SNS Ring Extraction Kicker Impedance-Driven Instability

Jeff Holmes
Oak Ridge National Laboratory
Spallation Neutron Source

ICFA Mini-Workshop on
Electromagnetic Wake Fields and
Impedances in Particle Accelerators
Erice, Sicily
April 28, 2014

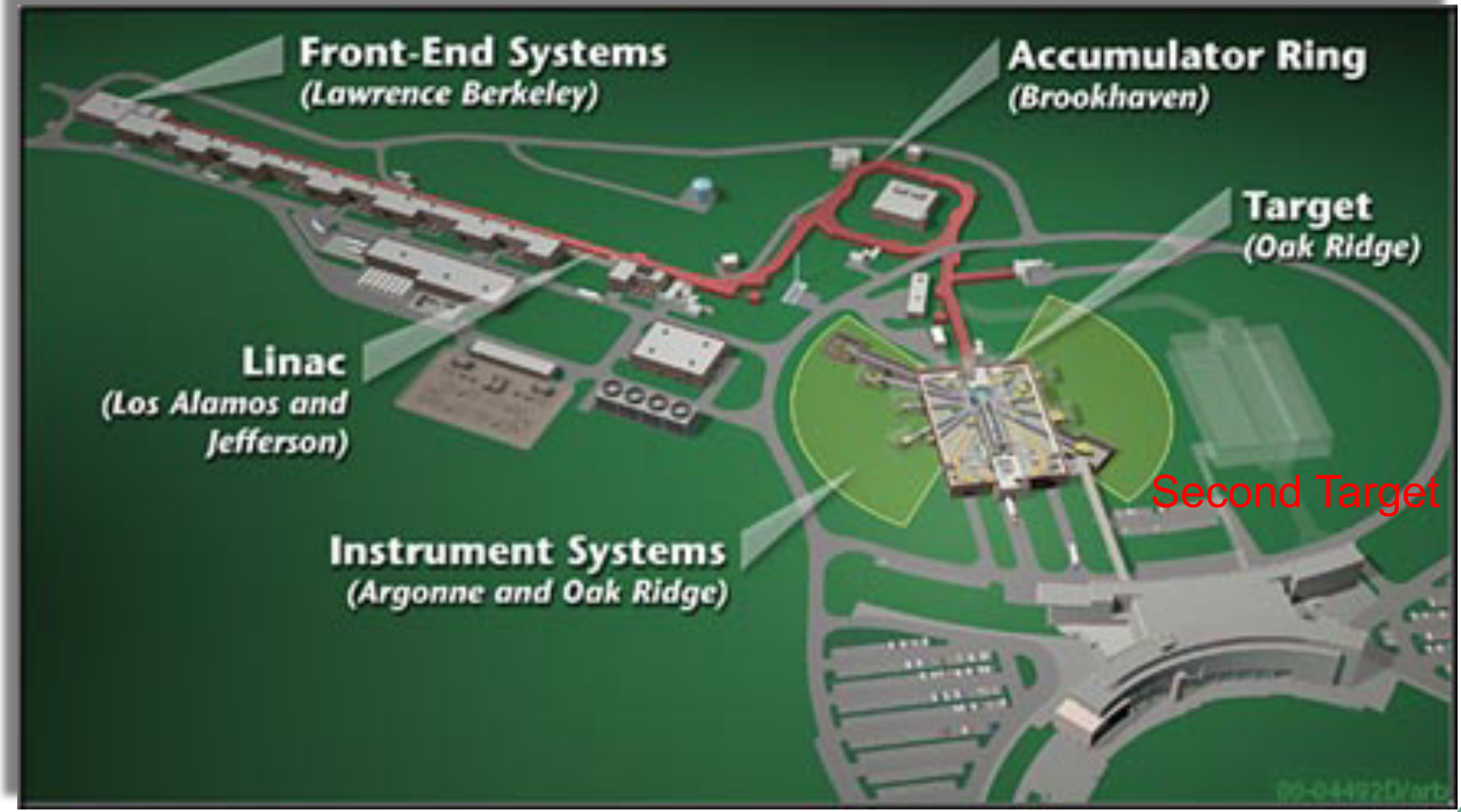
Overview of Presentation

- The extraction kickers constitute the dominant impedances in the SNS accumulator ring.
- Consequently, much care was taken in their design and fabrication to minimize these impedances.
- Also, because of their high impedances, the kickers have been the subject of theoretical, computational, and experimental studies.
  - This talk will present the highlights of this work.
  - Most complete summary can be found in: J.A. Holmes, S. Cousineau, V. Danilov, L. Jain, PRST-AB 14, 074401 (2011).
- Footnote: Although the kickers dominate the ring impedance budget, the most serious stability concern is the electron cloud instability, which is unrelated to the present topic.

