Novel Methods for Experimental Characterization of 3D Superconducting Linac Beam Dynamics

Andrei Shishlo,

SNS, Accelerator Physics Group

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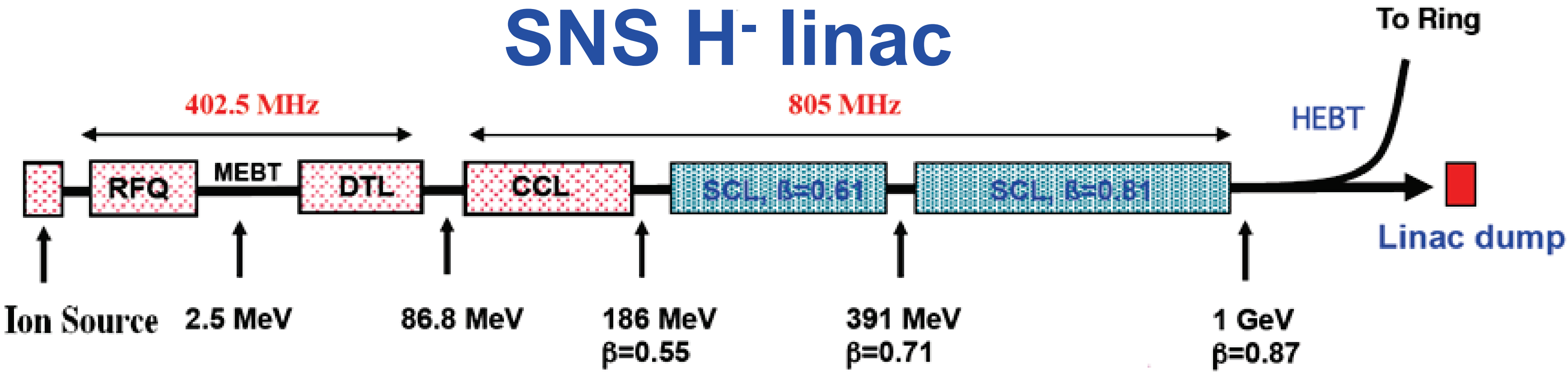
Outline

- SNS Accelerator Overview
- Beam Loss in Superconducting Linac (SCL)
  - Intra Beam Stripping Mechanism
  - Rationale for 3D Bunch Control
- Initial Transverse and Longitudinal Twiss
  - Algorithm for Twiss Parameter Measurements
  - Transverse Twiss
  - Longitudinal Twiss Measurements with BPM
- Longitudinal Twiss along SCL
- Conclusions

SNS Linac Structure

SNS H^- linac



Length: 330 m (Superconducting part 230 m)

Production parameters:

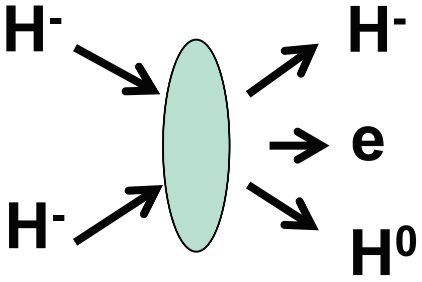
Peak current: 38 mA
Repetition rate: 60 Hz
Macro-pulse length: 0.8 ms
Average power: 1 MW

Diagnostics:
BPM - Beam Position Monitors through the whole linac
BSM - Beam Shape Monitors in CCL
LW - Laser Wire stations, 9 stations in SCL

Beam Loss in the SCL

- According to the design the SCL should be loss-free and activation-free because
  - Beam pipe aperture is about 10 times beam rms size
  - Vacuum is one order of magnitude better than in DTL, CCL
  - Residual gas is H^0 instead of nitrogen
- Loss and activation were reduced by reducing the SCL quad gradients – counterintuitive
- Now the SNS power is not limited by SCL loss and activation
- The Intra Beam Stripping (IBSt) mechanism was suggested to explain these losses
- Bam loss has been reduced, but we want to reduce it further based on the known loss mechanism

Intra Beam Stripping



$$\frac{1}{N}\frac{dN}{dz}=\frac{N\sigma_{IBSt}\sqrt{\gamma^2\left(\theta_x^2+\theta_y^2\right)+\theta_z^2}}{8\pi^2\gamma^2\cdot s_x\cdot s_y\cdot s_z}\cdot F$$

$$\theta^2_{x,y,z}=\varepsilon_{x,y,z}/\beta_{x,y,z}$$

$$F\approx 1\div 1.15$$

$$s_{x,y,z}=\sqrt{\varepsilon_{x,y,z}\cdot\beta_{x,y,z}}$$

ε,β Twiss parameters

- ☐ **According to the IBSt mechanism, beam loss is determined by the rms Twiss parameters: by the core of the beam, not by the halo.**
- ☐ **To control the losses we have to control the Twiss parameters along SCL. This should be easier than controlling the beam halo.**

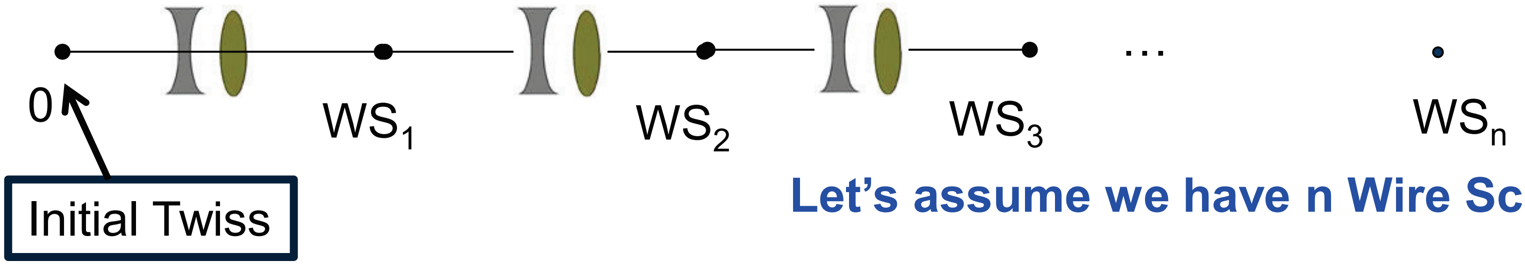
3D Twiss Parameter Control

To provide the control over the X,Y,Z RMS Twiss parameters along SCL we need:

