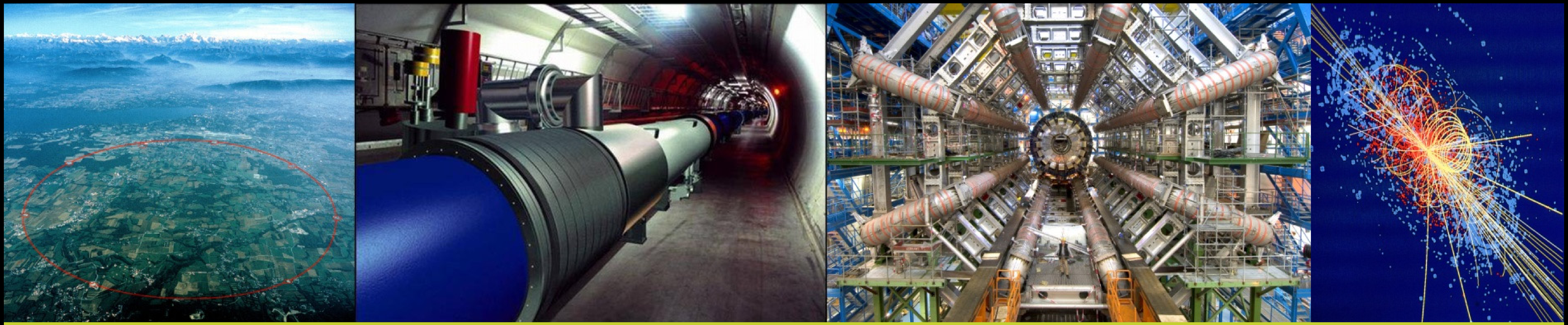


Beam Diagnostics Challenges for Beam Dynamics Studies

Rhodri Jones

CERN Beam Instrumentation Group

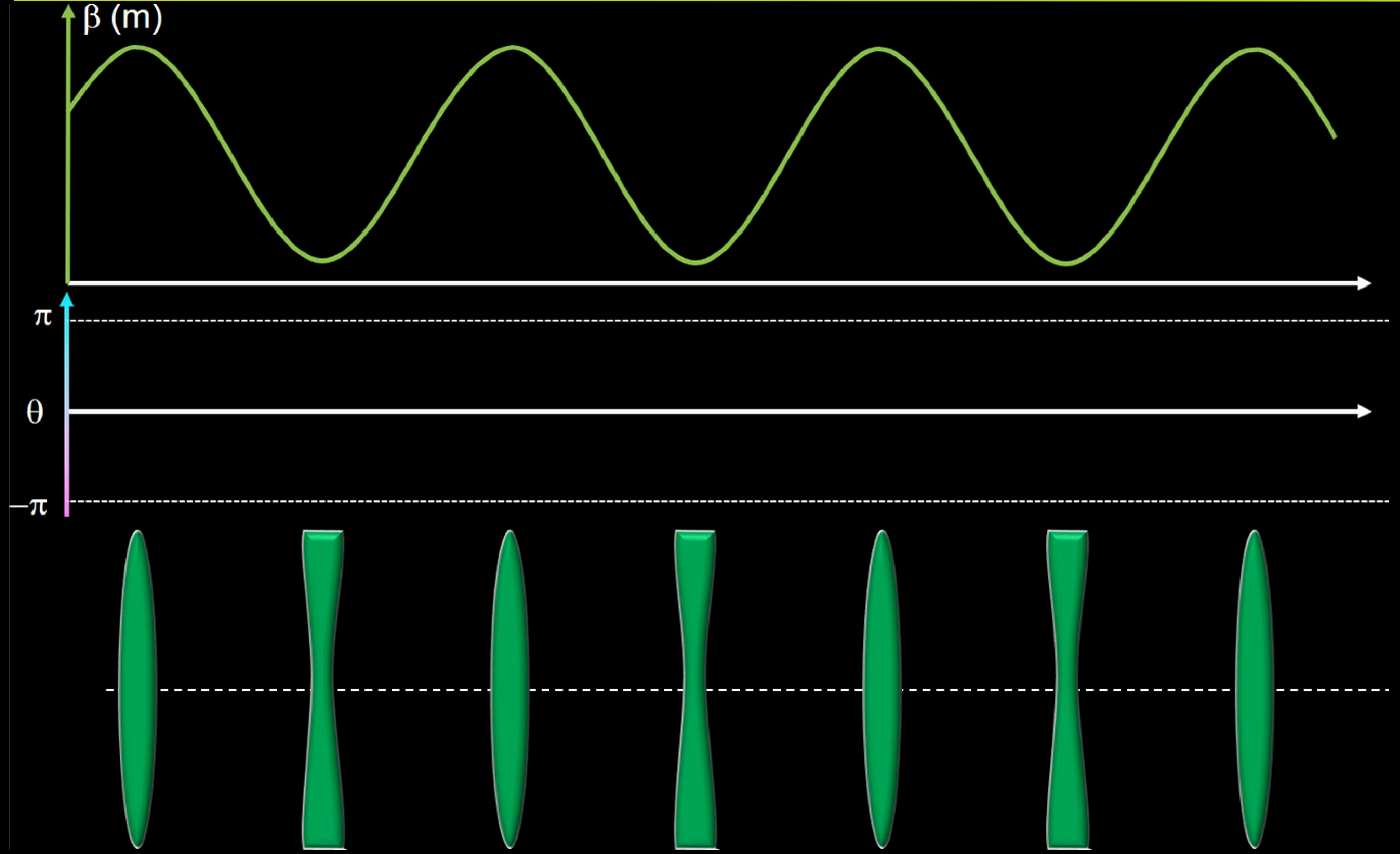
with input from A. Aleksandrov, V. Dimov, T. Levens, L. Nadolski, R. Tomas Garcia, M. Wendt.

Understanding our Machines

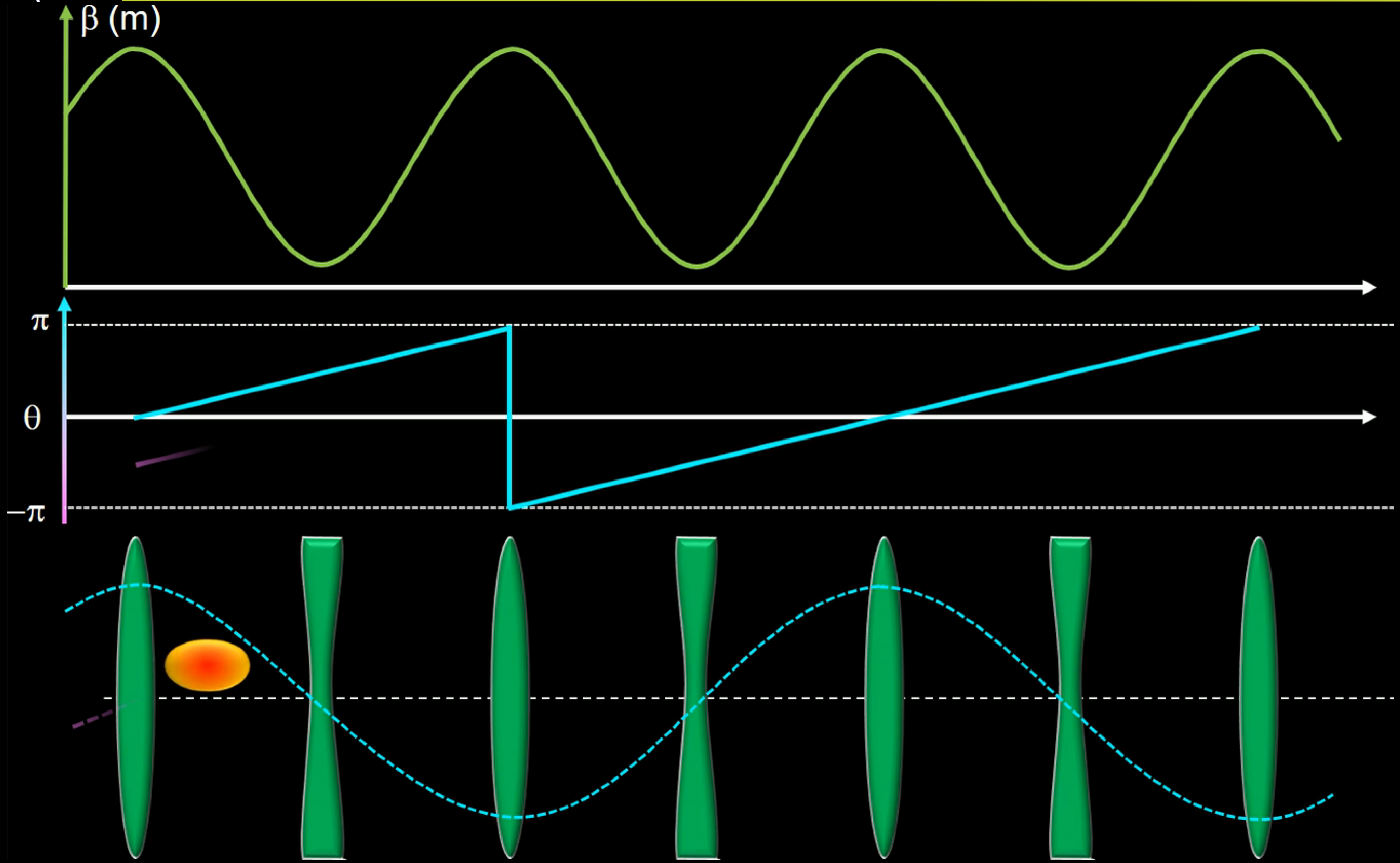
- Why do we need beam dynamics studies in accelerators?
  - For initial tuning of the machine
    - The closer we are to design parameters the better they (normally) perform
  - For modifying initial design parameters to increase performance
  - To understand the issues and challenges that arise during operation
- Routine measurements during standard operation
  - Orbit, tune, coupling, chromaticity
- Specific measurements during machine set-up
  - Measurement & correction of the Machine Optics
    - β function, dispersion, non-linear contributions
  - Beta Matching in LINACs or Transport Lines
- Advanced Measurements
  - Understanding impedance and space charge effects
  - Countering instabilities
  - Identifying sources driving the diffusion of particles to high amplitudes

The Machine β-Function

The Machine β-Function



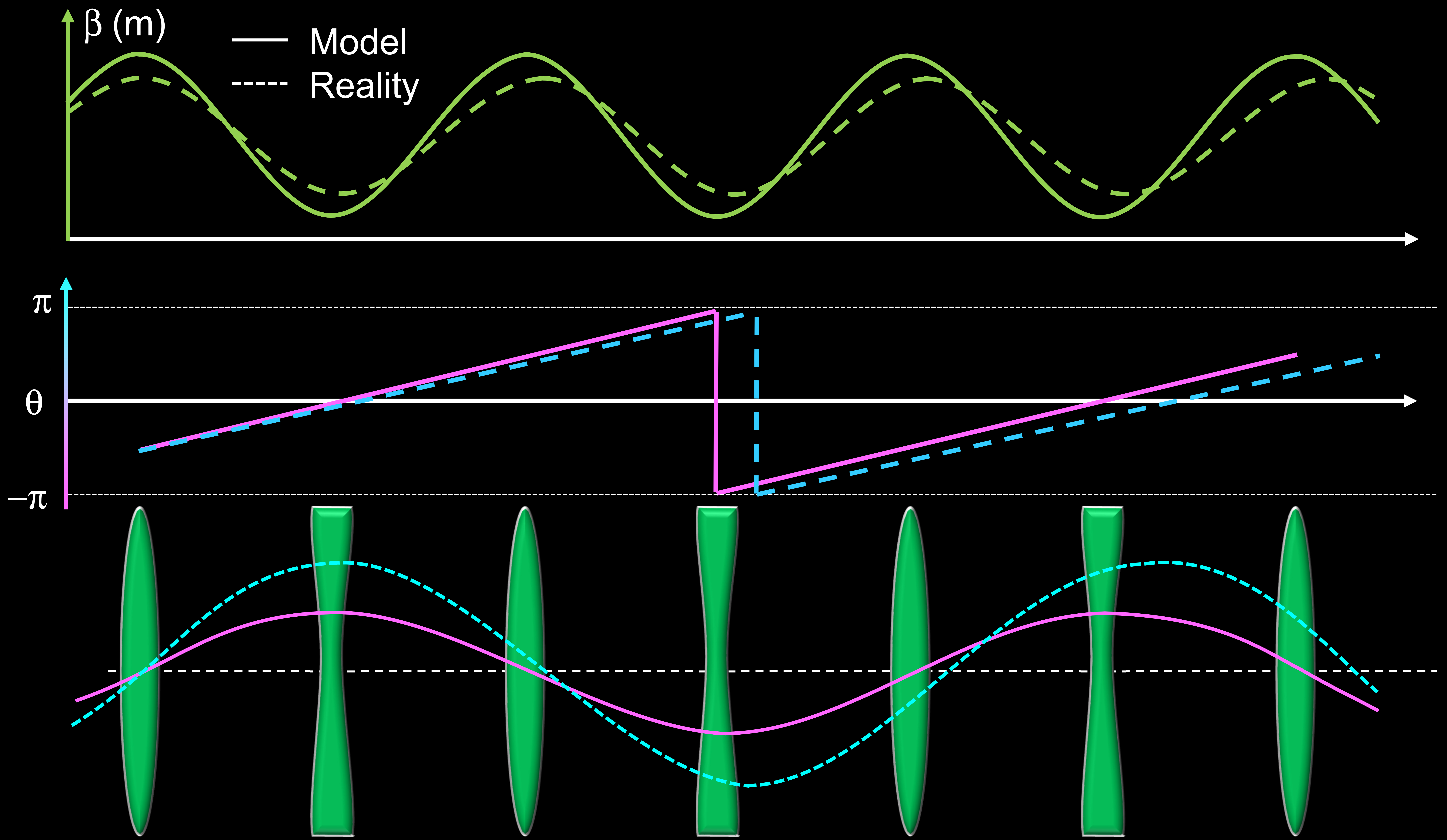
The Machine β-Function



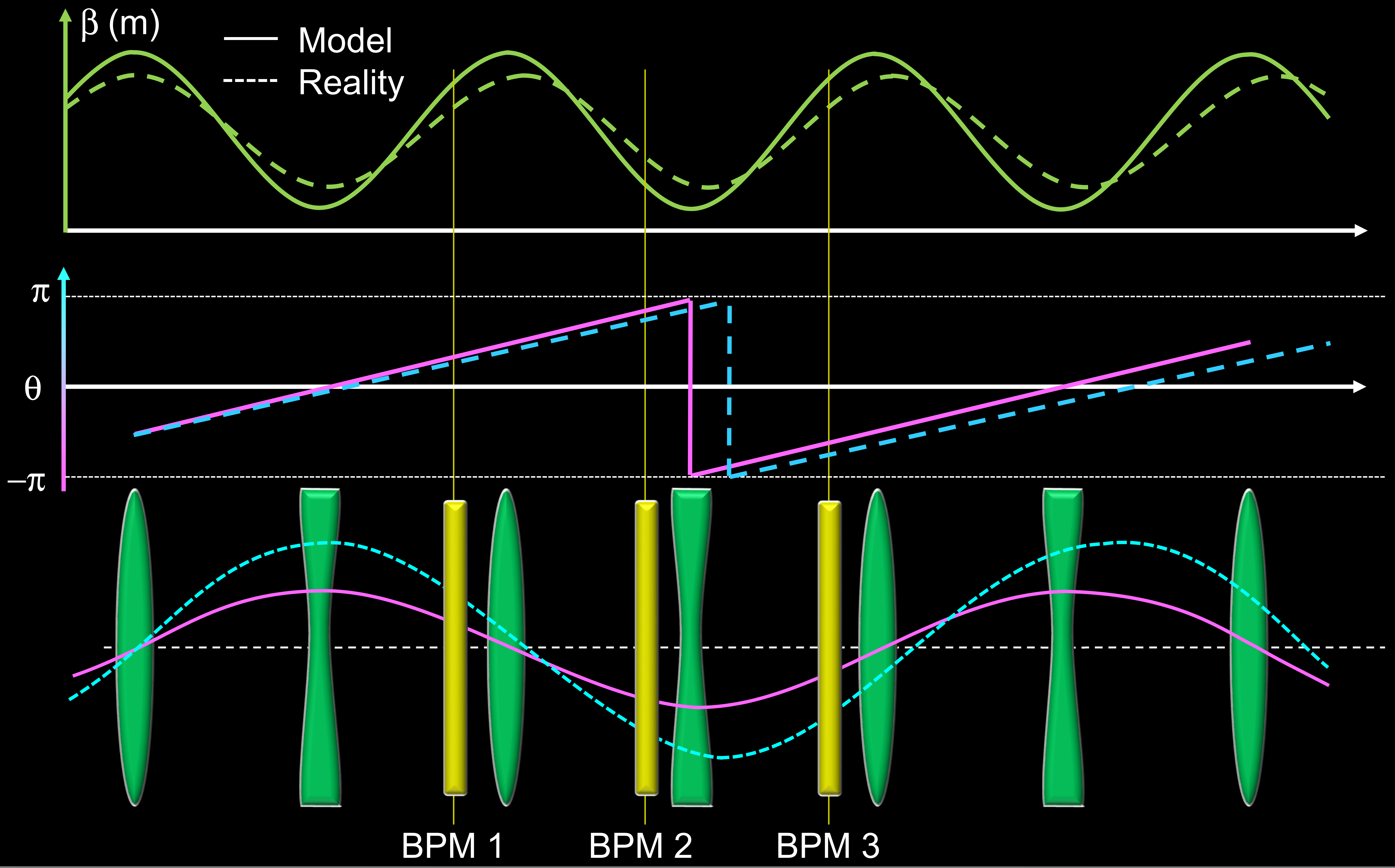
Oscillation Amplitude and Beam Size $\propto \sqrt{\beta}$

The Machine β-Function

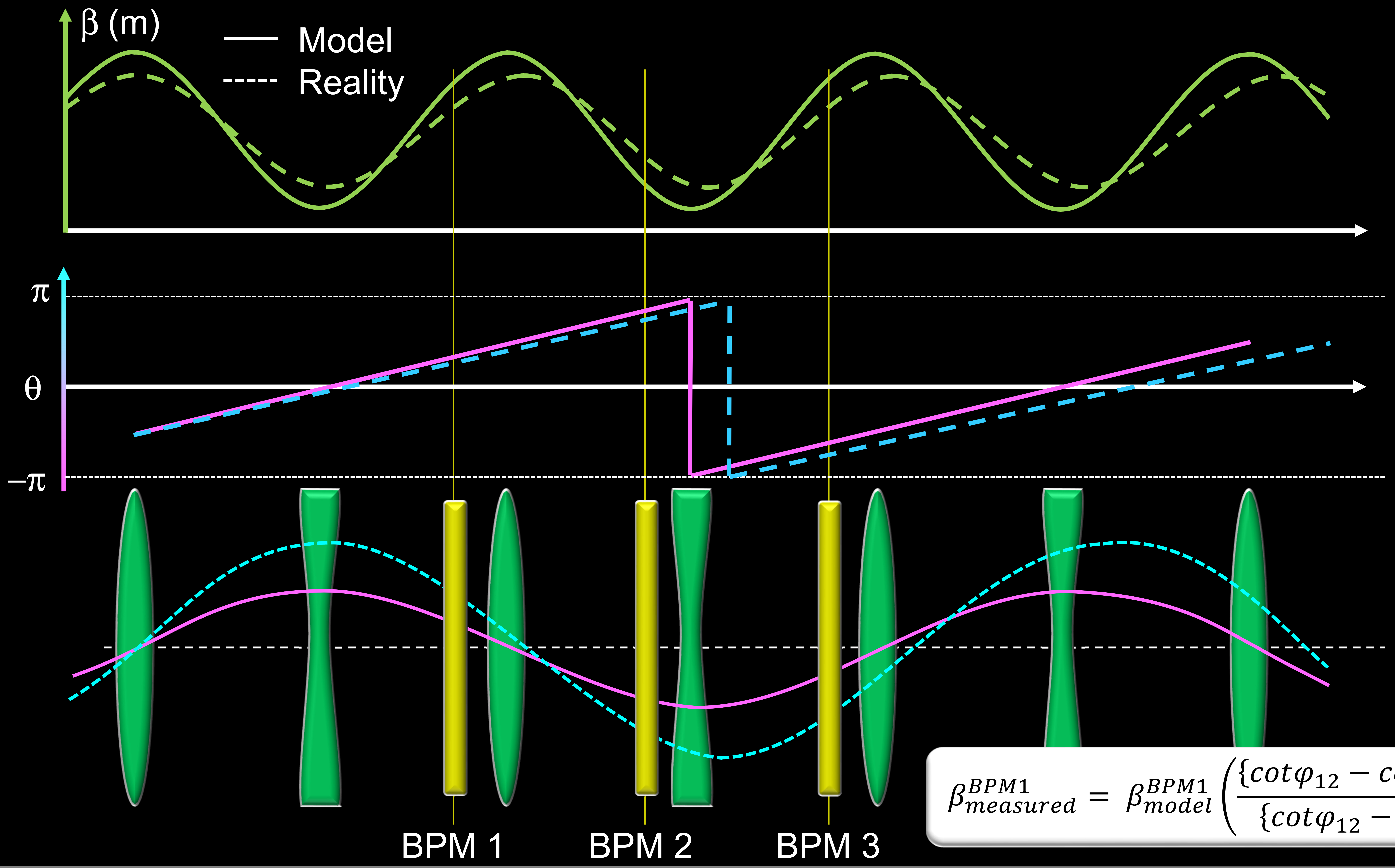
The Machine β-Function



The Machine β-Function



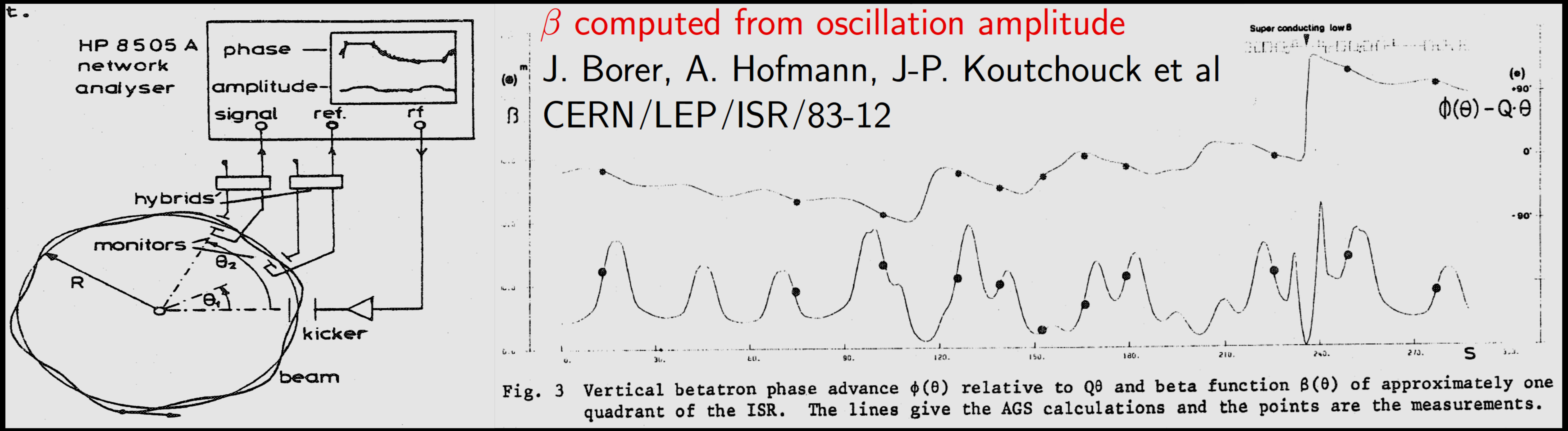
The Machine β-Function



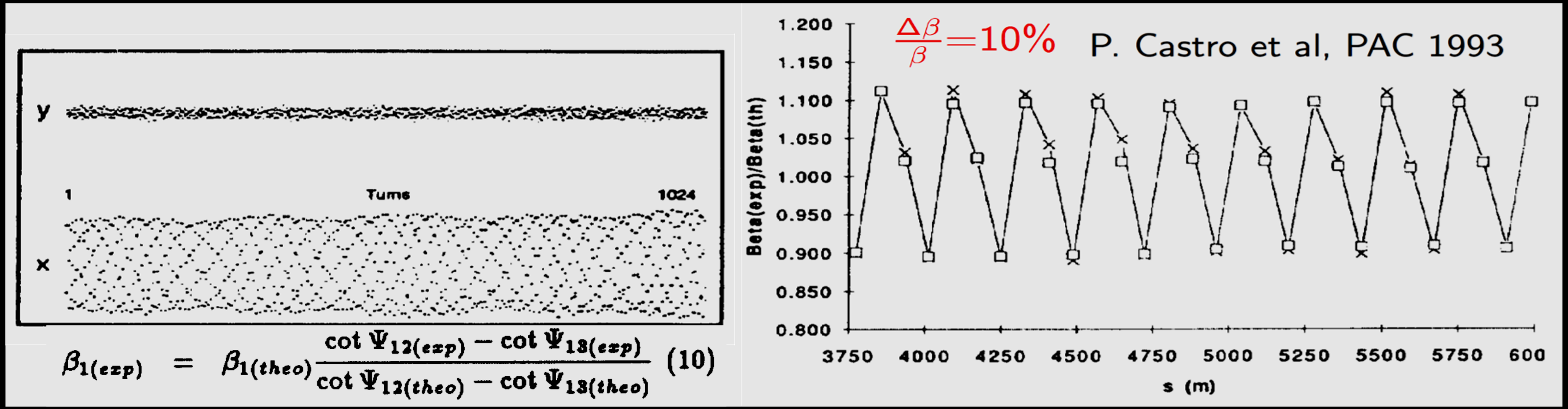
$$\beta_{measured}^{BPM1} = \beta_{model}^{BPM1}\left(\frac{\{cot\varphi_{12} - cot\varphi_{13}\}_{measured}}{\{cot\varphi_{12} - cot\varphi_{13}\}_{model}}\right)$$

