Longitudinal Diagnostics
part II

- Mario Ferianis –

Sincrotrone Trieste

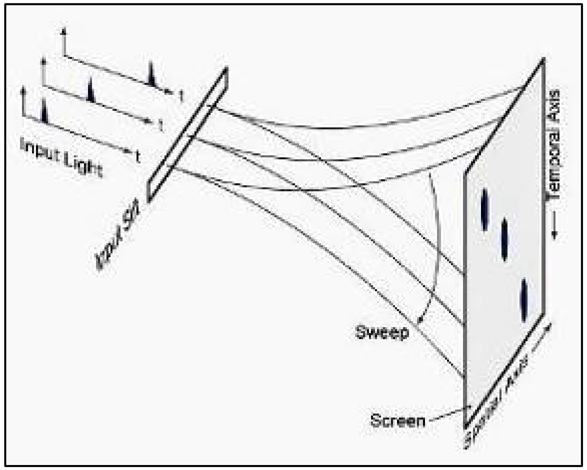
Outline
part II

- The ps Streak Camera (SC)
- SC acquisition examples
- Streak camera insights
- Example of longitudinal diagnostics
- Observation of instabilities
- Longitudinal manipulation

The Streak Camera (SC) **[1]**

- The *ps* SC is an instrument for **single shot** longitudinal profile measurement of ultra fast ($2ps<t_{FWHM}<50ps$) optical events (pulses)
- It is based on electrostatic acceleration and deflection of photo-electrons
- It operates a **time-to-space conversion** such that *photons arriving later are "streaked" transversally on a phosphor screen at spatially separated locations*
- It gives **ps resolution** on **10s ms time scale**: therefore it is very useful for observation of the dynamics of fast systems
- Typical resolution is $2ps_{FWHM}$, being the minimum $<300fs_{FWHM}$
- Streak Cameras operate down to X-rays (Hamamatsu, LBNL)

