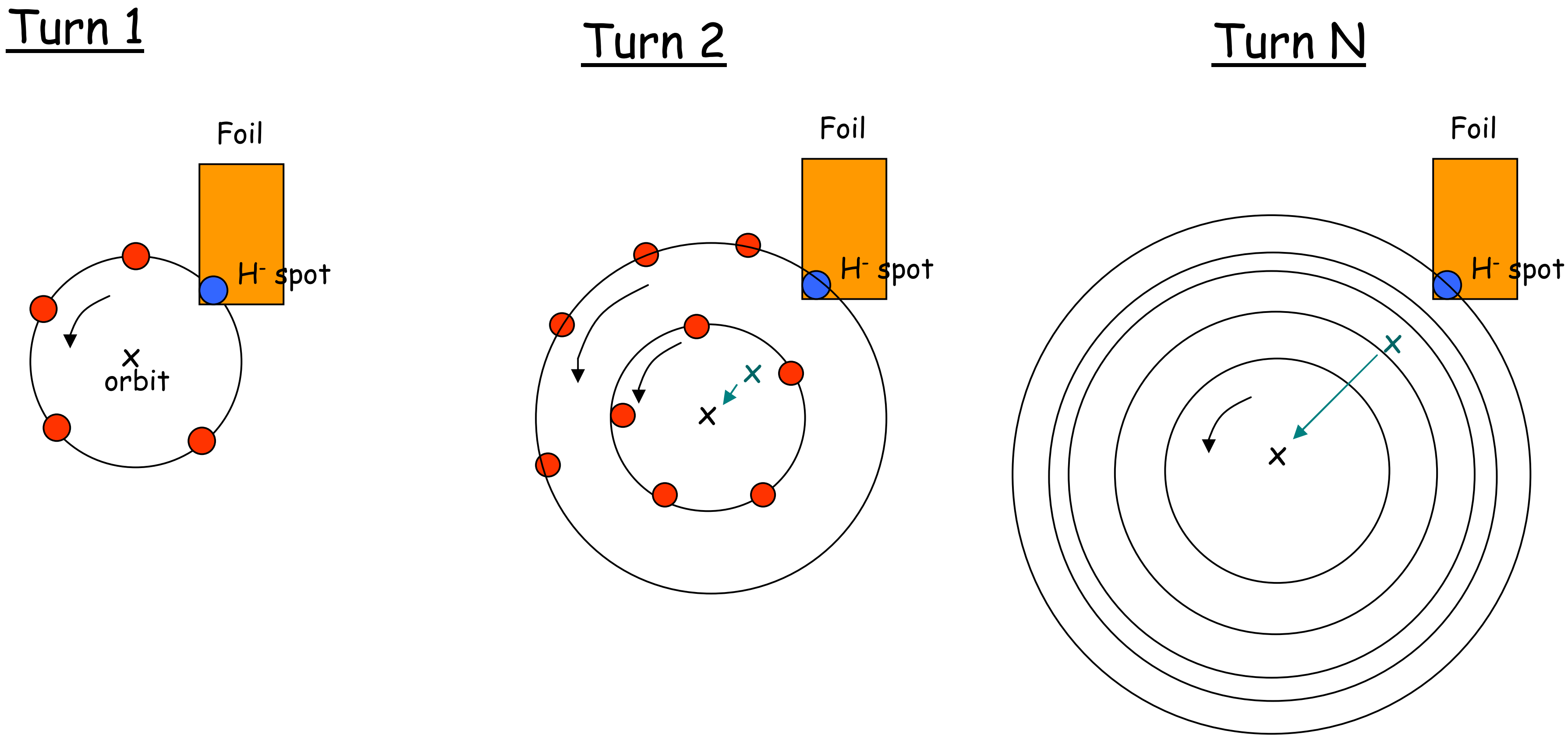
300 ug/cm³ carbon
Or diamond foil (under development)

Challenges to be met:

- Minimize circulating foil hits (scattering losses).
- Minimize space charge in the painted beam.
- Optimize chicane magnet fields to minimize H^0 (partially stripped beam) losses.

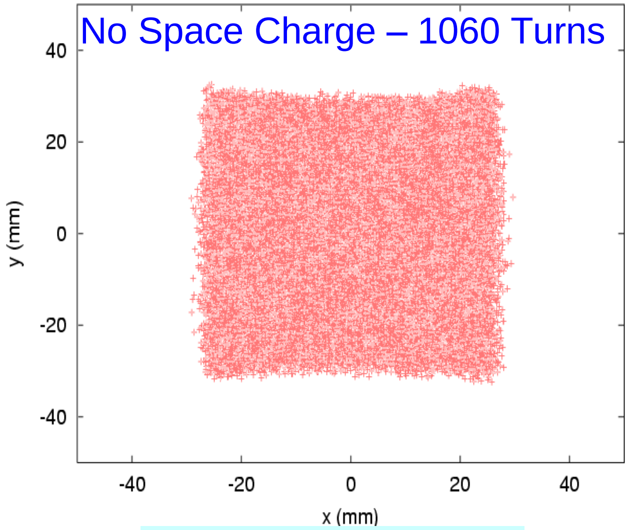
Injection Painting in the Ring

- Transverse painting the beam in the ring allows us to control the size and distribution of the beam.
- This is important for controlling space charge effects!

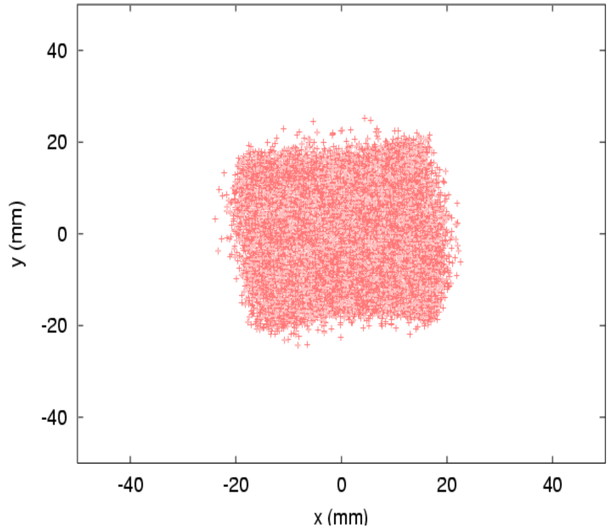


Phase-Space Painting with Space-Charge
Real Space: Y vs. X

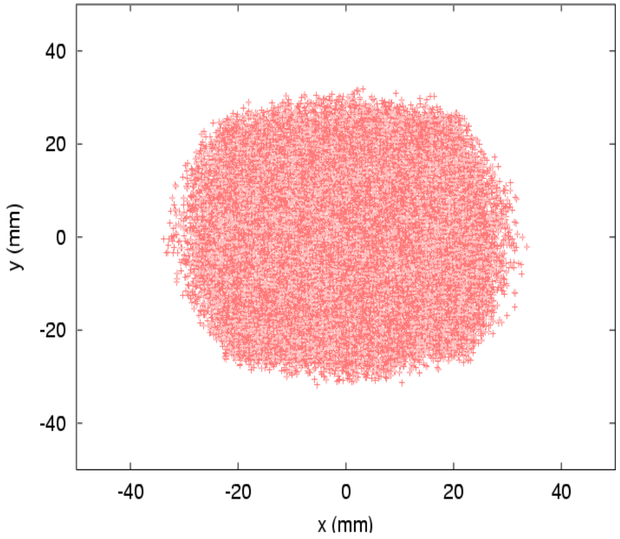
- Injection painting scheme optimized to minimize space charge: Paint with hole in the center to help create uniform density.
- Also try to keep circulating beam foil intercepts to a minimum (~6 foil hits per proton).
- Footprint suites stringent target requirements.


No Space Charge – 1060 Turns

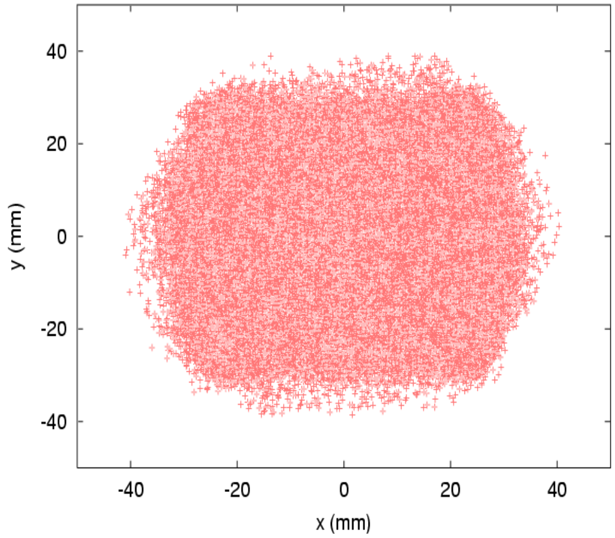
200 Turns



600 Turns



1060 Turns



Choice of Ring Working Point

Lattice point chosen to avoid strong resonances.

