Longitudinal Diagnostics

part I

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Outline - part I

- Basic of Longitudinal Diagnostics
- Longitudinal particle motion
- Beam parameters / effects measurable with longitudinal diagnostics
- Longitudinal phase space
- Longitudinal Instabilities
- Pick-ups for longitudinal diagnsotics
- Coaxial cables and connectors
- Diagnostics beam lines / photo-diodes
- Fast Oscilloscopes

Basic of longitudinal diagnostics

- Both the *near field* and the *far field* associated with relativistic particle beams may be used for the Longitudinal Diagnostics
- *Near field* is sensed by means of **Electro Magnetic pick-ups** (EM-PU) located on the beam trajectory, mounted directly on the vacuum chamber
- *Far field* is acquired by means of dedicated **diagnostic beam lines** where the radiation can propagate up to the **sensor/instrument**
- Typically, on **rings,** we do prefer *non-destructive* diagnostics (to perform the measurement while the beam is circulating), whereas on **single pass** machine also *destructive* or *quasi non-destructive* diagnostics are widely used (…new beam at each injector shot)

Basic of longitudinal diagnostics

- On single pass machines (*LINACs* and *Transfer Lines*) the different radiations generated by charged particles interaction with matter are also used for diagnostic purposes:

Optical Transition Radiation (OTR)	**D**
Optical Diffraction Radiation (ODR)	**N-D**
Cherenkov Radiation (CR)	**D**
Smith-Purcell Radiation (SPR)	**N-D**

- The above mentioned radiations are all "instantaneous" i.e. the temporal profile of the emitted field is a replica of the bunch profile
- Also, widely used in diagnosing the longitudinal profile of *ultra short bunches* (4GLS) as the emission is in the **Coherent** regime (ref. F*emto-second Diagnostics* lectures)

Basic of longitudinal diagnostics

- For EM-PU, the measurement set-up consists of:
  - the PU
  - the cable
  - the acquisition instrument
- For the far field based measurements:
  - the emitting portion on the beam trajectory
  - the extraction / transport / focusing optical line
  - the sensor and / or the instrument
- For the destructive/single pass measurements:
  - the “radiator” (*screen, slit, aero-gel, grating*)
  - the extraction / transport / focusing optical line
  - the sensor and / or the instrument

Longitudinal particle motion [1]

- Accelerating (aka longitudinal) fields are high frequency EM fields (radio frequency / RF fields)
- As free EM wave has no component along Z: need for accelerating structures
- Being the fields AC ➔ synchronicity, bunching

E field expression: $$\boxed{\vec{E}(z,t) = \vec{E}_0 \cdot e^{i(\omega t - kz)} = \vec{E}_0 \cdot e^{i\psi}}$$

where: $\psi=(\omega t\text{-}kz)$ is the phase; k wave number, constant.

- **Travelling wave** acc. structures: E phase velocity = $v_p=c\beta$
- **Standing wave** acc. structures: $$\boxed{\vec{E}(z,t) = \vec{E}_0(z) \cdot e^{i\omega t - \delta}}$$

where: δ is the phase as the particle enters the acc. structure

Longitudinal particle motion [1]

- Energy gain of the particle $$\Delta E = (\gamma - \gamma_0)mc^2 = e \cdot \int \vec{E}(\psi) d\vec{z}$$
- The degree of acceleration depends of the phase ψ of the field seen by the particle
- Small oscillation: $$\ddot{\varphi} + 2\alpha_s \dot{\varphi} + \Omega^2 \varphi = 0$$

Ω^2 ➔ synchrotron frequency; α_s damping term

- In a resonant cavity: $$V(\psi) = V_0 \sin\psi$$

expanded about the synch. phase: $\psi = \psi_S + \varphi$

and the synch. frequency is now: $$\ddot{\varphi} + \Omega^2 \varphi = 0$$

$$\Omega^2 = \omega_{REV}^2 \cdot \frac{h\eta_c eV_0 \cos\psi_S}{2\pi\beta c p_0}$$

η_C: *moment compaction*

α_C: *moment compaction factor*

$$\boxed{\alpha_C = \frac{\Delta L / L_0}{\Delta p / p_0}} \quad \boxed{\eta_C = \gamma^{-2} - \alpha_C}$$

Beam parameters / effects measurable with longitudinal diagnostics

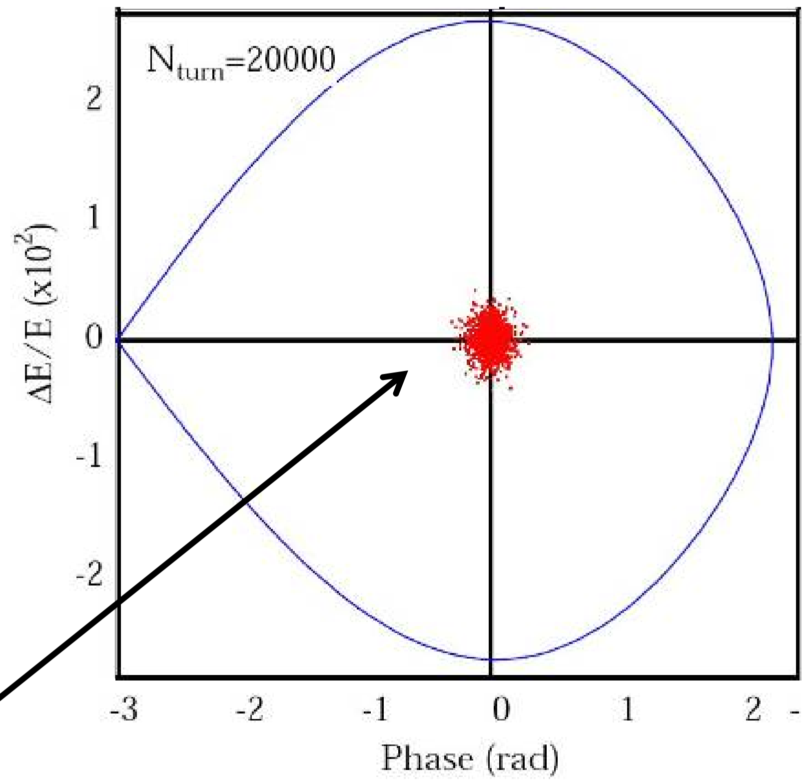
- The charge
- The bunch profile
- The bunch length
- The filling pattern / bunch purity
- The S-band satellites (on LINACs)
- The synchronous phase
- The energy loss / turn
- The coherent synchrotron frequency
- The longitudinal instabilities

Longitudinal phase space **[2]**

- The longitudinal motion of the particles is represented by the longitudinal phase space
- The conjugated variables in longitudinal phase space are:

  the **particle momentum deviation**: $\Delta E/E$, δ

  the **particle phase deviation**: φ, σ_l
- The longitudinal extension maybe expressed in **degrees** (of the RF) or **time units**
- The plot shows the result of a simulation [2] where the particles dump around the final equilibrium phase space coordinate values
- <u>**On-energy** and **nominal phase** bunch</u>



Longitudinal phase space [2]

- With respect to the nominal bunch we may have:
  - *Dipole oscillations*, excited by:
    - phase RF modulation
    - injection phase errors
  - *Quadrupole oscillations*, excited by:
    - amplitude RF modulation
    - injection phase space mismatch

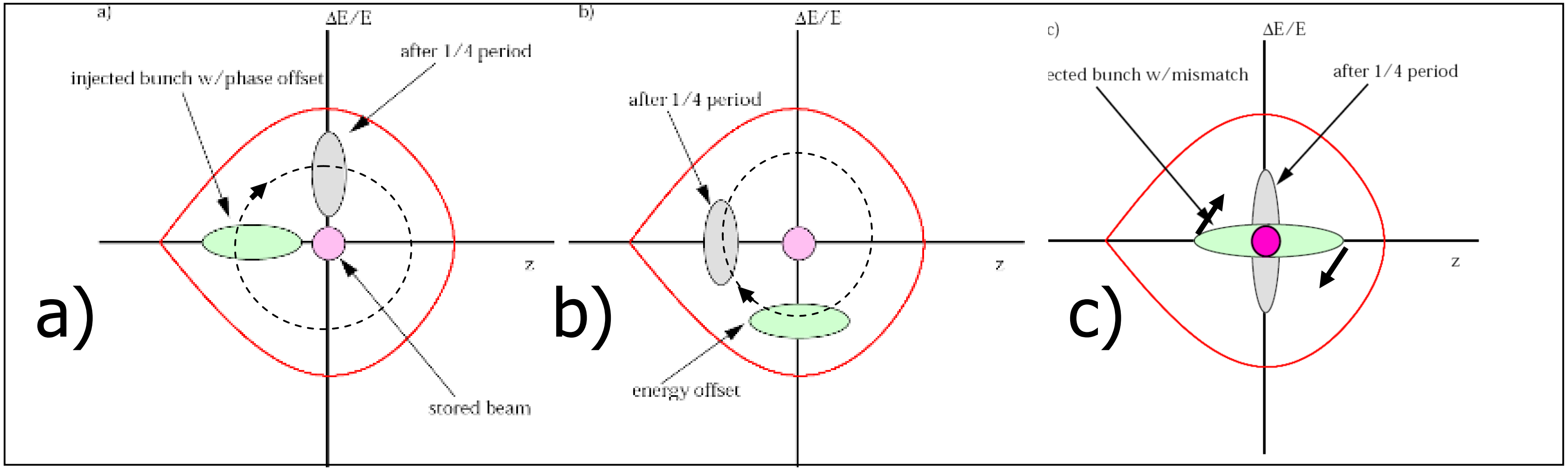


Illustration of bunch oscillations at injection [2]:

a) Phase offset along with phase space mismatch

b) Energy offset with phase space mismatch

c) Phase space mismatch only

Longitudinal phase space [1]

- Due to the energy loss (/turn) as per synch. rad. emission and successive energy recovery (RF fields) particles perform oscillations around the ideal momentum and the synchronous phase:

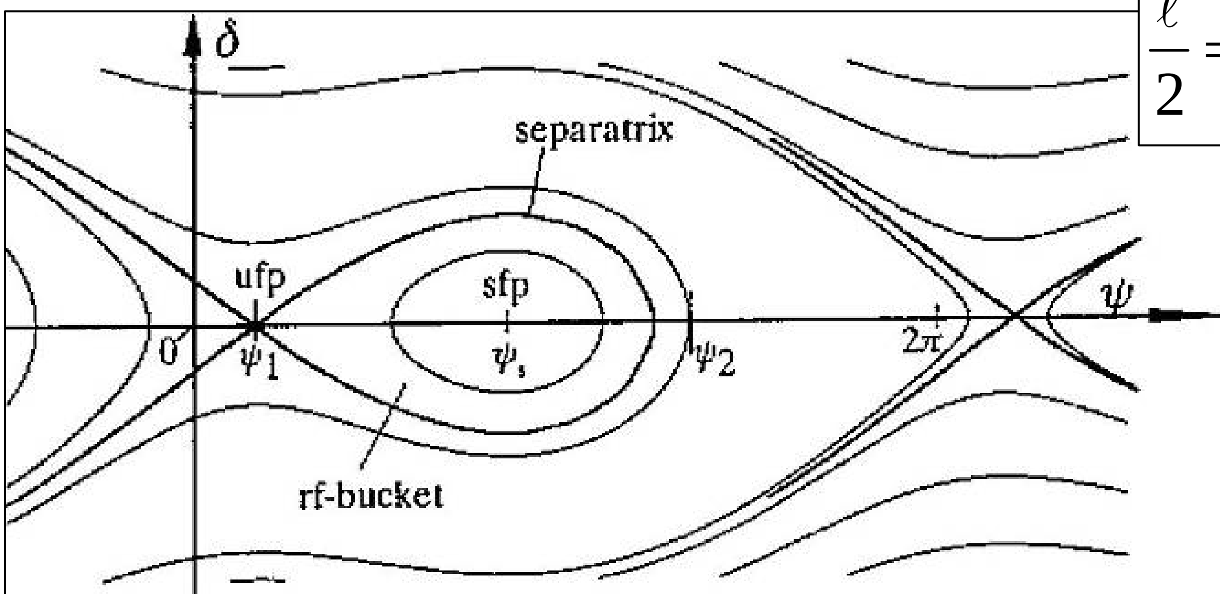
  sfp: stable fixed point

  ufp: unstable fixed point

- Particles perform incoherent phase oscillations around ψ_s
- The appearance is that of a steady state gaussian longitudinal distribution of the particles which we call the **bunch length**

$$\frac{\ell}{2} = \pm \frac{c}{h\omega_{rev}} \hat{\varphi} = \pm \frac{\lambda_{rf}}{2\pi} \hat{\varphi}$$

$\hat{\varphi}$: max phase deviation



Longitudinal instabilities **[3]**

- Focusing on bunched beams in e^- rings
- Impedance ➔ the interaction beam-boundary (vacuum chamber, cavities)
- Wake-fields are acting back on the bunch that produced them

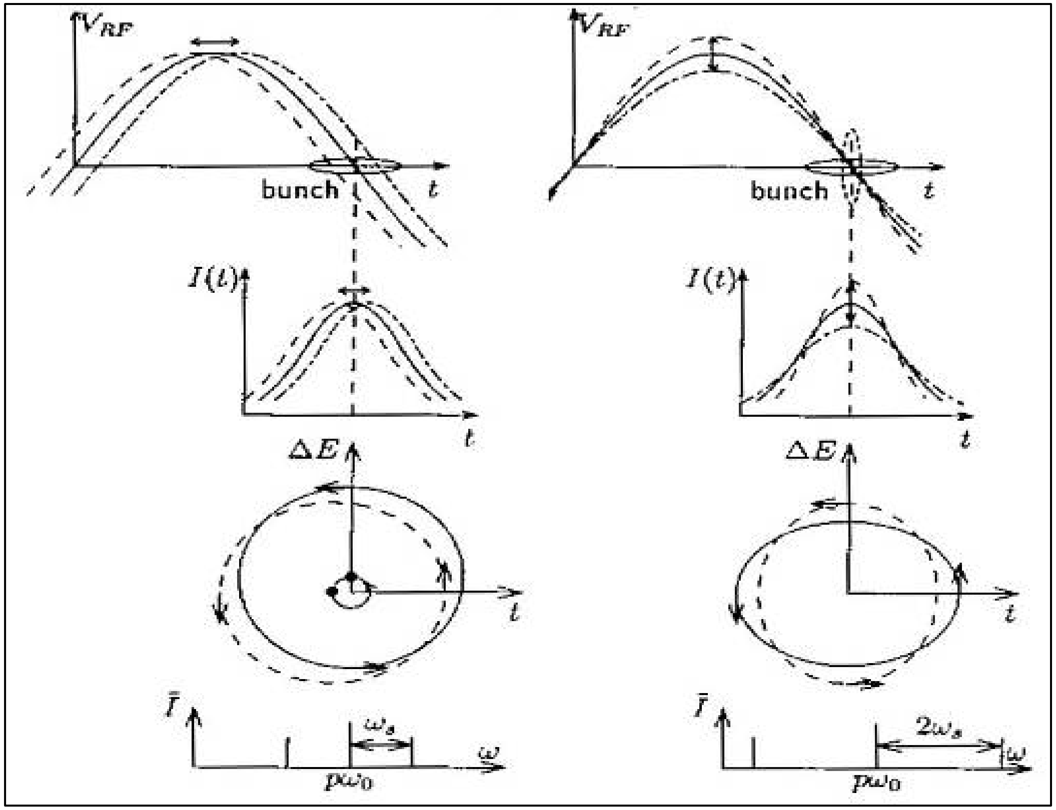
- *Collective effects* (many particles in a single bunch)
- Single traversal effects:
  - change in particle distribution (bunch lengthening)
  - potential well lengthening (inductive impedance)
  - strong self fields and broadband impedance
  - incoherent synchrotron frequency shift
- Multi traversal effects:
  - narrow band impedance (with memory)
  - start even with low self fields
  - energy loss, parasitic mode loss factor
- Robinson instability

  Synchrotron oscillations + narrow band cavity ➔ could lead to growing amplitude of oscillations