Brief History of Accelerator Optics Measurement

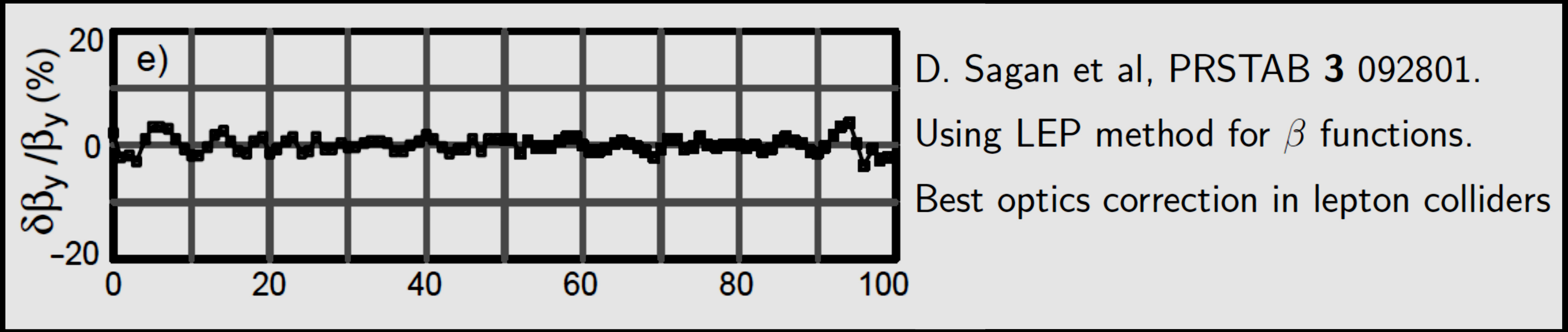
ISR 1983
β computed from oscillation amplitude



LEP 1993
β from phase, 3 BPM method, model dependent

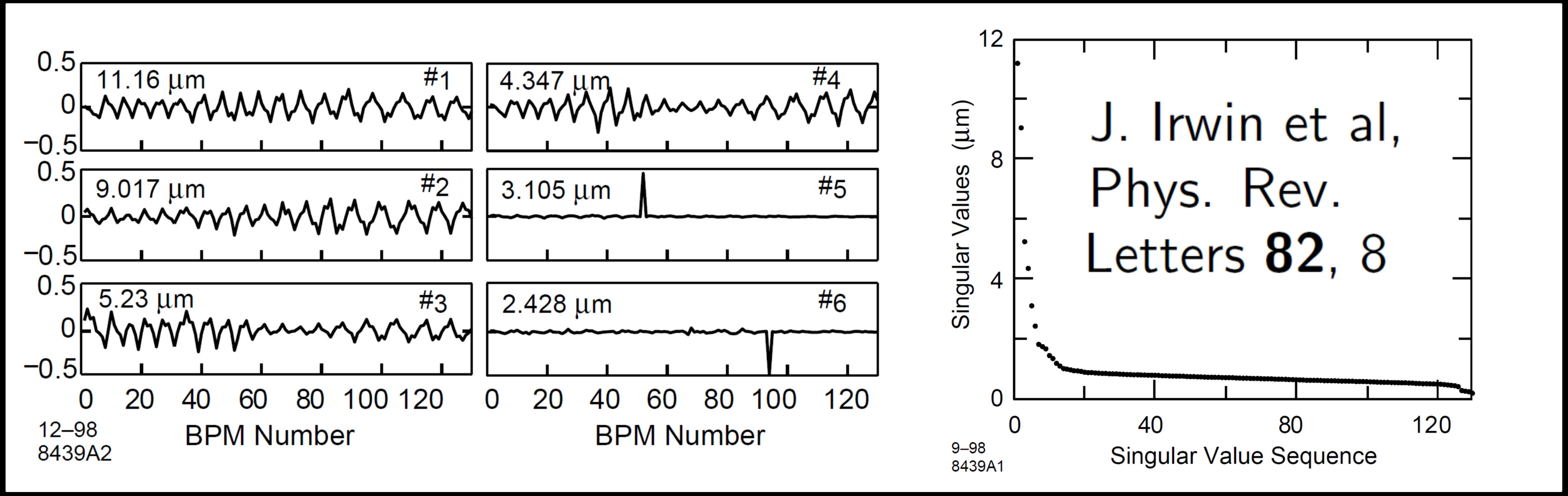


Cornell 2000
β from phase, 3 BPM method

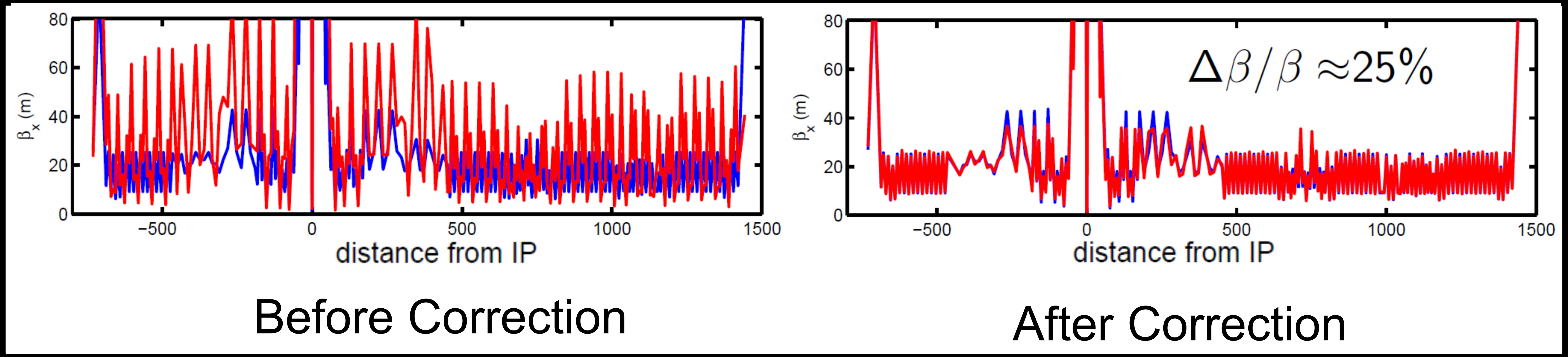


Brief History of Accelerator Optics Measurement

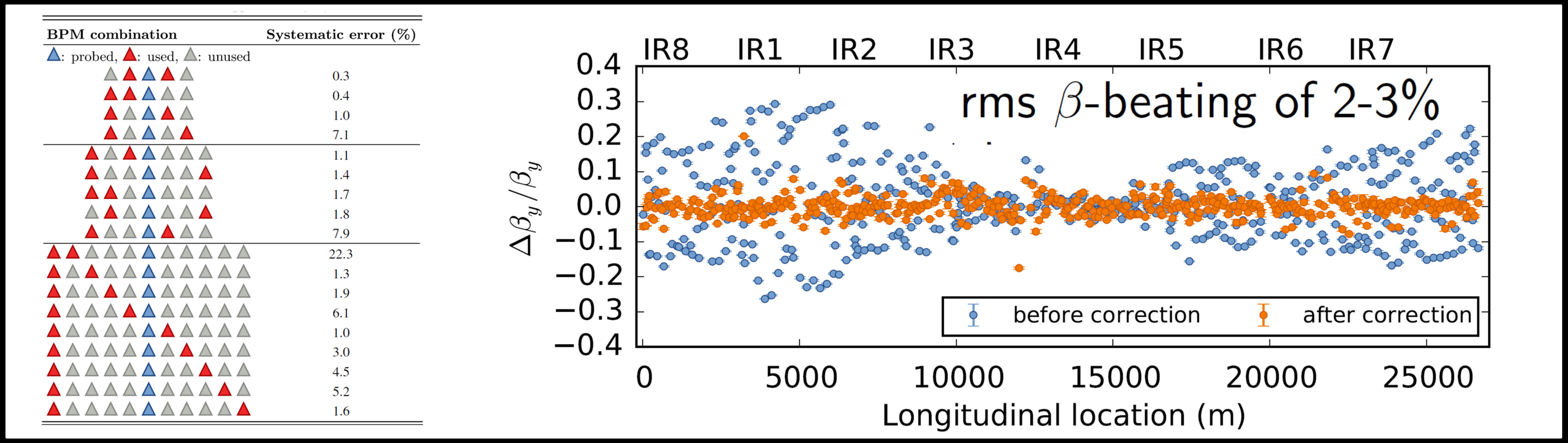
SLAC 1999
Singular Value Decomposition (SVD) used to remove bad BPMs & reduce measurement noise



PEP II 2006
From phase to virtual model to β

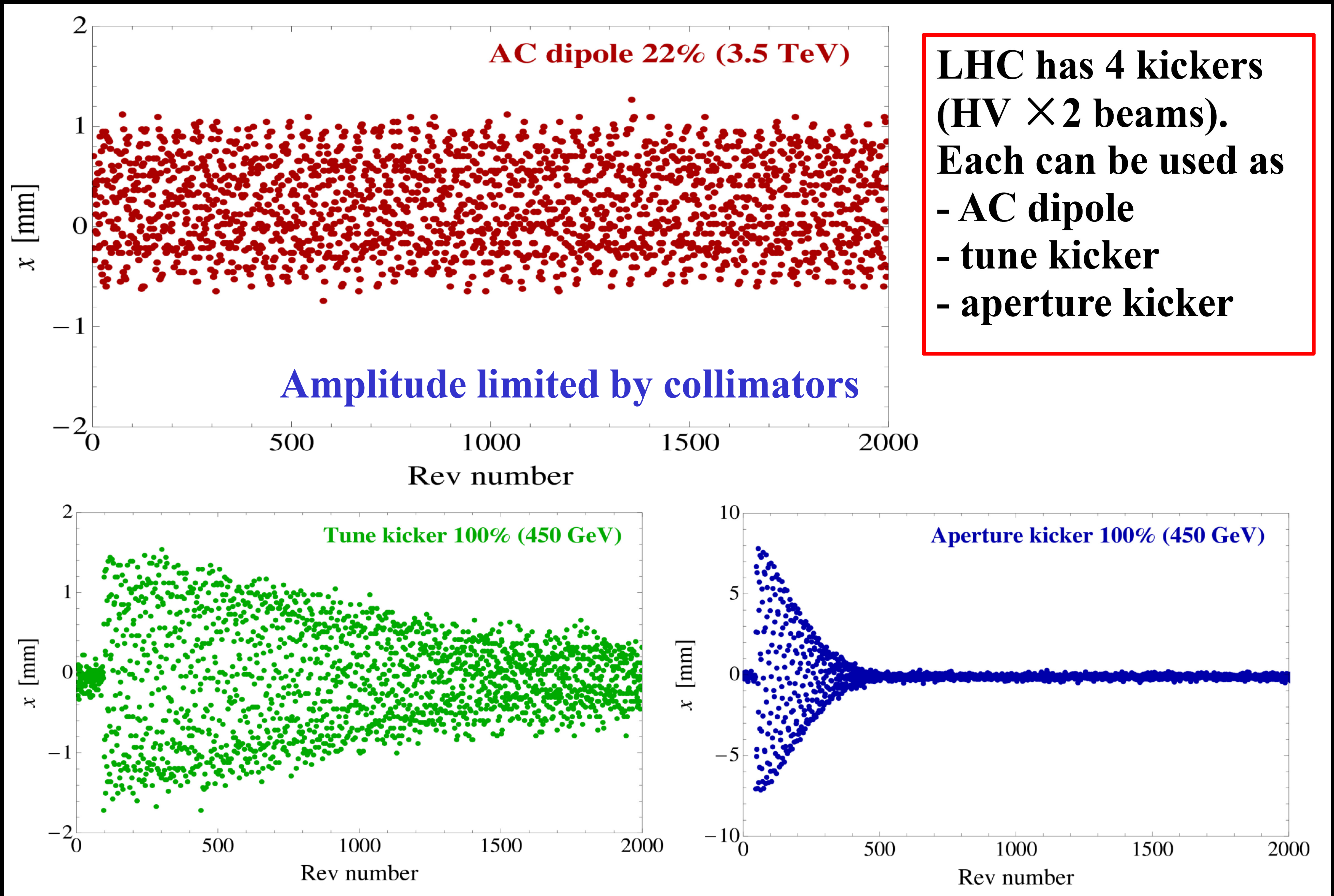


LHC 2015
3 BPM to N BPM extension but good knowledge of lattice uncertainties fundamental



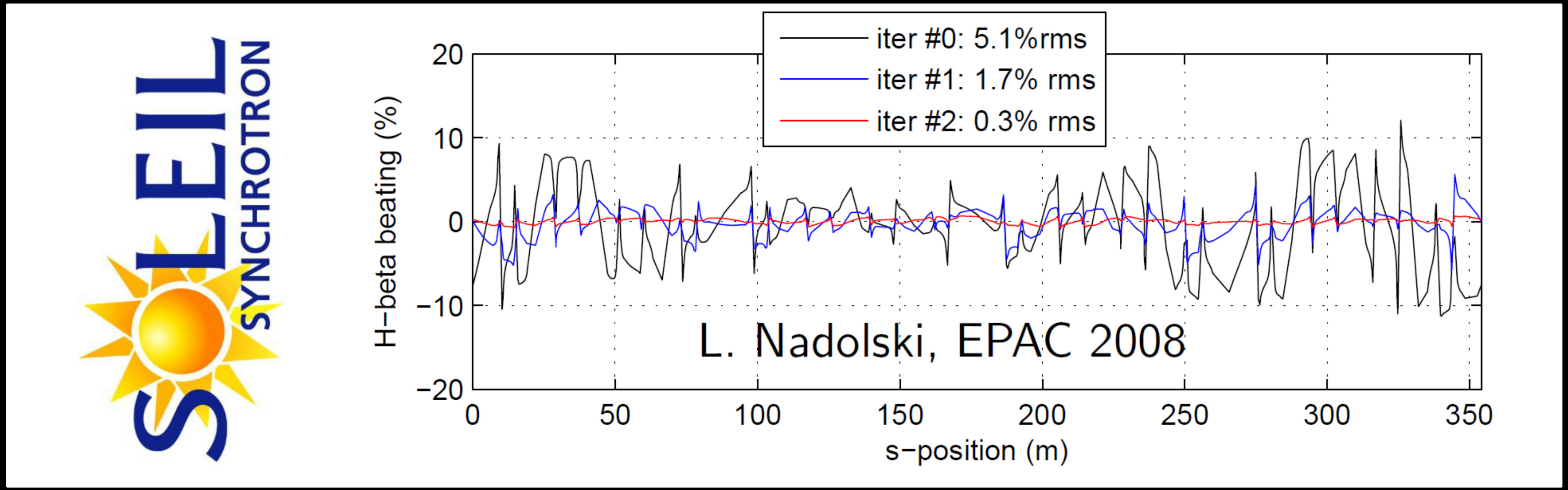
Excitation for Optics Measurement

- LHC Examples
  - Tune or aperture kicker
    - Single strong kick
      - Leads to emittance blow-up in hadron machines
    - Quantity of useful data depends on de-coherence time
      - Itself dependent on machine optics
  - "AC Dipole" excitation
    - Developed at RHIC for crossing polarisation resonances
    - Forced oscillation near the tune, but well outside tune spread
    - Leads to steady, high amplitude oscillation without emittance blow-up
    - Long, steady excitation amplitude excellent for optics measurements



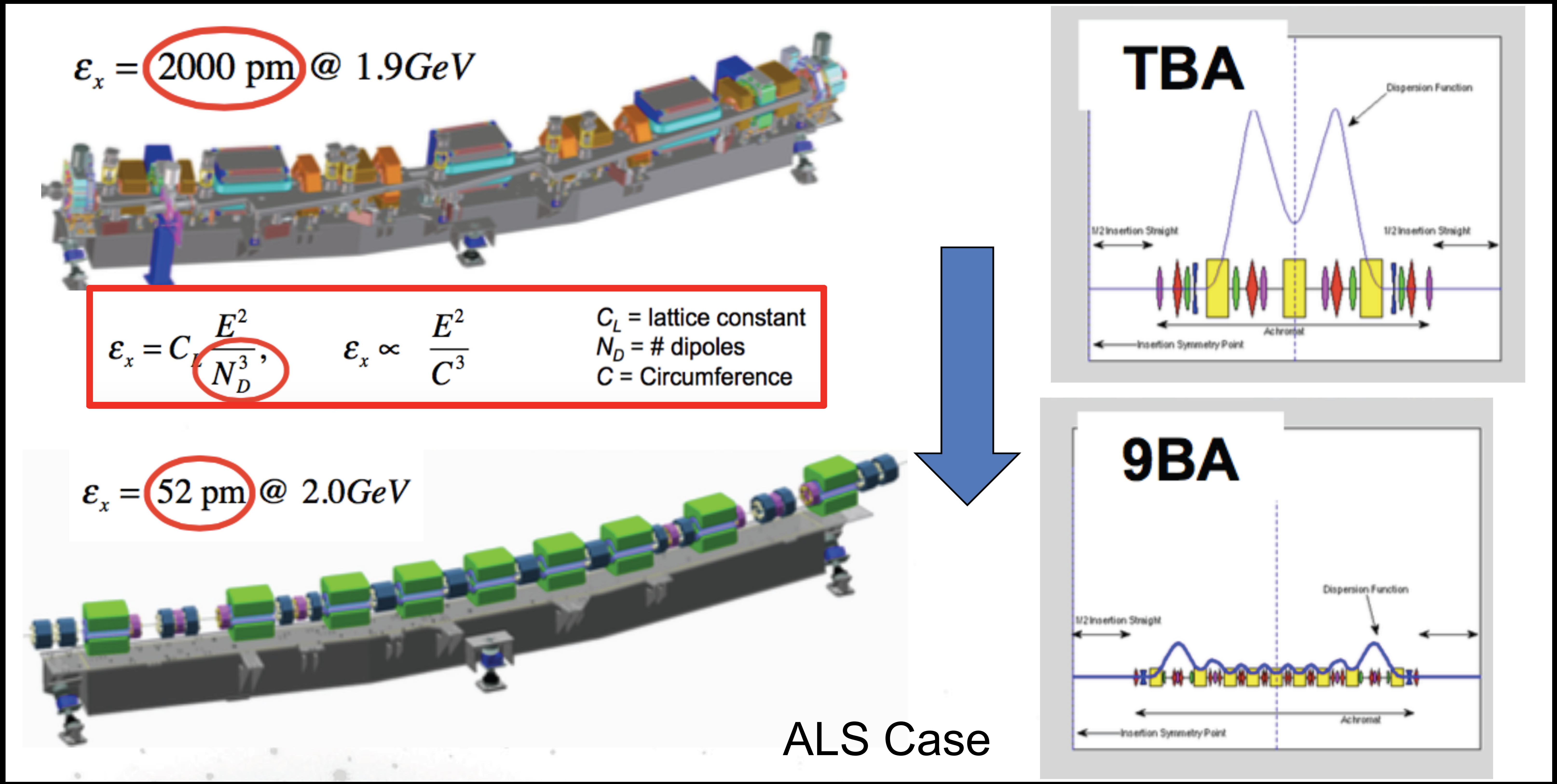
Brief History of Accelerator Optics Measurement

SOLEIL 2008
Orbit Response Matrix



- Optics measurements at Light sources
  - Dominated by closed orbit techniques (Orbit Response Matrix – e.g. LOCO)
    - SOLEIL & DIAMOND achieved 0.3 - 0.4% β-beating
    - Discussion ongoing on whether this measurement is slightly underestimated
  - Recently improved BPM electronics
    - Now allows turn-by-turn techniques to start competing with orbit response
    - Potential to be faster than orbit response techniques
  - Comparison campaign on-going at various labs
    - Turn by turn techniques do not yet have sensitivity to measure β-beating at sub 1% level

