CI-ACC-212
Beam Diagnostics #1: Introduction to measuring beams

Thomas Pacey | CI Lecture Series

06/03/2023

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Introductions & Course Structure

Housekeeping & Zoom

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I will do my best to lecture hybrid, expect some teething problems

Please use raise hand and/or chat function to get my attention on zoom!
(Shout if I miss you out)

Find me in person or by email for questions after ☺

3 lectures, Monday 6th , 13th , 20th March ‘23, 2pm.
Slides on Indico.
Aiming 50mins/lecture. Short break at 25min mark.

There are no assessments/homeworks/exercises for this course ☺

Please ask questions, there are no silly questions!

Who Am I?

Background

- **2015** – Completed MPhys, University Manchester
- Started at CI, PhD on 'Novel Acceleration' (DWA)

- **2019** – Finished my PhD in Accelerator Physics
- Supervised by Yuri Saveliev (ADI group leader)
- Performed 2 experiments at CLARA in 2018
  - Generating THz, measuring beam energy modulation

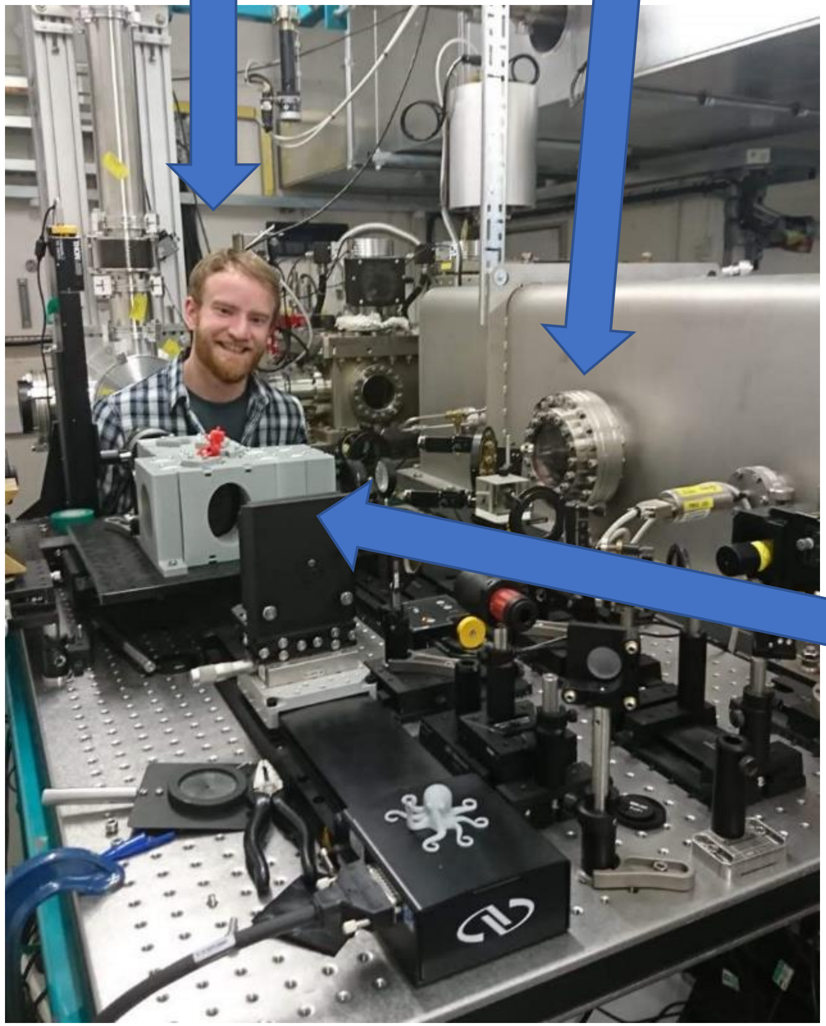
- **Jan 2019 –** Joined STFC in ASTeC's ADI group

I work on CLARA, BA1, FEBE instrumentation
Making novel transverse and longitudinal measurements
Supporting user experiments 2019-2023

Novel acceleration experiments require novel diagnostics!

Me

CLARA BA1



Martin-Puplett Interferometer Measures <1ps bunch lengths using THz radiation…

Who are you?

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What projects are being done?

Who is working on…

- Beam dynamics?
- Storage rings?
- FELs?
- Ion beams?
- Novel acceleration?
- Vacuum systems?
- RF systems?
- Magnet systems?

- Diagnostics?

- Anything else?

Course Structure

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Aim to give an overview of the complex topic of beam diagnostics and instrumentation
Focus on linear, relativistic, electron beam machines
(based off my experience on CLARA)

Focus on practical aspects of making measurements

First run of this version, feedback welcomed!
Future versions may include ion beams and storage rings…

- Lecture #1 : Introduction to measuring beams
  - What am I trying to measure? How can I measure it?
- Lecture #2 : Measuring bunch charge and transverse properties
  - How much beam do I have? Where is it going? How is the shape changing?
- Lecture #3 : Longitudinal beam measurements
  - What is the beam energy? How short is the pulse?

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Outline

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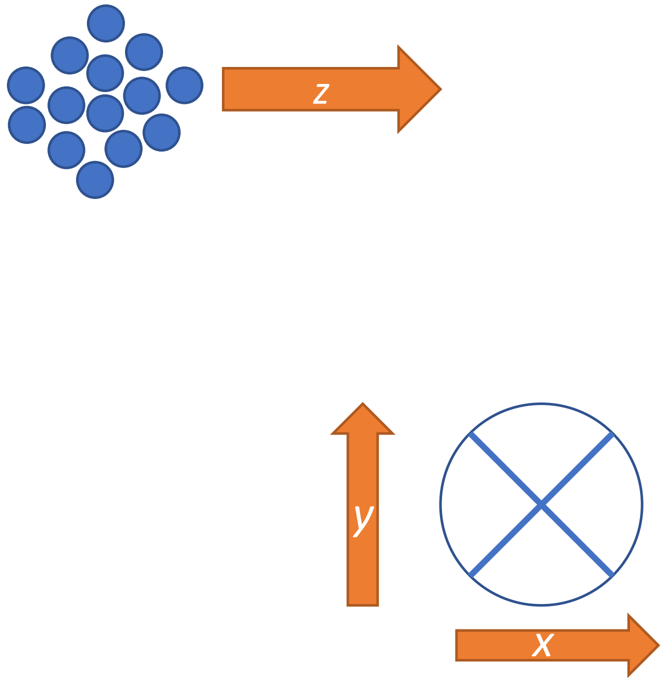
- **Properties of beams we want to measure**
- ***Destructive vs Non-invasive* and *Measuring vs monitoring***
- **Common diagnostic systems *and their acronyms***
- **Summary**

Properties of beams we want to measure

This may seem abstract, but we will refer back in later lectures

A beam & A coordinate system

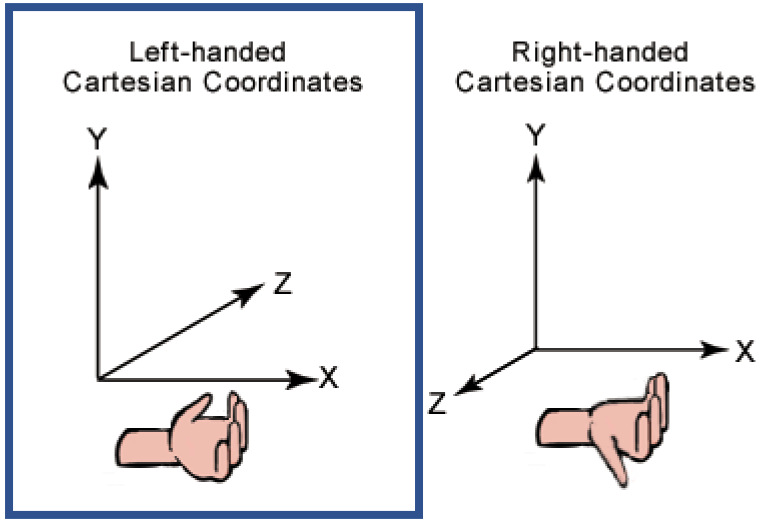
Our ‘operational’ or ‘natural’ coordinate system



Beam into page

Fun fact

This means *formally* our natural operational coordinate system is left handed



Not very important

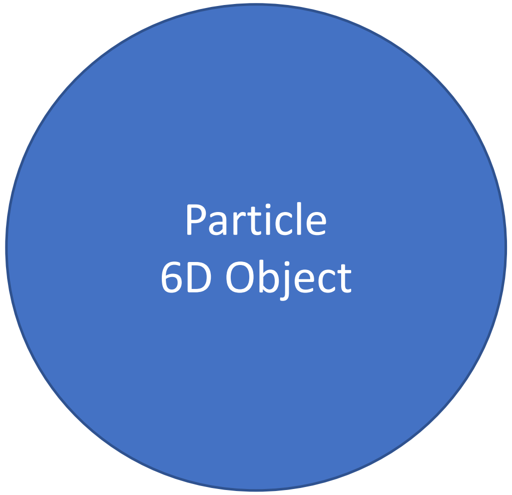
Unless comparing some simulations with measurements

Or drawing a diagram

Always know how you expect diagnostics to perform.

