Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Towards Linac RF Optimization with Machine Learning

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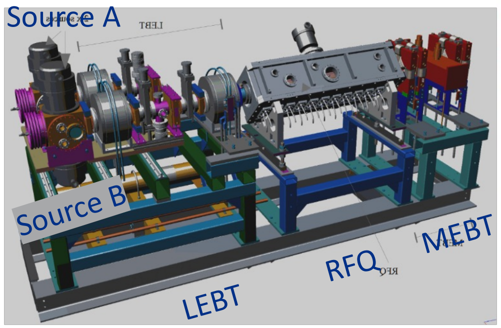
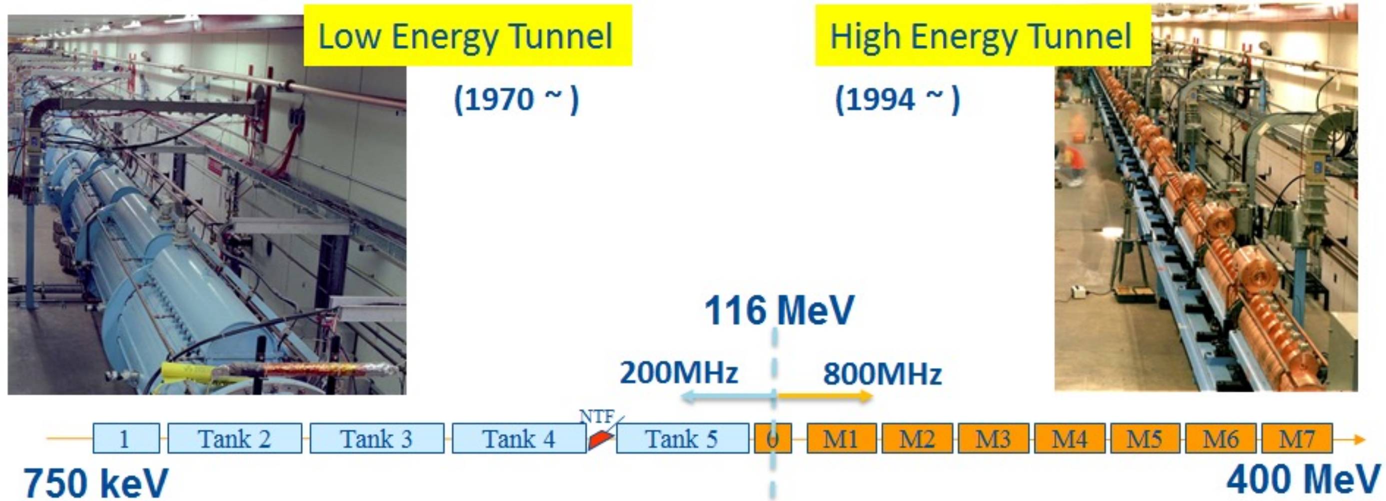
3rd ICFA workshop
3 November 2022

Contents

The Fermilab Linac





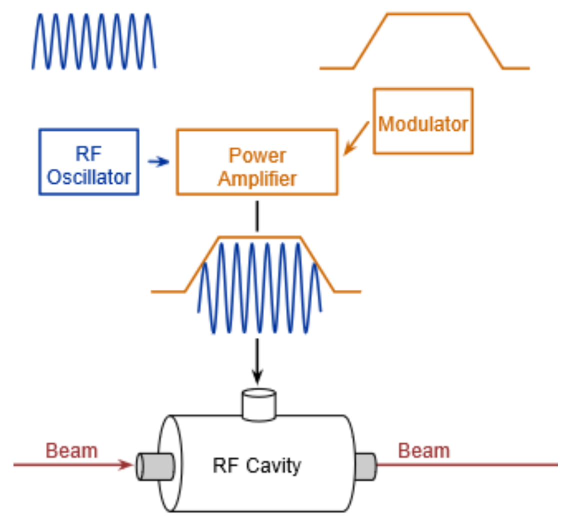
- Pre-accelerator
  - Magnetron H- source + LEBT + RFQ + MEBT
- Linac: Drift tube (DTL) and side-coupled (SCL) parts
  - DTL: 5 tanks, 201 MHz RF
  - SCL: 7 modules, 805 MHz RF
  - Transition section: buncher and vernier

Status

Linac output:	~20mA
Pulse length:	35 μsec
Efficiency:	95%

Linac RF Systems

DTL RF system elements & schematic

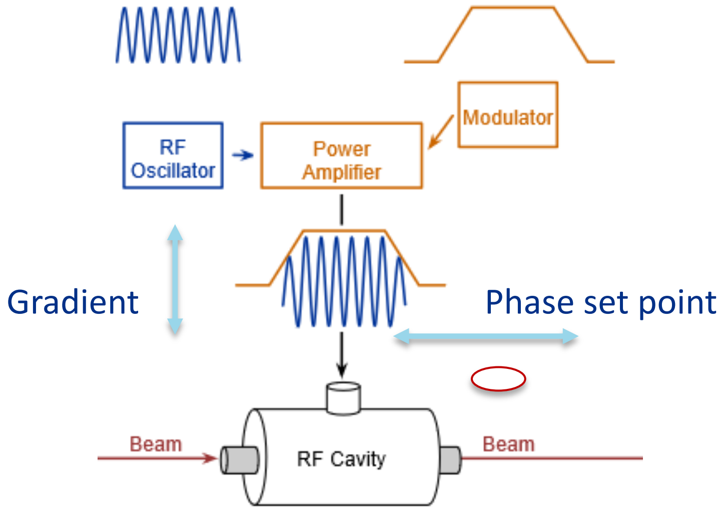


- DTL RF system main components
  - LLRF pulse generator
  - Driver: pre-amplification of RF pulse
  - Modulator: provides high-power
  - Power Amplifier
  - Transmission line to cavity
- SCL RF system components
  - LLRF pulse generator
  - PFN: modulator equivalent
  - Klystron
  - Waveguide to cavity

RF Parameter Optimization: Goals

- We strive to deliver stable beam energy and maximal beam current
- Beam emittance and energy can drift (both short and long timescale)
  - Ambient temperature affects cavity resonant phases
  - Source conditions affect emittance & energy
- Tuning RF cavity parameters can help minimize emittance (reduce losses, increase beam current) and stabilize energy
  - Phase: field timing w.r.t. beam
  - Gradient: magnitude of acceleration

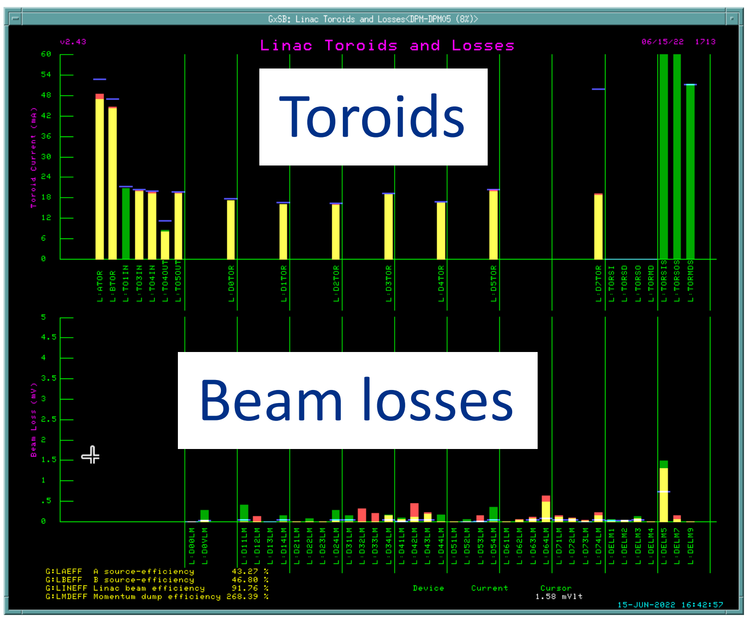
Preacc + Linac + debuncher = 17 cavities x2 = 34 parameters



