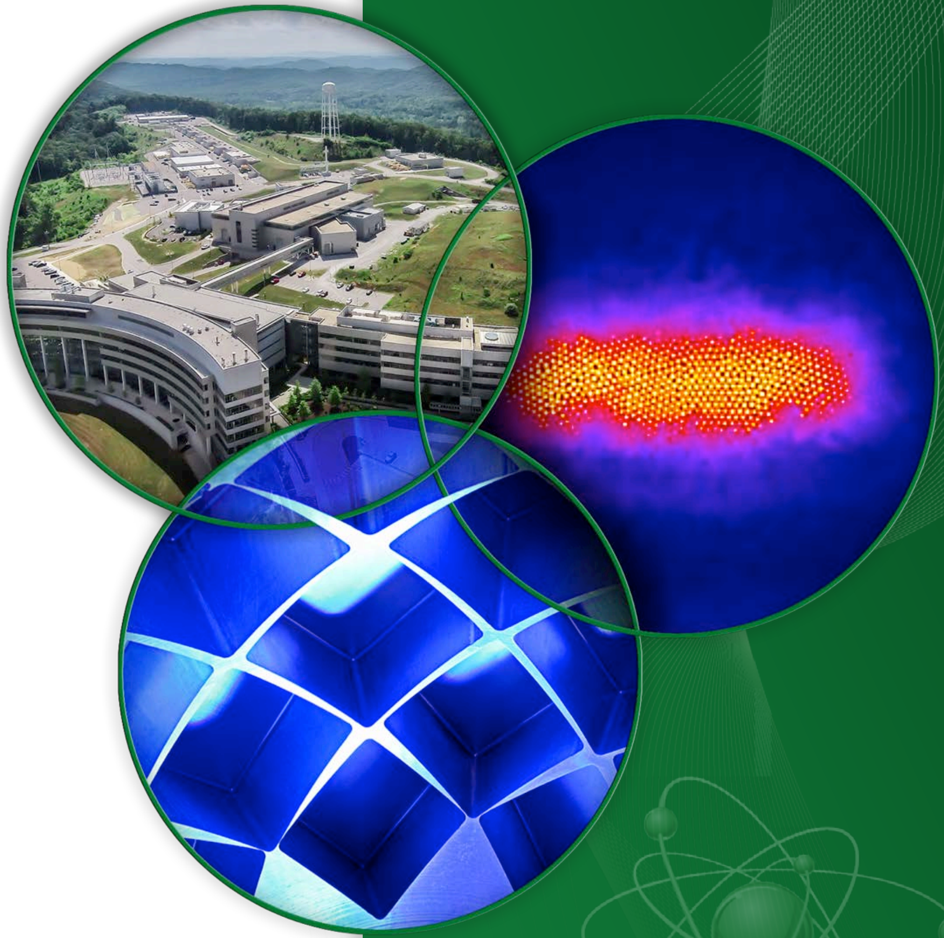
Model Benchmark with Experiment at SNS Linac



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July 6, 2016

HB2016, Malmö, Sweden

Outline

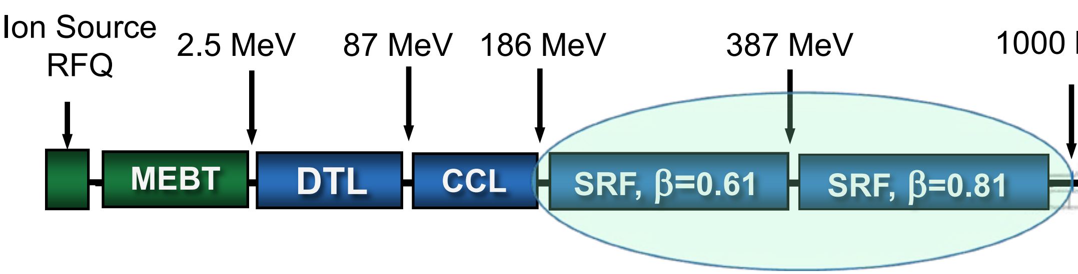
- SNS Accelerator and SNS Superconducting Linac
- SCL Transverse Matching Problem
- Linac Models
- Transverse Twiss Parameters Measurements
- SCL RF Tuning Technics
- Longitudinal Twiss Parameters Measurements
- Final results
- Conclusions

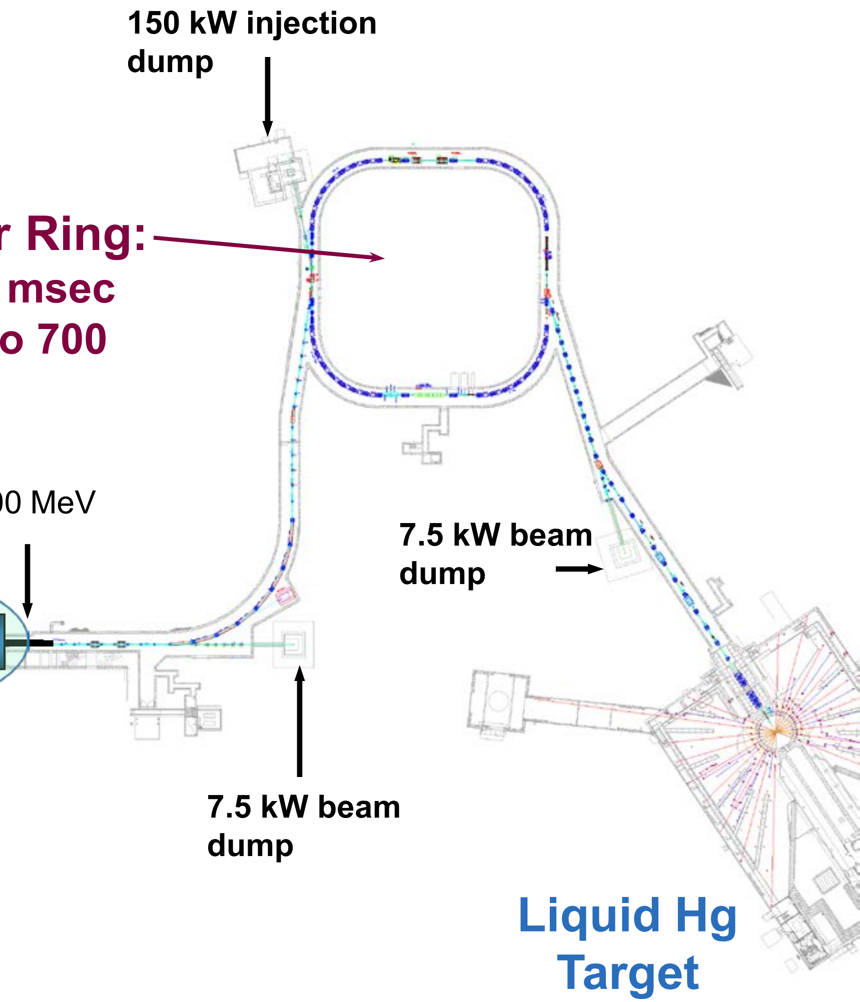
SNS Accelerator Complex

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

1 GeV LINAC

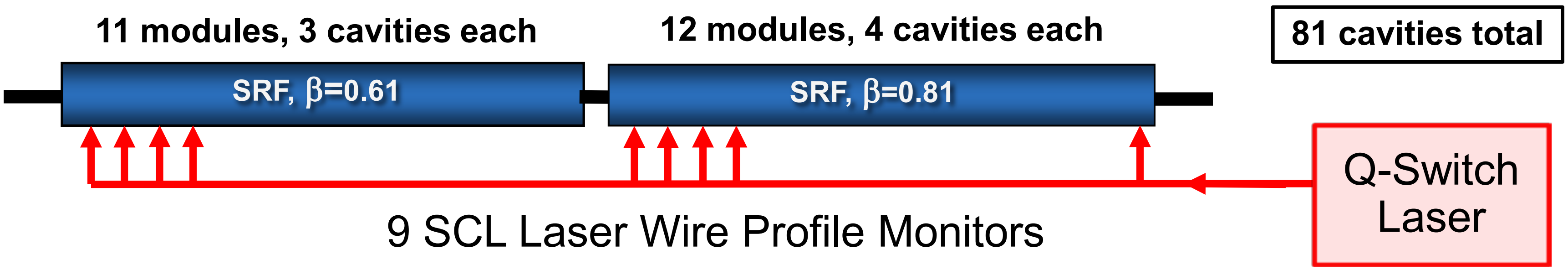
Accumulator Ring:
Compress 1 msec long pulse to 700 nsec





