Commissioning Strategies

CERN School on High Power Hadron Machines

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Commissioning Phases

- Equipment testing
  - Individual equipment
  - Systems
  - Integration
- The first beam
  - Initial "beam pulling"
  - 1st order problems
  - Simple tools needed
- Intensity increase, power rampup, …
  - 2nd order problems
  - More sophisticated diagnostics required

Pre-Beam Tasks

- Hardware tests
  - Systems tested independently
  - Quad polarity test
- RF conditioning
  - Good test of minimal integration (vacuum, LLRF, high power RF, cooling, controls, …)
  - Good opportunity to get to know your equipment
- Software tests
  - Virtual accelerator
- Beam simulations
  - When will the beam debunch, can detectors measure it?
  - Simulations form the basis of the commissioning plan

"First Beam" Tasks

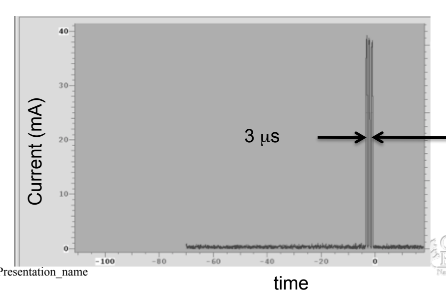
- General advice:
  - Don't trust any measurements
    - If an instrument indicates no beam, cross check
- Get the beam down the pipe
- Calibrate loss monitors
  - Use controlled beam spills
  - Test machine protection systems
- Use the most simple direct measurements
  - Beam loss
  - Current monitors
  - Beam Position Monitors (BPM)

General Beam Commissioning Sequence

- Linac section
  1. Drift low intensity beam (if possible), RF off
  2. Sequentially set RF phase and amplitudes
  3. Correct trajectory
  4. Adjust quadrupoles
  5. Perform fault study (calibrate machine protection)
  6. Increase intensity
  7. Set collimation
  8. Adjust 2-4 to minimize beam loss
- Ring
  1. *Circulate* beam
  2. Correct orbit
  3. Perform fault study (calibrate machine protection)
  4. Set RF
  5. Adjust quadrupoles
  6. Increase intensity / tune injection scheme
  7. Set collimation
  8. *Turn on and set higher order magnets*

Commissioning Beam

- Make sure you can provide a very low intensity beam that will not damage the machine during initial commissioning
  – Setting up the RF structures is inherently "dirty"
  – Low peak current
    - Detune source or insert aperture limitation
  – Short pulse
    - Use low energy chopper
- Beam instrumentation should be designed to detect this "commissioning" beam
- Calculate how much beam you can lose without damage

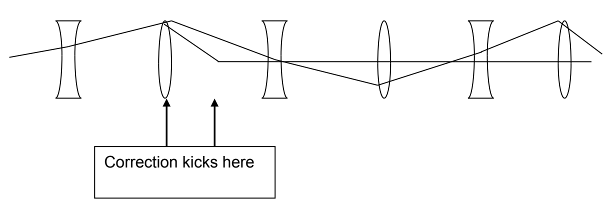


Model Based Applications

It is possible to create simple beam model representations prior to commissioning

- Control system can provide required input
  - Quadrupole magnetic fields can be provided close to measurement accuracy (10^{-3} – 10^{-4})
  - Corrector strengths can also be made available
  - RF field amplitudes can be provided to within 10-20% before beam
    - Synchronous phase offset and the final amplitude calibration are beam based

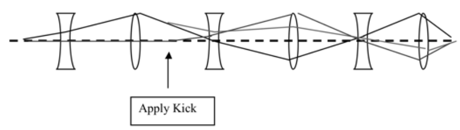
Trajectory Correction I



- Without special effort, the beam path is not on the ideal reference defined by the middle of the quadrupoles
- In general 2 dipole correctors/plane are required to remove a wave
- Be careful where you place BPMs (avoid 180 degree phase advance!)

