SNS Experience with a Megawatt Beam

N. J. Evans

(On behalf of the SNS project)

FNAL MW Beams

May 2018

ORNL is managed by UT-Battelle
for the US Department of Energy

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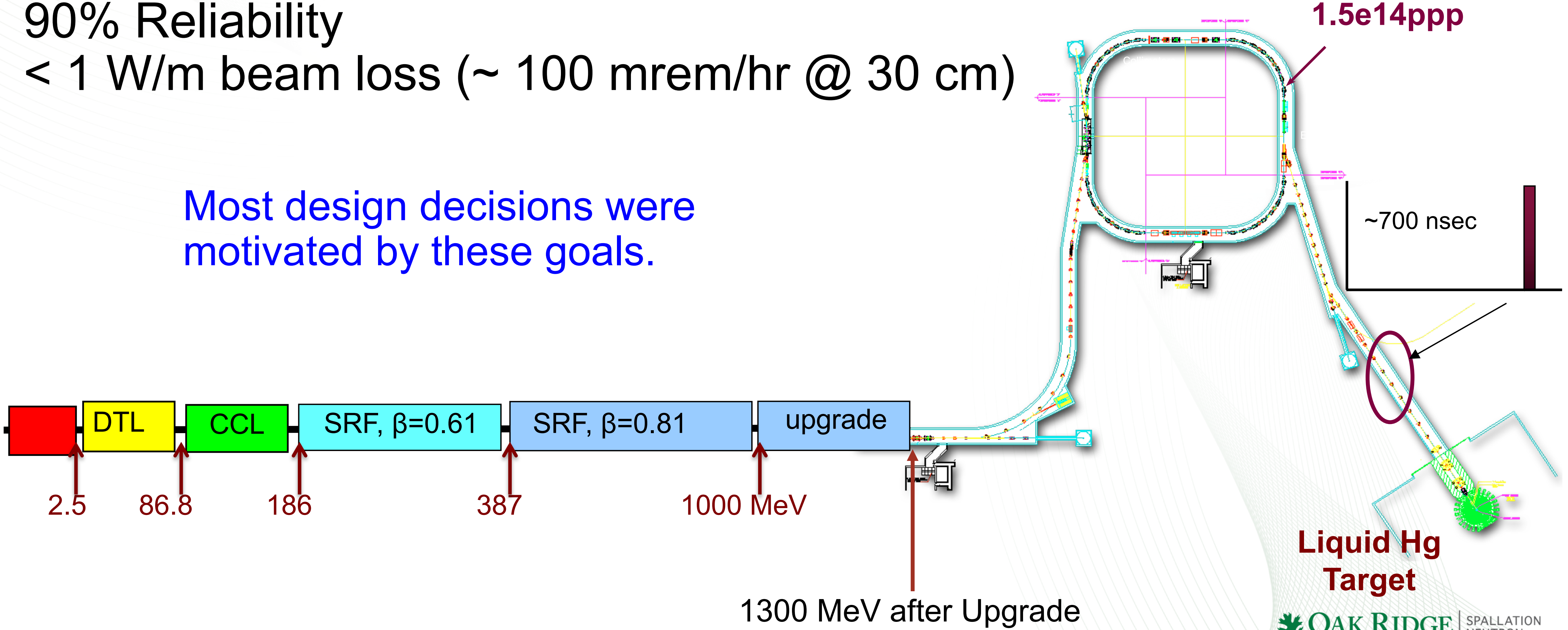
The SNS Accelerator

Top Level Goals:
1. 1.4 MW (designed for up to 2 MW)
2. 90% Reliability
3. < 1 W/m beam loss (~ 100 mrem/hr @ 30 cm)

Most design decisions were motivated by these goals.



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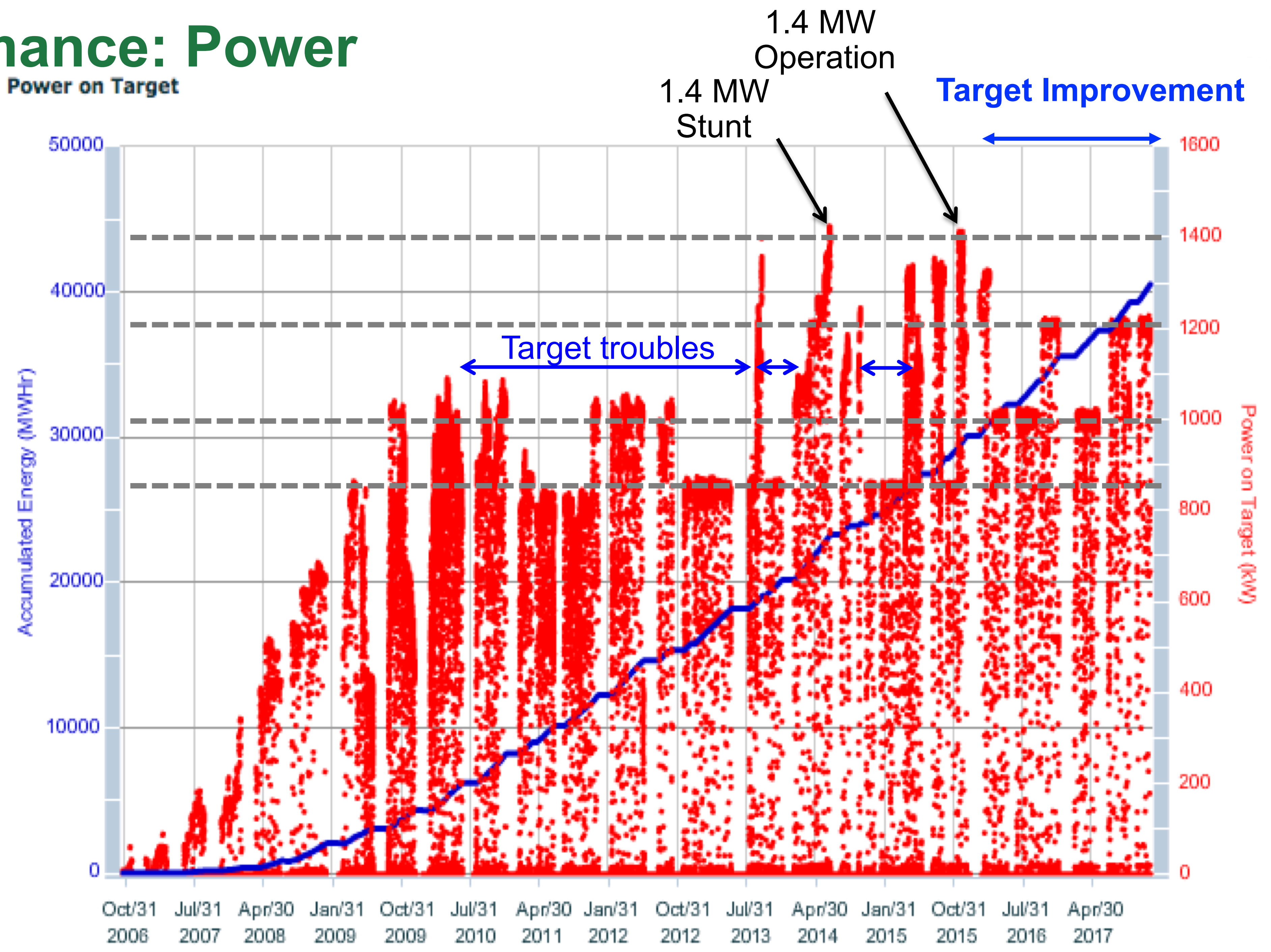
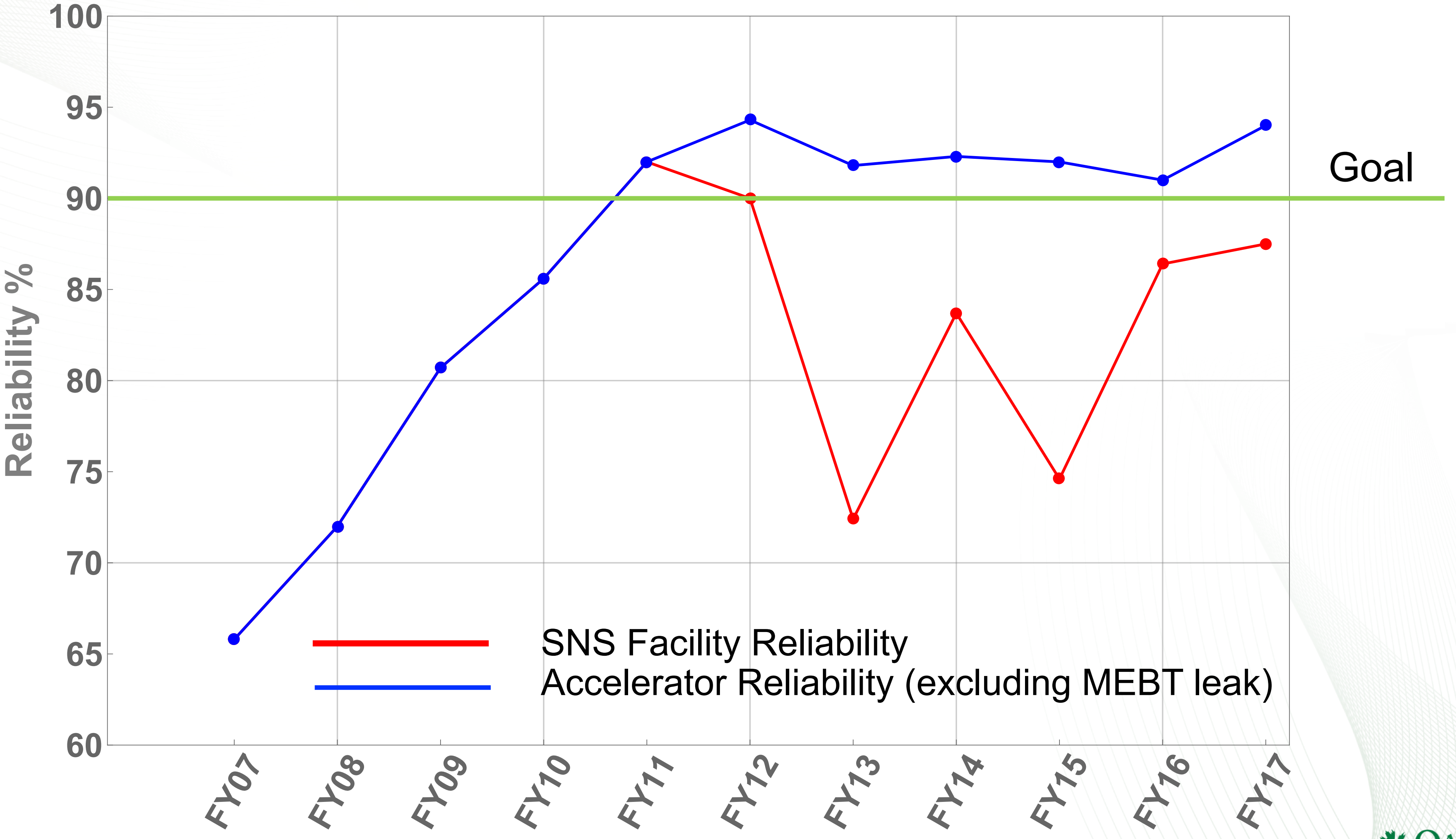
Performance: Power



Performance: Reliability

Outside of target failures, IRP leak, and catastrophic MEBT event, accelerator exceeds 90%



