THZD1

NAPAC 2022

FRIB

Instant Phase Setting in a Large Superconducting Linac

Alexander Plastun, Peter Ostroumov

NAPAC22, Albuquerque, NM, USA,

August 11, 2022

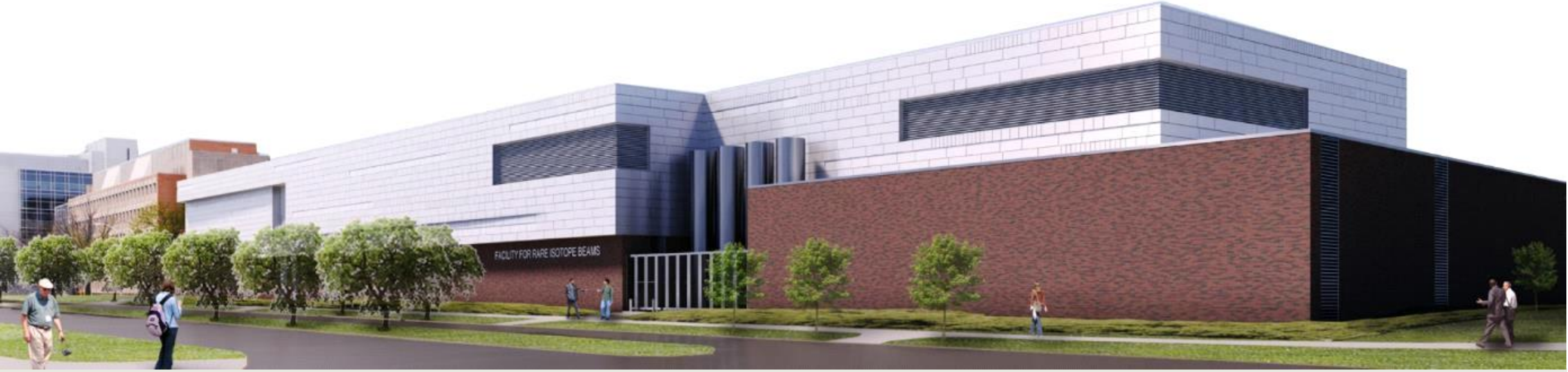
MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

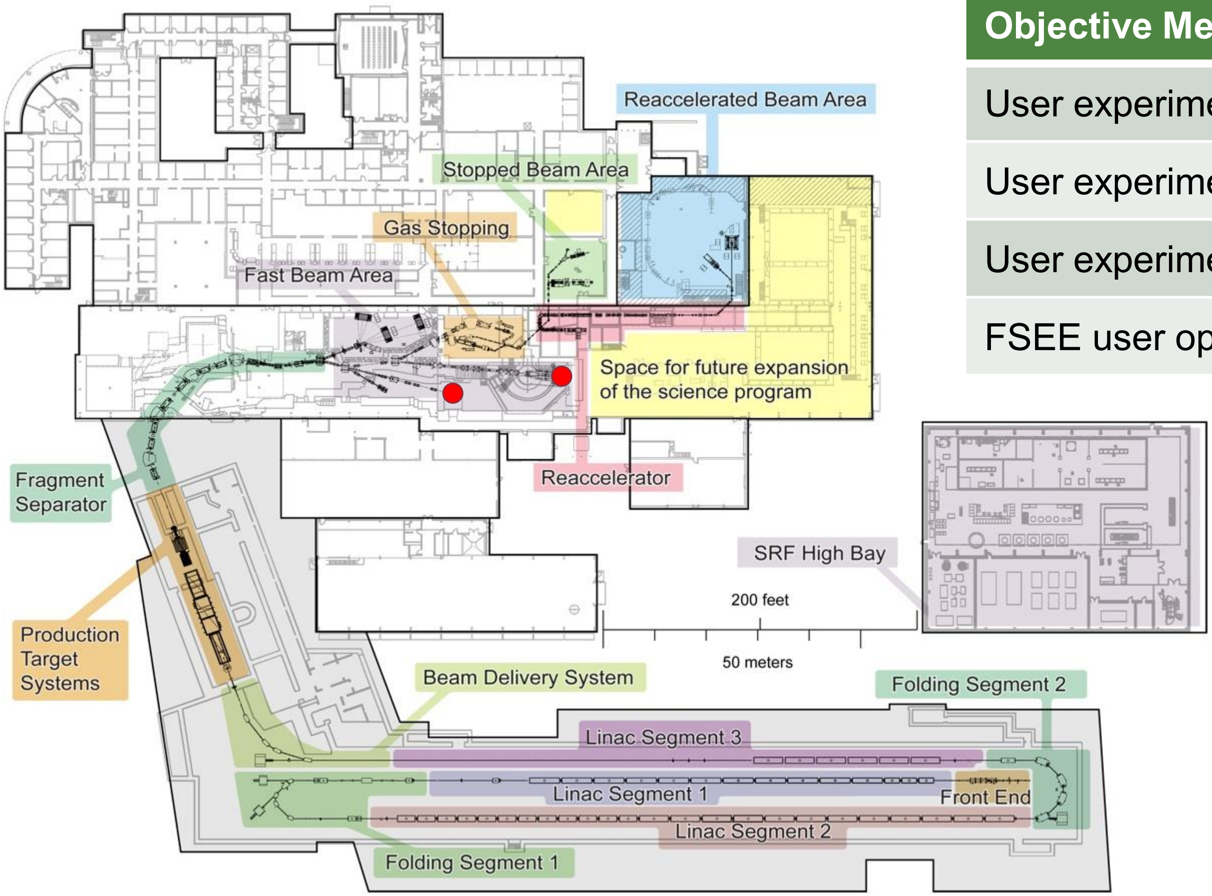
FRIB Construction Completed in Jan. 2022 On Cost and Five Months ahead of Schedule

- FRIB Project constructed a $730 million national user facility funded by the U.S. Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB construction completed in January 2022, on cost and five months ahead of schedule
- FRIB is now a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC



Started User Program May 11, 2022

- FRIB provided isotope beams to the decay station (FDSi) and S800 from 11 May to 2 August for 3 user experiments

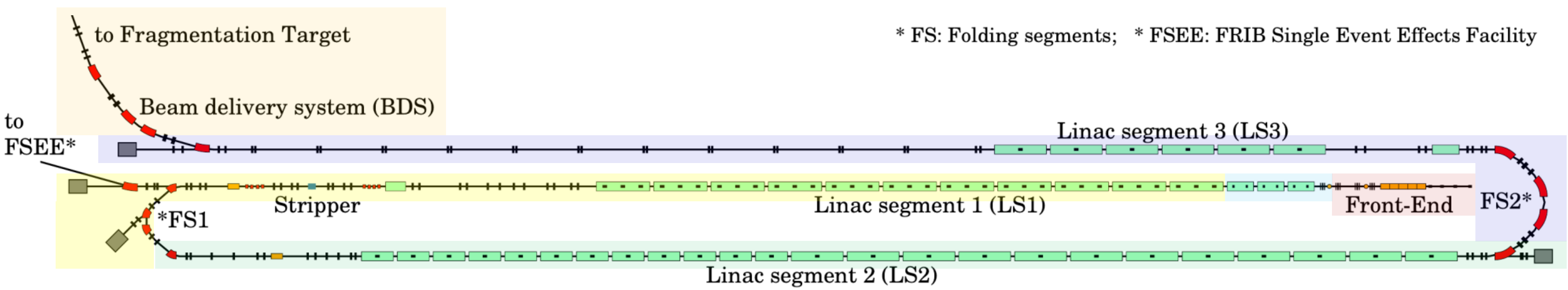


Objective Measures	Date
User experiment #21062 at FDSi	May 2022 ✓
User experiment #21069 at FDSi	Jun 2022 ✓
User experiment #21007 at S800	Aug 2022 ✓
FSEE user operation start	Jan 2022 ✓

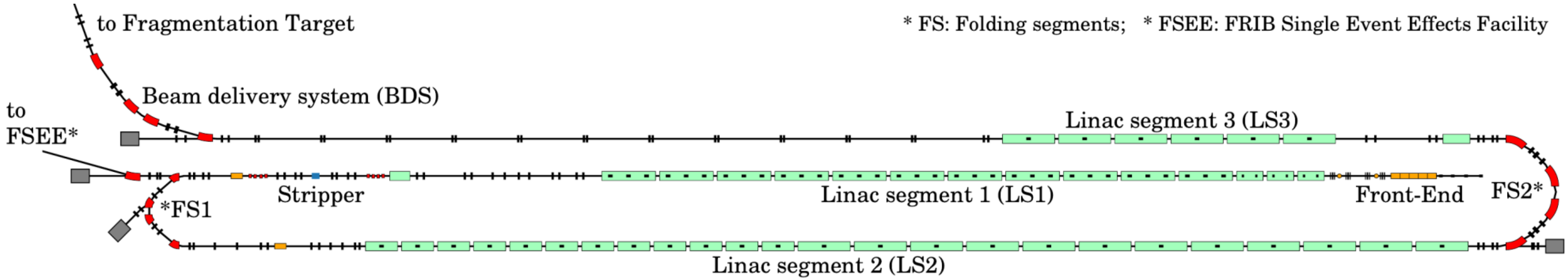
- Primary beam: 1 kW of
  - ^{48}Ca; ^{82}Se; ^{70}Zn
- RI beams:
  - ^{42}Si
  - ^{49}K and ^{52}K
  - ^{65}Co and ^{64}Fe

