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Development of Large Scale Optimization Tools for Beam Tracking Codes

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High-Intensity, High-Brightness Hadron Beams

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Outline

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- Future Developments: Parallel Optimization Tools
- Summary

Why Optimization for Beam Tracking/Dynamics Codes ?

Beam optics codes
(example: Trace-3D)

- Matrix based, usually first order
- Hard-edge field approximation
- Space charge forces approximated
- Usually limited to a single charge state
- Beam envelopes and emittances
- Fast, Good for preliminary studies
- Simplex optimization: Limited number of fit parameters

Beam dynamics codes
(example: TRACK, IMPACT)

- Particle tracking, all orders included
- 3D fields including realistic fringe fields
- Solving Poisson equation at every step
- Multiple charge state capability
- Actual particles distribution: core, halo …
- Slower, Good for detailed studies including errors and beam loss
- Larger scale optimization possible

➢ **It is more appropriate to use beam dynamics codes for optimization:**

– More realistic representation of the beam especially for high-intensity and multiple charge state beams (3D external fields and accurate SC calculation).
– Include quantities not available from beam optics codes: minimize beam halo formation and beam loss.
– Now possible with faster PC's and parallel computer clusters …

Typical Optimization Problems: Nature and Scale

- Typical beam matching: Match beam size and Twiss parameters
  - Limited number of parameters: ~ 10 or less
  - Few particles are needed, enough for statistical significance: 100-1000
  - Small number of iterations: ~ 100 or less
  - Fast: few minutes to an hour on a regular PC

- Tune/retune a whole linac section for a given beam
  - Large number of parameters: ~ 100
  - Large number of particles needed for SC calculation: 1E4 -1E6
  - Large number of iterations: ~ 1000 or more
  - Slow: a day to several days on a regular PC

- Fine-tuning for smooth beam dynamics and reduce beam loss
  - The size is similar to the tuning problem
  - Should not be too long if we start from a good configuration

➢ **Large scale computing will be required for most applications**

Potential Application: Model Driven Accelerator

- The Idea/Objective: Use a computer model to guide the real time operations of an accelerator system.

- The Benefits:
  - Faster automatic tuning/retuning of the machine
  - Reduce the recovery time after a failure
  - Increase the efficiency of the machine: more time available for users
  - Reduce the operating budget of the machine

- The Means: Develop a realistic computer model of the machine
  - Reduce the Gap between the design and the actual machine by using 3D model for every element and measured data if available.
  - Tailor the computer model to the machine by reproducing the beam data from diagnostic devices: better done during commissioning.
  - Fast turn-around optimizations to support decision making for real-time operations

➢ **More optimization tools are needed for the realization of the concept of the model driven accelerator**

Model Driven Accelerator: More Optimization Needs

- An accelerator project may be sub-divided into three phases, namely the design, commissioning and operations phases.

- Design

  - Optimize the design parameters for different design options to produce a robust and cost-effective design → Fit for the best general beam properties

- Commissioning

  - Tailor the computer model to the actual machine by reproducing the experimental data at beam diagnostic points → Fit the actual data

- Operations

  - Use the computer model to retune the machine or to rapidly restore the beam after a failure with limited beam loss → Fit element settings for desired beam conditions

➢ **Different optimization needs for the different phases of an accelerator project: design, commissioning and operations.**

Tools Developed for TRACK: Optimization Algorithm

- Most Optimization/Minimization algorithms rely on an analytical expression of the function to be minimized with explicit dependence on the fit parameters.
- The derivatives of the function are used to guide the minimization process.
- In Matrix based codes you can derive such an analytical expression → Fast fit.
- In particle tracking codes we cannot but we can define the function to be minimized from the statistical beam parameters without explicit dependence on the fit parameters: local derivatives calculated at every iteration → Slower fit.
- We need to use an algorithm that does not require an analytical expression or the derivatives of the function to be minimized → **MINUIT, …**
- We use MINUIT for most of our optimization needs.

➢ **A minimization algorithm without explicit dependence on the fit parameters is needed for beam dynamics codes**

Tools Developed for TRACK: Automatic Transverse Tuning

- **Purpose:** Tune the linac for a given beam and produce smooth transverse beam dynamics.