  Modulation of the revolution frequency

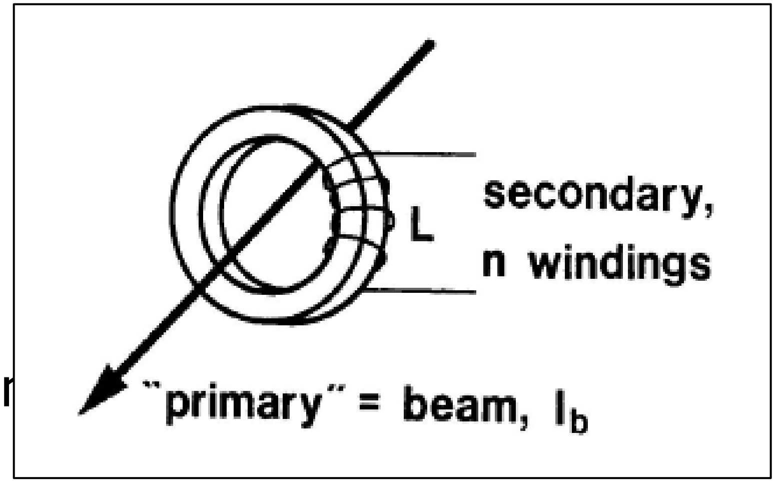
Longitudinal instabilities **[3, 33]**

- Observation of beam spectrum provides useful information
- Bunch with revolution frequency ω_0
- Synchrotron frequency ω_s
- At each *revolution harmonics* $\mathbf{p\omega_0}$ there are sidebands:
  - dipole: $\omega_{s1} = \omega_s$
  - quadrupole: $\omega_{s2} = 2\omega_s$



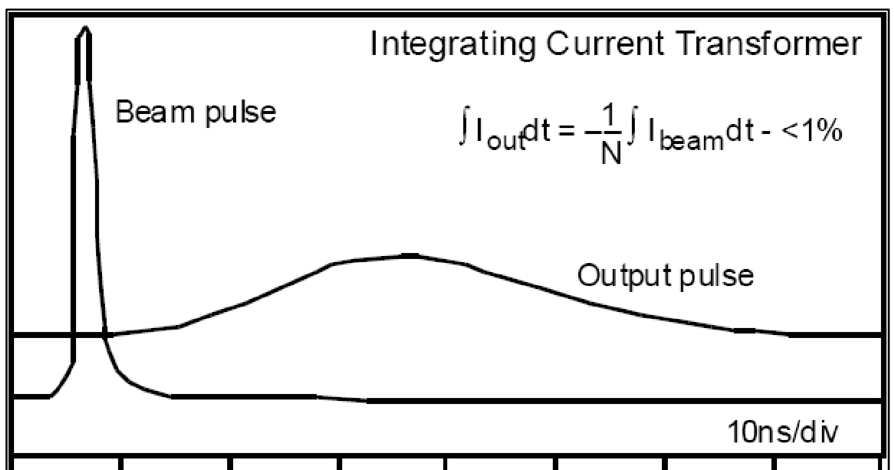
Current Transformer (CT)

- The CT is a widely used non-destructive instrument sensing the longitudinal profile of the bunch
- Due to its limited bandwidth, typical in the 100s of MHz range, the CT measures (integrating) the bunch charge
- The CT is based on the transformer principle, being the primary circuit the beam and the windings on the magnetic core the secondary
- In order for the beam field to be sensed outside the vacuum chamber, the CT is located across a ceramic gap and conducting shield assembly to close the wall current out of the CT itself



Current Transformer [4]

- CTs are available both for single pass machines (pulse transformer) and for circular machine (PCT or DCCT)
- Recently, Fast Current Transformer became available which go up to a bandwidth of 1.75 GHz (200-ps risetime)
- CT are also available in the space saving “in-flange” format

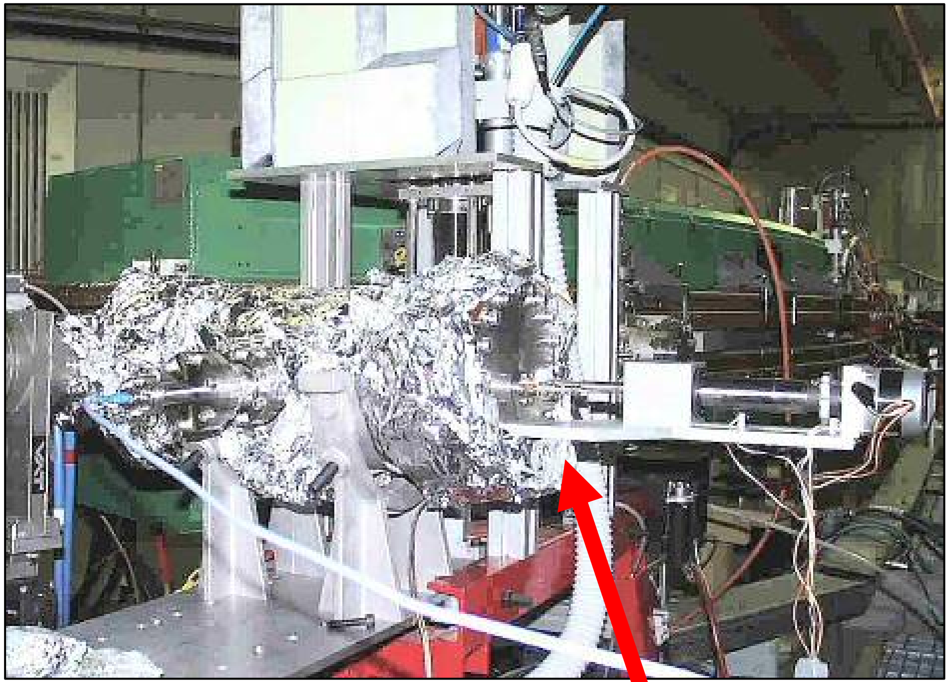


Fast Faraday Cup (F-FC)

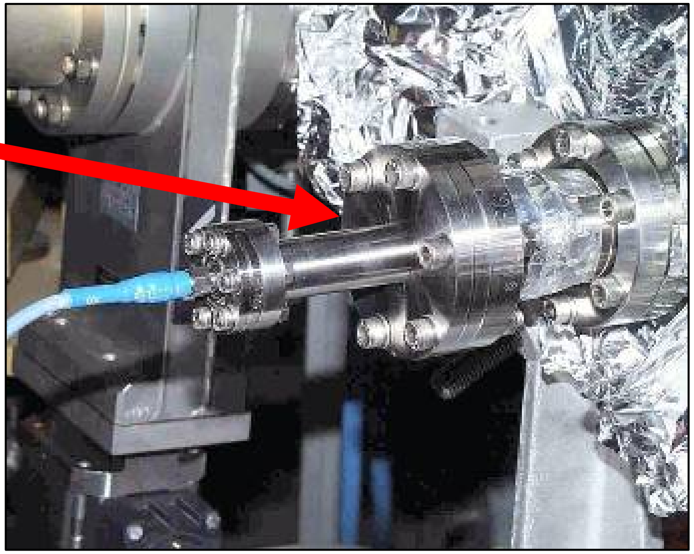
- The FC is typically a limited bandwidth device used for the absolute bunch charge measurement
- There are also so called *fast* FC which are not meant for charge measurement, but rather to obtain the longitudinal distribution of charges
- A coaxial structure is therefore adopted
- The BW is in the several GHz range
- Typically used on LINACs (it's destructive)

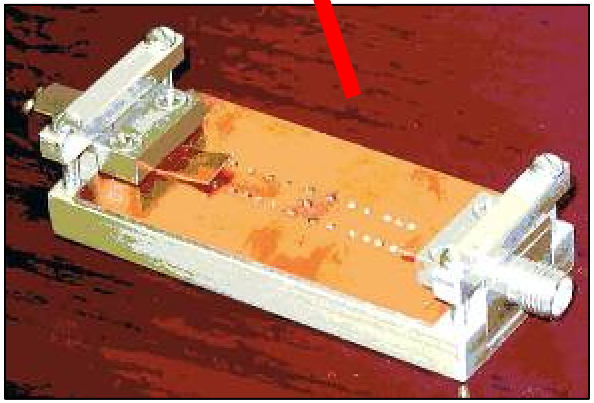
Fast Faraday Cup **[5]**

- Two different Fast FC have been mounted on the Elettra 1Gev LINAC:
- A coaxial Fast Faraday Cup adopts a 50Ω SMA vacuum feed-through from Caburn MDC Company (ref. SMAD, part number 9251001), welded to a CF16 flange
- A strip-line FFC has been designed by optimizing the electromagnetic-match of the beam-target to the connecting strip-line circuit



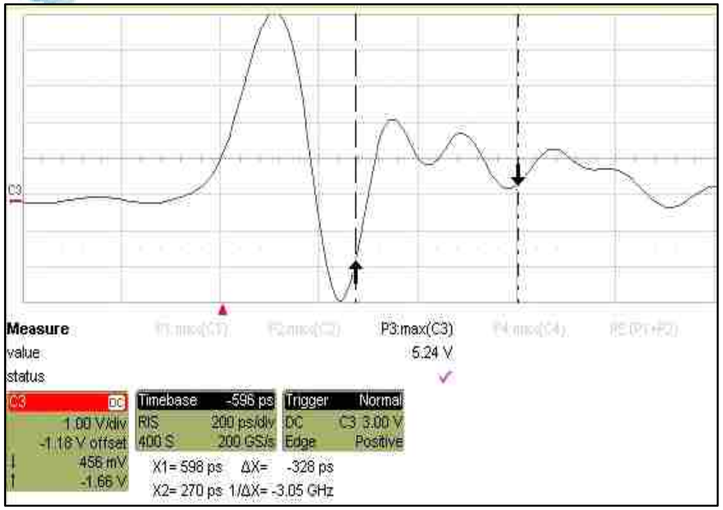
Coaxial FFC



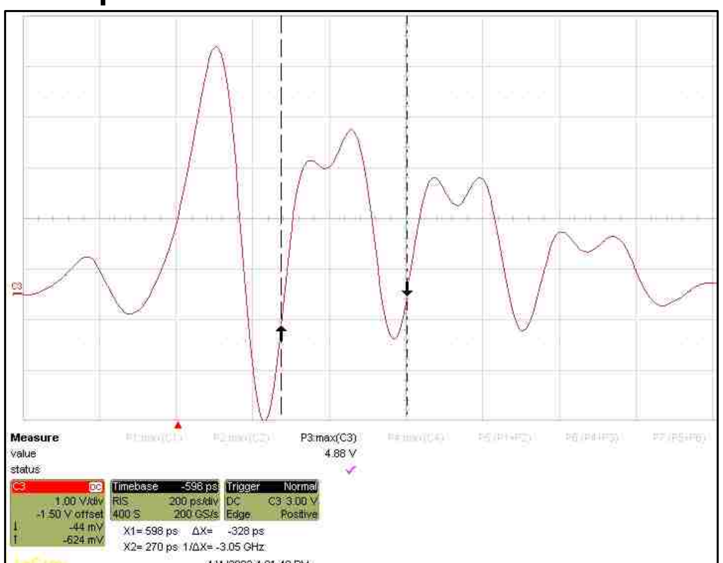


Strip-line FFC

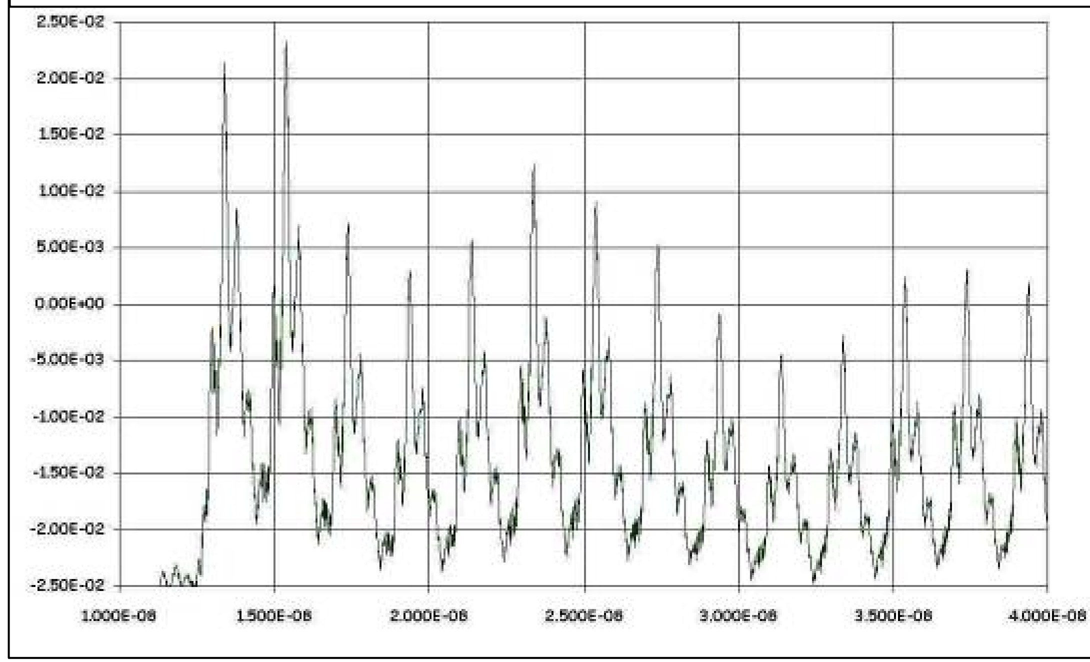
Fast Faraday Cup [5]



At V_{phase}=2.7V, one 3GHz bunch



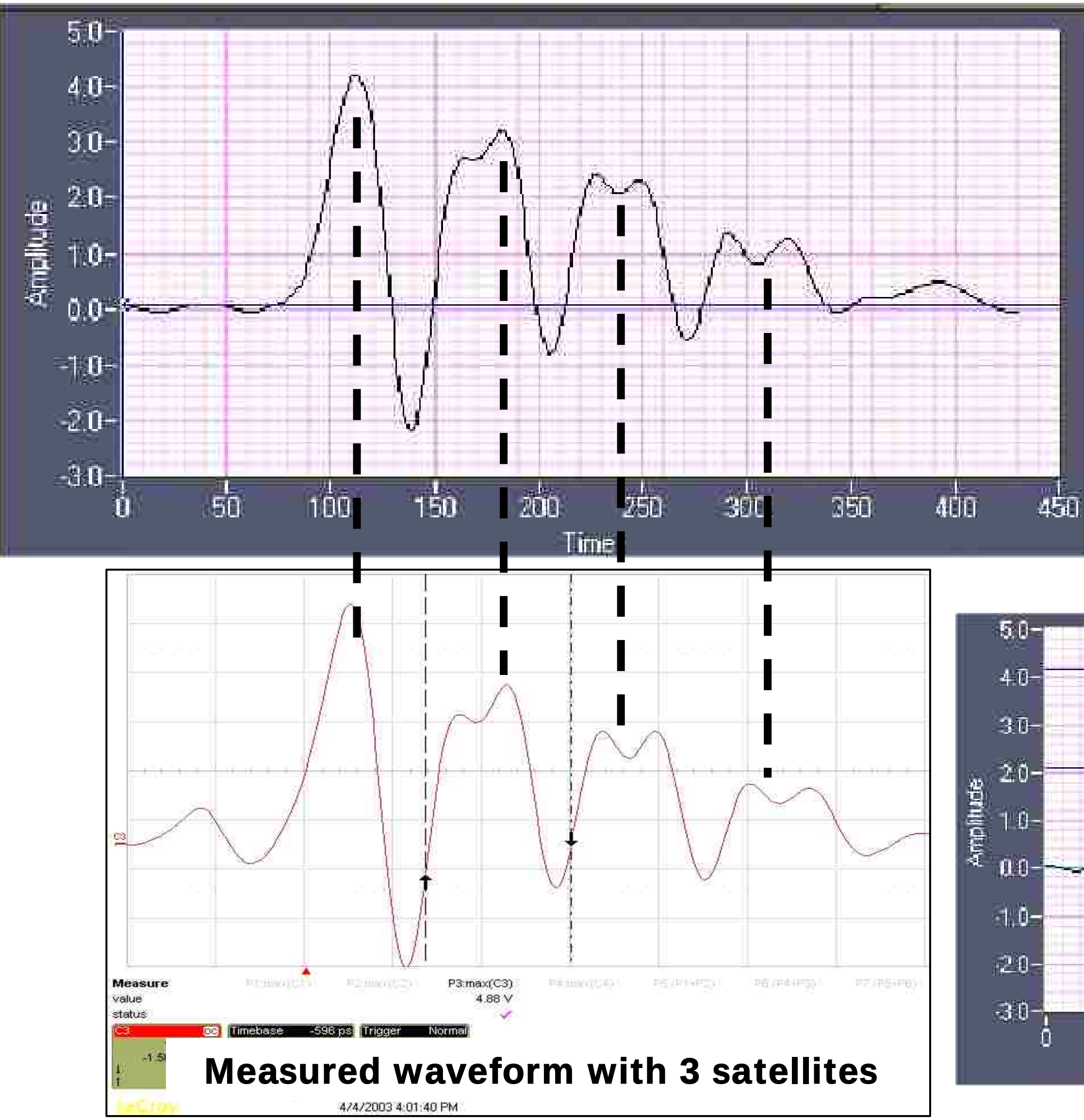
Multi Bunch Linac macro pulse acquired with the coaxial FFC and the **Tek 5104 1GHz oscilloscope** HOR: 5ns/div, VERT: 5mV/div.
The 3GHz satellites are clearly visible on both sides of the main bunches.



