CI-ACC-212
Beam Diagnostics #3: Longitudinal Measurements

Thomas Pacey | CI Lecture Series

20/03/2023

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Outline

- Longitudinal profile measurements
- Energy & Energy Spectrum measurements
- Summary
- Hands-on with some typical systems

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Summary from Lecture #1

Recap

- There are a lot of properties to measure!
- Bunch is a 6D object, Beams are made of many different bunches

- Somethings are measured - **destructive** or **multi-shot**
- Others can be monitored - **single-shot** *and/or* **non-invasive**

- There is a whole zoo of diagnostic systems and devices
- *Ask what a TLA is and what it does*

- You need a **combination of systems** to operate the accelerator
- Even more systems needed to understand the beam!

- All diagnostics have limits…

Summary From Lecture #2

Recap

- There are many well established off the shelf systems for measuring bunch charge
  - Still have to be setup correctly and calibrated accurately
- Imaging the beam profile is a important for doing accelerator physics
  - Scintillators are a powerful tool to view beam profiles
- Consider the performance of the whole system for imaging
- Chain of physical processes produces the profile and contribute to performance
  - Beam properties, crystal properties, optics properties, camera sensor properties, etc.
- Emittance can be measured by imaging multiple beam(-let) profiles on a screen
  - Appreciate the limitations of the screen system when you measure emittance
- Appreciate the whole system, make sensible choices for the beam you (expect to) have

Any questions from Lecture #2?

Measuring longitudinal profile

How long is the pulse? What does it look like?

Longitudinal Measurements

Overview

- Aiming to measure either σ_t or complete $\rho(t)$
- Making and measuring short pulses important for:
  - Wakefield accelerators
  - FELs
  - Electron diffraction (pump-probe generally)

- (Another) large topic - could be multiple lectures on variety of techniques and their limitations

- Focus on 3 techniques to provide an overview:

1. Using external field to manipulate particles: The TDC
2. Generating radiation from the bunch: CTR based BCM
3. Using beams own field to streak particles: Passive Wakefield Streaker

- Detail is beyond scope of course, focus on key limitations

Transverse Deflecting Cavity

Overview

TDC = **T**ransverse **D**eflecting **C**avity

Single shot destructive measurement of longitudinal profile

RF cavity profiles a longitudinally varying streaking force to beam

Maps longitudinal profile onto spatial coordinate with appropriate beam optics

Can be used to measure longitudinal phase space and slice properties…

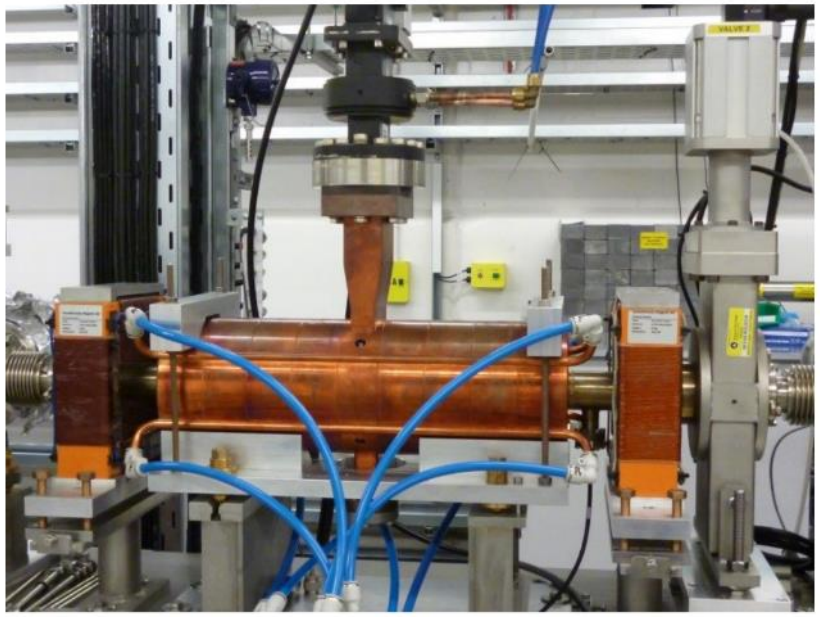


Figure 1: VELA Transverse Deflecting Cavity.

Wheelhouse, A. E., et al. "Commissioning of the Transverse Deflecting Cavity on VELA at Daresbury Laboratory." *Proc. IPAC'15* (2015).

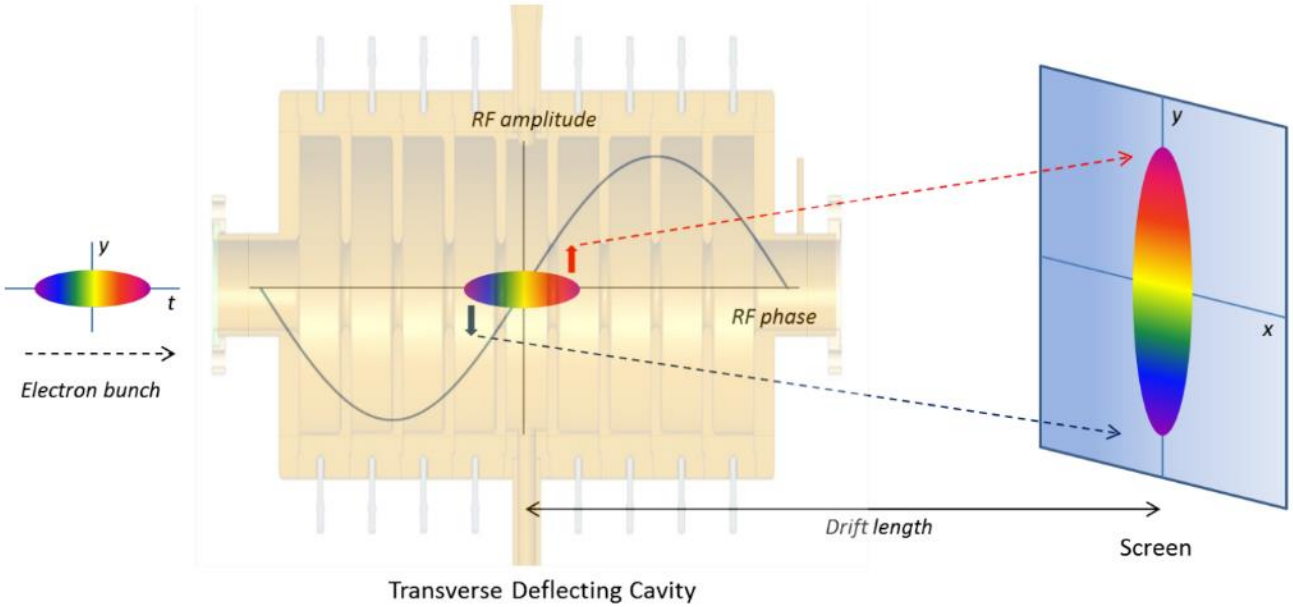
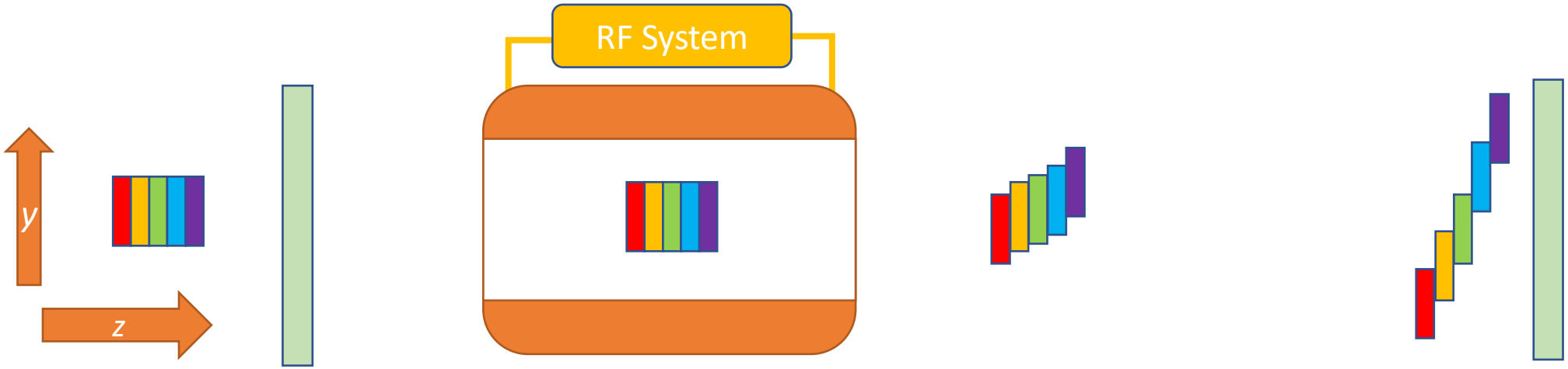
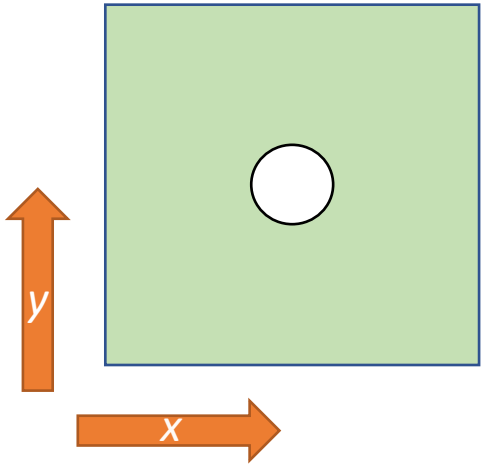