- **Method:** Minimize the fluctuations in the RMS beam sizes along the considered section.

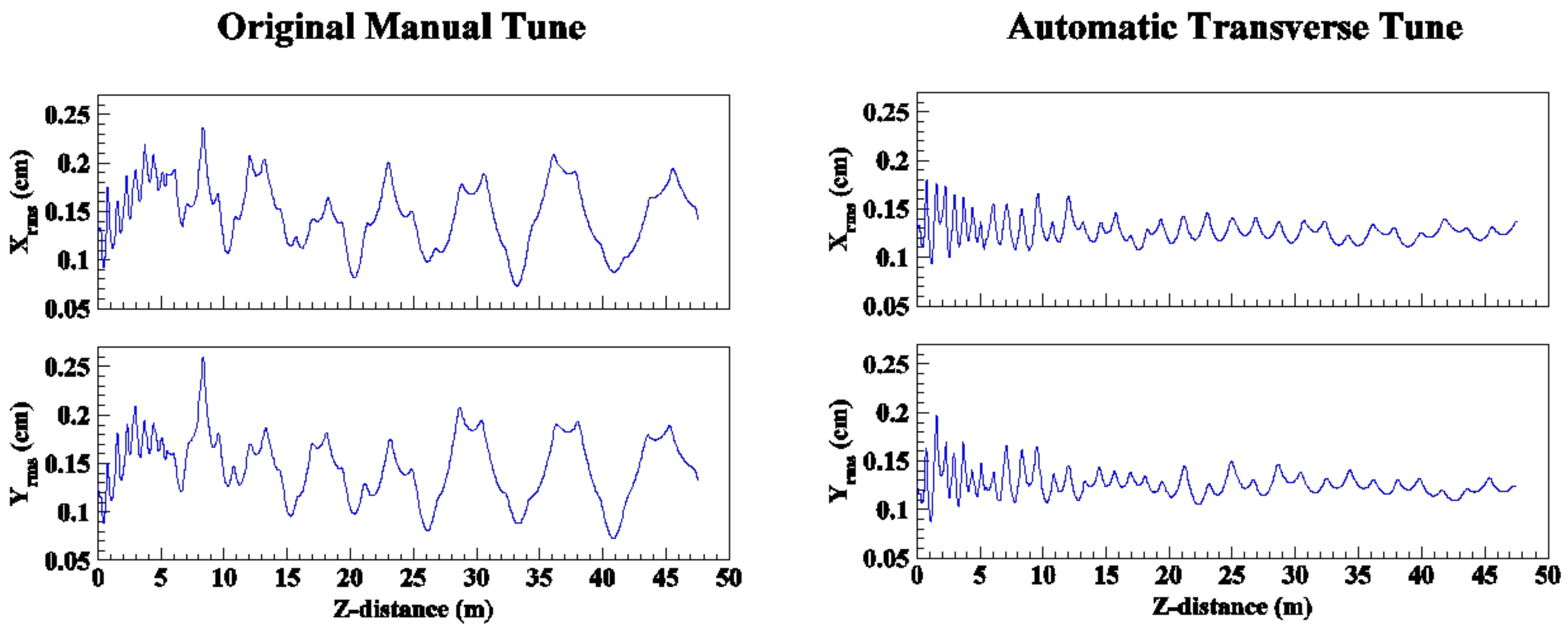
- **Fit Function:** $F = X^0_{rms} + \sum_i \frac{(X^i_{rms} - X^0_{rms})^2}{\varepsilon^2_{X_{rms}}} + Y^0_{rms} + \sum_i \frac{(Y^i_{rms} - Y^0_{rms})^2}{\varepsilon^2_{Y_{rms}}}$

  where X^0_{rms} and Y^0_{rms} are the RMS beam sizes at the entrance of the section or after the first focusing period, the sum index i runs over the focusing periods in a given section and ε_{Xrms} and ε_{Yrms} are the allowed errors on the RMS beam sizes.

- **Fit Parameters:** Field strengths in focusing elements

- **This method is general and should produce good results for both periodic or non periodic accelerating structures.**

Automatic Transverse Tuning: Application to RIA/FRIB Linac



X- and Y-rms beam sizes before and after applying the automatic transverse tuning procedure. The beam is a two-charge state uranium beam in the first section of the RIA/FRIB driver linac.

