Karlsruhe Institute of Technology

Institute for Beam Physics and Technology

Particle Accelerator Physics

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V - Measurement and control of beam parameters

- Beta functions and dispersion
  - Gradient modulation / response matrix

- All around the betatron tune
  - FFT & LNP
  - Results from multi-turn measurements
  - Phasen space reconstruction

- Beam energy
  - Transverse polarisation
  - Resonant spin depolarisation
  - LEP and external effects

References to beam diagnostics

- D. Brandt, Editor, *CERN Accelerator School on Beam Diagnostics*, CERN-2009-005, 2009.
  http://cdsweb.cern.ch/record/1071486/files/cern-2009-005.pdf

- M.G. Minty, F. Zimmermann, *Measurement and Control of Charged Particle Beams*, Springer, 2003.

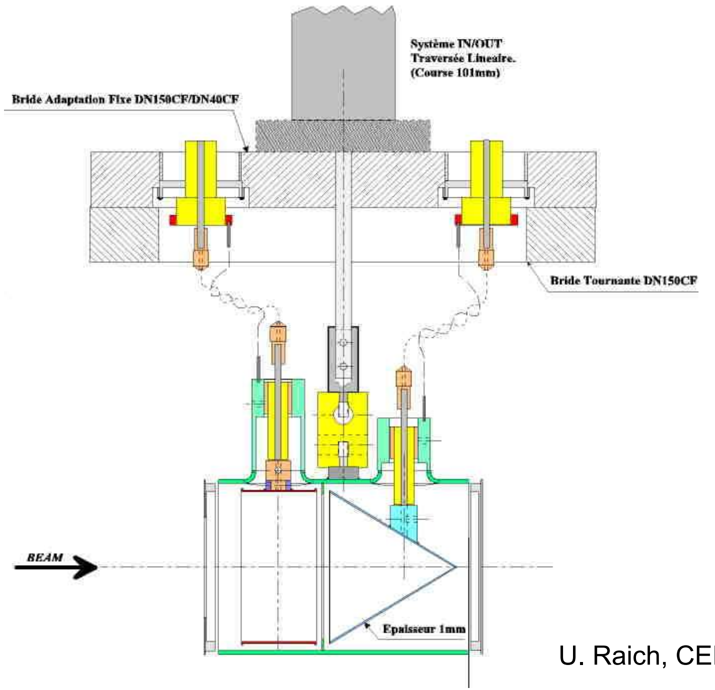
- A.W. Chao, M. Tigner, *Handbook of Accelerator Physics and Engineering*, World Scientific, 1999.

Examples for beam diagnostics

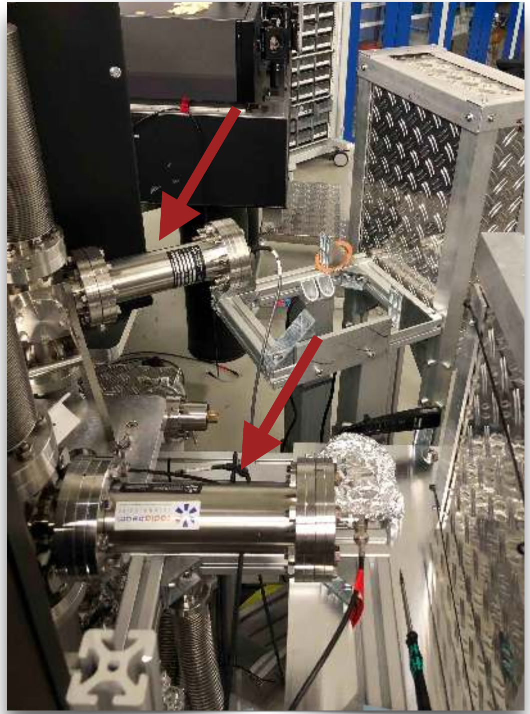
Device	Physical effect	Parameter	Destructive
Faraday cup	Charge collection	Beam intensity	yes
Wall current monitor	Mirror current	Beam intensity, long. profile	no
Current transformer	Magnetic field	Beam intensity	no
Wire scanner	Secondary particles	Transverse profile	interfering
Beam position monitor	Electric/magnetic field	Beam position	no
Fluorescent screen	Fluorescence	Transv. profile, position	yes
Residual gas monitor	Ionisation	Transverse profile	no
SEM	Secondary emission	Transv. profile, emittance	interfering

Faraday cup

- beam intensity -



U. Raich, CERN Accelerator School, Zakopane 2006



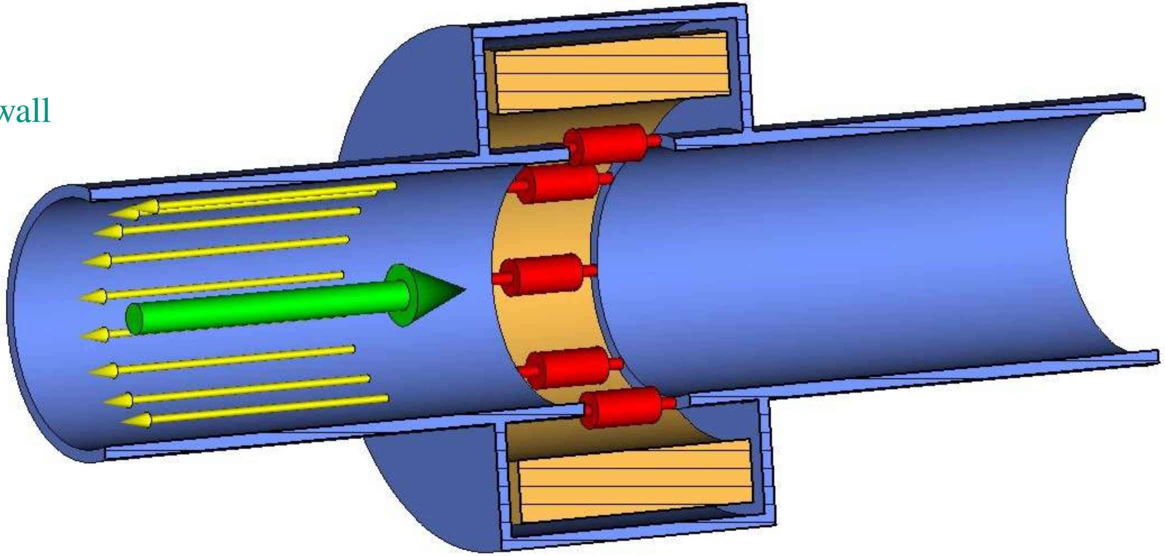
Faraday cups at FLUTE

Wall current monitor

- beam current -

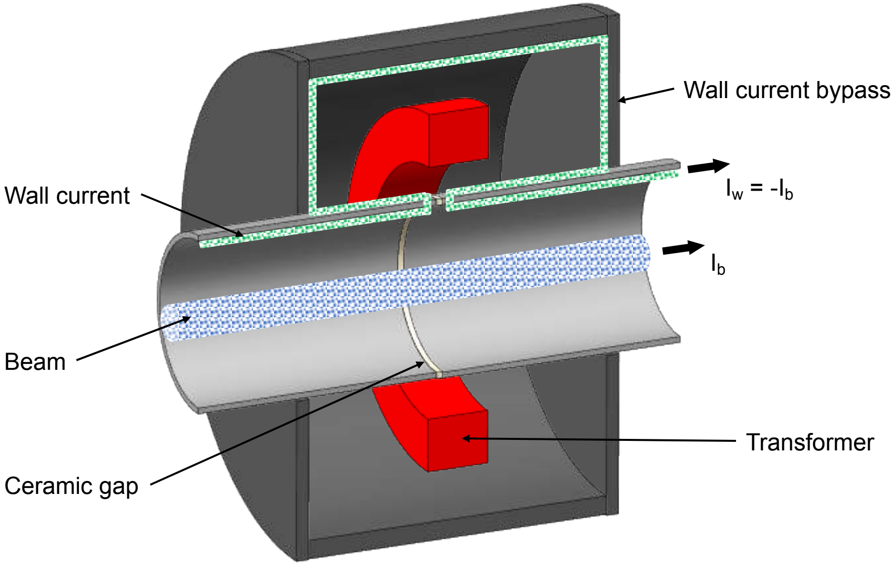
- Measure the voltage created by the image current of the beam on resistors in the vacuum chamber

$$U_R = RI_{\text{beam}} = -RI_{\text{wall}}$$



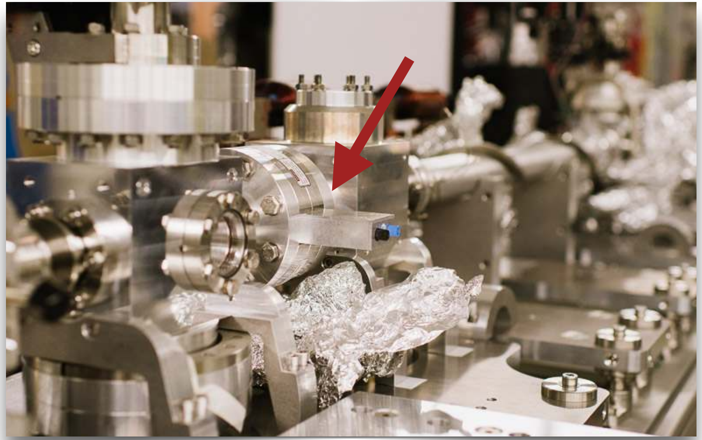
Integrated current transformer (ICT)

- beam charge, pulse duration -



© BERGOZ Instrumentation, Integrating Current Transformer, user's manual

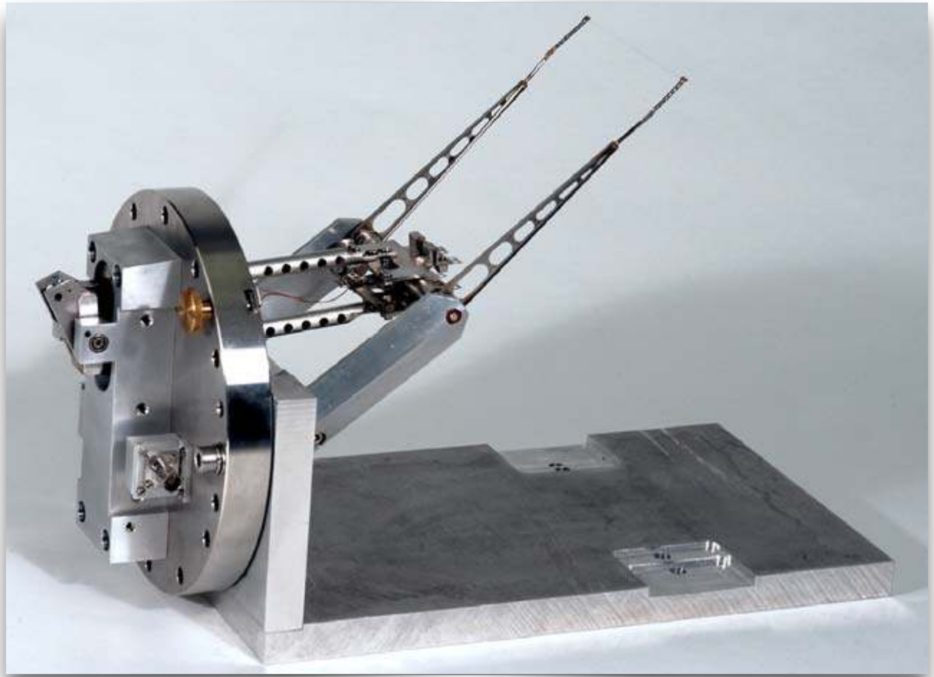
- Measure the charge of very short pulses via induced magnetic field
- Integrated signal, linear integrator
  - since eddy currents are negligible
  - but original shape of signal is lost



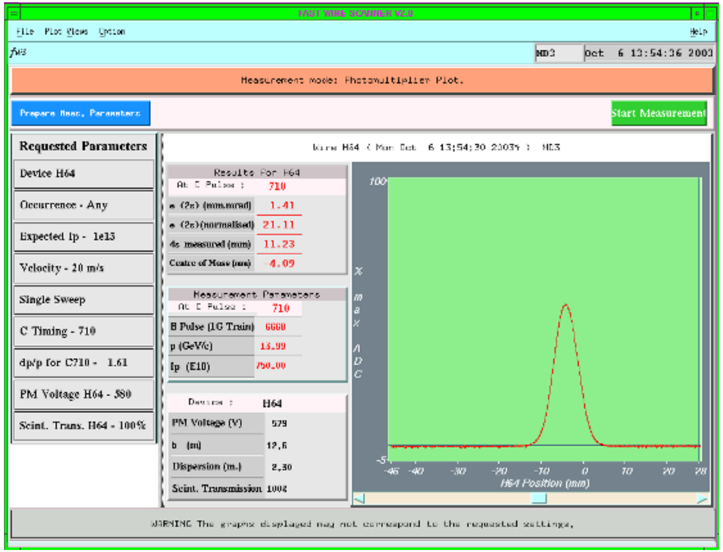
turbo ICT at FLUTE

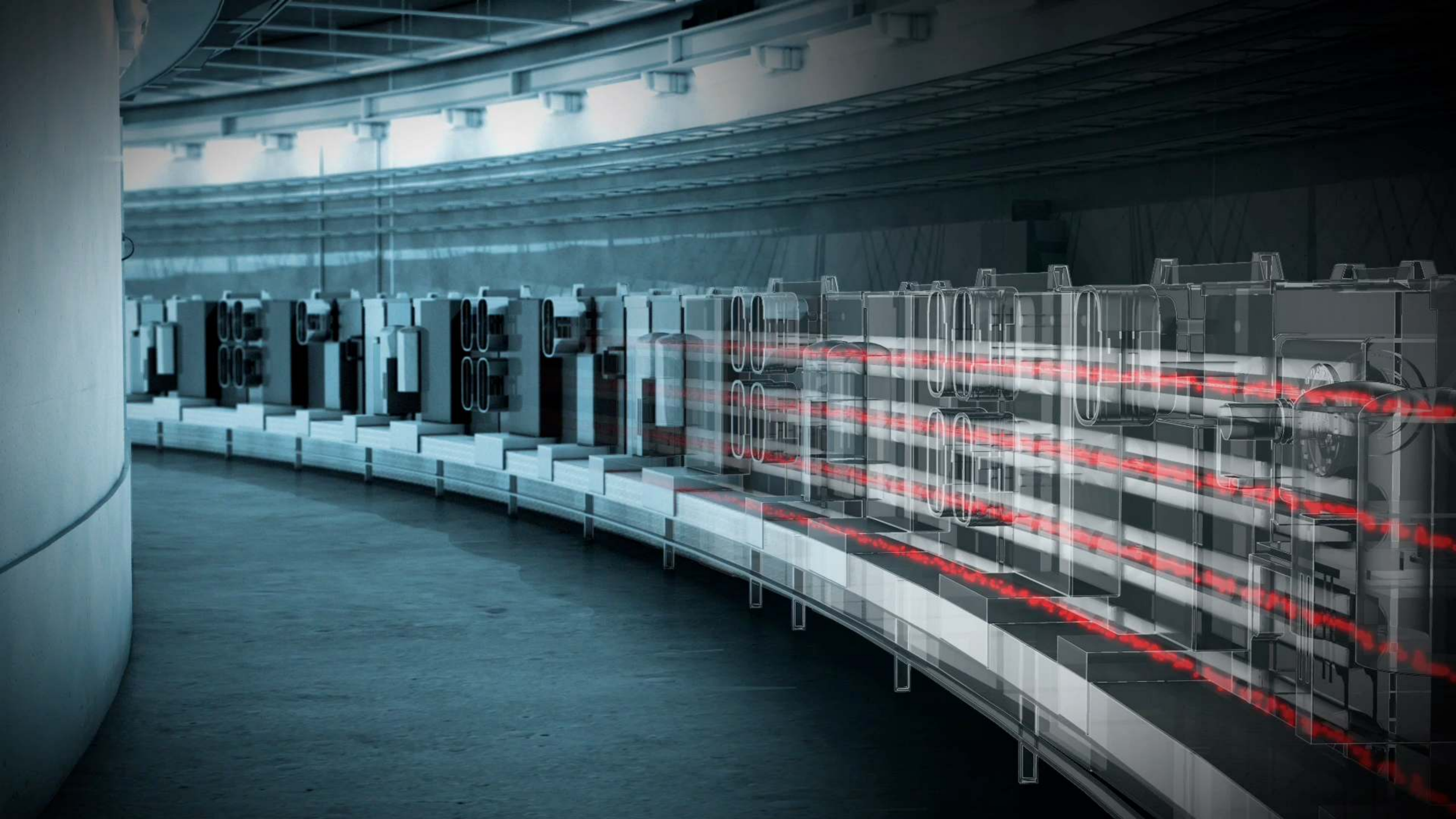
Wire scanner

- transverse beam profile -



- Scattered particles are measured outside the vacuum chamber



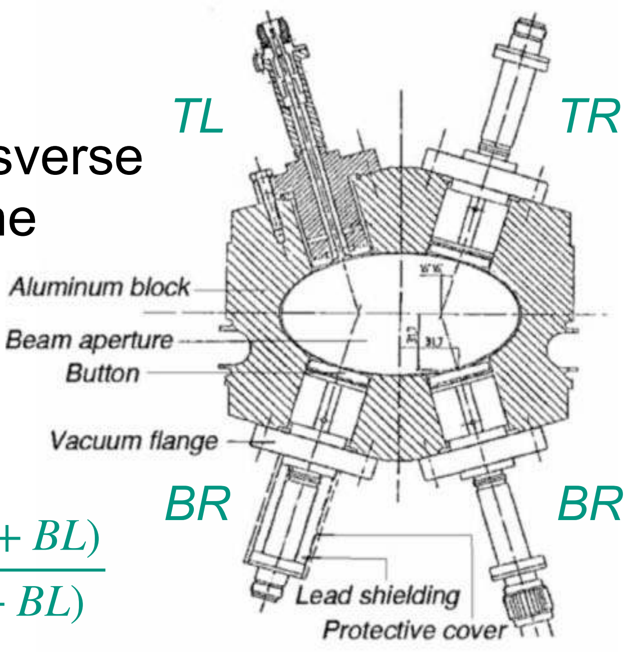


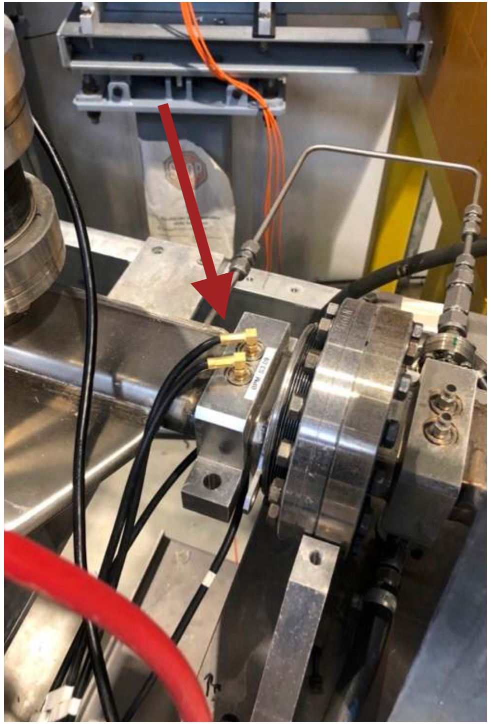
Beam position monitor (“BPM”)

