What is missing for the Design and Operation of High-Power Linacs?

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Outline

- **What is Missing in Design:**
  - **Tuning/Retuning: Diagnostics + Algorithms**
  - **Parameter Tolerances: Realistic Approach + Model**

- **What is Missing in Operations:**
  - **Model based Beam Loss Control**
    - **Initial Distributions**
    - **Real Life PIC Codes Benchmark**
    - **Model-Based Tuning using PIC codes**

- **Summary**

Hadron Linac Design/Operations

Design

Engineering Design

- Cost Minimization
- Real Estate Limitations
- Hardware Choices
  - Types of Cavities
  - Frequencies
  - Feasibility
  - …
- Tolerances
- …

Iterations

Beam Physics Design

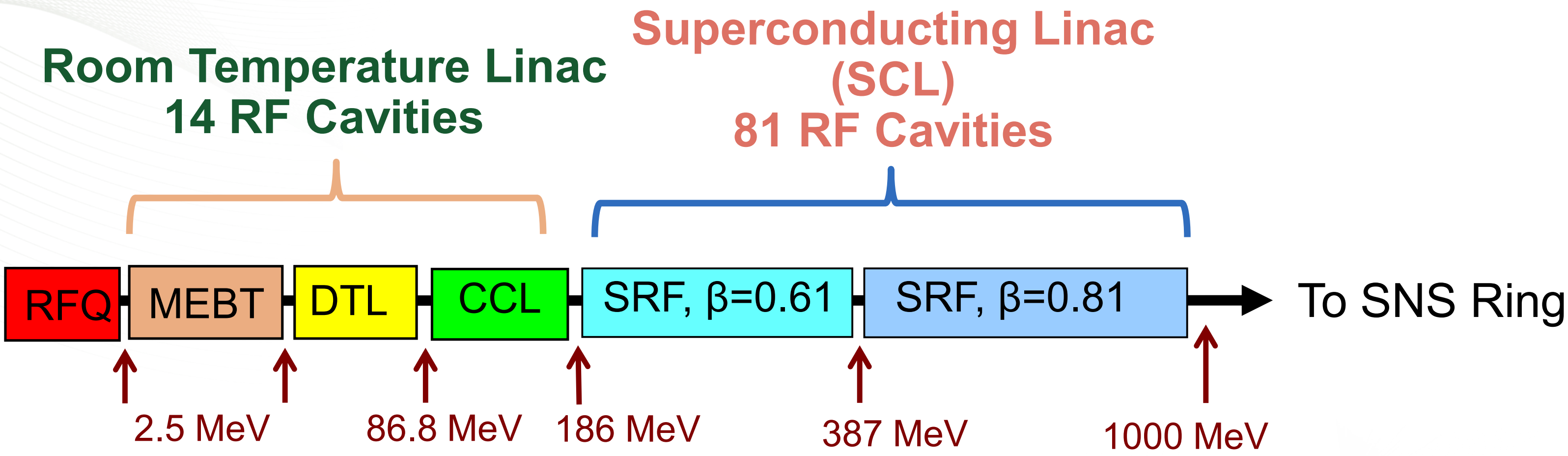
- Design Power
- Design Beam Properties
- Acceptable Beam Loss/Activation
  - Emittance growth
  - Halo formation
  - Apertures
  - Diagnostics
  - …
- …

Not enough Attention

Operation

Maintenance / Upgrades → Commissioning / Tuning → Operations / Re-Tuning

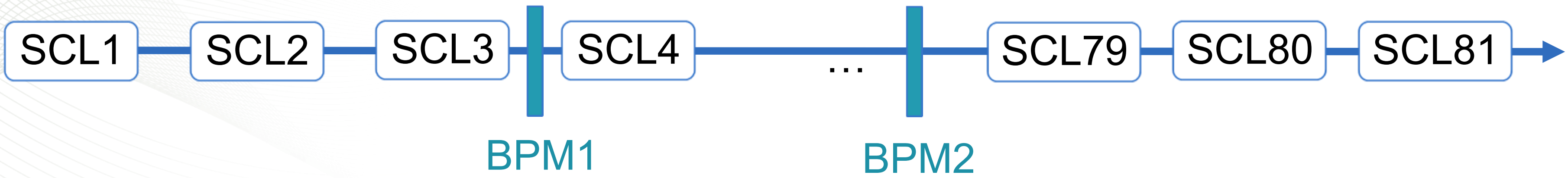
SNS Linac : 1.4 MW H^- Linac



Pulsed Linac
Macro Pulse Frequency: 60 Hz
Macro-Pulse: about 1 ms
Chopped beam: yes
Number of Mini-Pulses in Macro: about 1000
Peak Current: 38 mA