Design parameters	
Kinetic Energy [GeV]	1.0
Beam Power [MW]	1.4
Repetition Rate [Hz]	60
Peak Linac Current [mA]	38
Linac pulse length [msec]	1.0
SRF Cavities	81

SNS Superconducting Linac (SCL)



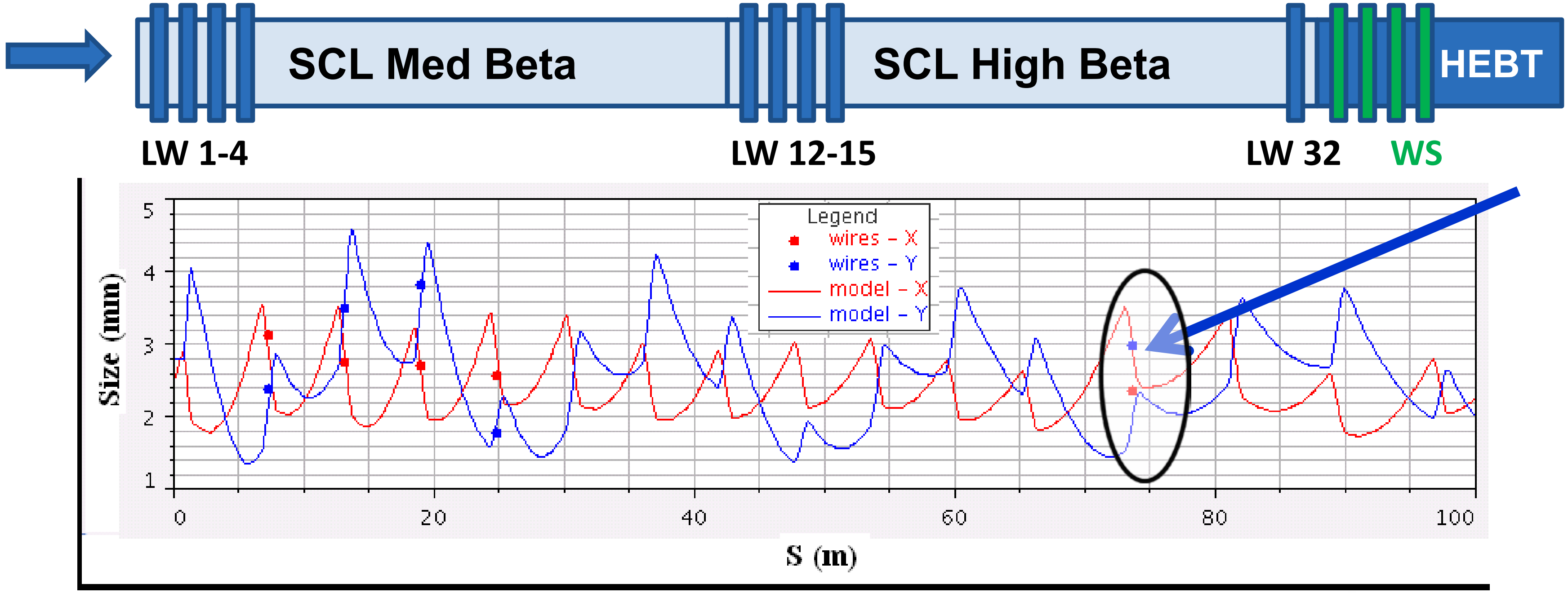
SNS SCL:

- **81 SC cavities**
- **Each cavity has its own klystron**
- **Each cavity tuned independently**
- **23 cryomodules**
- **Doublet quads after each module**

SCL Diagnostics:

- **All diagnostics are non-intercepting**
- **Beam Position Monitors (BPM) after each module**
- **BPMs measure:**
  - **transverse position of the beam center**
  - **Longitudinal phase (arrival time)**
  - **Fourier amplitude of the sum signal from 4 electrodes**
- **Laser Wire stations to measure transverse profiles of the beam**

Transverse Beam Matching in SCL



"Figure 7 shows one of the general cases: fit beam size for the first 4 laser wires with the online model, and then compare model prediction against measurement at the 5th wire – they do not agree at all."

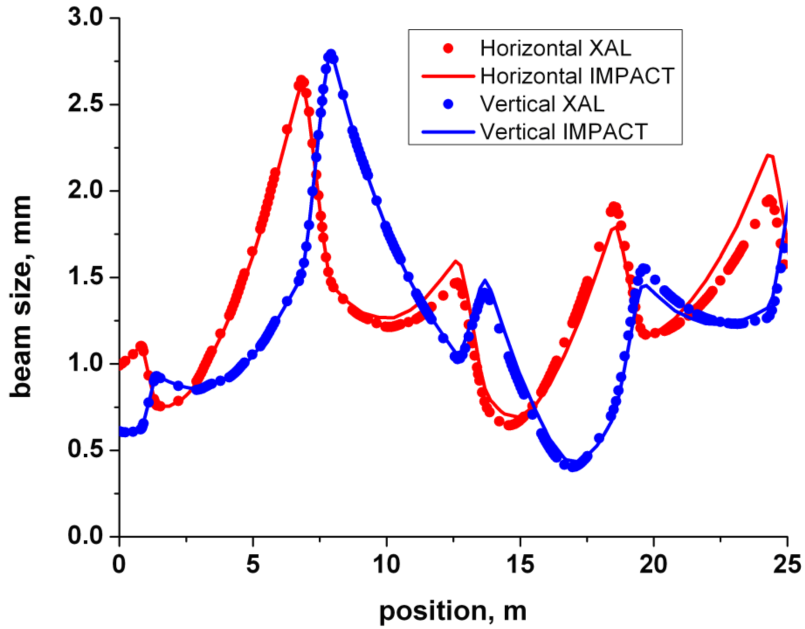
EXPERIENCE AND LESSONS WITH THE SNS SUPERCONDUCTING LINAC

Yan Zhang, Proceedings of IPAC'10, Kyoto, Japan, pp 26-30

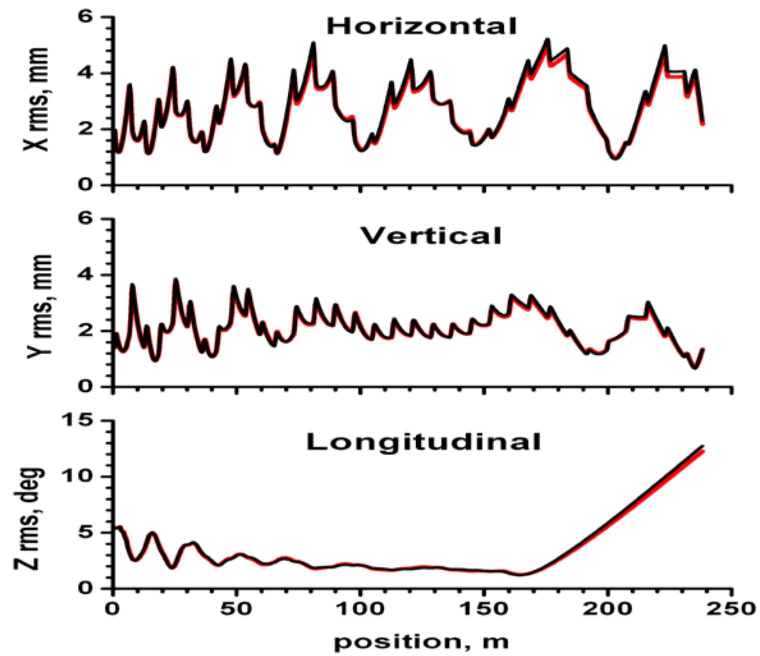
- Never could get LW data in agreement with the models including Impact code
- Multiple quads settings data do not agree for LW 1-4

