Fully Automated Tuning and Recover of a High Power SCL

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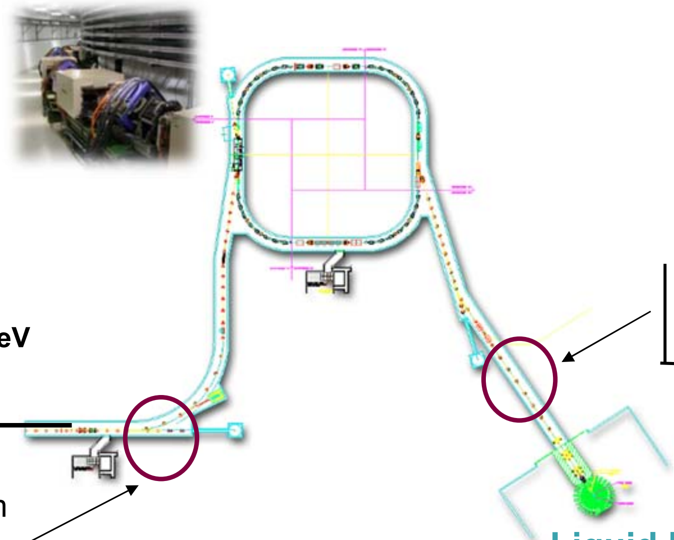
Outline

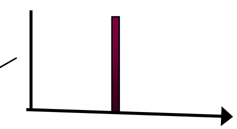
- SNS Accelerator Complex
- SCL Parameters
- SCL Tuning Process and Automation
- Beam Power Restoration after SCL Cavity Failure
- Conclusions

Spallation Neutron Source (SNS) Accelerator

The accumulator ring compresses the pulse to ~700 nsec



~700 nsec



186 MeV

~1000 MeV

Warm Linac | Superconducting LINAC

The linac accelerates 26 mA, ~1 msec long H^- beam

Liquid Hg Target

@ 60 Hz, this represents a 1.4 MW proton beam power

SNS Superconducting Linac (SCL)

- 23 Cryomodules, 81 cavities (July 2022)
  - Two types of cavities – medium and high beta
- 2 K operation temperature
- Individual klystrons for each cavity
- 805 MHz RF frequency
- Energy from 185.6 to 1 GeV
- 60 Hz pulsed RF, 1 ms pulse length, chopped ~1000 mini-pulses
- Diagnostics:
  - 34 Beam Position Monitors (also measure bunch arrival time -phase)
  - 9 Laser Wires Stations to measure transverse profiles

SNS Superconducting Cavities

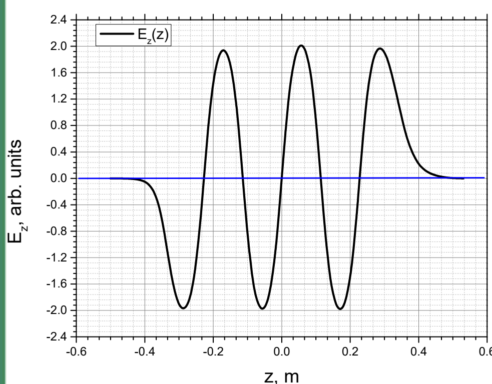
33 cavities, β_g=0.61

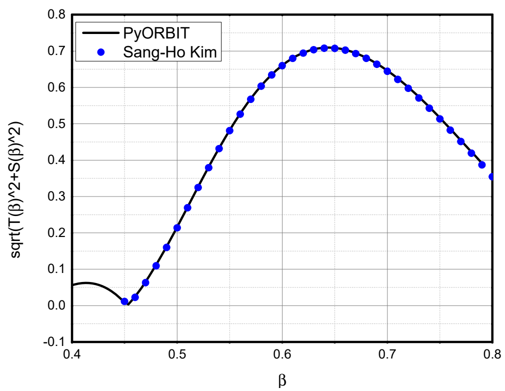
48 cavities, β_g=0.81

Manufactured at Jefferson's Lab
Design peak surface gradient 35 MV/m

Cavity β	0.61	0.81
E_{acc}, MV/m	10.1	12.5->15.9
E_{peak}/E_{acc}	2.7	2.19
R/Q[Ω]	279	483
RF Power, kW	550	550