Overall: great design. Linac is working even in presence of unanticipated Intra-Beam Stripping beam loss for H^-

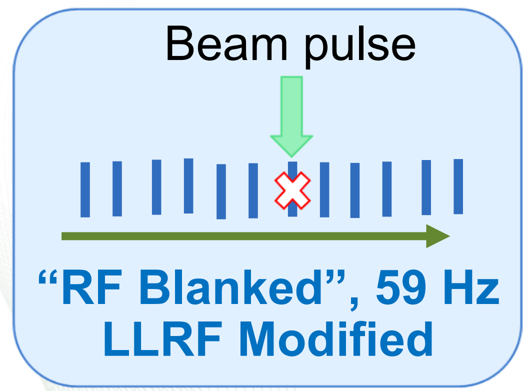
SCL RF Tuning



- **Initial Tuning Algorithm**
  - **100 us beam**
  - **360^0 RF Phase scans with “Time of flight” method by using two BPMs**
  - **All downstream RF are “Off”**
  - **Cavities done one by one, bringing them to “On Resonance” state**

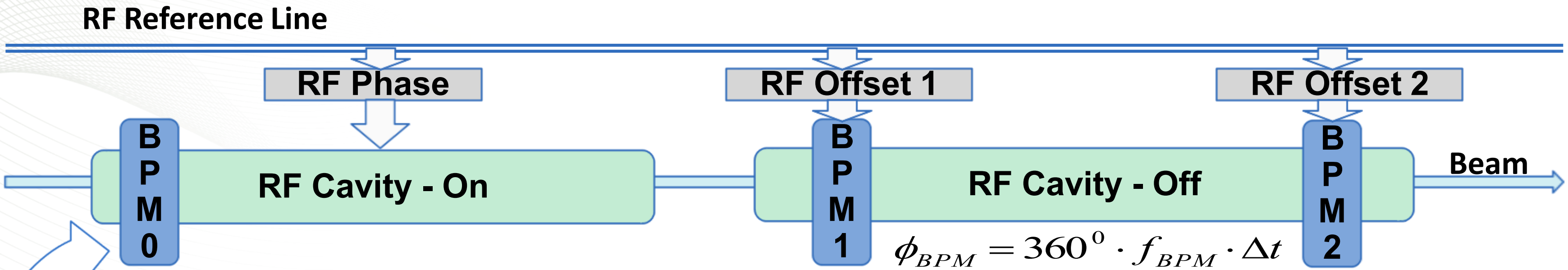
Problem: (81 cavity) x (10-15 minutes) = about 2 shifts if everything is Ok

- **Today’s Tuning Algorithm**
  - **“Time of flight” with all BPMs**
  - **360^0 RF phase scan**
  - **All downstream RF are “On”, but in “RF Blanked” State**
  - **Use just a few mini-pulses (few us) of beam**
  - **Beam 80/90% attenuation in the MEBT to avoid beam loading: new hardware in MEBT**
  - **Process automated: 40 min**

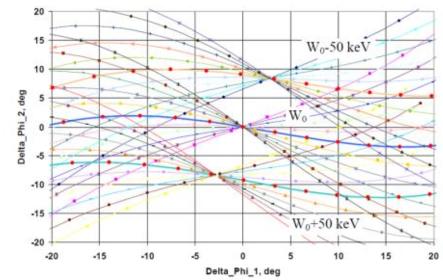


FRIB has 330 cavities
ESS has 200

Warm Linac RF Tuning: DTL , CCL

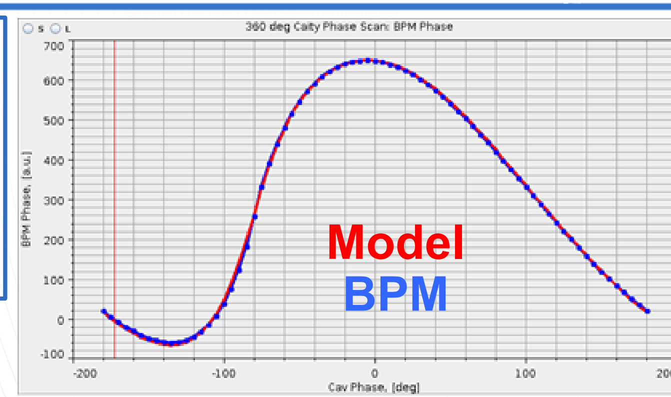


- ❑ Initial Plan: Delta-T procedure developed at Los Alamos uses two BPMs from the next tank
- ❑ Backup plan for DTL tanks: Acceptance scans with Faraday Cup