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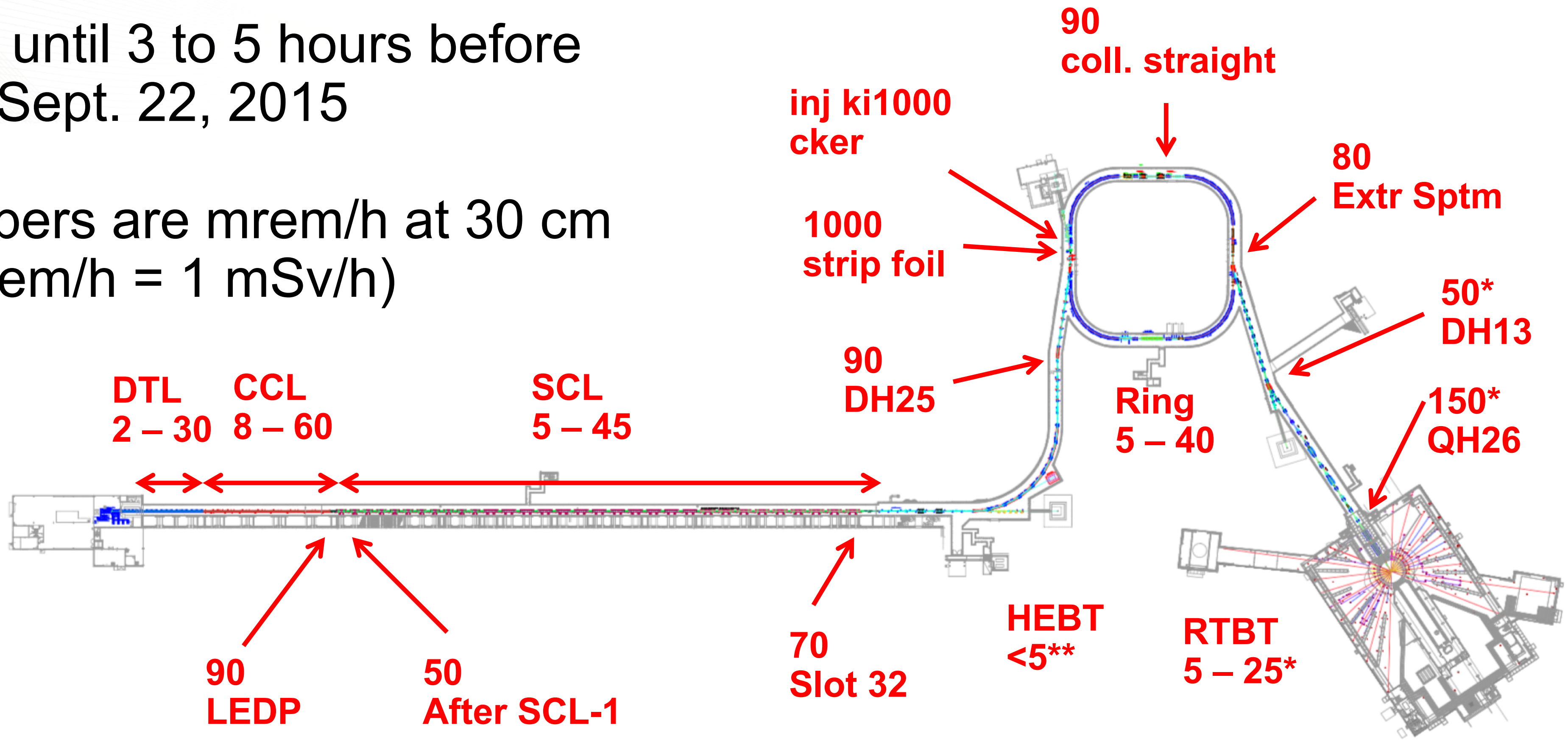
Performance: Activation levels

- 1.3 MW until 3 to 5 hours before survey, Sept. 22, 2015
- All numbers are mrem/h at 30 cm (100 mrem/h = 1 mSv/h)



Except for a few hot spots, the dose rates are relatively low (< 1 W/m).

* 3 days after 1.3 MW
** No survey near this time, indicated does rates are typical

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Part I
The Linear Accelerator

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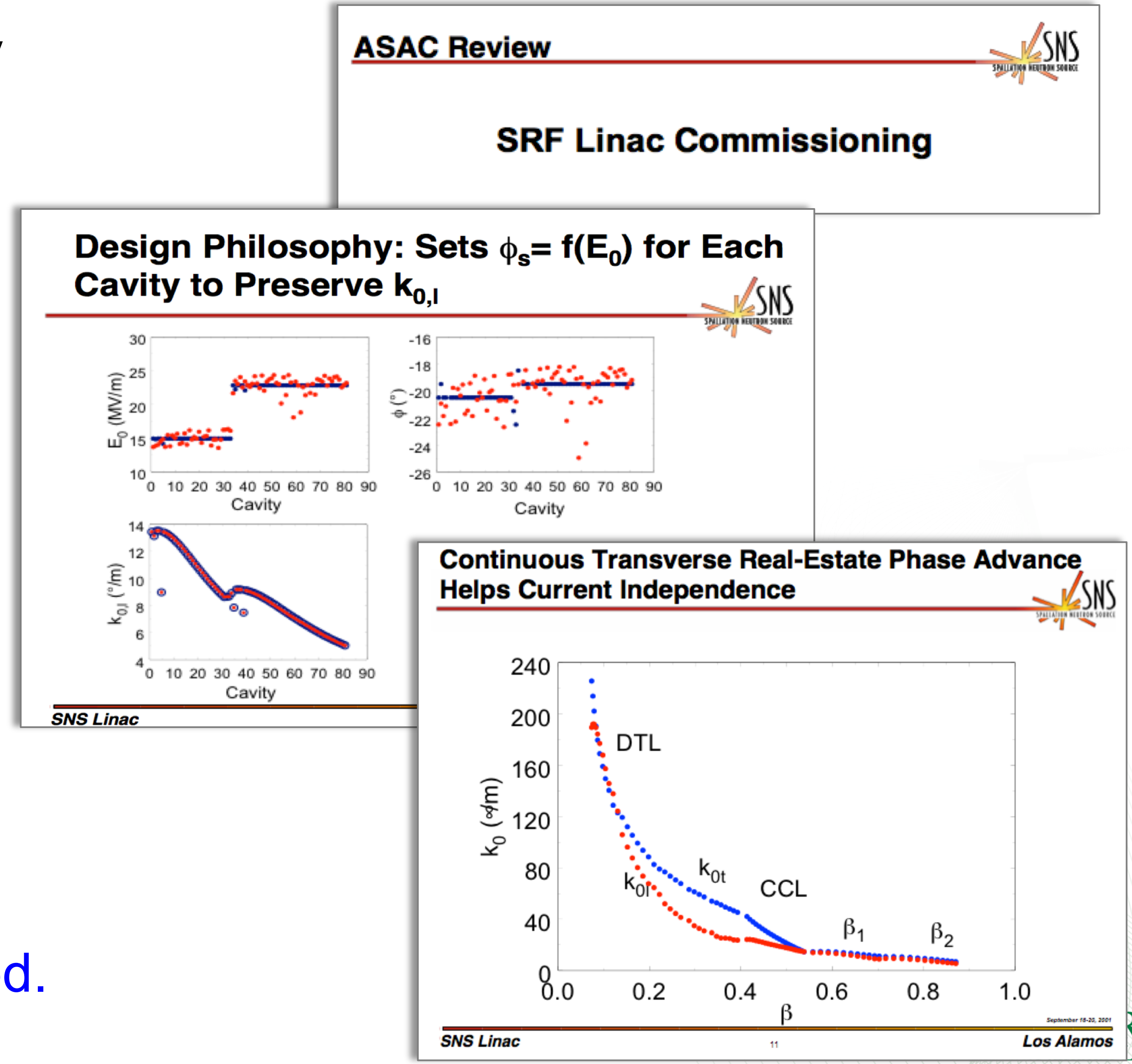
Expectations: SCL Tune Up Scenario

It was the first H^- SCL – Nobody really knew what would happen. Relied heavily on simulations



Some expectations:

1. Cavity gradients to be near design values.

2. Set longitudinal phase to preserve matching along SCL.

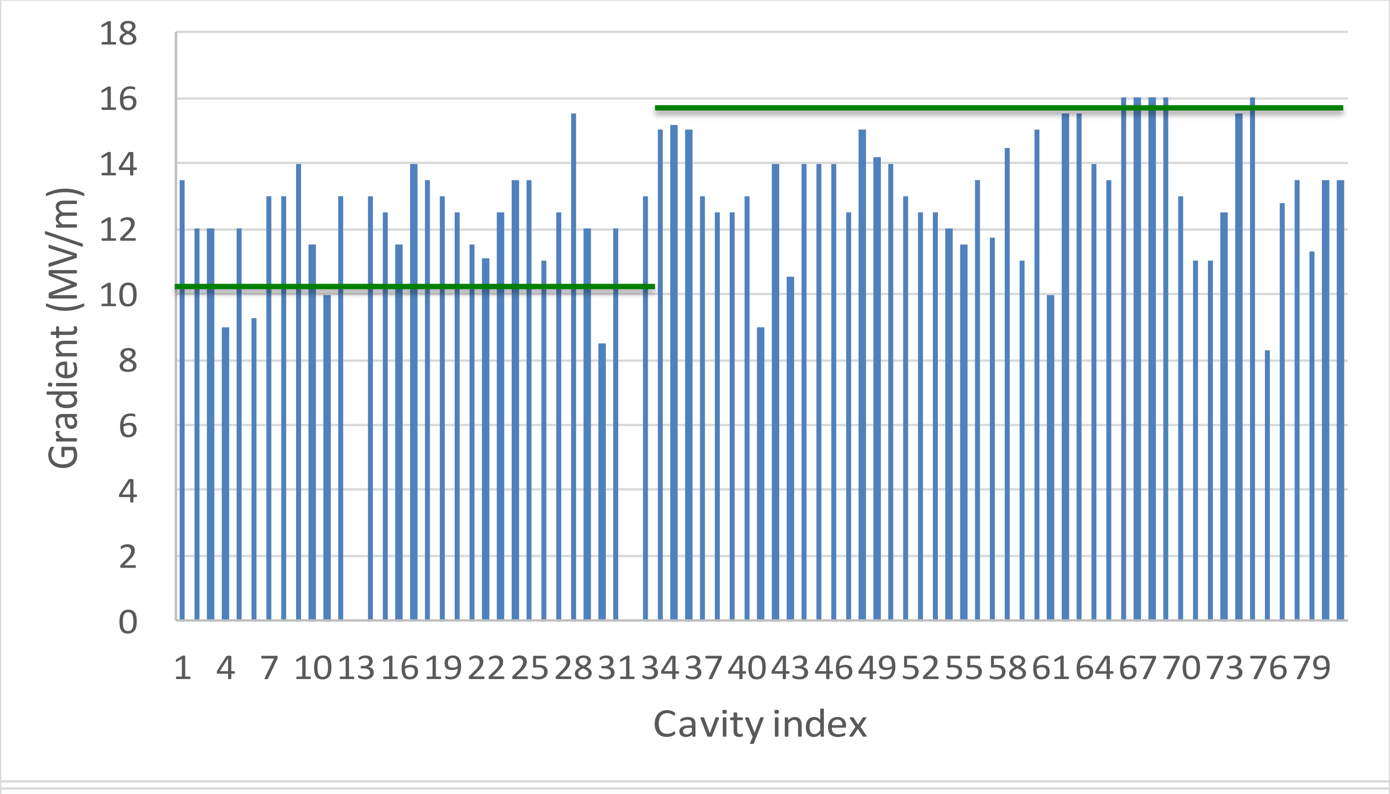
3. Maintain a relationship between transverse and longitudinal phase.

Reality Struck:
NONE of this happened.

Reality: SCL Cavity Gradients

- High beta cavity gradients did not come on at design levels: Biggest problem was electron activity (51 cavities); also some hardware issues.

- Progress made over the years – as Spring 2018 we will be operating at 1.01 GeV with some headroom



SCL has demonstrated superb operational flexbility: Energy reserve (spare cavity), easy retune (individual klystrons), allows removal of cavity with no impact on beam energy.

