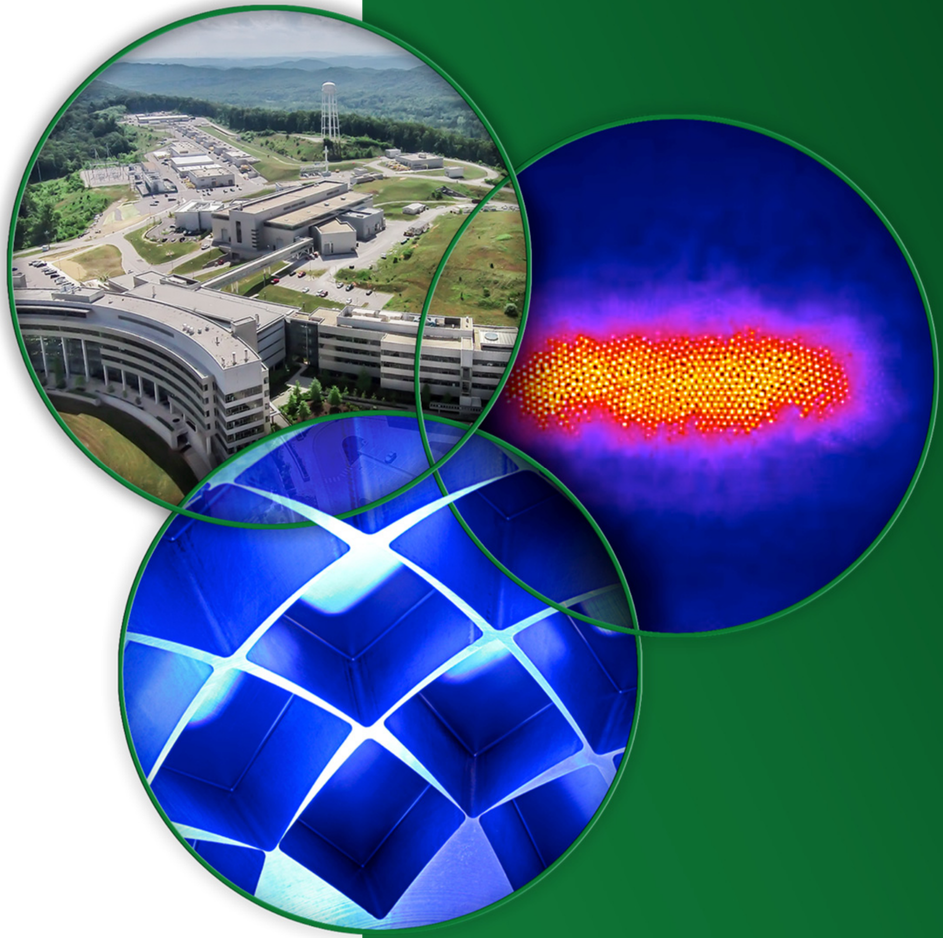
A Fifteen Year Perspective on the Design and Performance of the SNS Accelerator



S. Cousineau

(On behalf of the SNS project)

HB2016, Sweden

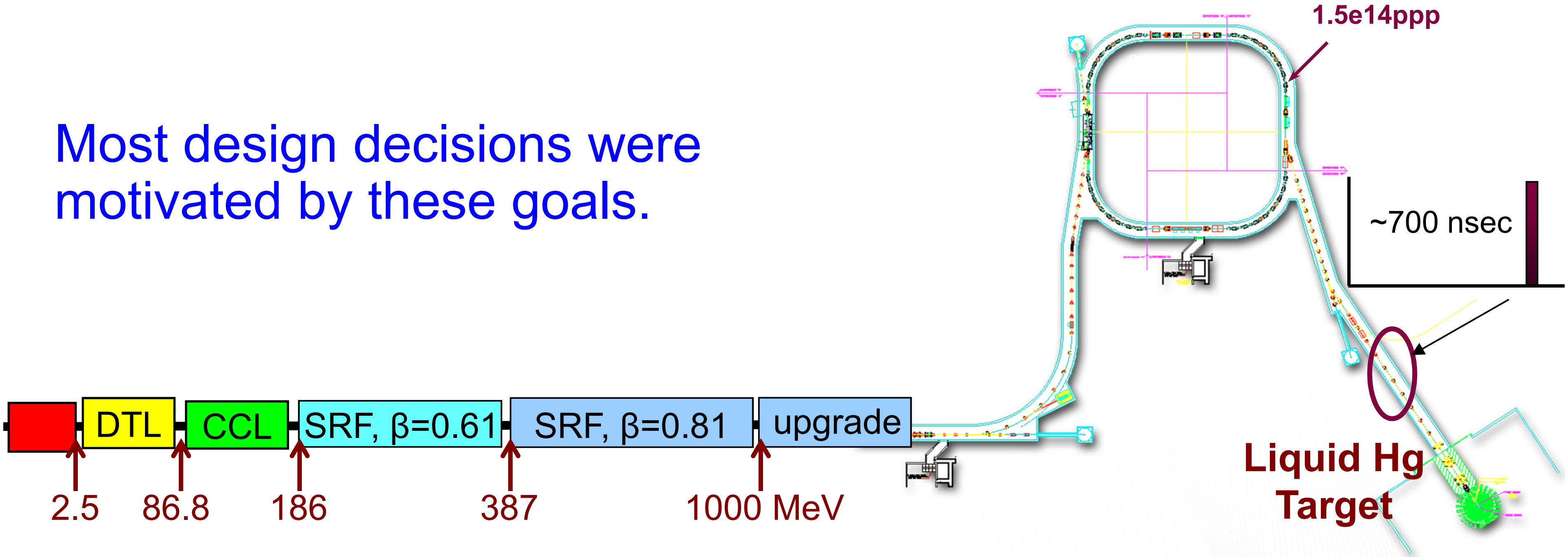
July 04, 2016

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

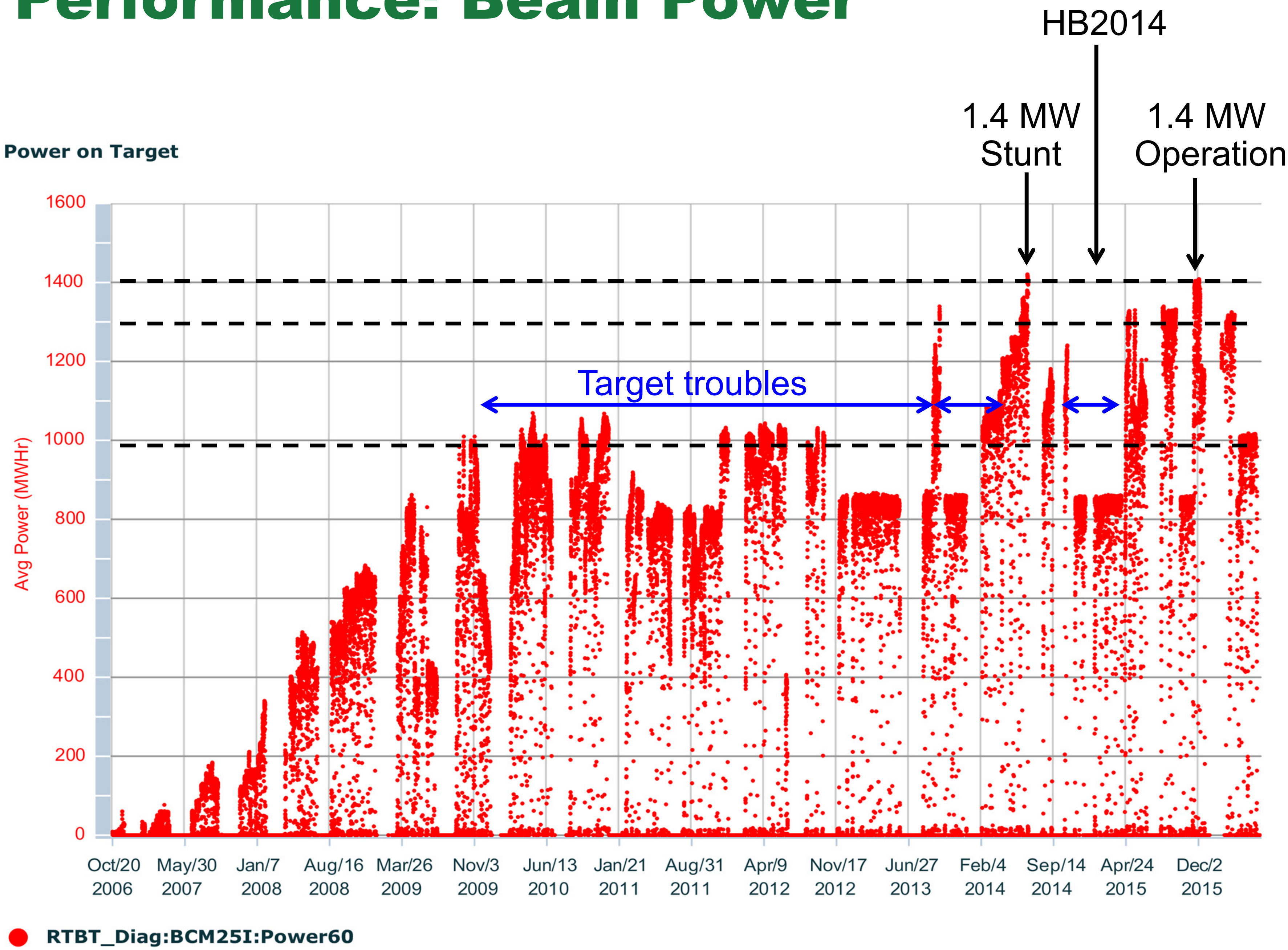
The SNS Accelerator

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)

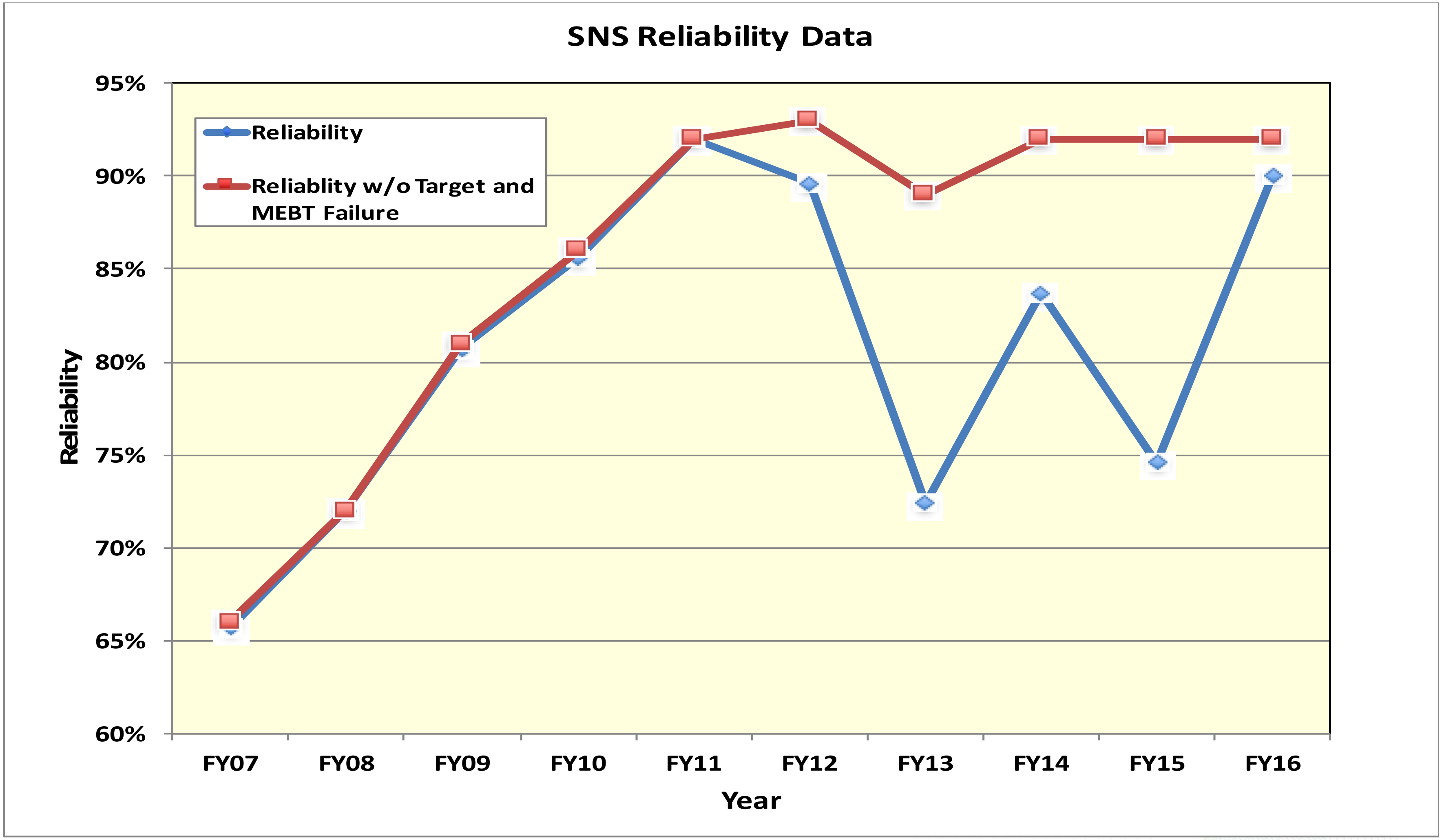
Most design decisions were motivated by these goals.