TTF for medium-beta SCL cavity





THE SNS SUPERCONDUCTING LINAC SYSTEM
C. Rode and the JLab SNS Team
IPAC2001, Chicago, USA

Transit Time Factor $$T(k) = \frac{1}{V_0}\int_{-\infty}^{+\infty} E_z(z)\cdot\cos(k\cdot z)dz$$

SCL Tuning Process

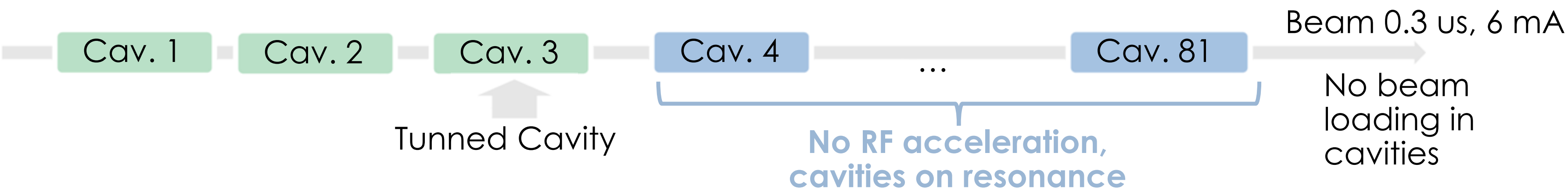
Goal: deliver 1 GeV beam with low beam loss
How: setup SCL cavities phases, quadrupoles gradients and trajectory

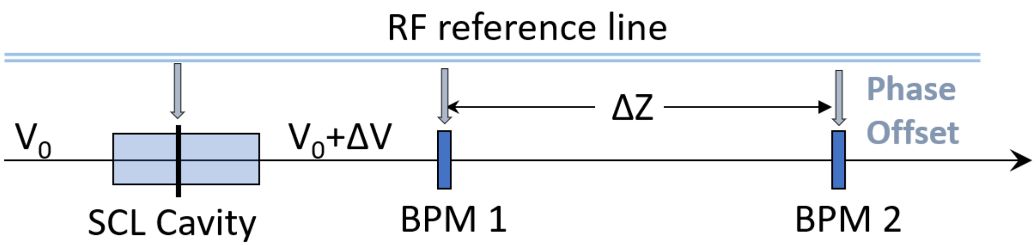
4 Stages of SCL Tuning:

- **Set cavities phases using TOF-like approach. No knowledge of BPMs timing calibration is needed**
- **Measuring beam energy using SNS ring**
- **Perform BPM timing calibration by backward analysis of cavities phase scans data**
- **Perform a model-based analysis and model calibration**

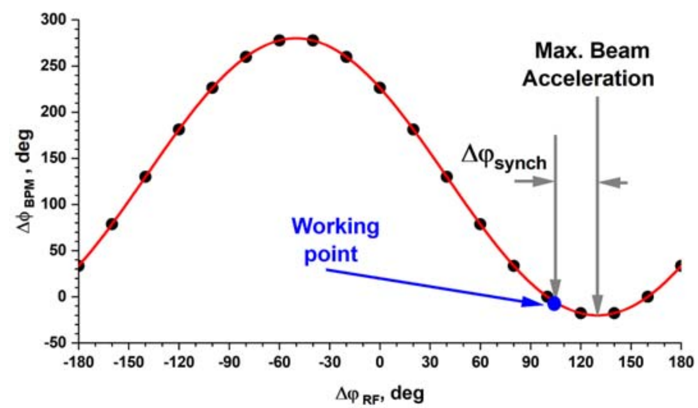
Could be done only once,
If nothing changed