✓ **A similar procedure was developed to produce smooth longitudinal envelopes by fitting the RF cavities field amplitudes and phases.**

Automatic Longitudinal Tuning: Minimize the Longitudinal Emittance of a Multi-Q Beam Before a Stripper

- **Purpose:** Tune a linac section to minimize the logitudinal emittance of a multiple charge state beam right before stripping.

- **Method:** Match the longitudinal beam centers and Twiss parameters of the different charge state beams: $W_{q0} \rightarrow W_0$

$$\Delta W_{qi} \rightarrow 0; \Delta\phi_{qi} \rightarrow 0$$

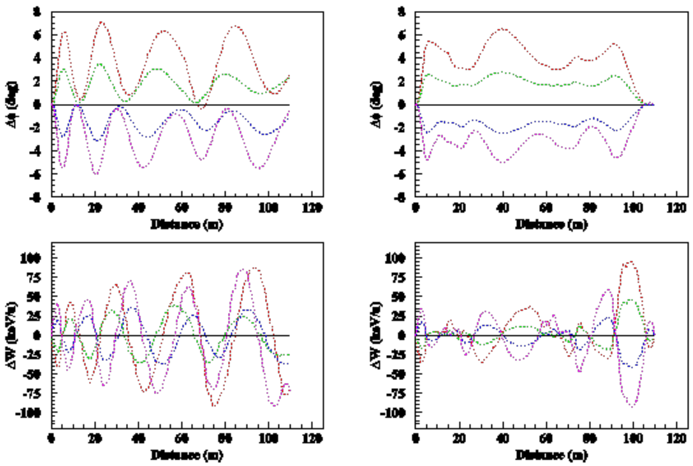
$$\alpha_{qi} \rightarrow 0; \beta_{qi} \rightarrow \min$$

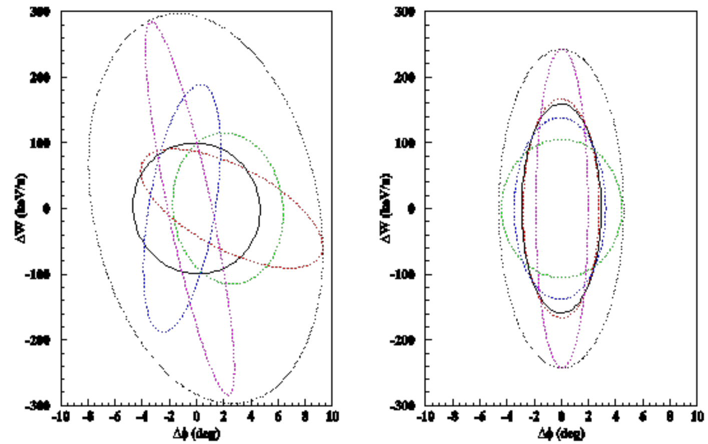
- **Fit Function:** $F = \frac{(W_{q0} - W_0)^2}{\varepsilon_w^2} + \sum_{qi} \frac{\Delta W_{qi}^{\ 2}}{\varepsilon_{\Delta w}^2} + \sum_{qi} \frac{\Delta\phi_{qi}^{\ 2}}{\varepsilon_{\Delta\phi}^2} + \sum_{qi} \frac{\alpha_{qi}^{\ 2}}{\varepsilon_{\alpha}^2} + \sum_{qi} \beta_{qi}$

  where W_0 is the desired beam energy and ε_W is the corresponding error. $\varepsilon_{\Delta W}, \varepsilon_{\Delta\phi}, \varepsilon_{\alpha}$ are the allowed errors on the relative energy, phase and α shifts of the individual charge state beams from the central beam.

- **Fit Parameters:** RF cavities field amplitudes and phases.