Which way have I bent the beam? Where should it go on a screen?

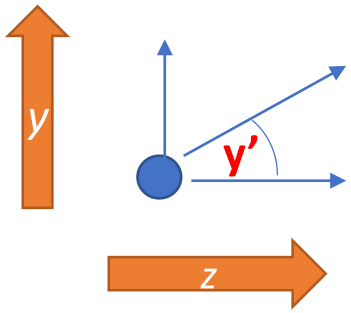
Particle properties



Our 'particle' has a charge *q* & 6 degrees of freedom

1. Horizontal position - x
2. Horizontal divergence - x' *(/momentum - p_x)*
3. Vertical position - y
4. Vertical divergence – y' *(/momentum - p_y)*
5. Longitudinal momentum - p_z *(/ energy E)*
6. Longitudinal position - z *(/ timing t)*

Approx. for divergences:



$$p_z \gg p_y$$
$$y' = \frac{p_y}{p_z}$$

Relativistic approx. for timings vs z

$$z = \beta c t$$
$$\beta \approx 1$$
$$z = ct$$

Useful for comparing particles within a 'bunch'
Often see liberal switching between bunch lengths in *z* or *t*
When working with simulations
Be wary of switching and keep track of head and tail of bunch

Bunch properties

Bunch is a population of particles

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Our bunch has a 6D phase space made up of *N* particles.
There are **<u>many</u>** interesting *projections and correlations*

These are *common properties* we want *to measure*

1. Horizontal position - $\langle x \rangle$
2. Horizontal propagation angle - $\langle x' \rangle$
3. Vertical position - $\langle y \rangle$
4. Vertical propagation angle - $\langle y' \rangle$

Where is the beam?
Where is it going?

5. Horizontal beam size - σ_x
6. Horizontal beam divergence – $\sigma_{x'}$
7. Vertical beam size - σ_y
8. Vertical beam divergence – $\sigma_{y'}$

What is the beam size?
How is it changing?

9. Horizontal RMS emittance – ε_x
10. Vertical RMS emittance – ε_y

What is the transverse beam quality?

11. Momentum/Energy - $\langle p_z \rangle$
12. RMS Energy spread - σ_{pz}
13. Bunch length - σ_t

What is the bunch energy?
How long is the pulse?

14. Charge - *Nq*

How much have I got?

Aside on bunch properties & statistics

We could go on and on

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There are **many ways** to describe a statistical distribution of points in 1D, 2D…etc.
For example *'beam size'*:
Standard Deviation is common in acceleration physics: see Gaussian beams and Twiss parameters ☺
but see also FWHM, $1/e^2$, D4σ … etc. (e.g. laser physics)

$$< u > = \frac{1}{N}\sum_{i}^{N} u_i$$

Know what you have measured and communicate this clearly!

Use appropriate metrics for your data – more in Lecture #2

$$\sigma_u^2 = \frac{1}{N}\sum_{i}^{N} (u_i - < u >)^2$$

Sometimes we divide our beam down into sub-samples
Longitudinally typically we call this 'slices' - > Slice energy spread, slice emittances, slice Twiss values

Transversely we typically call this core and halo -> 'core beam size', 'core charge'

Sub-samples typically have different properties to the whole beam
A lot of applications (e.g. FEL) care about properties of the sub-samples (e.g. slices)
Important to be able to measure sub-samples, but also difficult!

Aside on measuring a ‘profile’

Going on a little more

Multi-shot tomographic techniques

1D Profile: measuring *u* as a function of *charge density* ρ

e.g Longitudinal profile = $\rho(t)$

2D profile: measuring u_1 , u_2 as a function of ρ

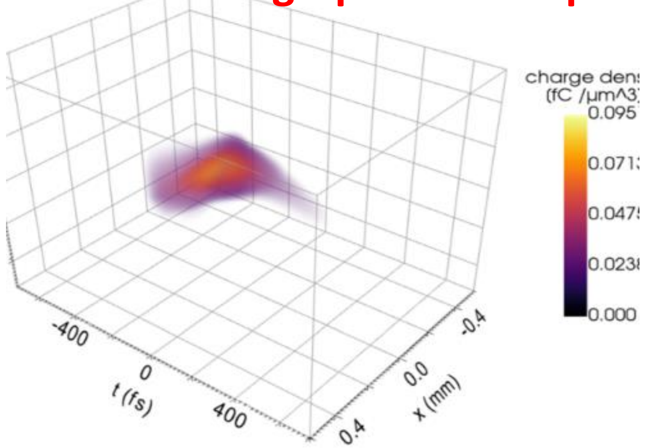
e.g. Transverse profile = $\rho(x,y)$

3D profile: u_1 , u_2 , u_3 as a function of ρ

e.g. 3D spatial profile = $\rho(x,y,t)$

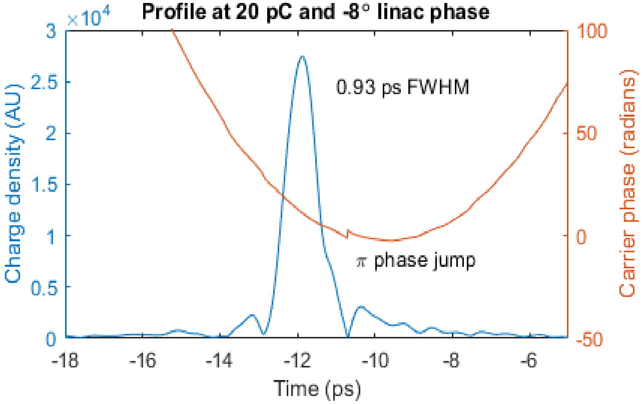
4D profile: u_1 , u_2 , u_3 , u_4 as a function of ρ

e.g. 4D transverse phase space $\rho(x,x',y,y')$



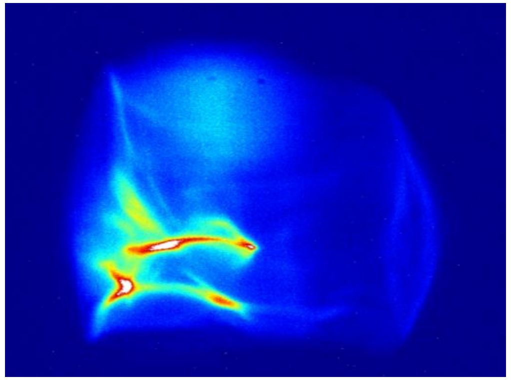
3D spatial profile from FlashForward variable Polarisation TDC

Fig 5 in Marchetti, Barbara, et al. *Scientific reports* 11.1 (2021): 3560. https://www.nature.com/articles/s41598-021-82687-2



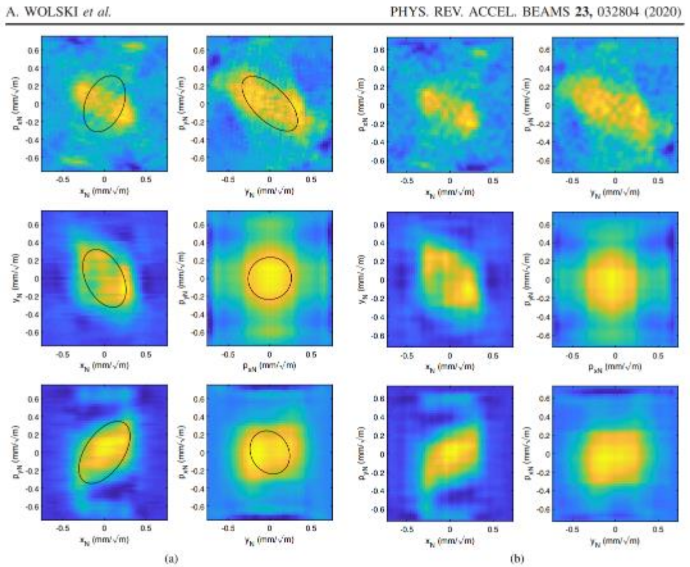
1D Longitudinal profile of CLARA BA1 beam