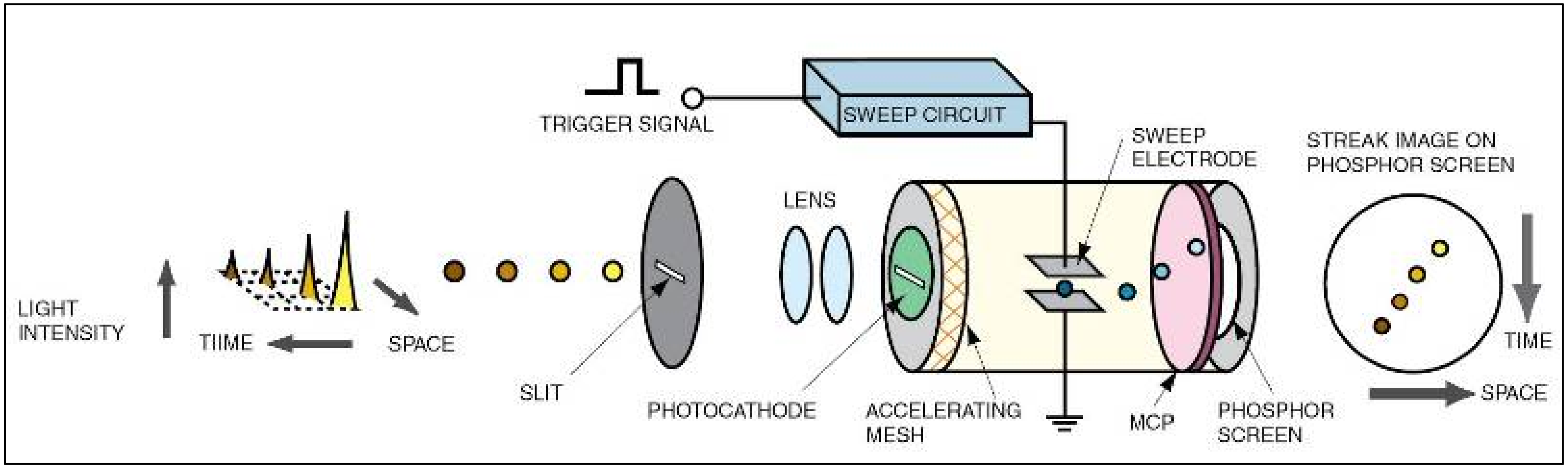
The Streak Camera **[2, 3, 4]**

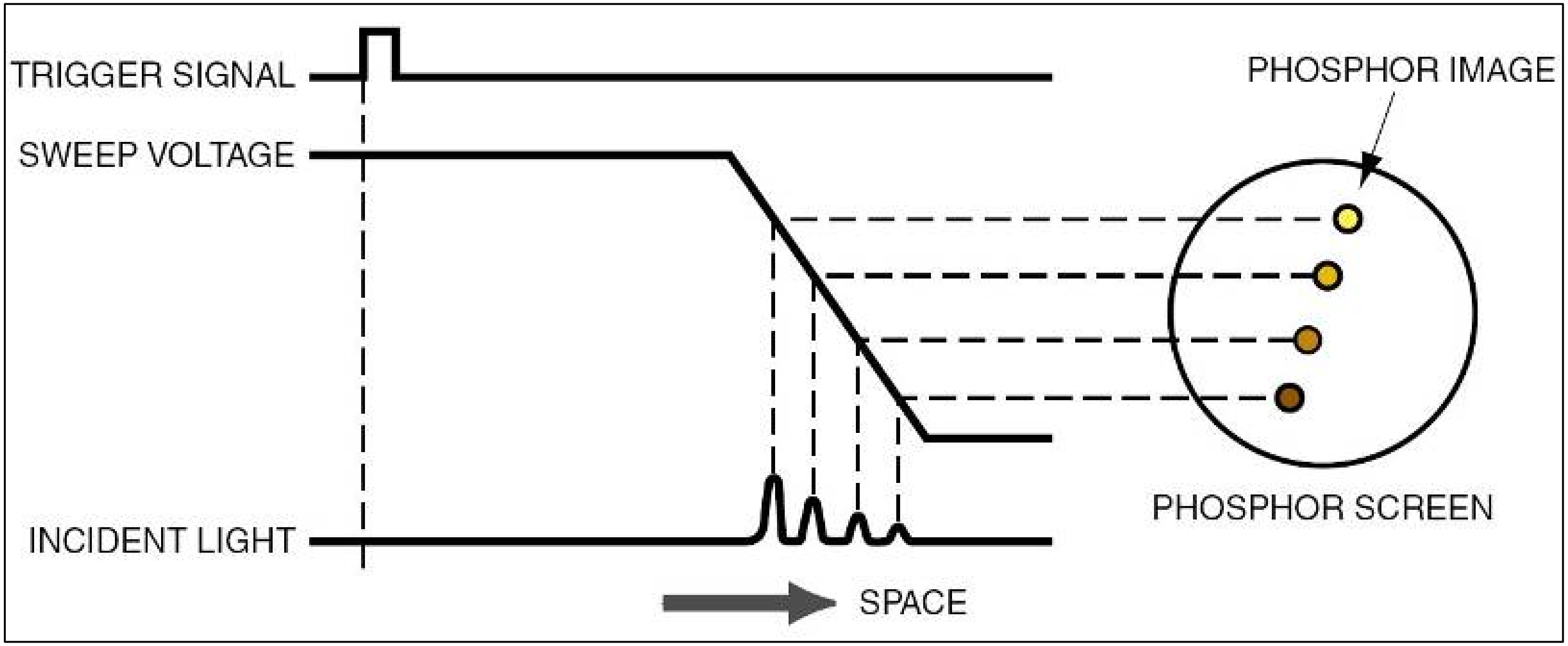


- Main SC components are:
  - Input optics
  - Photo cathode
  - Focusing and accelerating electrodes
  - Deflecting electrodes
  - 1st phosphor screen
  - Image intensifier; Micro Channel Plate (MCP)
  - 2nd phosphor screen and acquisition CCD
  - Electronic modules to drive the deflection electrode
- The Photo-cathode converts impinging **photons** (λ_{TYP}=200÷800nm) into **photo-electrons** which are then accelerated and transversely deflected
- It can be equipped with one or two deflection electrode pairs

(along orthogonal axis)

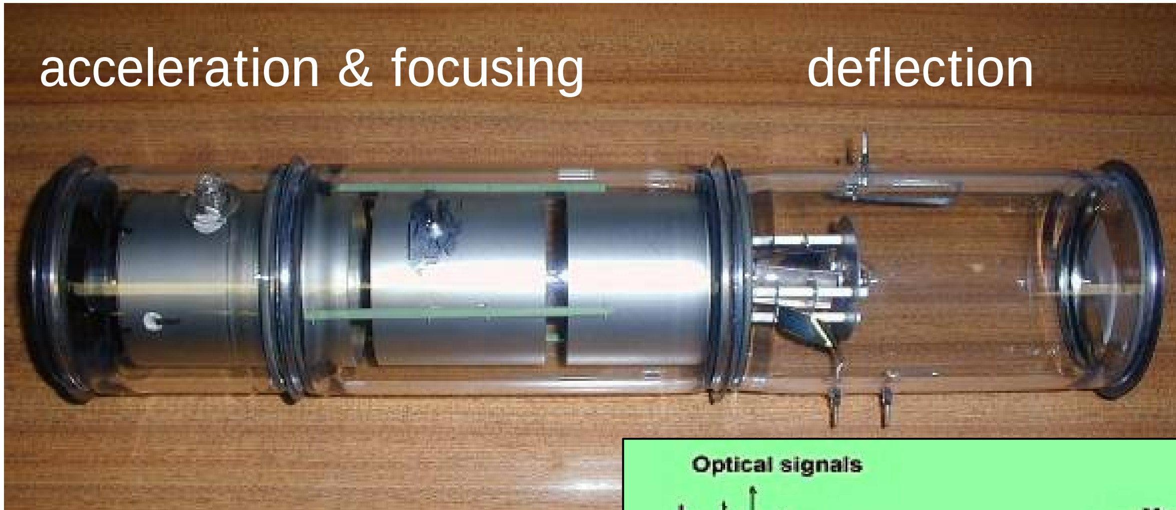
The Streak Camera: single deflection electrode pair



