SNS Linac Beam Dynamics: What We Understand, and What We Don't

Andrei Shishlo

On Behalf of Beam Science and Technology Section (BeST)

SNS, Oak Ridge National Lab, TN USA

HB2023, CERN Geneva, Switzerland

9-13 October, 2023,

Outline

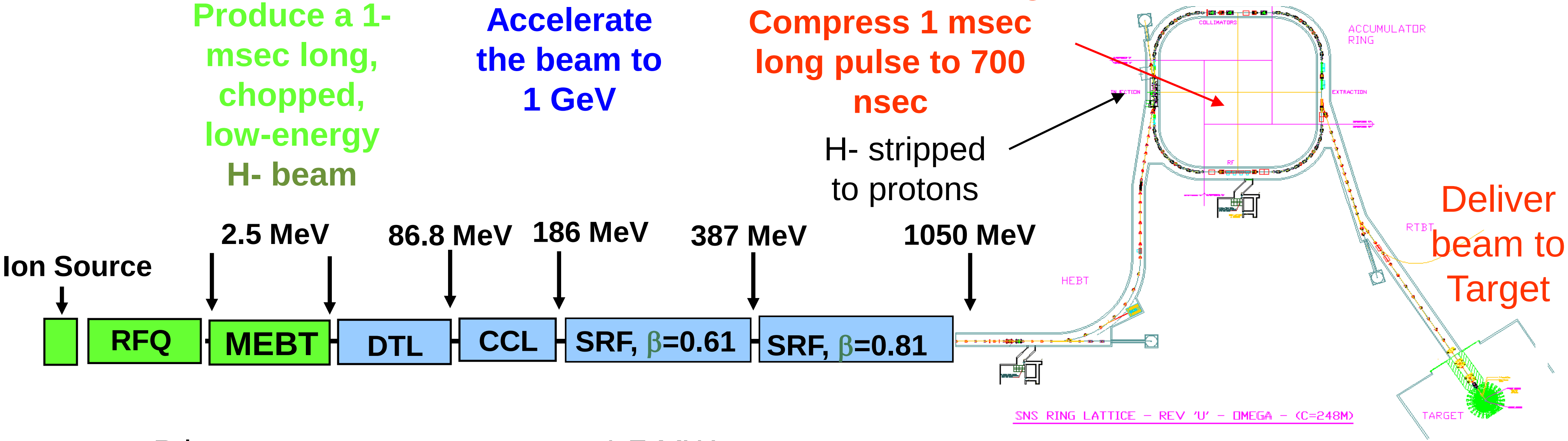
- SNS Accelerator Complex and SNS Linac
- Results Comparison: HB2010 vs. HB2023
- Transverse and Longitudinal Center of Mass Motion
- Transverse and Longitudinal Sizes
- Operational Parameters vs. Design
- SCL Beam Loss and RF Phase Accuracy
- Conclusions

SNS Accelerator Complex

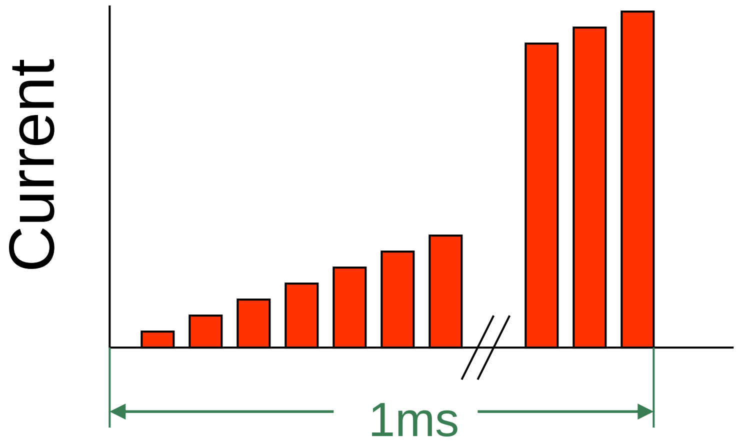
Front-End: Produce a 1-msec long, chopped, low-energy H- beam

LINAC: Accelerate the beam to 1 GeV

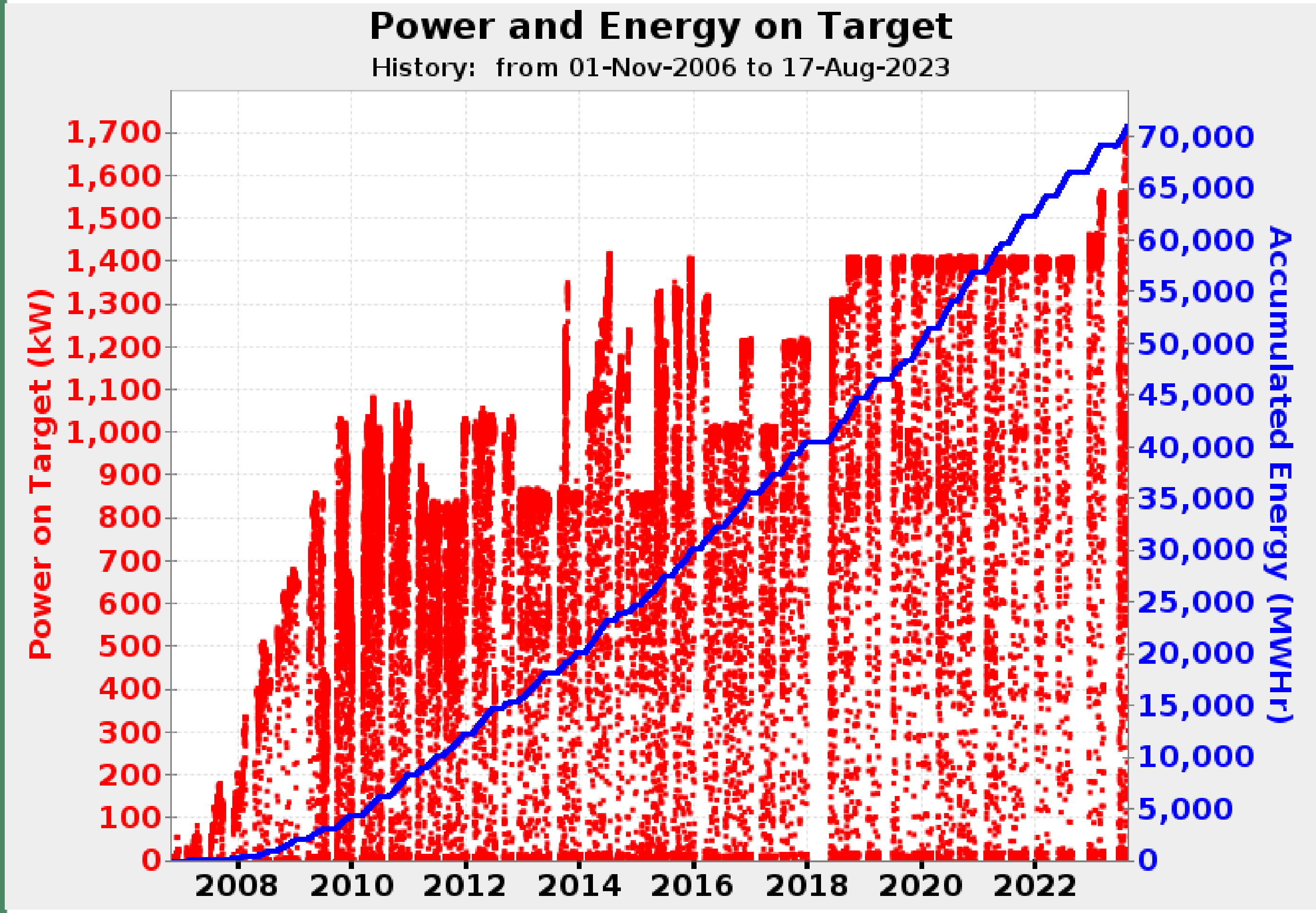
Accumulator Ring: Compress 1 msec long pulse to 700 nsec