SCL Cavity Phase Scan – Time-Of-Flight Method





Goal: set the phase only

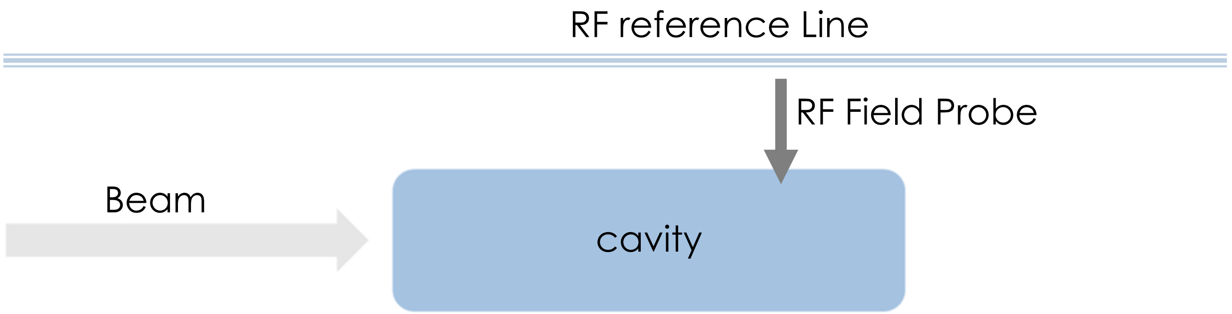


- ❑ Cavities amplitudes are defined during conditioning – higher the better
- ❑ Synchronous phase -18^0 for all cavities if we start from scratch
- ❑ We can add / subtract 360^0 to/from BPMs phase differences to get "sine"-like curves
- ❑ Final Energy at SCL – just an educated guess

Whole SCL (81 cavity) – 30 -45 minutes

Could Other Tuning Method be Used?

Answer: Yes.



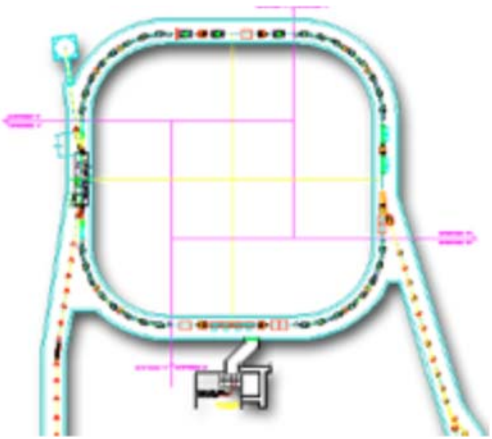
- Beam will excite RF field in cavity
- Arrival time will define phase relative to RF Line
- We can setup cavity phase

Problems:

1. **Beam should be powerful enough to excite measurable response**
2. **No information about cavity RF amplitude**

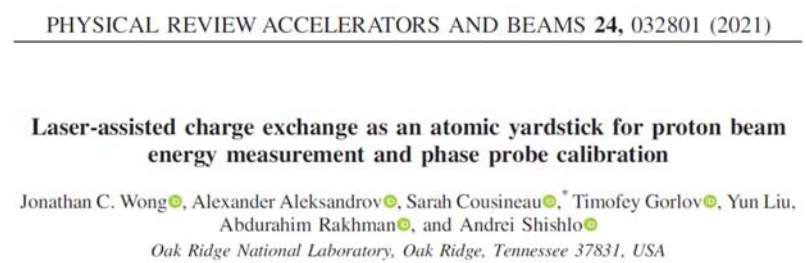
Our SCL group especially did not like 1 because of possible damage to downstream cavities by beam loss.

Measuring SCL Final Energy with SNS Ring



Method 1
- 1 us mini-pulse injected into ring
- Beam circulates for 1000 turns (no acceleration)
- FFT of wall monitors signals gives frequency
- We know ring circumference
- We calculate velocity and energy after SCL

Method 2
- Resonance stripping H^- beam with laser light
- Angle and laser frequency give beam velocity



PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 032801 (2021)

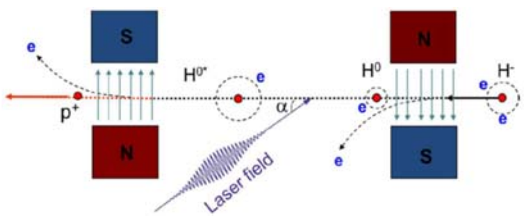
Laser-assisted charge exchange as an atomic yardstick for proton beam energy measurement and phase probe calibration