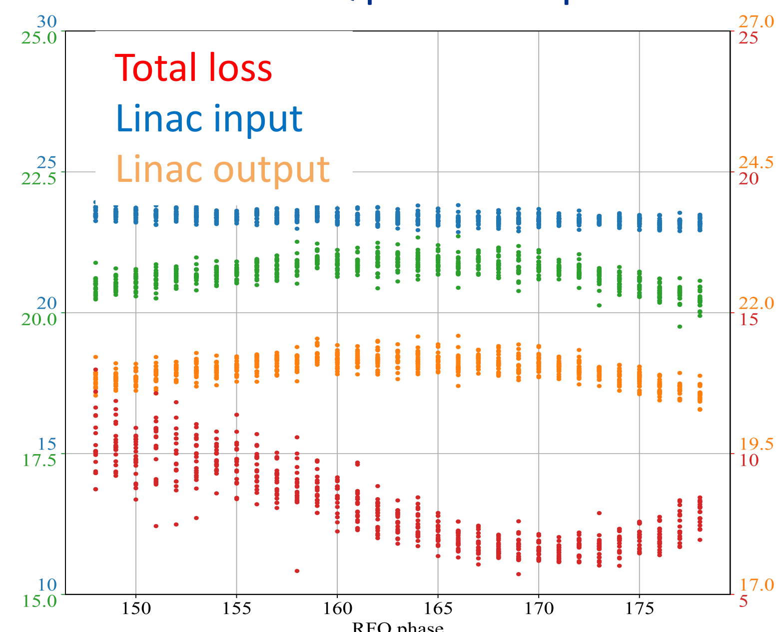
RF Parameter Tuning in Operations

- Hand scan params for min beam losses and max beam current
  - Done ~1/day by operators or experts
- Typically, only tune:
  - Phase set points of RFQ, MEBT buncher, and DTL Tank 5
  - SCL Module 7 phase to improve energy flatness along 35us pulse

Linac TOR and BLM display



Scan of RFQ phase set point



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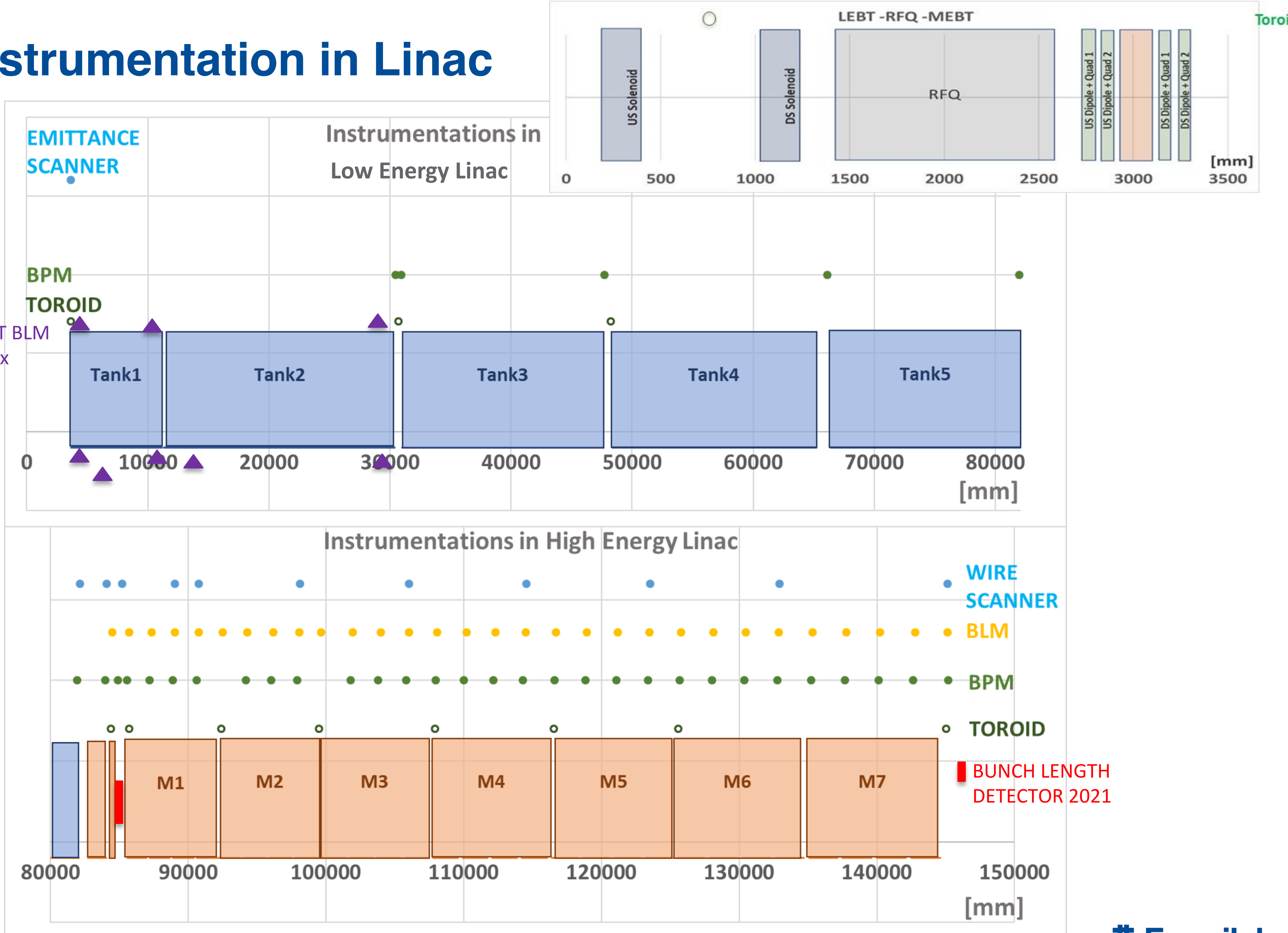
RF Parameter Optimization: Going Forward

- Challenges:
  - Losses and currents not always best diagnostic; limited diagnostics in DTL
  - Can only tune 1 param at a time: may be local minima
  - Limited by operator/expert availability
- Ultimate goal: automate Linac RF tuning for all cavities (w/ ML techniques)
- Our approach:

  Crucial for successful ML training!