- beam position, tunes, … -

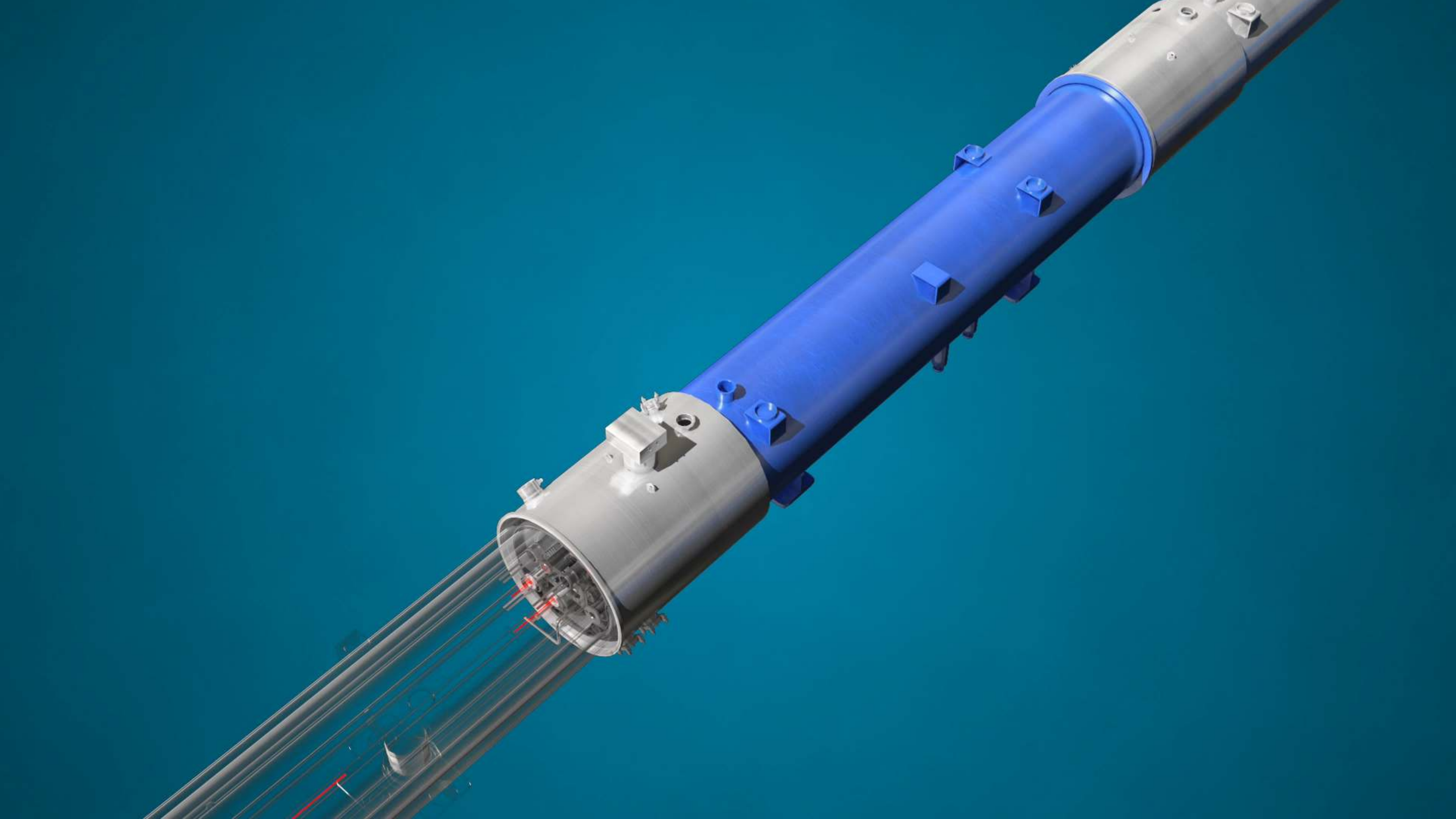
- Measurement of transverse beam position from the differential signal of the “buttons”

$$U_{\Delta x} = A \, \frac{(TR + BR) - (TL + BL)}{(TR + TL + BR + BL)}$$

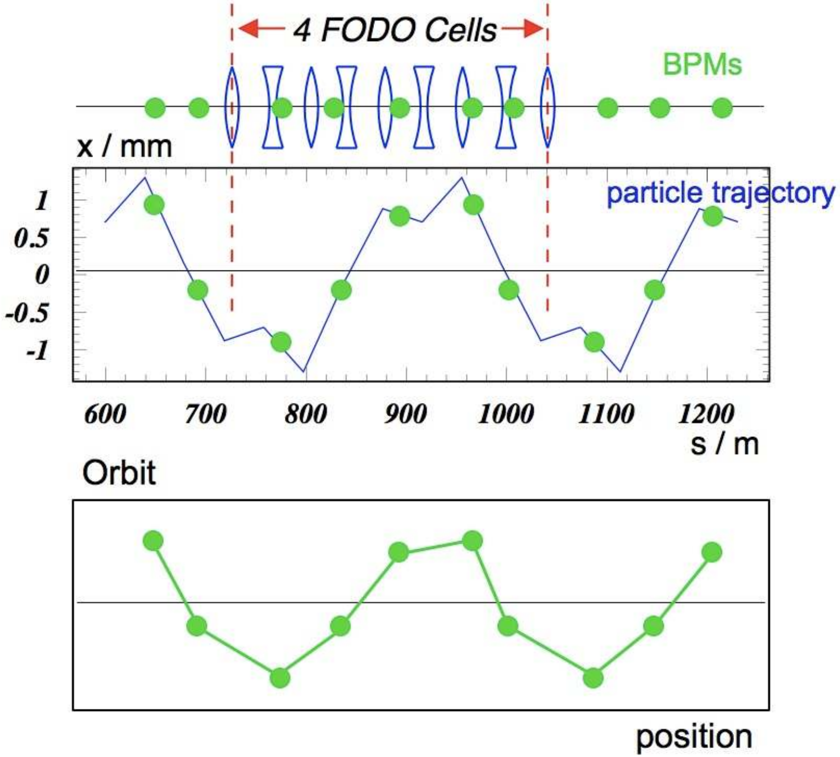




beam position monitor at KARA



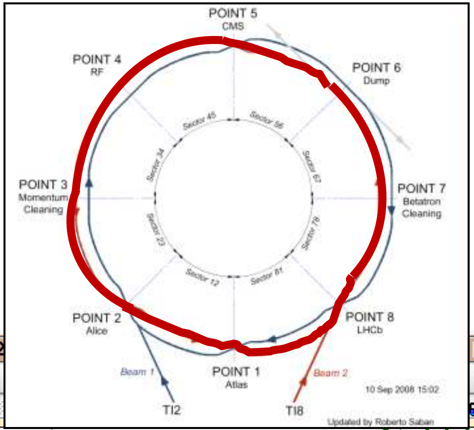
Orbit measurement and correction

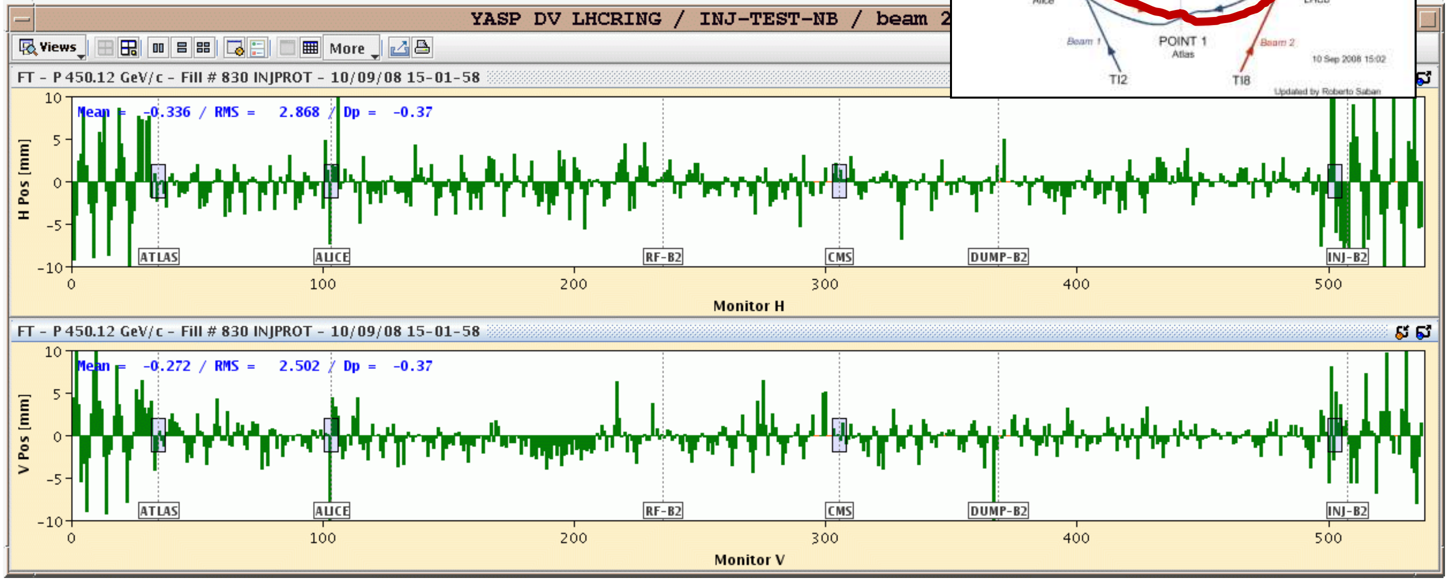


Vertical orbit corrector at KARA

LHC beam commissioning

- Threading the beam: First steering sector-by-sector, one beam at a time





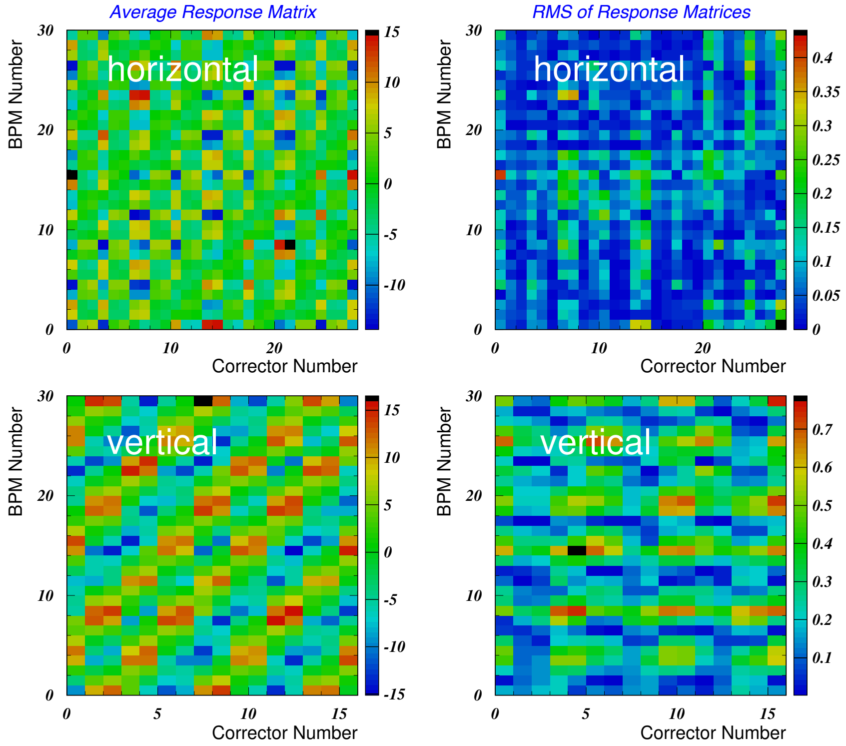
Beam through one sector (1/8 ring), correct trajectory, open collimator and move on.

Orbit response matrix

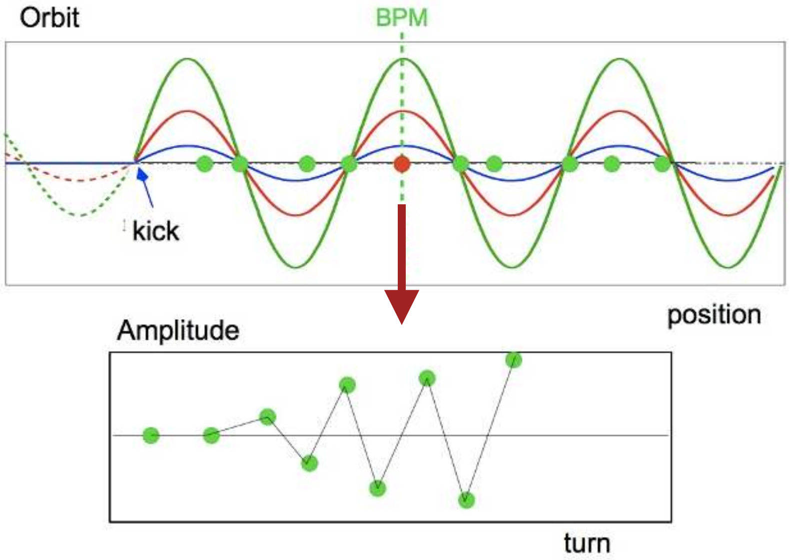
- **Idea:** A small dipole perturbation θ_k, caused by a corrector dipole, results in an orbit change of

$$u_k = \frac{1}{2} \beta_k \, \theta_k \cot \pi Q$$

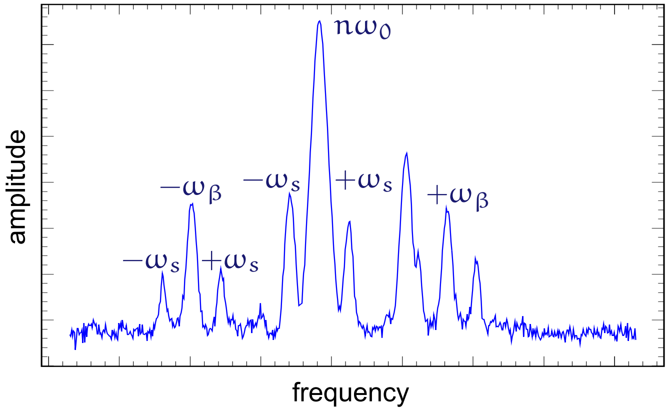
- The resulting disturbed orbit therefore contains information about the beta function and the tune.
- Measurements of the beam positions along the ring for a large number of such "kicks" are summarized in the "Orbit Response Matrix".



Turn-by-turn measurements



- **Sum signal** of all buttons gives spectrum of longitudinal components.
- In the spectrum there are orbital harmonics, sidebands of the betatron and synchrotron frequencies and synchrotron sidebands to the betatron sidebands.



- **Transverse signal:** Tune, beta functions, …

Lomb normalized periodograms (LNP)

- Harmonic analysis without restriction to 2^N points or time interval of individual measurements
- Data is weighted “per point” (not “per time interval” as with Fourier transforms)
- For each frequency, the significance with which it occurs is examined.
- The LNP indicates how many points occur at a certain frequency.
- The LNP is for N data points h_i at times t_i:

$$P_N(\omega) = \frac{1}{2\sigma^2}\left(\frac{\left[\sum_j d_j \cos\left(\omega(t_j-\tau)\right)\right]^2}{\sum_j \cos^2\left(\omega(t_j-\tau)\right)} + \frac{\left[\sum_j d_j \sin\left(\omega(t_j-\tau)\right)\right]^2}{\sum_j \sin^2\left(\omega(t_j-\tau)\right)}\right)$$

with

$$d_j = h_j - \frac{1}{N}\sum_{i=1}^{N} h_i$$

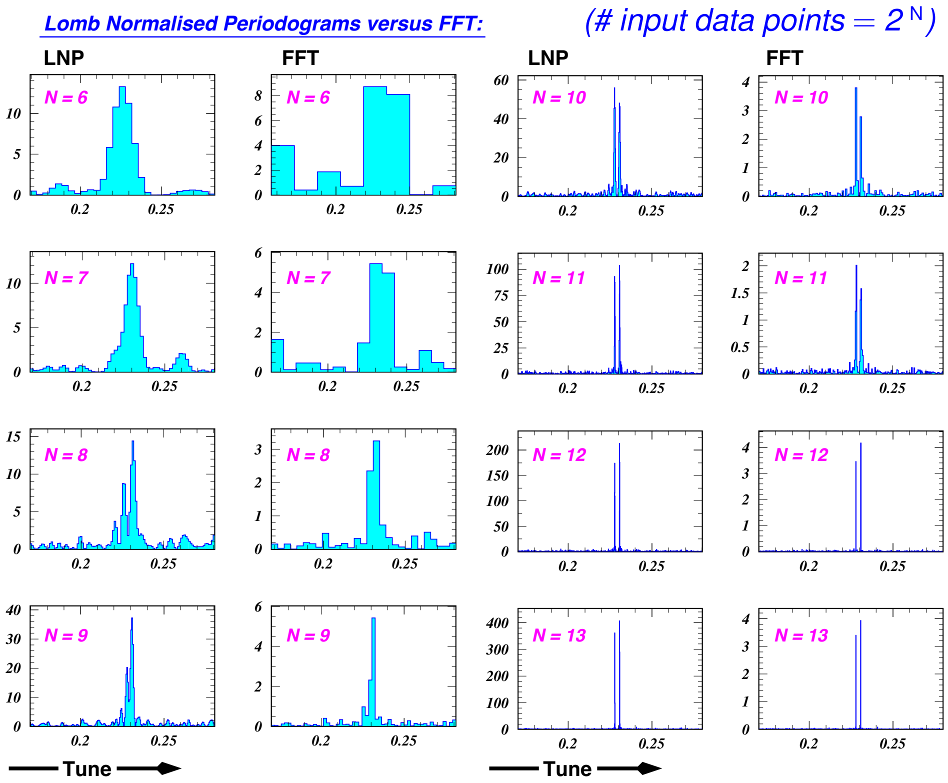
$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N} d_i^2$$

$$\tan(2\omega\tau) = \frac{\sum_j \sin(2\omega t_j)}{\sum_j \cos(2\omega t_j)}$$

- Only frequency information, no phase information
- Faster convergence than FFTs (all points are used), higher resolution, independent of amplitude

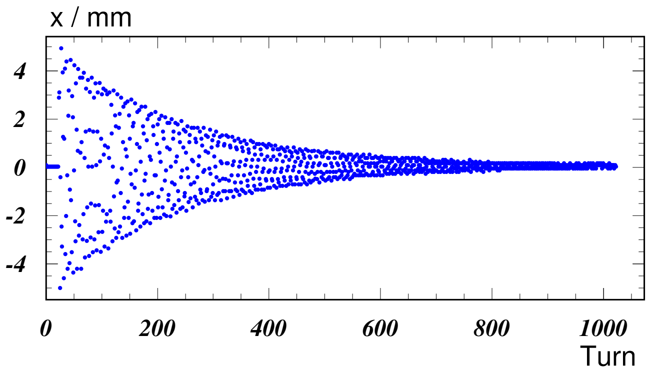
Harmonic analysis

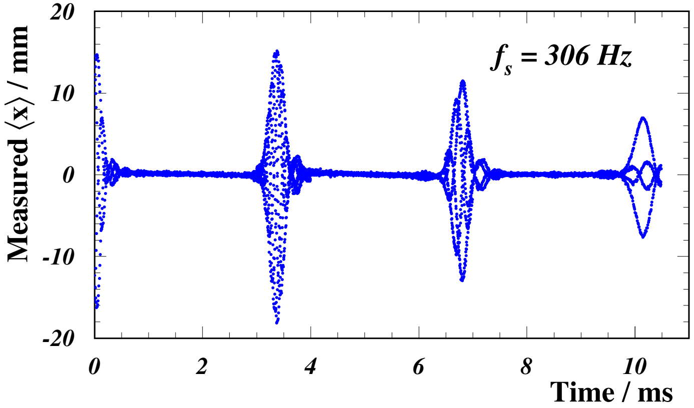
- Gives tunes
- Fast Fourier Transform (FFT) or Lomb Normalised Periodograms (LNP)



Multi-turn measurements

- Measurement of the transverse beam position with beam position monitors ("BPMs") for many consecutive transitions
- Only the center of gravity of the charge distribution is visible
- Many analyses possible, e.g.
  - tune as a function of e.g. amplitude from harmonic analyses,
  - phase space reconstruction,
  - energy loss measurement





Amplitude detuning

- Beam position after single kick

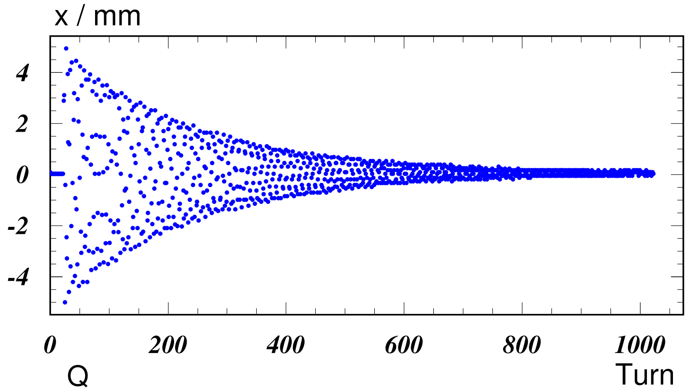
- Tune from LNPs for small sections of 50 envelopes
- It applies

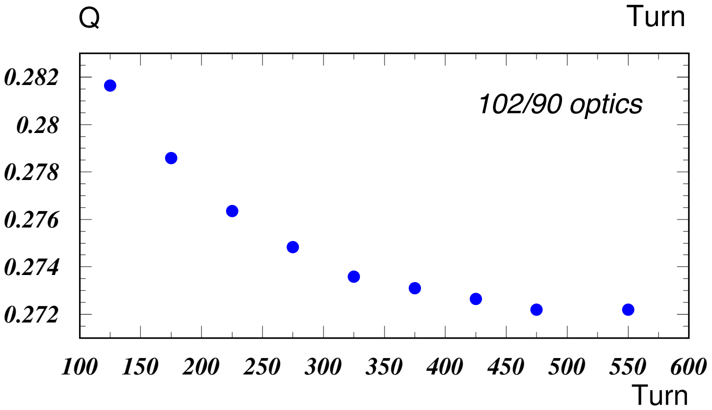
$$x(t) = x_0 + A_0\, e^{-t/\tau} \sin\left(2\pi\, \Phi(t) + \varphi\right)$$

$$\Phi(t) = \int_0^t dt' \left(Q_0 + \alpha_q\, A_0^2\, e^{-2t'/\tau}\right)$$

$$= tQ_0 + \frac{\tau}{2}\, \alpha_q\, A_0^2 \left(1 - e^{-2t/\tau}\right)$$

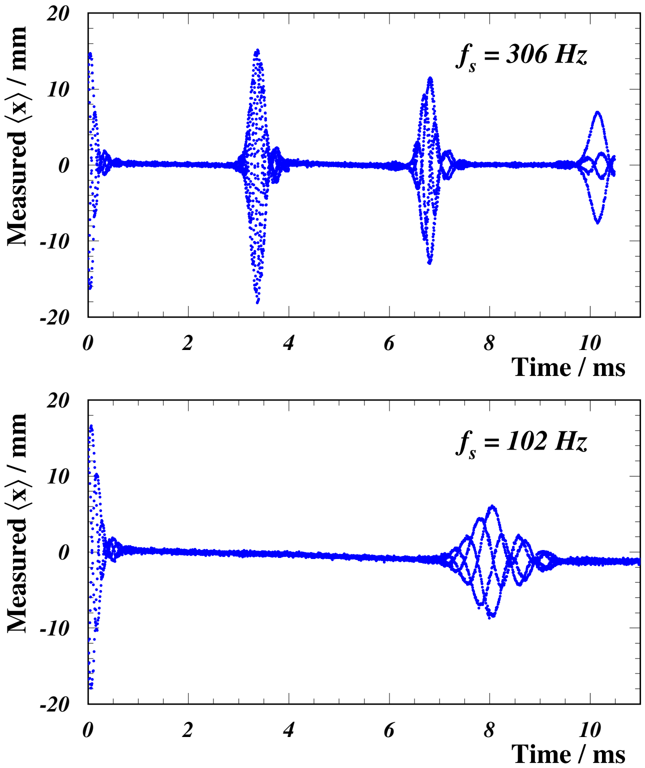
- Stability criterion
- Adjustment of sextupoles





De- and recoherence

- Decoherence due to energy dependent single particle tunes
  - Dependent on synchrotron frequency



Phase space and BPM position

- Due to differences in the individual tunes, the distribution in the phase space diverges over time and possibly merges again.