Problem: hard to find working region, it needs calibrated BPMs

- ❑ Final Approach: Use only one BPM for 360^0 phase scan for one RF amplitude
- ❑ Automated – 22 min for whole warm linac
- ❑ It was suggested at Fermilab in 1994

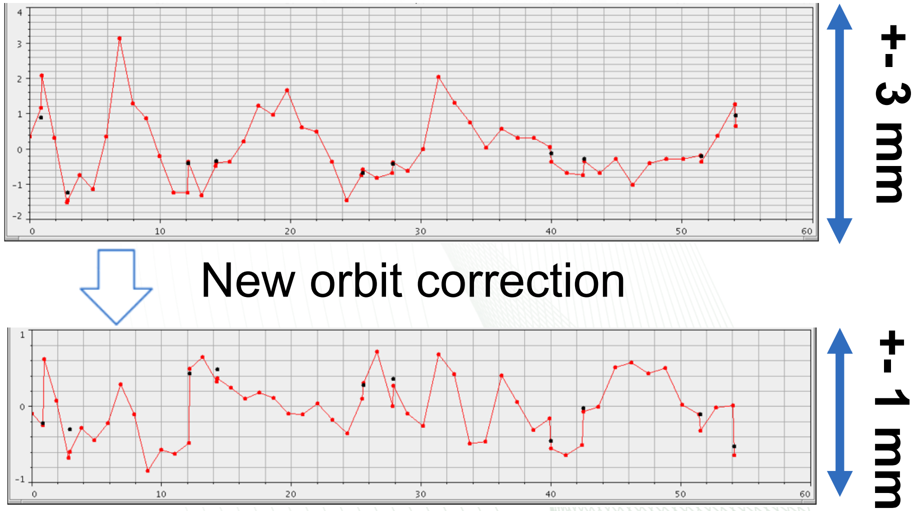


DTL1 tank does not have BPM inside!

CCL Orbit Correction

- **CCL has 10 BPMs and 48 quads: cannot correct orbit using only BPMs**
- **The number of BPMs was reduced: a budget optimization**
- **Can use quad gradients scan, but it too time consuming for operations**

Solution: Created a model with BPMs' and quads' transverse offsets and specialized CCL orbit correction app



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Optimal Tolerance Design Problem

- Tolerance of parameters influence the cost and feasibility
- The goal is a cost minimization with acceptable beam loss

Lattice Design

Envelope Code used

All general rules should be satisfied

Static and dynamic errors are generated

PIC Code

Lattice initialized with errors

Particles are generated and tracked to the end

Beam Loss calculated

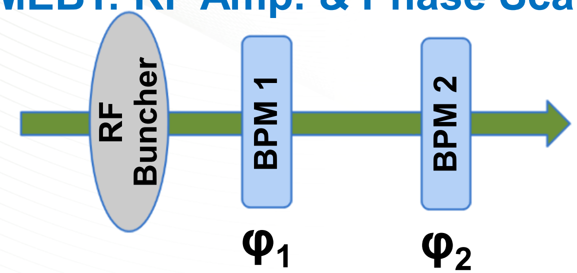
Hundreds or thousands iterations

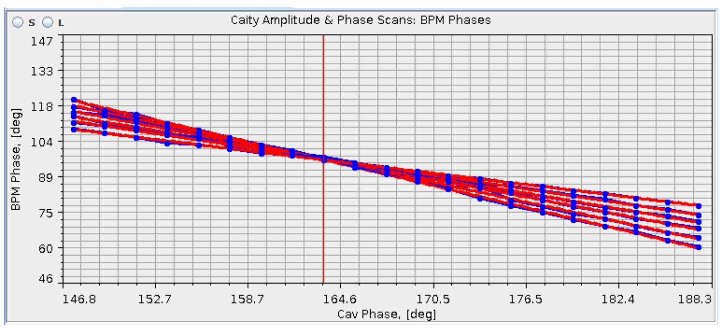
In this process some errors are straightforward like alignment, magnet currents, and some are less clear like RF amplitudes and phases.
Usual numbers: 1% for amplitude and 1^0 for RF phase

RF Tolerances: Static and Dynamic Errors

From SNS experience: RF related static errors tolerance should be much larger then 1%,1^0.