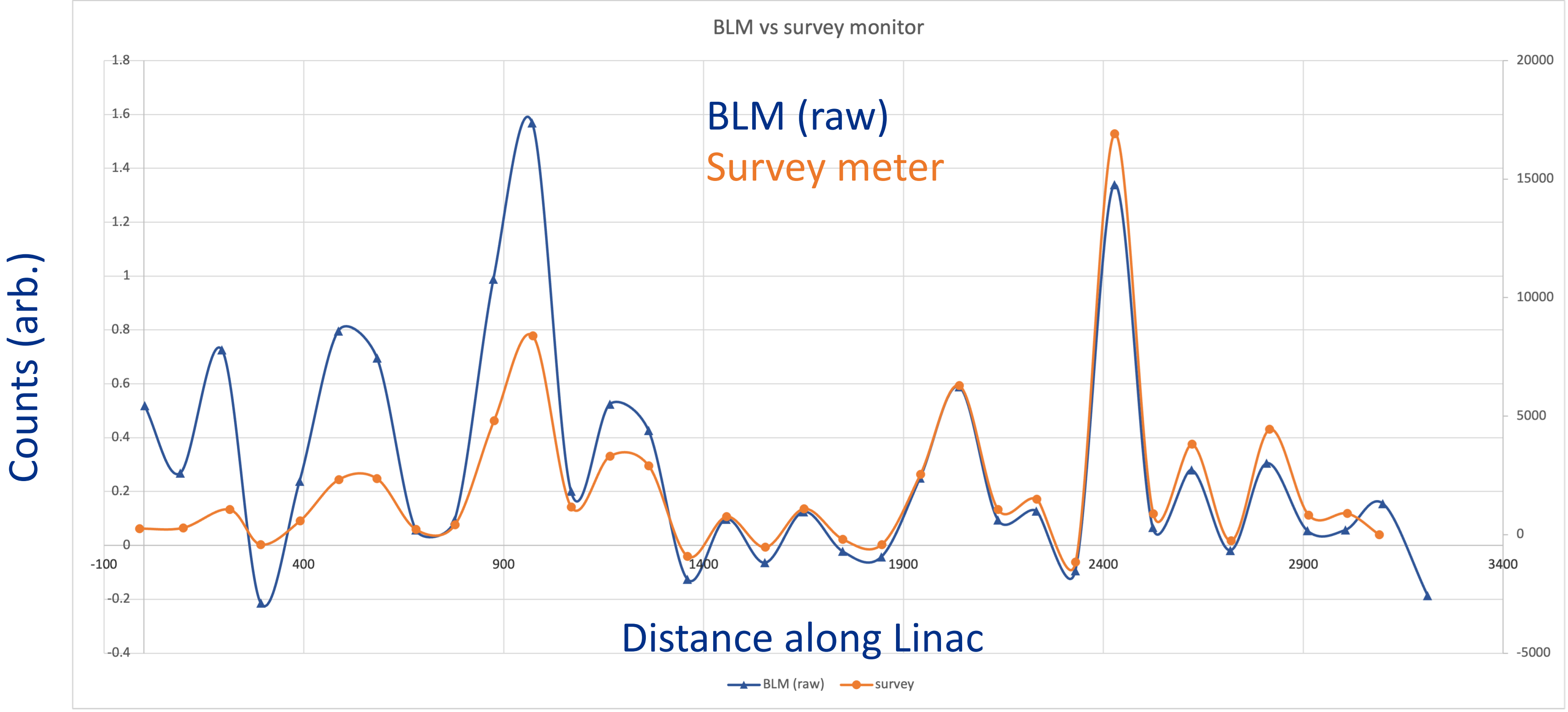
  - Step 0: revisit old & develop new diagnostics to ensure **robustness** of data
  - Step 1: demonstrate ML algorithms can accurately model RF parameters given diagnostics data
  - Step 2: demonstrate offline momentum control (single/multi cavity)
  - Step 3: develop near-line momentum control (using FPGA or other fast hardware)

Instrumentation in Linac



Beam Loss Monitors (BLMs)

- Measure particle loss: can hint at large longitudinal/transverse emittance
  - Useful for relative comparison rather than in absolute (losses change w/ beam current)
  - Caveat: do not carry information about cause of loss
- ➢ BLM distance to beampipe was non-uniform – fixed during shutdowns 2021&2022



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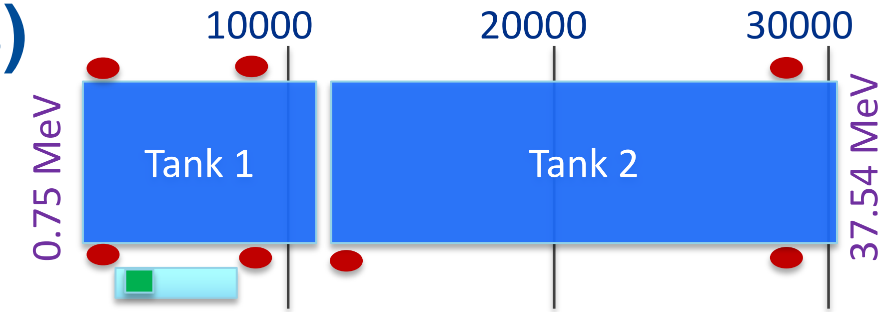
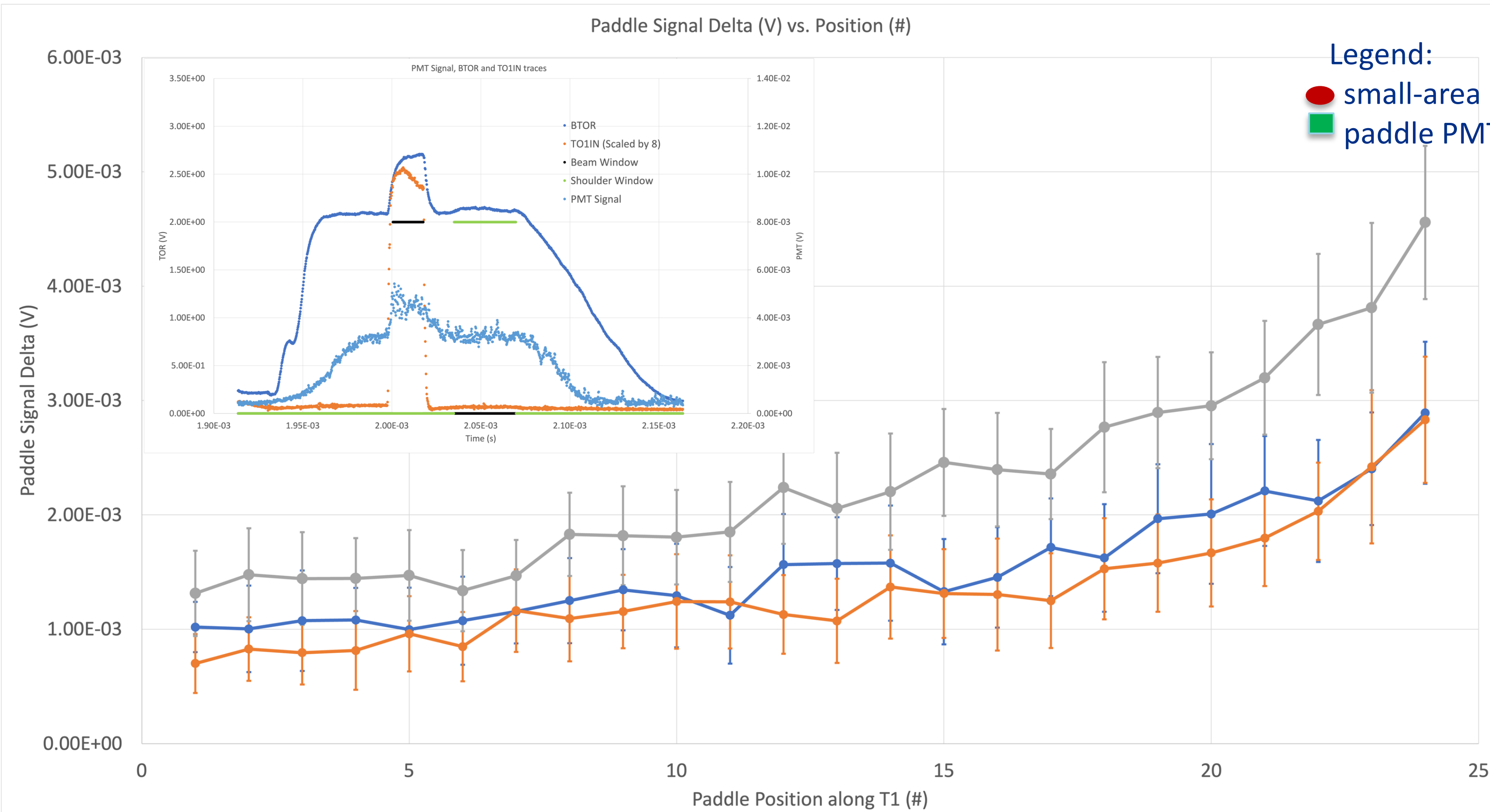
Beam Loss Monitors (BLMs)