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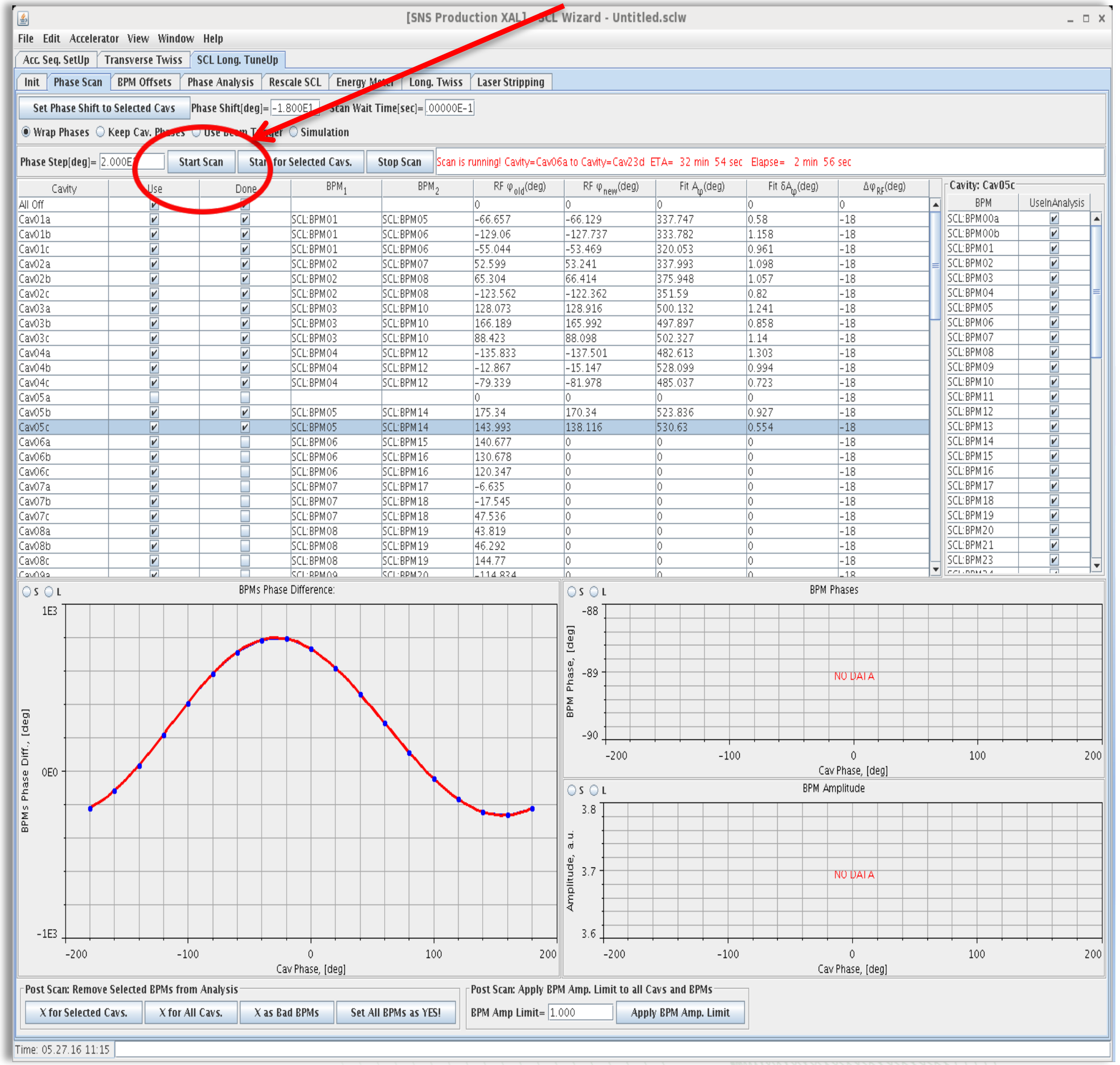
Reality: SCL Tune Up is Fast and Flexible

Fabled “tune it up” button



Tune times, all 81 cavities:

– From scratch: 40 minutes
– Rescale: 20 seconds

Confluence of:

1. Robust BPM system
2. Beam Blanking
3. Andrei Shishlo

Contrary to expectations:

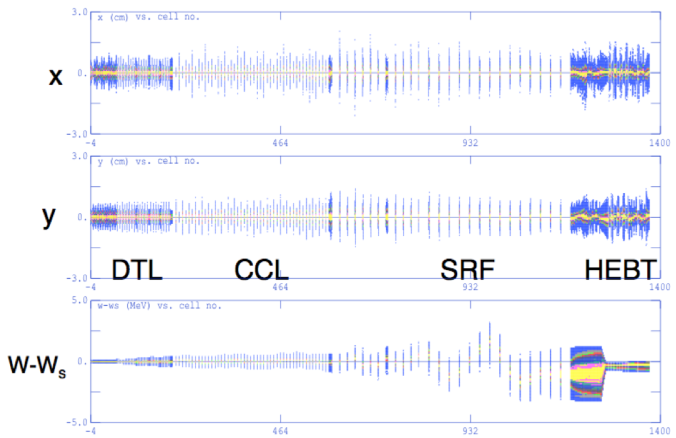
No longitudinal matching is applied.

Expectations: Linac Beam Dynamics

ASAC Review

FINAL DESIGN &
EXPECTED BEAM PERFORMANCE
OF THE SNS LINAC

Reference Beam is Also Matched,
Energy Corrector ϕ Feed-Forward Off



September 18-20, 2001
SNS Linac 20 *Los Alamos*

Beam Loss Mechanisms

- Gas Stripping: predicted from vacuum measurements
- Magnetic Stripping: negligible
- Longitudinal beam loss
  - **poor MEBT matching** **will be derived from matching algorithms**
  - turn-on transients: minimized by beam current ramp
  - dynamic phase & amplitude errors: no effect is observed
  - static (mistuned) modules (ϕ & E_0): no effect is observed
- Transverse beam loss
  - misalignments & missteering: simulated
  - **halo**
    - **initial beam distribution:** simulated
    - **poor MEBT matching:** **will be derived from matching algorithms**
- No beam loss is observed in the SRF linac

September 18-20, 2001
SNS Linac 31 *Los Alamos*

Expected to match the beam in linac.

Expected negligible SCL beam loss.

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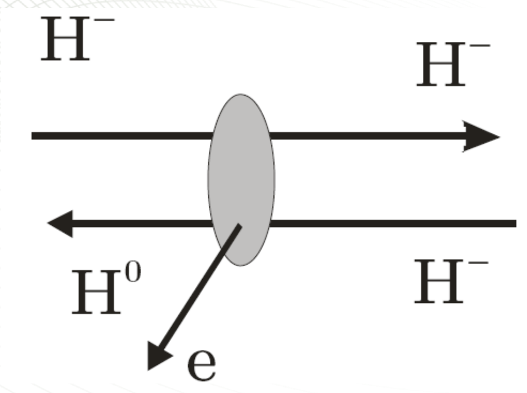
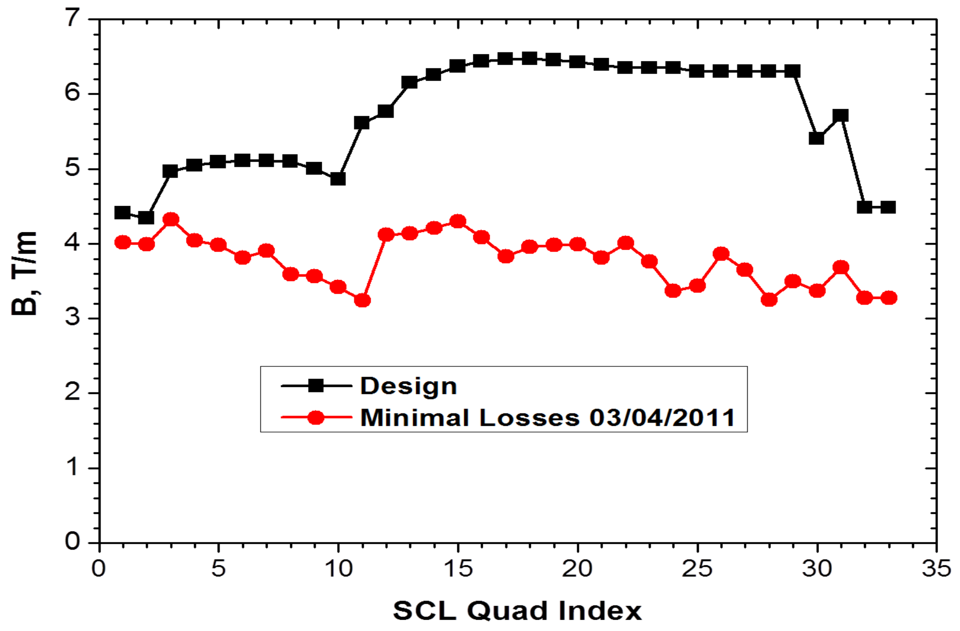
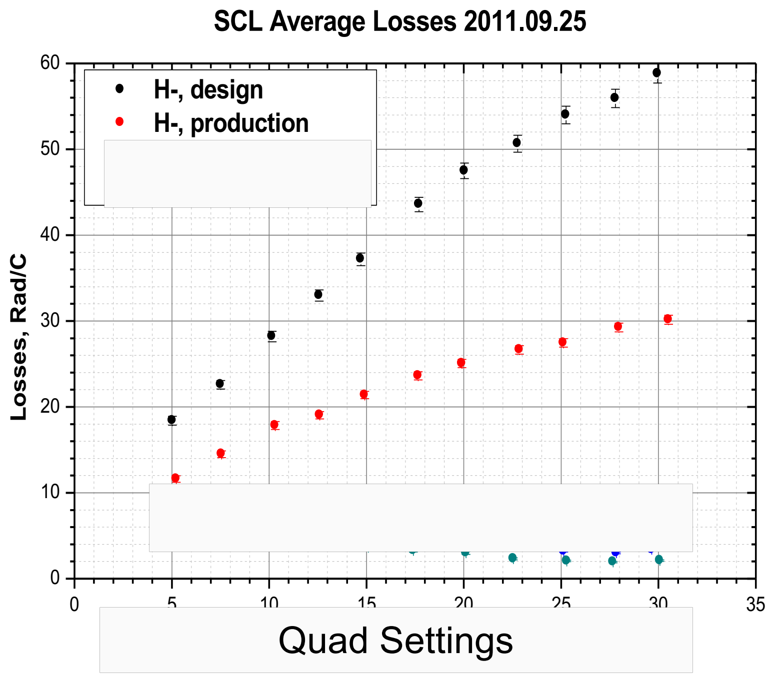
Reality: Impact of H^- Intrabeam Stripping



- Saw much more beam loss than expected – not hard when you don't expect any loss
- Factor ~2 decrease in quad strength reduced losses significantly.
- V. Lebedev suggested* that H- intrabeam stripping was to blame and provided calculations, eventually confirmed via experiment**





*Lebedev, et al.25th International Linear Accelerator Conference LINAC 2010. 12-17 Sep 2010. Tsukuba, Japan
Shishlo, et al. Phys. Rev. Lett. **108, 114801 2012

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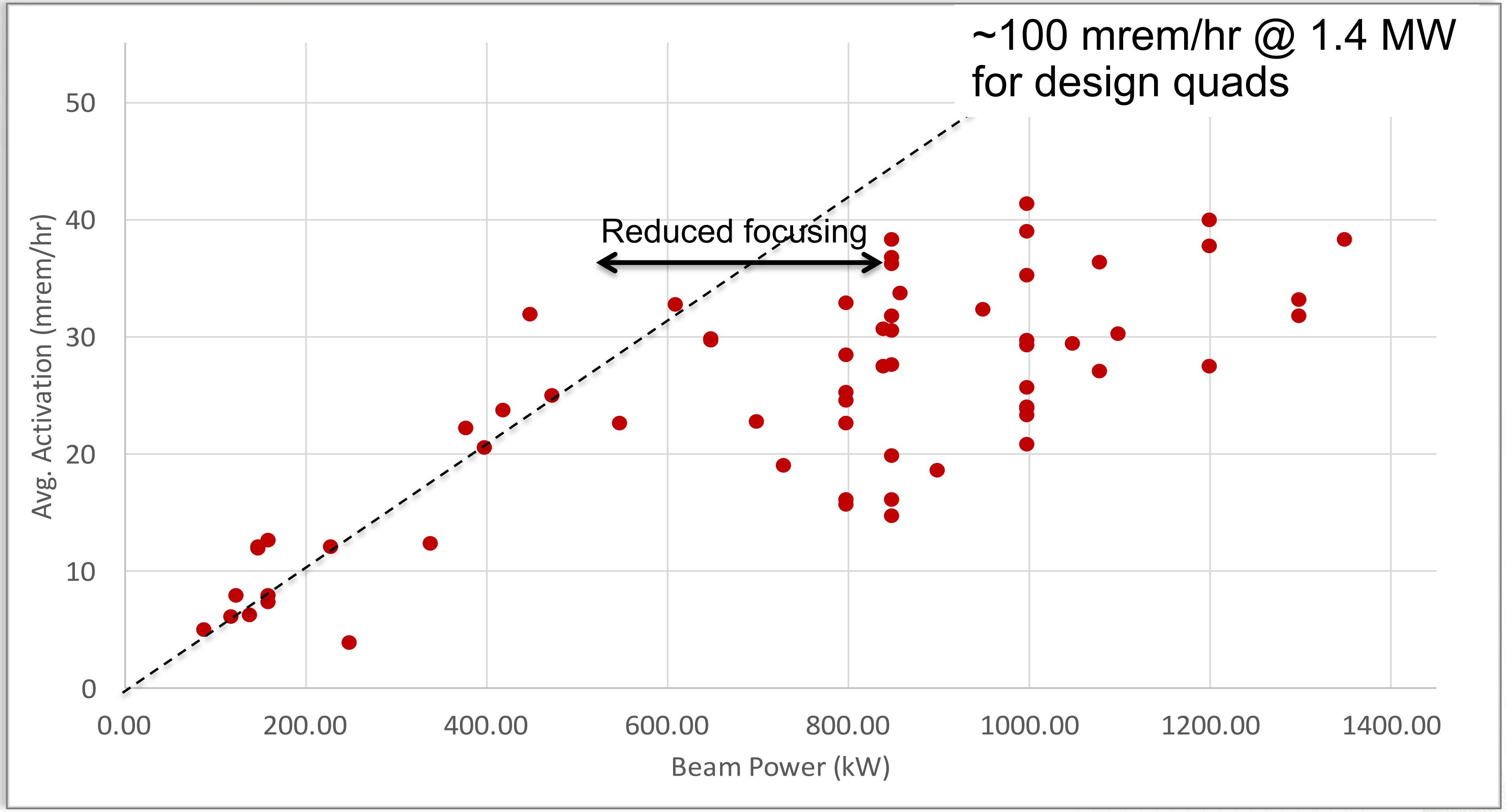
SCL Activation History