Jonathan C. Wong, Alexander Aleksandrov, Sarah Cousineau,* Timofey Gorlov, Yun Liu, Abdurahim Rakhman, and Andrei Shishlo

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

Laser interaction

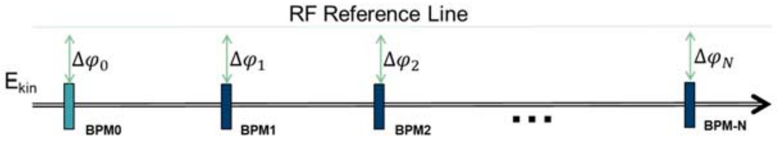
Injected beam



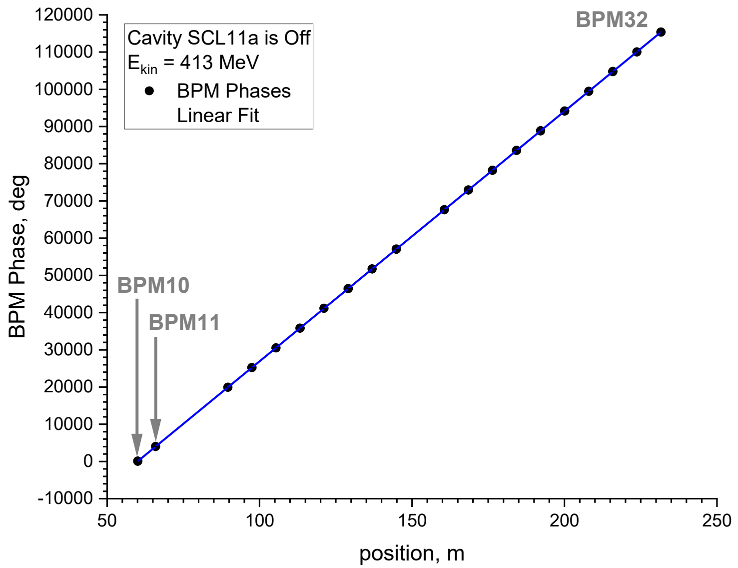
Both method are good! Absolute accuracy 0.7 MeV

BPM Timing Calibration

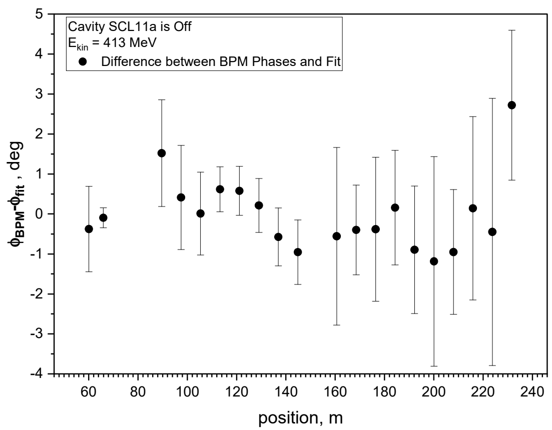
- We have scan data for all cavities – BPMs' phases vs. cavities' phases
- After last SCL cavity beam energy = const
- This energy is known
- We calculate phase offsets (relative to RF reference line) of all BPMs after last cavity
- Then we go upstream to the scan data of next cavity and use calibrated BPMs to calibrate BPM after next cavity
- Repeat previous step until we reach start of SCL
- All BPMs are calibrated!



$$\varphi_i = 360 \cdot f_{BPM} \frac{s_i}{\beta \cdot c} + \Delta\varphi_i$$



Error of beam energy measurements with calibrated BPMs is around 10-30 keV on top of 186-1000 MeV



