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CI-ACC-212
Beam Diagnostics #2: Measuring charge and transverse properties

Thomas Pacey | CI Lecture Series

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Outline

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- Measuring bunch charge
- Transverse profile measurements and limitations
- Emittance measurement techniques
- Summary

Summary from Lecture #1

Some take homes

- 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…

Any questions from Lecture #1?

Measuring bunch charge

How much beam have I got?

Measuring charge

Counting up all the particles

Measuring bunch charge/beam current is important.

Having a *precise and accurate* understanding of shot-by-shot charge variation is vital for example:

- Beam dynamics (can be) charge sensitive – e.g. collective effects impact beam jitter

- Some experiments are charge sensitive (signals go with Q^2) – e.g. development of novel diagnostics

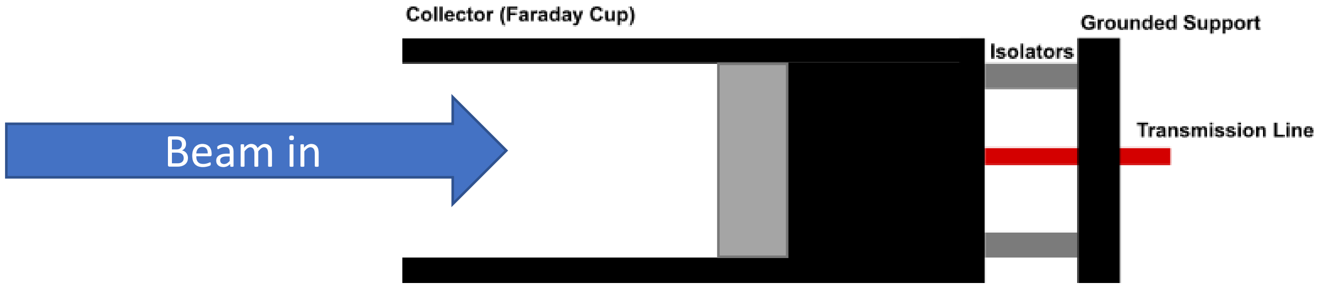
- Dosimetery experiments for (medical) research – absolute charge measurement is vital for meaningful science

The precision and accuracy of a charge measurement system is a function of

- Physical device/pick-up
- Read-out front end electronics
- Digitising back end (feeds into control system)

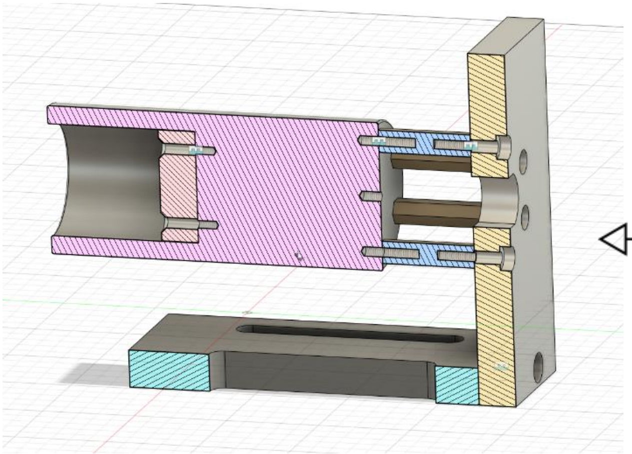
Faraday Cups

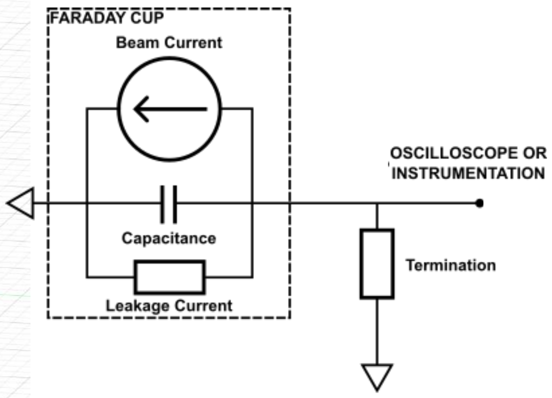
Courtesy of Storm Mathisen, ASTeC ADI



- Metal collector cup is charged by incident particles
- Discharged to instrumentation through transmission line

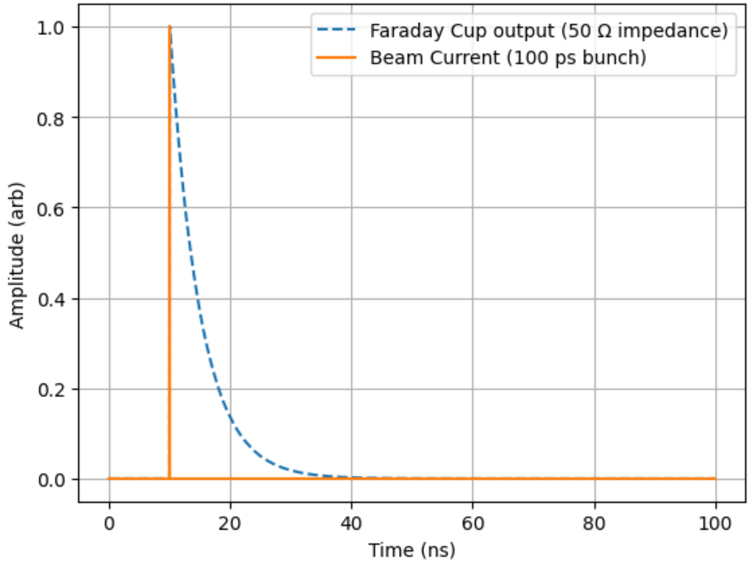
- Simple design for <u>high energy electrons</u> as long as absorption is 100%
  - Primary charges penetrate deep into metal so they (nor secondaries) cannot backscatter out of cup





- For lower energy/heavier particles, backscatter and secondary emission leads to lost charges
  - This is suppressed with: static voltage grids, magnetic fields, low Z absorbers, complex geometries

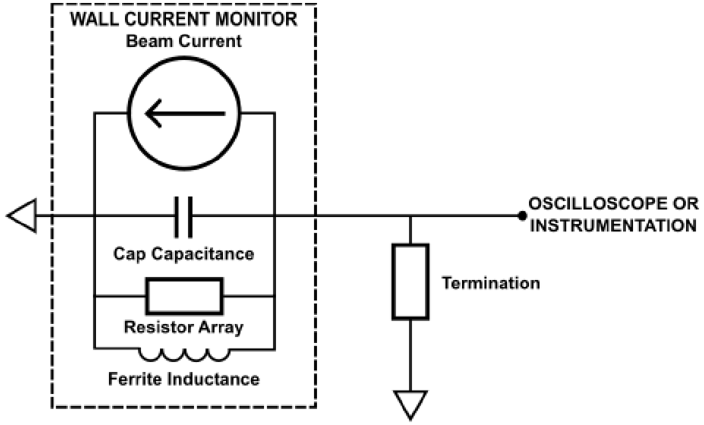
- High <u>power</u> beams can deposit substantial energy in Faraday cups; active cooling/heat dissipation needed
- High energy electrons can activate Faraday cups, often used in beam dumps
- $Q = \int_0^t i_{term}(t)\,dt = \int_0^t \frac{v_{term}(t)}{R_{term}}\,dt$