MEBT: RF Amp. & Phase Scan



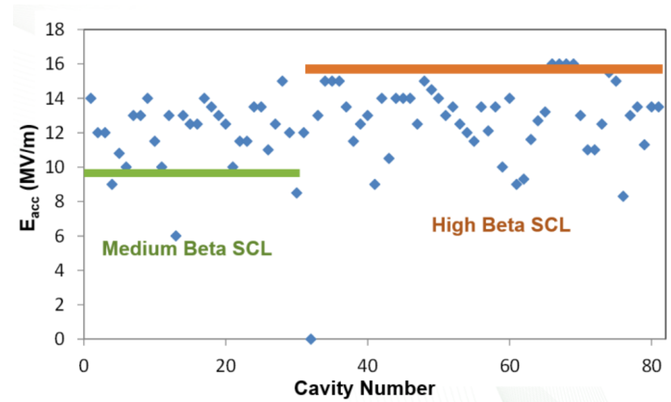


It is model independent!

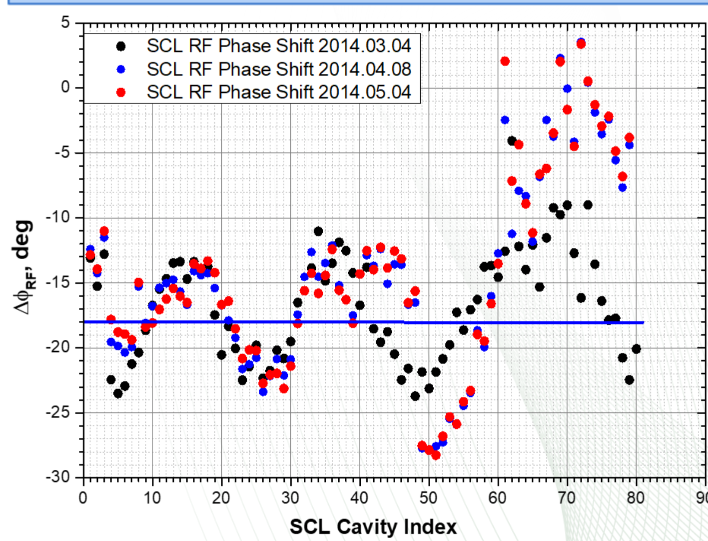
BPM #	Pos. [mm]	φ, deg
1	887	163.5
2	1653	171.7

Phase difference = 8^0

Both settings are good as a starting point for loss tuning!



SCL Cavity Gradients +- 40%



Synchronous Phases in SCL Production

Design -18^0

RF System Static Errors Treatment

- **We have to be careful applying static RF errors to the models**
- **It should be like the transverse alignment errors: apply errors, and then apply orbit correction. The result will be low beam loss.**
- **For RF we can use the simulation of a real life tuning procedure.**

Example

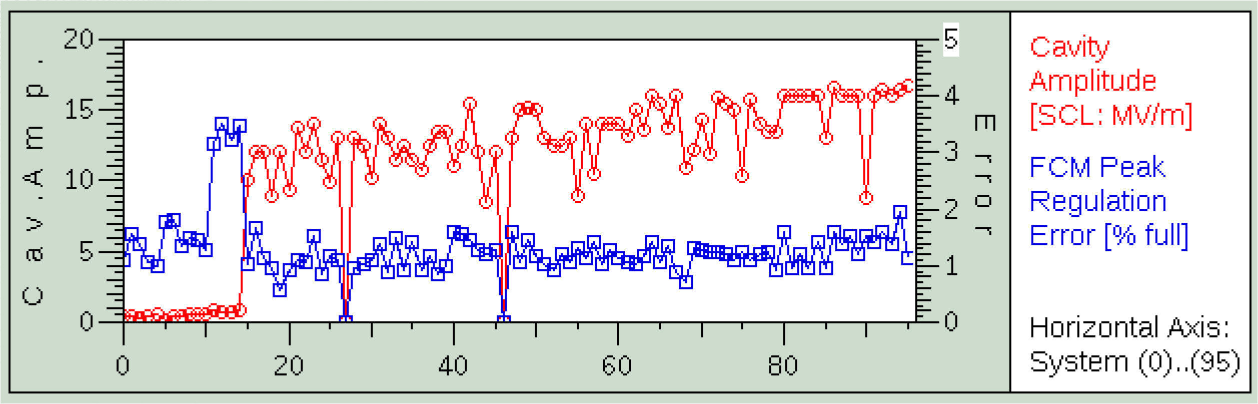
IMPROVEMENT OF THE RF FIELD PHASE & AMPLITUDE ERRORS SIMULATION IN TRACEWIN CODE