- **Model**
  - **We will use the XAL Online Model (OM). OM is an envelope tracking code developed at SNS and Los Alamos. It includes space charge effects.**
- **Initial Twiss parameters at the entrance of SCL**
  - **Laser Wire stations for transverse profile measurements.**
  - **SCL BPMs for longitudinal.**

The lattice parameter optimization (quad gradients and rf cavity phases) to reduce the beam loss is a subject of future studies.

Measurements of Initial Twiss



Let's assume we have n Wire Scanners

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

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

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

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

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

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

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 !

Initial Twiss Errors

$$\left(M^T \cdot W \cdot M\right)^{-1}$$

Covariance matrix for

$$\left\langle x_0^2 \right\rangle, \left\langle x_0 x_0' \right\rangle, \left\langle (x_0')^2 \right\rangle$$

$$\begin{pmatrix} \mathrm{cov}(\left\langle x_0^2 \right\rangle) \\ \mathrm{cov}(\left\langle x_0 \cdot x_0'' \right\rangle) \\ \mathrm{cov}(\left\langle (x_0'')^2 \right\rangle) \end{pmatrix} = \left\{ \left(M^T \cdot W \cdot M\right)^{-1} \right\}_{Diagonal}$$

---------------- Correlations Analysis ---------------

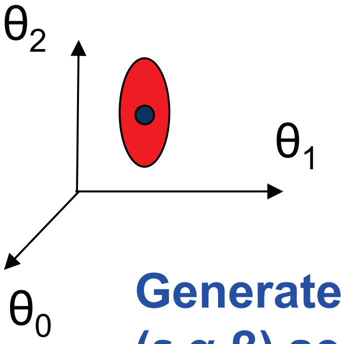
$$\left(M^T \cdot W \cdot M\right)^{-1} = V \cdot \boxed{D} \cdot V^T;$$

Diagonal matrix

$$\begin{pmatrix} \left\langle x_0^2 \right\rangle \\ \left\langle x_0 \cdot x_0'' \right\rangle \\ \left\langle (x_0'')^2 \right\rangle \end{pmatrix} = \mathrm{V}^{\mathrm{T}} \cdot \vec{\theta}$$

"Diagonal" variables

$$\left\langle \theta_i \theta_j \right\rangle = 0 \quad \text{for i} \neq \text{j}$$



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

$$\alpha = \frac{\left\langle x_0 \cdot x_0'' \right\rangle}{\varepsilon_{rms}}$$

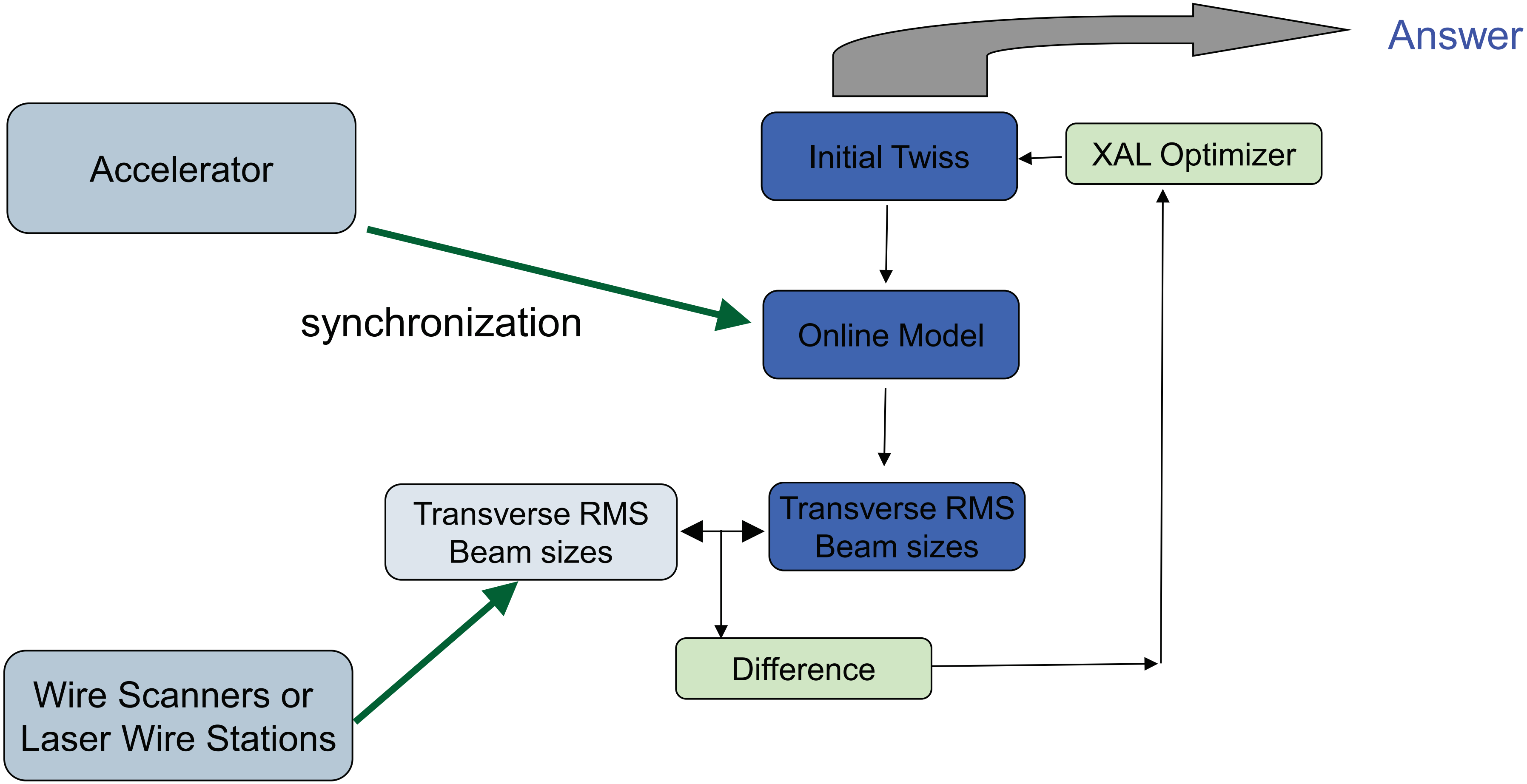
$$\beta = \frac{\left\langle x_0^2 \right\rangle}{\varepsilon_{rms}}$$