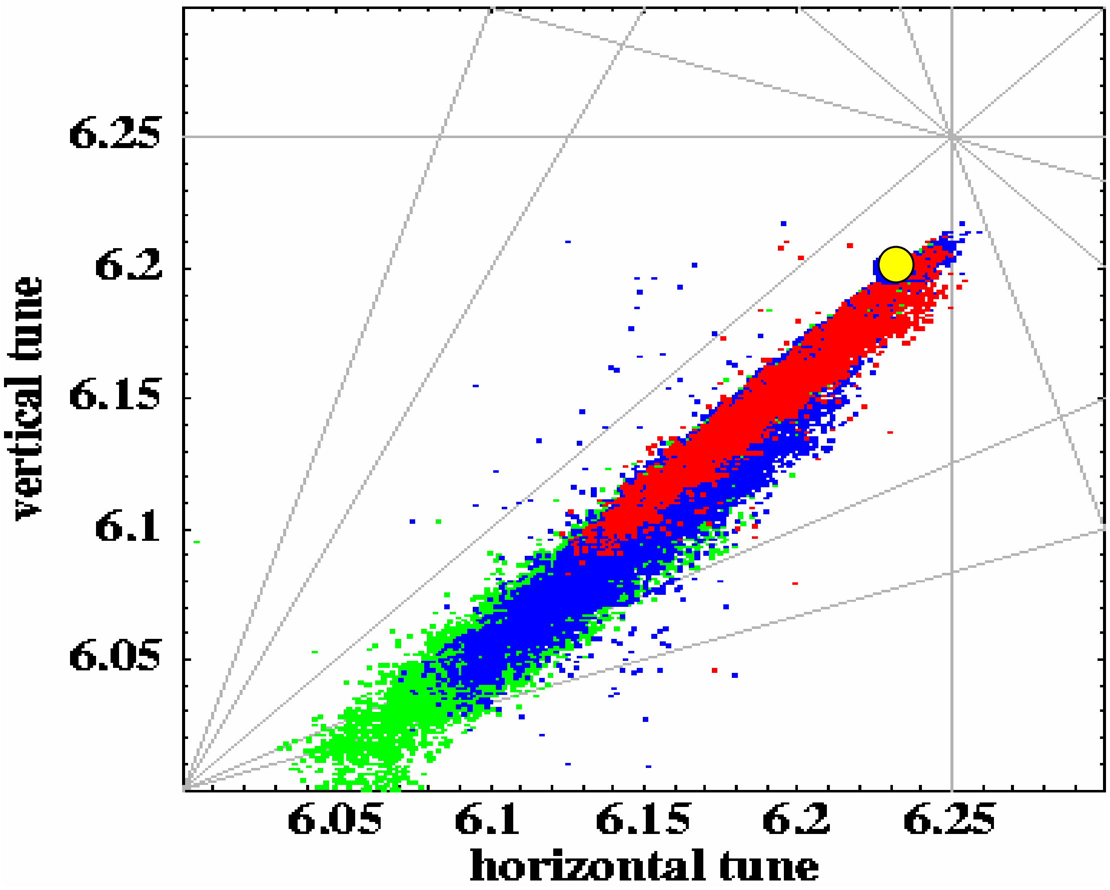
- Design lattice tune for 1.4 MW operation: Q_x=6.23, Qy=6.20.
- Tune shift is ~ 0.15 by the end of accumulation.
- Intensity limitation for this tune is half-integer coherent resonance.
- Chromaticity adds another 0.05 tune shift.

N=0.5*10^{14} – 263 turns

N=1.0*10^{14} – 526 turns

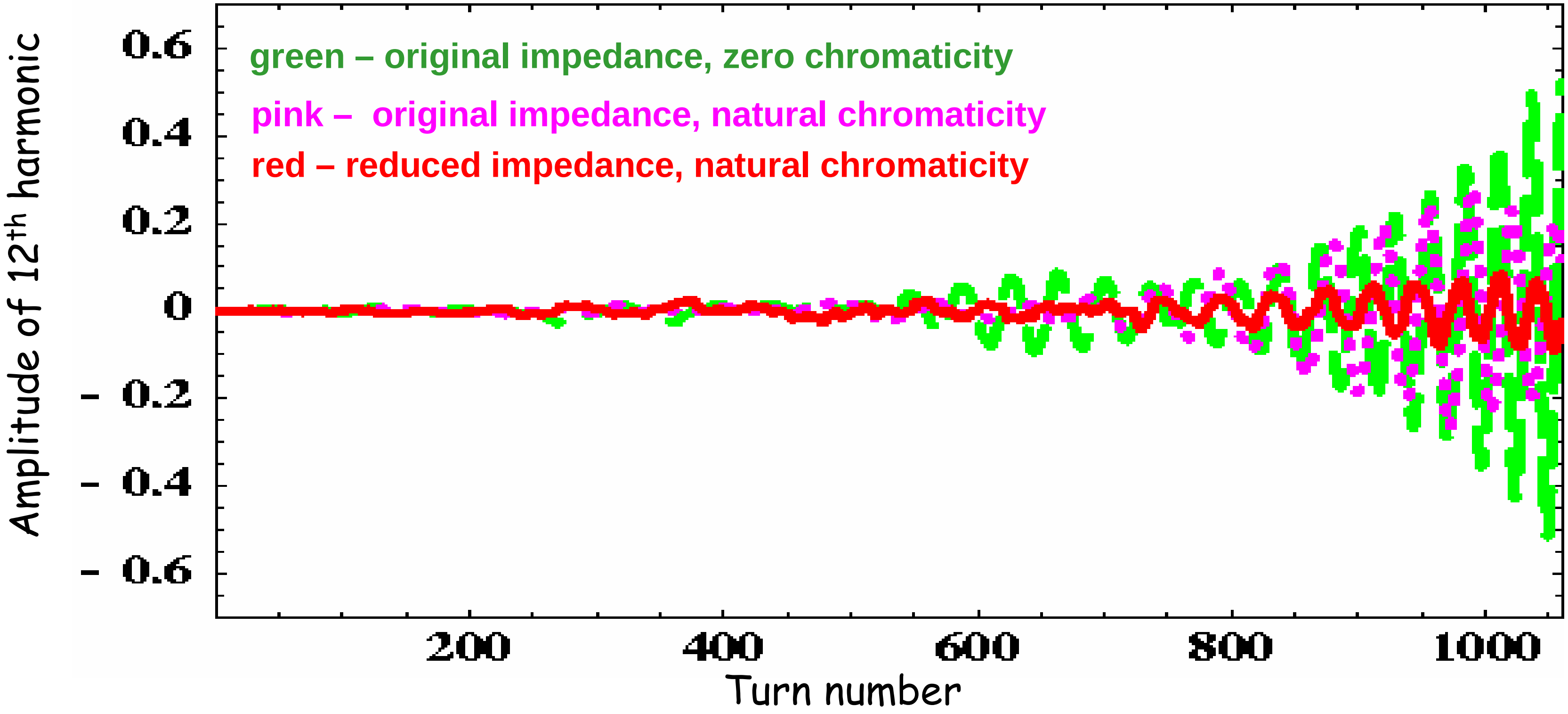
N=2.0*10^{14} – 1052 turns

SC Tune Footprint



Impedances: Extraction Kickers

The original extraction kicker design gave impedances beyond the SNS stability limit: Induced transverse microwave instability.

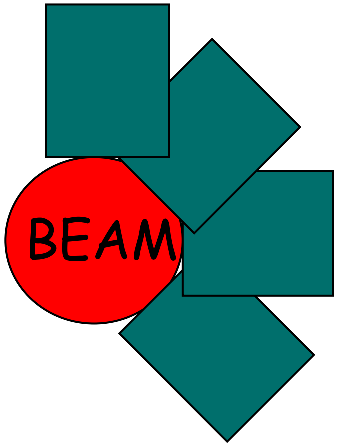


A re-design of the extraction kicker lowered the impedance by a factor of 2.

The Collimation System

The collimation system in the ring provides the last line of defense against uncontrolled beam loss in the ring.

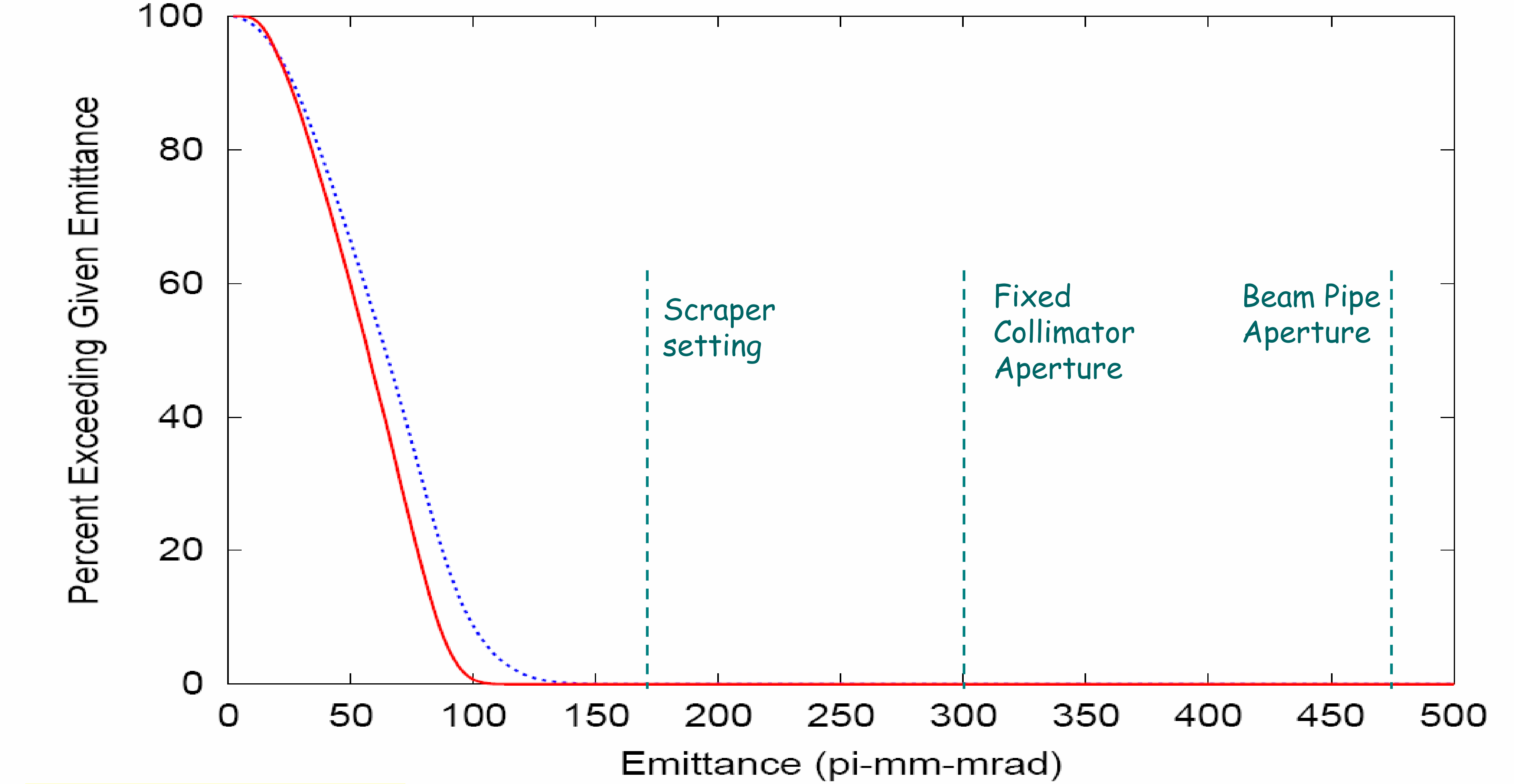
Scraper system



- 4 scrapers adjustable scrapers between 0 – 480 pi mm-mrad. Collimators at 300 pi. Beam at 160 pi.
- Scrapers/collimators can handle 0.1% of beam intensity.
- Collimator system must deliver ~90% efficiency.
- Challenge: No diagnostic on scrapers for how much beam is being intercepted.
- No a priori knowledge of beam shape.