P beam on target :	1.7 MW
I beam average:	1.62 mA
Maximum beam energy:	1.05 GeV
Linac duty factor:	6%
Rep. rate:	60Hz
Linac pulse width:	1ms



SNS Accelerator Performance History



- More than 15 years in operation
- High power operation (> 1 MW) for 13 years
- Availability ~90% (sometimes above, sometimes below)
- Linac activation 45 mR/h max after 1.7 MW last run

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HB2010, Morschach, Switzerland – A. Aleksandrov

Proceedings of HB2010, Morschach, Switzerland WEO2D01

CHALLENGES OF RECONCILING THEORETICAL AND MEASURED BEAM PARAMETERS AT THE SNS ACCELERATOR FACILITY

A. Aleksandrov, Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

NA – Not applicable
NSG – Not so good
G – Good
VG – Very Good

Improved

Worse

Table 1 Beam Modeling Accuracy in the SNS Linac

Section	Transverse				Longitudinal				Beam Loss, Transmission	
	Centroid		RMS Size		Centroid		RMS Size			
Year ->	2010	2023	2010	2023	2010	2023	2010	2023	2010	2023
RFQ	NA	=	NA	=	NA	=	NA	=	NSG	G
MEBT	G	=	G	NSG	NSG	=	G	=	NA	NSG
DTL	G	VG	NSG	=	VG	=	NA	=	NA	NSG
CCL	VG	=	NSG	=	VG	=	NSG	=	NA	NSG
SCL	NSG	VG	NSG	=	VG	=	NA	G	NSG	G

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Simulation Codes ever Used for SNS Linac

Code	Type	Used for				
		Orb. Correction	RF Phase & Amplitude	Transverse Sizes * WS	Long. Sizes & Twiss	Beam Loss Transmision
PARMILA	PIC			*	*	**DTL1**
OpenXAL OM	Env.	*	*	*	*	
Impact3D	PIC		*	*		*
Track3D	PIC			*		
PyORBIT	PIC					**DTL1**

- PARMILA (PIC), Trace3D (Envelope) – design codes for SNS linac
- OpenXAL Online Model (Envelope) – code started at SNS
- PyORBIT (PIC) – linac part, homegrown

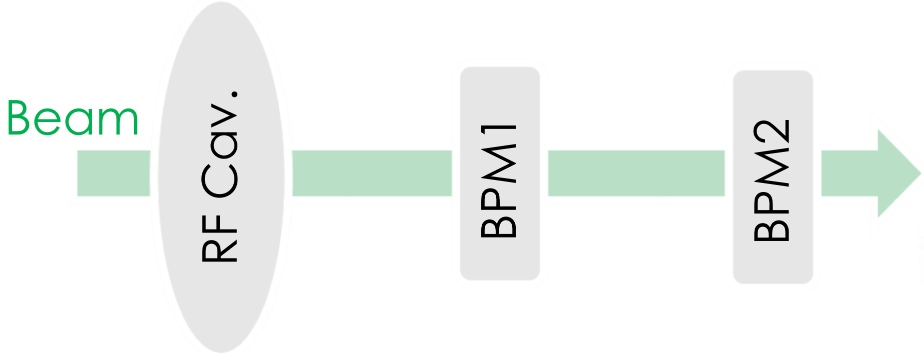
Most progress was achieved with OpenXAL Online Model.
We hope to use PyORBIT as PIC code in the future

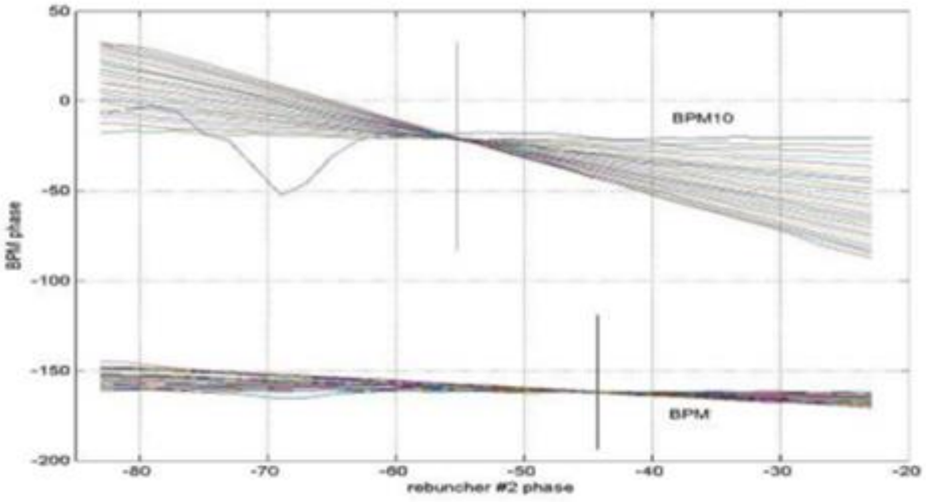
Transverse Motion of Beam Centroid

Model – OpenXAL – Envelop Model

- Orbit (centroid) difference – BPMs' data vs Model – is working well in all parts of linac
- Orbit correction does not work everywhere
  - DTL – too few BPMs and correctors
  - CCL – too few BPMs
- In DTL and CCL Operations use saved BPMs data as a goal and manual small corrections
- In MEBT and SCL model-based orbit correction is working fine
- Sometimes the model-based correction needs several iterations. A probable reason for that is model imperfections (RF settings)