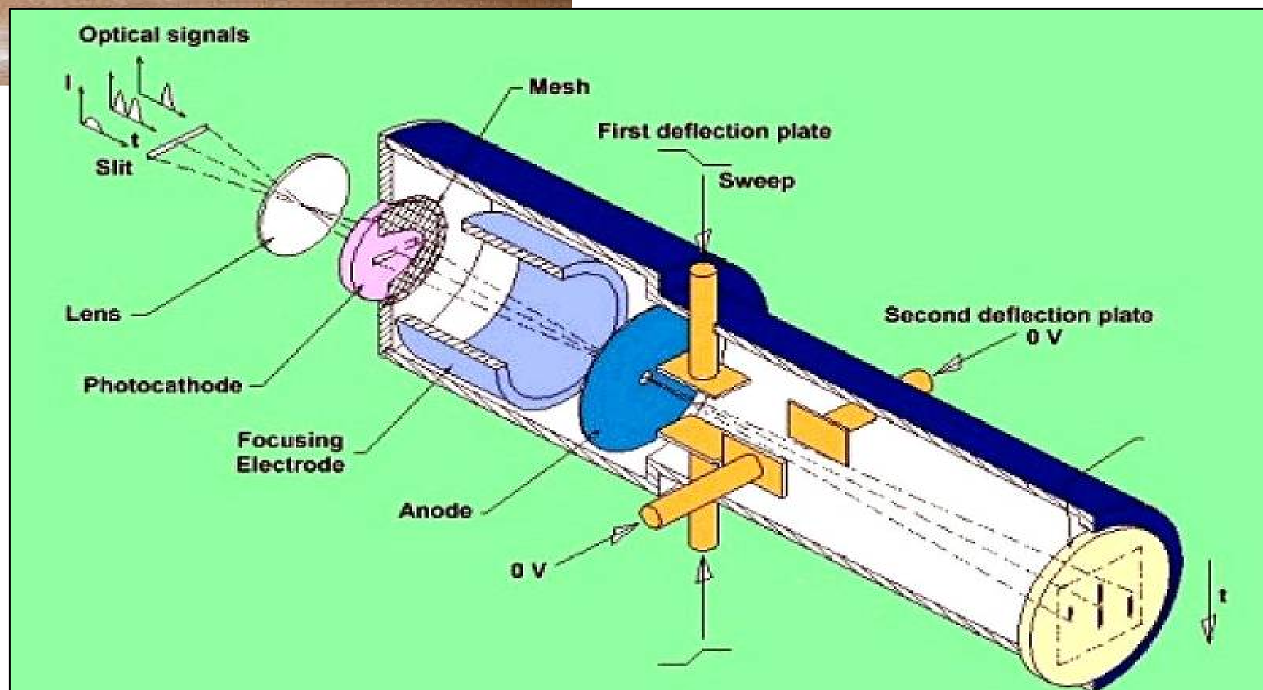


Courtesy of Hamamatsu Photonics [2]