SNS SCL: Linac Models

IMPACT – XAL Online Model



PyORBIT – XAL Online Model

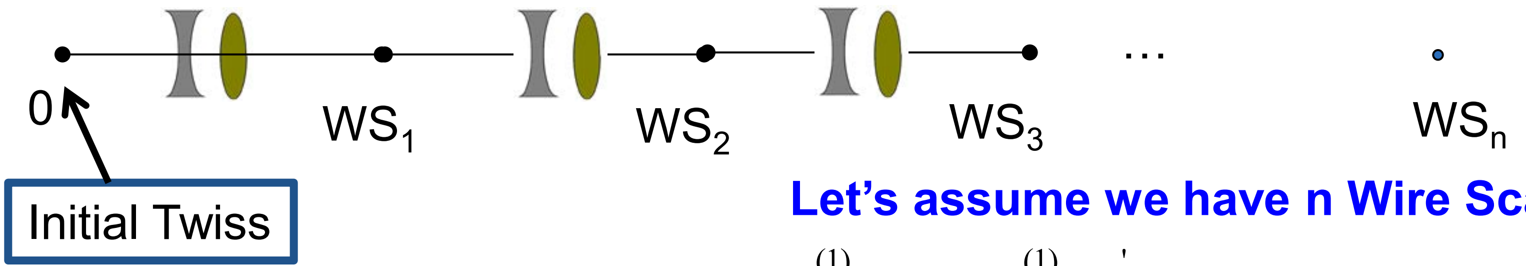


- ❑ **We benchmarked several available computer codes (Parmila, Impact, Track, Trace3D, XAL Online Model)**
- ❑ **We concluded that the problem is not in the codes**
- ❑ **Possible reasons: bad optics, unknown RF settings and longitudinal Twiss at the beginning of SCL**

XAL Online Model is an envelop tracking code

Initial Transverse Twiss Parameters

Measurements of Initial Twiss – LSQM



Let's assume we have n Wire Scanners

$m^{(i)}, i = 1,\ldots,n$ **Transport Matrices from OM**

$$x_1 = m_{1,1}^{(1)} \cdot x_0 + m_{1,2}^{(1)} \cdot x_0^{'}$$

$$\left\langle x_1^2 \right\rangle = \left(m_{1,1}^{(1)}\right)^2 \left\langle x_0^2 \right\rangle + 2 \cdot m_{1,1}^{(1)} m_{1,2}^{(1)} \cdot \left\langle x_0 x_0^{'} \right\rangle + \left(m_{1,2}^{(1)}\right)^2 \left\langle (x_0^{'})^2 \right\rangle$$

$$M = \begin{pmatrix} \left(m_{1,1}^{(1)}\right)^2 & 2 \cdot m_{1,1}^{(1)} \cdot m_{1,2}^{(1)} & \left(m_{1,2}^{(1)}\right)^2 \\ \left(m_{1,1}^{(2)}\right)^2 & 2 \cdot m_{1,1}^{(2)} \cdot m_{1,2}^{(2)} & \left(m_{1,2}^{(2)}\right)^2 \\ \bullet & \bullet & \bullet \\ \left(m_{1,1}^{(n)}\right)^2 & 2 \cdot m_{1,1}^{(n)} \cdot m_{1,2}^{(n)} & \left(m_{1,2}^{(n)}\right)^2 \end{pmatrix};$$

$$\begin{pmatrix} \left\langle x_0^2 \right\rangle \\ \left\langle x_0 \cdot x_0^{''} \right\rangle \\ \left\langle (x_0^{''})^2 \right\rangle \end{pmatrix} = \left(M^T \cdot W \cdot M\right)^{-1} \cdot M^T \cdot W \cdot \begin{pmatrix} \left\langle x_1^2 \right\rangle \\ \left\langle x_2^2 \right\rangle \\ \ldots \\ \left\langle x_n^2 \right\rangle \end{pmatrix} \quad \textbf{(1)}$$

$$\mathrm{W}_{i,i} = \frac{1}{\mathrm{cov}(\left\langle x_i^2 \right\rangle)}$$

Weights of each individual beam size measurement

$$\varepsilon_{rms} = \sqrt{\left\langle x_0^2 \right\rangle \cdot \left\langle (x_0^{''})^2 \right\rangle - \left\langle x_0 \cdot x_0^{''} \right\rangle^2}$$

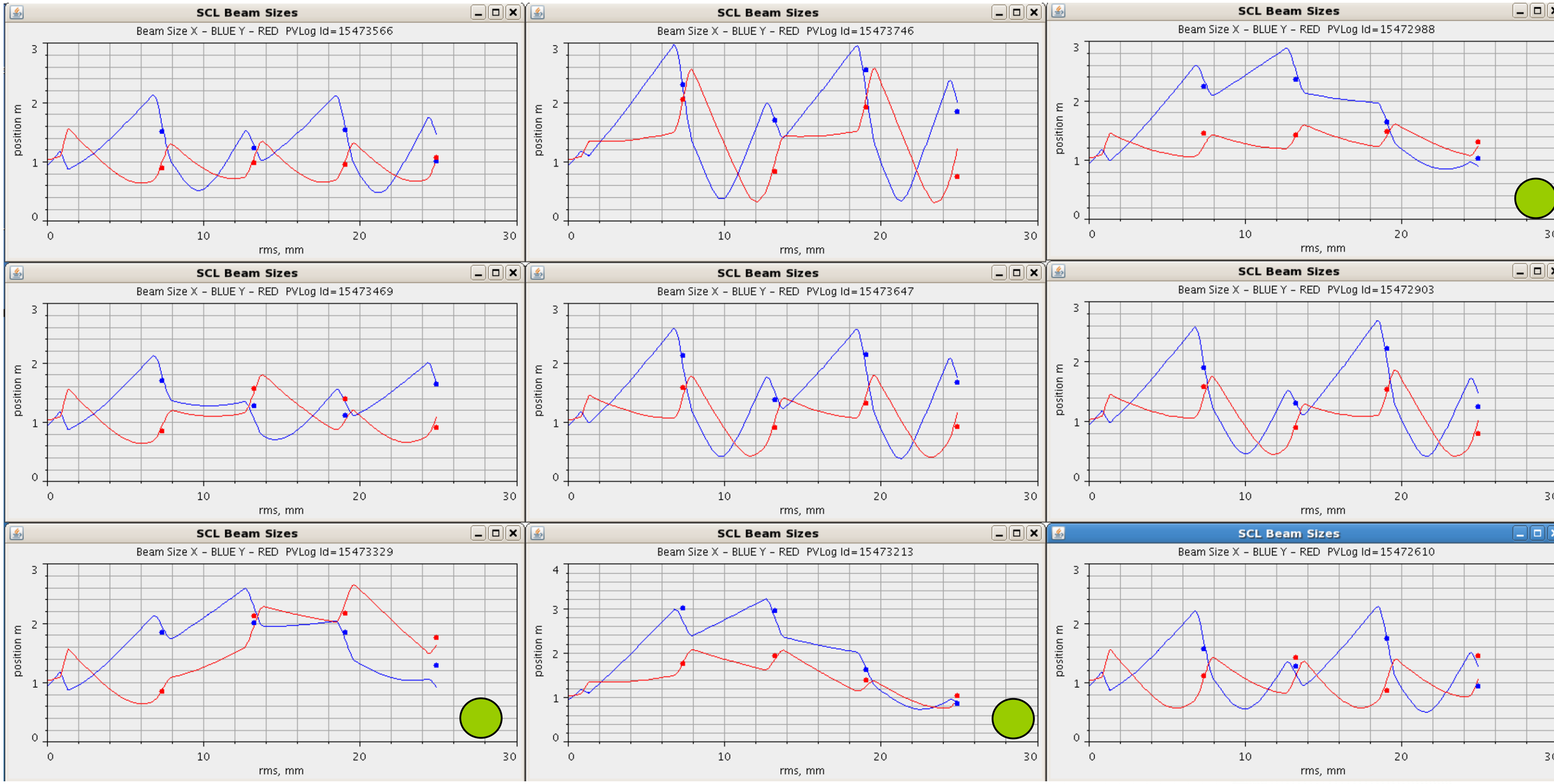
$$\alpha = -\frac{\left\langle x_0 \cdot x_0^{''} \right\rangle}{\varepsilon_{rms}} \qquad \beta = \frac{\left\langle x_0^2 \right\rangle}{\varepsilon_{rms}}$$

Initial Twiss !

