# Progress with MW-Class Operation of the Spallation Neutron Source

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On behalf of the SNS Team

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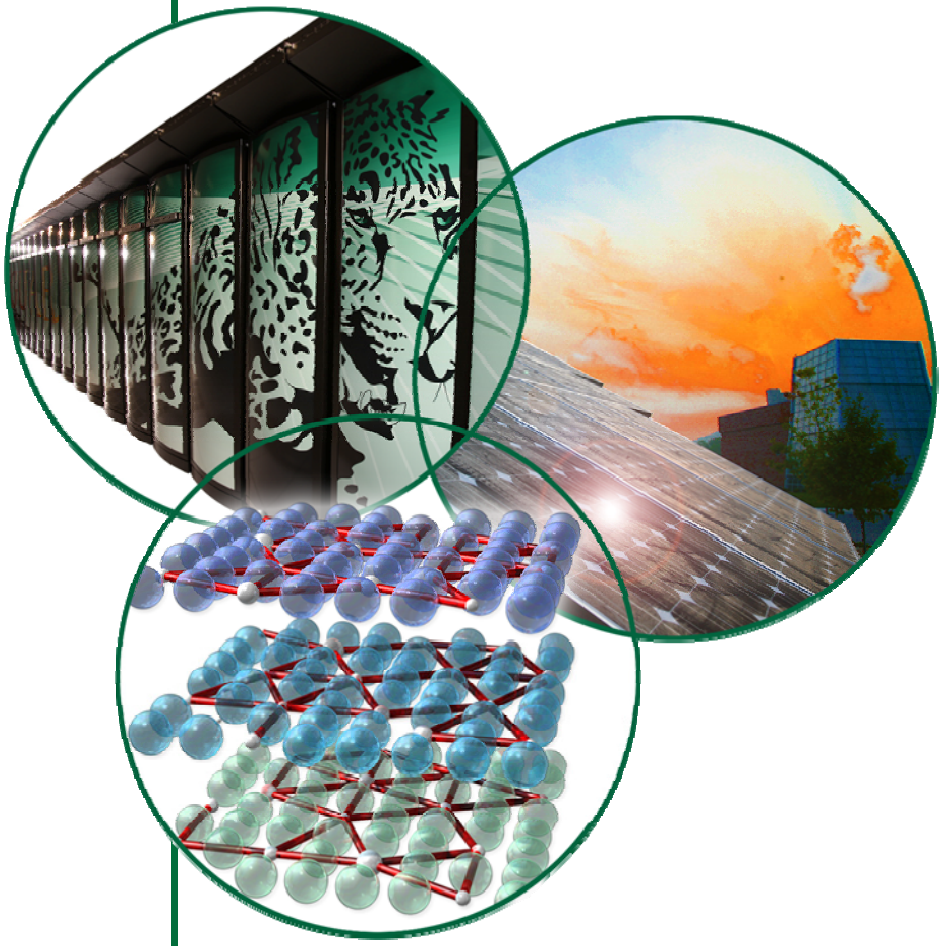

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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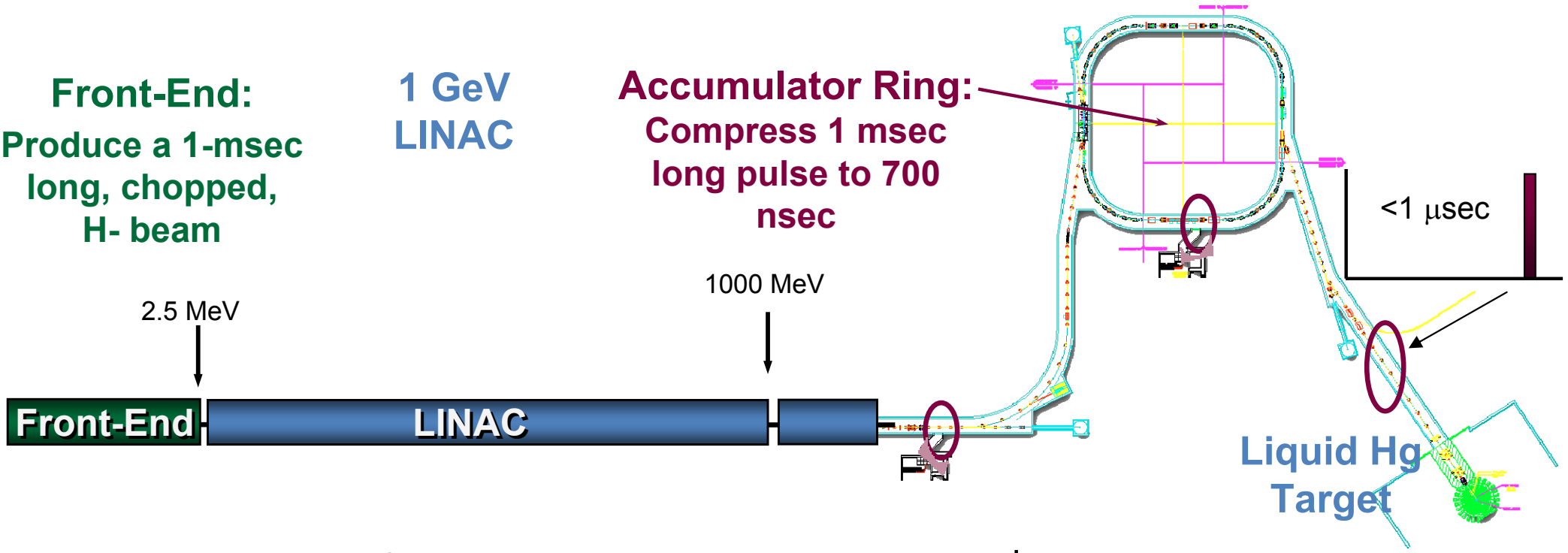
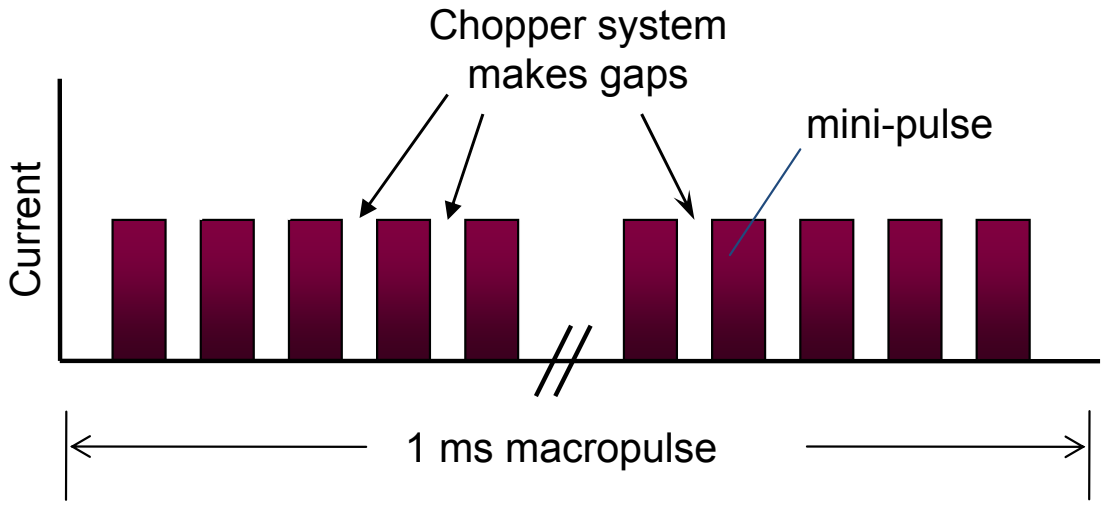
# SNS Accelerator Complex

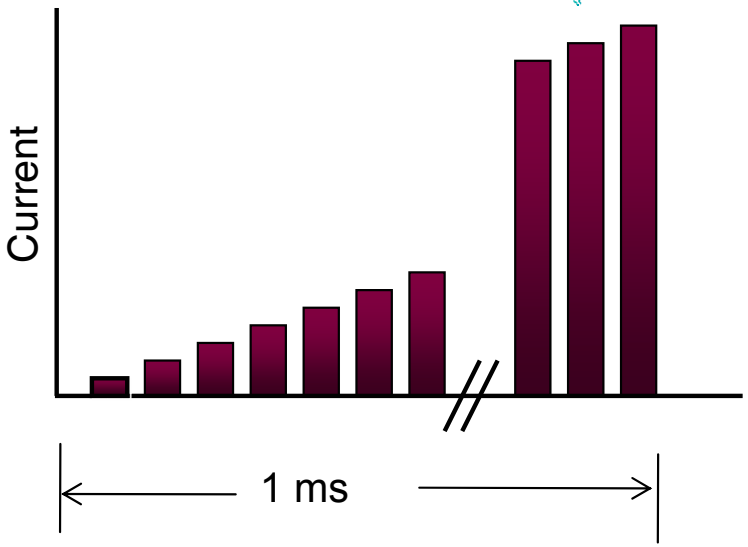
**Front-End:**
**Produce a 1-msec long, chopped, H- beam**