The Streak Camera: the streak tube with two deflection electrode pairs



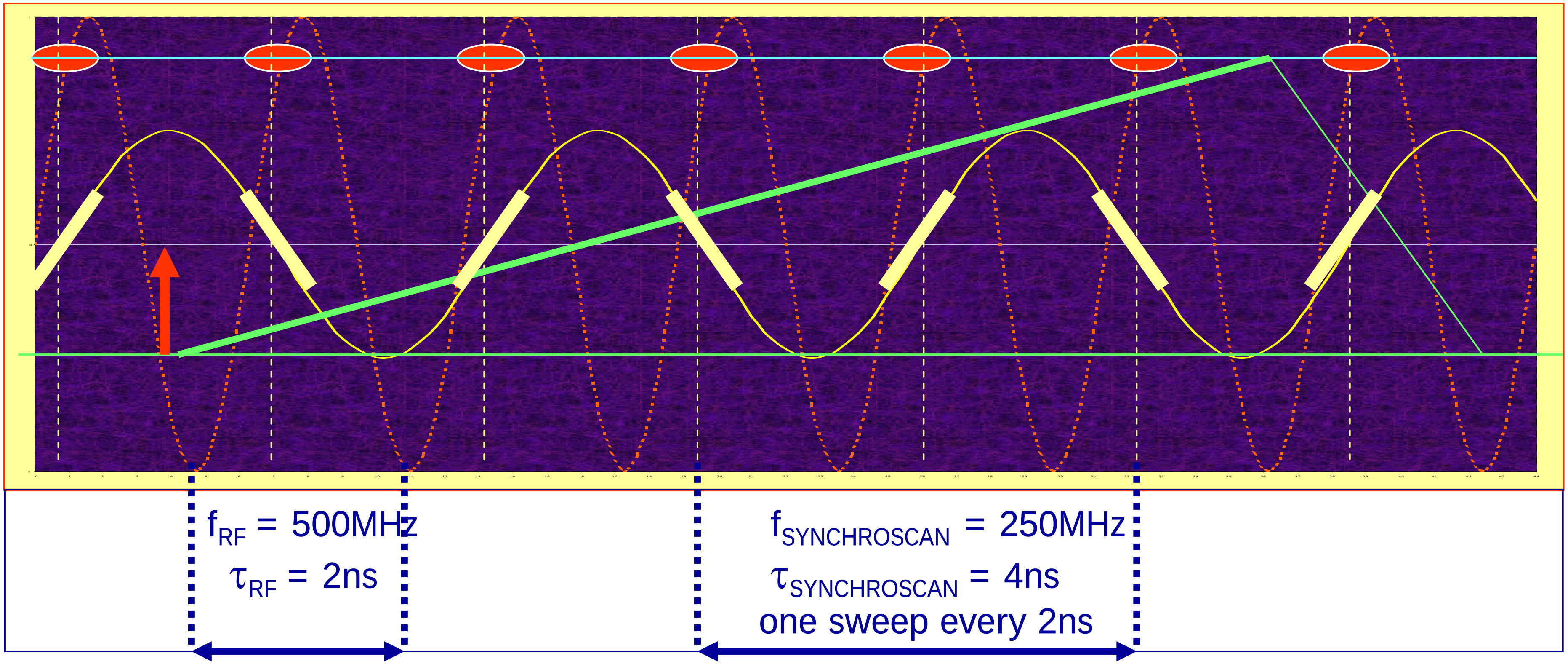
Picture of a streak tube



Courtesy of Photek Ltd [3]

3D cross section of a streak tube

The Streak Camera: two deflection pairs + synchro-scan (double sweep)



Orange = machine RF (f=500MHz)

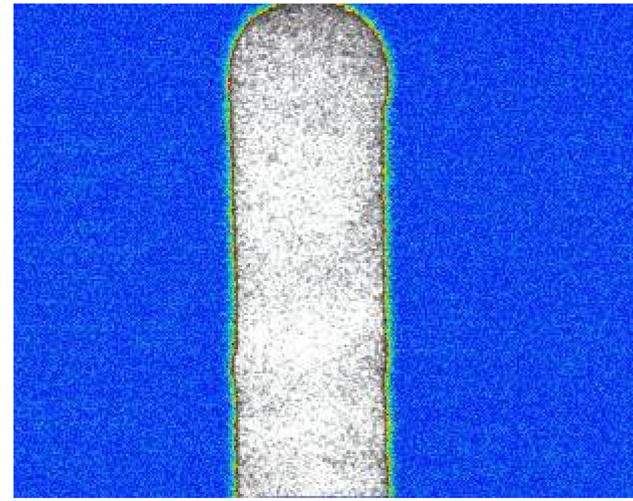
Green = Linear Ramp (1 to 10Hz) **1st deflection pair (slow)**

Yellow = synchroscan @250MHz **2nd deflection pair (fast)**

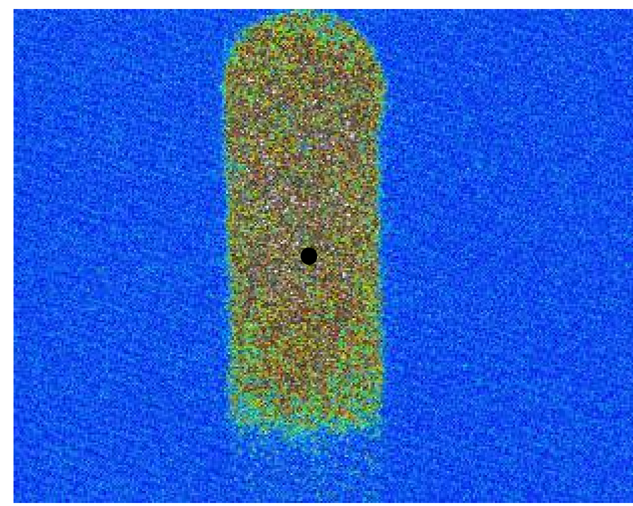
Orange arrow ➔ Linear ramp trigger pulse

The Streak Camera:
the photo-cathode (PC)