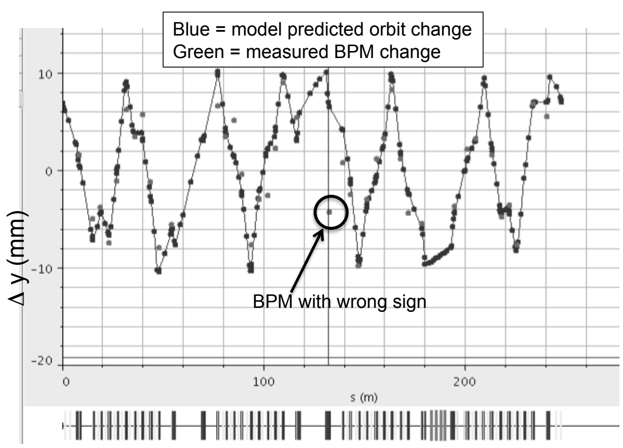
Difference Techniques

- Predicting the exact beam behavior (e.g. trajectory) a-priori is difficult
  - Unknown initial conditions
- Predicting the change in the beam behavior (e.g. trajectory) to a change in an external influence (e.g. corrector strength) is much easier
- Comparing the measured change in the beam behavior to a model predicted change can be very useful



Black = original trajectory
Blue = trajectory after applying a dipole kick
Red = difference in trajectory

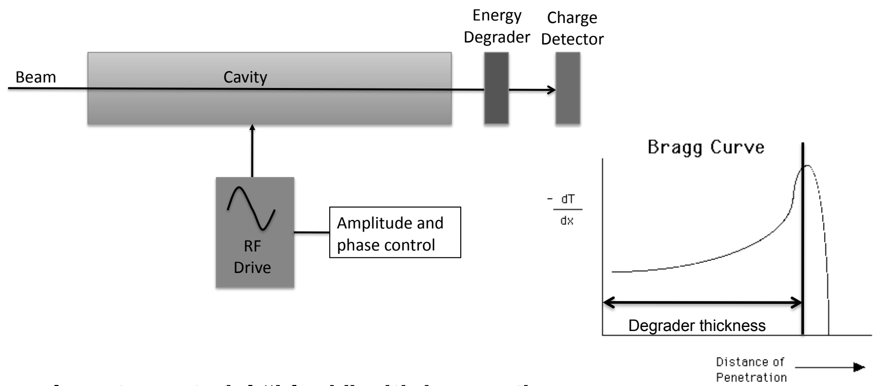
Orbit Difference



1 Wed, Nov 28, 2007 15:29 **Re: Ring BPM C13 orbit difference** *George Link* Repair {Operations} (Accelerator Electronic Logbook) Ring Service Building Lower Level (8540)
The up and down cables were found to be corected to the wrong ports on the heliax patch panel. The cable have been reconnected to their correct ports.

