Beam Instrumentation at MAX-IV

Big Science Sweden – November 2023

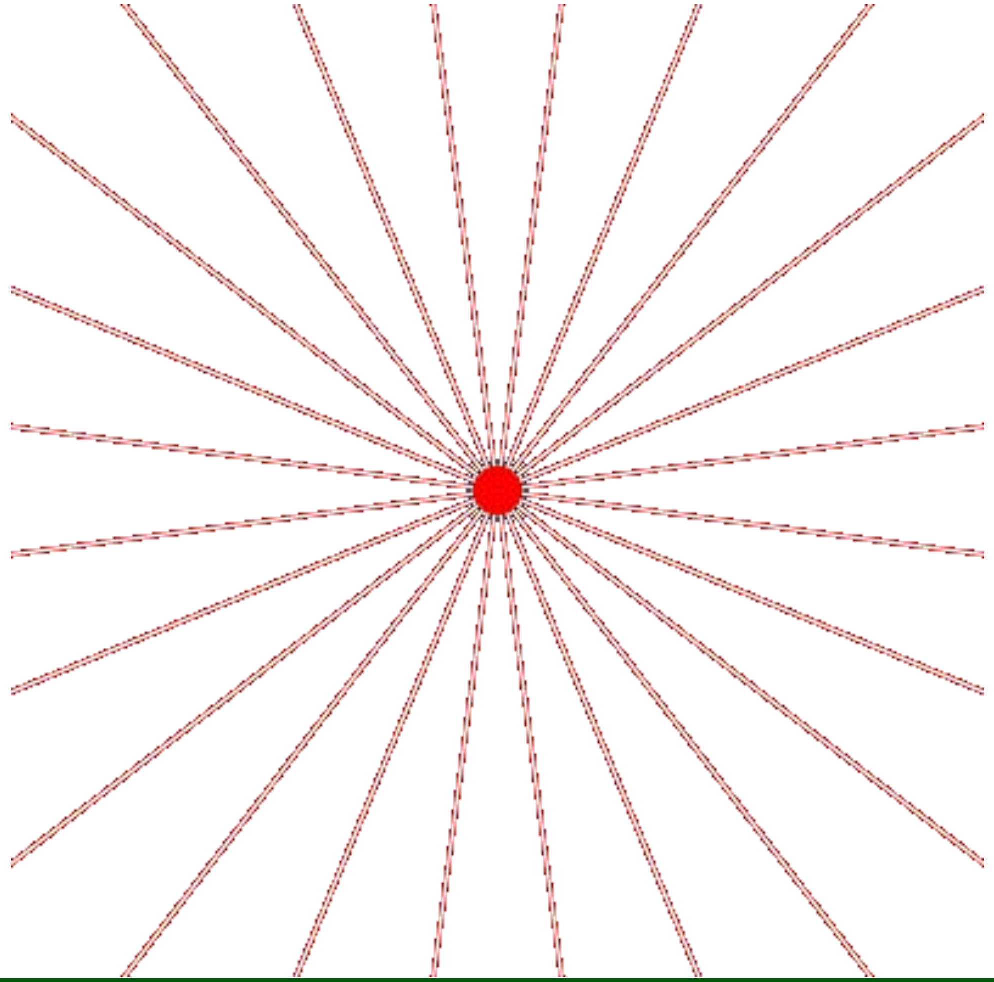
Head of Accelerator Operations, MAX-IV
Stephen Molloy, on behalf of many people

Outline

- Introduction to MAXIV
- Examples of diagnostics
- Position, timing, quality, particle distribution
- A real-life example of solving a problem
- Summary

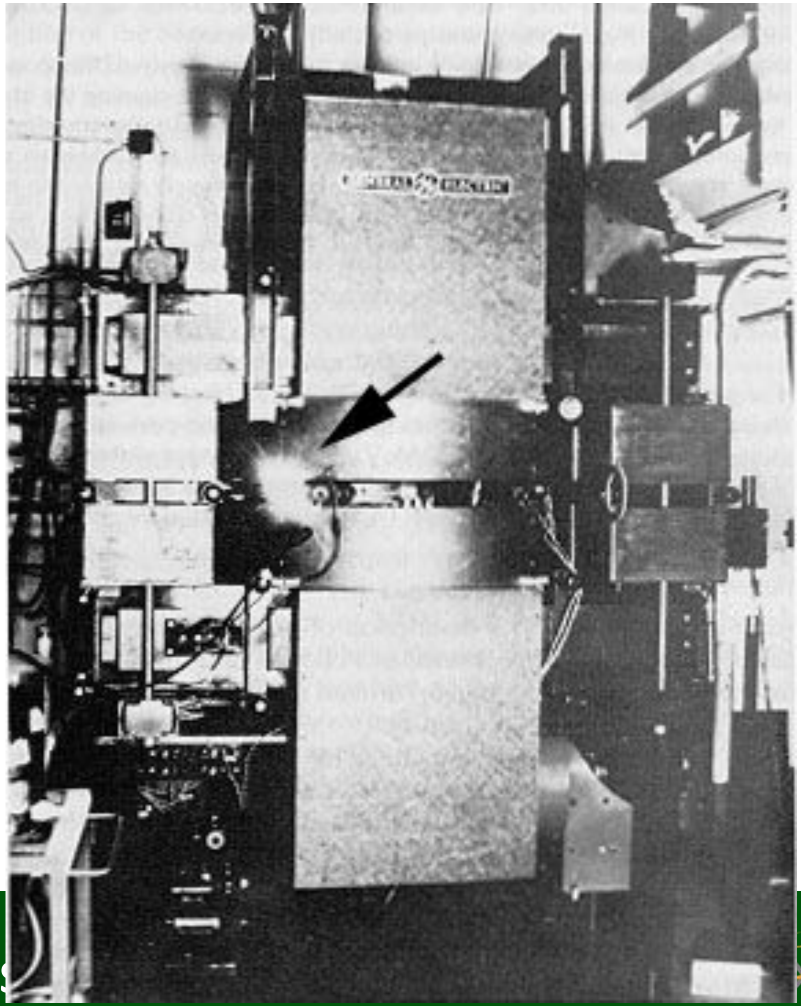
What is synchrotron light?

- E-field around a charge is disrupted by acceleration
- This disruption moves at *c*, and is observed as a flash of light