- Running 1.4 MW would have been very hot for design quadrupoles
- Probably would have had High Radiation Areas in linac tunnel.

Motivation for an SCL

Preliminary Design Report

Superconducting Radio Frequency Linac
for the Spallation Neutron Source

December 20, 1999

The general advantages of a superconducting linac for the SNS are:

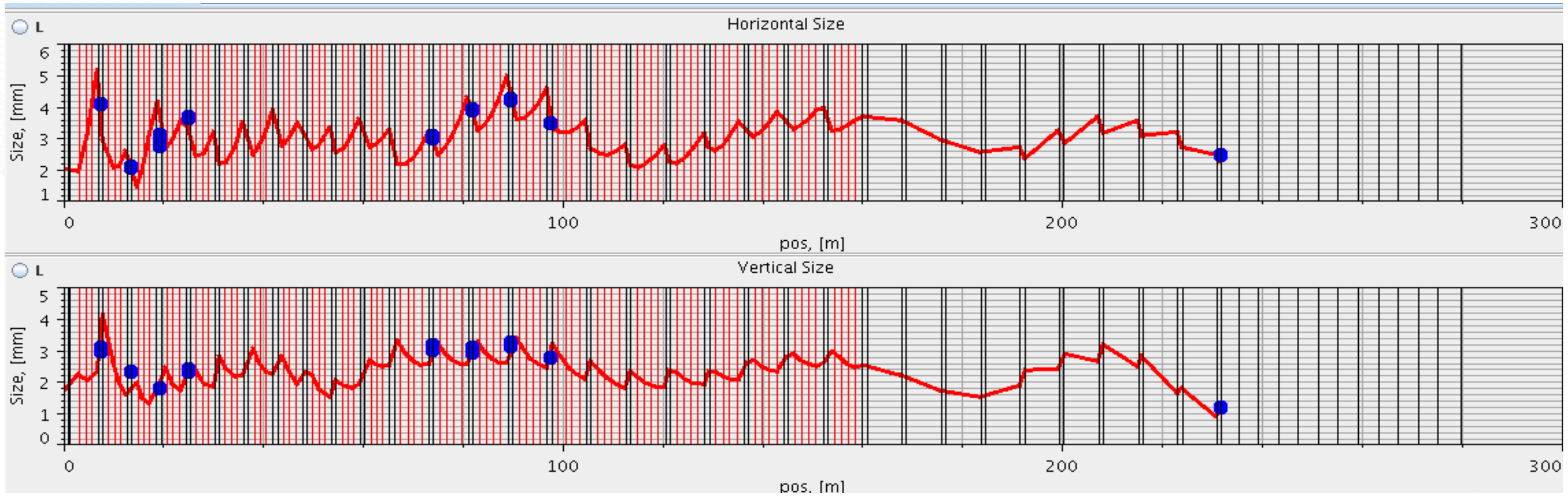
1. Construction and operating costs are considerably less compared to the warm linac. Expected power consumption is about 12 MW (50%), including cryo-plant, less than in the normal-conducting linac case.
2. Availability of the SC linac can be designed to be higher than the warm linac. This is due to the fact that each SC cavity has substantial reserve capability.
3. The reserve capability can be used later to upgrade the linac energy to about 1.3 GeV by increasing the klystron power. This corresponds to a beam power of 4.3 MW.
4. Energy stability is better than for the warm linac resulting in lower beam loss in the high-energy beam transport.
5. Ultra-high vacuum from the cryogenic system creates less beam-gas scattering resulting in less beam loss in the linac.
6. The much larger bore of the SC cavity reduces linac component activation due to beam loss.

If SNS had chosen the warm linac option, we could not have achieved 1.4 MW beam power with < 1 W/m, due to intrabeam stripping.

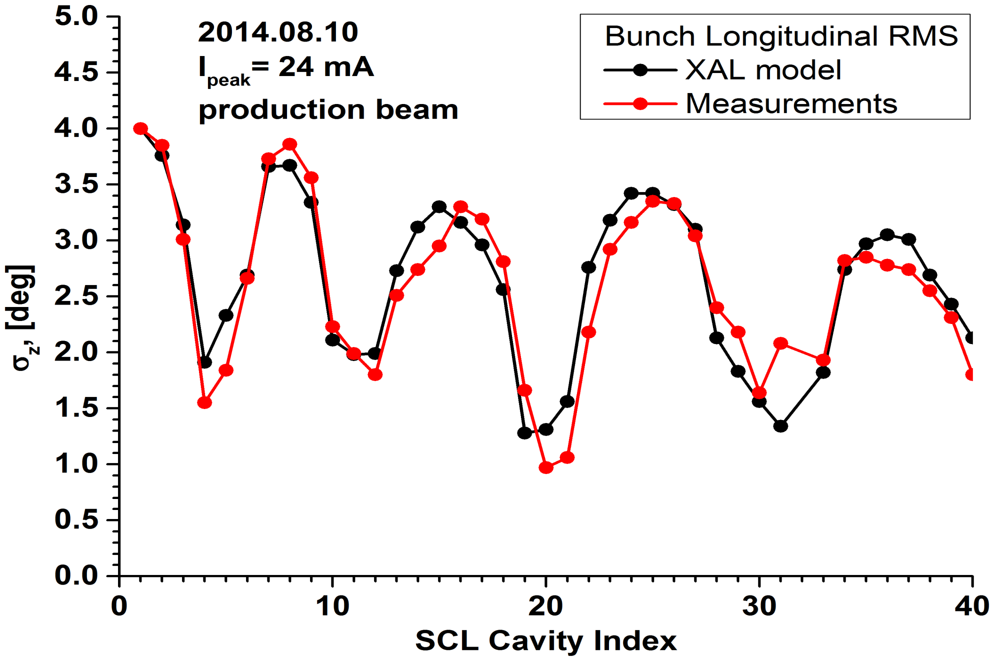
-- We *narrowly* escaped this fate!

Reality: No Matching in the Linac

Transverse Beam Size SCL, fit to measured RMS



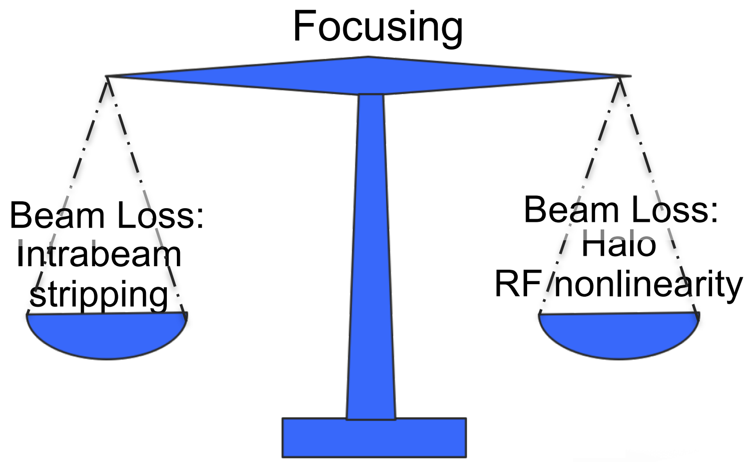
- Beam is mismatched, transverse and long., throughout entire linac.
- After multi-year effort, model now agrees with measurement for RMS



Understanding Our Linac Beam Loss

More quad defocusing increases beam loss – we have reach the limit.

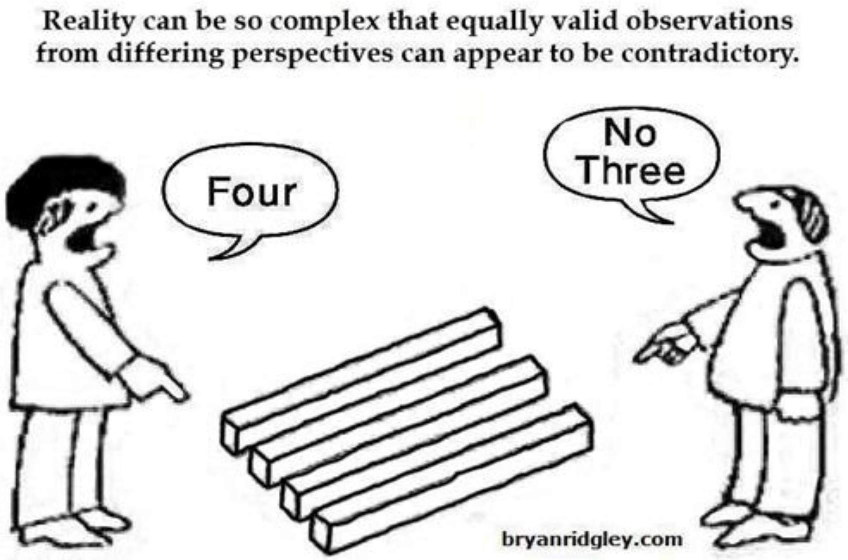
Presently, $\frac{\text{RMS Beam Size}}{\text{SCL Bore}} \approx 10$



We don't understand the remaining beam loss.

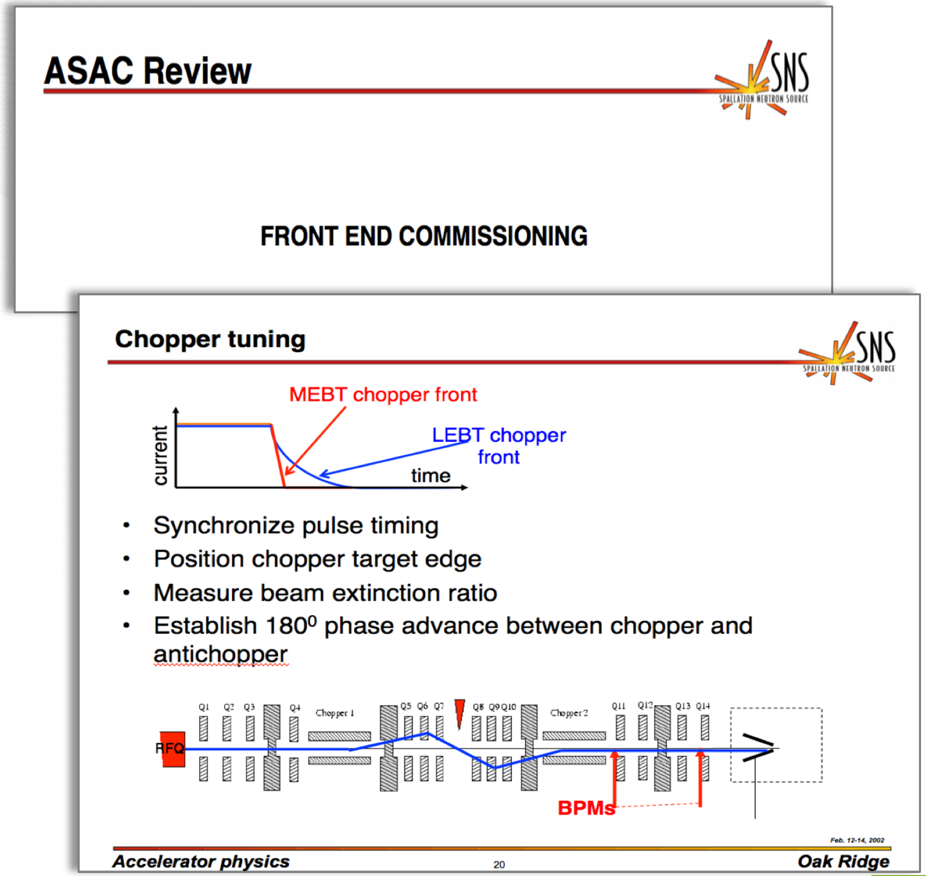
Probably 'halo', but from what? How much?