Longitudinal Motion of Beam Centroid - MEBT

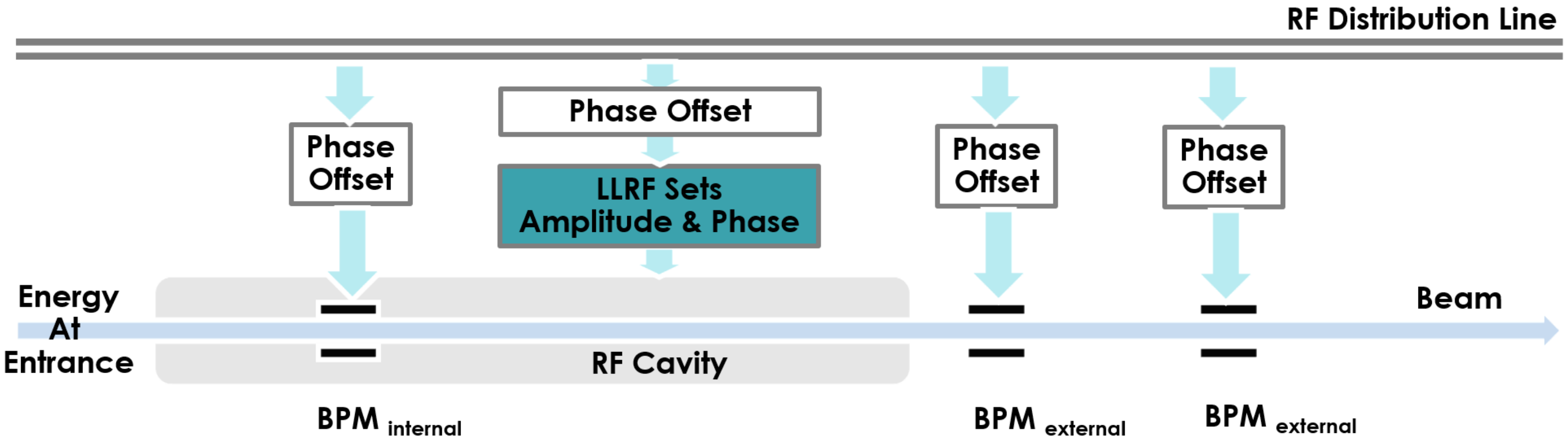


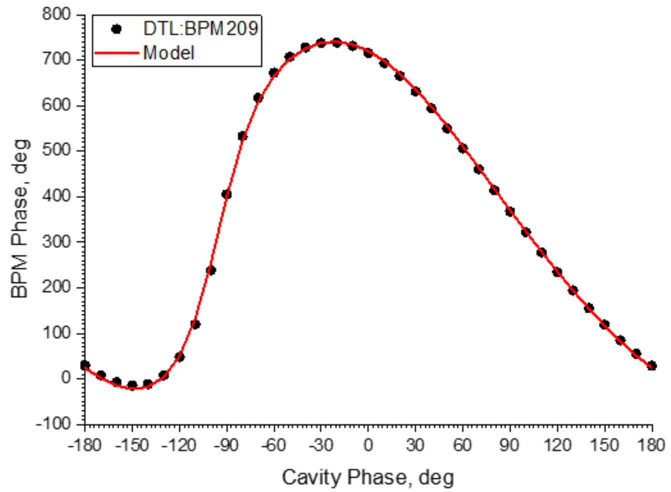


Phase scan RF re-buncher in MEBT.

- Non-accelerating phases are different for different BPMs
- Initially was explained by space-charge effects
- After installation and use of MEBT attenuator (metallic grid mesh) for space-charge suppression did not disappear
- Cannot be reproduced by OpenXAL envelope code or by PIC code with symmetrical (gaussian, waterbag) initial bunches

Longitudinal Motion of Beam Centroid – DTL, CCL



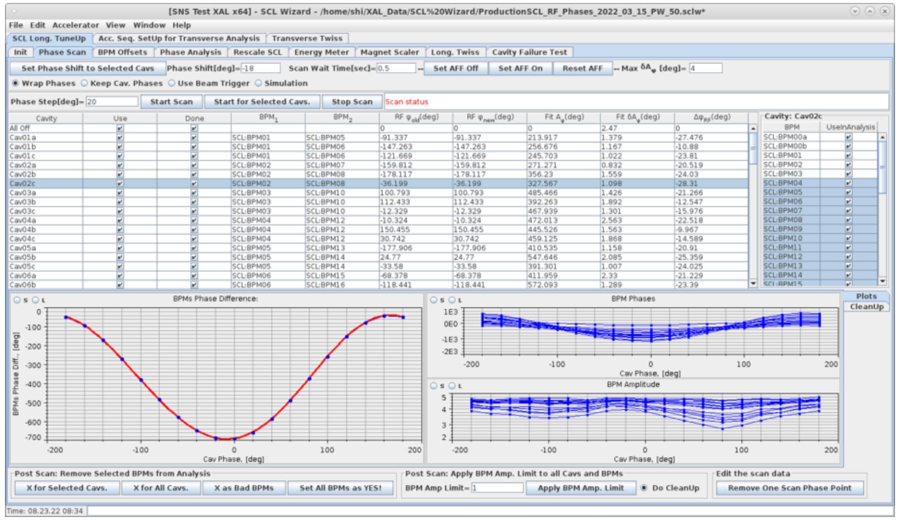


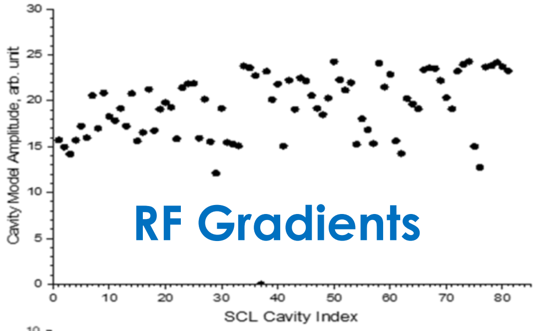
DTL2 Cavity Phase Scan

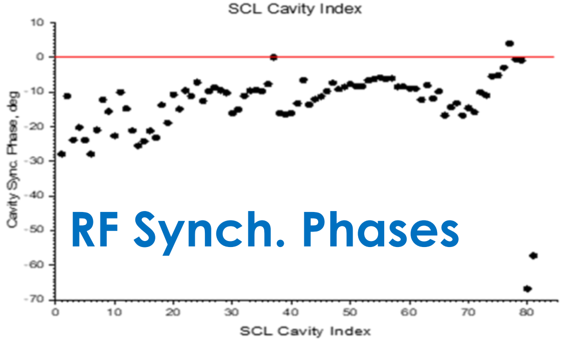
The cavities RF amplitude and phase settings:

- We abandoned Delta-T and Phase Signature Fitting methods with external BPMs (except for DTL1 which does not have inner BPMs)
- We use only inner BPMs and model-based analysis (OpenXAL) of 360^0 range phase scans
- Our accuracy is about 1^0 for the phase and 1% for cavity amplitude
- Automated: 22 minutes for RF setup in MEBT, DTL, CCL