New, good looking PC:
it's uniform, no blind area



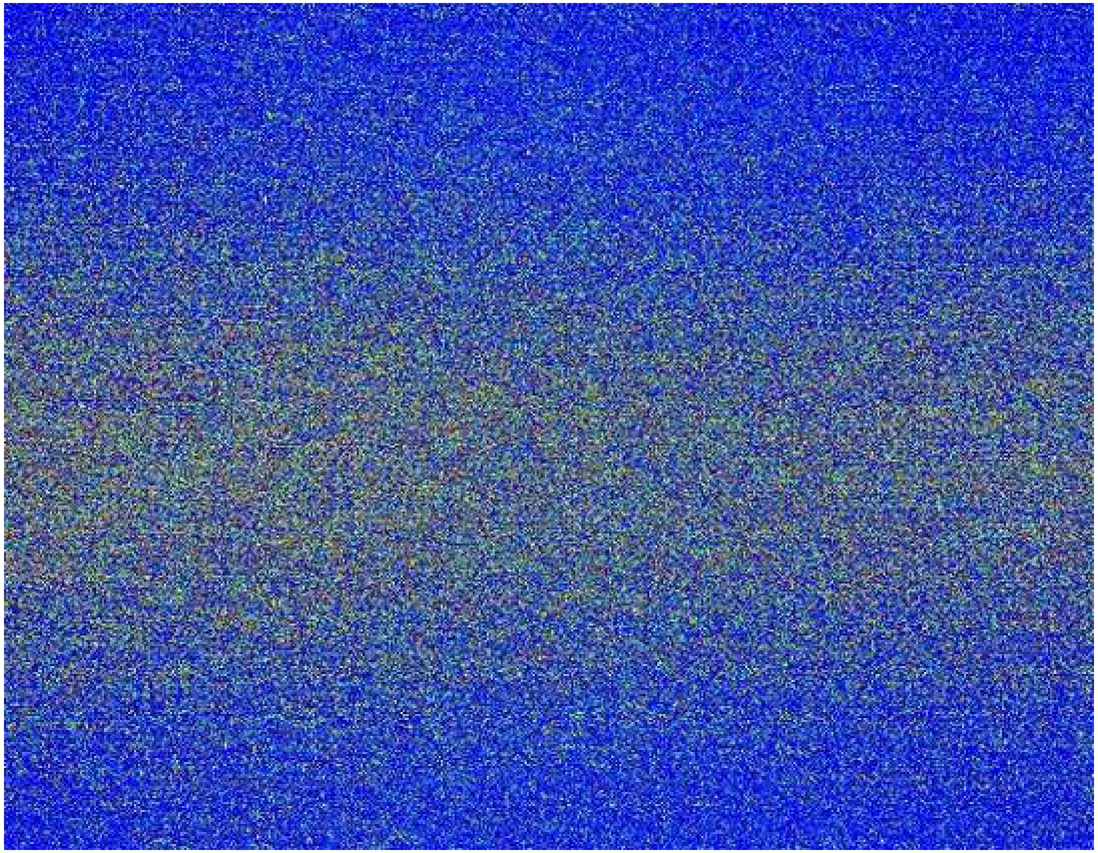
...there is a dark area at the bottom...we burned part of the PC?



...the problem was an MCP degradation, between the two phosphor screens just in front of the CCD

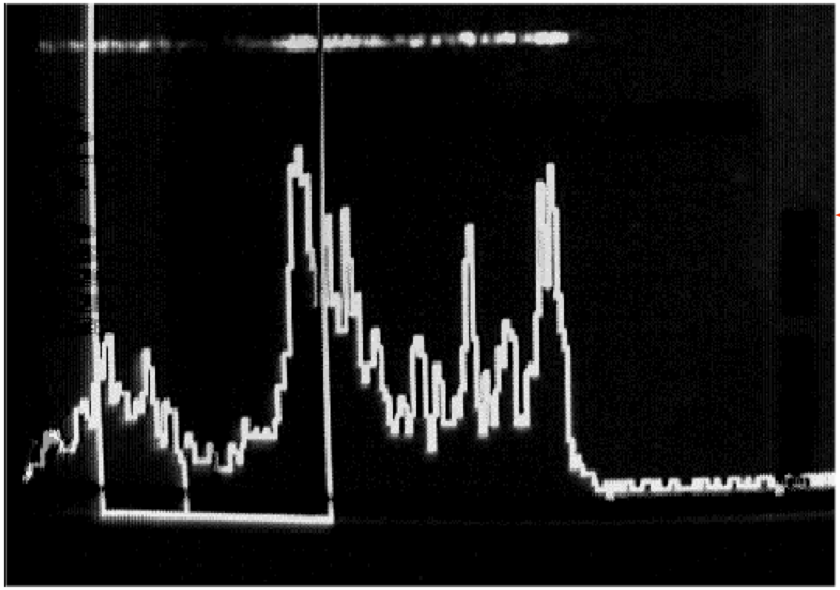
The Streak Camera:
the photo-cathode (PC)