Performance: Beam Power



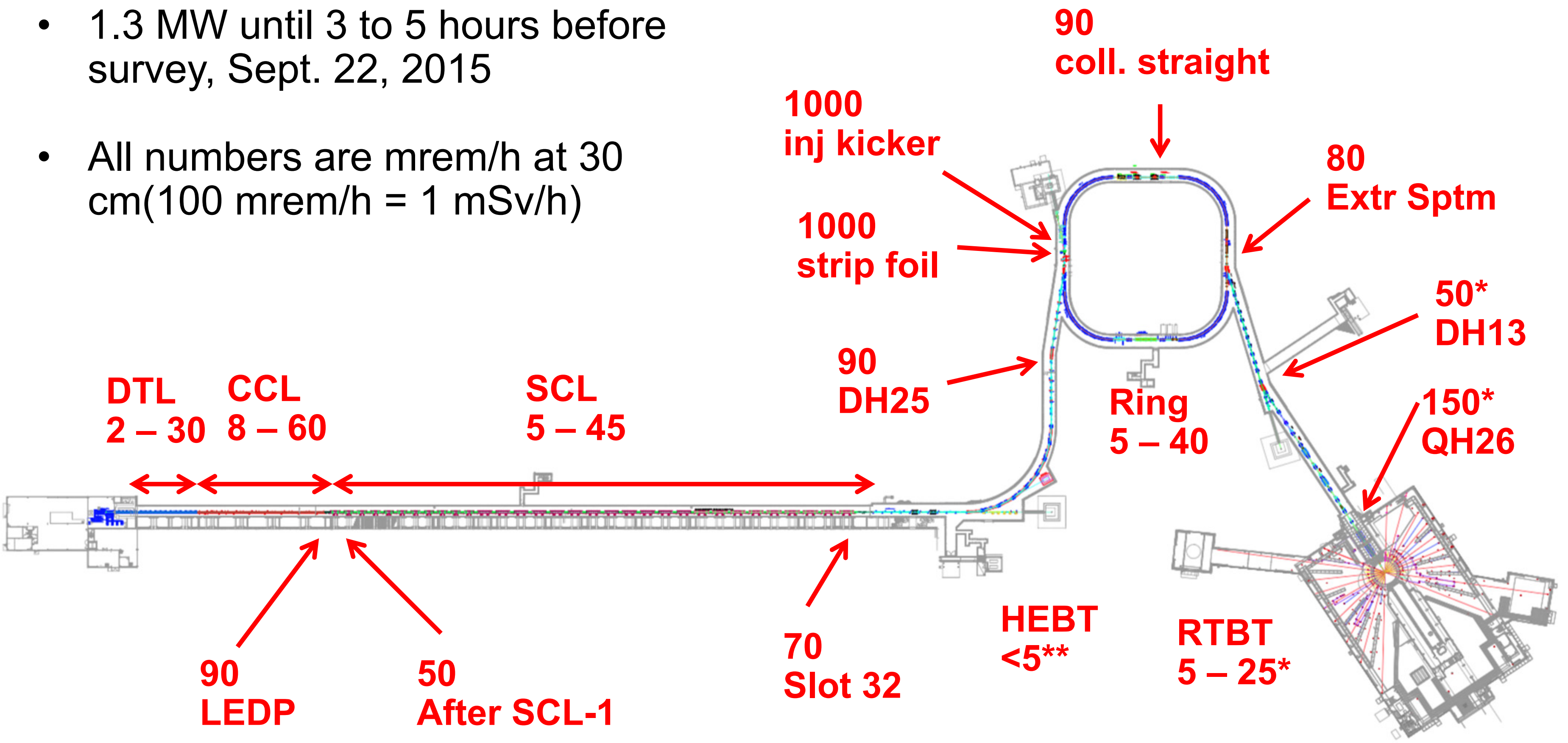
Performance: Reliability



- Outside of target failures and one catastrophic MEBT event, reliability for remainder of accelerator exceeds goals.

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)



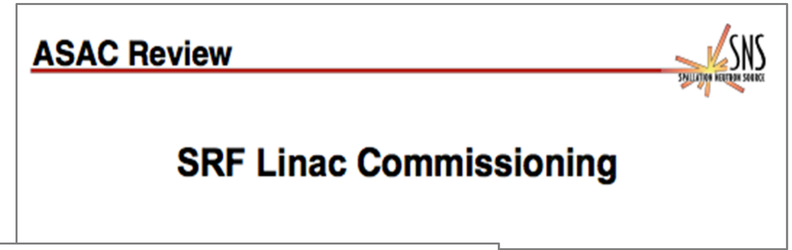
Except for a few hot spots, the dose rates are relatively low (< 1 W/m).

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

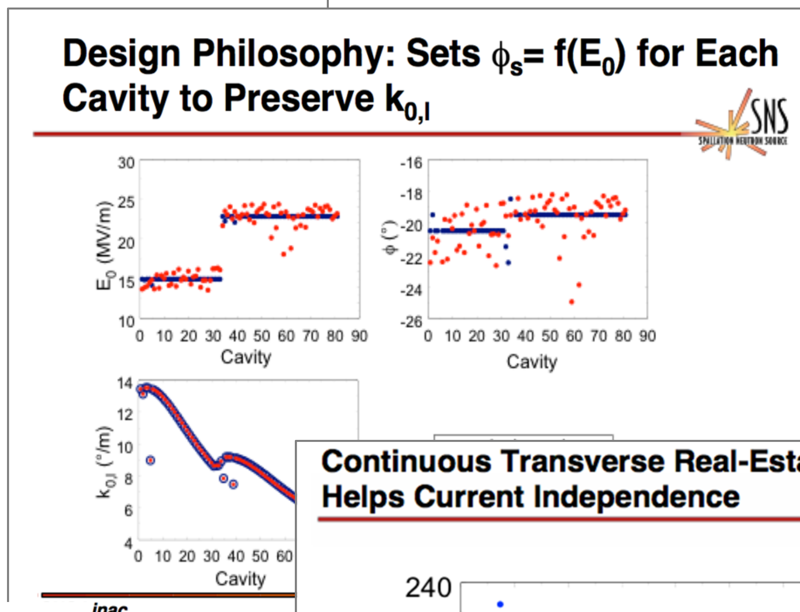
Part I
The Linear Accelerator

Flashback 2002: SCL Tune Up Scenario

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

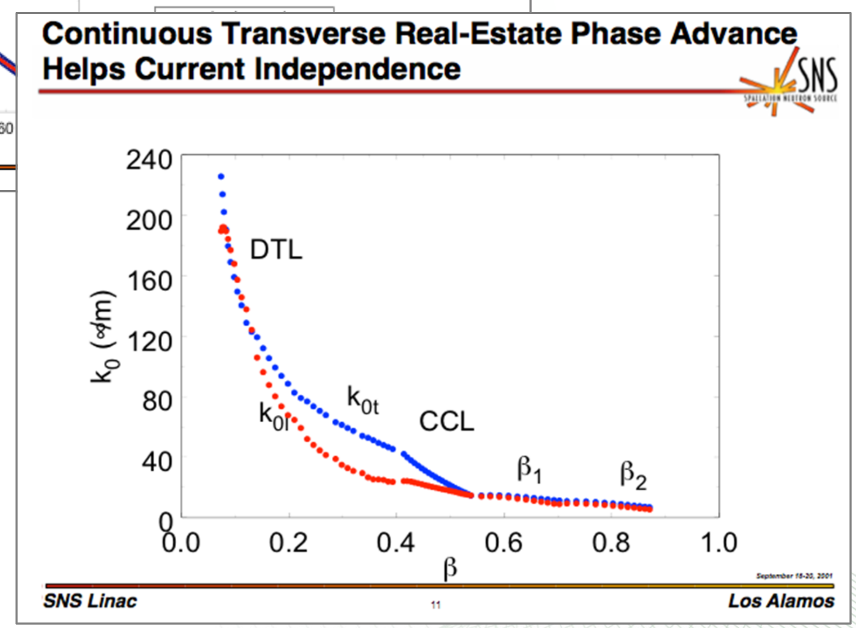


Some expectations:



1. Cavity gradients to be near design values.

2. Set longitudinal phase to preserve matching along SCL.



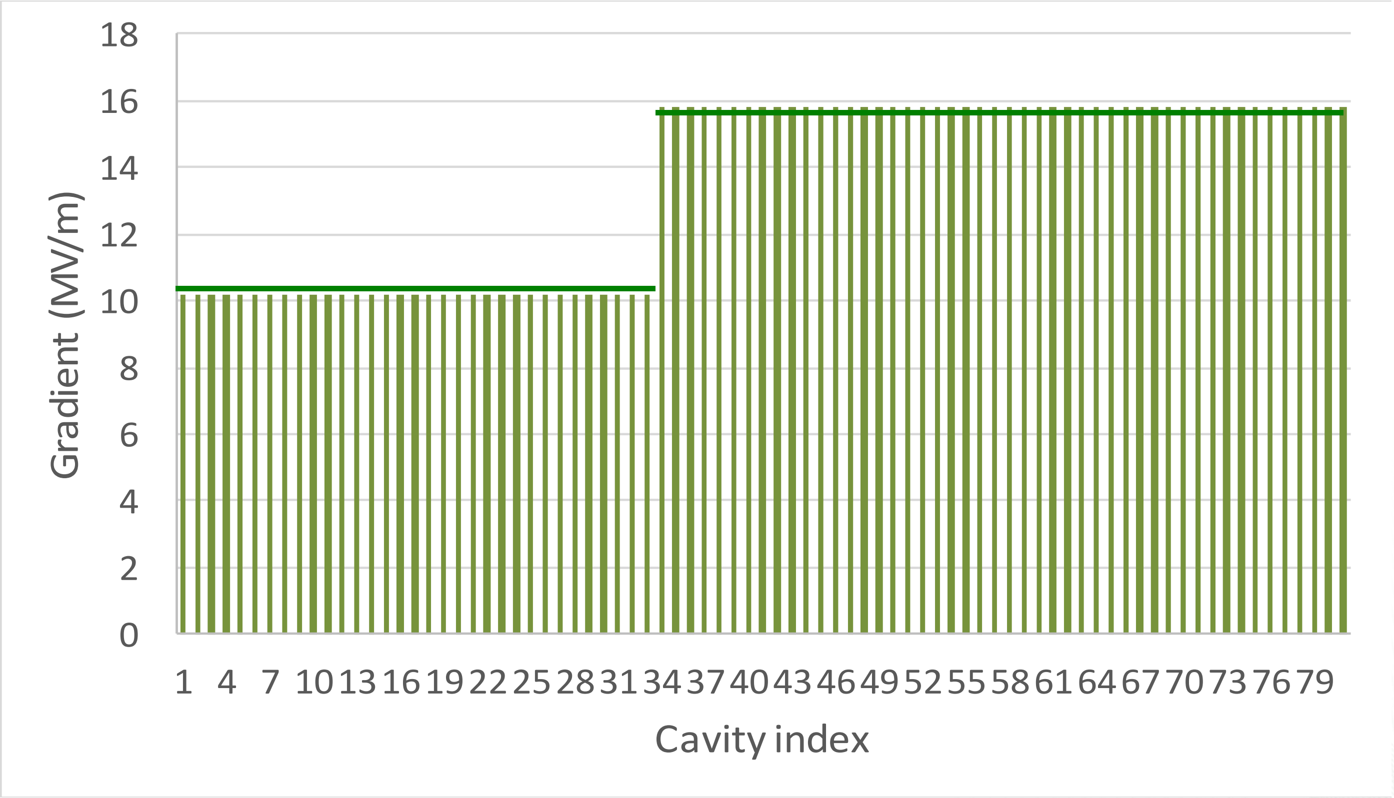
3. Maintain a relationship between transverse and longitudinal phase.

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.



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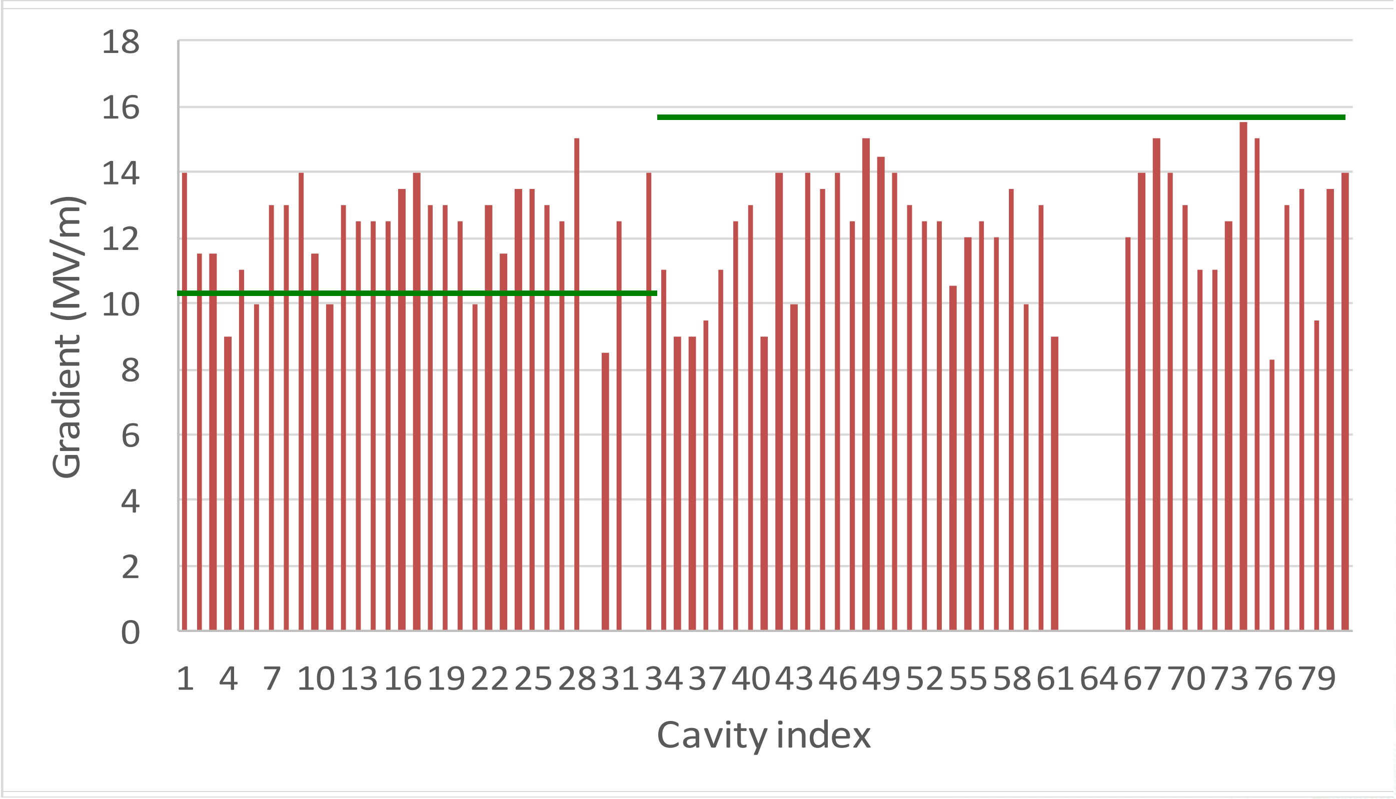

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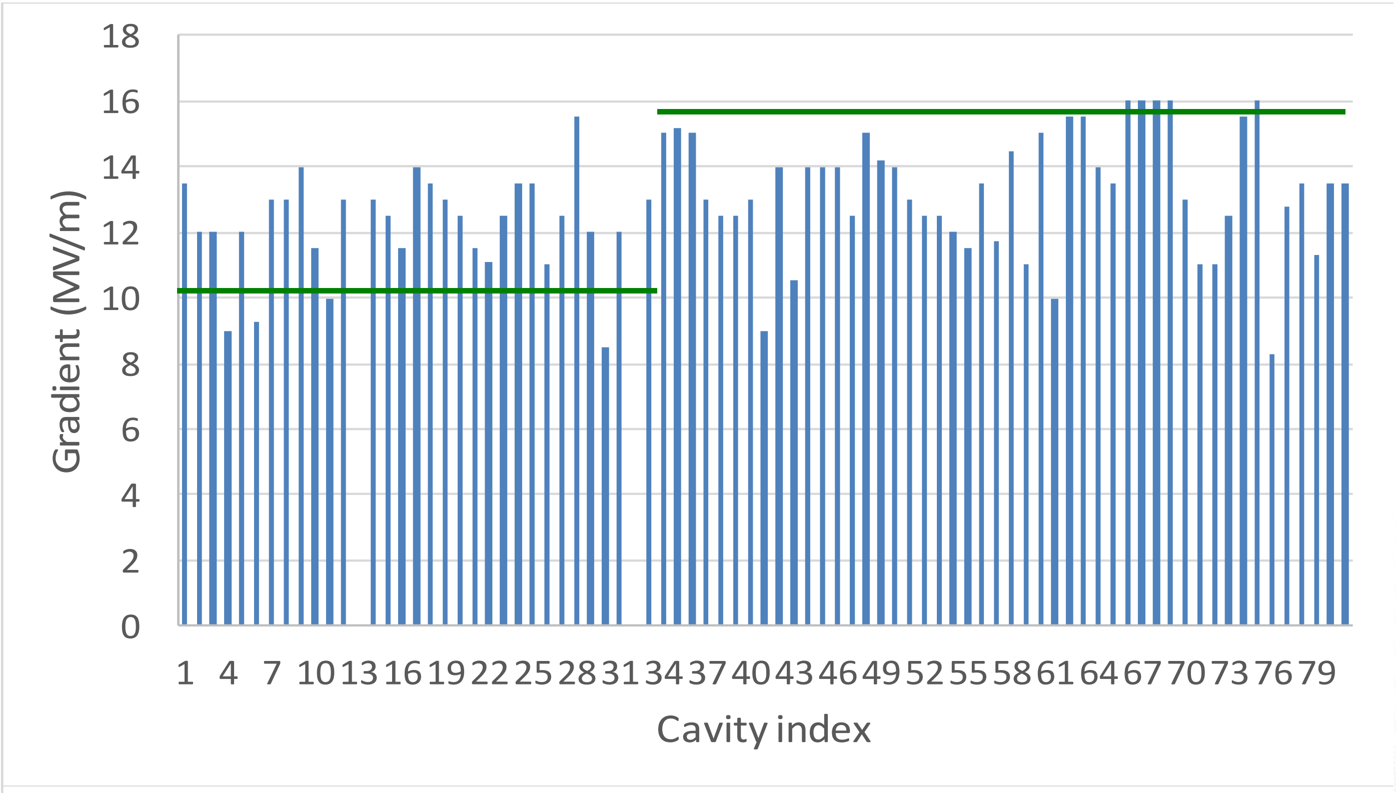


SCL has demonstrated superb operational flexbility: Energy reserve (spare cavity), easy retune (individual klystrons), allows removal of cavity with no impact on beam energy.

Reality: SCL Tune Up is Fast and Flexible

We used to joke about a ‘tune it up’ button

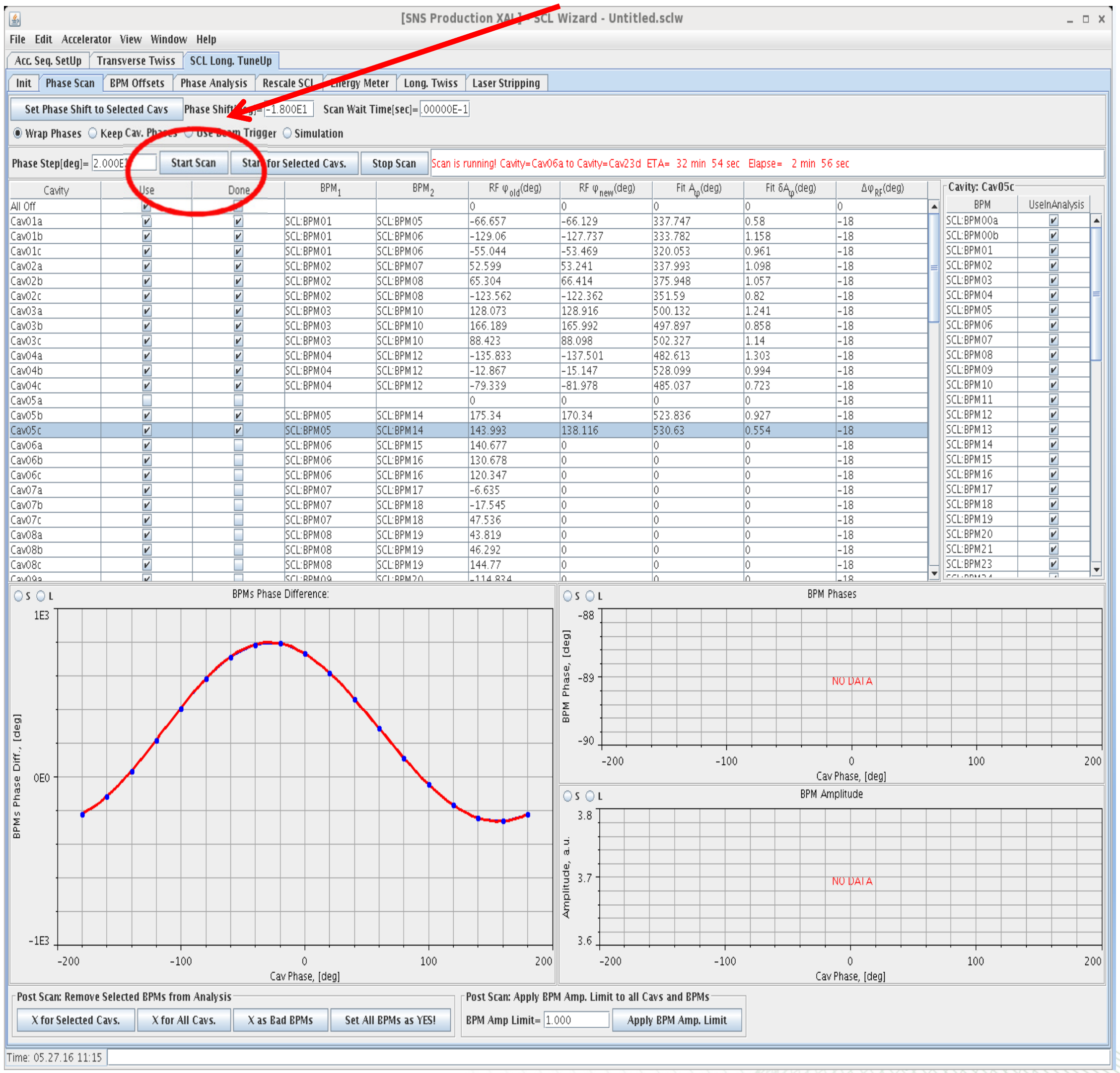
…. Now we have it!