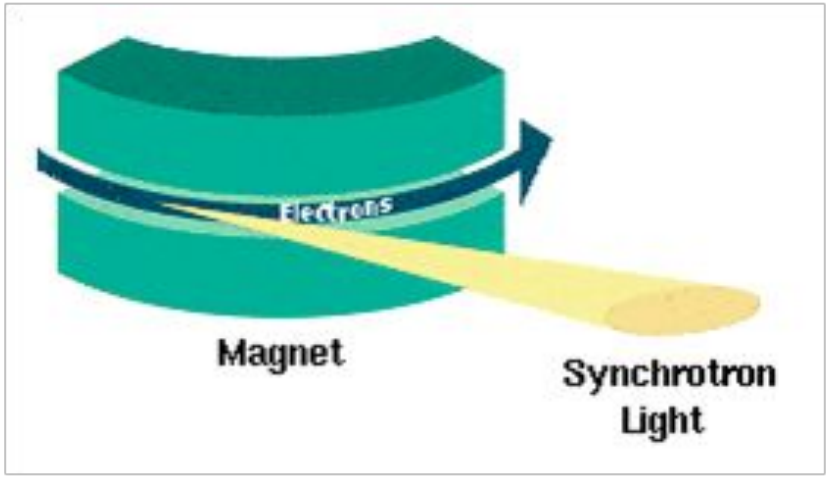


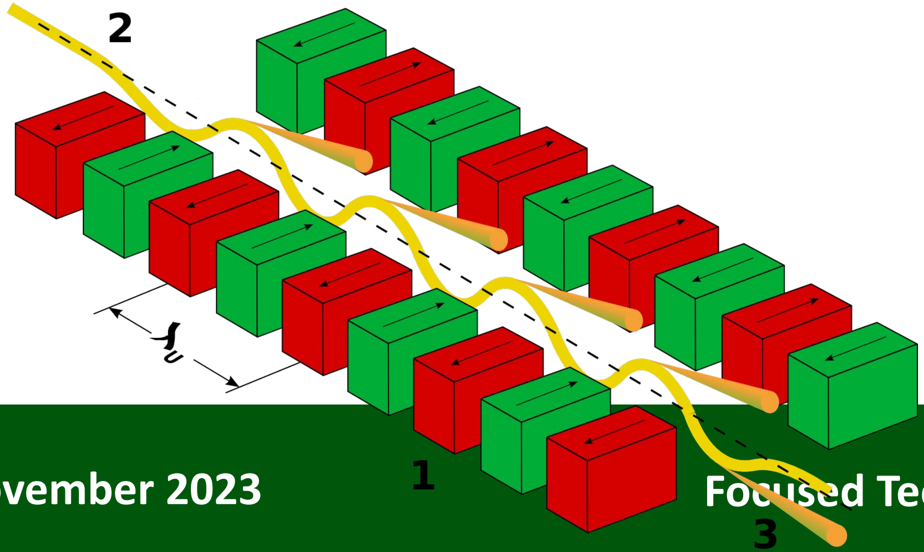
First observation

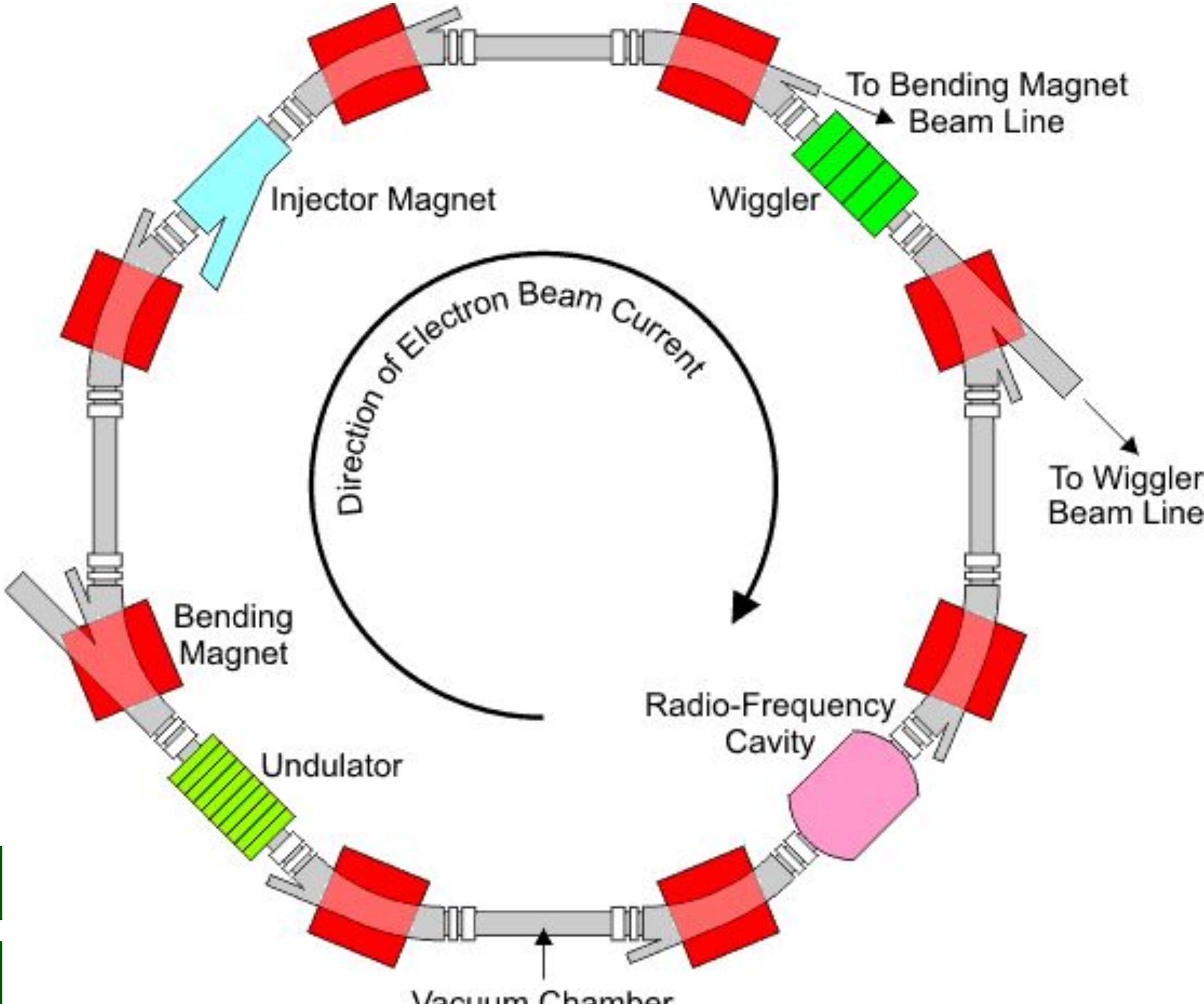
- 24th April, 1947, this light was first observed in the GE 70 MeV synchrotron
- Initially thought to be arcing, they soon realised they were observing direct emission from orbiting electrons



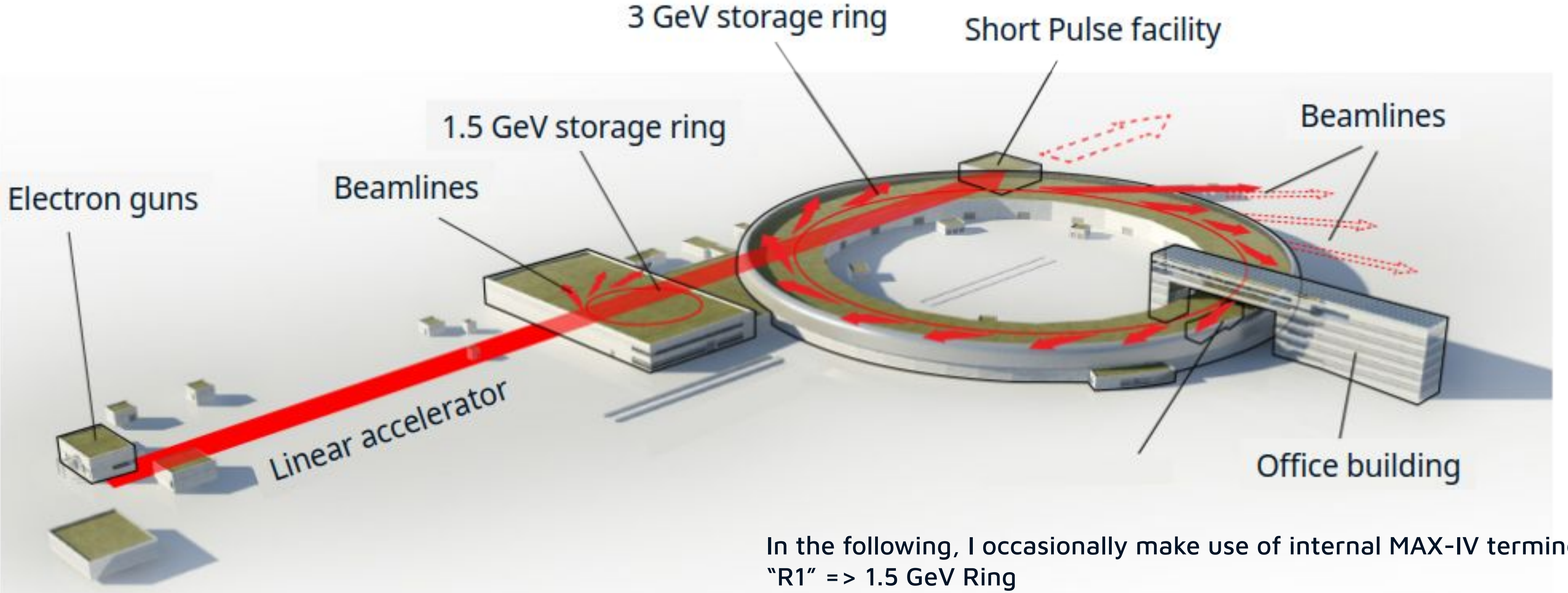
Synchrotron Light Sources







MAX-IV Facility



In the following, I occasionally make use of internal MAX-IV terminology:
"R1" => 1.5 GeV Ring
"R3" => 3.0 GeV Ring
"SPF => Short Pulse Facility

Facility Goals

	Beam intensity	Delivery hours/year	Availability	MTBF
3.0 GeV Ring	500 mA	5000	>97%	~100 hours
1.5 GeV Ring	500 mA	5000	>97%	~100 hours
Short Pulse Facility	100 pC @ 100 Hz	4500	>95%	~12 hours

Rings:

- Low emittance (diffraction limited)
- Stability (transverse and longitudinal)
- High reliability

SPF:

- Very short (tens of femtoseconds)
- Well focused through the undulator
- High repeatability in time
- Low jitter

Beam diagnostics

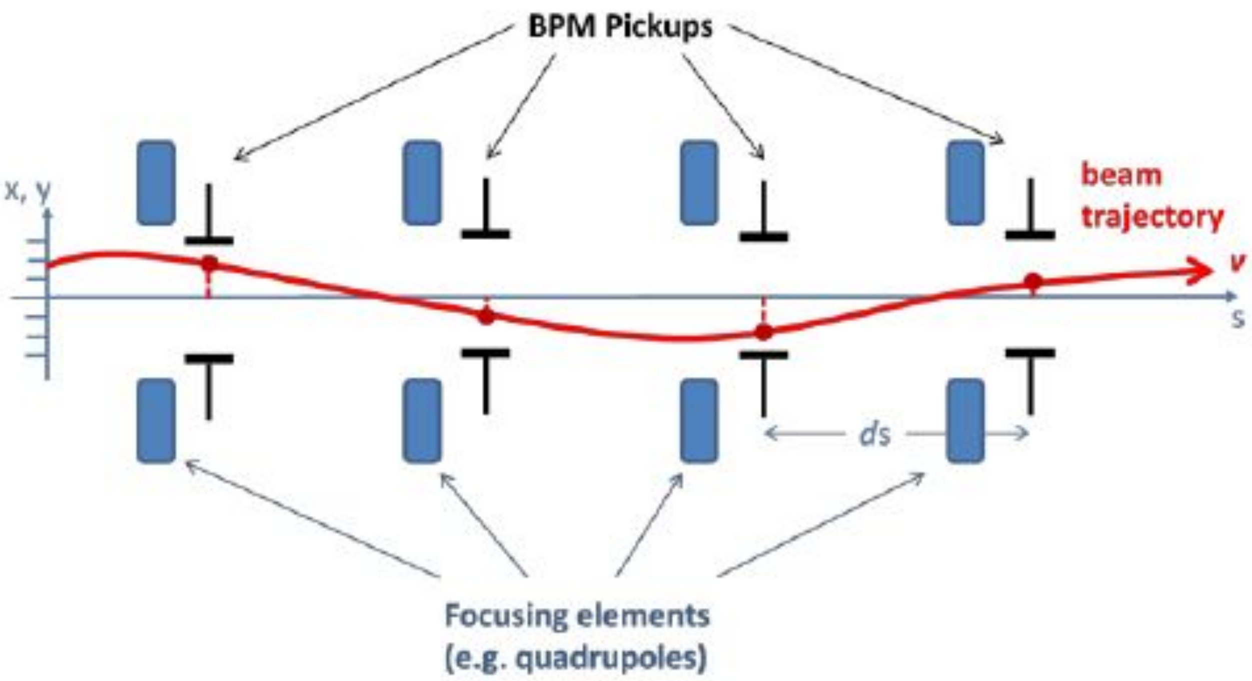
- Measurements of properties of the accelerator
  - This is a wider view than most, perhaps due to my role in Accelerator Operations
  - My perspective is on measurements of the machine as a whole
- Why are these needed?
  - Confirmation/validation of performance
  - Looking towards improvements and upgrades
  - Detection of problematic behaviour
  - Understanding/analysis of downtimes