Image: J McKenzie Thesis

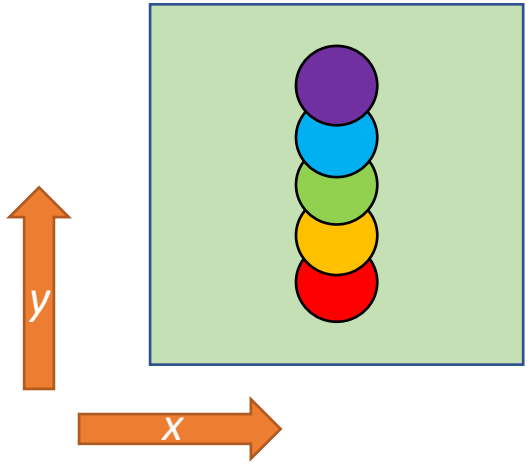
TDC Process Schematic

Simple case





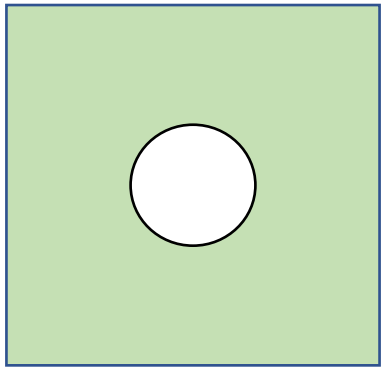
Applying RF field to give a kick which varies in amplitude longitudinally within bunch.
Map kick onto transverse position within bunch.
Transversely image bunch, extract longitudinal information.

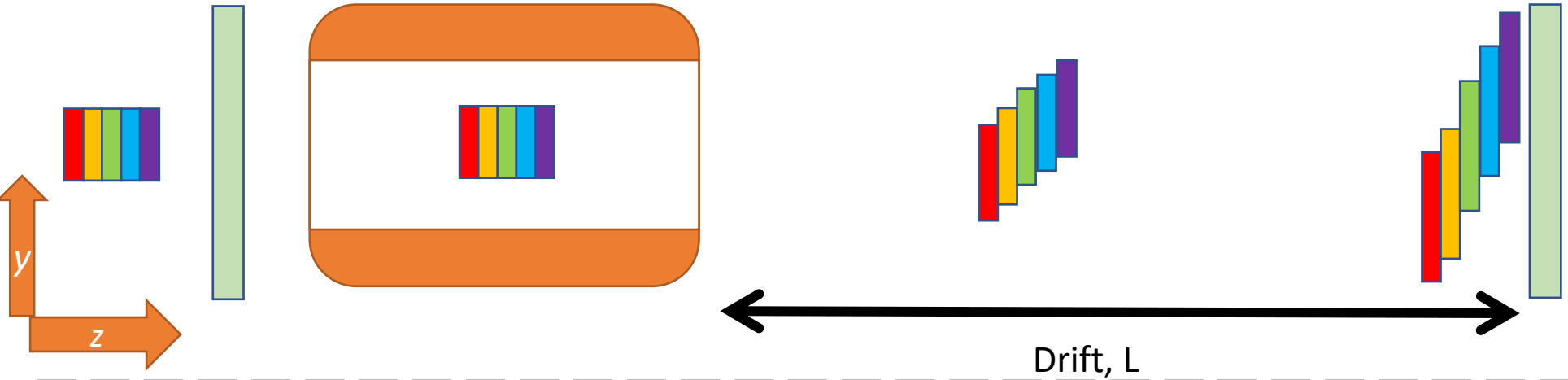


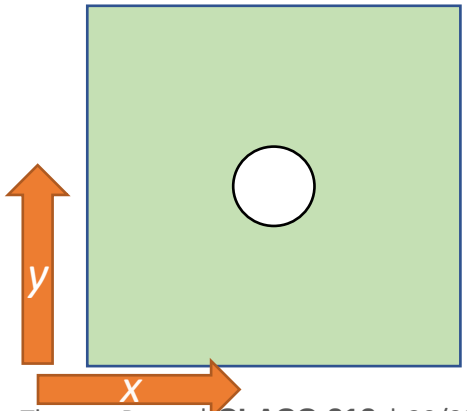
With beam divergence

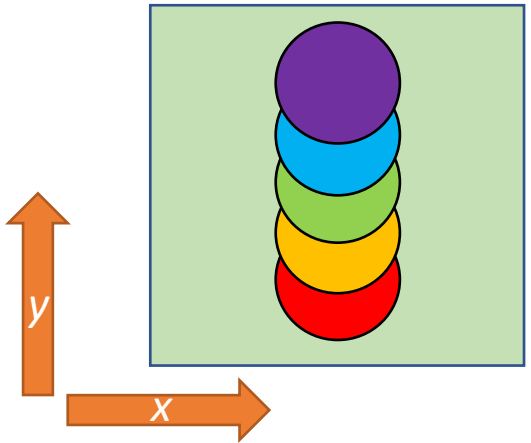
Just drift length

With TDC off, Beam size on screen is given by divergence and drift length







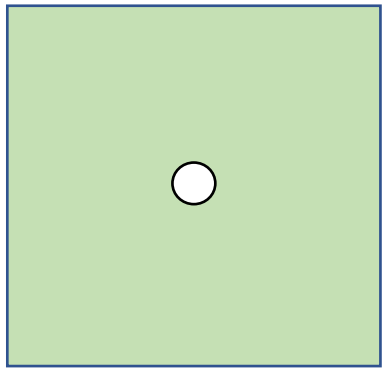


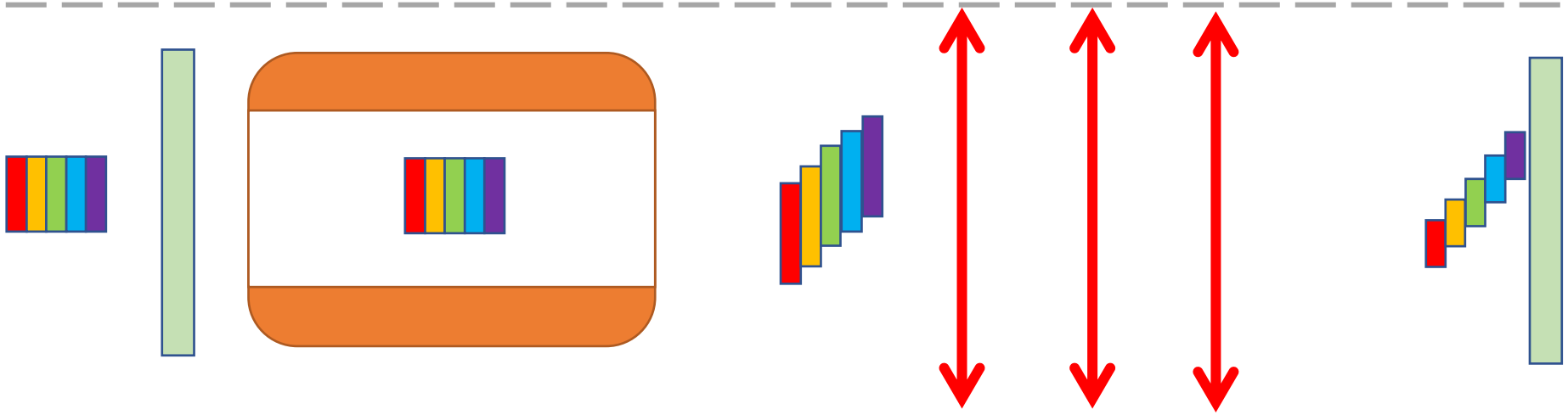
TDC On
Longitudinal slices separated on screen
Each slice has grown through divergence

With additional optics

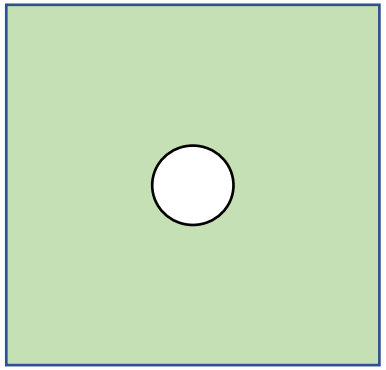
Some quads

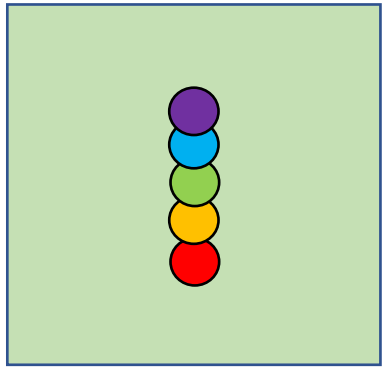
With TDC off, Beam is focussed onto screen 90°w/ phase advance





Array of quadrupoles





Resolution of TDC measurements

What can you improve?

