

Fully Automated Tuning and Recover of a High Power SCL

Linac 2022, Liverpool, UK

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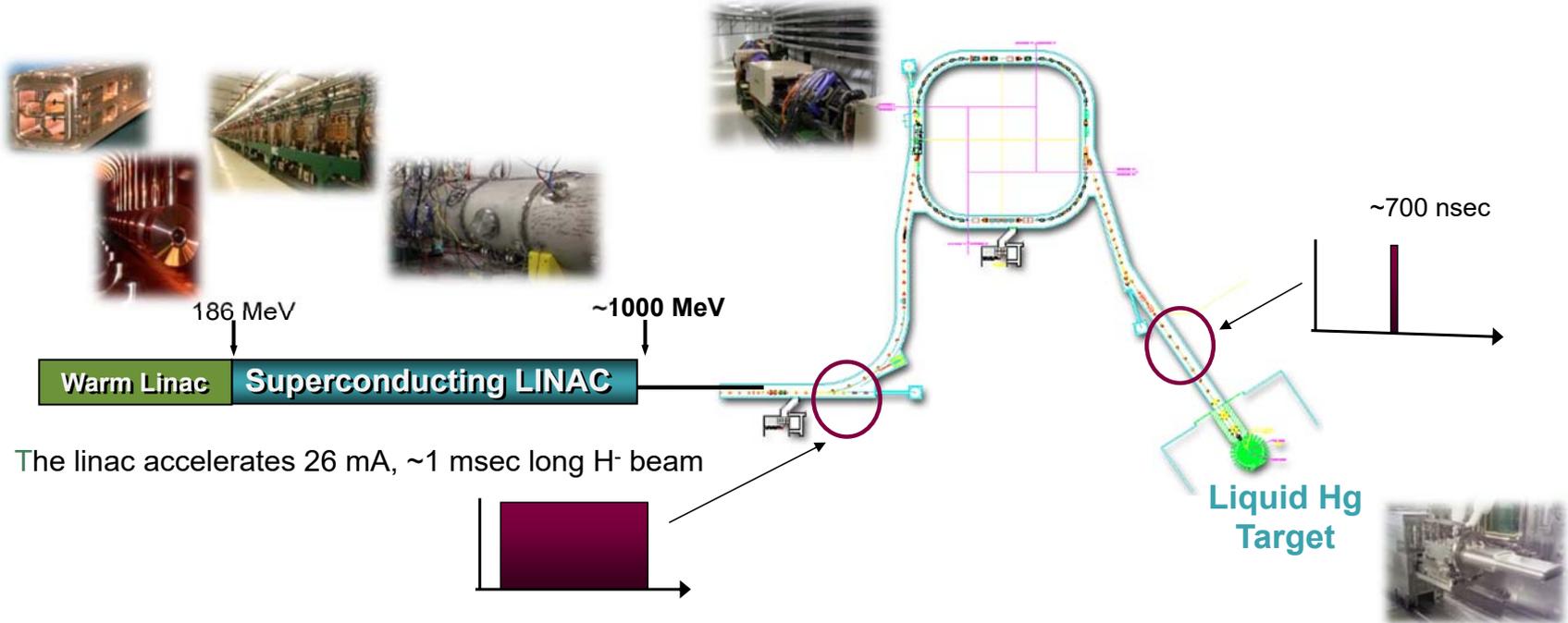
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Outline