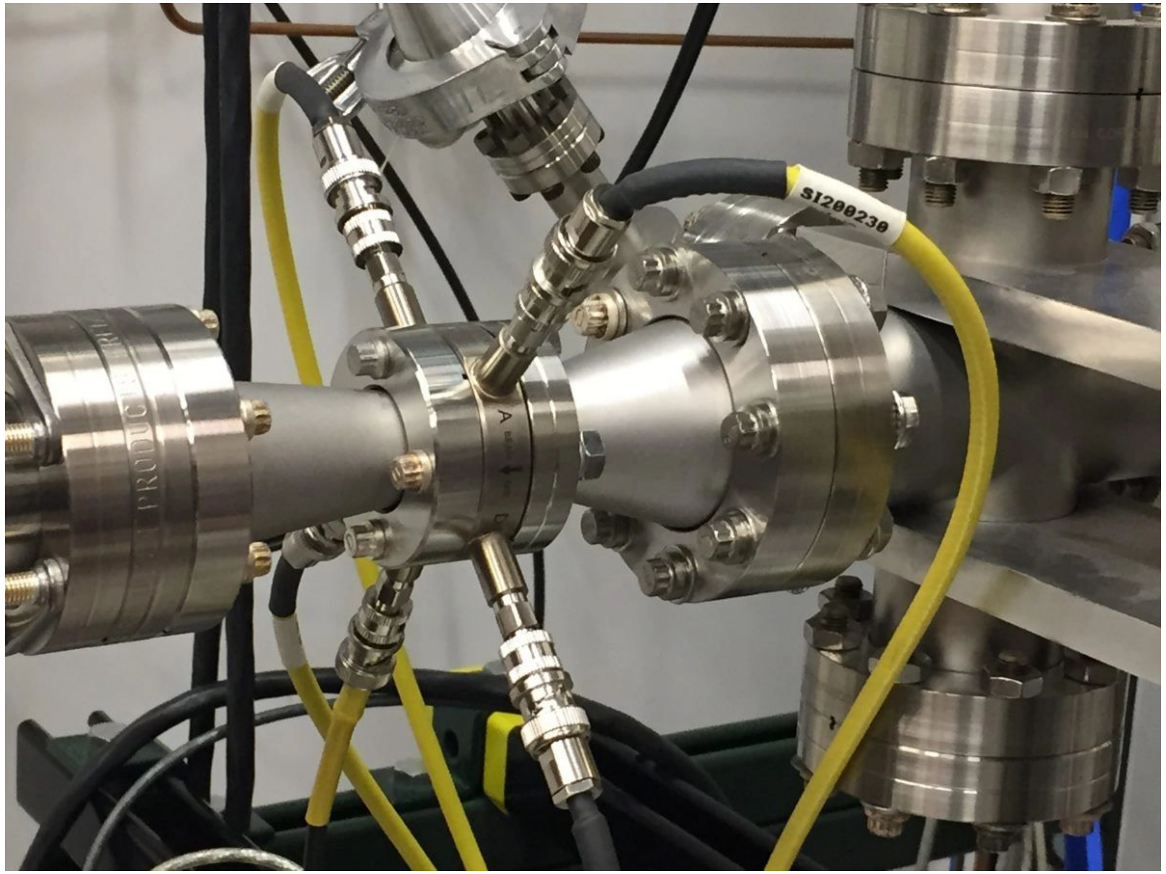
Measuring beam position

Key idea

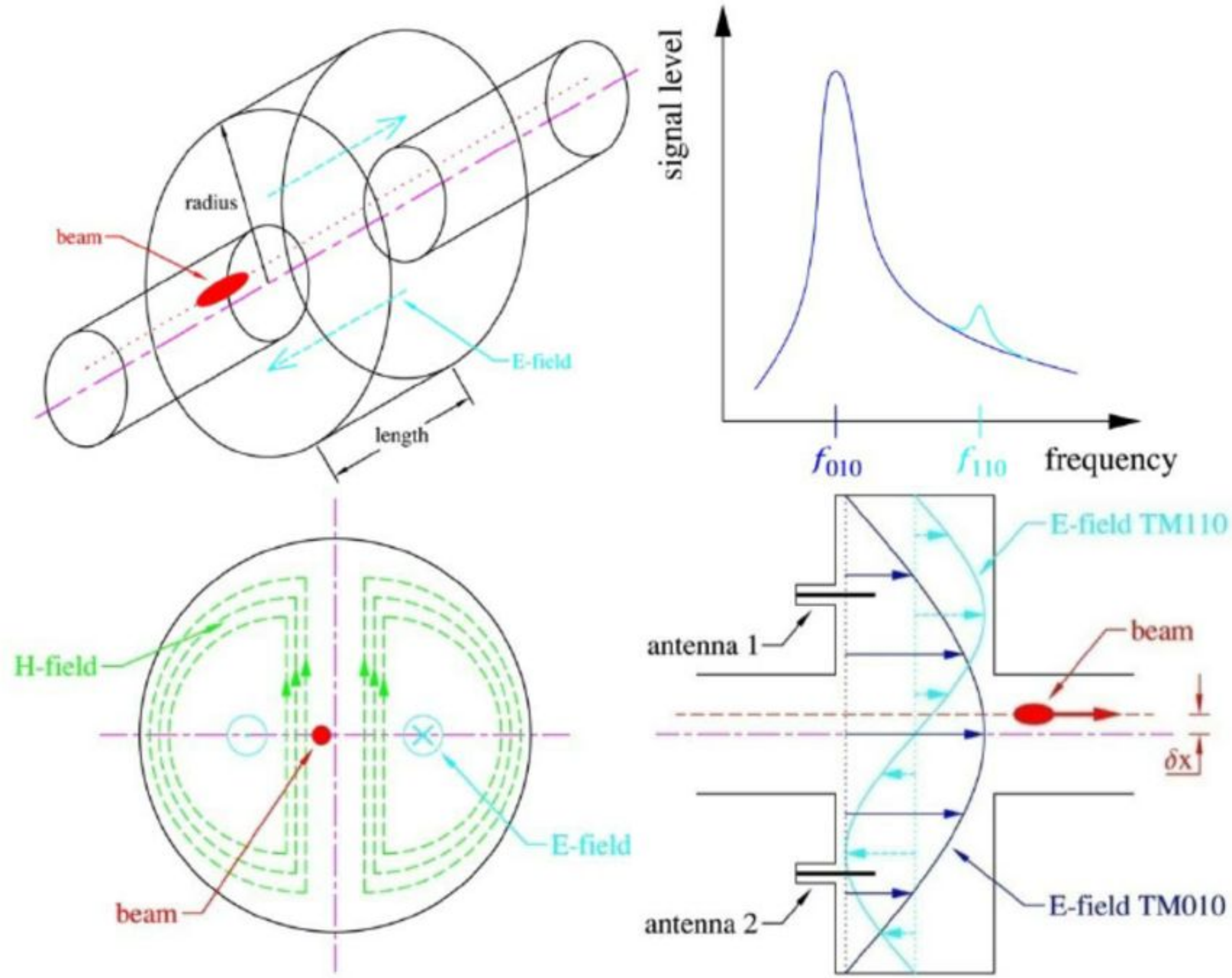
- Charged particles have an associated EM field
- This field can be easily sampled by in-vacuum electrodes
- It can also be manipulated by the design of the vacuum chamber
    - For example, to induce a resonance at a particular frequency

In-vacuum electrodes





Geometry affects the signal



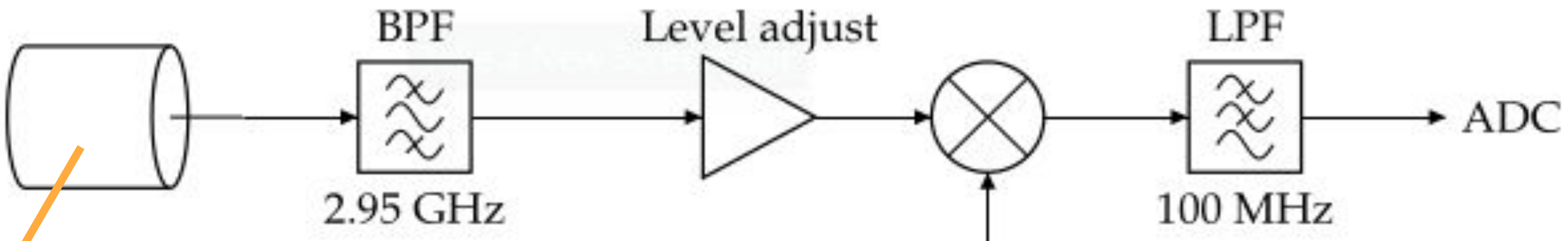
- Unlike the previous slide, this geometry causes the signal to resonate
- Longer lasting signal provides longer measurement time
    - Higher resolution
- But long decay time means bunch-to-bunch mixing

Measuring beam arrival time

Not “where is the beam?”, but “when is the beam?”

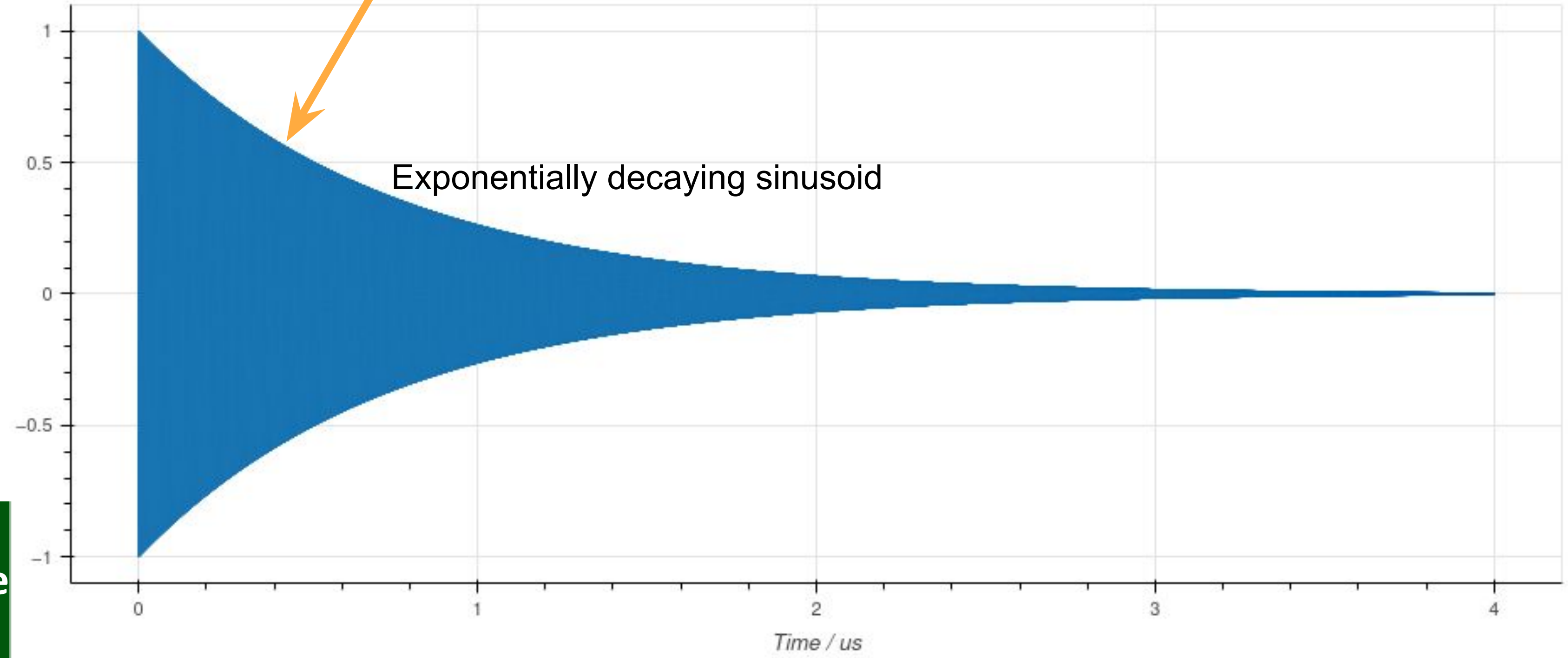
- Imagine you are experimenting with a fast system
  - Maybe a protein interaction
- You want to know **when** the light arrives in relation to the start of the process
- Sometimes to very high precision
  - <10 fs