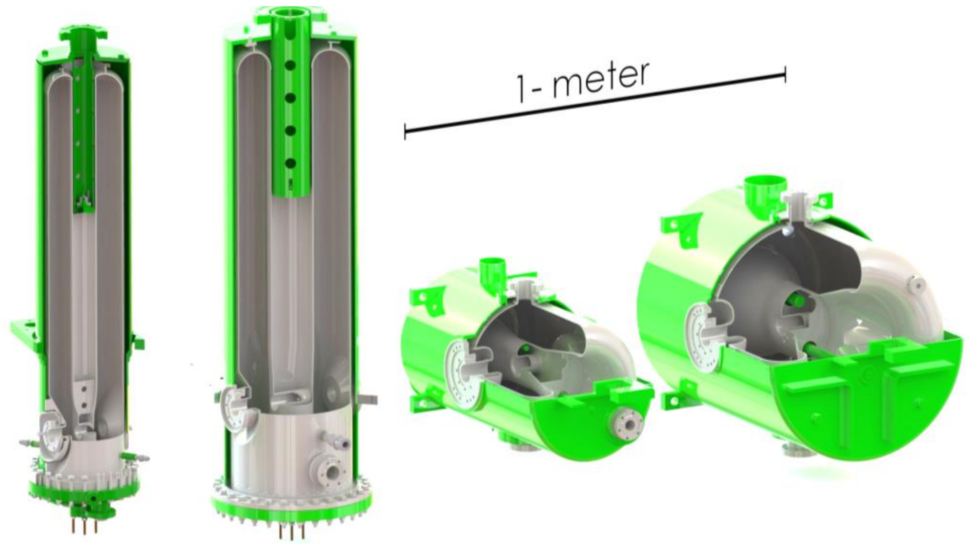
Beam Commissioning in 7 phases over 5 years

	Area with beam	Energy	Date
1	Ion source, LEBT, RFQ, MEBT	0.5 MeV/u	July 2017
2	Linac Segment 1 with β=0.041 cryomodules	2 MeV/u	July 2018
3	LS1 with β=0.041 and 0.085 cryomodules	20 MeV/u	February 2019
4	Linac Segment 2 β=0.29 and 0.53 cryomodules	200 MeV/u	March 2020
5	Linac Segment 3 β=0.53 cryomodules	> 200 MeV/u	May 2021
6	Target hall pre-separator		December 2021
7	Entire FRIB construction scope		January 2022



FRIB Cavities



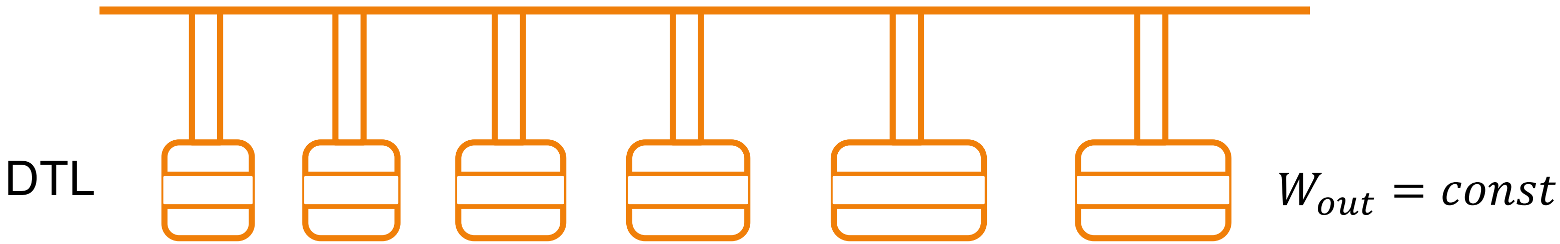


	QWR 80.5 MHz β = 0.041	QWR 80.5 MHz β = 0.085	HWR 322 MHz β = 0.29	HWR 322 MHz β = 0.53
#	12	92	72	148

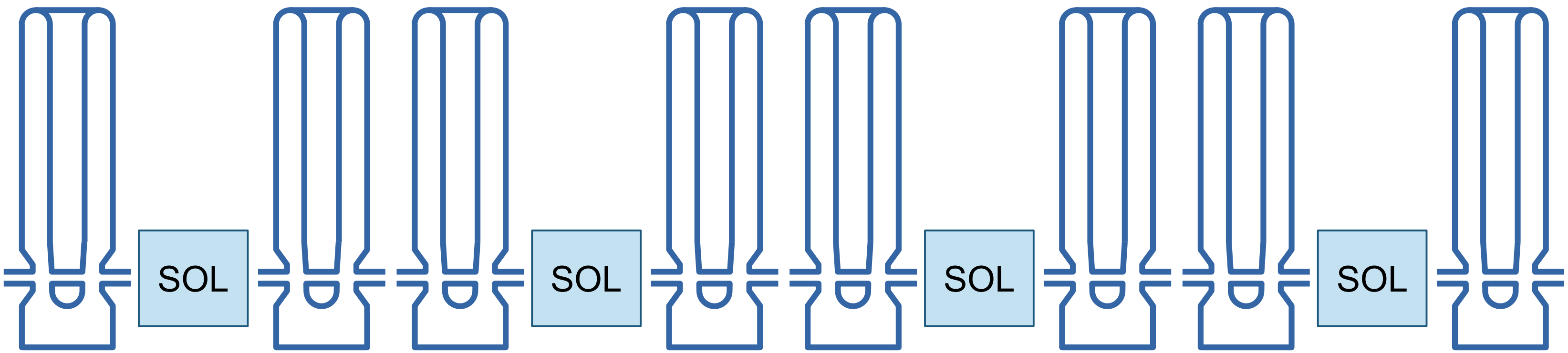
324 SRF cavities!
+ RT RFQ & 4 bunchers

Phase Setting Purpose

- Establish the design velocity profile $\beta(z)$



Fixed velocity profile: defined by geometry

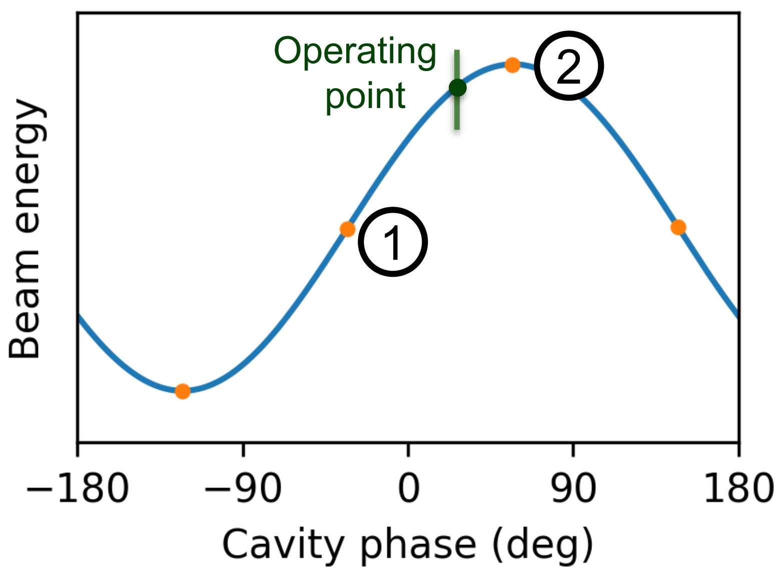


Variable velocity profile: defined by synchronization of independently phased cavities

Lighter ions can be accelerated to higher energies

Phase Setting

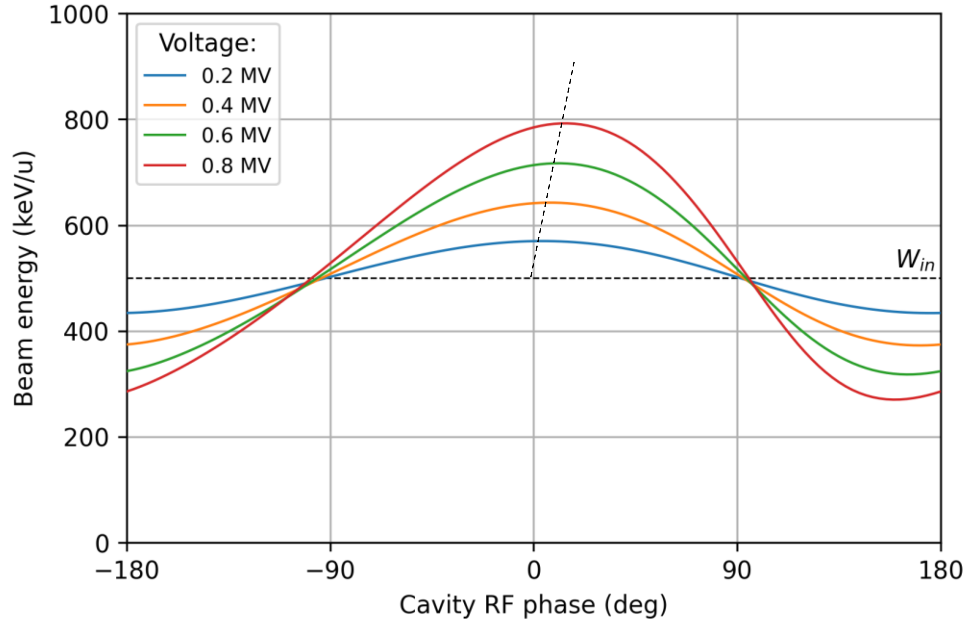
- The phase of a cavity is varied in the range of [-180 deg, 180 deg]
- The beam energy can be measured…
  - using a calibrated dipole magnet
  - using a dipole magnet in a combination with a beam position detector
  - using silicon detectors
  - using various time-of-flight techniques by means of
    - gamma-ray detectors
    - fast current transformers
    - beam position/phase monitors (BPPMs or BPMs)
    - cavities as the beam phase detectors.
- Measurements fit into a model
- Reference points are found
  - ① "zero crossing" (easy to find since $W_{in} = W_{out}$)
  - ② maximum (used in theory of RF linacs)
- Operating point is selected