Tune times, all 81 cavities:
- From scratch: 40 minutes
- Rescale: 20 seconds

Confluence of:
1. Robust BPM system
2. Digital LLRF (beam blanking)
3. Andrei Shishlo

(See Shishlo WEPM2Y1)

No longitudinal matching is applied.

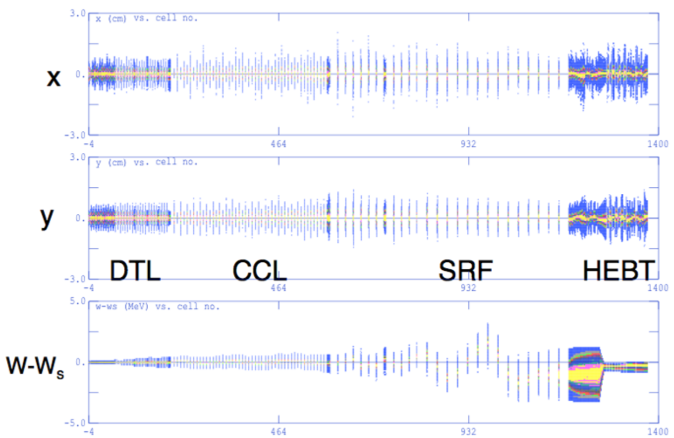


Flashback 2001: Linac Beam Dynamics

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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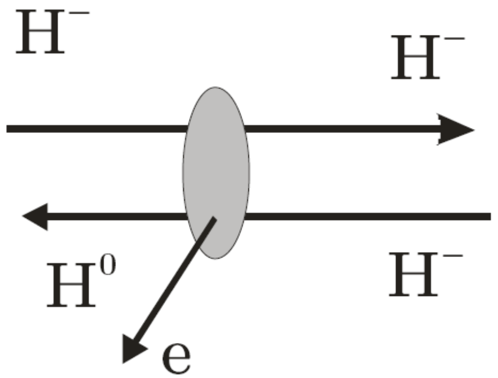
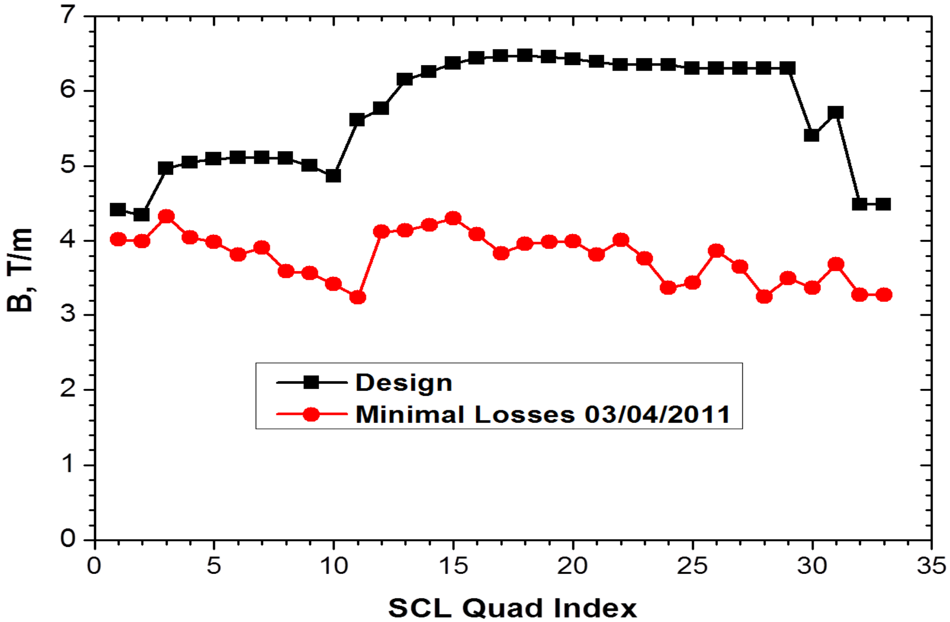
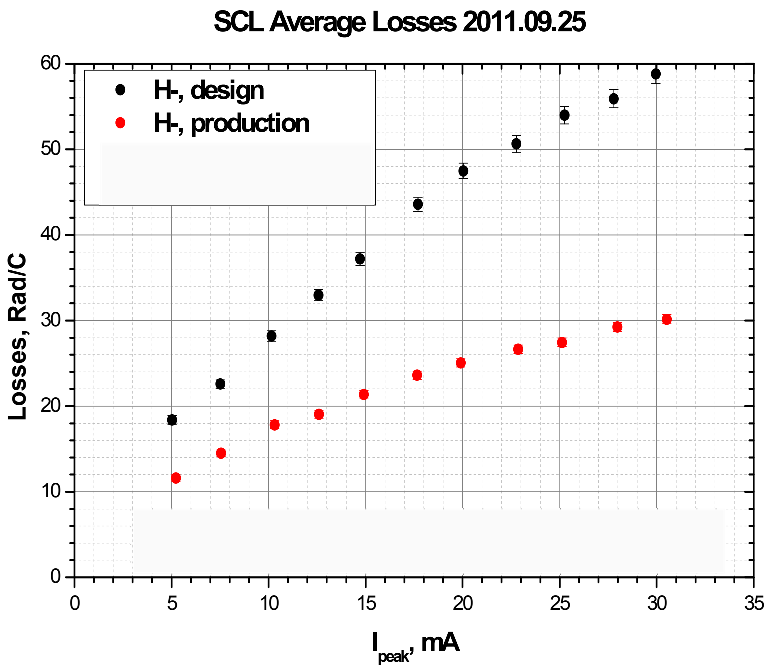
Reality: Impact of H^- Intrabeam Stripping

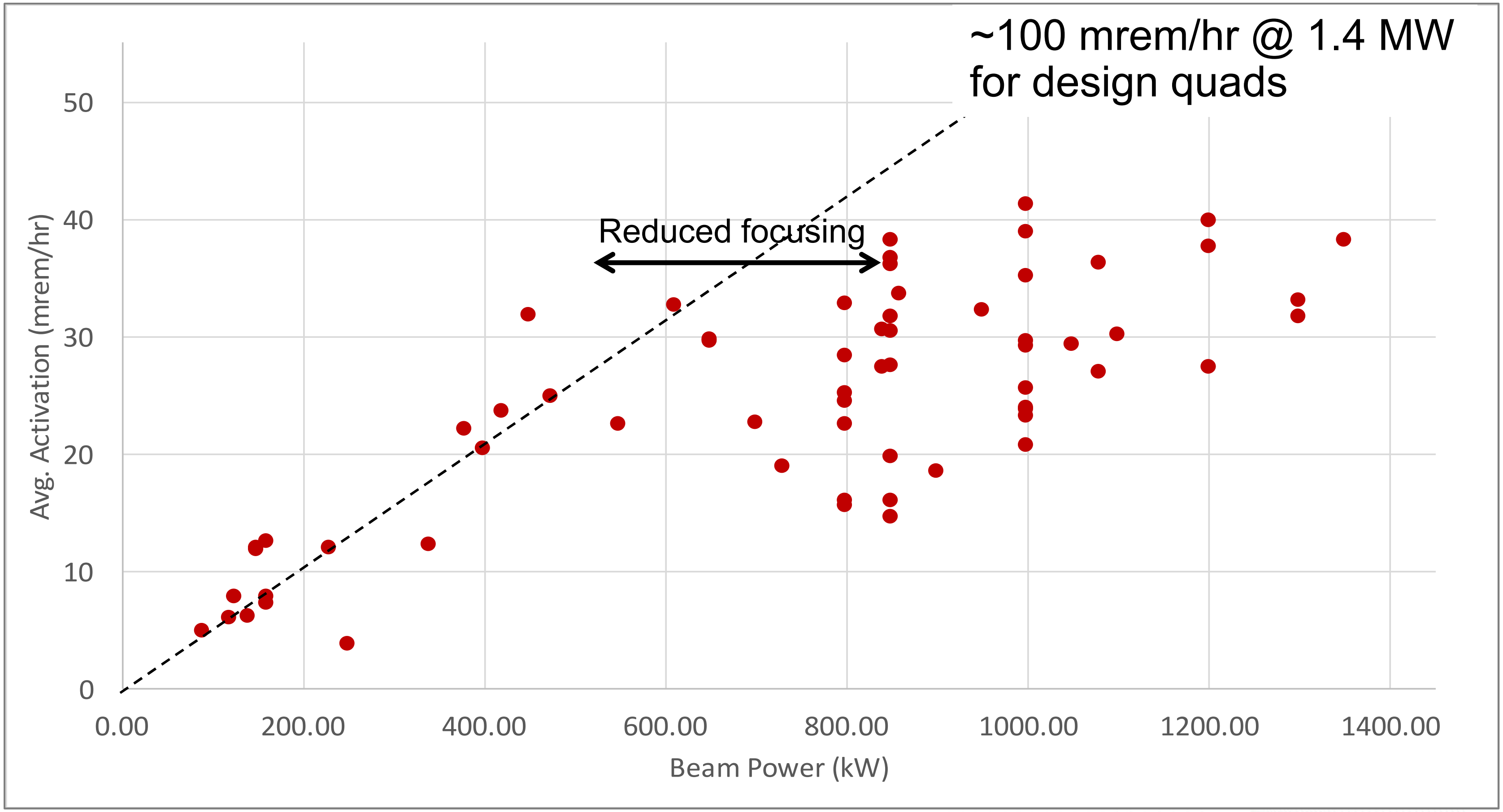


- Saw much more beam loss than expected.
- Factor ~2 decrease in quad strength reduced losses significantly.
- Later realized (and confirmed) H^- intrabeam stripping.





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.