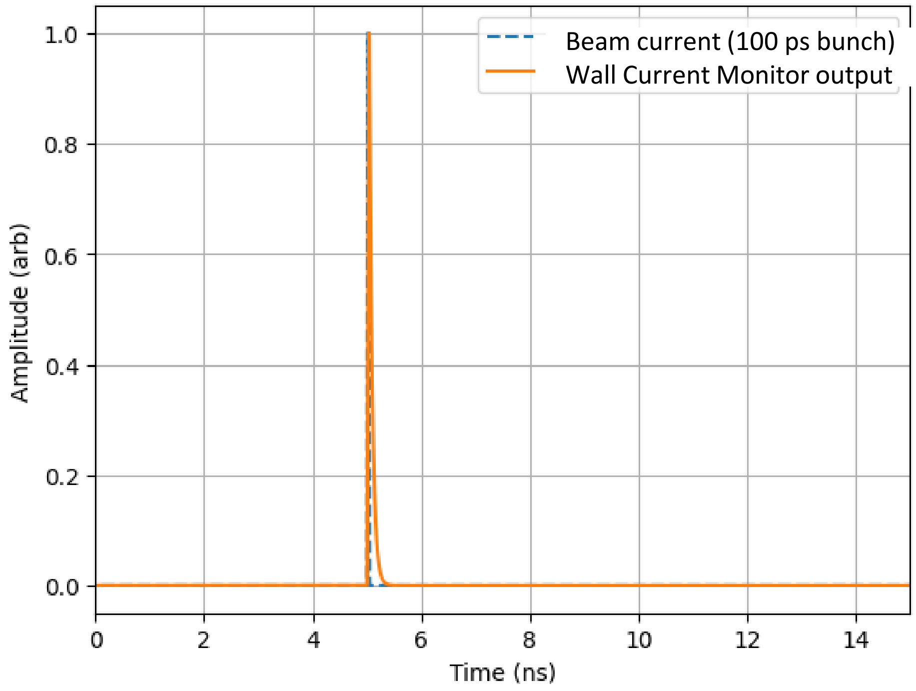


Wall Current Monitor

Courtesy of Storm Mathisen, ASTeC ADI

- Beam generates image currents propagate in beam pipe
- Ceramic break in beam pipe with resistor array to measure voltage, with ferrites to guide the image current.
  - Stray capacitance across ceramic gap
  - Ferrites have inductance
- Modelled as RLC circuit (bandpass filter)
- Array of resistors to ensure equal path length for fields from offset beams
- $R_{wcm} = \frac{1}{\frac{1}{100\Omega}+\frac{1}{100\Omega}\cdots\frac{1}{100\Omega}}$ for ~30-40 resistors
- Typical value ~1.5-2.5 ohms (CLARA ~1.8)
- Low resistance reduces beam impedance
- Output signal very high bandwidth (~6GHz),
  - Can measure bunch profile for long bunches (ns scale)

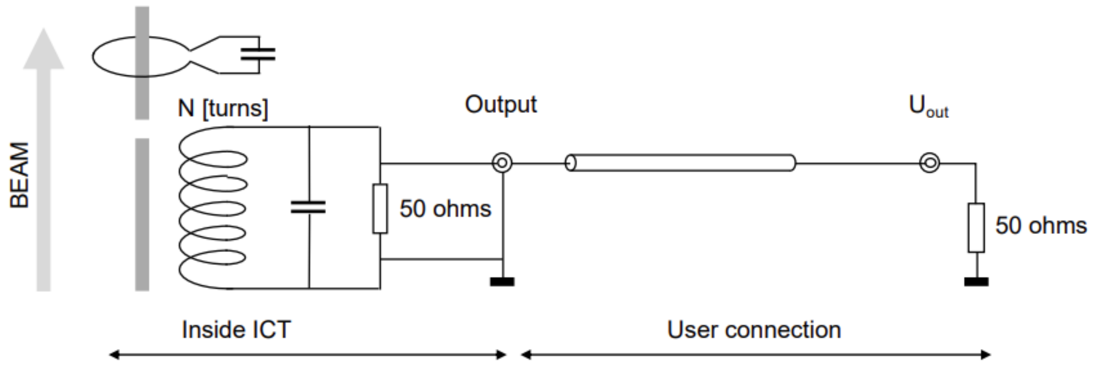


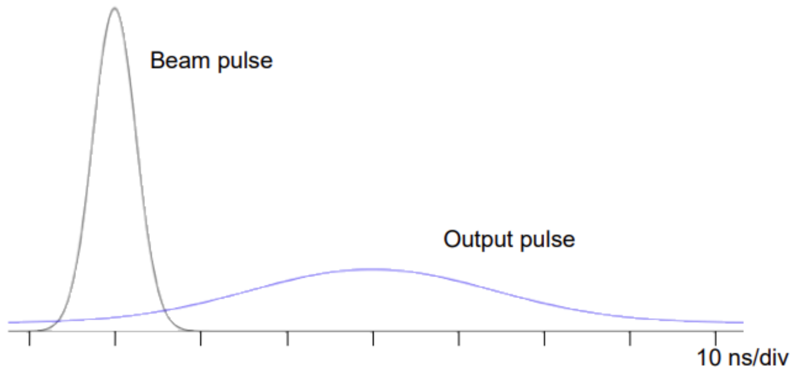


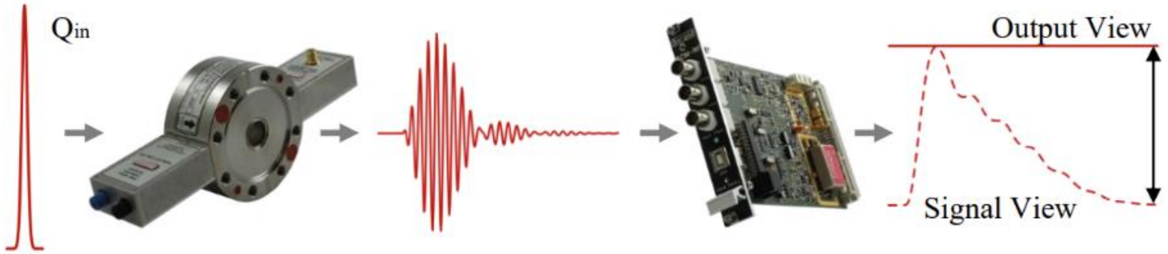
Integrating Current Transformer

Courtesy of Storm Mathisen, ASTeC ADI

- Passive current transformer, coils in ceramic coupled to beam fields.
- Integrates very fast pulses,
    - Output bandwidth independent of bunch length.
- Turbo-ICT applies narrowband processing to an ICT, with front-end amplification, to improve sensitivity and dynamic range
    - Capable of 10 fC - > 300 pC







Pictures from Bergoz manuals:
https://www.bergoz.com/wp-content/uploads/ICT-manual-4-2.pdf
https://www.bergoz.com/wp-content/uploads/Turbo-ICT-manual-3-1-1.pdf

Transverse profile measurements

What does the beam look like? How is the shape changing?

Transverse profile measurements

What does a beam look like?