"Rule of thumb" – 90^0 /(n-1) betatron phase advance between "WS stations"

We violated it!

No RF, No Space Charge Case LW 1-4



- ❑ One initial Twiss for all 9 cases (different quad settings)
- ❑ For Twiss calculations were used only three "green dots" measurements
- ❑ The lines are the model results, and the agreement is good for all cases

Now we know how to handle the optics.
Laser Wire Profile Stations are working correctly!

OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR | SPALLATION NEUTRON SOURCE

SCL RF Parameters: Amplitudes and Phases of Cavities

SCL RF Setup Algorithms

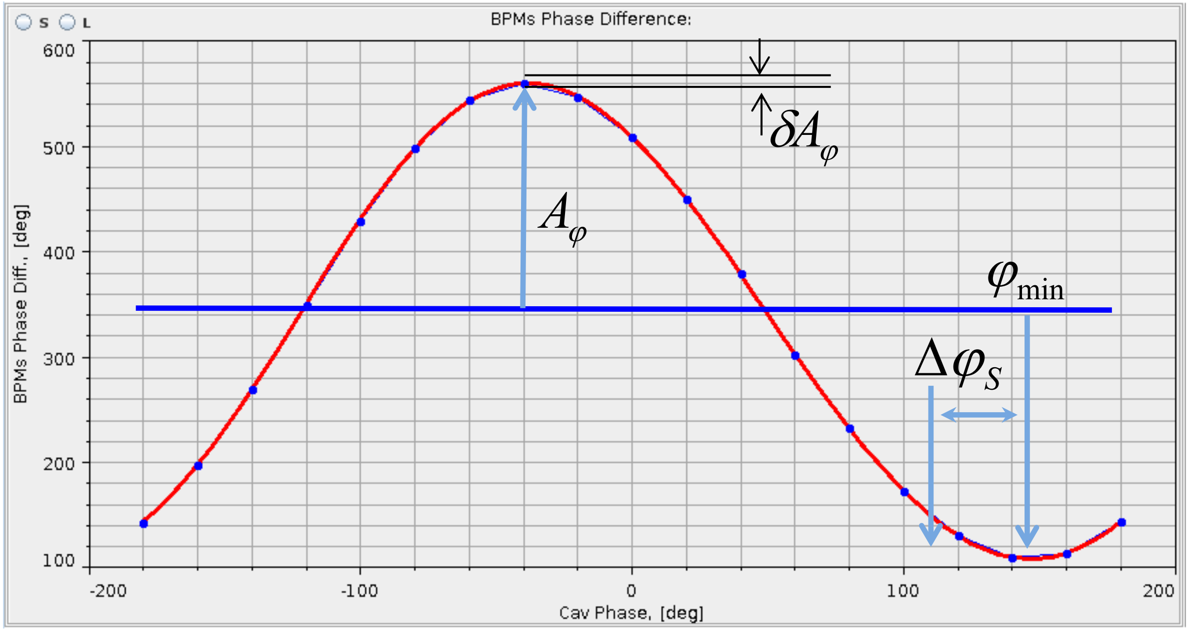
- Phase Scan of each SCL Cavity by using TOF with two BPMs
- Always have almost "sin"-like curve and set synchronous phase
- No model needed on this stage

- Send beam into the ring and measure the energy
- Perform BPMs' timing calibration using known energy
- Translate BPMs' calibration to the beginning of SCL linac
- No model needed on this stage

- Analysis of all data for each cavity using the Online Model
- After analysis we have amplitudes and phases of all RF in OM
- Model is initialized

- ❑ Algorithm has been automated: takes about 40 min for SNS SCL
- ❑ We can perform "non-destructive" scans to figure out what we have after beam loss tuning

SCL RF Cavity Phase Setup - Errors



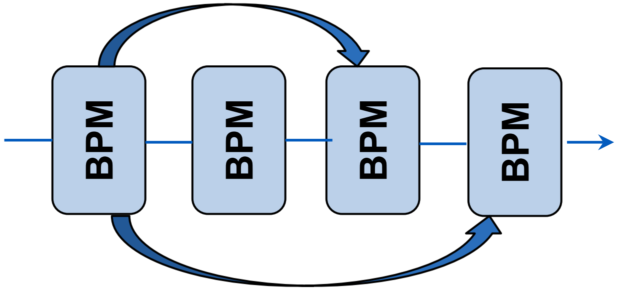
We do not need time-calibrated BPMs!

$$\delta\varphi_{\min} \approx \frac{1}{\sqrt{N}} \frac{\delta\phi_{BPM}}{A_{\varphi}}$$

$$A_{\varphi} \approx \Delta z_{BPM} \cdot \frac{1}{(\gamma \cdot \beta)^3} \cdot E_0 TL$$

Conclusions

- **Two neighbor BPMs – worst case**
- **More energy – less accurate the RF phase**
- **Smaller step – 1/square effective**



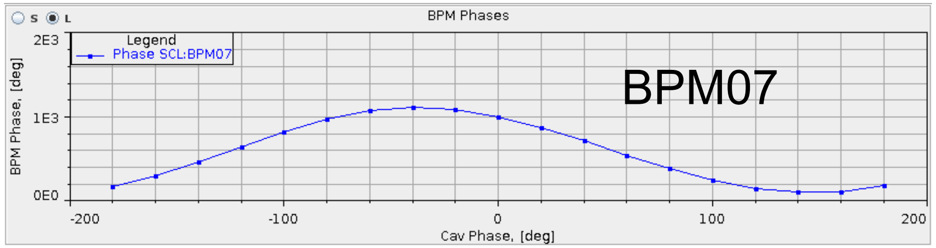
We want to use BPMs as far as possible!

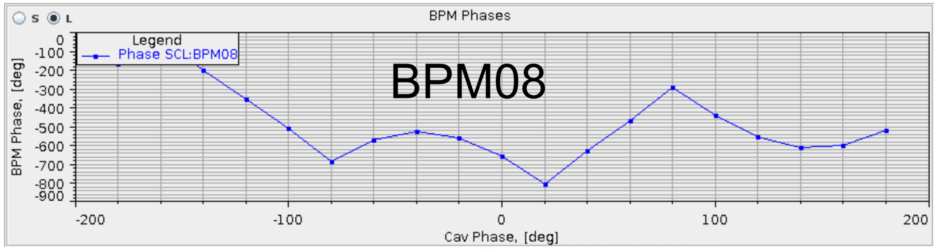
Less steps (N) – faster the scan!

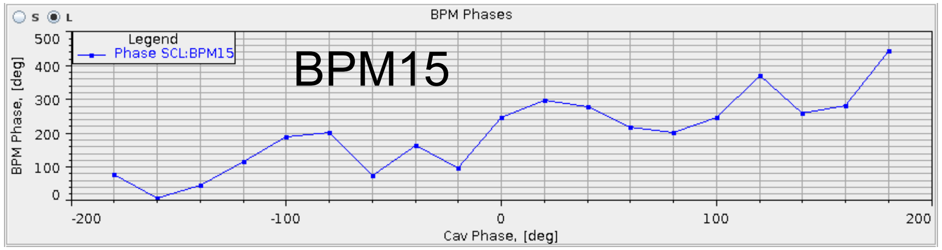
A "Big Phase Step" Problem

- BPMs measure phase in -180^0 to $+180^0$ range
- To get sinusoidal curve we have to unwrap the phase scan
- Usually, we do this by using the previous phase point of the scan
- Therefore we have to use small steps to avoid more that 180^0 gain in one step
- If we use far away BPM pairs, it could be problem for the "big phase step"