Final Emittance Distribution

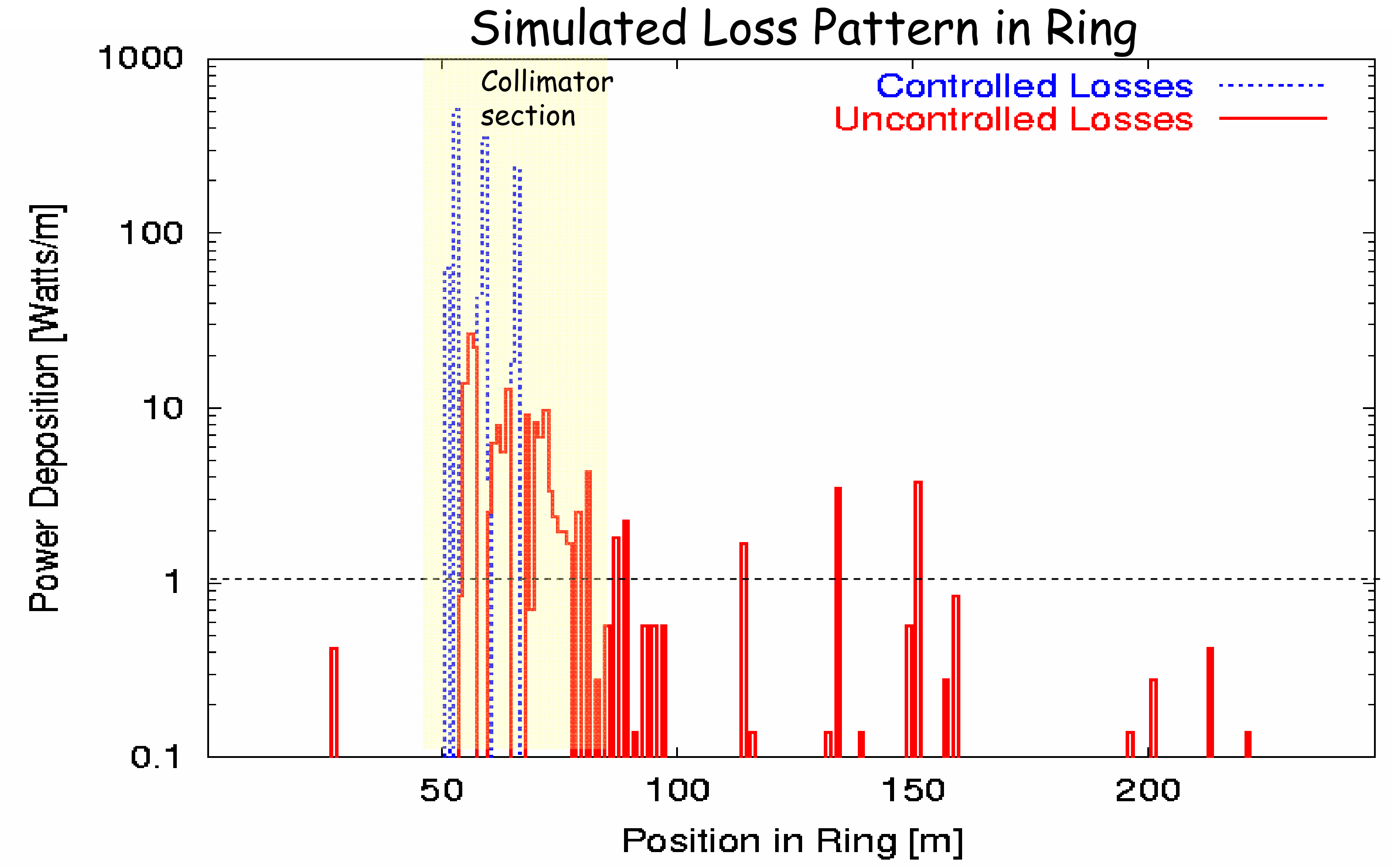
Finally, including all effects (injection, space charge, impedance) the final emittance distribution is well-within the SNS beam pipe aperture:



Courtesy J. Holmes

Final Collimator Loss Distribution

- Approximately 1 W/m is ring radiation limit for hands-on maintenance.
- Losses higher in collimation straight, some bends.

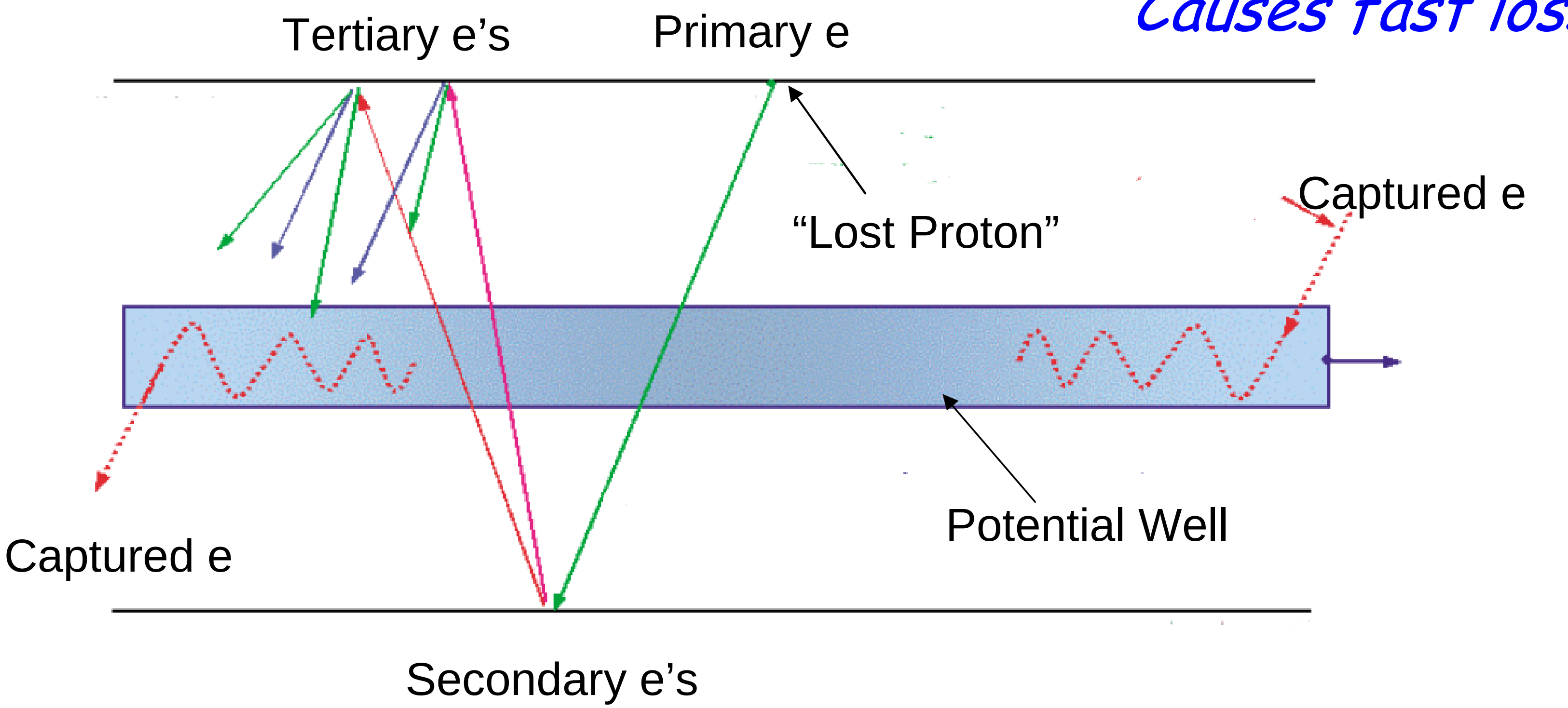


Note: Apertures modeled as zero length elements.

Electron Cloud Instability at SNS

We do not anticipate having e-p instability in the SNS ring for the baseline intensity, but we can't be sure.

Causes fast losses



A number of pre-emptive measures taken:

- ✓ TiN coating on beam pipe high loss areas.
- ✓ Solenoidal windings in high loss areas.
- ✓ Efficient electron clearing near injection area.