**1 GeV LINAC**

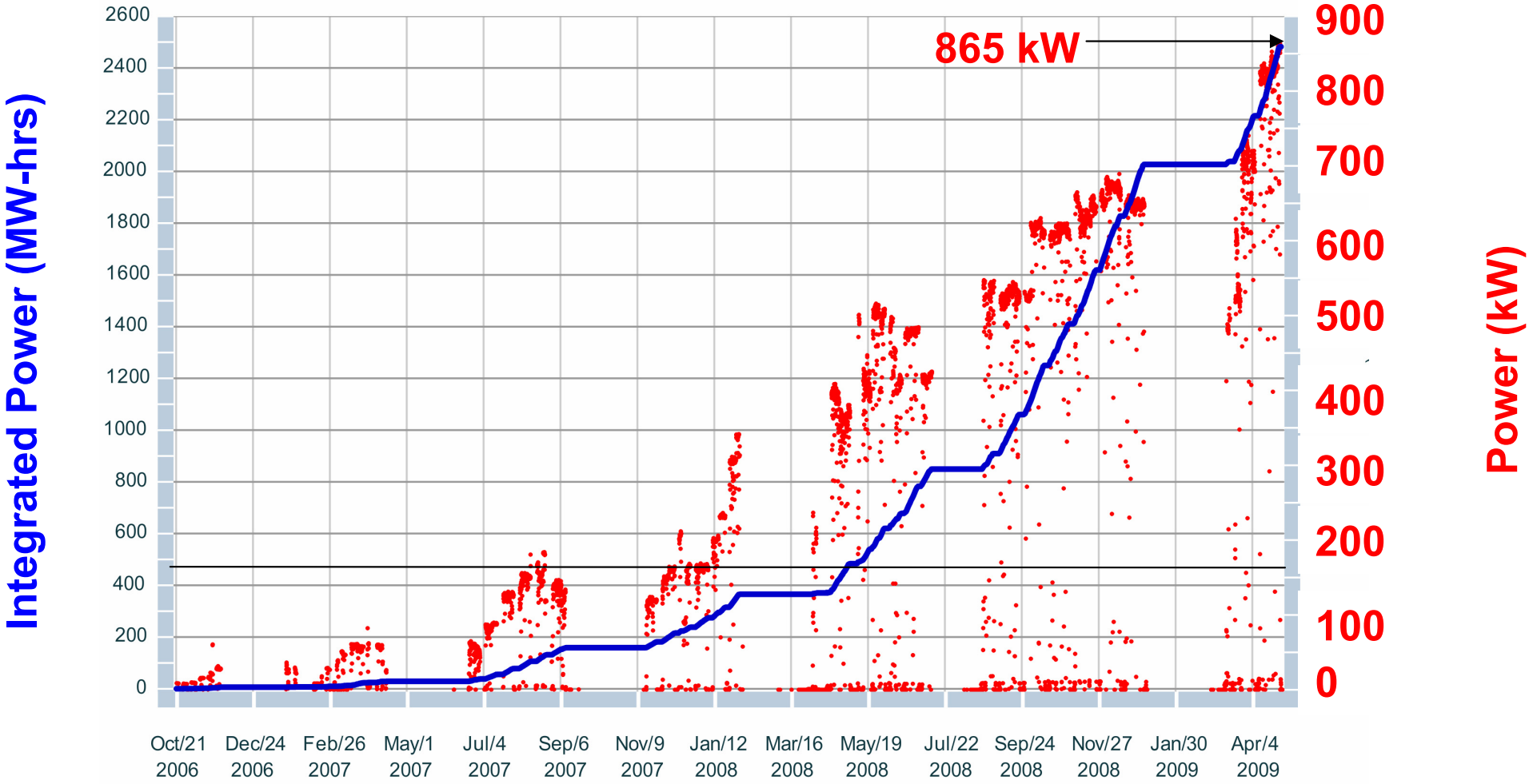
**Accumulator Ring:**
**Compress 1 msec long pulse to 700 nsec**



# Progress Towards ~ 1 MW Beam Operation




- Power Ramp-up since start of operations in October 2006
- Integrate power delivery is increasing faster than peak power delivery
  - Important for activation considerations

# Outline: High Pulsed Power, High Intensity Operation at SNS

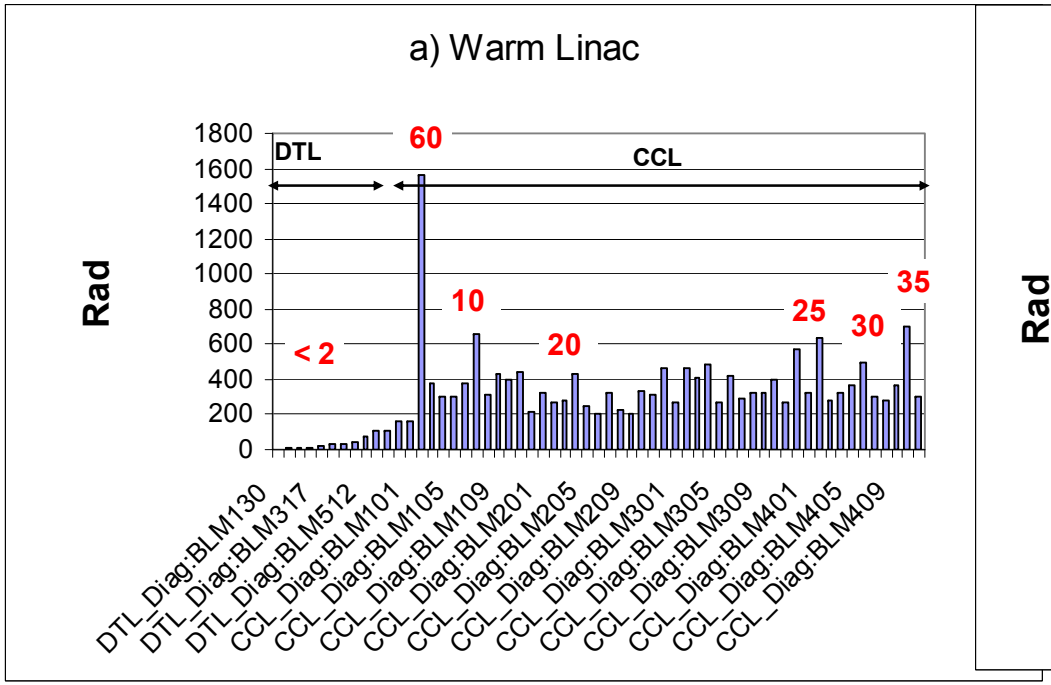
- Beam loss / activation 
  - Design requirement: uncontrolled beam loss < 1 W/m
  - SNS is not beam loss limited
- Machine Protection 
  - No melted beam pipe or targets
- Equipment robustness (availability)
  - Keep the customer happy 
- Future Concerns 

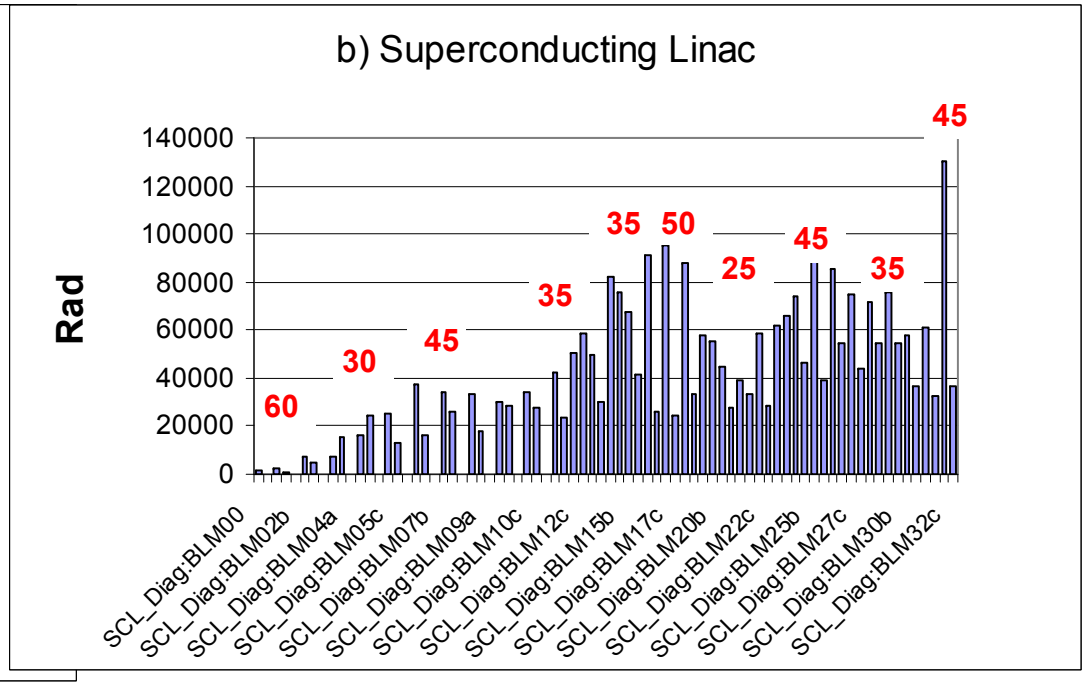
# SNS Performance Relative to Design

| | Design | Best ever, not simultaneous | Highest power, simultaneous |
|---|---|---|---|
| Beam Power (kW) | 1440 | 865 | 865 |
| Kinetic Energy (MeV) | 1000 | 1010 | 928 |
| Linac Pulse Length (mSec) | 1000 | 990 | 670 |
| Peak Accelerated Current (mA) | 38 | 40 | 36 |
| Average linac current (mA) | 26 | 23 | 23 |
| Repetition Rate (Hz) | 60 | 60 | 60 |
| Operational SC cavities | 81 | 80 | 80 |
| Ring accumulation turns | 1060 | 1020 | 700 |
| Ring Bunch Intensity | $1.5 \times 10^{14}$ | $1.3 \times 10^{14}$ | $9.7 \times 10^{13}$ |
| Ring Space Charge Tune spread | 0.15 | 0.18 | 0.11 |