From electro-optical sampling



2D transverse profile of CLARA BA1 beam

From YAG screen



2D projections of 4D CLARA beam phase space

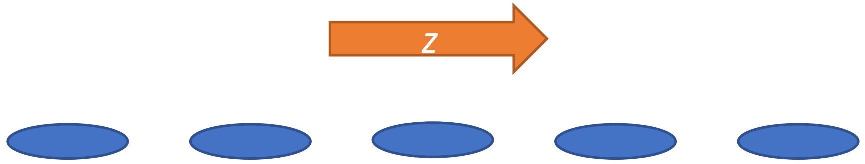
Fig 7 in Wolski, A., et al. Physical Review Accelerators and Beams 23.3 (2020): 032804.https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.23.032804

Single-shot techniques

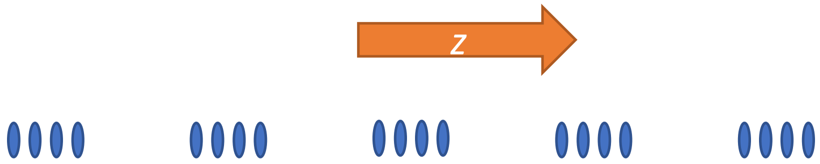
Beam properties

Beams are made of bunches

Bunches can be separated uniformly or with a sub-structure(‘train’/pulse)



Uniformly separated bunches



Uniformly separated bunch ‘trains’

Beam properties are ***time averaged*** properties of bunches or
Shot to shot variation in bunch properties
Beam properties we could measure include:

Beam current
Average energy

Energy instability
Charge instability
Pointing instability

To diagnose a **bunch** we must be able to pick it out from the **beam**

To fully diagnose a **beam** instability
We must be able to measure the **bunches** at their rep. rate…

Diagnostic modes

Some useful definitions

Single vs Multi-shot

Further definitions…

Diagnostics operate in either **single shot** or **multi-shot** modes:

Single shot = One bunch is captured to make a measurement
(This can be done at the beam rep. rate, but not necessarily)
Instabilities can be seen, fast feedback can be provided

e.g. Beam Position Monitor

Multi-shot = many bunches needed to make a measurement
Time averages bunch behaviour over many shots
Will smear out fast instabilities, *may* smear out slower drifts
Can provide slow feedback

e.g. Emittance Quad Scan

Single shot is always better, but for *some* systems means compromising on precision, accuracy

How much precision or accuracy you need depends on what you want to do with the system…

Destructive Vs Non-Invasive

Obvious statements & Buzzwords

Making a measurement of a bunch typically affects the bunch in some way…

If the bunch is lost or cannot be ‘used’ afterwards this is **DESTRUCTIVE**
If it isn’t useful, it may as well be lost

If no *measureable change* is made to the bunch this is **NON-INVASIVE**
If you can’t measure it, did it even happen?

If there is a measurable change but the beam can still be ‘used’ this is **MINIMALLY INVASIVE**
This is highly dependent on beam parameters & application

Typically we have destructive & non-invasive diagnostics

Measuring vs Monitoring

My view/definitions

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When we operate an accelerator we either want to:
Monitor the beam (and do something else up/downstream)
Or
Measure the beam (to find out its properties in detail and do nothing else)

A **monitoring** system is **single-shot** *and/or* **non-invasive**
The best monitors are both!

A **measuring** system is either **destructive** or **multi-shot**

Diagnostics impact how an accelerator is **operated**

Without diagnostics, you can't operate.
How you operate is defined by what diagnostics you have!

Break

Questions?

Common diagnostic systems

Know your BPMs from your TDCs and your OTR from your CSR

A zoo of systems

Always a new species to discover

The following is a set of common systems and their acronyms
Also included alternative acronyms that other labs use

Non-exhaustive list. There are many systems out there

Beware: some of the acronyms are the same, but mean different systems to different people/labs
There is no agreed 'dictionary'!

Brief description of what that system is for

Detail will come in later lectures/slides for most systems (but not all!)

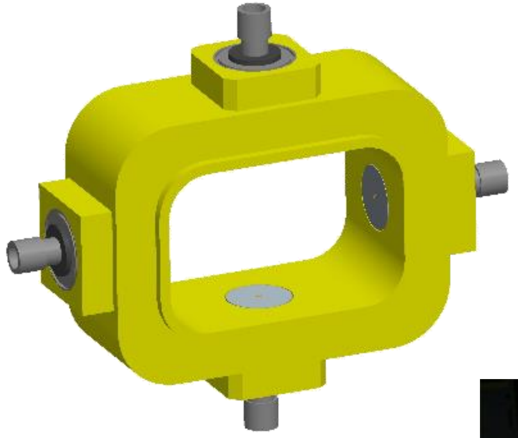
This is an introductory overview!

We love TLAs, do you?

Make sure you know someone actually means!

Common systems

Transverse #1



BPM = **B**eam **P**osition **M**onitor

Non-invasive single shot monitor for <x> and <y>

Uses 4 pick-ups to measure proximity of electric field within the beam-pipe

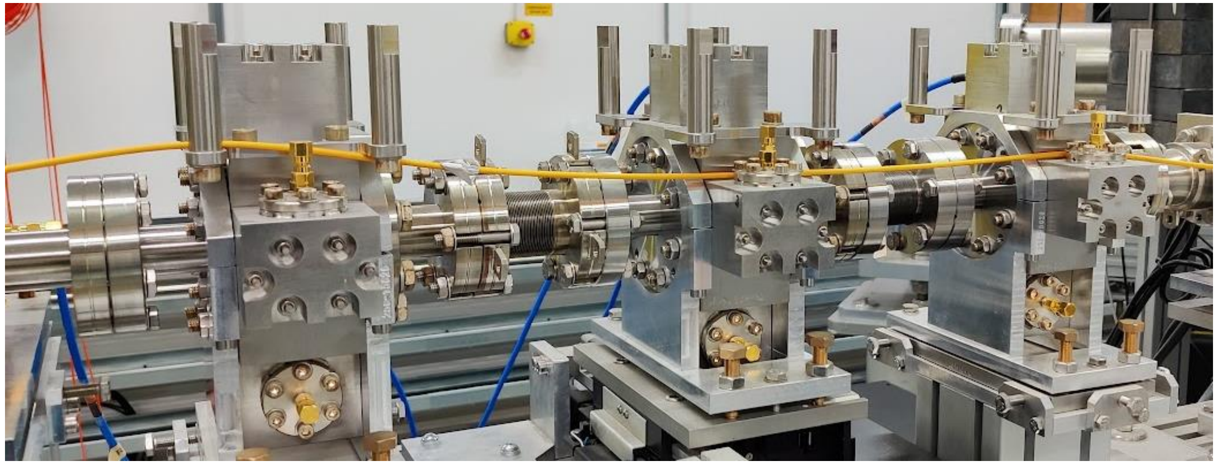
Can be calibrated to estimate charge

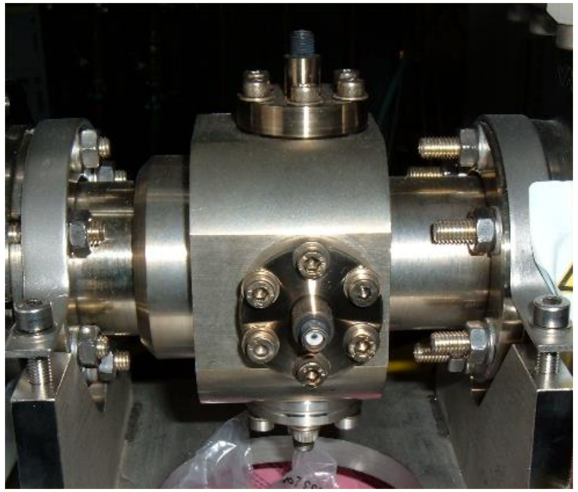
Example pick-up types: buttons, striplines

cBPM = **C**avity **BPM**

Uses a cavity to create a wakefield

Typically higher resolution than standard BPM





More info in Lecture #2 on how this works

Common systems

Transverse #2

SCR = Scintillator **Scr**een

Single-shot destructive measurement of x-y profile of beam

With additional beam optics/systems can measure other profiles, e.g. energy spectrum