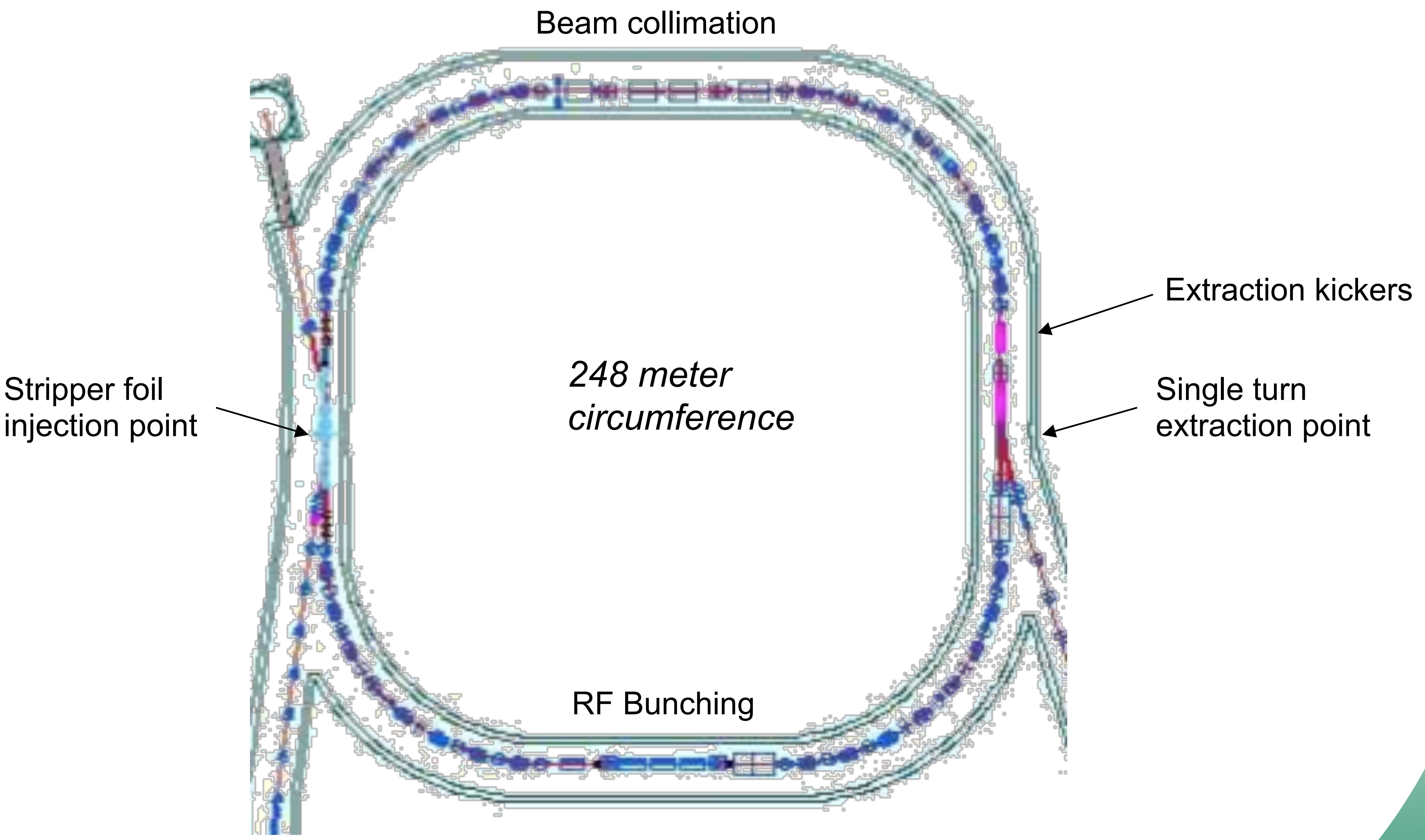
SNS: Overview of a Pulsed Neutron Source

- Proton pulses at 60 Hz
- Full energy H^- Superconducting Linac
  - 1 GeV upgradable to 1.3 GeV
- Accumulator ring compresses pulses
  - 248 m circumference
  - More than 10^{14} protons per pulse
- Single turn extraction to liquid mercury target
  - Beam is kicked vertically to Lambertson septum
  - 200 ns gap -> kicker rise time
  - 750 ns pulse -> kicker pulse "on" time

SNS Facility Layout



The Accumulator Ring



SNS Ring Parameters

Table 1. SNS Ring Parameters

Parameter	Units	Design	Present Production	Upgrade	Instability
Circumference	meters	248	248	248	248
Kinetic Energy	GeV	1.0	0.940	1.3	0.860
Bunch Population	$\times 10^{14}$ protons	1.5	1.1	2.3	0.77
γ Relativistic Gamma		2.066	2.002	2.386	1.917
β Relativistic Beta		0.875	0.866	0.908	0.853
γ_T Gamma Transition		5.246	5.246	5.246	5.246
η Phase Slip Factor		-0.198	-0.213	-0.1394	-0.236
ν_x, ν_y Tunes		6.23, 6.20	6.23, 6.20	6.23, 6.20	6.23, 6.20
Revolution Frequency	MHz	1.058	1.047	1.097	1.031
Ring RF Harmonics		1, 2	1, 2	1, 2	Off
Ring RF Voltages	keV	40, 20	15, 9	40, 20	Off
Ring Bunch Length	meters	165	174	174	248 (Coast)
RMS Energy Spread	MeV	3.5	2.5	3.5	0.5
ξ_x, ξ_y Chromaticity		-9.40, -7.32	-9.40, -7.32	-9.40, -7.32	~0.0, ~0.0
ε_x, ε_y RMS Emittances	mm-mradian	30, 30	~30, ~30	30, 30	~30, ~30
$<\beta_y>$ Avg. Beta-y Ring, Kickers	meters	6.36, 9.30	6.36, 9.30	6.36, 9.30	6.36, 9.30