Generate points in θ space and get (ε,α,β) sets to plot regions of correlation

Initial Twiss Analysis

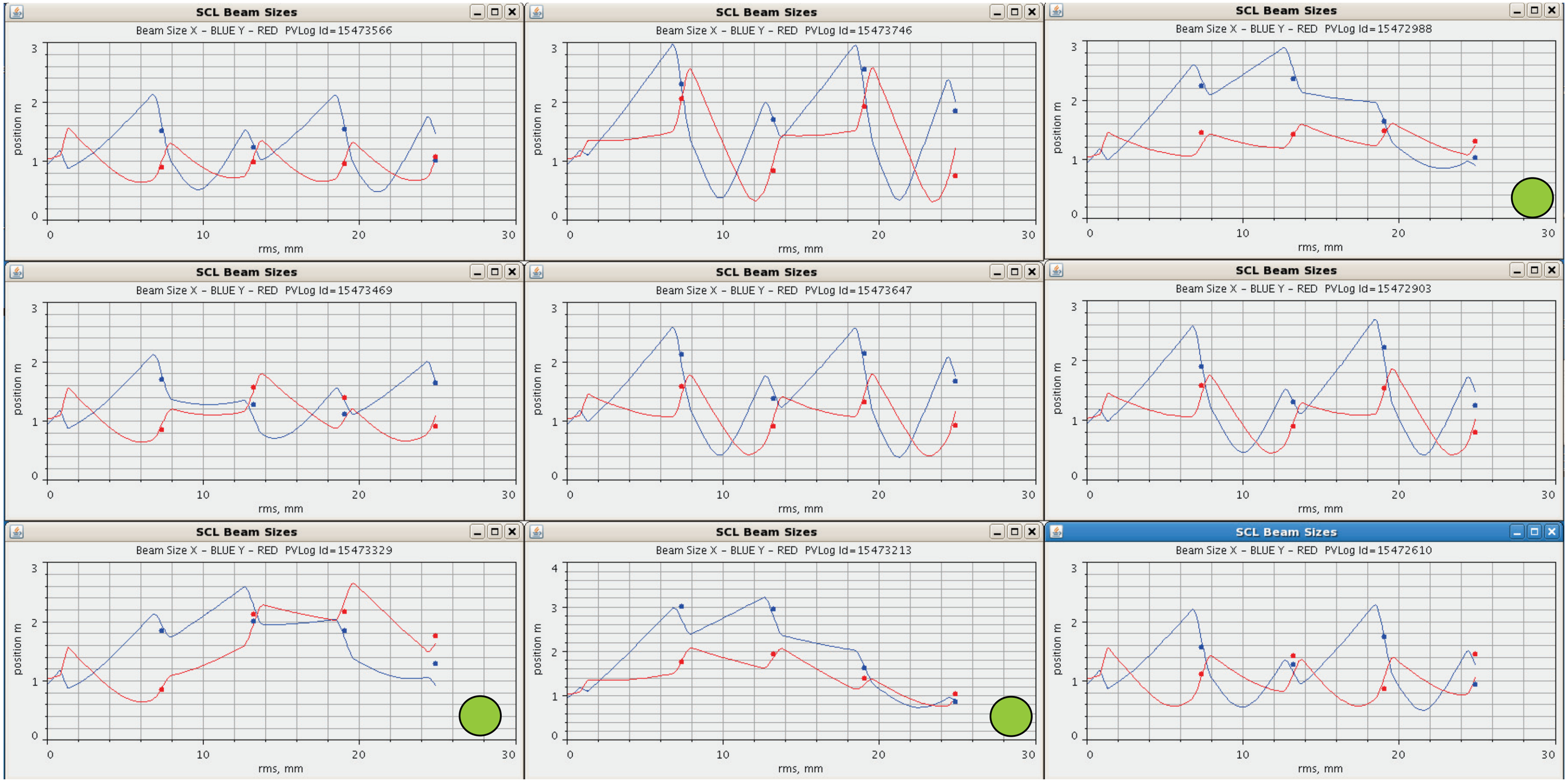
- “Rule of thumb” – 90^0 /(n-1) betatron phase advance between “WS stations” or lattices
- Plan how to reduce errors. The design is not always a good starting point.
- If there is no space charge everything is straightforward.
- Space Charge makes equation (1) transcendental, because the transport matrices are functions of the initial Twiss. A special treatment is needed.