Single Bunch acquisition, Coaxial FFC+Le Croy 8500 oscilloscope. HOR: RIS 200ps/div, VERT: 1V/div.
At V_{phase}=3V three 3GHz satellites can be observed

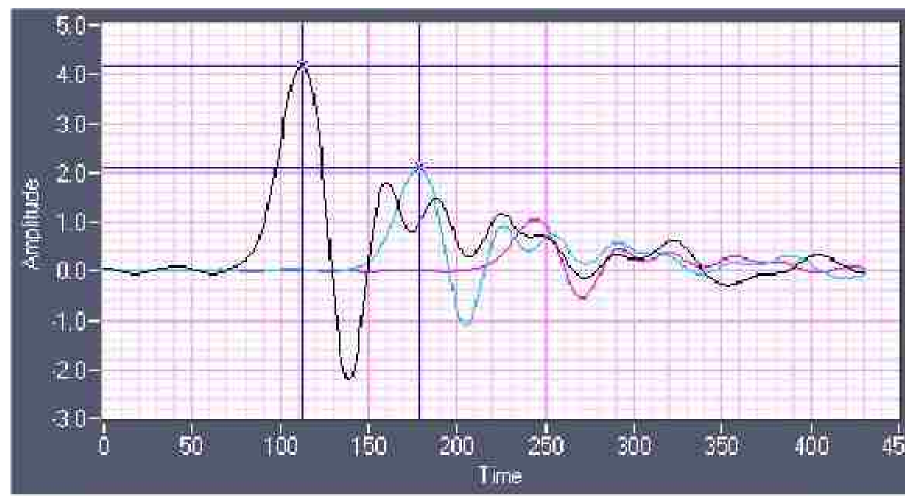
LeCroy8500-Wavemaster (BW=5GHz)

Fast Faraday Cup [5]



Measured waveform with 3 satellites

The simulated (LabView) waveform obtained by summing three equal shifted "single bunch waveforms" matches very well with the measured one with three 3GHz satellites



The (main+3 shifted) waveforms shown

Electro Magnetic (EM) pick up **[6]**

- EM pick-ups (PUs) are used to obtain an electrical signal whose temporal profile approximates the temporal profile of the bunch
- EM PU are used also to obtain the "centroid" of the bunch i.e. to measure the phase of the bunch (typically w.r.t. the RF)
- EM PU are non destructive devices
- The ability to replicate the longitudinal bunch profile depends on their bandwidth which may be as wide as several GHz
- Broadly used EM PU on electron machines are:

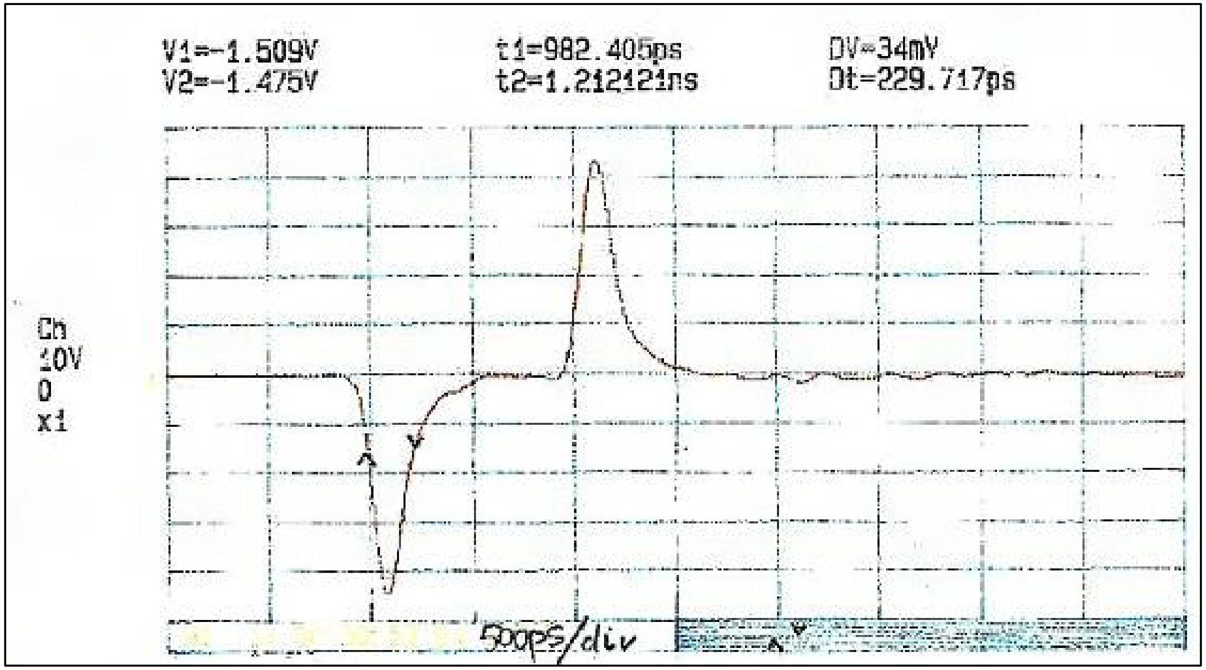
    Strip line monitor

    Button pick-up

    Wall current monitor

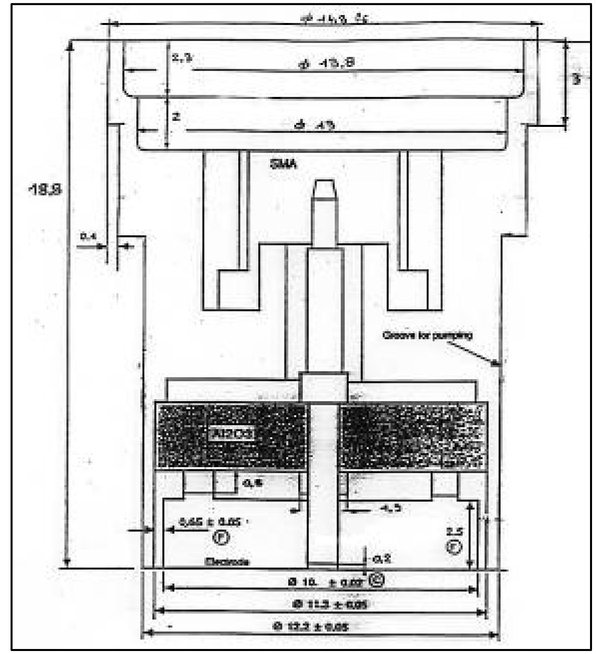
The strip line monitor

- $\lambda/4$ (quarter wavelength) monitor
- Frequency response is periodic (for a L=15cm strip-line:
  - 1st peak at 500MHz , 2nd at 1.5GHz, …
  - 1st zero at 1GHz, 2nd zero at 2GHz, …
- Measurement of a Single Bunch beam   March 1994
- Digitizer Tek SCD 5000   BW = 5.3 GHz
- 15 m. long cable BW_{eq} = 3.5 GHz
- Δt=1ns (15cm x2)

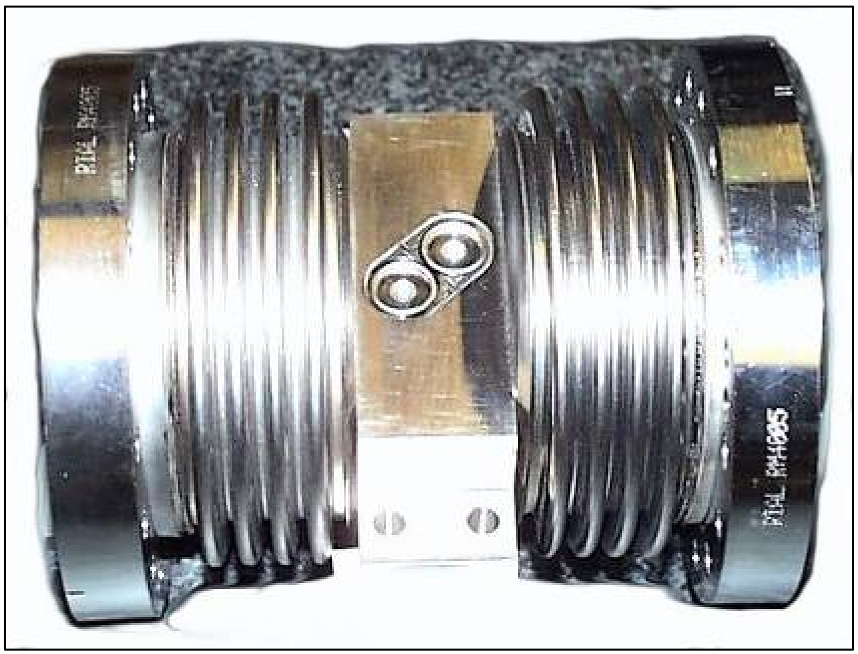


The button pick-up

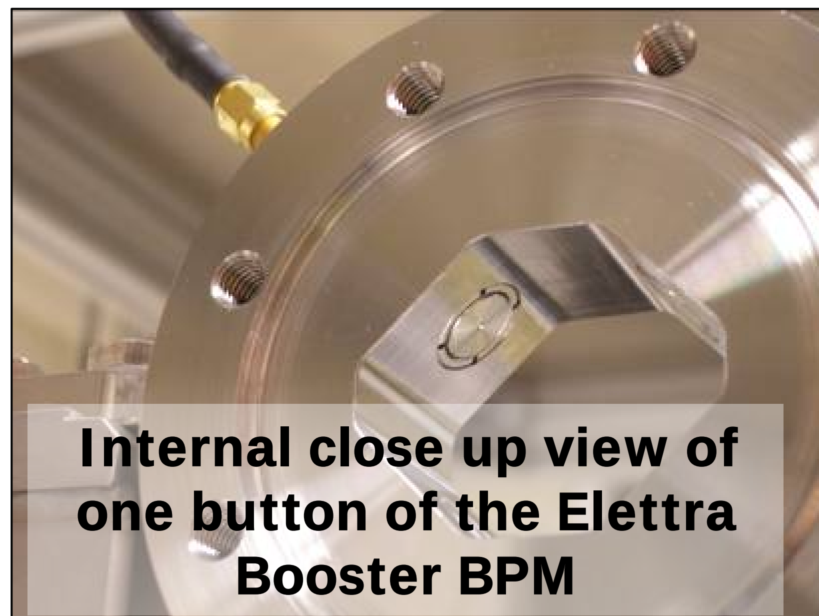
- Mostly used in St. Ring BPMs
- Very large and pretty flay BW (typ. 12.5GHz)
- Non invasive to the beam



Cross section of an SMA button (D=10mm) vacuum feed-through



Picture of Elettra low gap BPM fitted with 14mm buttons



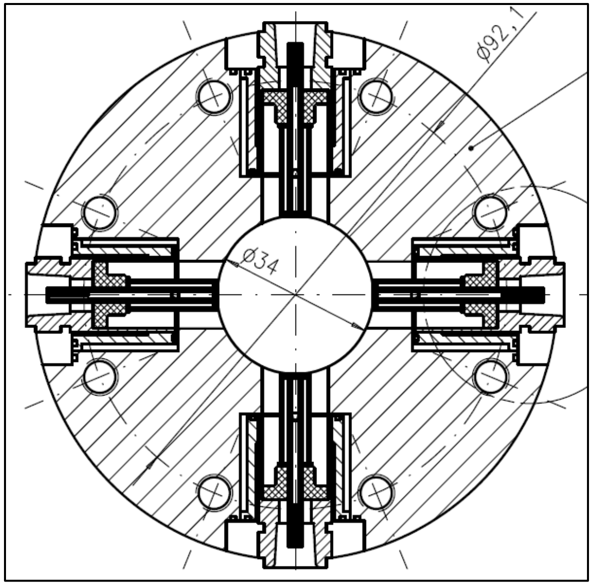
Internal close up view of one button of the Elettra Booster BPM

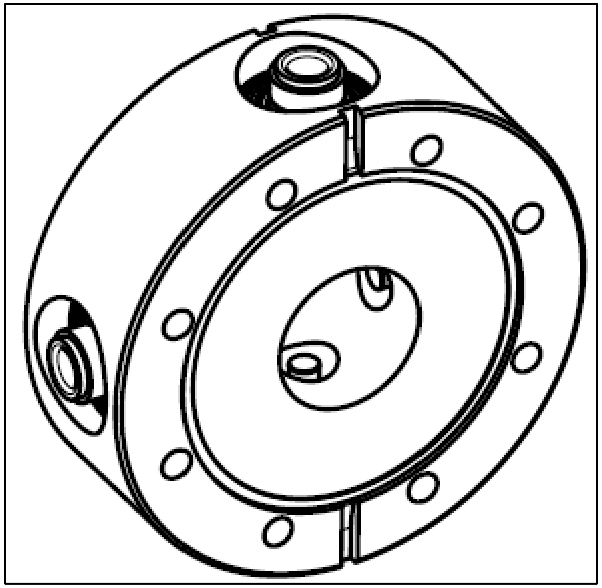
The *no-button* pick-up

- For bunch phase information retrieval…
- Bunch Arrival Monitor (BAM) P.U.

  Four N-type vacuum feed-through

  no button: antenna!