Ring Collective Instability Threshold Summary

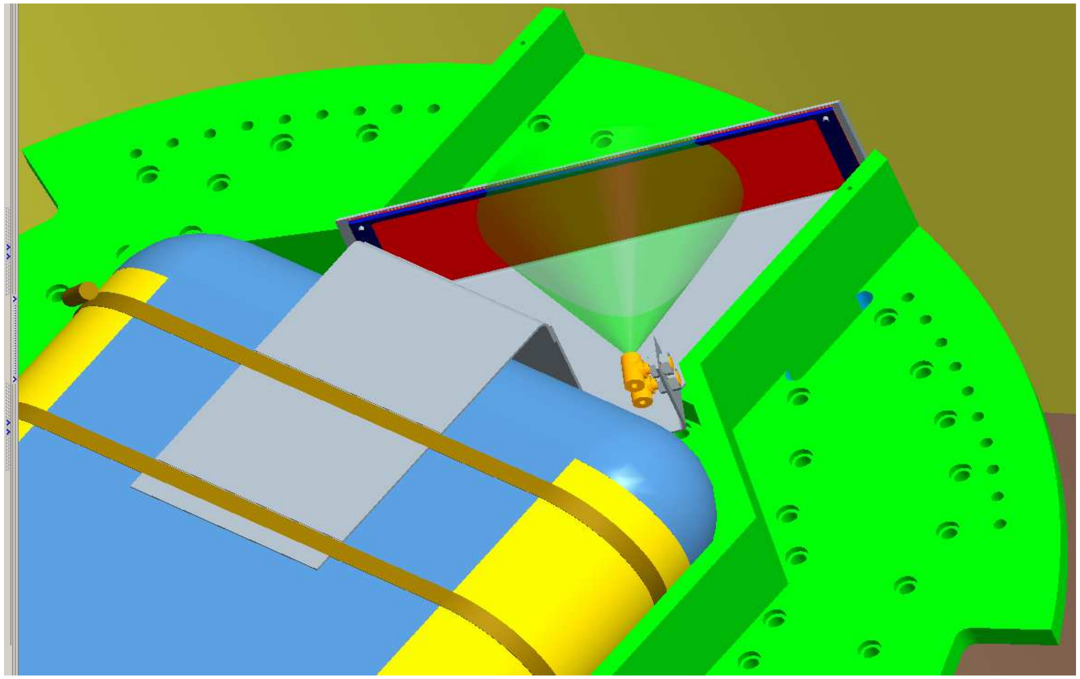
Simulations predict that we will not encounter collective instabilities in the ring up to the baseline intensity (1.44 MW, 1.5×10^{14} protons) :

- Transverse Microwave Instability (EK impedance):
  - 3×10^{14} (ξ_{nat}), 2×10^{14} ($\xi=0$)
- Longitudinal Microwave Instability (EK + RF impedance):
  - 3×10^{14}
- Resistive Wall (Walls + EK impedance):
  - Stable at nominal tunes
- Electron Cloud Instability
  - Stable at design intensity, design RF.
  - Can be considered conservative estimate since not all mitigative features included, and code overestimates required RF in PSR
- Losses due to Space Charge itself set a limit of just above 2 MW *for baseline operating point* in simulations.

Challenges Unrelated to Beam Intensity

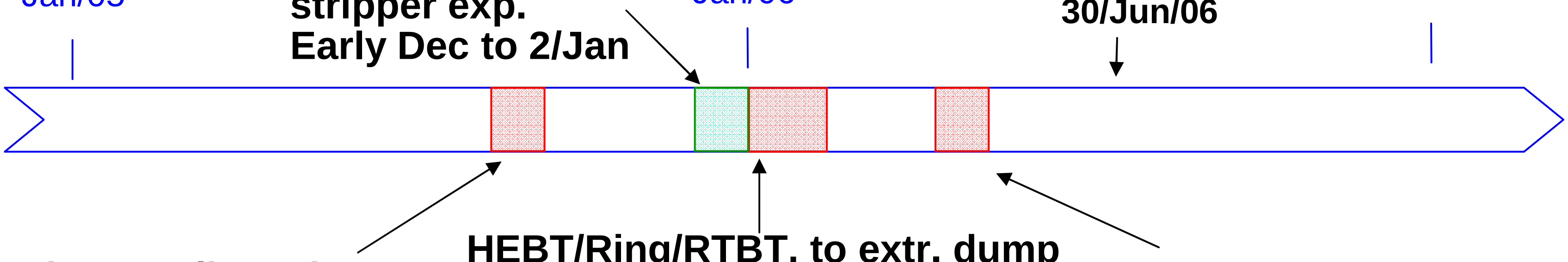
Diagnostics challenges:

- Long stretch of transfer lines with no diagnostics.
- For instance, final drift to target is 9 m with no diagnostics or steerers.
- Video foil ($Al_2O_3(Cr)$) for first shot on target to calibrate diagnostics.



Hg Target Front Section & Core Vessel Interface

The Remaining Commissioning Schedule



Jan/05

Linac tune-up and stripper exp.
Early Dec to 2/Jan

Jan/06

CD-4 deadline
30/Jun/06

Jan/07

Linac, to linac dump
25/Jul – 19/Sep/05

HEBT/Ring/RTBT, to extr. dump
3/Jan – 19/Feb/06 (47 days)

RTBT, to target
1/Apr – 28/Apr/06

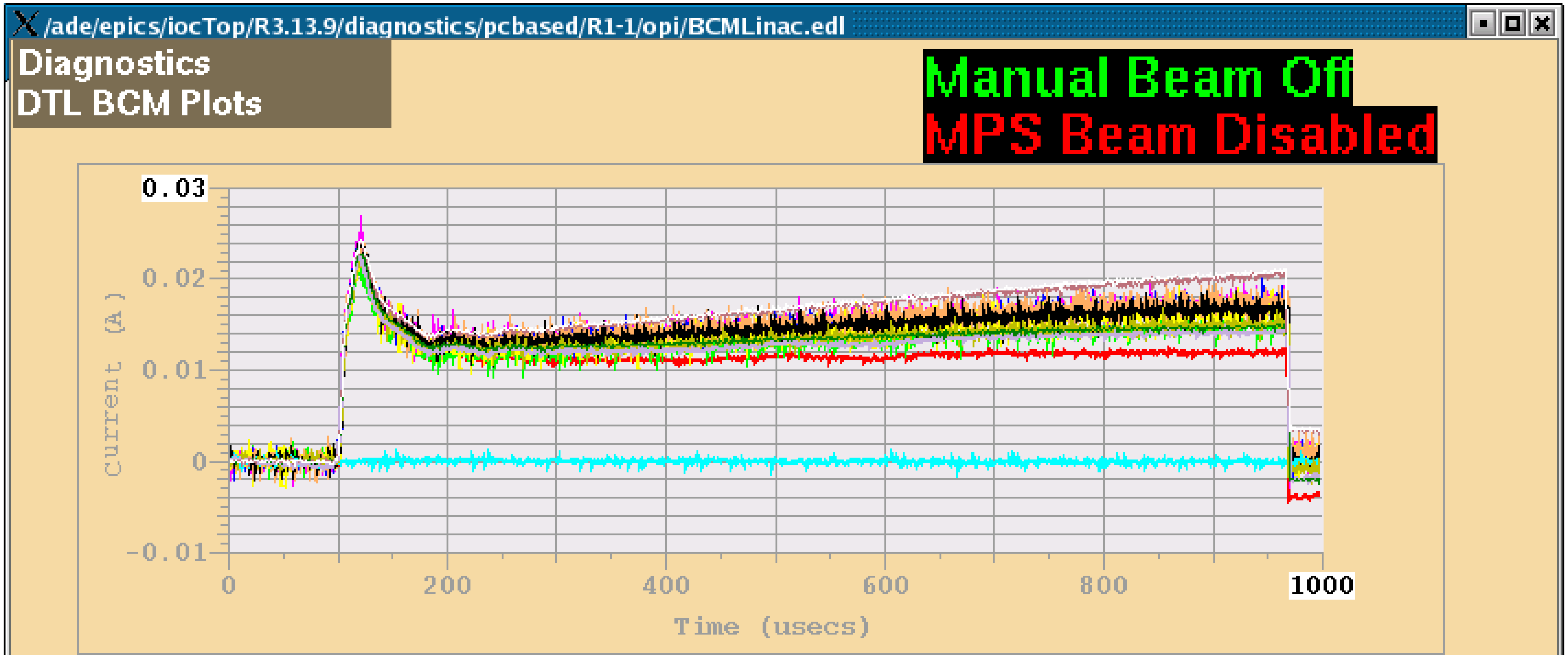
Compared to original plan, ring commissioning will be performed within a smaller time frame and with a very reduced suite of diagnostics.

Ring Diagnostics List

1. **Beam current monitors**
2. **Beam position monitors**
3. **Beam loss monitors**
4. **Video foil and target monitor**
5. **Target harp**
6. Wire scanners
7. Coherent tune monitor
8. Ionization profile monitor
9. Electron detectors
10. Beam-in-gap Cleaning System/Halo Monitor
11. Incoherent tune monitor