- that’s gone...hopelessly gone!
- at this point you need a new Streak Tube ...€€€!!!
- Some manufacturers integrate in a single piece of HW the **streak tube** and the **intensifier (MCP)**

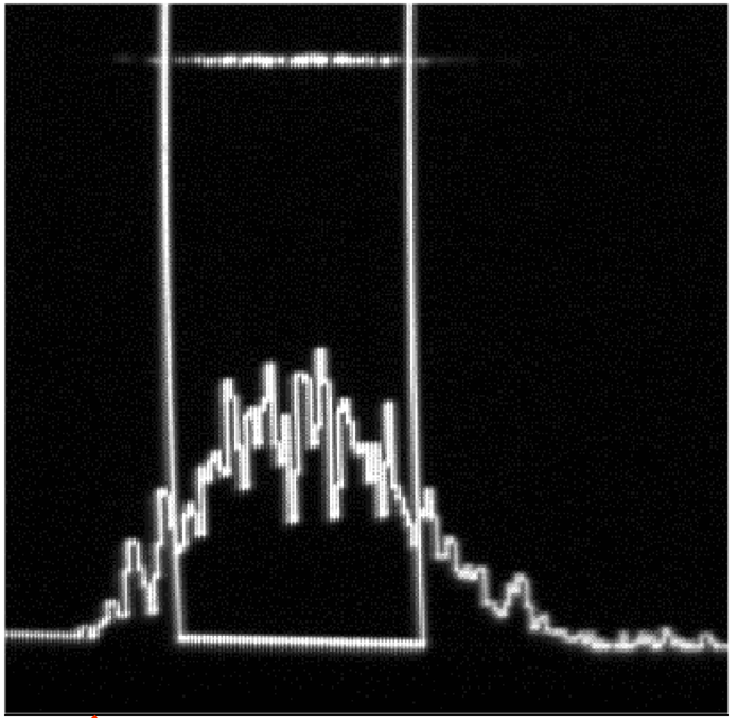


First SC (single sweep) measurements at Elettra [5]

collaboration with ENEA Frascati, L. Giannessi (1996)