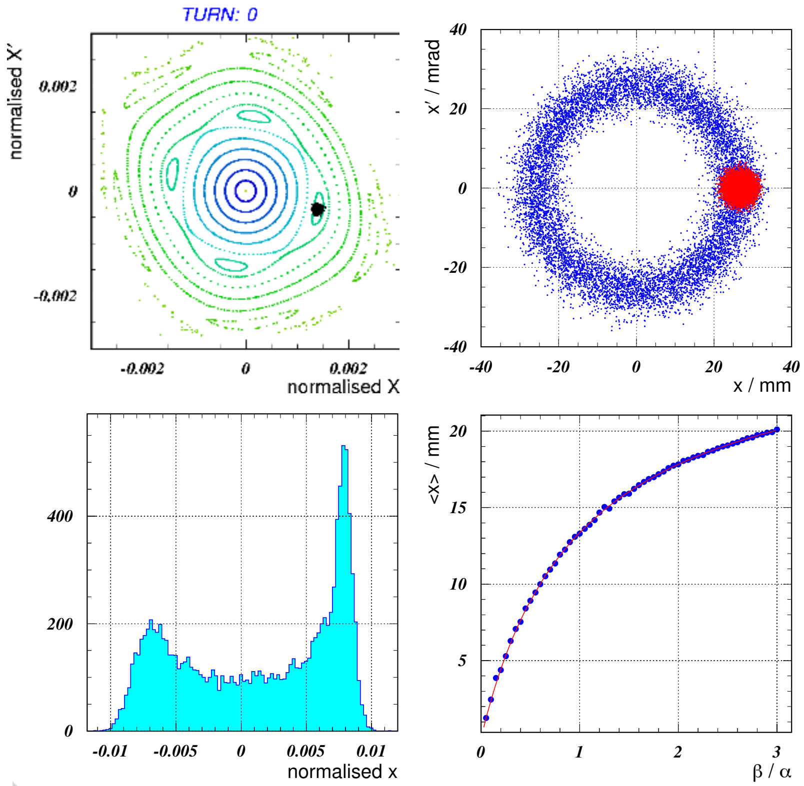
- Composite distribution: “ring + island”

$$f(x) \;=\; \alpha\, f_A(x) \;+\; \beta\, f_I(x)$$

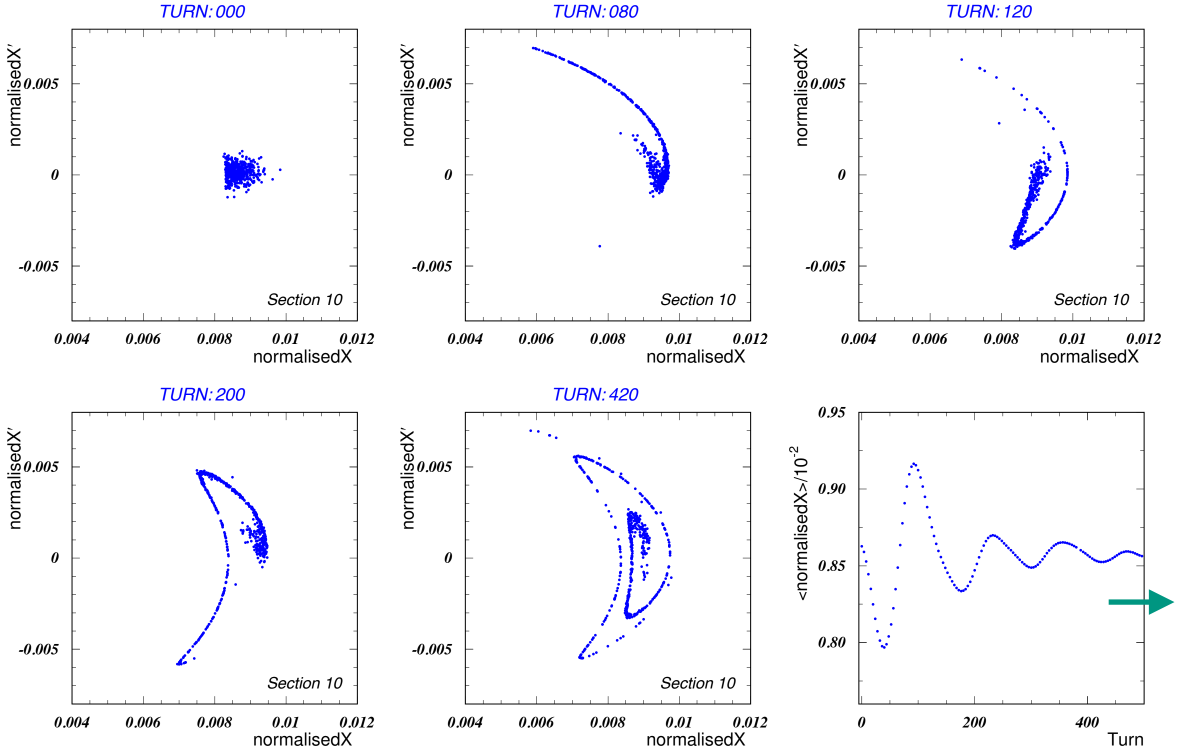
- Mean value of $f(x)$:

$$\tilde{\mu}(z) \;=\; \frac{\beta\, \mu_I}{\alpha \;+\; \beta} \;=\; \frac{\mu_I}{1 + \frac{1}{z}}$$

- Measured beam position reflects asymmetry of the distribution.



Filamentation



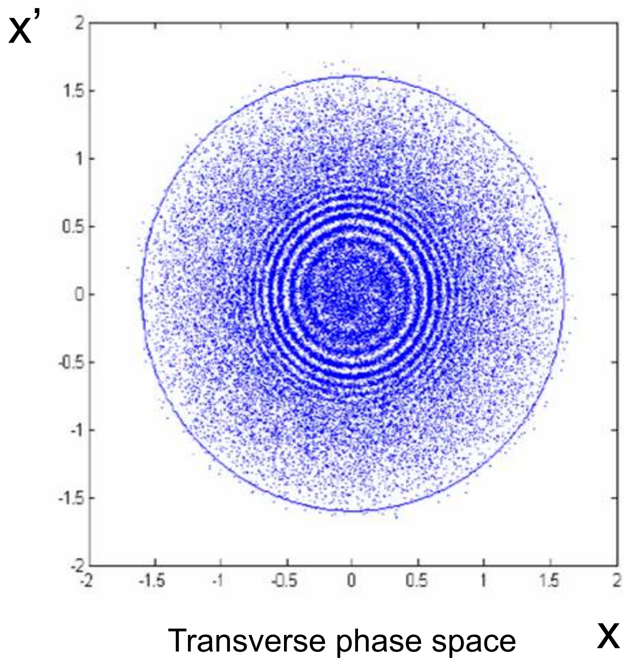
- Injection into resonant island

Only mean values are actually observed!

Filamentation and emittance

Injection errors (mismatched position or angle) dilute are a source of filamentation.

- Non-linear effects (e.g. magnetic field multipoles) distort the harmonic oscillation and lead to amplitude dependent effects into particle motion.
- Over many turns, a phase-space oscillation is transformed into an emittance increase.



Transverse phase space

Measurement of beta functions: “k modulation”

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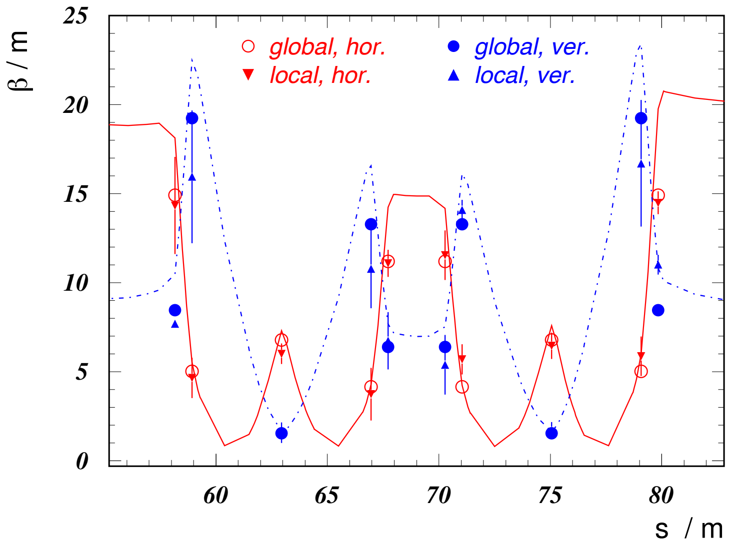
The beta function can be determined in several ways:

- from a measurement of the tune change as a function of a gradient change of a single quadrupole (“local β”)
- from a measurement of the tune change as a function of a gradient change of a quadrupole family (“global β”)
- Relation for a gradient error:

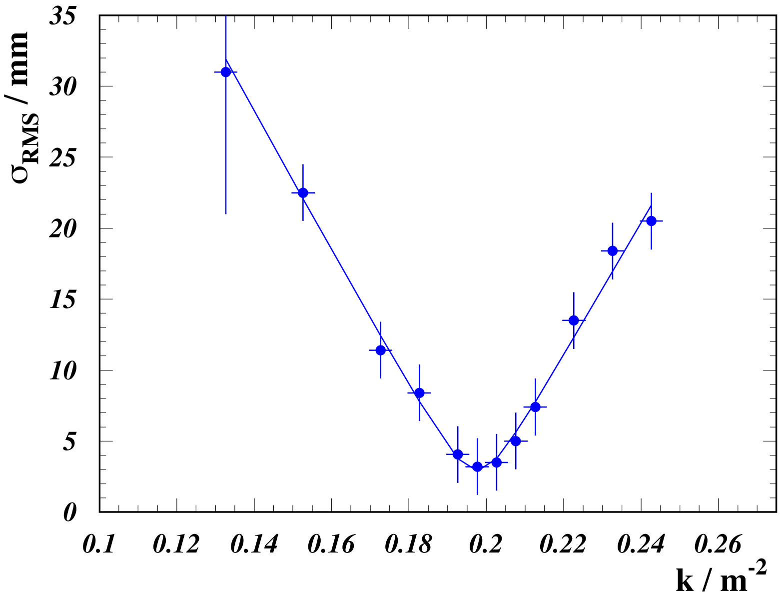
$$\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta k(s) ds$$

$$\beta_{x,y} \approx \pm \frac{4\,\pi\,\Delta Q_{x,y}}{\Delta k}$$



Optical functions and emittance

- The beam size at a specific location is given by $\sigma_{i,11}^2 = C_i^2 c_{11}^b + 2S_iC_ic_{12}^b + S_i^2 c_{22}^b$
- C_i and S_i are elements of the transport matrix between the location of the measurement and the location at which the parameters are to be determined.
- c_{ij}^b are the elements of the beam matrix at the location where the parameters are determined and $\sigma_{i,11}$ are the measured beam sizes.



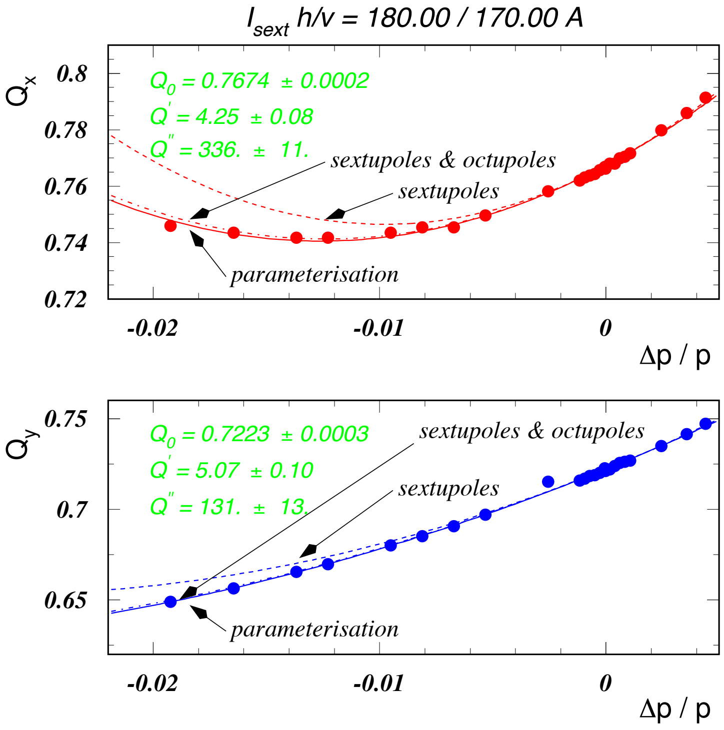
- Several measurements are carried out as a function of a quadrupole gradient. Fitting calculations then provide both the optical functions and the emittance.

Chromaticity

- Measurement of betatron tunes as a function of momentum offset
- Variation of momentum offset with

$$\frac{\Delta p}{p_0} = -\frac{1}{\alpha_c}\,\frac{f_{\mathrm{RF}} - f_{\mathrm{RF}}^c}{f_{\mathrm{RF}}^c}$$

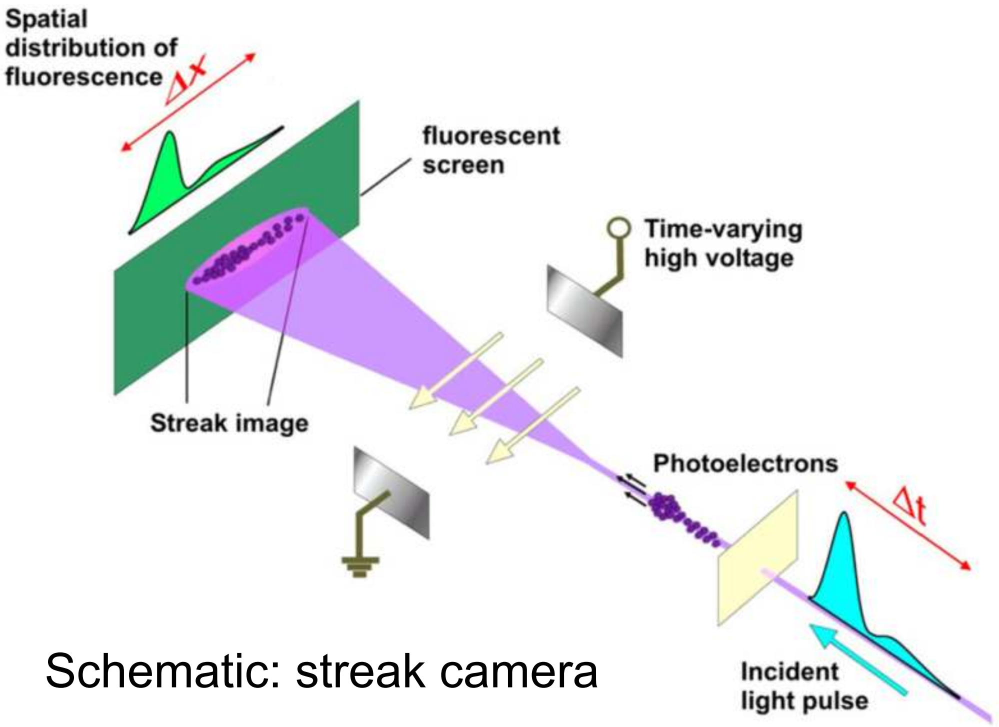
- Slope gives chromaticity
- Curvature provides information about higher multipole orders



Bunch length, longitudinal profile

- Longitudinal profile can determined from image current or the electrical field of the bunch

- Length of SR light pulse: Interferometer or Streak Camera

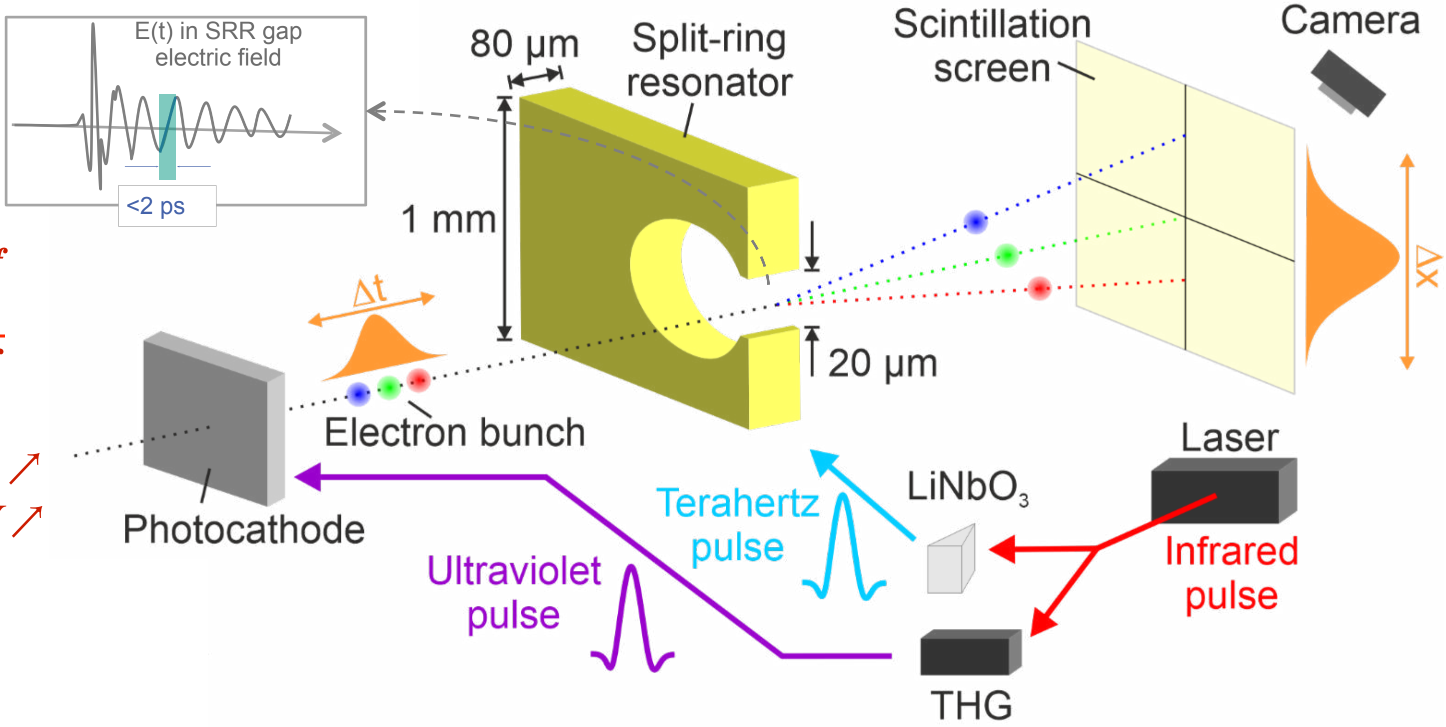


Schematic: streak camera

Principle split-ring resonator (SRR)