Extraction Kicker Requirements and Implications

- Must kick beam vertically by 167 mm and by 14 mradian at entrance to Lambertson septum
- Rise time ~200 ns
- Maximum field ~750 ns
- Use 14 ferrite window frame magnets, each with its own pulse forming network (PFN)
- Transverse impedance could be an issue
- Longitudinal stability also considered, but not a problem

Extraction Kicker Assembly

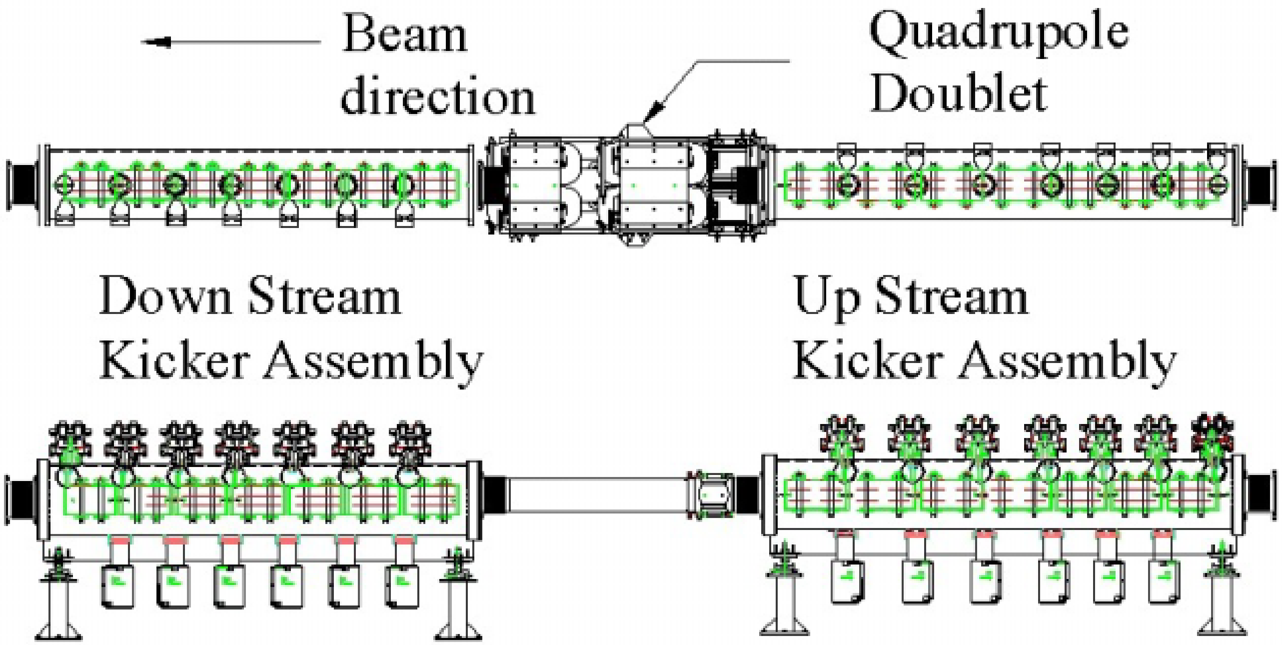


Figure 1: Extraction kicker magnets section layout.

Overall length of assembly ~10 m

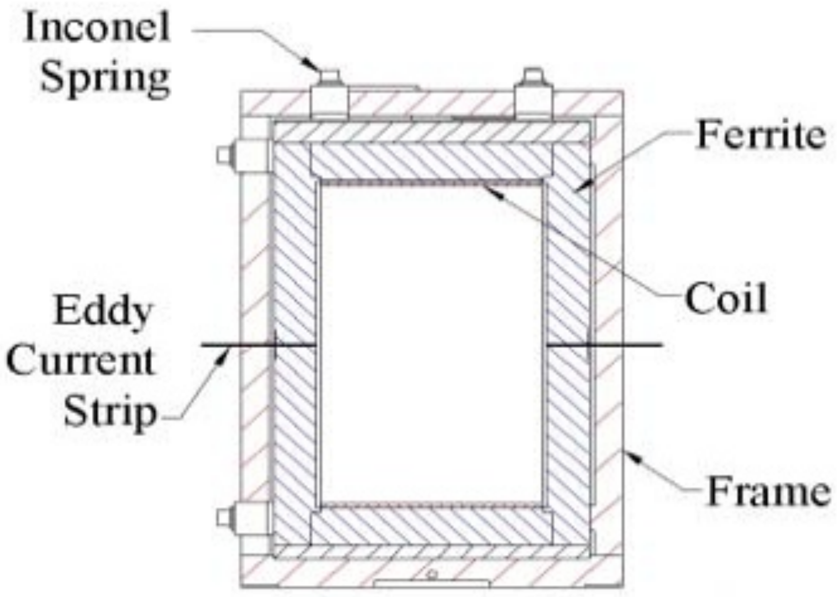
Kicker Design and Development - BNL

- Many Brookhaven National Laboratory (BNL) papers at EPAC, PAC, and IEEE meetings between 2000 and 2004, as well as BNL Technotes. Some definitive papers are listed below:
- D. Davino, H. Hahn, PRST-AB 6, 012001 (2003).
- C. Pai, D. Davino, H. Hahn, H. Hseuh, Y. Lee, W. Meng, J. Mi, J. Sandberg, N. Tsoupas, J. Tuozzolo, D. Warburton, W. Zhang, "Mechanical Design of Fast Extraction Kicker and PFN for SNS Accumulator Ring," PAC 2003 (Portland, OR, USA), p. 2147.
- W. Zhang, J. Sandberg, H. Hahn, J. Mi, C. Pai, N. Tsoupas, Y. Tan, N. Tsoupas, J. Tuozzolo, D. Warburton, J. Wei, "SNS Extraction Kicker Pulsed Power System," EPAC 2004 (Lucerne, Switzerland), p. 1810.
- H. Hahn, PRST-AB 7, 103501 (2004).
- Additional guidance provided by M. Blaskiewicz, V. Danilov, S. Kurenoy, R. Gluckstern