$$A_\varphi \cdot \sin(\Delta\phi_{RF}) < 180^0$$







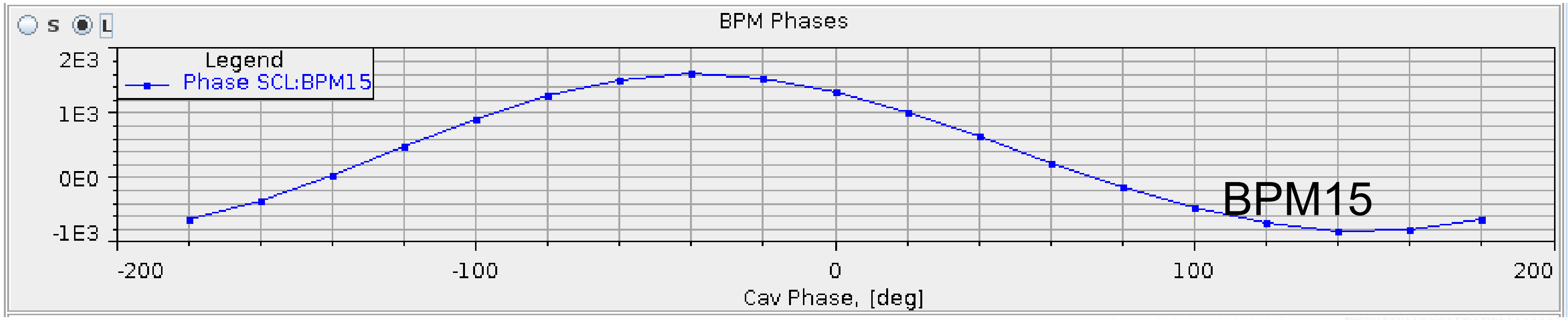
An example of Cav01a scan. We cannot go further BPM07 with the step size 20^0

Solution for the "Big Step" Problem

Most simple – iterative approach – the unwrapping is done by using not only the previous point, but also the previous and current points from the previous BPM. The iteration starts with the BPM closest to the cavity.

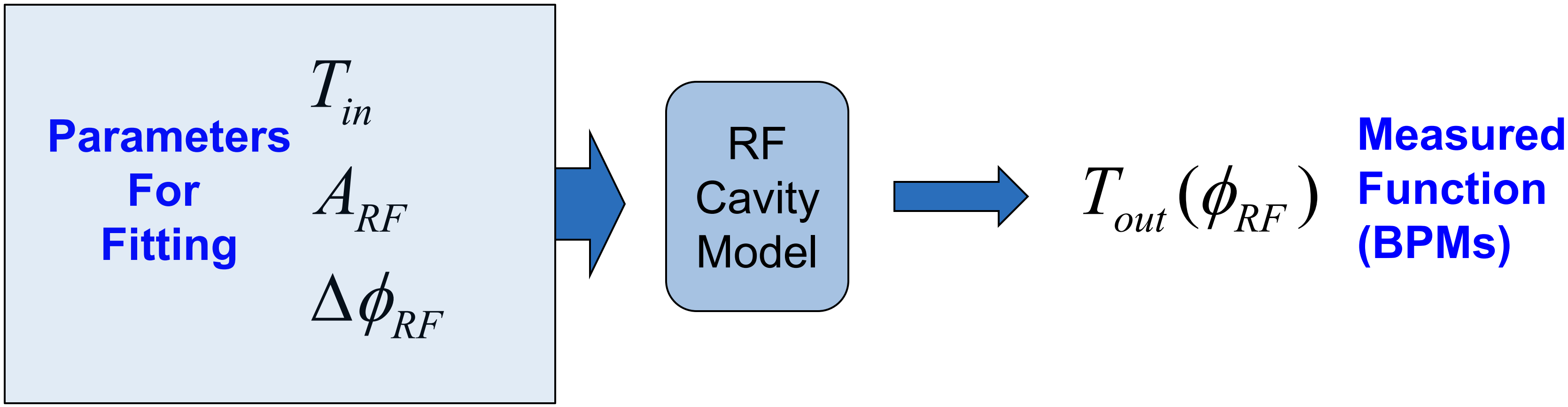
$$(A_{\varphi}^{(k)} - A_{\varphi}^{(k-1)}) \cdot \sin(\Delta\phi_{RF}) < 180^0$$

Phase step size can be 40^0, 60^0 or may be even 90^0.
It means 10-15 minutes scan for the whole SCL.
In reality, we limit ourselves by 30-40 mins.



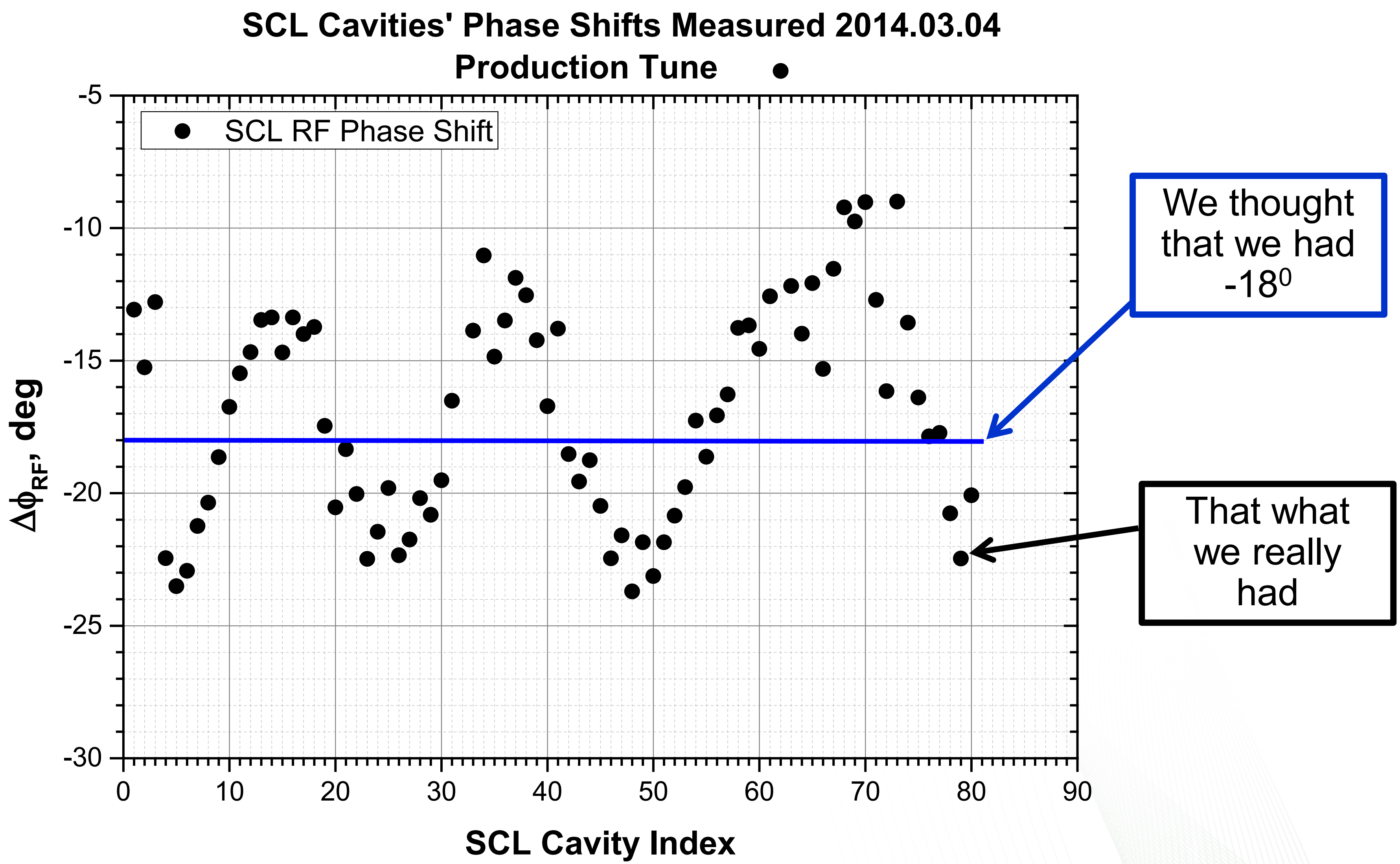
BPM15 after iterative unwrapping

Model Based Phase Scan Analysis



- After using the SNS ring for BPMs' calibration we know the energy for each phase point of each cavity
- We fit the measured kinetic energy vs. cavity phase by using the input energy, the cavity amplitude, and the cavity phase offset.
- We use XAL Online Model
- The input energy for one cavity is not the output energy of the previous one. The difference shows the model imperfections.