Streak field

$V\sin(2\pi f t + \phi)$



Streaking strength: $S \propto Vf$

Temp. resolution: $R_z \propto \frac{1}{Vf}$

12 GHz → 280 GHz: $f \nearrow$

SRR enhancement x100: $V \nearrow$

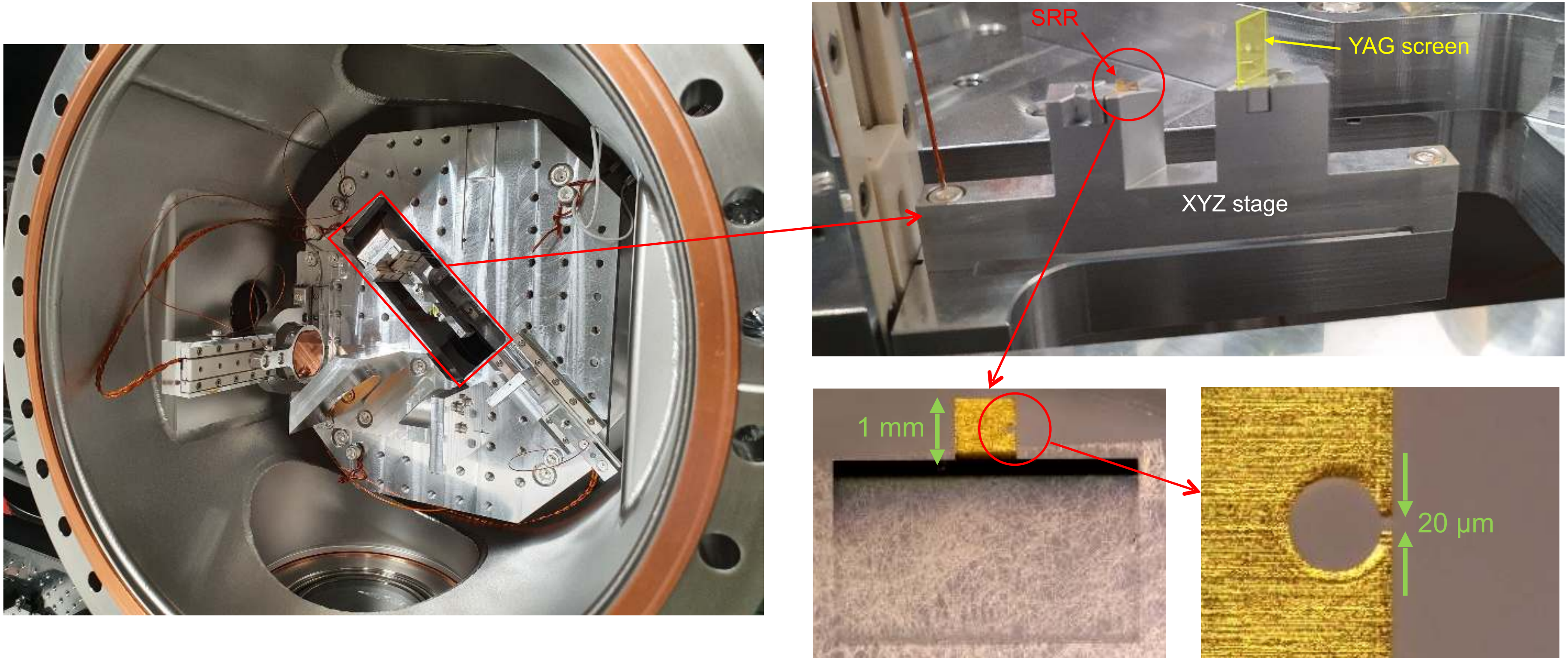
⇒ **Improved R_z** $\searrow$

Femtosecond scale

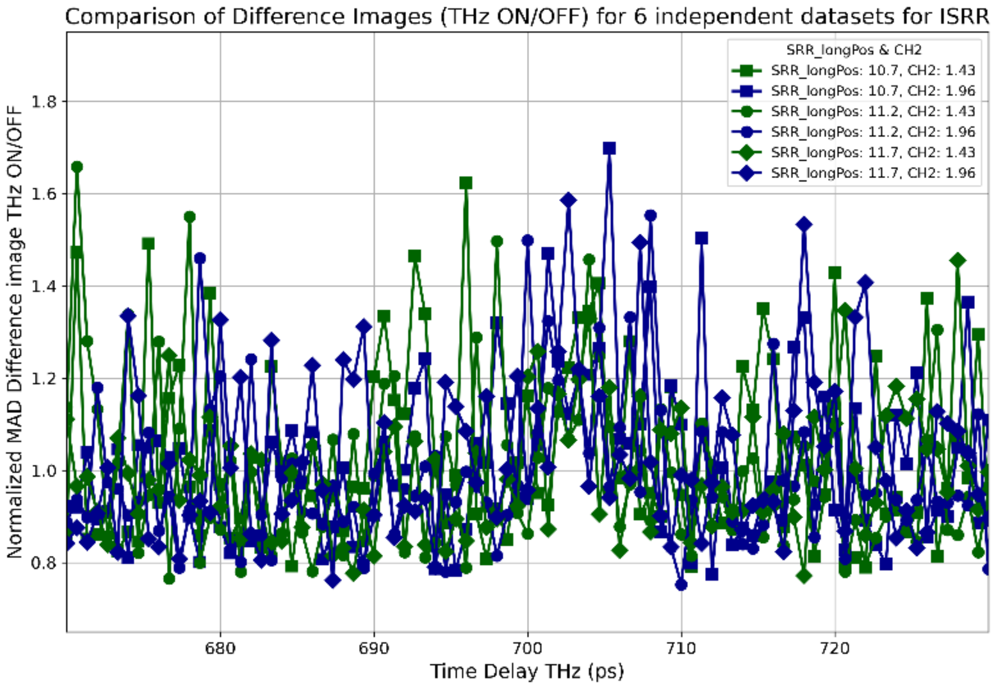
J. Fabiańska, G. Kassier, T. Feurer. Sci. Rep. 4, 5645 (2014)

Courtesy: M. Nabinger

Split-ring resonator (SRR)



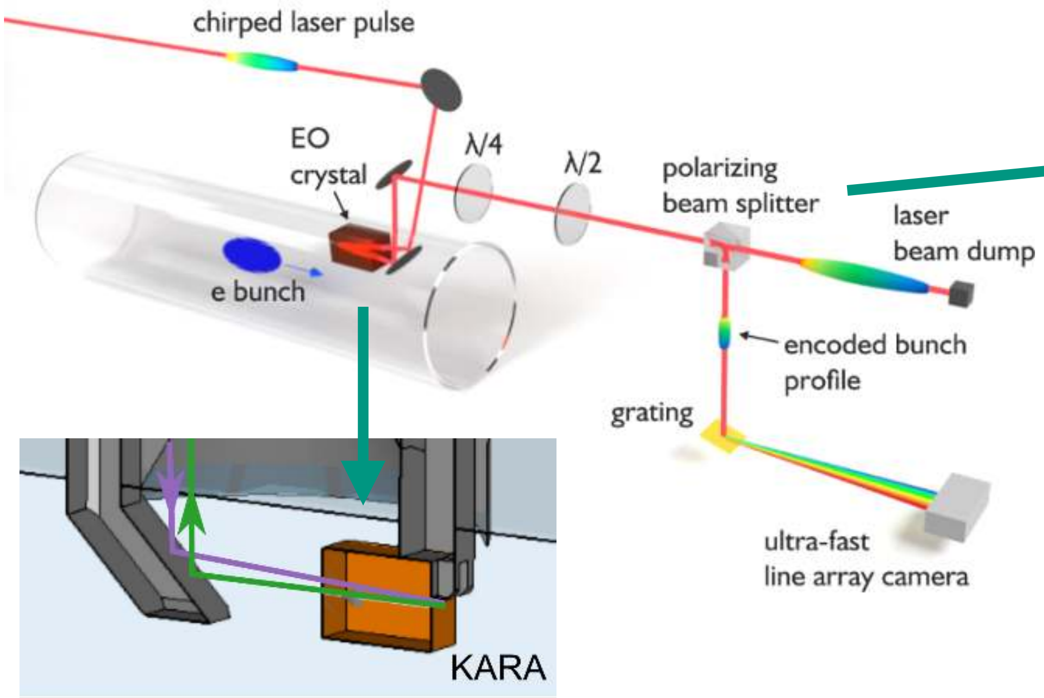
Split-ring resonator (SRR)

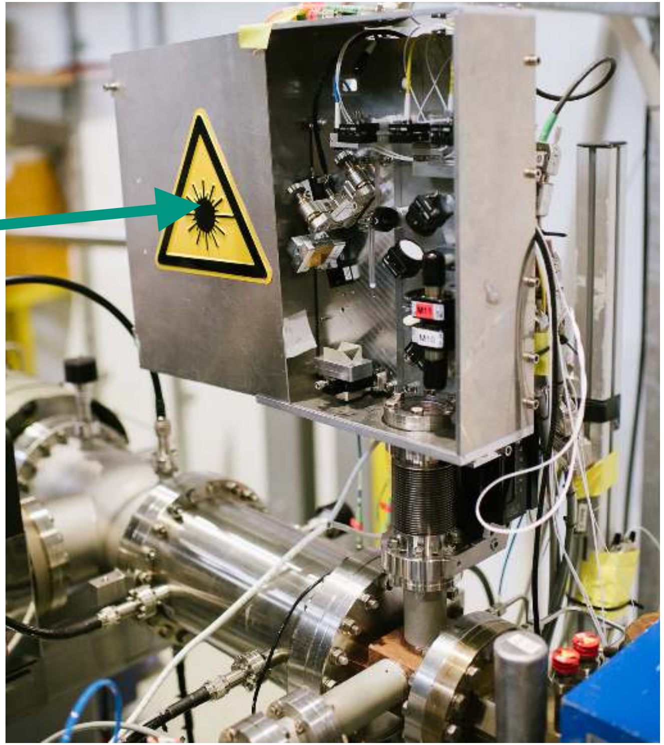


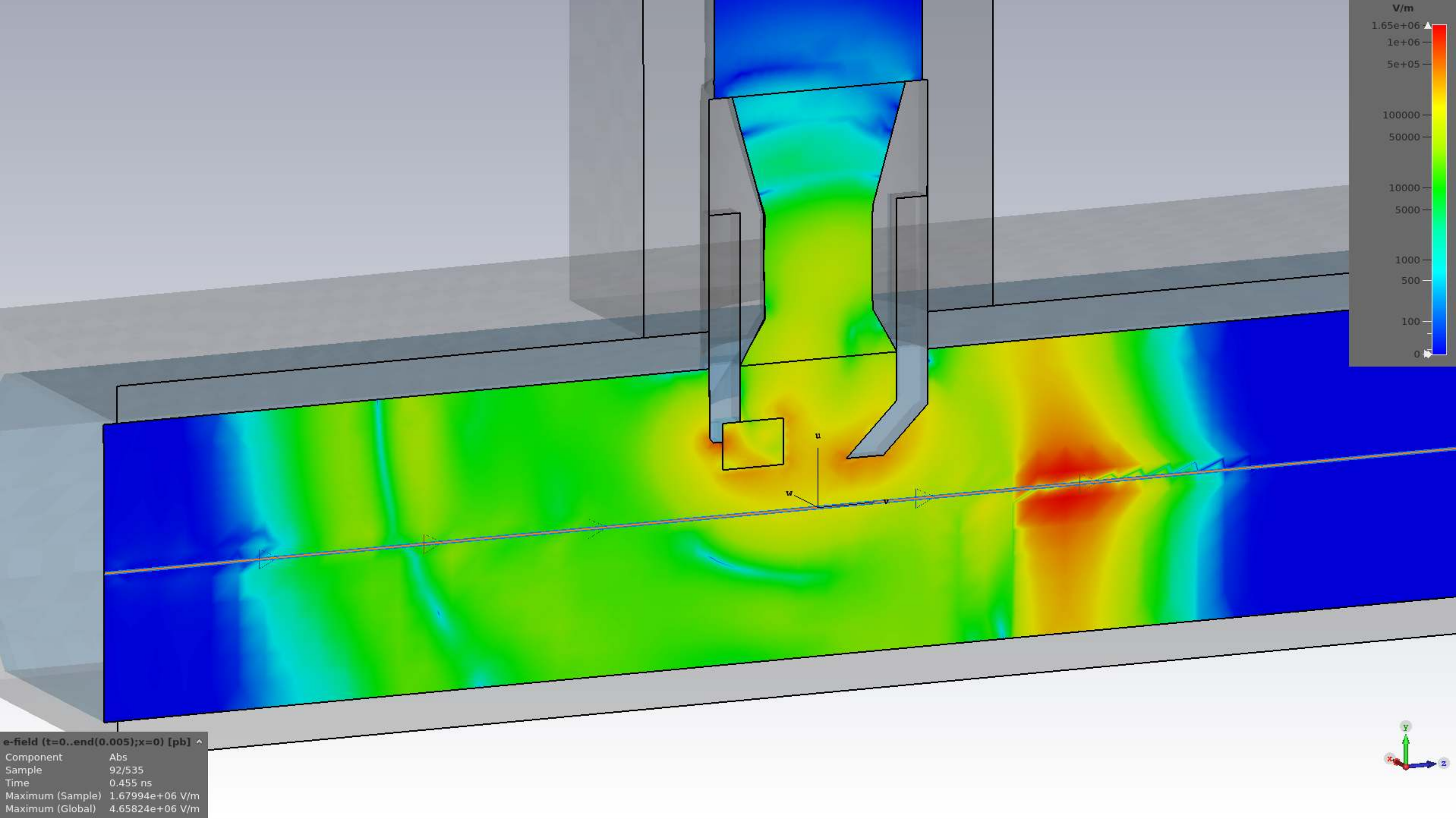
First streaking results (November 2024)

Courtesy: M. Nabinger

Electro-optical bunch profile monitor






V/m
1.65e+06
1e+06
5e+05
100000
50000
10000
5000
1000
500
100
0
e-field (t=0..end(0.005);x=0) [pb]
Component Abs
Sample 92/535
Time 0.455 ns
Maximum (Sample) 1.67994e+06 V/m
Maximum (Global) 4.65824e+06 V/m
u
v
w
Y
X
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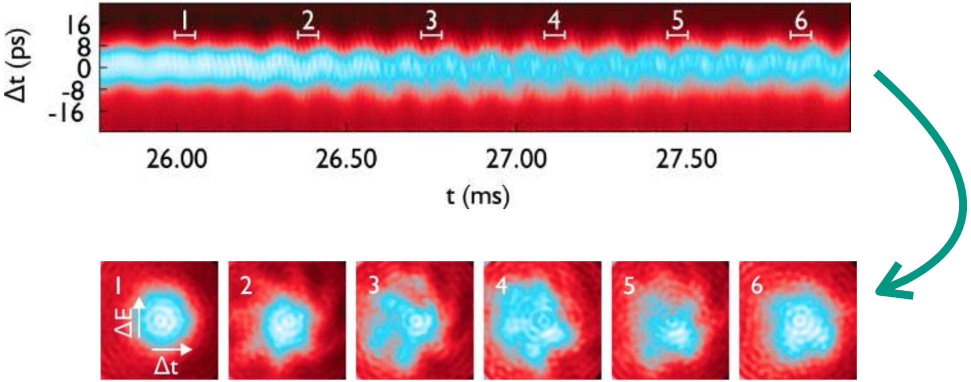
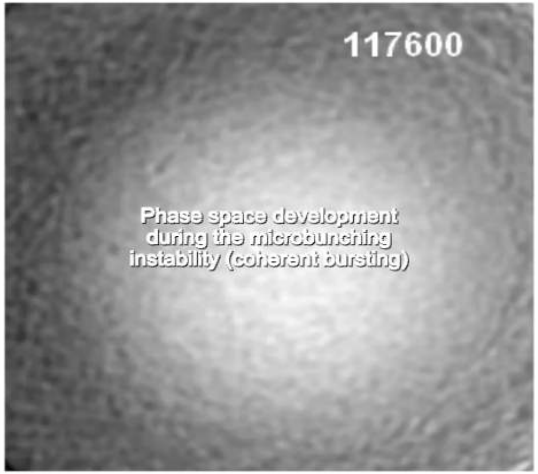
Electro-optical phase space tomography

- electro-optic spectral decoding
- bunch profile measurement
- single-bunch @ 2.7 MHz





Complete phase space image reconstructed from time interval of 61 μm

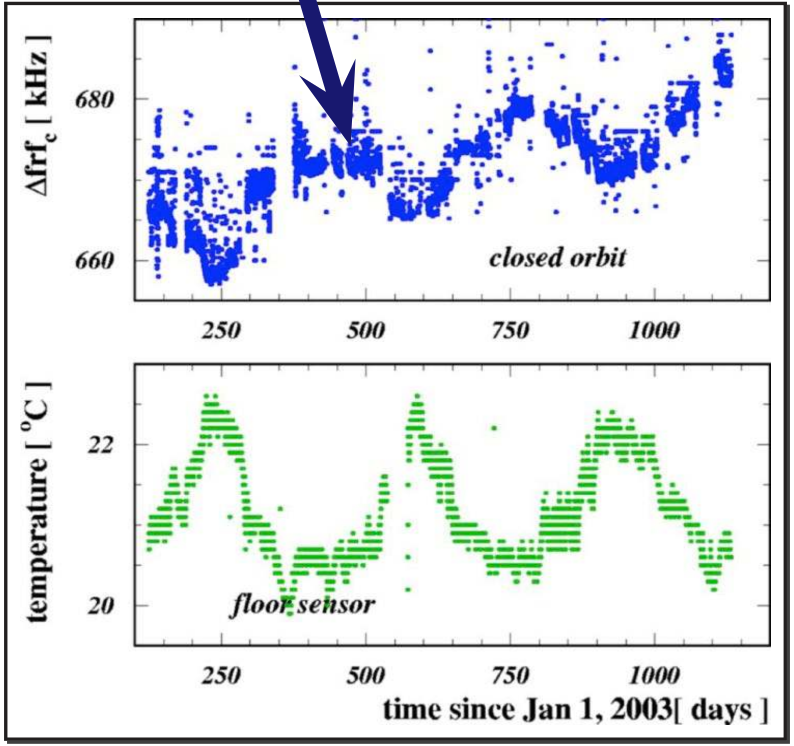
External influences

change of central RF frequency at KARA

- The RF frequency keeps the orbit length constant

$$\frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}}} \propto \frac{\Delta C}{C} \propto -\frac{\Delta E}{E}$$

- **Daily drifts** through injection and ramp
- Significant **seasonal dependence**
  - Hall floor expands with the temperature
- **Long-term drifts**:
  - Drying of the concrete leads to shrinkage of the hall floor



Optics and energy offset

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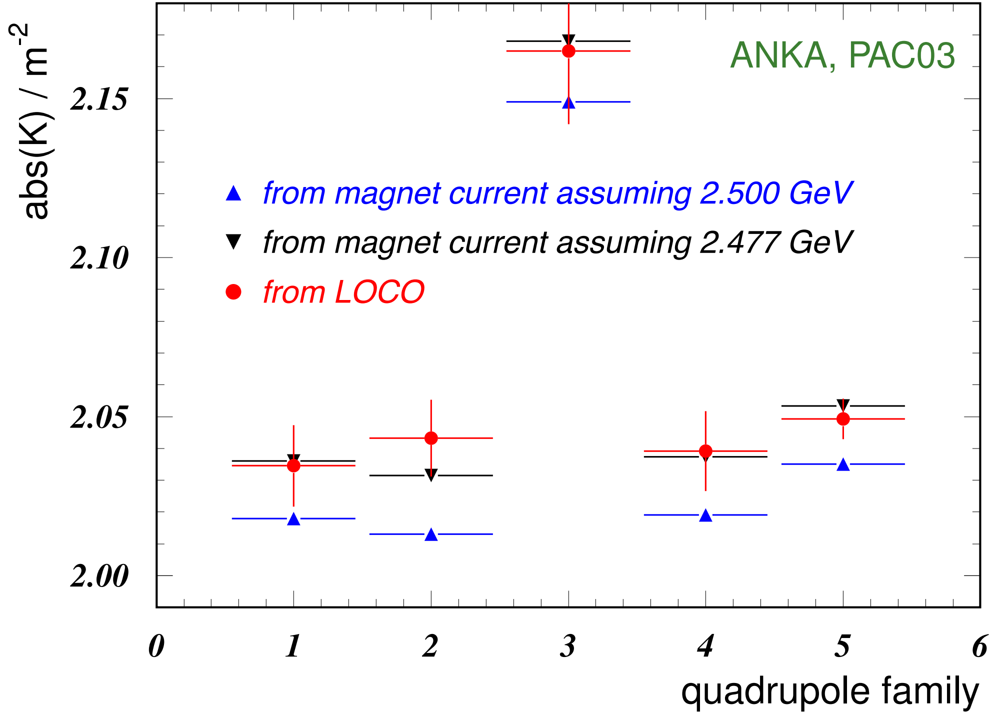
- Measurements of the quadrupole gradients show systematic shift relative to the model when the beam energy is incorrect.
- This applies to both lepton and hadron accelerators.

⇒ It is very important to know the beam energy precisely!