Very bright, has fundamental resolution limits

Synonym: **OPT** = **Opt**ical screen

Variants:

YAG = **Y**ttrium **A**luminium **G**arnet scintillator screen

Very common *material* in electron machines for scintillator screen

LYSO = $Lu_{1.8}Y_{0.2}SiO_5$:Ce

(crystal formula for Cerium-doped Lutetium Yttrium Orthosilicate)

Another bright scintillator for electron beams with a fun name

Has issues with saturation/quenching at high charge density

GAGG = **G**adolinium **A**luminium **G**allium **G**arnet

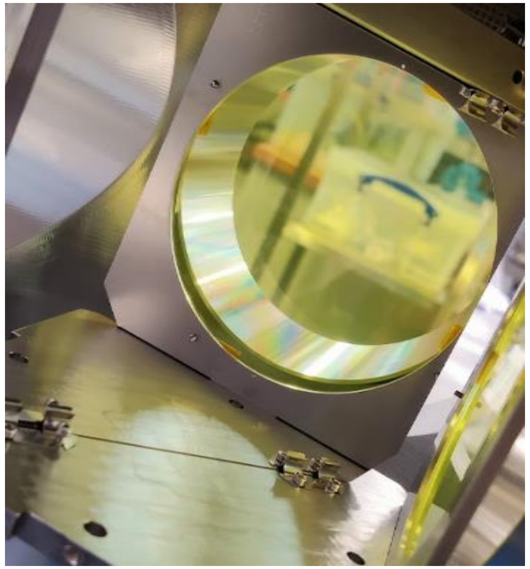
Very bright scintillator with high saturation point

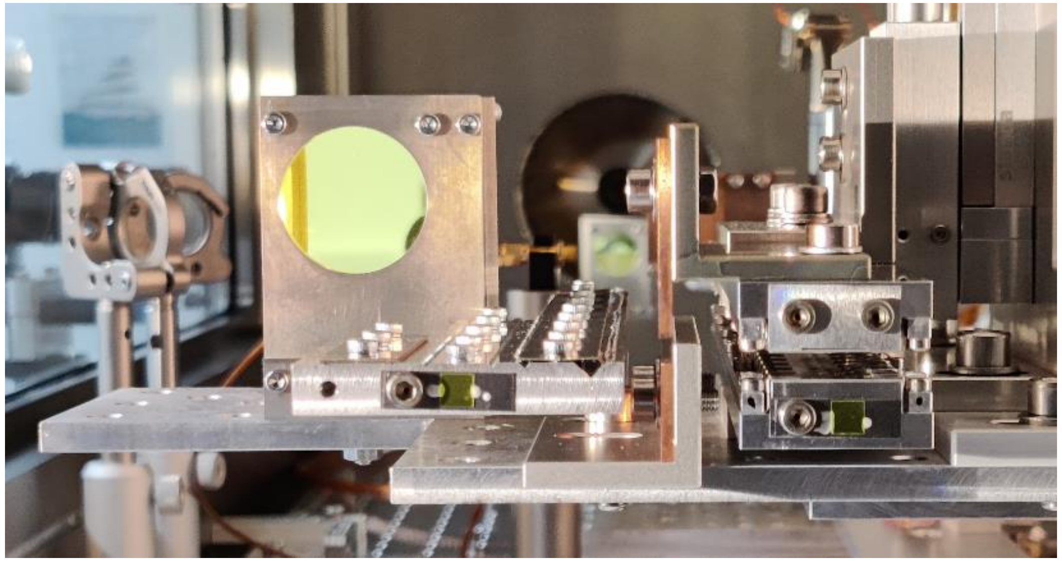
Gaining in popularity!

LANEX = Trade name for kodax scintillator sheets

Cheap, large, can be cut to shapes

Poor transverse resolution & Finite lifetime!





More info in Lecture #2 on how this works

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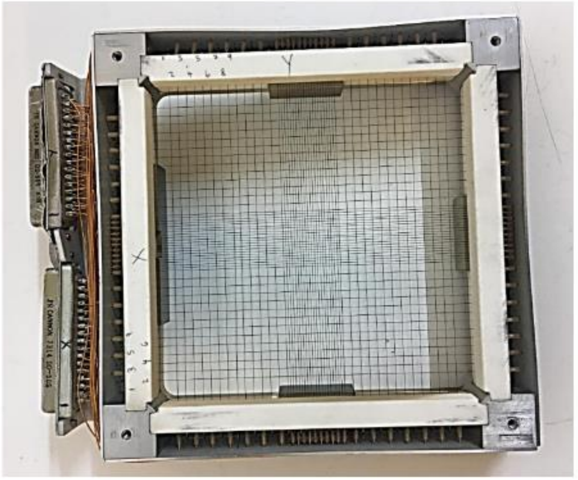
Common systems

Transverse #3



Joint ICTP-IAEA Workshop 21 – 29 October 2019 Trieste Italy

WS = **W**ire **S**canner

Multi-shot minimally invasive measurement of x or y profile

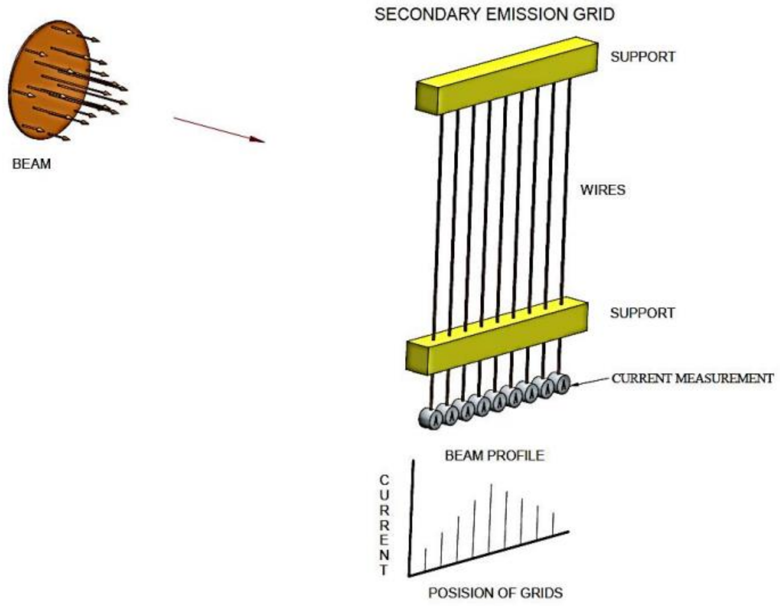
Uses wire to intercept beam and scatter a transverse slice. Scan wire across beam

Either:

Additional detector to pick-up intensity scattered *Or*

secondary electrons liberated from wire, current measured by electrode

High resolution technique



SEM = **S**econdary **Em**ission Grid

Single shot minimally invasive measurement of x or y profile

Uses a grid of wires to intercept beam and secondary electrons liberated from each wire and measure current on electrode

Images: Joint ICTP-IAEA Workshop on Accelerator Technologies, Basic Instruments and Analytical Technique
Lowry Conradie https://indico.ictp.it/event/8728/session/8/contribution/32/material/slides/0.pdf

Common Systems

Transverse #4

OTR = <u>O</u>ptical <u>T</u>ransition <u>R</u>adiation

Single-shot destructive transverse profile measurement

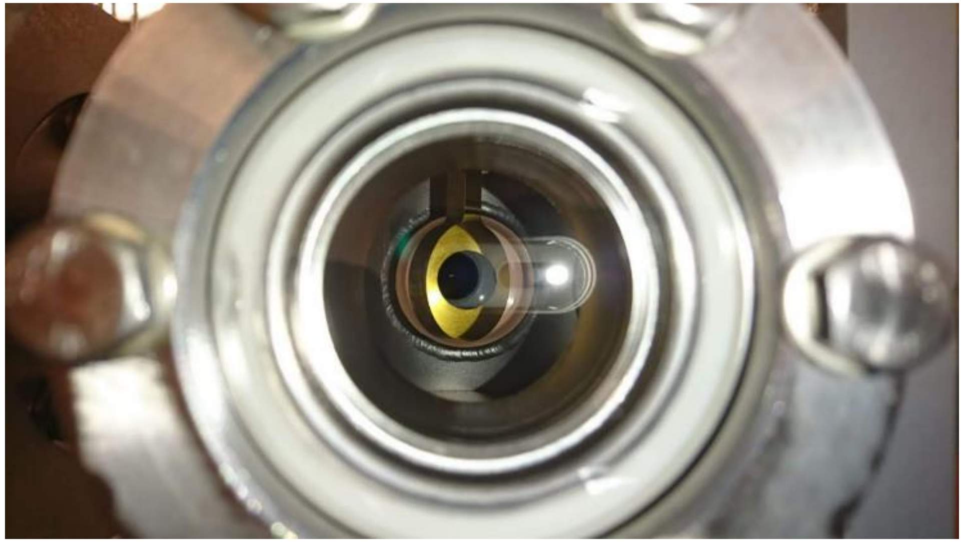
Bunch passes through thin foil or metallic target