# Beam Loss in the SNS Linac

Red numbers = residual activation @ 30 cm, 24 hrs after 15 day 860 kW production run

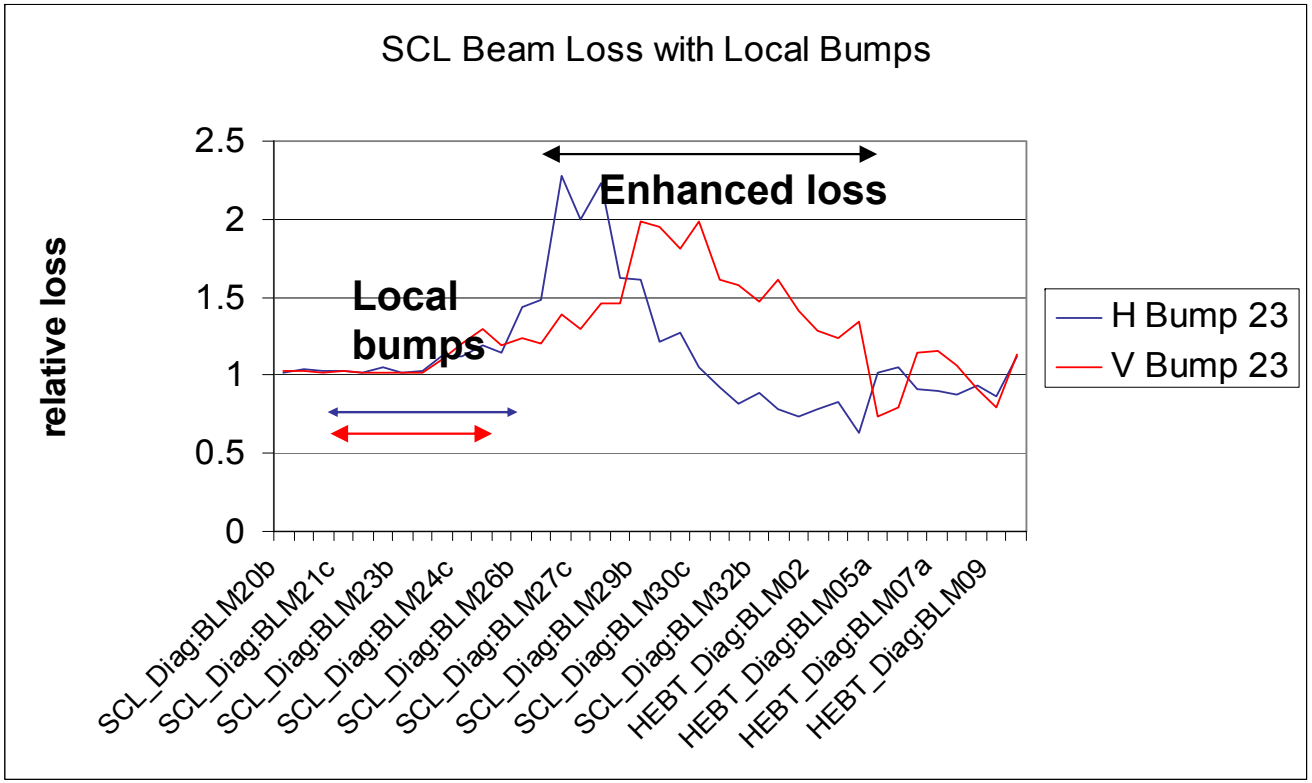



- **Loss is < 1 W/m everywhere**
  - **Residual activation numbers are after a recent 850 kW run**
- **Warm linac loss close to expectations**
- **The SCL loss is higher than expected, and the cause is under study**
- **RMS transverse emittance measurements are close to expected values**

# Beam Loss / Activation – Superconducting Linac

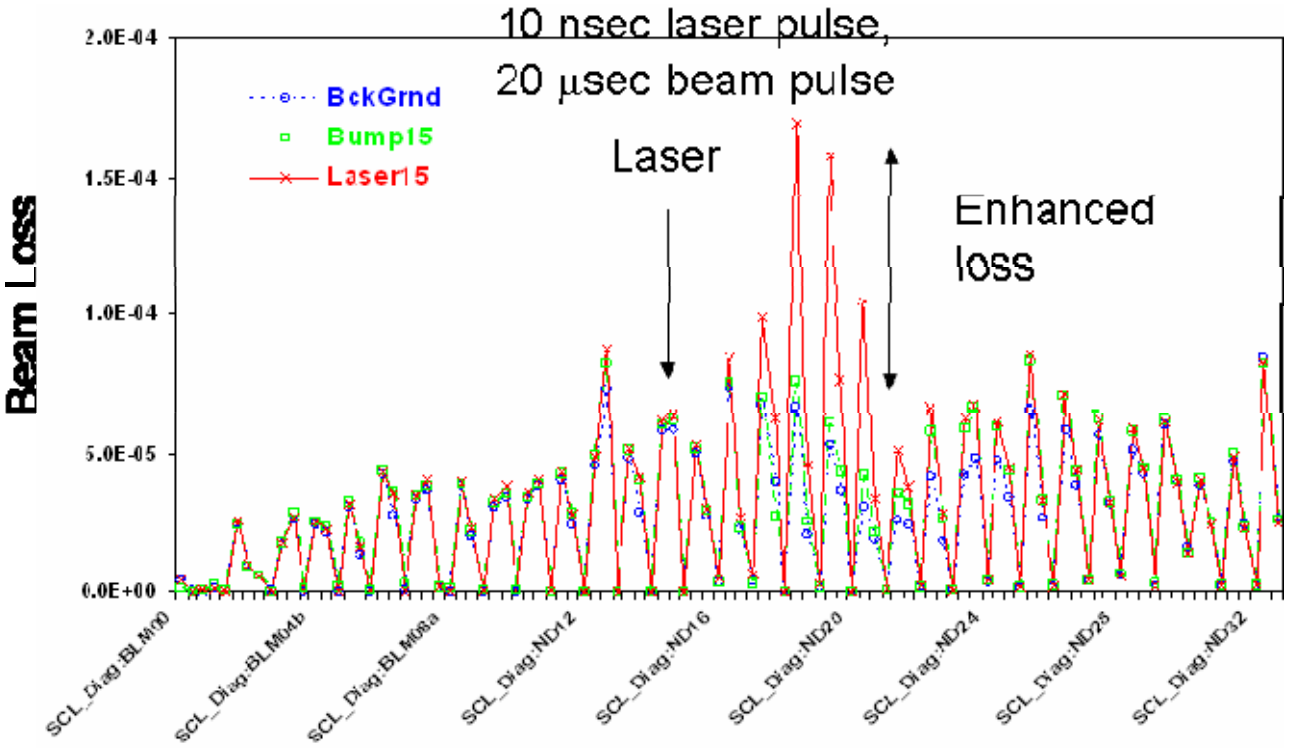
## see TH6PFP089 Y. Zhang et. al., Beam Transverse Issues at the SNS Linac




- Low level of beam loss throughout the SCL is not understood
  - Recent lowering of the SCL quadrupole strength (~10%) reduced loss ~ 40%
  - Local bumps cause increase in downstream loss

# Quantifying Low Fractional Beam Loss

## A. Zhukov "TH6REP013 Measurement and Detailed Simulation of Beam Losses Caused by Thin Interception Devices (Wire Scanners, Scrapers) at SNS"




Used to estimate that < $2 \times 10^{-6}$ beam is lost per SCL cryomodule

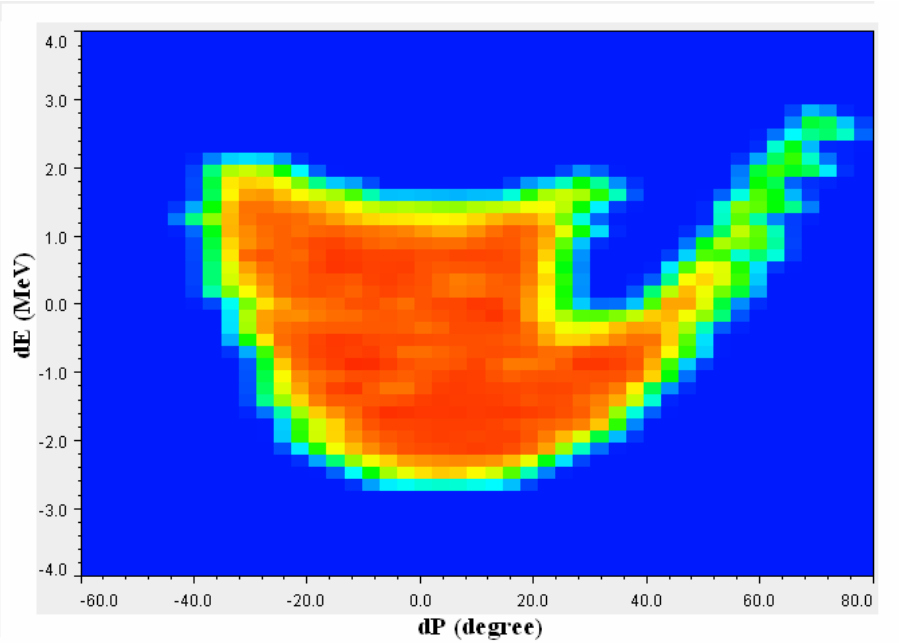
< $10^{-4}$ beam is lost in the SCL

- **Compare residual activation to benchmark value of ~100 mrem/hr @ 30 cm after 4 hrs for long term 1 W/m beam loss**
- **Need controlled spills of very small amounts of beam to calibrate loss signals**
- **Loss monitors are the most sensitive measurement instrument**
  - **Response is highly energy and geometry dependent**