Flashback 1999: 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:

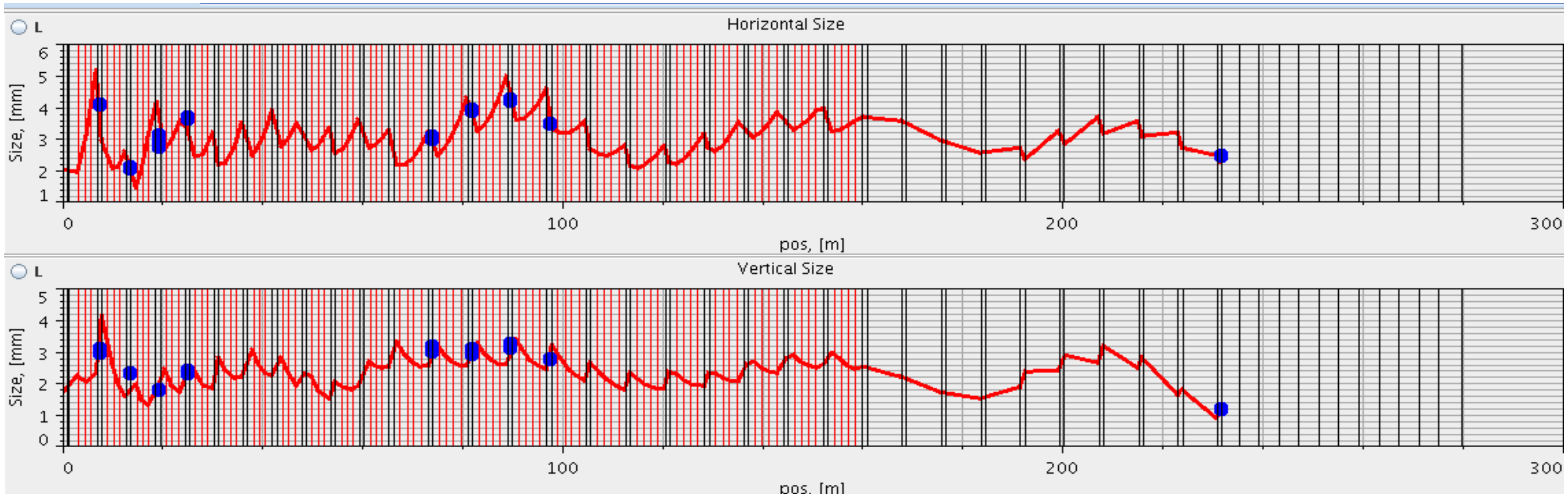
1. Construction and operating costs are considerably less compared to the warm linac. Expected power consumption is about 12 MW (50%), including cryo-plant, less than in the normal-conducting linac case.
2. Availability of the SC linac can be designed to be higher than the warm linac. This is due to 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!

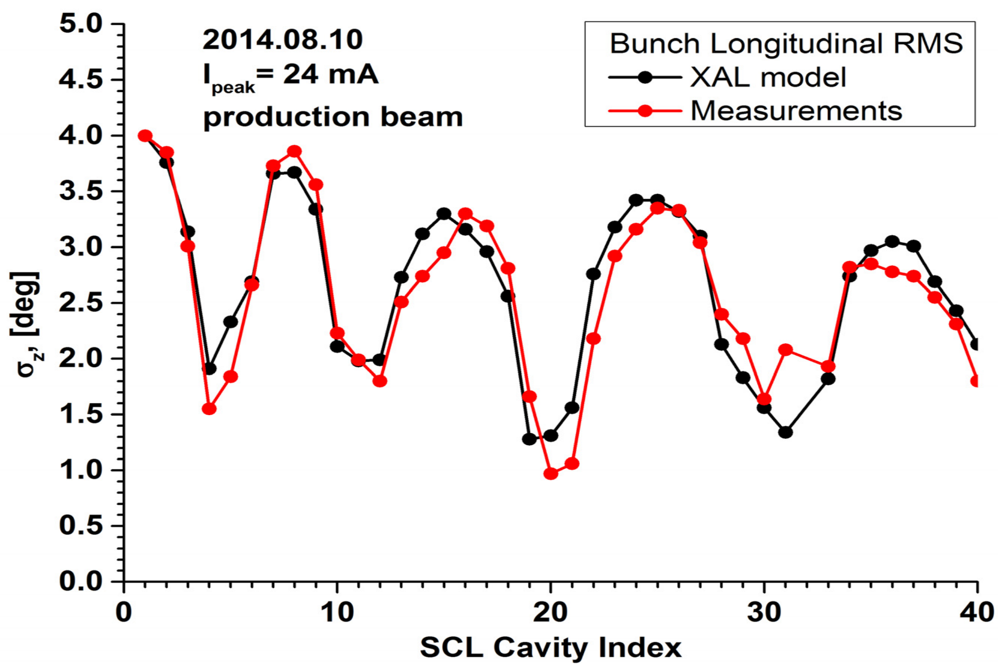
Reality: No Matching in the Linac

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

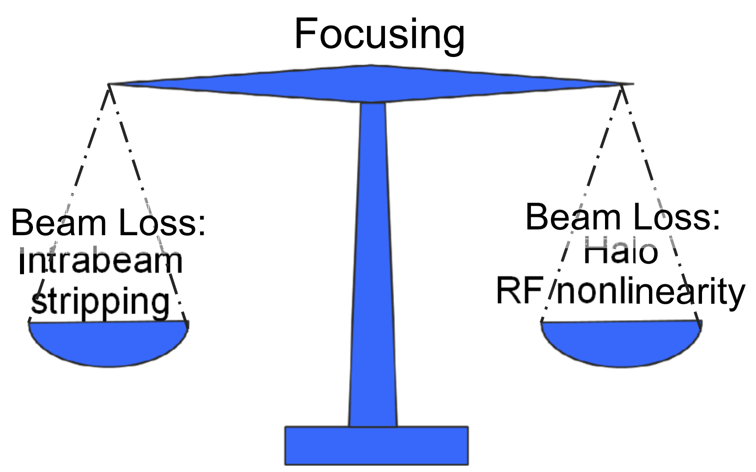
See Shishlo WEPM2Y1



Understanding Our Linac Beam Loss

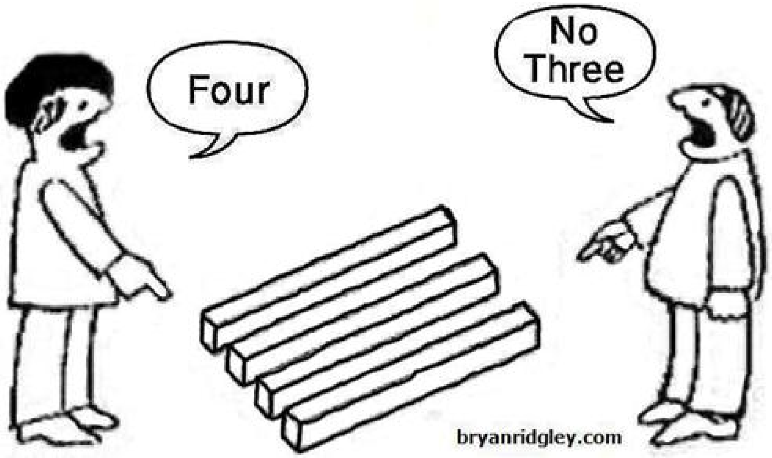
More quad defocusing increases beam loss – we have reach the limit.

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



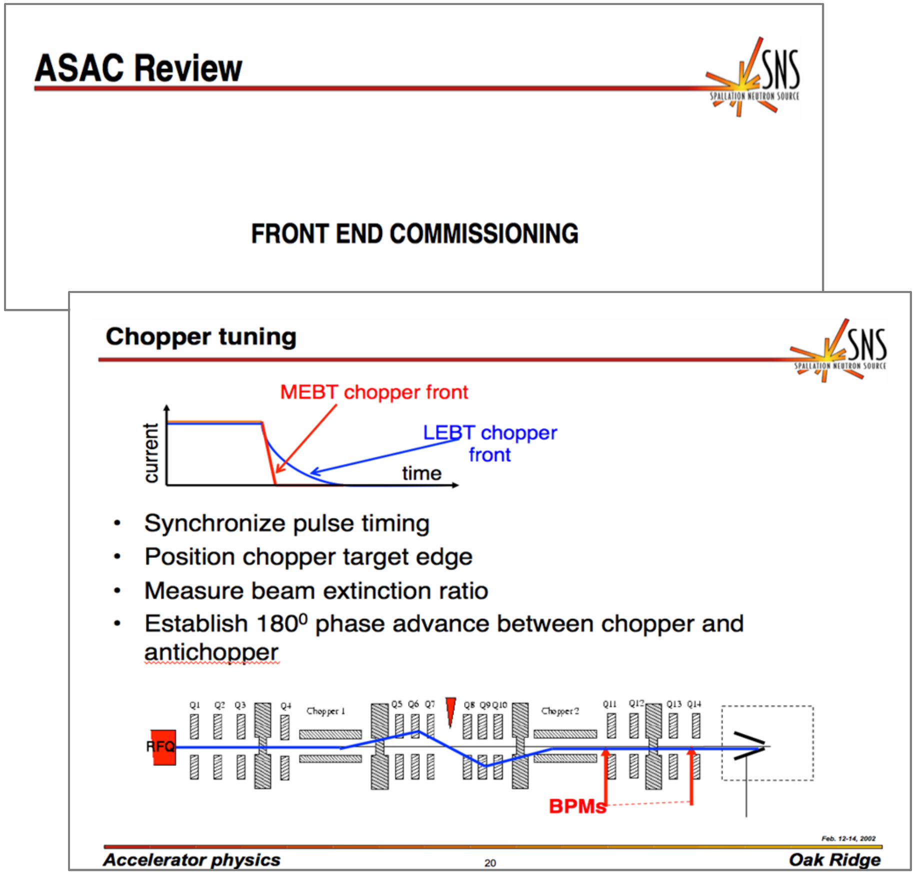
We don't understand the remaining beam loss.
Probably 'halo', but from what? How much?

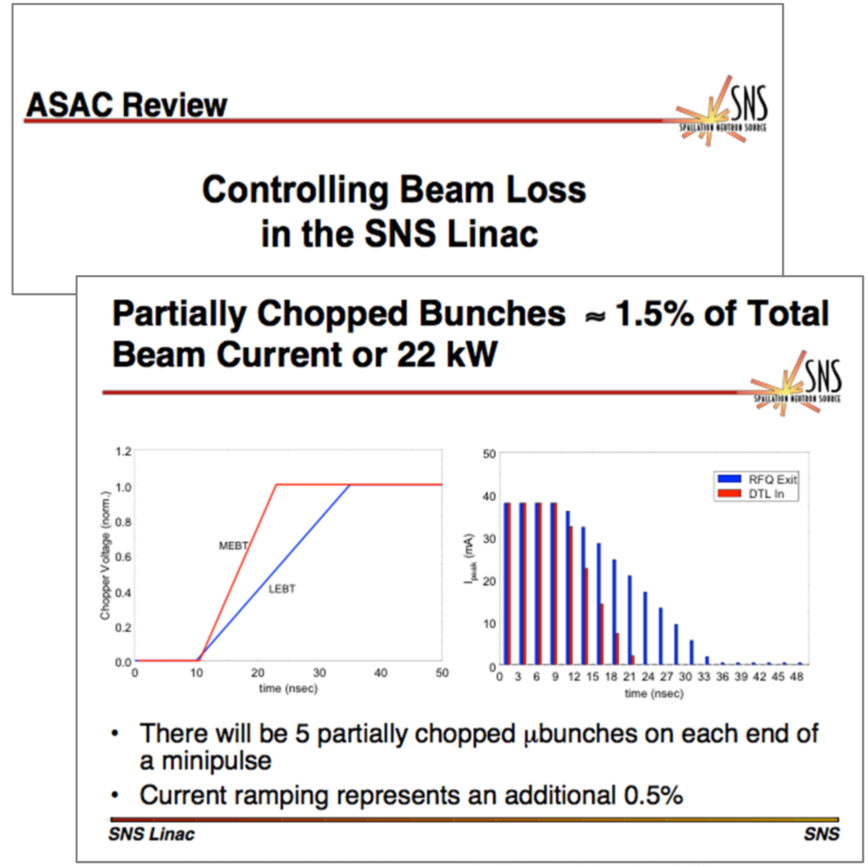
Many ideas of what defines "halo":