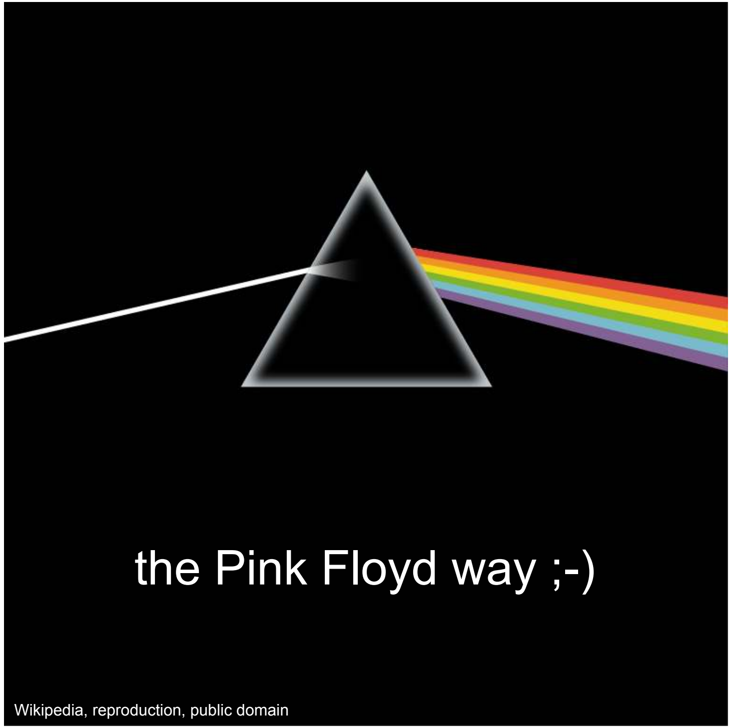


Energy measurement

There are several methods to measure the beam energy

- classical way: spectrometer
- exotic way: from particle/nuclear physics processes
- photon based measurements
- energy measurements from the central frequency
- from energy loss
- highest precision: resonant spin depolarisation

Spectrometer

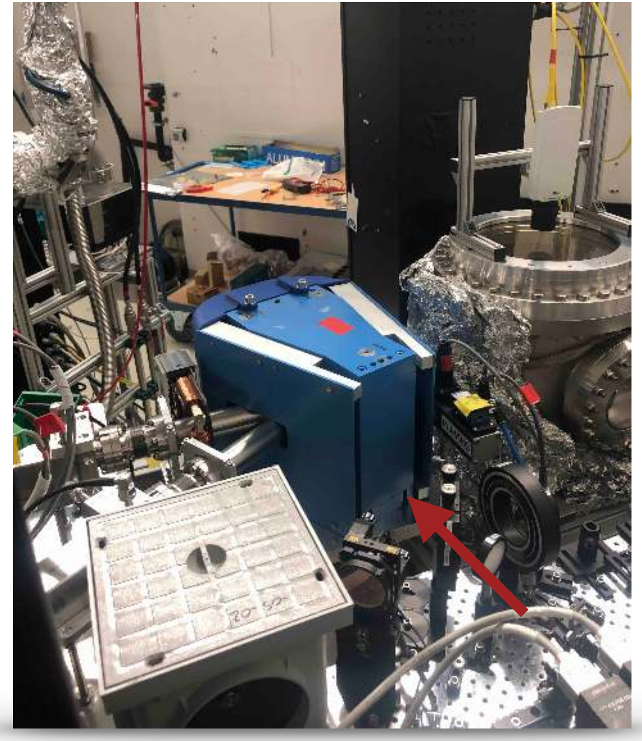


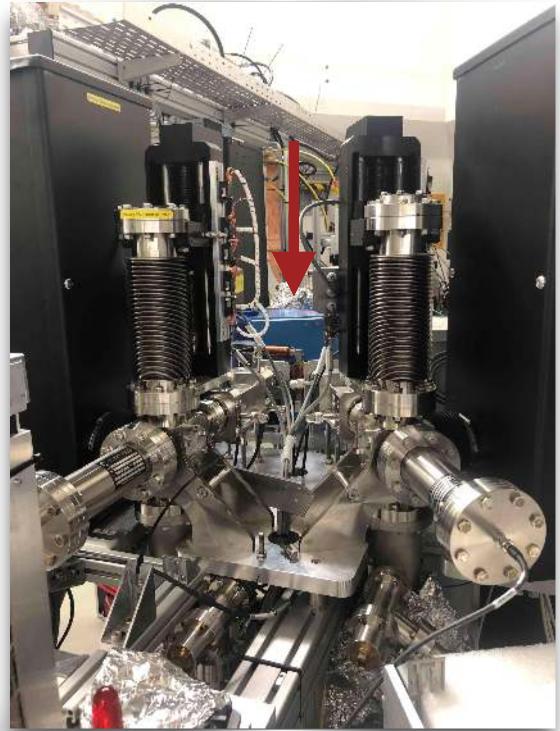
- Spectrometers measure the particle momentum by precisely determining the deflection angle in a dipole magnet

$$\theta \propto \frac{1}{E_0} \int B ds$$

- **Requirements:**
  - Beam position $\mathcal{O}(1\,\mu\text{m})$ at entrance and exit of the dipole magnet
  - Magnetic field $\mathcal{O}\left(10^{-5}\right)$ or better
- **Single Pass Systems**
  - position measurement with position sensitive detector at the beam stop (possible attenuation)
- **Storage rings**
  - circulating beam, measurement of beam position with BPMs after deflection

FLUTE spectrometer



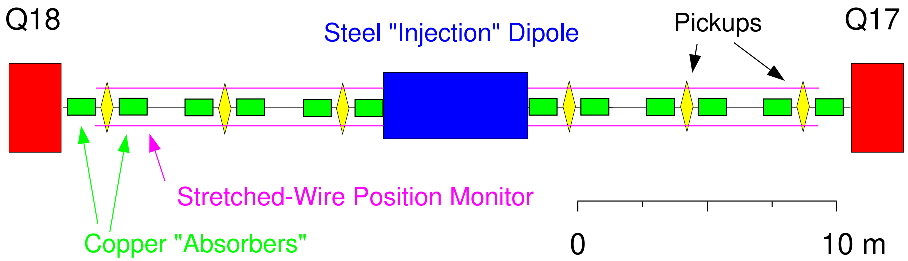


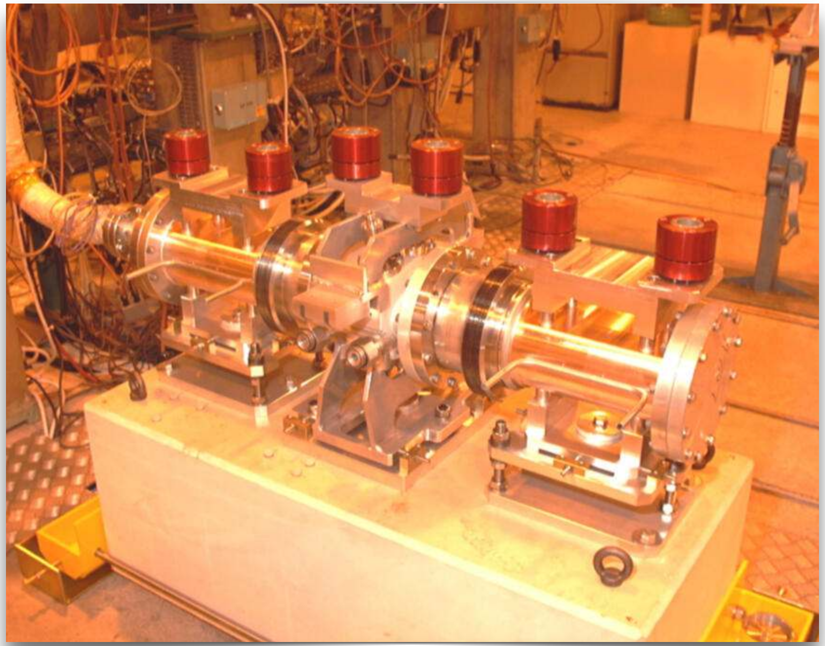
Magnet parameters

- L = 157 mm
- B = 0.08 T
- ρ = 300 mm
- $\theta = 30^\circ$

Drift length to screen station: L = 0.609 m

LEP spectrometer



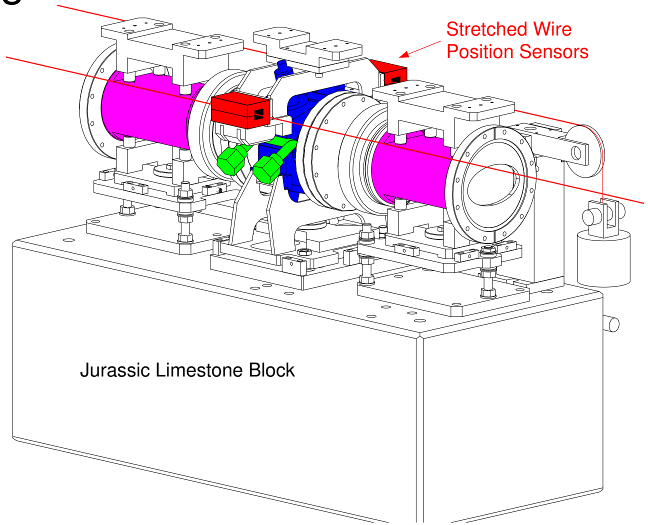


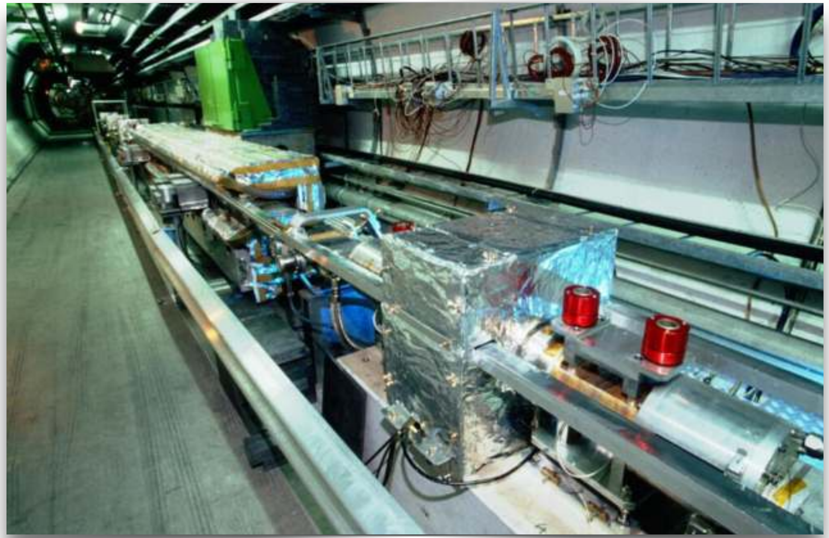
- Position measurement: 1 µm
- Magnetic field: $\Delta B/B = \mathcal{O}\left(10^{-5}\right)$

- Energy resolution: $\Delta E/E = \mathcal{O}\left(10^{-4}\right)$

LEP spectrometer II

- Pickup positions monitored with a stretched wire system (beware of thermal effects due to synchrotron radiation etc.)
- Take into account the local magnetic field of the earth and fields generated by close-by power lines



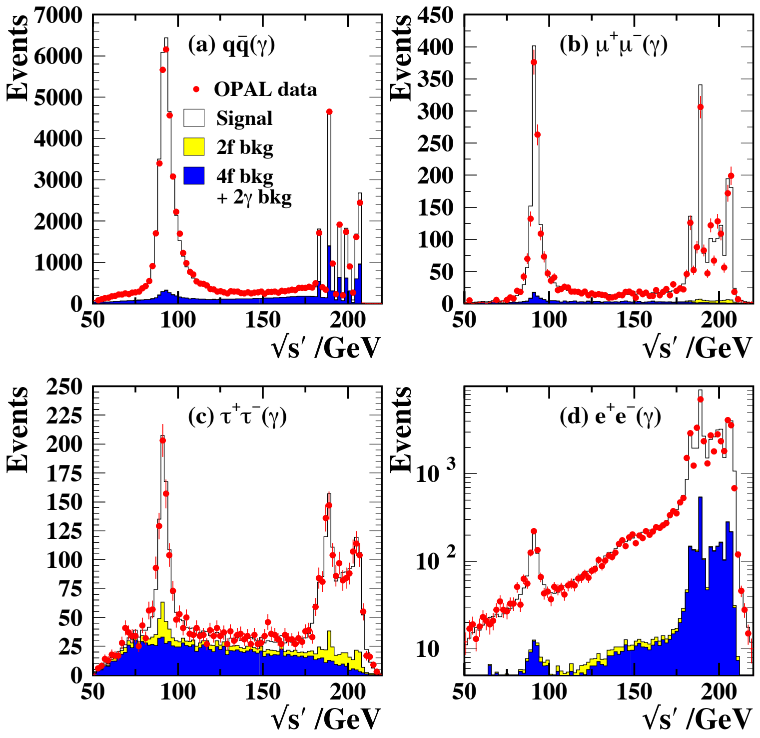


Determine energy from the Z boson

- Cross-check E_{cm} using events of the type $e^+e^- \to Z\gamma,\ Z \to f\bar{f}$ where the fermion f is a quark, electron, muon or τ-lepton

- $m_Z = 91\,\mathrm{GeV}/c^2$ is the well-known Z mass from LEP I
  $\Rightarrow$ invert the problem and conclude collision energy of the event

- $\Delta E/E = \mathcal{O}\left(3 \times 10^{-4}\right)$



G. Abbiendi et al., Phys. Lett. B (604) 2004.

Central frequency and momentum

- The particle velocity relative to the speed of light is

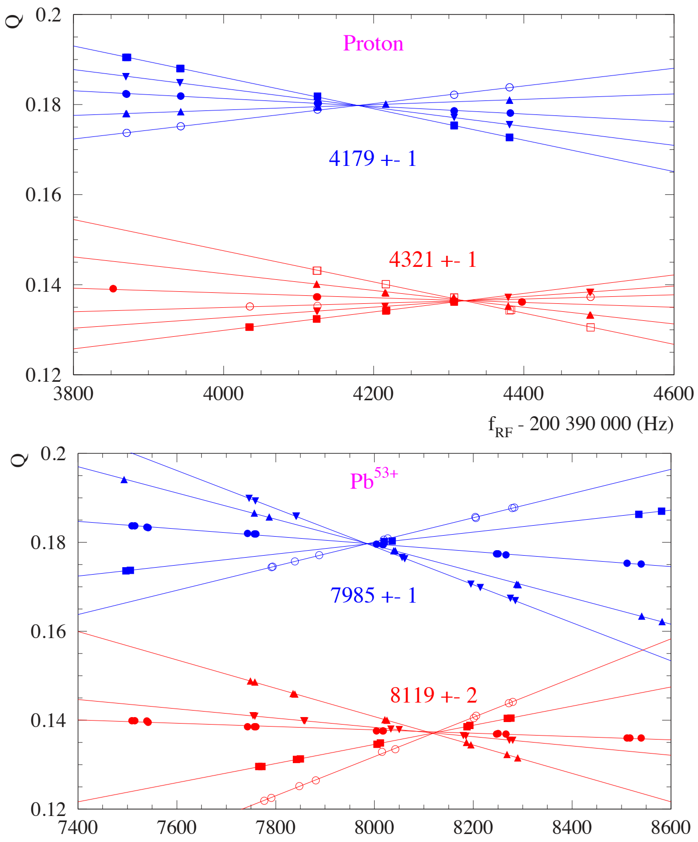
$$\beta = \frac{C\, f_{\mathrm{rev}}}{c} = \frac{C\, f_{\mathrm{RF}}}{hc} = \frac{pc}{E}$$

- To simultaneously determine p and C, measure f_{rev} for two particle types with different Z/m under the same machine conditions (e^+/p, p/Pb^{53+})

- The momentum is given by

$$p \approx m_p c \sqrt{\frac{f_{\mathrm{RF,p}}}{2\Delta f_{\mathrm{RF}}}\left[\left(\frac{m_i}{Z m_p}\right)^2 - 1\right]}$$

  - difficult for high energies since $\Delta f \propto (m_i/Zm_p)^2/p^2$
  - maximize m_i/Zm_p (Pb^{53+})
- $\Delta p/p = \mathcal{O}\left(10^{-4}\right)$



J. Wenninger, SPS 2003: 449.16(14) GeV

For details see: CERN note „AB-Note-2003-014 OP“

V - Measurement and control of beam parameters

- Beta functions and dispersion
  - Gradient variation / response matrix

- All around the betatron tune
  - FFT & LNP
  - Results from multi-turn measurements
  - Phasen space reconstruction

- Beam energy
  - Transverse polarisation
  - Resonant spin depolarisation
  - LEP and external effects

next time

Karlsruhe Institute of Technology

IBPT

Institute for Beam Physics and Technology

Particle Accelerator Physics

Anke-Susanne Müller, Axel Bernhard, Bastian Härer, Bennet Krasch, Nathan Ray

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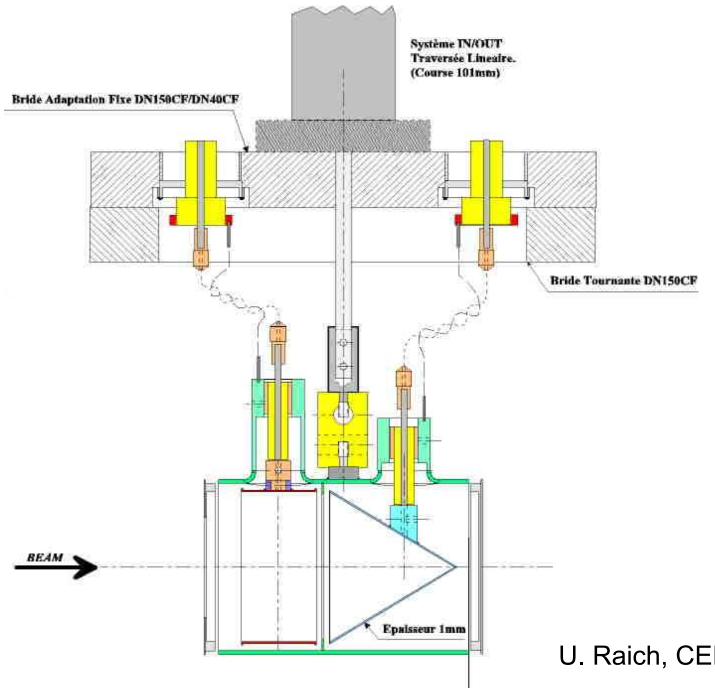
Examples for beam diagnostics

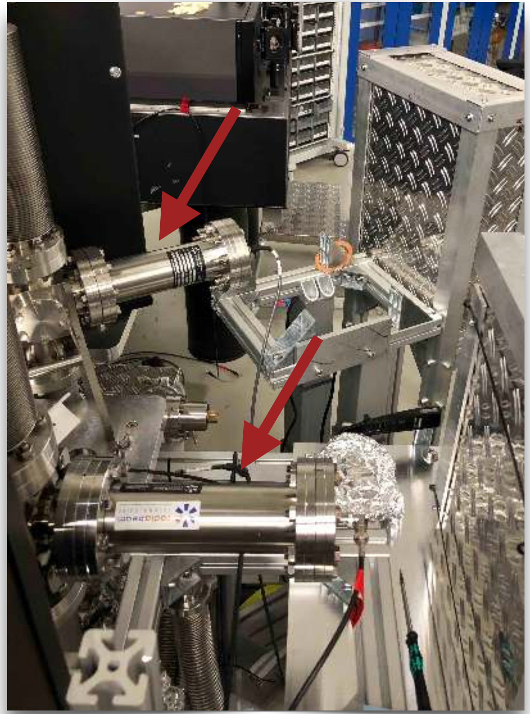
Device	Physical effect	Parameter	Destructive
Faraday cup	Charge collection	Beam intensity	yes
Wall current monitor	Mirror current	Beam intensity, long. profile	no
Current transformer	Magnetic field	Beam intensity	no
Wire scanner	Secondary particles	Transverse profile	interfering
Beam position monitor	Electric/magnetic field	Beam position	no
Fluorescent screen	Fluorescence	Transv. profile, position	yes
Residual gas monitor	Ionisation	Transverse profile	no
SEM	Secondary emission	Transv. profile, emittance	interfering

Faraday cup

- beam intensity -



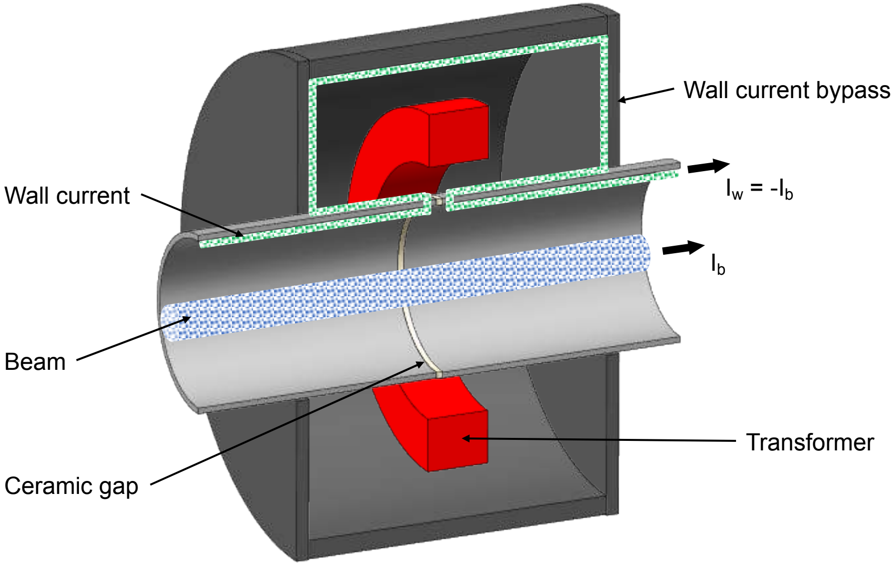
U. Raich, CERN Accelerator School, Zakopane 2006