Again, make use of the EM field surrounding the beam



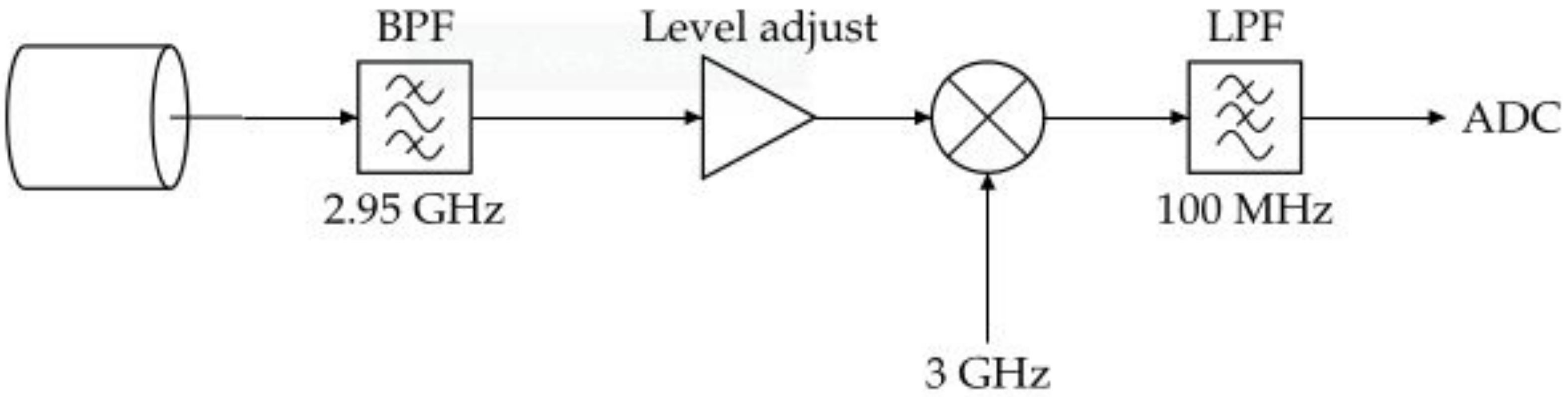
$$E = q^2 \frac{\omega_0}{2} \left(\frac{R}{Q} \right)$$

= ~9 nJ → ~15 dBm



MAX IV

Again, make use of the EM field surrounding the beam



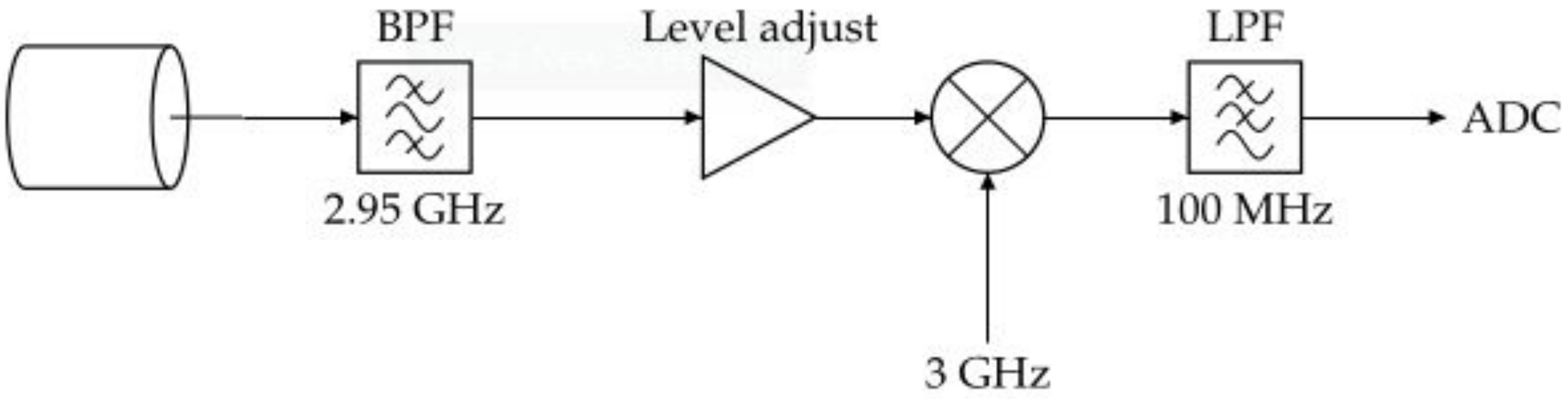
A mixer multiplies two signals.

$$\sin(\omega_1 t) \cdot \sin(\omega_2 t)$$

RF Input (from the cavity)

LO Input (a CW signal with well-known phase)

Again, make use of the EM field surrounding the beam



A mixer multiplies two signals.

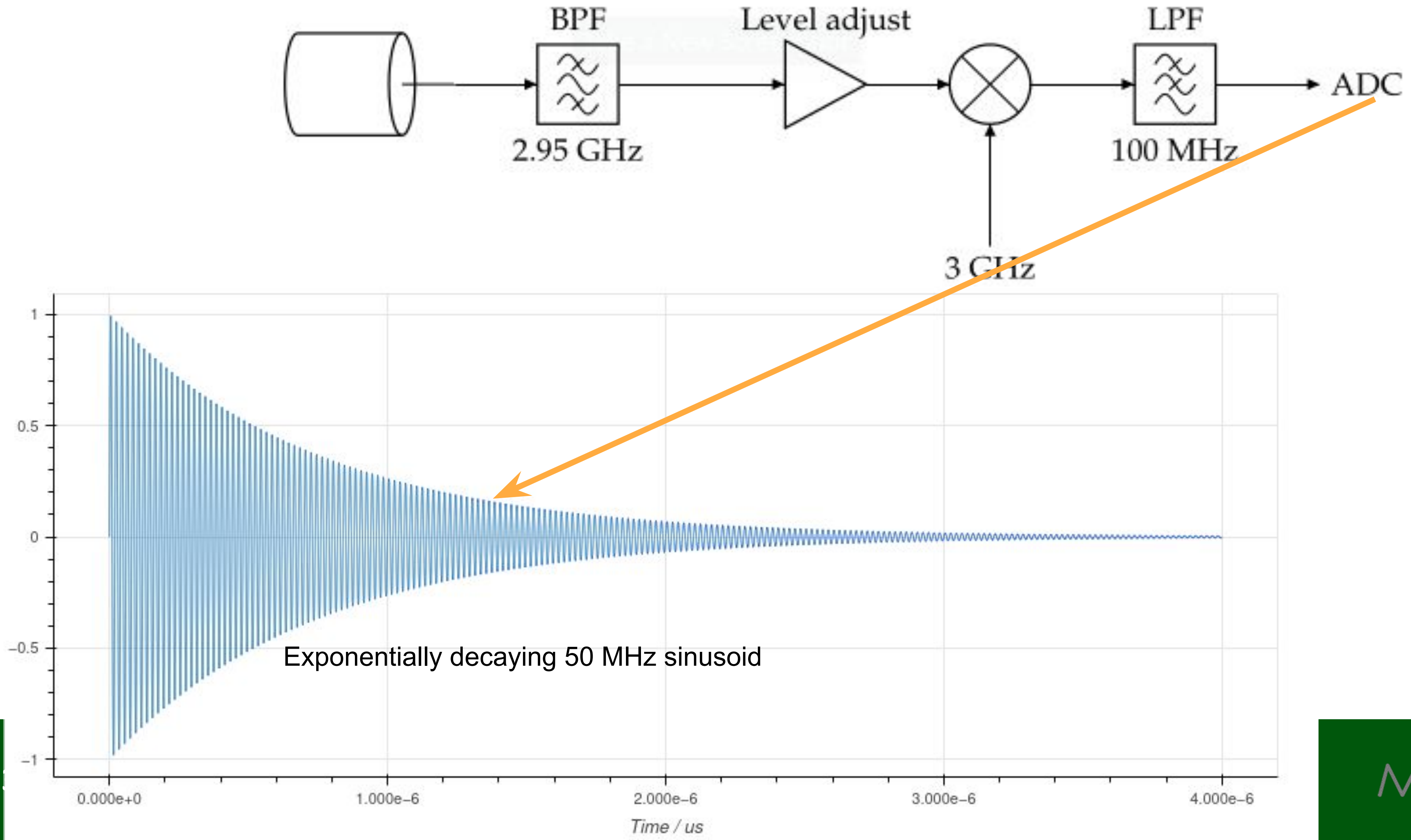
$$\sin(\omega_1 t) \cdot \sin(\omega_2 t) = \frac{1}{2}cos((\omega_1 - \omega_2)t) + \frac{1}{2}cos((\omega_1 + \omega_2)t)$$

RF Input (from the cavity)

LO Input (a CW signal with well-known phase)

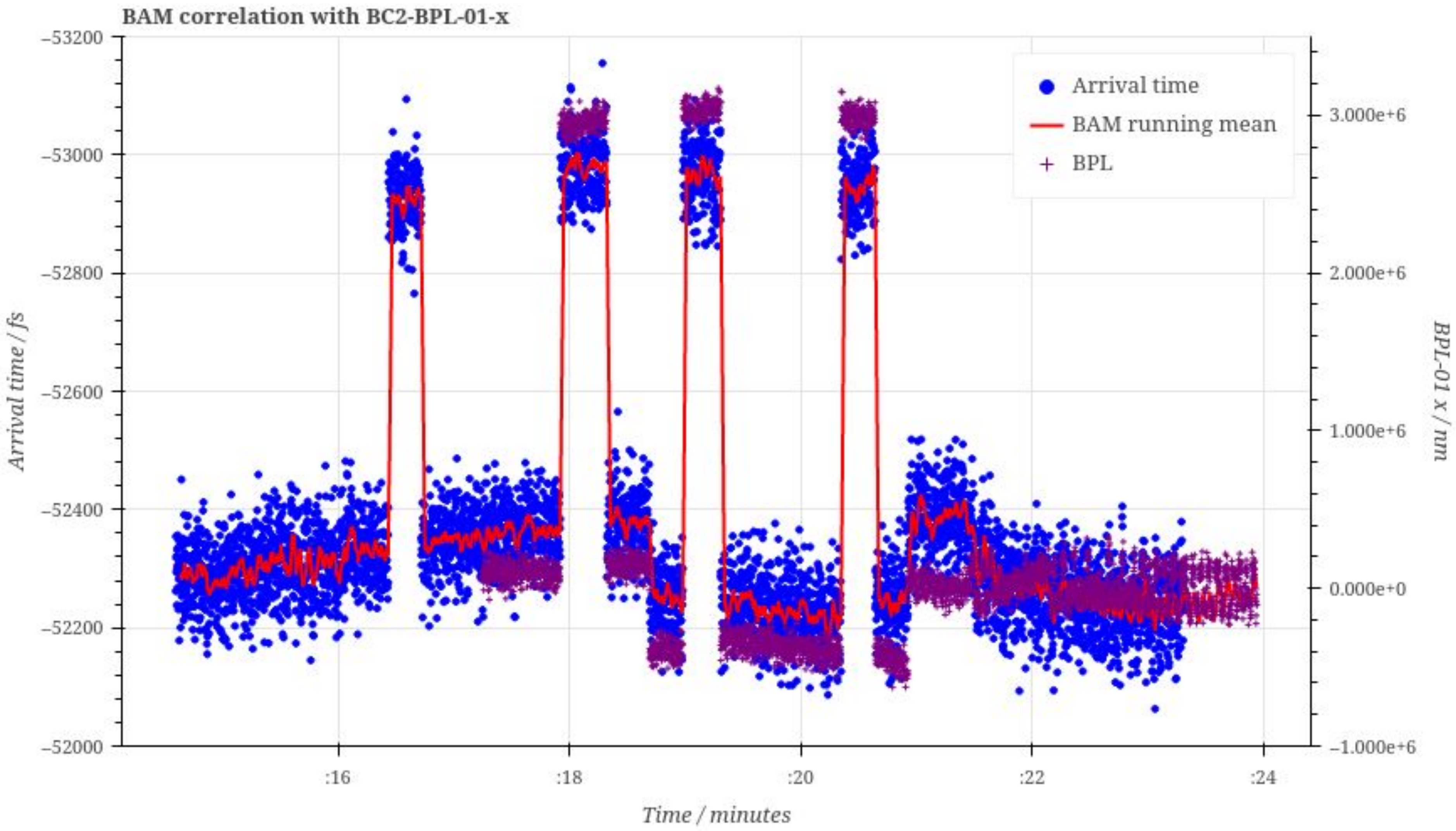
Sum of two signals. One whose frequency is the difference, and one whose frequency is the sum, of the inputs.
LPF to discard the sum, and you're left with a signal you can digitise.
Note that the phase of this will be the relative phase of the RF and LO inputs. That is, **the relative phase of the beam with respect to the accelerating RF** as desired.