Example: FRIB QWR041

QWR 80.5 MHz
β = 0.041

$\Delta W = qU_{eff} \cdot \cos(\varphi + \varphi_0)$ follows from the Panofsky equation



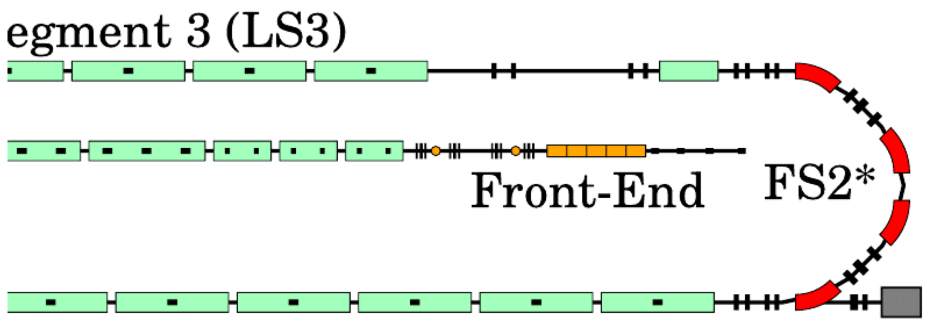
Phase scan waveform changes with cavity field!

- Solutions:
  - follow beam dynamics codes' approach
  - use higher order approximations

Cubic-spline Interpolation of Phase Scans

- TRACK is used at FRIB
  - Calculates output energies for 900 cavity phases in [-180 deg, 180 deg]
  - Creates a cubic spline with the calculated data
  - Evaluates the spline at 36,000 points in [-180 deg, 180 deg]
  - Selects the point of highest energy
  - Adds the value of synchronous (accelerating) phase, and sets it as a cavity operating phase

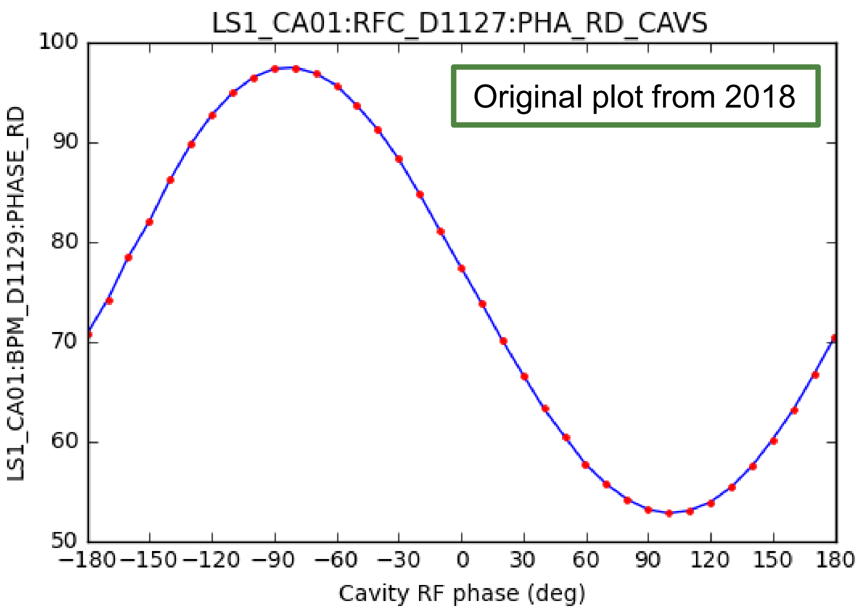
- Beam commissioning in July 2018



Cubic-spline Interpolation of Phase Scans

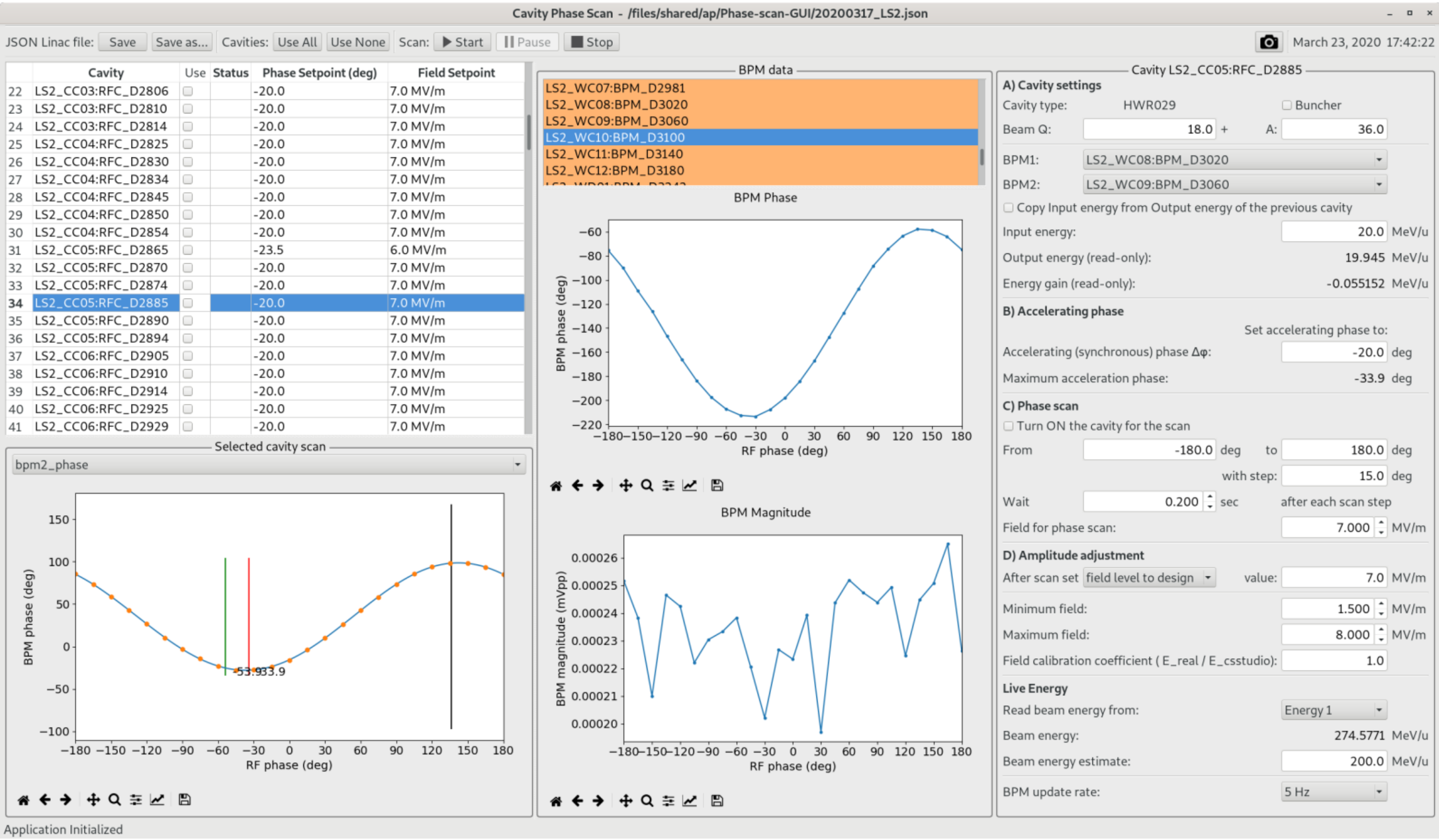
- TRACK is used at FRIB
  - Calculates output energies for 900 cavity phases in [-180 deg, 180 deg]
  - Creates a cubic spline with the calculated data
  - Evaluates the spline at 36,000 points in [-180 deg, 180 deg]
  - Selects the point of highest energy
  - Adds the value of synchronous (accelerating) phase, and sets it as a cavity operating phase

- Beam commissioning in July 2018
  - One-page python script
  - Cavity phase vs BPM phase
  - 10-deg steps
  - Cubic-spline interpolation
  - The minimum was found by eye
  - 5 hours for 12 cavities