- Many techniques for measuring or monitoring transverse profile: defined as $\rho(x,y)$

- Following focuses on *imaging the radiation* released from bunch at a screen

- Common operational process provides precise and (typically) accurate $\rho(x,y)$

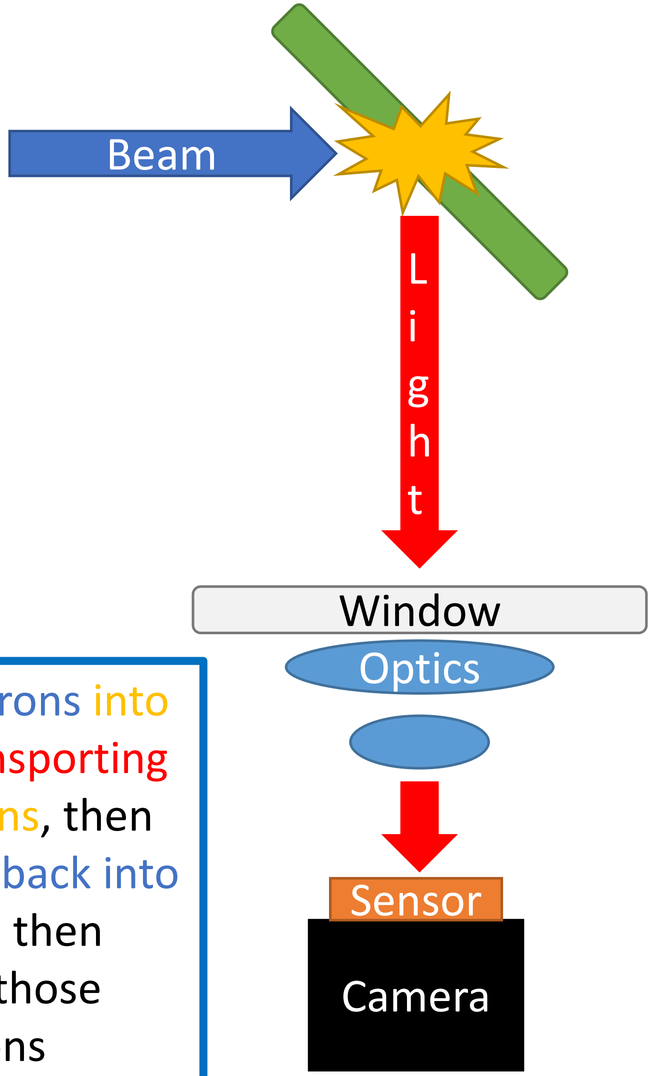
- In medium energy linac test facilities (CLARA) screens are the work horse for beam physics!

- Screens also provide measurement of:
  - **Beam optics** (Twiss values; beam waist size and location)
  - **Emittance**
  - **Bunch length** (with a TDC)
  - **Energy spectra** (with a dipole + optics)
  - **Longitudinal Phase Space** (with a TDC + dipole)

- 2 common processes:
  - Optical Transition Radiation (OTR)
  - Scintillation (YAG, GAGG,LYSO etc.)

Imaging Radiation from a Screen

System Analysis

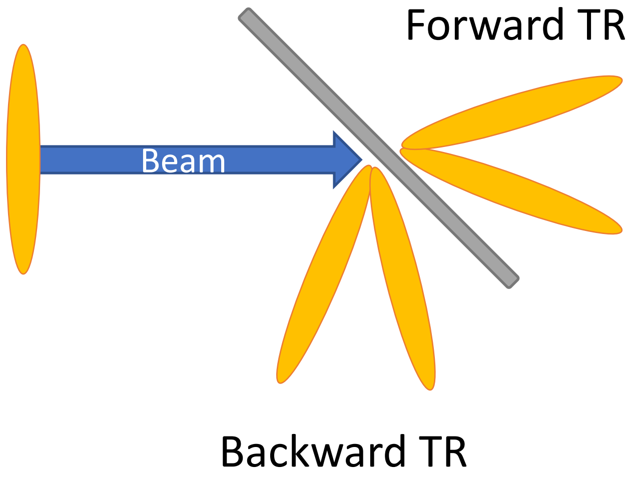


Turning electrons into photons, transporting those photons, then turning them back into electrons, then counting those electrons

- Physical processes converts beam field into light – scintillation, transition
    - Process can depend on beam energy as well as transverse size
    - Can be a combination of processes,
    - Can be broadband or narrowband light
- Transport of light to window
    - Including observation angles, reflection from other optics, apertures
- Transmission of light through vacuum window
    - Is an aperture, can be an absorber
- Imaging optics (chromaticity) and associated PSF of imaging system
- Sensor pixel pitch, array size, quantum efficiency (wavelength dependent), dark noise
- Readout electronics speed, global vs rolling shutters, shutter stability
- Bit depth and dynamic range

Optical Transition Radiation

Physical process



Opening angles of TR goes ~ $1/\gamma$

TR is radially polarised

Far field (angular) distribution has characteristic 'donut' shape

- Relativistic charged particle transitions between 2 different electro-magnetic media (e.g. vacuum – metal or metal-vacuum)
- Fields 'attached' to particle must *transition* from one steady state to another
- Releases pulse of broadband *transition radiation*
  - *This is not Cherenkov Radiation*

- Can have components THz – IR – Optical – UV
  - Cut offs at high/low frequency depend on target/pipe geometries and (non vacuum) medium properties
- Field can be coherently enhanced by transverse or longitudinal **bunch** properties
  - Coupling of longitudinal – transverse not good for measuring transverse profile!

- Energy lost by beam is minimal

Optical Transition Radiation

Pros, Cons, and Uses

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Pros

- Linear with charge, no saturation of emission process
- High spatial resolution achieved straightforwardly:
  - Needs a mirror-like target and suitable imaging
- Can be used to measure beam profile & divergence
  - Imaging near-field or far-field respectively
- Very fast process that can produce timing signals
- Target can be very thin (foil); for high energy beams target is minimally invasive

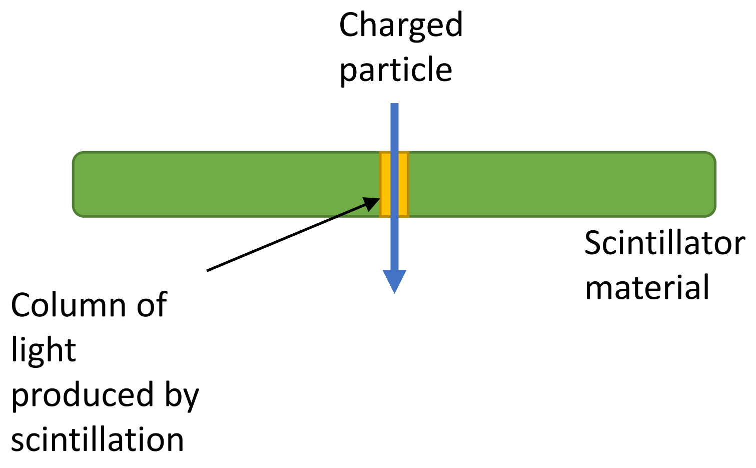
Cons

- No light multiplication process, can be limited by SNR
  - Might require be multi-shot integration
- Broadband emission, best resolutions found by bandpass filtering, reduces intensity further
- If coherent emission happens at optical wavelength (COTR) any useful transverse signal is lost
- Sufficient average power or instantaneous intensity beam/bunch will destroy target…

OTR is useful for measuring small beam sizes (<20um) of relativistic high intensity bunches.
Under right conditions will provide most accurate beam size measurements.
Encoding of beam divergence gives access to emittance information.