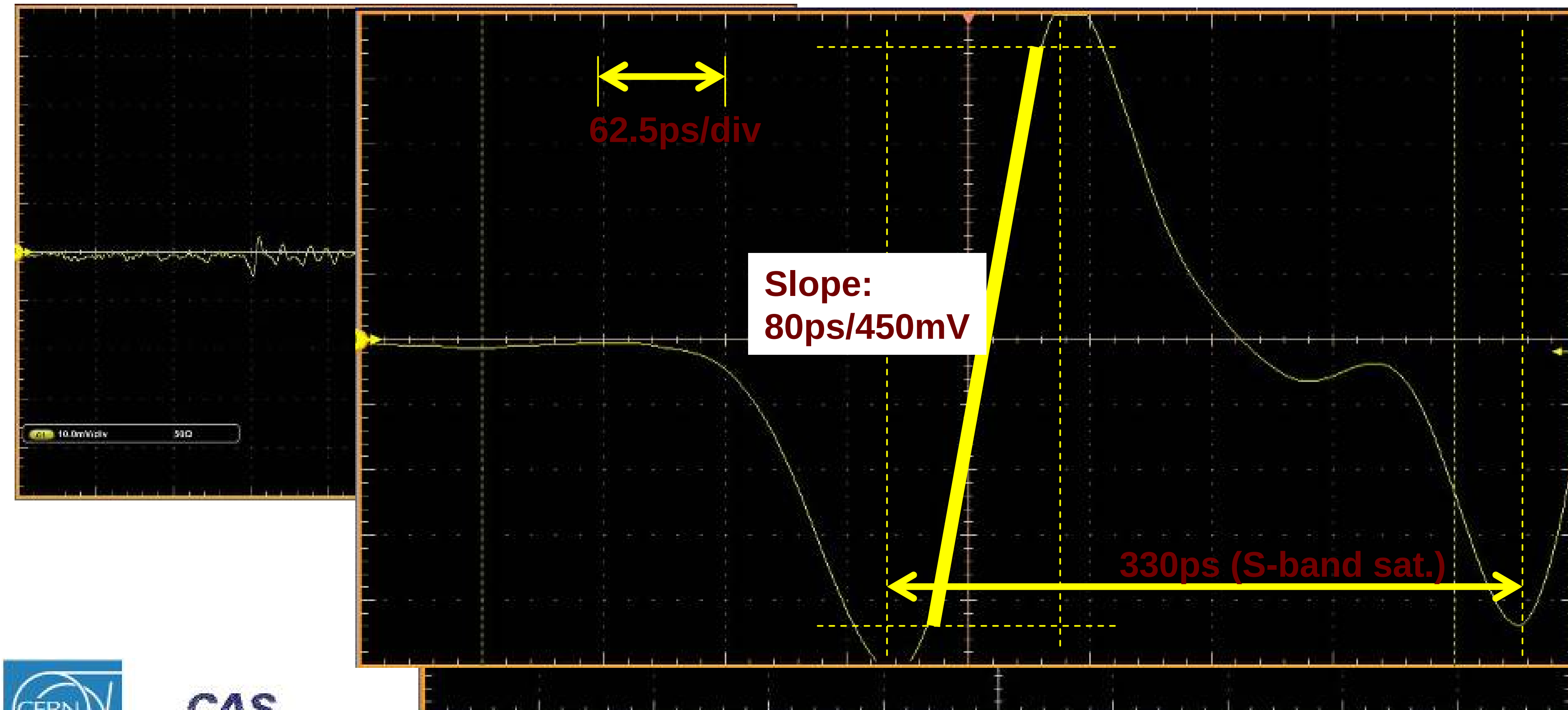


Courtesy of K. Hacker and H. Schlarb, DESY

The *no-button* pick-up

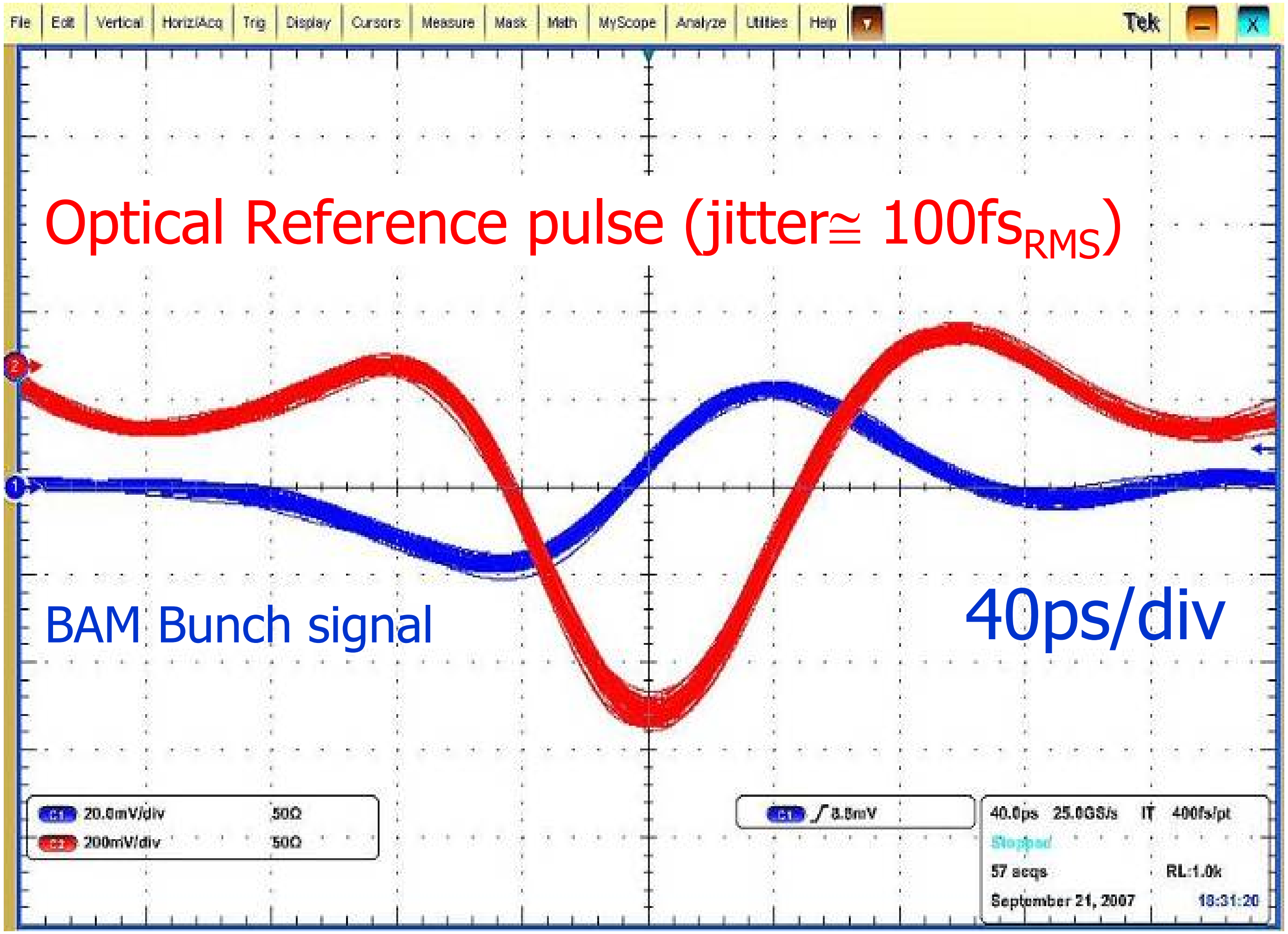
BAM P.U. has been installed on Elettra LINAC

acquired with a 6GHz real time oscilloscope and <10m wideband cable



The *no-button* pick-up

BAM signal (@10Hz) has been used as trigger for acquisition of the 3GHz optical clock (after O/E conversion)

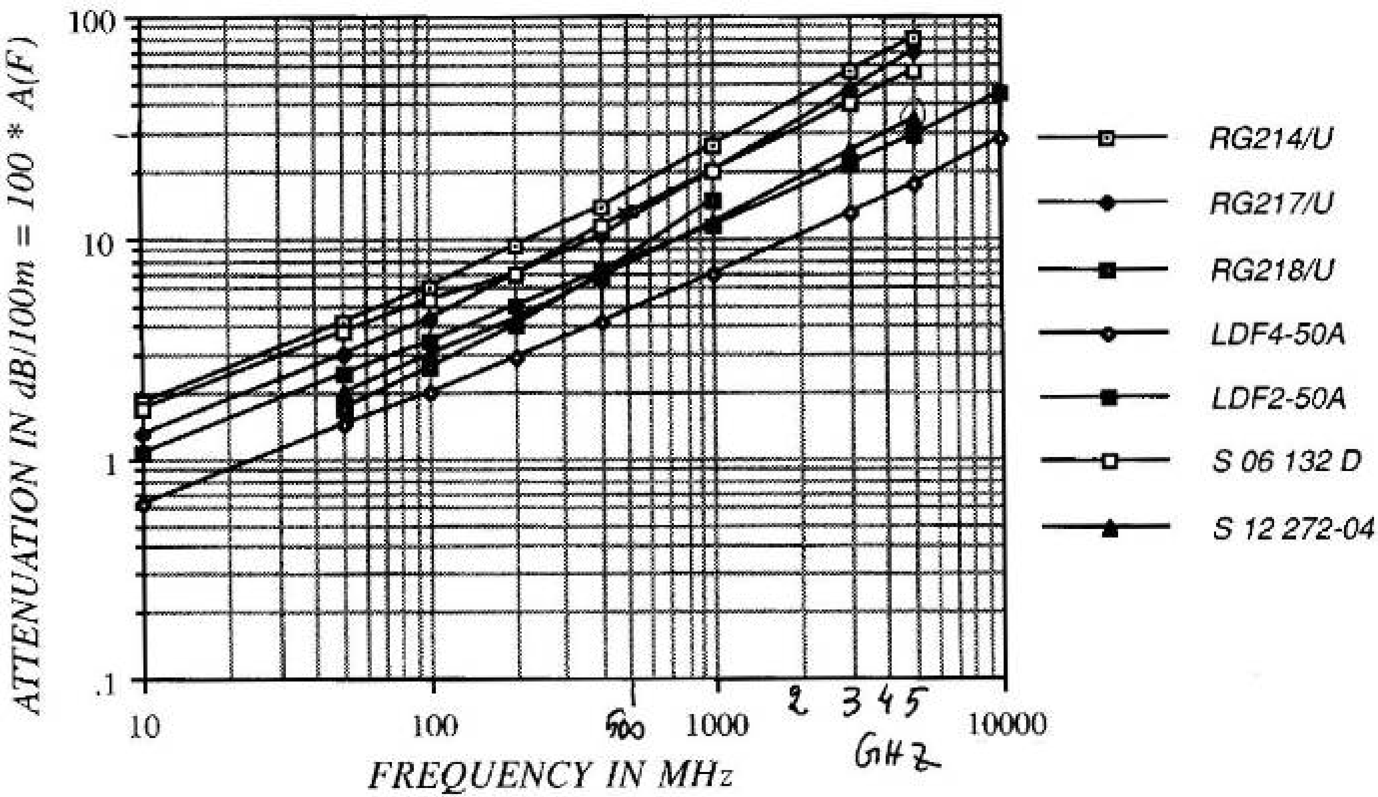


Coaxial cables

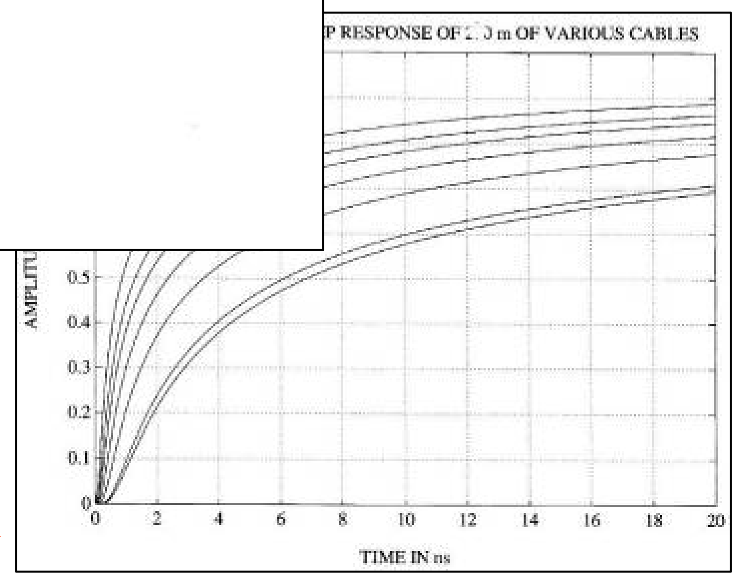
- Once the EM PU has "captured" the bunch profile (i.e. the spectral content within the PU BW) this signal has to be routed up to a measuring instrument, outside the tunnel
- Dealing with *10s* ps profiles (e^- LINAC or SR) the transmission of the electrical signal from the EM PU to the measuring instrument may be critical
- To preserve a $50ps_{FWHM}$ pulse, a short (L<5m) broadband (≅10GHz) coaxial cable has to be used
- Microwave companies have cables that have acceptable losses up to 50GHz
- As a matter of fact, due to the intrinsic low-pass nature of the cable, the spectral content of the pulse will be altered

Coaxial cables & …[7]

Frequency response of 100m: pulse distortion



Step response for
various cable types



…wide band connectors

- There are several wide band co-ax connectors
- When designing a wide-band measurement system, the choice of suitable connector matched to the cable (BW and diam.) is very important not to spoil the resulting bandwidth
- For multi GHz application:

  N-type 18GHz

  SMA 24GHz

  Wiltron K 34Ghz
- Minimize the adapters (between series), "T" etc. etc.

Connector Type	Frequency Range	Compatibility
BNC (Bayonet Navy Connector)	DC - 2 GHz	
SMC (Sub-Miniature C)	DC - 7 GHz	
APC - 7 (Amphenol Precision Connector-7)	DC - 18 GHz	
Type N (Navy) 50 Ω	DC - 18 GHz	
SMA (Sub-Miniature A)	DC - 24 GHz	3.5 mm, 2.92 mm, Wiltron K
3.5 mm	DC - 34 GHz	SMA, 2.92 mm, Wiltron K
2.92 mm or Wiltron K	DC - 40 GHz	SMA, 3.5 mm
2.4 mm	DC - 50 GHz	1.85 mm, Wiltron V
1.85 mm or Wiltron V	DC - 65 GHz	2.4 mm

taken from: New Focus Application Note:
"Insights into High-Speed Detectors and High-Frequency Techniques"
http://www.newfocus.com/products/documents/literature/Insights.pdf

…and we see the light
(out of the tunnel)

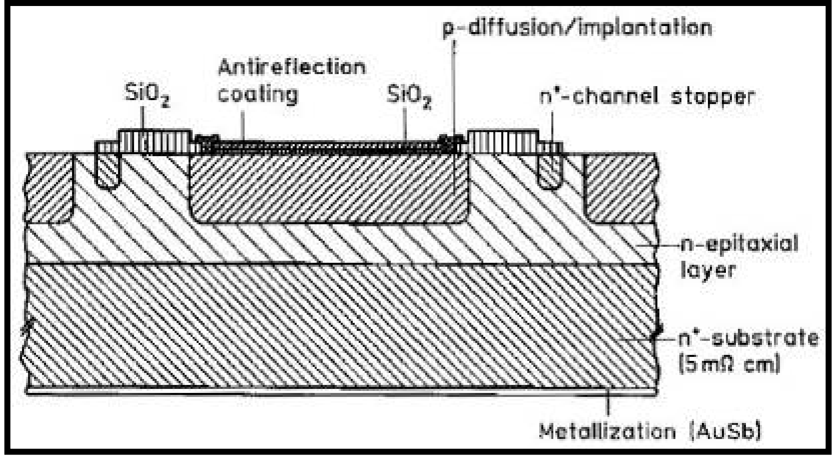
- It is more convenient to transport out of the tunnel visible (λ**>200nm**) radiation instead of an electrical signal
- A protected air pipe may be adopted for air turbulence /dust protection
- The length of the link can be of tens of meters
- Optical component mechanical stability is not an issue for **ps pulses** (ΔL=100mm ➔ Δt_{air}=0.5ps)
- For λ**<200nm** the optical path need to be in vacuum due to absorption of UV rad. (water line)

Photo-diodes (PD)

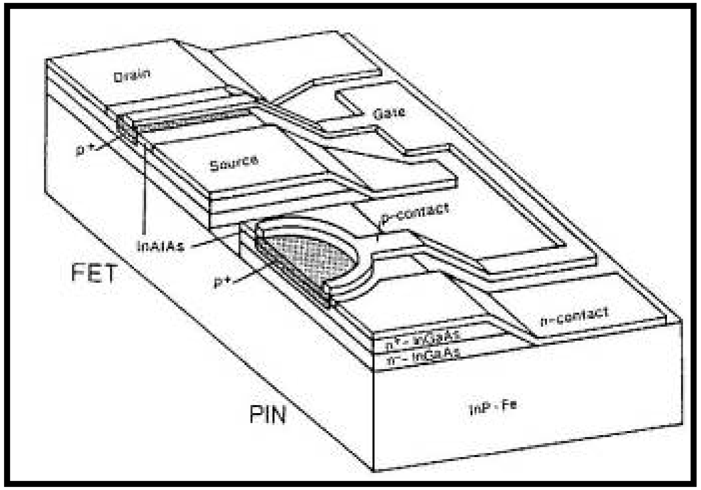
- PD are semiconductor light sensors that generate a current or voltage when the P-N junction in the semiconductor is illuminated by light
- The term photodiode usually refers to sensors used to detect the intensity of light (vs. time or position)
- Photodiodes can be classified by function and construction as follows:
- For this application they are particularly attractive as the cable for the PD to the acquisition head can be very short (L<0.5m)

Photo-diodes

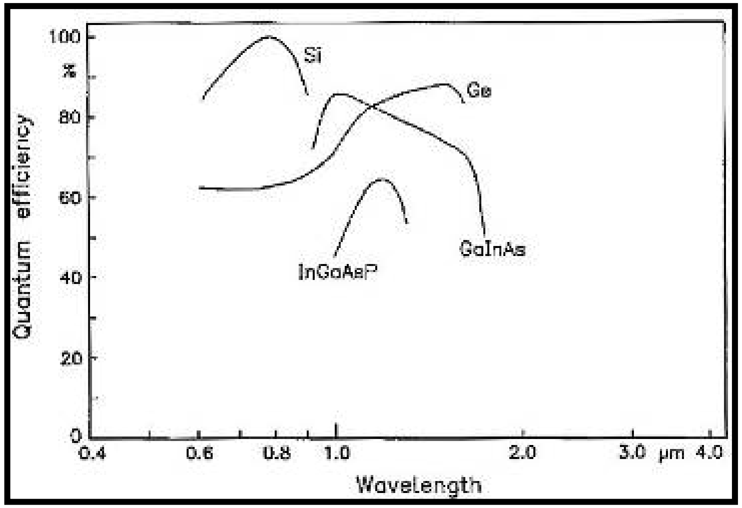
- Main features of photodiode are:
  - excellent linearity with respect to incident light
  - low noise
  - wide spectral response
  - mechanically rugged
  - compact and lightweight
  - long life