- 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. (See Aleksandrov -THAM5Y01)
- Models are now ready to attack this problem (see Shishlo WEPM2Y1)

Flashback 2002: MEBT Chopper Paranoia





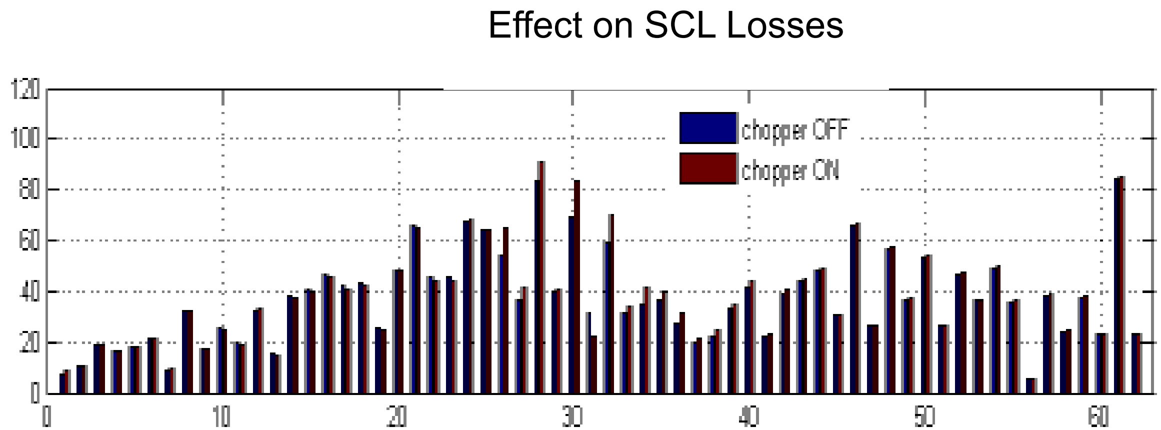
MEBT chopper drove MEBT design:

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

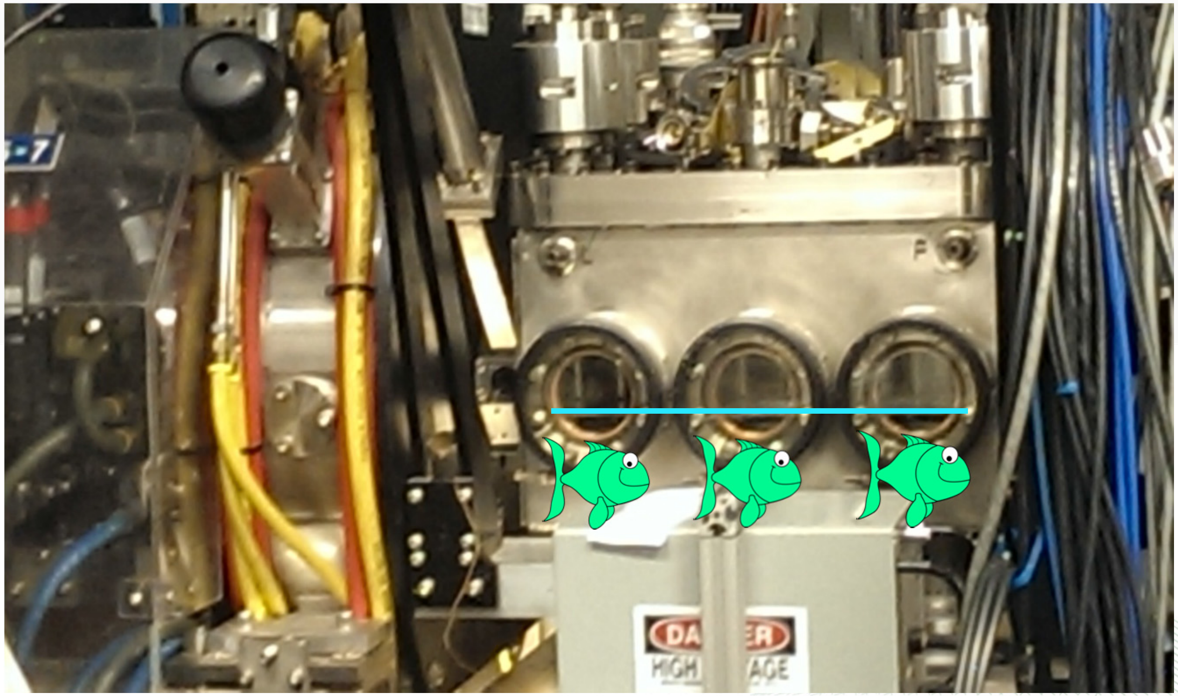
	No MEBT Chopper	With MEBT Chopper
# Quadrupoles	4	14
# Bunchers	1	4

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.



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



Part I
Accumulator Ring

SNS Accumulator Ring Design Parameters

Design Parameters

Circumference: 250 m

Energy: 1 GeV

Intensity: 1.5e14 ppp

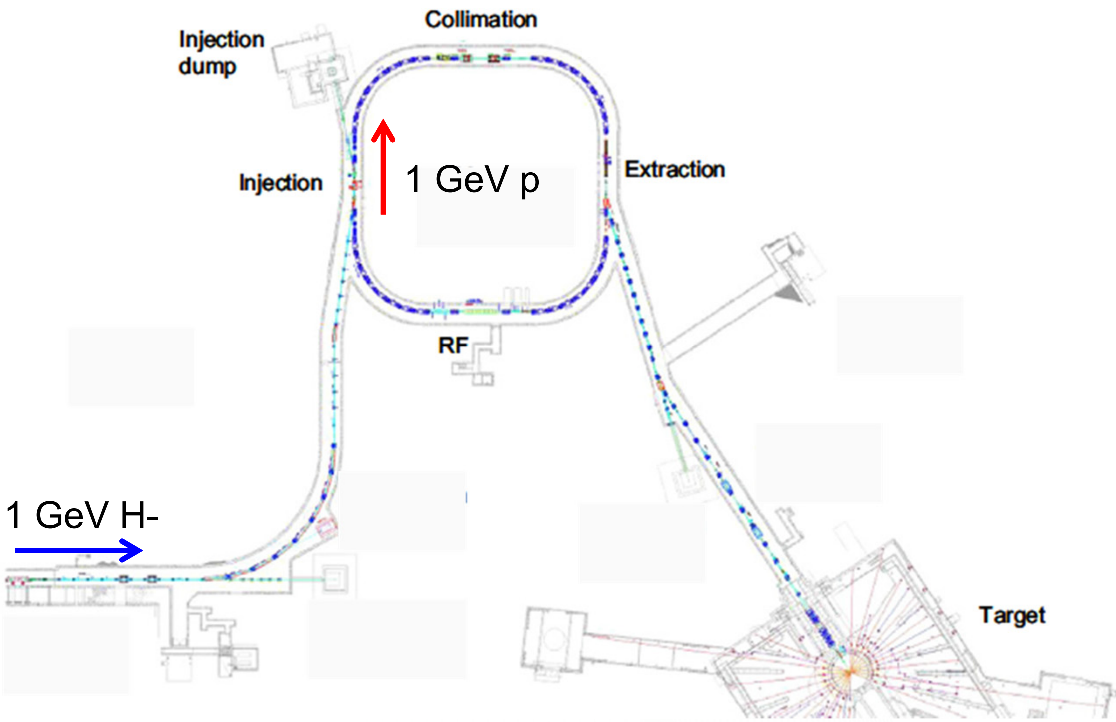
bunches: 1

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.

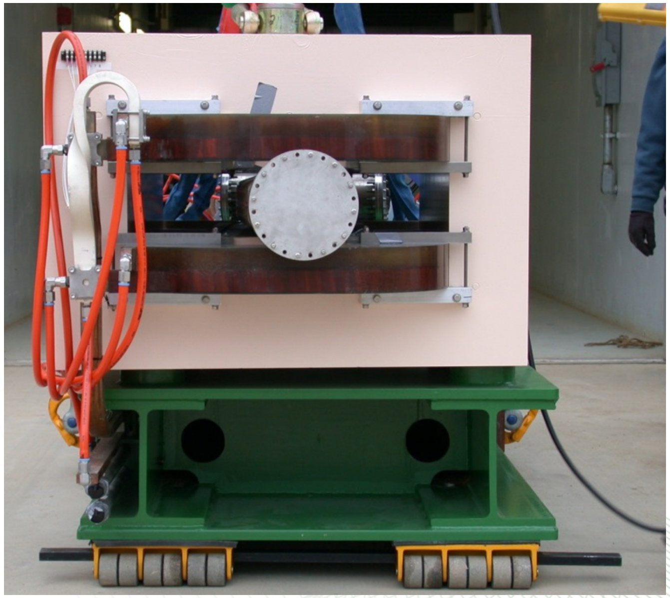
Outline

1. Performance measures.
2. What we got right: High pay-off investments
3. Stuff we worried too much about.
4. Stuff we should have worried more about.
5. The power upgrade project.

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 pi
Dipole	23 x 15	480 pi
Quadrupole	21 – 30	480 pi
Collimator	10 – 16	300 pi

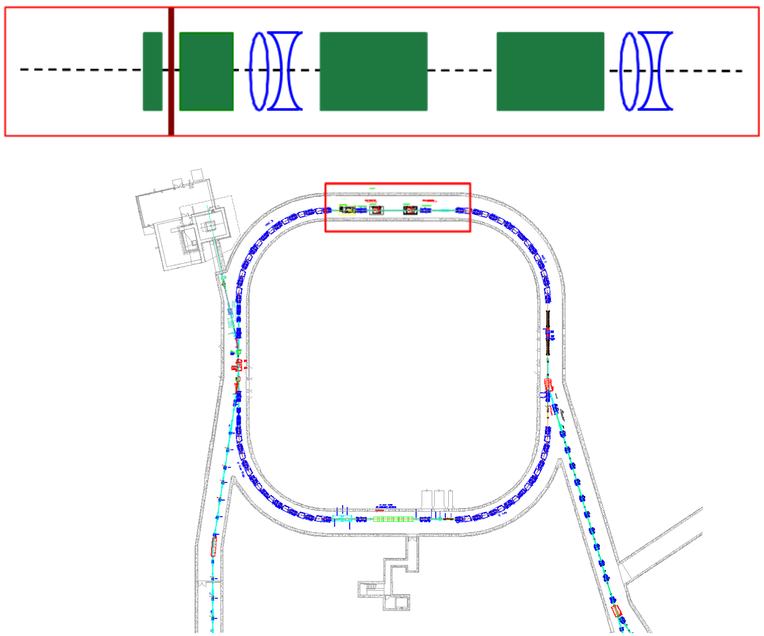


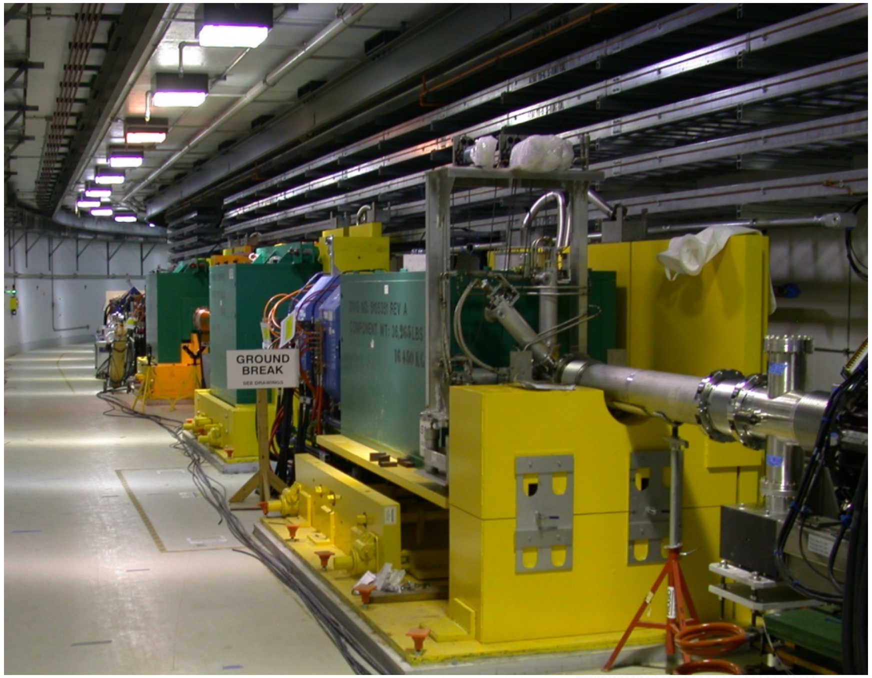
And it works. We use it all.