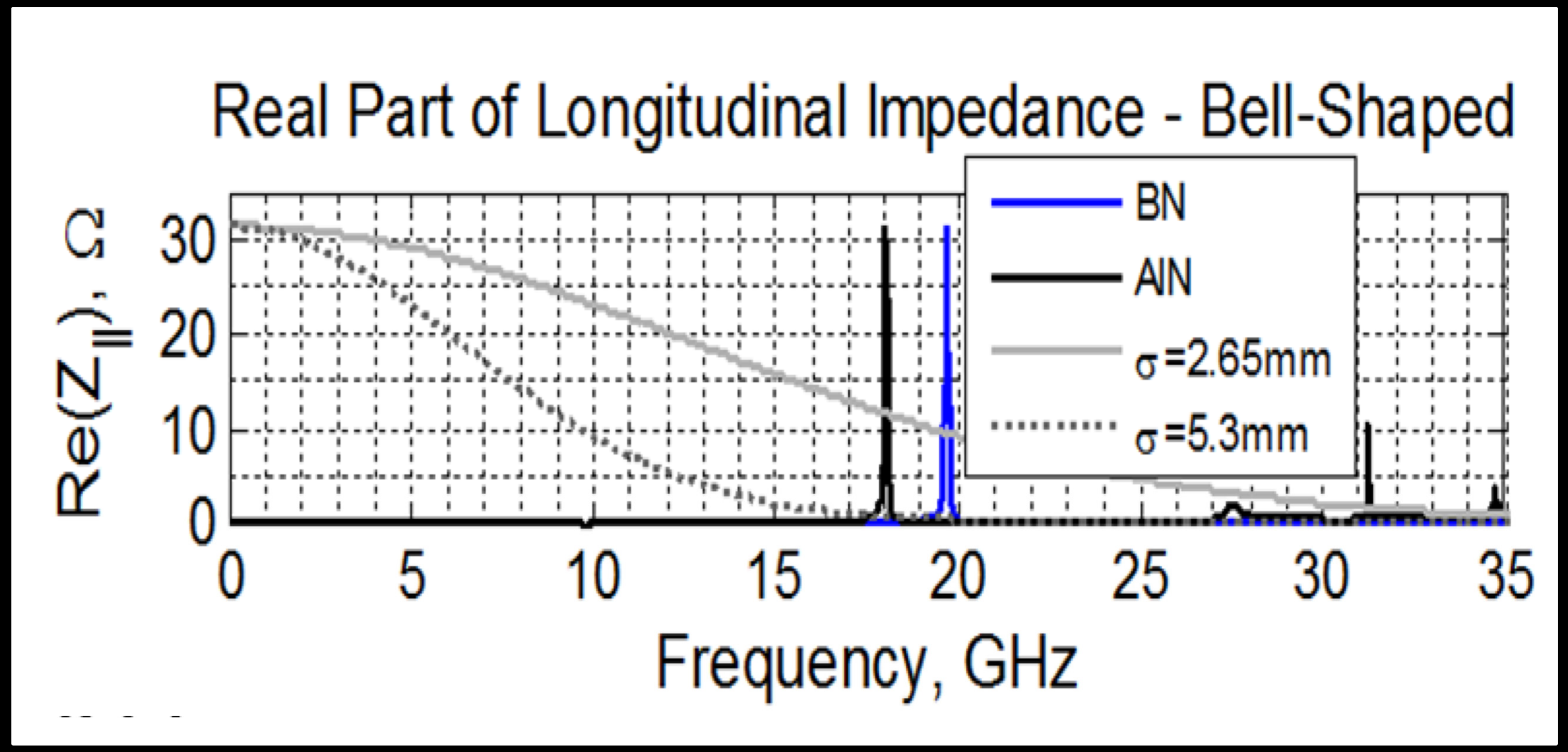
Future Beam Dynamics Challenges

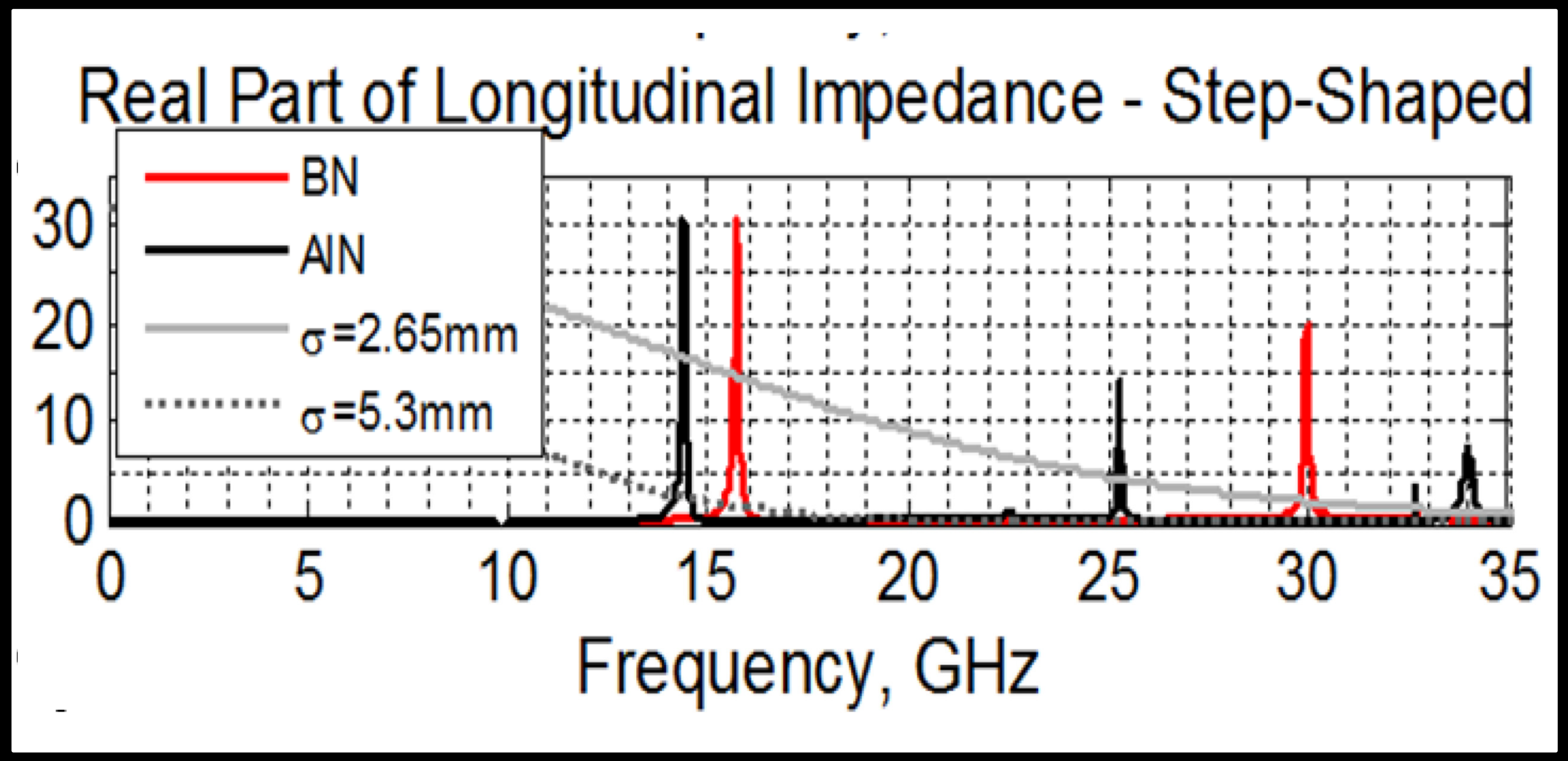


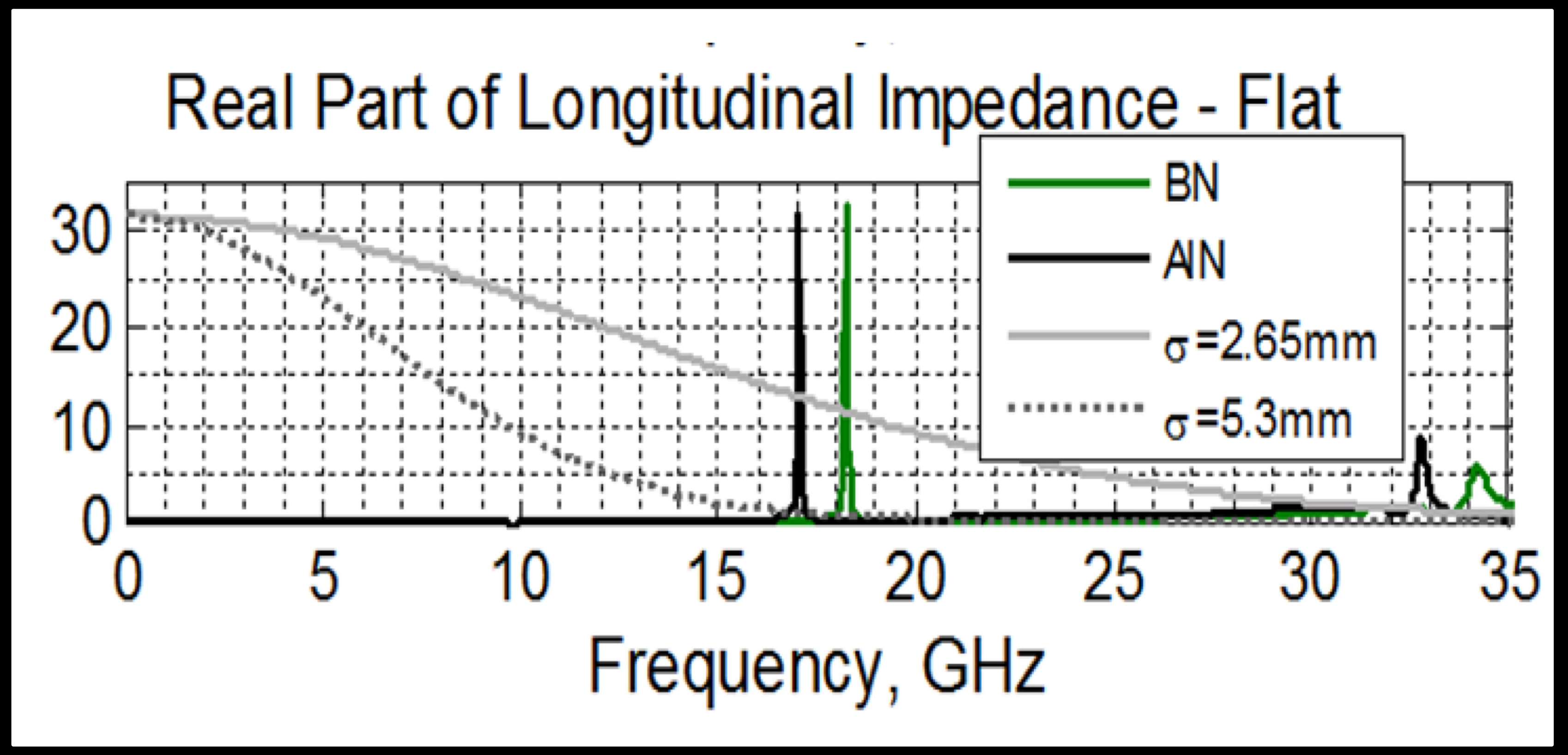
- From the simple to the complex
  - Looking to reduce the horizontal emittance by orders of magnitude
  - Use of non-linear lattice design for next generation synchrotron light sources
  - Improved simulation tools need to go hand in hand with excellent BPM systems
    - Turn by turn, bunch by bunch, over many turns & able to handle small & large beam charge

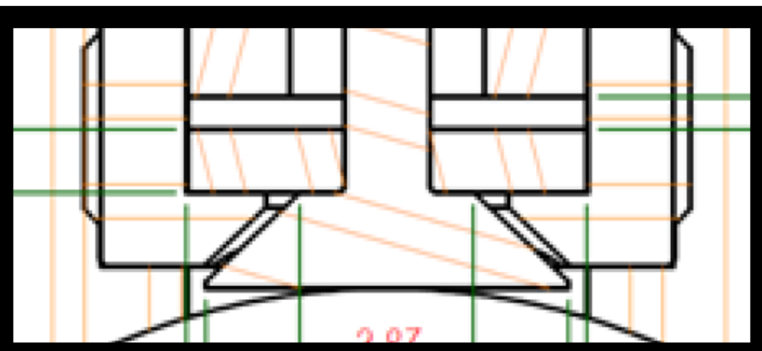
BPMs – a Problem for Low Emittance Rings

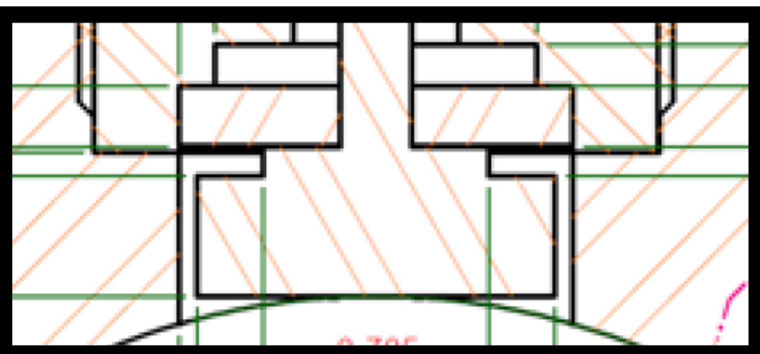
- BPM Wake-Potential & Impedance
  - A serious issue for synchrotron light sources
    - Machine becomes more sensitive to collective effects as lower beam emittances are achieved
    - Short range, high frequency wakes can result in beam induced heating
    - BPMs account for significant fraction of total impedance budget
- Optimisation of pickup design (examples from SIRIUS, Brazil)
  - Reduce impedance & trapped modes
  - Allows maintaining many BPMs for efficient feedback & beam dynamics measurements

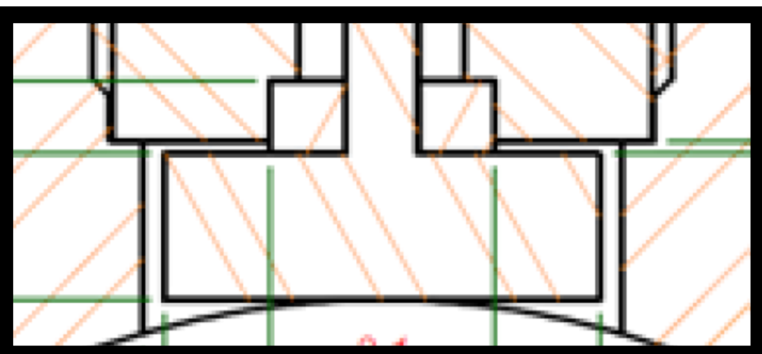










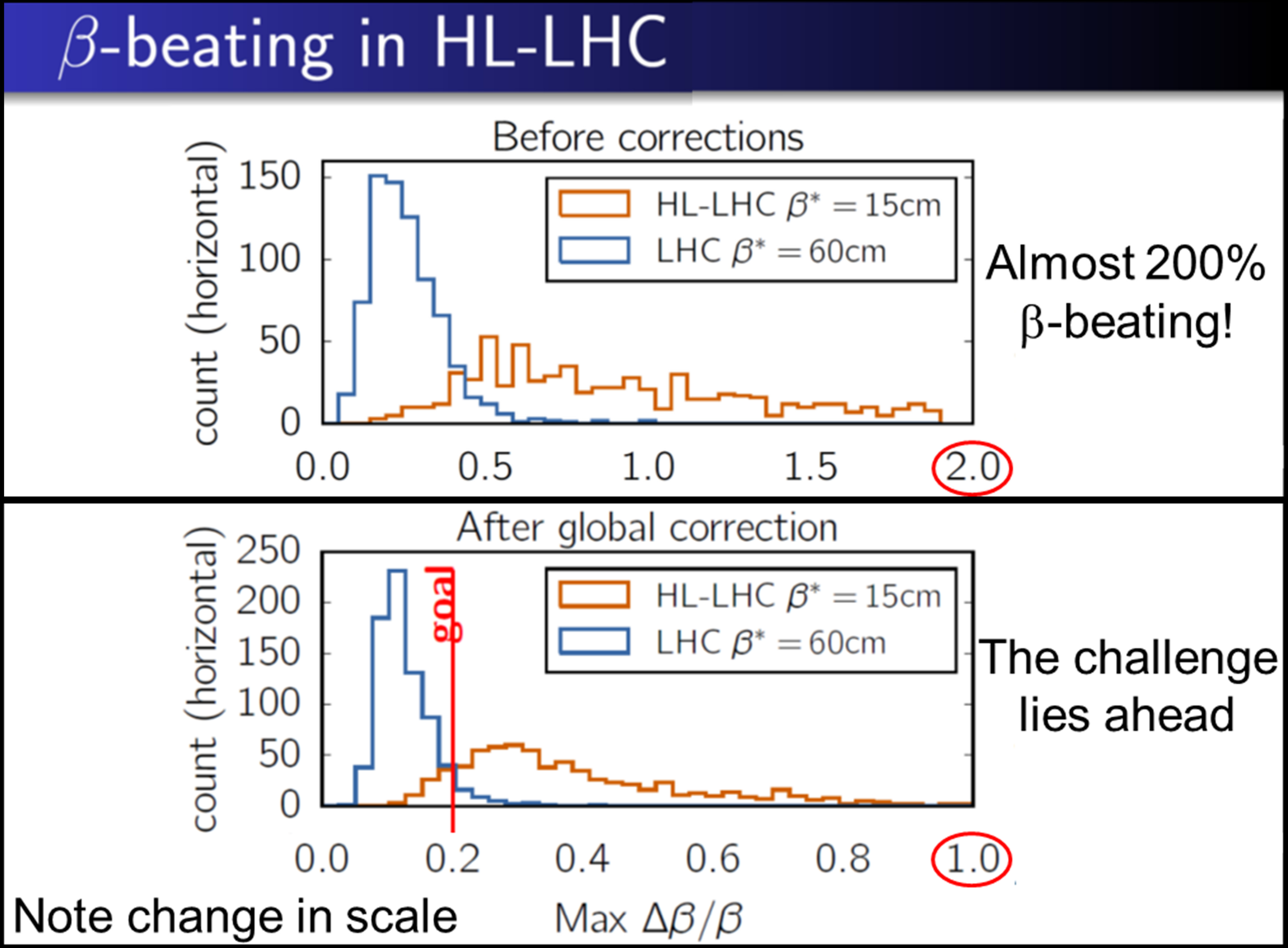


Main Beam Instrumentation Challenges for Improving Future Optics Measurement & Correction in Synchrotrons

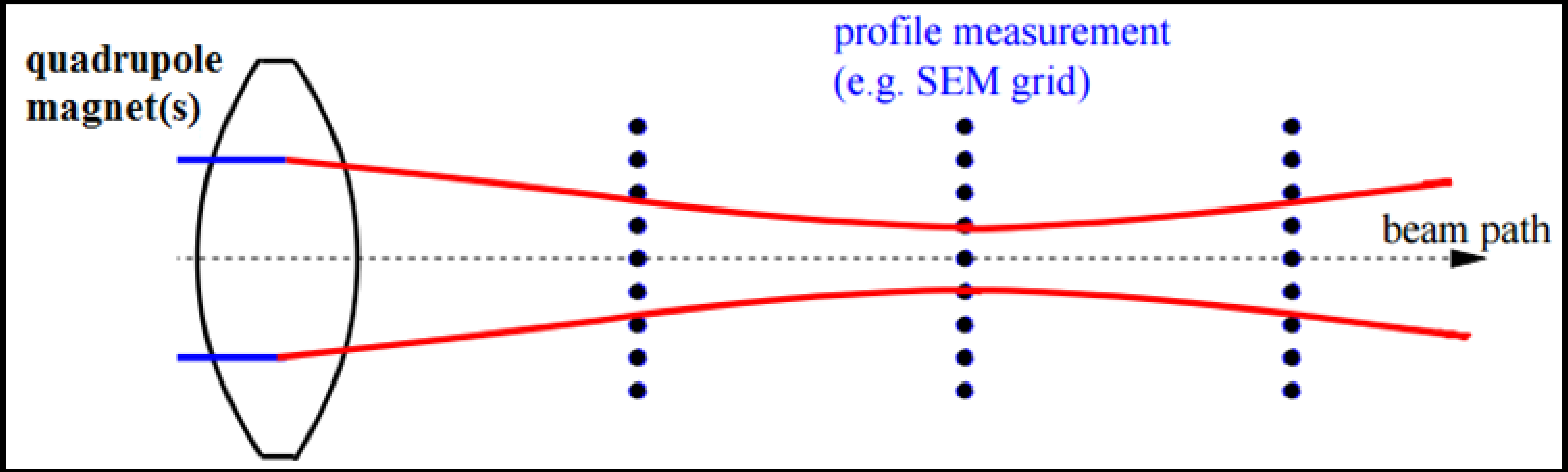
- Limiting excitation strength
  - Important for hadron machines where emittance needs to be conserved
  - Important for light sources to avoid non-linearities due to strong sextupoles
- Better BPM resolution – linked to excitation level required
  - Would allow smaller excitation to achieve the same accuracy
  - Resolution NOT currently limiting accuracy of β-beating through phase advance
- Better BPM calibration
  - Limiting the use of amplitude for β-beating measurements
  - Light sources currently at the 1-2% level with LHC at the 3-4% level
  - To surpass accuracy of phase measurement requires sub % level linearity over excitation range & overall scale calibration from BPM to BPM
- Longer acquisition times
  - Improves resolution when used in conjunction with AC dipole type excitation
  - Allows time dependent effects to be studied
- Better BPM design for lowering coupling impedance
  - Ensure the measurement device is not perturbing the measurement!

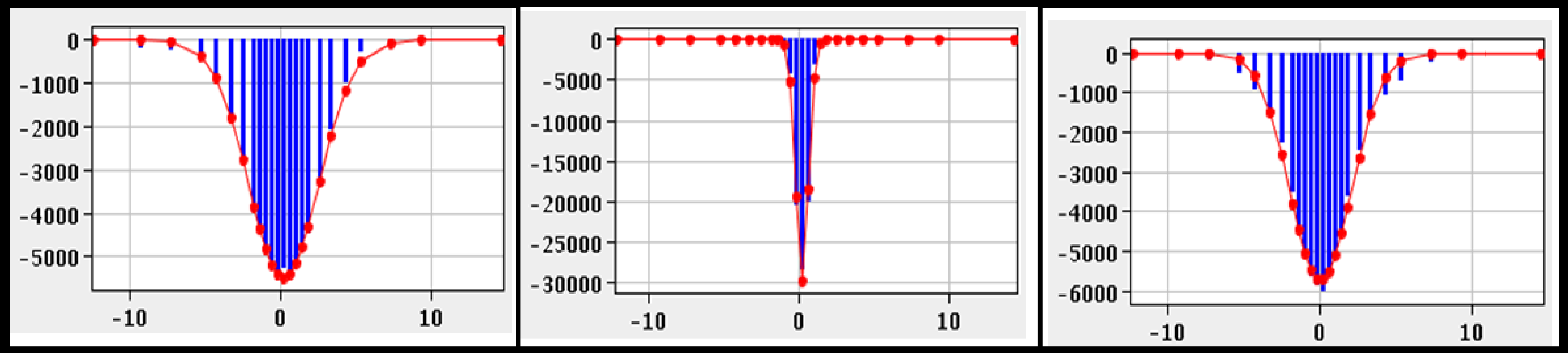
Future Challenges for Optics Measurement

- Combining better optics correction techniques with better BPM performance

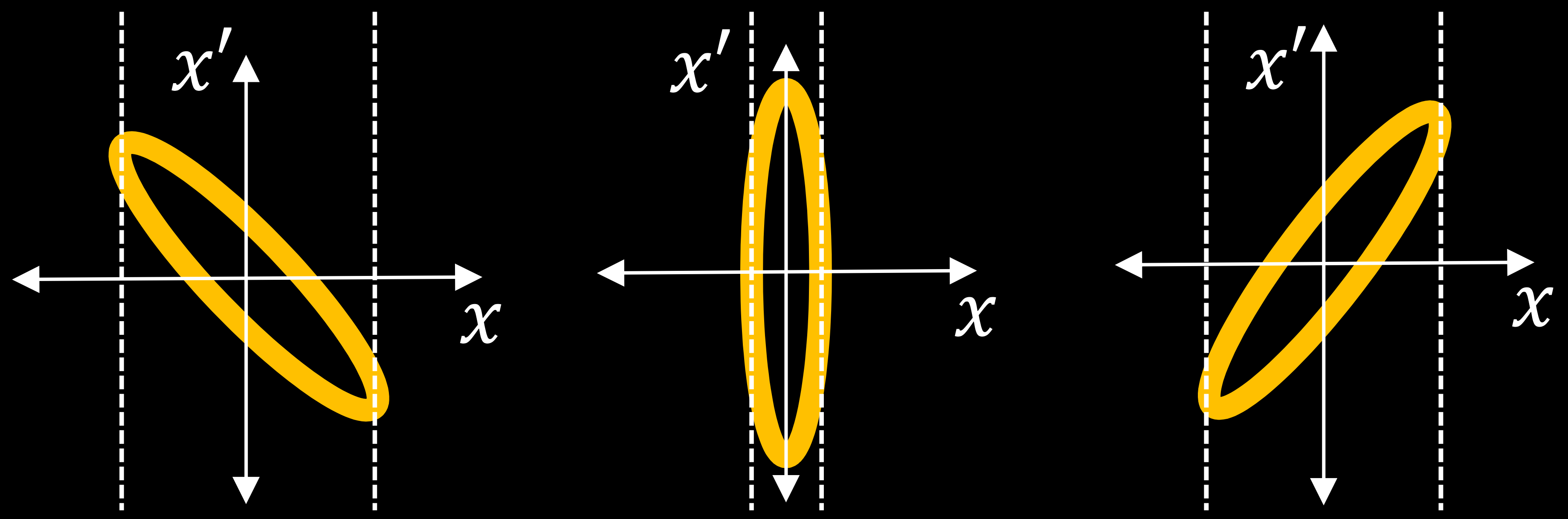


Optics Measurement in LINACs





Measured Beam Profiles

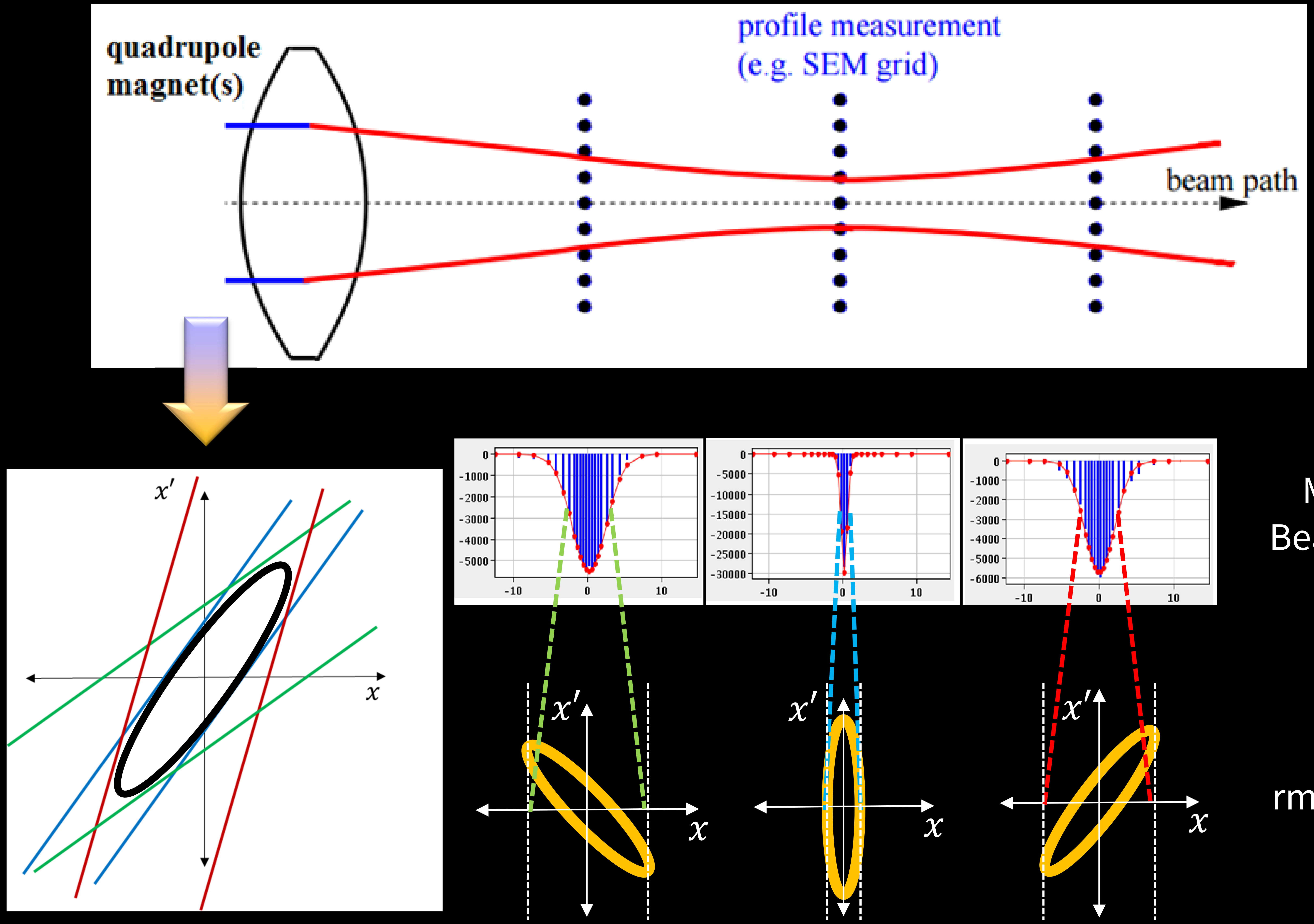


rms ellipses

3 monitor method

- Optics functions & initial emittance reconstructed assuming known, linear transport matrix