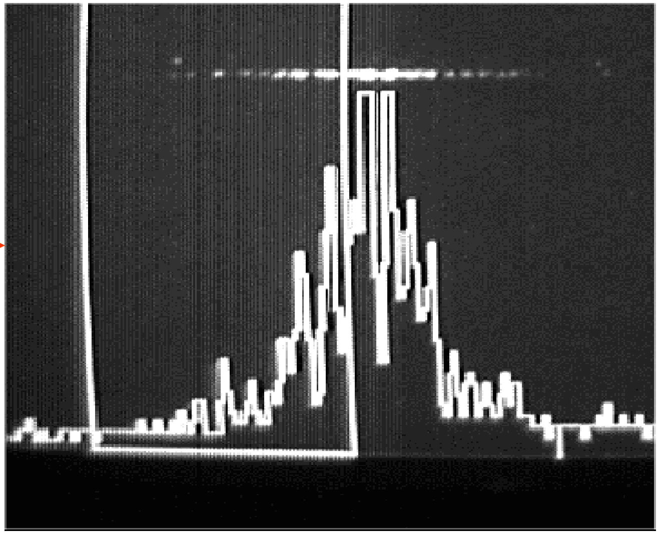


MULTI BUNCH
Unstable beam
I= 192.2mA; **Window 140 ps**



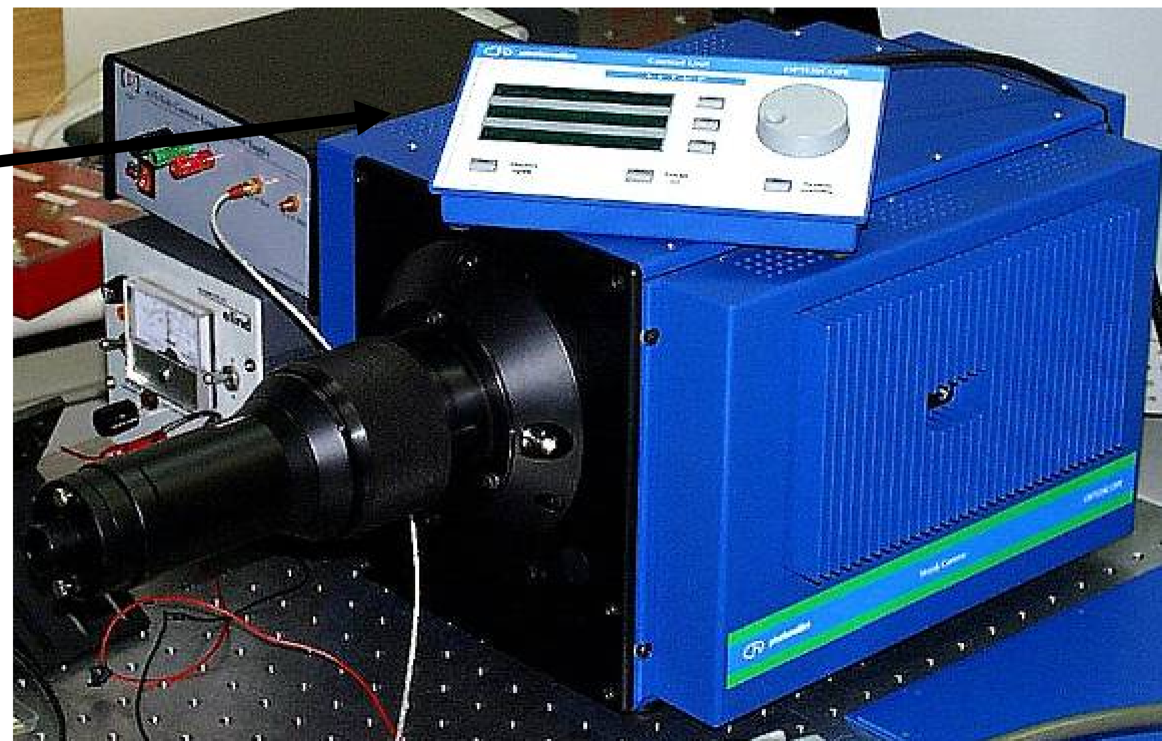
SINGLE BUNCH
Ib=8.1mA; E=0.9GeV;
Window 46.8ps

Stabilized beam
I=108.9mA;
Window 58ps



The Streak Camera
the Elettra SC **[4]**

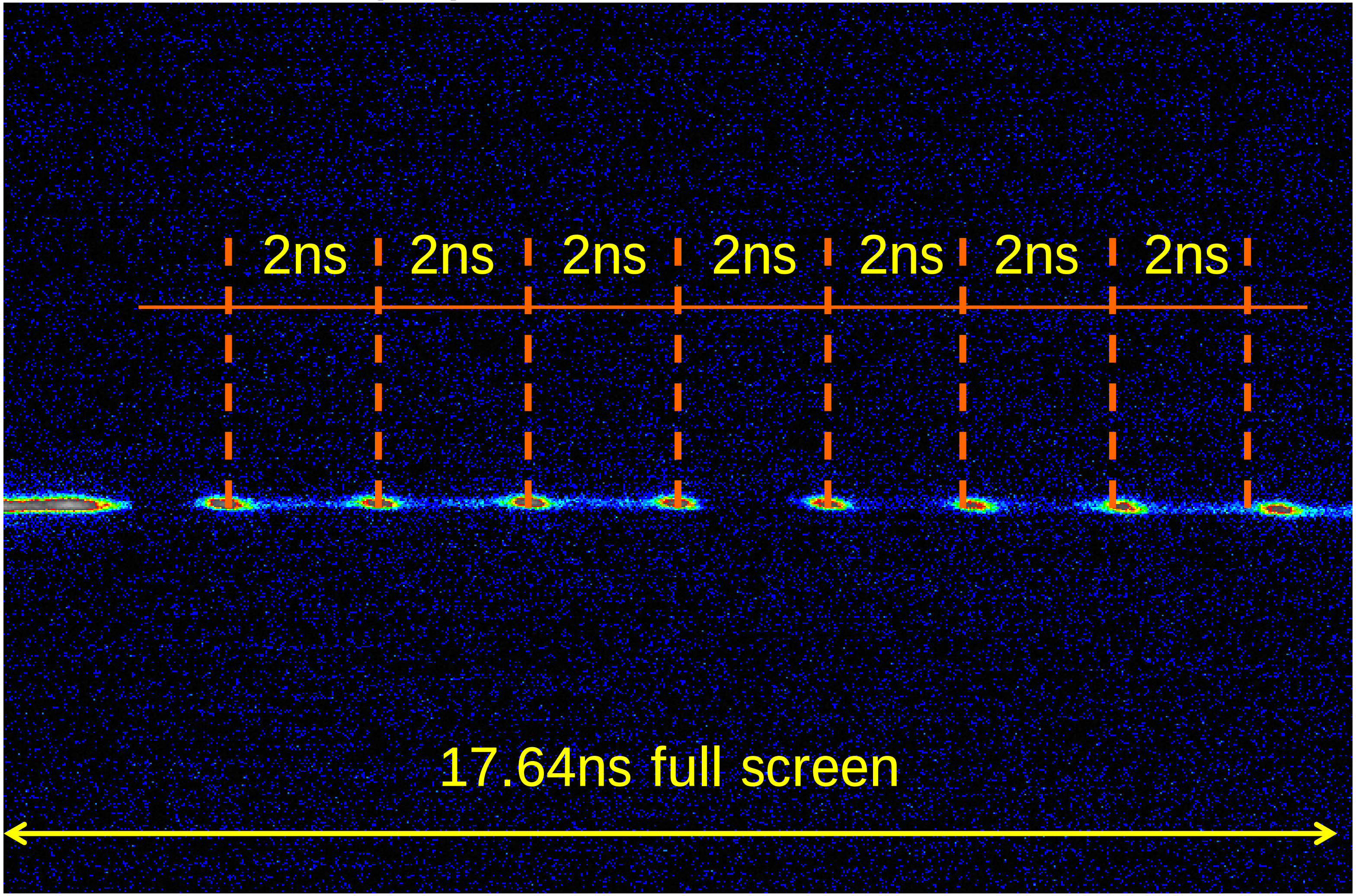
- The Elettra SC: Optoscope **double sweep** unit by Optronis
- First (1999) SC equipped with a 250MHz **synchroscan** deflection unit
- Input optics adjustable (λ_{IN})
- resolution <2ps$_{FWHM}$ (@λ=800nm)
- On top: control keypad