SCL Production Tune



Beam loss for this tune is good!

Initial Longitudinal Twiss Parameters

BPM as WS in Longitudinal Direction

$$\lambda(z) = q \cdot N \cdot \frac{1}{\sqrt{2\pi\sigma_z^2}} \cdot \exp\left(-\frac{z^2}{2 \cdot \sigma_z^2}\right)$$

Gaussian Longitudinal Distribution

SNS BPMs report the amplitude of Fourier transformation of the electrode sum signal

$$U_{BPM}(\sigma_\varphi) = A_0 \cdot \exp\left(-2 \cdot \pi^2 \cdot \left(\frac{\sigma_\varphi}{360^0}\right)^2\right)$$

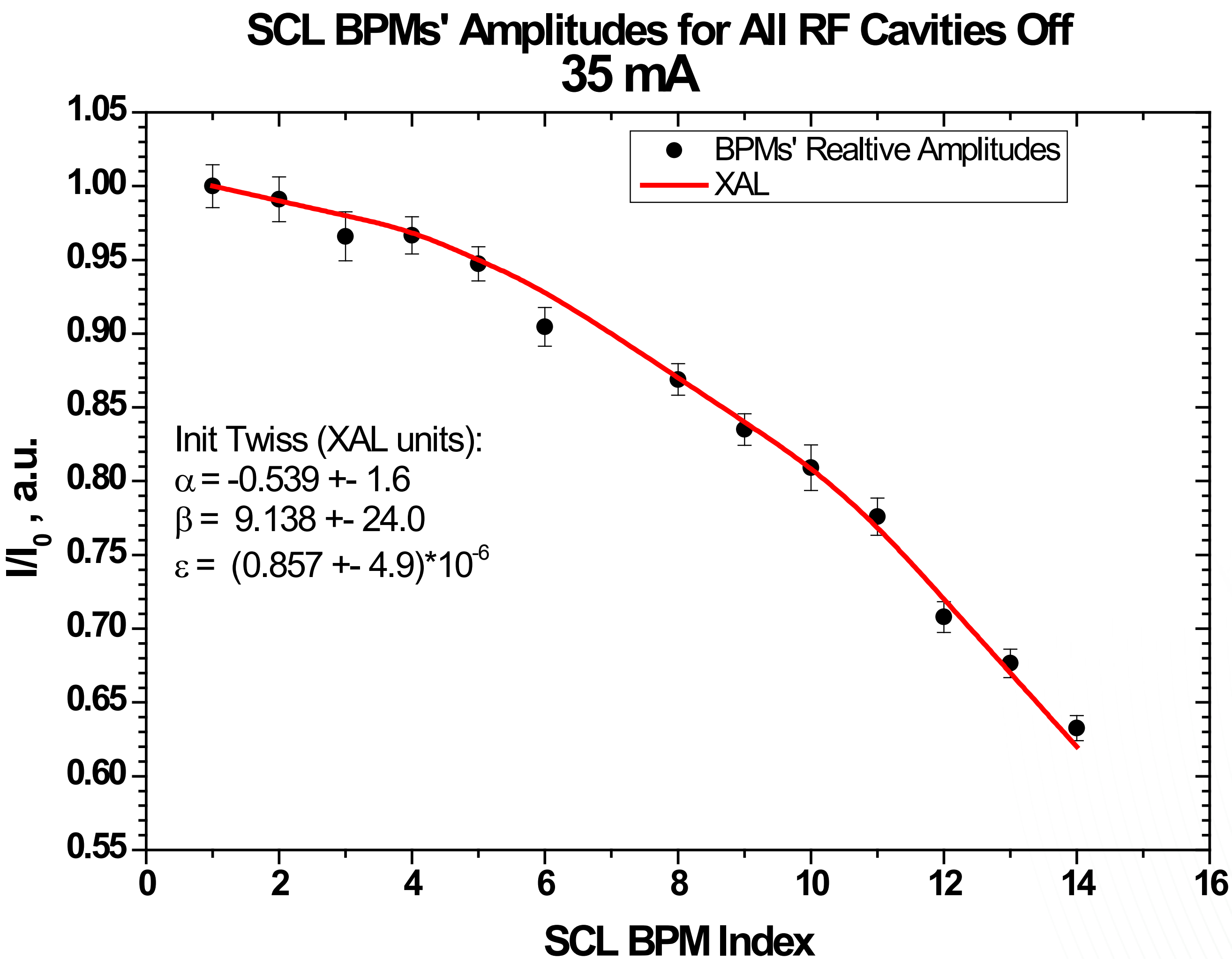
σ_φ **- Longitudinal RMS bunch size in deg.**

$$\sigma_\varphi = \frac{360^0}{\sqrt{2} \cdot \pi} \sqrt{\ln\left(\frac{A_0}{U_{BPM}}\right)}$$

BPMs give RMS size only. No profiles are available.

(Formulas assume a constant energy. For details see the paper)

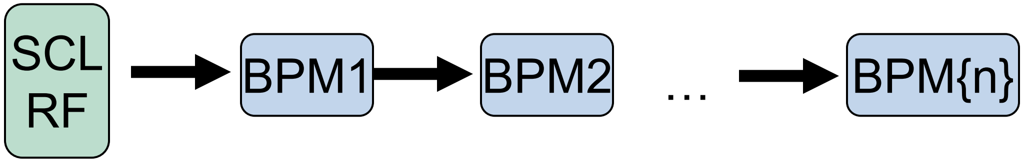
The Free Debunching Case



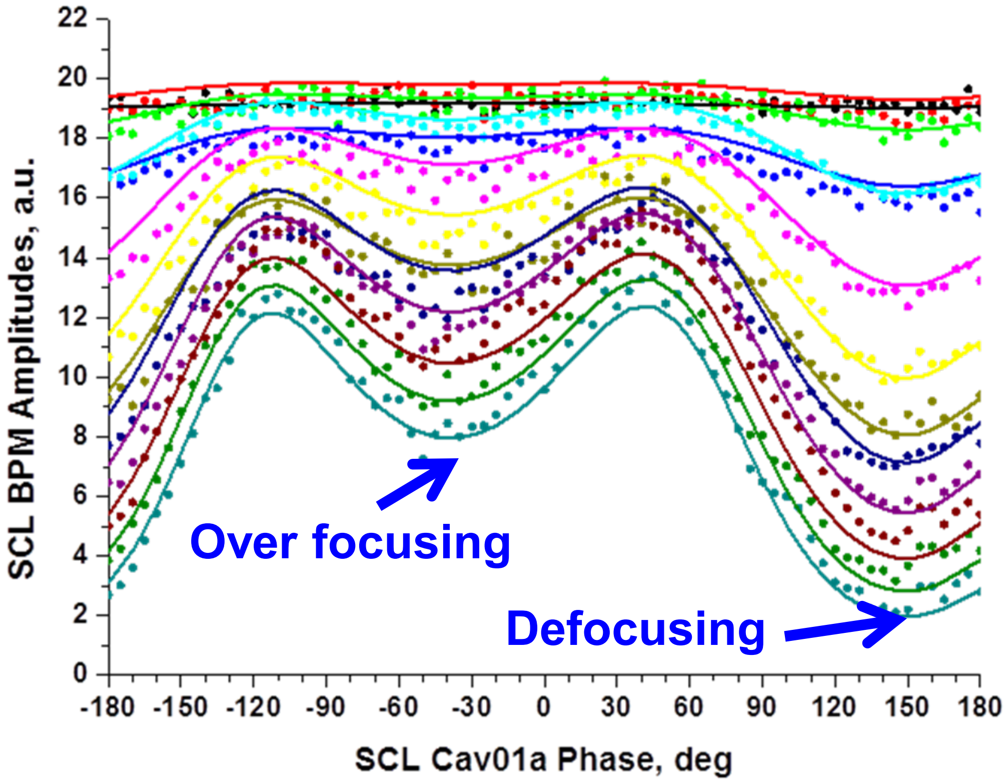
All SCL RF are OFF
Statistics:
40 measurements
13 BPMs

Errors are too big!