Twiss Analysis with Space Charge



- ❑ **We have a special XAL application based on OM and optimizer.**
- ❑ **After the initial Twiss parameters are found, we generate transport matrices and calculate the errors**
- ❑ **There are uncertainties. The best way to reduce them is to increase the number of meaningful measurements.**

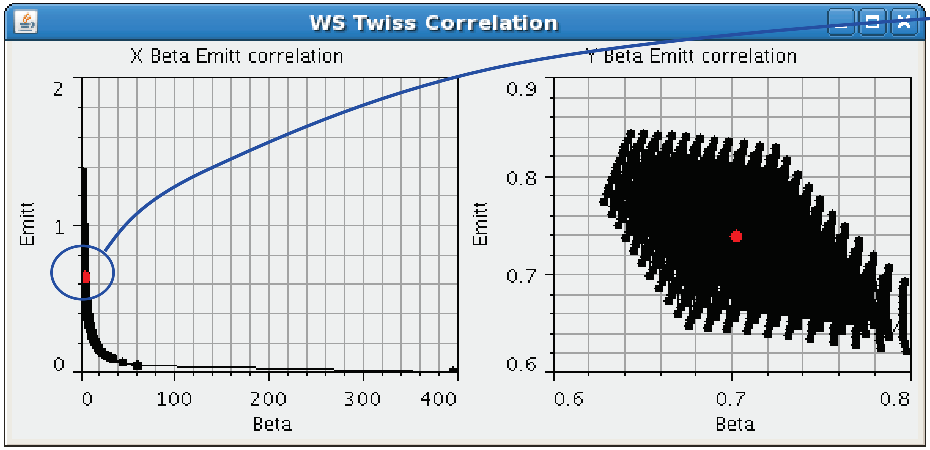
No RF, No Space Charge Case LW 1-4



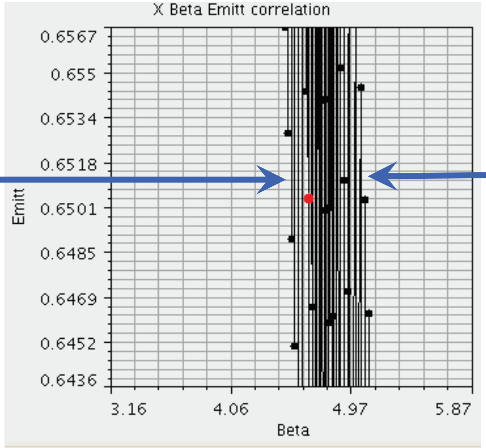
- One initial Twiss for all 9 cases
- The lines are the model predictions, and the agreement is good
- The 9-cases were analyzed by using the technique described above
- Laser Wire Profile Stations are working correctly

● Good cases

Correlation of Twiss Parameters



zoom



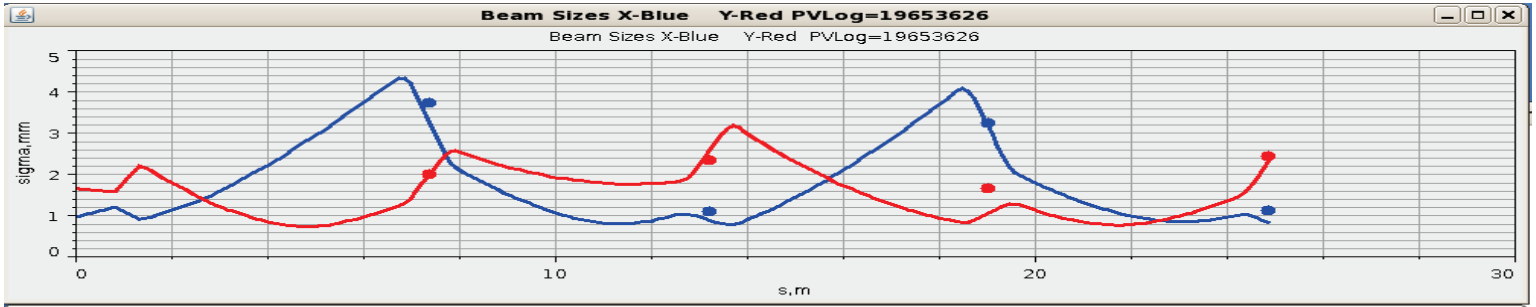
The projection of the ellipse in "diagonal" variables space onto the emittance-beta plane. Very strong correlation in the horizontal plane.

The error for beta is much smaller if we assume that we know the emittance

Error and correlation analysis is a very useful tool

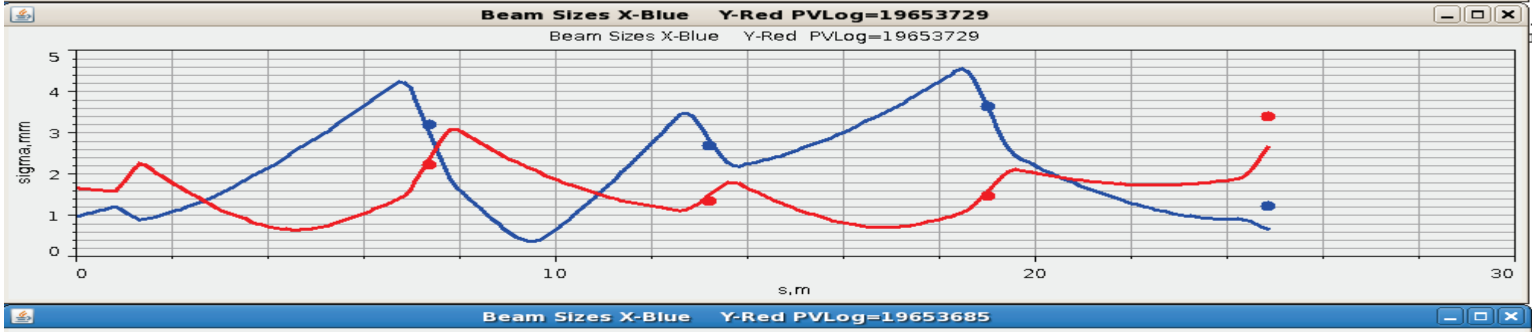
Emittance – beta correlations are very common!
Usually it means that the size is almost fixed.