Some Features of the Kickers

- Two sets of seven kickers upstream and downstream of quad doublet
- External PFNs in another building, connected by cables of length 90 m
- Septum as far downstream as possible (~6 m) to maximize beam displacement
- Vertical apertures increase downstream to accommodate beam
- Copper eddy current strips break ferrite magnetic circuit and reduce beam-ferrite interaction, heating, and longitudinal impedance
- Ferrite also coated with TiN strips, mostly for electron cloud mitigation, but also to minimize eddy currents and heating
- Impedance measurements conducted on prototype and actual sample magnets to determine:
  - Reduction of impedance with resistive termination of the external PFN circuit
  - Effect of different choice of ferrite (none with resistive termination of external circuit)
  - Impedance scaling law with height of window frame aperture (h^{-2})
  - Test reduction of impedance by novel winding loop (above 32 MHz only)
- Results:
  - Horizontal impedance mostly inductive, due to ferrite. Small resistive component not a concern.
  - Vertical impedance has large resistive component due to magnet termination. Imaginary part is similar to that of horizontal impedance.

The Kickers



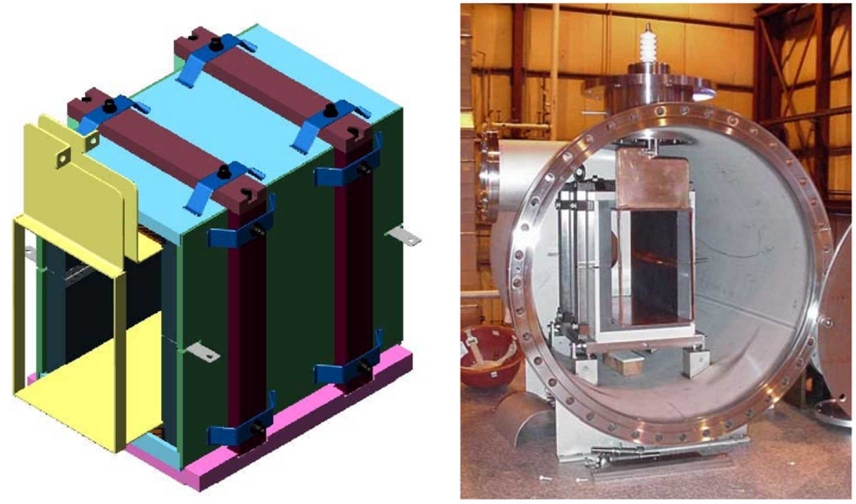
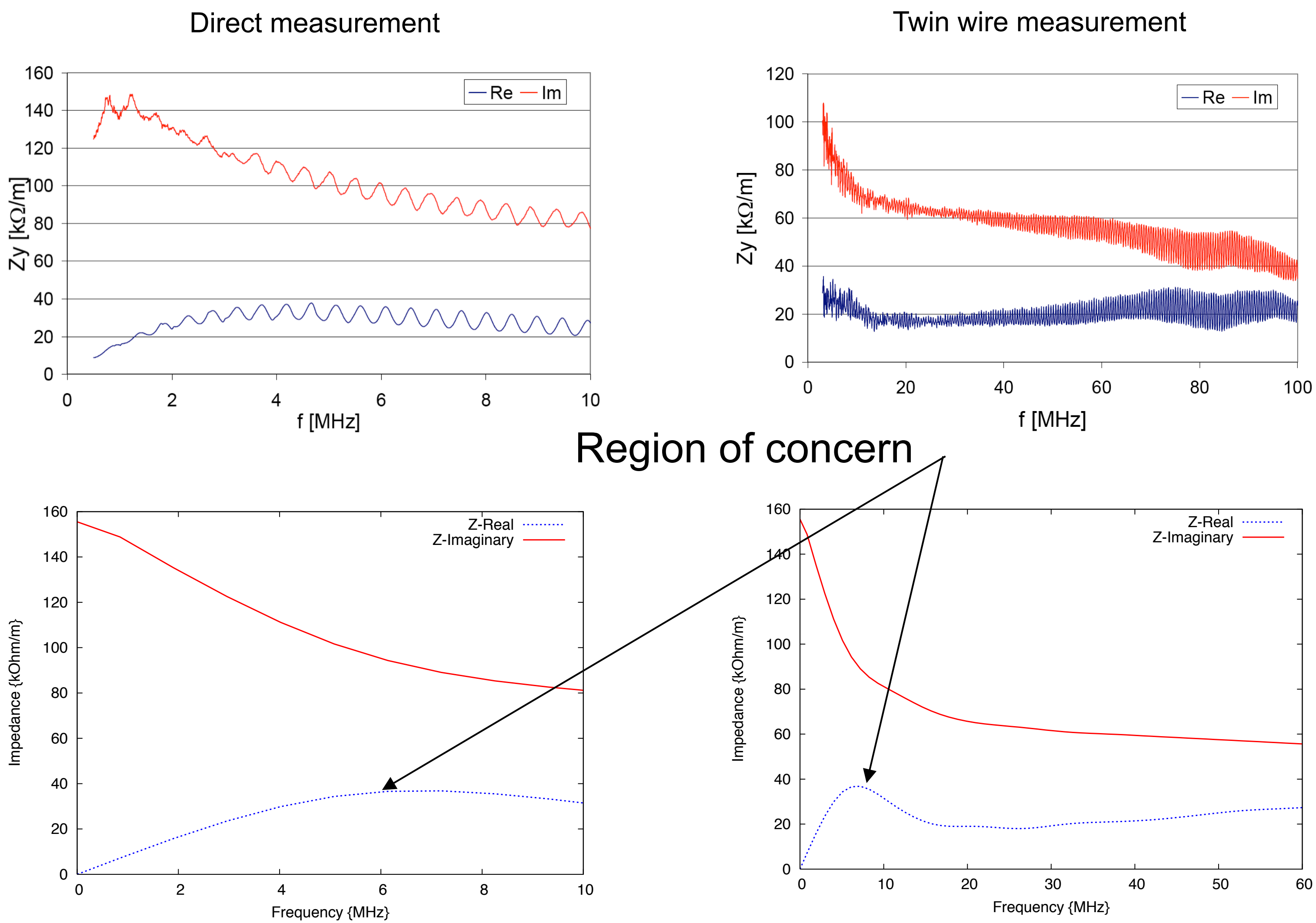