# Superconducting Linac Experience

## - Sang-Ho Kim, et. al, TU6PFP072 "SNS Superconducting Linac Power Ramp-Up Status and Plan"
## - T. Hardek – TU5PFP091 "Status of the SNS RF Systems"

- First pulsed proton beam application of SRF technology
- Now running at 928 MeV (1 GeV design) with 80 out of 81 cavities operational
  - Reliable, works well
- Have built an operational Superconducting RF test facility
  - Proof-of-principle plasma processing effort is encouraging



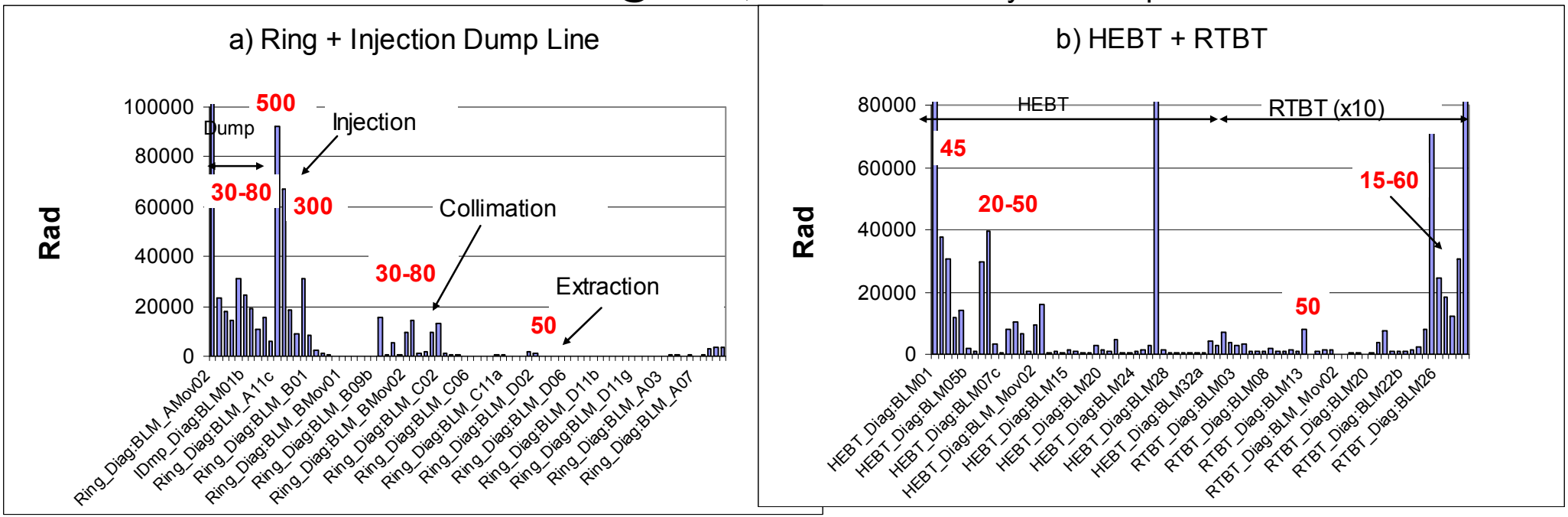

-- SCL RF setup is quite flexible

-Example of longitudinal acceptance measurement (Y. Zhang)

-Close to expected acceptance

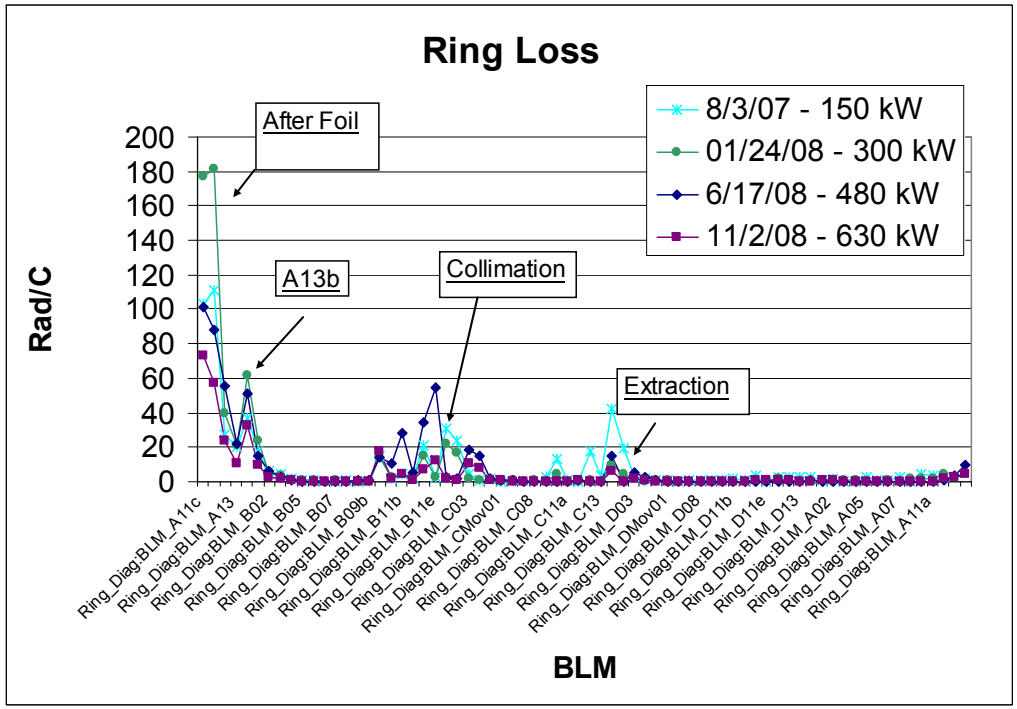
# Beam Loss in the SNS Ring

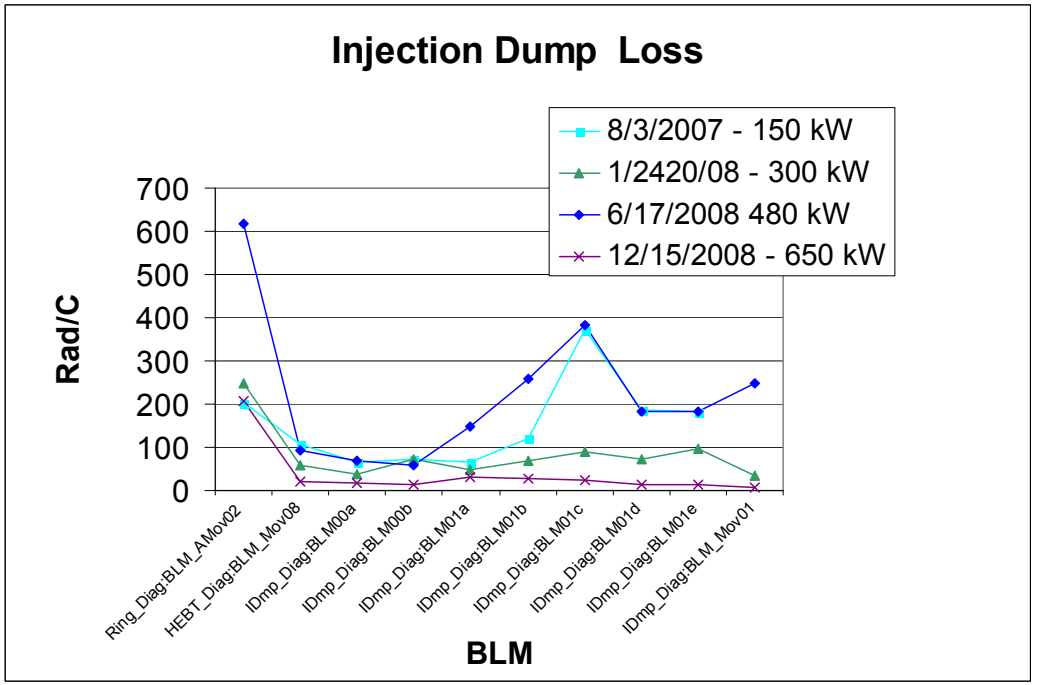
Red numbers = residual activation @ 30 cm, 24 hrs after 15 day 865 kW production run




- **Ring Injection (H- stripper foil) is the highest loss region in the machine**
  - **In expectation with predictions**
  - **~ 500 mrem/hr residual activation dose rates**
- **< $10^{-4}$ beam, uncontrolled loss in the remainder of the Ring and transport lines**