Define longitudinal shear parameter *S* such that

$$S = R_{3,4} \frac{2\,\pi\, f\, e\, V_0}{c^2\, p}$$

f = frequency of TDC, V_0 = voltage ,*p* = momentum, $R_{3,4}$ = transfer matrix element
$R_{3,4}$ = length of drift (*iff no quads*)

Work through to find resolution ,r_t ,for initial (TDC off) beam size $\sigma_{y,0}$ with emittance ϵ_y:

$$r_t = \frac{\sigma_{y,0}}{|S|} \propto \frac{\sqrt{\epsilon_y}\, p}{f\, V_0}$$

- Want 90° betatron phase advance -> map angles to positions
- Want either *correctly tuned* quads or *suitably long* drift
  - Adding 'more drift' (once 90° condition achieved) increases $\sigma_{y,0}$
    - Does not provide resolution increase

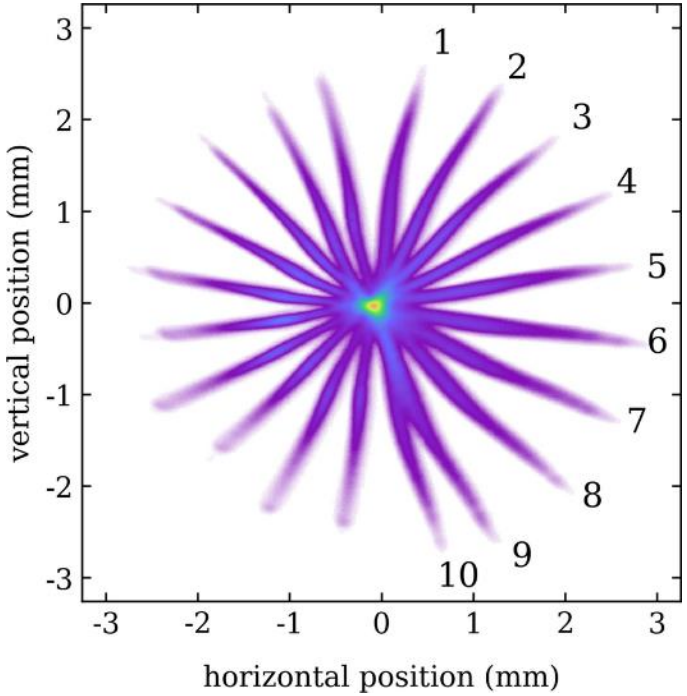
Meaningful resolution improvements: emittance, voltage
Typical fixed variables: momentum, frequency

Important note:
Imaging beam from a screen!
All resolution limits from Lecture #2 also apply!

More information and discussion in: Röhrs, Michael, et al. "Time-resolved electron beam phase space tomography at a soft x-ray free-electron laser." *PRSTAB* 12.5 (2009): 050704.

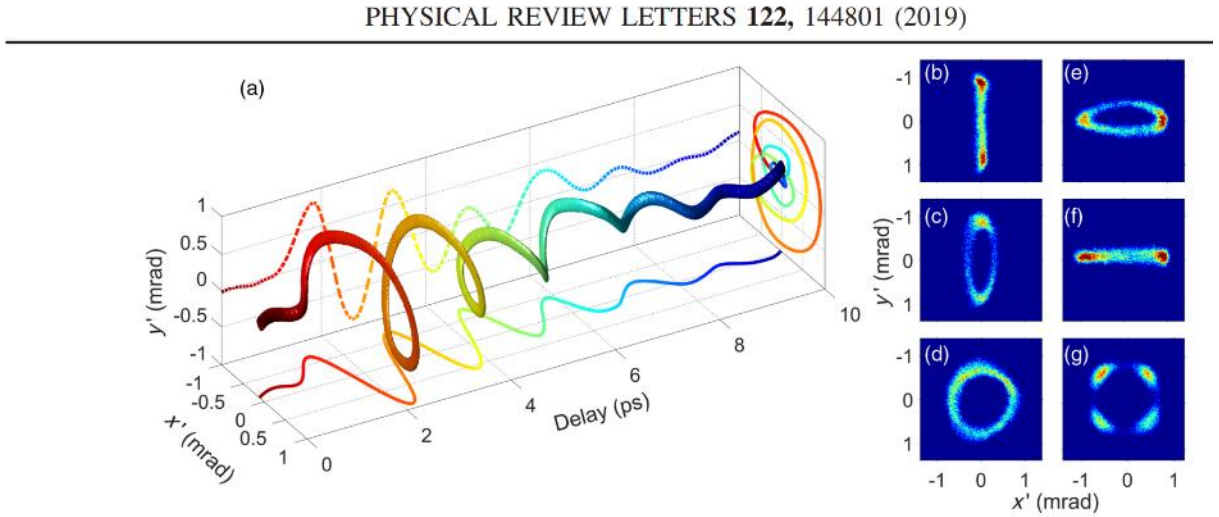
Advanced techniques

Cutting edge schemes



DESY variable polarisation X band TDC PolariX: Produces *ρ(x,y,t)*

Marchetti, Barbara, et al. "Experimental demonstration of novel beam characterization using a polarizable X-band transverse deflection structure." *Scientific reports* 11.1 (2021): 3560.



Zhao, Lingrong, et al. "Terahertz oscilloscope for recording time information of ultrashort electron beams." *Physical review letters* 122.14 (2019): 144801.

Shanghai University circularly polarised THz streaker: Broadband bunch length and timing measurements for UED

Shanghai university THz slit system: Ultrashort bunch length and timing measurements for UED

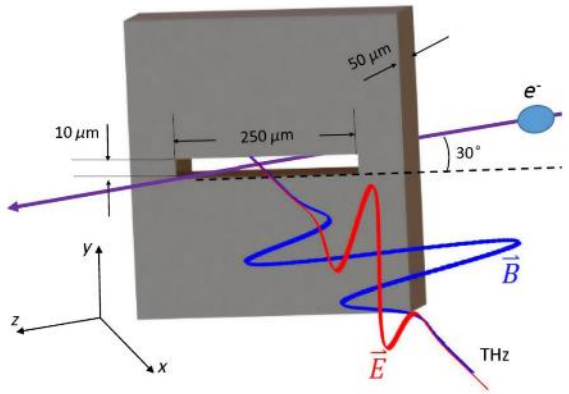


FIG. 2. Schematic of the THz-electron interaction at the narrow slit.

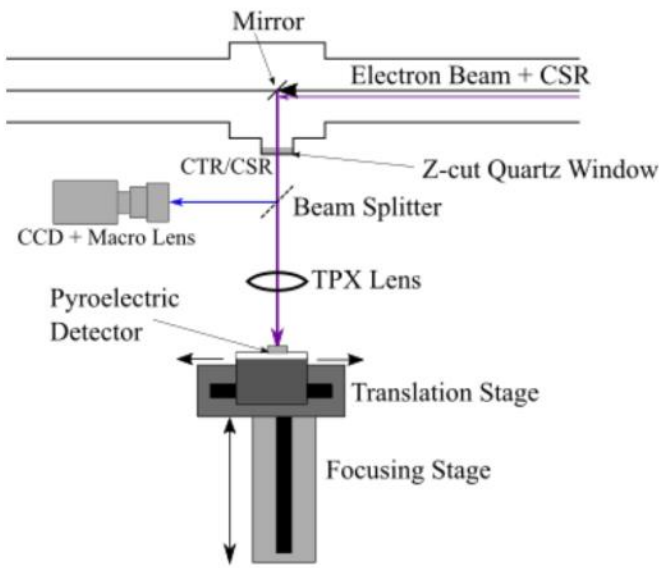
Zhao, Lingrong, et al. "Terahertz streaking of few-femtosecond relativistic electron beams." *Physical Review X* 8.2 (2018): 021061.