Faraday cups at FLUTE

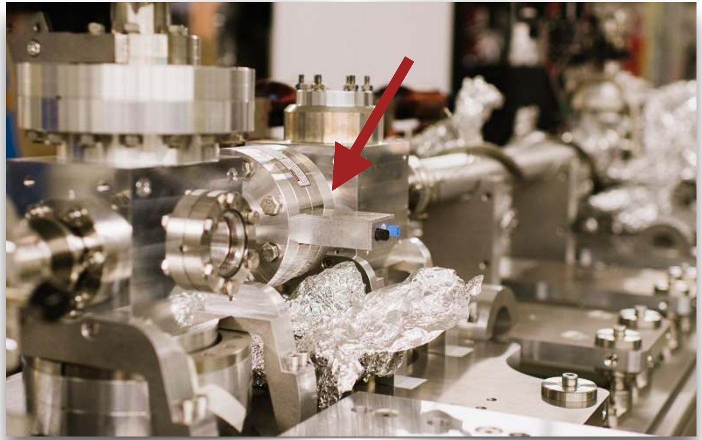
Integrated current transformer (ICT)

- beam charge, pulse duration -



© BERGOZ Instrumentation, Integrating Current Transformer, user's manual

- Measure the charge of very short pulses via induced magnetic field
- Integrated signal, linear integrator
  - since eddy currents are negligible
  - but original shape of signal is lost



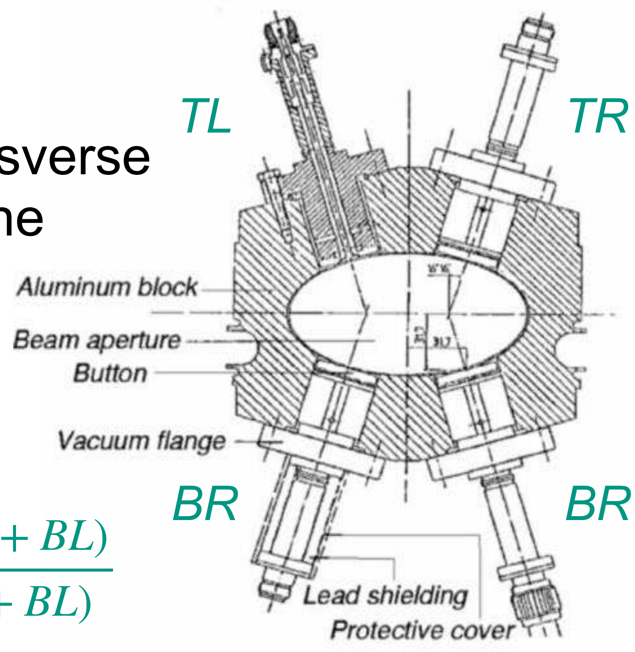
turbo ICT at FLUTE

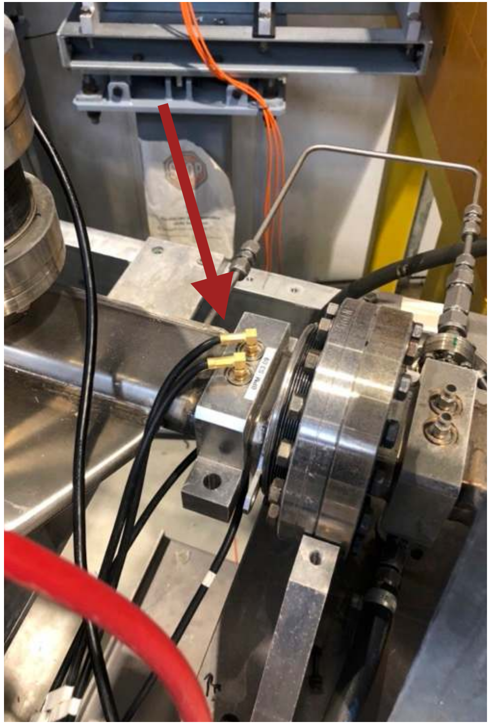
Beam position monitor (“BPM”)

- beam position, tunes, … -

- Measurement of transverse beam position from the differential signal of the “buttons”

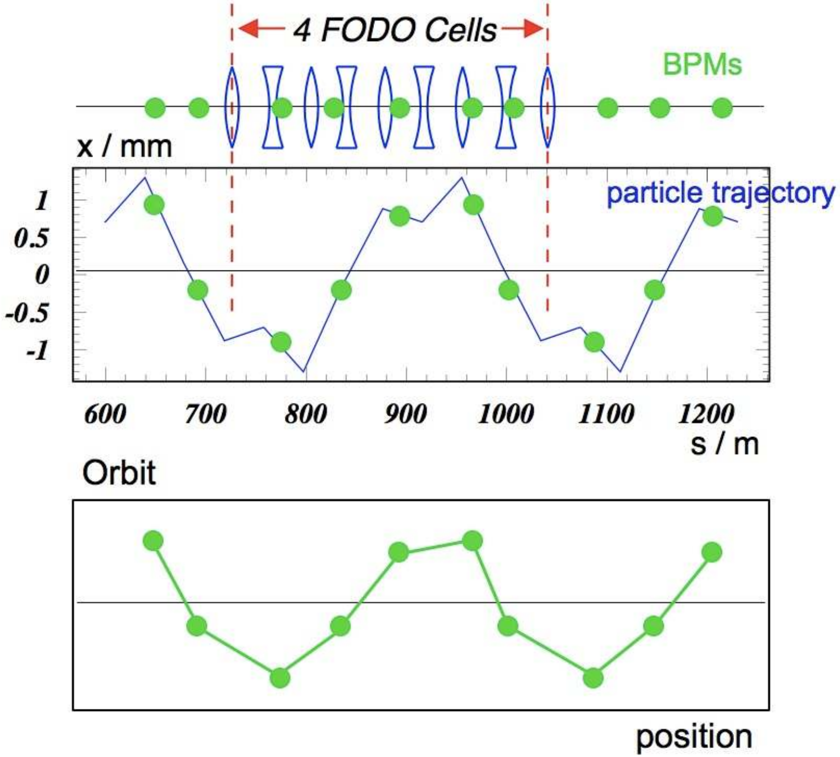
$$U_{\Delta x} = A \frac{(TR + BR) - (TL + BL)}{(TR + TL + BR + BL)}$$





beam position monitor at KARA

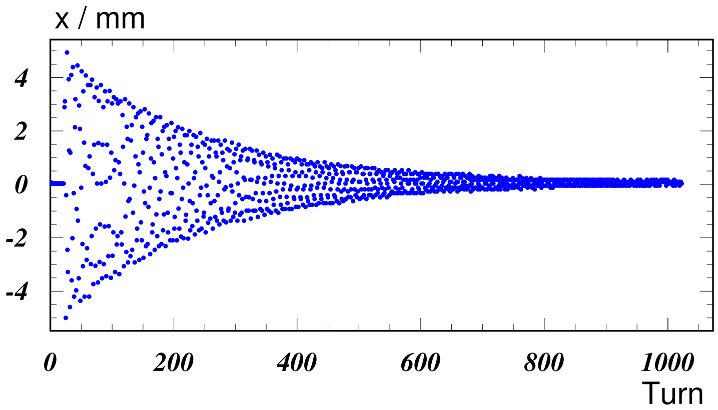
Orbit measurement and correction



Vertical orbit corrector at KARA

Multi-turn measurements

- Measurement of the transverse beam position with beam position monitors ("BPMs") for many consecutive transitions
- Only the center of gravity of the charge distribution is visible
- Many analyses possible, e.g.
  - tune as a function of e.g. amplitude from harmonic analyses,
  - phase space reconstruction,
  - energy loss measurement



Measurement of beta functions: “k modulation”

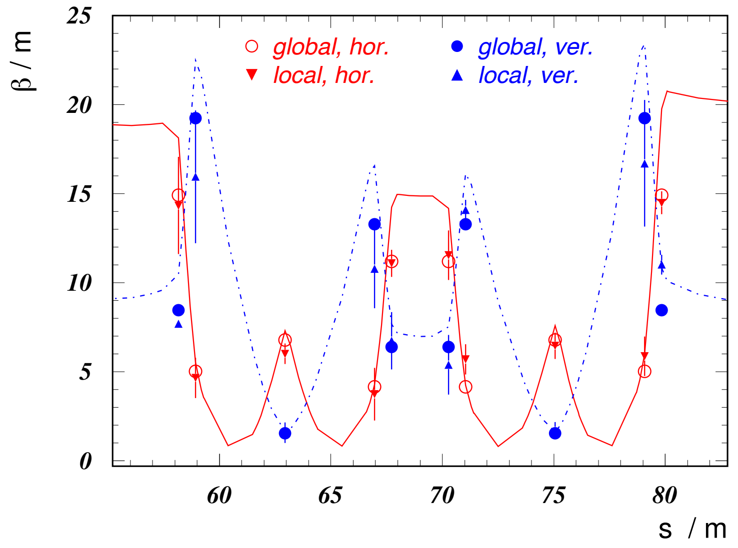
Karlsruhe Institute of Technology

The beta function can be determined in several ways:

- from a measurement of the tune change as a function of a gradient change of a single quadrupole (“local β”)
- from a measurement of the tune change as a function of a gradient change of a quadrupole family (“global β”)
- from the relation for a gradient error:

$$\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta k(s) ds$$

$$\beta_{x,y} \approx \pm \frac{4\,\pi\,\Delta Q_{x,y}}{\Delta k}$$



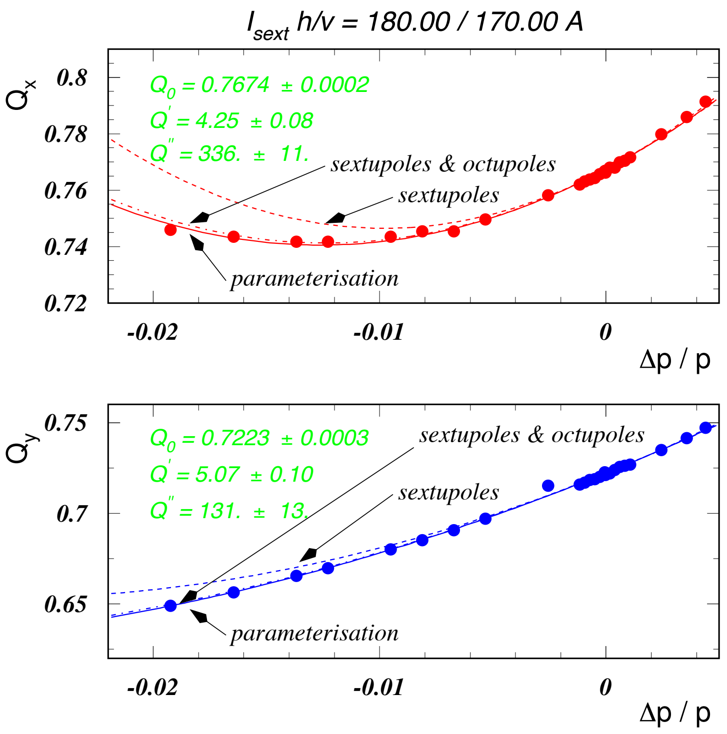
Chromaticity

- Measurement of betatron tunes as a function of momentum offset

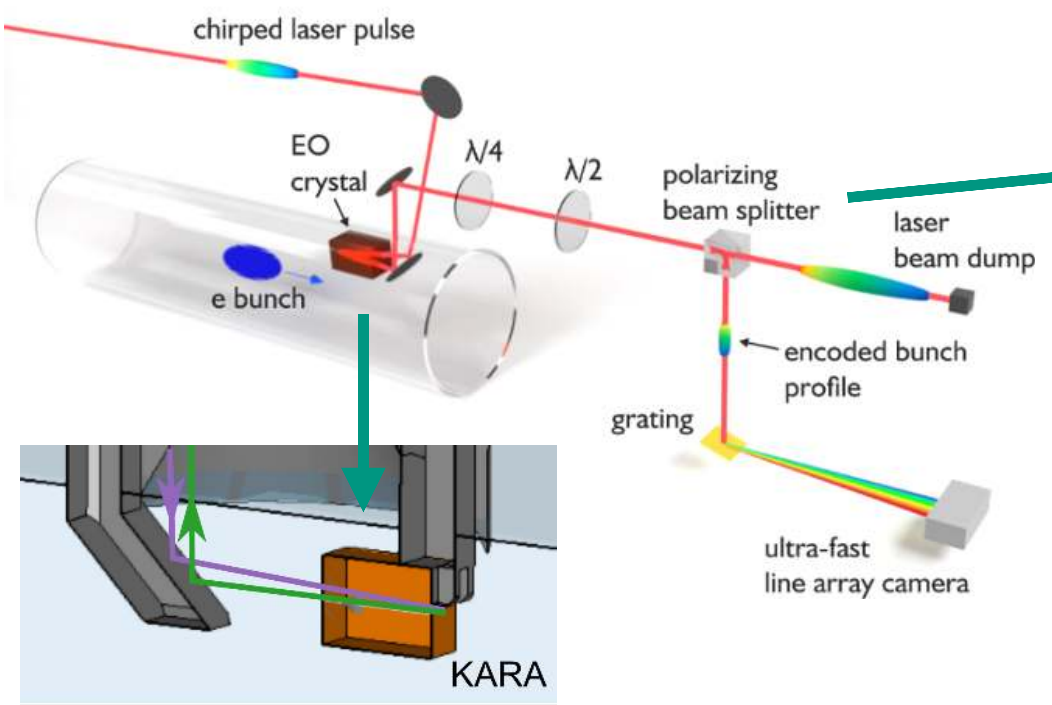
- Variation of momentum offset with

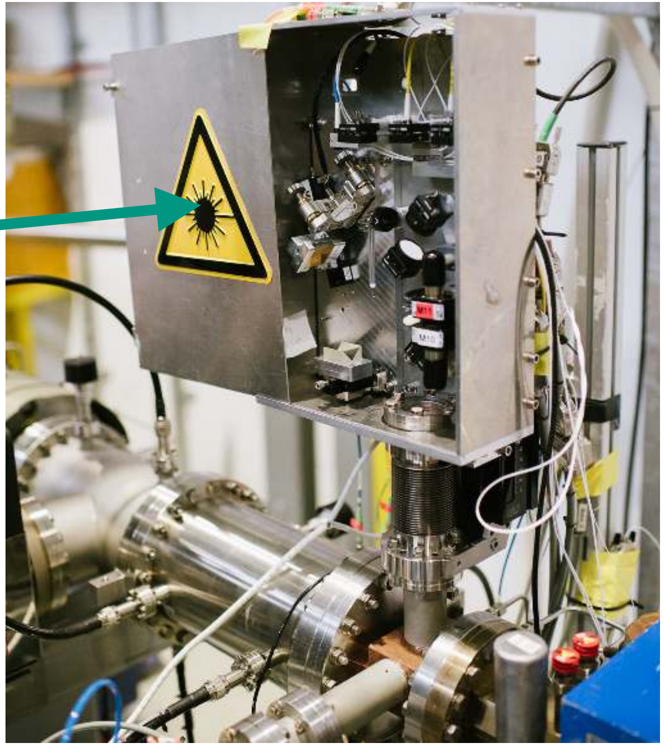
$$\frac{\Delta p}{p_0} = -\frac{1}{\alpha_c}\frac{f_{\mathrm{RF}} - f_{\mathrm{RF}}^c}{f_{\mathrm{RF}}^c}$$

- Slope gives chromaticity
- Curvature provides information about higher multipole orders



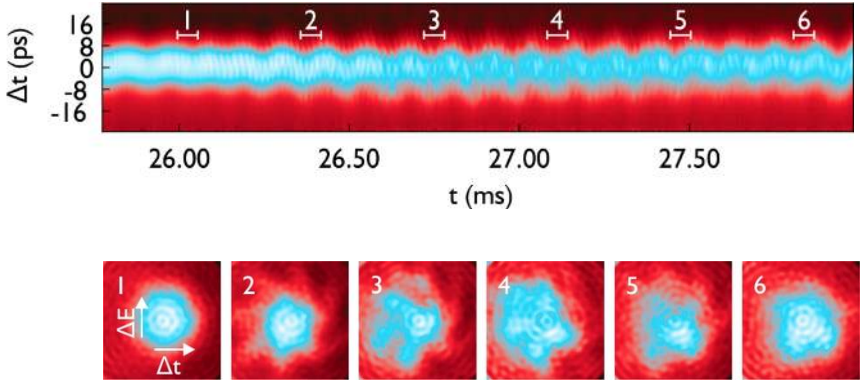
Electro-optical bunch profile monitor

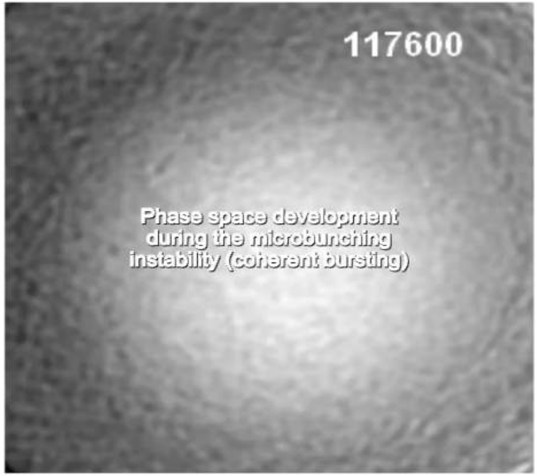




Electro-optical phase space tomography

- electro-optic spectral decoding
- bunch profile measurement
- single-bunch @ 2.7 MHz





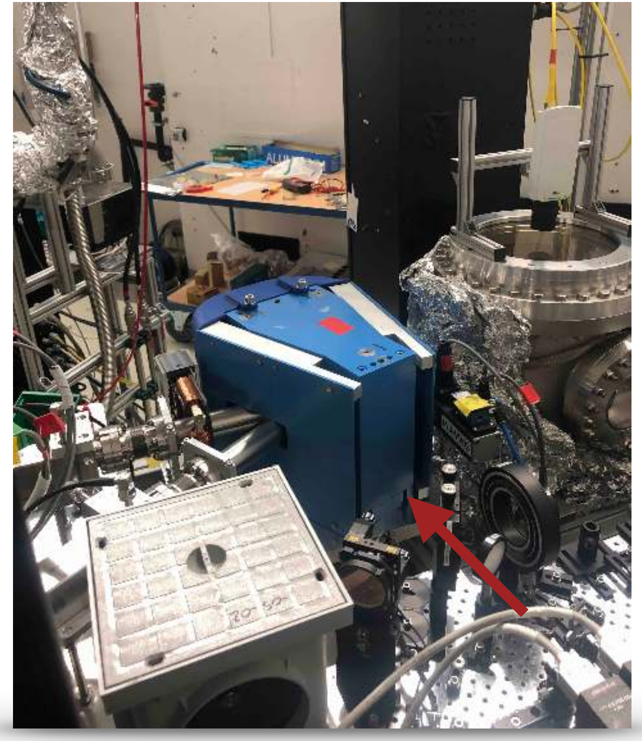
Complete phase space image reconstructed from time interval of 61 µm

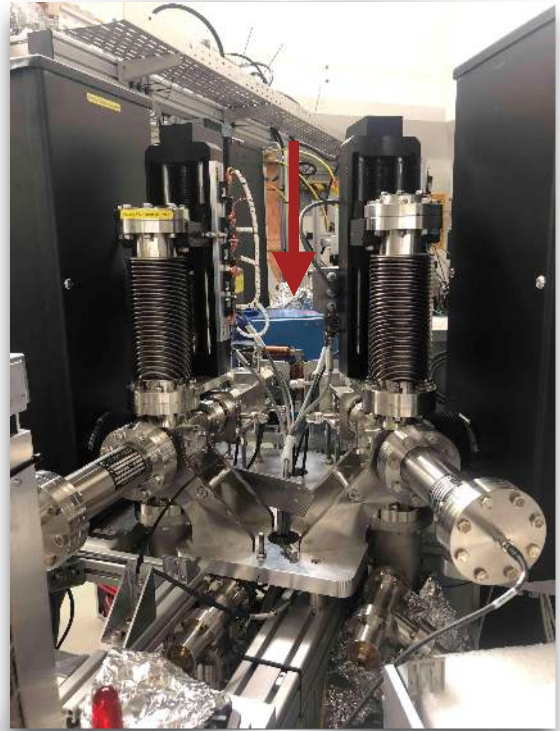
Energy measurement

There are several methods to measure the beam energy

- classical way: spectrometer
- exotic way: from particle/nuclear physics processes
- photon based measurements
- energy measurements from the central frequency
- from energy loss
- highest precision: resonant spin depolarisation