Again, make use of the EM field surrounding the beam



MAX IV

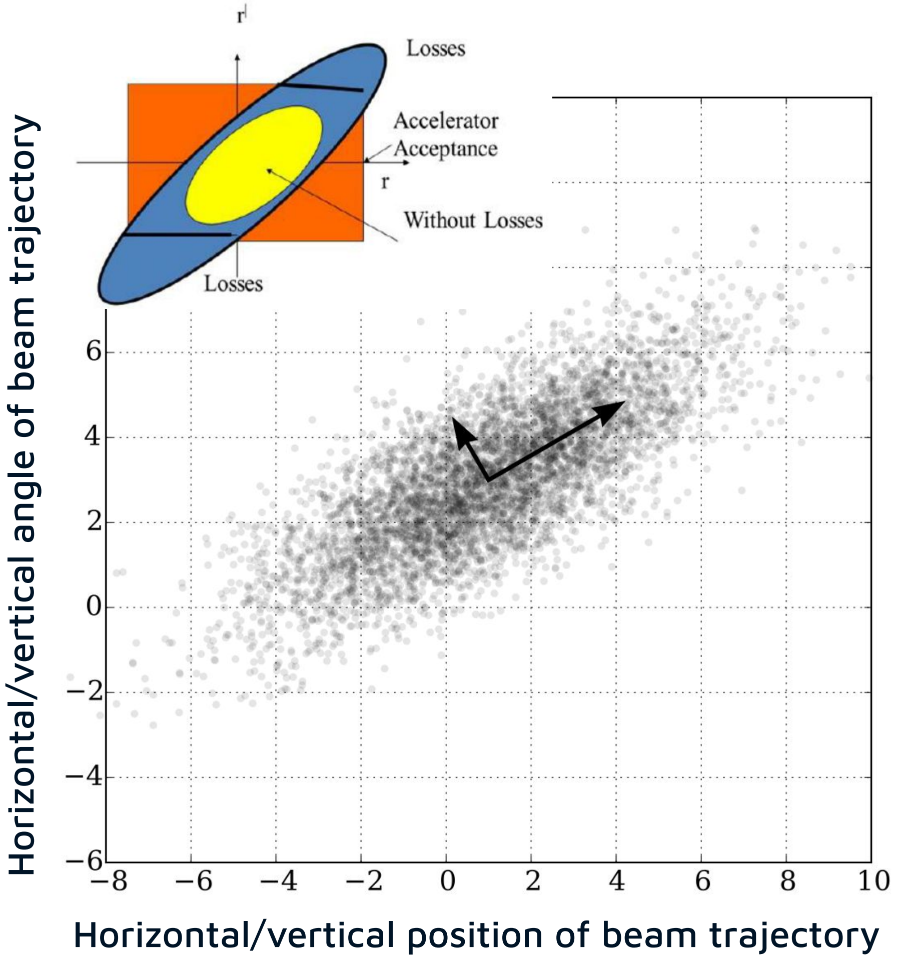
Measuring timing in the SPF



MAX IV

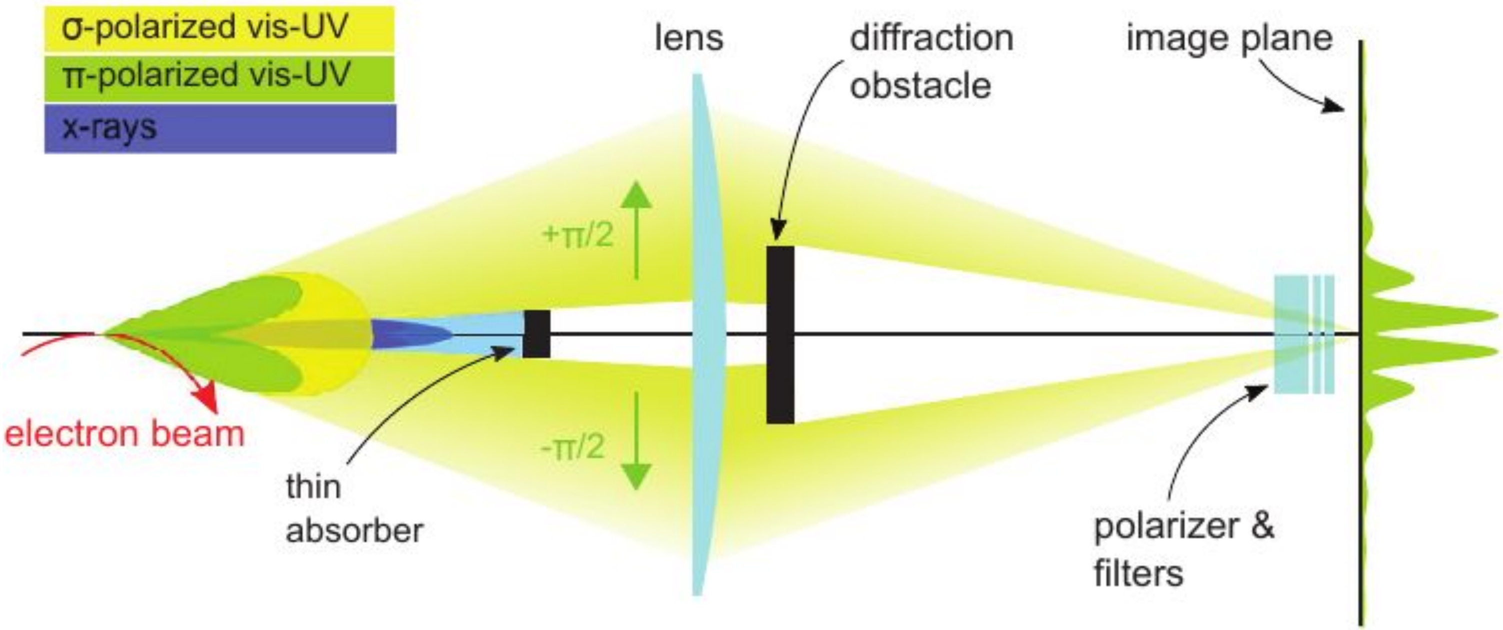
Measuring beam emittance

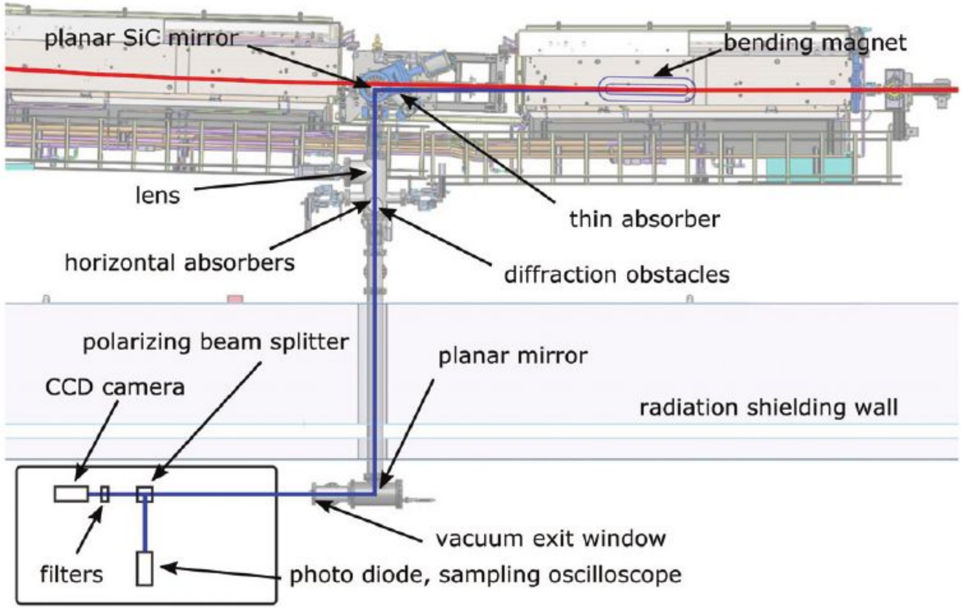
What is emittance?



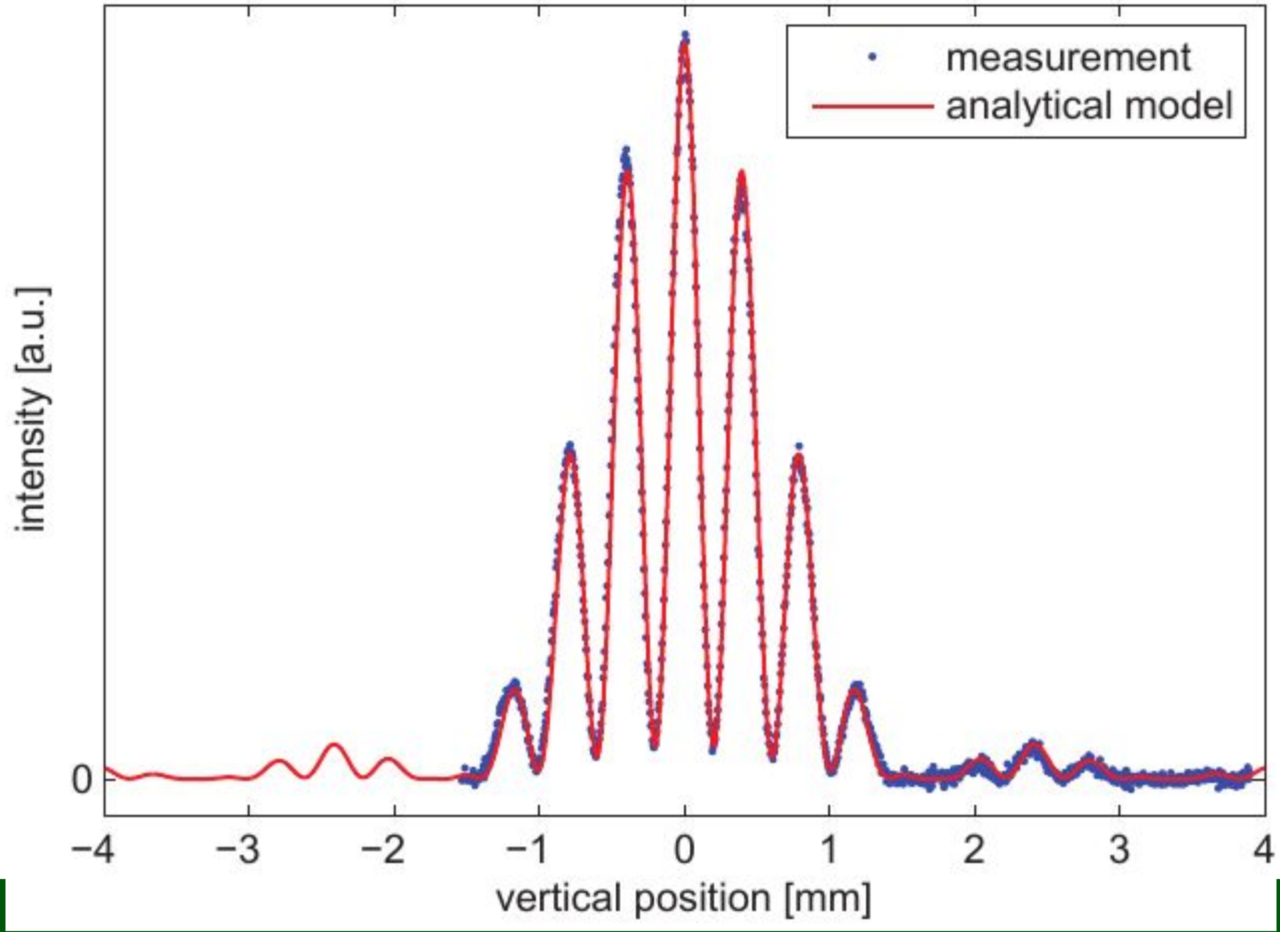
- Each particle has a position and an angle
  - Vertically and horizontally
- Emittance is the area occupied by the beam in this "angle/position" plane
- Can be thought of as the size of the random motion of the particles
  - Lower emittance ⇒ highly correlated motion
- A constant of the dynamics
  - Under certain circumstances…
- Directly linked to quality