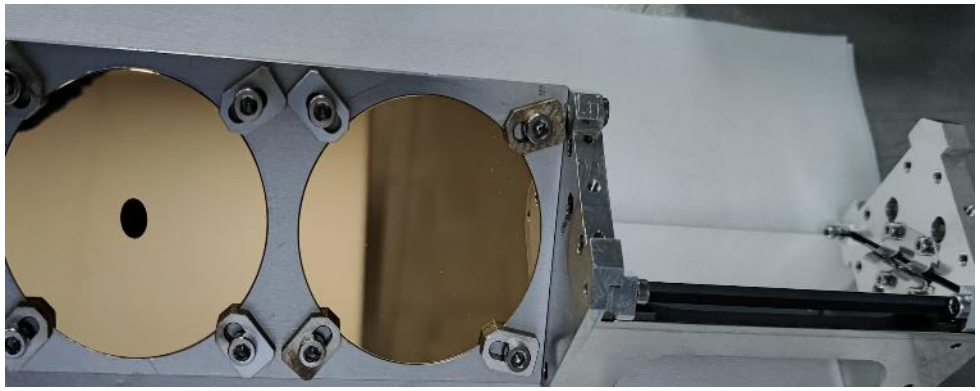
Coherent Transition Radiation BCM

Overview

BCM = **B**unch **C**ompression **M**onitor
Single-shot monitor for bunch length
Detects intensity of coherent radiation emitted by bunch
Shorter bunches -> higher intensity of radiation

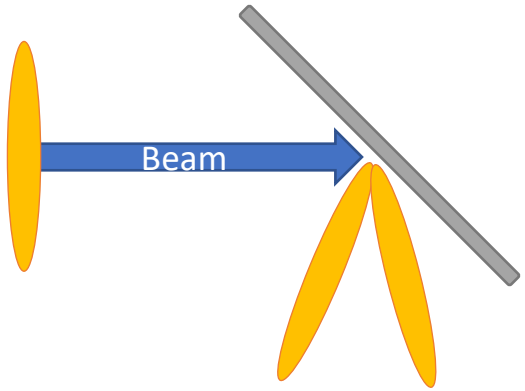
CTR BCM = **C**oherent **T**ransition **R**adiation **BCM**
Single-shot destructive monitor for bunch length
Detects coherent radiation emitted as beam goes through metal target





CTR Bunch length information

Subtitle



Broadband TR lobes from a single electron

- Coherent enhancement occurs when we have multiple emitters in phase
- For a bunch with *N* particles:

$$\frac{dI(\omega)}{d\omega} = \frac{dI_1(\omega)}{d\omega}\left[(N + N(N-1)|F(\omega)|^2\right]$$

Spectral intensity

Single particle spectrum (target properties, particle energy etc.)

Coherent enhancement with N^2

Form factor: Fourier transform of longitudinal profile

Bunch emits radiation with a spectrum depending on bunch profile. Transport the radiation, measure the spectrum, extract bunch profile.

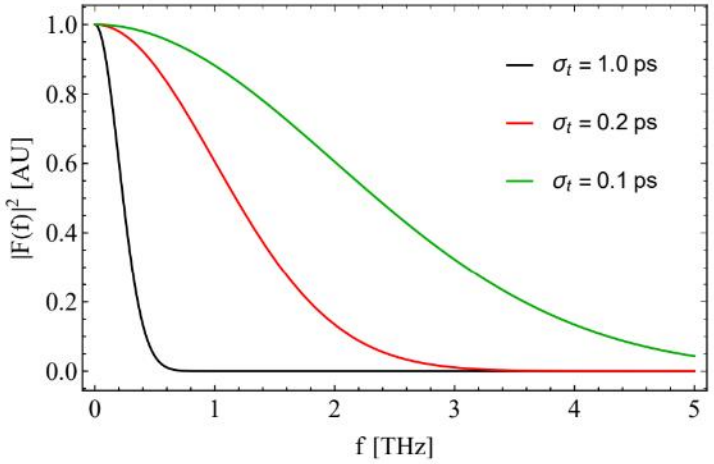


Figure 6.14: Variation of a Gaussian bunch form factors - $F(f) = \exp[-(2\pi f)^2\sigma_t^2]$ - with RMS bunch length.

CTR measurement schemes

Generally applicable to other 'beam generating THz' diagnostics

- Highly compact (low footprint) longitudinal diagnostic
- For picosecond and below electron beams: working in THz – far IR regime
- Challenges: Optics, detectors, alignment, signal levels, vacuum windows…

- Three potential options for measurement:

1. Capture intensity of CTR emitted -> single shot, more CTR, shorter bunches…
   - Pros: Straightforward, low cost, single shot
   - Cons: limited information, prone to errors

2. Use an interferometer to measure CTR spectrum
   - Pros: Off shelf optics, well developed in spectral range of interest, can maintain broadband response
   - Cons: Multi-shot limitation, time consuming, transport & alignment non-trivial

3. Directly measure spectrum of CTR in single shot spectrometer
   - Pros: High quality information, single shot
   - Cons: High cost, custom components needed, developing broadband difficult, fine spectral resolution difficult

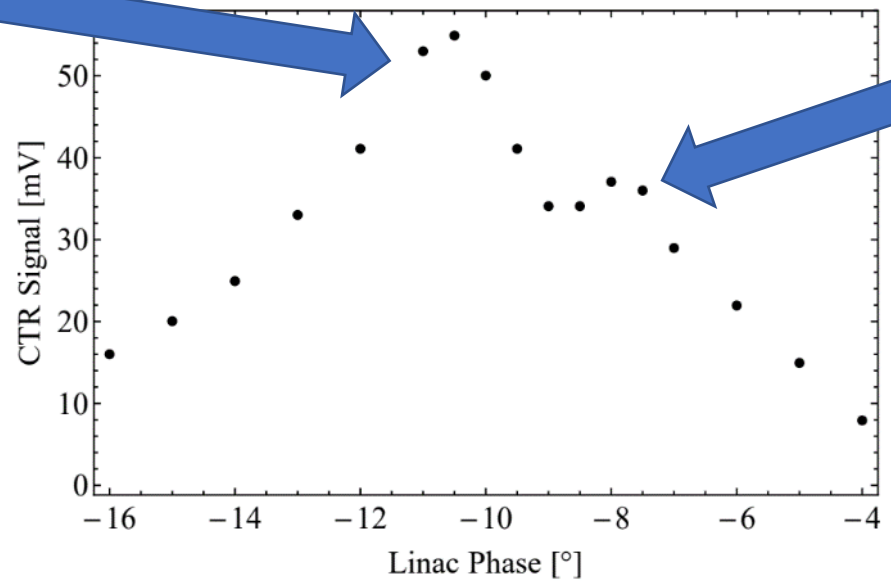
Other techniques are possible, beyond scope here

Real beams – Intensity Measurements

Limitations of simple techniques

- Real beams aren't Gaussian
- Variation of Form Factor with 'compression' isn't straightforward
- Even in simulation can develop 'high frequency' features

Over-compression:
Enhances high frequency features
High frequency features transported with reduced losses.
More CTR detected even though bunch is longer



Maximum compression (Bunch length RMS & FWHM shortest)

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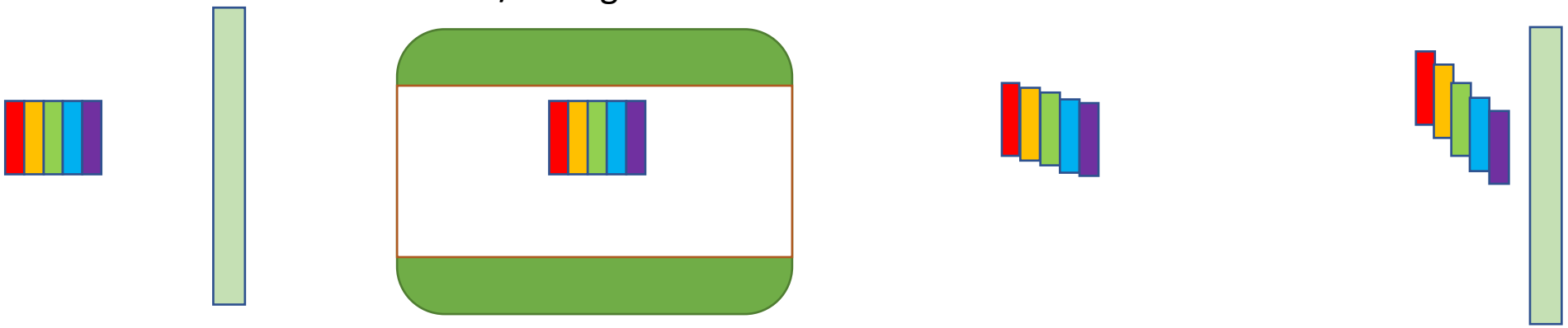
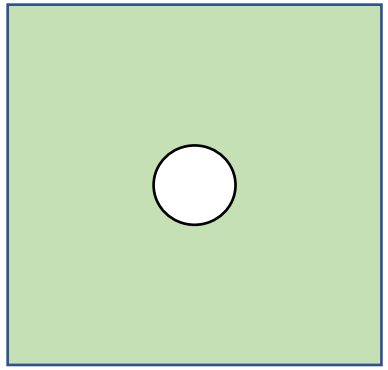
Passive Wakefield Streaking