Releases radiation as the electric field transitions vacuum - > metal

Not very bright, but high resolution measurement

Resolution limited by imaging system

More info in Lecture #2 on how this works



SRM = **<u>S</u>**ynchrotron **<u>R</u>**adiation **<u>M</u>**onitor

Single shot non-invasive transverse profile measurement

Detect radiation (Optical/UV/X-ray) as beam passes round dipole (or undulator)

Use this to infer electron beam profile

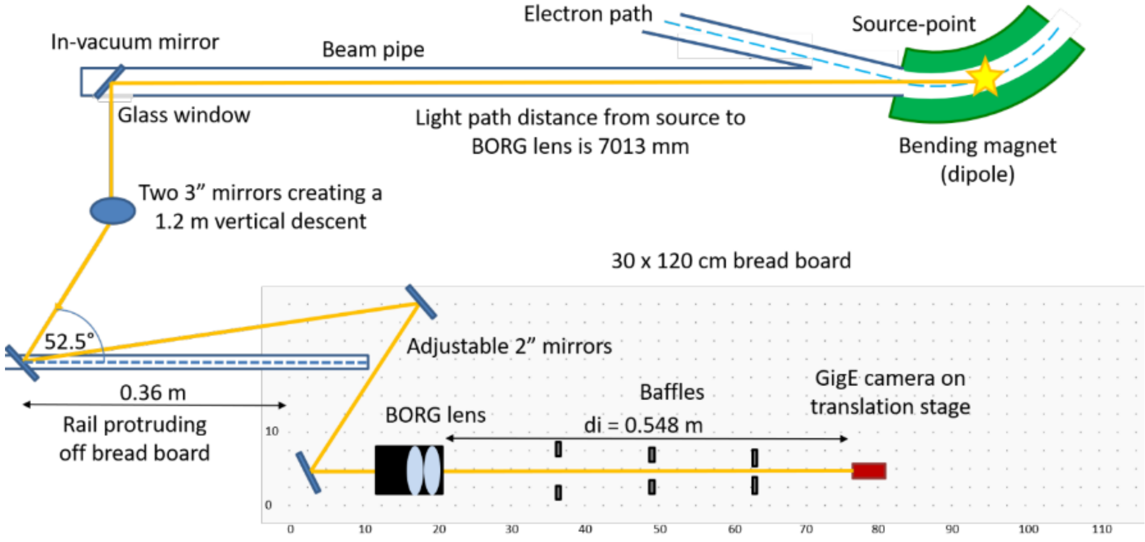


Image: Howling, E., and L. Bobb. "Development of a Beam Halo Monitor Using Visible Synchrotron Radiation at Diamond Light Source." IBIC21 (2021).

Common systems

Charge #1

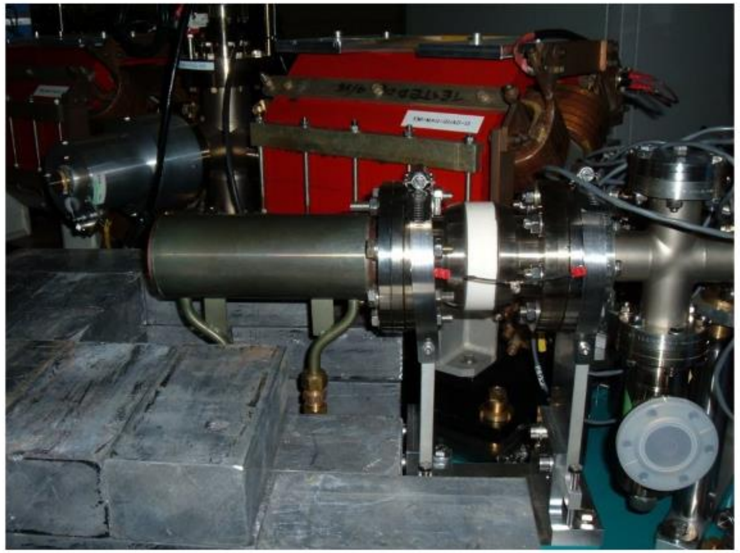
FCUP = **F**araday **Cup**

Destructive single-shot measurement of bunch charge

Metal cup which captures and stops beam charge

Discharge of cup can be measured and absolute charge can be measured

Synonyms: FC



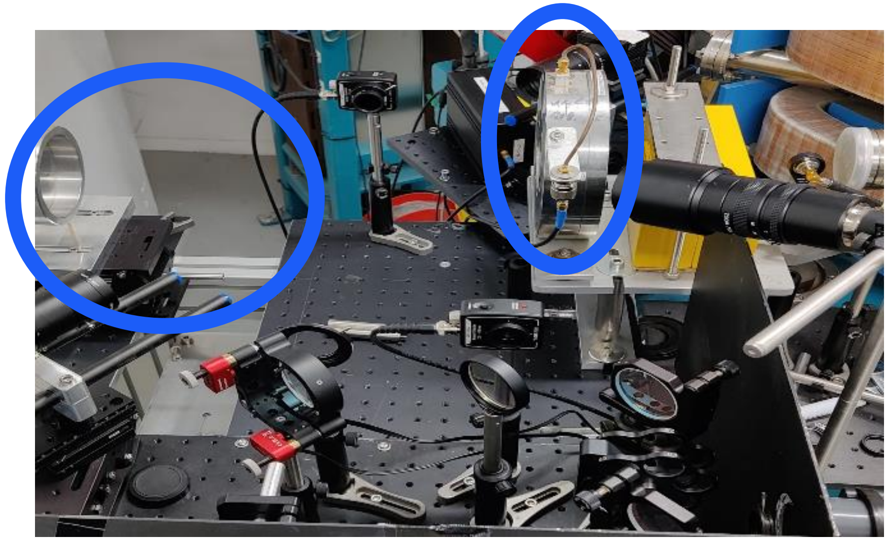
More info in Lecture #2 on how this works

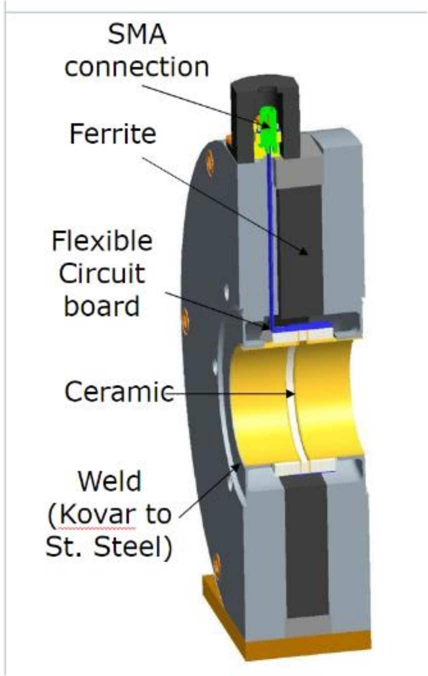
WCM = **W**all **C**urrent **M**onitor

Non-invasive single-shot measurement of bunch charge

Measures image current following through beam pipe

Requires calibration





Common Systems

Charge #2

ICT = Integrating Current Transformer

Single-shot non-invasive bunch charge measurement

Limited by bunch pulse length and beam repetition rate

Can be in-flange or 'in air' or in vacuum

Variants:

Turbo-ICT: Filtered version, works with shorter pulses (<1ns) and higher resolution