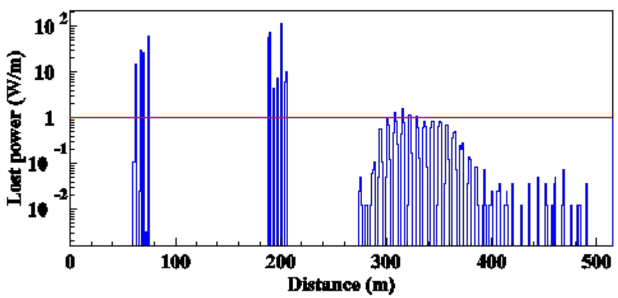
Application to RIA/FRIB Linac: Minimum Multi-Q Beam Longitudinal Emittance at the Stripper → Less Beam Loss

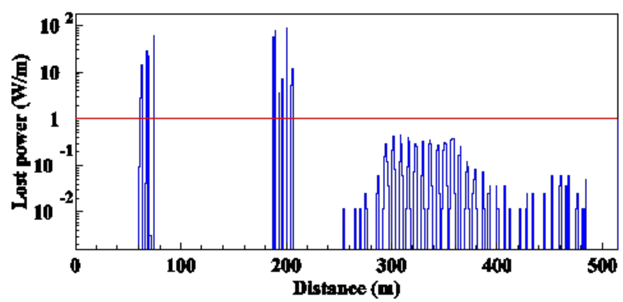




Varying only phases: ~ 50 variables
Black: Ref. charge state: 74+ of U-238
Colors: 72+,73+,75+ and 76+ beams

Colors: Individual charge states
……… : Effective beam ellipse of all charge states