High Speed with epitaxially grown active area



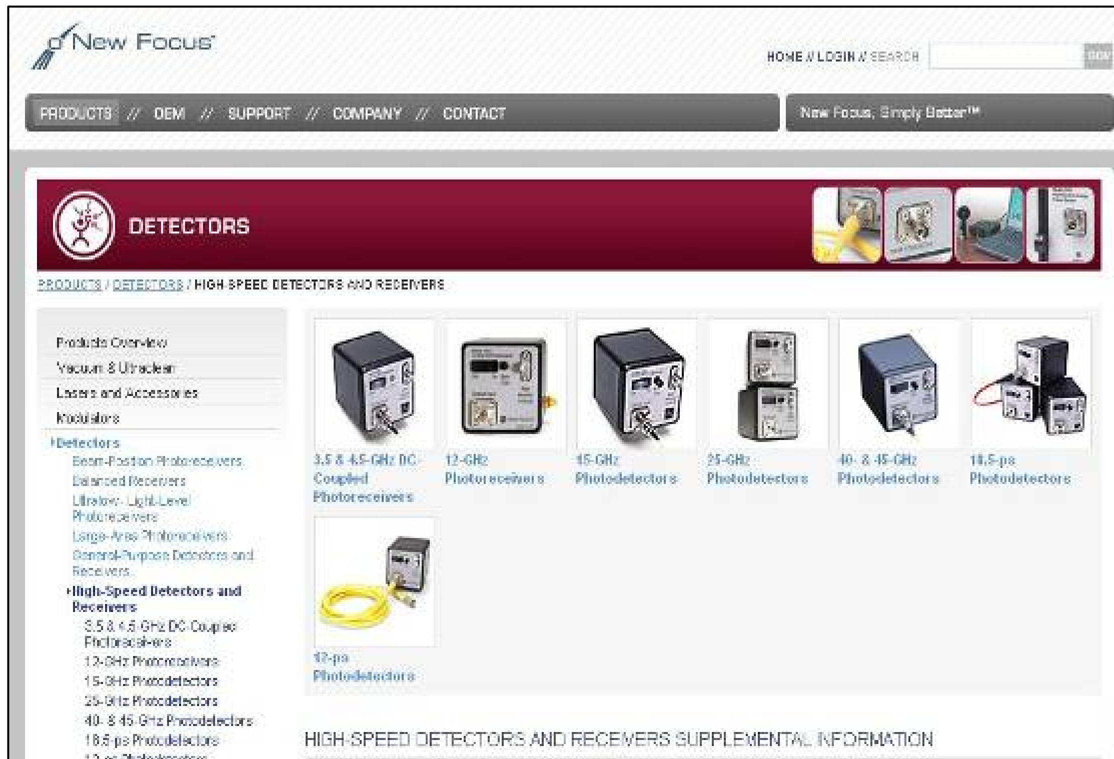
Monolithically integrated detector PD and FET on InP (Trans Impedance Amplifier)



Quantum Efficiency (QE) vs. material

Photo-diodes **[8, 9]**

- Hamamatsu, New Focus…offer a broad range of PDs
- New Focus: up to BW=45GHz
- Choice criteria:
  - wavelength
  - responsivity
  - bandwidth / area
  - radiation coupling

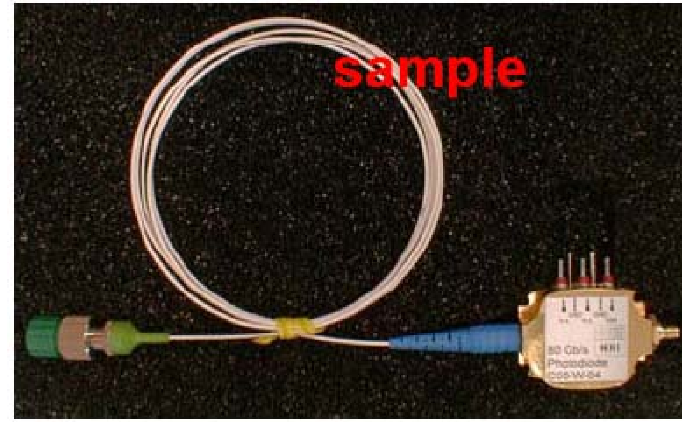


Ultra wide band photo-diodes [10]

- Ultra wide band PD have been developed at Fraunhofer Institute
- The 100Gb/s Photodiode C05-W-26

lfd. Bf-Nr.	Parameter	Actual value Module C05-W-26	
1	O/E-power -3dB bandwidth (1.55µm) calibrated ($P_{opt.}$, AC-level)	94 GHz (@ 1.7 mW) @ +2 V)	
2	Photodiode responsivity (1.55µm)	0.52 A/W	
3	Polarisation dependent loss	0.8 dB @1.55 µm	
4	Power linearity (1dB compression)	$P_{opt.} \geq + 12.5$ dBm	
5	Photodiode dark current(+2V)	1400 nA (in module @ Z5.6)	
6	Optical return loss @ 1,55 µm	> 25 dB (?)	
7	Optional: synthesised eye pattern	80 / 1	

1-4: Specs, (device: Warp80#252.5x20 BIASPDRL2 feld: 00



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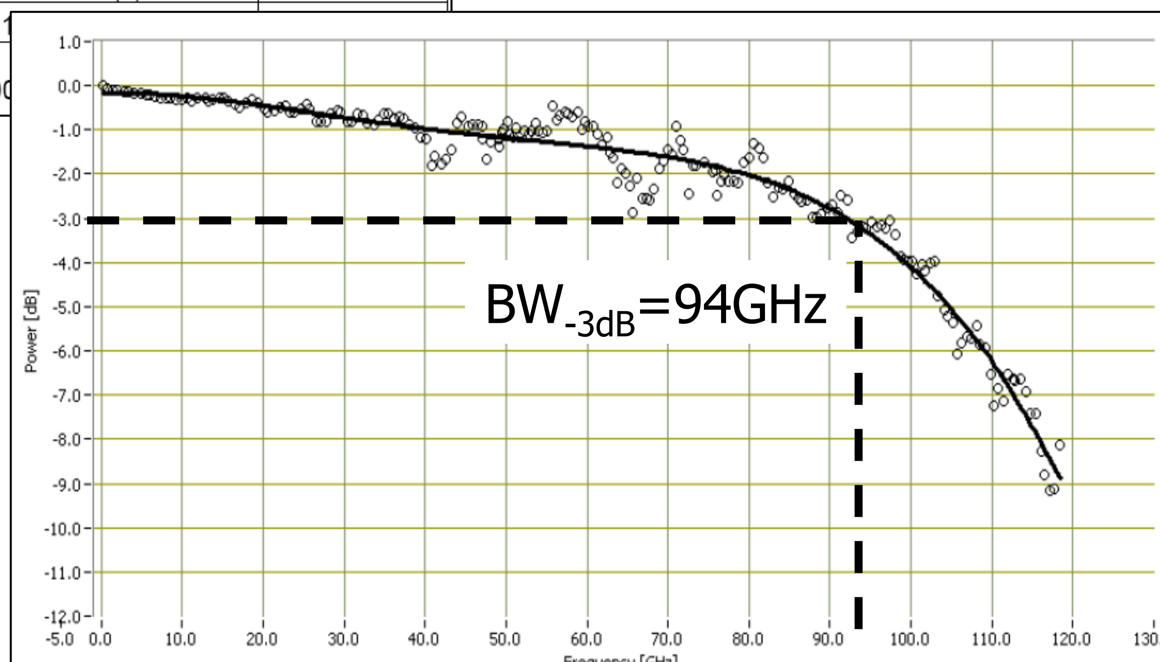

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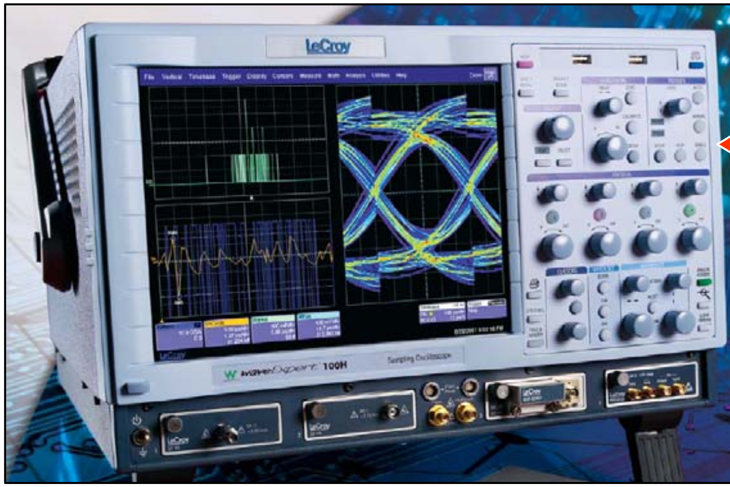
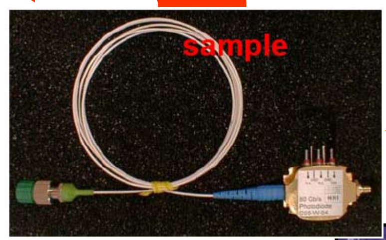
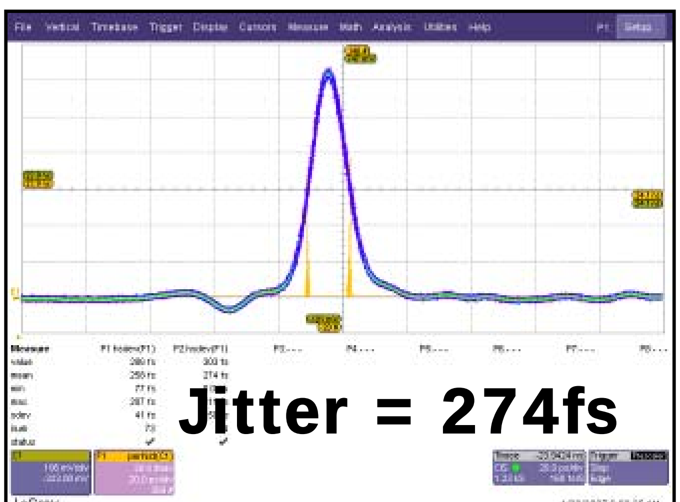
Ultra wide band photo-diodes [11]

- Test at ELETTRA: output from the Pico source 3GHz fiber laser to the 100GB/s Fraunhofer PD acquired with LeCroy **100GHz** Wave Expert sampling scope

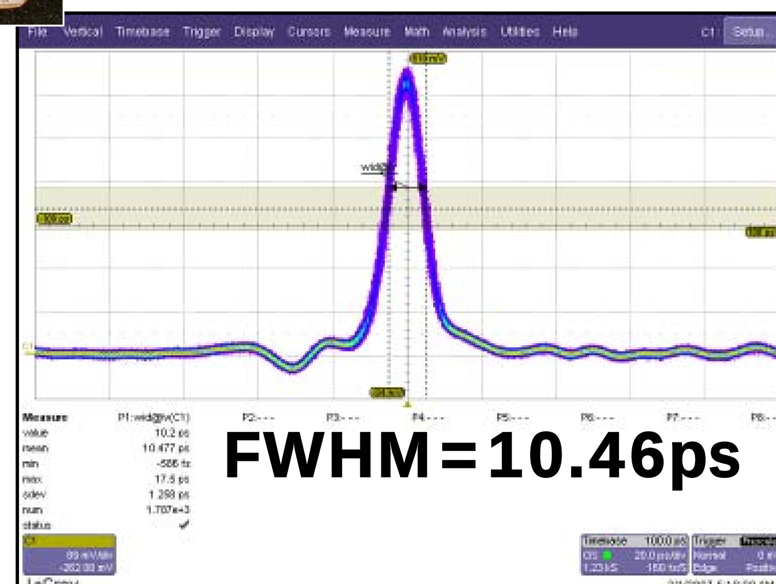
t_{RISE}=3.5ps







Jitter = 274fs



FWHM=10.46ps

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Ultra wide band photo-diodes [11]

- 3GHz optical pulse stream at 3HGHz

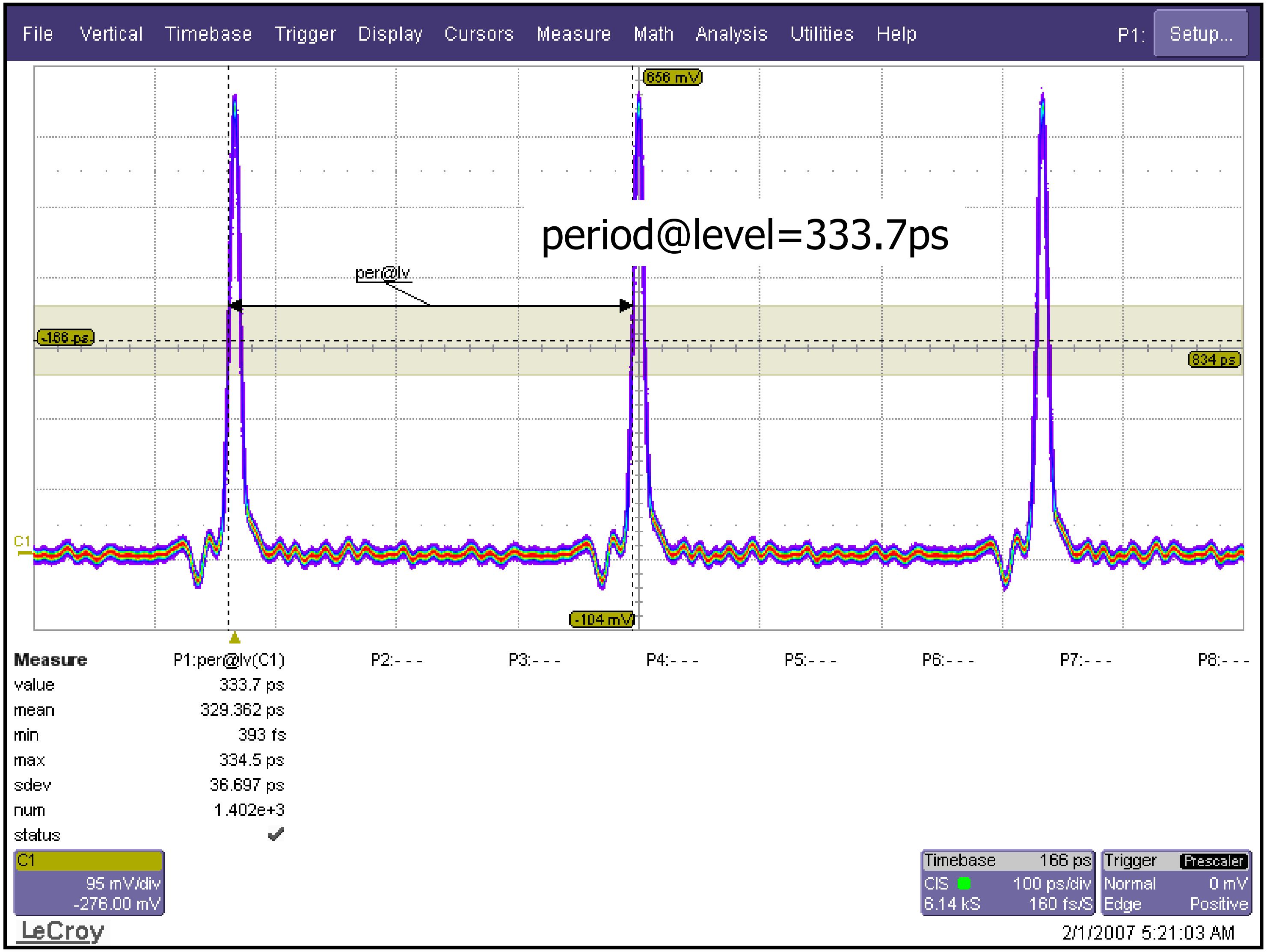


Photo-diodes: bending magnet (ID) diagnostic beam-line (T&L)

On a Storage Ring, you need first to extract the Synchrotron radiation in order to measure it, typically outside the tunnel

Elettra Optical Laboratory [9]