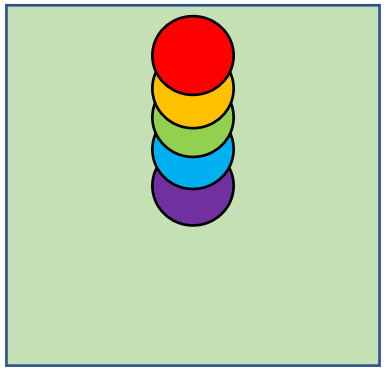
Hybrid technique - beams own field kicks particles

Dielectric/corrugated structure





Beam generates a streaking wakefield.
Head of the beam kicks the tail.
Map kick onto transverse position within bunch.
Transversely image bunch, extract longitudinal information.



Passive Streaking

Pros and Cons

Pros

- Single shot
- Fully passive – no power needed
- Self-Synchronised – timing jitter does not impact resolution
- Generates high fields for short pulses
- Cheap structures
- Dielectric wakefields supported up to >MV/m level
- Small total footprint, no RF, no lasers

Cons

- Requires sufficient charge for a given momentum (to get kick angle high enough)
- Non-linear wakefields have to be considered
- Reconstruction of profile non-trivial
- Requires on-shot charge measurement for accuracy
- Resolution of measurement varies with bunch length
- Resolution of measurement varies *along bunch*, poor at head
- Relatively novel technique, still optimising schemes

Break

Questions?

Measuring Energy Spectrum

What is the beam energy? What is the spectrum?

Overview – Measuring Energy & Energy Spread

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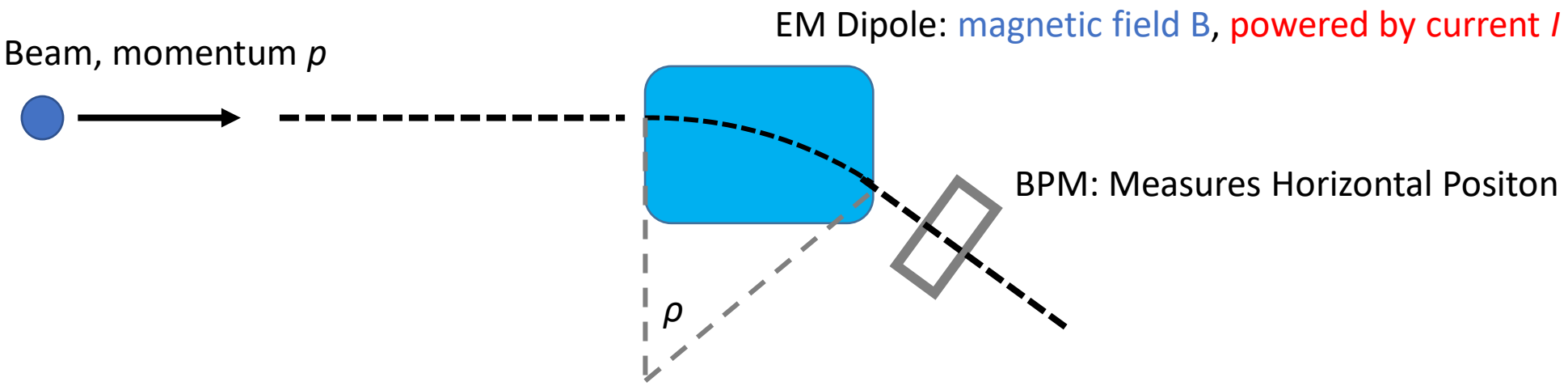
- Aiming to measure $<p_z>$ or complete $\rho(p_z)$
- Describing components needed and the beam dynamics process
- Indicative/instructive example based on ‘imagined beamline’
  - Other experimental techniques possible
- Identify error sources, add systems to correct what we can
- Other equivalent lattices for measuring momentum
- Procedure matters

All schematic/sketch diagrams, all first order considerations.

Bending with a EM dipole

Simplest case



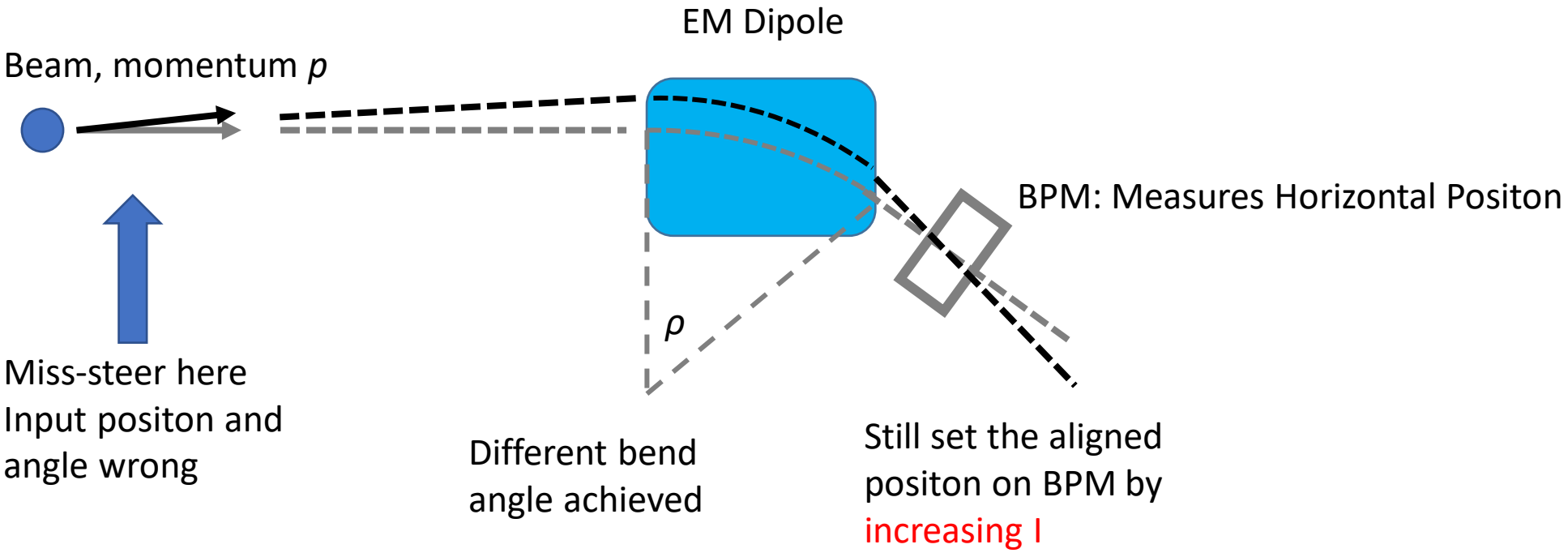
$$\rho \approx \frac{p_0}{eB}$$

$$B\rho\ [Tm] \approx 3.3356\, p_0\ [\text{GeV/c}]$$

- ρ is a fixed property of lattice;
  - dipole bends so many degrees to get beam into centre of pipe
- Zero position of BPM tells when on axis
- **Procedure to find p_0:**
  - Find current I such that beam is central on BPM
  - Infer B from I, or have direct B measurement
  - Momentum is calculated directly