FIG. 7. (Color) SNS extraction kicker: schematic view (left), the kicker in the vessel (right).

Measured Vertical Impedance of Kickers



H. Hahn, PRST-AB 7, 103501 (2004). Two kickers were measured and scaling applied to the remainder.

Stability Investigations at SNS

- In the same time frame as BNL carried out the kicker design, fabrication, and impedance measurements, the SNS group began studies of the ring impedance:
- Computational: Longitudinal and transverse dipole impedance models developed in the ORBIT code. Use convolutions of impedance with current (longitudinal) or current × dipole moment (transverse).
- Analytic: Linearized analysis of stability boundaries and mode growth for coasting beams incorporating effects of phase slip, chromaticity, and linear space charge, treated using an impedance formulation.
- Comments:
  - Although theoretical work on nonlinear space charge and bunched beam effects is an active research area, we did not pursue this –> limitation.
  - The adopted computational models are the primary tool because they can be applied to more general situations than our simple theoretical approach.
  - Benchmarks between the analytic and computational models were performed for a variety of coasting beam calculations, with excellent agreement:
    - V. Danilov, J. Holmes, "Halo and RMS Beam Growth Due to Transverse Impedance," Halo 2003, ICFA Advanced Beam Dynamics Workshop (Montauk, NY, USA) 2003.
    - J. Holmes, V. Danilov, L. Jain, "Transverse Stability Studies of the SNS Ring," PAC 2005 (Knoxville, TN, USA) 2005.

Assumptions for Analytic Model

- Coasting beam in periodic lattice with linear transverse focusing
- Beam energy distribution with small spread
- Phase slip factor and chromaticity
- No explicit space charge – treat as impedance
- Single localized impedance kick/lattice period, with linear betatron motion elsewhere
- Impedance and dipole moment taken at single harmonic
- Average over rapid motion to solve for slowly varying parts
- Get first order integral-differential equation
- Assume complex exponential time dependence

Equations for Analytic Model

$$\frac{\partial d_s(\delta,\phi)}{\partial \phi} + i\Delta(\delta) d_s(\delta,\phi) = \chi \int_{-\infty}^{\infty} g(\delta) d_s(\delta,\phi)\, d\delta$$

Equation for dipole moment

$$\Delta(\delta) = \frac{2\pi\delta}{\beta^2}[(n+\nu_b)\eta + \xi]$$

Phase slip and chromaticity

$$\chi = \frac{-Nr_p Z_\perp (n\omega_0 + \omega_b)}{\gamma\beta Z_0} \frac{2\pi\beta_{s_0}}{\Pi}$$

Impedance driving term

$$h(n) \equiv -\frac{Nr_p Z_\perp (n+\nu_b)\beta^2 E_{Tot}}{2\pi i \gamma\beta Z_0 \left|(n+\nu_b)\eta + \xi\right|} \frac{2\pi\beta_{s_0}}{\Pi}$$

$$= \frac{1}{\displaystyle\int_{-\infty}^{\infty} \frac{g(\Delta E)\, d(\Delta E)}{\Delta E - \frac{\beta^2 E_{Tot}}{\left|(n+\nu_b)\eta + \xi\right|}\Omega}}$$

$$\equiv \frac{1}{a(\Omega) + ib(\Omega)}$$

$$\mathrm{Re}(Z) = \frac{2\gamma\beta^2 E_0}{\tau\beta_{s_0} I}$$

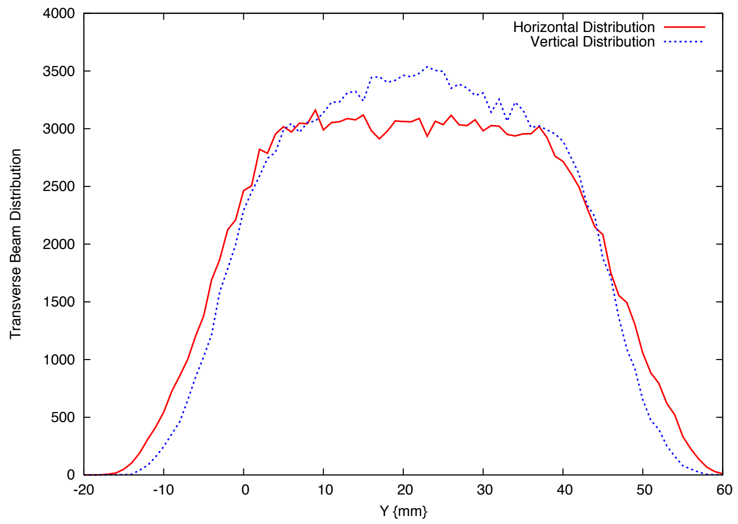
Prediction for growth rate – impedance relationship