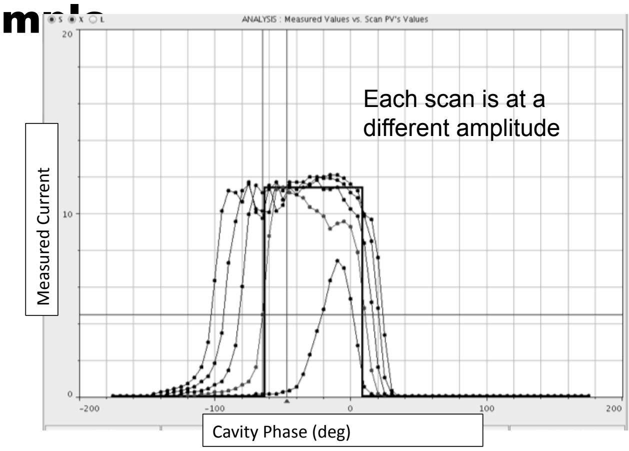
- Example

Linac RF Setup : Energy Degrader Method



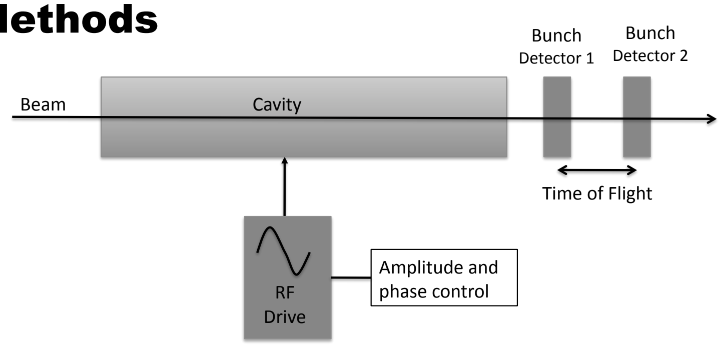
- Insert a material "block" with known thickness after the cavity
  - Absorb beam with energy just below design cavity output energy
  - Must know a priori the expected output energy of the cavity
  - More useful at low energy, warm structures

Linac RF Setup : Energy Degrader Example



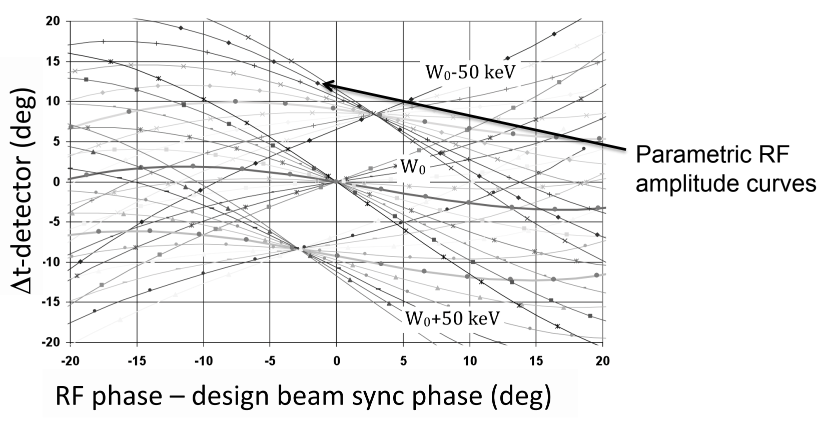
- Compare the measured profile widths with pre-calculated simulations
- Set the amplitude to the value corresponding to the appropriate curve, phase at the appropriate offset to the "edge"

Linac RF Setup: Time-of-Flight Methods



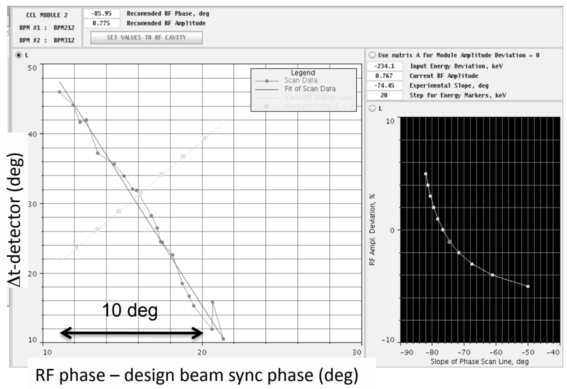
- Vary the phase and amplitude control of an RF structure and measure the change in the "Time-of-Flight" between downstream bunch detectors
- Usually non-intercepting!
- Use low intensity beam to not perturb RF fields

RF Setup: Time-of-Flight, Δ-T



- Pre-calculate beam response maps to RF amplitude and phase errors and input energy errors
- Scan RF phase at a fixed amplitude and compare to pre-calculated clusters
- Use a linearized fitting algorithm to determine best fit amplitude, phase calibrations and beam energy error

RF Setup: Time-of Flight, Δ-T Example

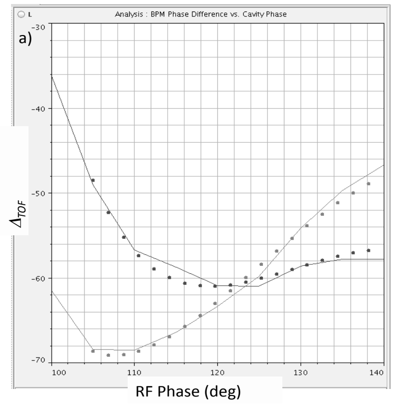


- Works well if you start close to the correct solution
- Used for warm linac structures with predictable beam setup

