Sensors for Particle Accelerators

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Outline

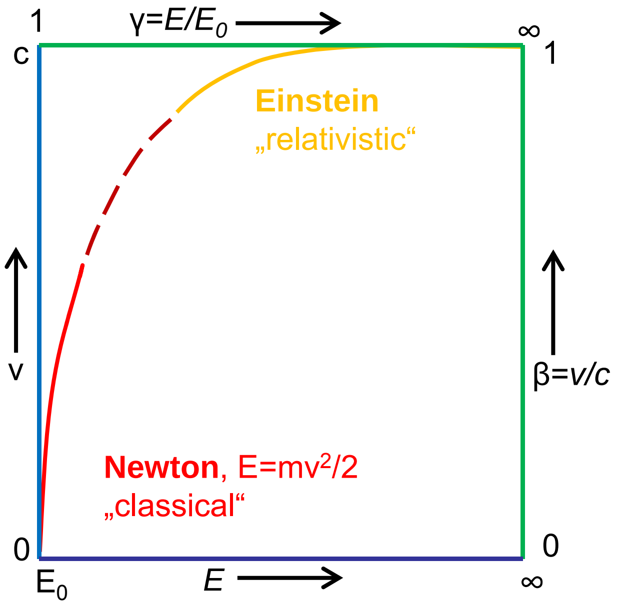
- History of Particle Accelerators
- Particle Accelerator Techniques
- Beam Diagnostics for Particle Accelerators
    - Schottky Measurement
    - Beam Position Measurement
    - Arrival-time Measurement
    - Bunch shape diagnostics

Particle Accelerators

- **Modern accelerators** can accelerate particles to speeds very close to that of light.
- At **low energies**, the velocity of the particle increases with the square root of the kinetic energy (**Newton**).
- At **relativistic energies**, the velocity increases very slowly asymptotically approaching that of light (**Einstein**).
- It seems as if the velocity of the particle ‘saturates’ to the velocity of light.

- The speed increases, but not as spectacularly as the mass. In fact, it would be more correct to speak of the momentum (m·v) increasing.

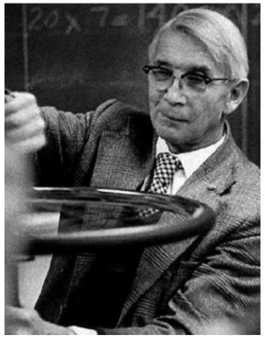
$$1eV = 1.6022 \cdot 10^{-19} J$$



Energy	**1 MeV**	→		**1 GeV**
$\beta = v/c$	**0.95**	**0.99**	**0.999**	**0.999 999 9**
$\gamma = m/m_0$	**3**	**7**	**22**	**2000**

Courtesy: P.J. Bryant - History and Applications of Accelerators CERN Accelerator School, Varna 2012

History of Accelerators


Gustaf Ising
(1883-1960)


Rolf Wideröe
(1902–1996)

Theory and proof-of-principle

1924 **Ising** proposes time varying fields across drift tubes. This is a „true“ accelerator that can achieve energies above that given by the highest voltage in the system.

1928 **Wideröe** demonstrates Isings principle with an 1 MHz, 25 kV oscillator to make 50 kV potassium ions; the first **LINAC** was born.


Ernest Orlando
Lawrence
(1901–1958)


Stanley
Livingston
(1905-1986)

Practical devices

1928 **Lawrence**, inspired by Wideröe and Ising, conceives the cyclotron; a **coiled LINAC**.

1931 **Livingston** demonstrates the cyclotron by accelerating hydrogen ions to 80 keV.

1932 **Lawrence**‘s cyclotron produces 1.25 MeV protons and he also splits the atom just a few weeks after Cockroft & Walton. Lawrence received the Nobel Prize in 1939.

Courtesy: P.J. Bryant - History and Applications of Accelerators CERN Accelerator School, Varna 2010

History of Accelerators

The birth of a true accelerator

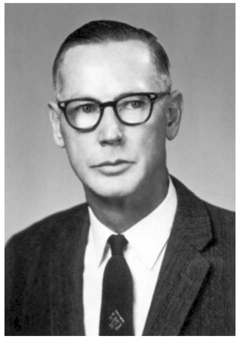
1923 Wideröe, a young Norwegian Ph.D. student draws in his laboratory notebook the design of the **betatron** with the well known 2 to 1 rule. Two years later he adds the condition for radial stability, but he doesn‘t publish.

1927 In Aachen Wideröe constructs a model betatron, but it does not work. Discouraged he changes course and builds the world’s first **LINAC**.

All is quiet until 1940, when

1940 Kerst re-invents the betatron and builds the first working machine for 2.2 MeV electrons at the University of Illinois

1950 Kerst also builds the world‘s largest **betatron** (300 MeV)



Donald William Kerst
(1911-1993)

History of Accelerators

The main development

1944 E. McMillan & V. Veksler discovers the principle of phase stability and invent the **synchrotron.**

1946 F. Goward & D. Barnes make a synchrotron works.

1946 First **proton linear accelerator** of 32 MeV is built at **Berkley.**

1946 First **electron linear accelerators** are studied at **Stanford** and **MIT**.

1952 **BNL** builds 3 GeV **Cosmitron.**

1959 **CERN** builds 28 GeV proton synchrotron.

1960 **BNL** builds 33 GeV alternating gradient synchrotron.

1960 **DESY** builds 7.4 GeV synchrotron.

1962 First single-ring e^+-e^- collider **AdA** of 2*250 MeV is build at **Frascati.**

1969 **GSI** builds 140 MeV **UNILAC.**

1972 First **double-ring proton collider** IS`R 2*28 GeV is build at **CERN.**

…

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Acceleration of Particles
Some Mathematics

$$E = -\nabla\phi - \partial A/\partial t$$

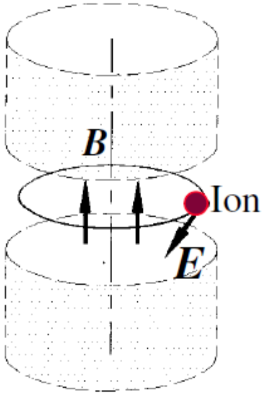
Acceleration by DC voltages

- Cockroft & Walton rectifier generator
- Van de Graaff electrostatic generator
- Tandem electrostatic accelerator

Acceleration by time-varying fields

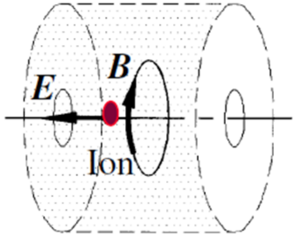
$$\nabla \times E = -\partial B/\partial t$$

Betatron or unbunched acceleration



Resonant or bunched acceleration

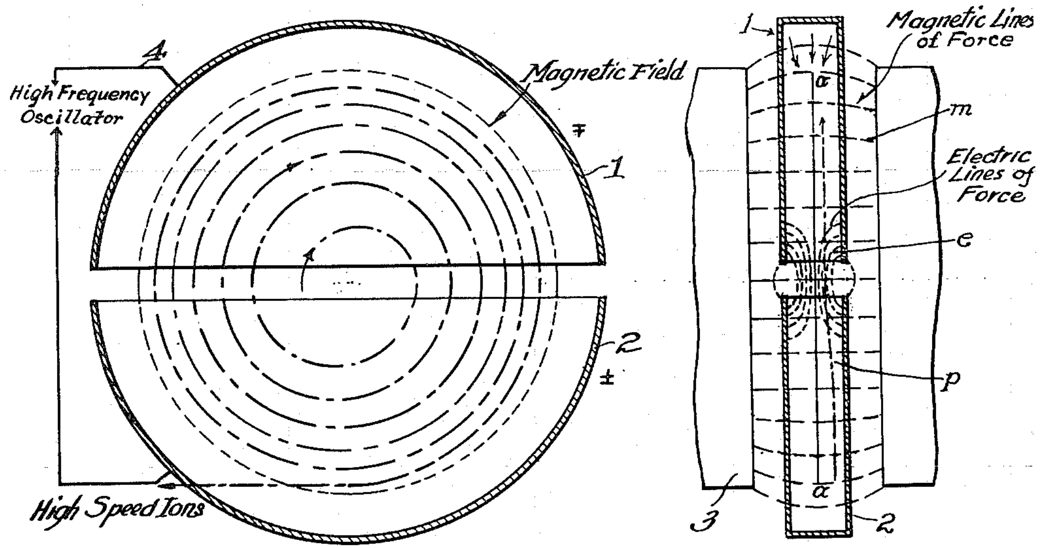
- Linear accelerator (LINAC)
- Synchrotron
- Cyclotron (‚coiled LINAC‘)



- P.J. Bryant – History and Applications of Accelerators, CERN Accelerator School, Varna 2012

Acceleration of Particles
Cyclotron

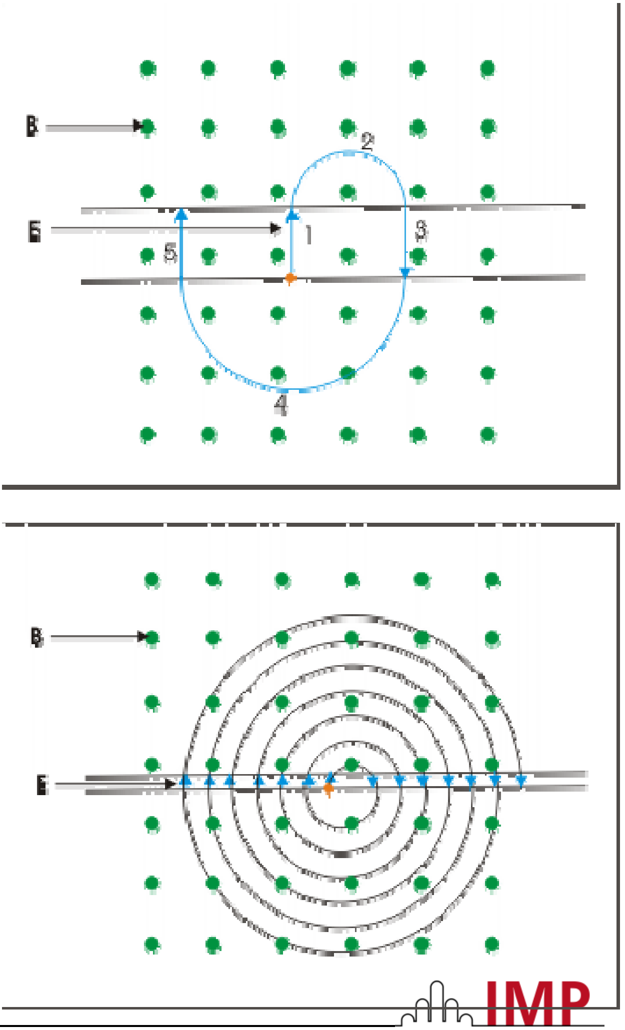
- DC electric fields beyond 20 MV are very difficult to achieve.
- Above 20 MV, it is easier to use an electric field created by an alternating current (AC).
- In 1932 Lawrence designed a „Cyclotron“, a circular device made of two electrodes placed in a magnetic field.



Acceleration of Particles
Cyclotron (2)

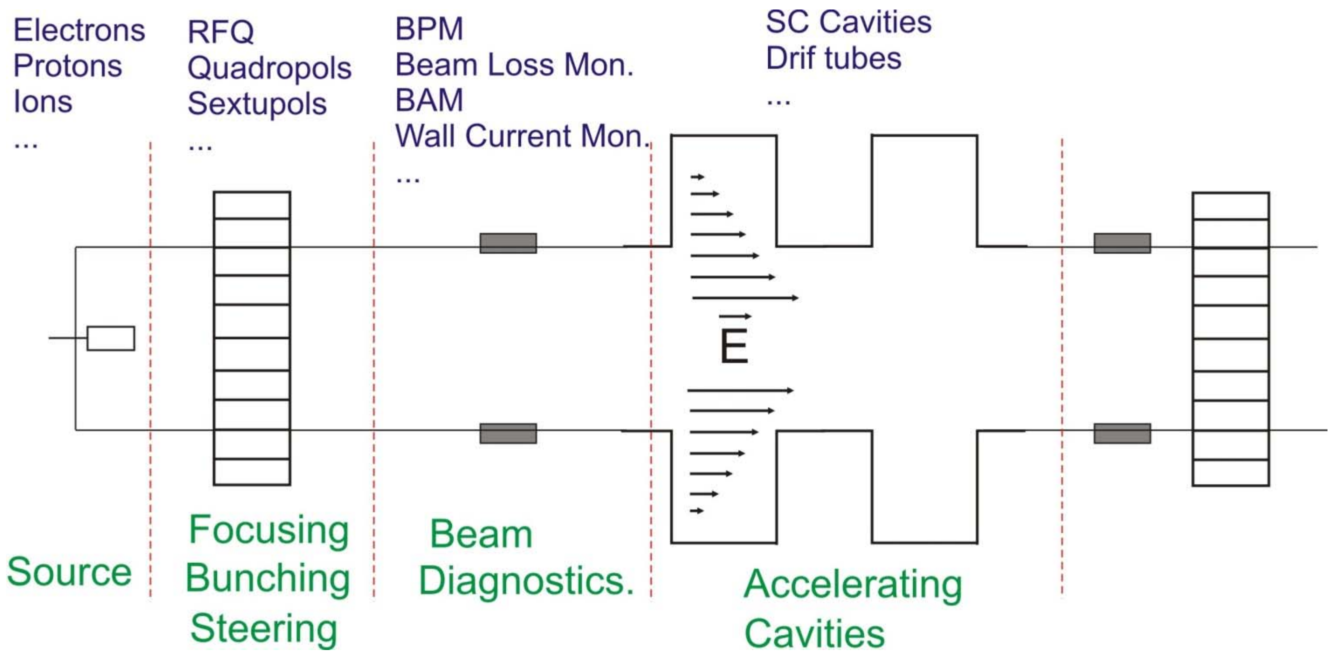
1: Particle is accelerated due to **electric force**.
Speed and kinetic energy of the particle increase.
2: Particle is accelerated due to **magnetic force**.
This acceleration is centripetal acceleration without any change in speed and kinetic energy of the particle.
3: Particle is accelerated due to **electric force** in the direction opposite to the direction as in case 1.
Speed and kinetic energy of the particle increase by same amount as in the case 1.
4: Particle is accelerated due to **magnetic force**.
This acceleration is centripetal acceleration without any change in speed and kinetic energy of the particle.
5: Particle is accelerated due to **electric force** in the direction opposite to the direction as in case 1.
Speed and kinetic energy of the particle increase by same amount as in the case 1 or 3.