Optics Measurement in LINACs

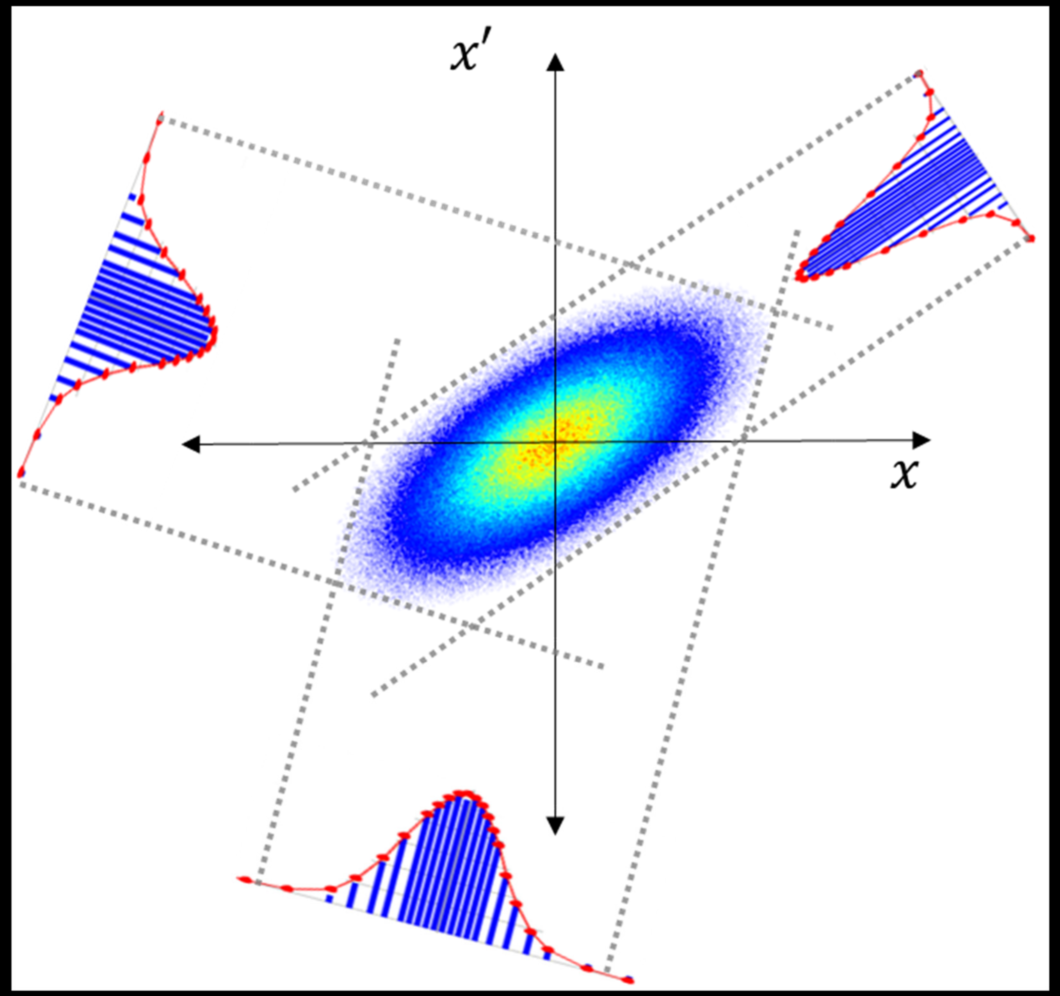


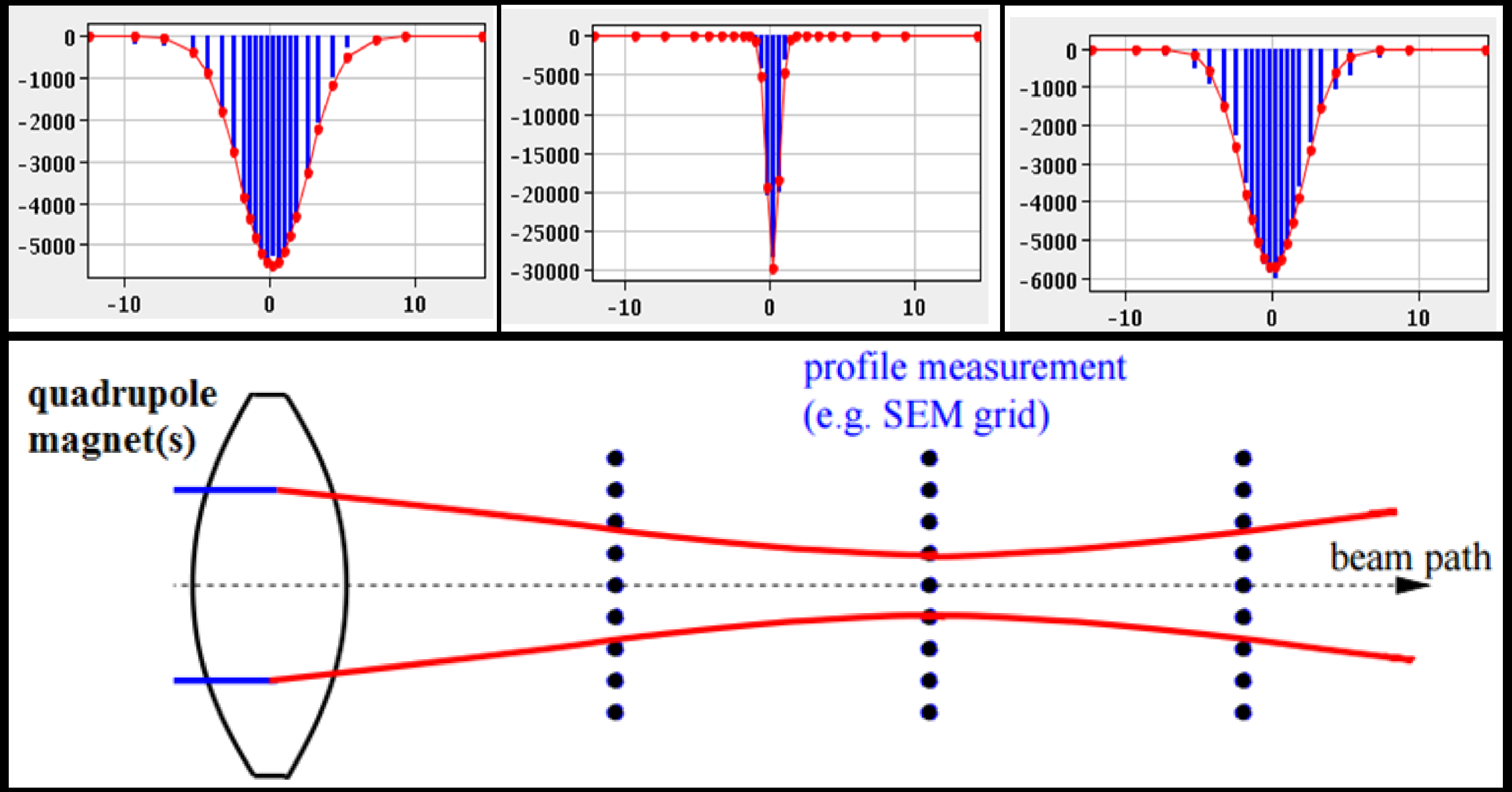
Measured
Beam Profiles

rms ellipses

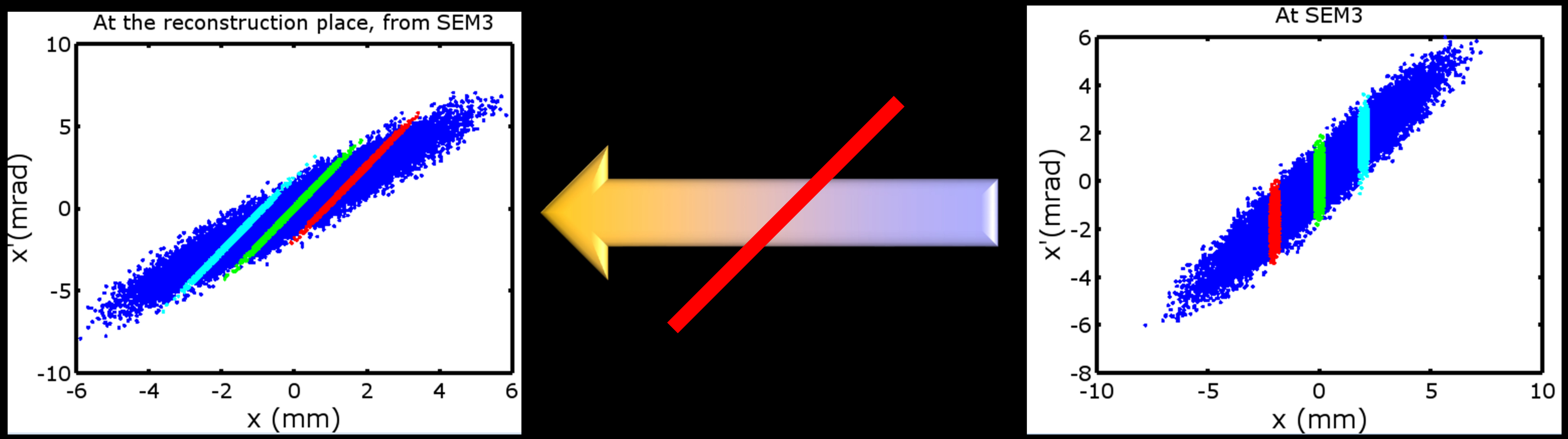
Optics Measurement in LINACs

- More advanced reconstruction
  - Linearly map measured profiles onto initial phase space
  - Use tomography to reconstruct particle density distribution





- But things get more complicated when you add space charge



Optics Measurement in LINACs

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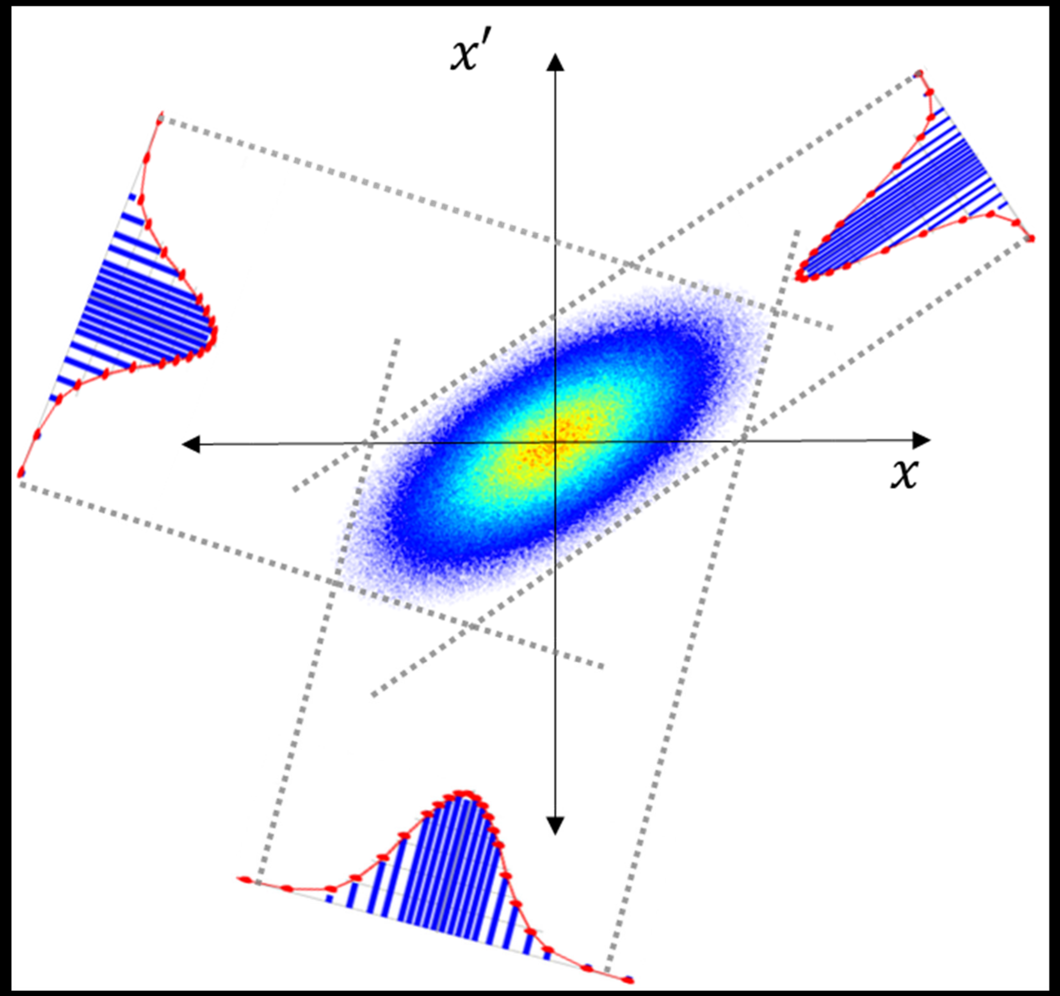

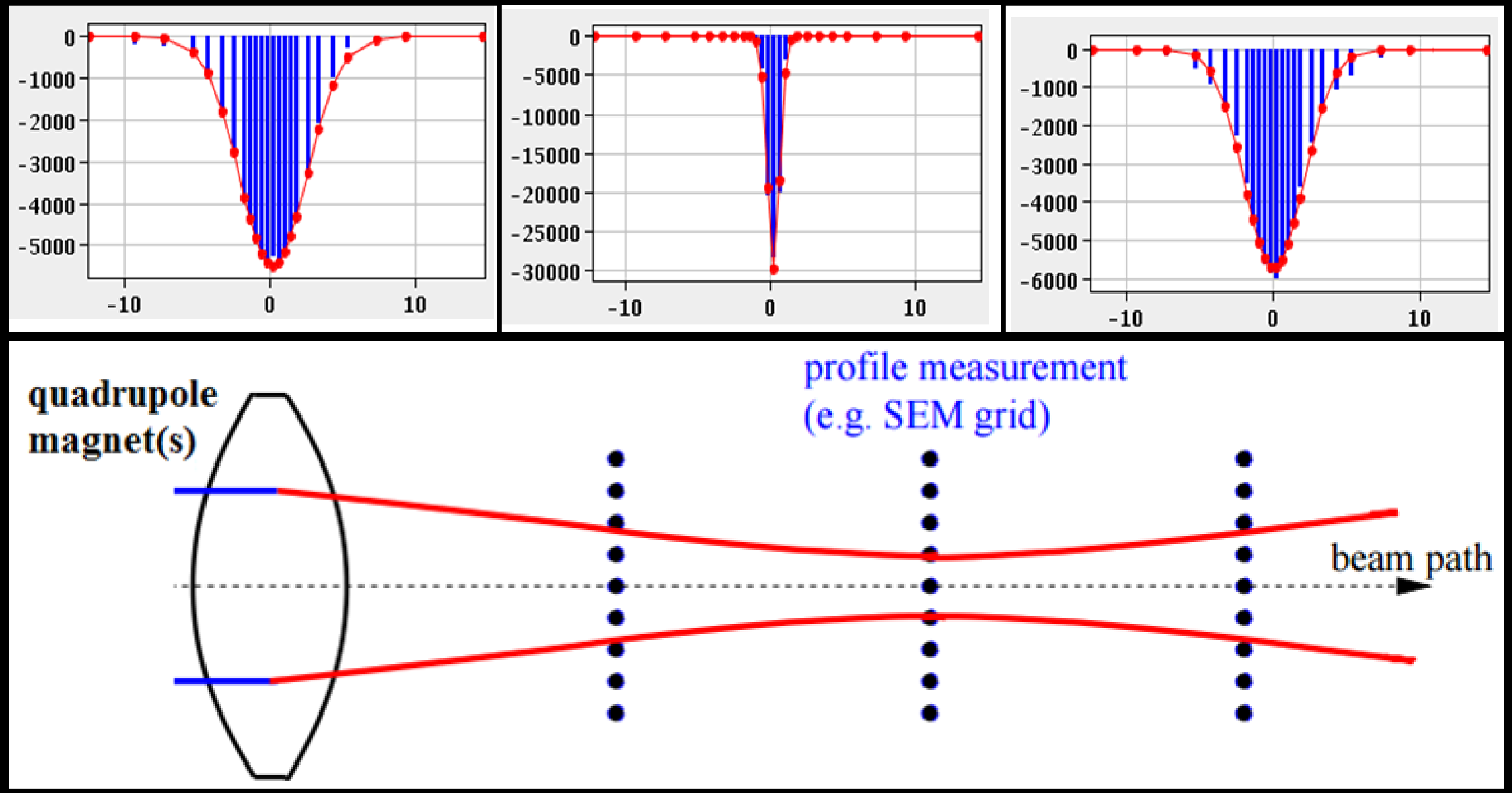

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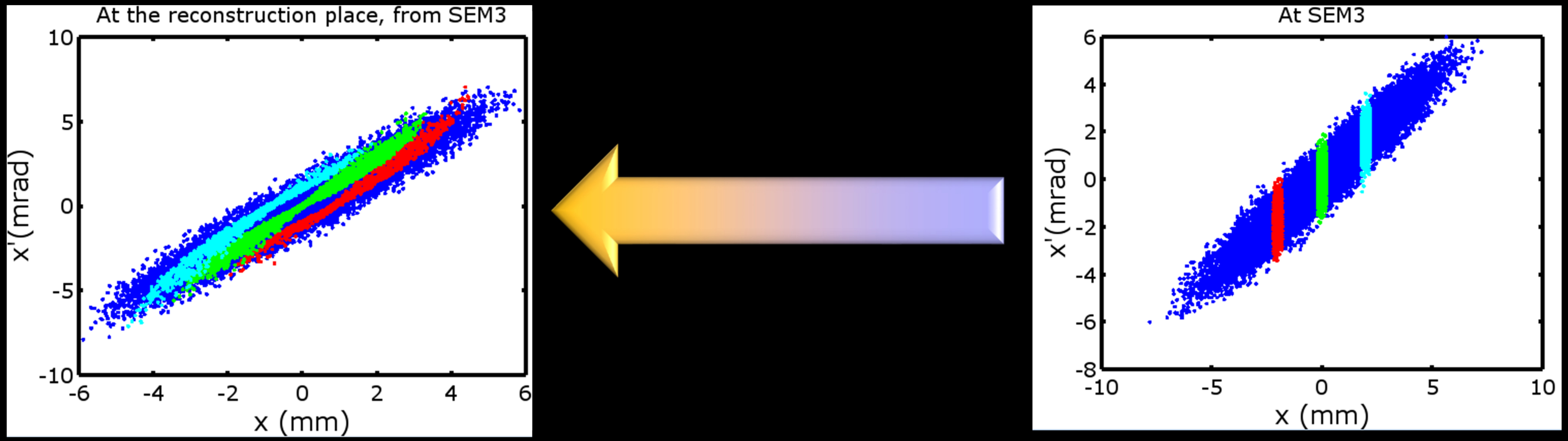
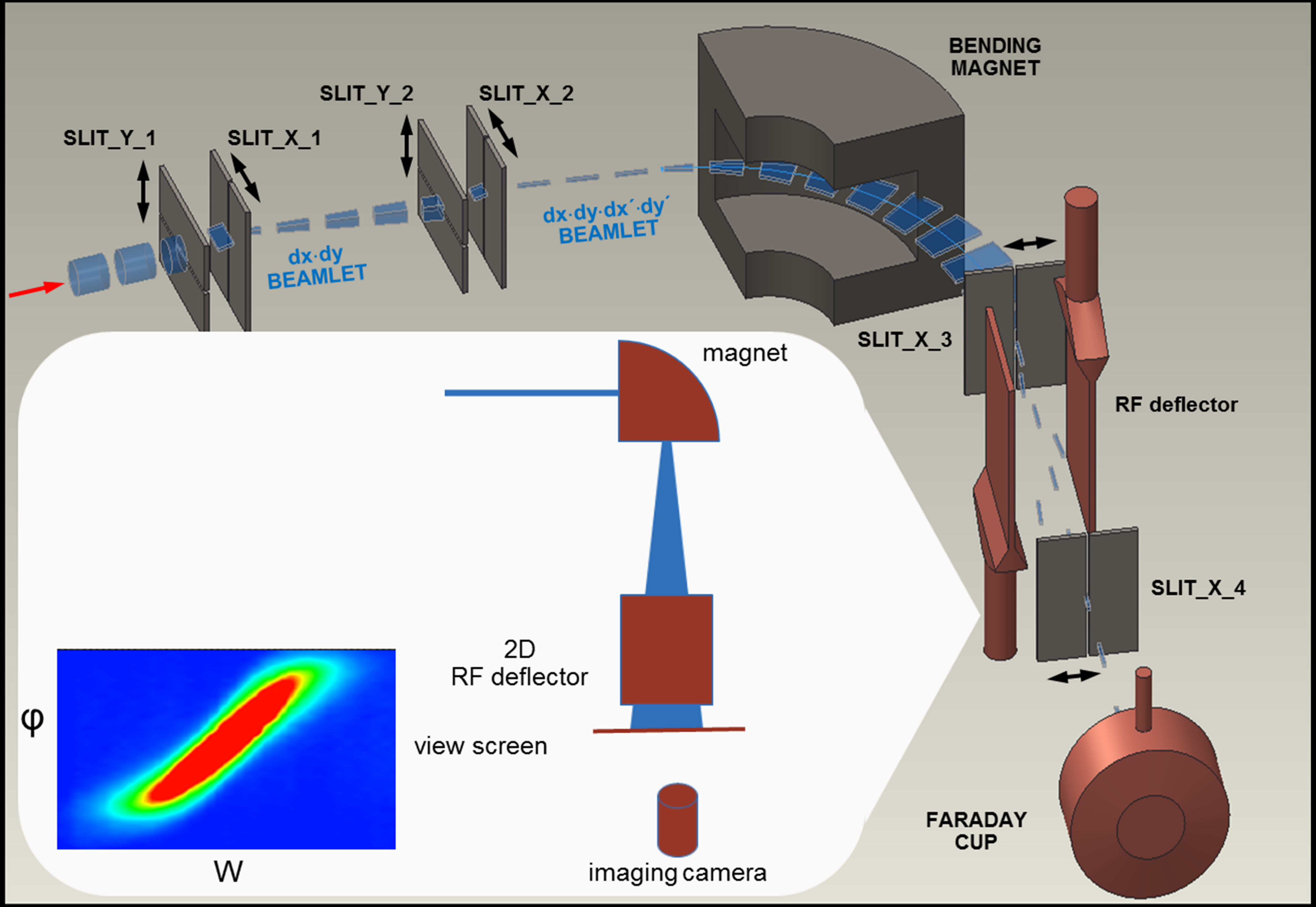