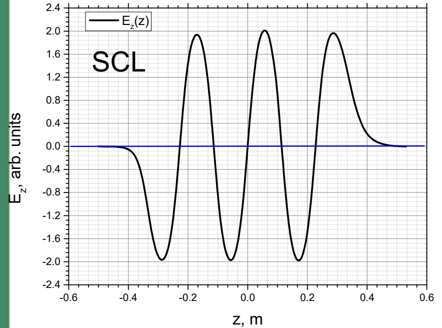
Calibration of SCL Model

After using calibrated BPMs, we have for each cavity:

$$E_{kin}^{(out)} = F_i\left(E_{kin}^{(in)}, \phi_{Cavity}\right), i = 1 \div 81$$

Fitting Procedure for Model Parameters

Fitting results:
- Amplitude of field in cavity
- Phase offset of the 1st RF gap



6 RF gaps cavity

$$\Delta W = q \cdot \int_{-\infty}^{+\infty} E_z\left(z, t = \frac{z}{c \cdot \beta}\right) \cdot dz = qV_0 \cdot (T(k) \cdot \cos(\varphi_0) - S(k) \cdot \sin(\varphi_0))$$

$$E_z(z,t) = E_z(z) \cdot \cos(\omega \cdot t + \varphi_0)$$

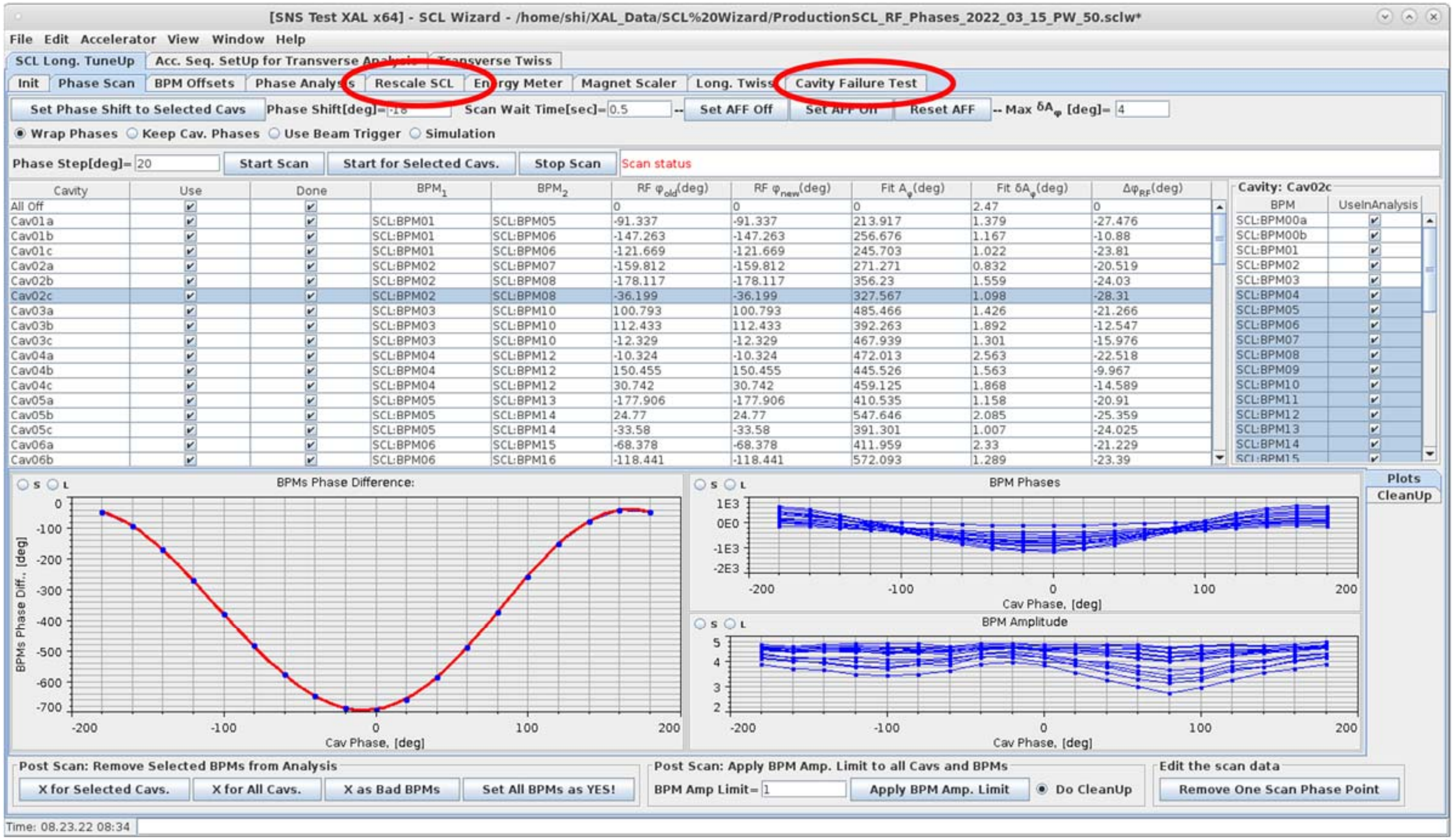
$$T(k) = \frac{1}{V_0} \int_{-\infty}^{+\infty} E_z(z) \cdot \cos(k \cdot z) dz$$