RF Setup: Signature Matching

- Similar to the Δ-T method, except no pre-calculated responses
  - Measure the beam response over an arbitrary range of RF phases and amplitudes
  - Use a model to fit the RF amplitude calibration, RF phase offset and input beam energy to best match the observed beam response
- General method
  - Slower analysis than Δ-T, but not really a problem with modern computers

RF Setup: Signature Matching
DTL Tank Example

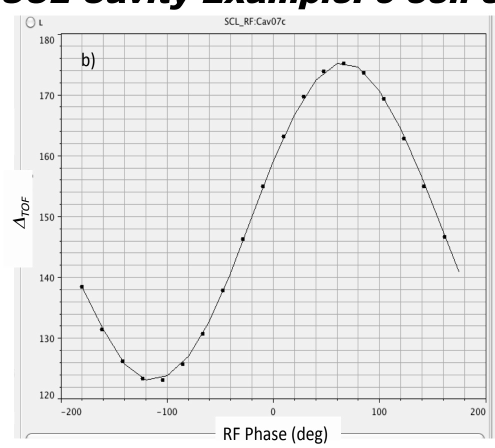


Lines = measurements
Dots = model predictions

Blue = RF amplitude 1
Red = 5% lower amplitude

- **Scan the RF over larger parameter ranges**
  - **Fit to non-linear response – easier to get it right**
  - **Fit is sensitive to phase, amplitude and input beam energy !!**

RF Setup: Signature Matching
SCL Cavity Example: 6 cell elliptical, β = 0.61

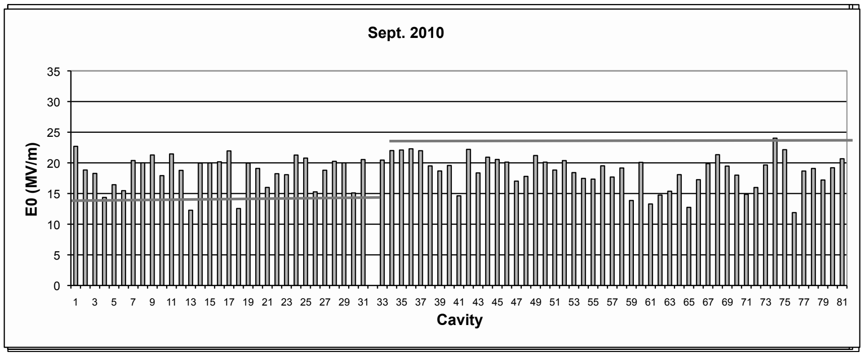


Line = measurements
Dots = model predictions

- **SCL cavity acts as an ideal RF kick**
- **Scan 360 degree (beam easily stays bunched at high enough energies)**
- **Trivial to calculate RF field, phase set-point and input beam energy**

Superconducting Cavity Amplitudes

SNS Gradient History



- **SCL cavity gradient levels may not be as expected**
  - **SCL are operationally quite flexible**
  - **But have tools available for quickly adjusting lattices for different energies**