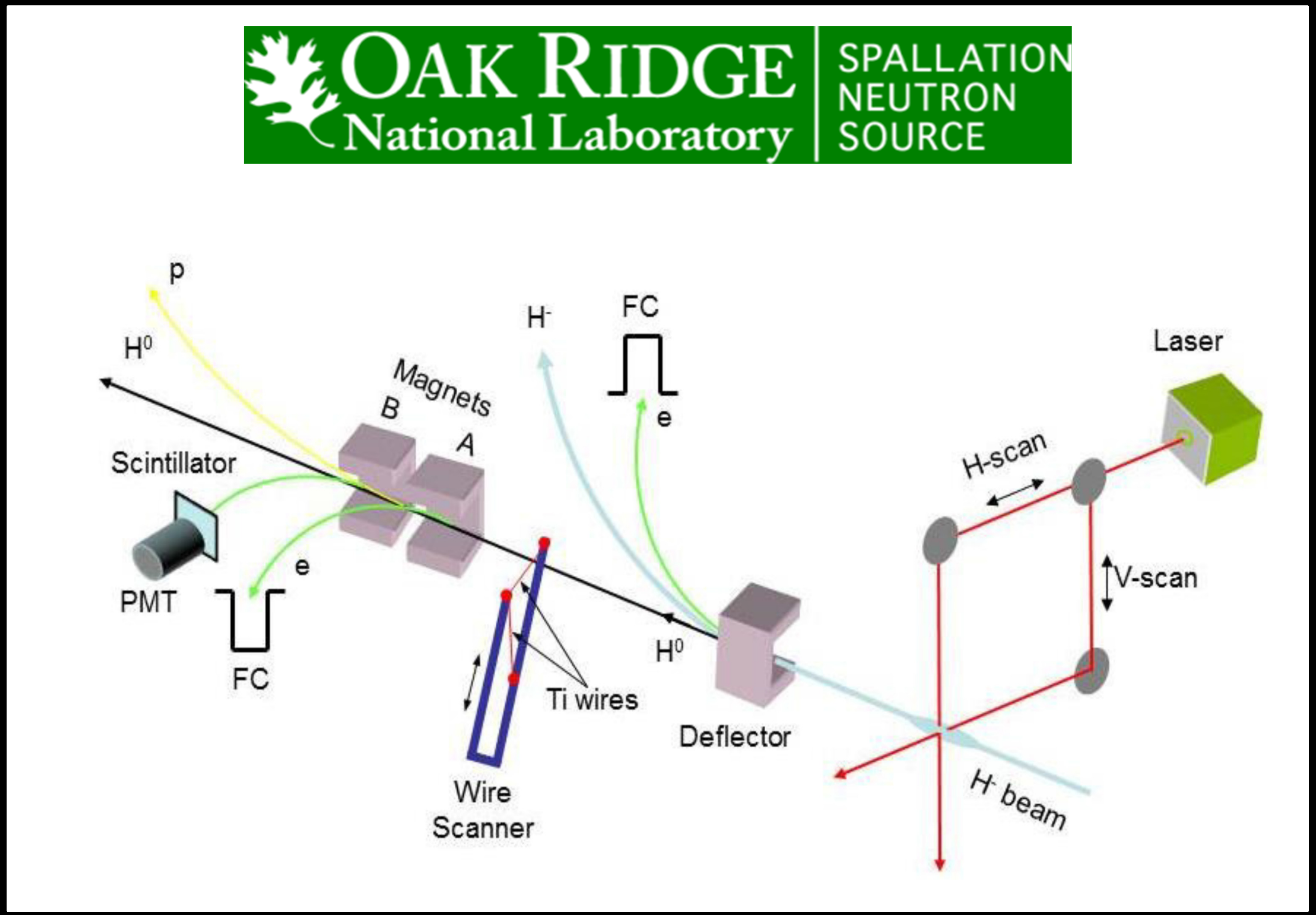
Optics Measurement in LINACs

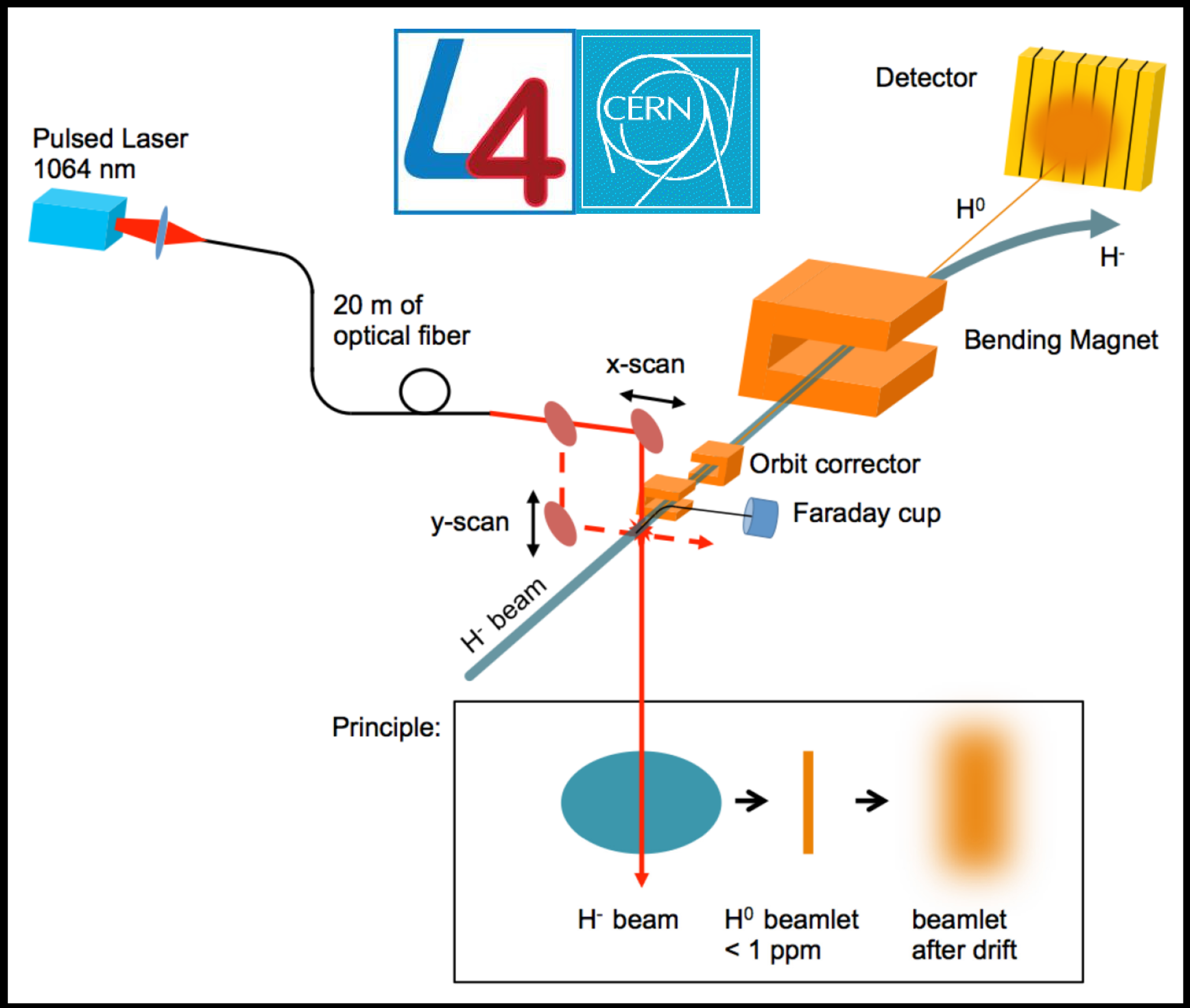
- From 2D to 6D Phase Space Measurements
  - Required to fully characterise the beam & compare to simulation codes
  - Challenges lie in reducing time required for a scan & detecting the low intensity to be measured
  - Currently being investigated at the SNS Integrated Test Stand Facility



BI Challenges for BD Studies in LINACs

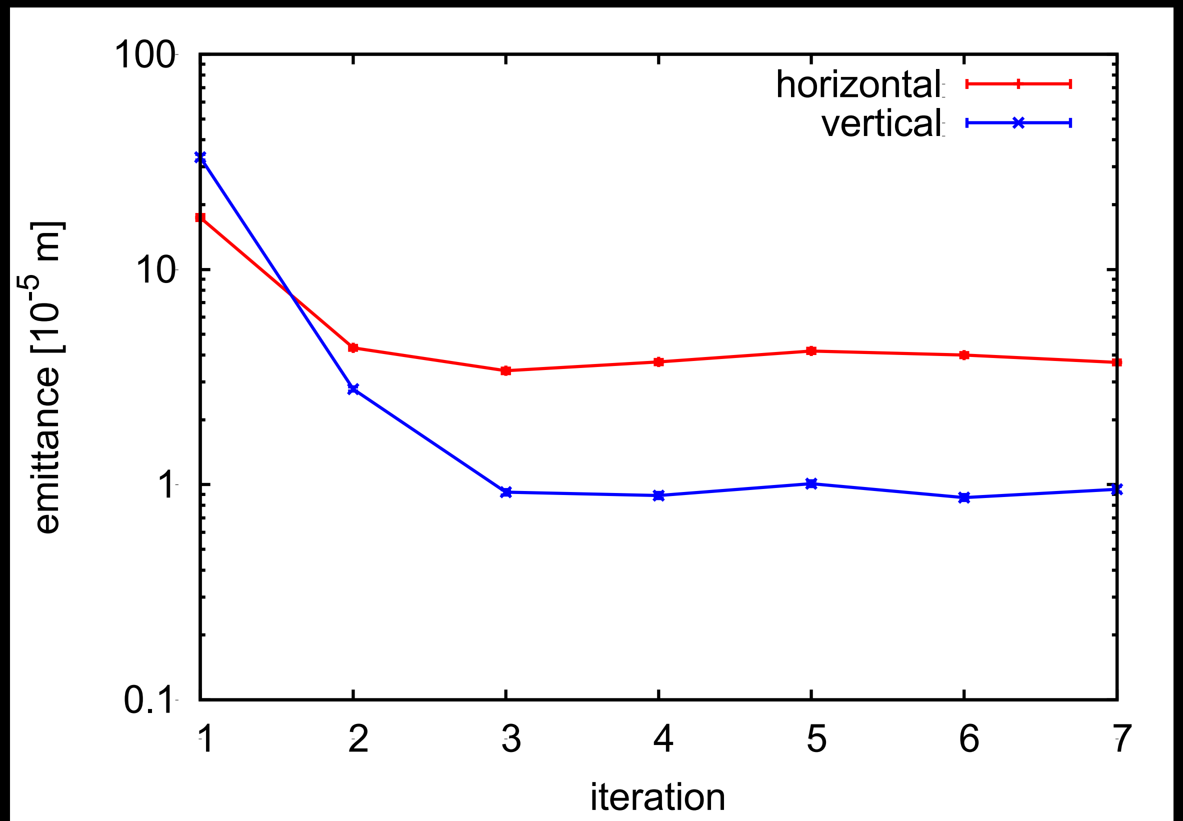
- Non-invasive measurements
  - A must for measurement of high intensity beams
    - Important for understanding space charge effects
  - Laser based systems developed for H^- LINACs
    - e.g. SNS (Oak Ridge) & LINAC4 (CERN)
  - Viable systems for proton LINACs still need development
    - Ionisation profile monitors suffer from space charge issues for high intensity beams
    - Luminescence monitors limited by low light yield for operational vacuum pressures





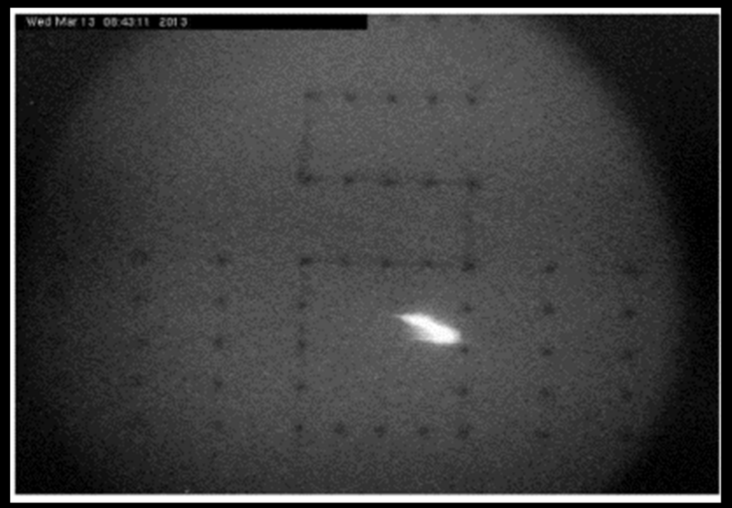
BI Challenges for BD Studies in LINACs

- Dispersion Free Steering
  - Beam-based alignment method
    - Optimisation of choice for next generation linear colliders
  - Aims to minimize emittance growth due to BPM & quadrupole misalignment
    - Chromatic dilution scales with square root of number of BPMs
    - For linear colliders, sheer number of BPMs can increase emittance significantly even at 10µm alignment level
  - Measure beam position variation with energy
    - Extract quadrupole & BPM misalignment & steer accordingly
  - Requires high resolution BPMs with good temporal resolution for single shot measurements
    - e.g. CLIC : 4000+ BPMs with 50nm position resolution & 10ns temporal resolution
    - Single shot at each location when measuring position v energy modulation along train
  - Then needs single shot measurement of very small emittances to quantify success!



Example from the SLAC LINAC (FACET)

Before correction (#1)

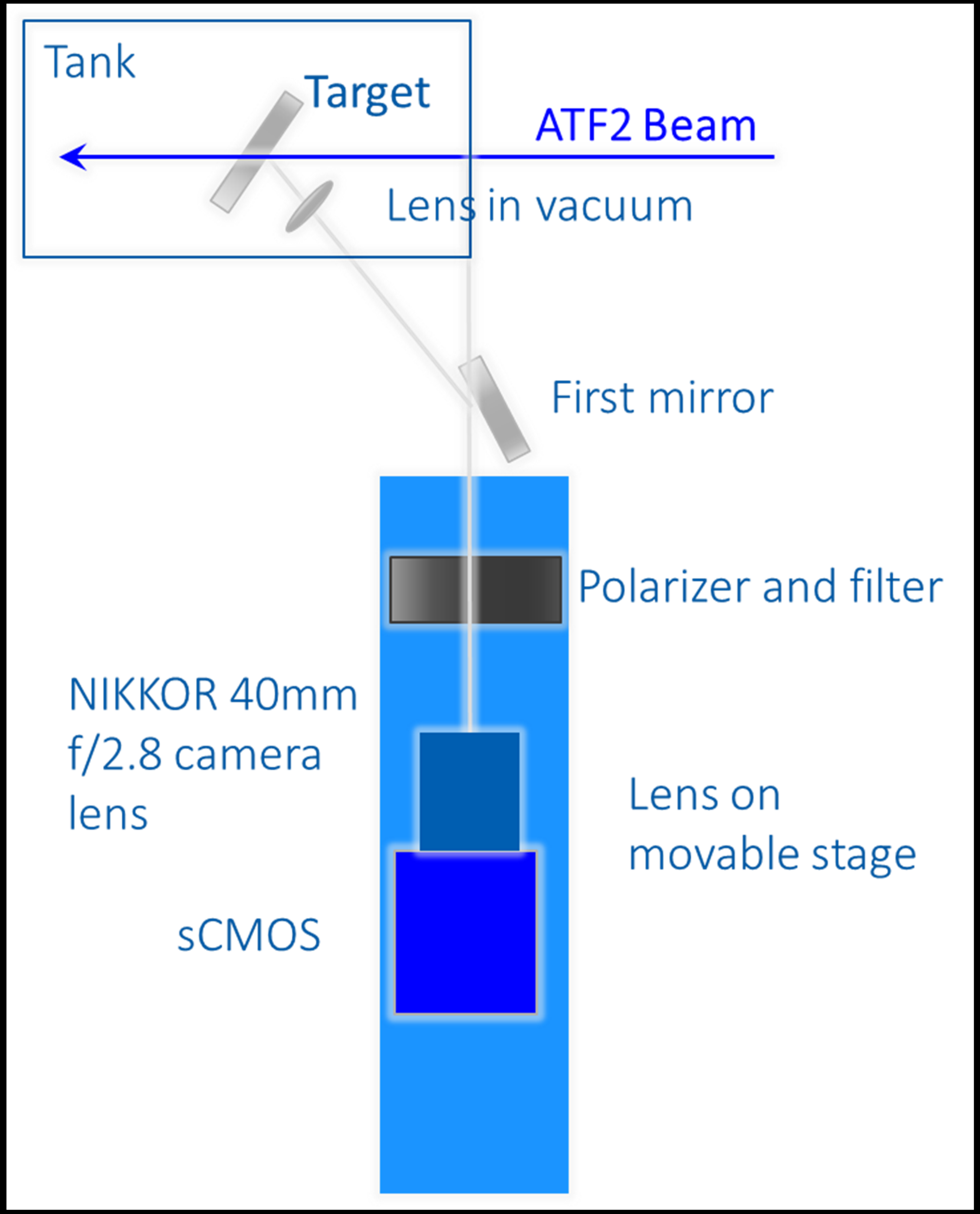


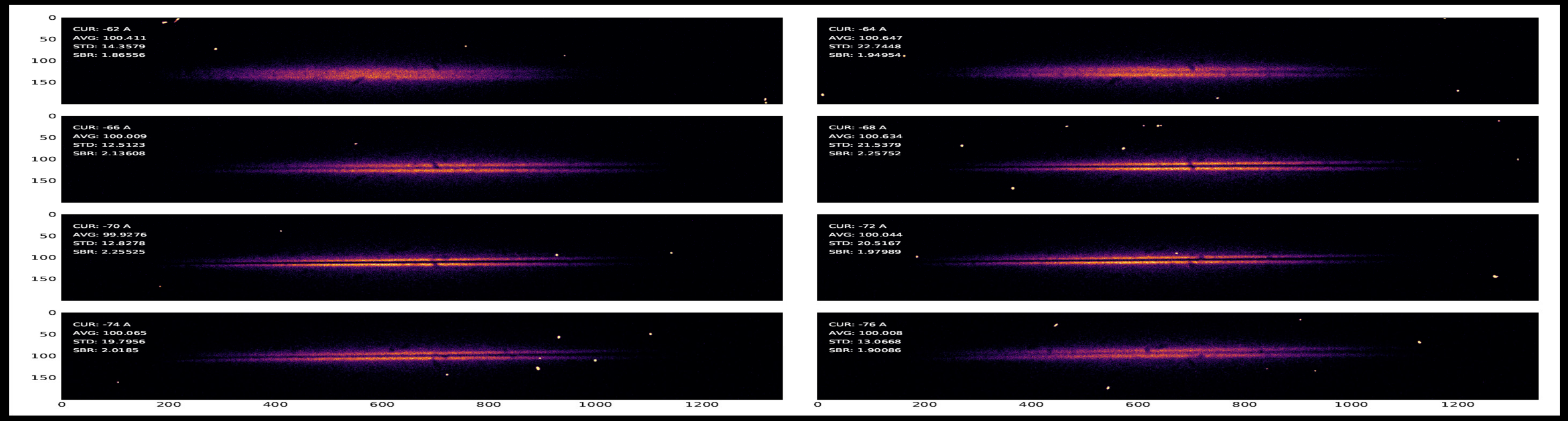
After 1 iteration (#2)

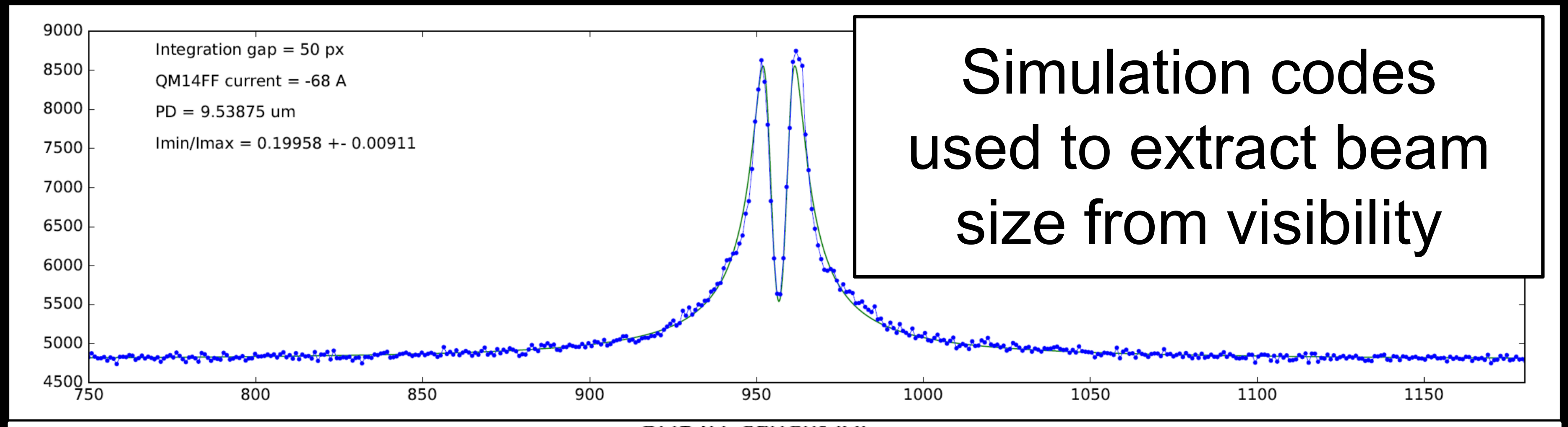
After 3 iterations (#4)

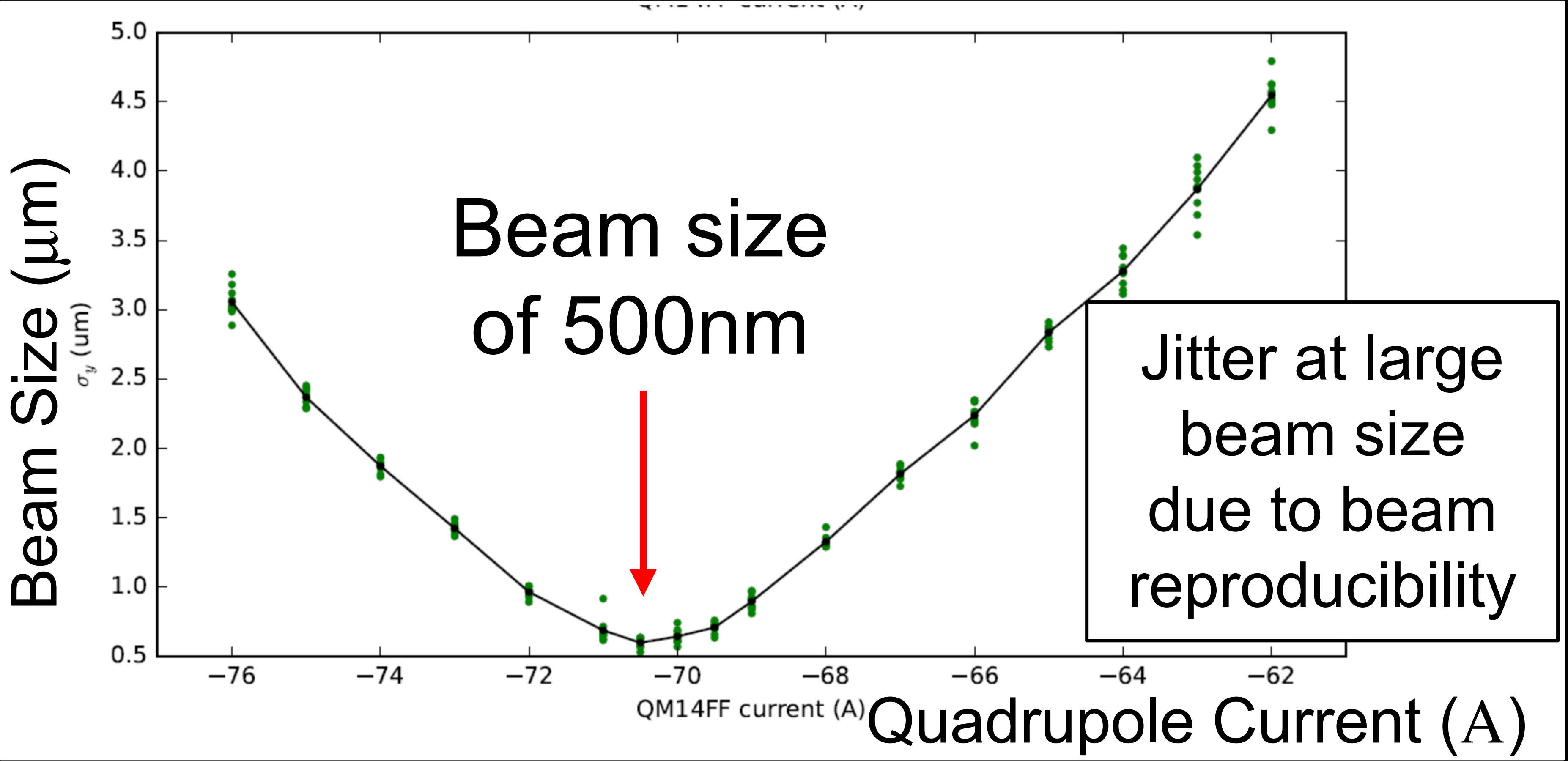
BI Challenges for BD Studies in LINACs

- Measuring extremely small beam sizes
  - A must for next generation linear colliders - example of OTR@ATF2
    - Recent direct imaging results of 500nm beam size during quadrupole scan