Scintillators for beam imaging

A simple model



- Many forms of scintillator (solid, liquid, gas) and material types (inorganic crystals, plastics, powders)
- Focus on the inorganic crystals used in electron machines

- Scintillators also used in particle and nuclear physics – calorimetry, photon energy (gamma ray) measurements
  - Application is different, some of features that matter are different

- Physical process:
  - Charged particle (e-, p+, ion) deposits energy to atom in crystal lattice
    - Assume enough momentum so beam particle then continues though material
  - Promotes atomic electron to very high energy state (hot electron) and a creates a resulting hole
  - Hot electrons scatter, cascading to create further 'hot electrons' (lower energies) – multiplying the potential emitters
  - Eventually excited electrons either:
    - Captured by a crystal lattice hole and emits photon
      - Photon can be reabsorbed by crystal lattice
    - Captured by *dopant* atom, relaxes and emits photon
      - Photon emitted will leave material – light is observed!

How scintillator screens affect beam measurement depends on:

- **Input beam properties**
  - (momentum, charge density)
- How these properties interact with of the **crystal lattice**:
  - its energy states, dopant atoms and mobility of hot electrons
- **Imaging** of the resulting scintillation column

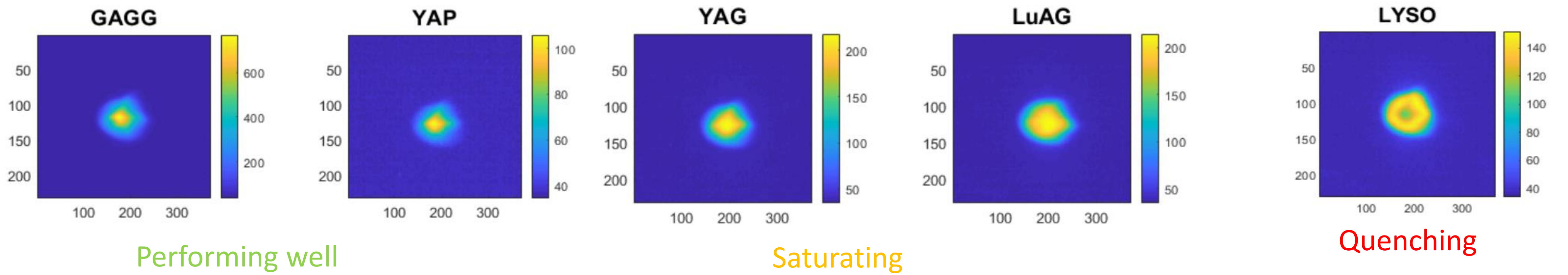
Issues with scintillators: Saturating & quenching

Material considerations: 'Solid state' physics

- Width of the scintillating column is a property of the material
  - How far hot electrons travel before they are captured by dopants

- If have enough incoming charges we can liberate enough hot electrons to saturate all the emitting dopants
  - Increasing charge density does not produce more light!
  - Once material saturates, nothing you can do

- There are additional processes by which the captured electrons and dopants can be recombined without emission.
  - If enough overlapping scintillating columns then the process quenches and light output is reduced
    - Produces a characteristic smoke-ring effect, seen at EuXFEL 2018/19 with LYSO screens



Images from Pitz, 22 MeV, 6nC bunches, ~ 100 RMS size – IBIC '22 SCINTILLATOR NON-PROPORTIONALITY STUDIES AT PITZ doi:10.18429/JACoW-IBIC2022-TUP21

Issues with scintillators: COTR

Beam collective effects spoiling the image

Scintillator light can be >100x brighter than OTR from a mirror

However transition radiation will be released at vacuum-scintillator boundary

If the bunch is very short and/or has micro-bunching instabilities (e.g from CSR)

longitudinal profile can have 'features' at optical wavelength

Then COTR will be released with narrow opening angle at the vacuum boundaries

Effectively a donut shaped laser pulse fires from screen into imaging optics – forward and backward.

Observed at SLAC LCLS in 2008/9

OTR images cannot be saved. Scintillator images can be saved with appropriate geometry so that COTR pulse misses optics.

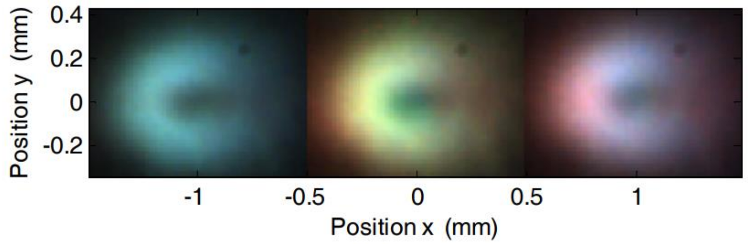


Figure 10: Series of COTR color images taken within one minute showing varying color content from shot to shot.

Image from:

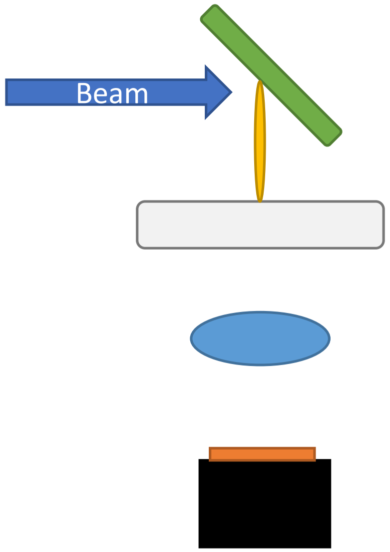
Loos, H., et al. "Observation of coherent optical transition radiation in the LCLS linac." *Proceedings of the 2008 Free-Electron Laser Conference (Gyeongju, Korea)*. 2008.

Imaging geometries

A few standard methods

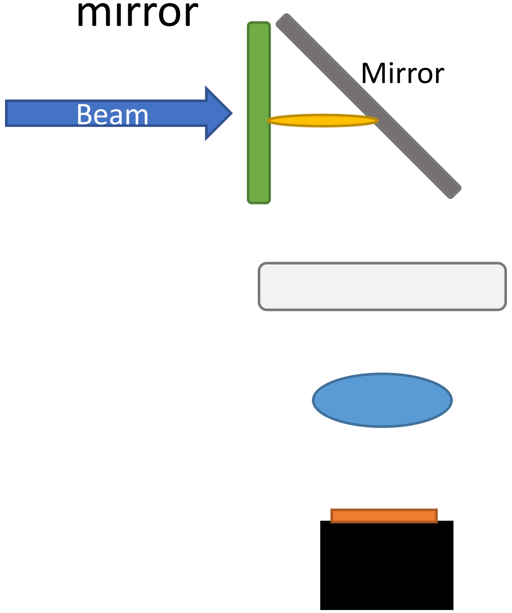
Potential COTR lobes

1. Crystal @ 45°



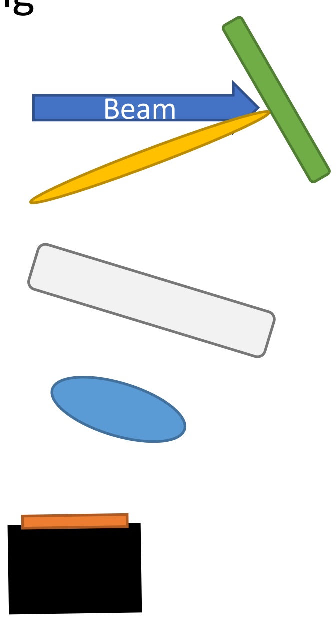
- Very simple to implement
- Poor optical resolution (depth of field)
- Resolution limited by scintillator thickness
- COTR can spoil image

2. Crystal normal & 45° mirror



- High resolution
- Compact design in vacuum, compact imaging
- Mirror subject to radiation damage over time
- COTR + upstream sources can spoil image