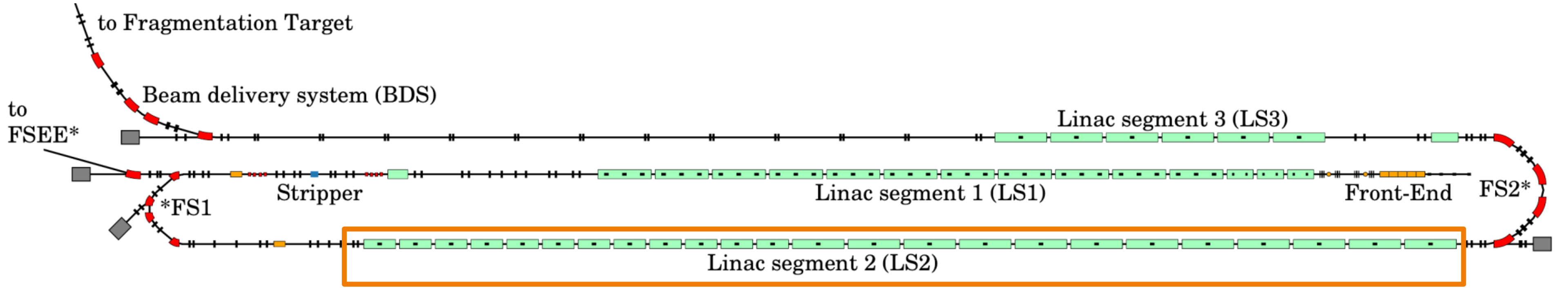


Automated Phase Scans

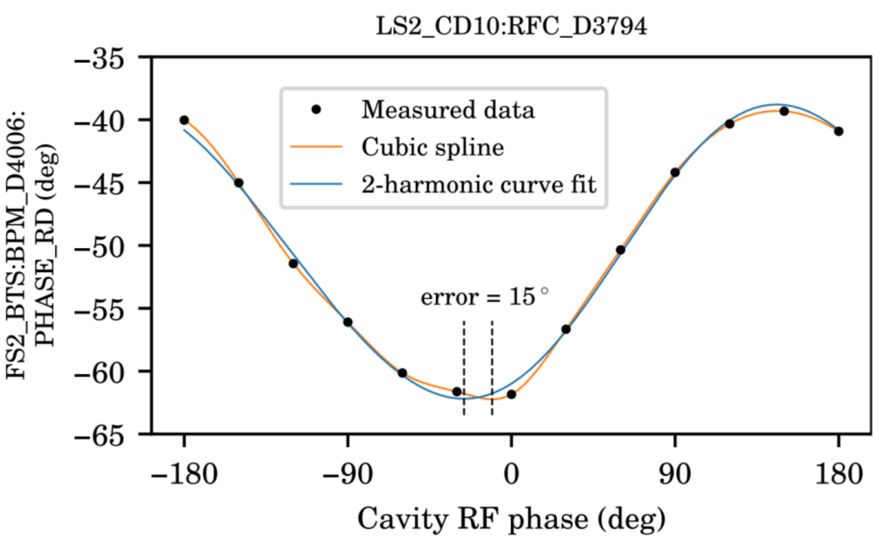
- ALPha (**A**utomated **L**inac **Pha**sing) high-level application



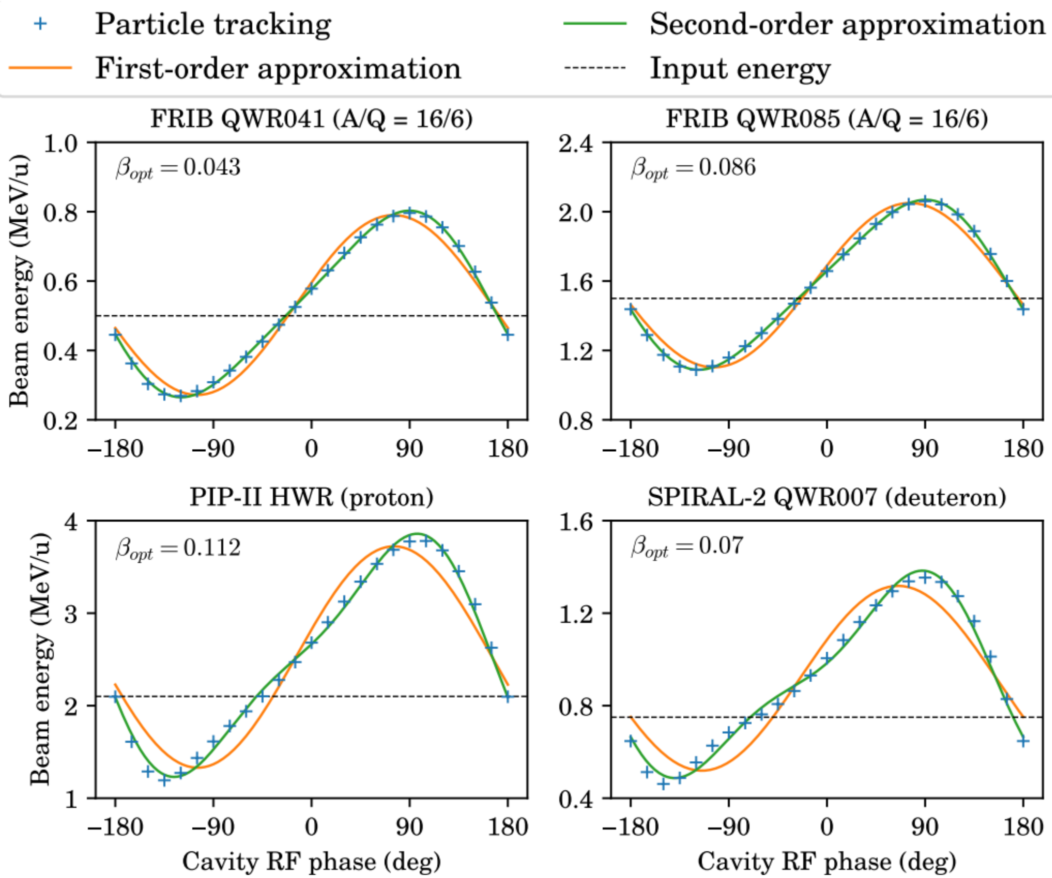
Accuracy Issue due to Cubic-spline Interpolation



- Beam power limit for phasing is 2 W in any linac segment
- Button-like BPM signal strength ~1/β
- No drift to develop significant phase advance between a pair of BPMs
- Energy variation << Beam energy, therefore the variation of the BPM phase is comparable with the signal noise



Approximation



- Cavities at their design fields
- PIP-II and SPIRAL2 field maps are not exact
- Second-order approximation was selected for ALPha

First-order approximation $W = A + B \cdot \cos(\varphi + C)$

Second-order approximation $W = A + B \cdot \cos(\varphi + C) + D \cdot \cos(2\varphi + E)$

Phase Scan Duration

- The best estimate of the phase scans' duration if they are done today:

Segment	Cavities	Duration
MEBT	2	0:10
LS1	12+88	5:00
FS1	4+2	0:20
LS2	72+96	12:00
FS2	4	0:15
LS3	48	2:00
Total	**328**	**19:45**

- Instant Phase Setting is highly demanded at FRIB

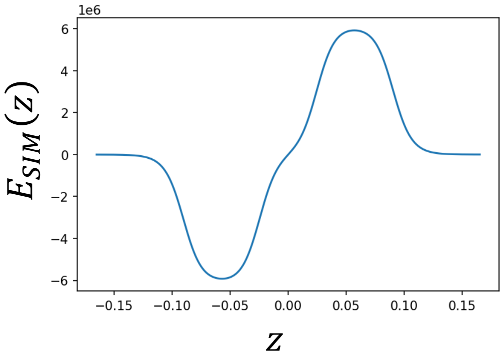
Instant Phase Setting (IPS) model

- Integration of the reference particle motion:

$$\begin{cases} \dfrac{dW}{dz} = qE_z(z,t); \\ \dfrac{dt}{dz} = \dfrac{1}{v_z}. \end{cases}$$

- A single cavity case:

Simulated on-axis field distribution



$$E_z(z) = \begin{cases} E_{SIM}, |z| < \dfrac{L_{cav}}{2}, \\ 0, |z| > \dfrac{L_{cav}}{2}, \end{cases}$$