- Installed 7+1 PMT BLMs along T1 and T2
  - Now commissioning

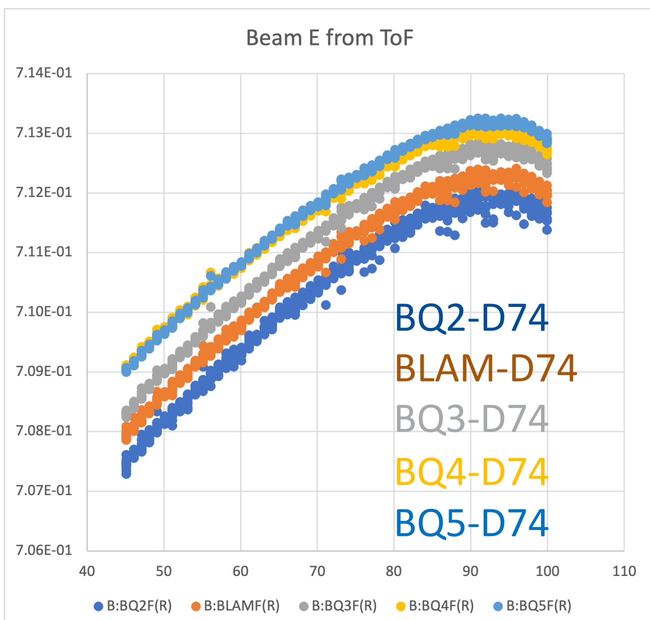




Beam Position Monitors (BPMs)

- Measure beam transverse (x&y) position and longitudinal phase
  - Enable energy measurement via ToF
- Fixed mis-labeled cable connections
- Performed cable length calibration for BPMs after last RF cavity
  - Some discrepancy on BPM positions being investigated

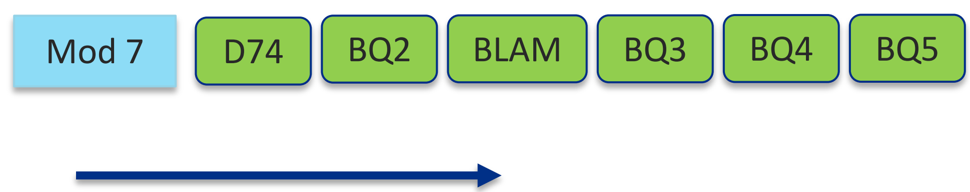
Beam energy (eV)



SCL Module 7 phase set point (deg)

Beam energy from BPM phase as a function of Module 7 phase set point

No acceleration past last Linac module:
BPM phase differences correspond to ToF*

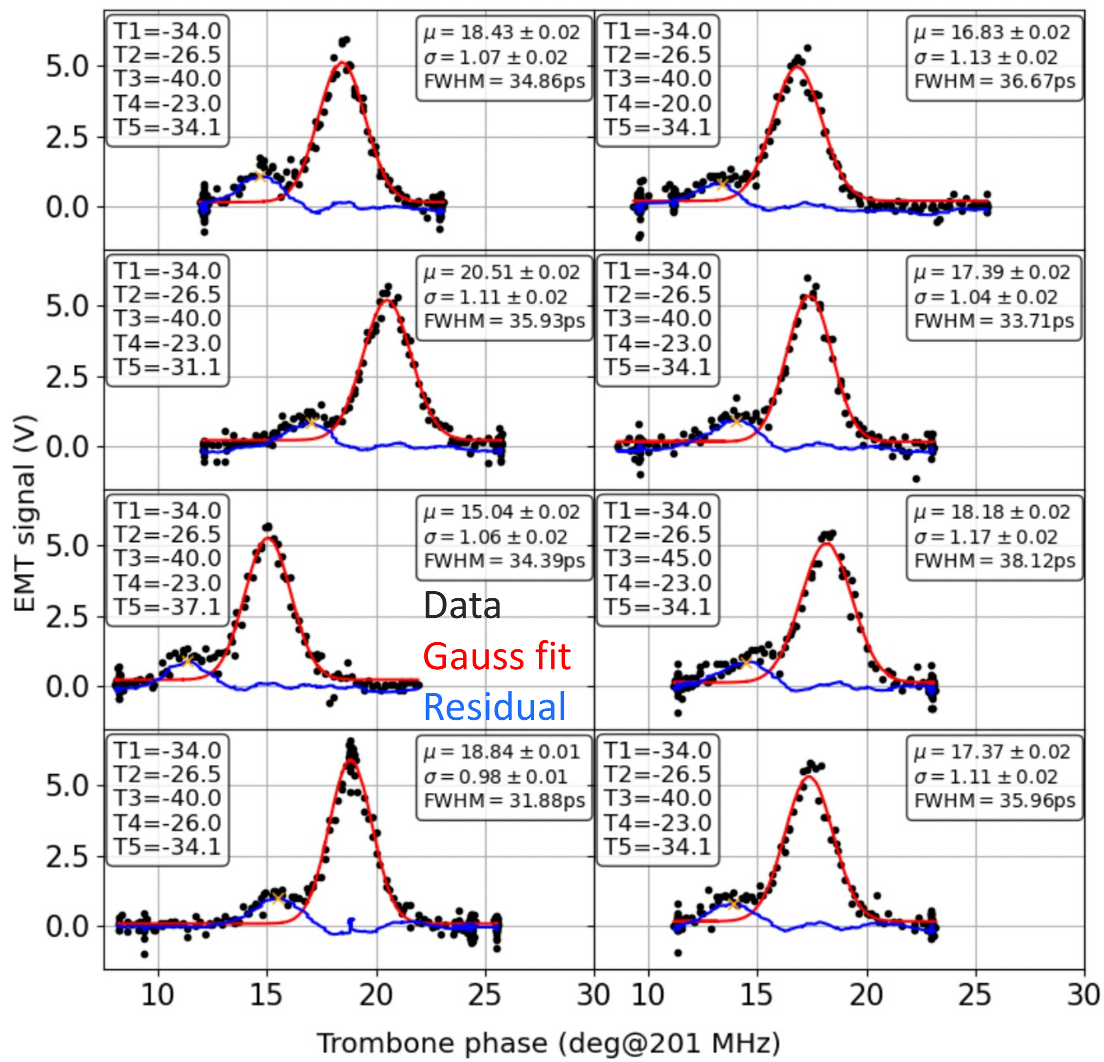


Beam direction

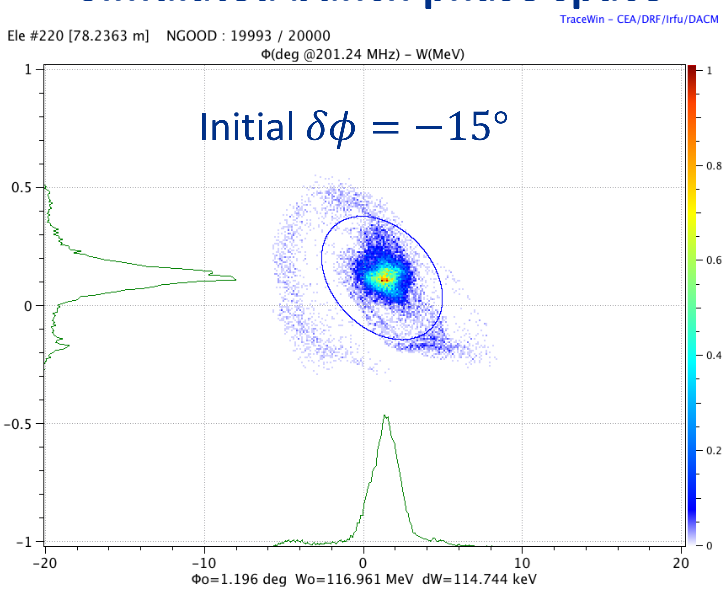
Bunch Length Detector (BLD)