Synonyms: BCM = Bunch Charge Monitor

ACCT = AC Current Transformer

Non-invasive beam current monitor for macropulse beams / quasi CW beams

Images:
https://www.bergoz.com/products/

Common Systems

Charge #3 / Losses

BLM = **B**eam **L**oss **M**onitor

Non-invasive monitor of beam charge loss

Discrete gas or solid sample outside beam pipe to detect ‘escaped’ particles or Secondary radiation

Used for machine protection

Variants

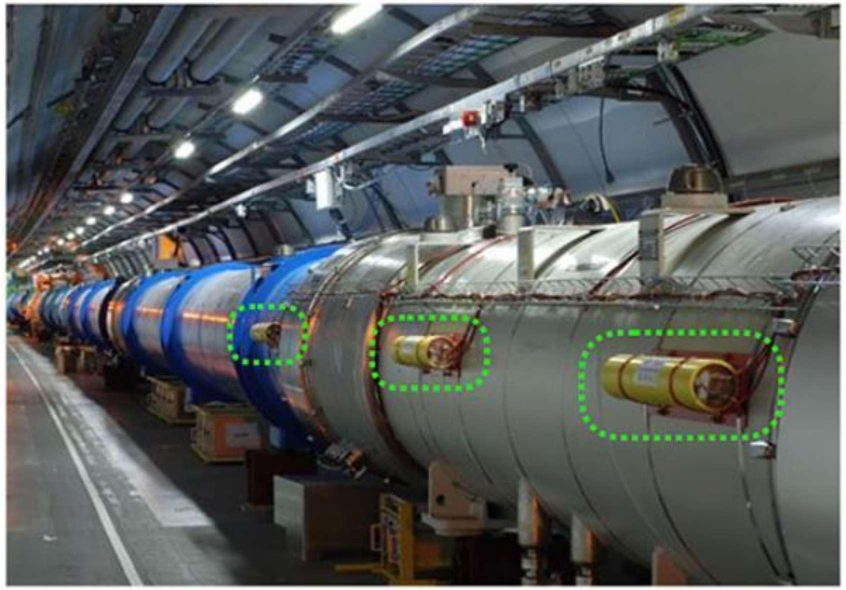
oBLM = **O**ptical **BLM**

Continuous Optical Fibres which run alongside beam pipe

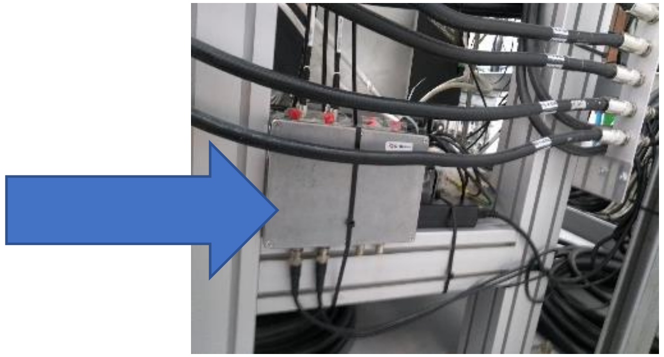
Secondary emission from beam loss creates Cherenkov radiation

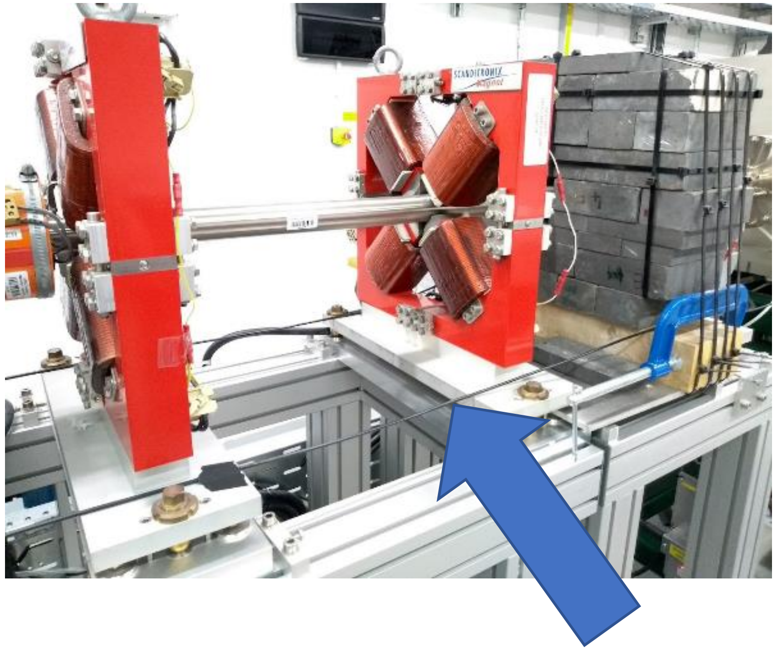
Can be detected at either end of figure.

Time of arrival of detection gives loss position information



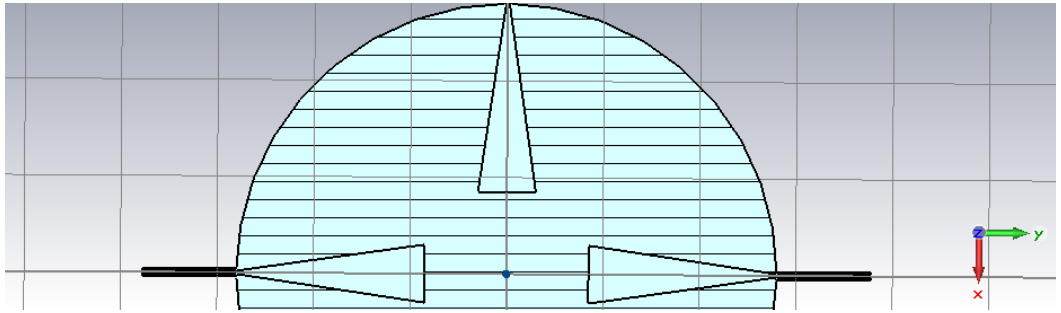
https://www.liverpool.ac.uk/quasar/research/beam-instrumentation/beam-loss-monitoring/