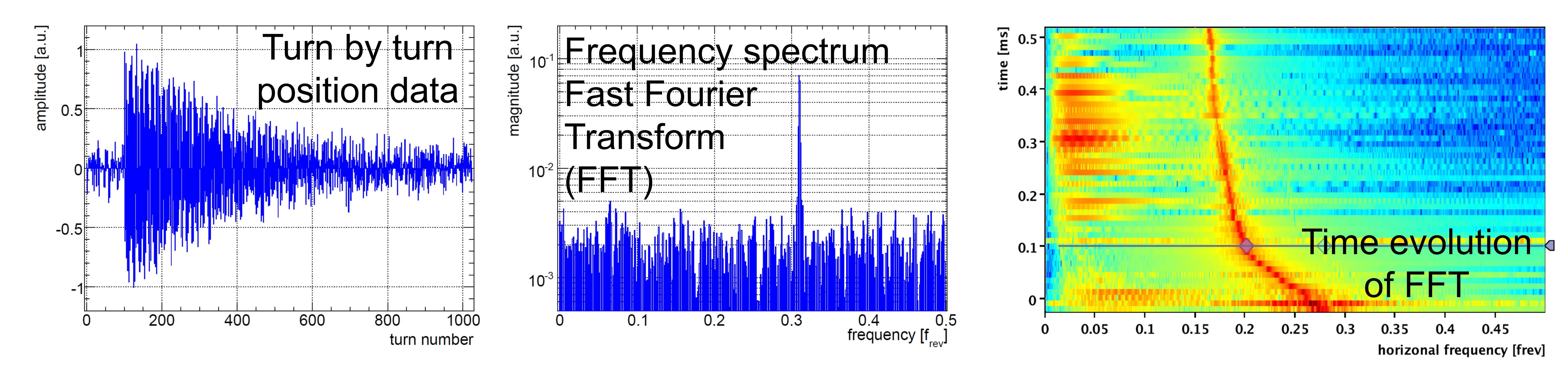




Beam Dynamics Studies using Tune Spectra

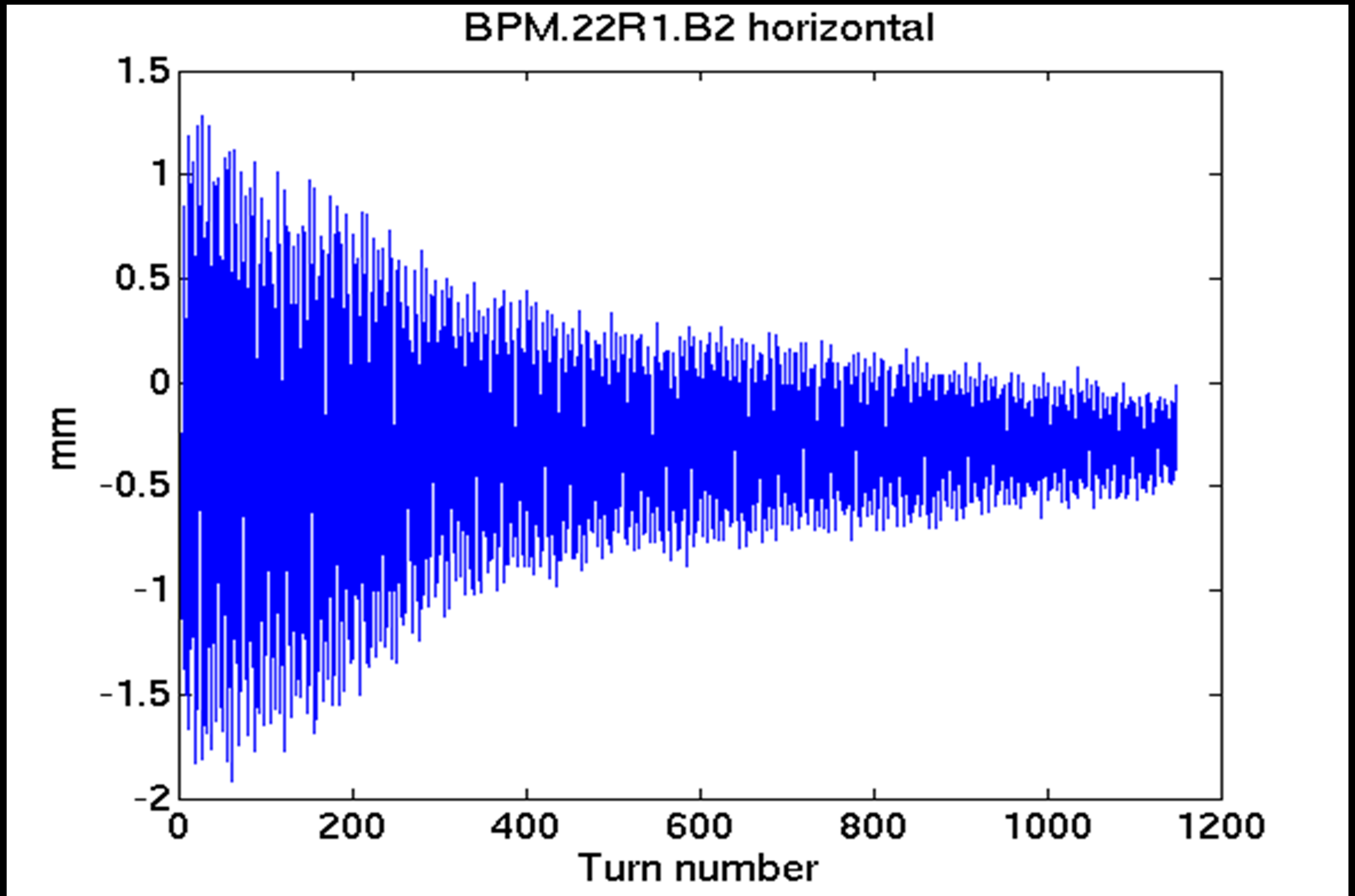
Beam Dynamics Studies using Tune Spectra

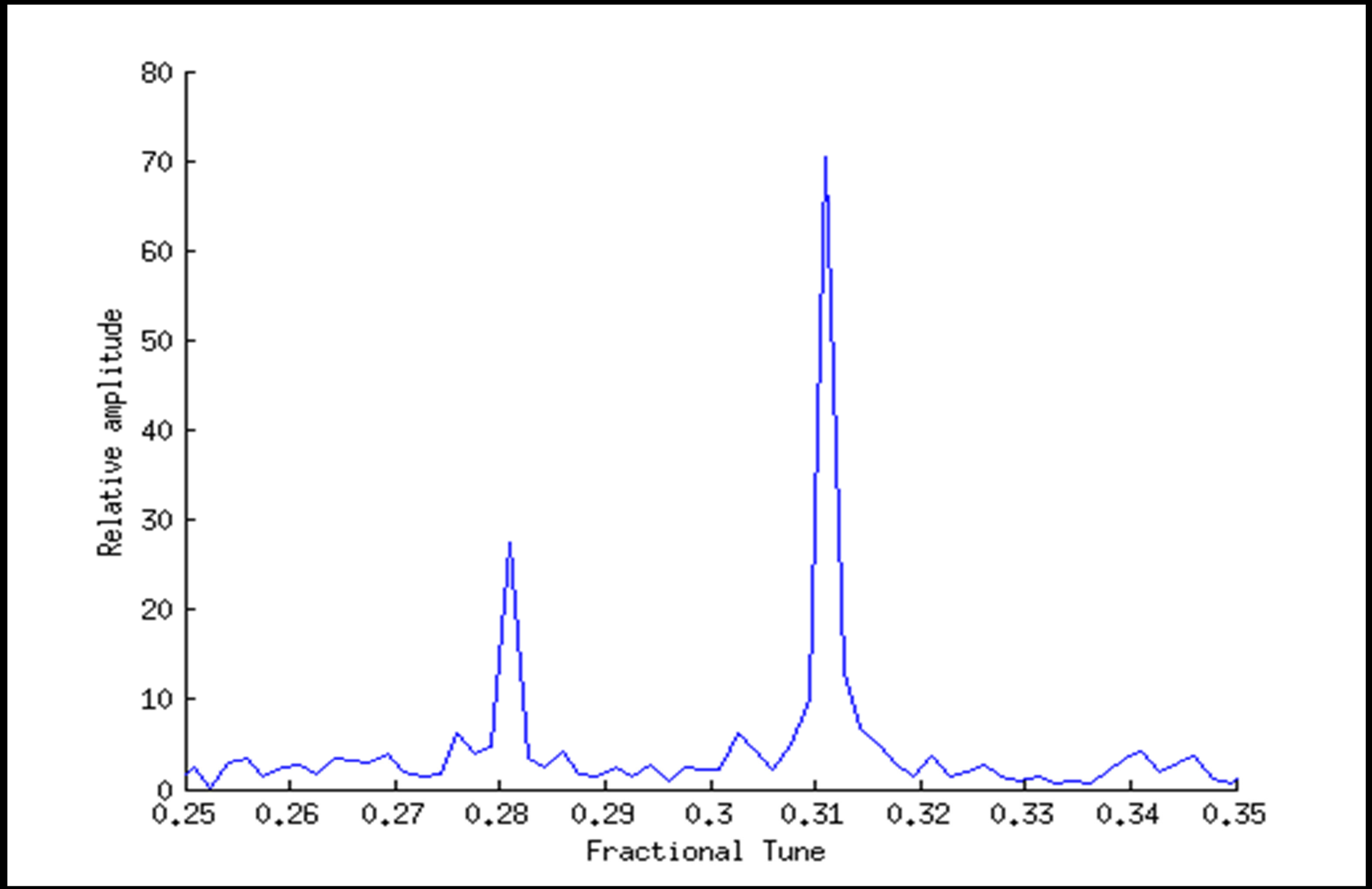
- Tune measurements useful for variety of applications
  - Tune shift with quadrupole strength the local beta function
  - Tune shift with RF modulation the chromaticity
  - Tune shift with current the effective transverse impedance
  - Tune shift with amplitude the strength of nonlinear fields
- Understanding tune spectra also important for
  - Optimisation of beam lifetime
  - Limiting emittance growth
  - Reducing beam losses
  - Understanding instabilities, space charge, beam-beam interactions,…..



Understanding Tune Spectra

- What do we (usually) see in a tune spectrum?
  - Revolution lines
    - Normally not displayed or removed by electronic filtering
  - Main tune peak (& coupled tune if coupling present)
    - From coherent transverse betatron motion of the beam
    - Displayed in units of tune (from 0 to 0.5 [0.5-1] of revolution frequency)





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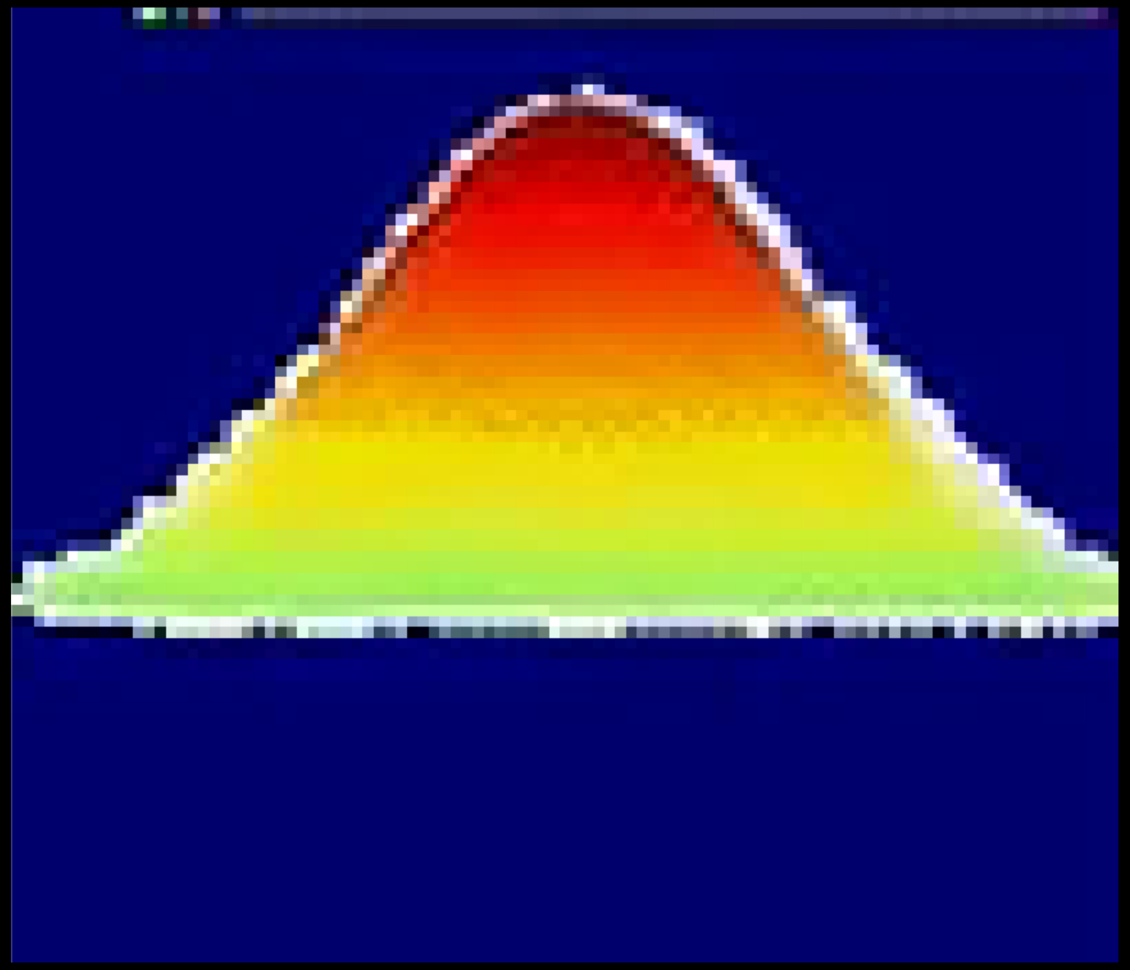
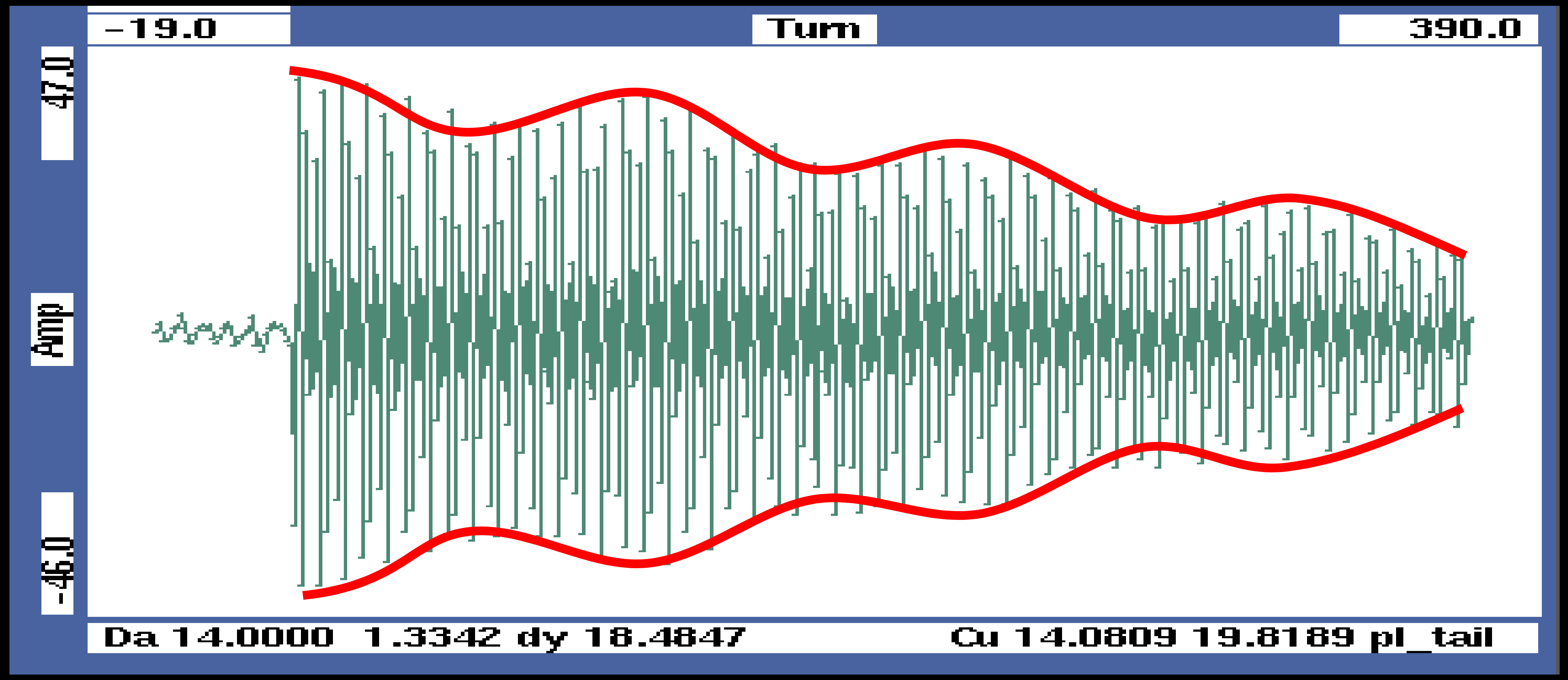
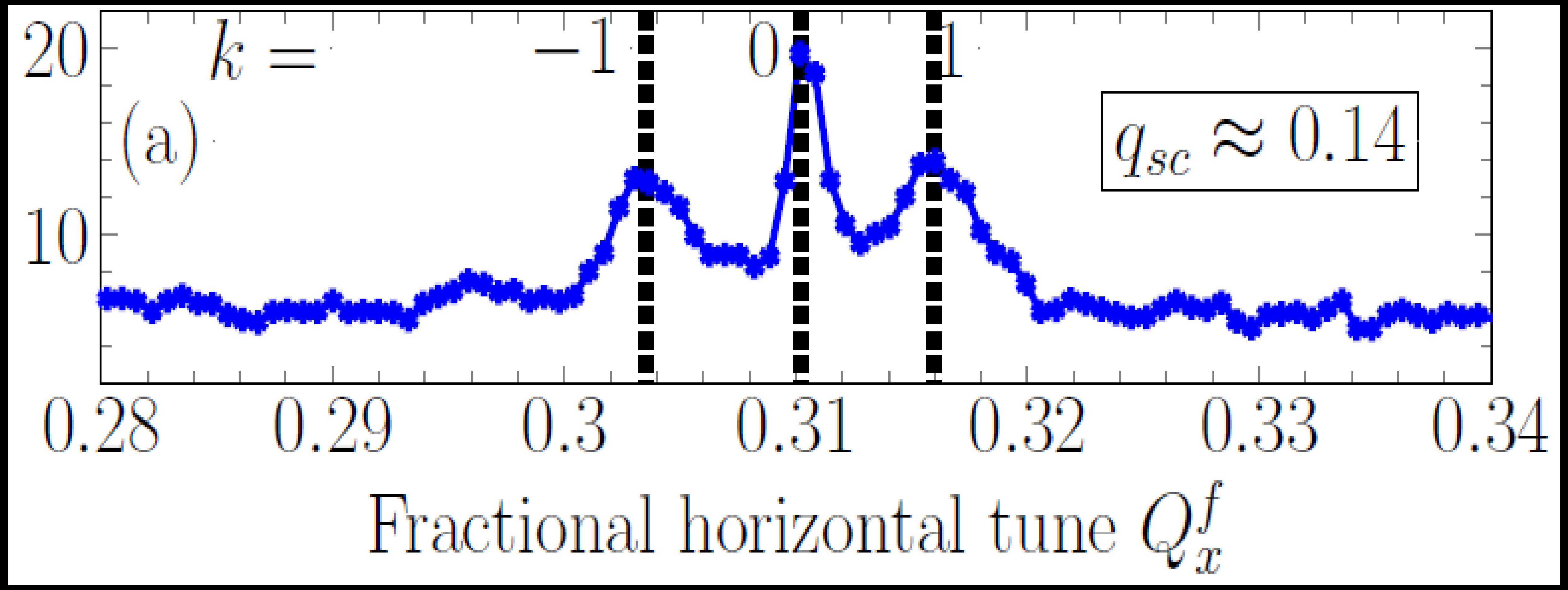
    - From coherent transverse betatron motion of the beam
    - Displayed in units of tune (from 0 to 0.5 [0.5-1] of revolution frequency)
  - Synchrotron sidebands (from AM modulation)
    - In presence of synchrotron motion (bunches beams)
    - Interplay of incoherent (single particle) & coherent motion
    - Amplitude depends on Chromaticity
    - Frequency depends on synchrotron frequency but also on beam dynamics effects



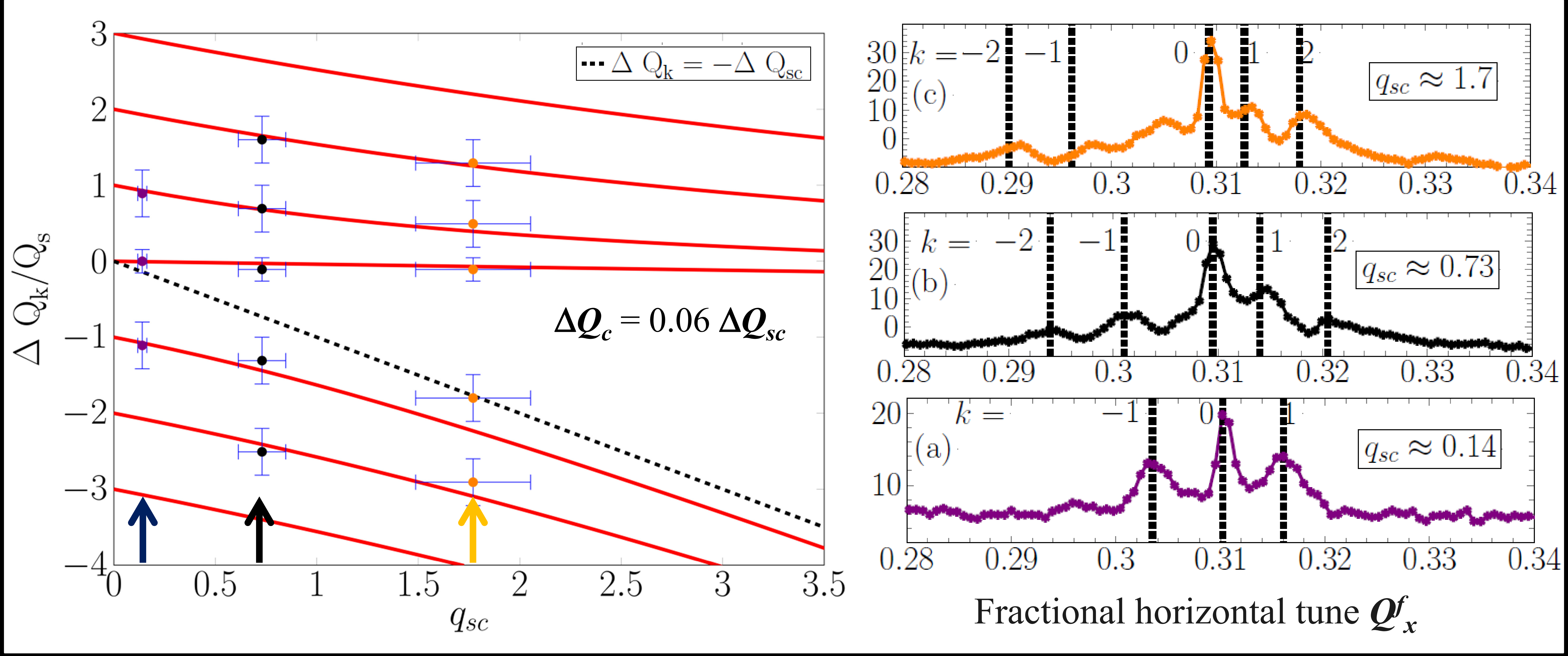
Bunch motion for non-zero chromaticity





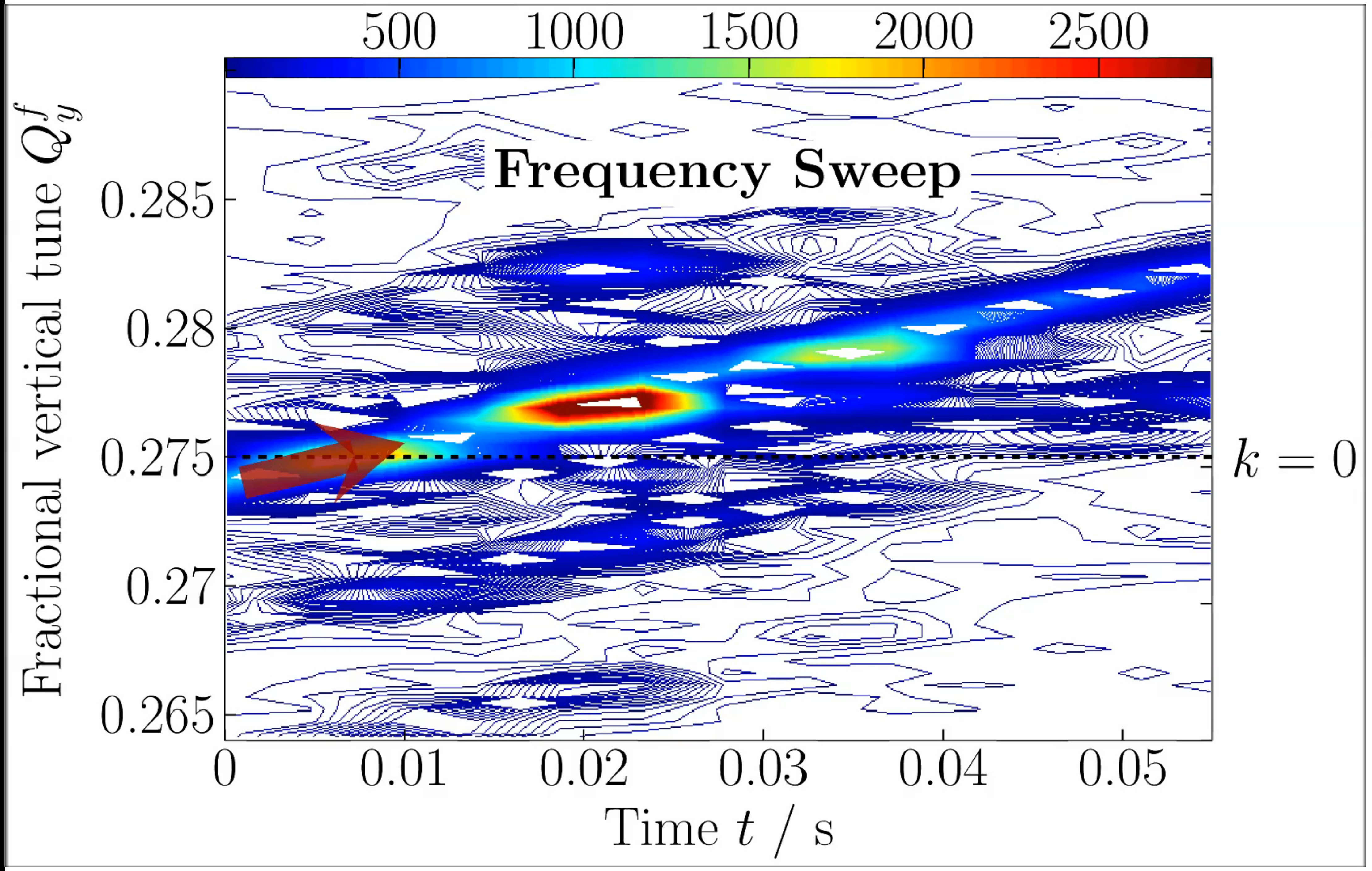
Understanding Tune Spectra

- Dealing with High Intensity Effects @ GSI
  - Modification of tune spectra by space charge & impedance
  - Relative heights & mode structure given by chromaticity
    - Can be calculated with simplified analytical models