Control system interface

LS1_CB01

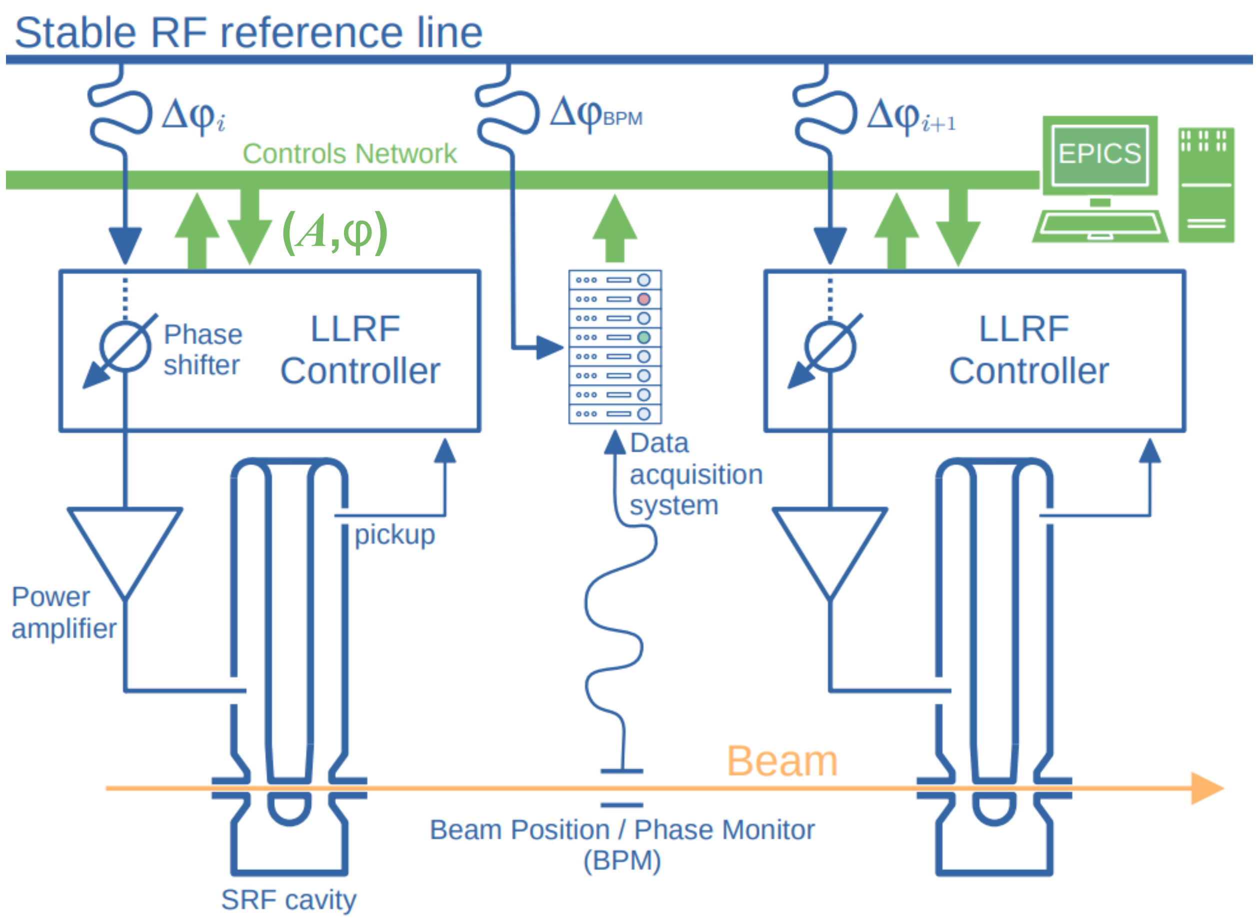
LS1_CB01:RFC_D1229	4.01 MV/m	0.00 MV/m	-141.06 °	41.65 °
LS1_CB01:RFC_D1241	4.55 MV/m	0.00 MV/m	-41.63 °	97.08 °
LS1_CB01:RFC_D1245	4.59 MV/m	0.00 MV/m	34.02 °	80.01 °
LS1_CB01:RFC_D1249	4.59 MV/m	0.00 MV/m	-31.15 °	56.28 °
LS1_CB01:RFC_D1261	4.59 MV/m	0.00 MV/m	-102.01 °	58.95 °
LS1_CB01:RFC_D1265	4.45 MV/m	0.00 MV/m	18.53 °	-65.52 °
LS1_CB01:RFC_D1269	3.77 MV/m	0.00 MV/m	-140.31 °	-106.87 °

$$E_z(z,t) = K \cdot A \cdot E_z\,(z) \cdot \cos(\omega t + \Delta\varphi + \varphi)$$

K – field scaling coefficient,
A – field setpoint in control system
$\Delta\varphi$ – offset relative to the reference signal
φ – cavity phase setpoint in control system

RF System Diagram

$$E_z(z,t) = K \cdot A \cdot E_z\,(z) \cdot \cos(\omega t + \Delta\varphi + \varphi)$$



Single Cavity

- Model:

$$\begin{cases} \dfrac{dW}{dz} = q \cdot K \cdot A \cdot E_z(z)\cos(\omega t + \Delta\varphi + \varphi), \\ \dfrac{dt}{dz} = \dfrac{1}{v_z}, \end{cases}$$

with initial conditions:

$$\begin{cases} W(-L_{cav}/2) = W_0, \\ t(-L_{cav}/2) = t_0. \end{cases}$$

- Calibration

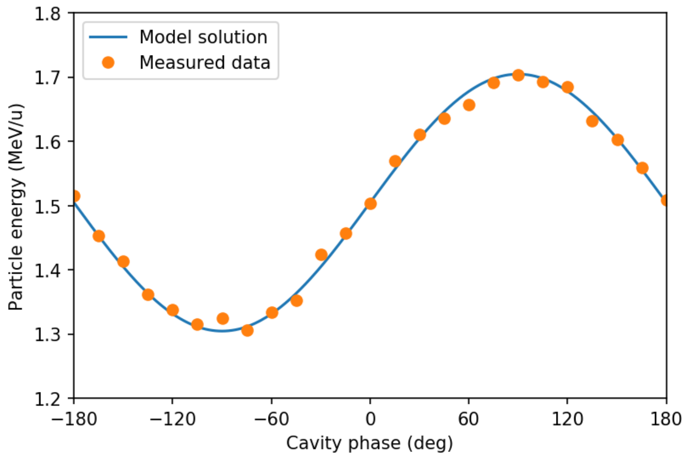
To find two parameters (K, $\Delta\varphi$), solve the system for $N > 1$ cavity phases with the same initial conditions, and fit the solution into the measurement data, i.e.

For $i = 1..N$ points

$$\begin{cases} \dfrac{dW_i}{dz} = q \cdot K \cdot A \cdot E_z(z)\cos(\omega t + \Delta\varphi + \varphi_i) \\ \dfrac{dt}{dz} = \dfrac{1}{v_{z\,i}}. \end{cases}$$

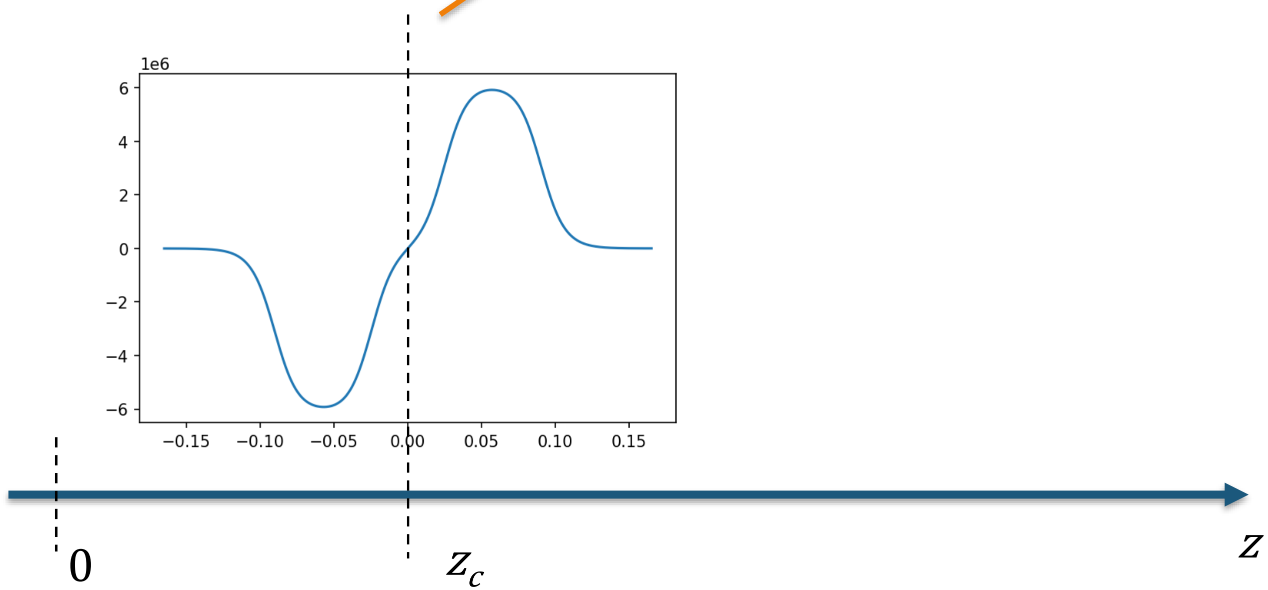
If $\varphi_i = i \cdot \frac{2\pi}{N}$ the set of $\{\varphi_i, W_i\}$ is the 2π phase scan of this cavity. $N = 2$ is the minimum requirement.

For $N > 2$ the parameters (K, $\Delta\varphi$) can be found using the least squares method, which greatly improves the accuracy of K and Δφ.