We see that the particle follows consecutive larger semicircular path due to increase in the speed at the end of semicircular journey. The resulting path of charged particle, therefore, is a spiral path – not circular.



Acceleration of Particles
Linear Accelerators and Synchrotrons

- Very simplified schematics (Linear accelerator - LINAC)

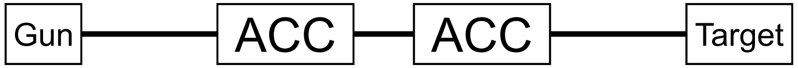


Acceleration of Particles
Linear Accelerators and Synchrotrons (2)

- Accelerate charged particles
  - Velocity is given by $\beta=v/c$ (0.971 for antiprotons @GSI)
  - Energy is given in eV (World Record by LHC@Cern with 3.5 TeV)
- Electron Gun – Acceleration – Focusing – Bending/Deflecting

LINAC

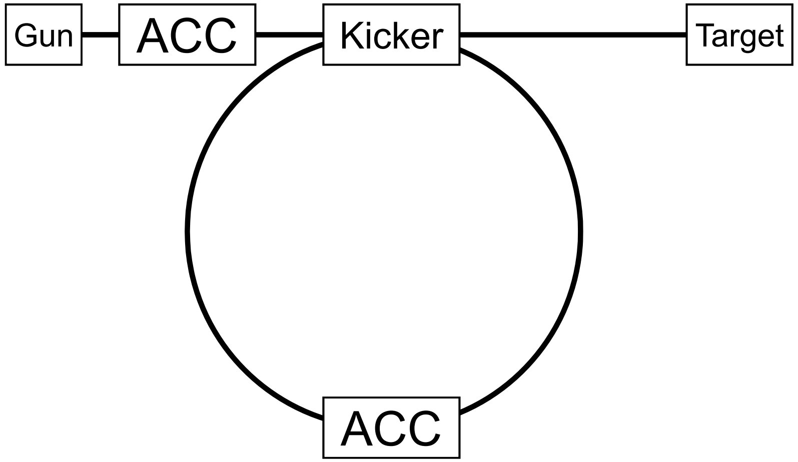
High beam quality, no bending magnets



Stanford Linear Accelerator Center, 3 km length

Synchrotron

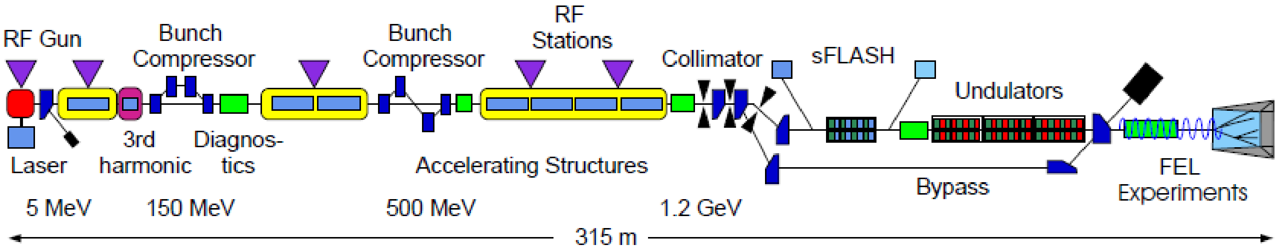
Higher energy, accelerating structure reuse



Dipol magnets for bending not shown

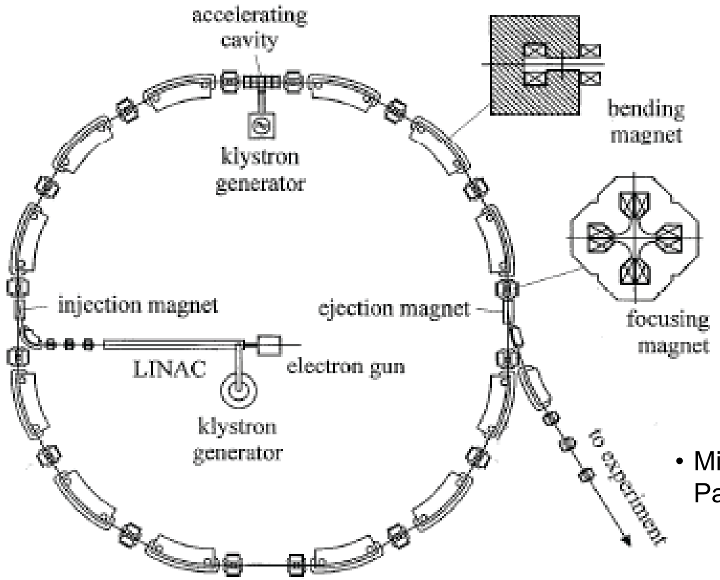
Acceleration of Particles
Linear Accelerators and Synchrotrons (3)

- Linear accelerators (LINAC)
  - Example: Free Electron Laser in Hamburg (FLASH)
    - Single pass
    - Modular design
    - Availability
    - High current
    - Strong focusing (FEL)



* DESY

- Circular accelerators
  - Example: Tevatron at FermiLab
  - Multi-turn Accelerator
  - Energy Ramps Up
  - Multiple Passes through
  - Same RF Cavities
  - High energy (7 TeV at LHC)



- Michael Billing: Introduction to Particle Accelerators

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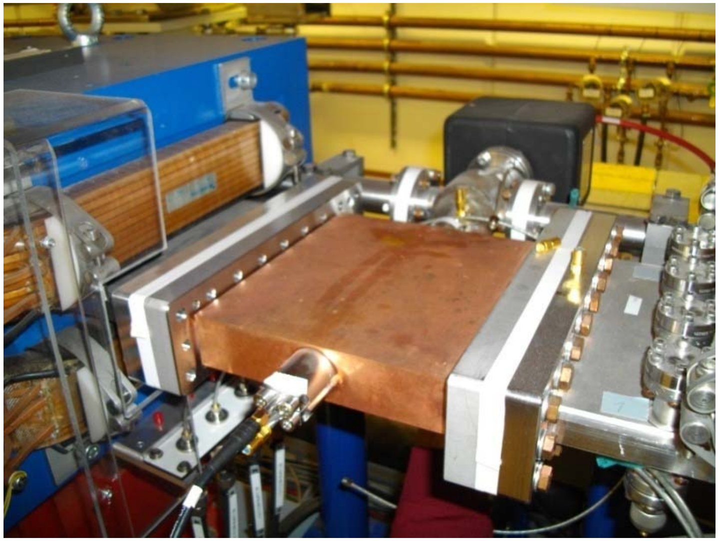
Beam Diagnostics for Particle Accelerators

- “An accelerator can never be better than the instruments which measure its performance! “- Ulrich Raich, CERN
- Good reasons for beam diagnostics:
  - Component tolerances and related random errors
  - Environmental effects
  - Equipment fault
  - Equipment set-up
  - Performance tuning and preservation



A. Angelovski: ITSS 2012

- What can be measured ?

✓ What is measured?

Beam current
" position
" phase
" arrival-time
" energy
" transverse profile
" transverse emittance
" longitudinal profile
" energy profile
" longitudinal emittance
" polarization
" Schottky noise longitudinal
" Schottky noise transverse
...

✓ Measurement flavors:

<u>average values</u>
i.e. closed orbit

<u>time resolved</u>
i.e. position of individual bunches in a bunch train

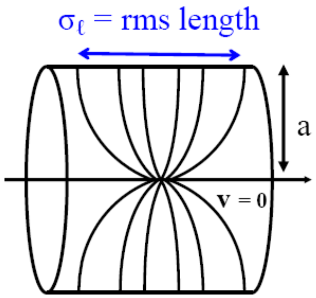
<u>correlations</u>
beam position at different locations to detect source of a beam jitter. This requires either real time readout system or time stamping of signals

<u>post mortem</u>
complete dump of signal buffer from last seconds before beam got lost

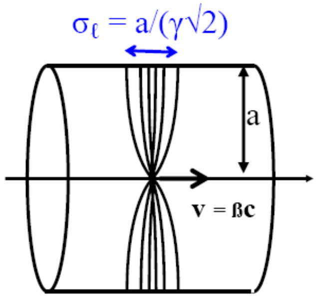
* CERN Accelerator School 2008, Hans Braun / CERN

Beam Diagnostics for Particle Accelerators
Field contraction

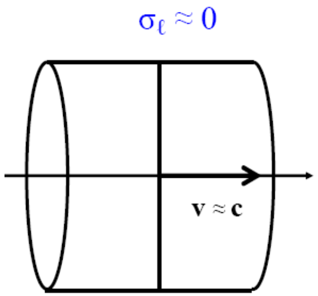
- Static charge



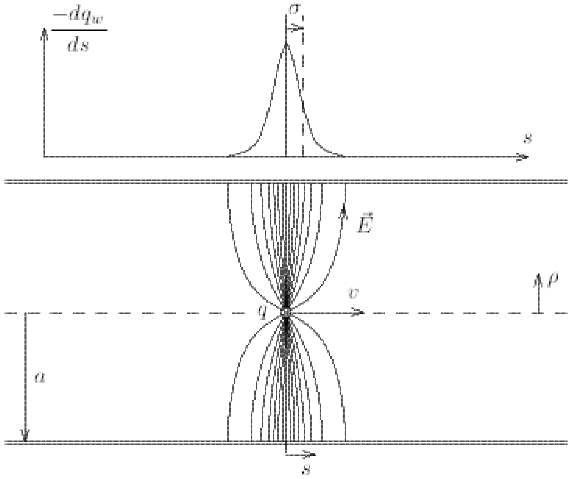
- Moving charge



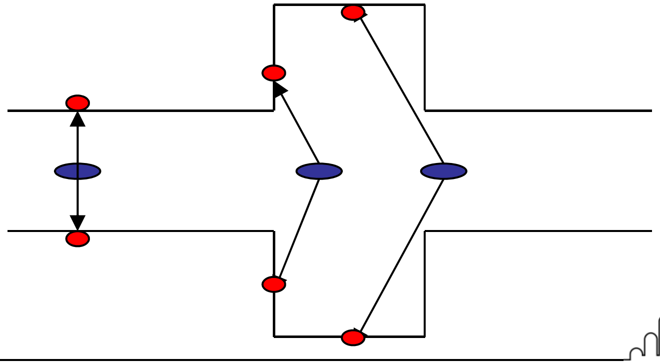
- Ultra-relativistic charge



Wall currents following the particles



Induced charges by a moving proton



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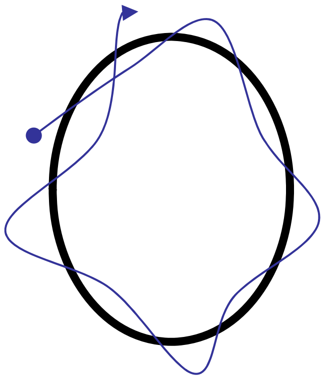
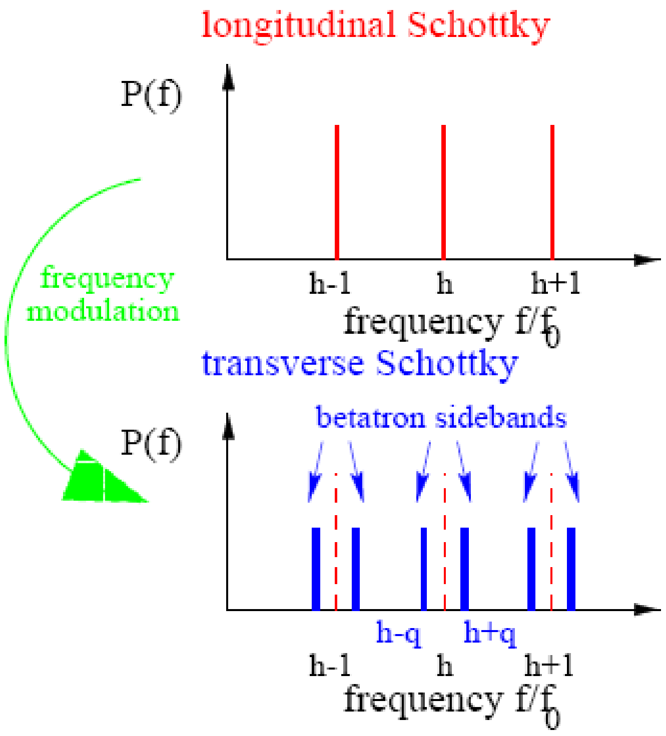
Schottky Diagnostic
What can be measured?