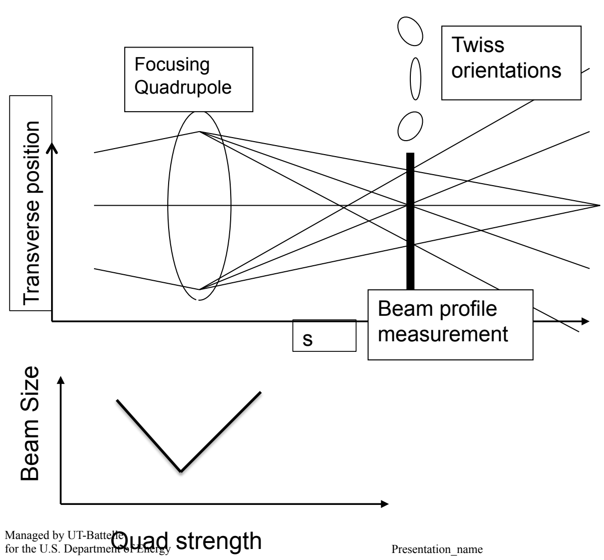
Transverse Matching

- **The Challenge : get the beam Twiss parameters set to desired values (usually design) at some place in the lattice**
- **The beam Twiss parameters characterize the beam size and divergence**
  - **Emittance (ε) is a measure of the phase space size (position/angle)**
  - **Beta (β) is characteristic of amount of beam with large displacement**
  - **Alpha (α) is indicative of whether the beam is converging or diverging**
- **First measure the Twiss parameters upstream of the place you will be matching to**
- **Adjust quadrupoles downstream of the point you solve the Twiss parameters to match to the "design" Twiss**
  - **With an envelope model**

Measuring the Twiss Parameters

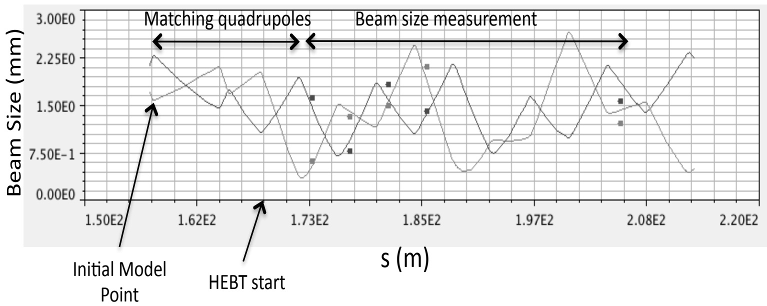
- You need at least three beam size measurements to calculate the Twiss parameters at some point upstream point
  - Per plane
- Configure the model based on the machine settings
  - Include space charge for high intensity beams
- Use a solver to find the initial Twiss parameters to best match the measured beam sizes
  - Variables are the initial Twiss values
  - Figure –of – merit is to minimize the difference between model predicted and measured beam sizes
  - If only three profiles are available, the solution is exact and can be done using linear algebra
  - The more general method should accommodate an arbitrary number of profile measurements

Single Profile Measurement Method for Twiss Calculation



- Vary a single quadrupole and measure the beam size downstream
- Solve for the initial Twiss parameters that give the right beam size for all the measured conditions
- Be sure to find a waist !

Transverse Matching

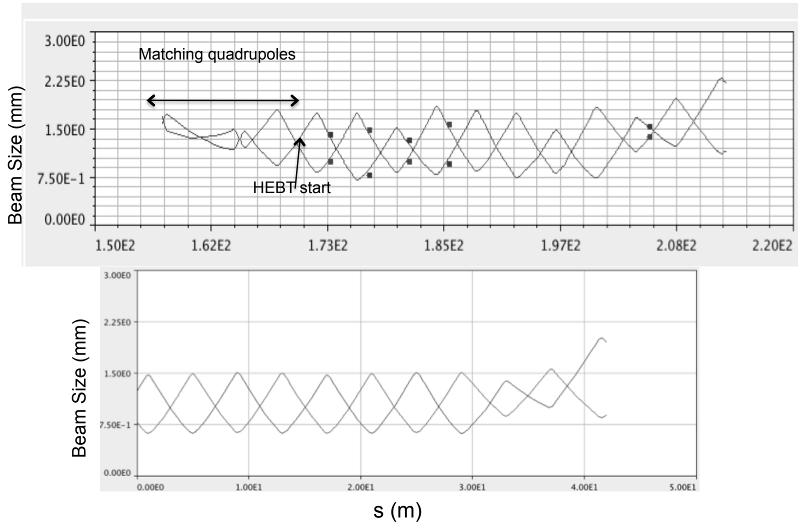


- **Example of matching with multiple profile measurements: before quadrupole adjustments**

Finding Quadrupole Values

- **Once the upstream Twiss parameters are known, it is possible to "match", or adjust quadrupole strengths**
  - **Usually the goal is to recover the design Twiss values along a beamline.**
- **Emittance cannot be affected (directly) by magnet settings but α and β can be**
- **You need at least 2 independent magnets to correct α and β in each plane (4 independently powered magnets to get horizontal and vertical both corrected)**
- **Sometimes magnet power supply limits are a problem – easier to match if you have more "knobs"**
- **Usually at lattice transitions there are independently adjustable quadrupoles for this purpose (matching quads)**