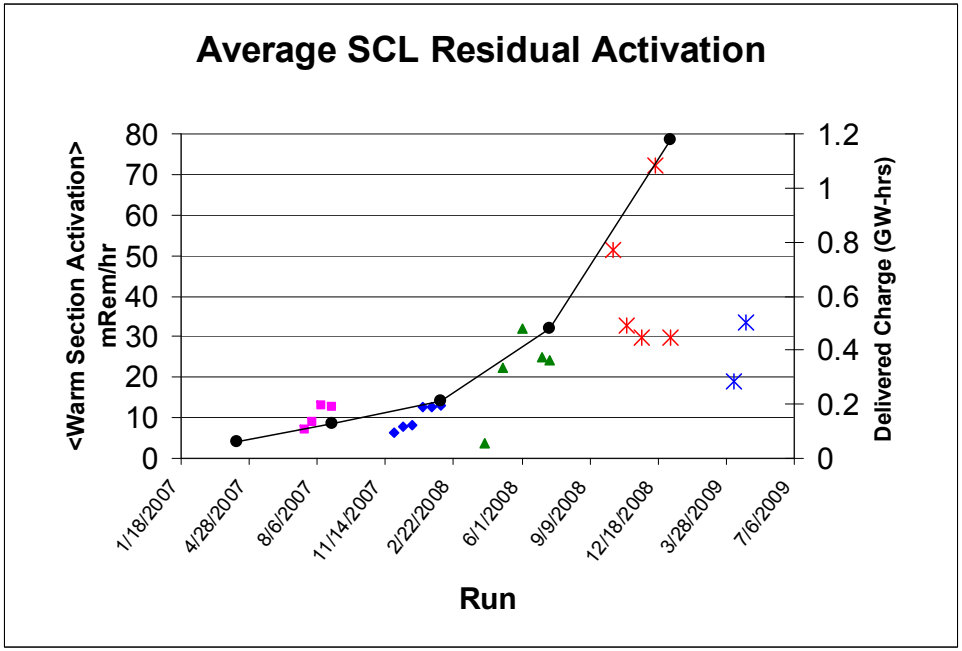
# Mitigation Efforts Help Minimize Ring Activation

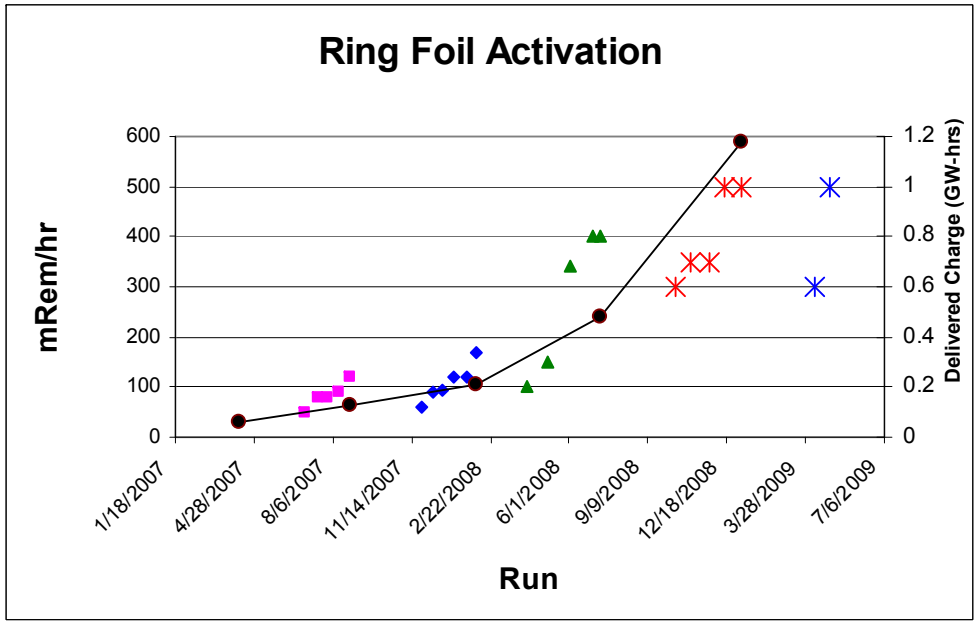



- **Improvements in the Ring injection area and linac chopping systems have mitigated the increase in activation over the power ramp-up**
  - **New Injection dump magnet, stripper foil modifications, added instrumentation**

# Activation Buildup Trends



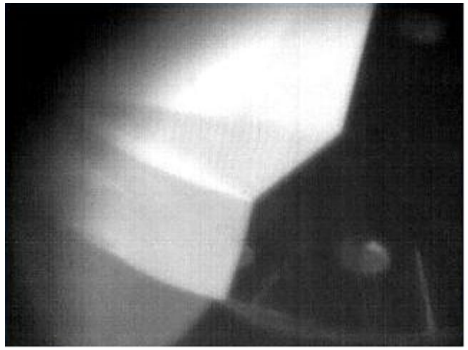

- **The increase in residual activation is less than the increase in delivered charge**

# Ring Experience - High Intensity

***- M. Plum, WE4PBC02, SNS Ring Operational Experience and Power Ramp Up Status***

***- M. Piller, WE5PFP093 High Intensity Beam Performance of the SNS Accumula***

**Thermal Image of e-catcher under stripper foil at Ring Injection**



**Transverse collimation in the HEBT transport line does reduce loss in the Ring Injection dump lines, at high intensities**



***M. Plum, et. al. WE6RFP027 "Performance and Upgrades to the SNS Collimator Systems"***

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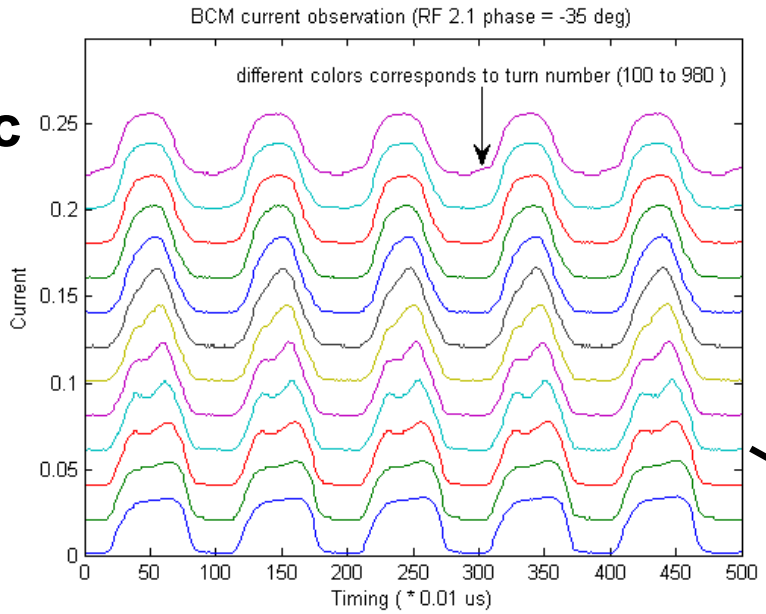
**Use of the 2nd harmonic Ring RF reduces beam loss in the Ring**