- 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



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

@ 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, $\beta_g=0.61$



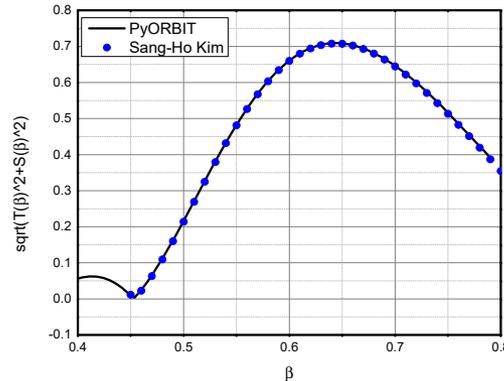
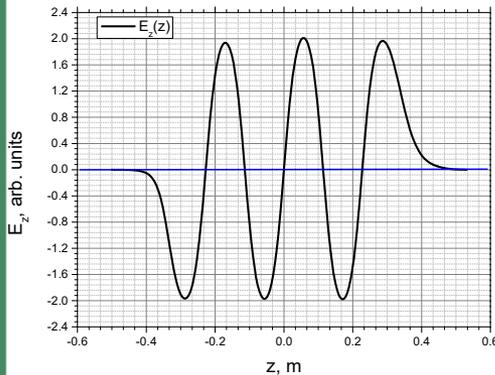
48 cavities, $\beta_g=0.81$



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



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

THE SNS SUPERCONDUCTING LINAC SYSTEM

C. Rode and the JLab SNS Team
IPAC2001, Chicago, USA

SCL Tuning Process

Goal: deliver 1 GeV beam with low beam loss

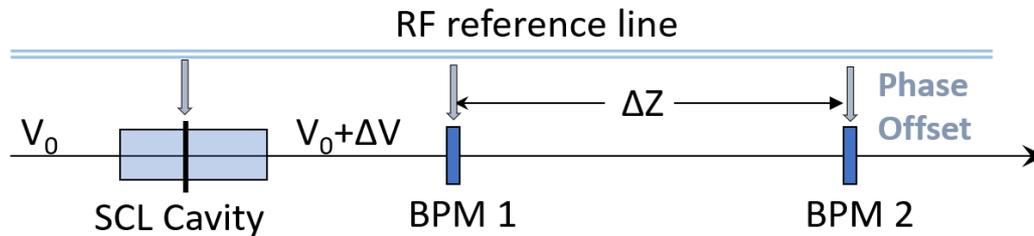
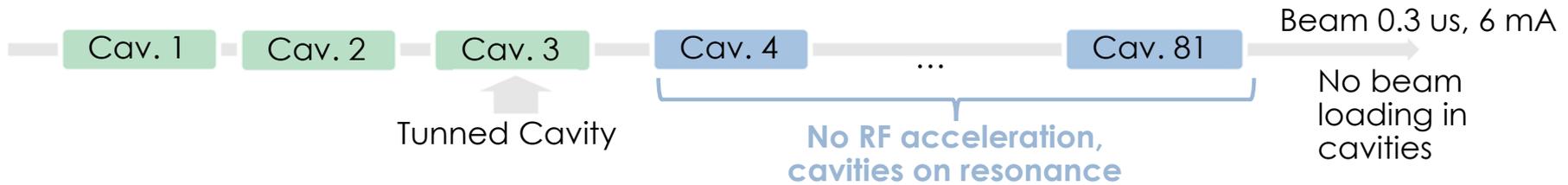
How: setup SCL cavities phases, quadrupoles gradients and trajectory

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

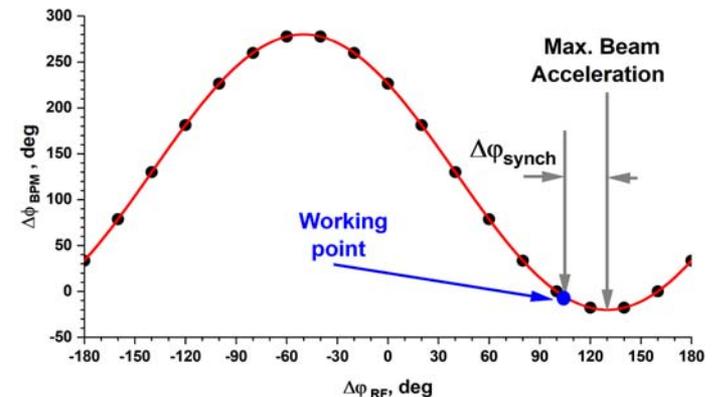
Could be done only once,
if nothing changed