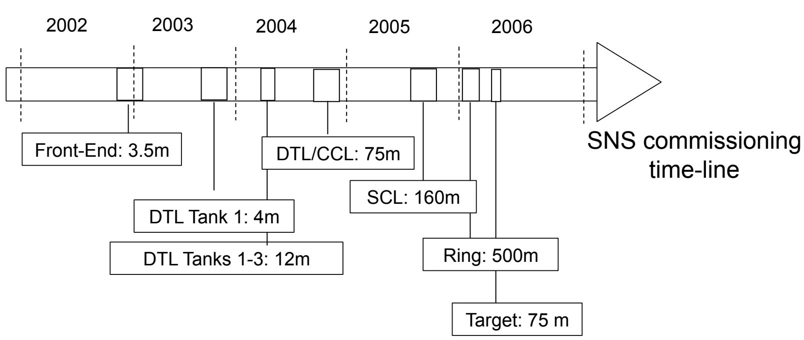
Matching Quadrupole Adjustment Example



- With Twiss parameters matched to design value at the HEBT start, beam is better "matched" to lattice

Overall Commissioning Strategies

- Staged deployment provides early integrated testing opportunities
  - Controls, timing, machine-protection, beam instruments, RF, …



- Requires coordination with construction activities

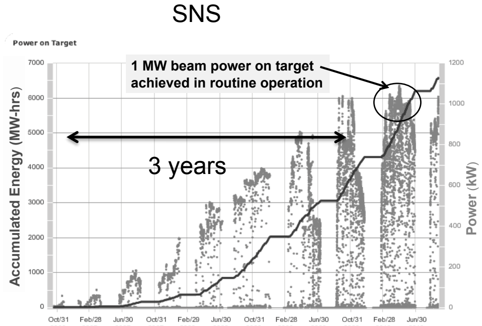
Overall Commissioning Strategies

- "Individual" approach
  - Create small teams that can be sustained 24/7 for week periods
  - Call in experts as needed
  - Used successfully at SNS
- "Team" approach
  - Have relatively large teams in the control room (important disciplines all have representatives)
  - Run 12 hr/day for week periods
  - Used successfully at J-PARC

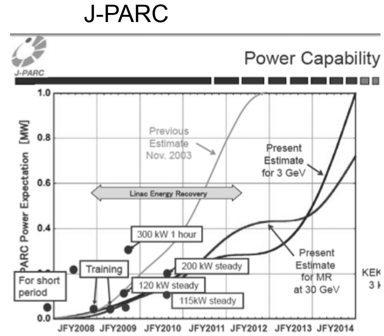
Power Rampup

- Going from low power commissioning to sustained high power operation is equally challenging as the initial "threading the beam" through the machine.

SNS



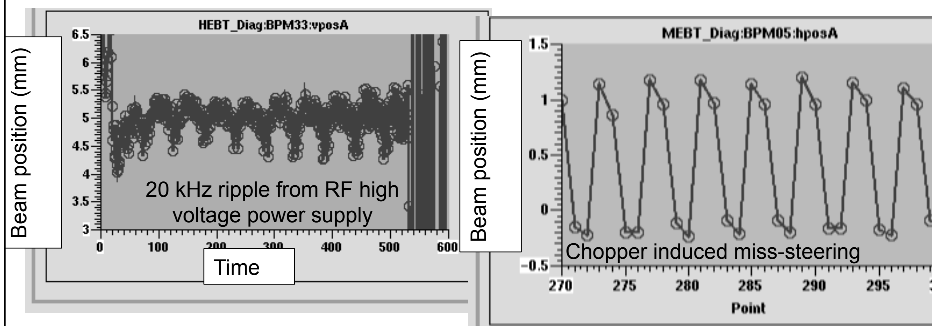
J-PARC



3 years

- Issues:
  - Equipment availability, operations coordination, beam loss!!!