Available for commissioning

Ring-Ready Beam Achieved in August


/ade/epics/iocTop/R3.13.9/diagnostics/pcbased/R1-1/opi/BCMLinac.edl

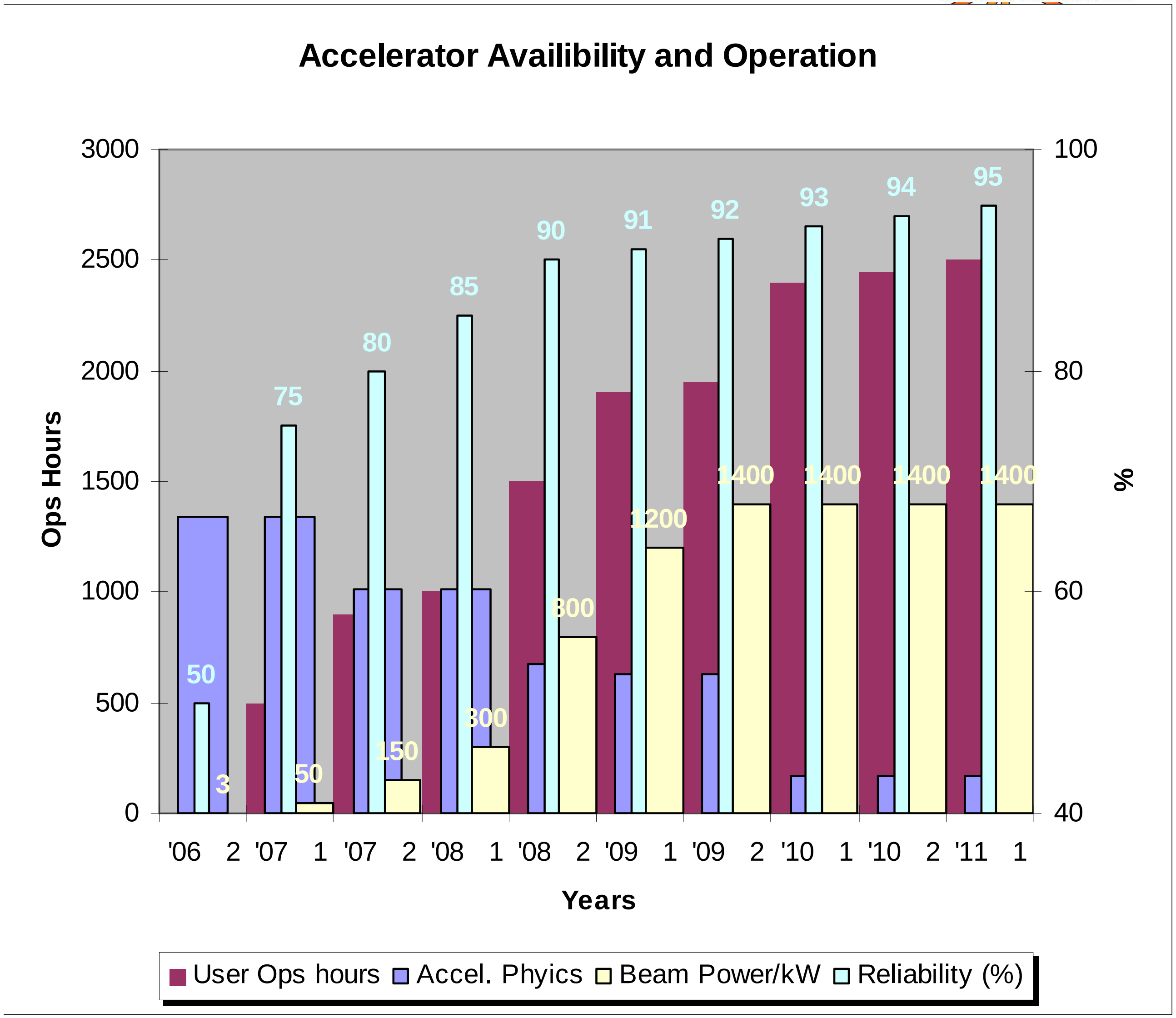
Diagnostics
DTL BCM Plots

Manual Beam Off
MPS Beam Disabled

- 880 μsec pulse, ~ 14 mA average current, 907 MeV, 0.2 Hz ($8\text{x}10^{13}$ PPP, or ~ 8 times the CD-4 requirement).
- Few cavities missing prevent acceleration to 1 GeV. Ring can accommodate as low as 850 MeV.

Post – CD4 Intensity Ramp-Up

- We will commission the beam with low intensity, ~2×10^{13} ppp (10 mA, 1 Hz).
- We will ramp up beam power gradually. Should reach 1.4 MW by 2010.
- Plans for second target station in ~2010.



Planning Ahead: The Beam Power Upgrade

SNS has been approved for a beam power upgrade to 3 MW, beginning in the year 2010.

Increasing the beam power to 3 MW is accomplished by:

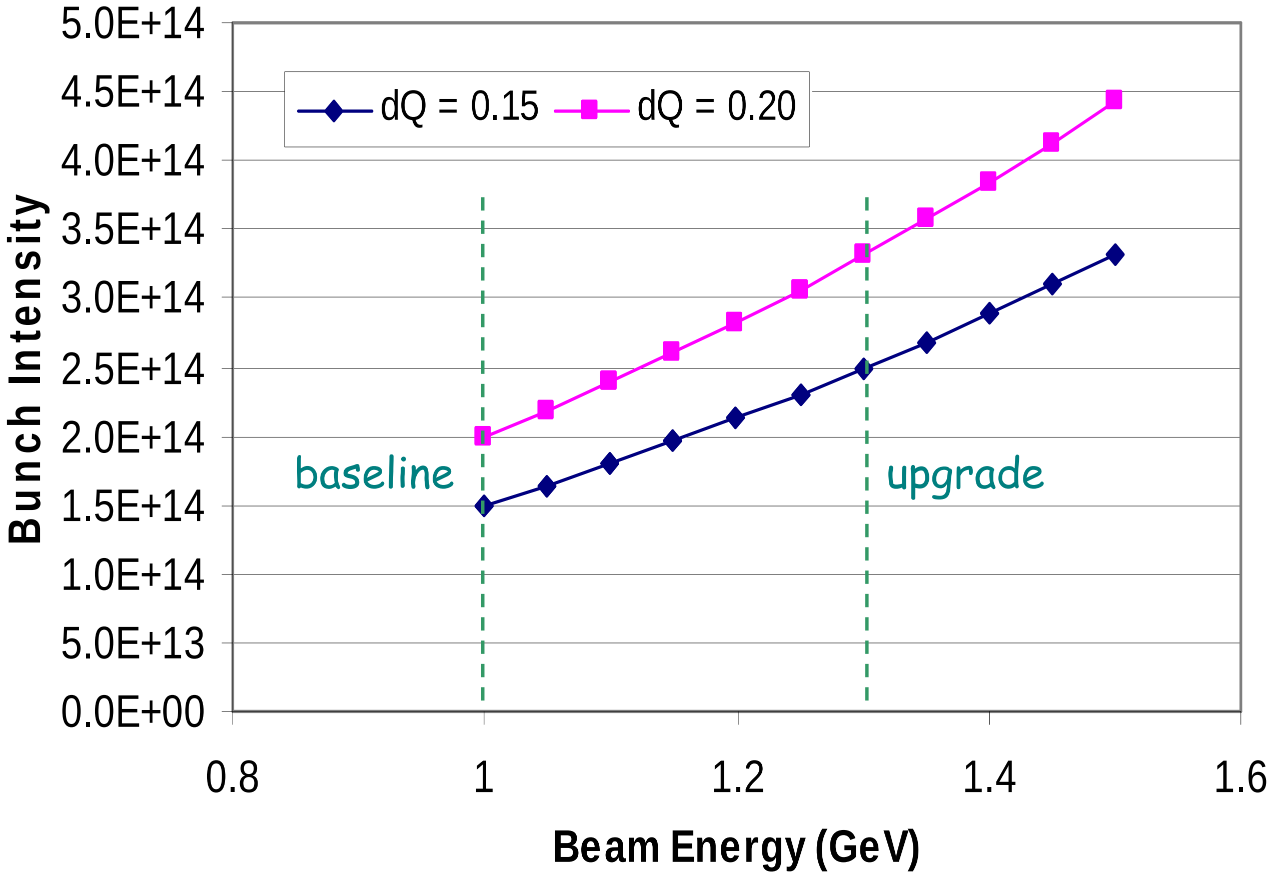
1) Increasing the peak H^- ion source current from 38 to 59 mA (2.5×10^{14} ppp on target).
2) Increasing the linac output energy from 1.0 to 1.3 GeV (adding extra cryomodules).
3) Modifying the injection and extraction regions in the accumulator ring to accommodate higher beam energy.

SNS Power Upgrade

	Baseline	Upgrade	Ultimate
Kinetic energy, E_k [MeV]	**1000**	**1300**	**1400**
Beam power on target, P_{max} [MW]	**1.4**	**3.0**	**5.0**
Chopper beam-on duty factor [%]	**68**	**70**	**70**
Linac beam macro pulse duty factor [%]	**6.0**	**6.0**	**6.0**
Average macropulse H- current [mA]	**26**	**42**	**65**
Peak Current from front end system	**38**	**59**	**92**
Linac average beam current [mA]	**1.6**	**2.5**	**3.9**
SRF cryo-module number (med-beta)	**11**	**11**	**11**
SRF cryo-module number (high-beta)	**12**	**12 + 8 (+1 reserve)**	**12 + 8 (+1 reserve)**
Number of SRF cavities	**33+48**	**33+80 (+4 reserve)**	**33+80 (+4 reserve)**
Peak gradient, E_p (β=0.61 cavity) [MV/m]	**27.5 (+/- 2.5)**	**27.5 (+/- 2.5)**	**27.5 (+/- 2.5)**
Peak gradient, E_p (β=0.81 cavity) [MV/m]	**35 (+2.5/-7.5)**	**31**	**34**
Ring injection time [ms] / turns	**1.0 / 1060**	**1.0 / 1100**	**1.0 / 1110**
Ring rf frequency [MHz]	**1.058**	**1.098**	**1.107**
Ring bunch intensity $[10^{14}]$	**1.6**	**2.5**	**3.8**
Ring space-charge tune spread, ΔQ_{sc}	**0.15**	**0.15**	**0.2**
Pulse length on target [ns]	**695**	**691**	**683**

Space-Charge Tuneshift Scaling

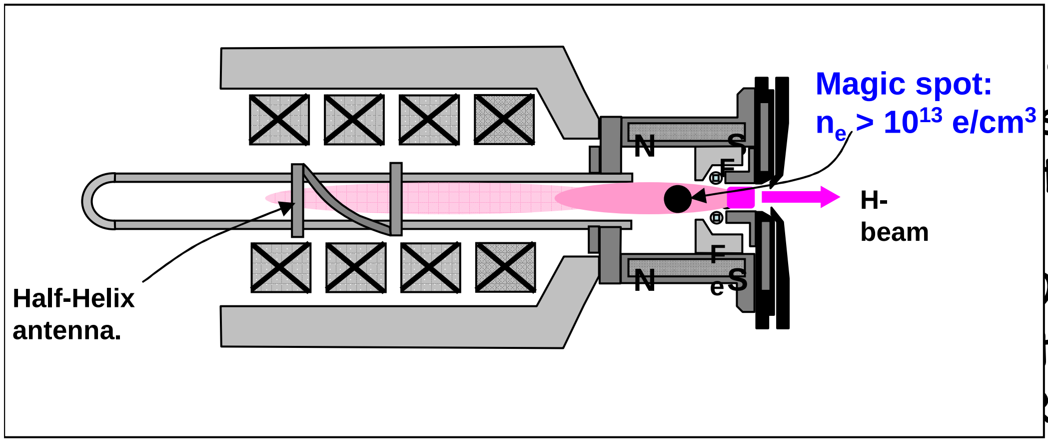
- The ring was originally designed to accommodate a 1.3 GeV beam. The higher energy + higher intensity follows along a curve of constant space charge tune shift.
- In terms of space charge, 3 MW upgrade a straightforward extension of baseline.