SCL Cavity Phase Scan – Time-Of-Flight Method



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

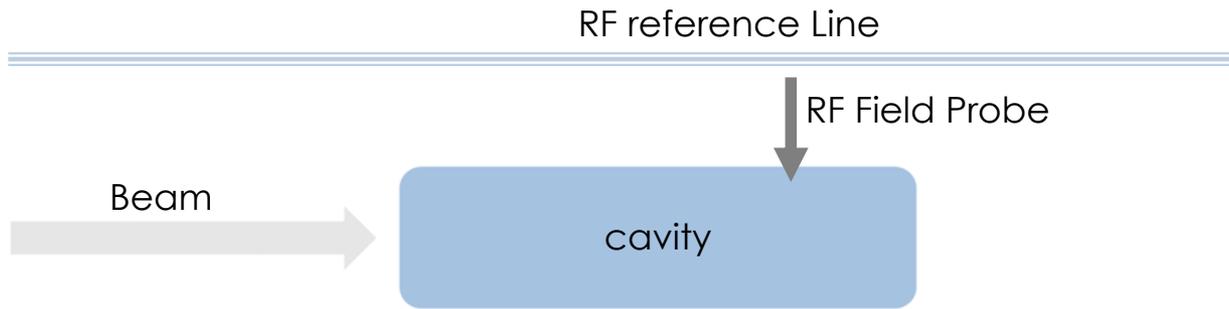
Goal: set the phase only



Whole SCL (81 cavity) – 30 -45 minutes

Could Other Tuning Method be Used?

Answer: Yes.



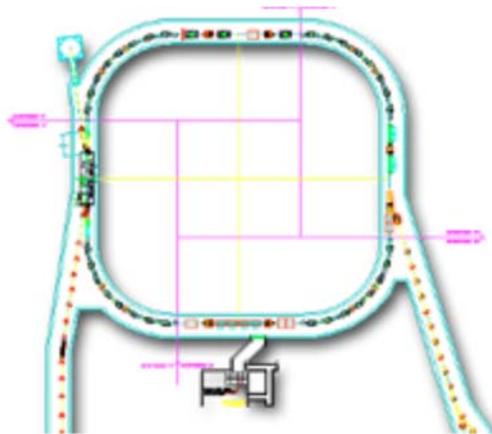
- Beam will excite RF field in cavity
- Arrival time will define phase relative to RF Line
- We can setup cavity phase

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 μs 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

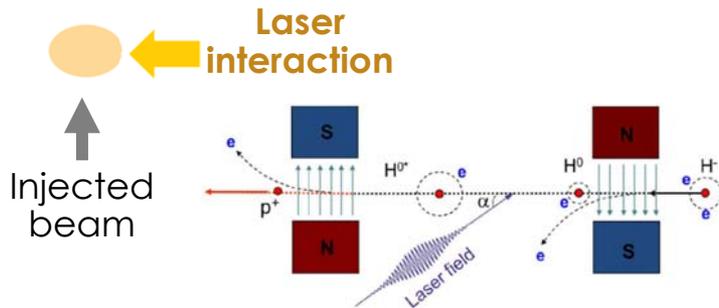
- Resonance stripping H^- beam with laser light
- Angle and laser frequency give beam velocity

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

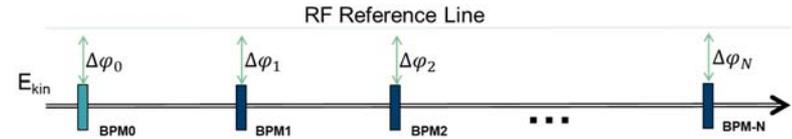
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA



Both methods are good! Absolute accuracy 0.7 MeV

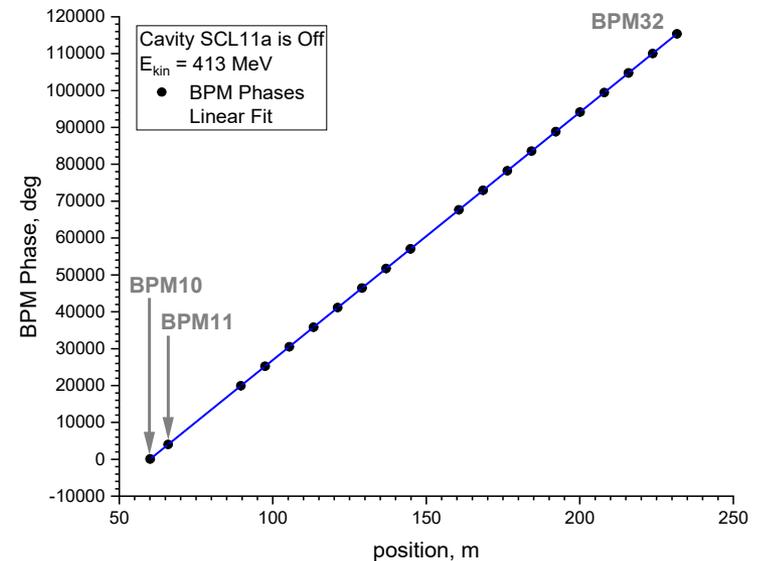
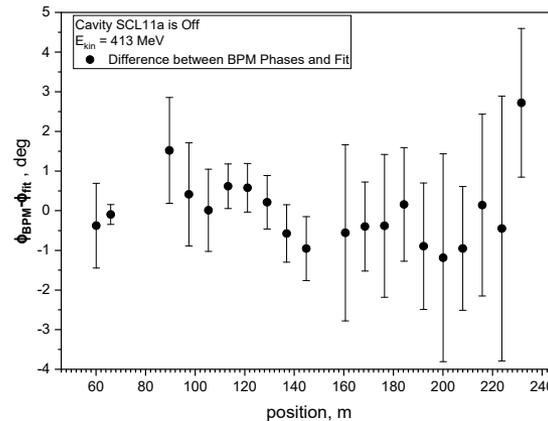
BPM Timing Calibration

- ❑ 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:

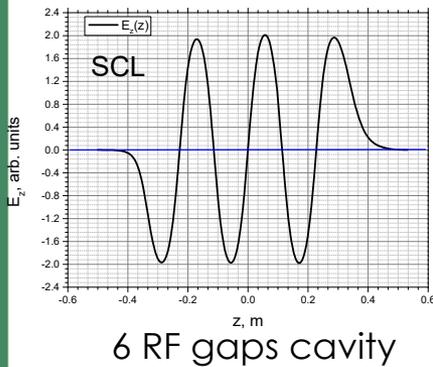
$$E_{kin}^{(out)} = F_i(E_{kin}^{(in)}, \phi_{Cavity}), i = 1 \div 81$$

Fitting Procedure for
Model Parameters



Fitting results:

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



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

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

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

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

For each gap!

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

Automation – OpenXAL SCL Tuner Wizard

[SNS Test XAL x64] - SCL Wizard - /home/shi/XAL_Data/SCL%20Wizard/ProductionSCL_RF_Phases_2022_03_15_PW_50.sclw*

File Edit Accelerator View Window Help

SCL Long. TuneUp Acc. Seq. SetUp for Transverse Analysis Transverse Twiss

Init Phase Scan BPM Offsets Phase Analysis **Rescale SCL** Energy Meter Magnet Scaler Long. Twiss **Cavity Failure Test**

Set Phase Shift to Selected Cavs Phase Shift[deg]=15 Scan Wait Time[sec]=0.5 Set AFF Off Set AFF On Reset AFF -- Max δA_{ψ} [deg]=4