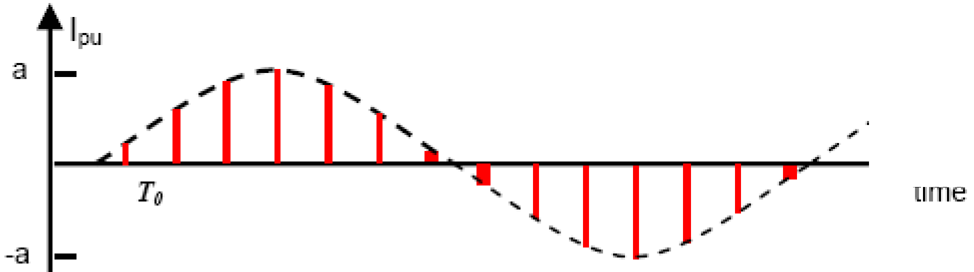
- Momentum spread (longitudinal)
- Tune (transversal)
- (And a lot more…)

- In most cases there are two sensors in each plane (horizontal and vertical)
- Sum is independent of position
  - Used for longitudinal diagnose
- Difference is modulated by the synchrotron frequency

Schematic showing good horizontal tune





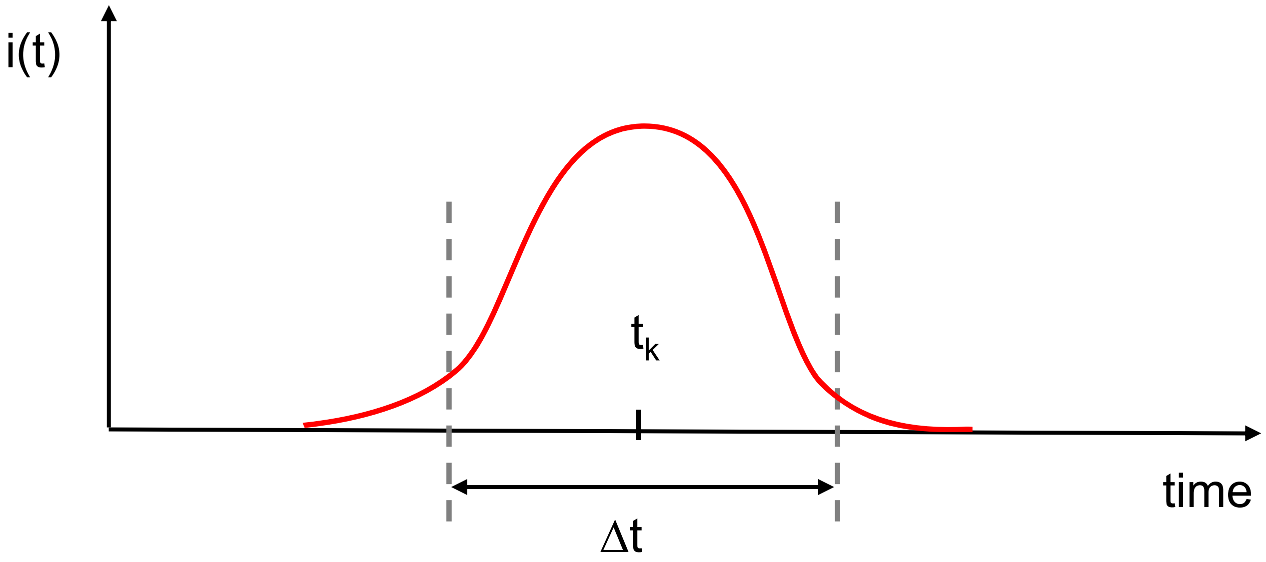


A single particle with betatron oscillation of amplitude a as seen by a transverse pick-up

Pictures by P. Fork and F. Caspers

Schottky Diagnostic
Single-particle Current

- A single particle is rotating in a storage ring.
- Constant revolution frequency
- Signal induced on a pick-up at passage time t_k.



From: F. Caspers - Schottky signals, CERN Accelerator School, Dourdan , 2008

Schottky Diagnostic
Single-particle Current (2)

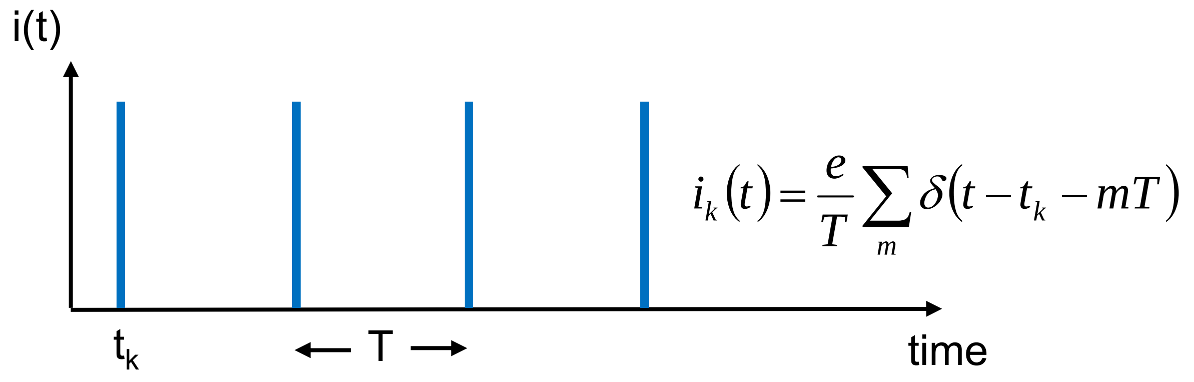
- Approximation by a Dirac distribution
- Periodic signal over many revolutions $i_k(t) = \frac{e}{T} \sum_m \delta(t - t_k - mT)$
- Applying the Fourier expansion to *$i_k(t)$*

$$i_k(t) = i_0 + 2i_0 \sum_{n=1}^{\infty} a_n \cdot \cos n\omega_0 t + b_n \cdot \sin n\omega_0 t$$

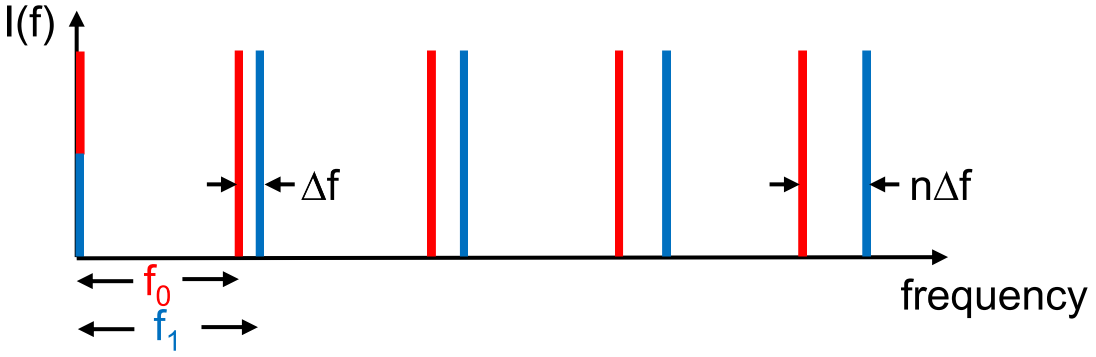
$$with \begin{cases} i_0 = ef_0 \ \text{DC part of the beam (single particle)} \\ a_n = \cos n\varphi_k \ \text{and} \ b_n = \sin n\varphi_k \end{cases}$$

From: F. Caspers - Schottky signals, CERN Accelerator School, Dourdan , 2008

Schottky Diagnostic
Time and Frequency Domains



$$i_k(t) = \frac{e}{T}\sum_m \delta(t - t_k - mT)$$



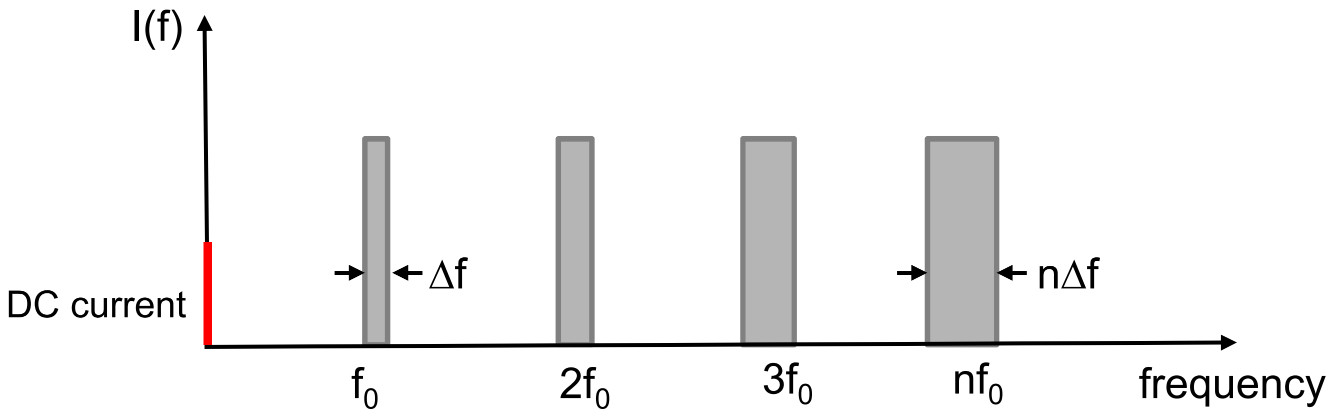
$$\Delta f = f_0 \eta \frac{\Delta p}{p}$$

A second particle of revolution frequency $f_1 = f_0 + \Delta f$ is added.

From: F. Caspers - Schottky signals, CERN Accelerator School, Dourdan , 2008

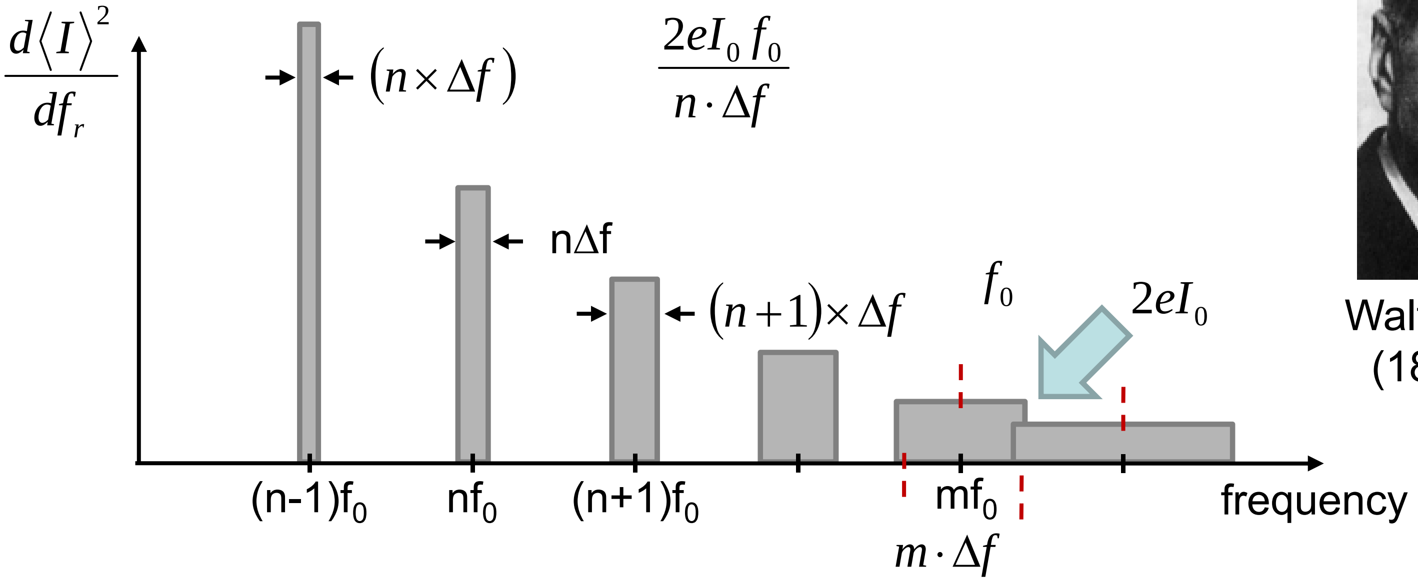
Schottky Diagnostic
Coasting Beam: Frequency Domain

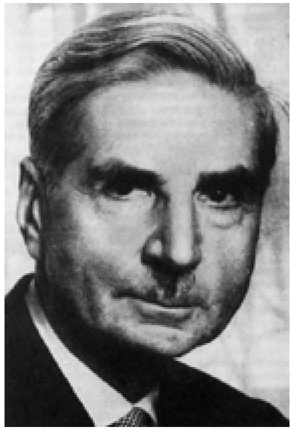
- N particles with a distribution of revolution frequencies $f_0 \pm \Delta f/2$ for $n=1$.
- One expects a spectrum with bands around each harmonic nf_0.
- The band height is arbitrary at this stage.



From: F. Caspers - Schottky signals, CERN Accelerator School, Dourdan , 2008

Schottky Diagnostic
Schottky Bands (2)



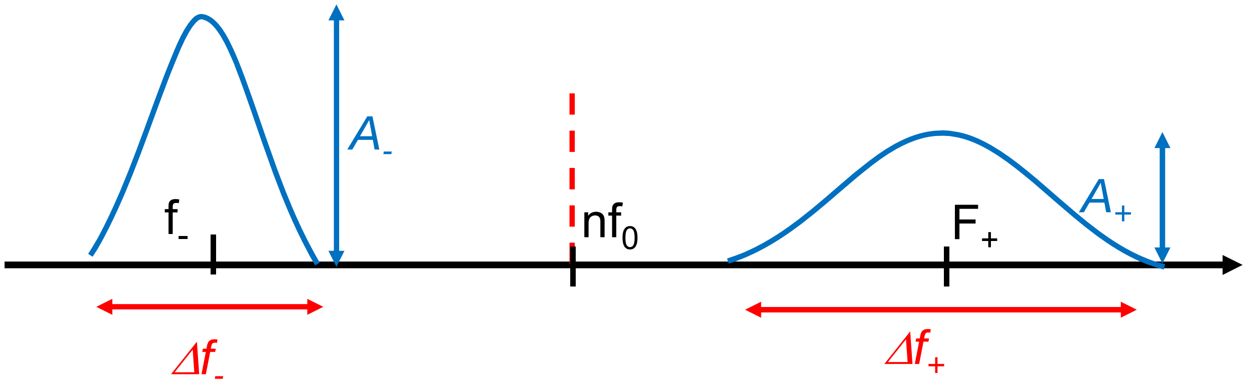


Walter Schottky
(1886 -1976)