Bending with a EM dipole

Sources of errors #1

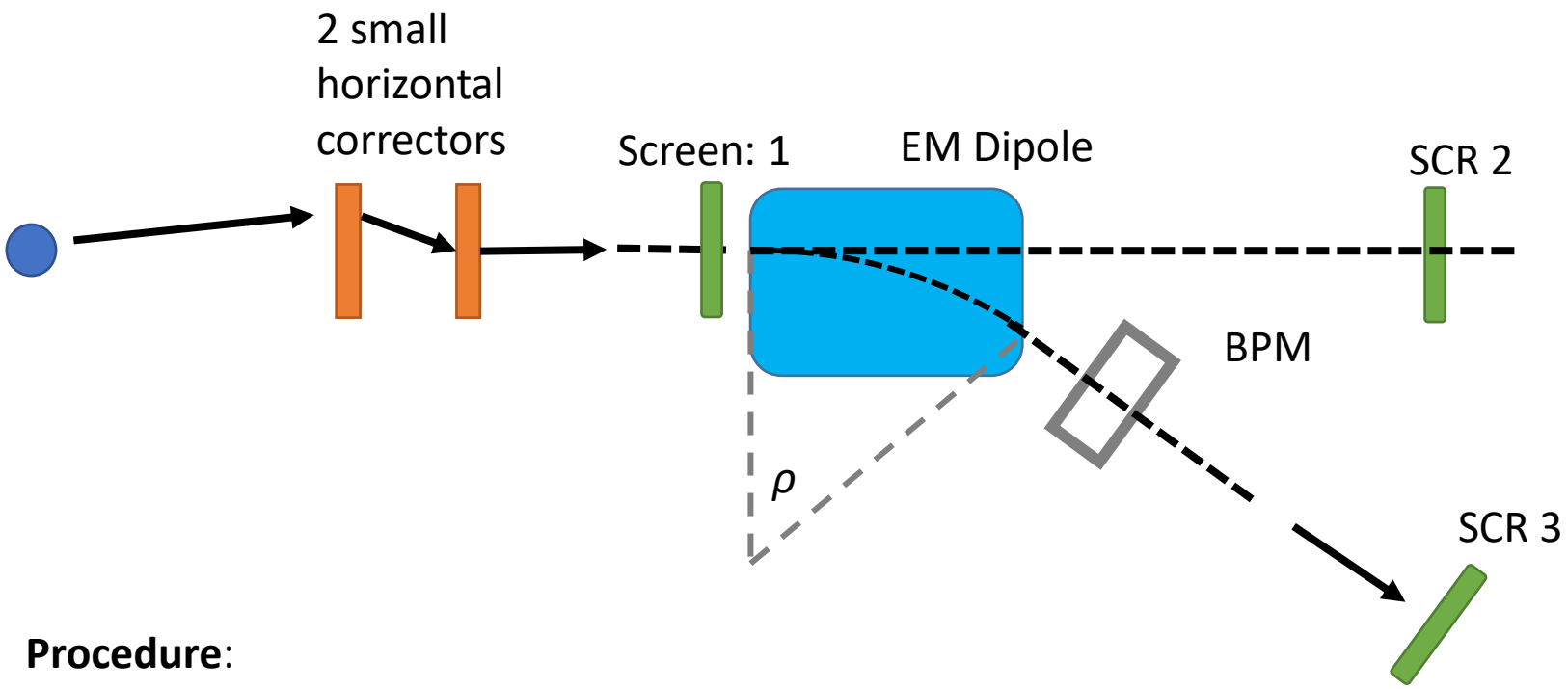


No longer know ρ

Inaccurately measure momentum!

Aligning into spectrometer

Fixing steering & offset errors



- **Procedure**:
- Set dipole off
- Using correctors, align beam onto SC1 and SC2
- Set dipole on, repeat p_0 procedure:
  - Find current *I* such that beam is central on BPM & on SCR3 (cross check)
  - Infer *B* from *I*, or have direct *B* measurement
  - Momentum is calculated directly

Bending with EM Dipole

More important error sources

- Procedure requires switching dipole ‘On’ and ‘Off’

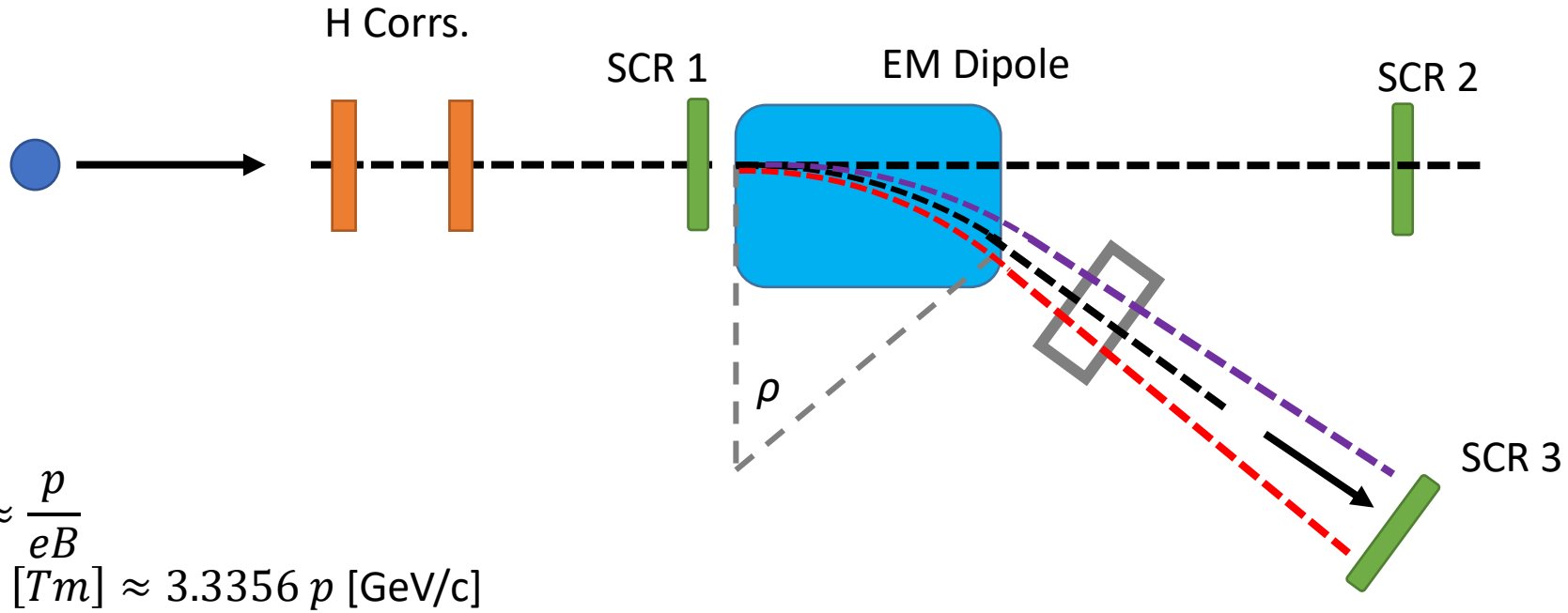
- If just controlling coil current I -> will create remnant field in poles
  - Setting current to 0 and beam still bends!

- For a given current, no longer know the true B field
- Produces inaccurate momentum measurement
- **Must degauss dipoles** (requires polarity reverse of power supply)

- Also note:
  - BPM & dipole power supply sets precision of measurement
  - BPM ‘zero position’ calibration contributes to accuracy
    - How well the BPM system ‘knows its centre’
  - Survey tolerances - mechanical accuracy of beamline – contributes to accuracy
    - How well the BPM centre is positioned in the beamline
    - How well the screen centres are aligned, SCR1 and SCR2

Measuring energy spectrum #1

Separating the energies



Understand your screen coordinates.
Lower energy particles are bent more by dipoles.