Common systems

Longitudinal #1



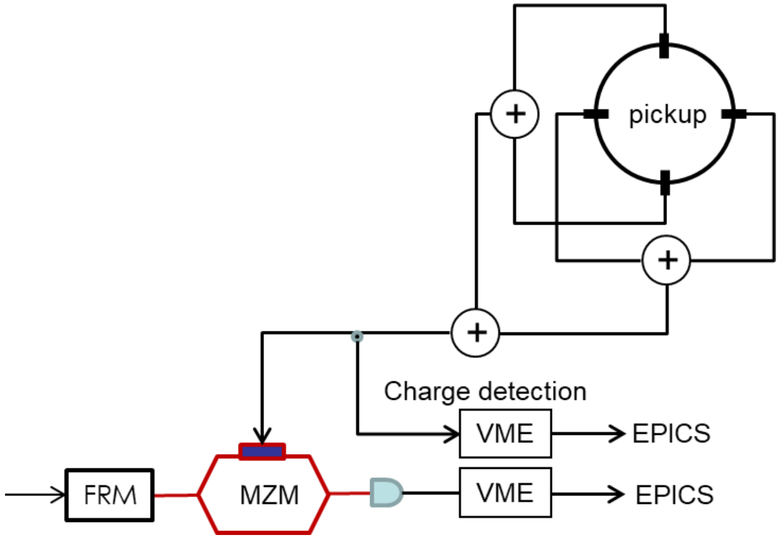
BAM = **B**eam **A**rrival **M**onitor

Non-invasive single shot measurement of time of arrival wrt global clock

High frequency cavity/pickups which detect bunch arrival

Signal needs to be converted to comparator to get TOA wrt global clock

Resolution limited by beam charge



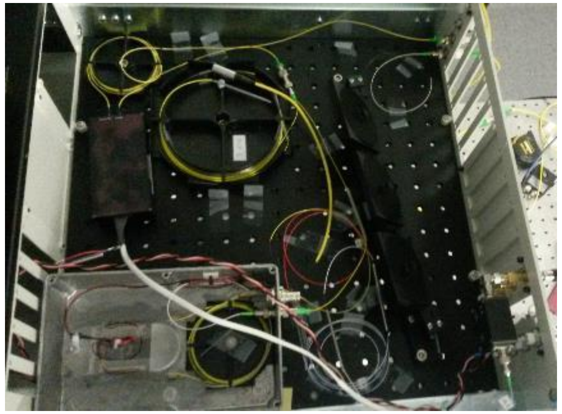
TOF = **T**ime **o**f **F**light system

Non-invasive single shot measurement of bunch energy

(at least) two pickups at different positions measure beam time of arrival

For known species, flight time between two points gives longitudinal momentum

Works for low energy, non-relativistic systems



Common Systems

Longitudinal #2

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…

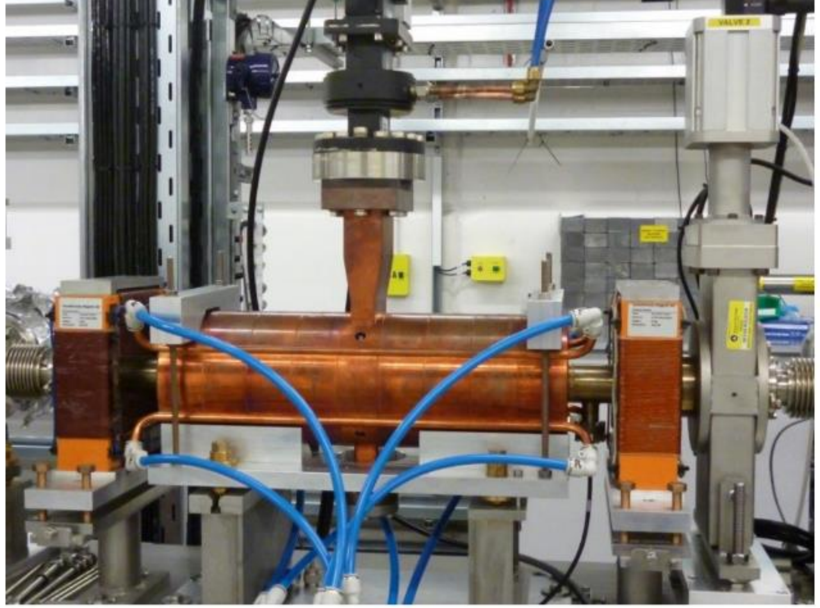


Figure 1: VELA Transverse Deflecting Cavity.

Synonyms:

TDS = **T**ransverse **D**eflecting **S**tructure

RFD = **R**adio **F**requency **D**eflector

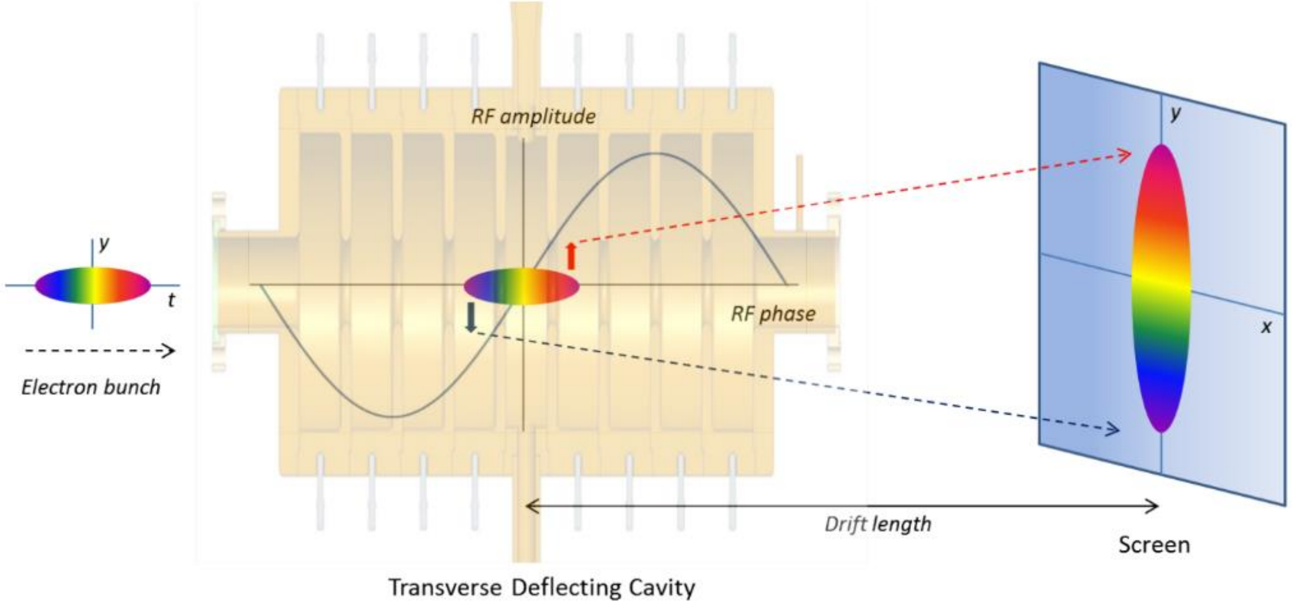


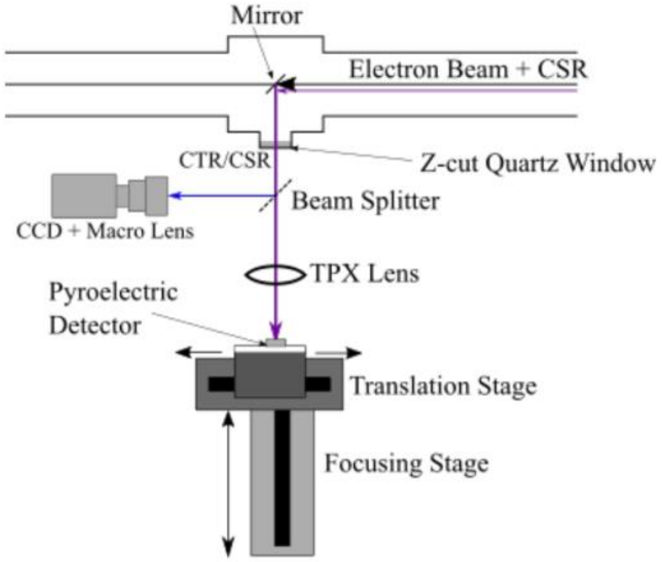
Image: J McKenzie Thesis

More info in Lecture #3 on how this works

Common systems

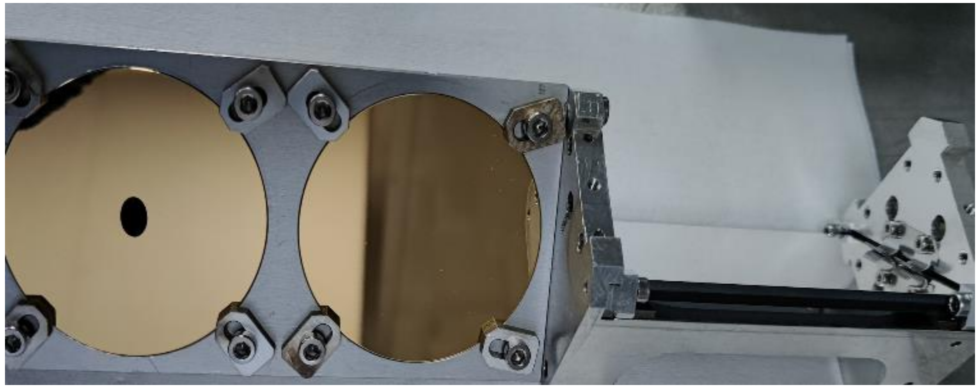
Longitudinal #3

BCM = Bunch Compression Monitor
Single-shot monitor for bunch length
Detects intensity of coherent radiation emitted by bunch
Shorter bunches -> higher intensity of radiation
Whether destructive or non-invasive depends on source of radiation…



Variants =
CSR BCM = Coherent Synchrotron Radiation **BCM**
Single-shot non-invasive monitor for bunch length
Detects coherent radiation emitted as beam goes around dipole

CTR BCM = Coherent Transition Radiation **BCM**
Single-shot destructive monitor for bunch length
Detects coherent radiation emitted as beam goes through metal target