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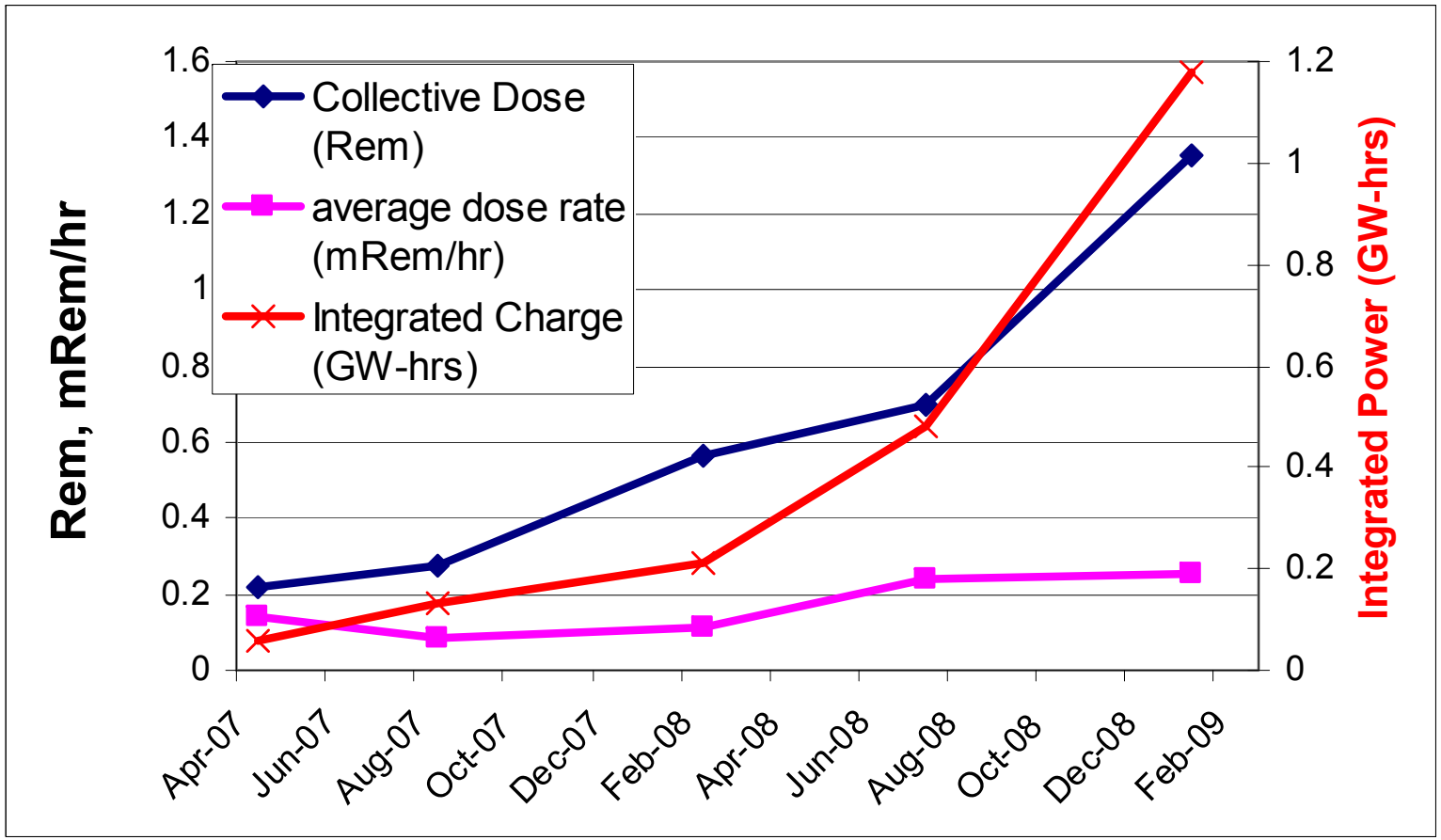
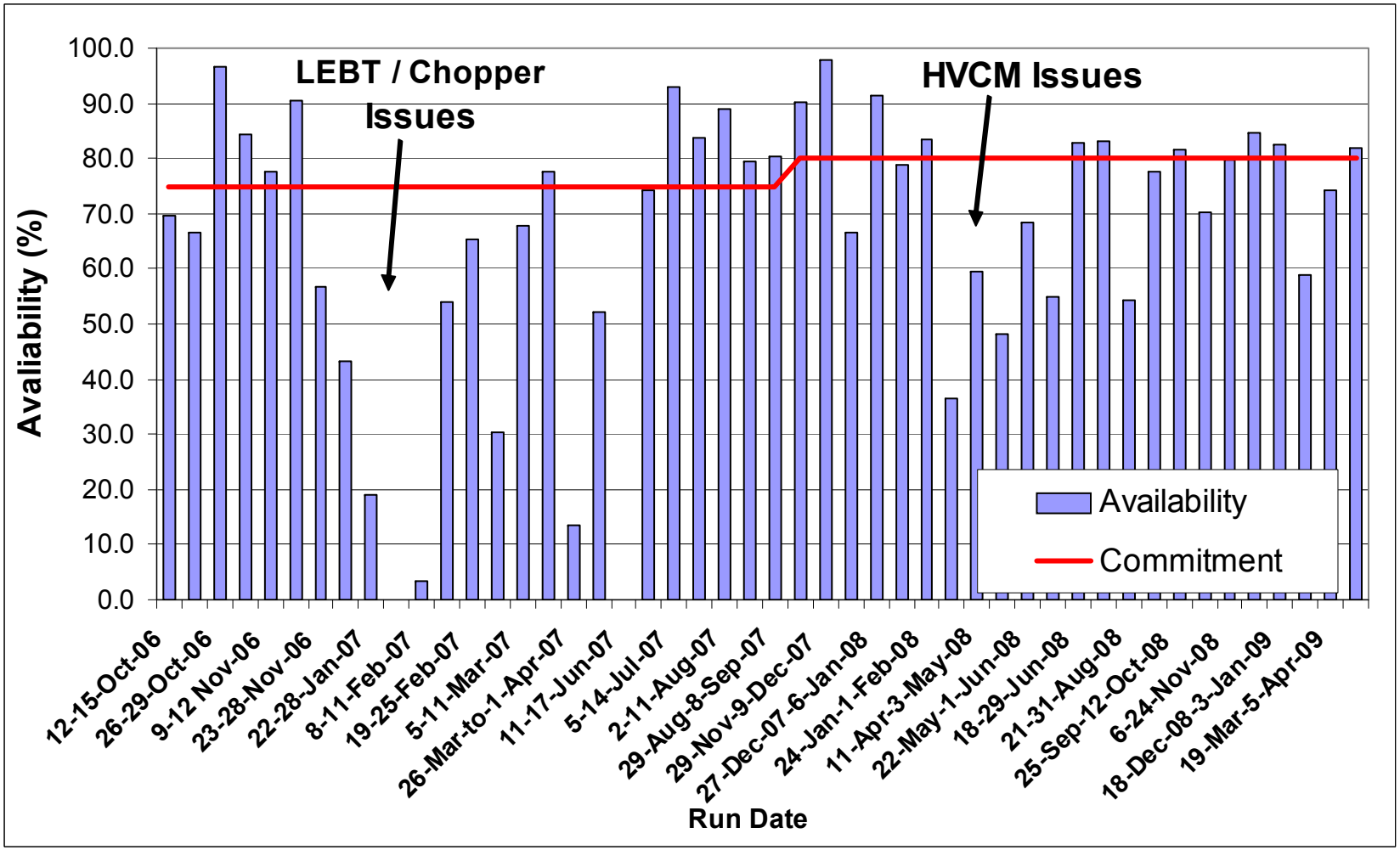
# Worker Dose




- **Collective worker dose is increasing slower than the beam delivery**
  - **Normalized by worker hours, there is a minimal increase over the power ramp-up**
- **Compared to other high power proton facilities SNS collective worker dose is still low**

# Availability

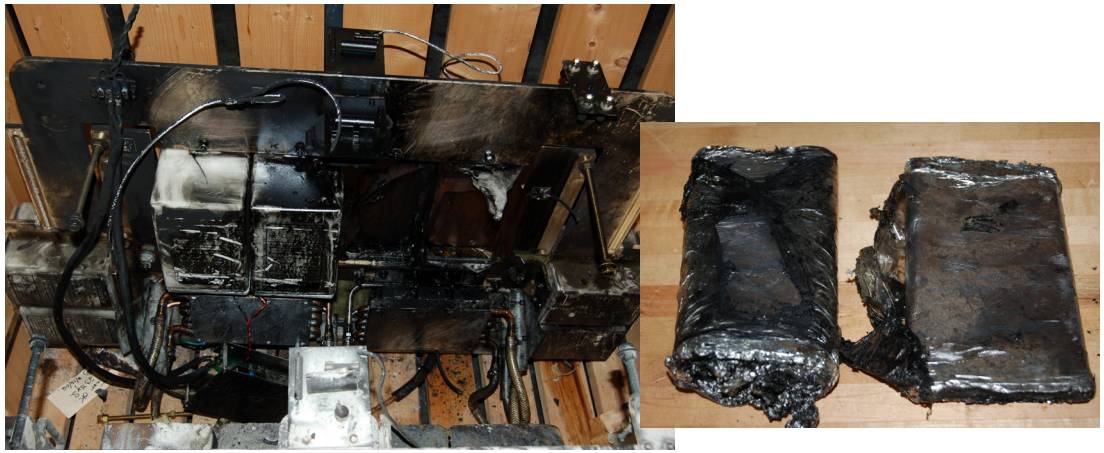



- Achieving the availability goals is at least as difficult as increasing the beam power
- Have run ~ 80% availability over the past 6 months