Wrap Phases Keep Cav. Phases Use Beam Trigger Simulation

Phase Step[deg]=20 Start Scan Start for Selected Cavs. Stop Scan Scan status

Cavity	Use	Done	BPM ₁	BPM ₂	RF ψ_{old} (deg)	RF ψ_{new} (deg)	Fit A_{ψ} (deg)	Fit δA_{ψ} (deg)	$\Delta\psi_{RF}$ (deg)
All Off					0	0	0	2.47	0
Cav01a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM01	SCLBPM05	-91.337	-91.337	213.917	1.379	-27.476
Cav01b	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM01	SCLBPM06	-147.263	-147.263	256.676	1.167	-10.88
Cav01c	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM01	SCLBPM06	-121.669	-121.669	245.703	1.022	-23.81
Cav02a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM02	SCLBPM07	-159.812	-159.812	271.271	0.832	-20.519
Cav02b	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM02	SCLBPM08	-178.117	-178.117	356.23	1.559	-24.03
Cav02c	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM02	SCLBPM08	-36.199	-36.199	327.567	1.098	-28.31
Cav03a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM03	SCLBPM10	100.793	100.793	485.466	1.426	-21.266
Cav03b	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM03	SCLBPM10	112.433	112.433	392.263	1.892	-12.547
Cav03c	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM03	SCLBPM10	-12.329	-12.329	467.939	1.301	-15.976
Cav04a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM04	SCLBPM12	-10.324	-10.324	472.013	2.563	-22.518
Cav04b	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM04	SCLBPM12	150.455	150.455	445.526	1.563	-9.967
Cav04c	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM04	SCLBPM12	30.742	30.742	459.125	1.868	-14.589
Cav05a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM05	SCLBPM13	-177.906	-177.906	410.535	1.158	-20.91
Cav05b	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM05	SCLBPM14	24.77	24.77	547.646	2.085	-25.359
Cav05c	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM05	SCLBPM14	-33.58	-33.58	391.301	1.007	-24.025
Cav06a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM06	SCLBPM15	-68.378	-68.378	411.959	2.33	-21.229
Cav06b	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	SCLBPM06	SCLBPM16	-118.441	-118.441	572.093	1.289	-23.39

Cavity: Cav02c

BPM	UseInAnalysis
SCLBPM00a	<input checked="" type="checkbox"/>
SCLBPM00b	<input checked="" type="checkbox"/>
SCLBPM01	<input checked="" type="checkbox"/>
SCLBPM02	<input checked="" type="checkbox"/>
SCLBPM03	<input checked="" type="checkbox"/>
SCLBPM04	<input checked="" type="checkbox"/>
SCLBPM05	<input checked="" type="checkbox"/>
SCLBPM06	<input checked="" type="checkbox"/>
SCLBPM07	<input checked="" type="checkbox"/>
SCLBPM08	<input checked="" type="checkbox"/>
SCLBPM09	<input checked="" type="checkbox"/>
SCLBPM10	<input checked="" type="checkbox"/>
SCLBPM11	<input checked="" type="checkbox"/>
SCLBPM12	<input checked="" type="checkbox"/>
SCLBPM13	<input checked="" type="checkbox"/>
SCLBPM14	<input checked="" type="checkbox"/>
SCLBPM15	<input checked="" type="checkbox"/>

S L

BPMs Phase Difference:

BPM Phases

BPM Amplitude

Plots CleanUp

Post Scan: Remove Selected BPMs from Analysis

X for Selected Cavs. X for All Cavs. X as Bad BPMs Set All BPMs as YES!

Post Scan: Apply BPM Amp. Limit to all Cavs and BPMs

BPM Amp Limit=1 Apply BPM Amp. Limit Do CleanUp

Edit the scan data

Remove One Scan Phase Point

Time: 08.23.22 08:34

30-40 min

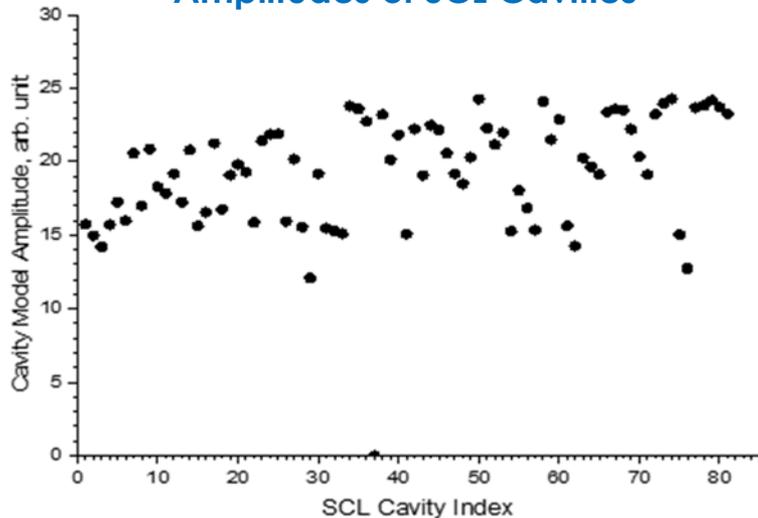
Cavity:
Phases $\pm 1^\circ$
Ampl. $\pm 1\%$