$$S(k) = \frac{1}{V_0} \int_{-\infty}^{+\infty} E_z(z) \cdot \sin(k \cdot z) dz$$

For each gap!

Our calibrated SCL model = physical model + found parameters + SCL input beam

Automation – OpenXAL SCL Tuner Wizard



30-40 min

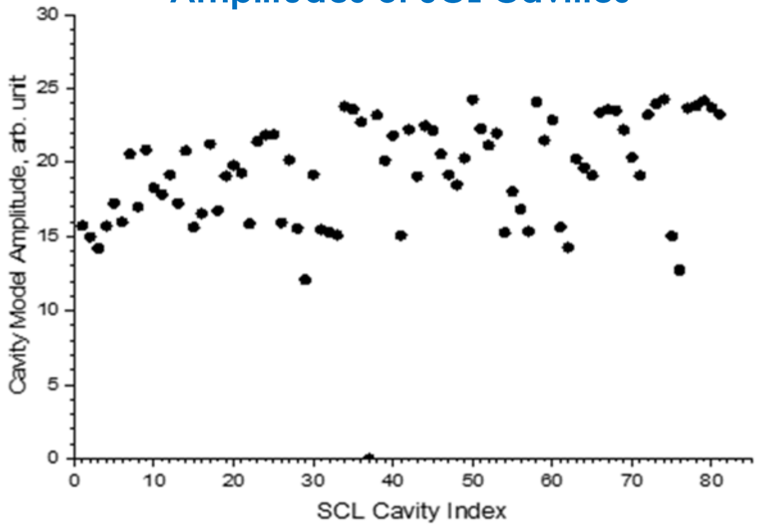
Cavity:
Phases $\pm 1^0$
Ampl. $\pm 1\%$

Conservative estimates

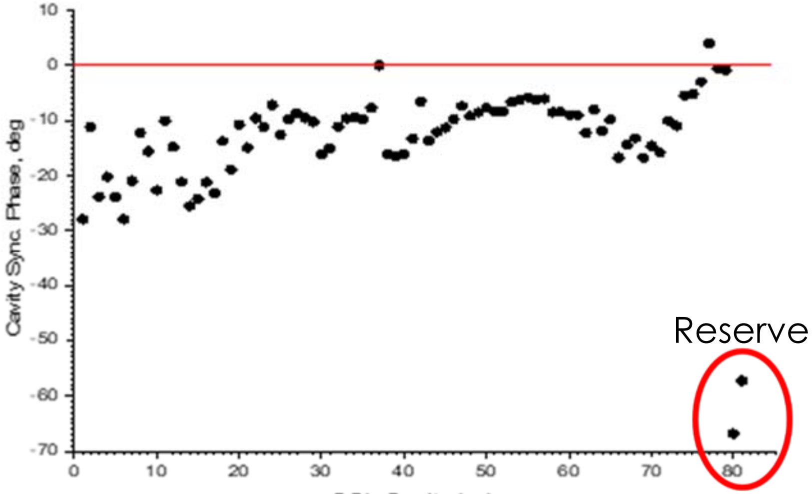
Some Practical Considerations

- Full tuning procedure includes empirical tweaking cavities' phases and amplitudes, quadrupoles' gradients to reduce beam loss in SCL
- Reason for this is Intra-Beam Striping H^- -> H^0 beam loss mechanism. No model for this
- After empirical tuning we perform "non-destructive" scan (no phase changes)
- Phase offsets for cavities and BPMs are good until any repair in RF systems