Longitudinal Motion of Beam Centroid – SCL





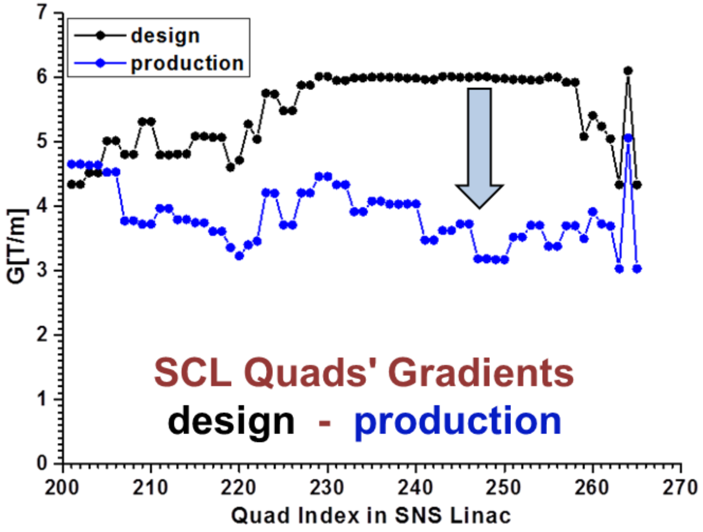


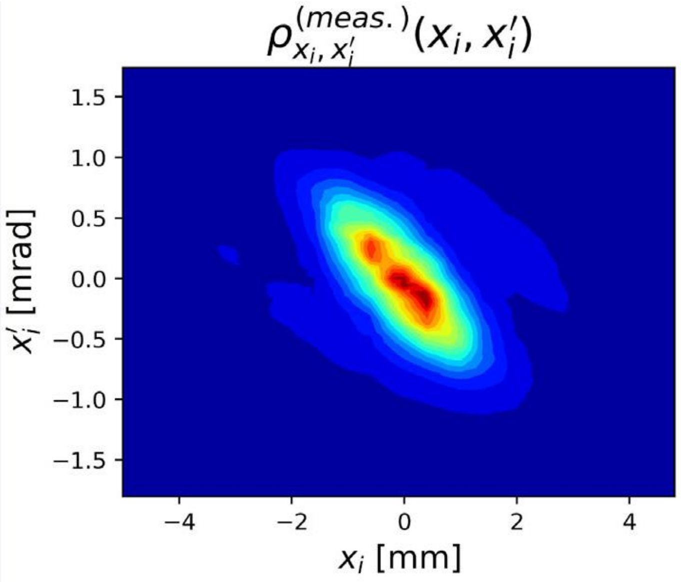
- 360^0 phase scans, RF amplitude fixed
- Setup physics – BPMs Time-Of-Flight
- BPMs' timing calibrated by ring energy
- Automated setup procedure (97 RF cavities)
  - Takes about 45 min
  - Initial (usually historic data)
  - Final by Operations – goals: beam loss * trip rate
- Accuracy of the model parameters about 1^0 for the phase and 1% for cavity amplitude
- Model-based (OpenXAL) instant rescaling of synchronous phases (in a case of cavity failure)
- Accuracy of rescaling < 1.5 MeV
- Can we do better? - Unknown

Transverse Beam Sizes and Profiles

- Right during commissioning: SCL beam loss too high (should be zero)
- Empirical beam loss reduction by lowering SCL quadrupole gradients
- Intra-Beam Stripping of H^- mechanism was identified

- Any attempt to improve beam loss by transverse matching in DTL and CCL failed
- Empirical loss tuning was applied to MEBT, DTL, and CCL
- Wire Scanners, laser wire scanners, and emittance devices data did not affect operation practices

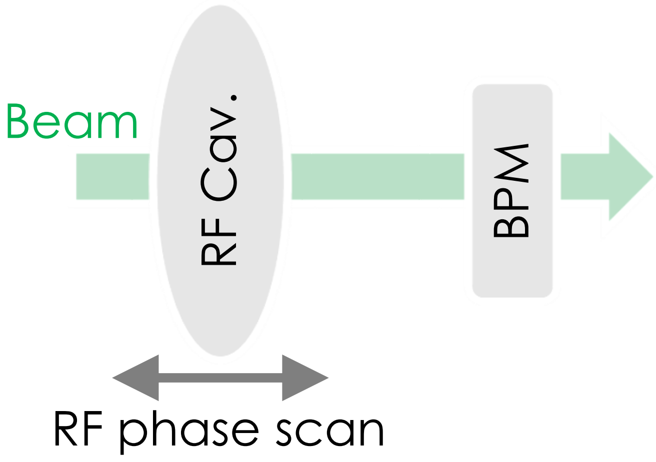




Horizontal Emittance after SCL

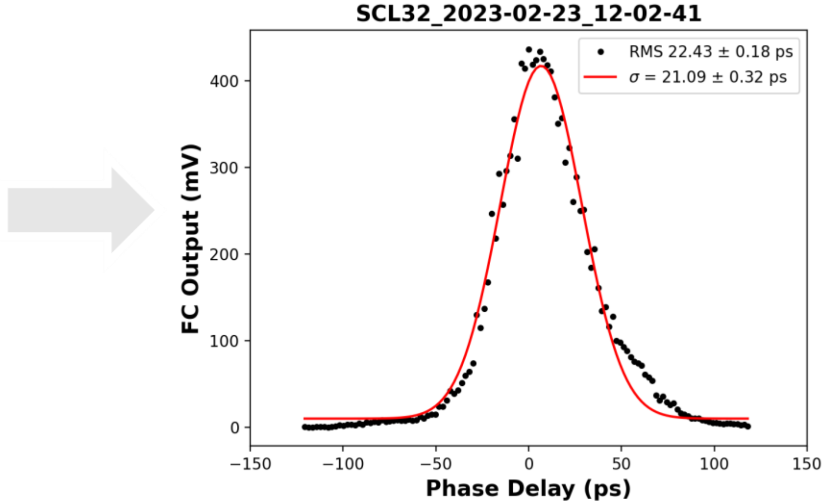
Longitudinal Sizes and Twiss

- Methods for longitudinal Twiss extraction from cavity phase scans were developed for SCL and MEBT
- Verified with Bunch Shape Monitors in CCL (for SCL) and DTL1 acceptance scans (for MEBT)
- We did not use these data to improve operations



$$I_{BPM} = I_{peak} \cdot \exp\left(-\frac{\sigma^2}{2}\right)$$

- Laser Wire "virtual slit" method was developed (by Yun Liu, SNS) to measure longitudinal profiles of beam in SCL
- Some of them show very non-Gaussian shapes
- That is recent development, no beam dynamics analysis was applied yet