$$\rho \approx \frac{p}{eB}$$

$$B\rho\ [Tm] \approx 3.3356\ p\ [\text{GeV/c}]$$

Dipole generates dispersion, D_x

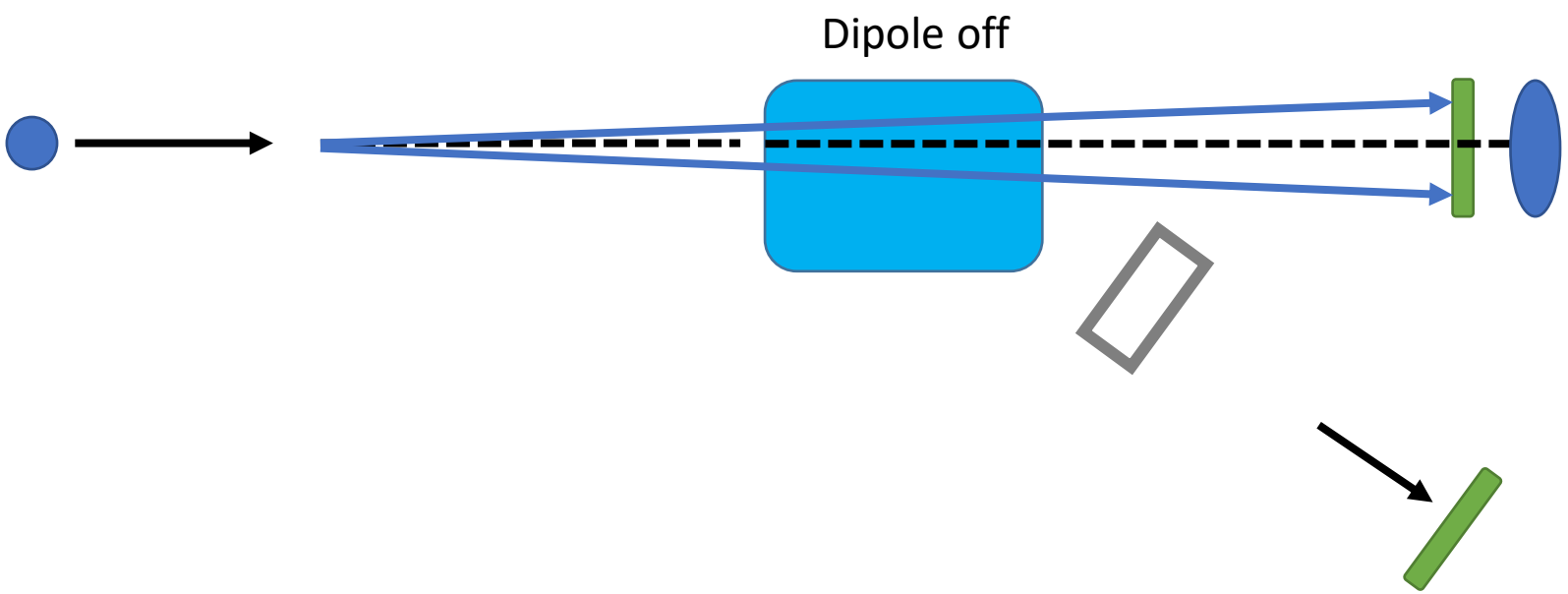
$$\Delta x = D_x \frac{\Delta p}{p_0}$$

- **Procedure**:
- Setup as in momentum measurement to evaluate p_0
- Measure distribution of particles on screen
- Find D_x at screen (measured or inferred)
- With a calibrated screen image map positions to momentum variation

Dx can be found through variation of <x> with B

Measuring energy spectrum #2

Vital transverse dynamics

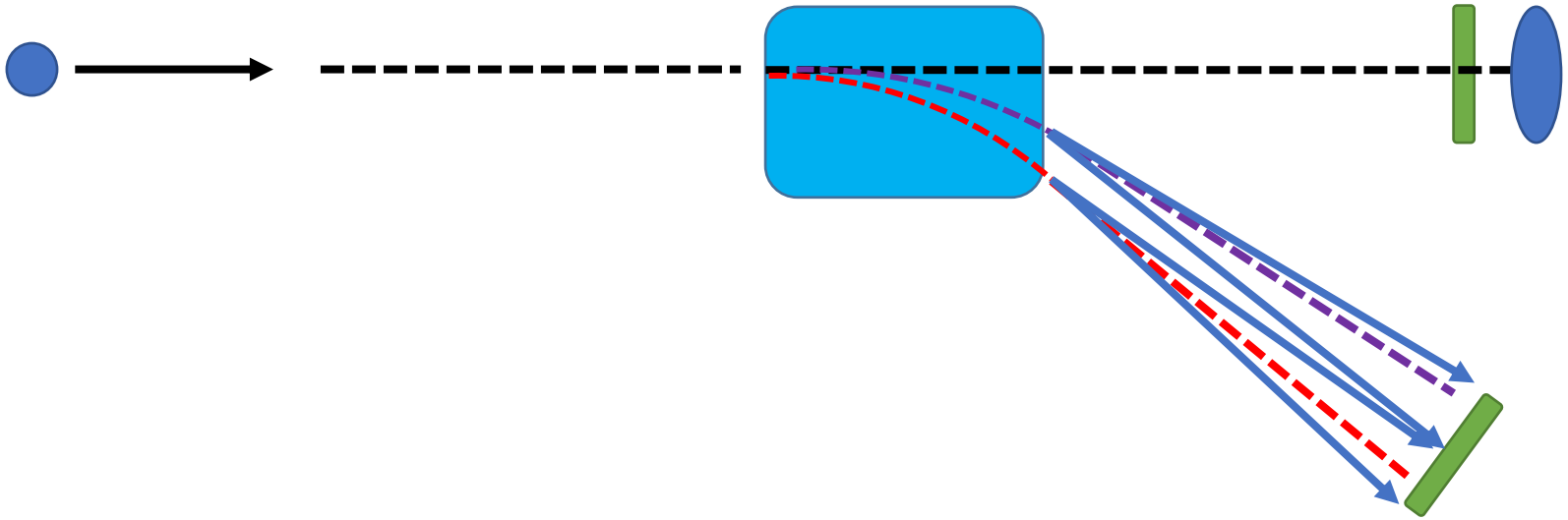


- In the absence of the dipole, the beam size changes
- Can diverge or converge. Will be different in both planes
- Size depends on emittance and beta function

- Obvious statements -> impacts the spectrum measurement!

Measuring energy spectrum #2

Vital transverse dynamics



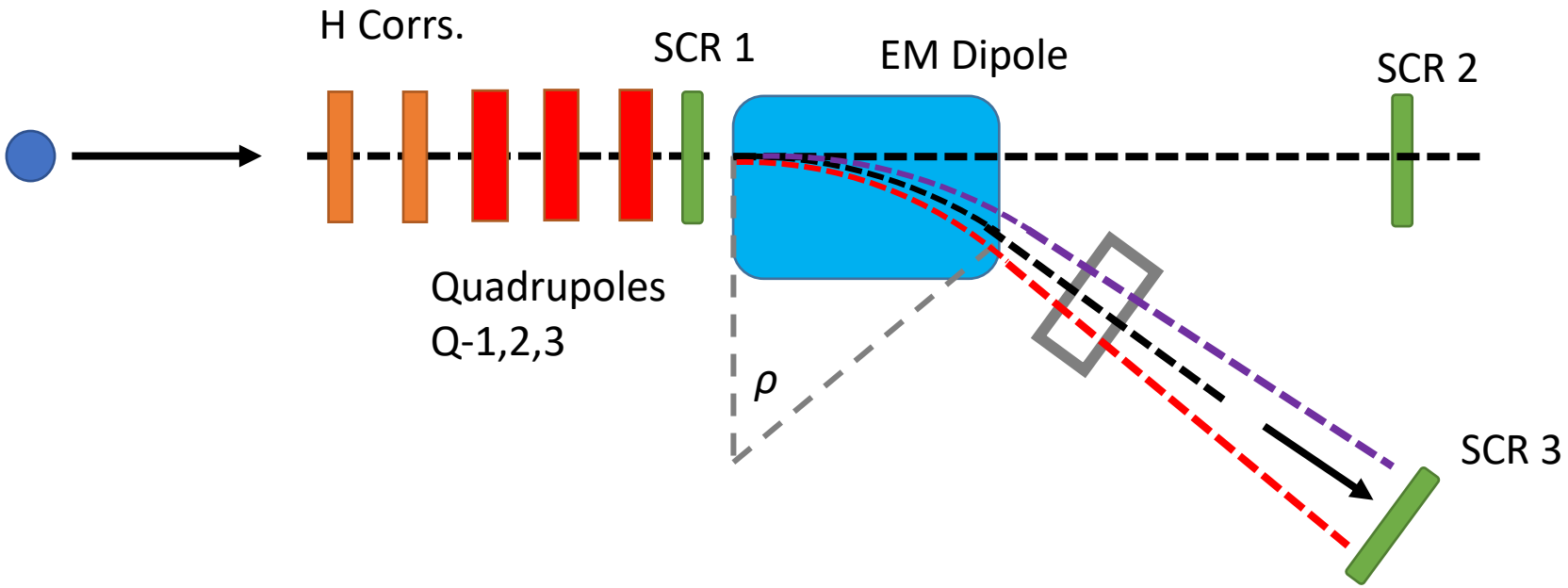
With the dipole on, particle location at screen depends on both Dispersion and Beta function

$$\sigma_x = D_x \frac{\sigma_p}{p_0} + \sqrt{\epsilon_x \beta_x}$$

To get a momentum spectrum must minimise β_x so that dispersion dominates the image