LW 1-4, Peak Current 37 mA, RF On



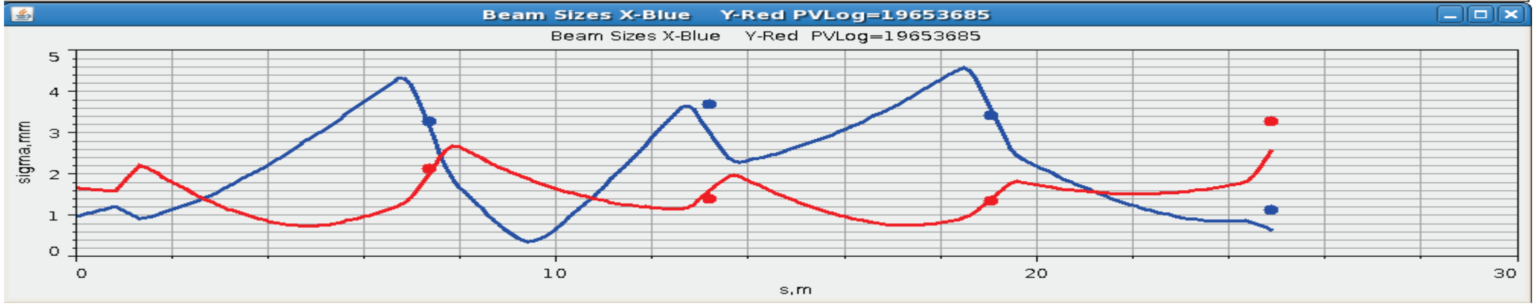
Beam Sizes X-Blue Y-Red PVLog=19653626

Beam Sizes X-Blue Y-Red PVLog=19653626



Beam Sizes X-Blue Y-Red PVLog=19653729

Beam Sizes X-Blue Y-Red PVLog=19653729



Beam Sizes X-Blue Y-Red PVLog=19653685

Beam Sizes X-Blue Y-Red PVLog=19653685

	Alpha	Beta	Emittance*10^6
Horizontal	-0.55 +- 0.22	2.35 +- 0.84	0.40 +- 0.08
Vertical	0.66 +- 0.14	7.65 +- 1.78	0.38 +- 0.05

How to Measure Longitudinal Twiss

- **We can use Bunch Shape Monitors**
  - For SNS they are in the CCL, which is a very long structure with many RF gaps. Data will be very sensitive to the model.

- **We can try to use Beam Position Monitors (BPM) as analogs of wire scanners to measure the longitudinal RMS size of the bunch**

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.**

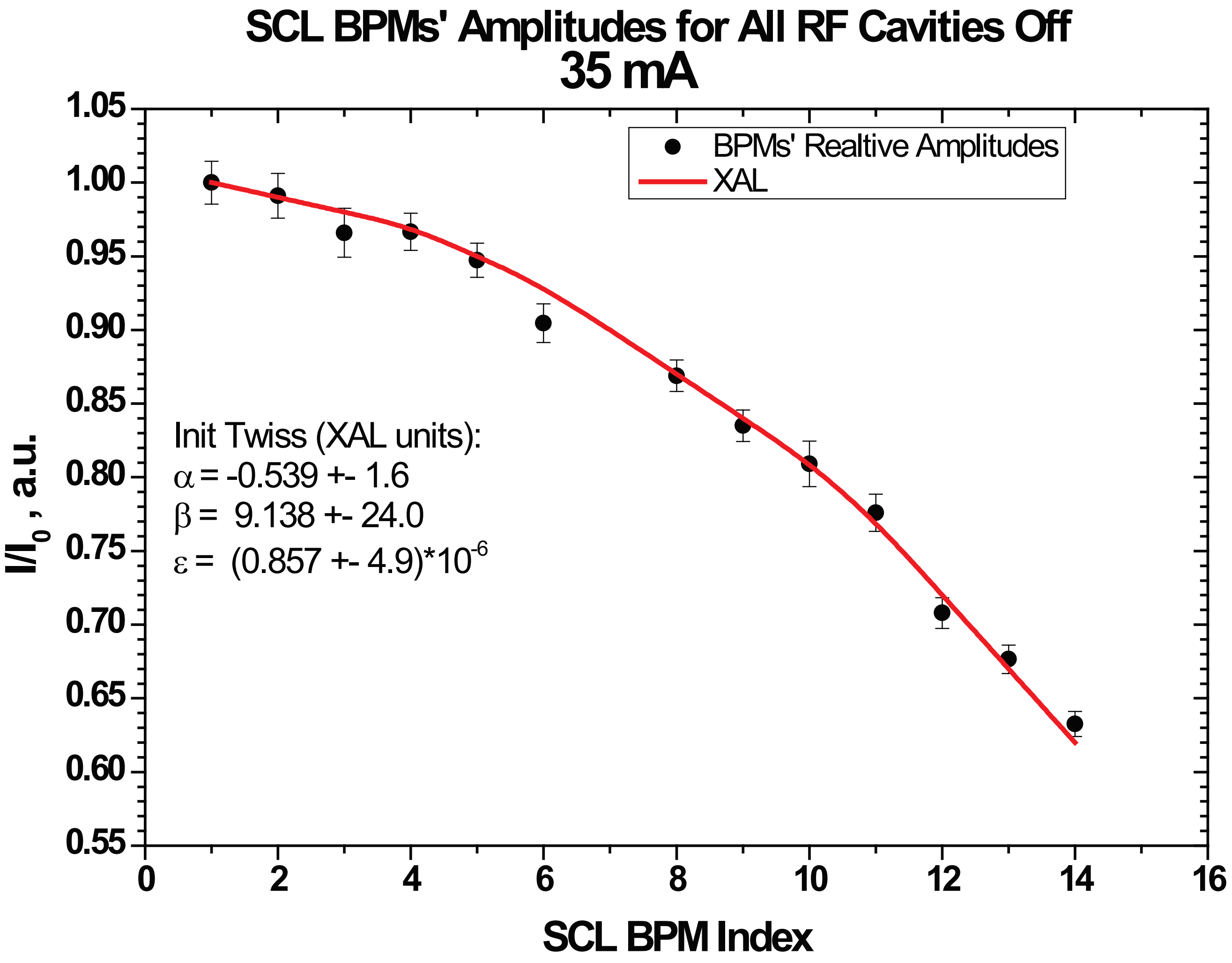
$$\sigma_\varphi = \frac{360^0}{\sqrt{2} \cdot \pi} \sqrt{\ln\left(\frac{A_0}{U_{BPM}}\right)}$$