- Measures average longitudinal profile of beam
  - Can help identify longitudinal mismatch (filamentation)
- ➢ Re-commissioned BLD in 2021

Bunch longitudinal profiles



Simulated bunch phase space



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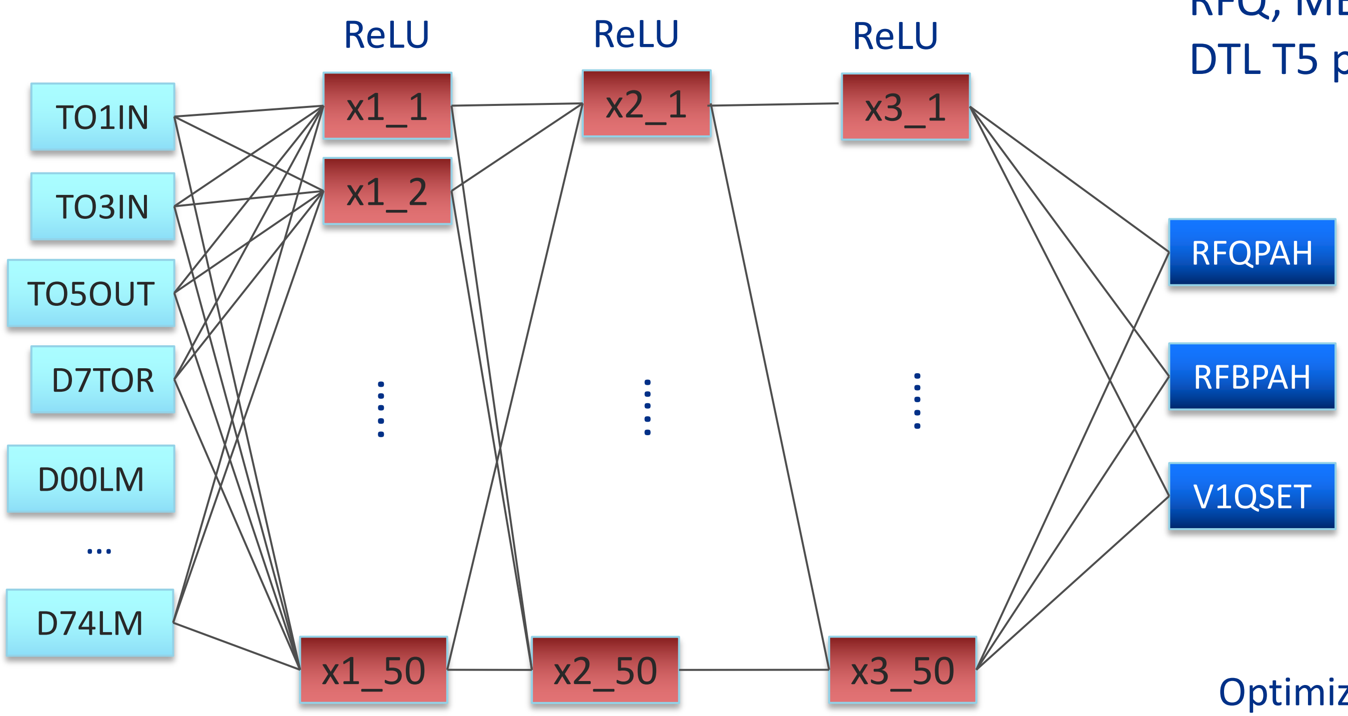
Modeling RF Parameters from Diagnostic Data (1)

- First attempt: use BLM and TOR data to predict RF phase set points
  - Inputs: 30 BLM + 4 TOR (all calibrated TORs and all SCL BLMs)

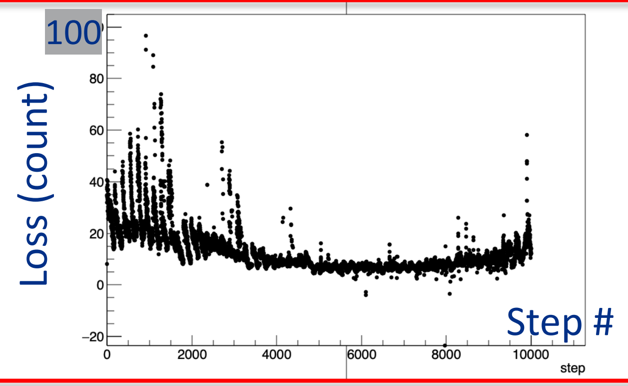
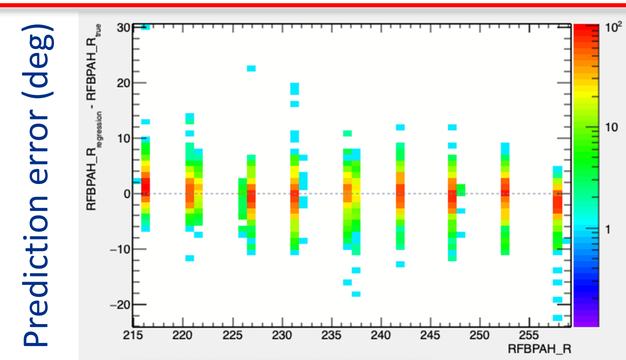
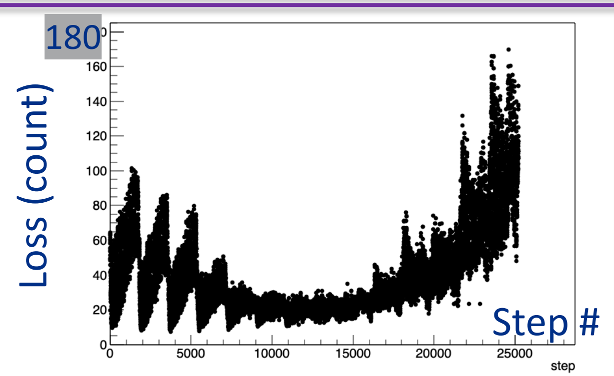
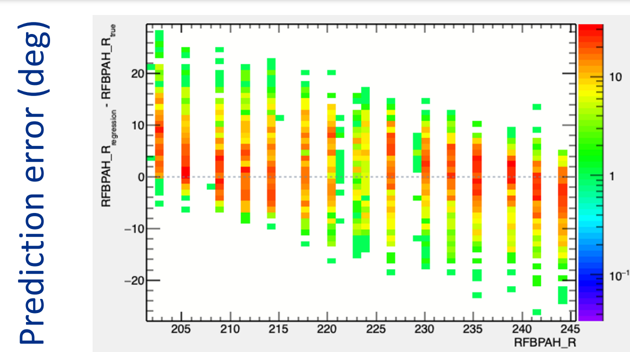