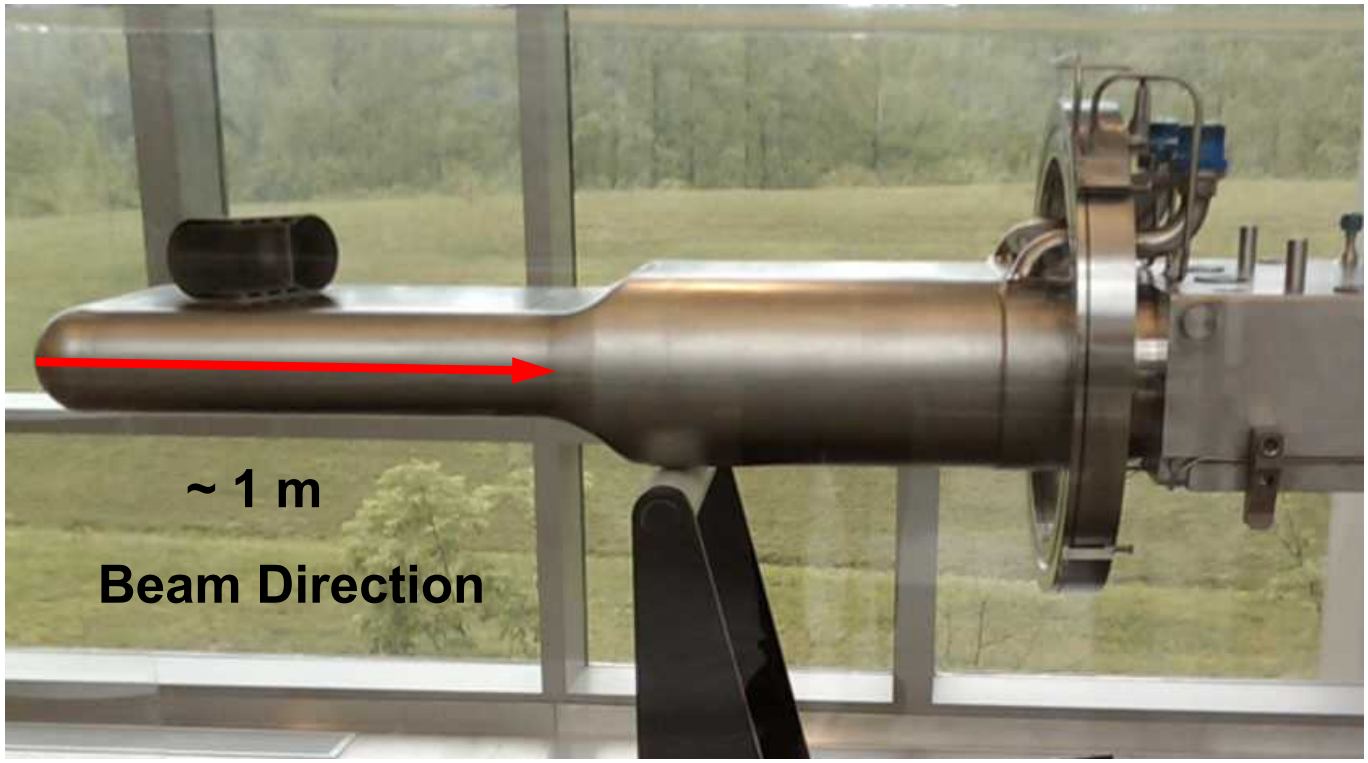
# Equipment Robustness | Reliability

## D. Anderson, MO4GRI02 "Developments in Solid-State Modulator Technology towards High Availability

- High Voltage Convertor Modulator (HVCM) component lifetimes
  - Creates the DC 60 Hz pulse forms using solid state technology
- Component lifetimes
  - New technology, minimal experience base
- Mitigation efforts have reduced the failure rate and damage/failure
  - Aggressive power ramp-up identified issues relatively early



# Mercury Target – Works well




- 1 MW operation corresponds to ~ 17 kJ/pulse
  - Serious concerns of cavitation induced erosion for short pulse (1 μsec) deposition
  - Ongoing cavitation mitigation R&D program
  - Beam power density limits have restricted beam power
- Reaching the "standard" dpa radiation lifetime limit

# Machine Protection

## see A. Zhukov, "FR5REP038 SNS BLM System Evolution: Detectors, Electronics and Software"

- Production beam tune-up involves careful qualification of injection waste beams and beam on target
  - Ring injection waste beam (from un-stripped H-) positions (30-50 kW)
  - Power density and size limits on Target
- Errant beam controls
  - Hardware limits on magnets that could affect the beam size and/or position on the Target
- Beam Loss monitors trip the beam < 10 μsec for single pulse loss

# Machine Protection

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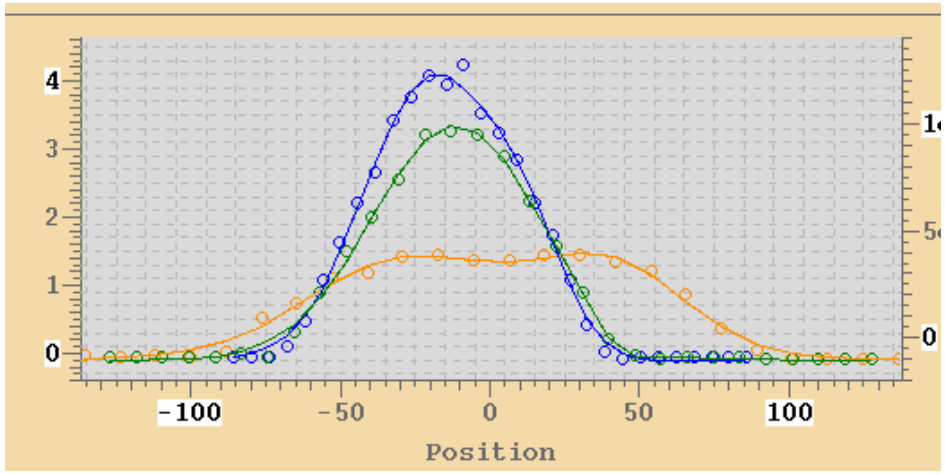
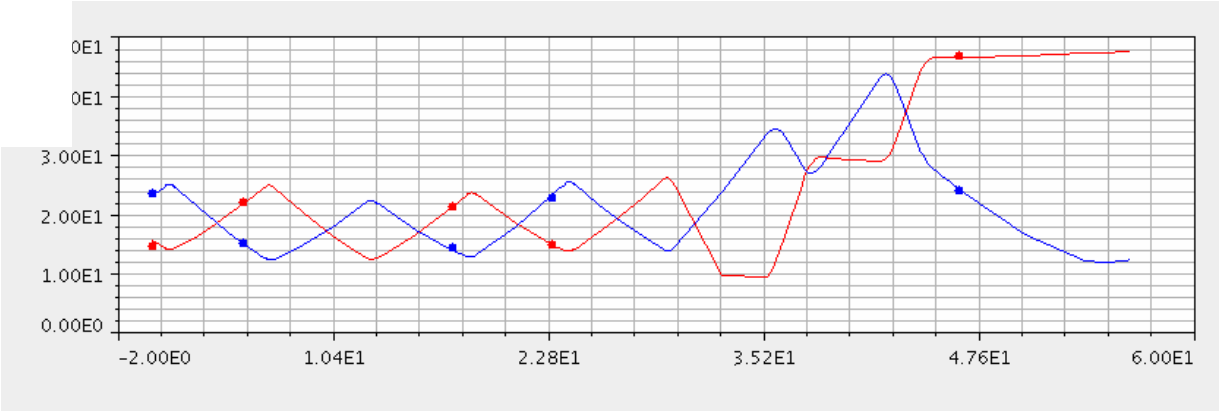
  - **Power density and size limits on Target**

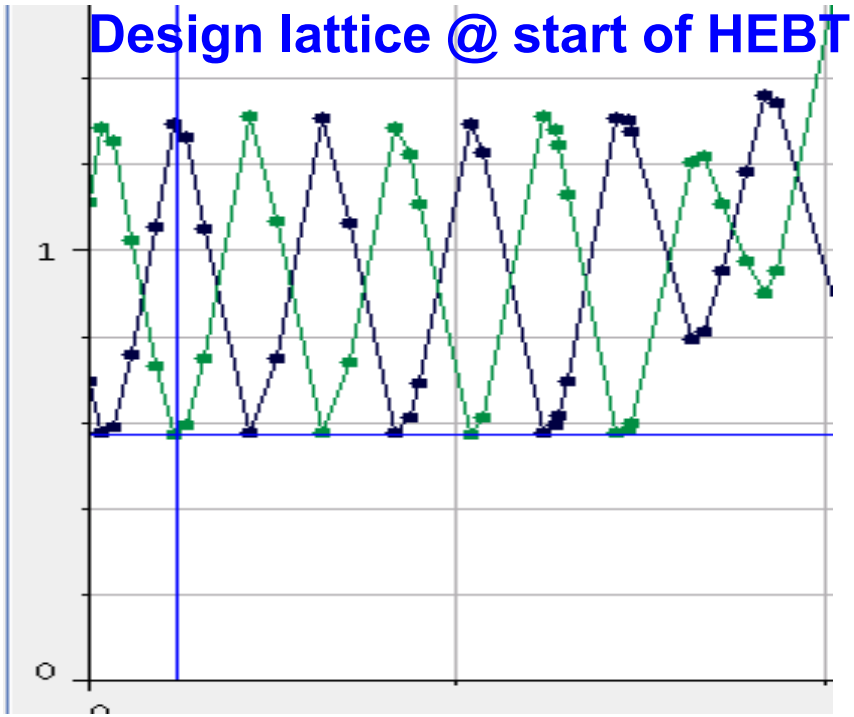
Harp measurement of beam distributions upstream of the Target (always inserted in the beam)