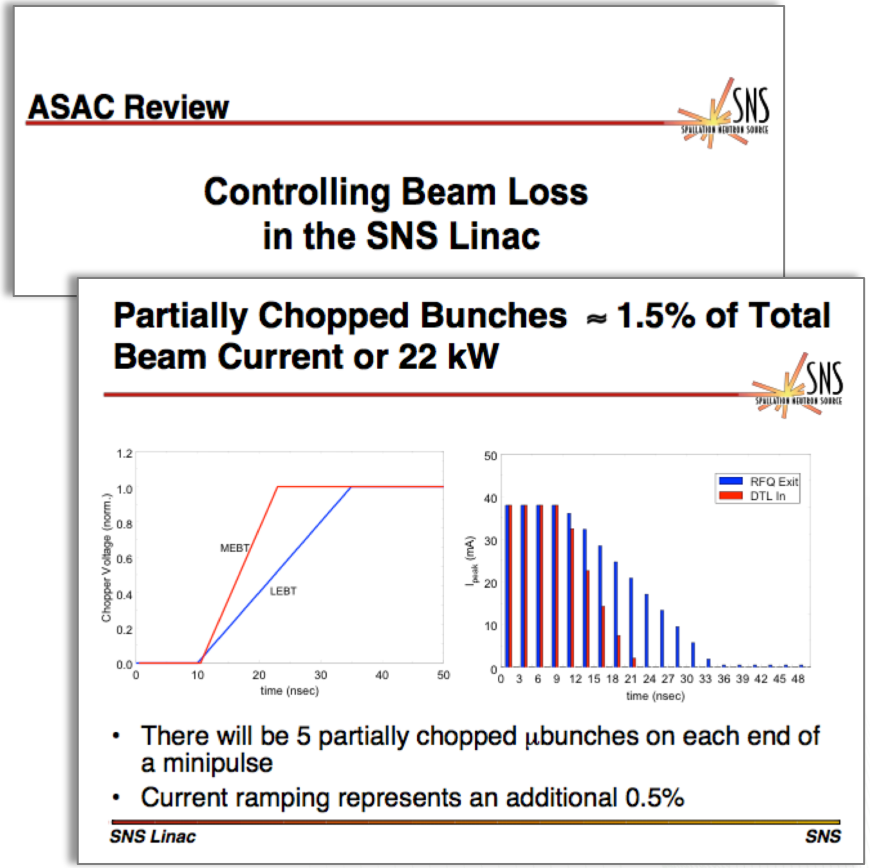
Many ideas of what defines "halo":



- At SNS we are going to define halo as 10^{-4} – 10^{-6} of peak density (per 2014 Workshop on Beam Halo Monitoring).
- Some SNS diagnostics can measure this level – High Dyn. Range wire-scanners, etc.
- Models are now ready to attack this problem – A. Shishlo's work

Expectations: MEBT Chopper Paranoia





MEBT chopper complicated MEBT design:

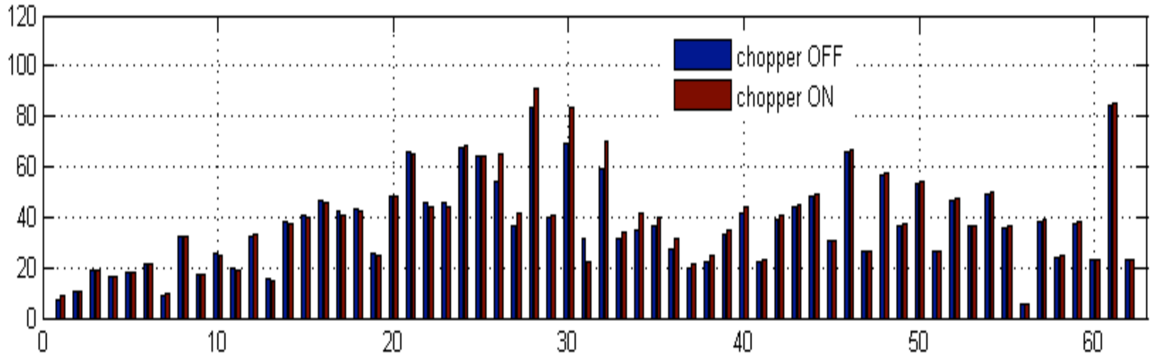
– Required 180 phase advance between chopper and anti-chopper.

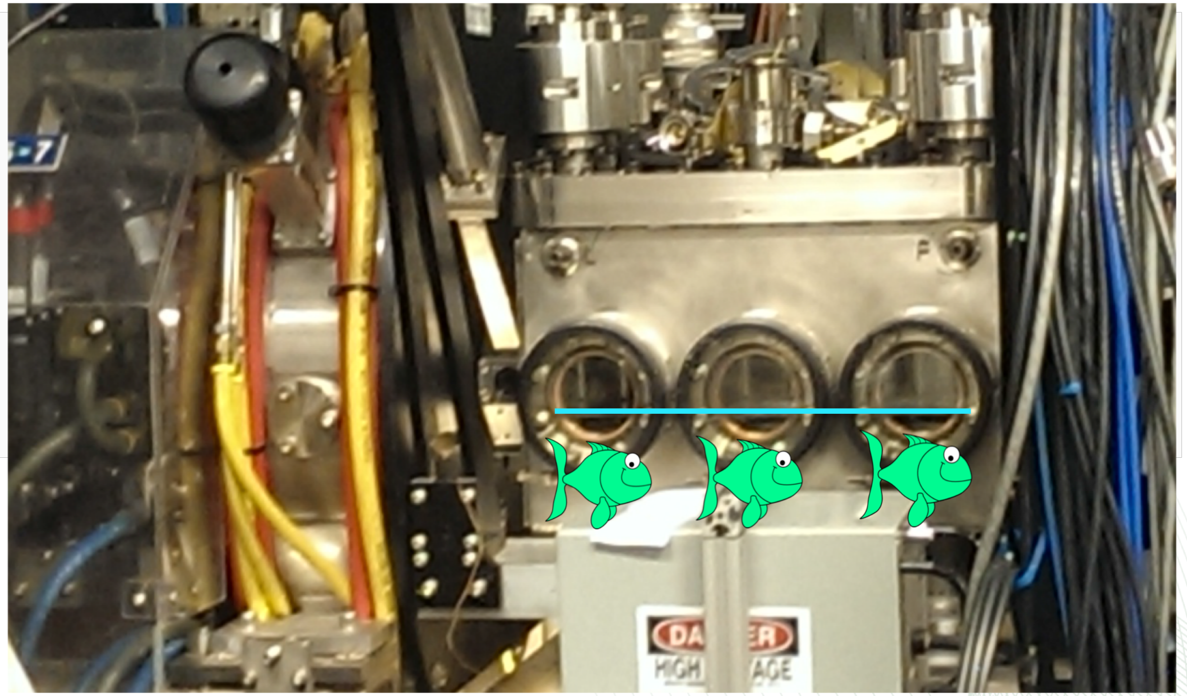
	No MEBT Chopper	With MEBT Chopper
# Quadrupoles	4	14
# Bunchers	1	4

Reality: MEBT Chopper Not Necessary

- Did not result in significant linac loss reduction.
- Slight loss reduction in ring collimation, extraction, but losses already low there.

Effect on SCL Losses





- In fall 2014, chopper target leaked and flooded the MEBT.
- Complete MEBT disassembly + reassembly. 4 weeks downtime
- MEBT chopper removed.

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Part II
Accumulator Ring

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SNS Accumulator Ring Design Parameters

Design Parameters

Circumference: 250 m

Energy: 1 GeV

Intensity: 1.5e14 ppp

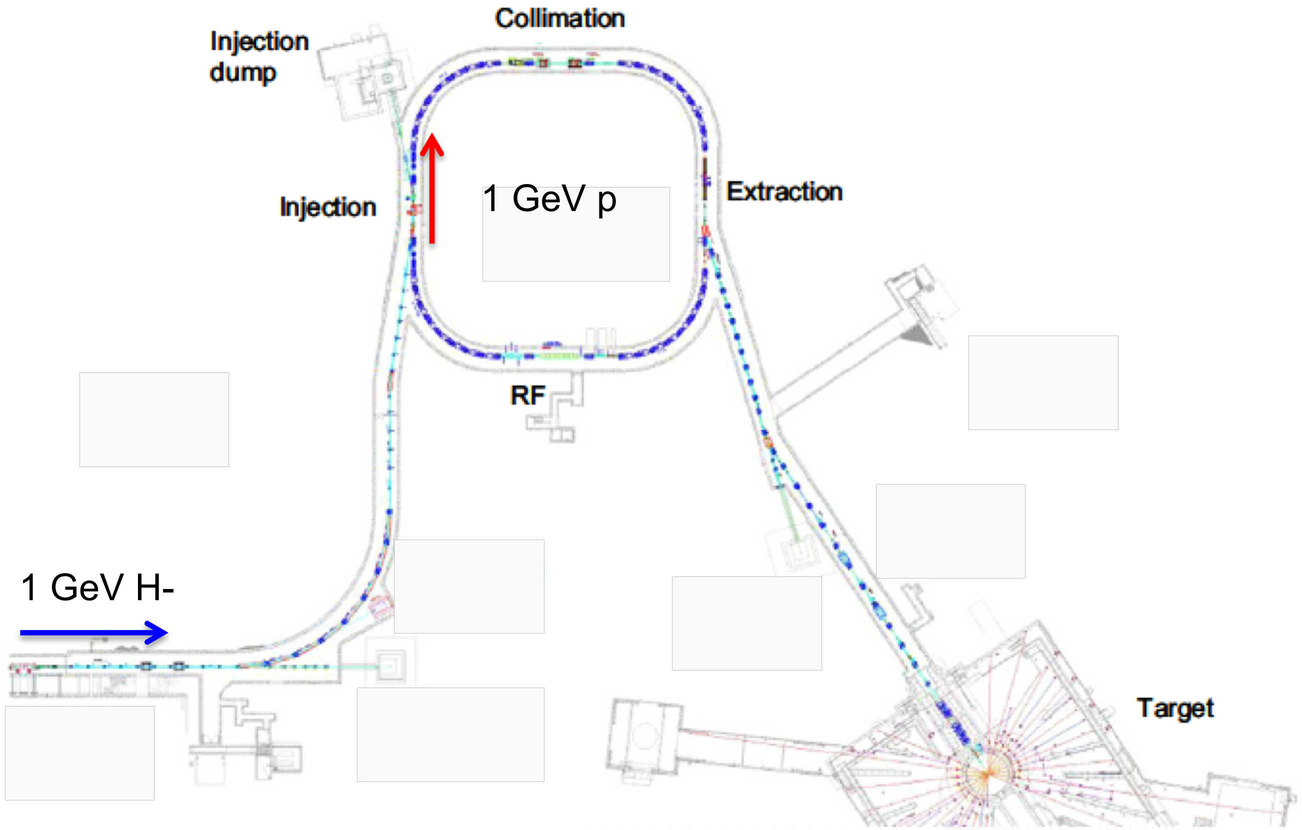
bunches: 1

Bunch length: 700 ns

Accumulation Time: 1 ms

Repetition Rate: 60 Hz

= Beam Power: 1.4 MW



The design of the ring was focused on beam loss control.

It has been in operation for 10 years.