Dispersion relation: stability boundary at $\Omega_R = 0$

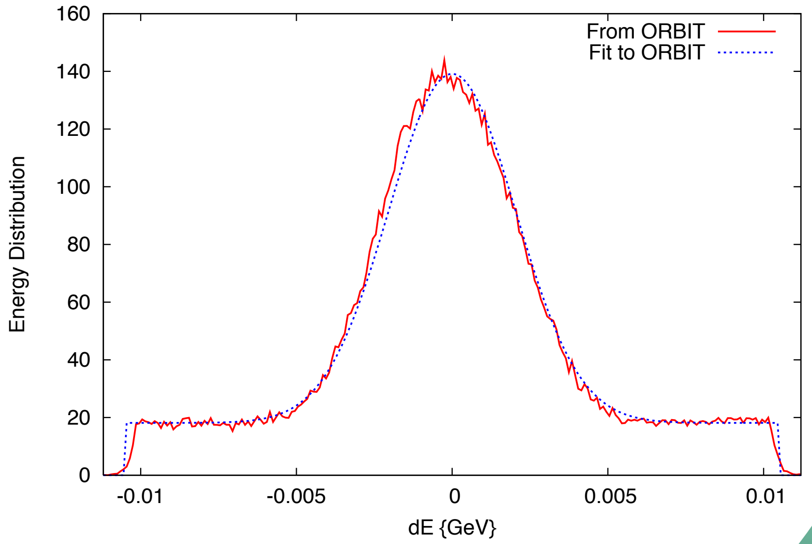
Analytic SNS Coasting Beam

The stability of analytic cases was benchmarked with ORBIT for various mode numbers, chromaticities, analytic energy distributions, space charge, etc., and excellent agreement was obtained. Here we show one case of interest - the analytic SNS coasting beam.

Using ORBIT, full intensity beam was injected into SNS ring. Using resulting beam parameters at longitudinal current peak, numerically created an SNS coasting beam distribution. The energy distribution was fitted analytically to provide input for the analytic model – rectangular + Gaussian distributions.



Transverse Beam Profiles

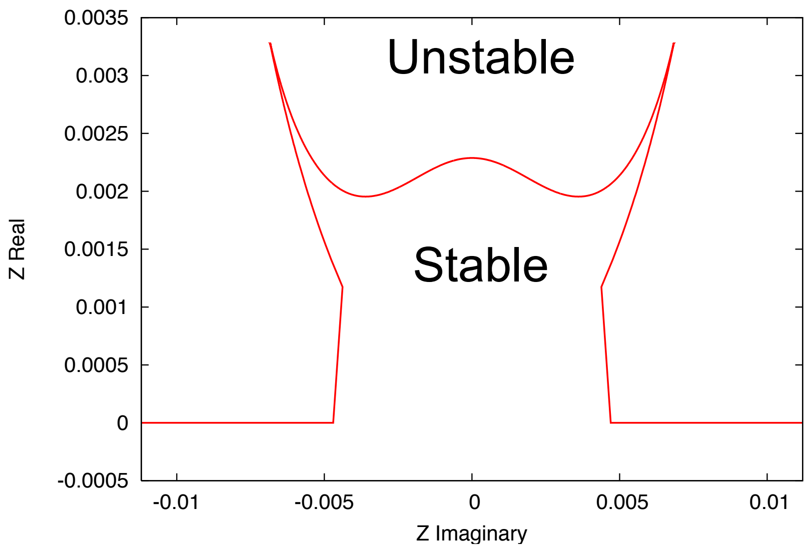


Energy Distribution and fit for analytic model

Analytic SNS Coasting Beam

- Parameters used in study:

✓ Tunes - ν_x, ν_y = 6.23, 6.20
✓ Gammas and phase slip - γ = 2.066, γ_T = 5.246 -> η = -0.198
✓ Chromaticity - ξ = -7.320 or 0
✓ N = 3.75×10^{14} protons (BF = 0.4)
✓ $\Delta\nu_{sc} \approx -0.2$
✓ $\Delta\nu_{chr} \approx \pm0.05$



SNS analytic coasting beam stability diagram. Scales are proportional to imaginary (horizontal) and real (vertical) impedances, but factors depend on parameters in dispersion equation.