Use the beam to identify equipment issues

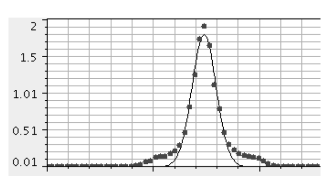


- Equipment issues are difficult to predict a-priori
- Use available diagnostics to identify sources of problems

Beam Loss

- Beam loss is the ultimate tuning objective in high power, high intensity hadron machines
  - 1 W/m is the acceptable loss criteria (10^{-6} /m at typical final energies)
  - Simulation tools cannot accurately predict beam loss at this level
  - Beam diagnostics cannot measure beam at this level, except:
    - Loss monitors
  - Have good loss detector coverage and a good loss measurement display

Profile Measurement: Good to $10^{-3} – 10^{-4}$



Commissioning General Purpose Application Toolkit

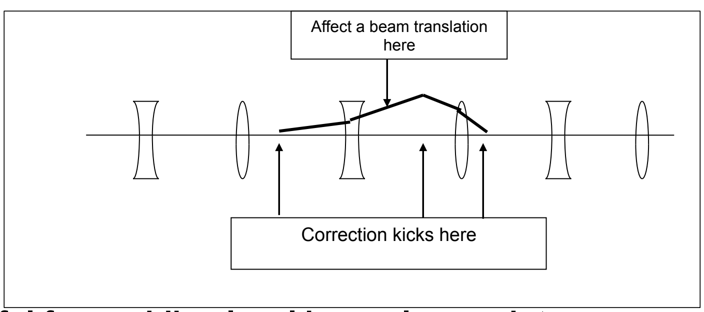
- Scan program
  - Vary one (or more) quantity and measure response of other quantities
- "Knob" capability
  - Easily vary a settable quantity "by hand"
- Strip tool
  - Time histories of quantities
- Save / compare / restore

Commissioning: A Period of Ups and Downs

- Beam commissioning can be extremely frustrating and is hard work (long hours)
- But is is ultimately extremely rewarding
- Enjoy it

Backup

Local Bumps



- **Useful for avoiding local beam loss points**
- **In general 3 kicks are required to achieve a localized beam translation in position or angle at a given location**
- **Sometimes you need more than 3 correctors**

Twiss Parameters

- Each plane (Horizontal and Vertical) have independent Twiss sets
- Each Twiss set contains 3 un-knowns (a, b, e) and needs at least 3 independent measurements to solve for these