Conservative
estimates

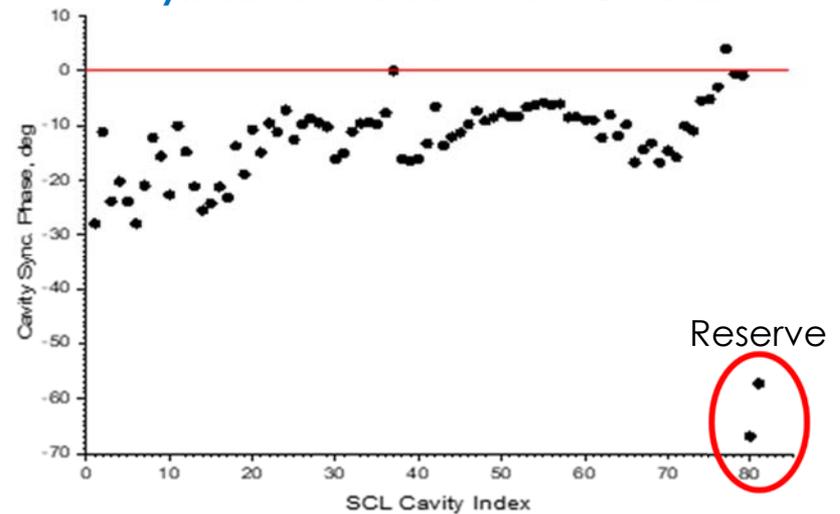
Some Practical Considerations

- ❑ Full tuning procedure includes empirical tweaking cavities' phases and amplitudes, quadrupoles' gradients to reduce beam loss in SCL
- ❑ Reason for this is Intra-Beam Stripping $H^- \rightarrow H^0$ 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.