D. Uriot †, Ifru, CEA, Université de Paris-Saclay, F-91191 Gif-sur-Yvette, France

Proceedings of IPAC2018, Vancouver, BC, Canada

- **In the TraceWin code the RF tuning command was implemented.**
- **The new command simulates "time of flight" measurements with two BPMs**
- **The "usual simulation (errors 1%,1^0)" gave 0.159 W beam loss in MYRRHA linac**
- **The use of the new tuning command reduced loss by factor 60 for "a huge error on the BPM position (1mm)" and +- 20% RF field errors.**

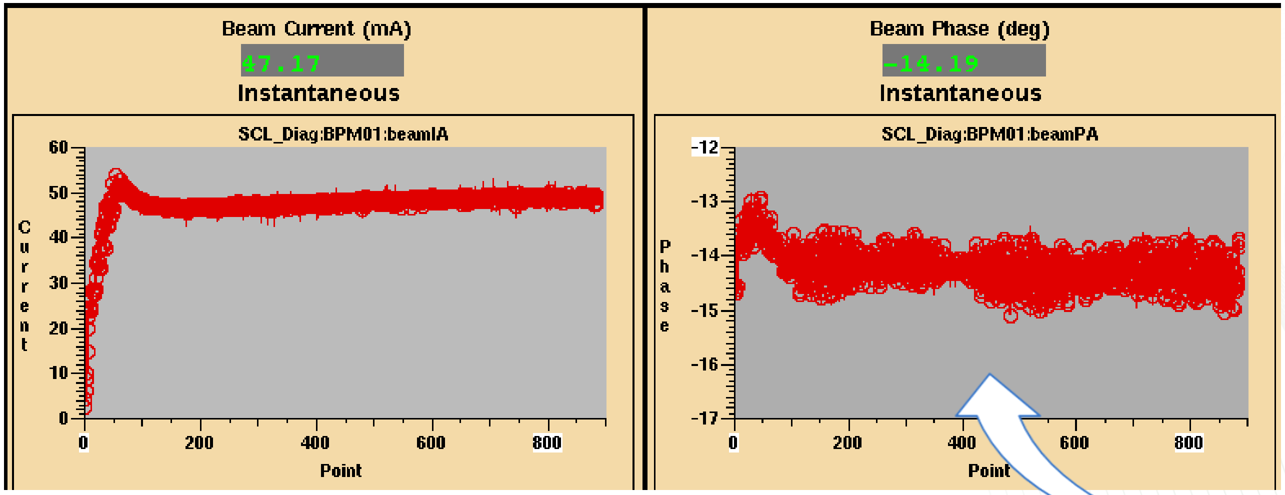
RF System: Dynamic Errors Level (SNS)



SNS Linac Cavity Index

Snapshots from Control Room

RF Amplitude
Error
1-2%



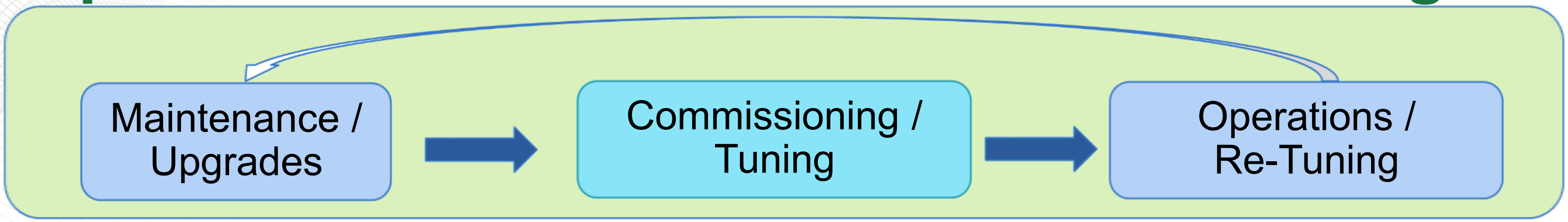
SCL BPM01
900 mini-pulses
about 1 us each