Blue - nominal

Pink - limit

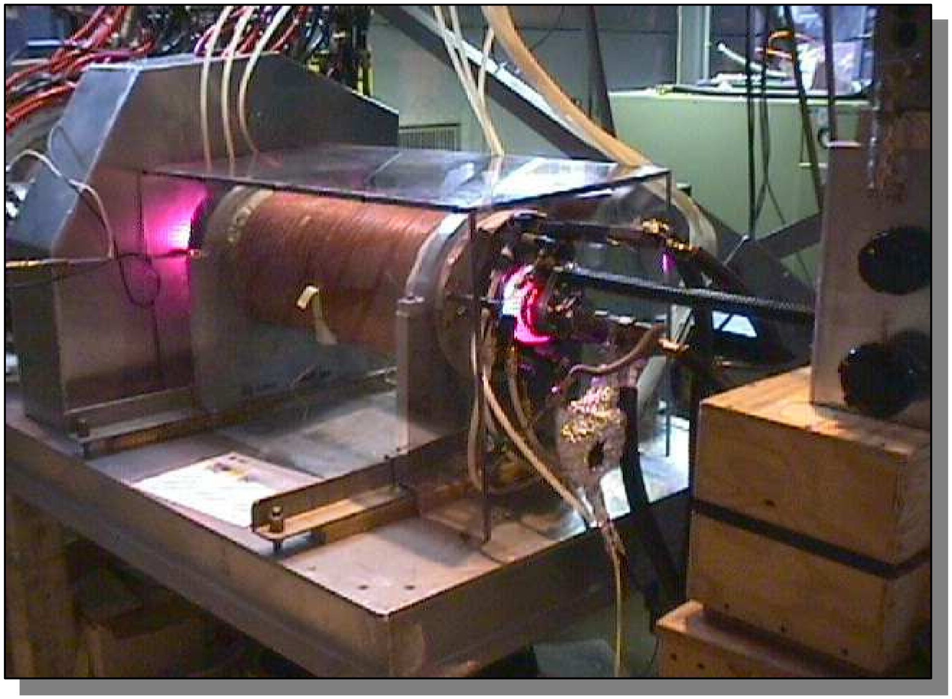
Upgrade Challenges: Ion Source Development



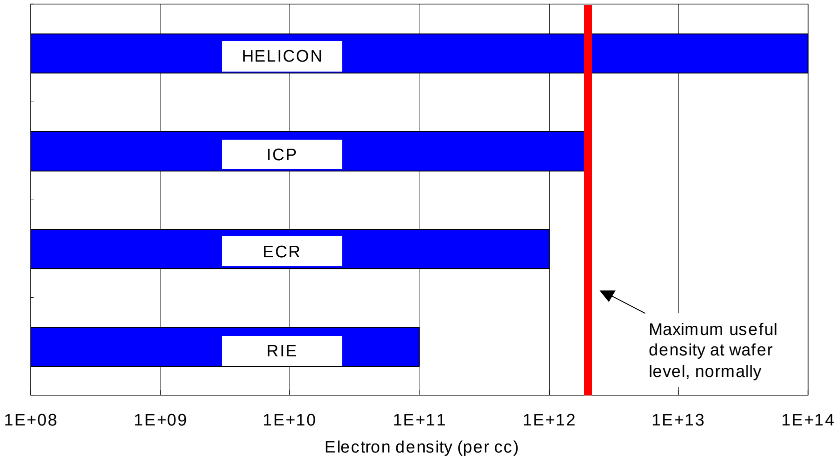
Courtesy R. Welton

&D on all fronts of ion source:
sium collar, external antennas,
traction systems, etc.

ne effort (among many!) is to
trofit VASIMR helicon system at
NL (developed for NASA jet
propulsion) to SNS ion source.



❖ Helicon plasma generators can produce much higher plasma densities (10 to 100 times) at lower gas pressure and cooler electron temperatures.



Upgrade Challenges: Injection Foil Upgrade

Ring Injection Area Will Need to be Redesigned:

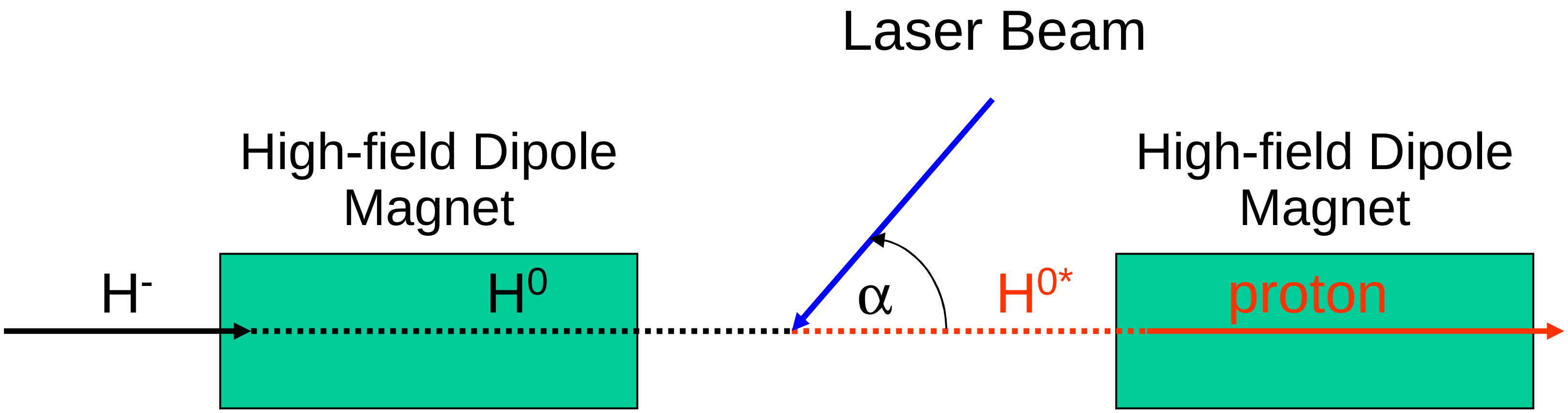
- Magnets need to be scaled for 1.3 GeV, designed to reduce H^o excited losses.
- Current foil will already operate near max foil temp of 2500 K; Upgrade will exceed this value.
  - May need multiple foils, or new foil technology.

Several foil R&D efforts underway, including:

- Diamond foil production (first testing results at PSR are very promising).
- Laser stripping. Proof-of-principal experiments this December.

Laser Stripping Proof-of-Principal Experiments

- Our team developed a novel approach for laser-stripping which uses a three-step method employing a narrowband laser [V. Danilov et. al., Physical Review Special topics – Accelerators and Beams 6, 053501]