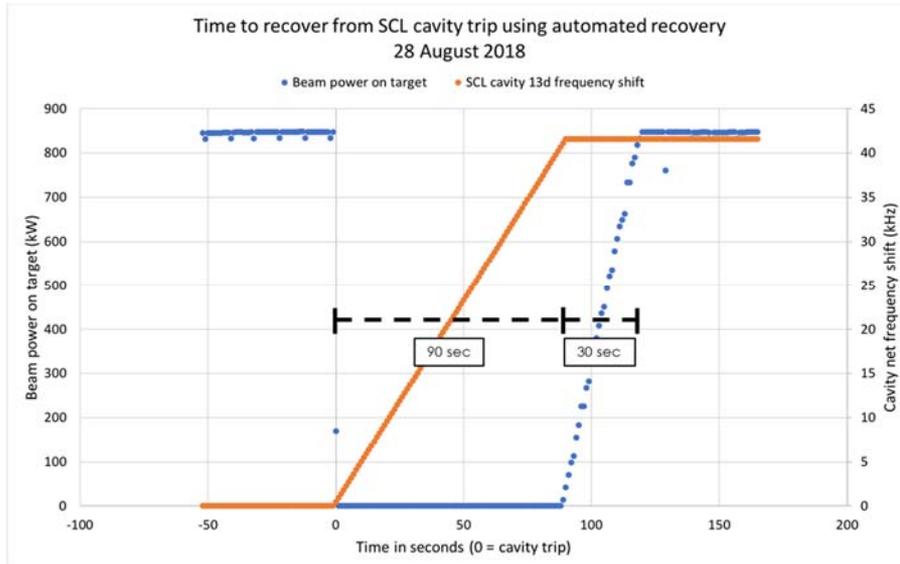
Automated Recovery of Beam Power

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

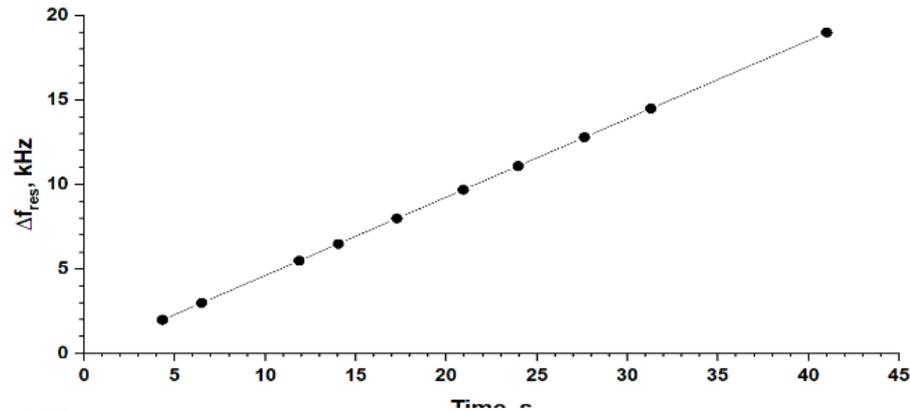
1. Application started to monitor chosen cavity
2. After operator “kill” the cavity, MPS stopped beam, and restoration process started
3. New phases and AFF waveforms were uploaded to cavities - < 1sec
4. “Bad” cavity detuning from the resonance frequency process started – 90 seconds
5. After cavity 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

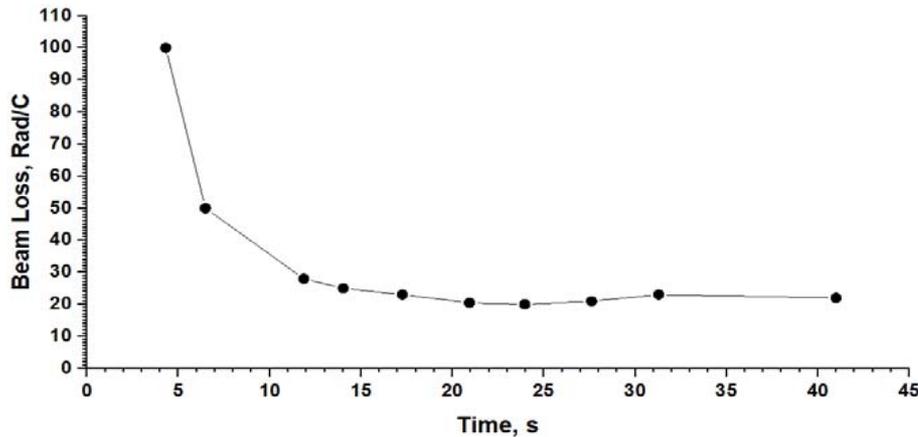
Beam Loss vs. Cavity Frequency Detuning



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

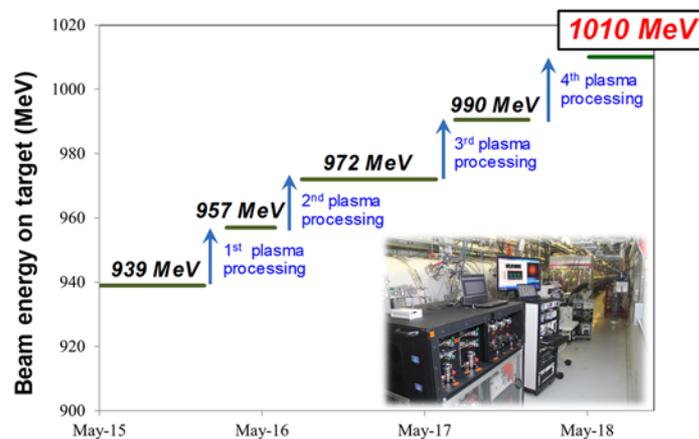


Conclusions

- 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