Bunch phases
+- 2^0
for RF frequency

Problem: Tolerance Simulations are not benchmarked with Real Beam Loss Data

- We can estimate losses from scattering / ionization / stripping on residual gas in the beam pipe
- We can estimate Intra Beam Stripping beam loss for H^- linacs
- But it is very difficult to predict beam loss from beam halo
- The PIC codes are not benchmarked with real beam loss
- This cast a shadow of doubt on the tolerances estimation procedure

Operations: Model Based Beam Loss Tuning



- **Linac Control Room Tuning includes**
  - **RF tuning: usually model based**
  - **Transverse matching: usually model based**
  - **Final beam loss tuning: always empirical**
- **Only PIC codes capable of beam loss prediction**
- **We do not use PIC codes in the control room:**
  - **It is difficult**
  - **There is no point – they do not work anyway**

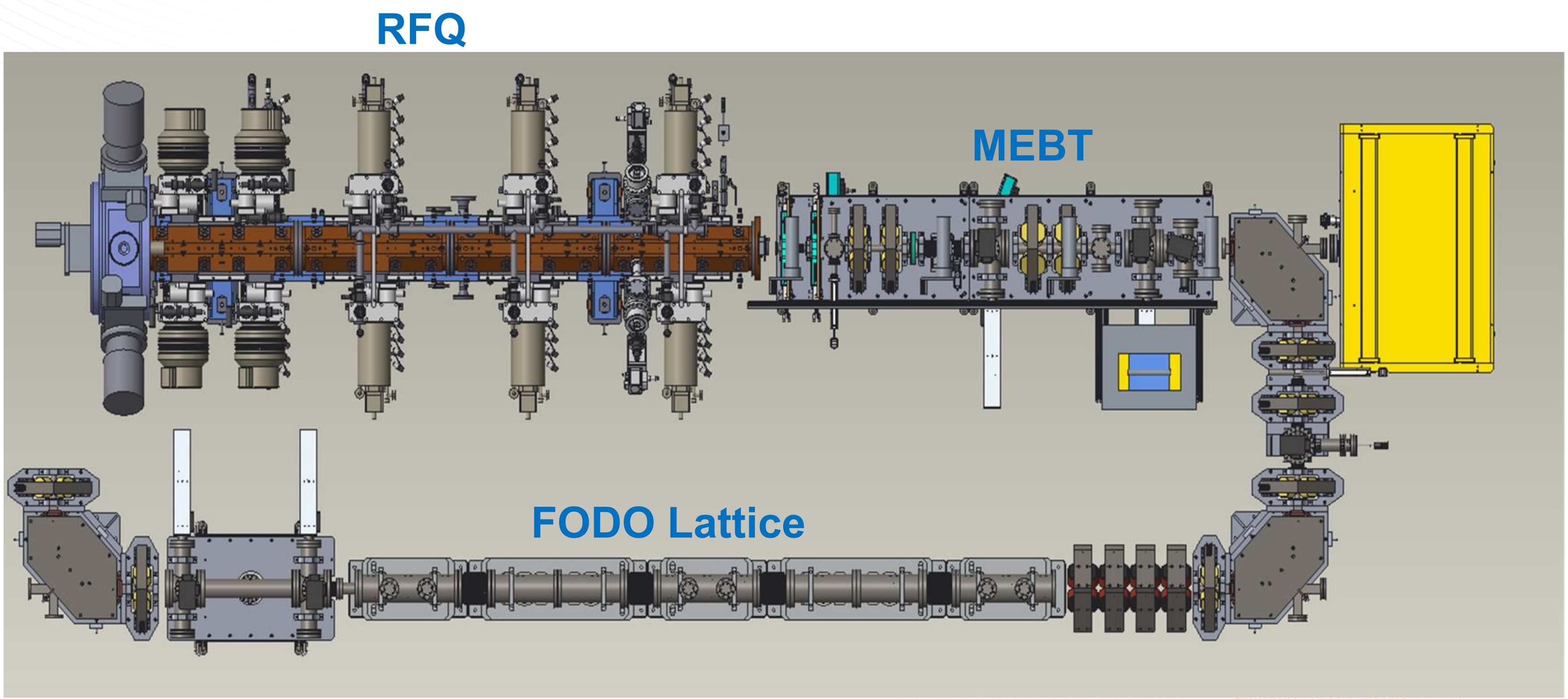
We need a PIC code benchmarked against beam halo formation and beam loss prediction