BPMs give RMS size only. No profiles are available.

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

The Free Debunching Case

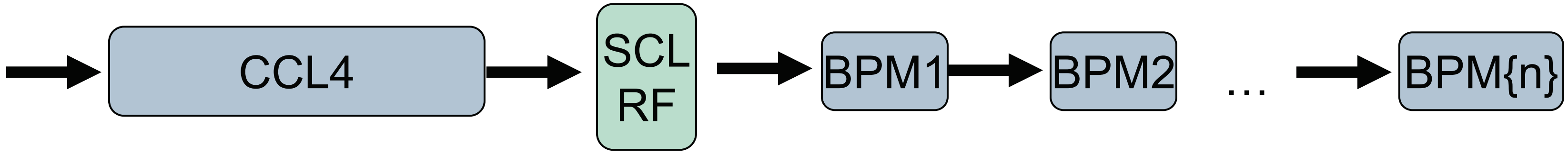
→ CCL4 → BPM1 → BPM2 … → BPM{n}



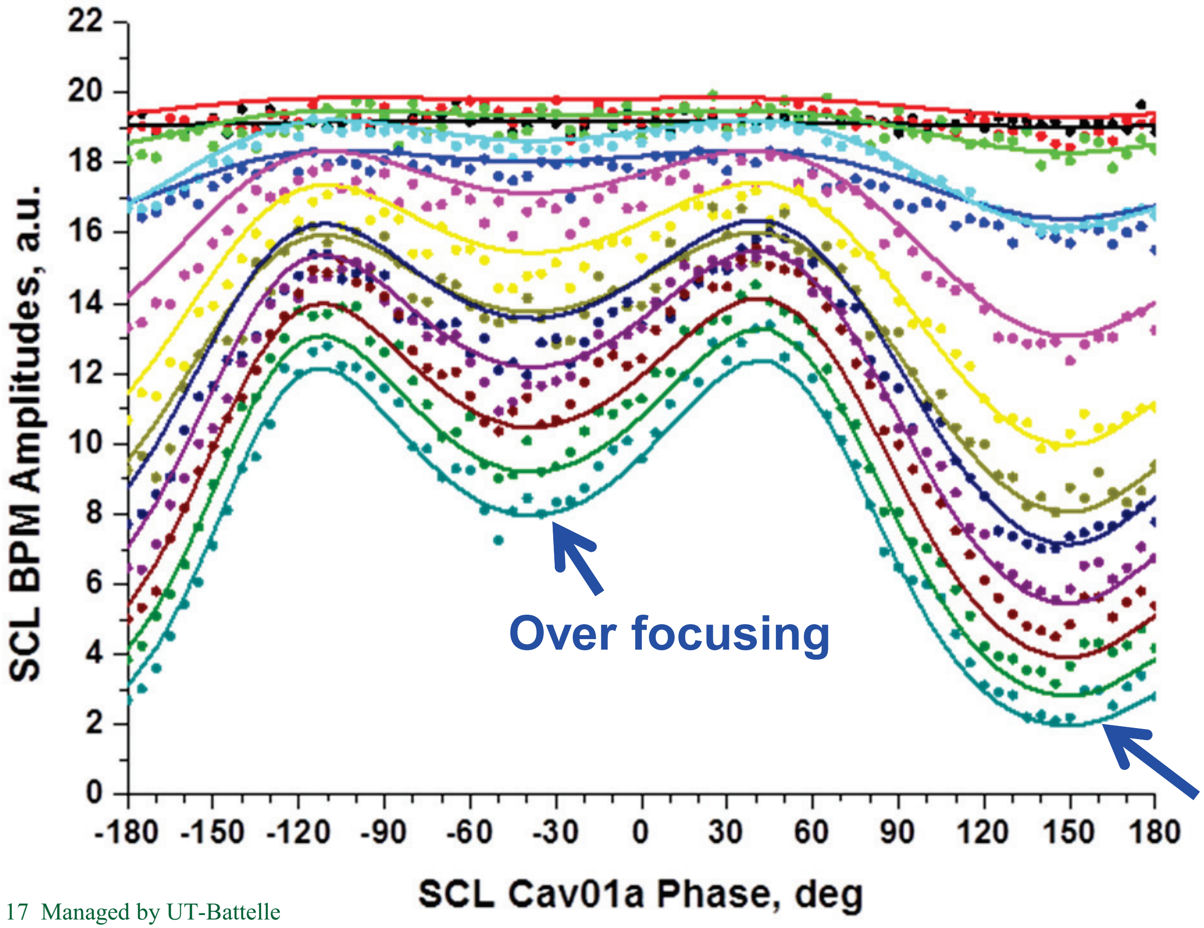
All SCL RF are OFF
Statistics:
40 measurements
13 BPMs

Errors are too big!

Longitudinal 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.