3. Observing obliquely and with Scheimpflug imaging

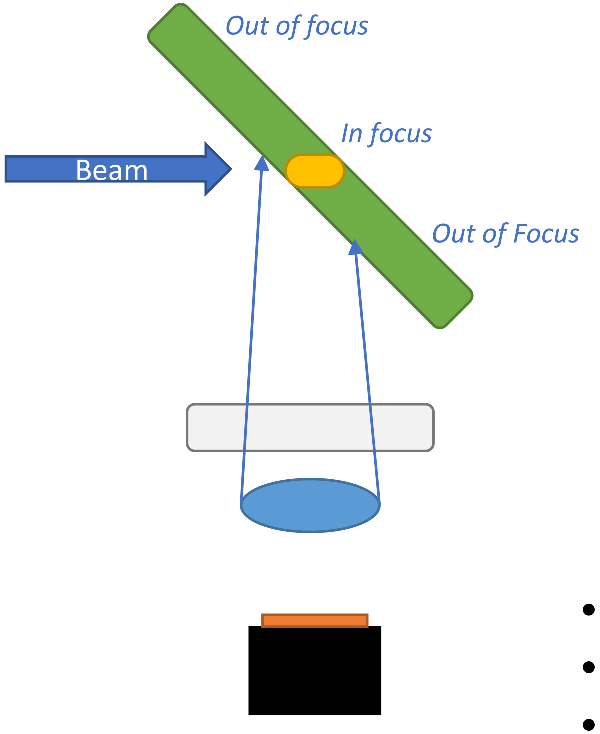


- COTR not transported to optics
- With correct angles (respecting refraction) will provide high resolution
- Less trivial imaging
- Non-compact design

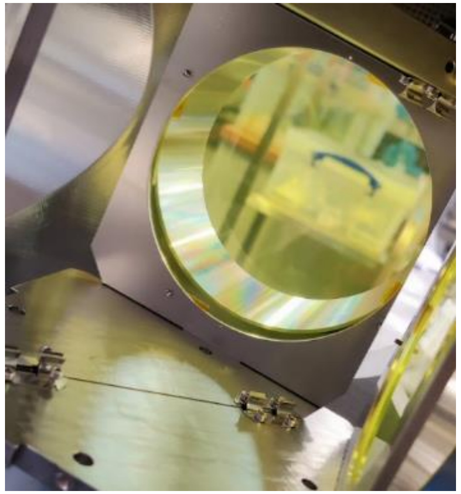
More detail can be found in: Ischebeck, Rasmus, et al. "Transverse profile imager for ultrabright electron beams." PRSTAB 18.8 (2015): 082802.

Issues with scintillators: Resolution & Imaging

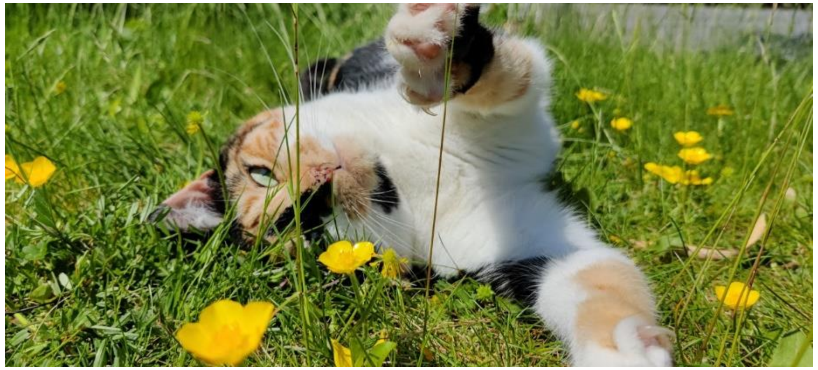
Geometric considerations – 'optical' physics & mechanics



- Thickness of scintillator impacts resolution
- Reasonable thinnest free standing crystal can be 200um thick
  - Remember a human being needs to handle it and assemble it!
  - Largest we buy is 100mm dia.
- Thinner scintillators can be made on a substrate, down to 5um thick
  - Substrate intercepting the beam can charge up…
- Imperfections (or dust) on surface will harm measurements

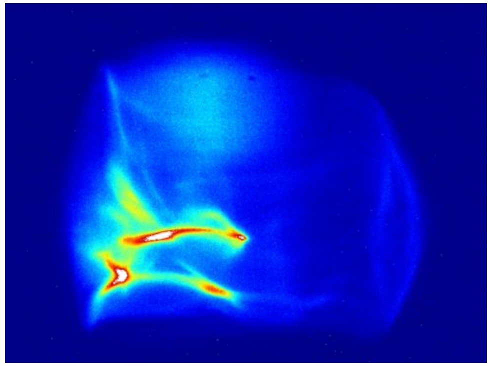


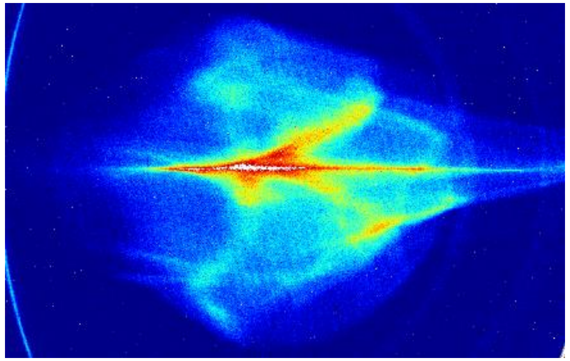
- Balancing Field of View , Magnification and Depth of Field can be a challenge
- Common problem in close up photography…
- Scheimpflug imaging is the solution for angled subjects – Google to learn more!