Measure synchrotron radiation





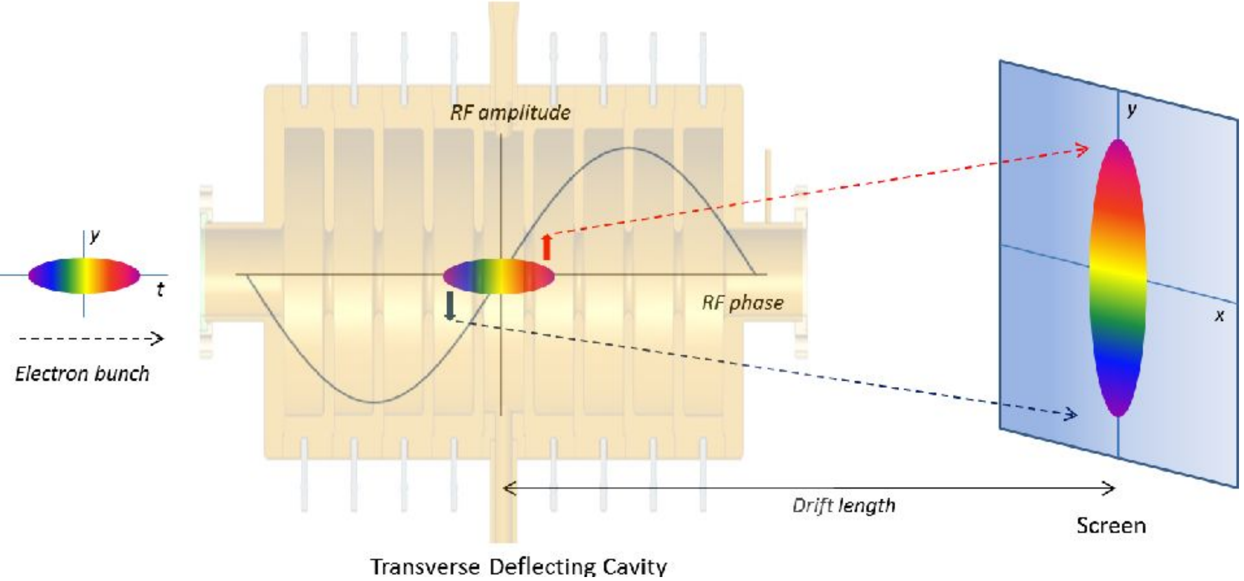
Beam size → emittance



- Beam size is a combination of emittance and focussing
- Uncouple these by measuring beam size at two points
  - e.g., weak & strong focus
- Then extrapolate emittance

Internal bunch properties

Transverse Deflecting Cavity (TDC)

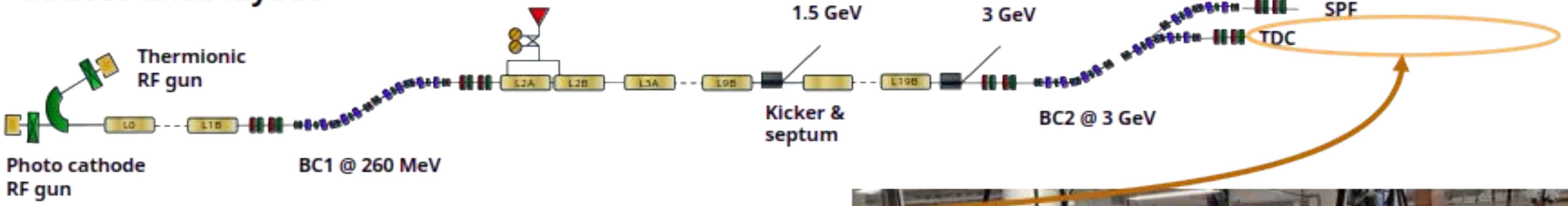


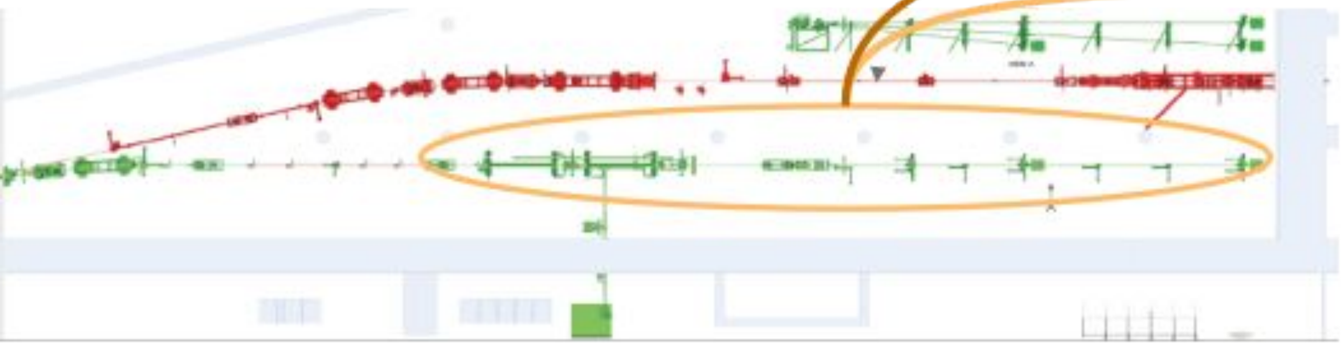
- Kick the beam with an amplitude that depends on z position of the particle
- Rotates longitudinal information into transverse