Overlapping or Mixing

From: F. Caspers - Schottky signals, CERN Accelerator School, Dourdan , 2008

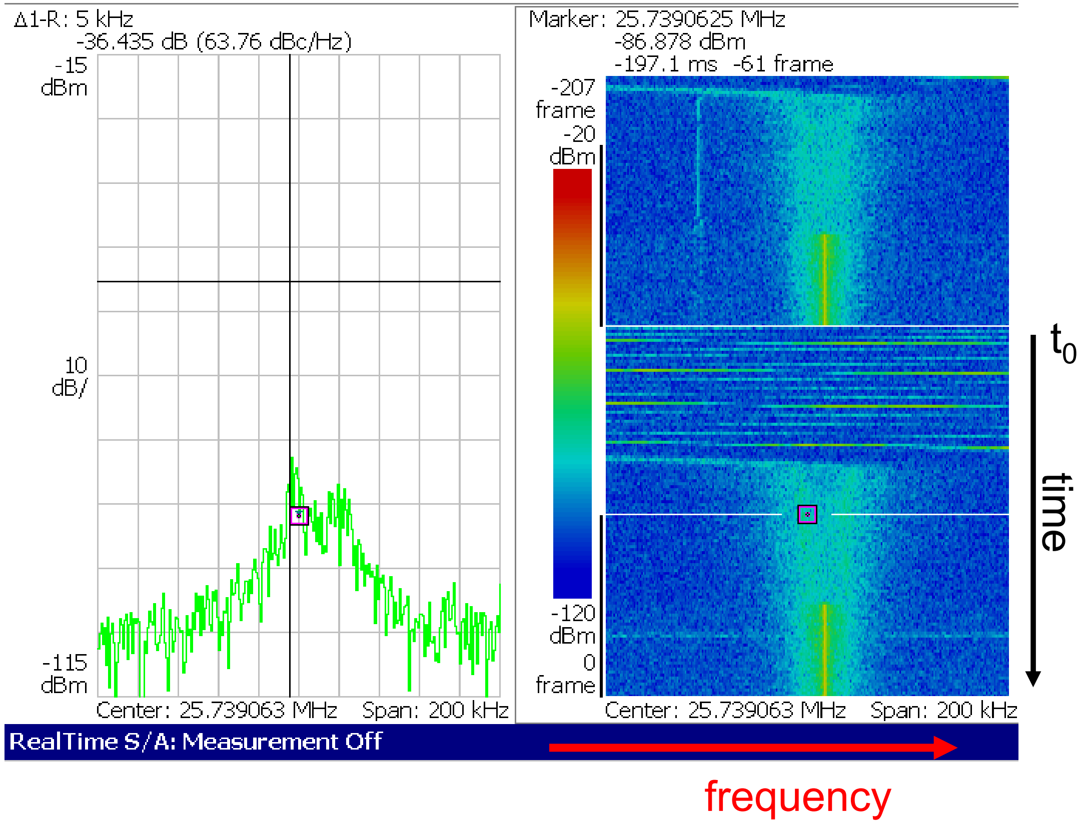
Schottky Diagnostic
The Spectrum Analyzer gives …



- the fractional part of the tune $$q = \frac{1}{2} + \frac{f_+ - f_-}{2 f_0}$$
- the tune spread $$\frac{dq}{Q} = \frac{\Delta f_+ - \Delta f_-}{2 f_0 Q}$$
- the momentum spread $$\frac{dp}{p} = \frac{1}{\eta} \times \frac{\Delta f_+ - \Delta f_-}{2 n f_0}$$
- the chromaticity $$\xi = \left(\frac{dq}{Q}\right) \Big/ \left(\frac{dp}{p}\right)$$
- the emittance $$\varepsilon \propto A_- \Delta f_- + A_+ \Delta f_+$$

Schottky Diagnostic
Example ESR@GSI

A typical display showing a normal FFT result at a fixed moment in time (left) and the evolution of the spectral lines vs. time acceleration ramp going into a flattop in a color coded plot (right).



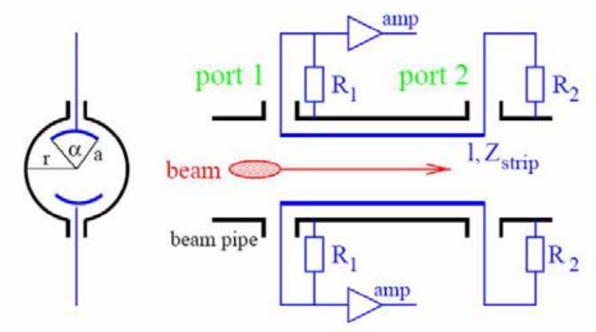
Δ1-R: 5 kHz
-36.435 dB (63.76 dBc/Hz)

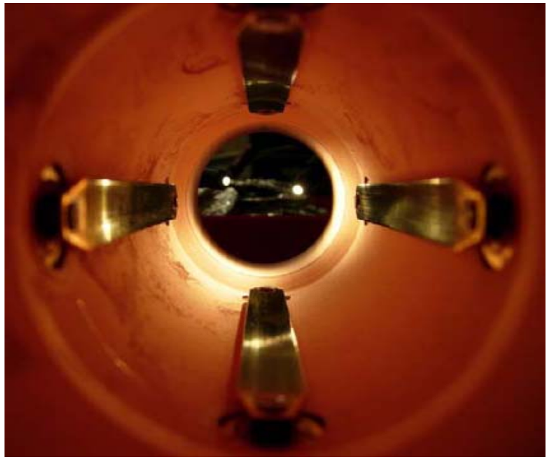
Marker: 25.7390625 MHz
-86.878 dBm
-197.1 ms -61 frame

RealTime S/A: Measurement Off

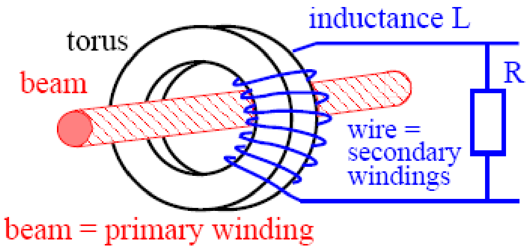
Schottky Diagnostic
Basic Pickup principles (non destructive)

Stripline

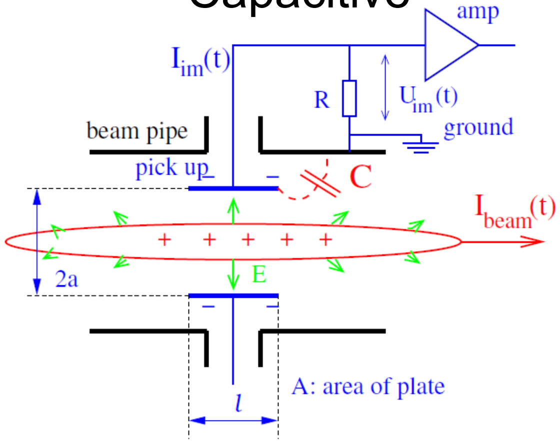


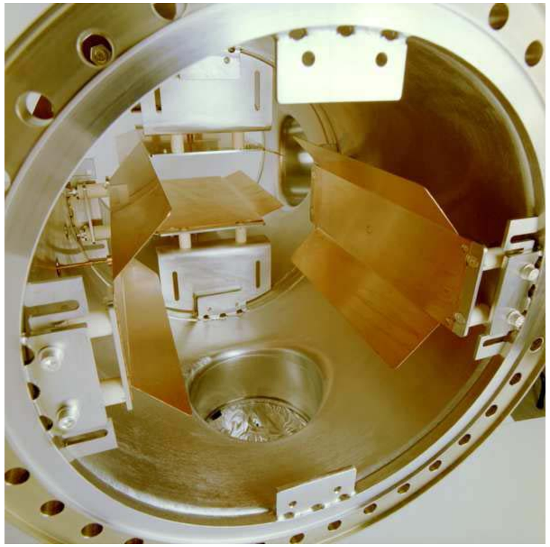


Current transformer

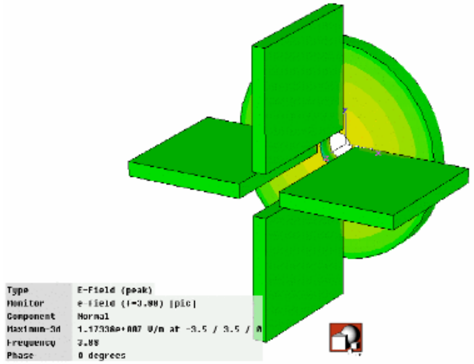


Capacitive





Cavity BPM



```
Type         E-Field (peak)
Monitor      e-field (f=3.00) [pic]
Component    Normal
Maximum-3d   1.17338e+007 V/m at -3.5 / 3.5 / 0
Frequency    3.00
Phase        0 degrees
```

Pictures: P.Fork slides of CAS 2008

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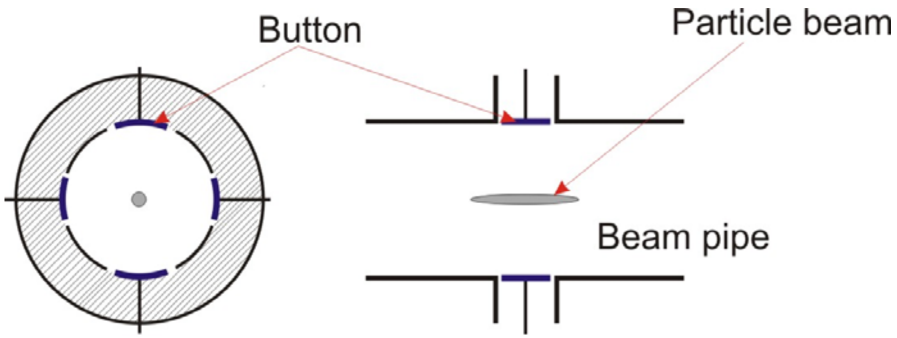
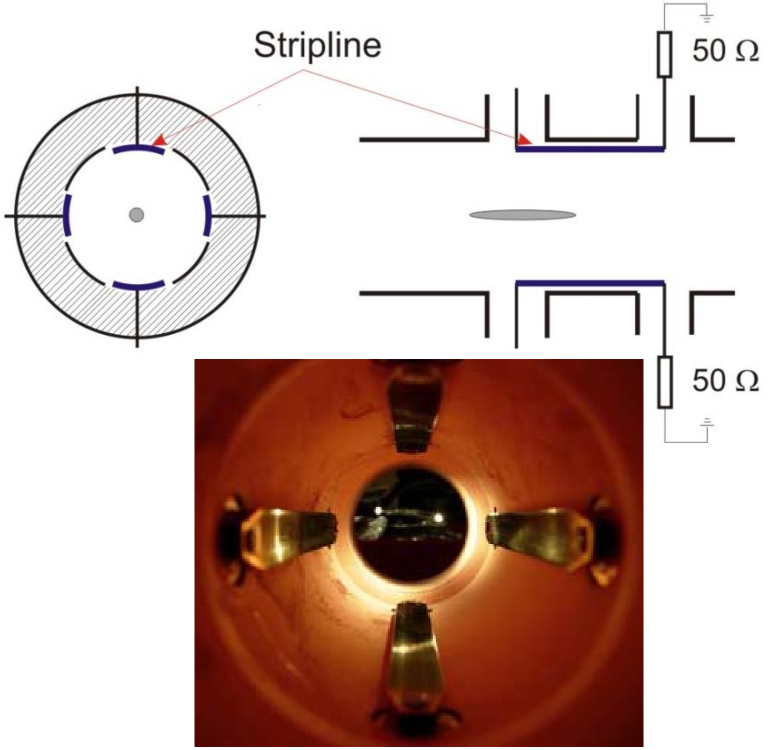
Beam Diagnostics for Particle Accelerators
Beam Position Monitors

- Beam position monitors
  - Button and stripline pickups, cavities, etc.
  - Measures the position of the beam inside the beam pipe.

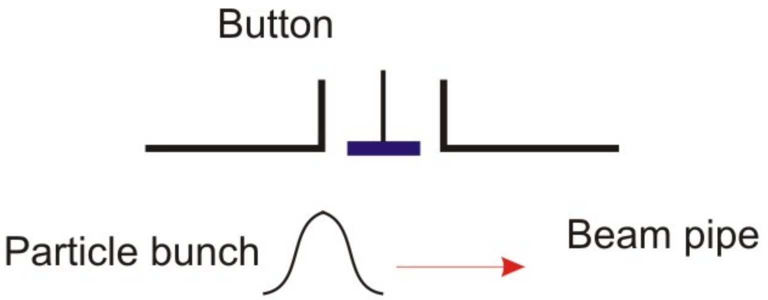


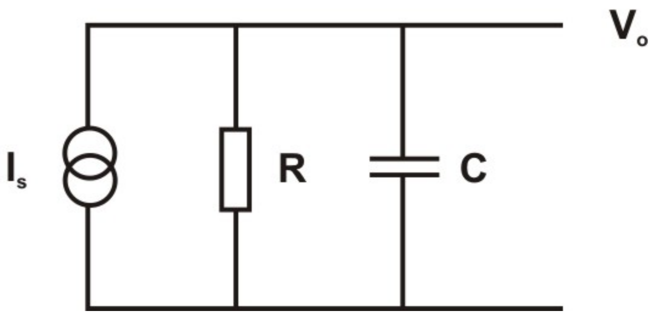


* K. Wittenburg, CARE-Conf-06-087-HHH

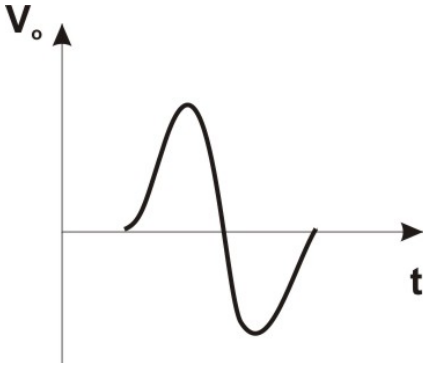
Beam Diagnostics for Particle Accelerators

- The beam is capacitive coupled to the pickup.
- Gaussian distribution of the beam charge





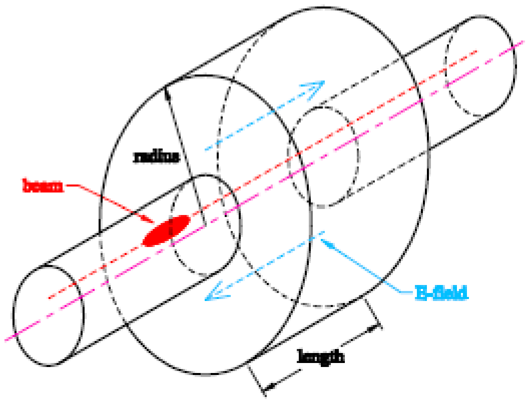
- The output voltage is proportional to the derivative of the bunch distribution.