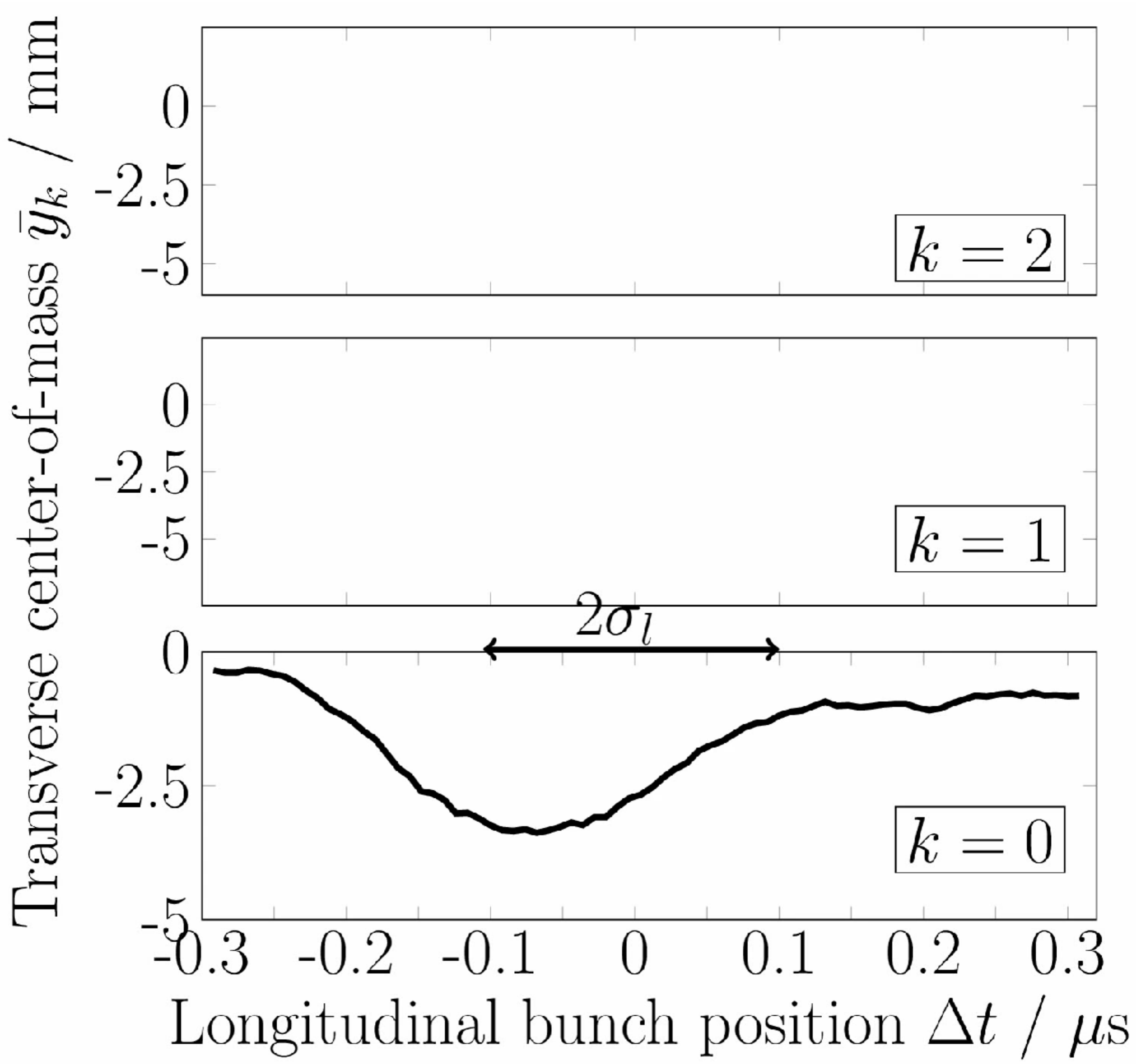


Understanding Tune Spectra

- Combining tune spectra with intra-bunch diagnostics
  - Head-Tail modes clearly visible
  - Gives important input to validate beam dynamic simulations in the presence of impedance and space charge

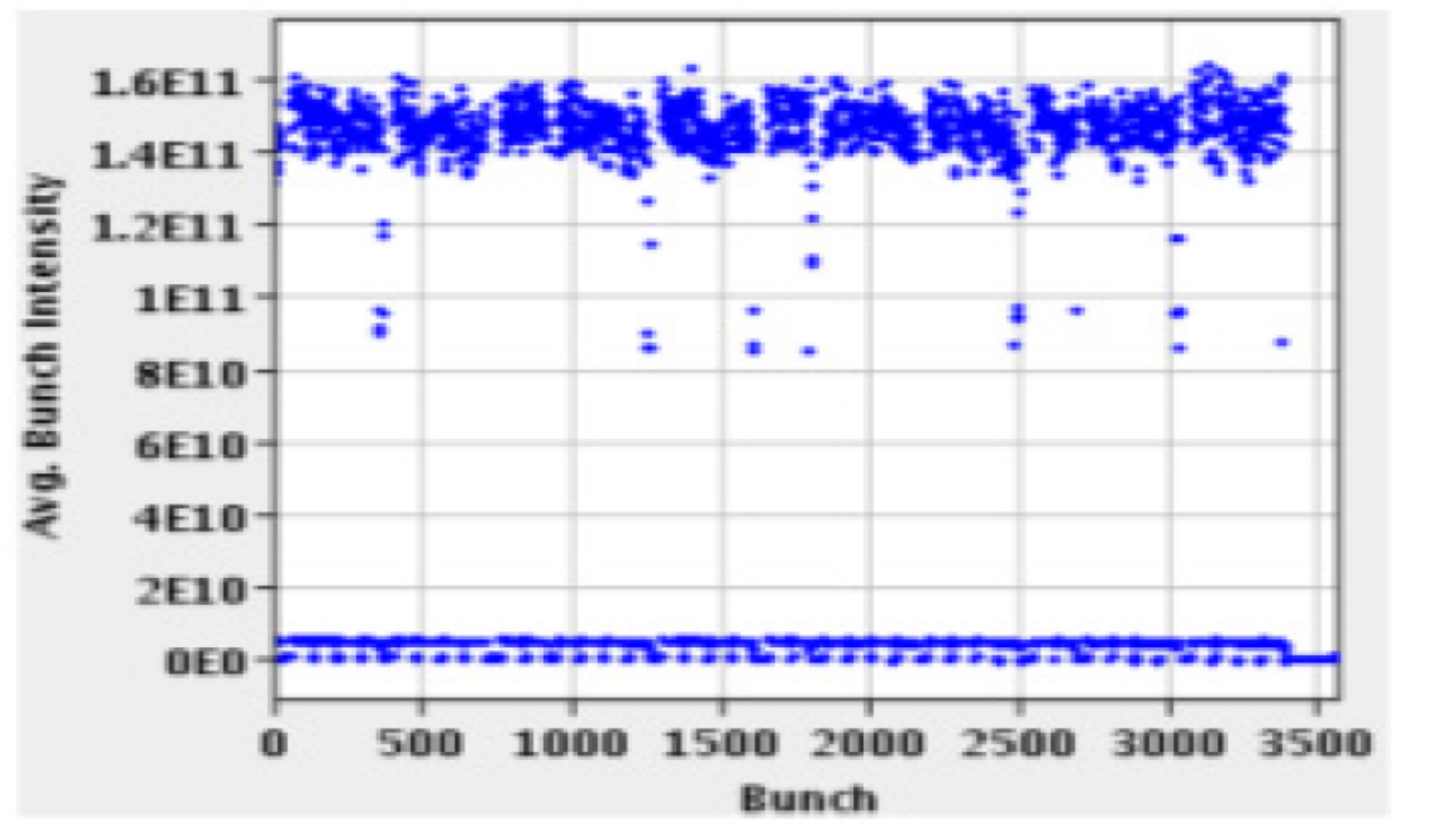


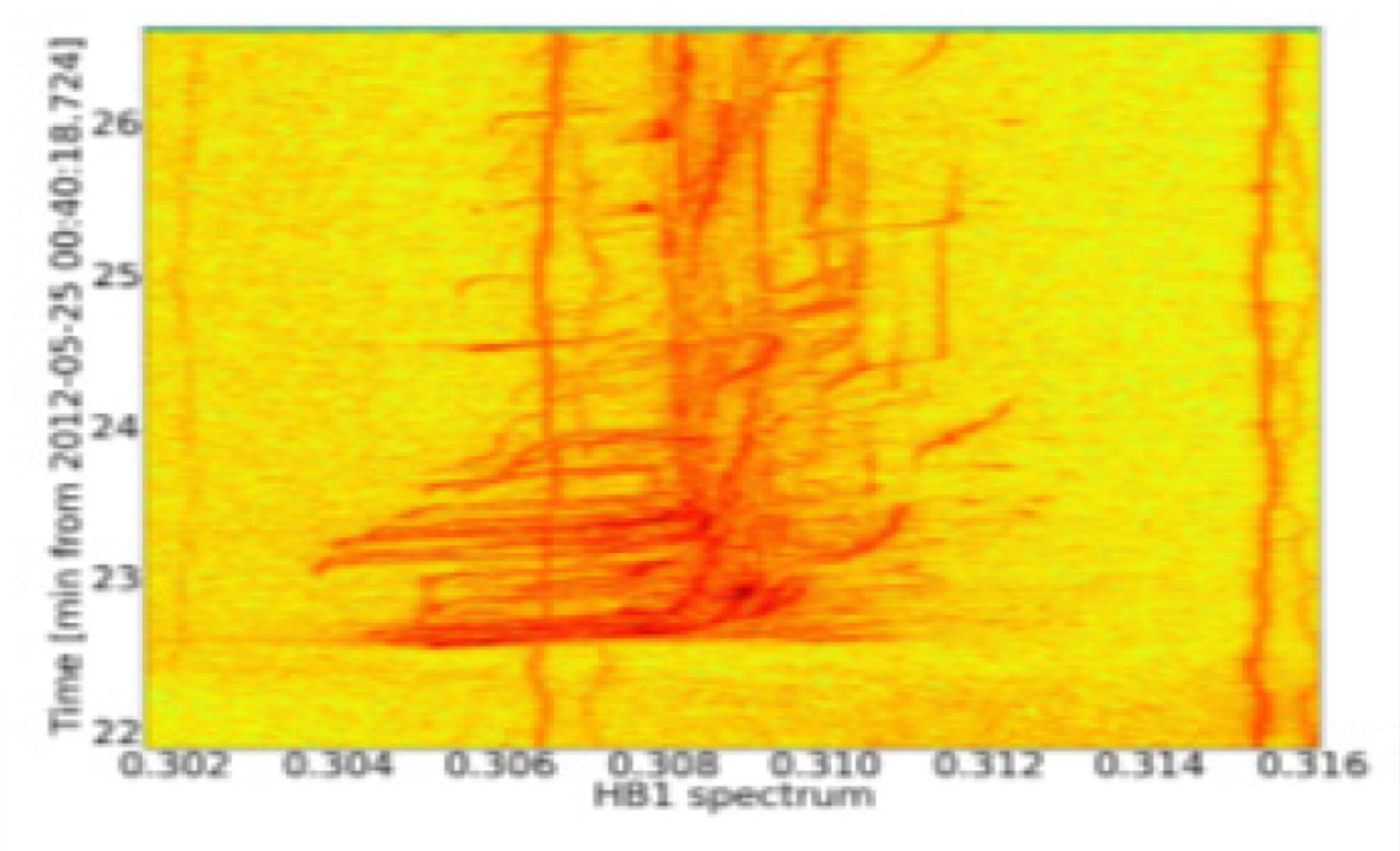
Tune spectrogram during sweep



Understanding Instabilities

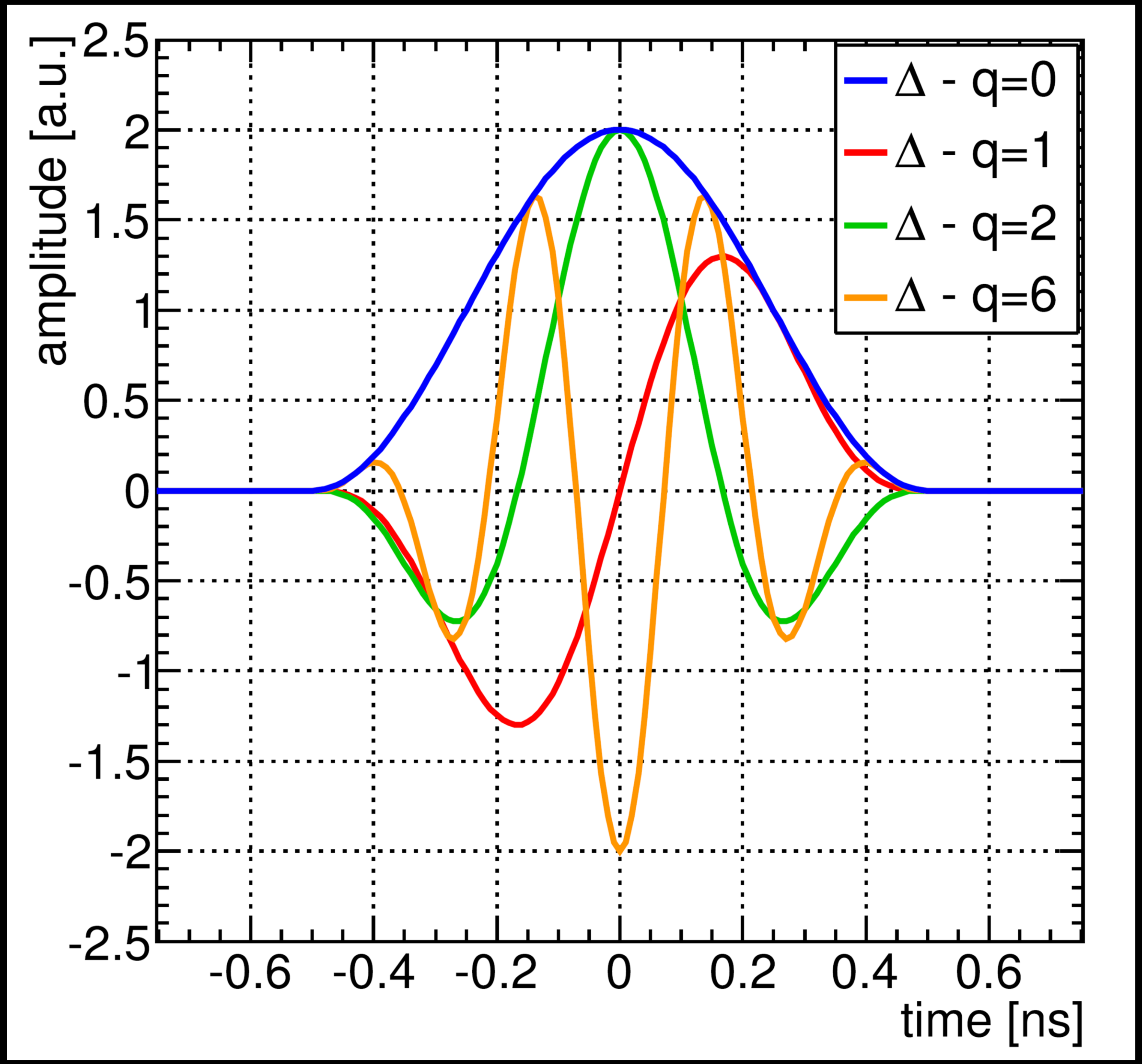
- Often a limiting factor for intensity increase
  - Caused by impedance, space charge, electron cloud, beam-beam, …
  - Understanding their origin important to find a cure
    - Transverse feedback, chromaticity, octupole current, …
  - Challenges lie in
    - Detecting onset of instability to allow triggering instrumentation
    - Instrumentation for intra-bunch diagnostics on sub-nanosecond bunches
      - Direct sampling limited by dynamic range, acquisition length & data volume
      - Requires detectors with wide bandwidth response from MHz to > 10 GHz