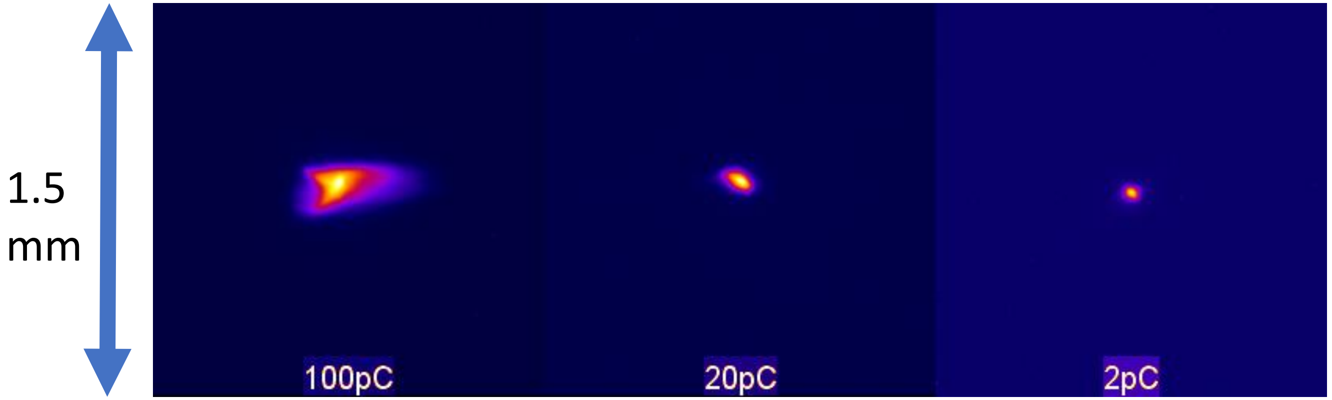


Real beam images

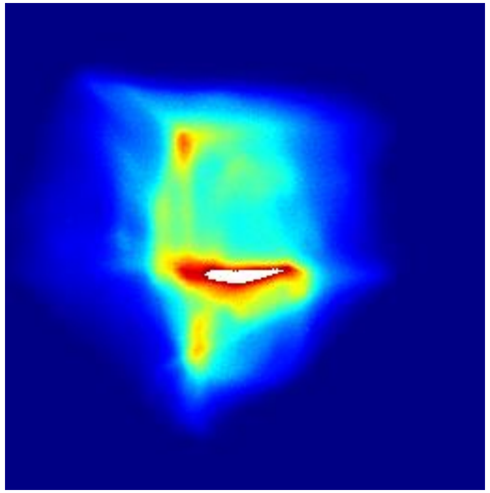
Holiday snaps from CLARA BA1

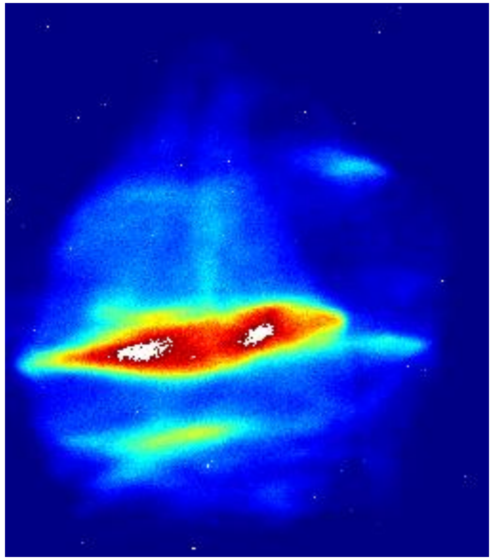






σ_x = 90 um σ_x = 35 um σ_x = 20 um





- Images can reveal lots of interesting features…
- Work of diagnostics research and engineering is to make sure it's a feature of beam and not feature of the diagnostic

- *Only x-y projection* of 6D charge density.
- One piece of a puzzle

- Takes a lot more work to produce useful physics from 'feature full' beam images

A warning: Statistical parameters & Data analysis

The RMS beam size is…

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- Accelerator physics often use 2nd moment of distribution – see Gaussian beams & Twiss parameters ☺

- Anscombe's quartet must be remembered:
- 4 (x,y) distributions with values:
  - $\langle x \rangle = 9$
  - $\langle y \rangle = 7.5$
  - $\sigma_y^{\,2} = 4.125$
  - $\sigma_x^{\,2} = 11$
  - Linear regression (fit): $y = 0.5x + 3$

- Warning applies when:
  - Using a beam image to make a beam size measurement
  - Using a set of beam sizes to calculate another parameter (e.g. emittance!)
  - *Whenever you use scripts to analyse large volumes of data*

Anscombe, Francis J. "Graphs in statistical analysis." *The american statistician* 27.1 (1973): 17-21.

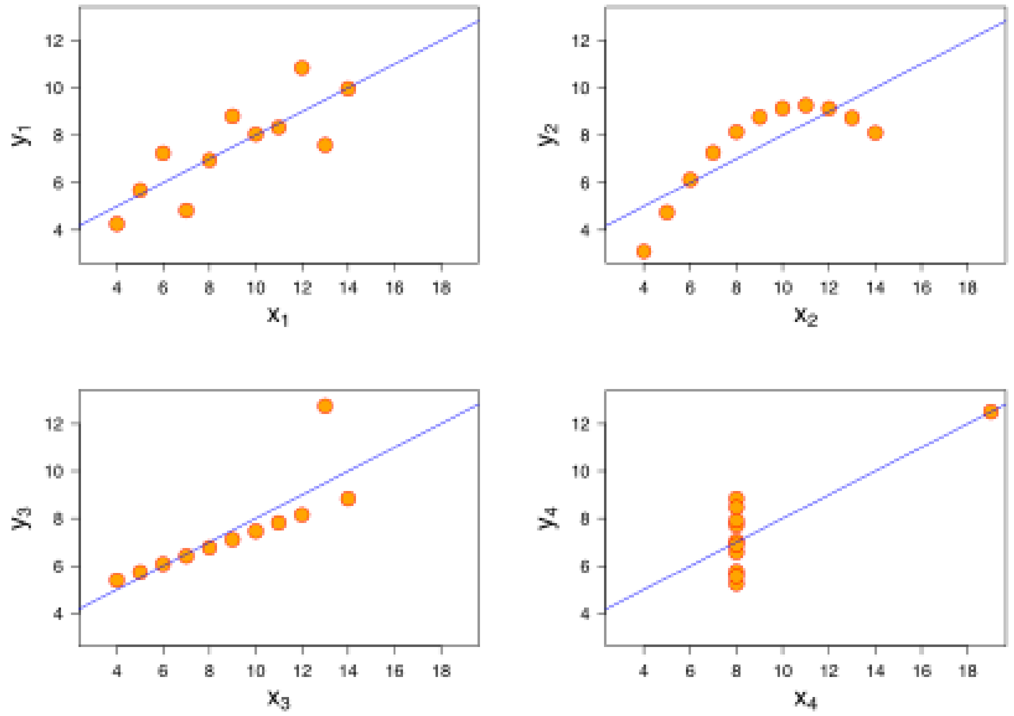


Image: https://en.wikipedia.org/wiki/Anscombe%27s_quartet

Beams can be messy.
Sense checks matter.

Break

Questions?

Measuring emittance

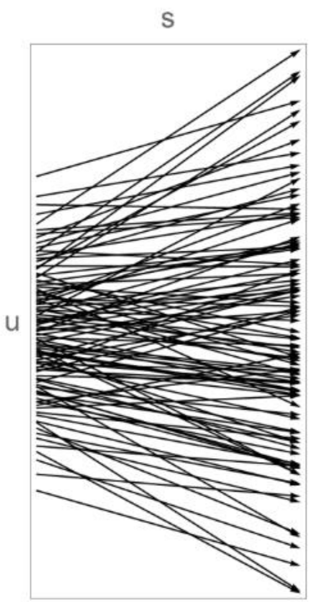
What is the transverse beam quality?

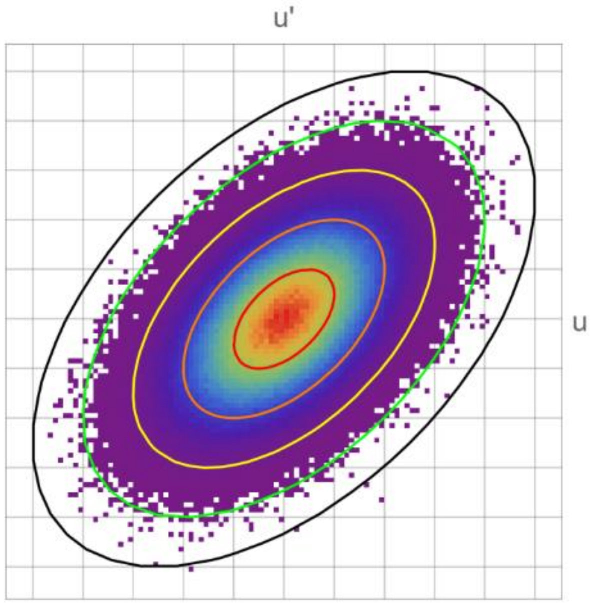
Emittance as a statistical value

Remembering Anscombe's Quartet

- 2 common equivalent definitions of 'emittance':
    - Area (of an ellipse) in transverse phase space the beam occupies
    - Measure of the non-laminarity of the particle propagation within the beam

Non-laminarity of particle trajectories with s





Area(s) of an ellipse in u-u' space

Image: J K Jones Thesis: DESIGN OF A NOVEL STACKED STORAGE RING FOR LOW EMITTANCE LIGHT SOURCES, UoM 2015

- Many flavours of emittance
    - RMS, 90% ,Full distribution
- Understanding emittance can be complex
- Measuring emittance could be several lectures!