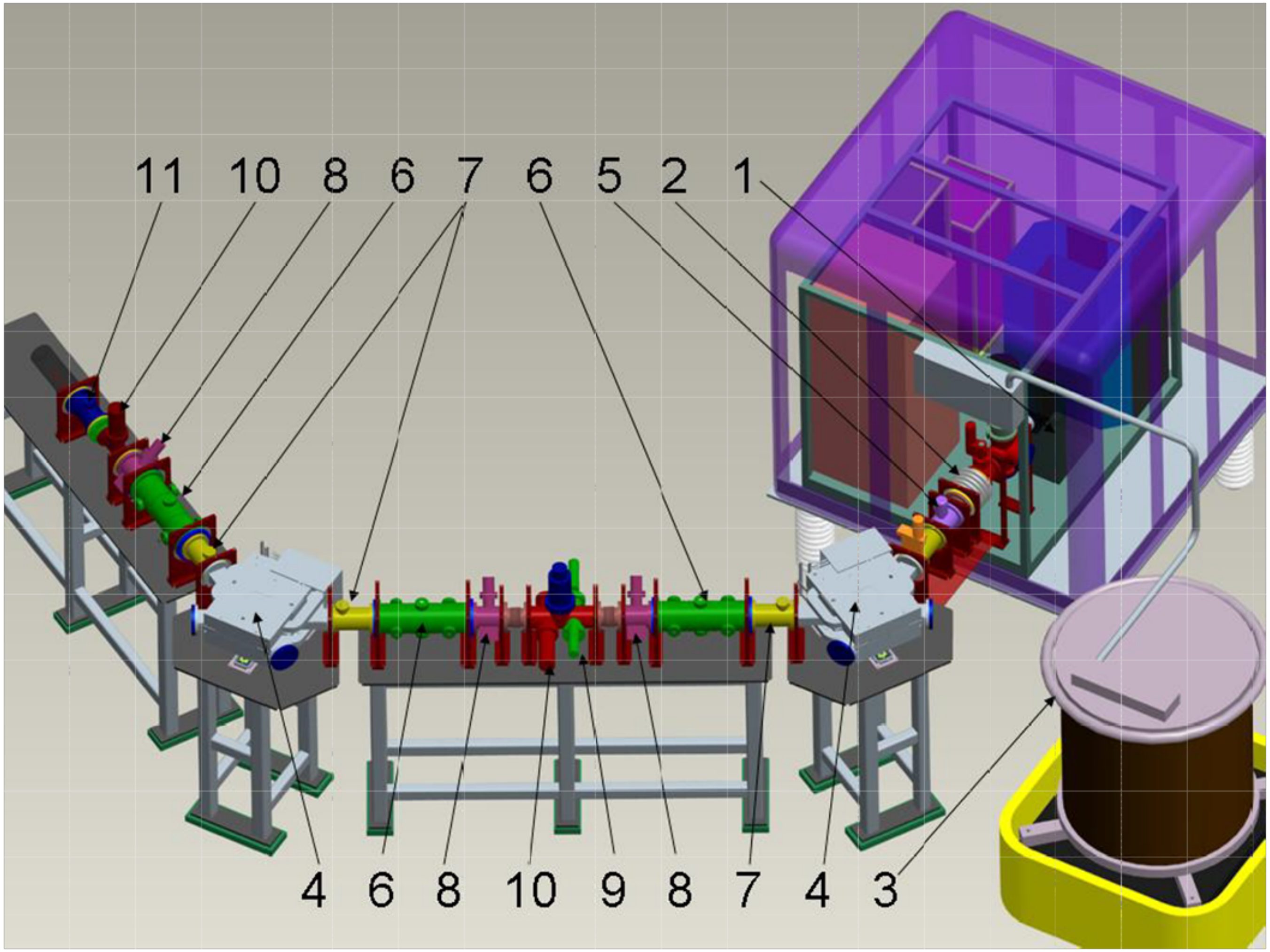


A reduction of a factor of ~ 3 in total beam loss after the stripper and an order of magnitude in peak beam loss between the manual (left) and the automatic tune (right).

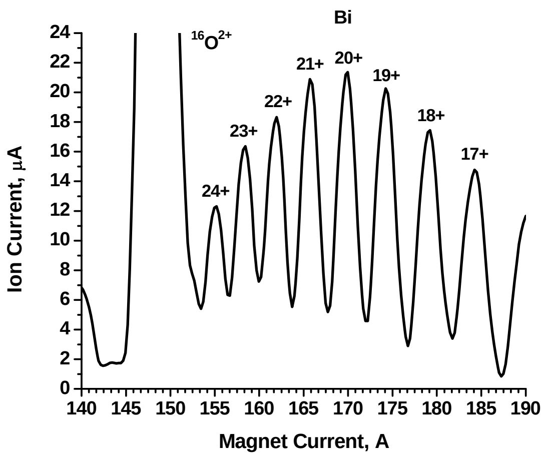
Application for the Operation of a Prototype 2Q-LEBT

General View of the Multi-Q Injector at ANL:

1- All permanent magnet ECRIS on HV platform
2- 75-kV Accelerating tube
3- Isolation transformer
4- 60° Bending magnet
5- Einzel lens
6- Electrostatic triplets
7- Electrostatic steering plates
8- Rotating wire scanner
9- Horizontal slits
10- Faraday cup
11- Emittance probe



Fit Beam Profiles to Extract the Initial Beam Parameters at the Source



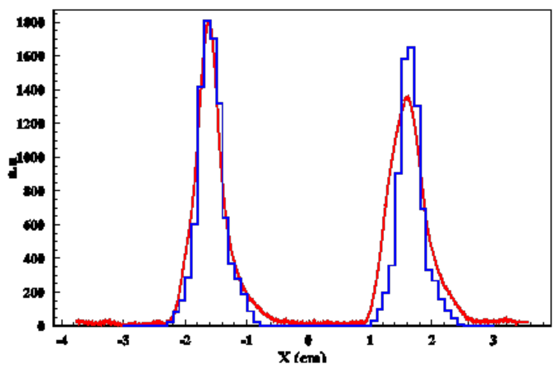
←Measured beam composition after the first magnet.

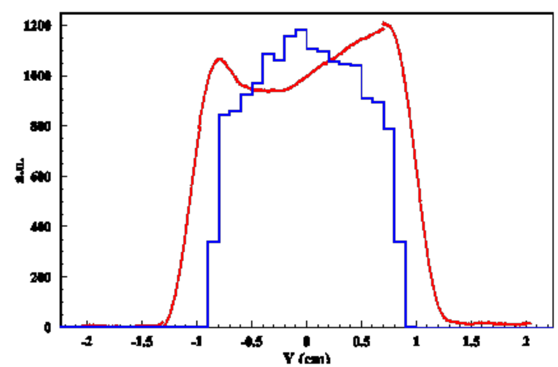
Simulation: 17 beams (O, Bi) are tracked simultaneously from the ion source through the LEBT. Current ~ 2 mA at the source

LEBT tuned for Bi-209, 20.5+ central

2Q beam: 90 kV, 20+ and 21+, ~ 50 µA

TRACK Fit: Vary initial emittance and Twiss parameters at the source to fit the horizontal and vertical beam profiles after the first magnet.