FLUTE spectrometer



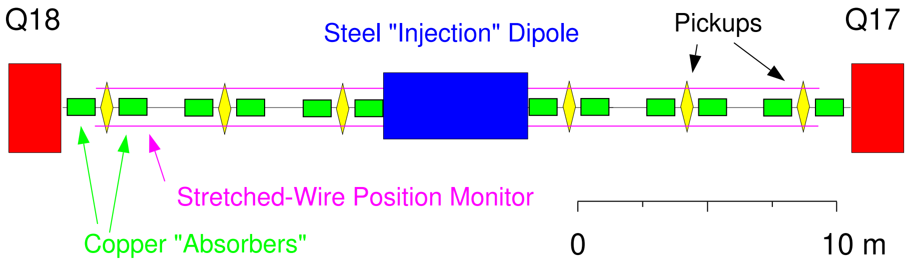


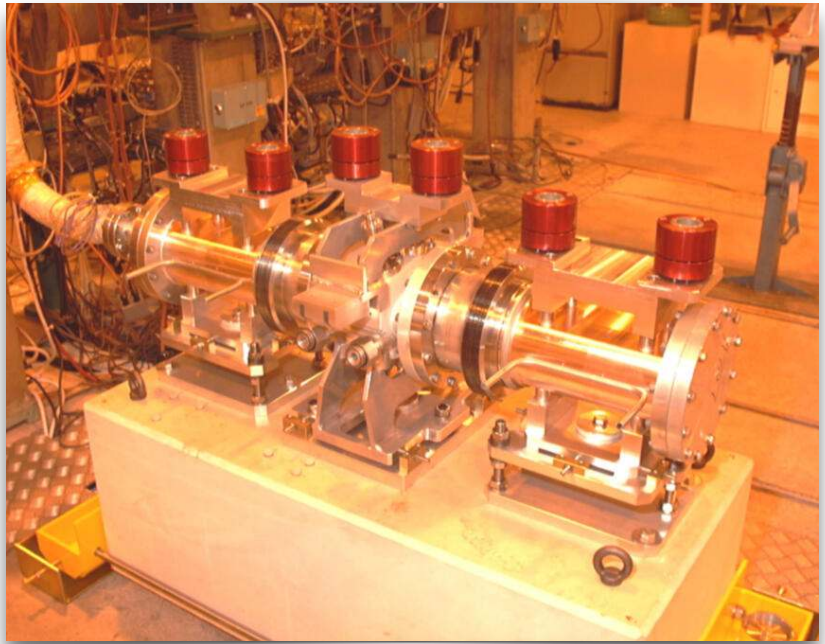
Magnet parameters

- L = 157 mm
- B = 0.08 T
- ρ = 300 mm
- $\theta = 30^{\circ}$

Drift length to screen station: L = 0.609 m

LEP spectrometer





- Position measurement: 1 µm
- Magnetic field: $\Delta B/B = \mathcal{O}\left(10^{-5}\right)$

- Energy resolution: $\Delta E/E = \mathcal{O}\left(10^{-4}\right)$

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today

Transverse spin polarization

- Spin polarization results from the emission of synchrotron radiation:
  - Asymmetry in the spin flip probability during photon emission leads to transverse polarization
  - maximum polarization from the size of the asymmetry term:

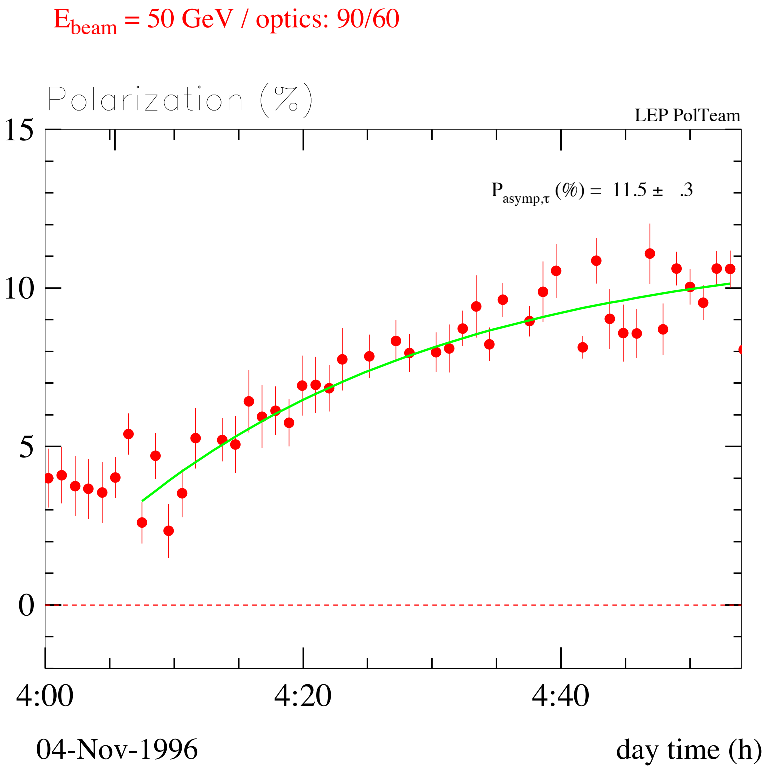
$$8/5\sqrt{3} \approx 92.4\,\%$$

- Polarization level increases exponentially with time

$$P(t) = P_0\left(1 - e^{-t/\tau_p}\right)$$

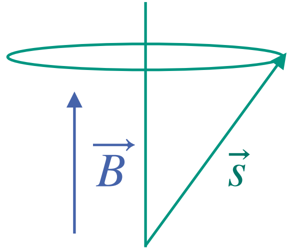
$$\tau_\mathrm{p} = \frac{8}{5\sqrt{3}} \frac{m_0^6 c^{10} \rho^3}{\hbar r_\mathrm{e} E_0^5}$$

  - Typical polarization time for electrons: some minutes till hours
  - LEP: 340’, KARA: 10’, FCC-ee: > 10 h



Spin precession

- The movement of the spin vector $\vec{s}$ of a relativistic electron in the presence of electric and magnetic fields $\vec{E}$ and $\vec{B}$ is described by the Thomas-BMT (Bargmann, Michel, Telegdi) equation:



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega}_{\mathrm{BMT}} \times \vec{s}$$

- The spin precession frequency $\vec{\Omega}_{\mathrm{BMT}}$ is

$$\vec{\Omega}_{\mathrm{BMT}} = -\frac{e}{\gamma m_0}\left[(1 + a\gamma)\,\vec{B}_{\perp} + (1 + a)\,\vec{B}_{\parallel} - \left(a\gamma + \frac{\gamma}{1+\gamma}\right)\vec{\beta} \times \frac{\vec{E}}{c}\right]$$

$$a = (g_{\mathrm{e}} - 2)/2 = 0.001159652193(10)$$

- The mean value of the number of spin revolutions per turn of all particles is defined as the “spin tune”

$$\nu = \frac{f_{\mathrm{spin}}}{f_{\mathrm{rev}}} = \frac{(g_e - 2)/2}{m_0 c^2} E_0$$

Resonant spin depolarization

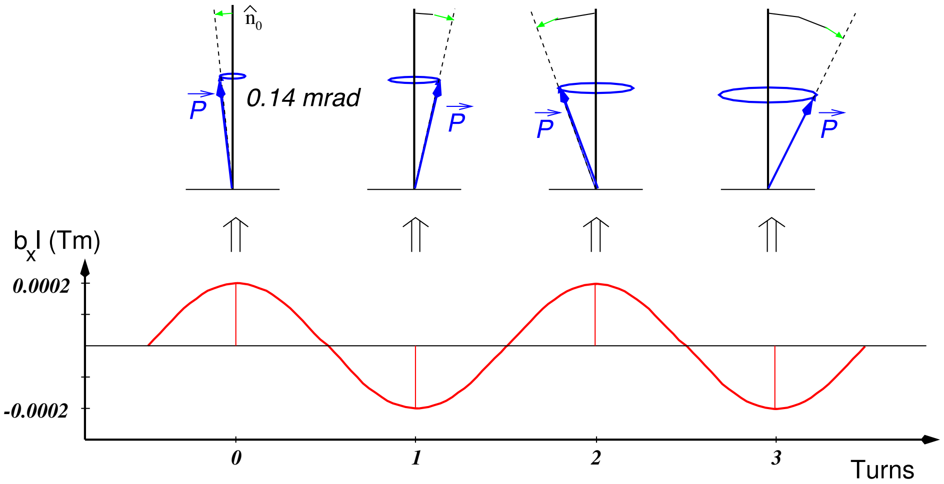
- Spins precede in the vertical magnetic bending field with the frequency f_{spin}:

$$\nu = \frac{f_{\mathrm{spin}}}{f_{\mathrm{rev}}} = \frac{(g_e - 2)/2}{m_0 c^2} E_0$$

→ Spin tune ν depends on beam energy!

- Apply a horizontal magnetic field B_x, which is modulated with frequency f_B
  - Resonant depolarisation at $f_{\mathrm{spin}} = f_B$

    $\Rightarrow \nu \Rightarrow E_0$
  - Precision: $\Delta E/E \approx 10^{-5}$



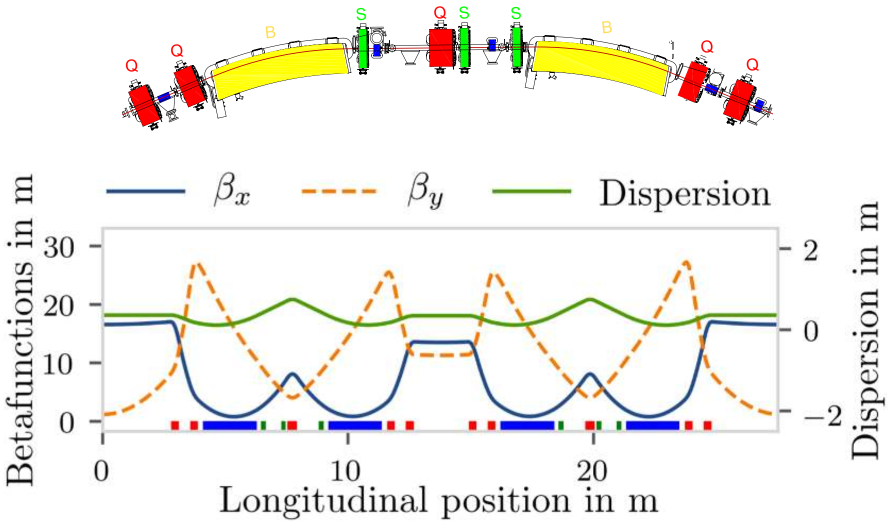
Resonant spin/polarization vector rotation for $\nu = n + 1/2, \quad n \in \mathbb{N}$

Polarization and loss rate

- The Touschek effect describes the transformation of small transverse momenta into large longitudinal momenta by Coulomb scattering leading the loss of particles.
- The Touschek cross-section depends on polarization

  → Touschek loss rate is a measure of the polarization level

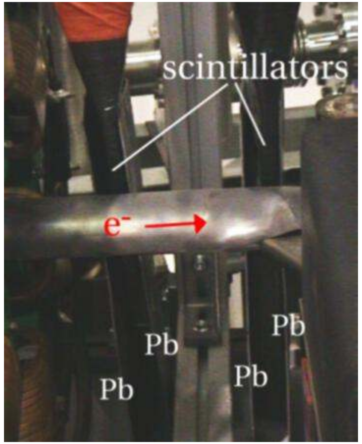
- A loss monitor in a region with high dispersion and small betafunctions serves as a polarimeter.

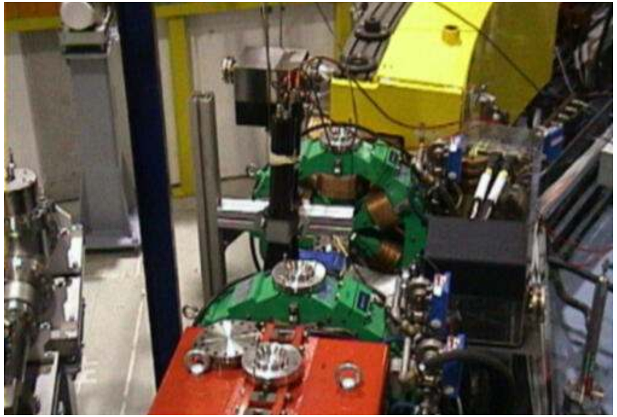


Proof of polarization

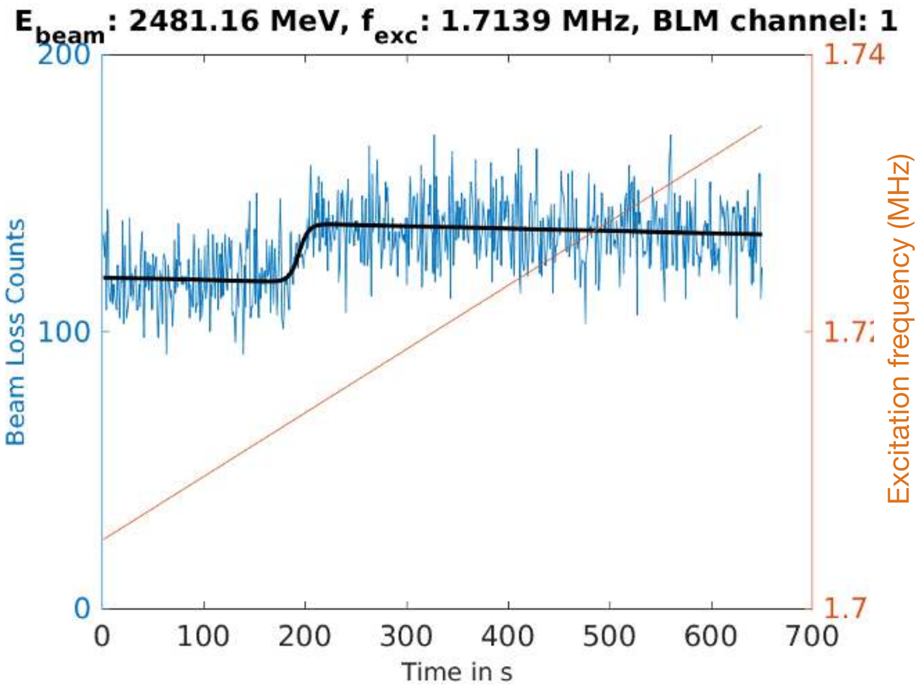
- For example, scintillators in lead shielding as protection against synchrotron radiation

- Or, lead-glass block with photo multiplier
- Photo multiplier pulses are converted into NIM signals and counted





Recent RDP results

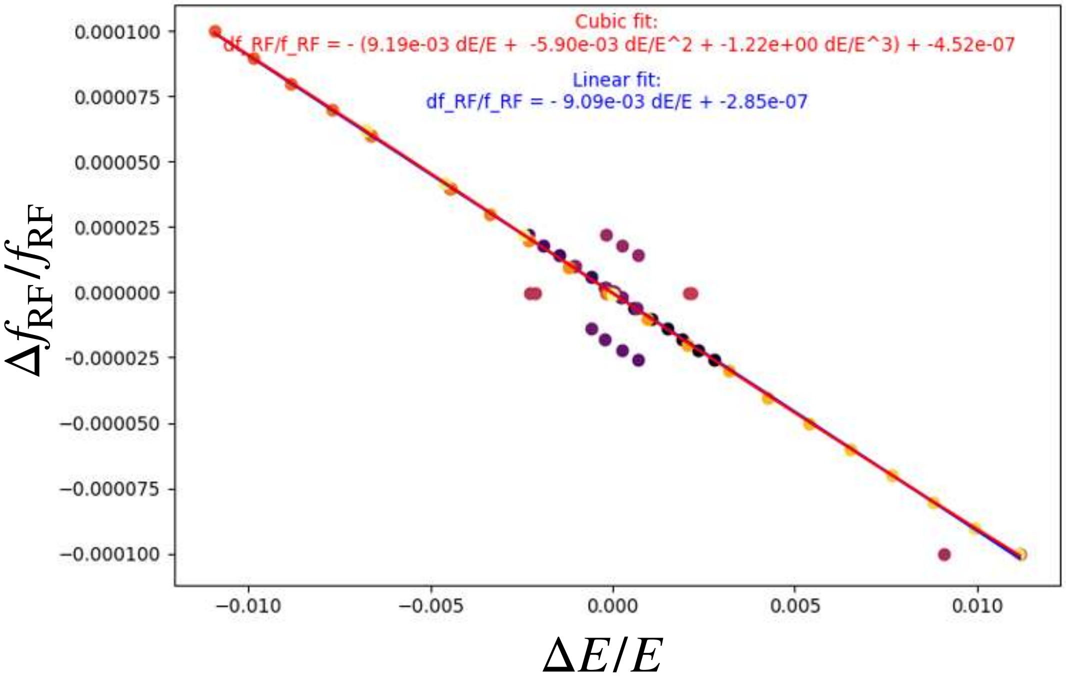


- The loss rate follows the step function

$$r = a - \frac{\partial r_I}{\partial t} t + \frac{\Delta r}{1 + \exp\left\{ - \frac{t - t_d}{\sigma_d} \right\}}$$

- Δr: change in count rate
- t_d: time of depolarization
- σ_d: duration of depolarization

Recent RDP results II

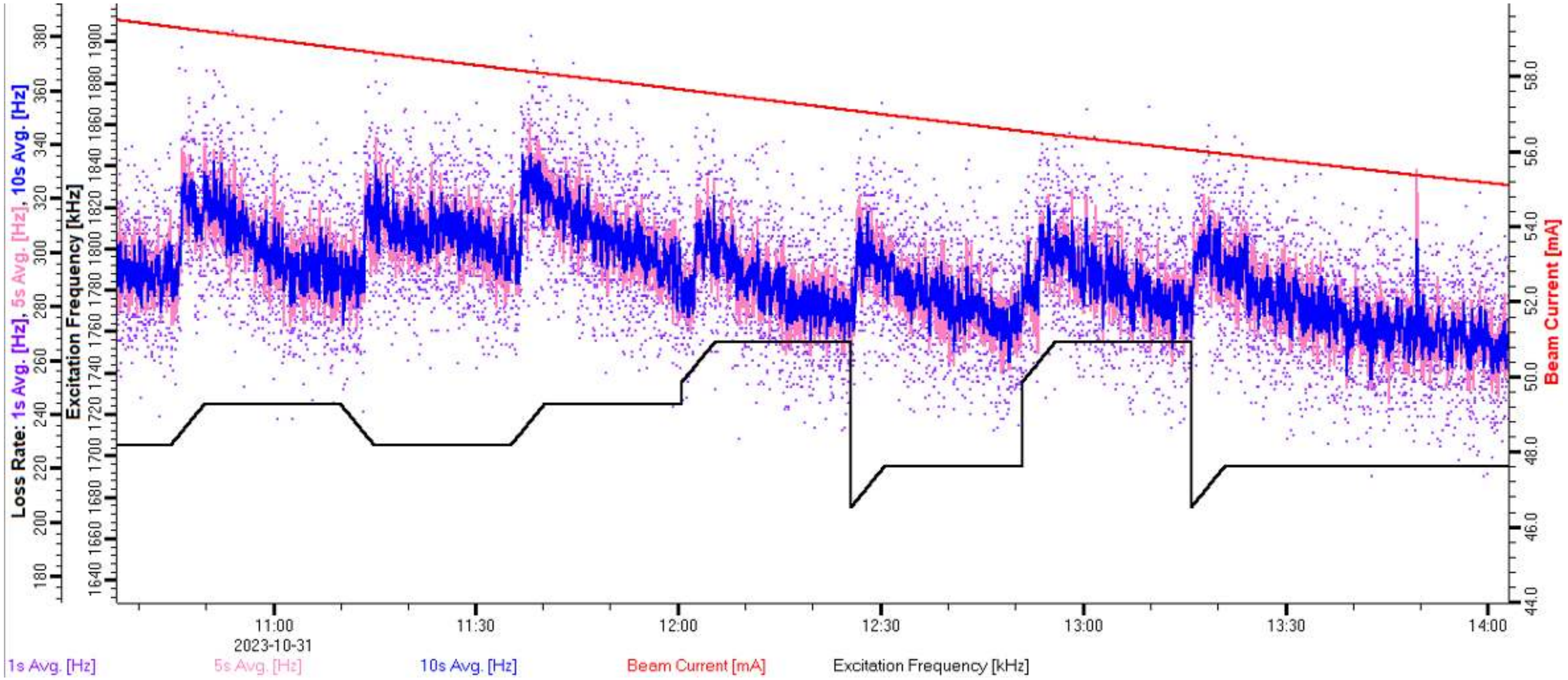


- Obtain momentum compaction factor α_c from scans at different RF frequencies f_{RF}