Amplitudes of SCL Cavities



Synchronous Phases of SCL Cavities



Model-Based SCL Retuning

- SNS SCL retuning is a routine operation.
- The main reason is a change in amplitude of one cavity.
- Sometimes cavity should be switched off completely.
- Problems with cavity: elevated trip rate, quench, tuner problems etc.
- Retuning is performed by operators.
- It takes around 15-30 minutes and includes, retuning using SCL Wizard, phone calls, documenting cavity state, and gradual restoring the full power on the target.

Retuning strategy:

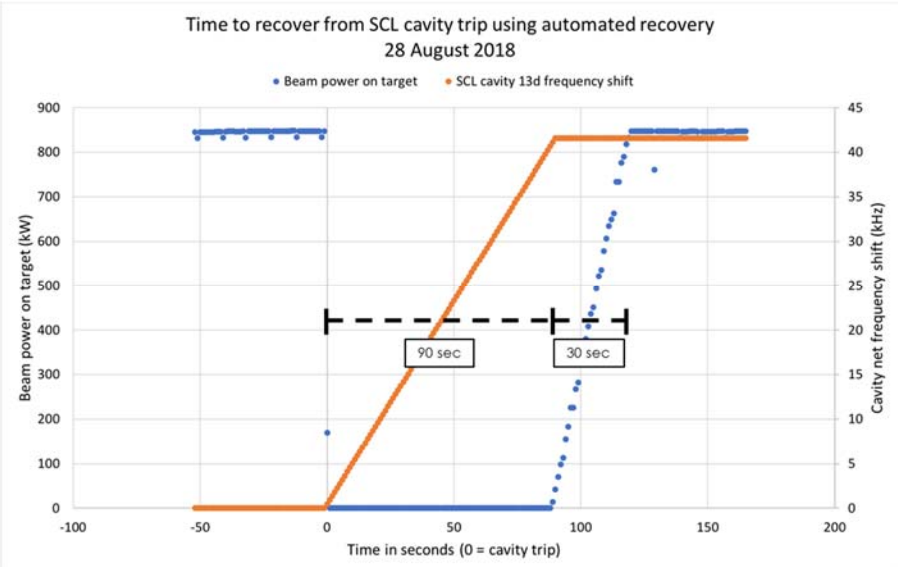
- **If cavity is switched off, it should be detuned to avoid interaction with beam**
- **Keep synchronous phases of all downstream cavities. Control system phases will be changed**
- **Use last cavities to restore the same output beam energy**
- **Adjust quads to reduce beam loss after the power has been restored**

Automated SCL Recovery after Cavity Failure:
We wanted to demonstrate that we can do it without human intervention and to find what are critical parameters.

Automated Recovery of Beam Power

Preparations

1. Cavity to switch off was predefined
2. New cavity phases were precalculated
3. New phases were tested, and Adaptive Feed Forward (AFF) waveforms were recorded for production power
4. Initial production settings were restored