Step 1: Lorentz Stripping

$H^- \rightarrow H^0 + e^-$

Step 2: Laser Excitation

$H^0\ (n=1) + \gamma \rightarrow H^{0*}\ (n=3)$

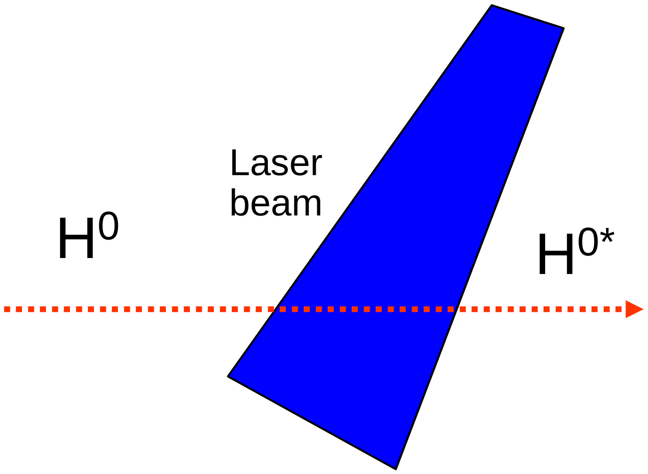
Step 3: Lorentz Stripping

$H^{0*} \rightarrow p + e^-$

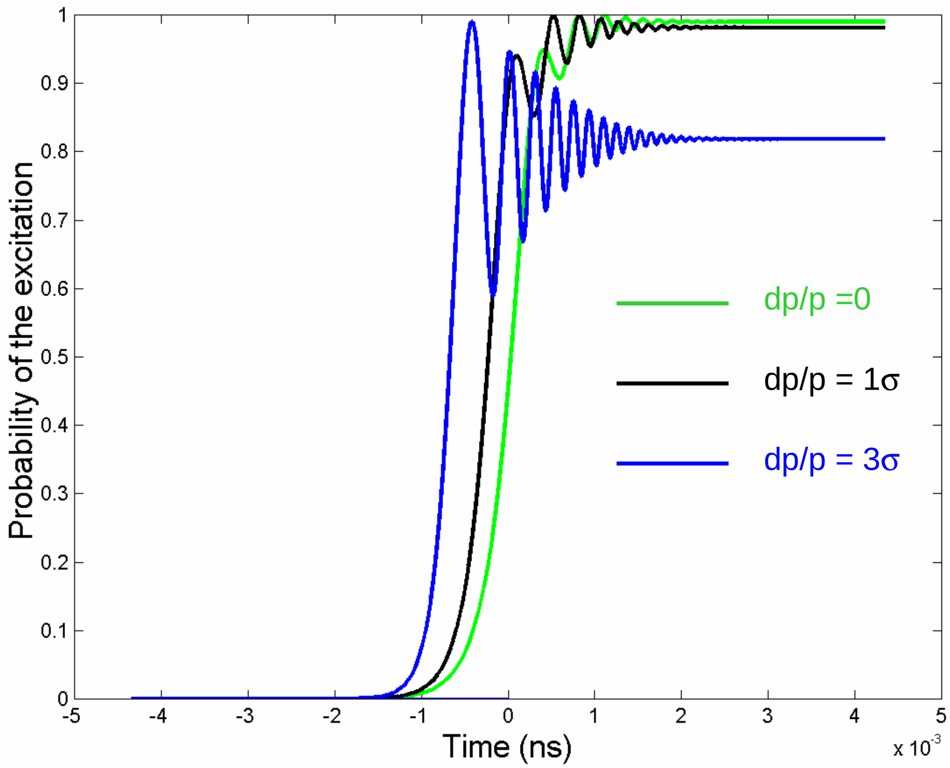
Courtesy S. Henderson

A Diverging Laser Beam Accounts for the Momentum Distribution

- By intersecting the H^0 beam with a *diverging* laser beam, a frequency sweep is introduced:



- The frequency sweep compensates for Doppler broadening due to momentum spread in the H^- beam.
- In this way, the excited state is populated with very high efficiency with greatly reduced laser power.

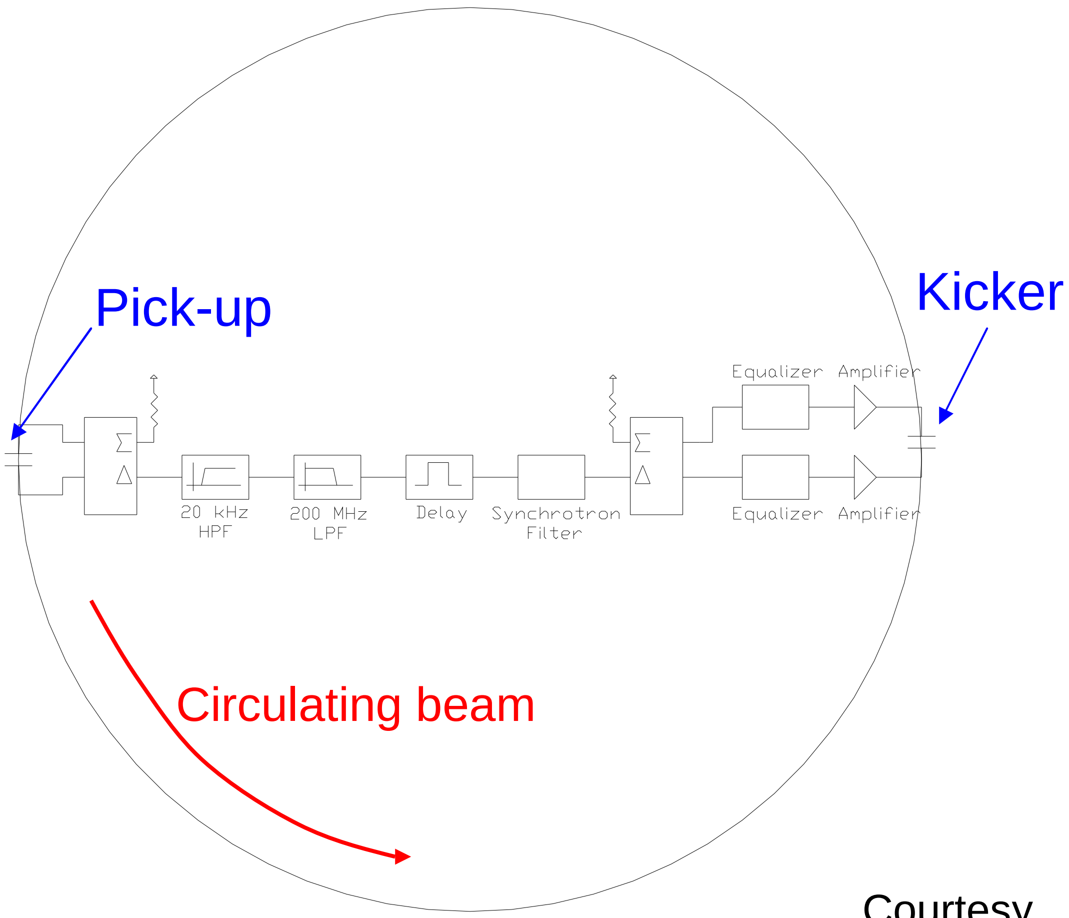


Courtesy S. Henderson

Active Feedback System for Upgrade

- Despite all measures, still anticipate seeing some instabilities in ring beam.
- Active feedback system planned for intensity upgrade.
- Can stabilize e-P and other instabilities resulting from collective effects.
- Proof-of-principle experiments done at PSR in spring, 2005 (SNS, ANL, LANL, Indiana University collaboration).

Active Feedback System



Courtesy
C. Deibele

First results of e-P feedback experiments

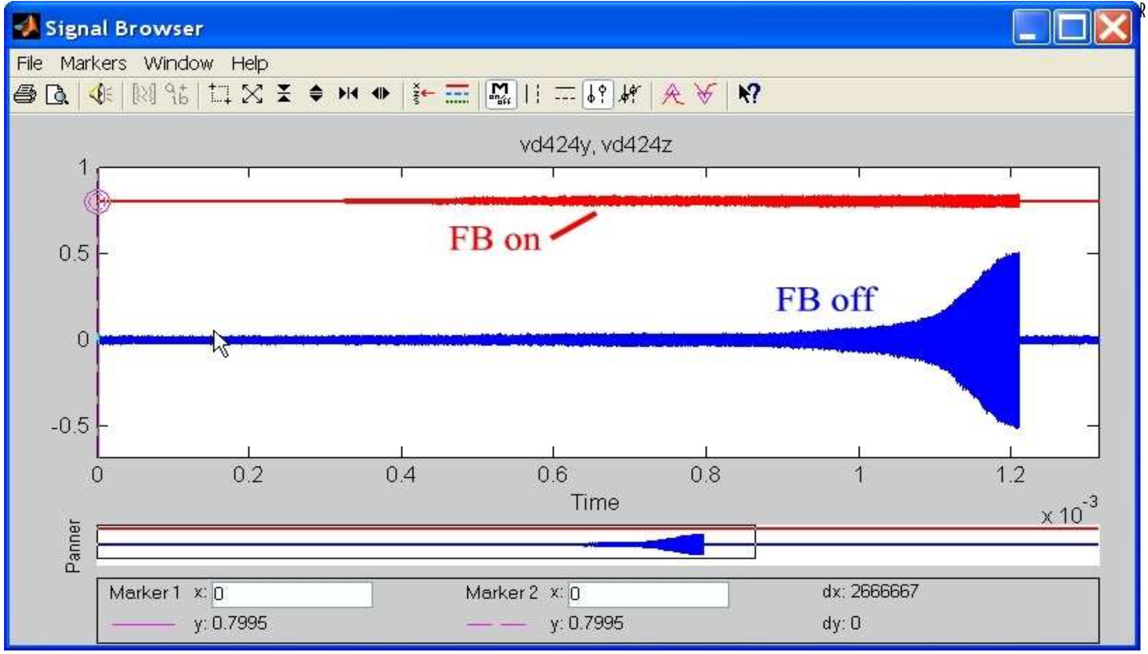
Results summary:

- Instability suppression observed.

- Have observed a 10 - 30% increase in e-p instability threshold with feedback on.

- System still needs optimization.