Slide by Sara Thorin

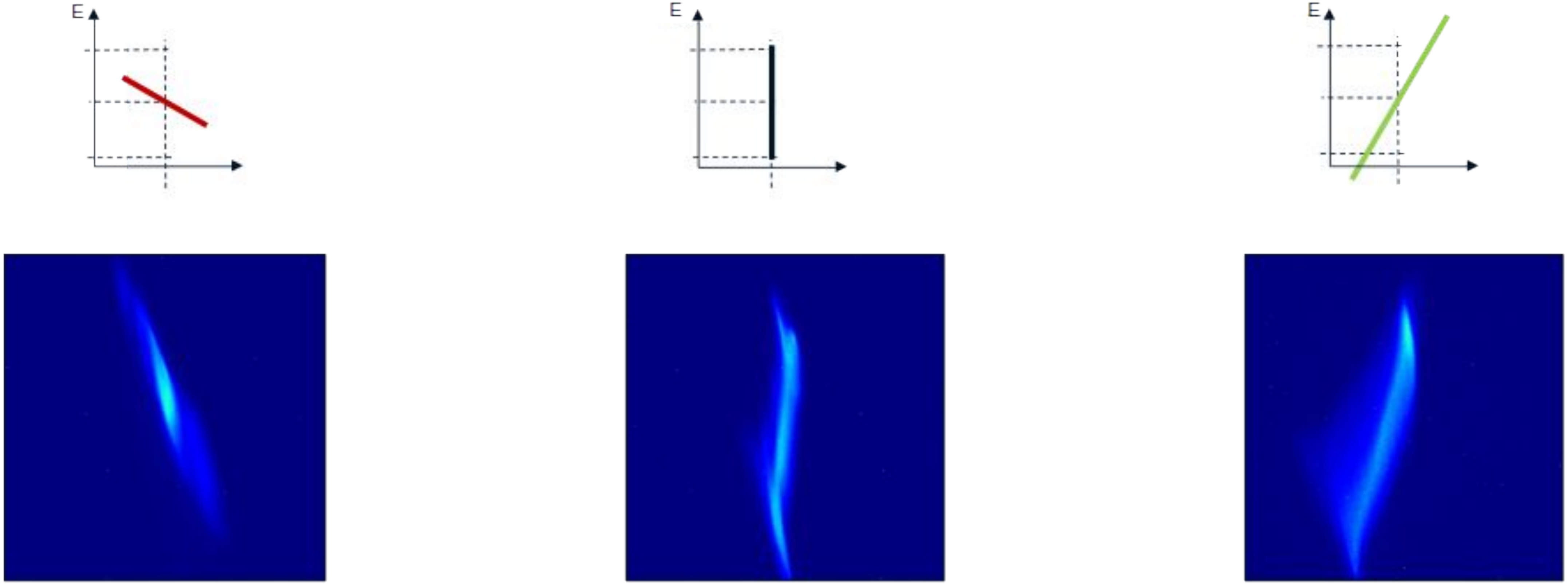
Transverse deflecting cavity

MAX IV linac layout



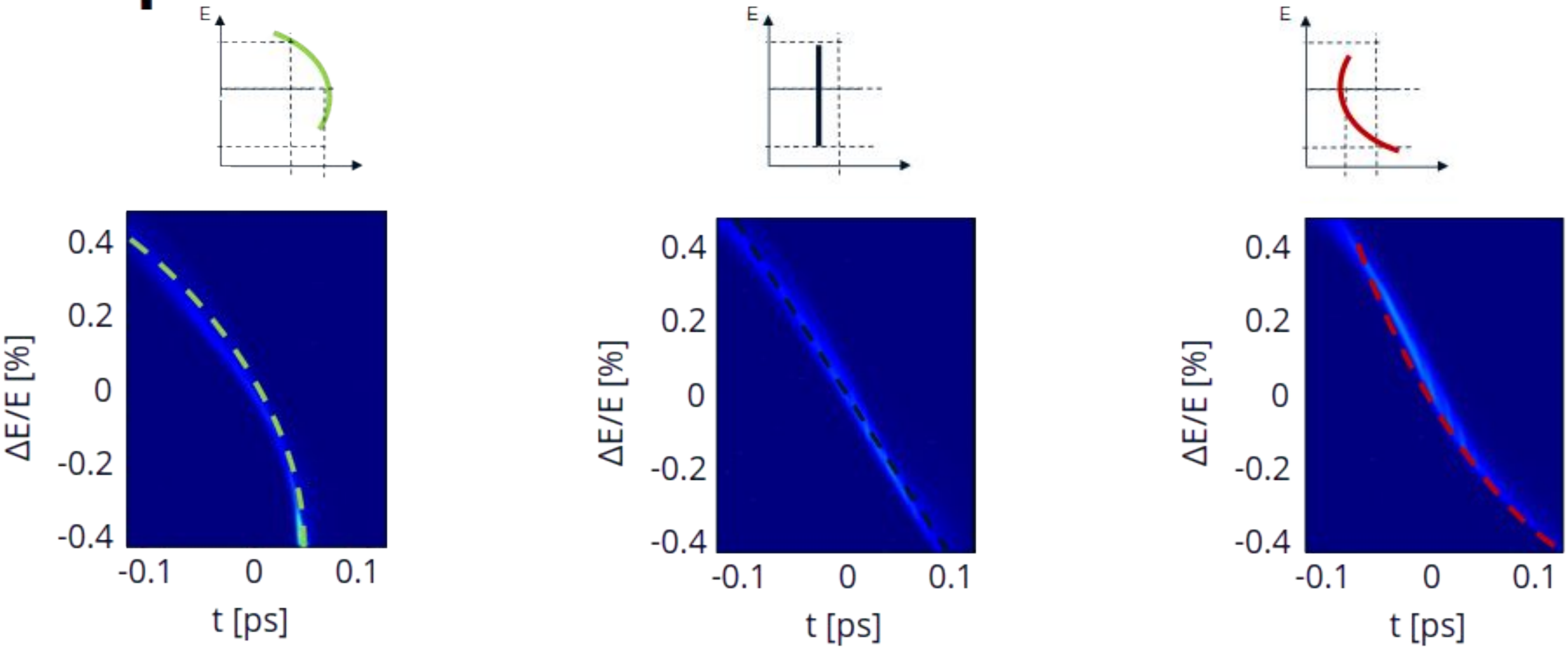


Compression scan – longitudinal phase space



Slide from Erik Mansten, Johan Lundqvist

Linearization scan – Longitudinal phase space

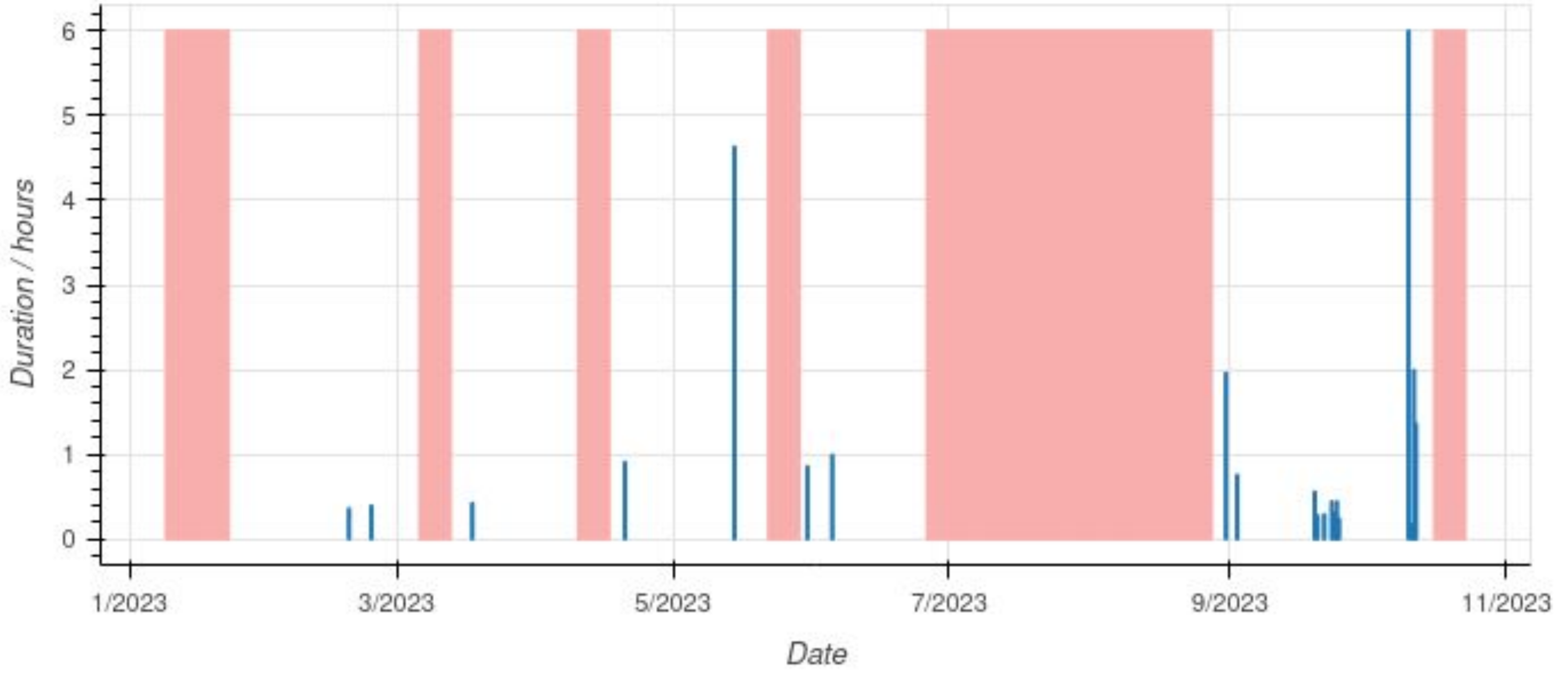


Slide from Erik Mansten, Johan Lundqvist

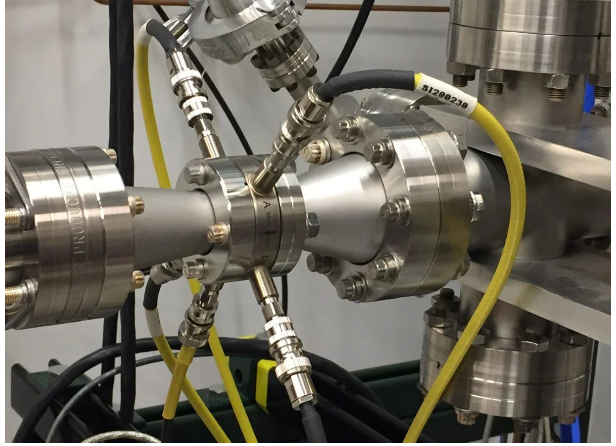
A real life example

Unknown downtimes in our big ring

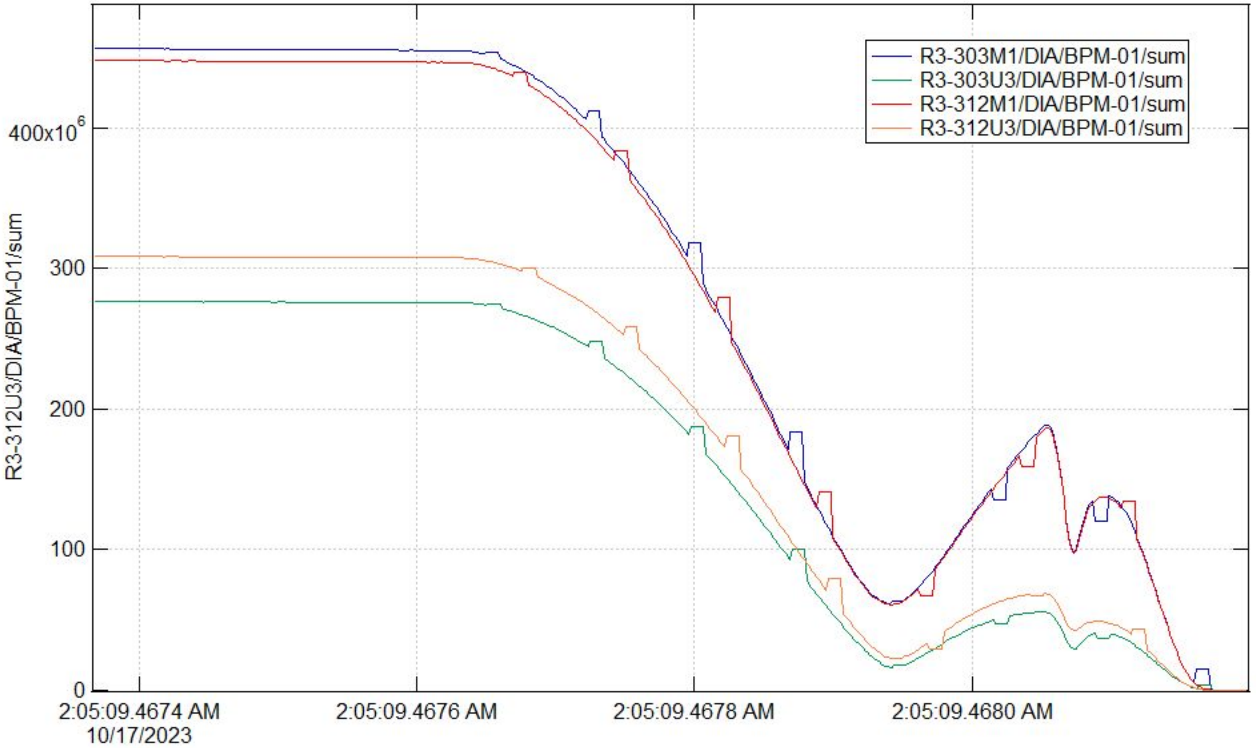
- Beam dumps with no readily apparent cause
- Appeared to become more frequent after summer