It has performed beautifully.

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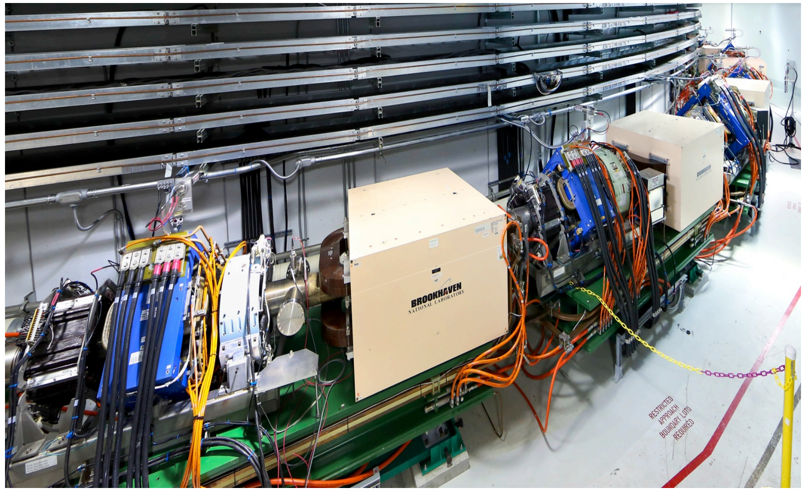
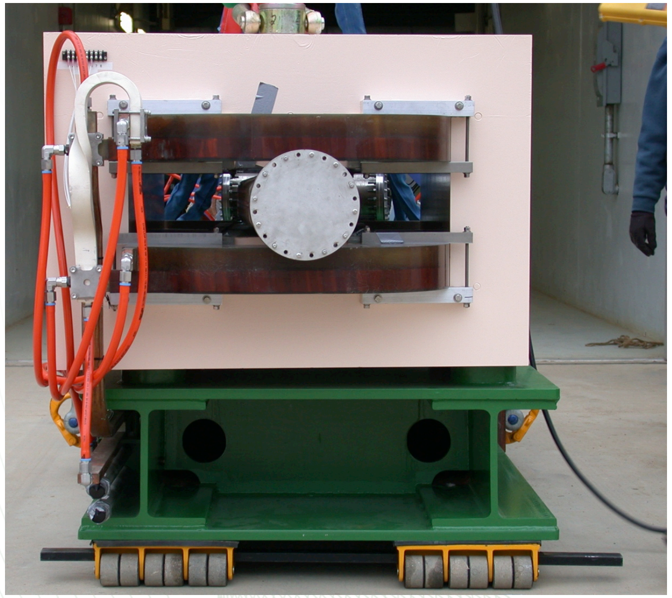
Large Aperture:
The Highest Payoff Investment We Made

Based on considerations of collective effects, decided to use a very big aperture.



Element	**Diameter (cm)**	**Acceptance (mm mrad)**
Vacuum Pipe	20 - 30	480 π
Dipole	23 x 15	480 π
Quadrupole	21 – 30	480 π
Collimator	10 – 16	300 π

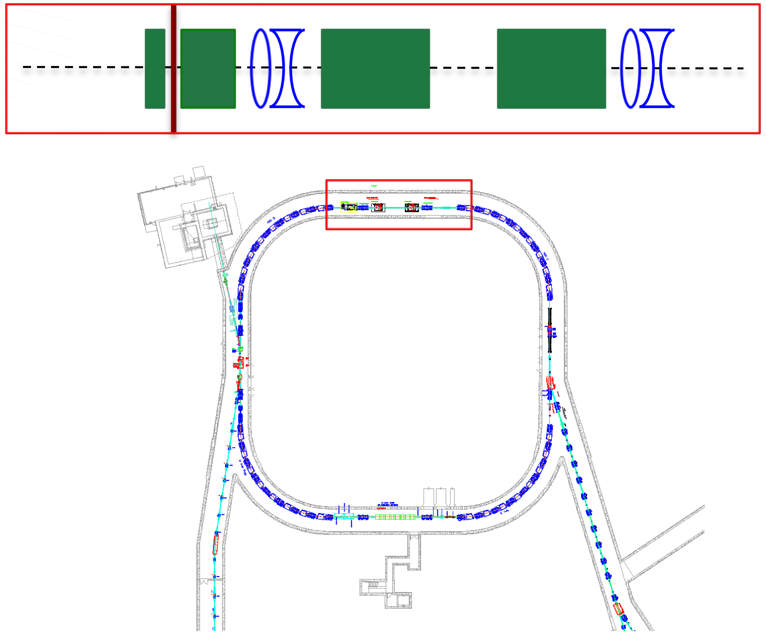


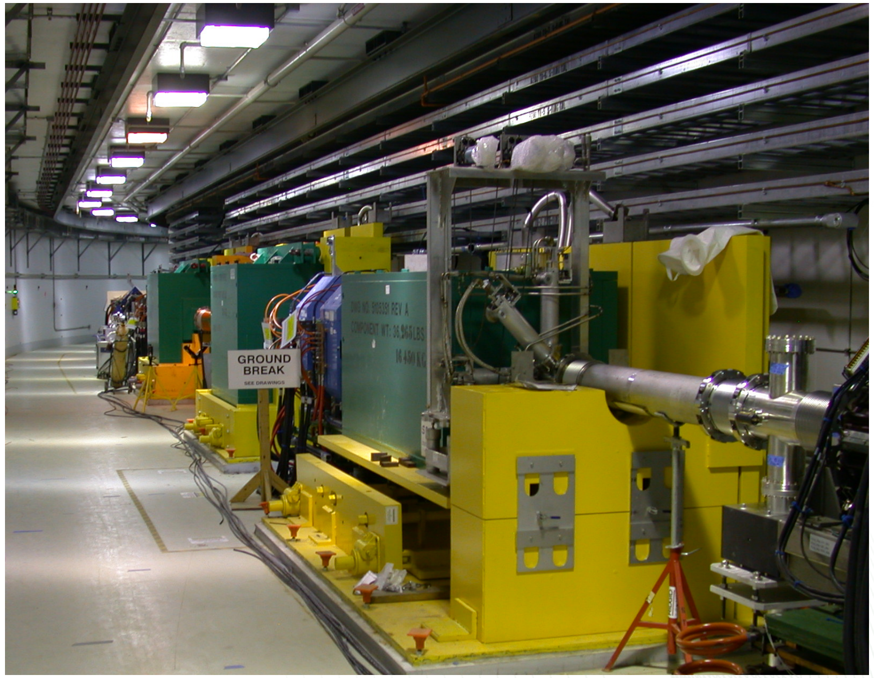
And it works. We use it all.

(Thanks Y.Y. Lee and B. Wang!)

Ring Betatron Collimation: High Payoff

- Two stage collimator occupies “an entire straight section”.
- Each secondary collimator can absorb:
  - ✓ 2 kW continuously, or
  - ✓ 2 consecutive 2 MW pulses in failure mode.





We credit the clean ring largely to the collimation system.

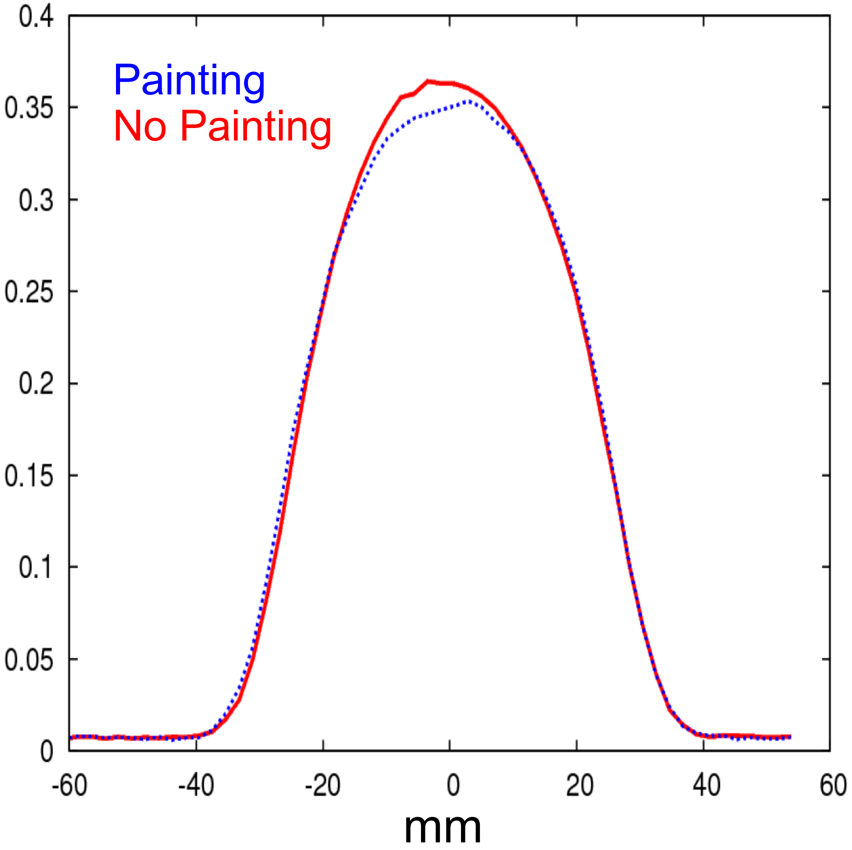
We do not use the collimator in a two stage fashion. Prioritize aperture.

Dual Plane Injection Painting: High Payoff

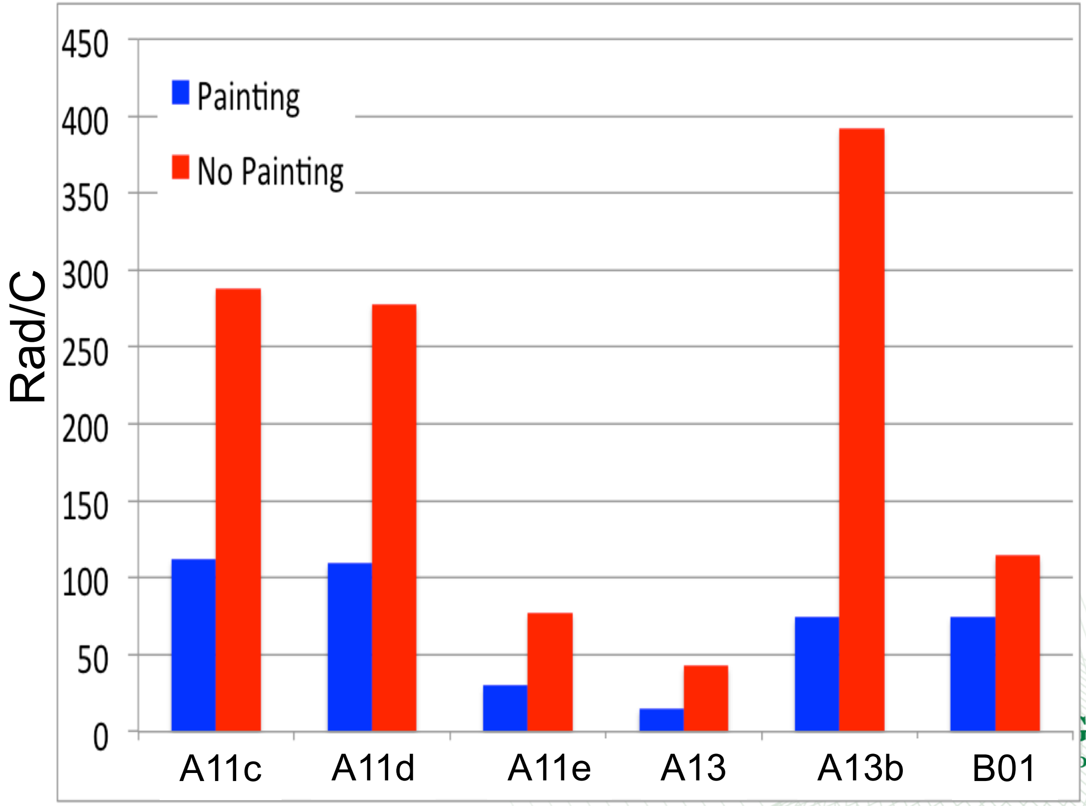
We paint in both planes with a correlated beam, **all the way to collimator aperture – (remember that big beam pipe!)**

Injection losses would be intolerable without it. (Currently about 5.5 foil hits/proton)