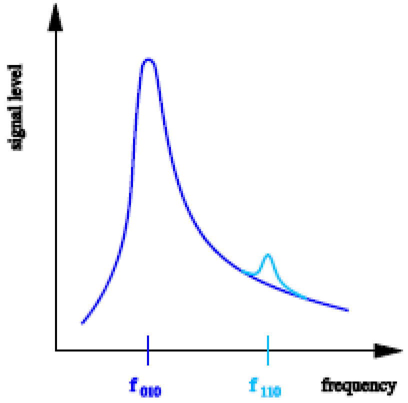


- The output signal is a function of :
  - Bunch characteristics (charge, length)
  - Button characteristics (impedance, material…)

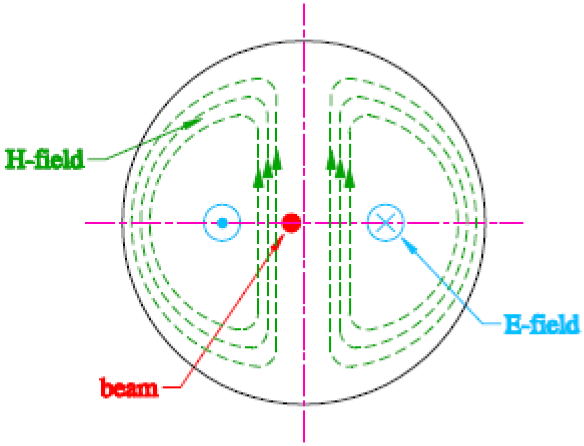
Beam Diagnostics for Particle Accelerators

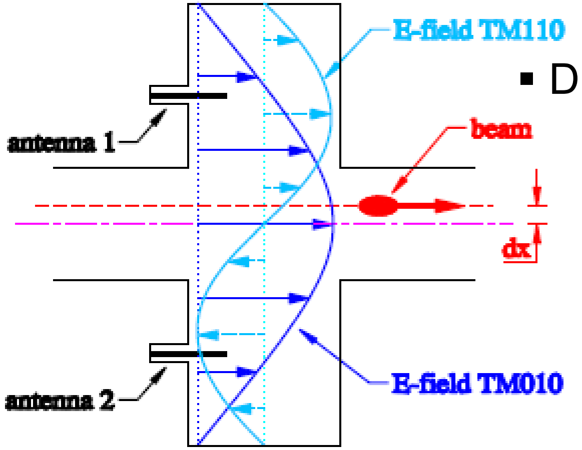
- Cavities as beam position monitors





- Beam excited eigen-mode
- The lowest transverse-magnetic dipole mode TM_{110} is of interest.
- Almost linear dependence between the E_z, the beam displacement and the beam
- High beam displacement sensitivity





- Drawbacks:
  - Common modes (mode TM_{101})
  - Cross talk (horiz./vert. alignment)
  - Wakepotential and heat-load
  - Transient response (high loaded Q)

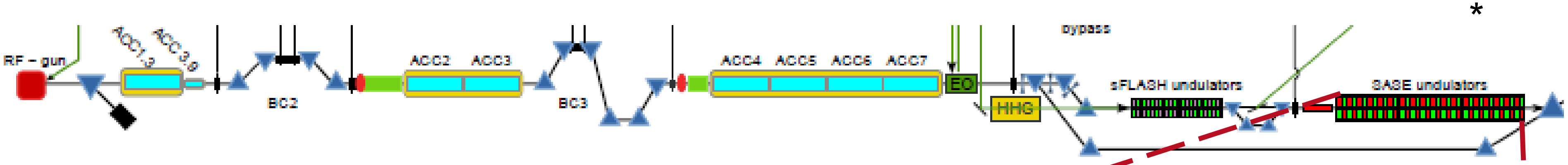
* K. Wittenburg, CARE-Conf-06-087-HHH

Outline

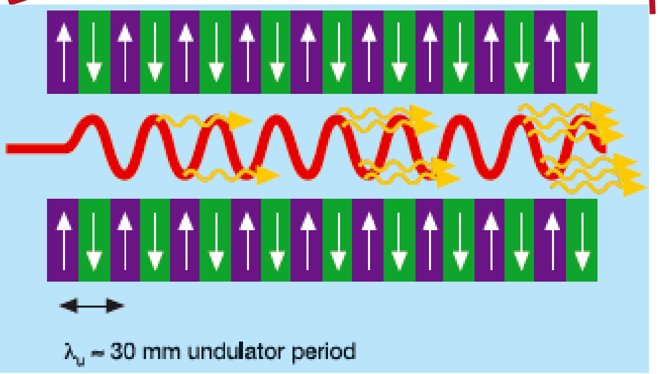
- History of Particle Accelerators
- Particle Accelerator Techniques
- Beam Diagnostics for Particle Accelerators
  - Schottky Measurement
  - Beam Position Measurement
  - Arrival-time Measurement
  - Bunch shape diagnostics

Free Electron Lasers

- Accelerated charged particles (electrons) with LINear ACcelerator
- Undulator – alternatively polarized magnets



- FLASH – Free Electron Laser in Hamburg (DESY)
  - Wavelength of 4.2 nm - 47 nm
  - Five 12m long accelerator modules
    8 superconducting cavities each
  - Linear accelerator 1.25 GeV
  - Average Single Pulse Energy = 10 - 100 µJ
  - Pulse Duration (FWHM) = 10 - 70 fs
  - Peak Power (from av.) = 1 - 5 GW
  - Average Power (ex. for 500 pulses/sec) ~ 15 mW



*

Undulator:
Electrons emit synchrotron radiation with a broad, continuous frequency spectrum.

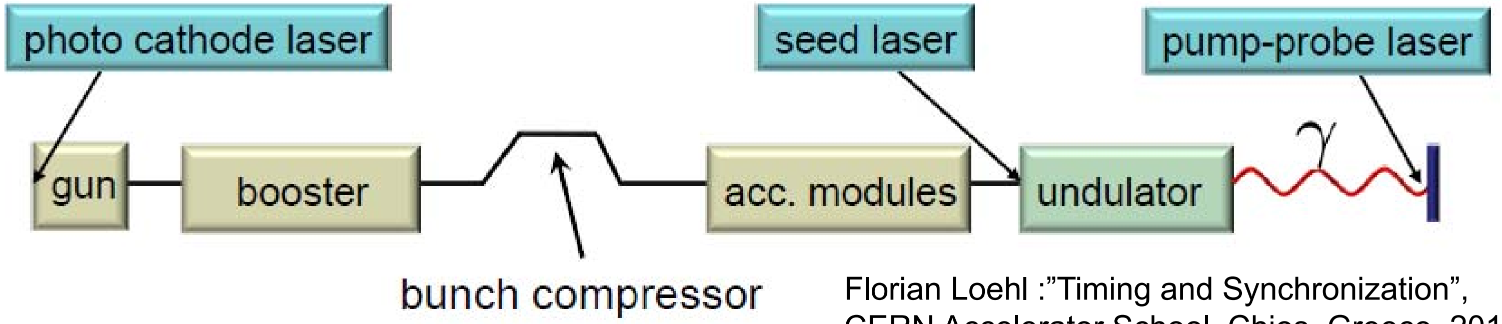
*FLASH brochure May 2007

Bunch Arrival-time Monitors at FLASH

- The arrival time has to be measured within the same order of precisions or better as the duration of the bunch charge (sub-10 fs).
- Bunch arrival-time jitter at the undulator has three main sources:

1. Arrival-time jitter generated at the beam generation
    - Photo cathode laser
    - Gun
2. Cavity field amplitude fluctuations in the booster module
3. Cavity field phase fluctuations in the booster module

Arrival-time stability between x-ray pulses and pump-probe laser pulses: fraction of pulse duration.

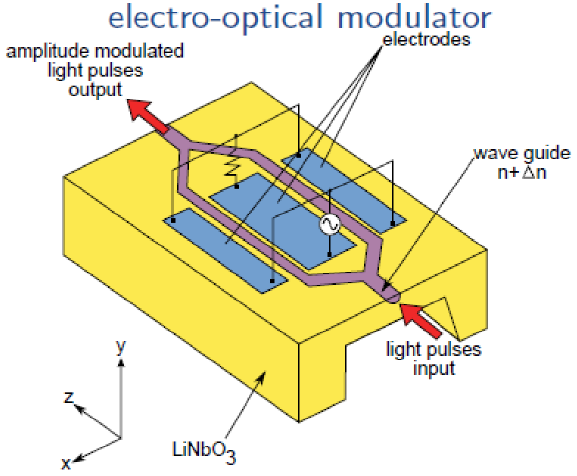


Florian Loehl :"Timing and Synchronization", CERN Accelerator School, Chios, Greece, 2011

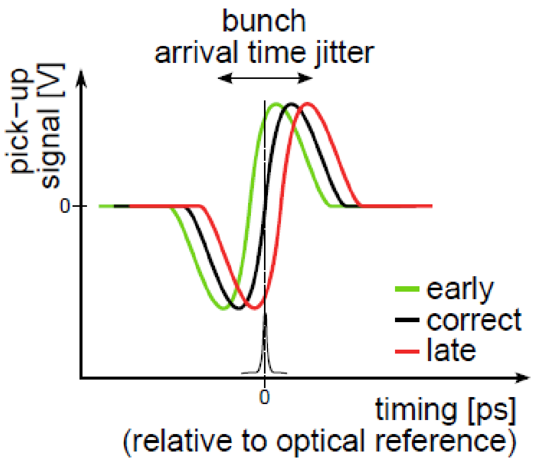
A. Angelovski: ITSS 2012

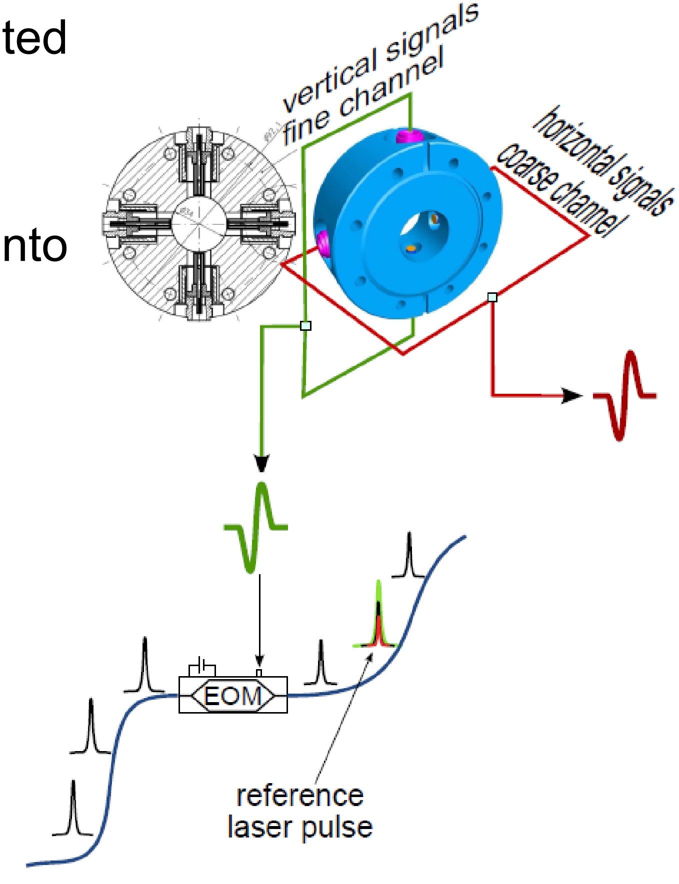
Bunch Arrival-time Monitors at FLASH

- Electro-optical detection scheme
- External reference laser pulse is amplitude-modulated with the induced voltage signal from the pickup in the Electro-Optical Modulator (EOM).
- The arrival-time of the electron bunch is encoded onto the laser pulse amplitude.
- The laser pulse is detected with a photo-detector.