New diagnostics

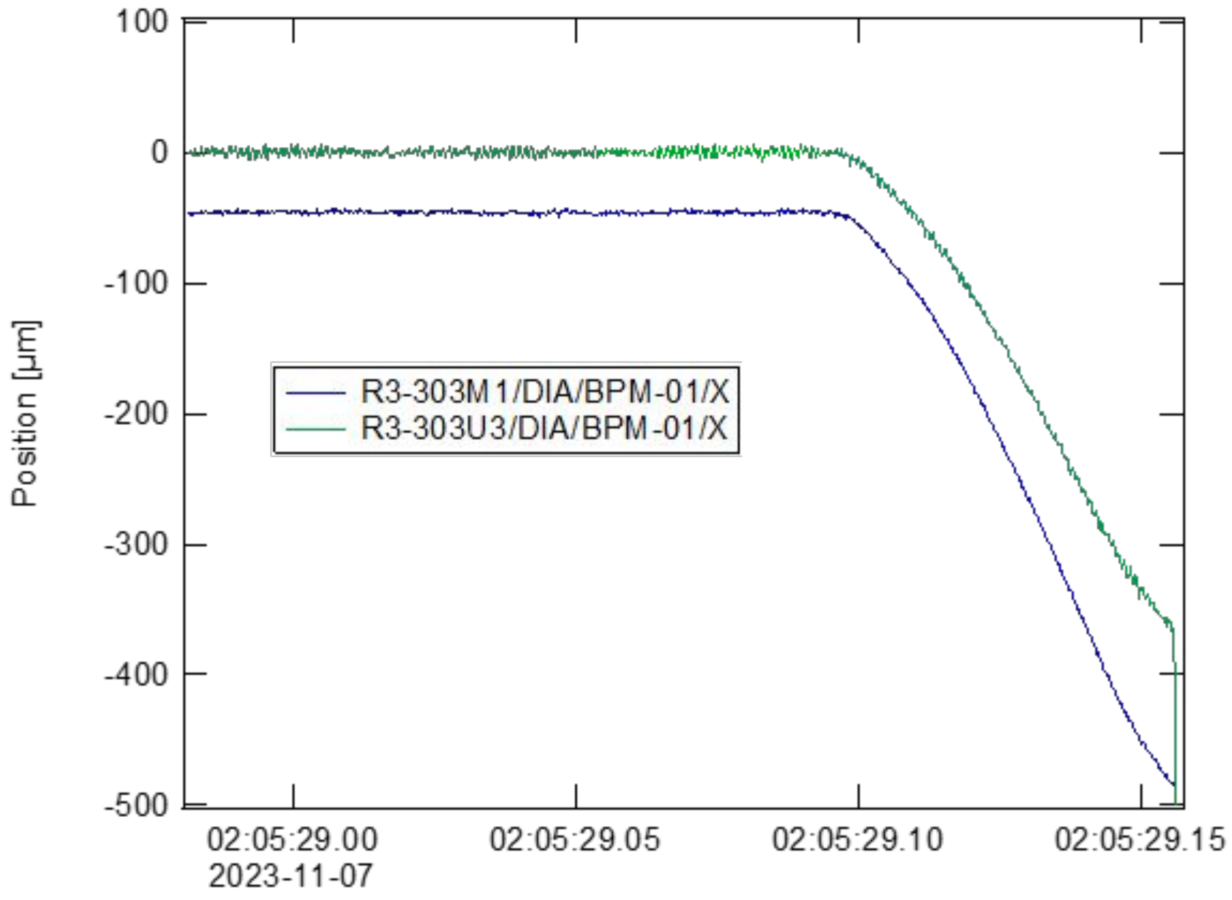


- Libera post-mortem system
  - TbT data for last 20k turns
  - Python tooling to extract, save, & parse this data
- Plot shows a deliberate dump
- Sum signal
  - Measures de-bunching & charge loss
  - Gives a signature



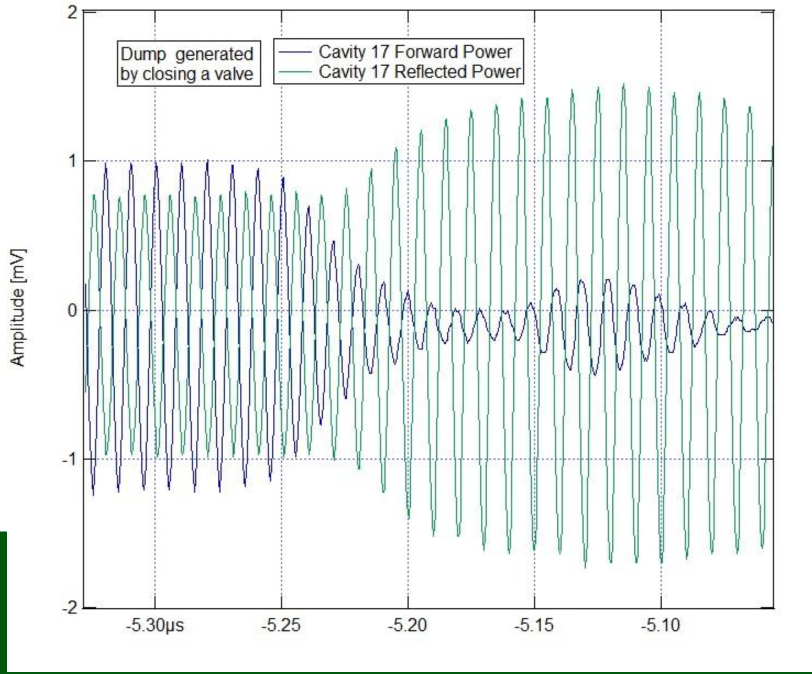
New diagnostics

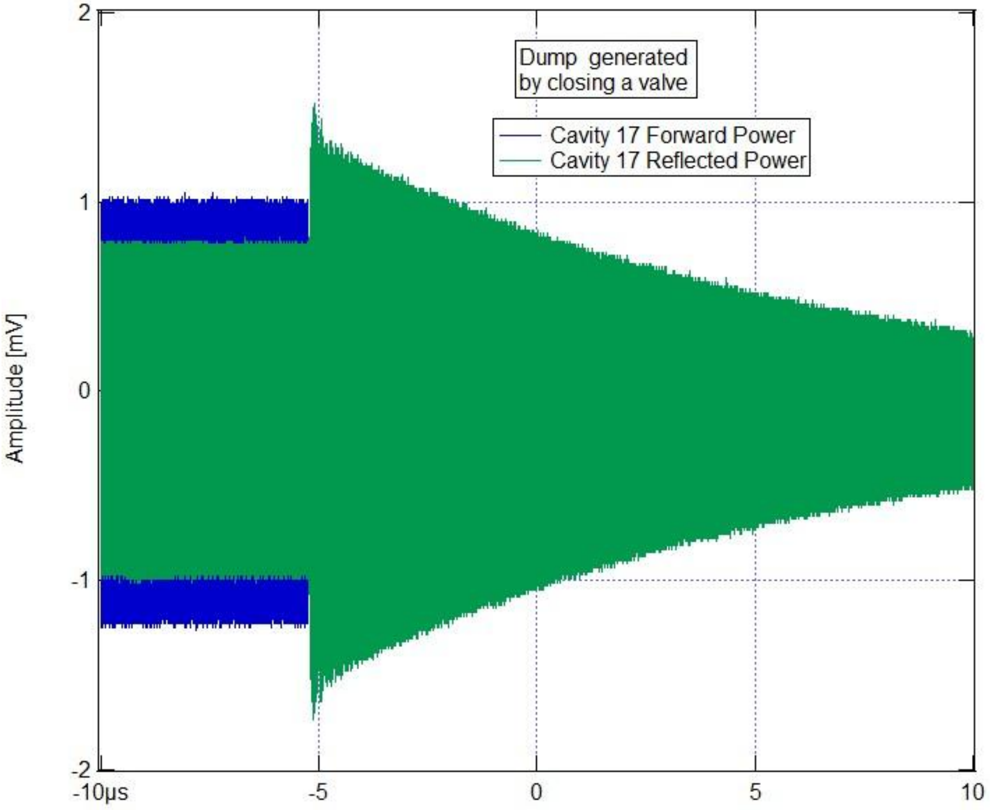
- Fast archiver system developed at Diamond Light Source, UK
  - Python tooling improved to provide faster turnaround
  - 10 kHz data
  - Last two weeks always accessible
  - Beam dumps trigger permanent saving of 2 seconds of data



New diagnostics

- Scopes watching forward and reflected power from the cavities.
  - Triggered by the post-mortem event triggered by MPS



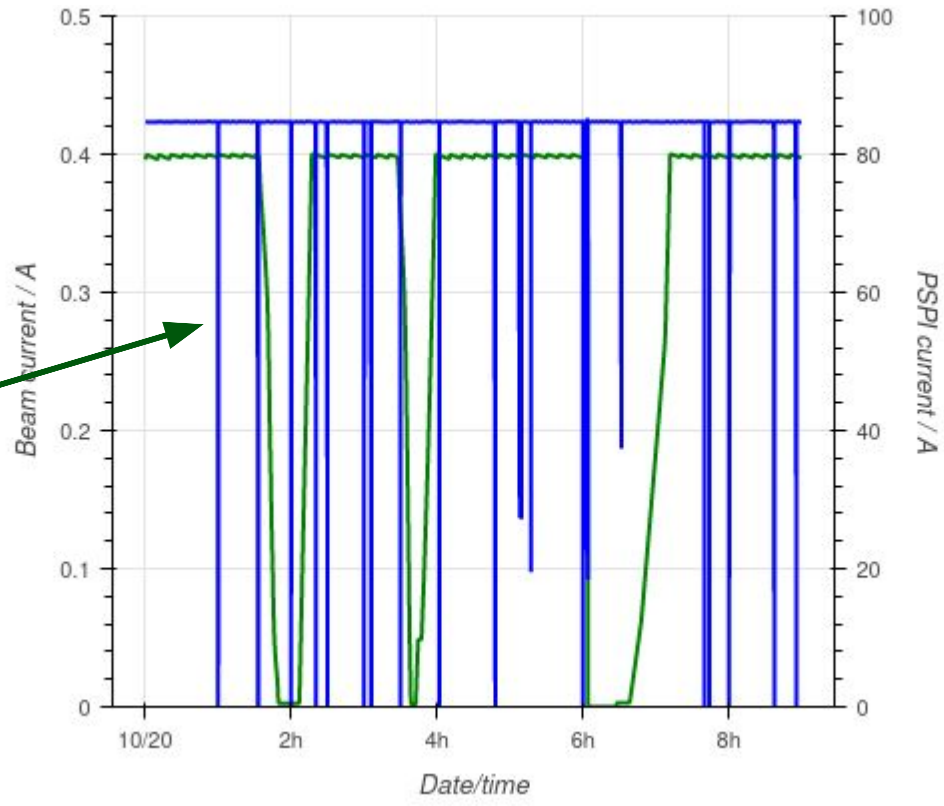


New diagnostics

- Software to combine all of this and streamline usage
  - Work ongoing to move this into the control system
- Large, and growing, catalogue of beam dump types
  - Based on deliberately generated dumps

Findings

- We now have a substantial (and growing) catalogue of R3 dump signatures
- The "all hands on deck" approach led to discovery of some intermittent failures
  - Beam dump accidentally generated by touching an MPS cable
  - Magnet power-supply with intermittent glitches
    - This PS had failed before, and was reinstalled after manufacturer repair
- No dumps of this type since...



Summary

A huge field!

- Beam instrumentation lies at the heart of every successful accelerator
- Requires an enormous array of skills and techniques
  - Digital software/hardware
  - Component manufacture
  - Detectors
  - Vacuum, surface science, materials science, …

Some personal notes

- Budgets are tight, the SEK is weak…
  - For Swedish labs, local talent is very attractive
  - Perhaps also for international labs
- Sweden has a huge talent pool
  - Highly educated hi-tech society

- Are Big Science facilities aware of what you can do?
- Are you aware of what Big Science needs?