Cavity Positioning

$$E(z,t) = K \cdot A \cdot E_z\,(z - z_c)\cos(\omega t + \Delta\varphi + \varphi)$$



Multiple Cavities

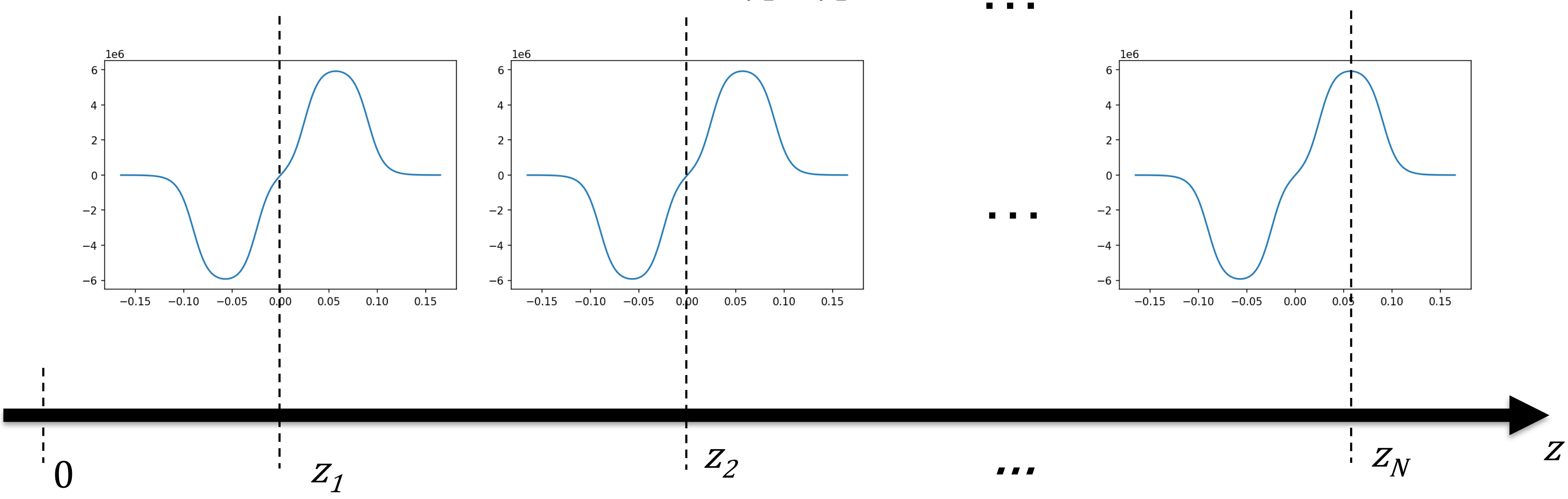
Linear segment consisting N independently energizes and phased cavities:

$$E_1(z,t) = K_1 \cdot A_1 \cdot E_z\,(z - z_1) * \\ * \ \cos(\omega t + \Delta\varphi_1 + \varphi_1)$$

$$E_2(z,t) = K_2 \cdot A_2 \cdot E_z\,(z - z_2) * \\ * \ \cos(\omega t + \Delta\varphi_2 + \varphi_2)$$

...

$$E_N(z,t) = K_N \cdot A_N \cdot E_z\,(z - z_N) * \\ * \ \cos(\omega t + \Delta\varphi_N + \varphi_N)$$



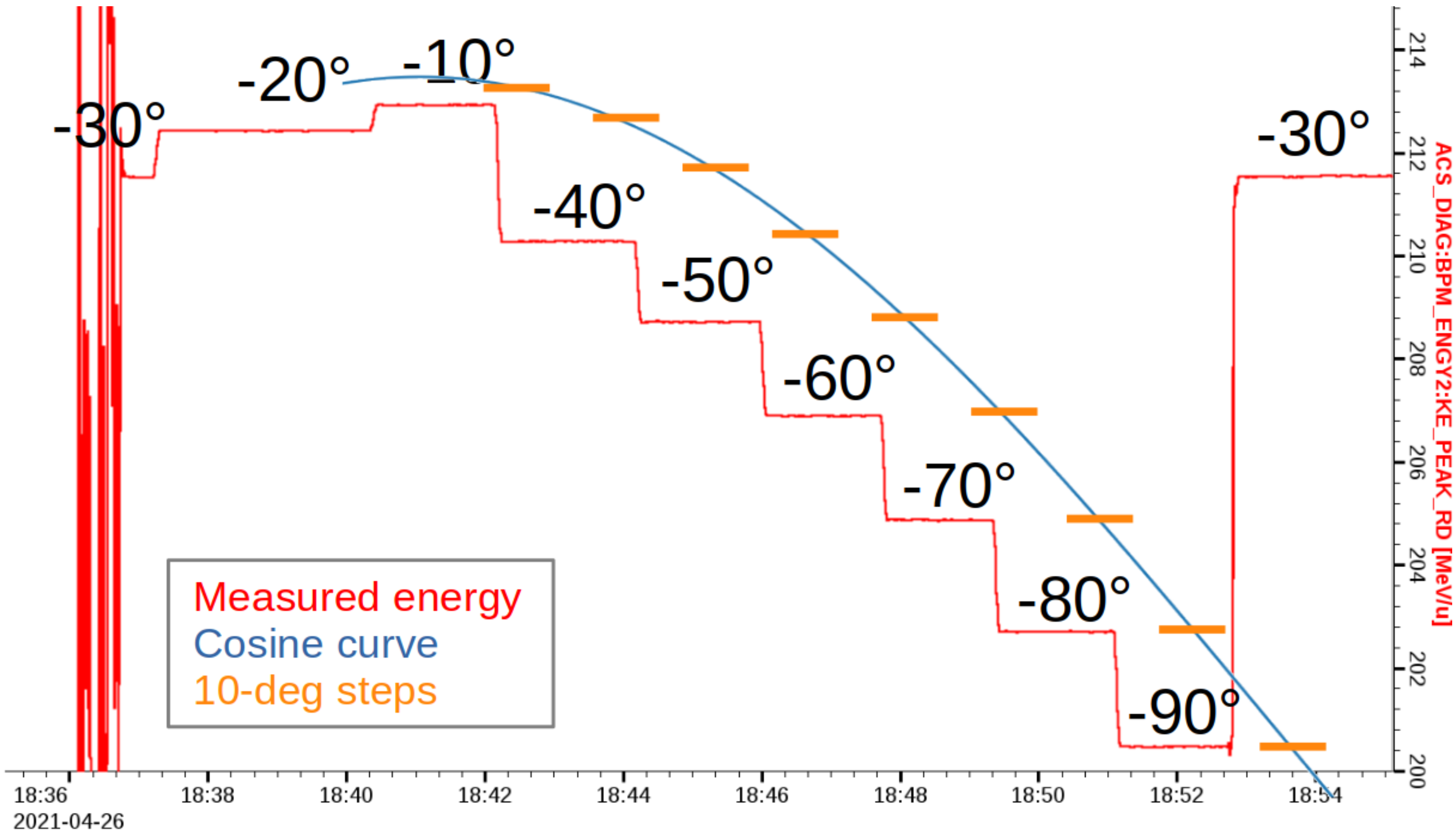
Model for a Sequence of Cavities

$$\begin{cases} \dfrac{dW}{dz} = q \displaystyle\sum_{i=1}^{N} K_i \cdot A_i \cdot E_z\,(z - z_i) \cos(\omega t + \Delta\varphi_i + \varphi_i), \\ \dfrac{dt}{dz} = \dfrac{1}{v_z}, \end{cases}$$

with initial conditions: $\begin{cases} W(0) = W_0, \\ t(0) = t_0. \end{cases}$

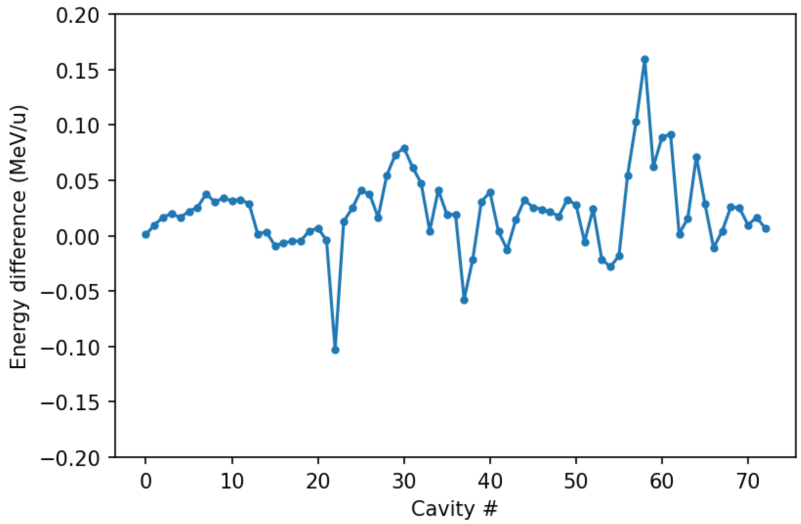
Model-based Phasing Demonstration

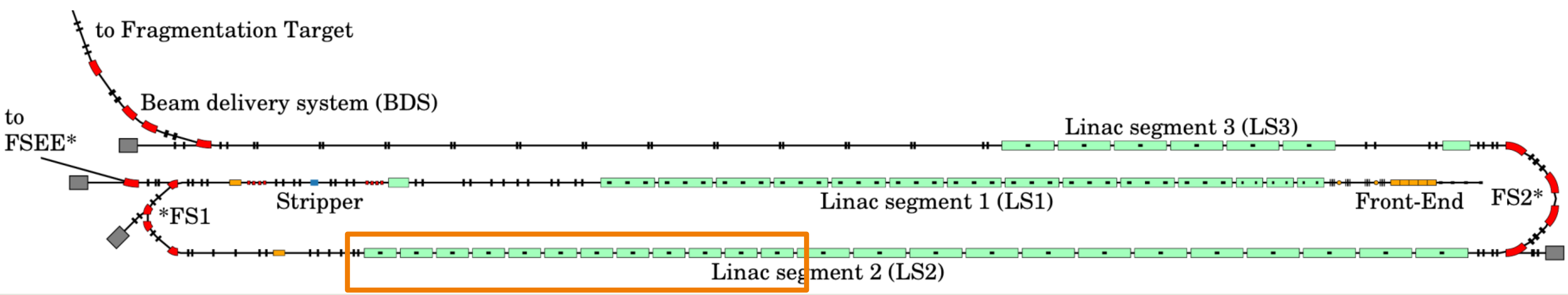
Last **17** cavities in LS3 were rephased based on the model prediction.
Synchronous phase was varied from -10 to -90 deg.