A. Angelovski: ITSS 2012

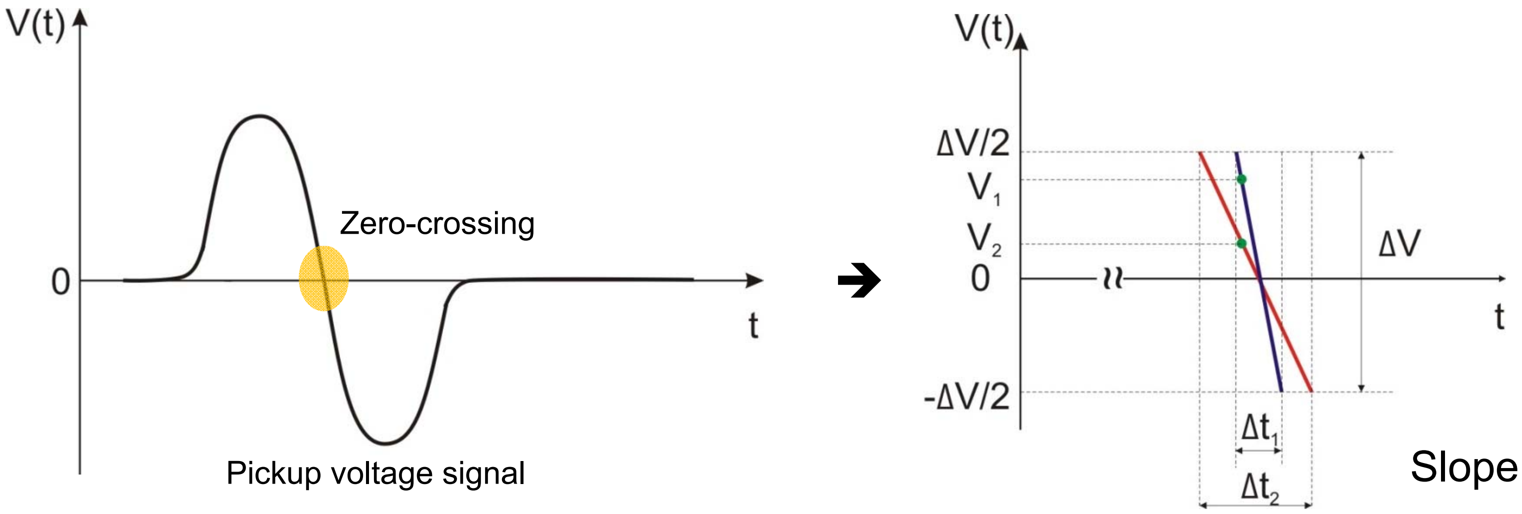




M.K. Bock, BMBF-Projektmeeting "Weiterentwicklung eines Ankunftszeitmonitors" - 06. September 2010

Bunch Arrival-time Monitors at FLASH

- Future operation with low charged bunches (20m pC and less)
- The lower the charge the less the induced voltage in the pickup.
- The time resolution of the BAM depends on the voltage slope at the zero crossing



Slope = ΔV / Δt

t_s - sampling time

- Higher slope at the zero-crossing increases the sensitivity of the BAM
  - Bigger amplitude difference at the receiver

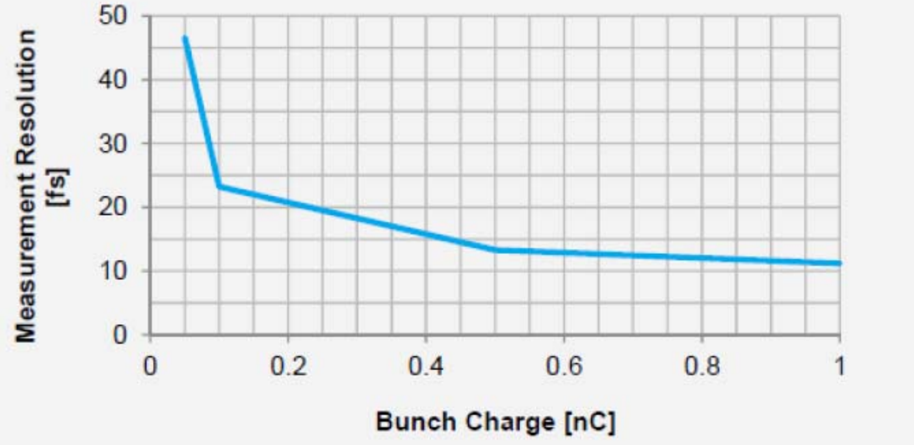
A. Angelovski: ITSS 2012

Bunch Arrival-time Monitors at FLASH

- Measurement resolution = f (pickup signal slope at the first zero-crossing)
- Signal slope = f (bunch charge)

Bunch charge ⇩ ➔ Slope ⇩ ➔ Measurement resolution ⇩

Bandwidth ⇧ ➔ Slope ⇧ ➔ Measurement resolution ⇧



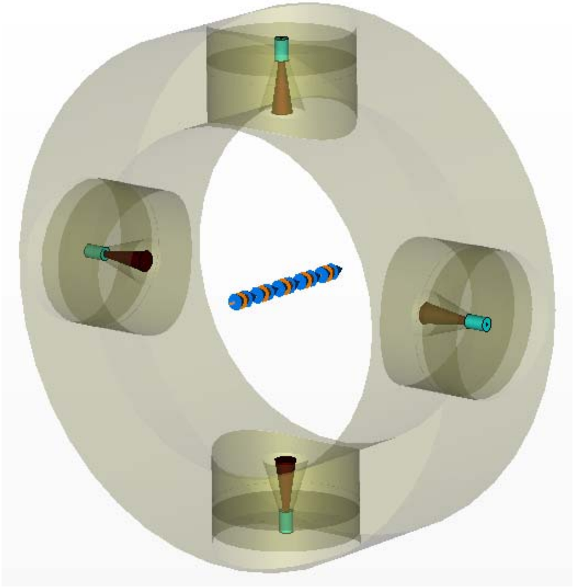
Measurement resolution vs. bunch charge (measured by M. Bock)

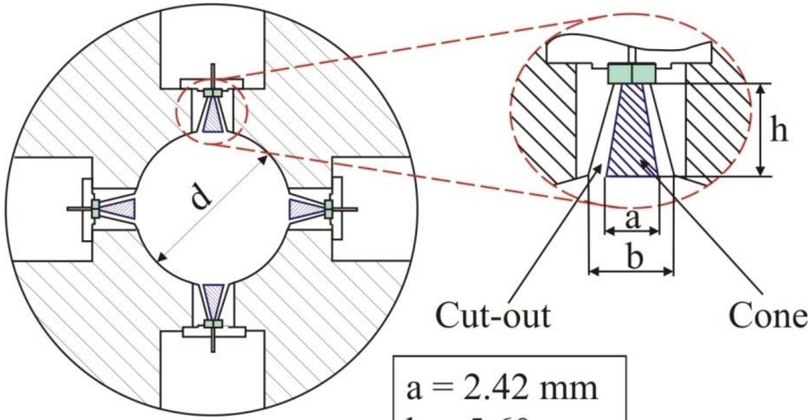
- Requirements for low charge mode:
  - Voltage slope > 300 mV/ps
  - Bandwidth up to 40 GHz
  - Ringing less than 0.01% after 222 nS (XFEL min. bunch spacing)

A. Angelovski: ITSS 2012

Bunch Arrival-time Monitors at FLASH

- Limiting factors of the BAMs bandwidth
  - Pickups, Cables, RF components, etc.
- Pickup design for the new BAM
  - Cone-shaped pickup



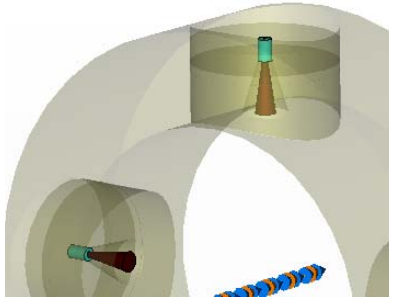


a = 2.42 mm
b = 5.60 mm
d = 40.50 mm
h = 6 mm

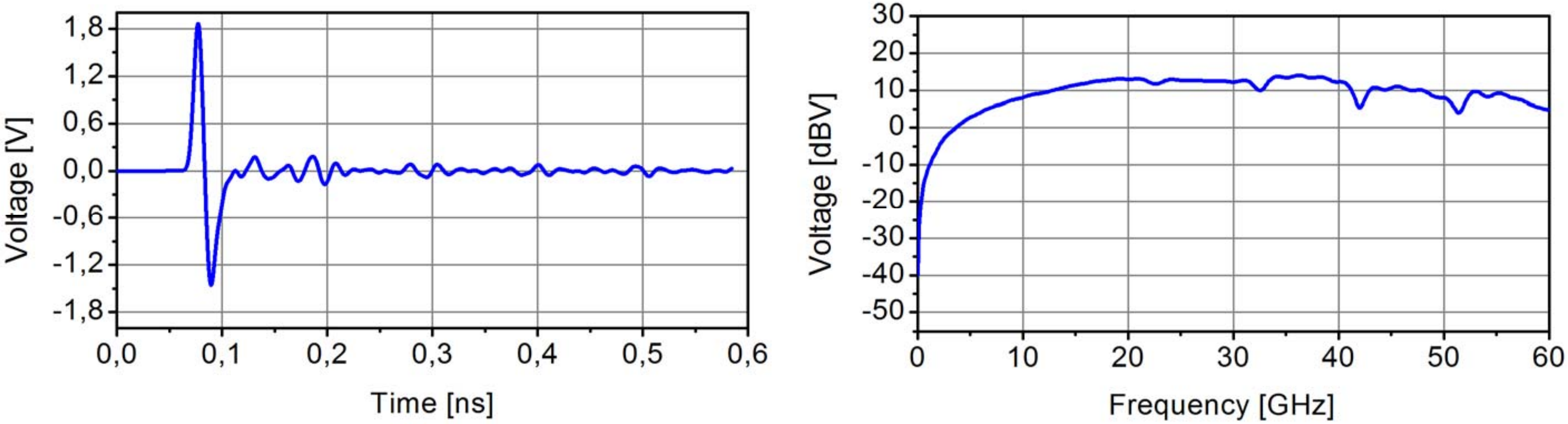
- Avoid resonances in the pickup structure
  - Gaps, discontinuities, sharp edges
- Match the pickup to impedance of 50 Ω
  - No reflections in the output signal
  - Smooth impedance transition from the beam pipe to the connector

A. Angelovski: ITSS 2012

Bunch Arrival-time Monitors at FLASH



- No button design
  - Pickup resonances
- Fast voltage response
  - Reduced capacitance (smaller time constant)
- Tapered cut-out with constant ratio b / a = 2.3 for 50 Ω matching
  - Coax structure, resonance-free (no higher order modes) up to 40 GHz

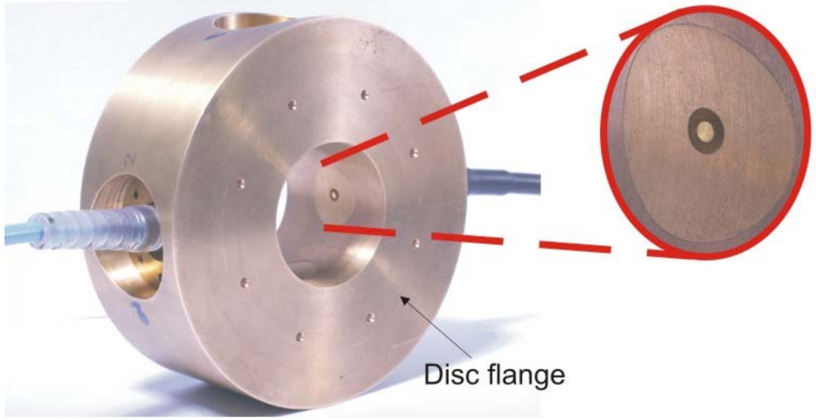


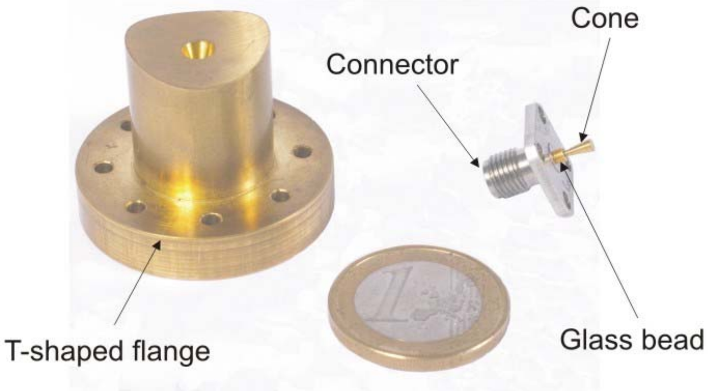
Pickup output signal. CST PARTICLE STUDIO simulation with bunch charge of 20 pC and bunch length of 1 mm.

A. Angelovski: ITSS 2012

Bunch Arrival-time Monitors at FLASH

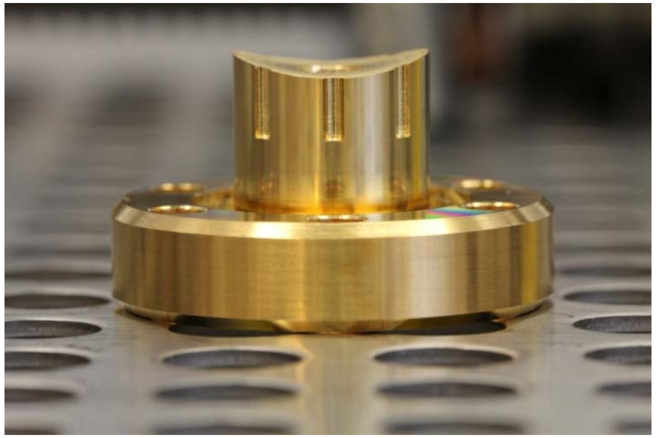
- Prototype of the BAM pickups (non-hermetic)





A. Angelovski: ITSS 2012

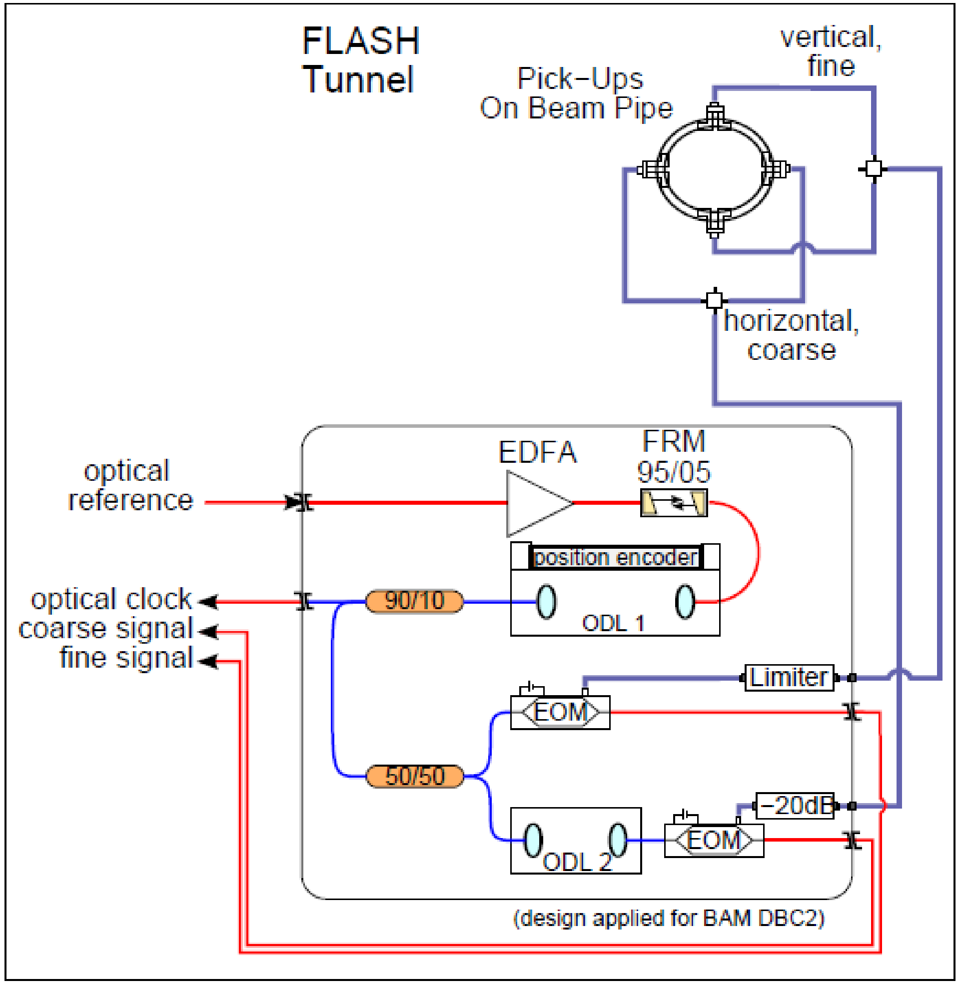
Fabrication at Orient Microwave



Bunch Arrival-time Monitors at FLASH

- The BAM comprises:
  - Four pickup electrodes
  - RF front-end
  - Read-out electronics