~ 1 MW Equivalent Beam Profiles For Two Equal Emittance Beams



Injection Region Beam Loss Monitor Signals



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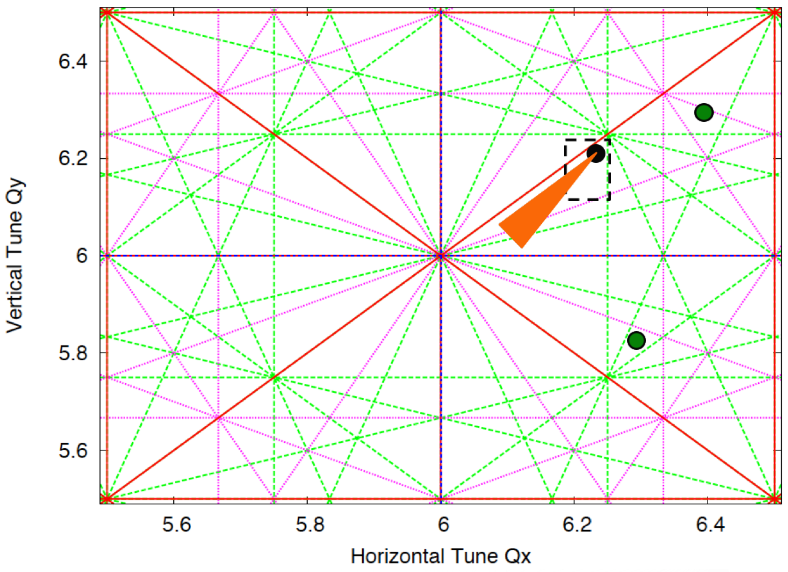
We Worried Too Much: Space charge, and Extraction

1. Space charge effects: Resonances, halo

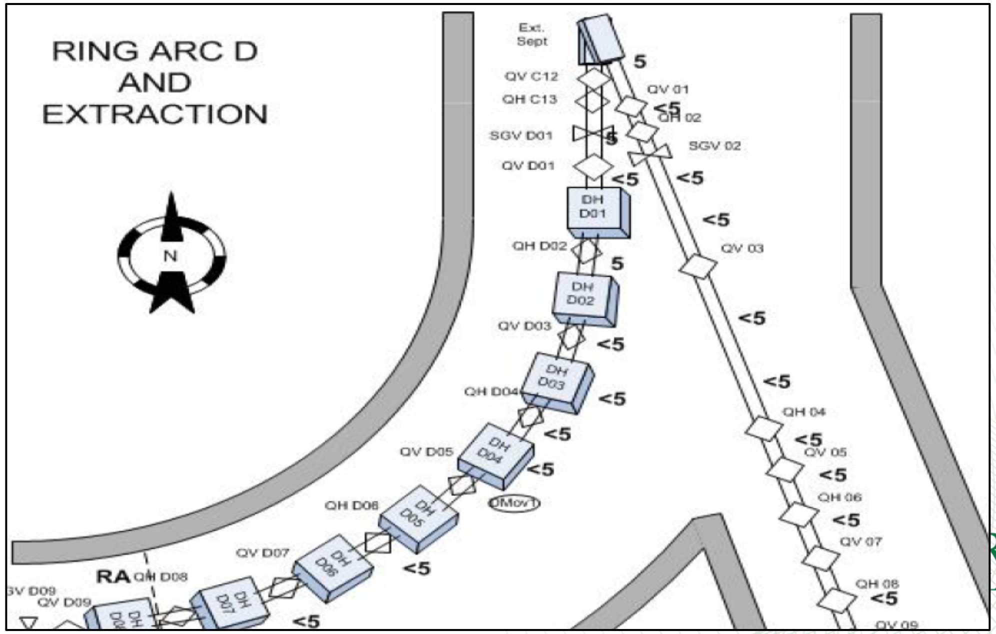
Feature	Usage Now
Sextupoles (4 families)	Never used during production
Octupoles (2 families)	Never used during production
Sextupole correctors	Never been used
Octupoles correctors	Never been used



2. Extraction loss:

- Beam in gap kicker – never installed
- Gap smaller, cleaner than expected:
    1. Very good LEBT chopping
    2. Reduced extraction kicker drift

*We are upgrading switches to solid state for stability – biggest extraction problemis with jitter in kickers



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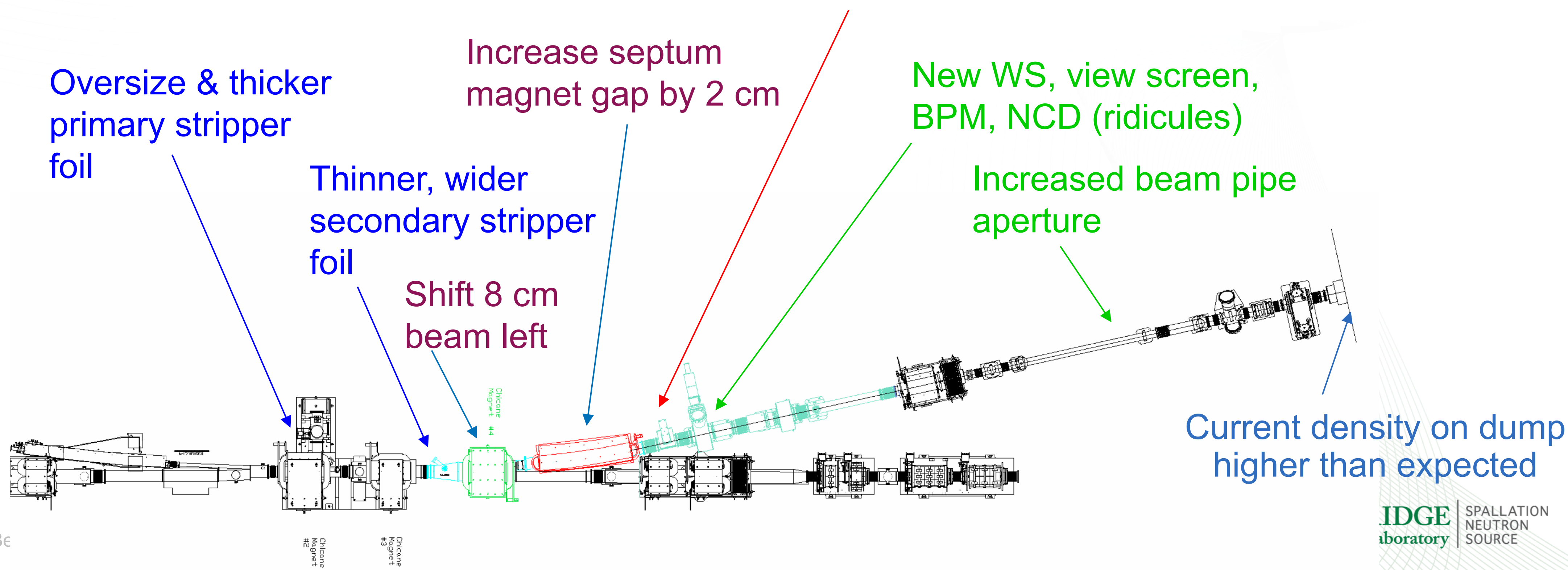
We Didn't Worry Enough: Injection

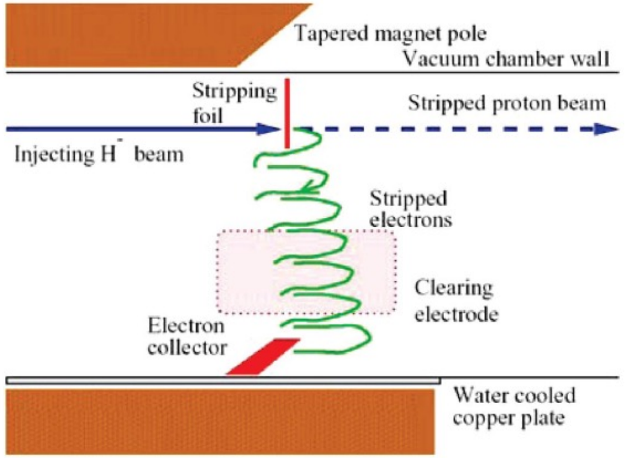
- Design changed led to unintended consequences.
- Trajectories were not sufficiently modeled.
- Fallout was many headaches once reality struck:

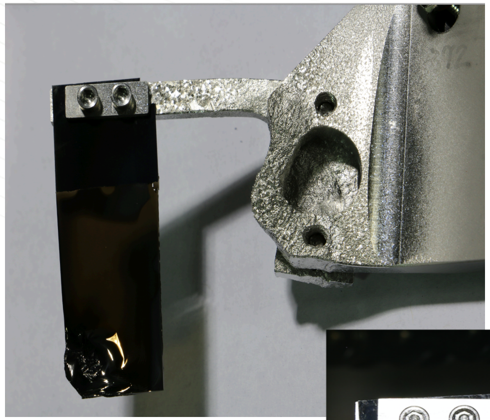
Stripper foil in wrong spot!



We Didn’t Worry Enough: Convoy Electrons

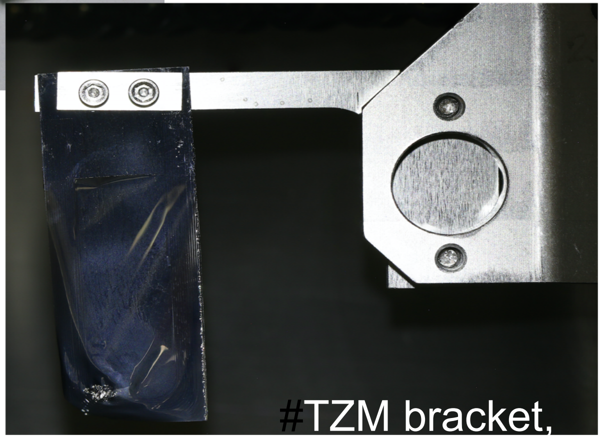
- Convoy electrons carry 1.6 kW power at 1.4 MW
- Reflected electrons have cause bracket damage
- Damage to electron catcher is worsening issue
- Largely due to misplaced foil. Would it be ok if catcher worked?

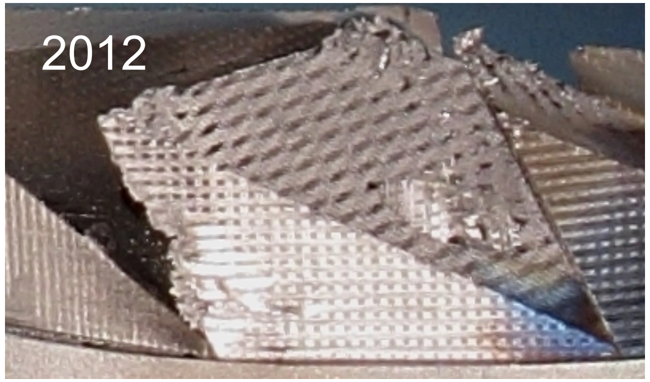




Ti bracket
3 months at
1.1 – 1.4 MW.