Beam Longitudinal Profile at End of SCL

Production RF Settings in Normal Conducting Section

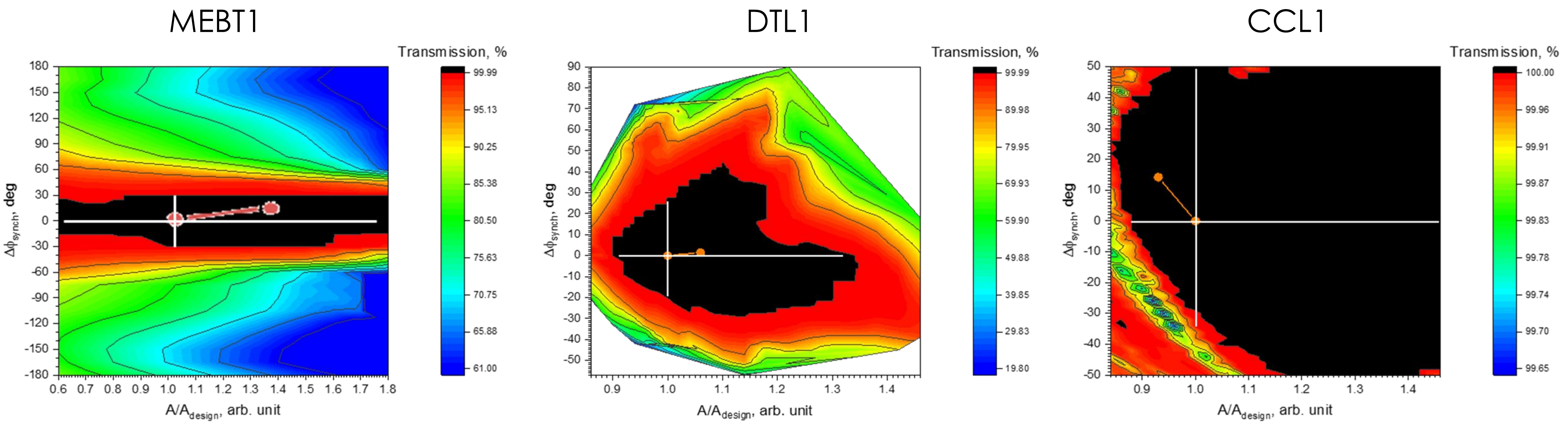
Cavity	Design φ_{synch} deg	Real φ_{synch} deg	$A_{RF}/A_{RF\ Design}$ %
MEBT 1	-90.0	-100.6	145
MEBT 2	-90.0	-85.6	131
MEBT 3	-90.0	-103.5	132
MEBT 4	-90.0	-91.6	129
DTL 1	-45.0	-43.6	106
DTL 2	**-33.4**	**-44.4**	103
DTL 3	**-32.4**	**-19.6**	99
DTL 4	-31.7	-30.7	101
DTL 5	**-31.7**	**-25.2**	92
DTL 6	-34.0	-34.4	97
CCL 1	**-30.9**	**-16.7**	93
CCL 2	**-30.8**	**-21.6**	95
CCL 3	**-30.7**	**-23.9**	98
CCL 4	**-29.3**	**-18.3**	93

Data on Feb. 7, 2021, 1.4 MW

Real SNS Practice

- **Perform RF phase & amplitude (or phase only) scan**
- **Figure out how far we are from the design amplitude and phase**
- **Move amplitude and phase to the values from previous production setup**
- **Empirically optimize beam loss and/or set amplitude to reduce RF cavity trip rate**
- **Perform scans and analysis again and save the deviations from the design**
- **If some changes will occur, we will use saved deviations to restore the previous state of all cavities**
- **The new scans take about 22 minutes for all 14 cavities**

Simulated Transmission through MEBT-DTL-CCL using PyORBIT Code



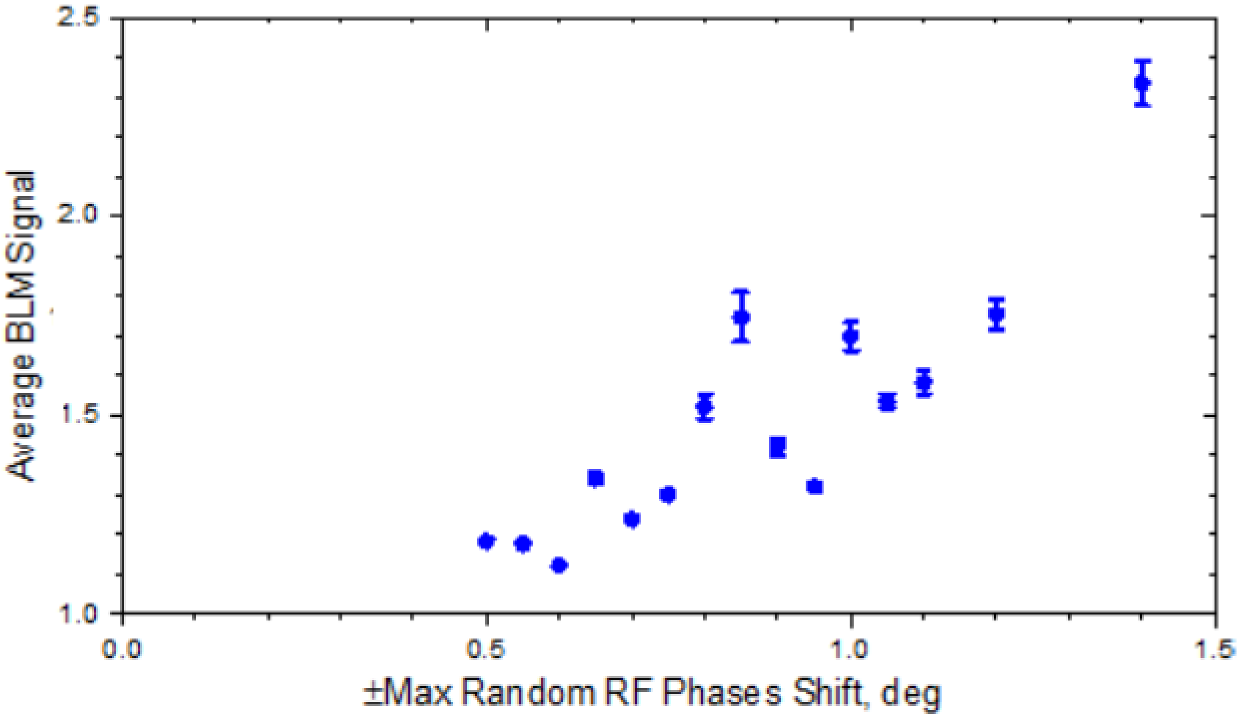
Simulation of Each cavity Phase & Amplitude 2D Scan

- We changed amplitudes and phases 14 cavities one by one
- For each cavity, all downstream ones were tuned according to design
- 100,000 macro-particles at the MEBT entrance with design Twiss
- Transmission was simulated to the end of warm linac

No contradiction to linac classical models

SCL Beam Loss and RF Phases Stability

- Existing LLRF phase stability is 0.1^0
- We wanted to know big this noise can be for the operational linac
- Several sets of average BLMs signals measurements were performed in SCL
- For each set we generated100 times RF phases randomly distributed around the production value. The maximal deviation was from 0.5^0 to 1.4^0 for different sets.
- Before 0.5^0 noise level we did not see any changes in beam loss.
- Even max. value of 1^0 gives us acceptable for production beam loss.



These results are for the linac state far from design:

- ❑ Transverse sizes are inflated to reduce IBSt beam loss
- ❑ There is strong variation (~5^0) of bunch phases along 1ms macro-pulse

Conclusions

- Most progress in our knowledge of SNS linac beam dynamics was achieved by using OpenXAL Online Model which is an envelope simulation linac code
- We understand very well transverse and longitudinal motion of bunch center
- Combination of empirical beam loss tuning and modeling of bunch center motion was beneficial for beam availability and low activation of SNS linac
- To improve our knowledge and operation practices further we have to use combination of envelope (fast) * PIC codes (more realistic)

Thank you for your attention!