Measuring energy spectrum #2

Vital transverse dynamics

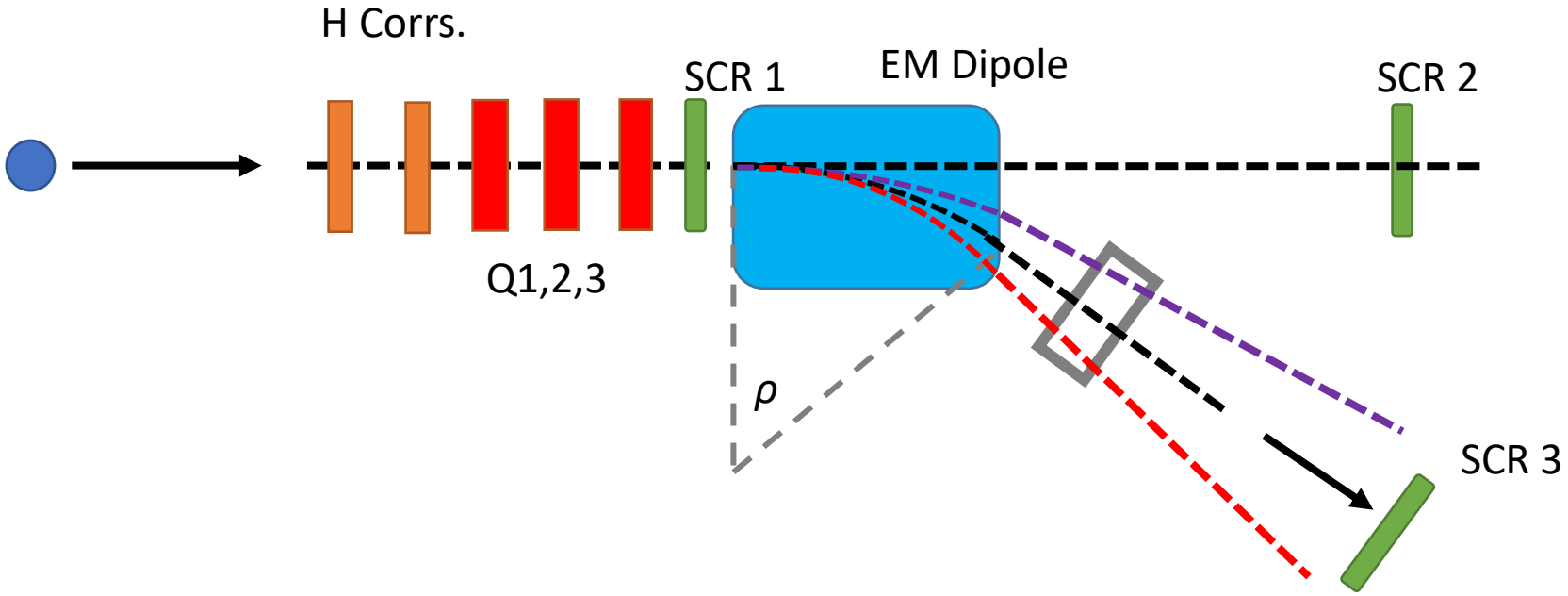


Can switch off EM dipole and focus onto SCR2 *as a starting point*
Requires matching *s* position in lattice
Some (sector) dipoles will also focus

- **Procedure**:
- Setup as in momentum measurement to evaluate p_0
- Use quads Q-1,2,3 to reduce horizontal beam size on SCR3
- Finding minimal beam size sets small β_x
  - Be mindful of introducing offsets, may need to iterate p_0 procedure
- Maintain control of vertical beamsize
- Now record measurements of momentum spectrum

Measuring energy spectrum #3

Dealing with large energy spread



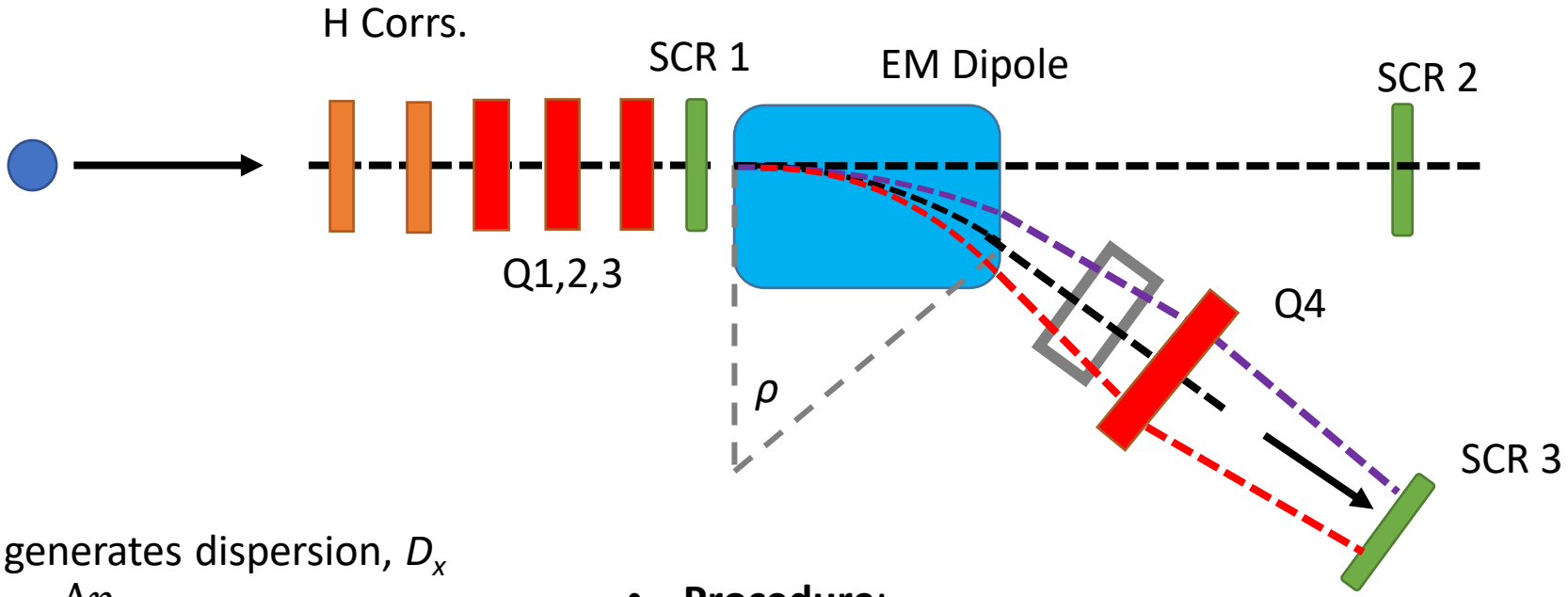
Dipole generates dispersion, D_x

$$\Delta x = D_x \frac{\Delta p}{p_0}$$

For large momentum spread, particles may not make it to screen.
Screen is at a fixed location and with a fixed size!

Measuring energy spectrum #3

Dealing with large energy spread



Q4 also changes β_x !!
If you touch it: repeat procedure.
If you change dipole: repeat procedure.
Be careful, keep track of procedures, iterate as needed.

Dipole generates dispersion, D_x

$$\Delta x = D_x \frac{\Delta p}{p_0}$$

Quad Q4 modifies D_x *at SCR3* so that Whole spectrum Δp fits within screen Δx

- **Procedure**:
- Setup as in momentum measurement to evaluate p_0
- Use quads Q4 to fit spectrum onto SCR3
- Measure D_x
- Repeat β_x minimisation procedure
- Collect energy spectra

Dx can be found through variation of <x> with B

Measuring energy spectrum #3

Dealing with large energy spread

Do not forget you are measuring a beam on a screen!

You are also limited by:

- Scintillator properties
- Imaging resolution
- Camera properties
- And the rest…

epeat

of

Dipole

$\Delta x = D$

Quad Q4 modifies D_x *at SCR3* so that Whole spectrum Δp fits within screen Δx

- Use quads Q4 to fit spectrum onto SCR3
- Measure D_x
- Repeat β_x minimisation procedure
- Collect energy spectra

Dx can be found through variation of <x> with B

Summary

Take homes

- Longitudinal profiles can be measured by
  - Kicking the particles with a TDC
  - Measuring spectrum of coherent radiation produced from the beam
  - Generating a wakefield to passively streak the beam
- Resolution of each method is affected by different bunch and diagnostic parameters
- Appropriate technique for each machine is a function of:
  - Control/flexibility of beam parameters, available space in lattice, money, and expertise
- Measuring momentum of particles requires several diagnostics to produce accurate results
- Measuring energy spectrum of particles requires a detailed procedure for precise and accurate results

Resources

References & links for images and further reading

Science and Technology Facilities Council

- DESY TDC measurements, longitudinal & LPS
  - https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.12.050704
- Theory of TR and CTR
  - https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.11.012801
- Variable Polarisation TDC
  - https://www.nature.com/articles/s41598-021-82687-2#article-info
- CLARA Front End Review (BCM measurements)
  - https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.23.044801
- J McKenzie thesis - VELA TDC measurements:
  - https://livrepository.liverpool.ac.uk/3031981/
- VELA TDC Commissioning – IPAC15
  - https://accelconf.web.cern.ch/ipac2015/papers/wepha054.pdf
- THz Slit streaker
  - https://journals.aps.org/prx/pdf/10.1103/PhysRevX.8.021061
- THz oscilloscope
  - https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.144801