- For n = 10:

✓ 0.001 on diagram ≈ 11.2 kΩ/m at ξ = 0
✓ 0.001 on diagram ≈ 105.5 kΩ/m at natural chromaticity
✓ $ZR_{kicker} \approx$ 30 kΩ/m
✓ $ZI_{kicker} \approx$ 30 kΩ/m
✓ $ZI_{sc} \approx$ 3.5 MΩ/m

Oak Ridge National Laboratory

Analytic SNS Coasting Beam Results

Coasting beam (mostly) results for n = 10:

A. Linear transport, ξ = 0, no space charge
B. Symplectic transport, fringe fields, ξ = 0, chromatic sextupoles, no space charge
C. Symplectic transport, fringe fields, natural chromaticity, no space charge
D. Linear transport, ξ = 0, space charge
E. Bunched beam, fringe fields, natural chromaticity, no space charge

Case	Analytic Threshold (kΩ/m)	ORBIT Stable (kΩ/m)	ORBIT Unstable (kΩ/m)
A	25.6	25	30
B	25.6	30	40
C	242	200	300
D	0	0	10
E		800	1000

Bunched Beam Computational Results

SNS Bunched Beam Computational Results:
$N = 1.5\times10^{14}$
Use extraction kicker impedance × constant factor Z, shown in table

A. Linear transport, $\xi = 0$
B. Symplectic transport, fringe fields, $\xi = 0$, chromatic sextupoles
C. Symplectic transport, fringe fields, natural chromaticity

Conclude: SNS should be stable with at least a factor of 2 margin for natural chromaticity and/or bunched beams. To observe instability, we need to use Coasting beams and corrected chromaticity.

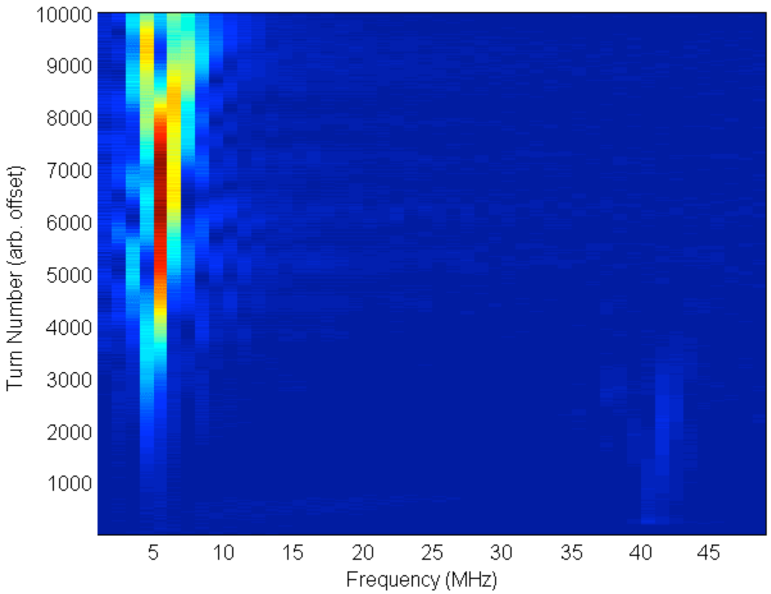
Case	Stable - No Space Charge	Unstable - No Space Charge	Stable - Space Charge	Unstable - No Space Charge
A	0.5	0.6	1.5	2.0
B	0.6	0.8	2.0	3.0
C	5.0	7.0	3.0	4.0

Experimental Observation of the Extraction Kicker Instability

Beam study time was dedicated during a physics shift to attempt to observe the SNS extraction kicker instability. Based on the analytic and computational results, it was decided to use corrected (zero) chromaticity and a coasting beam (ring RF turned off). After accumulation for 850 turns, the beam was stored for an additional 10000 turns to allow the instability to evolve. 1 turn = 970 ns at chosen energy.

- Conditions:
- ✓ Tunes - ν_x, ν_y = 6.23, 6.20
- ✓ Chromaticity - $\xi = 0$
- ✓ Coasting beam – ring RF off
- ✓ Kinetic E_k = 860 MeV
- ✓ N = 7.7×10^{13} protons

- Results:
- ✓ Growth in 4-10 MHz range ($10 \le n \le 16$)
- ✓ e-growth time of 6 MHz (n = 12) harmonic about 1036 turns.
- ✓ Observed growth time -> Z_R = 18 kΩ/m, compared to measured 30 kΩ/m. This is expected, since formula ignores Landau damping and assumes rapid growth.



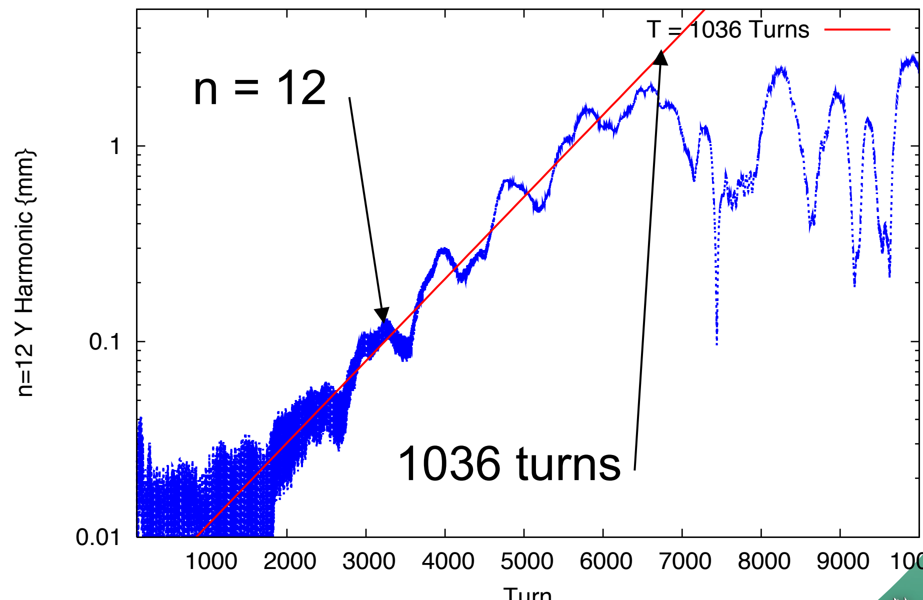
Observed Spectrum Evolution

Simulation of the Instability

ORBIT Code was used to simulate the observed instability following the experimental scenario precisely. In addition to the previously given parameters:

- ✓ Injected RMS energy spread set to 0.5 MeV, consistent with observations
- ✓ The nominal SNS transverse correlated injection painting was employed.
- ✓ A single impedance kick containing the total impedance of the kicker system was placed at a location in the kicker array where β = 9.3 m, the average over the kicker locations
- ✓ The number of macroparticles used in the calculation was 4.25 million, about double the number required for convergence of the space charge model.

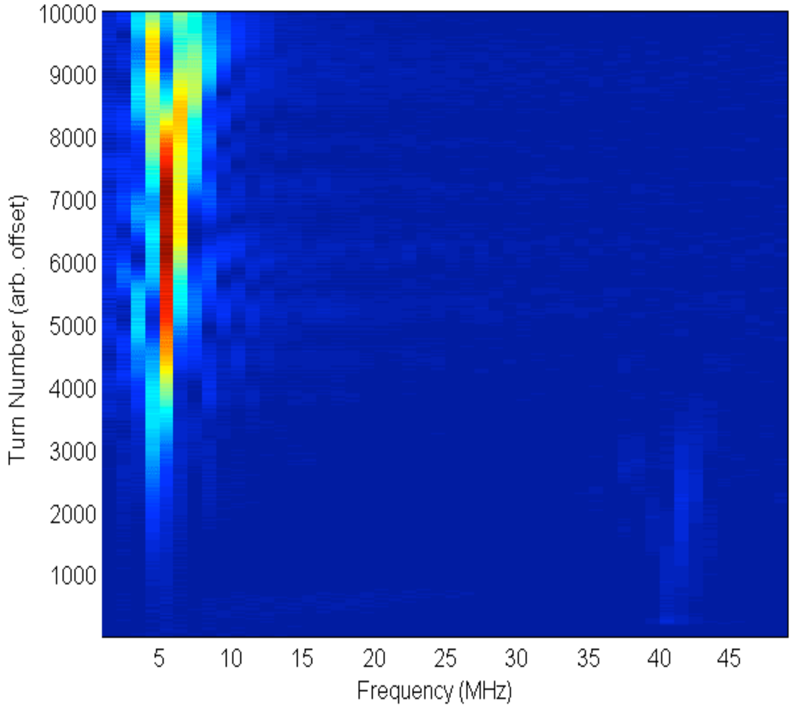
In the calculation, the n = 12 harmonic of the dipole moment × current was observed to grow fastest, and its growth time is in good agreement with the observed 1036 turns.



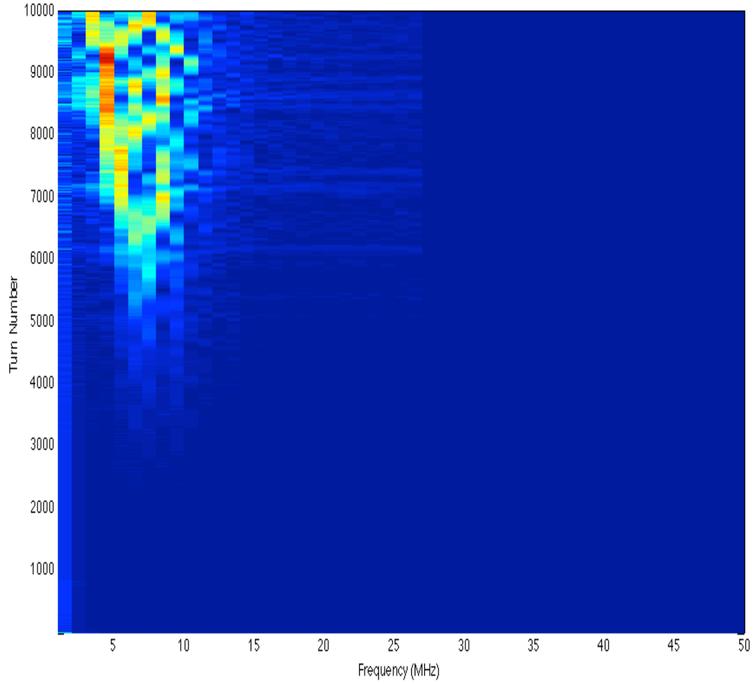
Observed and Simulated Spectra

Experimental and simulated spectra show activity at comparable frequencies. Details are different, but this is not surprising over such long times. Beam losses alone could differ sufficiently to account for such differences.

Experiment –
wide bandwidth BPM data



Simulation –
beam centroid harmonics



Conclusions

- ✓ Extraction kickers were identified as dominant impedance in the SNS ring.
- ✓ Kickers were carefully designed and constructed to minimize impedance.
- ✓ Simple theory, detailed simulations, and experimental measurements give a consistent picture of the stability.
- ✓ Under normal operating parameters, SNS has a wide margin of stability.
- ✓ We will revisit the stability question for an SNS upgrade, which will increase beam intensity and add two additional kickers.

Thank you