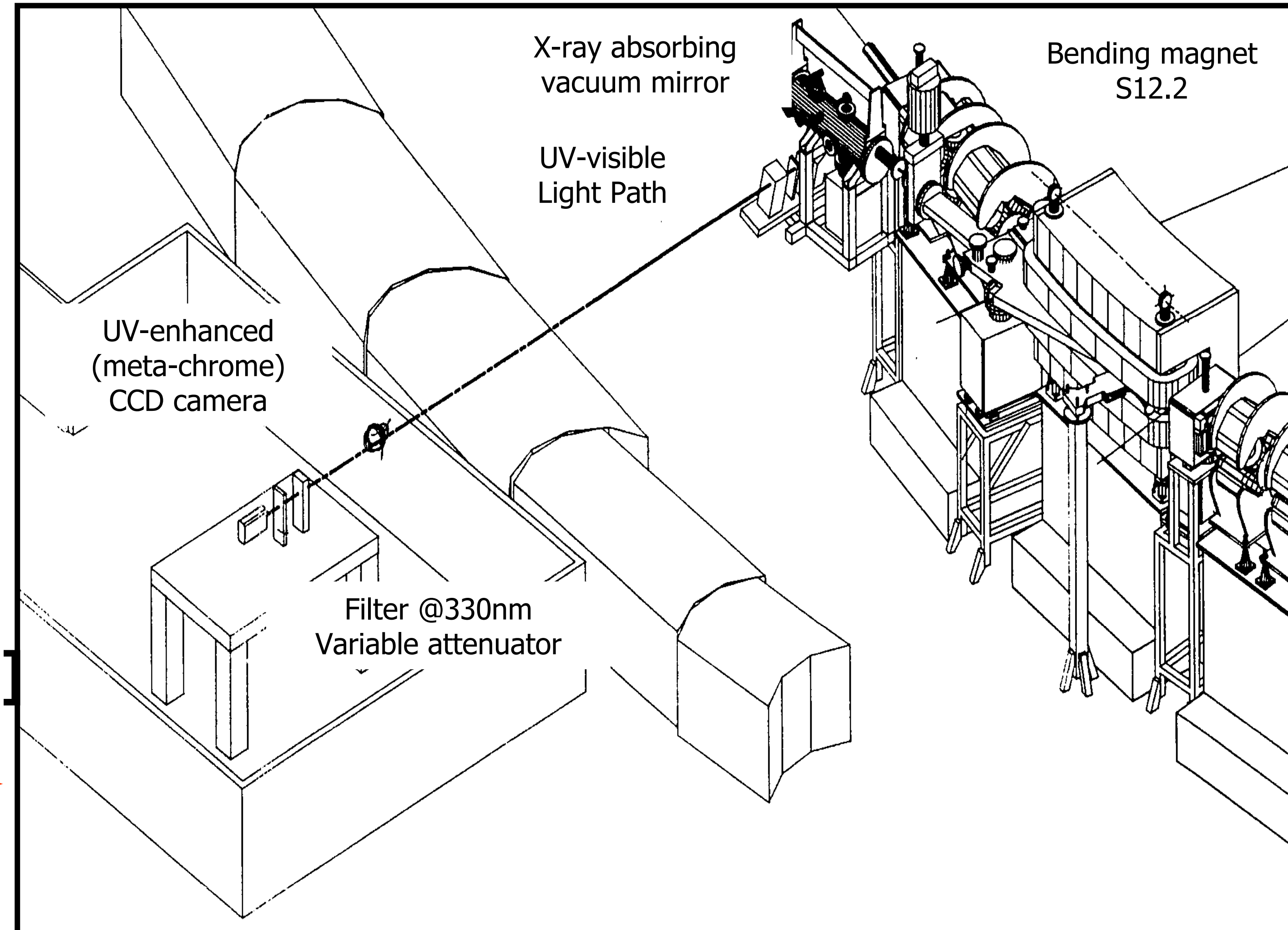
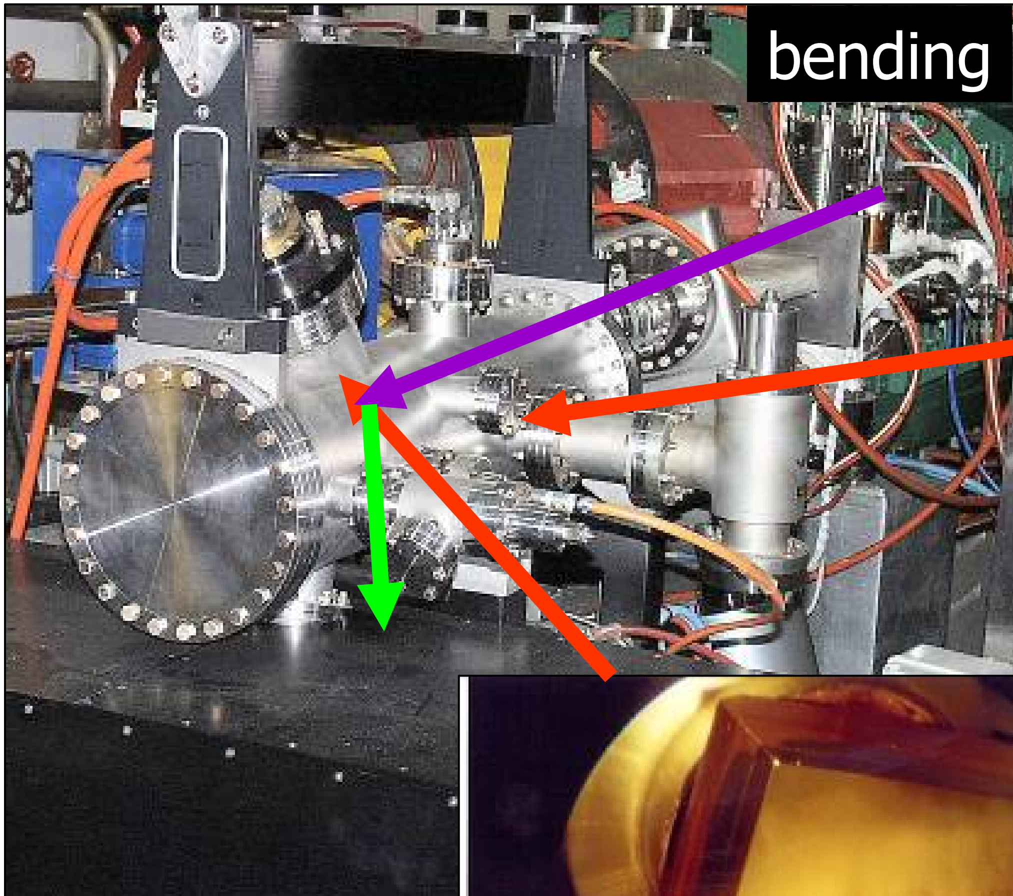
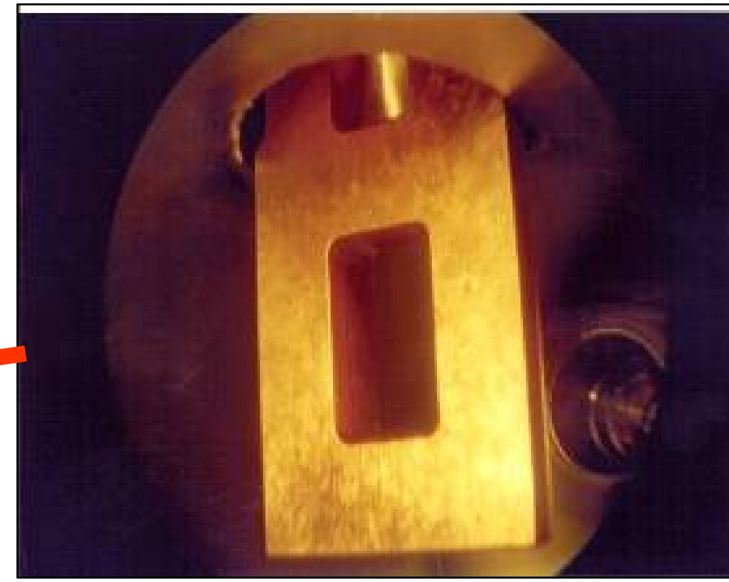


Photo-diodes: bending magnet diagnostic beam-line [12]



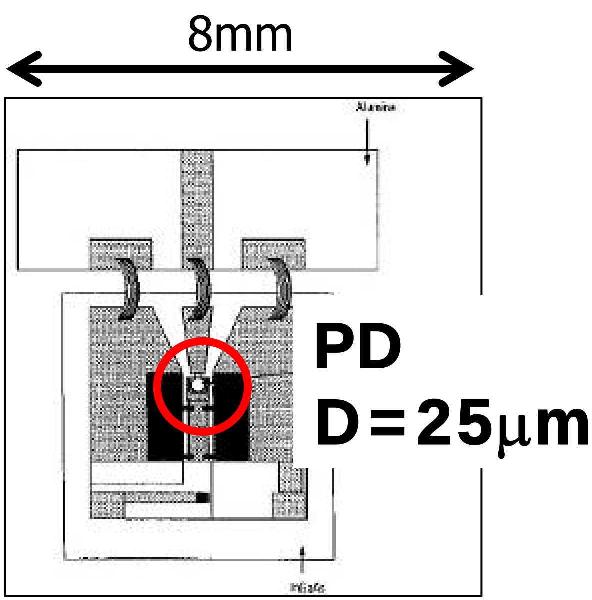


Cooled **copper slit**
To limit the S. Rad in the hor. plane

Cooled **GLIDCOP** extraction mirror; acts also as a **X-ray absorber**

Photo-diodes measurements at Elettra [12]

High speed Photo detector module:	ν1437 New Focus
Wide bandwidth device	**25 GHz** (Trise 14 ps)
Wavelength	400-1650 nm
Active area diameter	**25 μm**
Conversion gain (G)	5 [V/W]
No amplifier needed due to high levels	$180 mV_{pp}$ @14.8mA Single Bunch



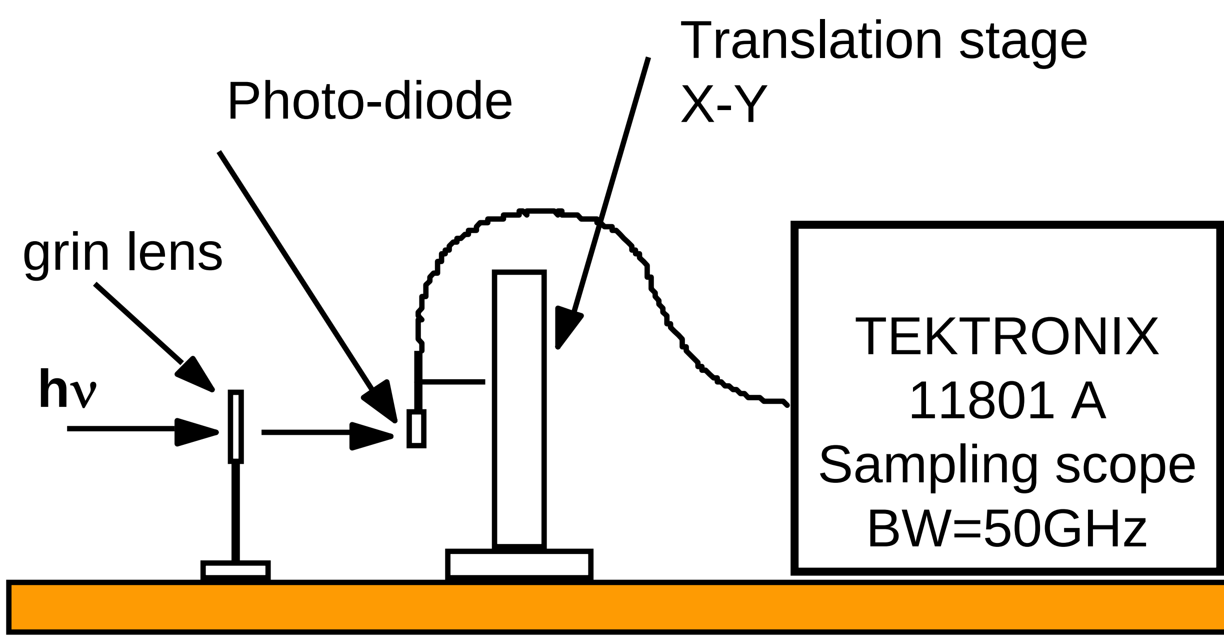


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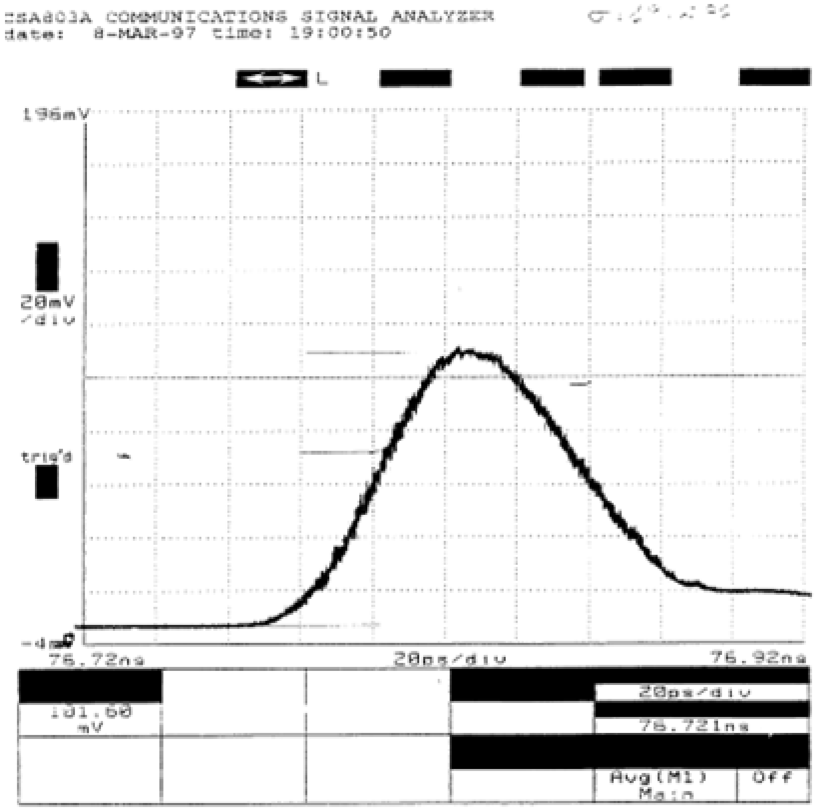
Photo-diodes measurements at Elettra [12]
Single Bunch @1GeV

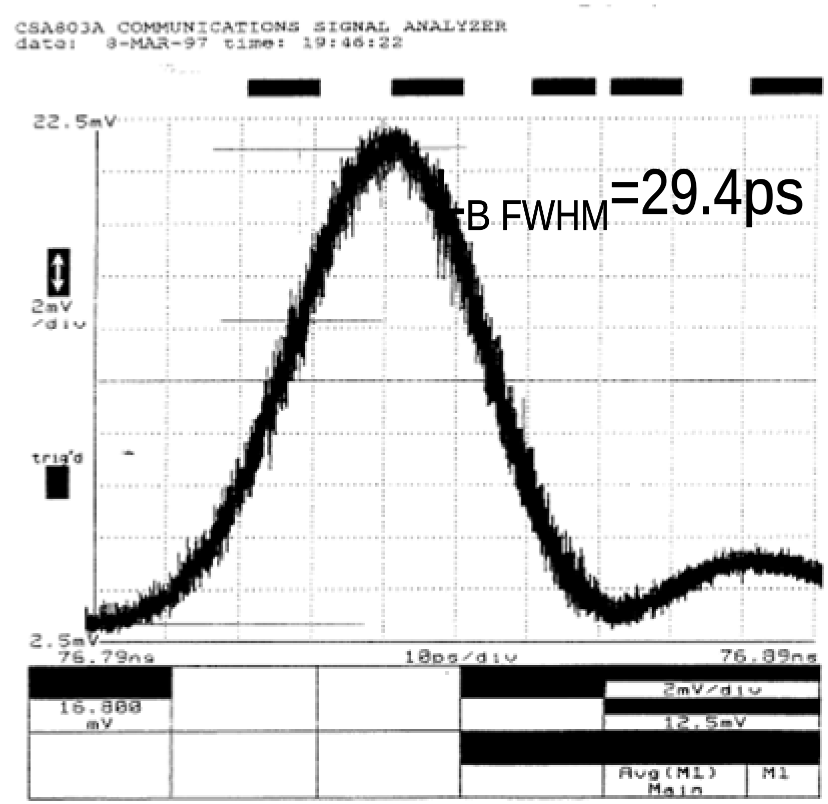
I=5.47mA @1GeV

σ=19.1ps



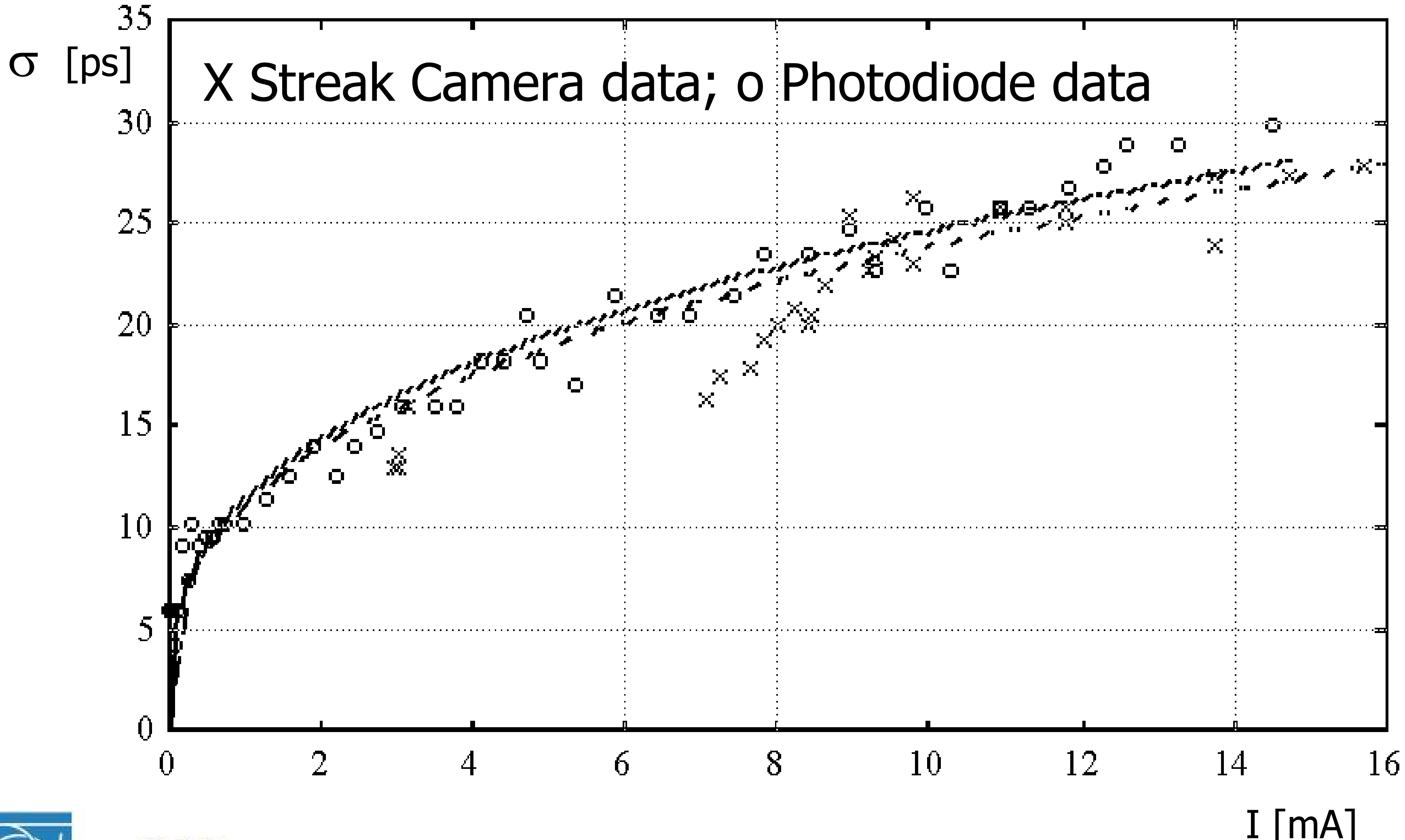
I_B=0.5mA @1GeV

σ=12.5ps



$$\sigma_{measured} = \sqrt{\sigma^2_{beam} + \sigma^2_{photo-diode}} = 12.45\, ps$$