(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.

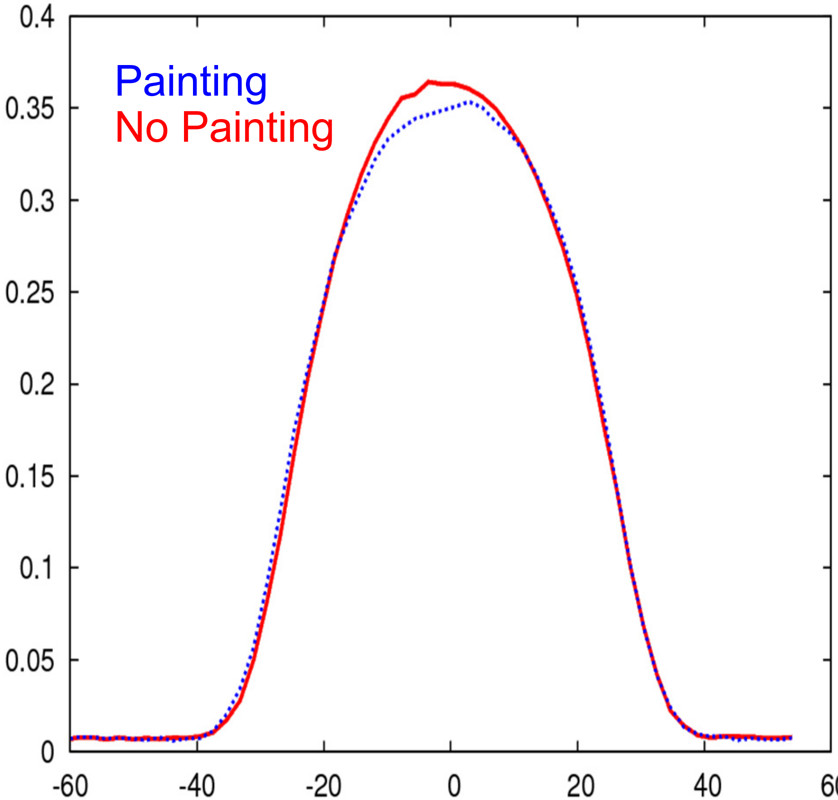
We do not use the collimator in a two stage fashion. Prioritize aperture.

Dual Plane Injection Painting: High Payoff

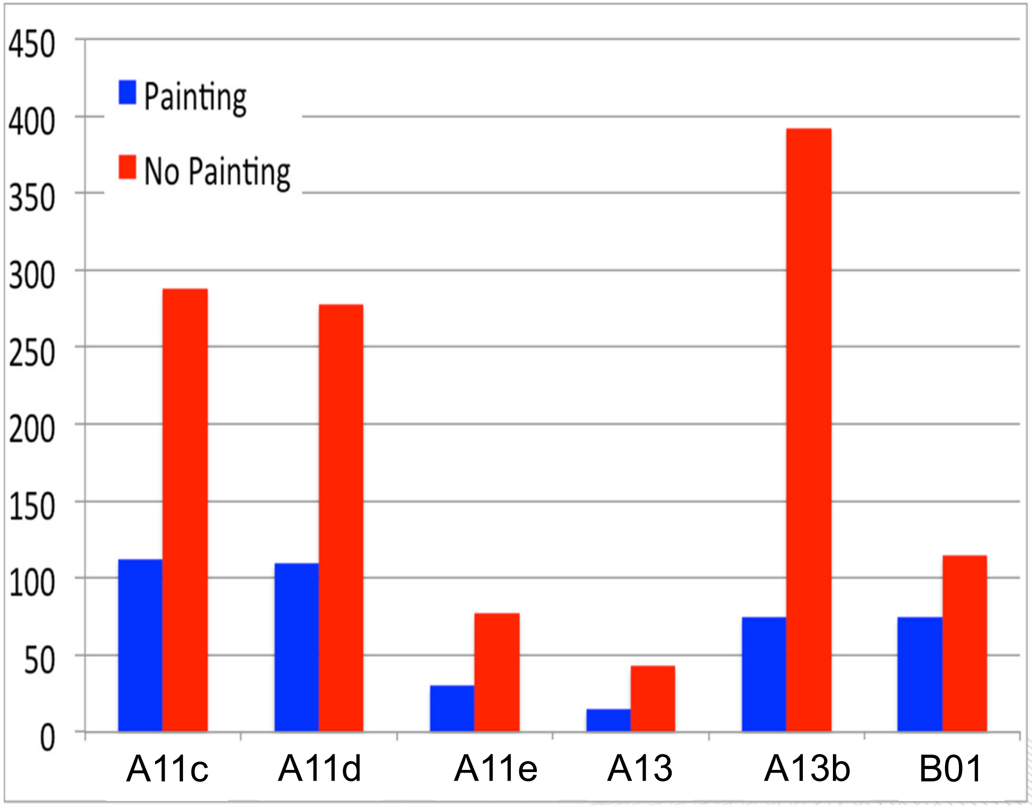
We paint in both planes with a correlated beam, all the way to collimator aperture.

The injection losses would be intolerable without it.

~ 1 MW Equivalent Beam Profiles For Two Equal Emittance Beams



Injection Region Beam Loss Monitor Signals



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

- No significant e-p seen during production so far.

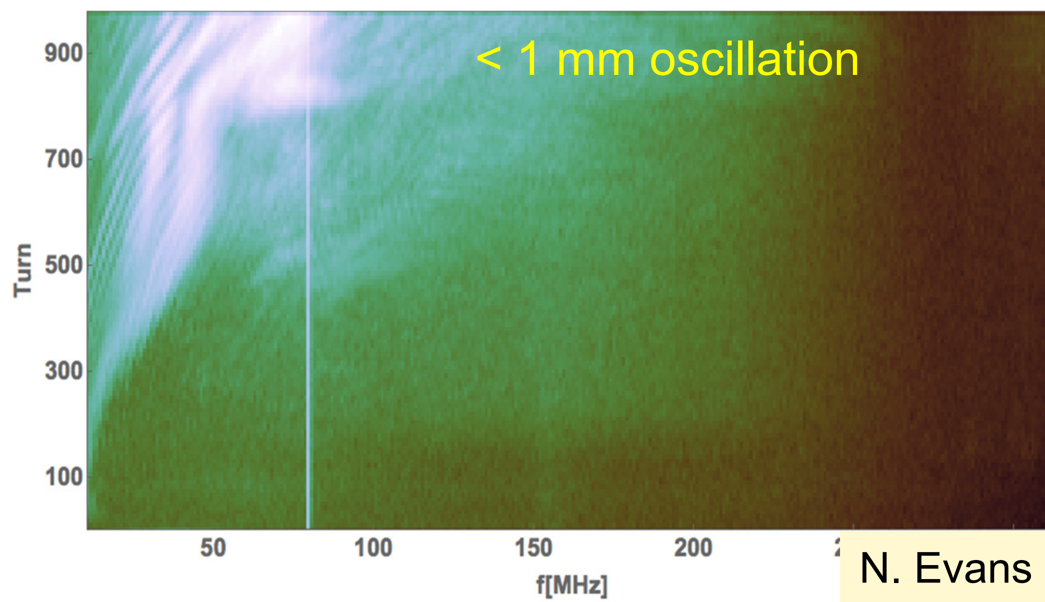
N o

- Trace levels after opening vacuum. No beam loss.

a p p r

See Evans TUPM1X01

e-p Activity for 1.4 MW Production Beam

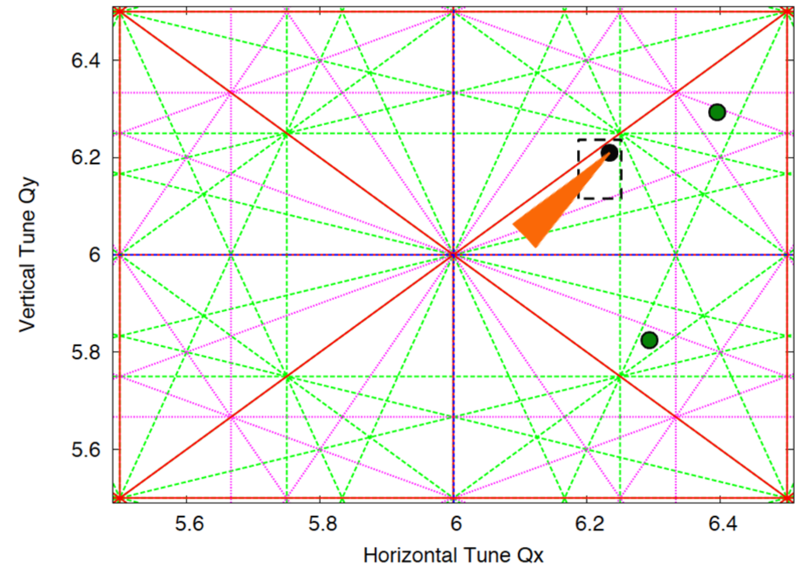


N. Evans

Two Things We Worried Too Much About

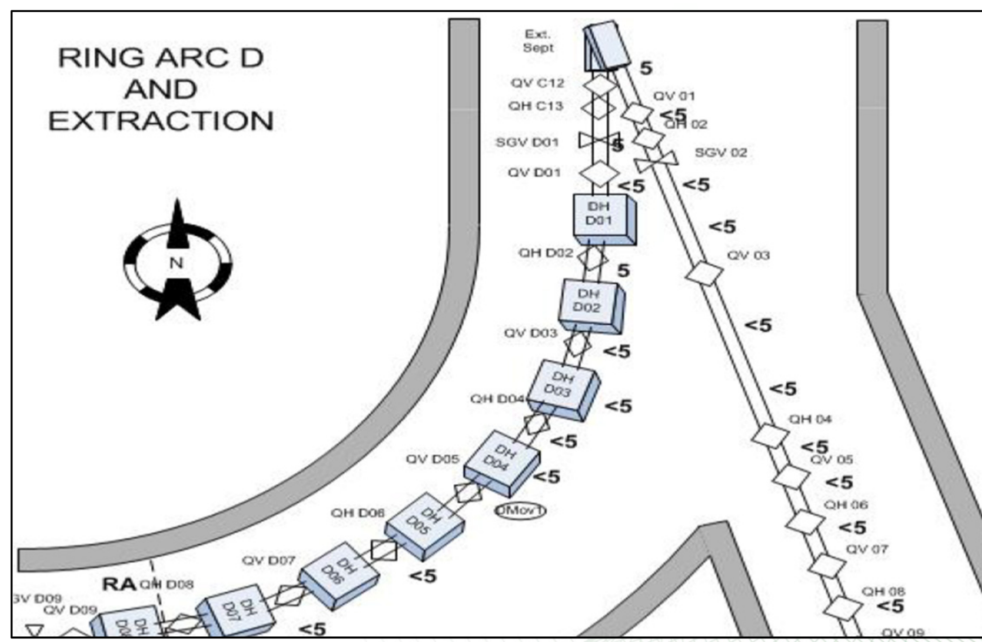
1. Space charge effects: Resonances, halo