- Two channels for the read-out
  - RF-signal + limiter:
    - large signal
    - small dynamic range: 4 ps
  - RF-signal + attenuator
    - small signal
    - large dynamic range: 65 ps
- Combine signals to reduce orbit dependency



M.K. Bock, FLASH seminar – 28 June 2011

A. Angelovski: ITSS 2012

Outline

- History of Particle Accelerators
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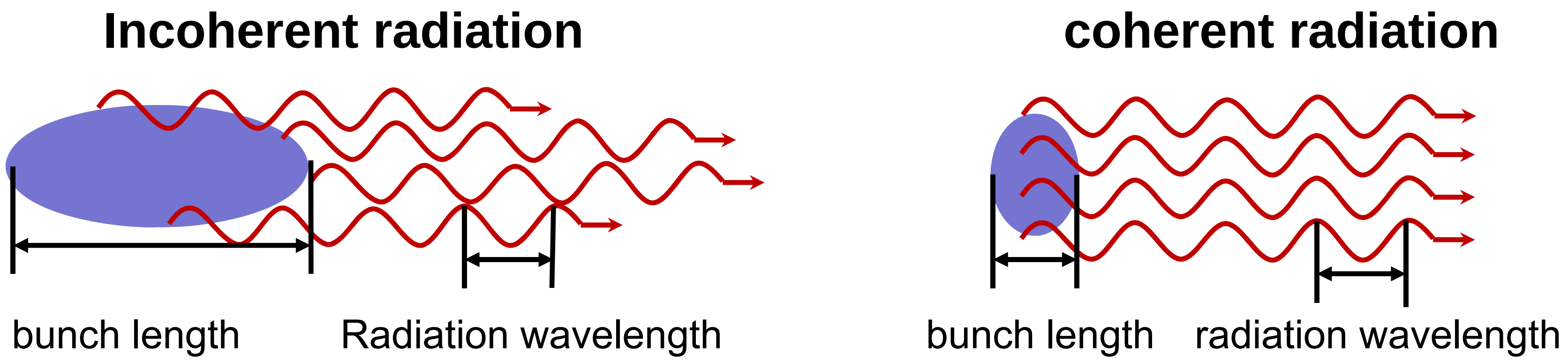
    - Beam Position Measurement
    - Arrival-time Measurement
    - Bunch shape diagnostics

Bunch length Diagnostics using Coherent Radiation

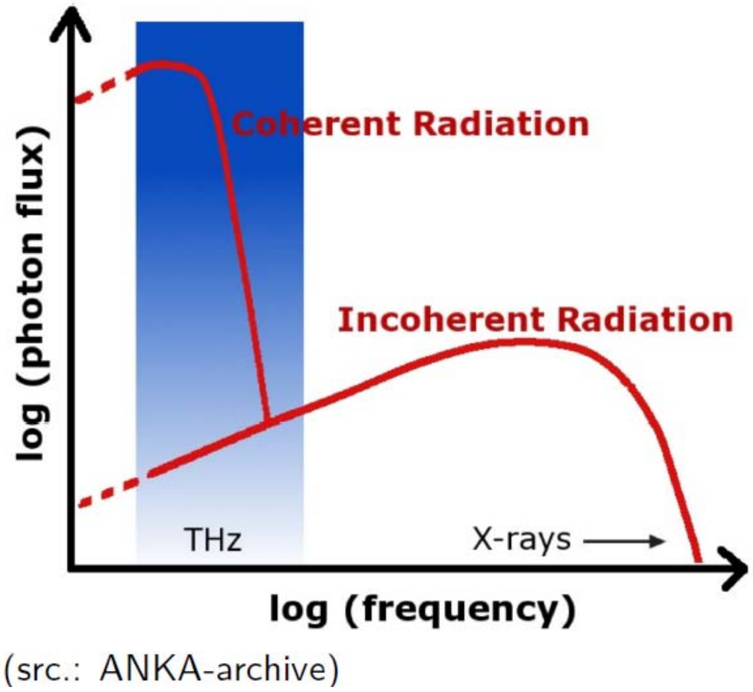
- Radiation emitted by relativistic particle beams contains information about the longitudinal and transverse bunch distribution.
- At wavelength (much) shorter than the bunch length the radiation is emitted incoherently because each electron emits its radiation independently from the others without a defined phase relation.



- Coherent enhancement occurs at wavelength, which are equal or shorter than the bunch length, where fixed phase relations are existing, resulting in the temporal coherence of the radiation.
- While the power of the incoherent radiation scales with the number N of particles in a bunch, the coherent radiation increases with square of the number of particles N^2.

V. Schlott: CAS 2008, Lecture on Femto-Second Diagnostics

Coherent Synchrotron Radiation

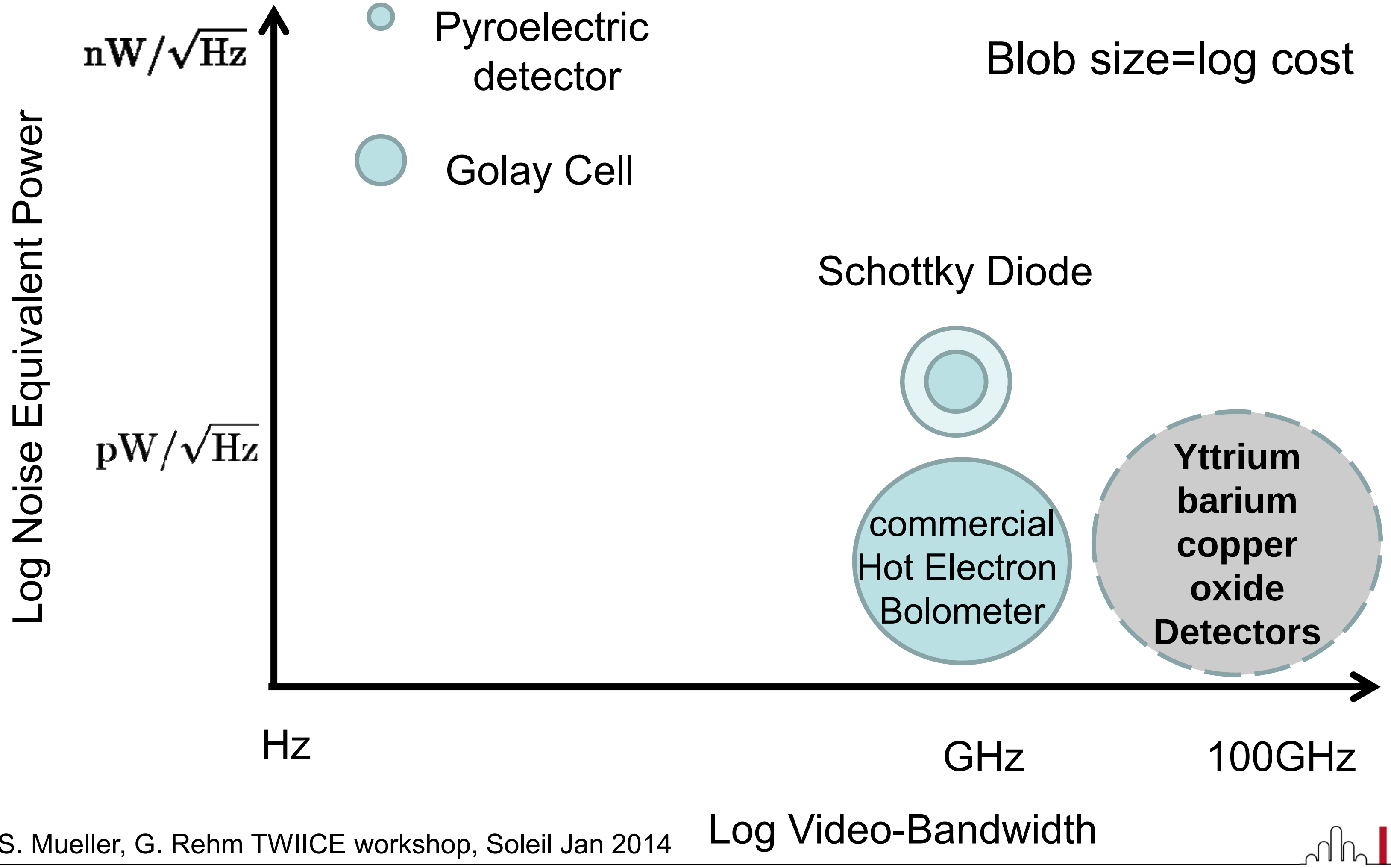


(src.: ANKA-archive)

- $P_n = n_0 * P1(1+N_e\, g_\lambda)$
- g_λ is a form factor and defines the spectral characteristics
- Typically $N_e = 10^9$
  Enormous increase in power in comparison to incoherent emission
- Intensity $\propto I^2_{bunch}$
- Very short bunch is needed

V. Judin: Longitudinal diagnostics at ANKA 2010

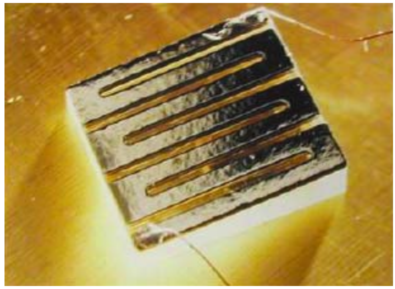
mm-Wave & THz Detectors
NEP vs. Video Bandwidth

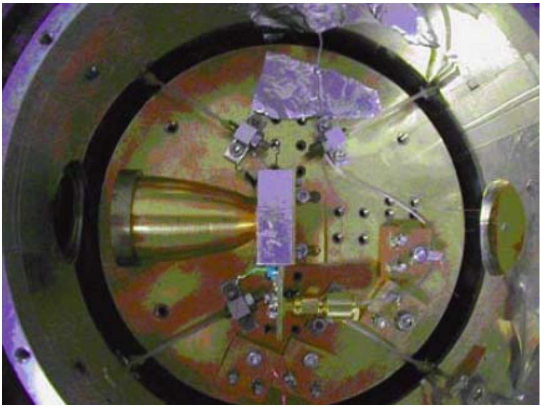


A.S. Mueller, G. Rehm TWIICE workshop, Soleil Jan 2014

Coherent Radiation – Detector Systems in the THz Regime

He- and N-cooled bolometers (InSb, Si, GeGa, Nb…)





Spectral response: ~5 mm to 50 μm
Optical NEP: ~1,5*10^{-12} W $Hz^{0,5}$
Dynamic Range: pW to μW
Opt. Responsivity: 15 kW / Watt
Detector BW: ~ 1 MHz
Operating Temp.: <4,2 °K

Golay Cell Detectors

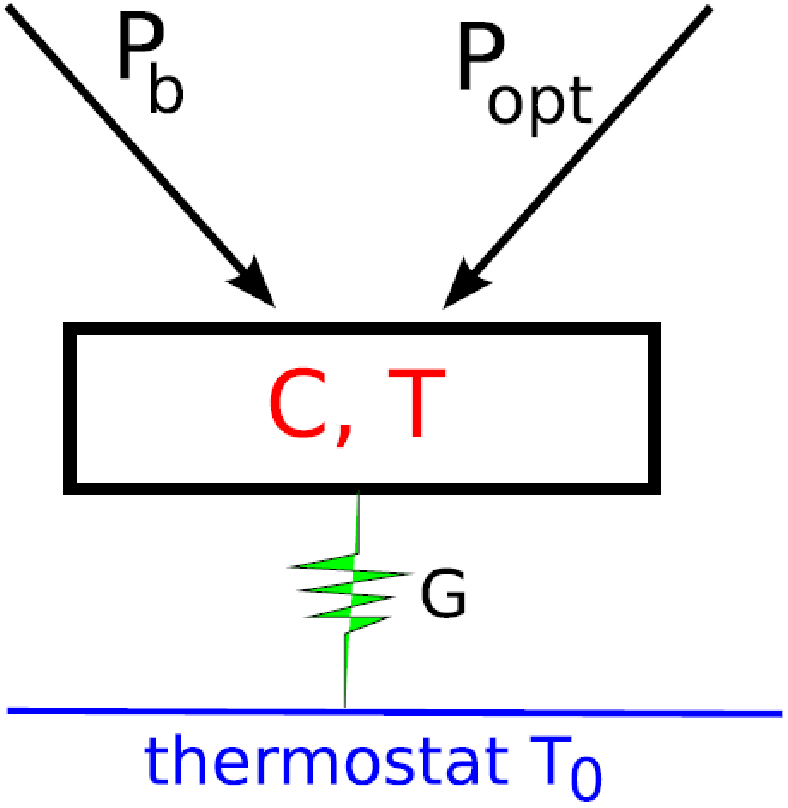
Spectral response: ~ 5 mm to visible
Optical NEP: ~ 1*10^{-10} W $Hz^{0,5}$
Dynamic Range: pW to μW
Opt. Responsibility: 100 kV / Watt
Detector BW: ~ 15 Hz
Operating Temp.: 300 °K