Questions?

Backup Slides

Other useful remarks

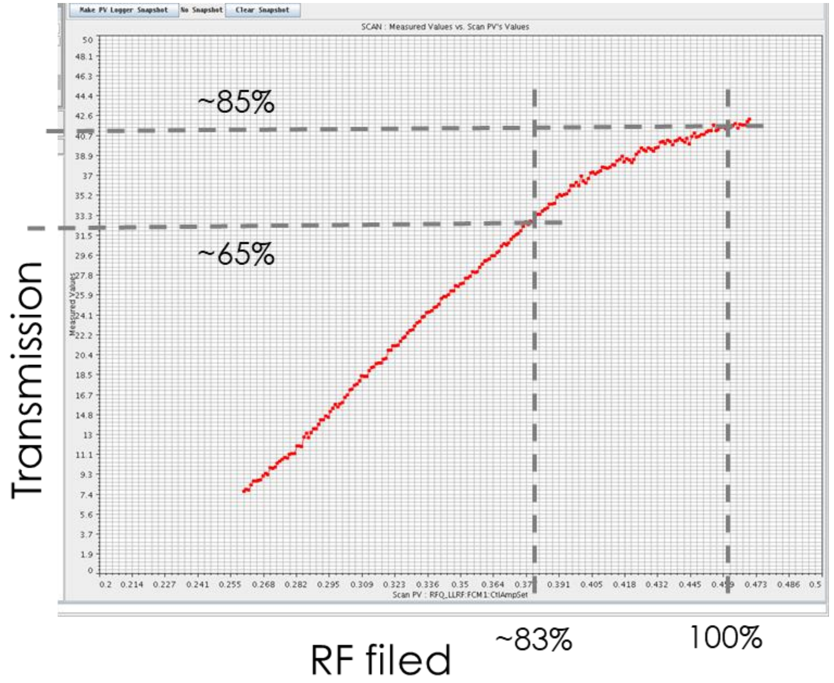
- Using low peak current and short beam (≈ 1-5 us)
  - Eliminates beam loading in RF cavities
  - Allow to use RF blanking during the tuning (cavities are kept on resonance)
  - Reduces beam loss in superconducting part during tuning
- Ability to shift RFQ phase is important for phase sign definitions RF/BPPMs ($\pm\omega \cdot t$)
- Application software
  - Save & Restore Application
  - Virtual accelerator models are useful
  - On early stages of commissioning, we used all kinds of tools and technologies (Matlab, Java, Fortran)
  - To tune and operate many RF cavities semi- and full-automation are important

What's for the future?

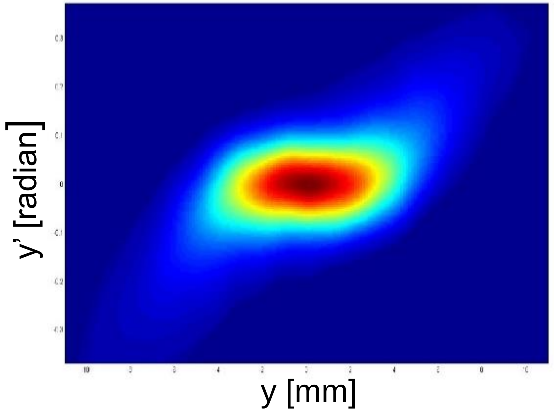
- Can we control beam loss based on knowledge rather than empirically?
  - Beam distribution measurements with dynamic range relevant for beam loss, e.g., up to 1ppm (halo)
  - Bunch characterization in 6-dimensional phase-space
  - Tools and techniques for model vs. real machine benchmarking
  - ???

What We Learned about SNS RFQ #1 : 2.5MeV, 402.5MHz

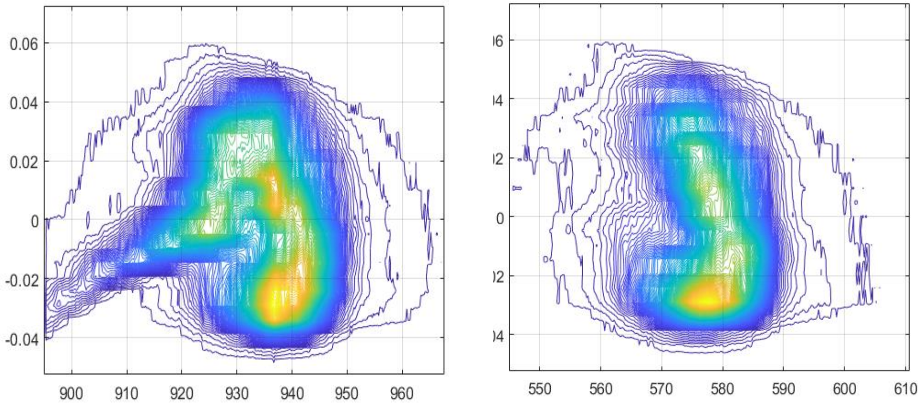
- 14 years of operation
- Very robust machines, capable to take some abuse
- RF amplitude acceptable range is much larger than expected
- Transmission is major figure of merit
- SNS linac does not require significant tuning when changing RFQ amplitude in wide range