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



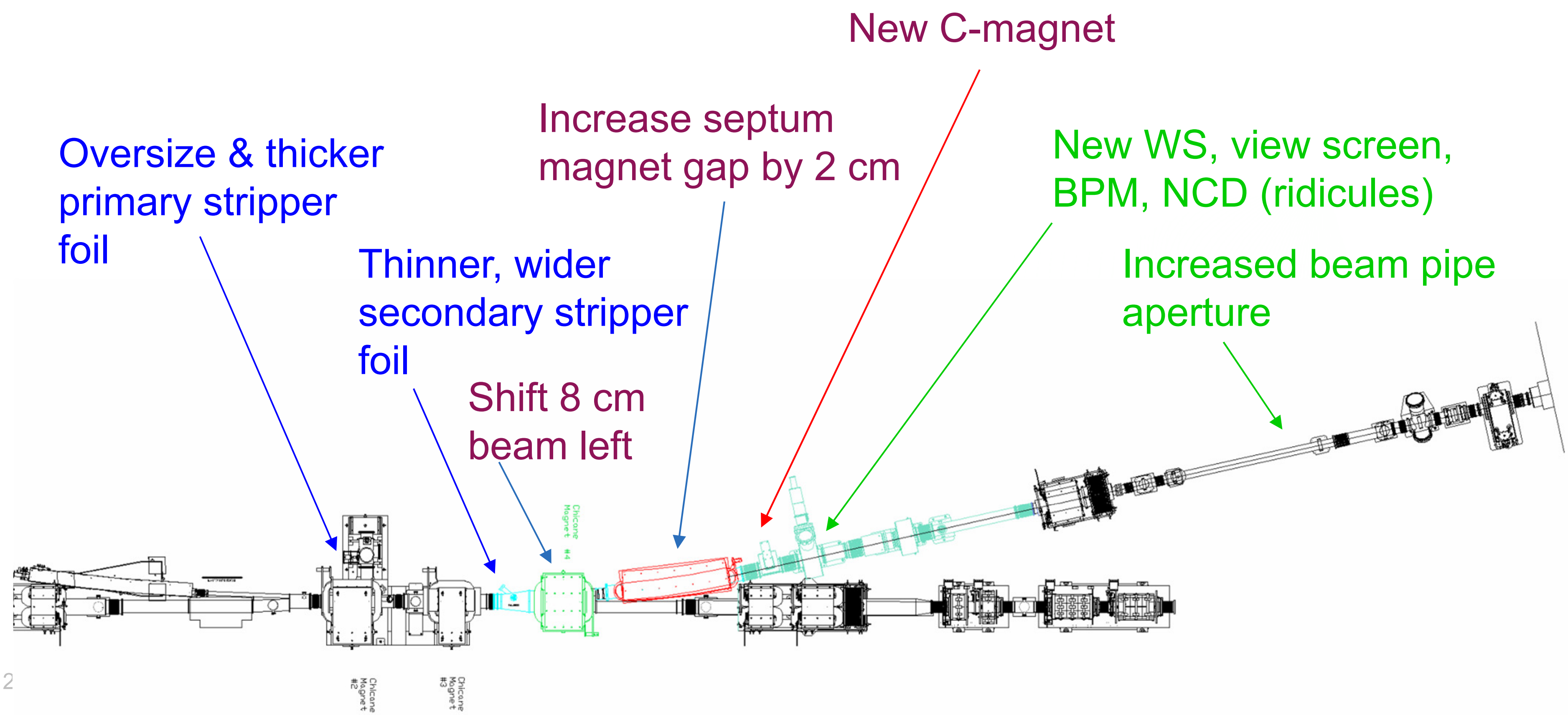
2. Extraction loss:

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



Injection: We Didn’t Worry Enough

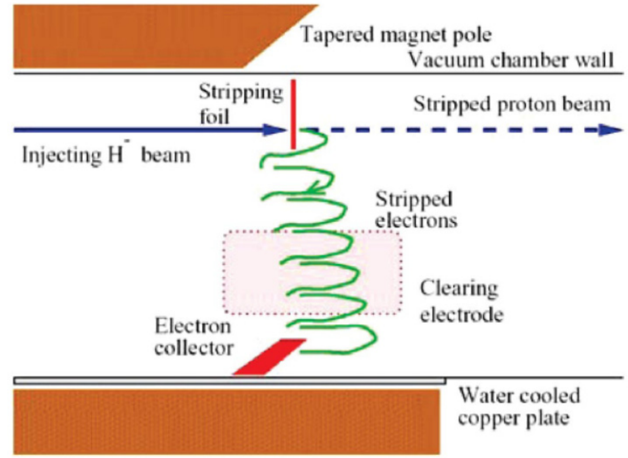
- Design changed caused unintended consequences.
- Trajectories were not sufficiently modeled.
- Fallout was many changes once reality struck:

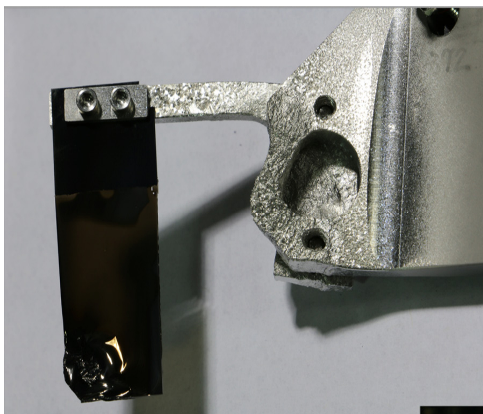


We Didn’t Worry Enough: Convoy Electrons

- Convoy electrons carry 1.6 kW power at 1.4 MW
- Reflected electrons have cause bracket damage
- Damage to electron catcher is worsening issue

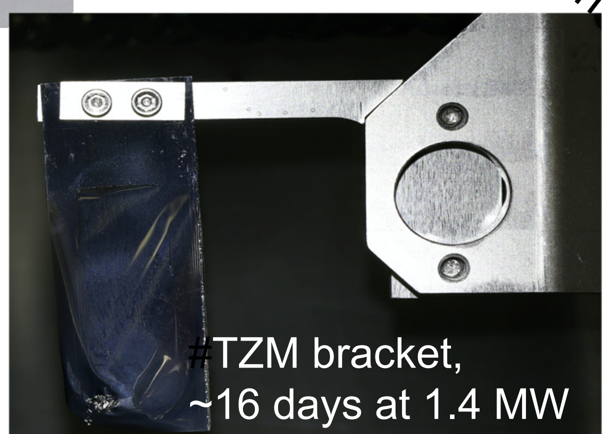
See Plum TUMA6X01



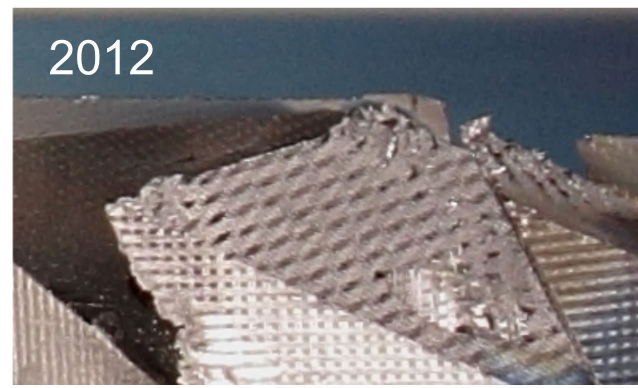


Ti bracket
3 months at
1.1 – 1.4 MW.

Geometry, material evolution



#TZM bracket,
~16 days at 1.4 MW



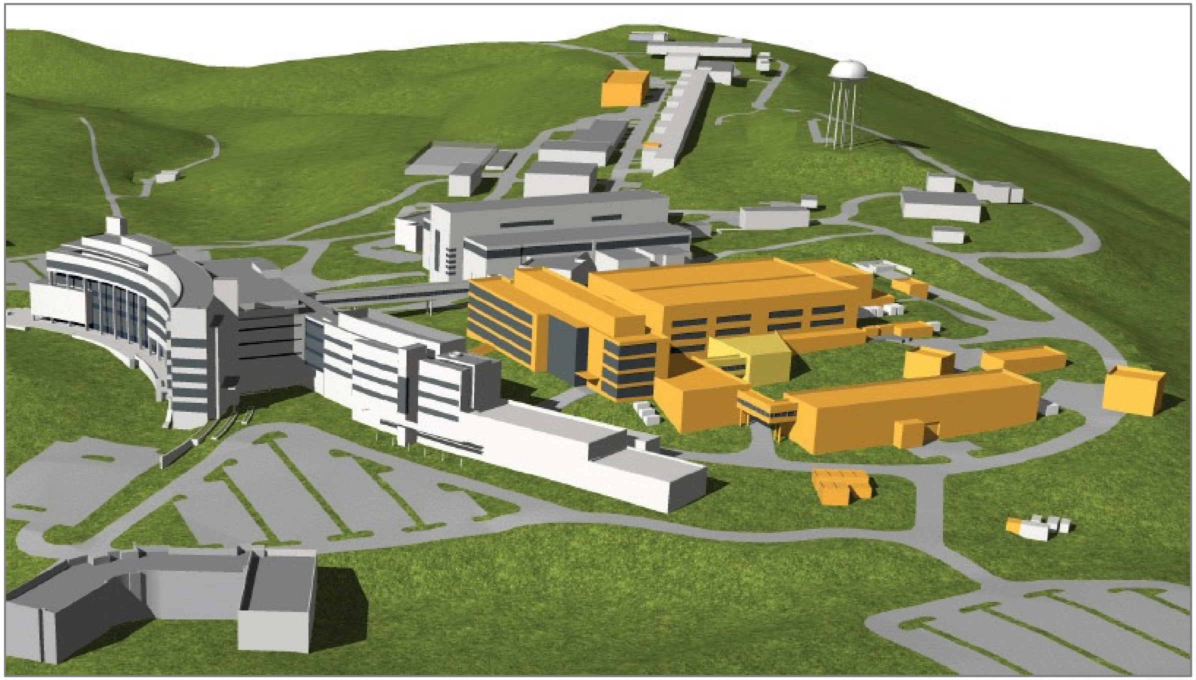
Menu of Initial Investments and Payoff

Feature	Cost	Payoff So Far
Large Aperture	$$$$	High
Injection Painting	$$$	High
Collimation	$$$	High
TiN coating	$$$	Unknown
2nd harmonic RF	$$	Medium
Main sextupoles	$$	Low
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.

STS and the Beam Power Upgrade

Parameter	Now	Upgrade
Beam Power	1.4 MW	2.8 MW
Beam Energy	1.0 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.