PIC Model = Initial distribution + Model Itself

SNS Beam Test Facility (BTF) is close replica of SNS Front End

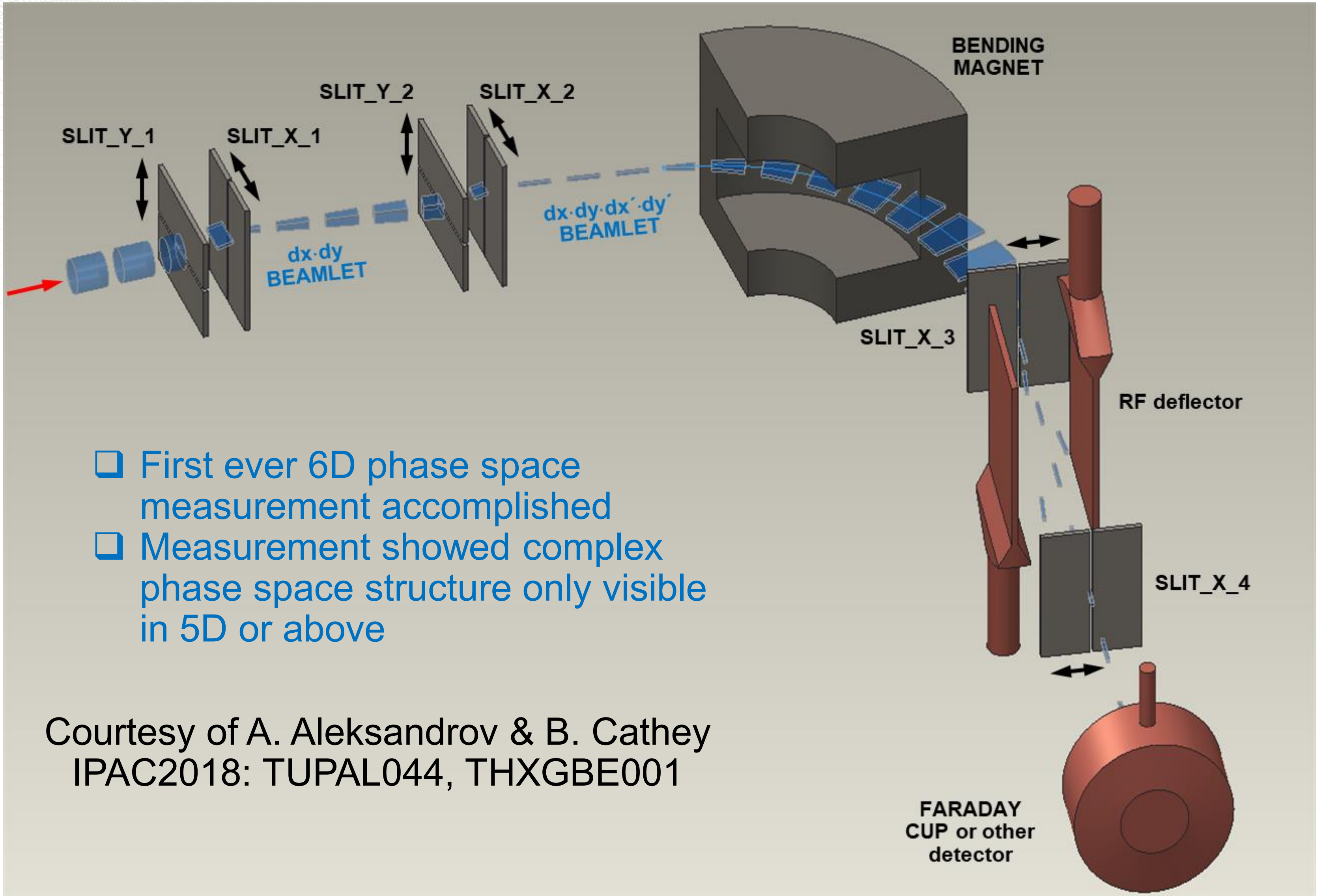
- **Built to commission RFQ**
- **Now a primary station for equipment development and beam dynamics R&D**

BTF Parameters
Species: H^- or p
Energy: 2.5 MeV
Beam current: < 50 mA
R&D duty factor: 10 Hz at 50 μS



Courtesy of A. Aleksandrov & B. Cathey, IPAC2018: TUPAL044, THXGBE001

6D Phase Space Measurement Principle



- ❑ First ever 6D phase space measurement accomplished
- ❑ Measurement showed complex phase space structure only visible in 5D or above