Often measure and use RMS emittance
Derived from measuring RMS beam sizes
Many potential diagnostic issues!

Multiscreen methods

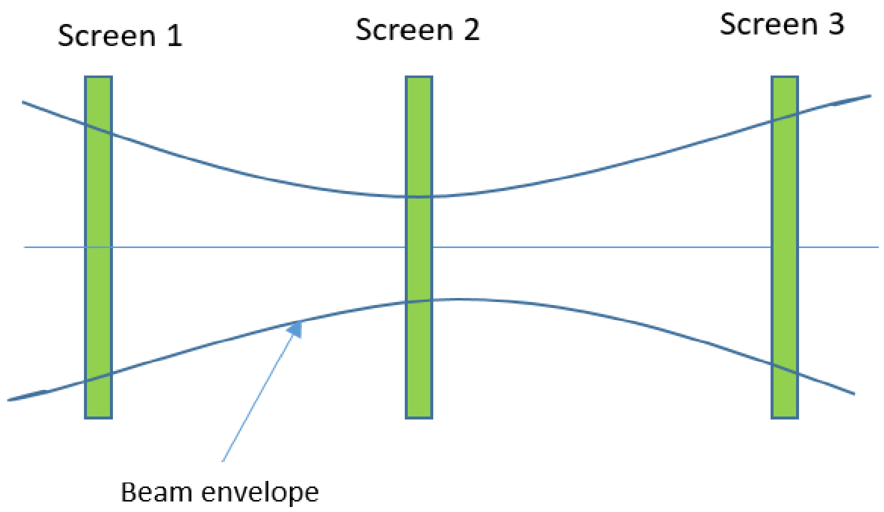
3-Screen method

The variation of beam size across (at least) 3 screens of known separation can be used to calculate the emittance.
Typically need some optics (quads) to have enough beam size variation (phase advance) between the screens

For an ideal Gaussian beam 3 screens is enough and emittance can be calculated directly from beam sizes.

With additional 'beam features' 4-5 screens and a fit will provide a more reasonable estimate of emittance

Considerable space and equipment required for multiple screens across a drift



More info can be found in SY Lee Accelerator Physics, 3rd pg 58

Quadrupole scans

Simple version

- Varying the quadrupole strength varies size of beam on screen
- Variation of the beam size is defined by emittance
- Systematically scan the quad strength, measure beam size
  - Multishot measurement

Need to know:

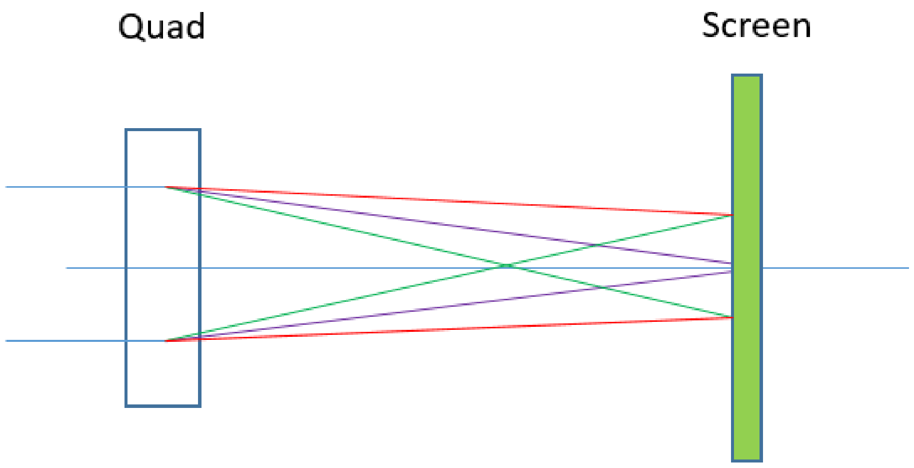
- Quad length - l_q
- Quad strength(s) - k_q
- Distance quad to screen- L_{qs}
- RMS beam size(s) on screen - σ_u

Plot $k_q l_q$ vs σ_u^2

Fit: $\sigma_u^2 = A\,(k_q l_q - B)^2 - C$

$$\varepsilon_{u,N} = \frac{\sqrt{A\,C}}{L_{qs}}$$

Ensure scan through a waist – fully sample beam phase advances



Schematic:

Initial beam

Increased focussing

Over focusing

Limitations of quadrupole scans

Sometimes too good to be true

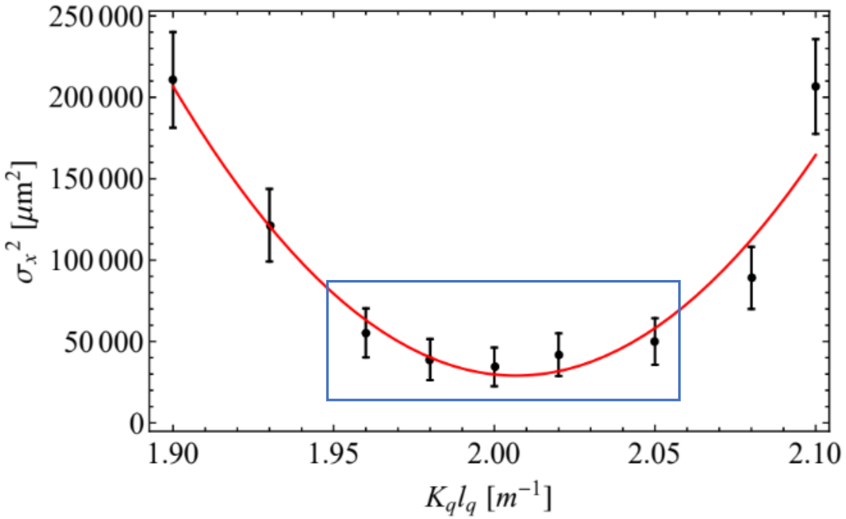
Watch out for:

1. Focussed beam size (e.g. x) becoming too small to accurately measure
2. Defocussed beam size (e.g. y) becoming so large it is lost from screen edges
3. Not having the available quad strength to find a waist at the screen

Means carefully setting upstream quads (non-scanned) to ensure 1 & 2 hold for entire range of scanned values

Assumes the measurement process doesn't change emittance
Tightly focusing a beam and transporting over a drift can cause space charge to increase the emittance
Problem for high charge densities or low energies, and/or long drift lengths

Real example of a poor quad scan measurement (Pacey, BA1 2018)



Did all beam optics and data analysis correctly…
Did not have the imaging resolution on the scintillator!