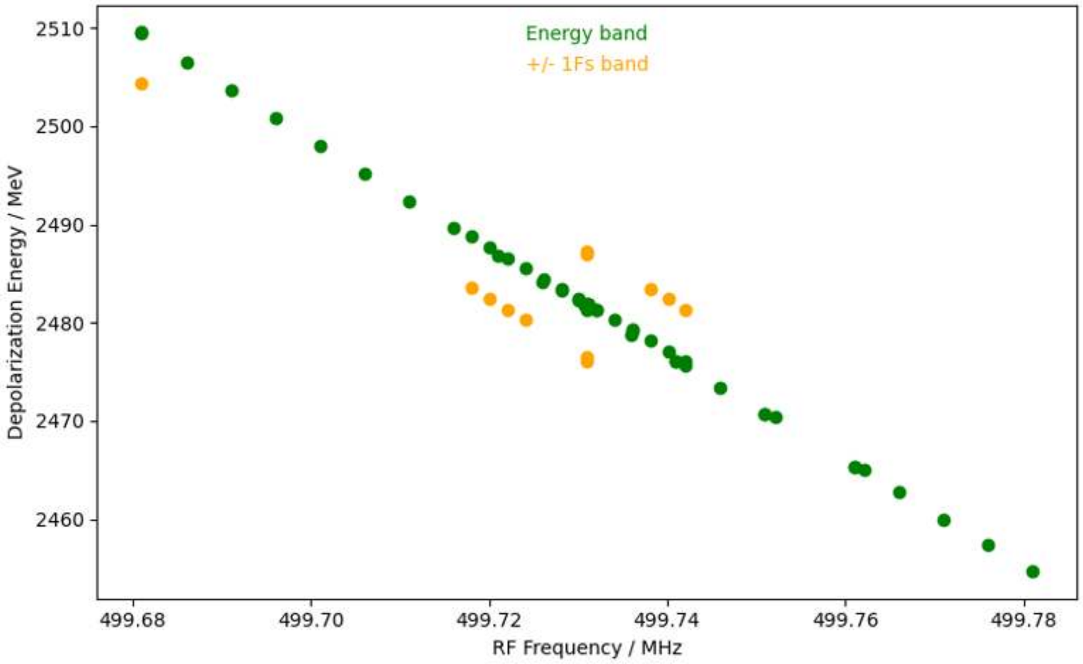
$$\frac{\Delta L}{L} = \frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}}} = \alpha_{c1}\delta\delta + \alpha_{c2}\ \delta^2 + \ldots$$

- α_{c2} is highly significant, but small

Automated scans



Recent RDP results II

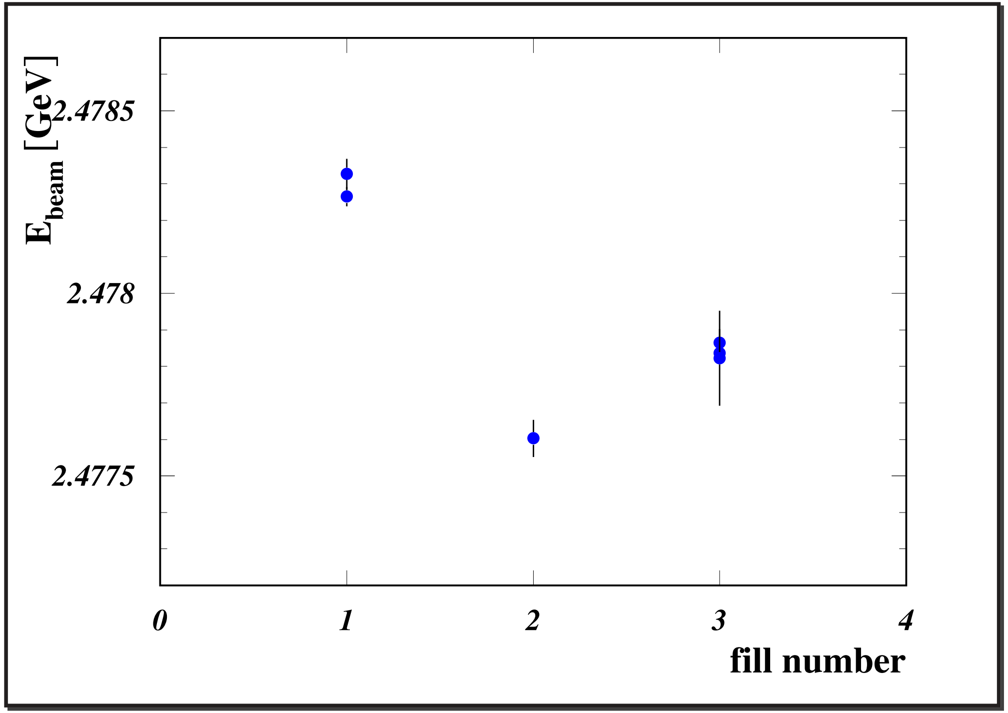


- Depolarisation is also possible on the synchrotron side bands
- Due to the single-particle nature of the depolarization process, this happens at

$$f_{\mathrm{dep}}/f_{\mathrm{rev}} = [\nu] \pm Q_s^{\mathrm{inc}}$$

Energy reproducibility

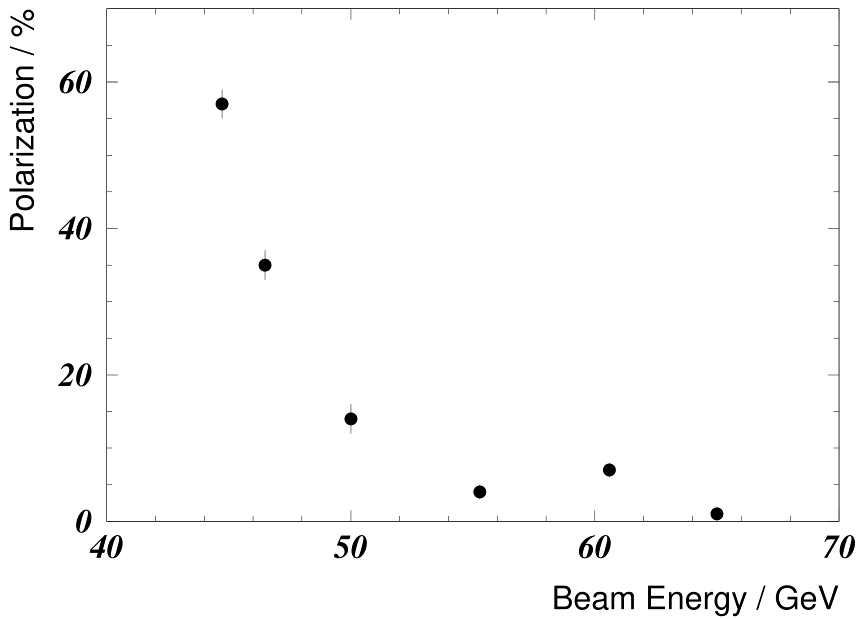
- Fill-to-fill variations: $\mathcal{O}\left(10^{-4}\right)$
- Within a single fill: $\mathcal{O}\left(\approx 10^{-5}\right)$



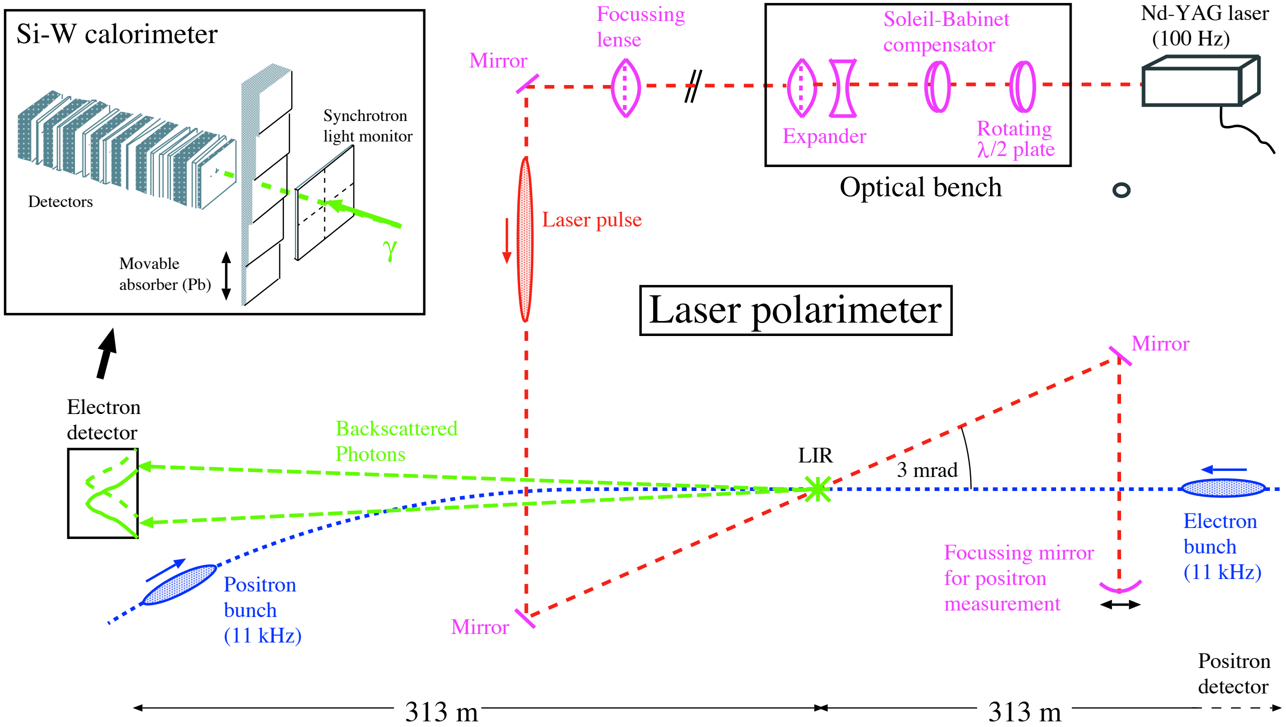
LEP energy calibration

- Emission of synchrotron radiation
  - Asymmetry in the spin flip probability leads to spontaneous transverse polarization
  - Maximum achieved transverse polarization: 92.4 %

- Measurement with a polarimeter based on Compton scattering
  - Circular polarized laser pulse collides with beam
  - Measurement of the vertical photon profile in Si-W calorimeter
  - $P_\perp \propto$ vertical displacement of the profile for the two polarization states



The Compton polarimeter of LEP

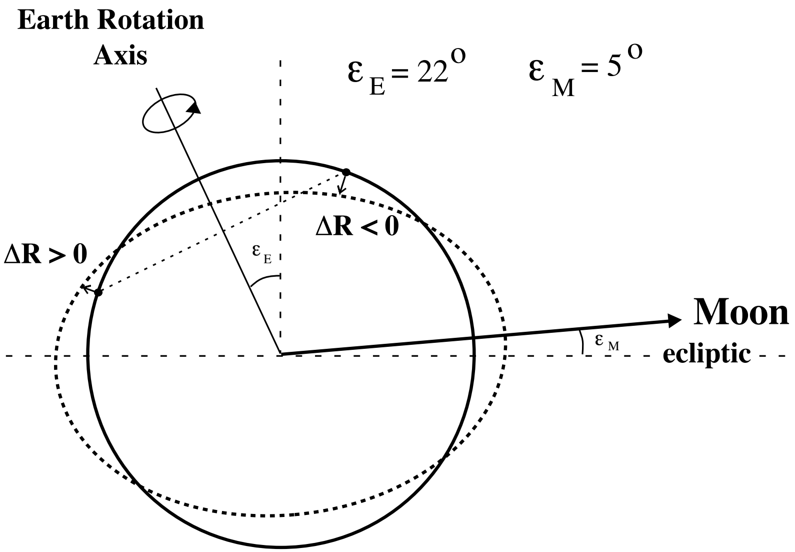


LEP and the moon

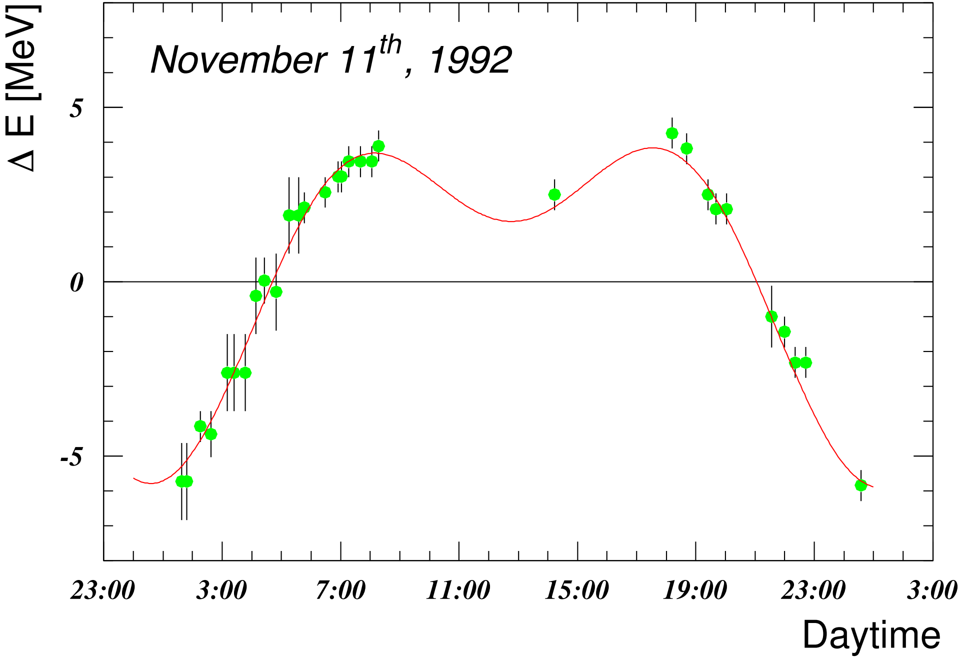
- Tidal range affects oceans and earth's crust
- Local change in radius ΔR due to a mass M in distance d and with the zenith angle θ:

$$\Delta R \propto \frac{M}{d^3}(3\cos^2\theta - 1)$$

- **Some facts:**
  - Solar tides are 50% weaker than lunar tides
  - Full moon tides at the equator $\Delta R \approx \pm 50\,\mathrm{cm}$
  - In Geneva: vertical motion $\approx \pm 12.5\,\mathrm{cm}$
  - Change of LEP circumference by $\approx \pm 0.5\,\mathrm{mm}$



LEP and the moon II



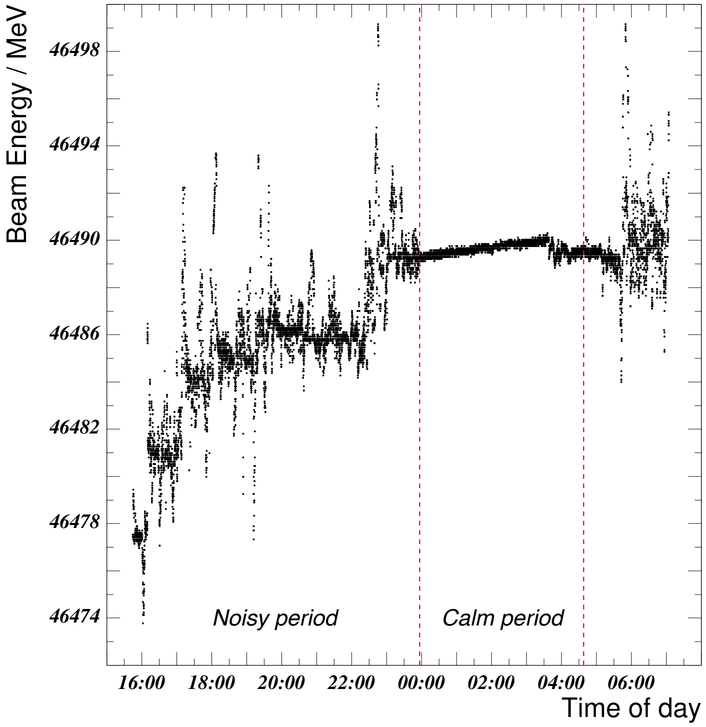
L. Arnaudon et al.: Effects of Terrestrial Tides on the LEP Beam Energy, NIM A357, pages 249--252, 1995.

- Relation between energy and circumference:

$$\frac{\Delta E}{E} = -\frac{1}{\alpha_c}\frac{(f_{RF} - f^c_{RF})}{f_{RF}}$$

$$= -\frac{1}{\alpha_c}\frac{\Delta C}{C}$$

Human activity



- Changes in the beam energy can be extrapolated from measurements of the magnetic field because

$$E_0 \propto \oint B \, \mathrm{d}s$$

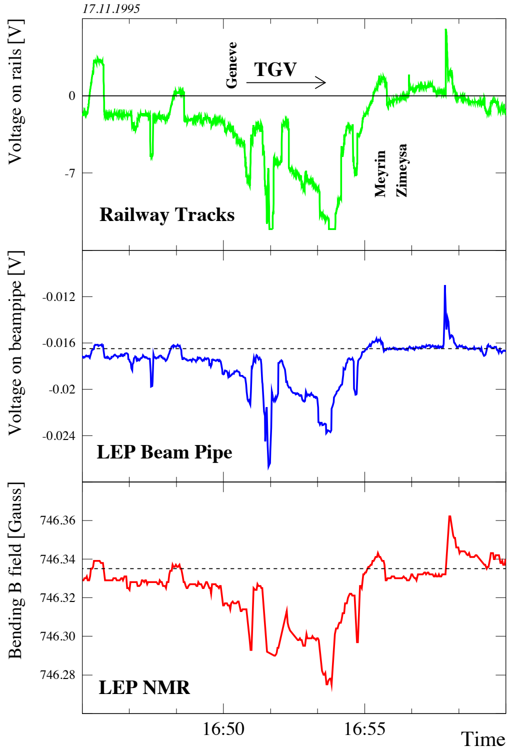
- In this case: B field measurements with NMR probes in some dipole magnets

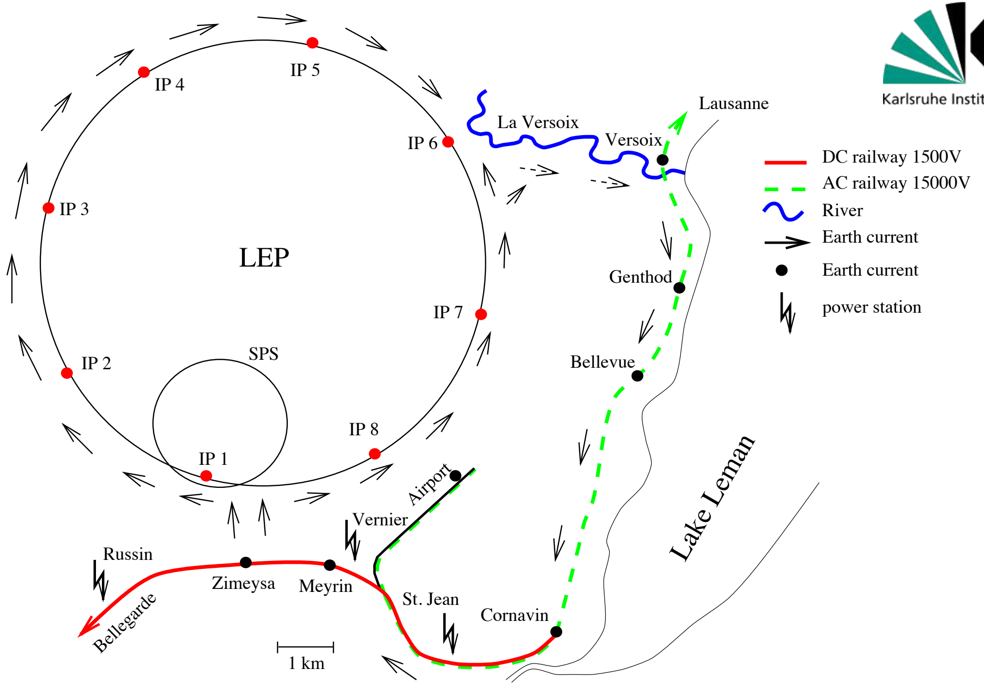
NMR: nuclear magnetic resonance

TGV

photo: S. Ingolstadt

LEP and the TGV





- About 20% of the current does not flow back via the rails
- In France: DC voltage for some lines

  ⇒ Lower voltage, higher current

Historical anecdote from 1895

Karlsruhe Institute of Technology

Nachtheile physikalischer Institute durch elektrische Bahnen

“Der bekannte, am 27. Mai in Charlottenburg angestellte Versuch hat eine beträchtliche Störung der feinen elektrischen Messinstrumente der physikalisch-technischen Reichsanstalt hervorgebracht. Die Abweichungen der Galvanometer betrugen bis 1,2 Bogenminuten, und die Unregelmässigkeiten bestanden in so fatalen, kurzen Stössen von so tückischem Charakter, dass sie jede Sicherheit der Beobachtung ausschliessen. Wenn diese von der Rückleitung des Stromes durch das Erdreich ausgehenden Störungen nicht zu beseitigen sind, so könne die Reichsanstalt nicht umhin, ihren Einspruch gegen den geplanten elektrischen Betrieb der Berlin-Charlottenburger Pferdebahn aufrecht zu erhalten. Die höchste zulässige Abweichung der Galvanometer sei 0,1 Bogenminute.”

(Central-Zeitung für Optik und Mechanik, XVI. Jg., No. 13, Seite 151)

Historical anecdote from 1895 — translation

Disadvantages of physical institutes through electrical operation of railroads

"The well-known experiment carried out in Charlottenburg on May 27th produced a considerable disturbance in the fine electrical measuring instruments of the Physikalisch-Technische Reichsanstalt. The deviations of the galvanometers amounted to up to 1.2 arcminutes, and the irregularities consisted of such fatal, short shocks of such treacherous character that they precluded any certainty of observation. If these disturbances caused by the return of the current through the ground could not be eliminated, the Reichsanstalt could not avoid maintaining its objection to the planned electrical operation of the Berlin-Charlottenburg horse-drawn railroad. The maximum permissible deviation of the galvanometers is 0.1 arcminute."

(Central-Zeitung für Optik und Mechanik, XVI. Jg., No. 13, page 151)