"Z" Twiss Analysis with SCL RF



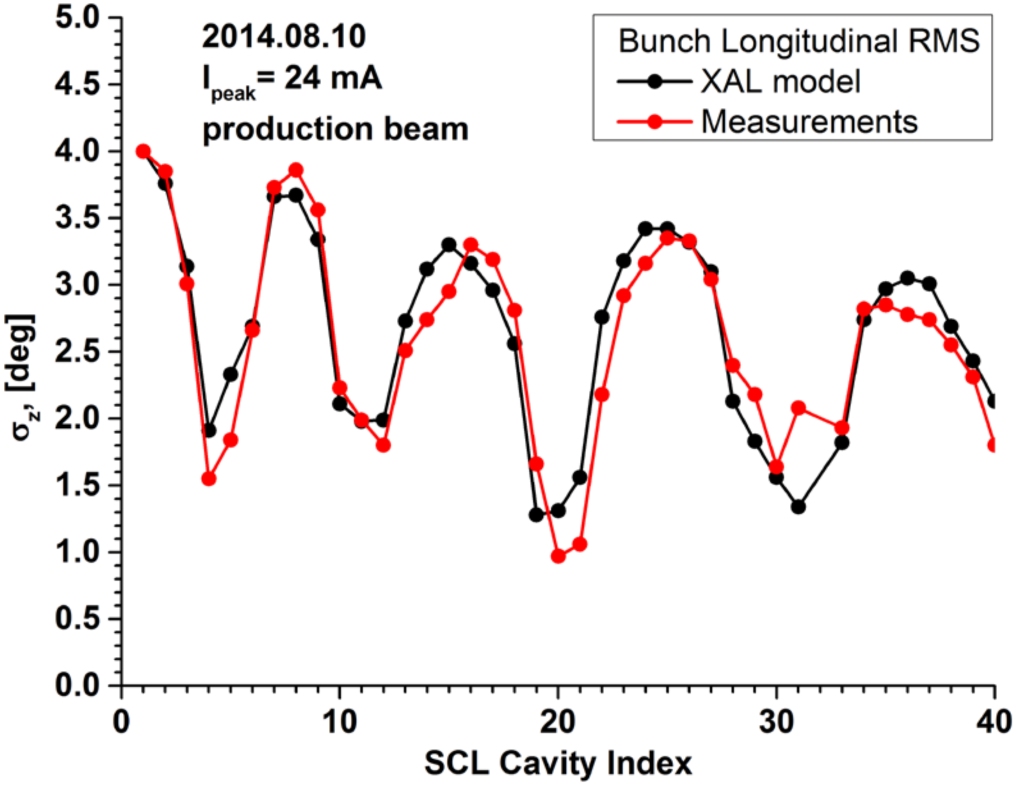
We can include a controllable element in the lattice and get more data
The Twiss errors should be reduced. For 5 deg step, matrix will be (72x14)x3.



Results (XAL units):
Alpha = 0.56 +- 0.02
Beta = 5.33 +- 0.13
Emitt = (0.928 +- 0.012)*10^{-6}

A. Shishlo, A. Aleksandrov, Phys. ST Accel. and Beams 16, 062801 (2013).

Results of “Z” Twiss Analysis 2014



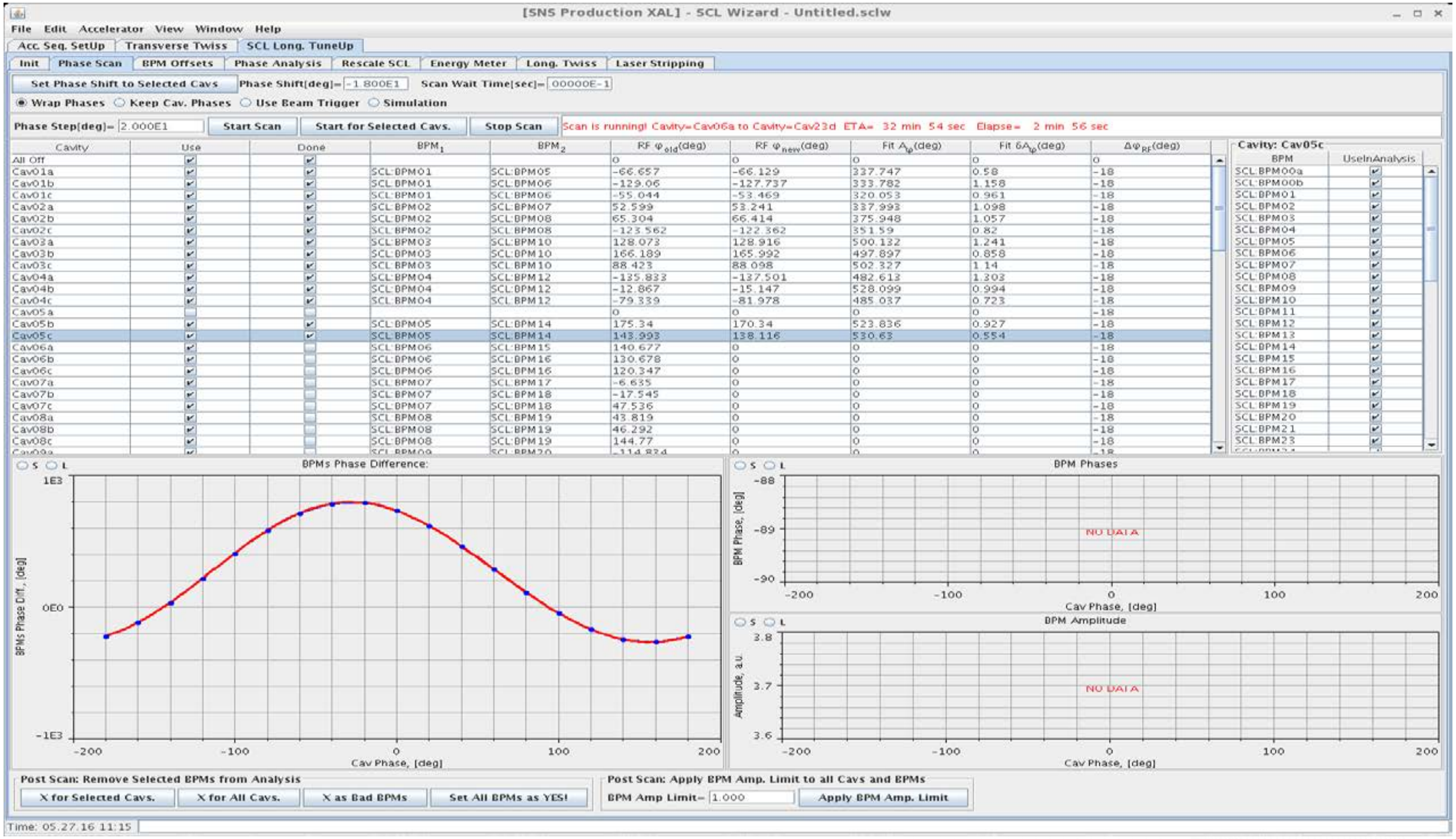
2014.08.10

Longitudinal beam size
Peak current 24 mA
Production beam

- Beam un-matched longitudinally
- Agreement Model/Measurements is good.