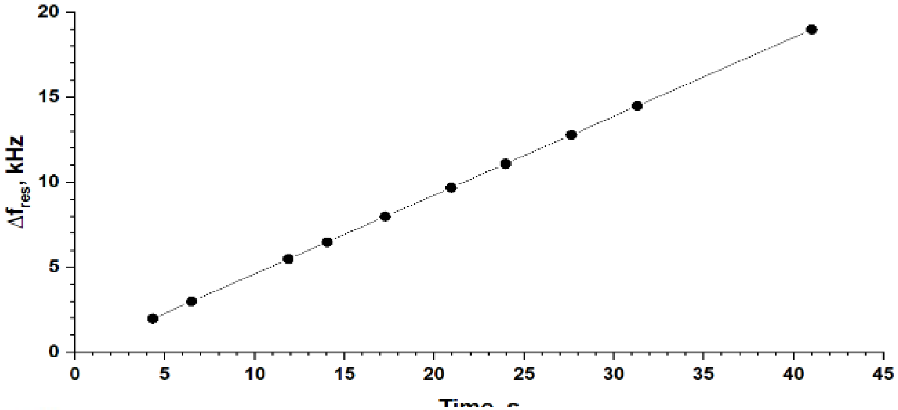


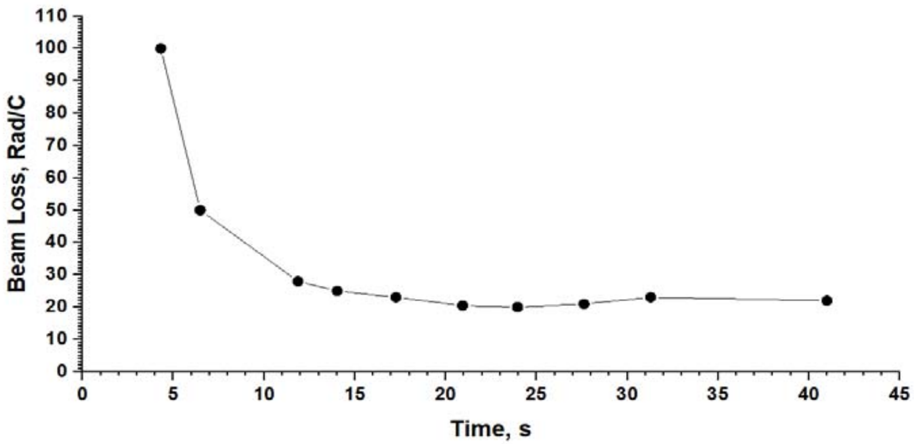
SCL Wizard Actions

1. Application started to monitor chosen cavity
2. After operator "kill" the cavity, MPS stopped beam, and restoration process started
3. New phases and AFF waveforms were uploaded to cavities - < 1sec
4. "Bad" cavity detuning from the resonance frequency process started – 90 seconds
5. After cavity is detuned enough, app started beam power ramp up to 800 kW – 30 sec

- **Most time was spent on cavity freq. detuning**
- **30 seconds power ramp-up administrative parameter at SNS**

Beam Loss vs. Cavity Frequency Detuning





If we consider average 100 Rad/C acceptable, we can get 5 sec restoration time

Average beam loss 20 Rad/C means < 10^{-4} beam loss along 250 m linac

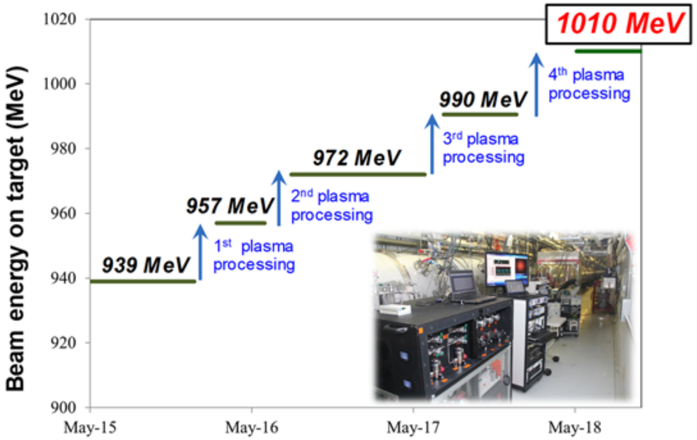
Probably we can tolerate more loss

Conclusions

- Automated Superconducting Linac tuning was implemented
- Tuning time 30-45 minutes for 81 cavity
- Automated retuning was implemented
- Cavity failure automated recovery experiment was performed
- Two weak points were identified
  – Adaptive Feed Forward waveforms should be generated from the cavity model
  – Cavity frequency tuner should be speed up

Thank you for your attention!

Plasma Processing of SCL Cavities



Plasma processing for in-site recovery and improvement of cavity gradient

Courtesy: Marc Doleans