Slit scans

Simple masking method

- Move a metallic slit across beam, forming a series of beamlets
  - Multishot measurment
- Drift beamlet to screen and measure their size, location, and intensity

- Creating discrete samples of x and then measuring x' profile

- Series of formula to return RMS emittance (see last slide)
  - Or can reconstruct full phase space
- Need to have beam size at slit >> slit width and understand if beam is diverging/converging
- Repeatable slit motion at <1um level is possible

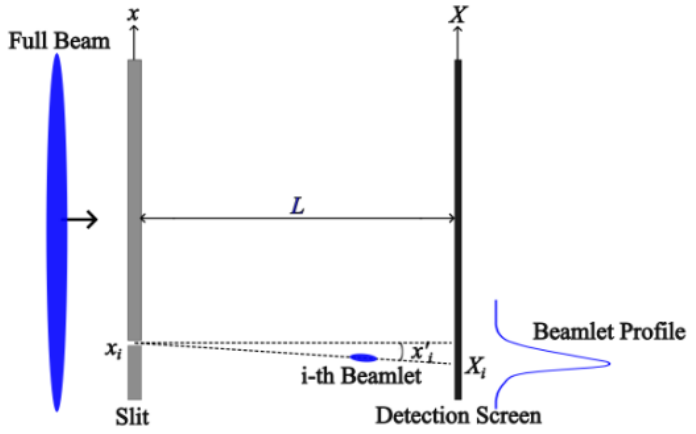
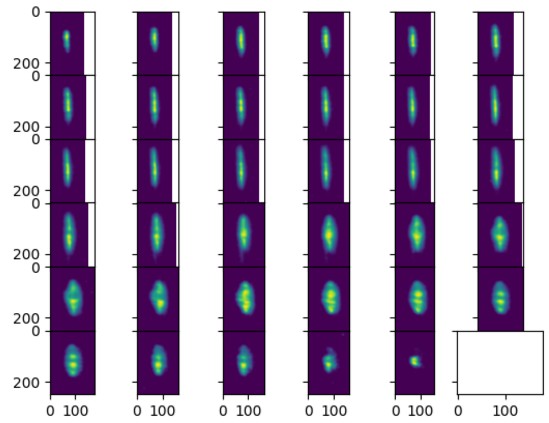
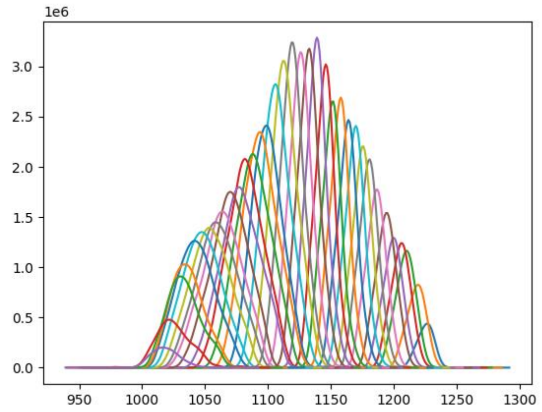


Image Courtesy T. Overton Thesis

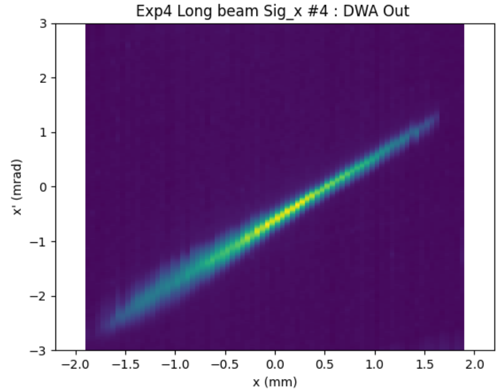
Pacey, BA1 (2021)



Capture images



Plot profiles



Produce phase space

Combs and Pepperpots

More complex masking

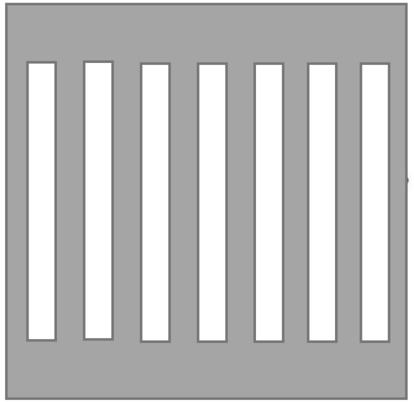
Instead of moving a slit to generate samples, have a static mask with many slits or holes

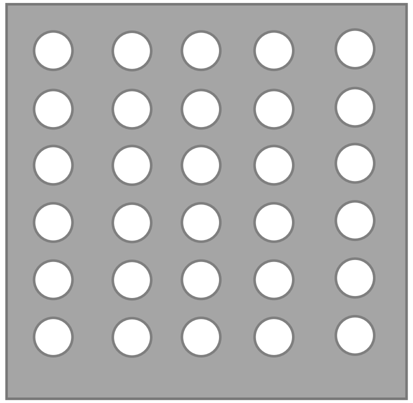
Comb – array of slits – single shot monitor for 1D
Pepperpot – array of holes – multishot monitor for 2D

Must avoid overlap of beamlets after slit

No variability in sampling -> need either several masks with different size holes or ability to tune beam optics

Fast, single shot emittance monitoring is powerful tool for machine optimisation





Machine learning optimisation requires good diagnostics.
This result uses slit comb!
Roussel, Ryan, et al. "Turn-key constrained parameter space exploration for particle accelerators using Bayesian active learning." *Nature communications* 12.1 (2021): 5612.

Limitations of masking methods

More things to watch out for

- Mask must be thick enough to scatter beam. Strong scaling with energy.
  - 2mm Tungsten -> 1 GeV electrons scatter 17mrad ☺
  - 5 Gev <1 mrad ☹

Jackson, Classical Electrodynamics,1975

$$\frac{d\langle\theta^2\rangle}{dz} \cong \left[\frac{16\pi NZ(Z+1)r_e^2}{\gamma^2\beta^4}\right]\ln\left(\frac{204}{Z^{0.33}}\right)$$

- Slit size must be smaller than beam
  - Easy to set with a movable slit + feeler gauge, hard to machine smaller holes a (thick) pepperpot

- Need sufficient samples across beam size
  - Easy to tune slit scan with a stage, slits/combs are fixed

- Need sufficient drift lengths for beam divergence to dominate beamlet size

- Beamlet size and location needs to be resolvable by **imaging system**
  - Low geometric emittance beams have small beamlets

- Intensity of beamlets will be low at beam edges
  - Need high dynamic range on camera and good SNR

- Difficult to perform masking for low absolute charges
  - Can combine with high-resolution Fcups to get accuracy and precision…

Detail on designing pepperpot here:
Apsimon, Oznur, Barney Williamson, and Guoxing Xia. "A numerical approach to designing a versatile pepper-pot mask for emittance measurement." NIMA (2019): 162485.

Summary

Take homes

- 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
- Appreicate the whole system, make sensible choices for the beam you (expect to) have

Resources

References & links for images and further reading

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- Using a slit comb and Ml to optimise machine
  - Roussel, Ryan, et al. "Turn-key constrained parameter space exploration for particle accelerators using Bayesian active learning." *Nature communications* 12.1 (2021): 5612.
  - https://www.nature.com/articles/s41467-021-25757-3
- Detailed discussion of slit comb technique
  - https://accelconf.web.cern.ch/PAC2013/papers/thpac13.pdf
- Best recipe for slit scan emittance calculation
  - Emittance Formula for Slits and Pepperpot measurement, M Zhang, FNAL
  - https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/018/28018451.pdf?r=1&r=1
  - O Mete-Apsimon: A Numerical Approach to Designing a Versatile Pepper-pot Mask for Emittance Measurement
  - https://arxiv.org/abs/1907.13515