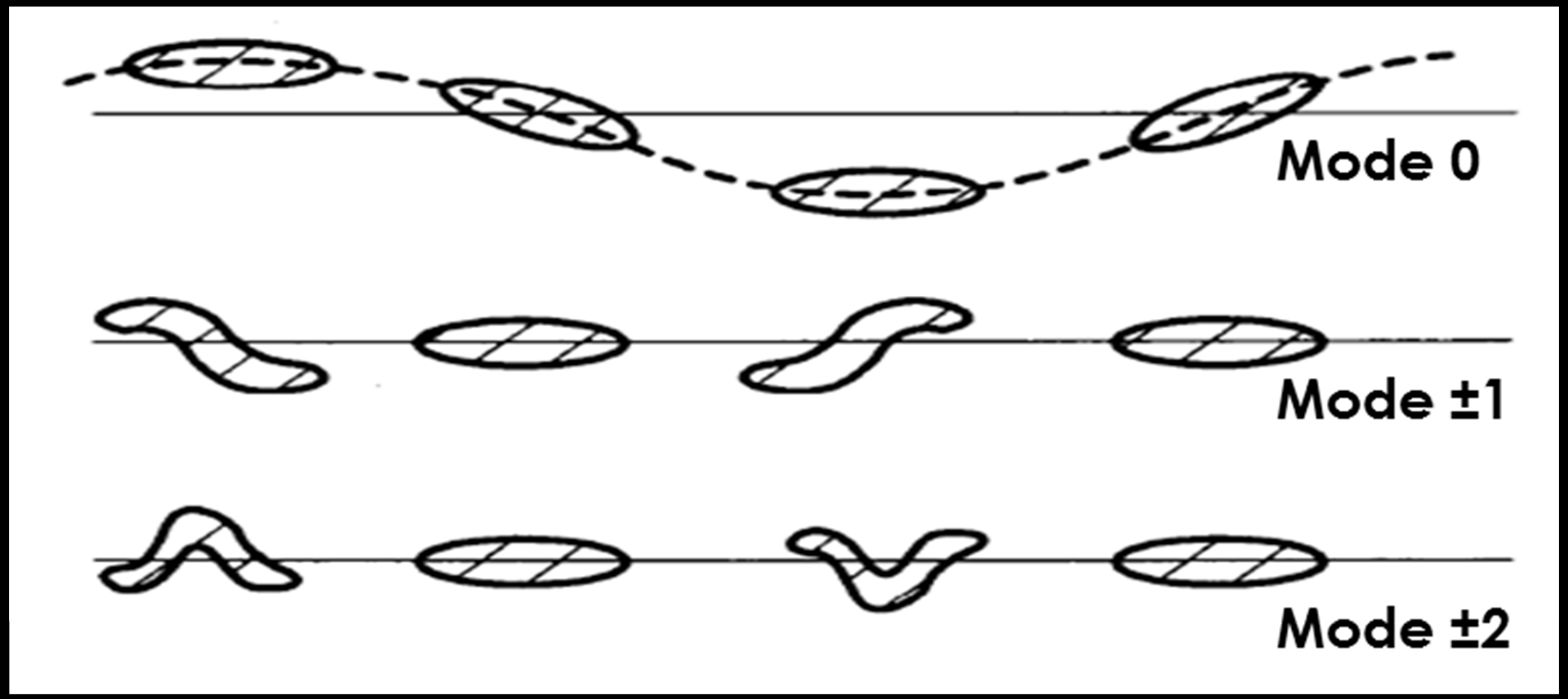


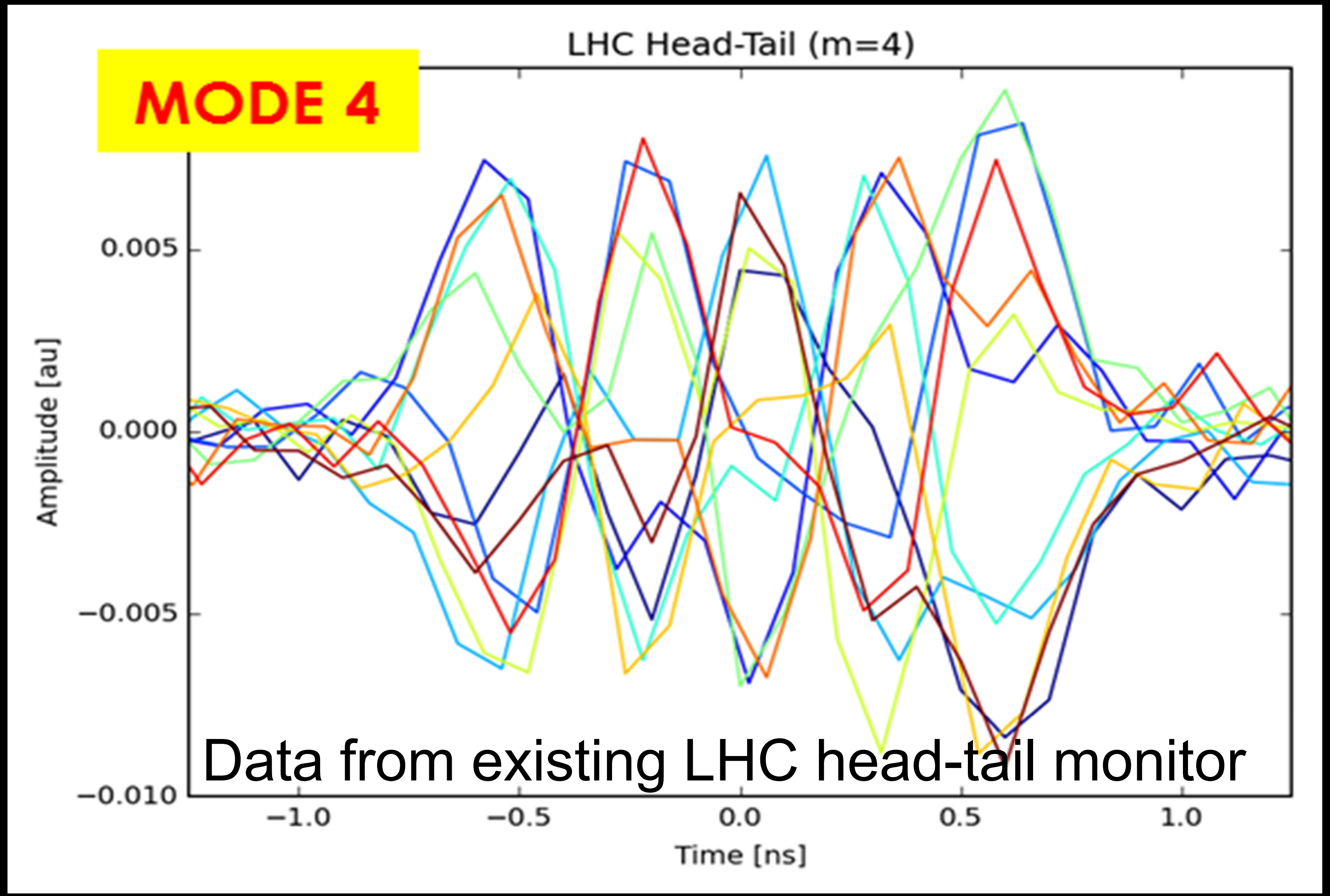


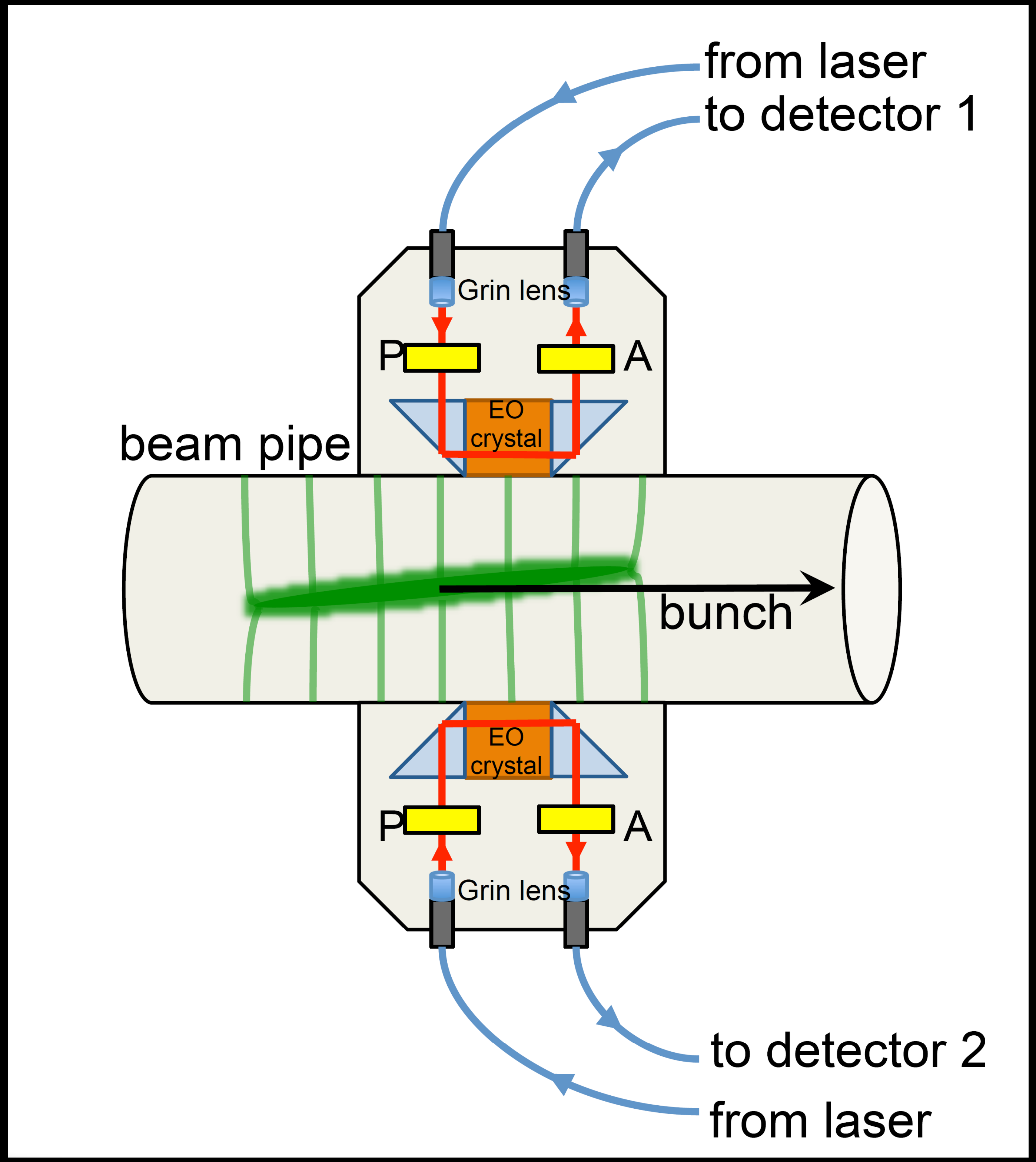
Understanding Instabilities

- Ongoing R&D
  - Electro-optical detection techniques to allow higher detector bandwidth
  - Frequency domain analysis to remove need for direct sampling







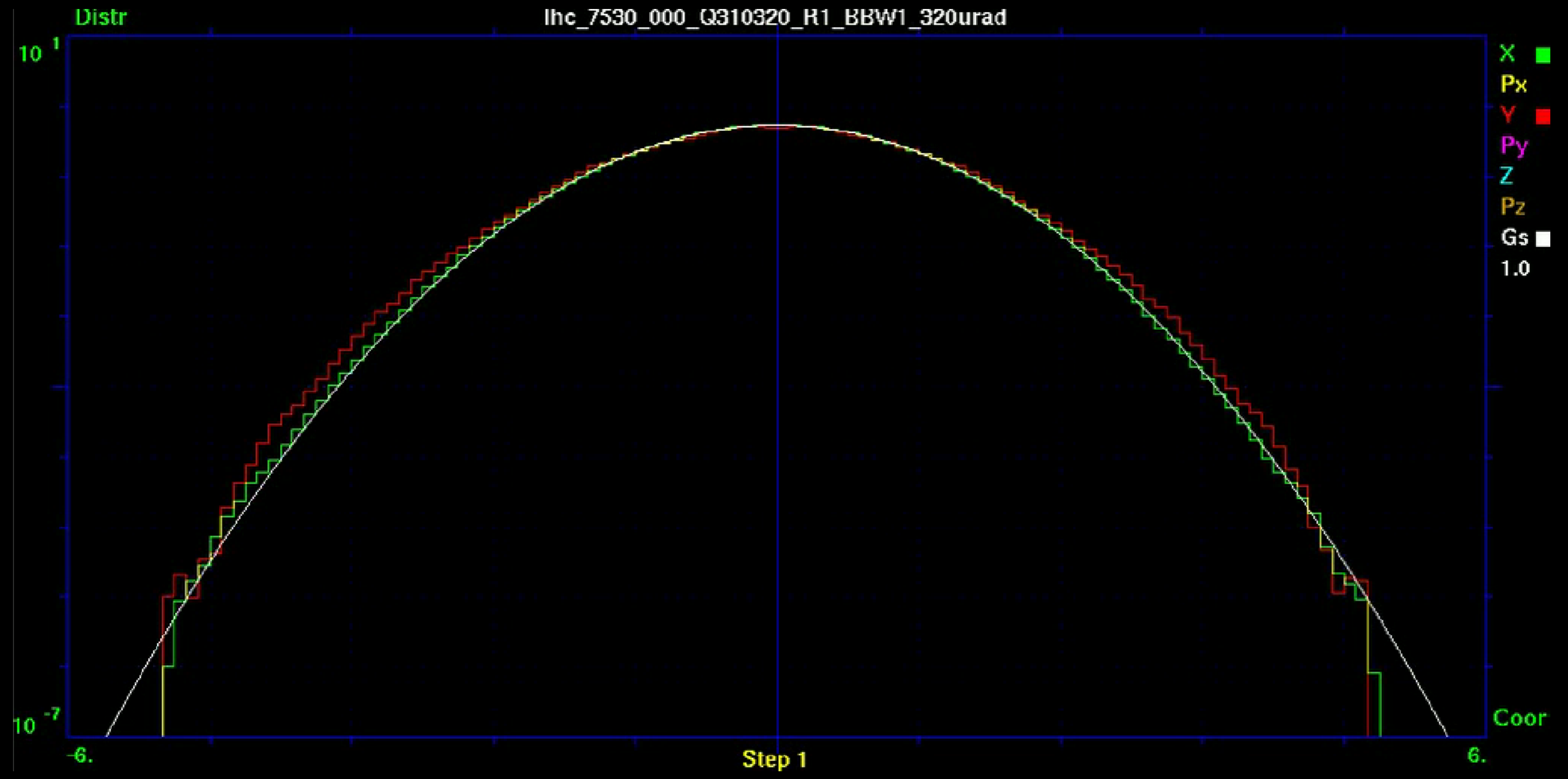


Understanding Beam Halo Formation

Understanding Beam Halo Formation

- Halo control essential to limit beam loss
  - Best done by tuning the machine to avoid populating the tails in the first place
  - For high energy or high power machines too much beam in the halo can lead to damage of accelerator components
    - Due to instantaneous losses or long term irradiation
- The Beam diagnostic challenges
  - The high dynamic range required
  - Developing non-invasive techniques

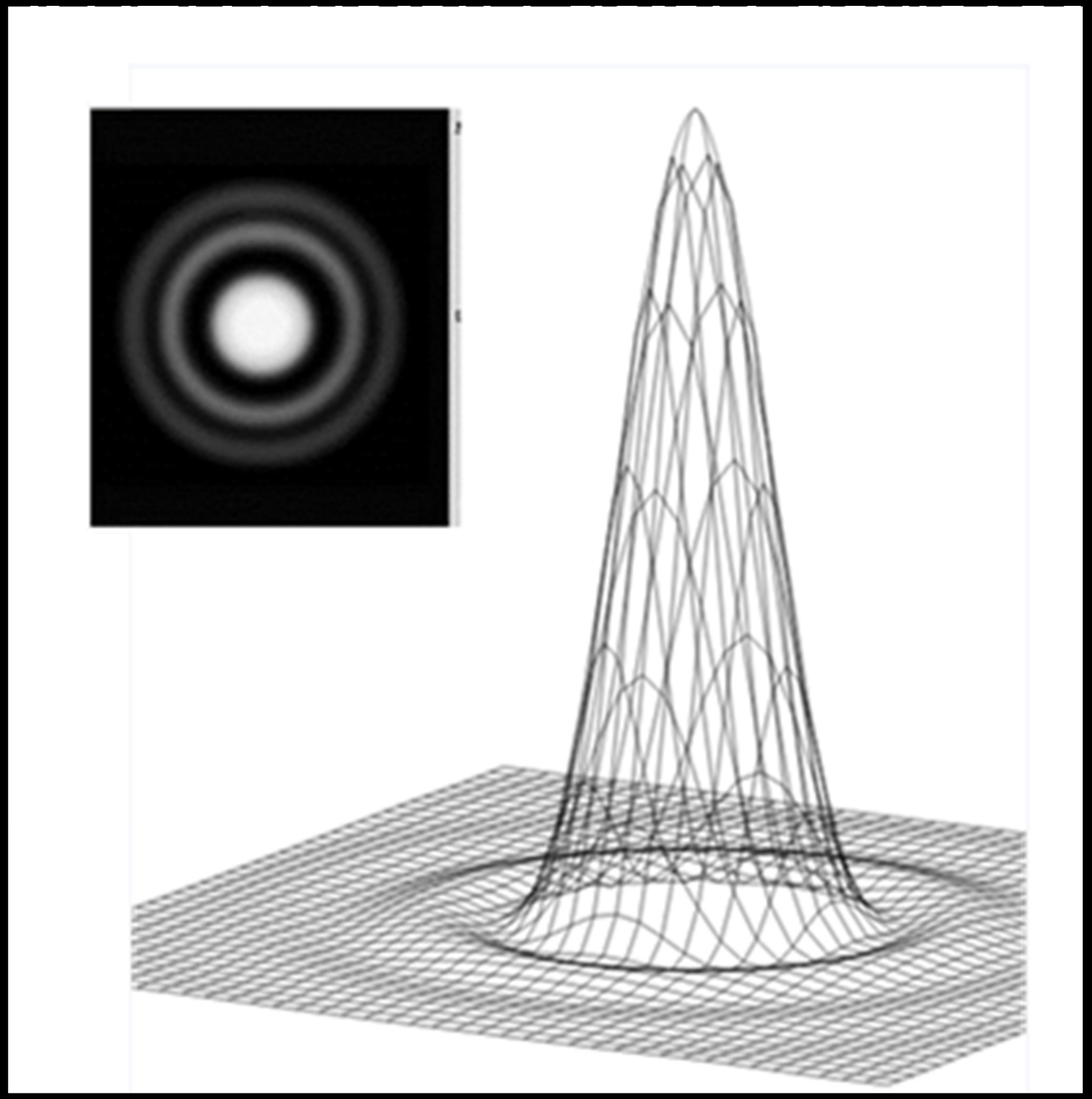
Simulation of halo formation from long-range beam-beam interactions

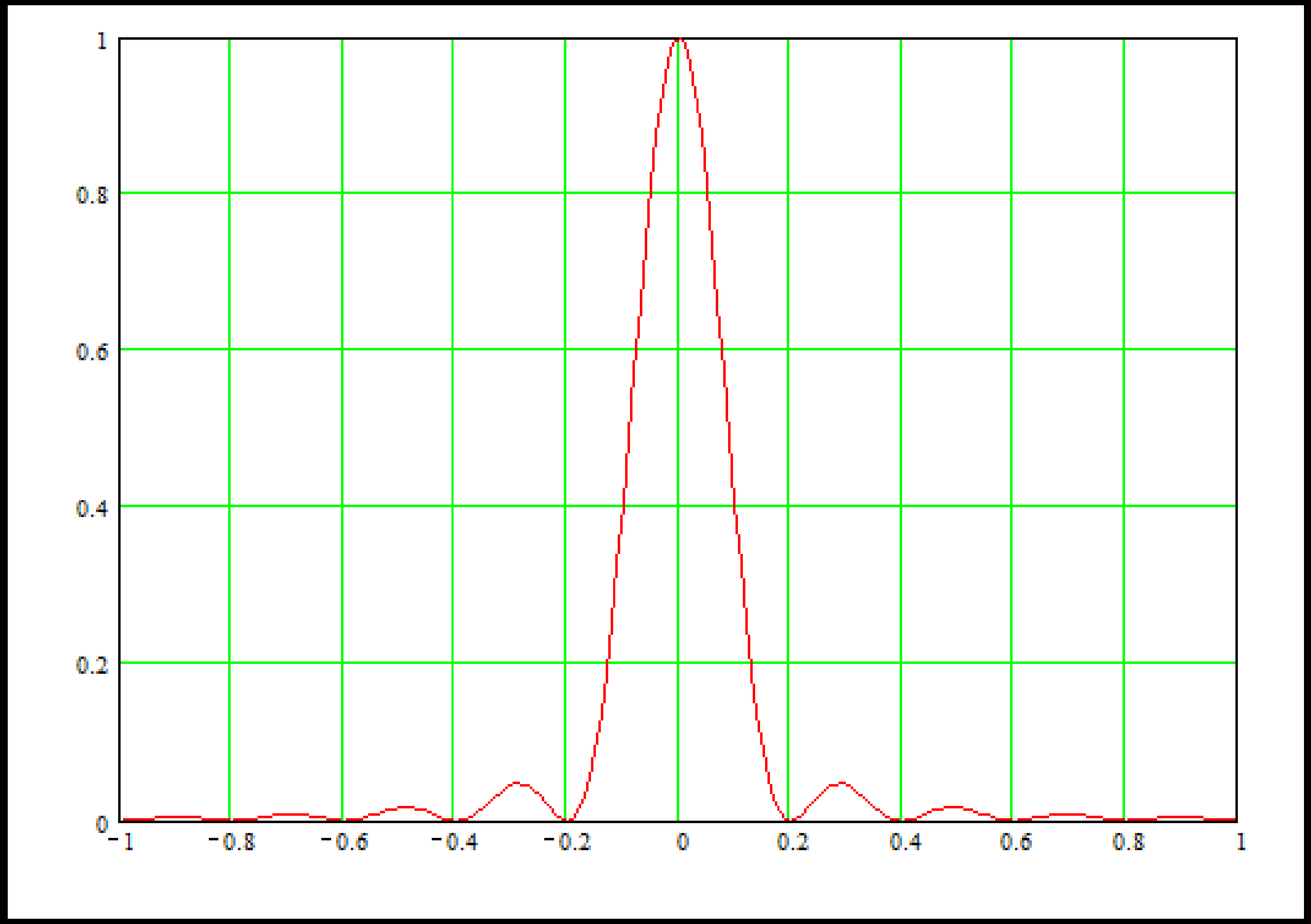


Courtesy of A. Valishev

Understanding the Beam Halo

- Non-invasive techniques being investigated
  - Coronagraph (prototype for HL-LHC now installed in LHC)
    - Uses synchrotron radiation
    - Need to limit diffraction from core
      - Intensity of fringes in range of 10^{-2} to 10^{-3} of peak intensity would mask any halo at 10^{-5} level





Understanding the Beam Halo

- Non-invasive techniques being investigated
  - Coronagraph (prototype for HL-LHC now installed in LHC)
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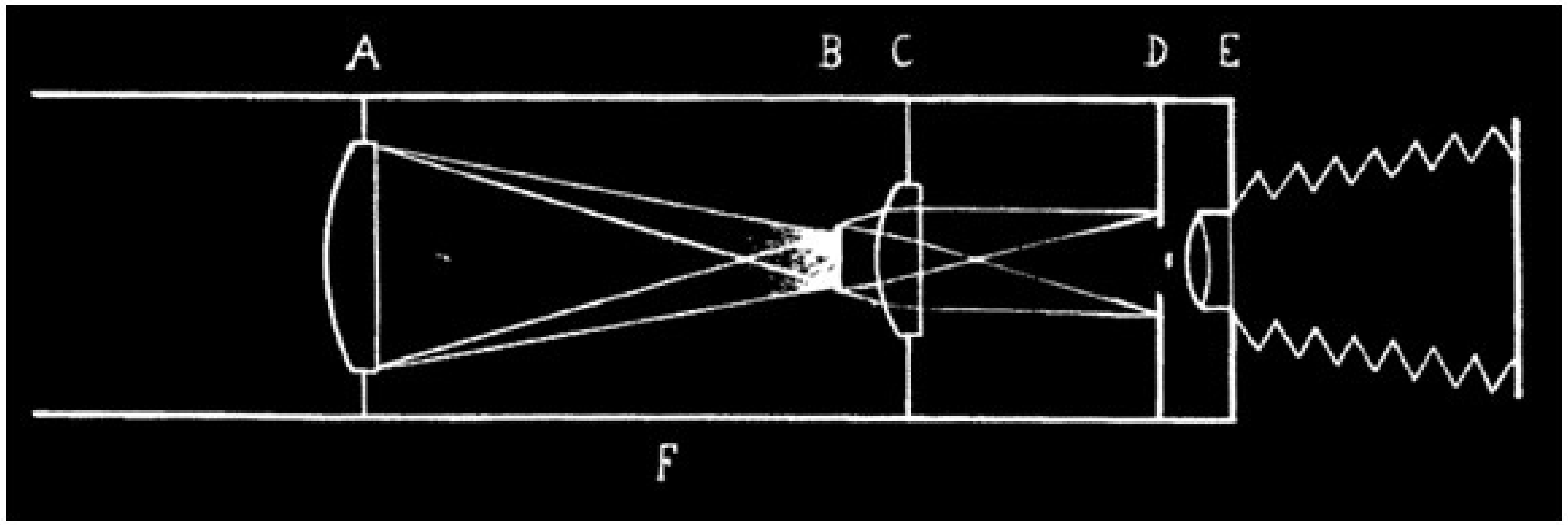
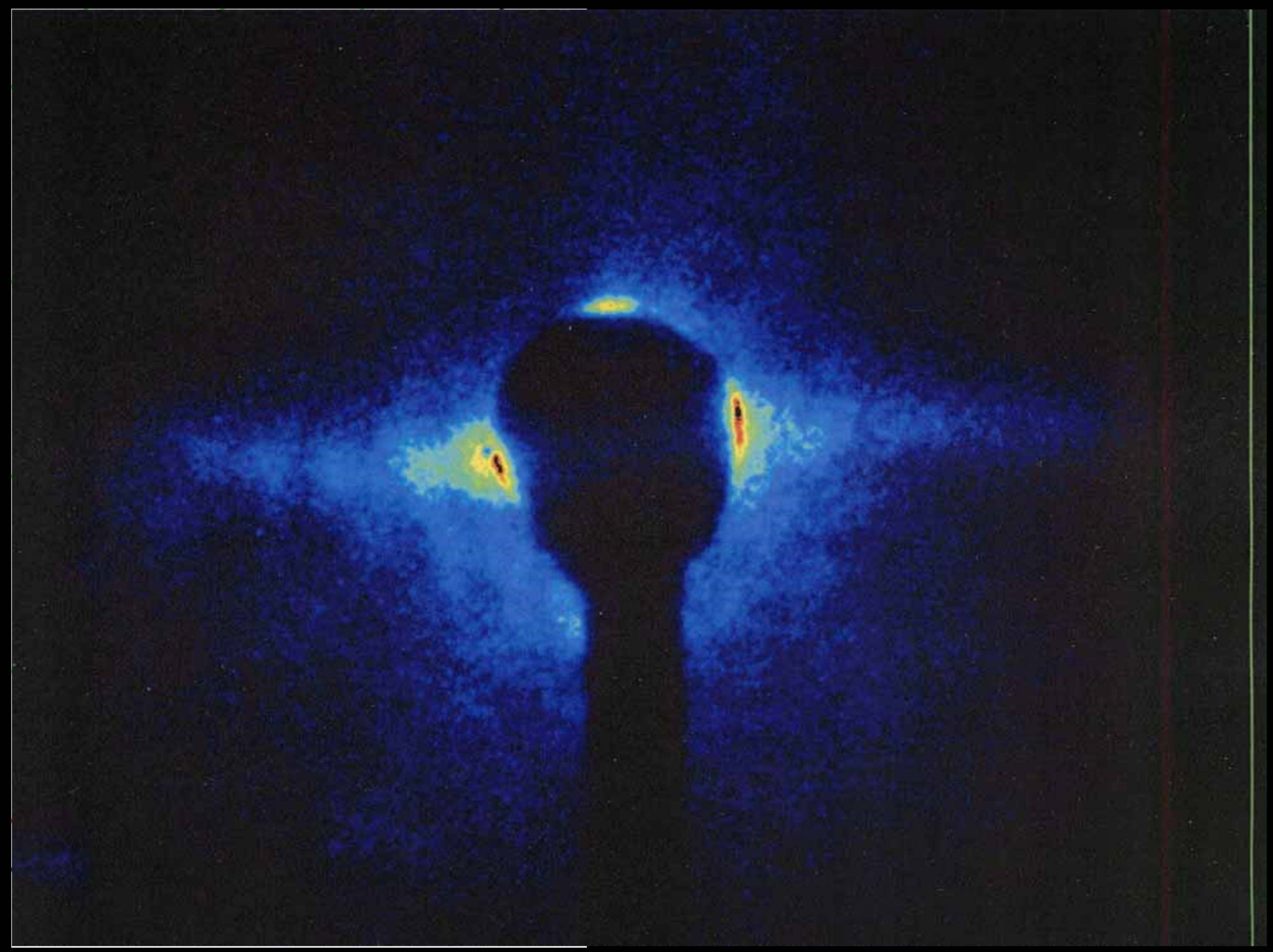
      - Intensity of fringes in range of 10^{-2} to 10^{-3} of peak intensity would mask any halo at 10^{-5} level
    - Reduce effect of diffraction fringes using Coronagraph developed for astronomy
      - At KEK Photon Factory achieved ratio for background to peak intensity of 6×10^{-7}



Lyot's Solar Coronagraph, 1936



Summary

- Beam Dynamics Studies extremely important
  - To push performance of existing machines
  - To understand beam stability issues that arise
  - To study new solutions for future accelerators
- Can only be done through partnership with Beam Instrumentalists
  - Improvements to beam instrumentation has resulted in a better understanding, pushing the accelerator physicist to develop enhanced correction algorithms and simulation tools
- Main Beam Instrumentation Challenges for the Future
  - High resolution, extremely linear, bunch-by-bunch BPM systems
  - Non-invasive beam size measurements
  - High bandwidth detectors for intra-bunch transverse diagnostics
  - High bandwidth readout systems with on-the-fly data processing and reduction
  - High dynamic range beam halo diagnostics
- Much of this talk based on an excellent workshop held last year
  - "Beam Dynamics meets Diagnostics" EuCARD2 Workshop 2015, Florence, Italy.
  - https://indico.gsi.de/conferenceDisplay.py?confId=3509