Photo-diodes measurements at Elettra [12] comparison PD data vs. streak camera measurement



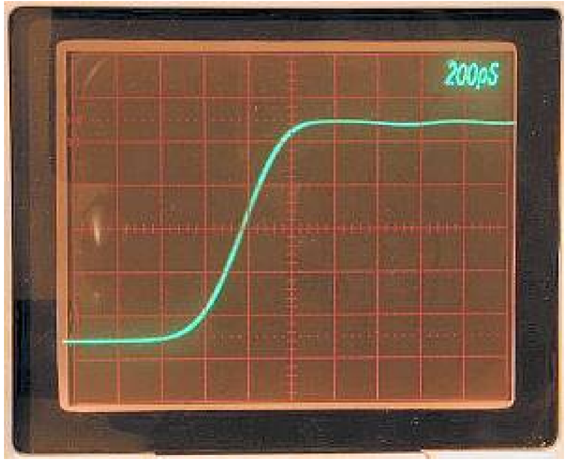
...we do all love them...

Fast Oscilloscopes (…from the last century)

- Since the early 80's, the fast scope was the:

  ***TEK7104*, the "1GHz" scope** (still in use)

- The display of the CRT was equipped with a **MCP** to enhance the visibility of very fast signals
- Unique in visualizing low occurrence events in high frequency signals
- Slow amplitude mod. on RF / 500MHz



Fastest sweep 200ps/div

CH1 | CH2 TDR | main secondary time base

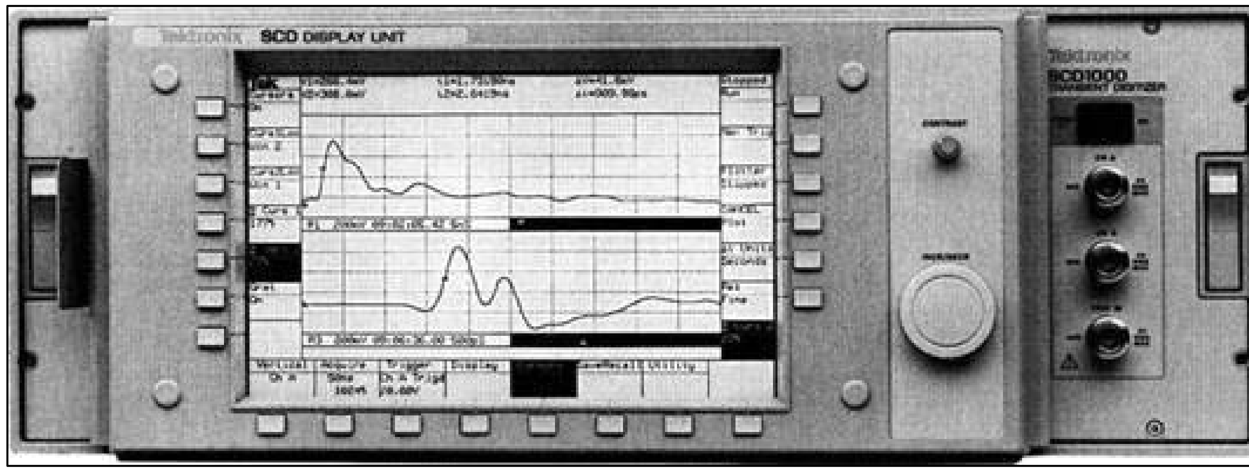
Fast Oscilloscopes (…from the last century)

- In early 90's, the **TEK SCD5000** was the *state-of-art :*

  High-Speed Transient Digitizer

  – BW=4.5GHz

  t_{RISE}=80ps



- Later, from TEK, the **11800** series was providing up to 50GHz (**sampling**)

11800 SERIES SELECTION GUIDE

Instrument	Bandwidth	Maximum # of Channels	Sample Rate	Maxium Record Length	Vertical Resolution	Digitizing Technology
11801B	50 GHz	136	200 kS/s	5 K	8-Bits	sequential
CSA 803A	50 GHz	4	200 kS/s	5 K	8-Bits	equivalent time

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Fast Oscilloscopes **[google]**

- Today, several ultra wide band oscilloscopes are available on the market, reaching "incredible" BWs
- "real time" (RT) and "sampling" (S) or Equivalent Time (ET)

RT	one waveform / trigger event
S / ET	multiple trigger events / waveform

- The choice depends on:

the signal characteristics	periodic / non periodic electrical / optical
the type of analysis	single shot / averaged
the required bandwidth:	are 20GHz OK or need for 100GHz?

- It remains good advice to use an oscilloscope that is 3-5 times faster than the fastest signal to be measured

Fast Oscilloscopes

- The quality of the instrument comes from:
  - analog input BW (magnitude flatness and phase linearity)
  - vertical deflection amplifiers
  - time base stability
    - sets the limit for jitter measurements
  - a flexible trigger
  - friendly and effective User Interface (UI)
- Rather than using the *bandwidth banner specification* as a determination of measurement accuracy, a better way of predicting the accuracy is by looking at the oscilloscope’s magnitude flatness and phase linearity

Fast Oscilloscopes: LeCroy RT

- SDA18000: BW_{-3dB}=18GHz

Vertical System	SDA 18000 18 GHz/Ch Mode	SDA 18000 11 GHz/Ch Mode	SDA 18000 6 GHz/Ch Mode	SDA 13000 13 GHz/Ch Mode	SDA 13000 6 GHz/Ch Mode	SDA 11000 11 GHz/Ch Mode	SDA 11000 6 GHz/Ch Mode	SDA 9000 9 GHz/Ch Mode	SDA 9000 6 GHz/Ch Mode
Analog Bandwidth @ 50 Ω (-3 dB)	18 GHz	11 GHz	6 GHz	13 GHz	6 GHz	11 GHz	6 GHz	9 GHz	6 GHz
Rise Time (Typical, 10–90%)	27 ps	40 ps	75 ps	35 ps	75 ps	40 ps	75 ps	49 ps	75 ps
Rise Time (Typical, 20–80%)	19 ps	28 ps		25 ps		28 ps			
Input Channels	1	1	4, 2, or 1	2 or 1	4 or 2	2 or 1	4 or 2	2 or 1	4 or 2
Bandwidth Limiters	Full BW only		20 MHz, 200 MHz, 1 GHz, 3 GHz, 4 GHz	Full BW only	20 MHz, 200 MHz, 1GHz, 3 GHz, 4 GHz	Full BW only	20 MHz, 200 MHz, 1 GHz, 3 GHz, 4 GHz	Full BW only	20 MHz, 200 MHz, 1 GHz, 3 GHz, 4 GHz
Input Impedance	50 Ω ±2.0%								
Input Coupling	DC, GND								
Maximum Input Voltage	±4 V_{peak}								
Vertical Resolution	8 bits; up to 11 bits with enhanced resolution (E								
Sensitivity	2 mV–1 V/div (< 10 mV/div through zoom)		2 mV–1 V/div (fully variable, < 10 mV/div through zoom)	2 mV–1 (< 10 m through zoom)					
DC Gain Accuracy	±1.5% of full scale								
Offset Range	±750 mV @ 2 mV– 141 mV/div ±4 V @ 141 mV–1 V/div		±750 mV @ 2 mV– 141 mV/div ±4 V @ 195 mV–1 V/div	±750 mV 2 mV– 159 mV/c ±4 V @ 159 mV–					
Offset Accuracy	±(1.5% of full scale +1.5% of offset value +2 mV)								

Fast Oscilloscopes: LeCroy RT

- SDA18000

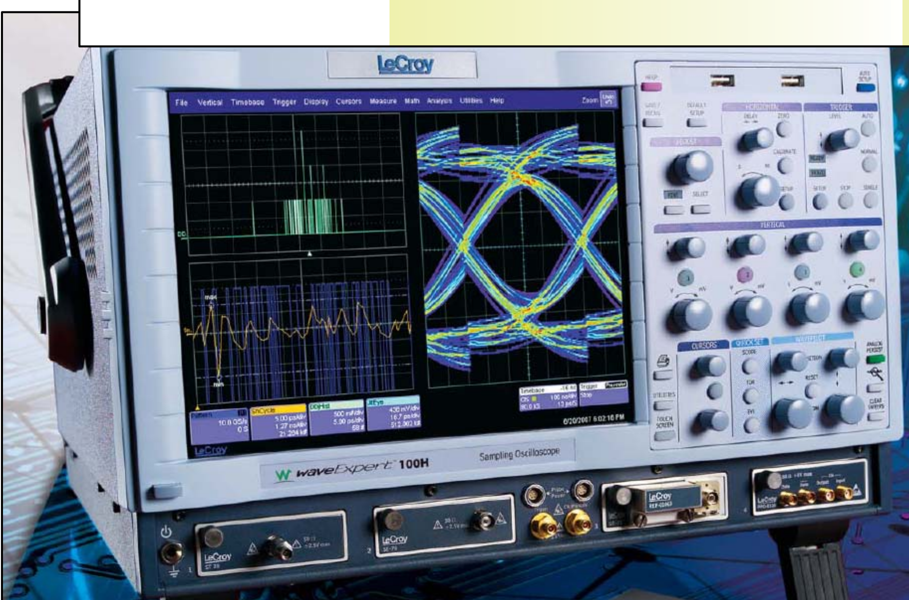
  timebase: <350fs$_{RMS}$ Jitter noise floor

Horizontal System								
Timebases	Internal timebase common to 4 input channels; an external 100 MHz reference may be applied on the rear panel		Internal timebase common to 4 input channels					
Time/Division Range, Real Time	10 ps/div–100 µs/div (standard memory) 10 ps/div–500 µs/div (-XL memory)	20 ps/div–10 s/div	10 ps/div–100 µs/div (standard memory) 10 ps/div–500 µs/div (-XL memory)	20 ps/div–10 s/div	10 ps/div–100 µs/div (standard memory) 10 ps/div–500 µs/div (-XL memory)	20 ps/div–10 s/div	10 ps/div–100 µs/div (standard memory) 10 ps/div–500 µs/div (-XL memory)	20 ps/div–10 s/div
Time/Division Range, Random Interleave sampling (RIS)	N/A	to 20 ps/div (upper time/div limit function of sample rate and memory length settings)	N/A	to 20 ps/div (upper time/div limit function of sample rate and memory length settings)	N/A	to 20 ps/div (upper time/div limit function of sample rate and memory length settings)	N/A	to 20 ps/div (upper time/div limit function of sample rate and memory length settings)
Math and Zoom Traces	8 independent zoom and 8 math or zoom traces							
Sample Rate and Delay Time Accuracy	±1 ppm, aging < 1 ppm/year @ 25°C							
Time Interval Accuracy	≤ 0.06/SR + (1 ppm, aging < 1 ppm/year * Reading) (rms)							
Jitter Noise Floor	< 350 fs rms measured with 35 ps rise time (typical)	1 ps rms (typical)	< 350 fs rms measured with 35 ps rise time (typical)	1 ps rms (typical)	< 350 fs rms measured with 35 ps rise time (typical)	1 ps rms (typical)	< 350 fs rms measured with 35 ps rise time (typical)	1 ps rms (typical)
Trigger and Interpolator Jitter	< 2.5 ps rms (typical)							

Fast Oscilloscopes: LeCroy Sampling

- Wave Expert 100H BW_{-3dB}=100GHz

Timebase		
Parameter	**Sequential**	**With Coherent Timebase (WE-CIS and WE-HCIS)**
Sample Rate	1 MS/s	10 MS/s
Frequency Range	DC to 5 GHz, using Trigger input 5 GHz–14 GHz, using CLK/Prescale input up to 40 GHz, using SDA-TPS accessory	62.5 MHz–125 MHz, using Trigger input 125 MHz–14 GHz, using CLK/Prescale input up to 40 GHz, using SDA-TPS accessory
Pattern Lock	N/A	YES, up to PRBS23
Minimum Time Per Division	1 ps	1 ps
Time Resolution	100 fs rms	100 fs rms
Timebase Range	1 ps/div to 1 ms/div	1 ps/div to 500 ns/div (4 M memory)
Timebase Delay Time Range	25 ns–10 ms	±1 pattern
Time Interval Accuracy	±1 ps ±0.1% of reading	Determined by trigger signal
Long Term Stability	±5 ppm	Determined by trigger signal
Maximum Record Length Standard Optional	 100k samples N/A	 64 M samples 1 Ch, 16 M samples 4 Ch 510 M / 1 Ch, 256 M / 2 Ch, 128 M / 4 Ch
Jitter	1 ps typical, 1.2 ps guaranteed	HCIS: 230 fs rms typical, 250 fs rms guaranteed CIS: 500 fs rms typical, 600 fs rms guaranteed (3 Gb/s–40 Gb/s)



	ST-20 (20 GHz)	SE-30 (30 GHz)	SE-50 (50 GHz)
	2.92 mm	2.92 mm	2.4 mm
	18 ps	12 ps	8 ps
	20 GHz	30 GHz	50 GHz
nge	2 V_{p-p}	2 V_{p-p}	2 V_{p-p}
ge Accuracy	< 1% (800 mV_{p-p} signal)	< 1% (800 mV_{p-p} signal)	< 1% (800 mV_{p-p} signal)
	First 40 ps: ±10%, 40 ps–200 ps: ±5%, 200 ps–10 ns ±2%	First 40 ps: ±10%, 40 ps–200 ps: ±5%, 200 ps–10 ns ±2%	First 40 ps: ±10%, 40 ps–200 ps: ±5%, 200 ps–10 ns ±2%
	700 µV max. (500 µV typical)	1 mV (max.)	2 mV (max.), 1 mV (typical)
	±1 V	±1 V	±1 V
	SE-70 (70 GHz)	**SE-100 (100 GHz)**	
	1.85 mm	1 mm	
	5 ps	4 ps	
	70 GHz	100 GHz	
nge	2 V_{p-p}	2 V_{p-p}	
ge Accuracy	< 1% (800 mV_{p-p} signal)	< 1% (800 mV_{p-p} signal)	
	First 40 ps: ±10%, 40 ps–200 ps: ±5%, 200 ps–10 ns ±2%	First 40 ps: ±10%, 40 ps–200 ps: ±5%, 200 ps–10 ns ±2%	
RMS Noise	3 mV (max.)	3 mV (max.)	
Offset Range	±1 V	±1 V	

Fast Oscilloscopes: Tektronix RT

- DPO 70000 series: up to 20GHZ real time; 50GS/s samplers
- Digital Phosphor Oscillscope