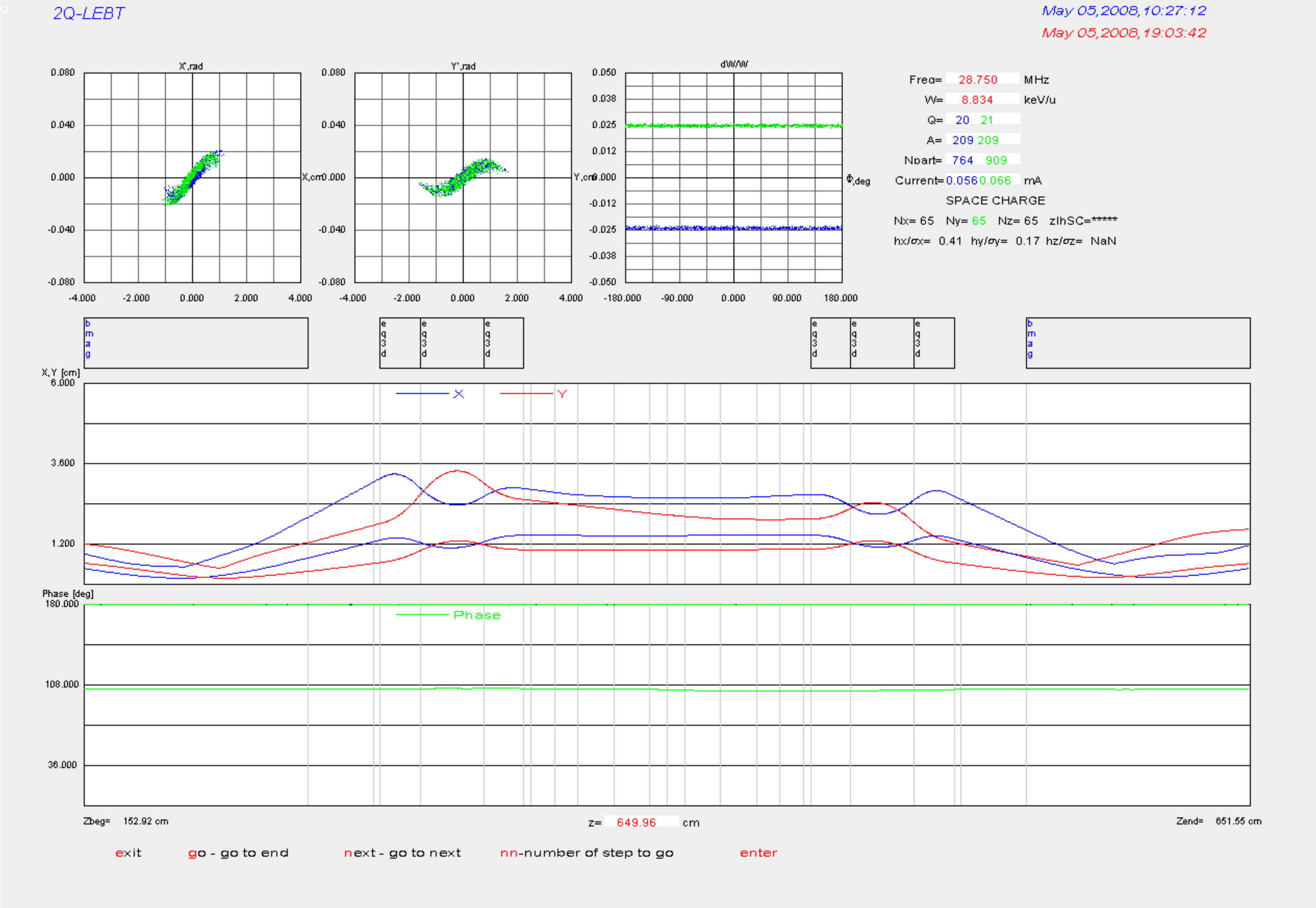
Red Curves: measured horizontal (left) and vertical (right) beam profiles.
Blue Histos: results of TRACK fit → the initial beam conditions at the source.