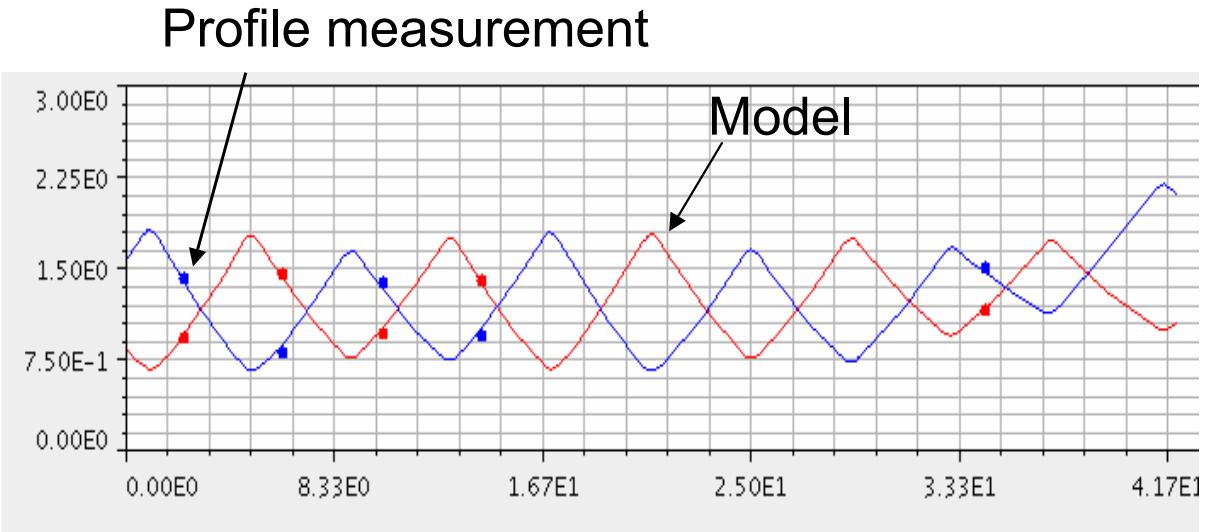


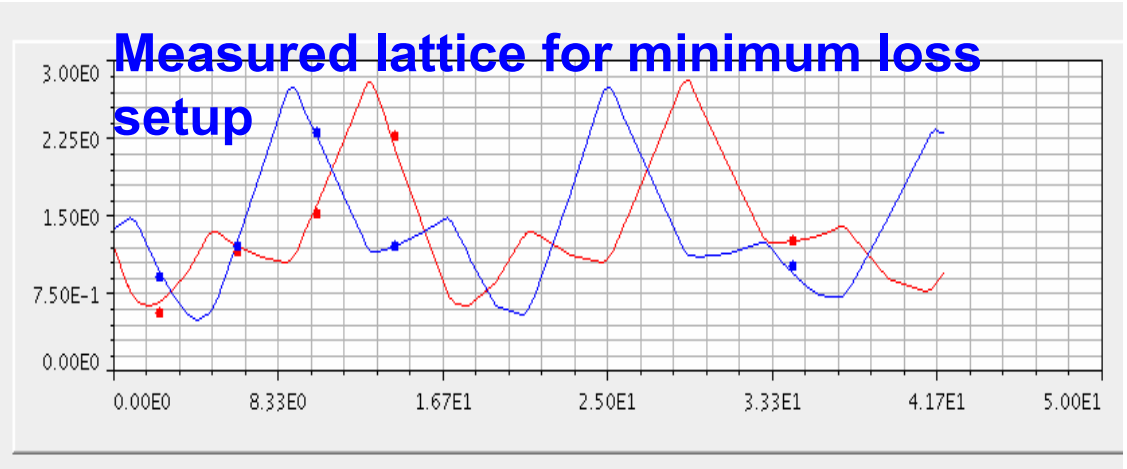

Model Extrapolations of beam size to the Target



# Tuning for Beam Loss



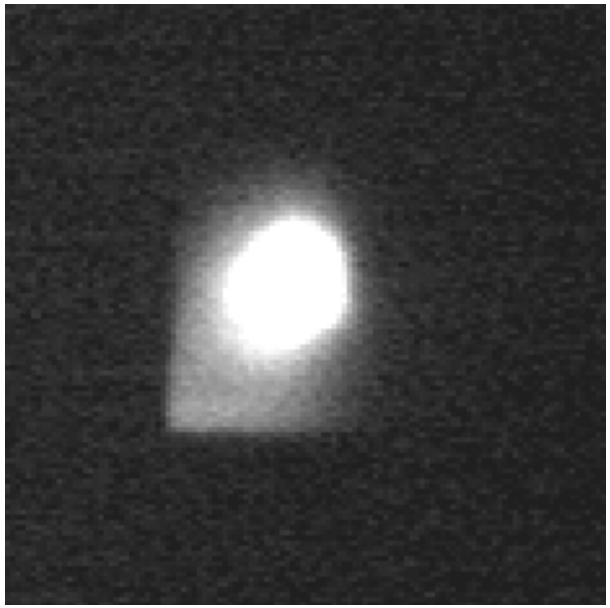




- Don't always setup the machine lattice based on design values
  - Tune to minimize beam loss

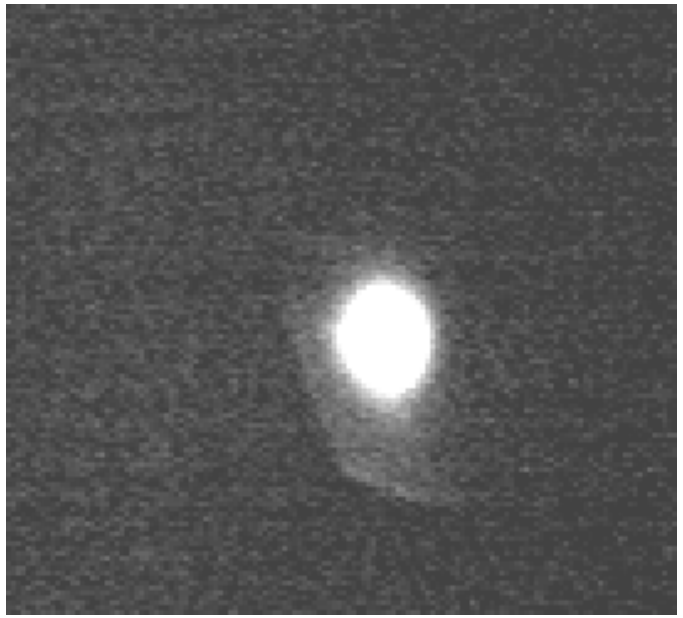
# Concerns I: Foil Survivability

## R. Shaw et. al., "An Electron Beam SNS Foil Test Stand"
## K. Beard et. al., TU6RFP039 "SNS Laser Stripping for H- Injection"
## T. Gorlov et. al., "TU6RFP041 Physical Model of Hydrogen Ion Laser Stripping"

Glowing foil during present operation @ 830 kW – day 1



Glowing foil during present operation @ 830 kW – day 9

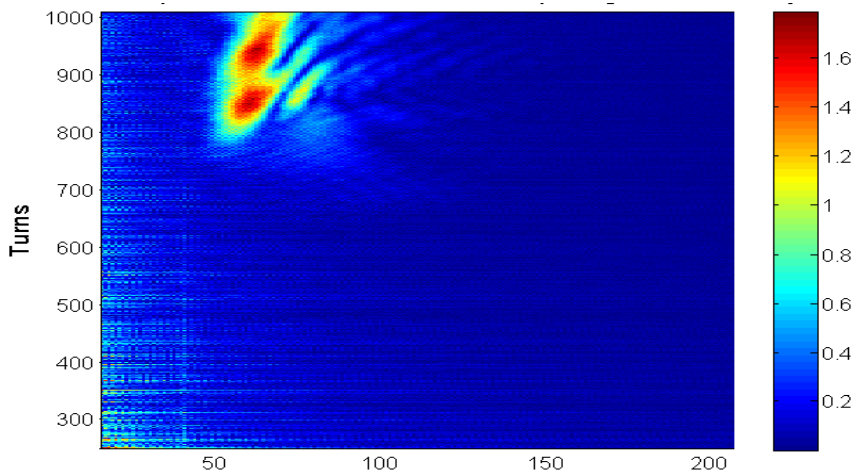


- **The foil survivability could prove to be a show stopper**
- **R&D efforts in foil development + laser stripping**

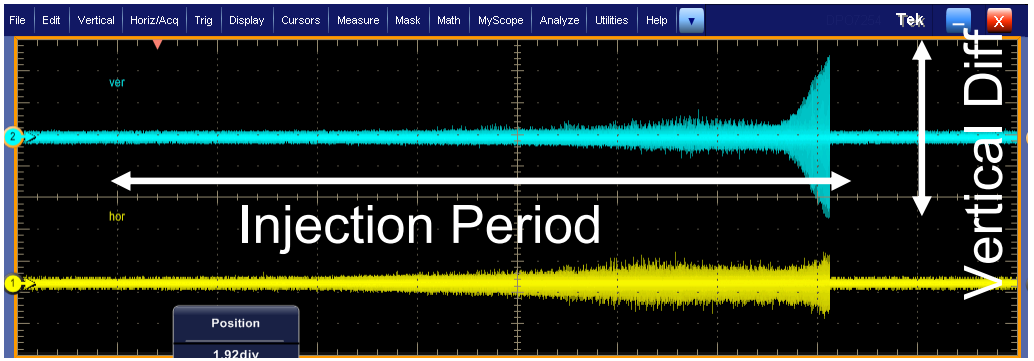
# Concerns II: Collective Effects in the Ring at High Intensity

## see TH6REP085 Z. Xie, C. Deibele, "Design and Analysis of a Mixed-Signal Feedback Damper System for Controlling Electron-Proton Instabilities"

Indications of an e-P instability observed during beam studies




Non-linear growth of beam position oscillations during macro-pulse (neutron production)




- **Space charge induced beam loss and beam instability concerns increase with intensity**
- **No obvious issue yet, but there is a large extrapolation from 15 uC of stored beam today to 2-3 times higher for ultimate performance improvements**

# Future SNS Project Plans

- Power Upgrade Project
  - Energy upgrade (1 to 1.3 GeV) + associated source current upgrades (power increase from 1.44 to 2-3 MW)
  - CD-1 approved
- Second Target Station
  - Add second target station (possibly long pulse)
  - CD-0 approved

# Summary

- SNS is approaching 1 MW beam operations (865 kW to date)
  - Beam loss is not limiting the power ramp up
  - Gained an appreciation of difficulties of understanding the behavior of the beam extremes (< $10^{-4}$)
  - Increasing the availability is a primary focus of attention