Train data: 3D scan of RFQ, MEBT Buncher & DTL T5 phases

Optimizer: Adam
Loss: sum of squares

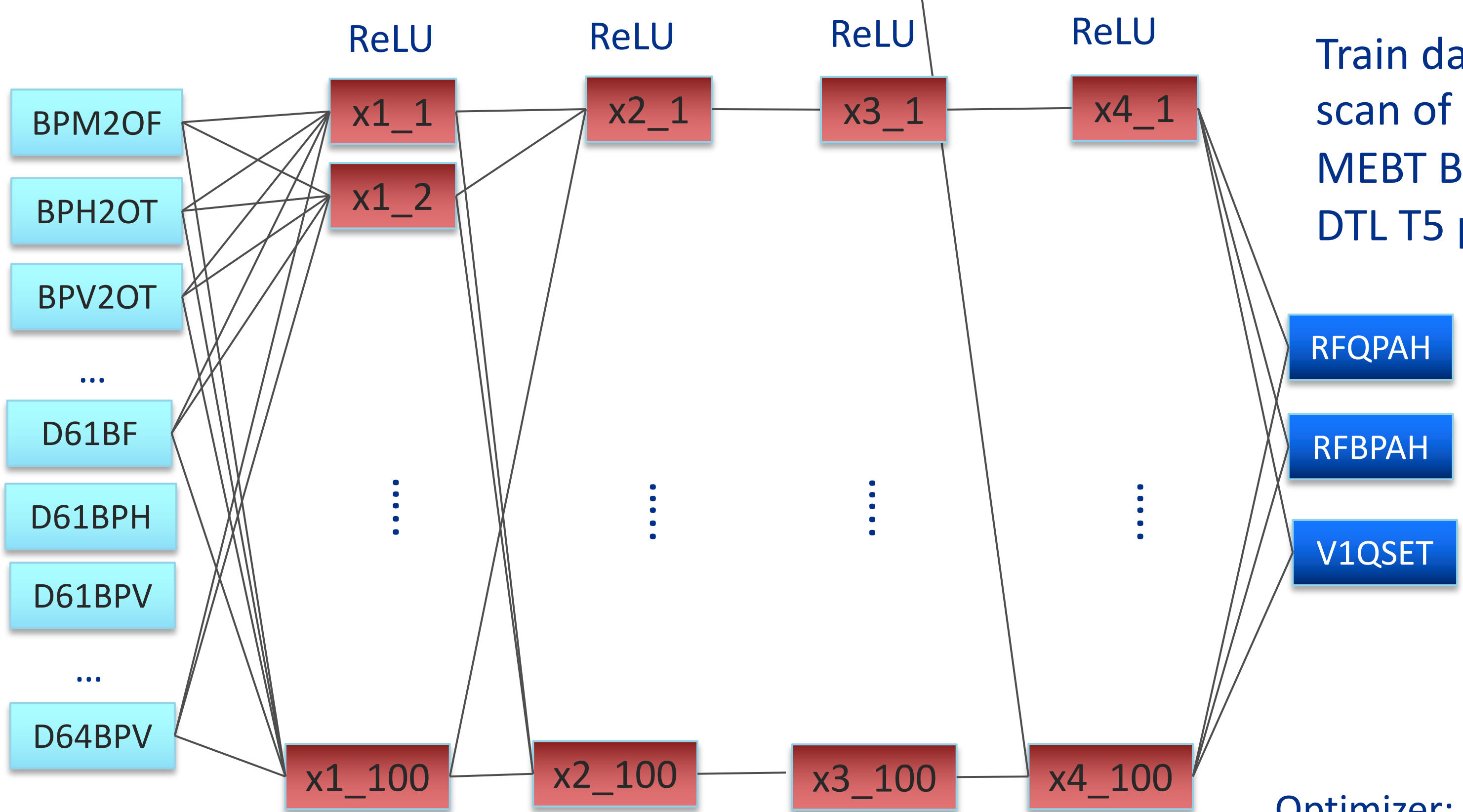
Modeling RF Parameters from Diagnostic Data (1)

- First attempt: use BLM and TOR data to predict RF phase set points for RFQ, MEBT Buncher, DTL T5
  - Model would not reach desired precision nor train consistently on data 6mo apart: not enough information in DTL; loss patterns **very** different 6mo apart

	Training input: total loss	Test output: buncher phase
29 June 2021		
22 Jan 2022		

Modeling RF Parameters from Diagnostic Data (2)

- Second attempt: use BPM data (x, y, long. phase) to predict RF phase set points
  - Inputs: 18 BPM in DTL + 12 BPM in SCL (all DTL BPMs and 1 module in SCL)



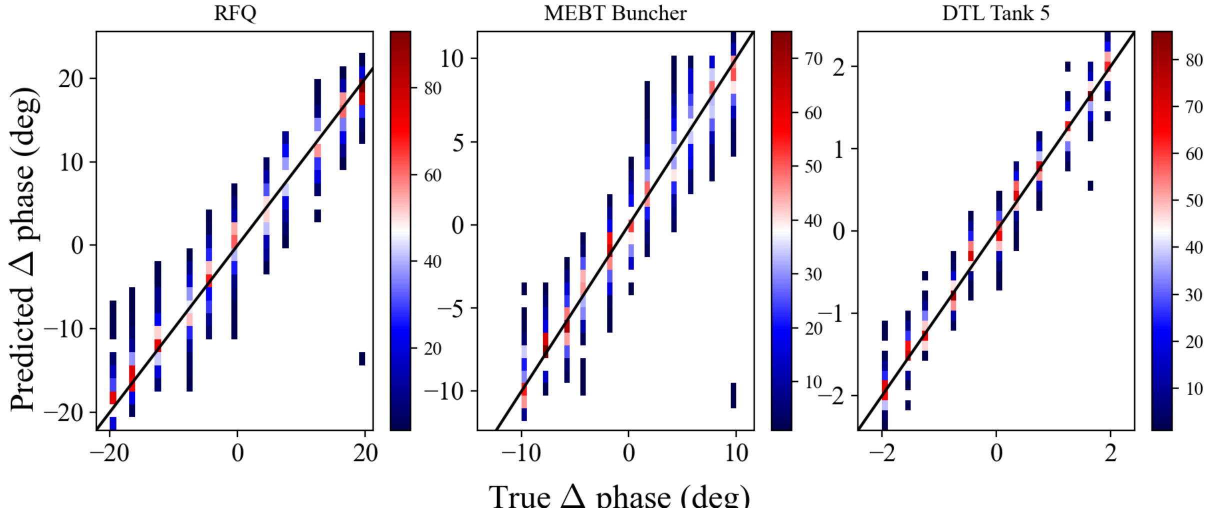
Train data: 3D scan of RFQ, MEBT Buncher & DTL T5 phases

Optimizer: Adam
Loss: sum of squares

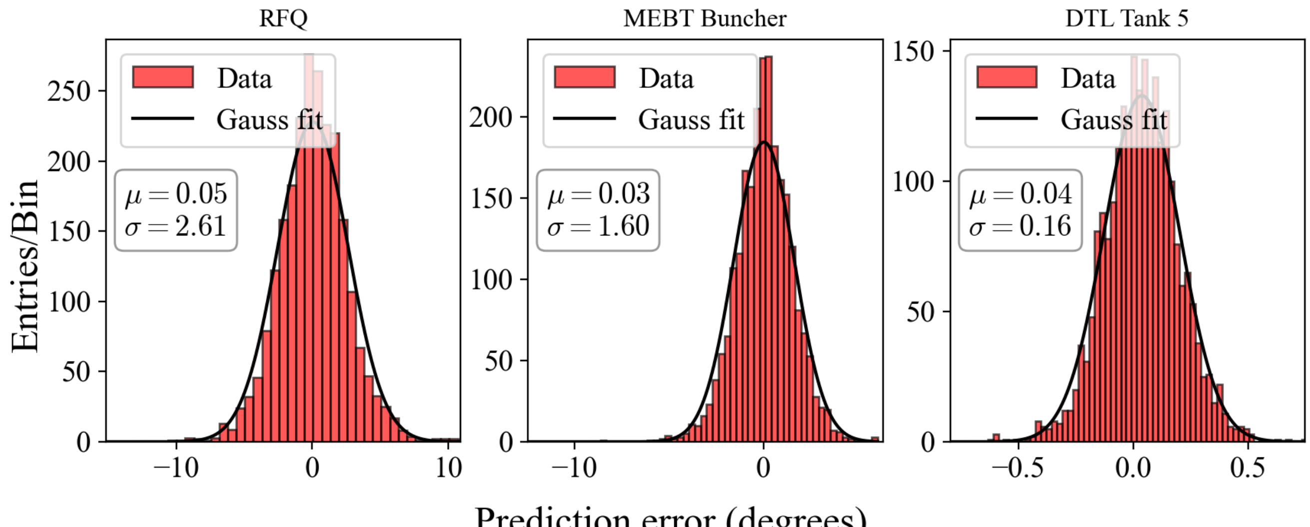
Modeling RF Parameters from Diagnostic Data (2)

- Second attempt: use BPM data (x,y,phase) to predict RF phase set points
  - Model trains equally well on data 3 weeks apart
  - Model predicts w/in desired precision for data close in time to training data.