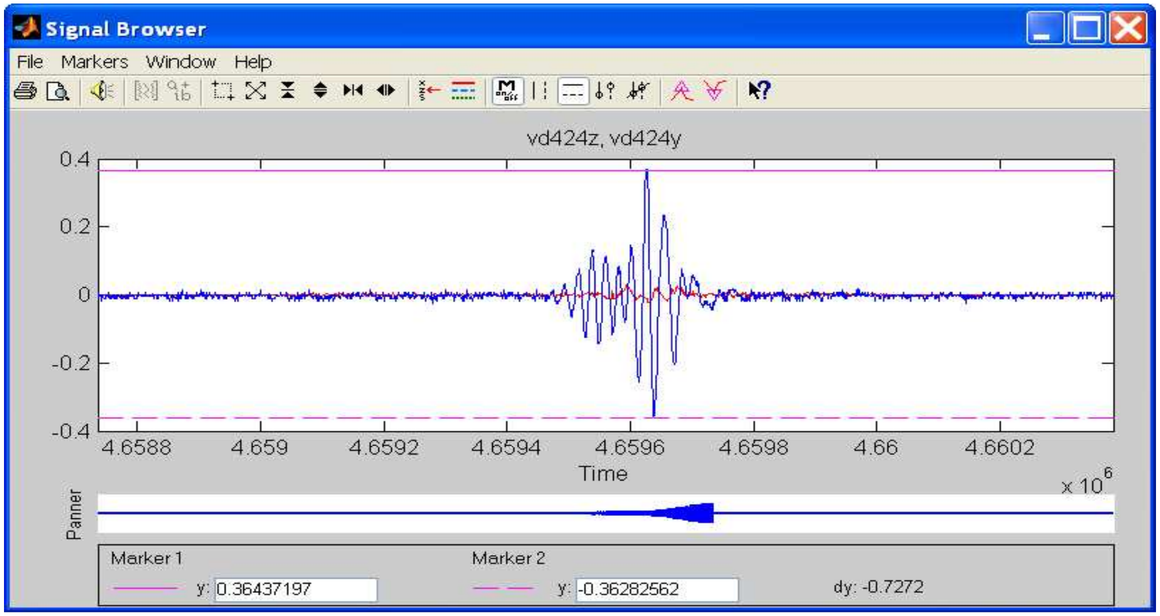
Courtesy S. Henderson



Marker 1 x: 0 y: 0.7995

Marker 2 x: 0 y: 0.7995

dx: 2666667 dy: 0



Marker 1 y: 0.36437197

Marker 2 y: -0.36282562

dy: -0.7272

Summary

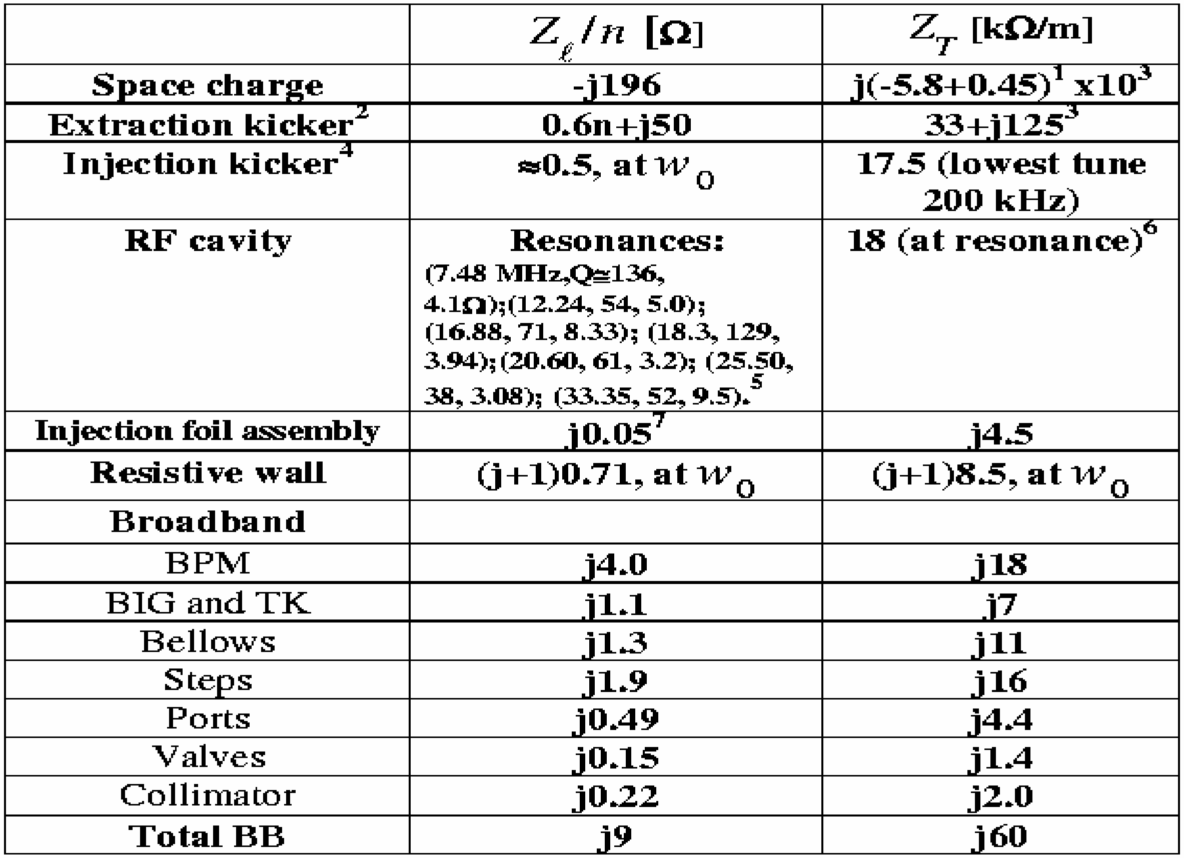
- The SNS will be the highest power pulsed neutron source when complete.
- The SNS ring was designed with a low-loss philosophy for mitigating collective effects, particularly space charge effects.
- Ring commissioning will commence on January 2nd.
- SNS has been approved for a beam power upgrade to 3 MW beginning in ~2010.
- In parallel with commissioning, lots of R&D work being done to prepare for the SNS power upgrade.

Auxiliary Slides

- Extra stuff…

Impedance budget:
low frequency approximation (below 10 MHz)

Key impedances were bench measured, as recommended.



	Z_ℓ/n [Ω]	Z_T [kΩ/m]
Space charge	-j196	j(-5.8+0.45)[1] x10^3
Extraction kicker[2]	0.6n+j50	33+j125[3]
Injection kicker[4]	≈0.5, at w_0	17.5 (lowest tune 200 kHz)
RF cavity	Resonances: (7.48 MHz,Q≅136, 4.1Ω);(12.24, 54, 5.0); (16.88, 71, 8.33); (18.3, 129, 3.94);(20.60, 61, 3.2); (25.50, 38, 3.08); (33.35, 52, 9.5).[5]	18 (at resonance)[6]
Injection foil assembly	j0.05[7]	j4.5
Resistive wall	(j+1)0.71, at w_0	(j+1)8.5, at w_0
Broadband		
BPM	j4.0	j18
BIG and TK	j1.1	j7
Bellows	j1.3	j11
Steps	j1.9	j16
Ports	j0.49	j4.4
Valves	j0.15	j1.4
Collimator	j0.22	j2.0
Total BB	j9	j60

[1] incoherent and coherent part

[2] 25 Ω termination at PFN

[3] measured inside vacuum vessel

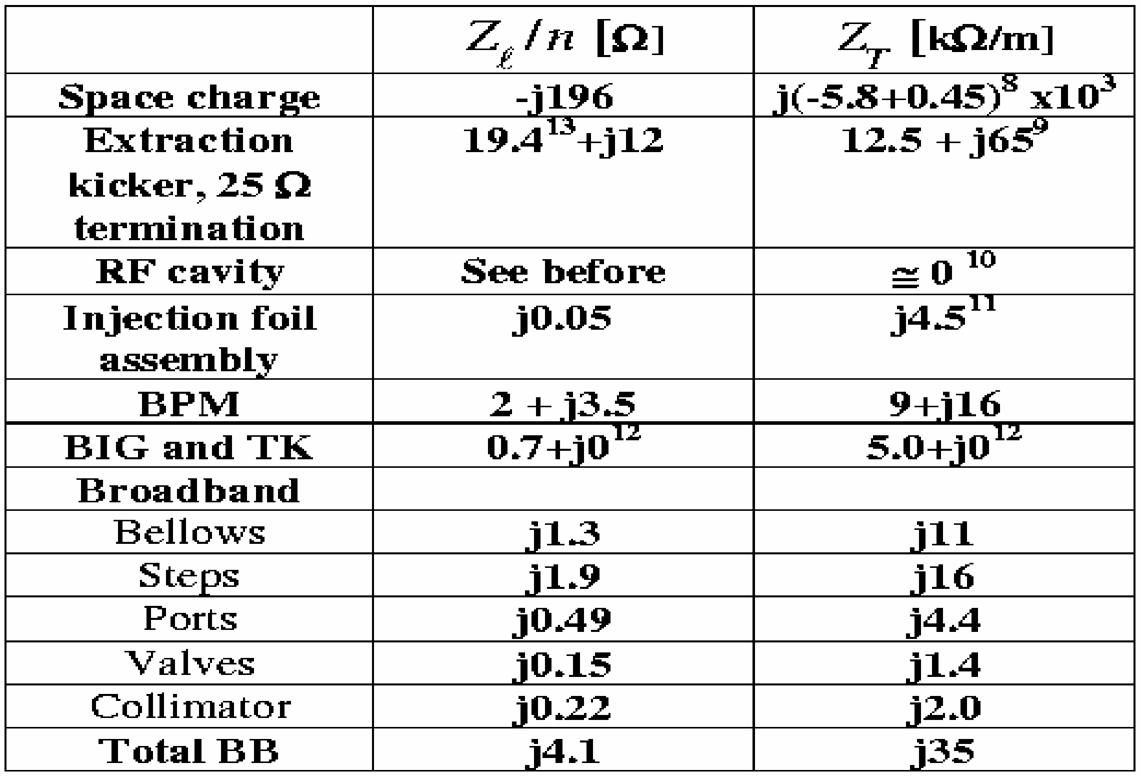
[4] ceramic pipe coated with 0.7 μm of copper and 0.1 μm of TiN

[5] modes will be damped (peak values per cavity without damping)

[6] without damping (at 17.8 MHz, contribution from 3 cavities), damping with glow bar

[7] based on MAFIA simulations

Impedance budget: (at 50 MHz)



	Z_ℓ/n [Ω]	Z_T [kΩ/m]
Space charge	-j196	j(-5.8+0.45)[8] x10^3
Extraction kicker, 25 Ω termination	19.4[13]+j12	12.5 + j65[9]
RF cavity	See before	≅ 0 [10]
Injection foil assembly	j0.05	j4.5[11]
BPM	2 + j3.5	9+j16
BIG and TK	0.7+j0[12]	5.0+j0[12]
Broadband		
Bellows	j1.3	j11
Steps	j1.9	j16
Ports	j0.49	j4.4
Valves	j0.15	j1.4
Collimator	j0.22	j2.0
Total BB	j4.1	j35

[8] incoherent and coherent parts

[9] measured inside vacuum vessel without feed-through

[10] damped resonance at 17,6 MHz

[11] possible high impedance around 170MHz (can be damped with lossy material)

[12] resonant frequency around 50MHz

[13] peak value 35Ω at 35MHz