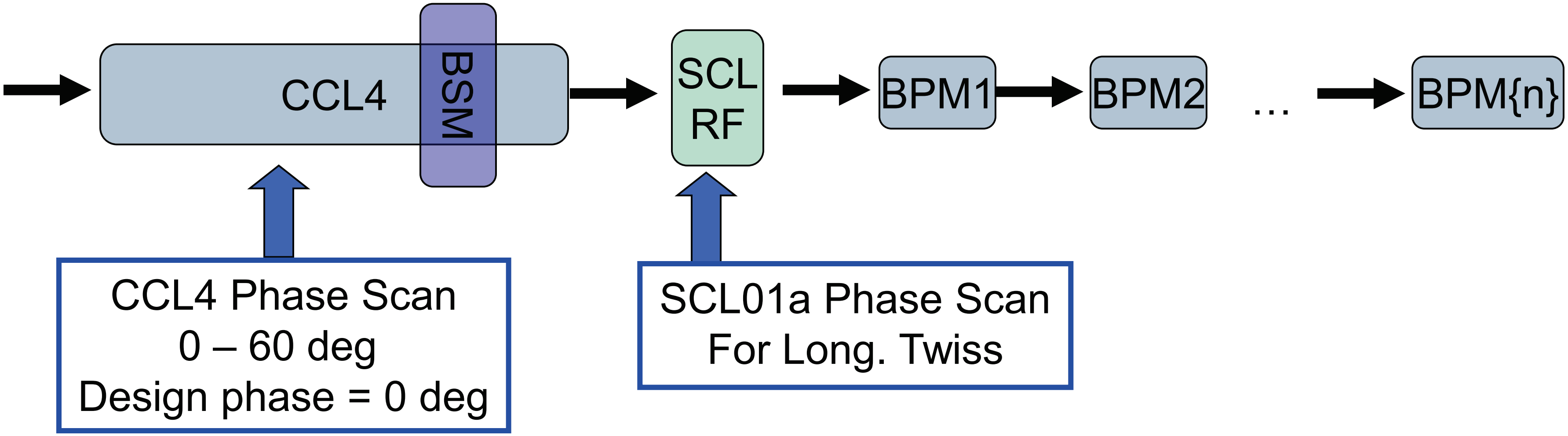
Over focusing

Defocusing

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).

SCL Twiss for CCL4 Phase Scan

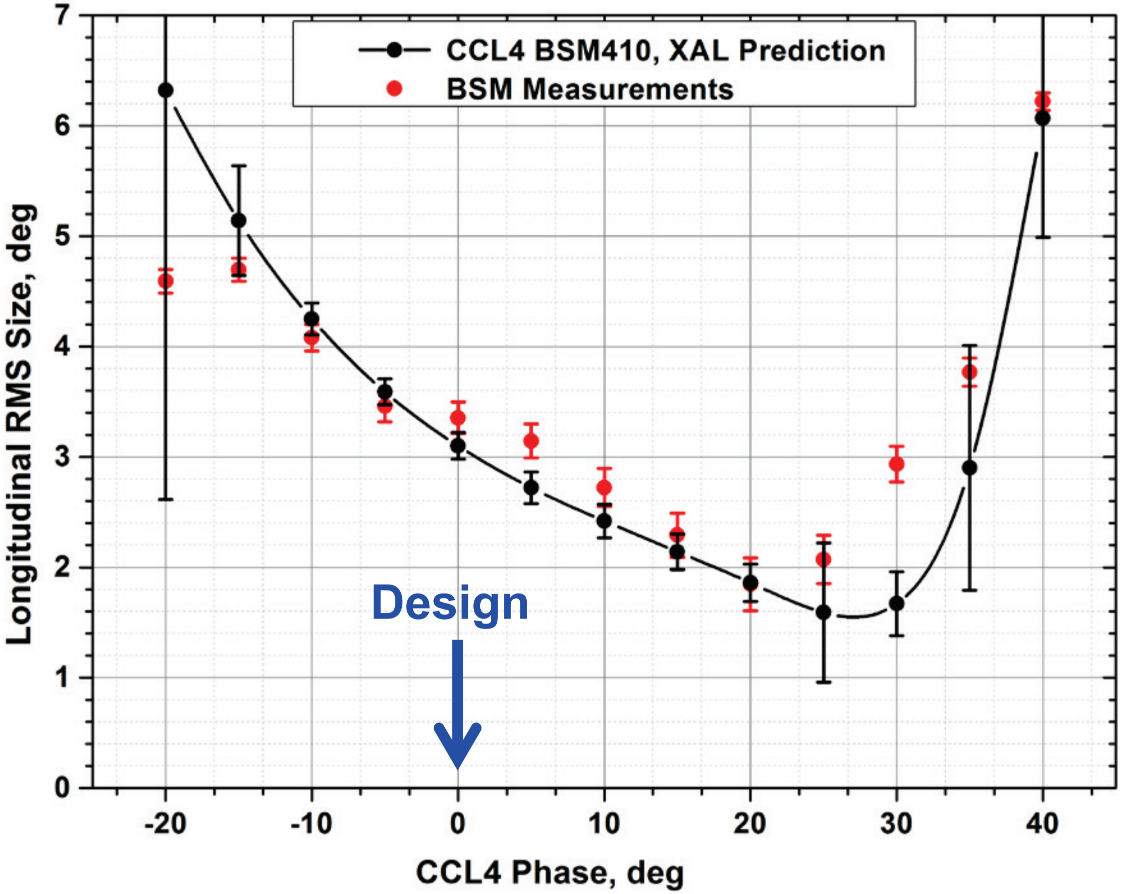


CCL4 Phase Scan
0 – 60 deg
Design phase = 0 deg

SCL01a Phase Scan
For Long. Twiss

- **We want to verify our method with something different**
- **Studies performed on 09.22.2012**
- **Simultaneous BSM-410 measurements**
- **Peak beam current 35 mA**