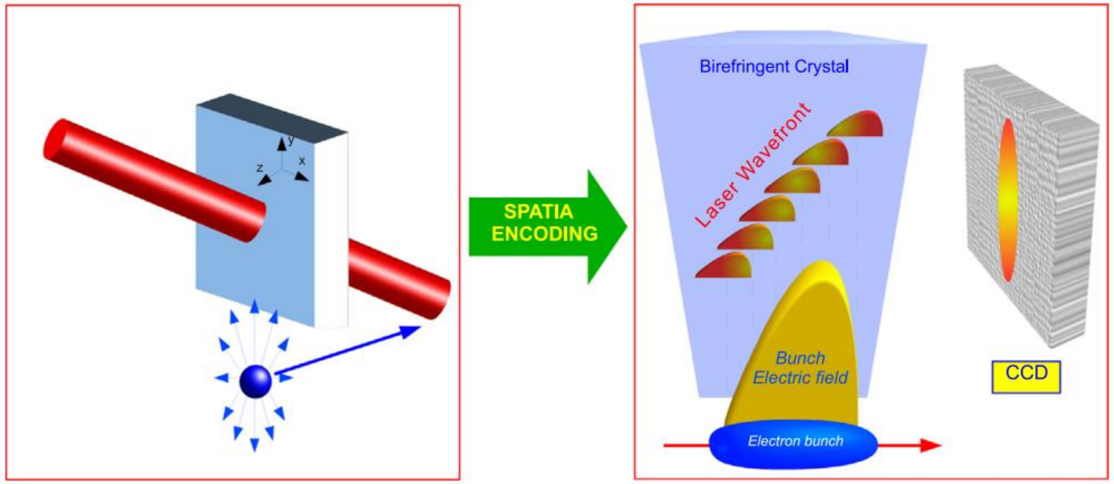
CDR BCM = Coherent Diffraction Radiation **BCM**
Single-shot non-invasive monitor for bunch length
Detects coherent radiation as beam goes through hole in metal target

More info in Lecture #3 on how this works

Common systems

Longitudinal #4

R. Pompili et al. / Nuclear Instruments and Methods in Physics Research A 740 (2014) 216–221



EOS = **E**lectro-**O**ptic **S**ampling

Single-shot non-invasive bunch profile monitor

Electric field of bunch interacts with non-linear crystal
Field changes polarisation properties of crystal
Simultaneously a laser pulse propagates in crystal
Changes in polarisation mapped onto laser
Measure change in polarisation as function of time/space in laser pulse

Synonyms: EO

Variants :

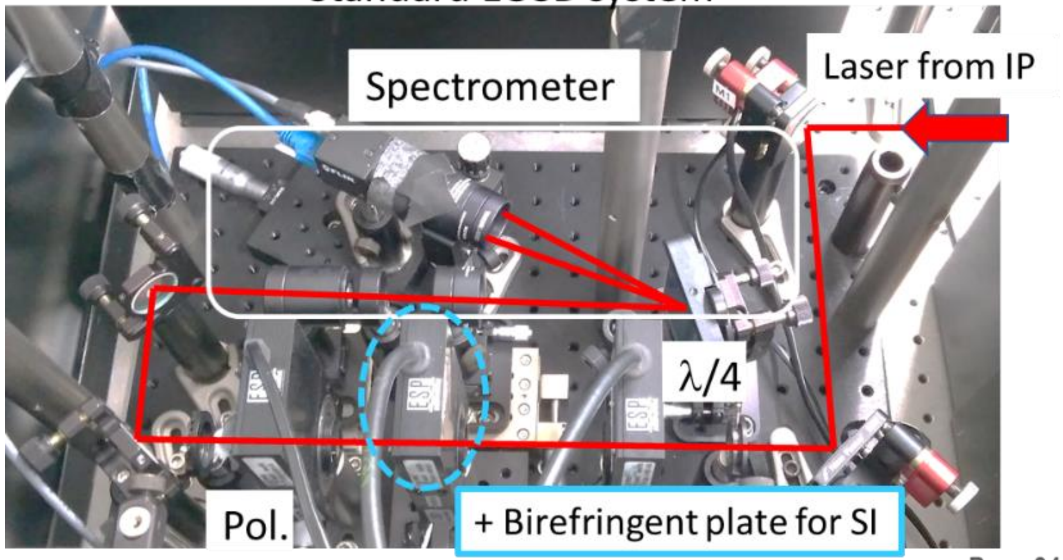
EOSD = **E**lectro-**O**ptic **S**pectral **D**ecoding

Chirped laser pulse means spectrum maps to time
Variation in polarisation of spectrum -> electron bunch length

EOSI = **E**lectro-**O**ptic **S**pectral **I**nterferometry

As EOSD but with higher resolution
and less ambiguous spectral interference for reconstruction

Standard EOSD system



Page 34

More info in Lecture #3 on how this works

Common systems

Longitudinal #5

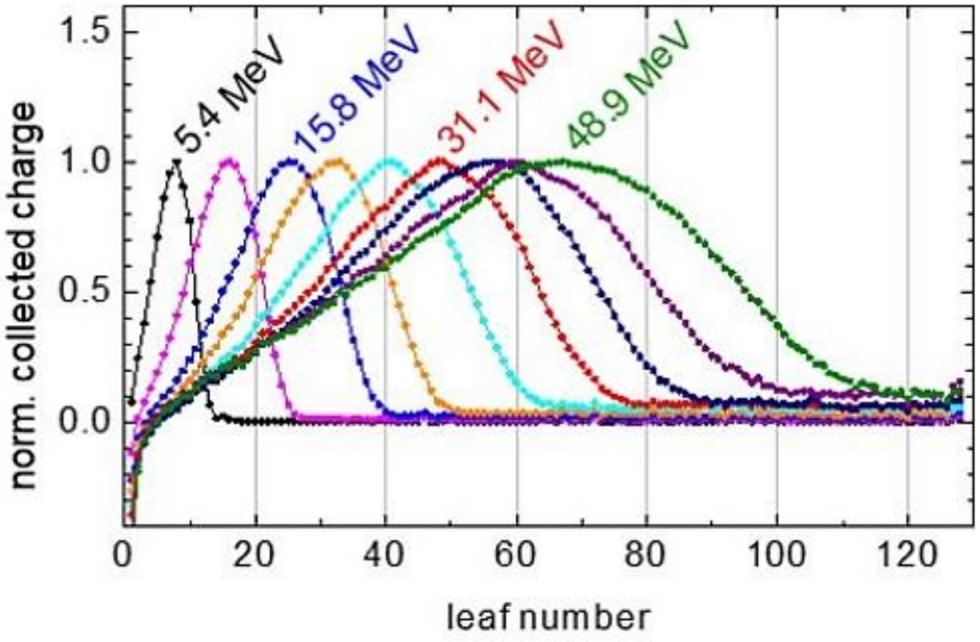
MLFC = Multi-leaf Faraday Cup

Single shot destructive measurement of energy spectrum

Multiple isolated faraday cup layers which stop beam and charge up

Depth of penetration gives particle energy

Coarse measurement, stochastic in nature (best for high charge bunches)



Images: https://www.ptb.de/cms/en/service-seiten/news/scientific-news.html?cHash=afc8730e344bcebbe77f3d3f8057e948&tx_news_pi1%5Baction%5D=detail&tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Bday%5D=20&tx_news_pi1%5Bmonth%5D=12&tx_news_pi1%5Bnews%5D=10186&tx_news_pi1%5Byear%5D=2019

Summary

Some take homes

Science and Technology Facilities Council

- 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…

Resources

References & links for images and further reading

- CAS notes on beam diagnostics
  - https://cds.cern.ch/record/499098/files/p154.pdf
- Berghoz product catalogue (ICTs etc.)
  - https://www.bergoz.com/products/
- SwissFEL SRM & BCM compressor measurements
  - https://arxiv.org/pdf/1905.08081.pdf
- FlashForward Variable Polarisation TDC
  - https://www.nature.com/articles/s41598-021-82687-2
- VELA TDC commissioning
  - https://accelconf.web.cern.ch/ipac2015/papers/wepha054.pdf
- UoL Quasar Article on BLMs
  - https://www.liverpool.ac.uk/quasar/research/beam-instrumentation/beam-loss-monitoring/
- https://livrepository.liverpool.ac.uk/3031981/1/200845969_Aug2018.pdf
- Overview of oBLMs
  - https://www.mdpi.com/1424-8220/23/4/2248
- DLS SR based halo monitor
  - https://accelconf.web.cern.ch/ibic2021/papers/tupp10.pdf
- Lowry Conradie notes on diagnsotics (see wire scanners and girds)
  - https://indico.ictp.it/event/8728/session/8/contribution/32/material/slides/0.pdf
- SPARCLab EOS results
  - https://www.sciencedirect.com/science/article/abs/pii/S0168900213013776