Validation in LS2

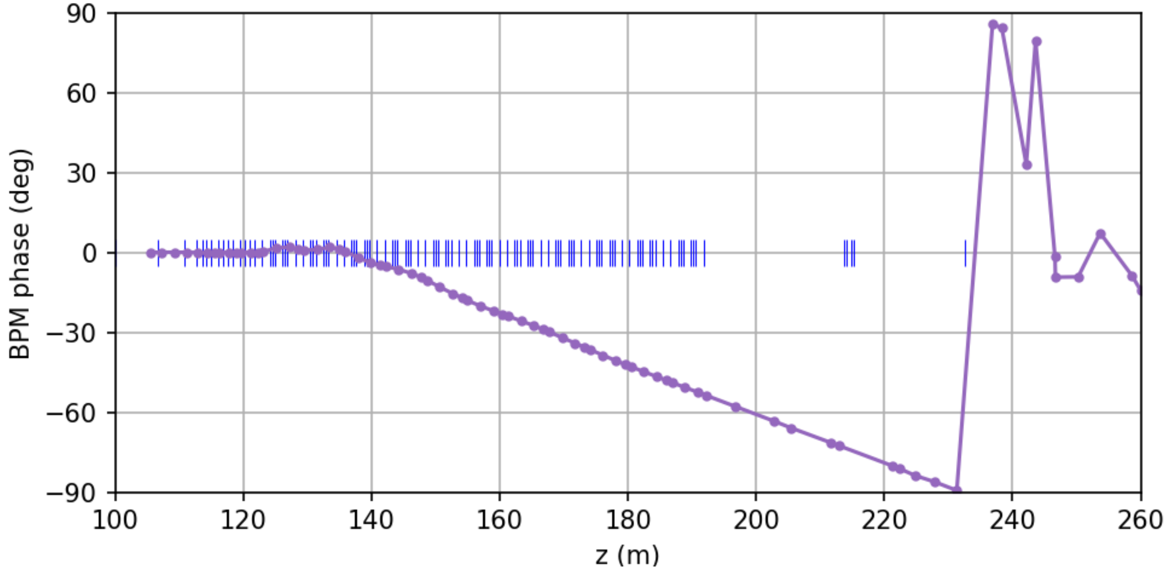
- During the Liquid-Lithium Stripper Commissioning, 12 cryomodules in LS2 were phased using the IPS model.
- Cavities were turned off one-by-one
- Energy is measured after each cavity
- The difference between the measurement and the model
- The difference does not accumulate





Validation in LS1

- LS1 was phased to 17 MeV/u using ALPha (conventional phase scans)
- The phase scan data was supplied to the IPS model for calibration
- ALPha phased LS1 to 20 MeV/u, BPM phases were recorded
- IPS phased LS1 to the same 20 MeV/u velocity profile
- BPM phases compared between the two methods:

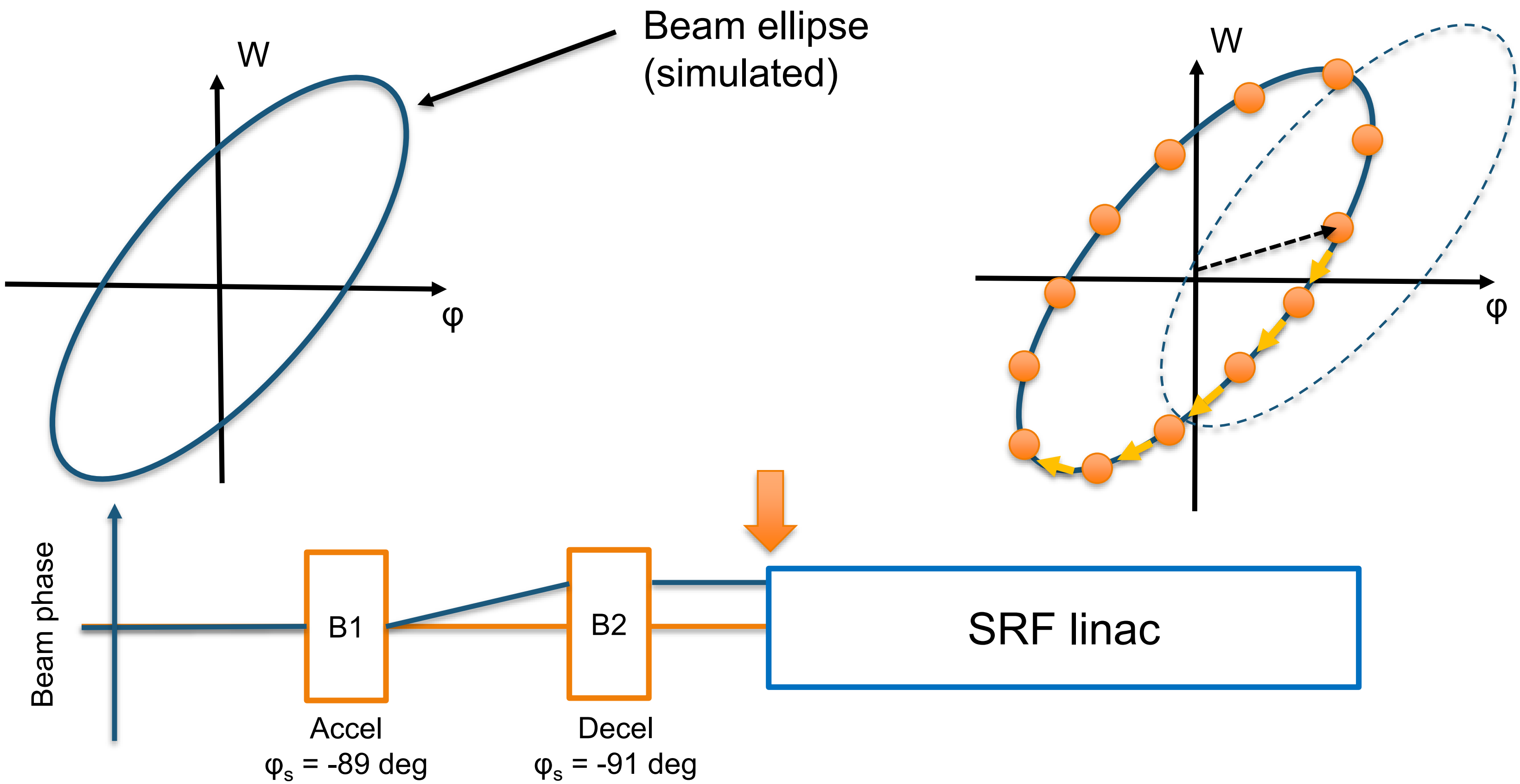


W_{ALPha} = 20.005 MeV/u

W_{IPS} = 20.084 MeV/u

- Cavity-to-cavity difference is less than 1 deg

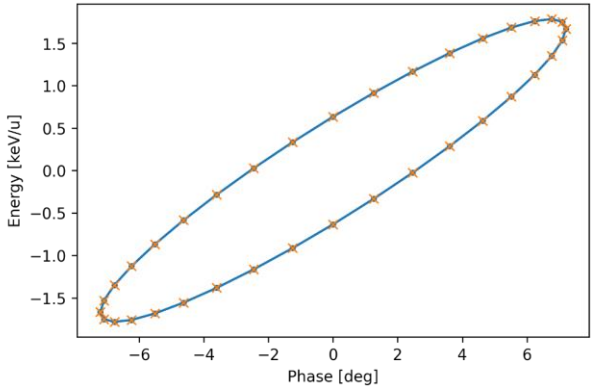
Verification: Envelope Mapping



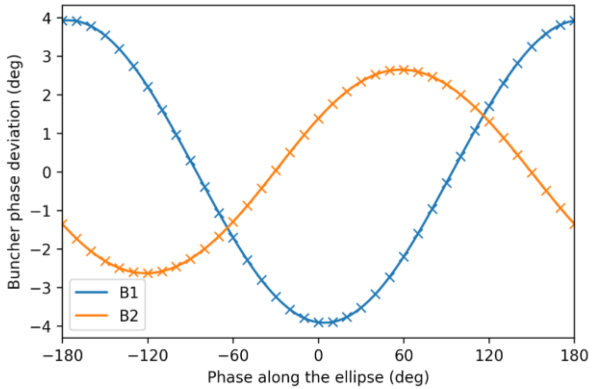
Beam centroid is kicked and the BPM response to steered beam is measured.
This approach is used to check the **lattice**, **not** to measure the **beam** emittance.