Truth vs. prediction



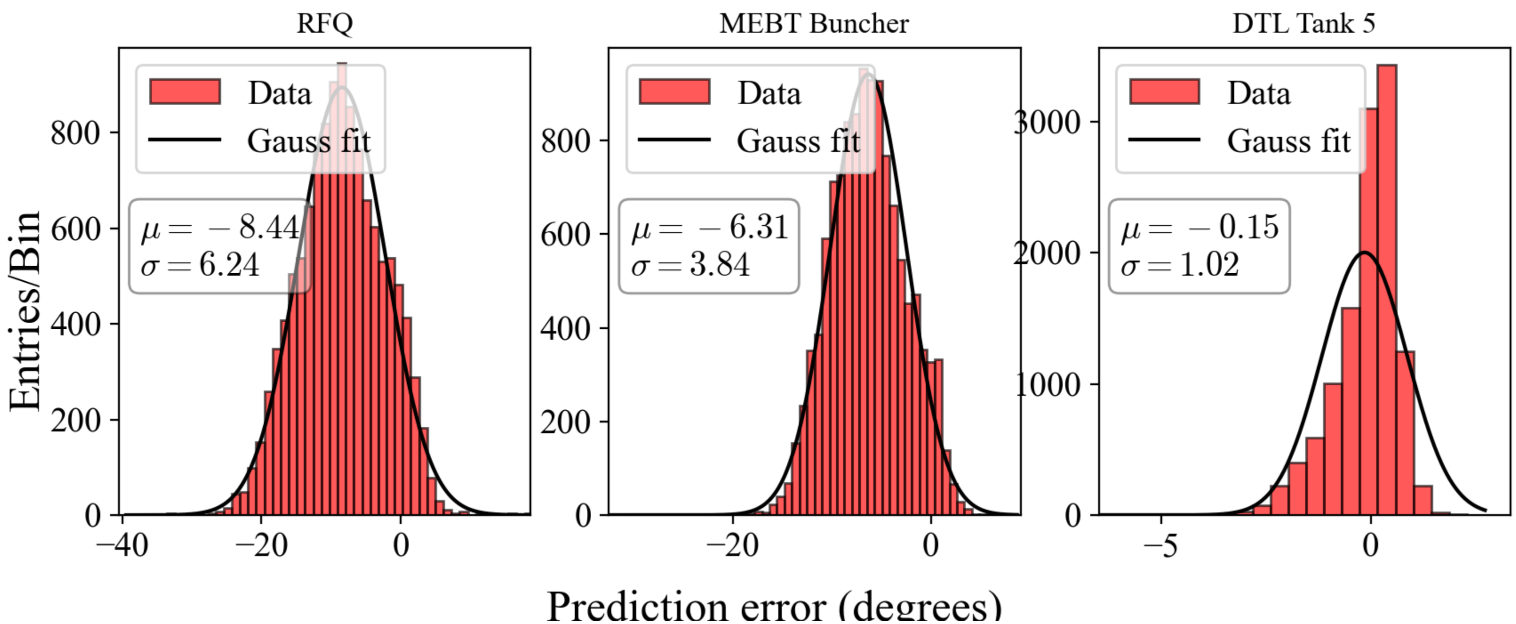
Phase prediction error (degrees)



Modeling RF Parameters from Diagnostic Data (3)

- Second attempt: use BPM data (x,y,phase) to predict RF phase set points
  - Model trains equally well on data 3 weeks apart
  - Model predicts w/in desired precision for data close in time to training data.
  - However prediction much worse on data 3 weeks apart

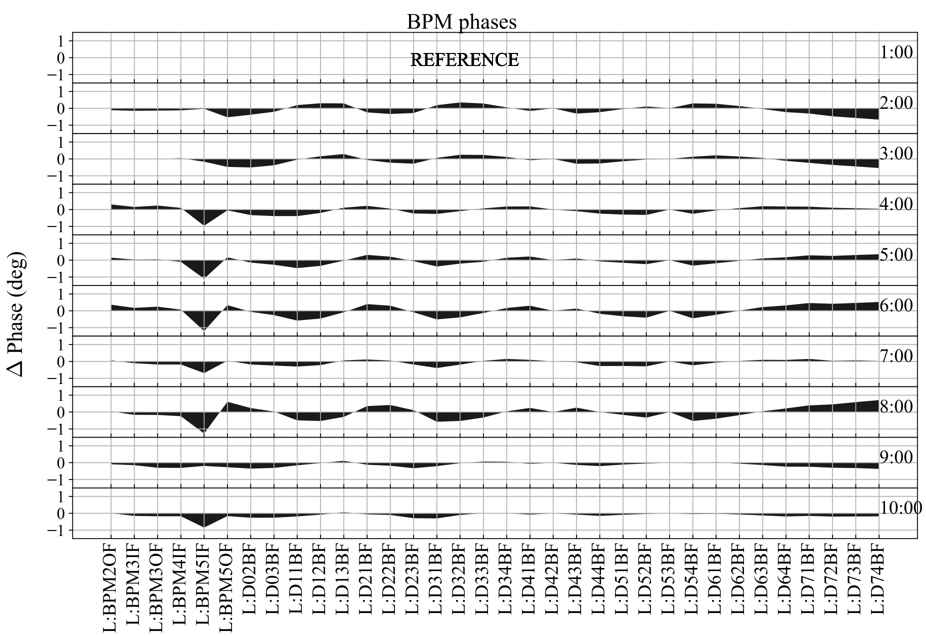
Phase prediction error (degrees)

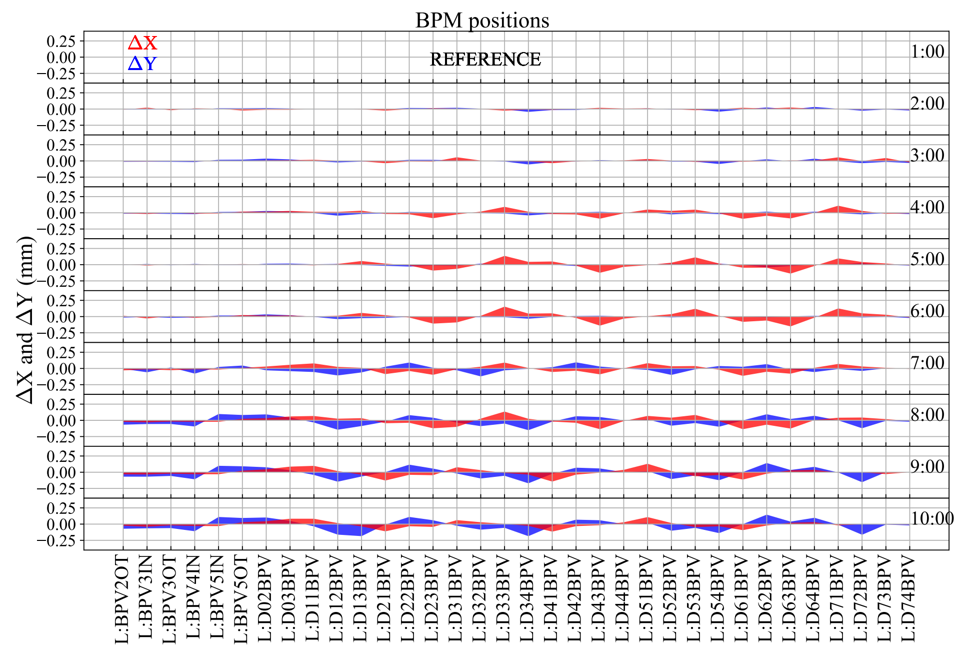


Why?