Integrated SNS SCL Optics OpenXAL Application

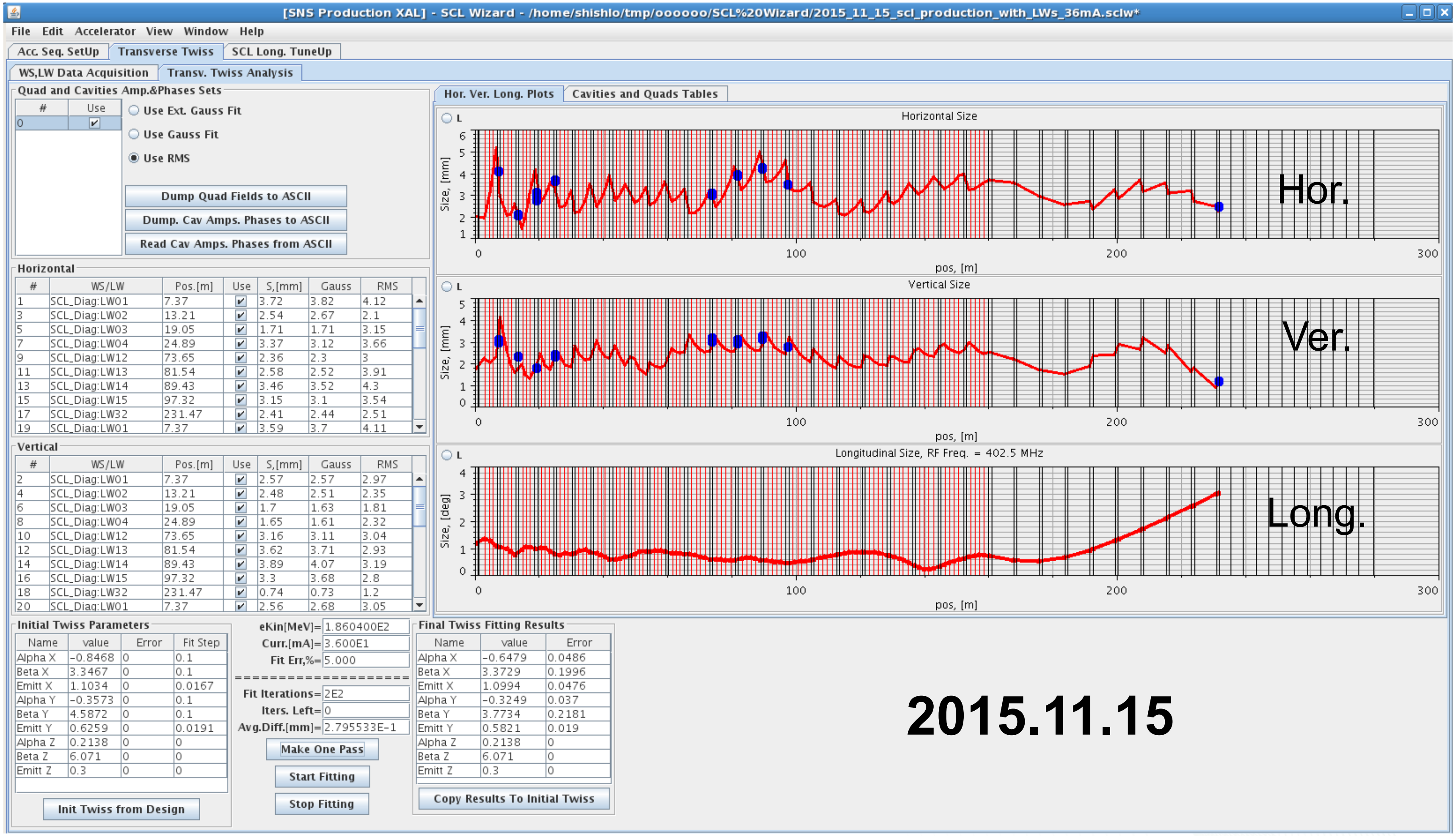
SNS SCL Wizard OpenXAL Application



The application includes:

- **Transverse LW data acquisition and analysis**
- **SCL RF phase scans and analysis**
- **Longitudinal Twiss analysis**
- **Based on OpenXAL Online Model**

Successful SCL Optics Control

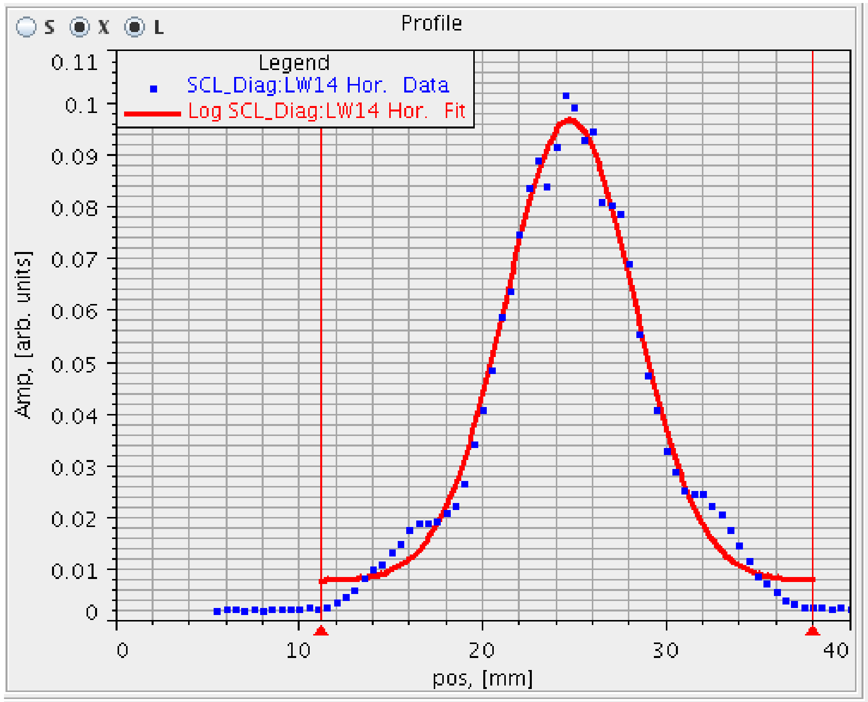


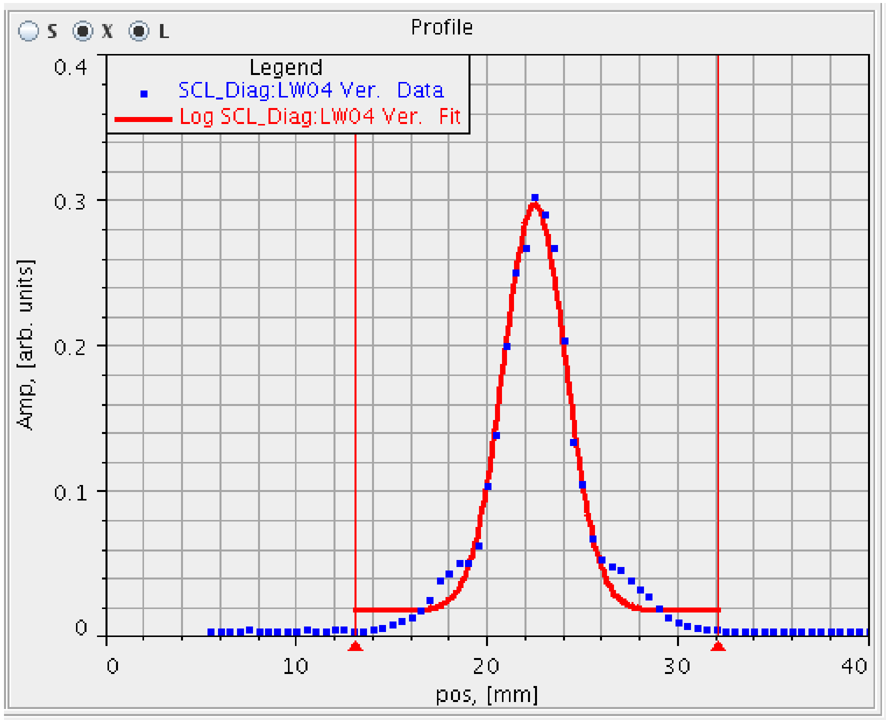
2015.11.15

Now we can reproduce RMS sizes along the whole SCL

Problem Non Gaussian Profiles

- Some LW profiles demonstrate big “shoulders”
- We can try to do transverse matching, but results may be different from expectations
- May be we need to check Warm linac settings and use multi-particle PIC code for optics planning





Summary

- A good agreement between the model and measured transverse RMS sizes has been achieved by
  - Correct handling of the errors and measurements planning
  - Correct measurements of the RF system parameters
  - Using the correct input longitudinal Twiss parameters
- It took some time (about 3 years) and persistence
- We are ready to try matching in the SNS SCL again

Thanks!