Geometry, material evolution





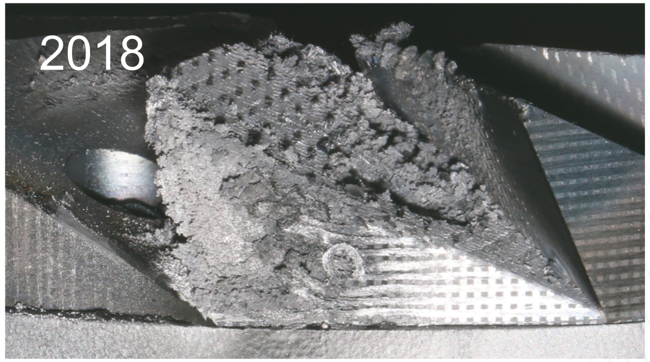


Photo: C. Luck

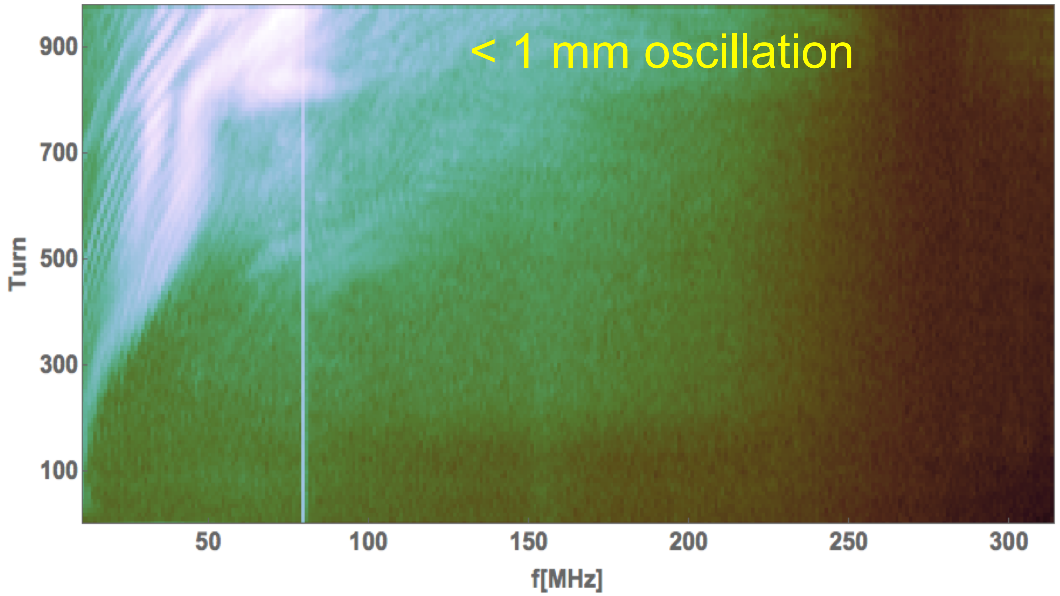
Foils are doing well.
#3073 survived
full run at 1.2 MW
(~2500 MW·Hr)

e-P Mitigation: Worth the Investment?

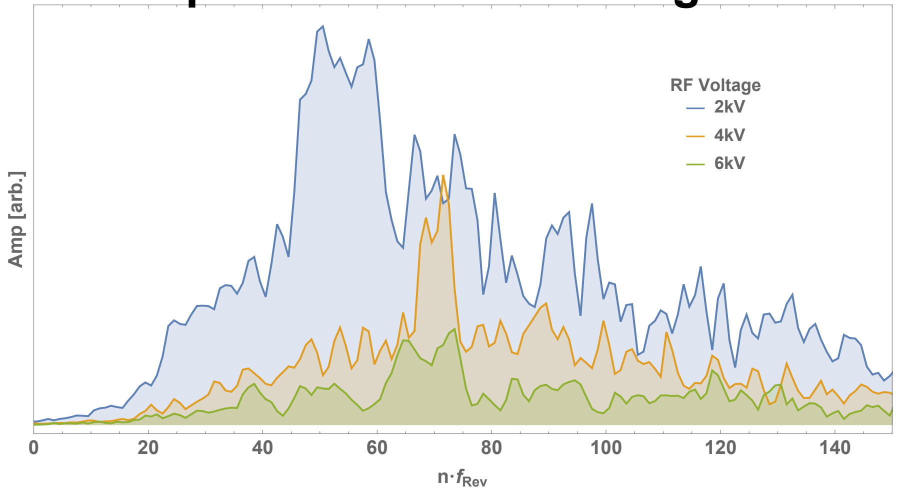
In the area of collective effects, e-p was the biggest concern.

Mitigation Feature	Usage Now
2nd Harmonic RF	Strong knob when e-P present
TiN coating	No way to know if it helps
Suppression solenoids	Not in use
Clearing electrodes	Not in use
Feedback system	Working but not needed

e-p Activity for 1.4 MW Production Beam



Spectrum vs. h=1 Voltage



- No significant e-p seen during production so far – despite RF Voltage well below design values
- Trace levels during normal operation. No beam loss.

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Menu of Initial Investments and Payoff

Feature	Cost	Payoff So Far
Large Aperture	$$$$	High
Injection Painting	$$$	High
Collimation	$$$	High
TiN coating	$$$	Unknown
2nd harmonic RF	$$	Medium+
Main sextupoles	$$	Low - None
Main octupoles	$$	None
Sextupole correctors	$	None
Octupole correctors	$	None
Clearing solenoids	$	None
Beam in gap kicker	$	None
Clearing electrodes	$	None

We spent the big bucks where it counted most.

Proton Power Upgrade and Second Target Station

Parameter	Now	PPU	STS
Beam Power	1.4 MW	2.0 MW	2.8 MW
Beam Energy	1.0 GeV	1.3 GeV	1.3 GeV
Beam Intensity	1.5e14 ppp		2.5e14 ppp

- We need to go from 35 mA to 50 mA in linac.
- We are worried about foil sublimation and e-P.

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Acknowledgements

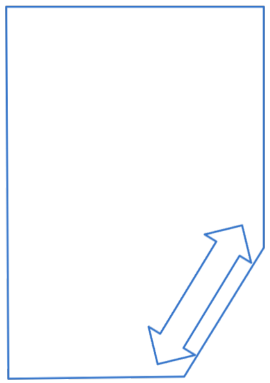
- Thanks to Sasha Aleksandrov, Wim Blokland, Jeff Holmes, John Galambos, Charles Peters, Mike Plum, and Andrei Shishlo for enlightening discussions
- Special thanks to Sarah Cousineau for providing slides

Backup slides

H- Stripping Foils

- We've run properly conditioned foils (~1 shift) for an entire run June-Dec. with ~ two weeks off at 1.2 MW (~2500 MW·Hrs)
- Nanocrystalline diamond, ~17x31mm, 400μg/cm^2

During the Foil Conditioning portions of the ramp the beam spot is moved between corners at each parameter change



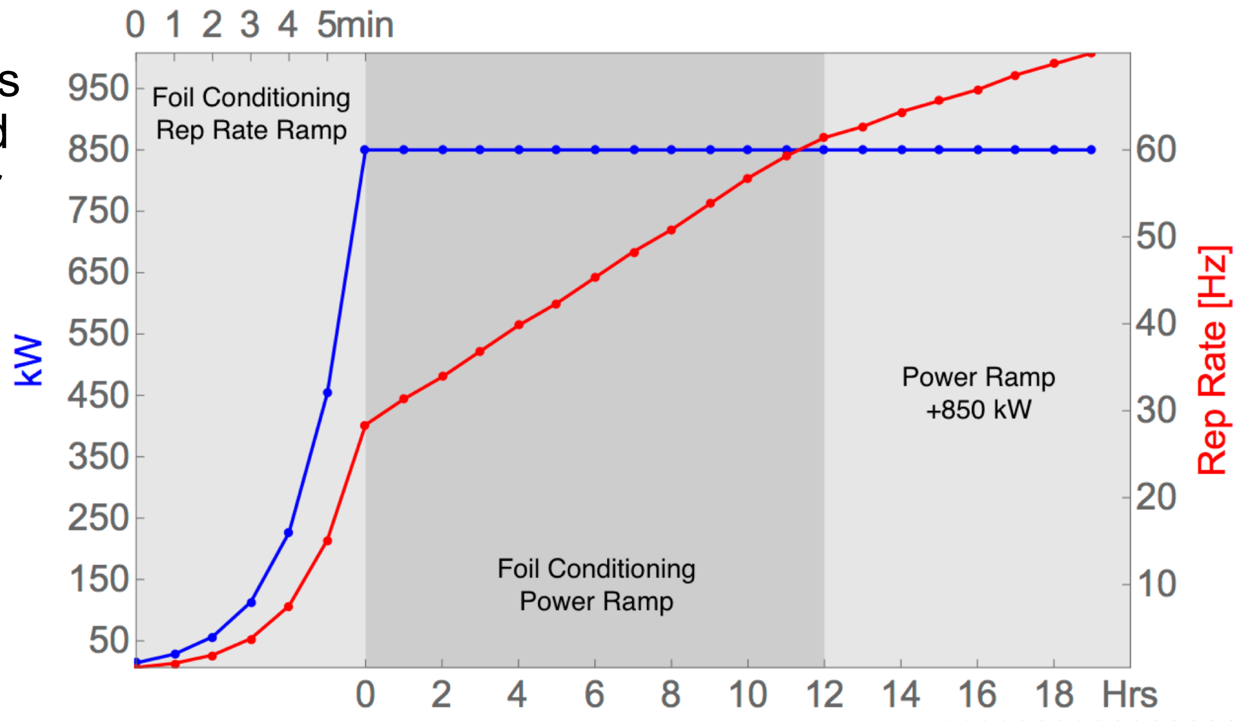


Photo: C. Luck

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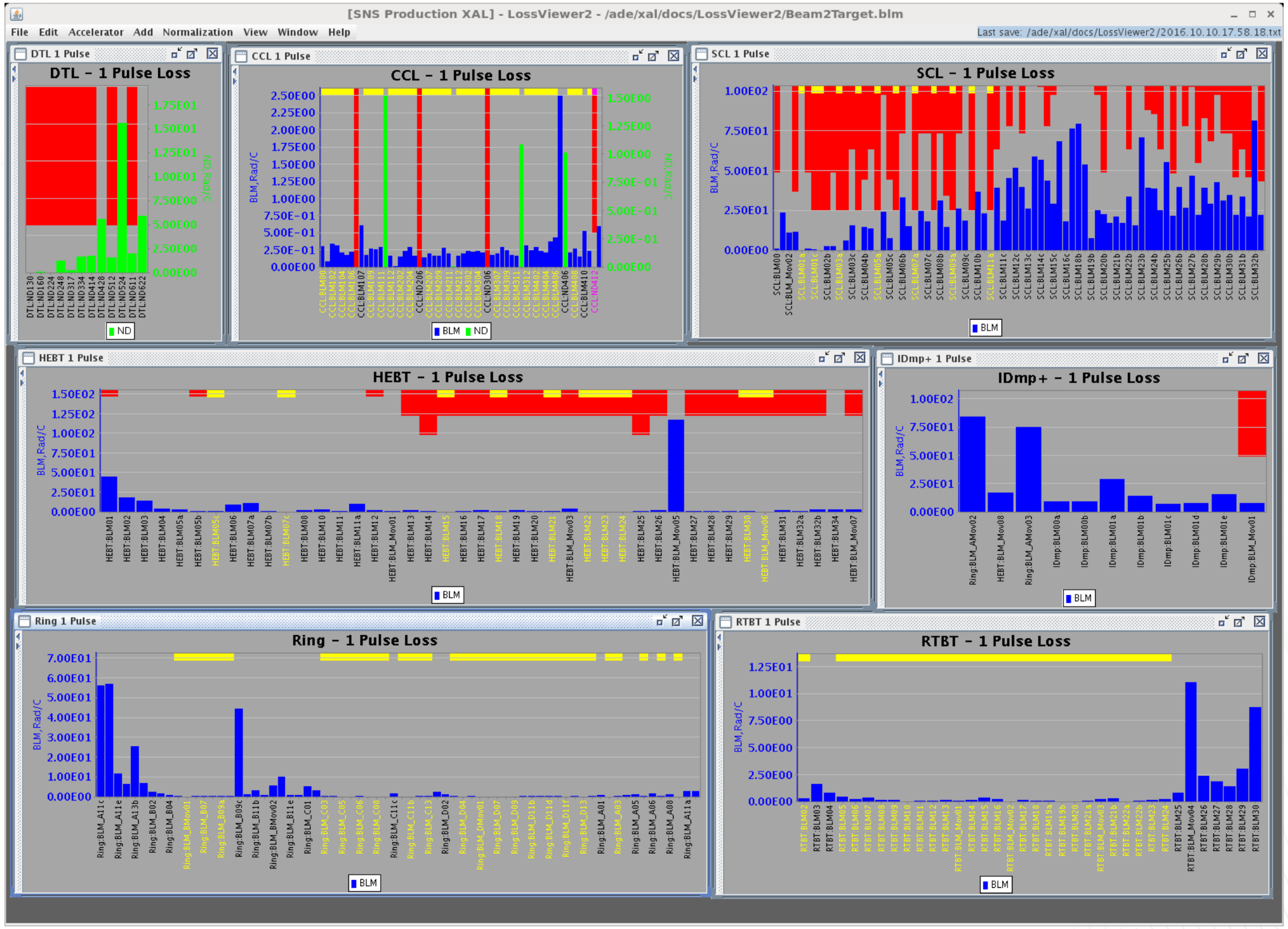
Production Losses – Oct. 2017



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