Daily Evolution of Beam Motion

- Started recording and comparing BPM and BLM data hourly several weeks before summer shutdown
  - Observed that beam phase and transverse positions drift even when no Linac RF parameters are changed by hand
  - Changes appear upstream of 1st available Linac diagnostic

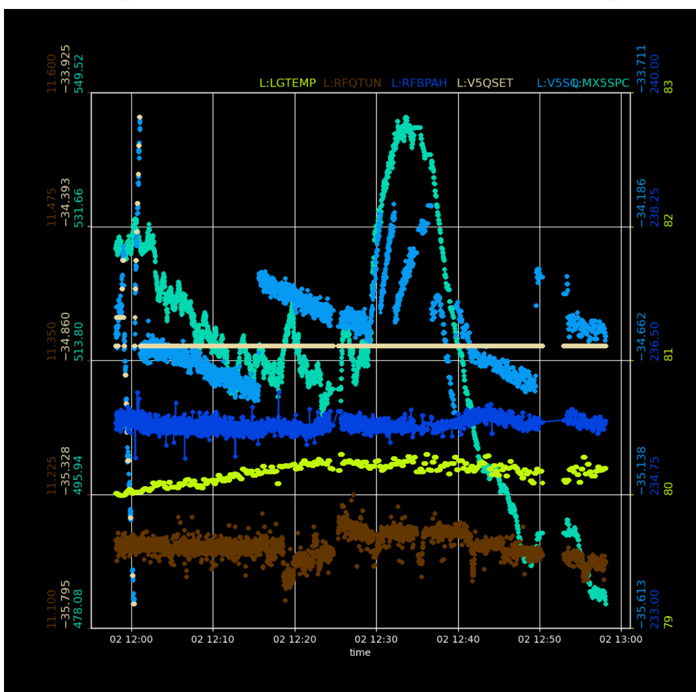




Exploring New Parameters for Training

- Have since identified a handful of parameters which seem to correlate with cavity/beam phase readback
  - RFQ phase regulation loop: responds to temperature changes, source output changes, etc. Reference is not cavity phase set point we tune on
  - DTL Marx modulator ‘special cell’ voltage: variable load capacitor cell used to account for beam loading effects
- In the process of training a new model including these parameters as input

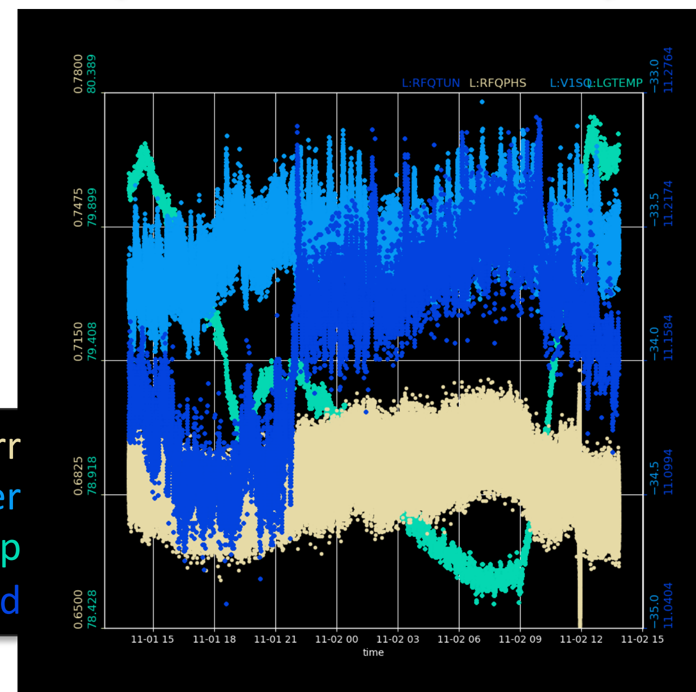
1h



T5 phase set
T5 phase read
T5 MX SPC
RFQ tuner
Glry temp
Buncher phase

1d

RFQ phase err
RFQ tuner
Glry temp
T1 phase read

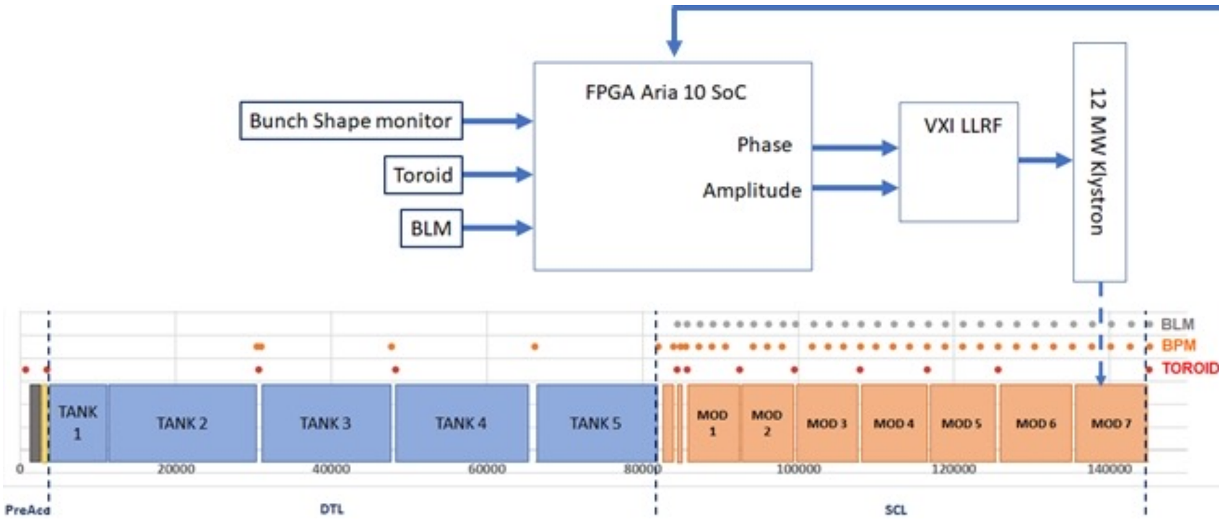


Single Cavity Momentum Control (1)

- US-JP Collaboration Project (Fermilab/PNNL/J-PARC)
- Measure beam energy at end of Linac using ToF (BPM or FCT)
- Model relationship between last RF cavity phase and energy change
- Offline control scheme:
  - Sample beam energy (single pulse or average several pulses)
  - Model inference predicts desired change (if any) to Mod 7 phase setting
  - Automated script enacts change via current control scheme (ACNET)

Single Cavity Momentum Control (2)

- Nearline control scheme:
  - Sample beam energy in slices of 35us pulse
  - Model inference predicts desired change (if any) to Mod 7 phase setting **per slice**
  - Automated script enacts change via fast hardware (e.g. FPGA)
- Requires a lot of software and hardware dev to implement



400MeV ToF signal

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Summary and Outlook

- Fermilab Linac delivers 400 MeV H- beam to downstream machines
  - Stable emittance and beam energy are crucial
- RF cavity parameter tuning can help controll emittance growth and energy changes
  - Currently hand-tuning ~1/day
- Our goal: automate RF tuning in stepped approach
  - Revisiting old & developing new beam diagnostics
  - ML modeling of RF phases from observed diagn. data
  - Aim for proof of concept of offline single-cavity momentum control in next couple of months

Supplementary Slides

Bunch length detector: working principle

- Originally designed by A. Freschenko at INR

- Beam hitting wire produces e-
- Wire potential repulses e- towards slit
- Lens focuses e-
- RF deflector: pass zero-phase e-, deflect the rest: slice the bunch longitudinally
- RF cavity phase manipulation allows to scan full bunch
- e- collected by EMT