V. Judin: Longitudinal diagnostics at ANKA 2010

THz Detectors
Bolometer

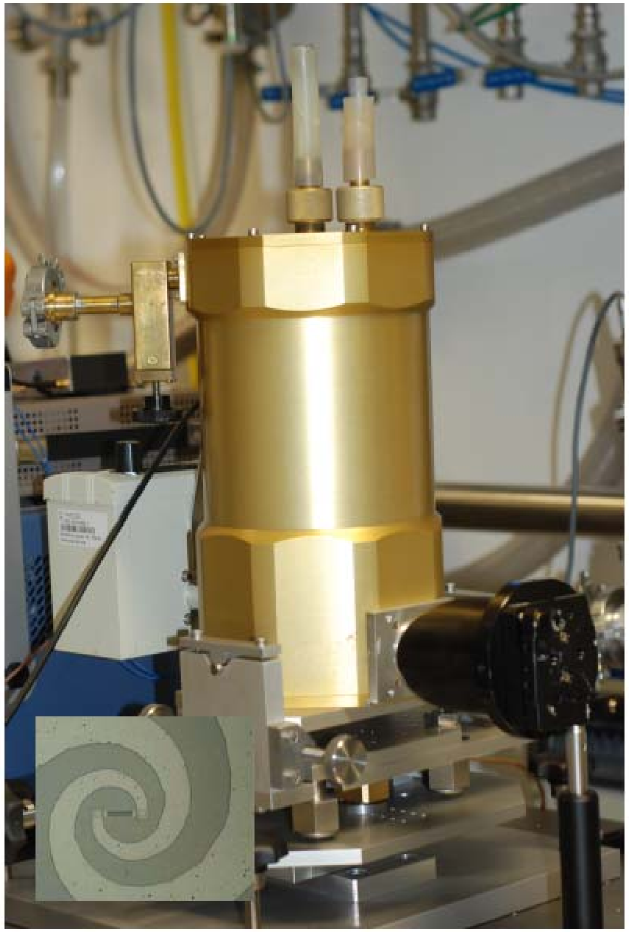
- Bolometer is a thermal detector
- dR/dT detection
- Fundamental determinants
  - Response time $\tau = C/G$
  - Responsivity $S \propto 1/G$
- Detector matter:

  e.g. Superconductor



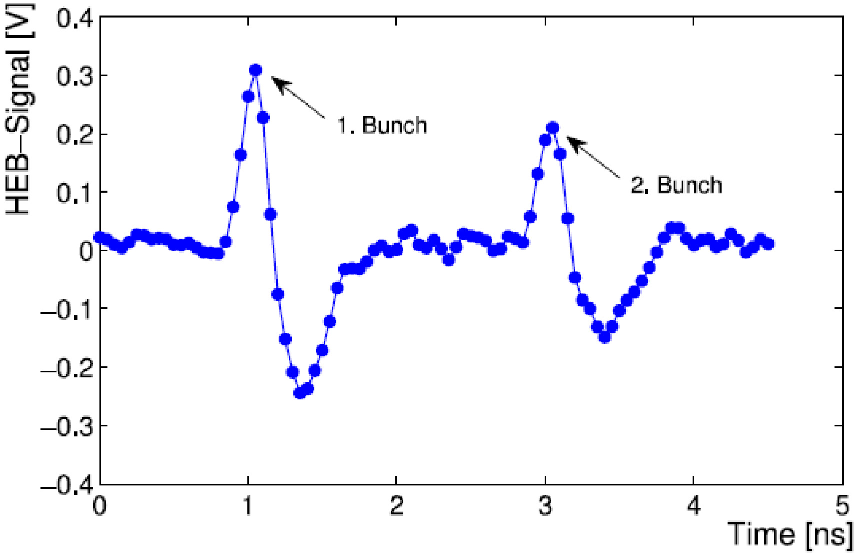
V. Judin: Longitudinal diagnostics at ANKA 2010

Hot Electron Bolometer



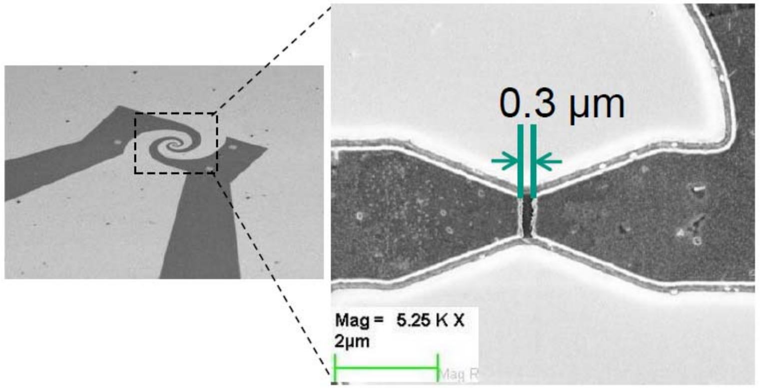
The HEB detector system

- SC niobium nitride detector
- Spectral range 150 GHz – 3 THz
- Response time < 160 ps

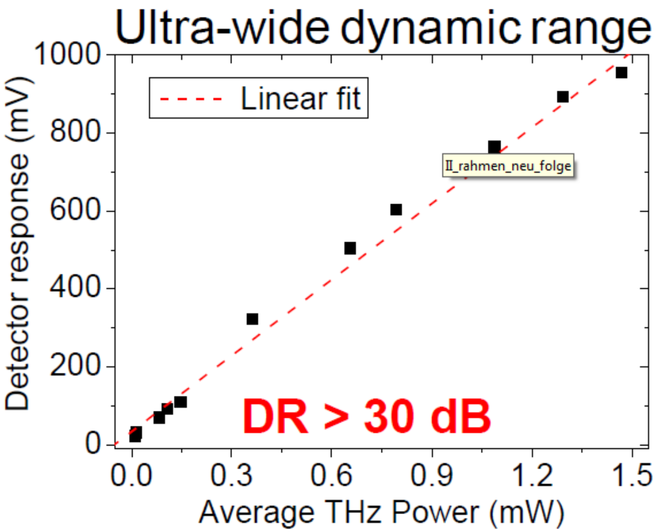


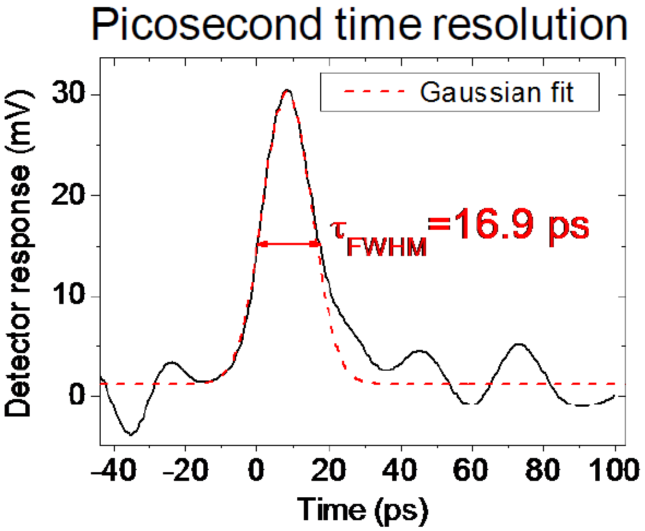
V. Judin: Longitudinal diagnostics at ANKA 2010

Ultra-fast YBCO THz detectors for picosecond synchrotron pulses



Nanometer-sized
YBCO detectors
in a high-speed
readout system
operated > 77 K

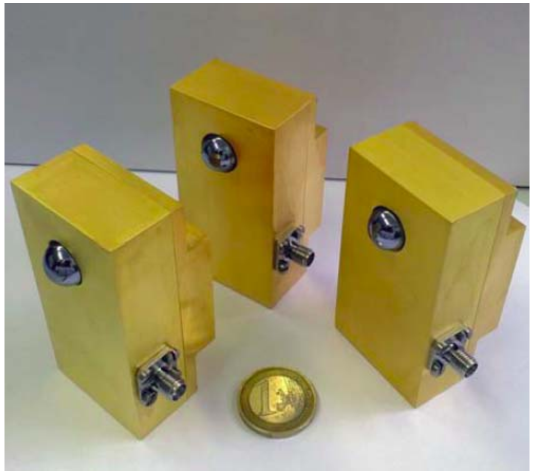


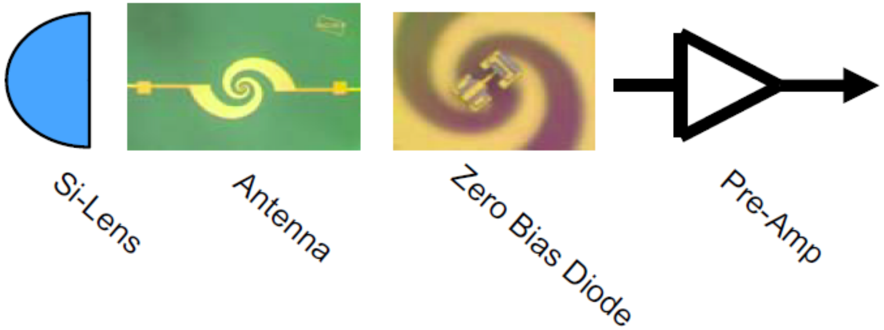


P. Thoma et al., *Applied Physics Letters*, 101, 142601, 2012
P. Probst et al., *Physical Review B*, 85, 174511, 2012

Quasi Optical Detector

Square-law detectors based on Zero-Bias Schottky Diodes





RF-Bandwidth, GHz	50 – 200	50 – 500	50 – 2000
Typ. responsivity, V/W	700 w/o ampl.	80000@100GHz 5000@500GHz	40000@100GHz 3000@1THz
Typical NEP, pW/Hz$^{1/2}$		4@100GHz 110@500GHz	6@100GHz 100@1THz

Application fields

- Scientific instrumentation
- Spectroscopy
- Imaging
- High bit rate telecommunication
- Monitoring of short-pulse and weak THz radiation

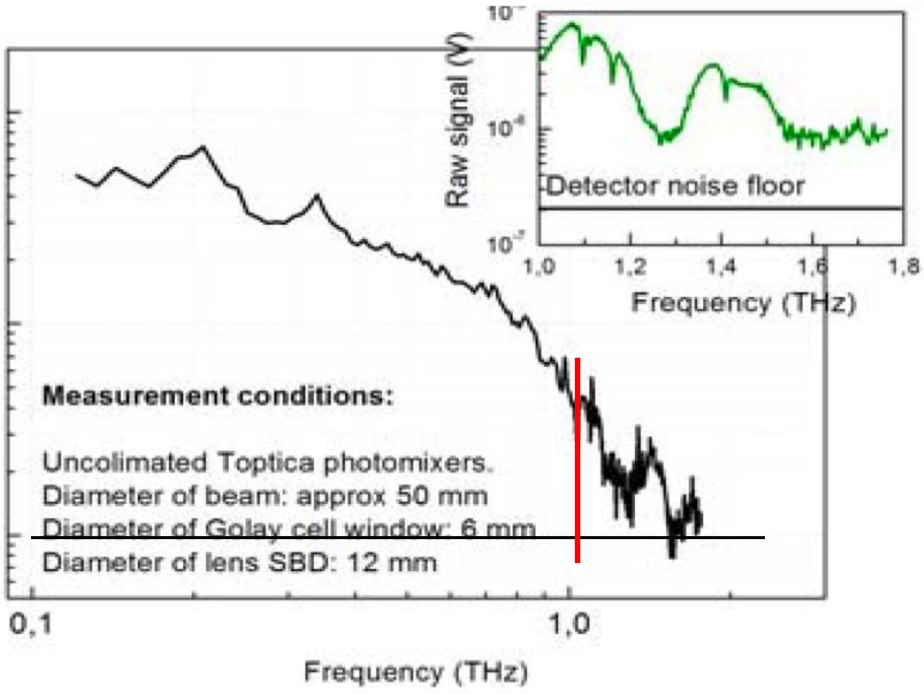
Source: ACST GmbH

Quasi Optical Detector
Zero Bias Detector vs. Golay Cell

Comparison: ZBD vs. GC

- faster response
- geometrically smaller
- better SNR up to 1 THz

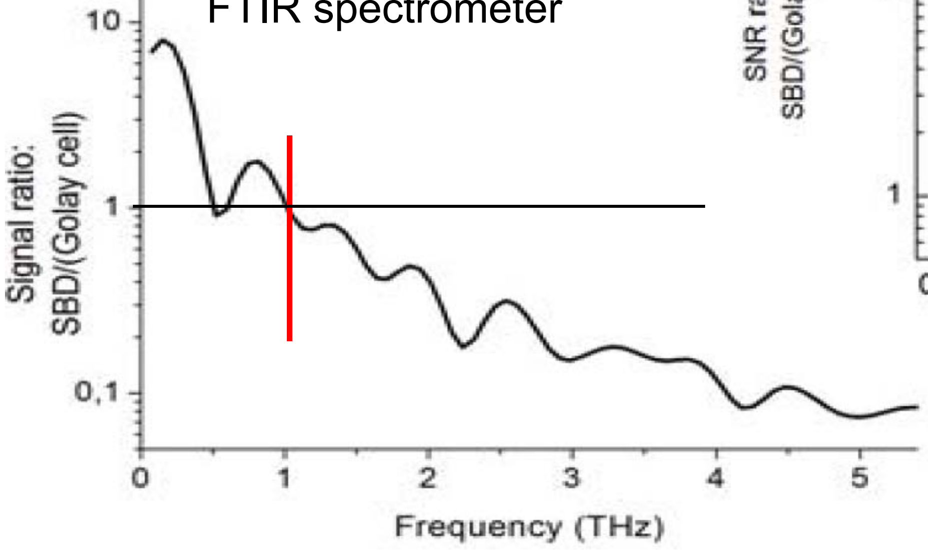
SNR ratio measured in a photoconductive setup



Measurement conditions:

Uncolimated Toptica photomixers.
Diameter of beam: approx 50 mm
Diameter of Golay cell window: 6 mm
Diameter of lens SBD: 12 mm

Comparative measurements with a FTIR spectrometer



Source: ACST GmbH