Detailed studies were performed at SNS Beam Test Facility



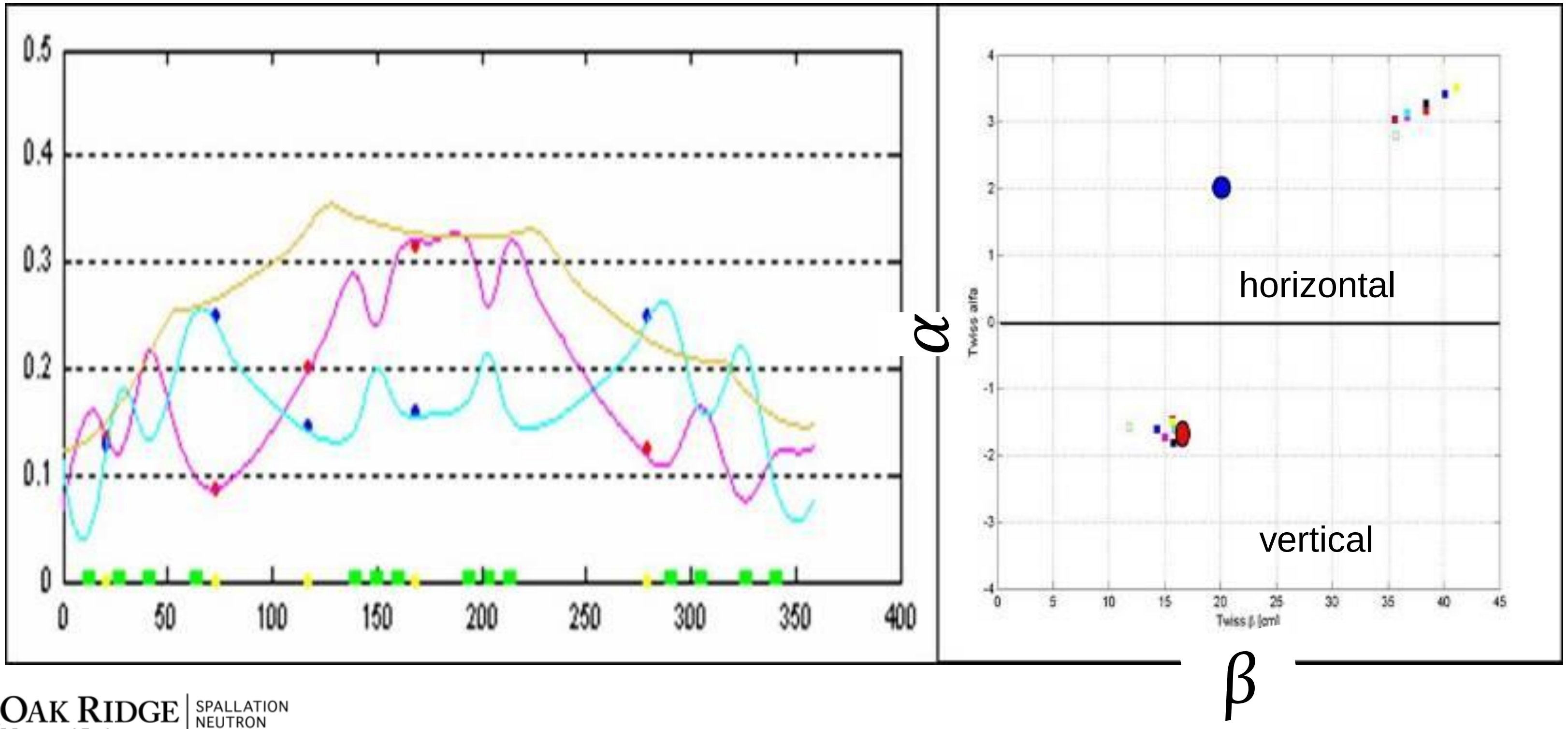
Transverse Emittance



Longitudinal Emittances
A = 83% and 100%

What we learned about SNS MEBT

- Can operate without fast chopper
  - Chopper was removed
- Linac operation is not very sensitive to MEBT optics



Measure transverse profiles using 5 wire scanners

Search for input Twiss parameters to best fit model to measured data

Repeat several times with different quad settings

Goals: Operations vs. Accelerator Physics

Operations

Performance (Power on Target)
- Linac energy
- Peak current
- Duty factor

Availability
- Short tuning/retuning time
- Elimination of expert interventions
- Low RF trip rate – RF parameters

Activation
- Low beam loss

Future problems and mitigation

Requests, Statistics, Data

Apps & Procedures

Accelerator Physics

Physical Models of Beam Transport
- Halo formation
- Beam loss
- RF acceleration
- Magnet models
- Space charge

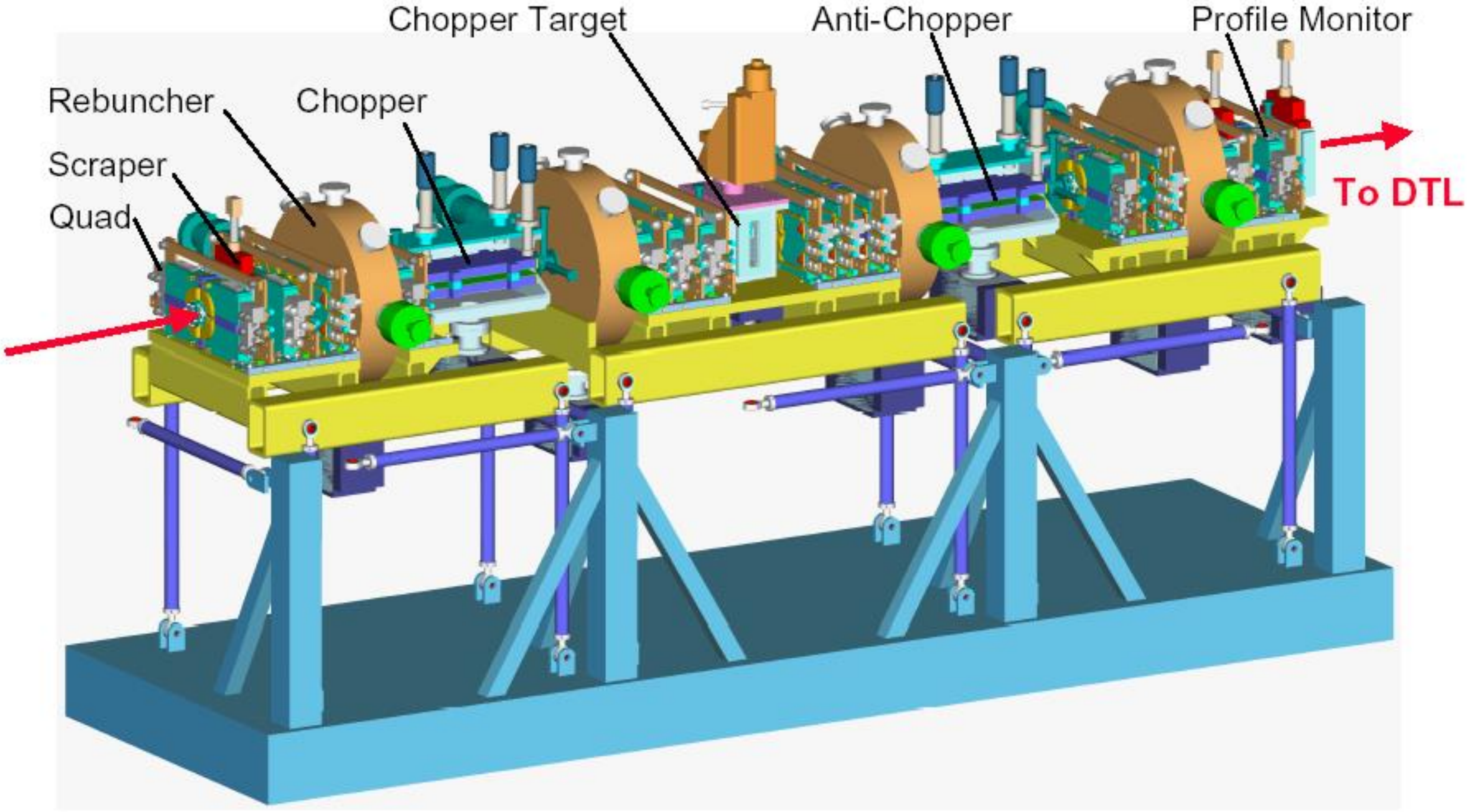
Accelerator Simulation Codes
- Development or what to choose
- Benchmarking with machine
- Improvements & additions

CCR High Level Applications
- Warm & SC linacs RF tuning
- Orbit correction
- SCL RF and magnets rescaling

AccPhys & BI interaction
- Collaborative effort as good as it gets – thanks to management and people

Following the design is not a goal!