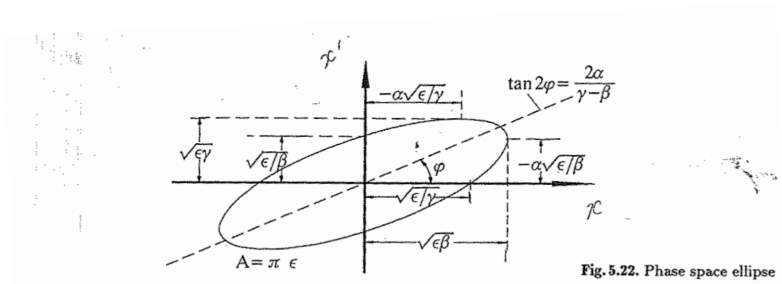


Fig. 5.22. Phase space ellipse

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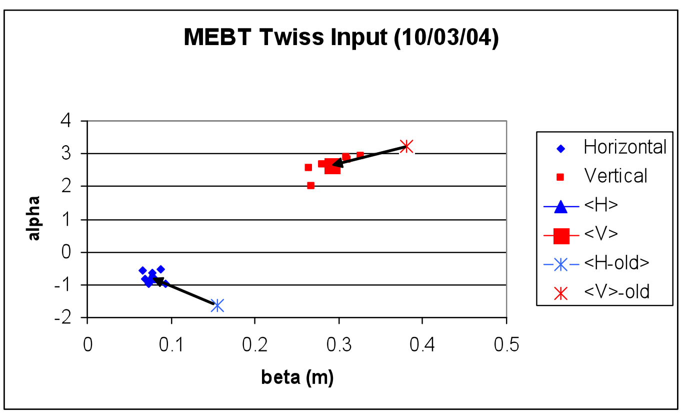
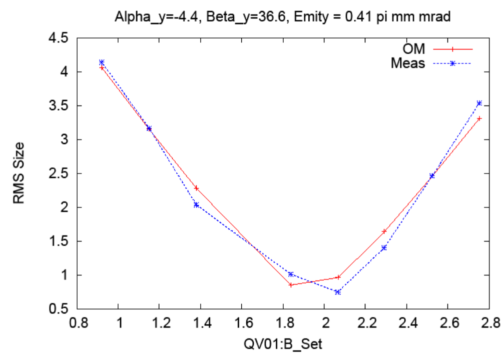
Example of Averaging the Measured Twiss Parameters

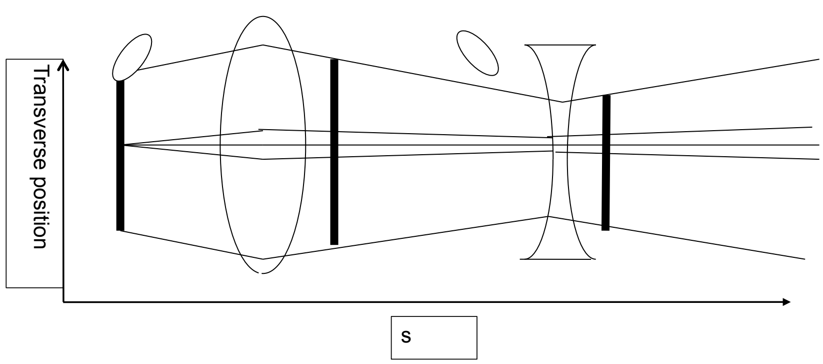


- Use the measurement cluster average for calculations and modeling

Example of Single Profile Measurement Twiss Calculation



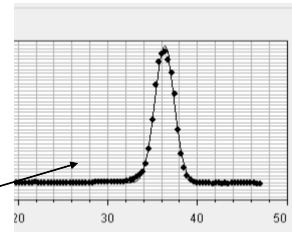
Beam Size vs. Focusing

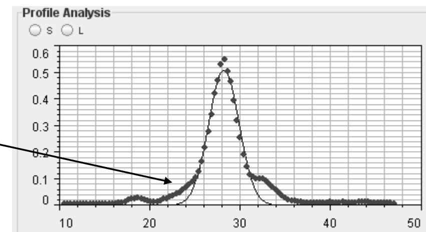


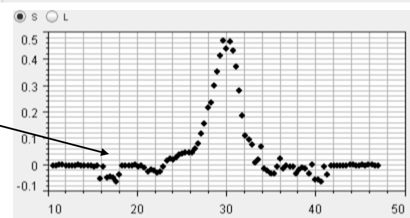
- The three measurements to solve for the Twiss parameters can be three separate profile measurements
- Need to know the optics affecting the beam between the measurements (magnet strengths and locations)

Profile Measurement

- Often beam profiles are fit with a Gaussian shape to get an RMS beam size
  - Easy
  - But it misses halo
- More precise method is a statistical RMS calculation
  - Choosing the noise-floor cut-off is tricky





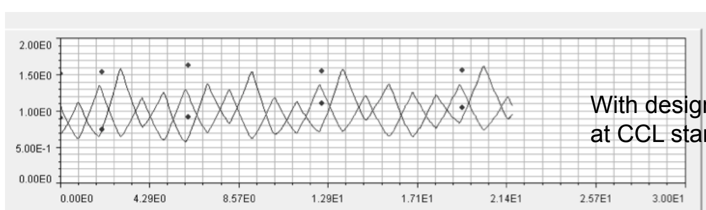


Initial Twiss Solution Example (SNS)

Beam size vs longitudinal position

Red – horizontal, blue = vertical

Dots = measurements, lines = model



With design Twiss at CCL start

After solving for Twiss at the start of the CCL to best fit measured beam size