  - Clever idea to emulate the "old" analogue oscilloscope to capture low occurrence events on ultra fast signals

  - Increased the transfer rate from the acquisition to the display memory

DPO/DSA70000 Series

Fast Oscilloscopes: Tektronix RT

▶ Vertical System

DPO/DSA Models	70404	70604	70804	71254	71604	72004
Input Channels	4	4	4	4	4	4
Bandwidth (user selectable DSP enhance)	4 GHz	6 GHz	8 GHz	12.5 GHz	16 GHz	2 settings: 20 GHz and 18 GHz
Rise Time 10% to 90% (typical)	93 ps	62 ps	47 ps	34.3 ps	27.5 ps	22.5 ps
Rise Time 20% to 80% (typical)	65 ps	43 ps	33 ps	23 ps	21 ps	17 ps
Hardware Analog Bandwidth (–3 dB)	4 GHz	6 GHz	8 GHz	12.5 GHz	16 GHz (typical)	16 GHz (typical)
DC Gain Accuracy	±2% (of reading)					
Bandwidth Limits	Depending on instrument model: 19 GHz, 18 GHz, 17 GHz, 16 GHz, 15 GHz, 14 GHz, 13 GHz, 12 GHz, 11 GHz, 10 GHz, 9 GHz, 8 GHz, 7 GHz, 6 GHz, 5 GHz, 4 GHz, 3 GHz, 2 GHz, 1 GHz or 500 MHz					
Input Coupling	DC (50 Ω), GND					
Input Impedance	50 Ω ±1.5%, 1 MΩ with TCA–1MEG adapter					
Input Sensitivity						
18 GHz and below						
20 GHz and 19 GHz						
Vertical Resolution						
Max Input Voltage, 50 Ω						

▶ Time Base System

DPO/DSA Models	70404	70604	70804	71254	71604	72004
Time Base Range	20 ps/div to 1000 s/div				10 ps/div to 1000 s/div	
Time Resolution (in ET/IT mode)	200 fs				100 fs	
Time Base Delay Time Range	–5.0 ks to 1.0 ks					
Channel-to-channel Deskew	Range ±75 ns					
Delta Time Measurement Accuracy (typical) Over <100 ns duration; single shot; with signal rise time = 1.2X scope rise time	888 fs	695 fs	611 fs	504 fs	482 fs	525 fs
Trigger Jitter (RMS)	1 ps_{RMS} (typical) with enhanced triggering OFF < 100 fs_{RMS} with enhanced triggering ON					
Jitter Noise Floor(typical) (With BW+ bandwidth enhance enabled)	450 fs	450 fs	450 fs	300 fs	300 fs	400 fs
Time Base Accuracy	±1.5 ppm initial accuracy, aging <1 ppm per year					

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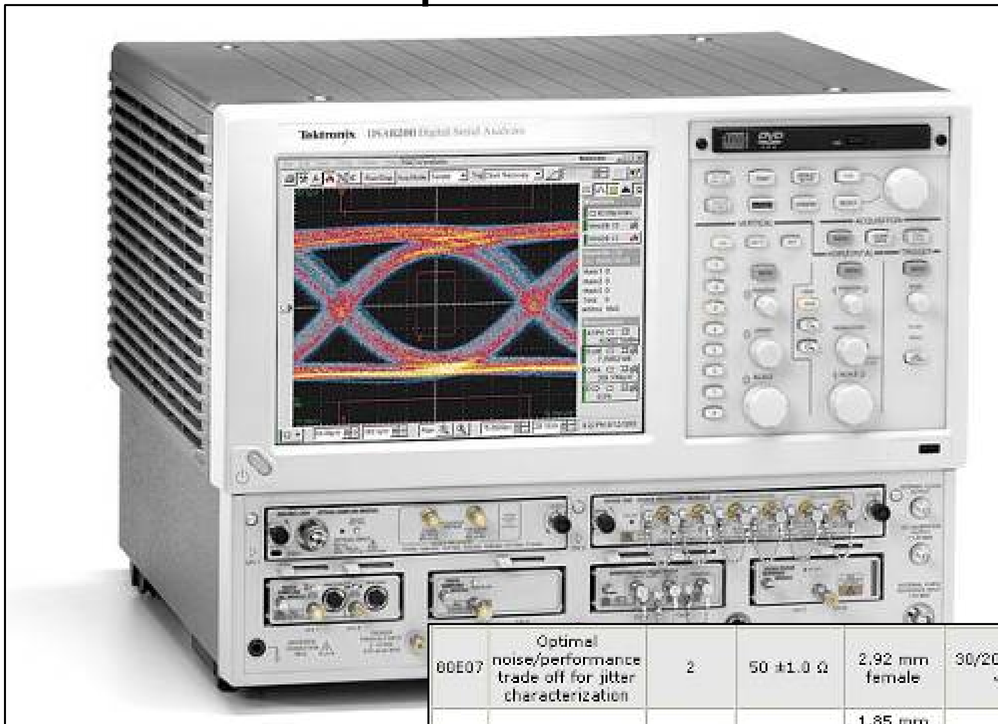
Fast Oscilloscopes: Tektronix sampling

- DSA8200: up to 70GHz



80E07	Optimal noise/performance trade off for jitter characterization	2	50 ±1.0 Ω	2.92 mm female	30/20 GHz*7,*15
80E06	High-speed Electrical Device Characterization	1	50 ±0.5 Ω	1.85 mm female, precision adapter to 2.92 mm included with 50 Ω SMA termination	70+ GHz
80E04	TDR Impedance and Crosstalk Characterization	2	50 ±0.5 Ω	3.5 mm female	20 GHz*7
80E03	Device Characterization	2	50 ±0.5 Ω	3.5 mm female	20 GHz*7
80E02	Low-level Signals	2	50 ±0.5 Ω	3.5 mm female	12.5 GHz*7
80E01	High frequency, high maximum operating range signal acquisition	1	50 ±0.5 Ω	2.4 mm female, precision adapter to 2.92 mm included with 50 Ω SMA termination	50 GHz

Trigger Sensitivity	
External Direct Trigger Output	50 mV, DC - 4 GHz (typical)
	100 mV, DC - 3 GHz (guaranteed)
Trigger Level Range	±1.0 V
Trigger Input Range	±1.5 V
Trigger Holdoff	Adjustable 5 μs to 100 ms in 0.5 ns increments
External Trigger Gate (optional)	TTL logic 1 enables gate, a TTL logic 0 disables gate, maximum non-destruct input level ±5 V
Pre-scaled Trigger Input	200 mV_{p-p} to 800 mV_{p-p}, 2 to 12.5 GHz (guaranteed)
Timebase Jitter	
Phase Reference*11 Timebase	System jitter of 200 fs_{RMS} typical on a 10 GHz or faster acquisition module, with f ≥ 8 GHz, 0.6 V ≤ VREF ≤ 1.8 V Phase Reference Signal.
	Jitter: system jitter of 280 fs_{RMS} typical on a 10 GHz or faster acquisition module, in DSA8200 mainframe, with 2 GHz ≤ f ≤ 8 GHz, 0.6 V ≤ VREF ≤ 1.8 V Phase Reference Signal.
	The Phase Reference timebase remains operational to 100 mV (typical) with increased jitter.
Short-term Jitter Optimized Sequential Mode	800 fs_{RMS} +5 ppm of position (typical)
	1.2 ps_{RMS} +10 ppm of position (max.)
Locked to 10 MHz Reference Sequential Mode	1.6 ps_{RMS} +0.04 ppm of position (typical)
	2.5 ps_{RMS} +0.01 ppm of position (max.)
Internal Clock	Adjustable from 25 to 200 kHz (drives TDR, internal clock output and calibrator).

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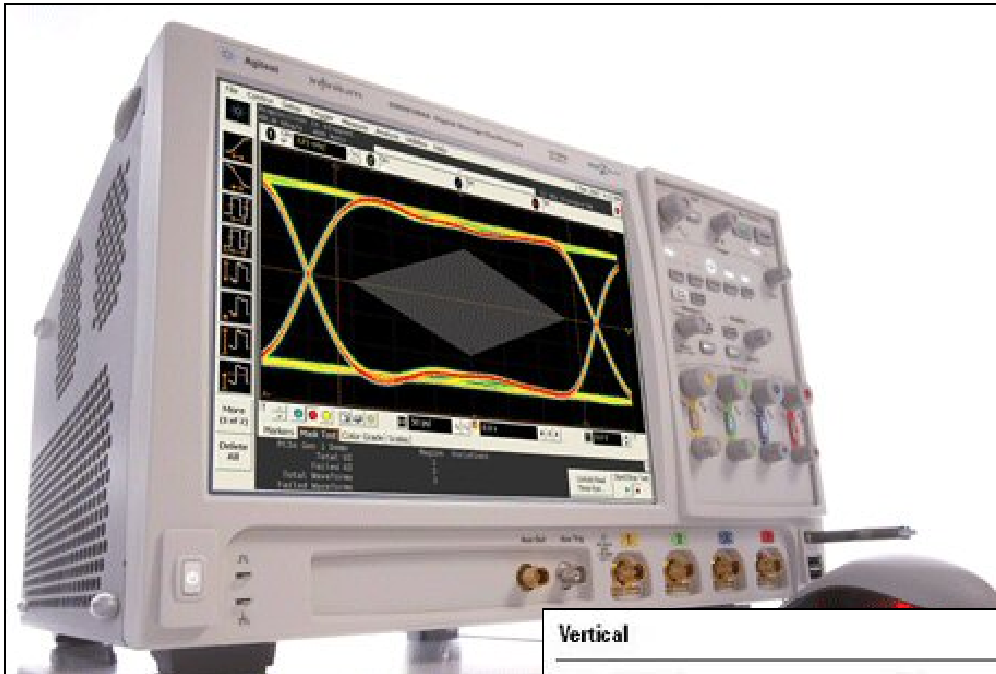
Fast Oscilloscopes: Agilent RT

- Infinium 9000A: up to 13GHz

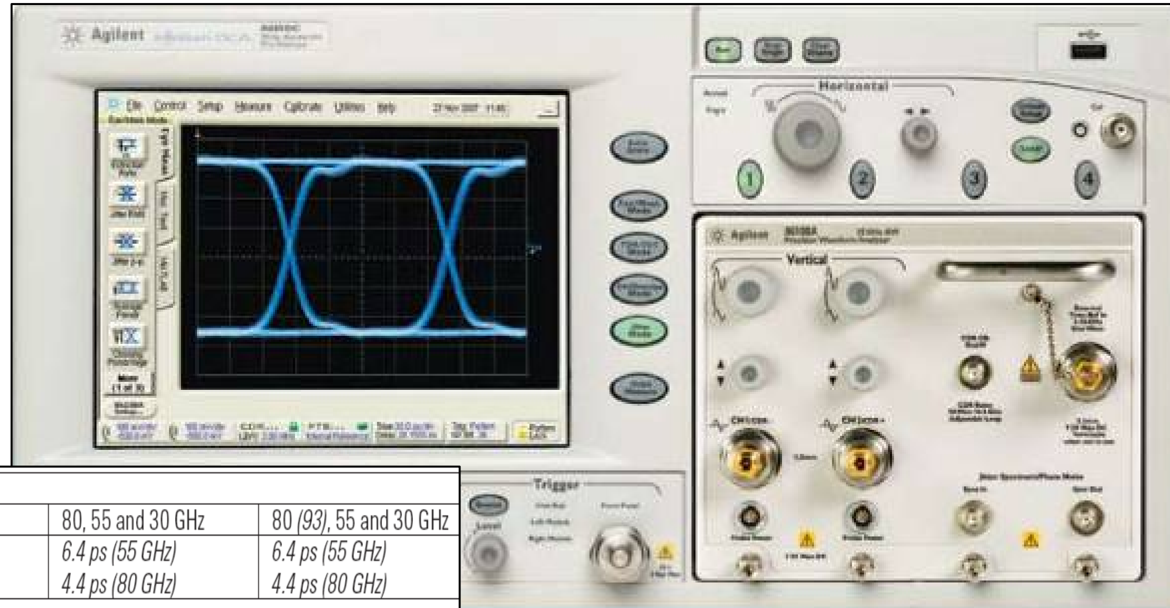


Horizontal	
Main timebase range	5 ps/div to 20 s/div real-time, 5 ps/div to 500 ns/div equivalent-time
Main timebase delay range	–200 s to 200 s real-time, –25 μs to 200 s equivalent-time
Zoom timebase range	1 ps/div to current main time scale setting
Channel deskew	± 25 μs range, 100 fs resolution
Time scale accuracy*	± (0.4 + 0.5 * YrsSinceCal) ppm pk
Delta-time measurement accuracy[5a, 6b, 7]	
Absolute, averaging disabled	$\sqrt{\left(\frac{5.0 \cdot Noise}{SlewRate}\right)^2 + 20x10^{-24}} + \frac{TimeScaleAccy \cdot Reading}{2}$ sec pk
Absolute, >- 256 averages	$\sqrt{\left(\frac{0.35 \cdot Noise}{SlewRate}\right)^2 + 0.1x10^{-24}} + \frac{TimeScaleAccy \cdot Reading}{2}$ sec pk
Standard deviation, averaging disabled	$\sqrt{\left(\frac{1.4 \cdot Noise}{SlewRate}\right)^2 + 0.6x10^{-24}}$ sec_{rms}
Standard deviation, >- 256 averages	$\sqrt{\left(\frac{0.1 \cdot Noise}{SlewRate}\right)^2 + 0.01x10^{-24}}$ sec_{rms}

Vertical						
Input channels	Four					
Analog bandwidth (–3 dB)*, 10	90254A 2.5 GHz	90404A 4 GHz	90604A 6 GHz	90804A 8 GHz	91204A 12 GHz	91304A 13 GHz
DSP enhanced bandwidth[3]	91304A: 13-GHz real-time, user-selectable DSP enhanced bandwidth					
Rise time/fall time[11]	90254A	90404A	90604A	90804A	91204A	91304A
10 - 90%	140 ps	105 ps	70 ps	54 ps	35 ps	32 ps
20 - 80%	105 ps	79 ps	53 ps	38 ps	26 ps	24 ps
Input impedance	50 Ω, ± 3%					
Sensitivity[1]	1 mV/div to 1 V/div					
Input coupling	DC					
Vertical resolution[2]	8 bits, ≥ 12 bits with averaging					

Fast Oscilloscopes: Agilent sampling

- DCA-J: up to 80GHz
- Precision Time Base:
  jitter on trigger <100fs



ELECTRICAL CHANNEL SPECIFICATIONS				
Electrical channel bandwidth	18 and 40 GHz	43 and 63 GHz	80, 55 and 30 GHz	80 *(93)*, 55 and 30 GHz
Transition time *(10% to 90% calculated from Tr = 0.35/BW)*	*19.5 ps (18 GHz)* *9 ps (40 GHz)*	*8.1 ps (43 GHz)* *5.6 ps (63 GHz)*	*6.4 ps (55 GHz)* *4.4 ps (80 GHz)*	*6.4 ps (55 GHz)* *4.4 ps (80 GHz)*
RMS noise				
Characteristic	*0.25 mV (18 GHz)* *0.5 mV (40 GHz)*	*0.6 mV (43 GHz)* *1.7 mV (63 GHz)*		
Maximum	0.5 mV (18 GHz) 1.0 mV (40 GHz)	0.9 mV (43 GHz) 2.5 mV (63 GHz)		

Precision time base 86108A

The 86108A can be triggered through clock recovery of the observed signal, through an external reference clock into the precision timebase section, or with the precision timebase operating on the clock signal recovered from the observed signal. The following specifications indicate the 86100 system timebase specifications achieved when using the 86108A plug-in module. (The 86100 mainframe and the 86108A module can also be triggered with a signal into the mainframe. In this configuration, the basic mainframe specifications are achieved)

	86108A
Typical jitter (clock recovery and precision timebase configuration)	< 60 fs
Maximum jitter (clock recovery and precision timebase configuration)	< 100 fs
Typical jitter (clock recovery without precision timebase active)	< 1 ps
Effective trigger-to-sample delay (clock recovery and precision timebase configuration, typical)	< 200 ps
Typical jitter (trigger signal applied to precision timebase input)	< 60 fs
Maximum jitter (trigger signal supplied to precision timebase input)	< 100 fs
Precision timebase trigger bandwidth	2 to 13.5 GHz
Precision timebase external reference amplitude	1.0 to 1.6 Vpp
Precision timebase input signal type[1]	Sinusoid
Precision timebase maximum input level	±2V (16 dBm)
Precision timebase maximum DC offset level	±200 mV
Precision timebase input impedance	50 Ω
Precision timebase connector type	3.5 mm male
Timebase resolution (with precision timebase active)	0.5 ps/div
Timebase resolution (precision timebase disabled)	2 ps/div

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