2.5MeV SNS MEBT (fast chopper beamline)

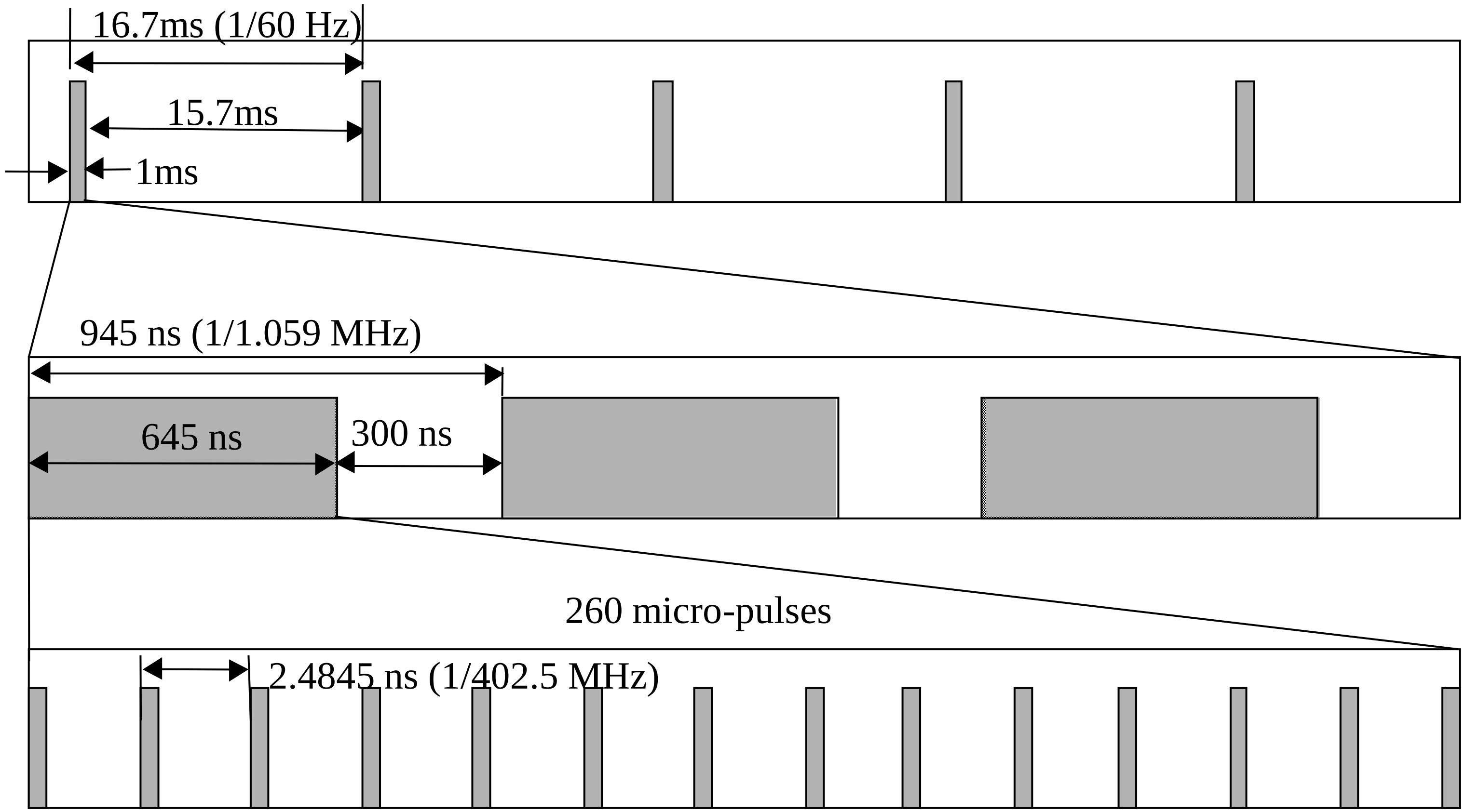


SNS beam pulse temporal structure

Macro-pulse
Structure
(made by the
Ion Source)

Mini-pulse
Structure
(made by the
choppers)

Micro-pulse
structure
(made by the
RFQ)



MEBT in-line diagnostics

	Measured parameter	quantity	Use for commissioning	Use for machine tuning	Use in operation	Use in Beam study
Beam Loss Monitor (BLM)	radiation Ionizing, n	2	Yes	No	No	No
Beam Current Monitor (BCM)	beam current	2	Yes	Yes	Yes	Yes
Beam Position Monitor (BPM)	x, y, z position	6	Yes	Yes	No	Yes
Wire scanner (WS)	x, y 1-d profile	5	Yes	No	No	Yes
Differential BCM	In-out beam current	1	No	No	Yes	No
Emittance Scanner	x, y 2-d emittance	1	Yes	No	No	Yes
Chopper monitor (ChoMPS)	Fast, HDR beam current	1	No	No	Yes	No
Laser Wire	longitudinal 1-d profile	1	Yes	No	No	No*

X eliminated

added later

DTL in-line diagnostics

	Measured parameter	quantity	Use for commissioning	Use for machine tuning	Use in operation	Use in Beam study
Beam Loss Monitor (BLM)	radiation Ionizing, n	11*12	Yes	Yes	Yes	Yes
Beam Current Monitor (BCM)	beam current	6	Yes	No	No	No
Beam Position Monitor (BPM)	x, y, z position	10	Yes	Yes	No	Yes
Wire scanner (WS)	x, y 1-d profile	6	Yes	No	No	Yes
Differential BCM (DBCM)	In-out beam current	1	No	No	No	No
Faraday Cup with energy degrader (FC)	beam current above energy cutoff	6	Yes	Yes	No	Yes

CCL baseline diagnostics

	Measured parameter	quantity	Use for commissioning	Use for machine tuning	Use in operation	Use in Beam study
Beam Loss Monitor (BLM)	radiation Ionizing, n	48* * 10	Yes	Yes	Yes	Yes
Beam Current Monitor (BCM)	beam current	2	Yes	No	No	No
Beam Position Monitor (BPM)	x, y, z position	10	Yes	Yes	No	Yes
Wire scanner (WS)	x, y 1-d profile	8	Yes	No	No	Yes
Beam Shape Monitor (BSM)	longitudinal 1-d profile	3 * 1	Yes	No	No	Yes*

X: eliminated

SCL baseline diagnostics

	Measured parameter	quantity	Use for commissioning	Use for machine tuning	Use in operation	Use in Beam study
Beam Loss Monitor (BLM)	radiation Ionizing, n	76 * 23	Yes	Yes	Yes	Yes
Beam Position Monitor (BPM)	x, y, z position	32	Yes	Yes	No	Yes
Laser Wire (LW)	x, y 1-d profile	9	Yes	No	No	Yes
Laser Emittance Scanner (LES)	x,y 2-d emittance; longitudinal 1-d profile	1	No*	No	No	Yes

added later

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