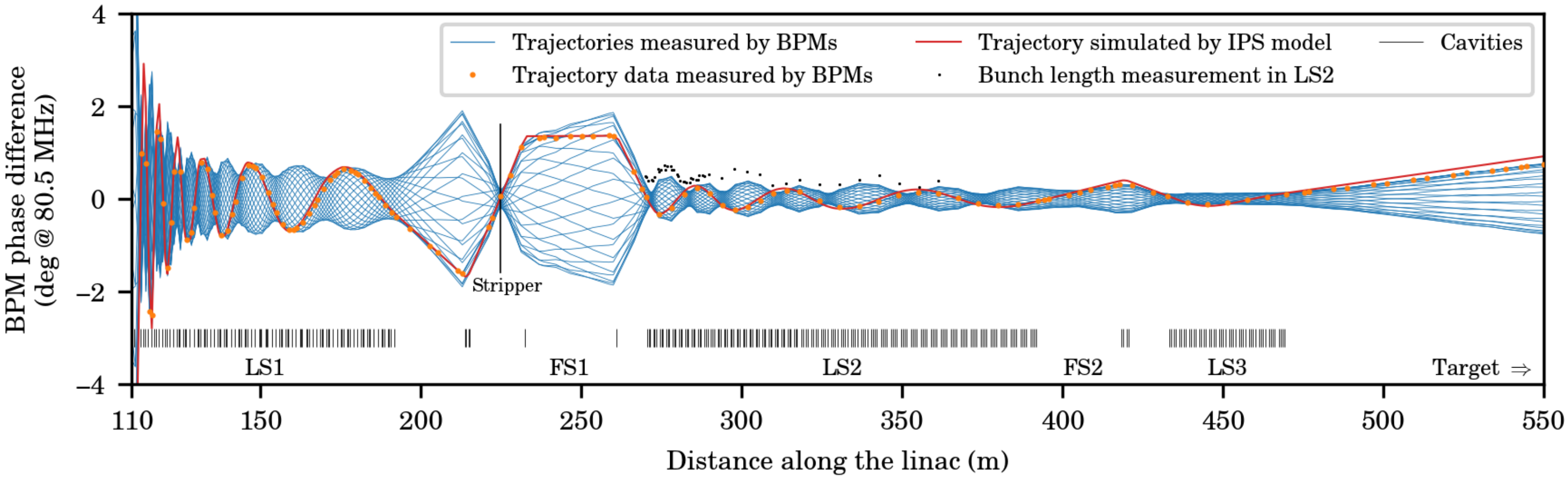
Envelope Mapping

Beam ellipse at the SRF linac entrance



Detuning of MEBT bunchers

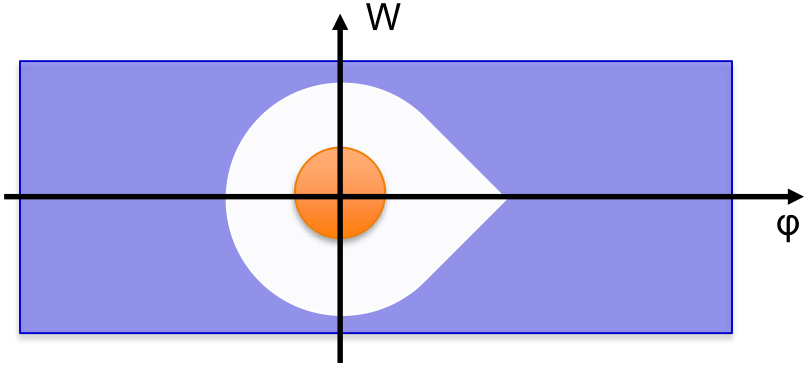




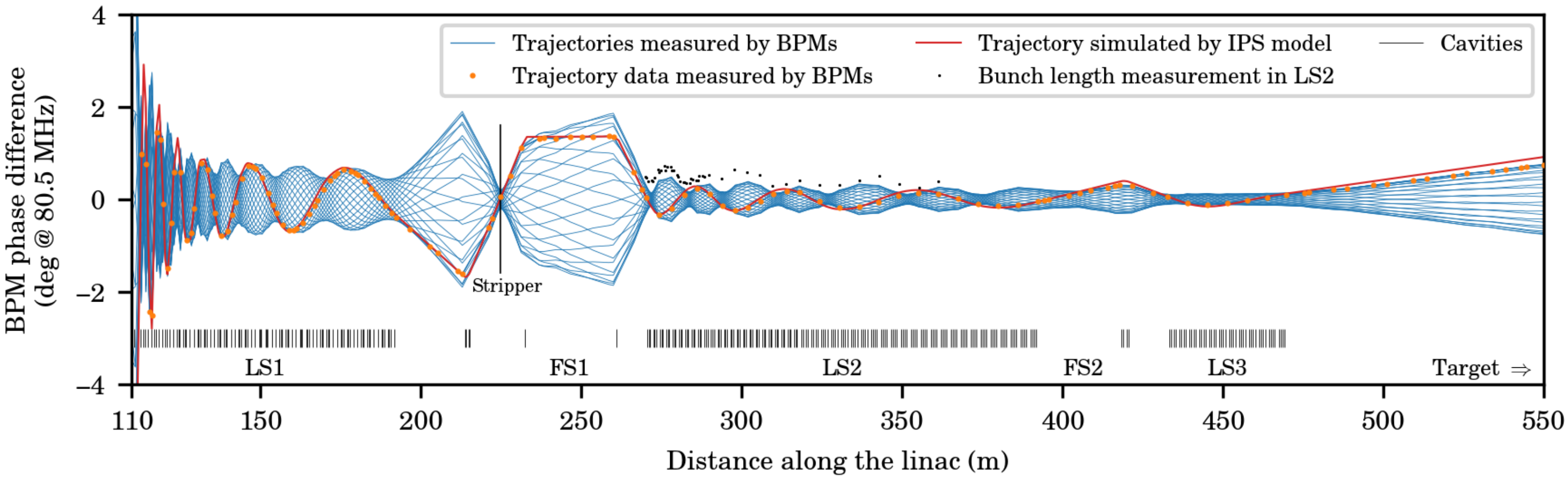
Envelope mapping cannot handle the emittance growth in the charge stripper

Bunch Length Measurements

- Phases of LS2 cavities shift by the same angle to scan the edge of longitudinal acceptance over the beam phase space
- Derivative of the measured transmission curve is fit into a Gaussian profile

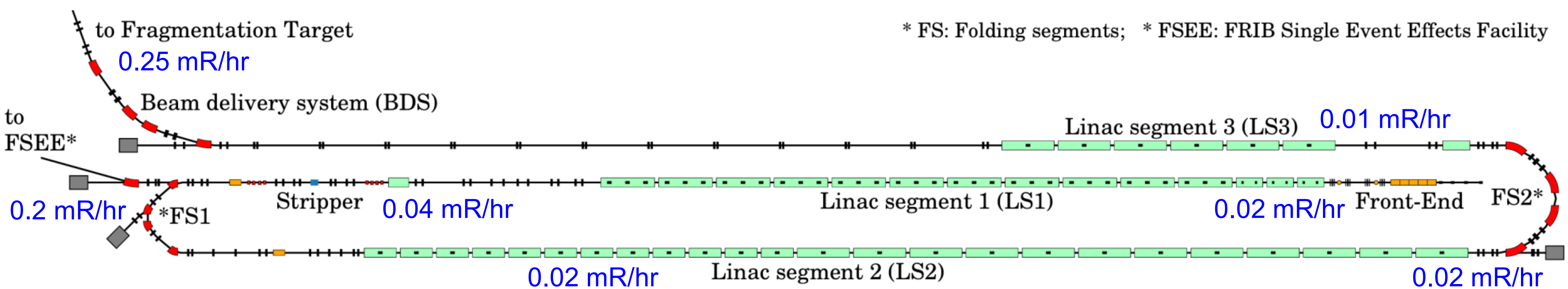


- Envelop mapping corresponds to emittance of **0.16** π·keV/u·ns.
- Measures rms beam size is ~1.4 times larger than the mapped envelope, i.e. the stripped beam emittance is around **0.32** π·keV/u·ns.
- The measured envelope profile looks reasonably close to the mapped envelope.



Conclusion

- Instant Phase Setting model has been implemented in a **new application** and is used for **operations.**
- Its **superior capabilities** have been demonstrated during the beam commissioning of a new FSEE beamline of the linac when during one evening we developed, applied, and tested four different velocity profiles in LS1 for three different ion species: $^{40}Ar^{14+}$ at 36.6 MeV/u, $^{16}O^{7+}$ at 41 and 44.7 MeV/u, and $^{129}Xe^{28+}$ at 27 and 15 MeV/u (these two share the same velocity profile).
- During one of the FSEE experiments, a faulty cavity had been **bypassed in just 10 minutes** and the beam **energy was recovered**.
- The IPS model was successfully applied to setup beams for the **first three FRIB user experiments**. For example, the settings for the first experiment were established by one accelerator physicist in **6 hours** from the ion source to the beam dump at the end.
- After a **two-week**-long user operation with **1 kW** on the target, **no beam loss** was detected by the measurement of the residual radiation in the tunnel (done next day after the operation).



ACKNOWLEDGEMENTS

- Andrei Shishlo from the Accelerator Physics group of SNS for sharing their accelerator tuning experience.
- Dan Morris and Shen Zhao from the FRIB RF and LLRF groups for discussions of RF circuits;
- Steve Lidia and Scott Cogan from the FRIB BIM department for discussions of BPM measurements.

Thank you!