Courtesy of A. Aleksandrov & B. Cathey
IPAC2018: TUPAL044, THXGBE001

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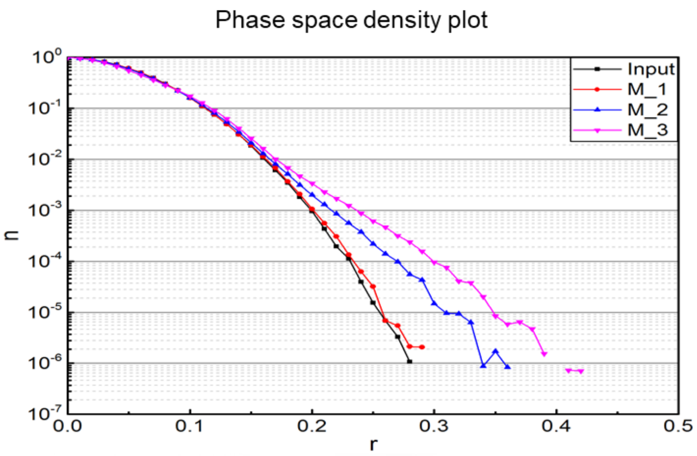
SNS BTF: High Intensity Beam Dynamics Experiment



- Experimental investigation of halo formation in high intensity beam and **computer simulation benchmarking**
  - Develop Six-dimensional (6D) particles distribution measurement system (Done)
  - Build a test FODO line (Done, not installed yet)
  - Develop reliable halo measurement system

(Courtesy of A. Aleksandrov)

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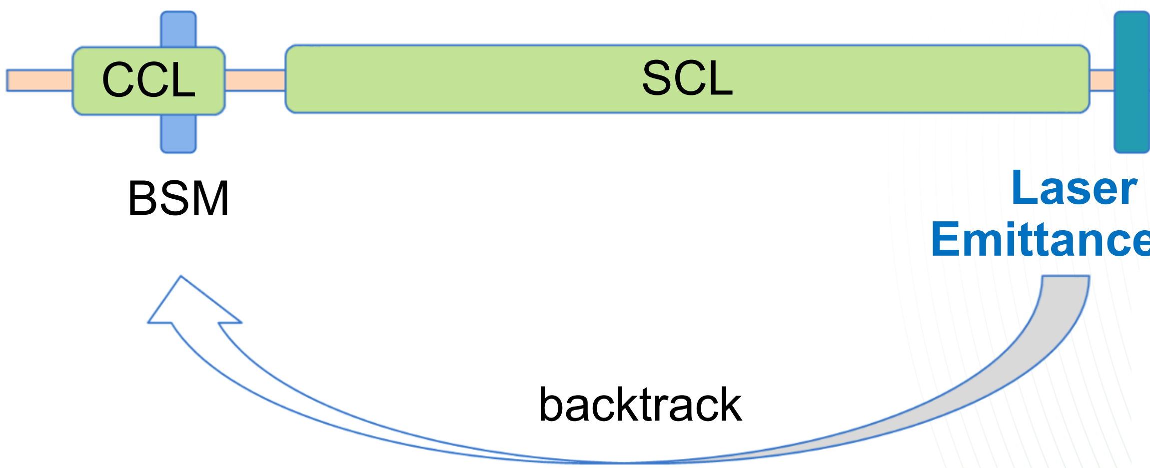
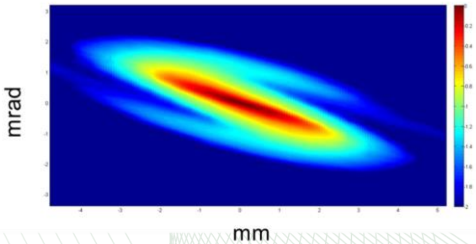
PIC Codes: Bunch Backtracking is needed

- 6D is coming, but right now we have transverse emittance stations, wire scanners, Bunch Shape Monitors etc.
- From 2D phase space emittance station measurements we can generate 2Dx2D particle distributions, but longitudinal measurements could be upstream
- To perform the benchmark we need an ability to track bunch backwards along the linac lattice
- We can do it: all our equations of motion are time reversable





Summary

- In design we are missing
  - more attention to hardware and algorithms for tuning
  - verified PIC model for beam loss calculations during tolerances estimation
- For operations we are missing
  - Verified PIC codes for interactive beam loss tuning
  - Knowledge about initial particles distribution
  - Backtracking feature in codes would be nice

Thanks for your attention!

Thanks for useful discussion to A. Aleksandrov (SNS, Oak Ridge), P. Ostroumov (FRIB, East Lansing), B. Mustapha (ANL, Argonne)

Backup slides