Fit Quad Strengths to Recombine the 2Q beams at end of LEBT

Fit criteria:
Symmetric Beam from M1 to M2 with respect to the Mid-plane to recombine the 2Q beam

Fit parameters:
Strengths of the 6 Quads of T1 and T2

Results:
RMS envelopes are ~ 100% symmetric
Max envelopes are OK



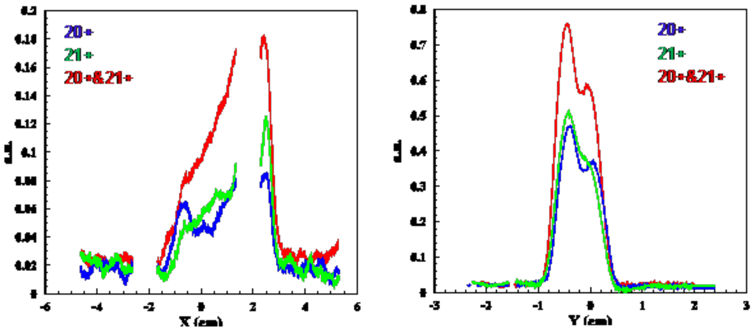
✓ A second fit is used to find the setting for the last triplet

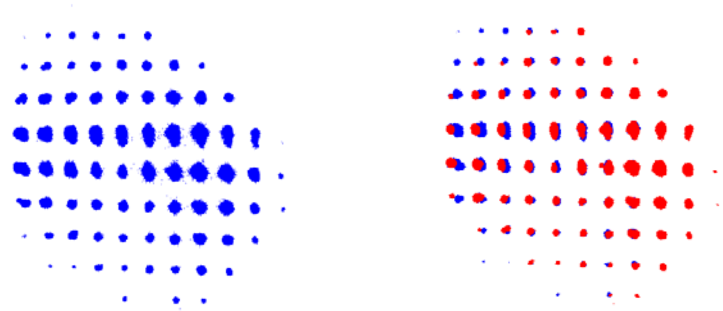
Successful Recombination of the 2Q Beams at the end of LEBT

Quads	Fit value kV	Set value kV	Diff %
Q-1	3.312	3.299	0.4
Q-2	-2.589	-2.793	7.9
Q-3	1.847	1.941	5.0
Q-4	1.794	1.922	7.1
Q-5	-2.595	-2.863	10.
Q-6	3.372	3.373	0.1
Q-7	2.487	2.492	0.5
Q-8	-3.225	-3.229	0.1
Q-9	3.743	3.431	8.3

There is still room for improvement:
- Initial beam conditions
- Modeling of the E-Triplet

Measured beam profiles at the end of LEBT: left: horizontal, right: vertical





Pepper-Pot images:
left: 20+&21+
right: 20+: blue, 21+:red

➢ **Small scale realization of the model driven accelerator**

Future Developments: Parallel Optimization Tools

- So far, the developed optimization tools were used only with the serial version of TRACK → Very time consuming.
- Large scale parallel computing is necessary for timely optimizations …
- The fully parallel version of TRACK is now ready (PTRACK, Jin Xu's Talk)
- Next: Test the existing tools with the Parallel version of TRACK
- First: Try parallel tracking and serial optimization.
- Second: Investigate the use of parallel optimization algorithms developed at the Mathematics and Computer Science division of Argonne (TAO: Toolkit for Advanced Optimization, PETSc).

Future Developments: Model Driven Accelerator

- More tools are needed to fit the experimental data using a beam dynamics code.
- Develop interfaces between the beam diagnostic devices and the beam dynamics code → Calibrate and analyze the data to input to the code.
- Numerical experiments could be used to test the tools before implementation to the real machine → Produce detector like data from the code.
- Larger scale realization: ATLAS at ANL, may be SNS Linac …
- Large scale parallel computing will be needed to support real time operations of the machine.

Summary

- For high-intensity beams, it is more appropriate to perform optimization using a beam dynamics code. More realistic: beam halo, beam loss, …
- Optimization tools are needed not only for design optimization but also to support commissioning and operations of an accelerator.
- Different phases of an accelerator project have different optimization needs.
- It is now time to develop and use a realistic computer model to support real-time machine operations.
- To bridge the gap between the design and the actual machine, we need realistic modeling of every beam-line element and detailed tailoring of the computer model to the actual machine by fitting the measured data.
- Large scale computing will be needed for all these applications, now possible.