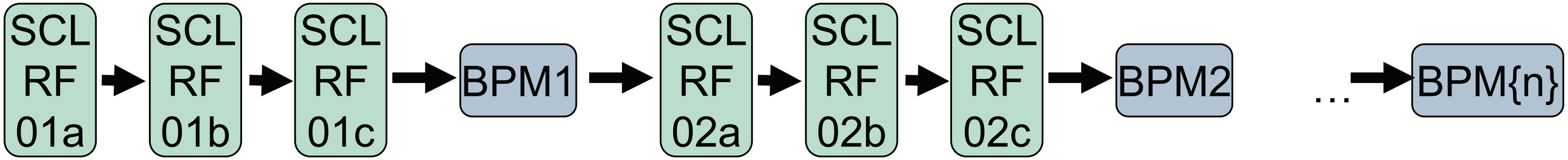
CCL Bunch Length for Two Methods



Results are very close. It proves the applicability of the new method.

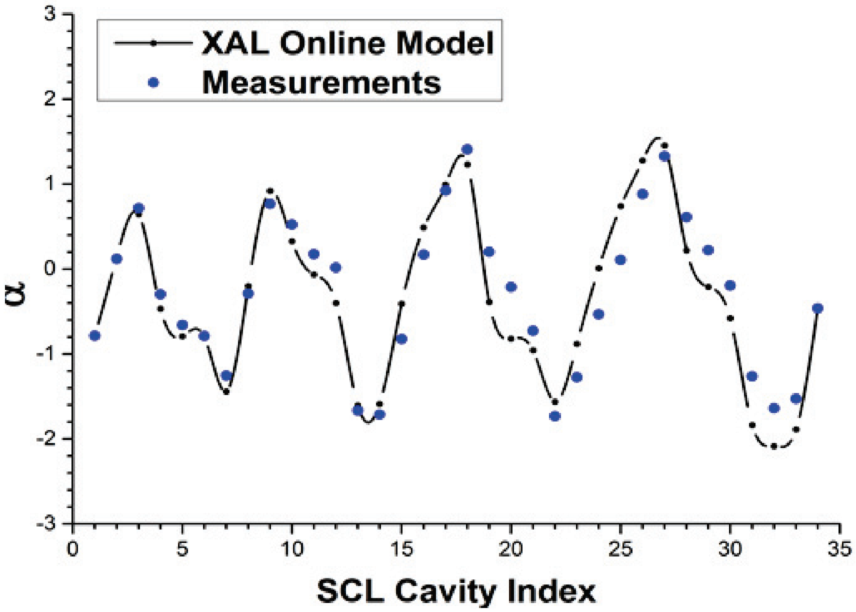
Limitations: assumption of Gaussian distribution in the bunch.
If we are far from the matched case (design) the bunch could be non Gaussian.

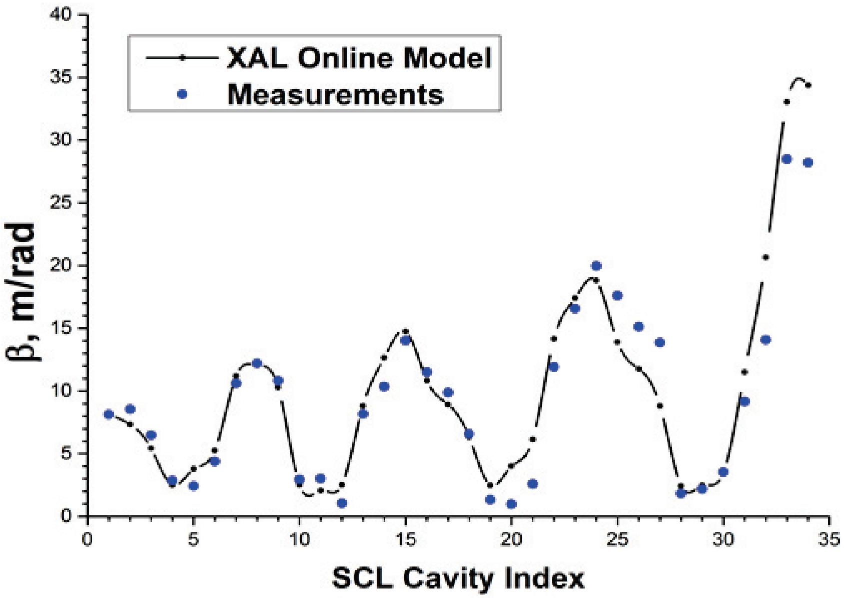
Longitudinal Twiss along SCL (1)



- **We can use each cavity in SCL as the measuring point for the longitudinal Twiss**
- **Data were collected in April, 2013**
- **Only cavities in the first 12 cryomodules were scanned (34 cavities)**
- **The BPM amplitude calibration was calculated by using the same scan data, so only about half of BPMs were calibrated properly.**
- **For the first cavity we used the analysis described, but for all downstream cavities we assumed a constant normalized emittance. It means we fitted α, β Twiss parameters only and un-normalized BPM amplitudes.**

Longitudinal Twiss along SCL (2)





- **We have measurements at the entrance of each cavity, and we can calculate Twiss by using Online Model and the initial Twiss**
- **Results are in a good agreement**
- **The existing discrepancies grow with the distance from the beginning. Probably OM is not very good for very unmatched beams.**
- **In longitudinal direction we have a very unmatched beam. The matching will be done in the future.**

Conclusions

- A new noninvasive method of measurement of longitudinal Twiss parameters in linacs is suggested
- The method was successfully tested at the SNS Superconducting linac
- First time the longitudinal Twiss parameters were measured continuously along the linac
- The XAL Online Model was validated for the SNS linac
- All components for the 3D bunch core control in the SCL are ready, and we can start model-based SCL tuning in the near future

Thanks!