Single sweep acquisition [6]

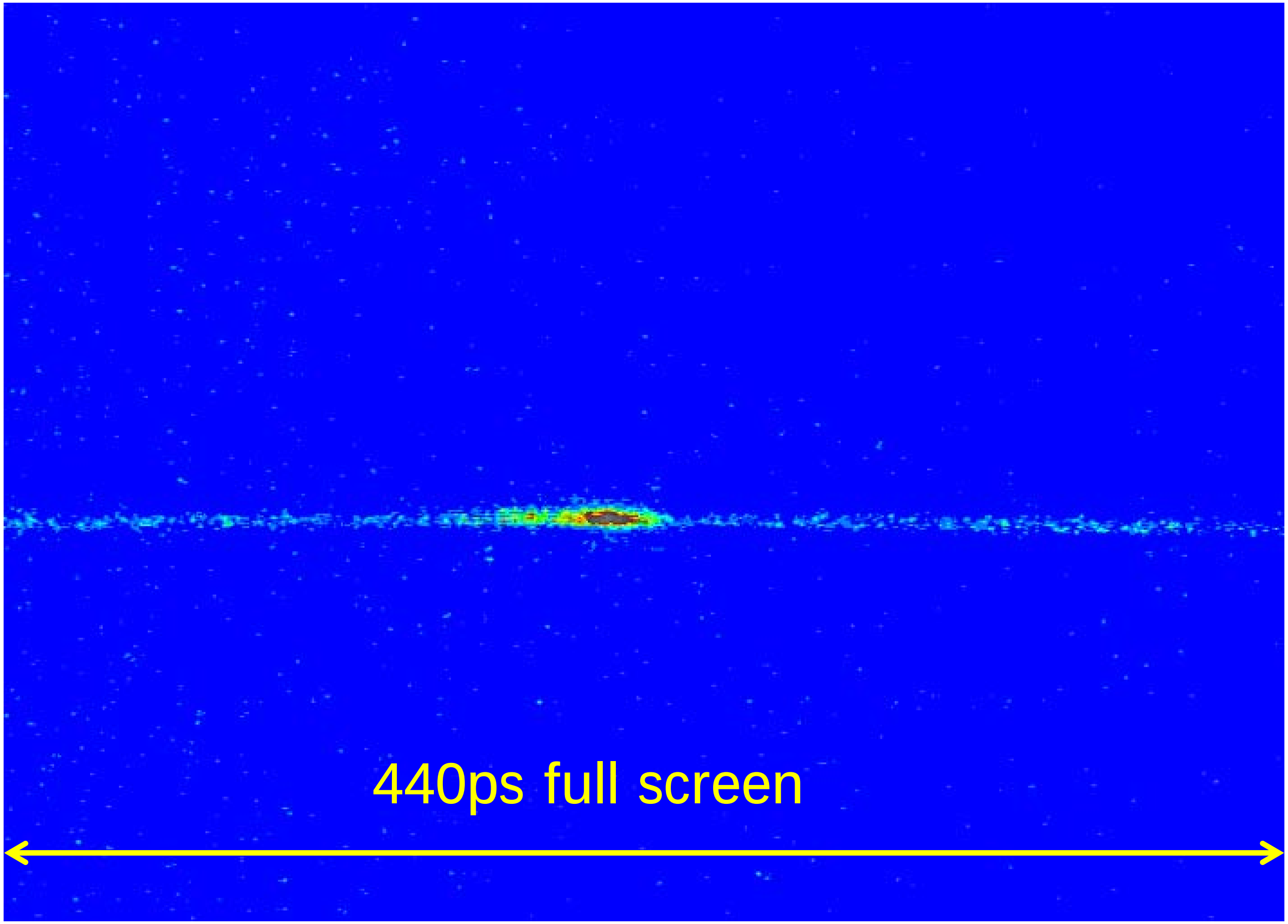
8 consecutive bunches;

sweep speed: 1ns/mm



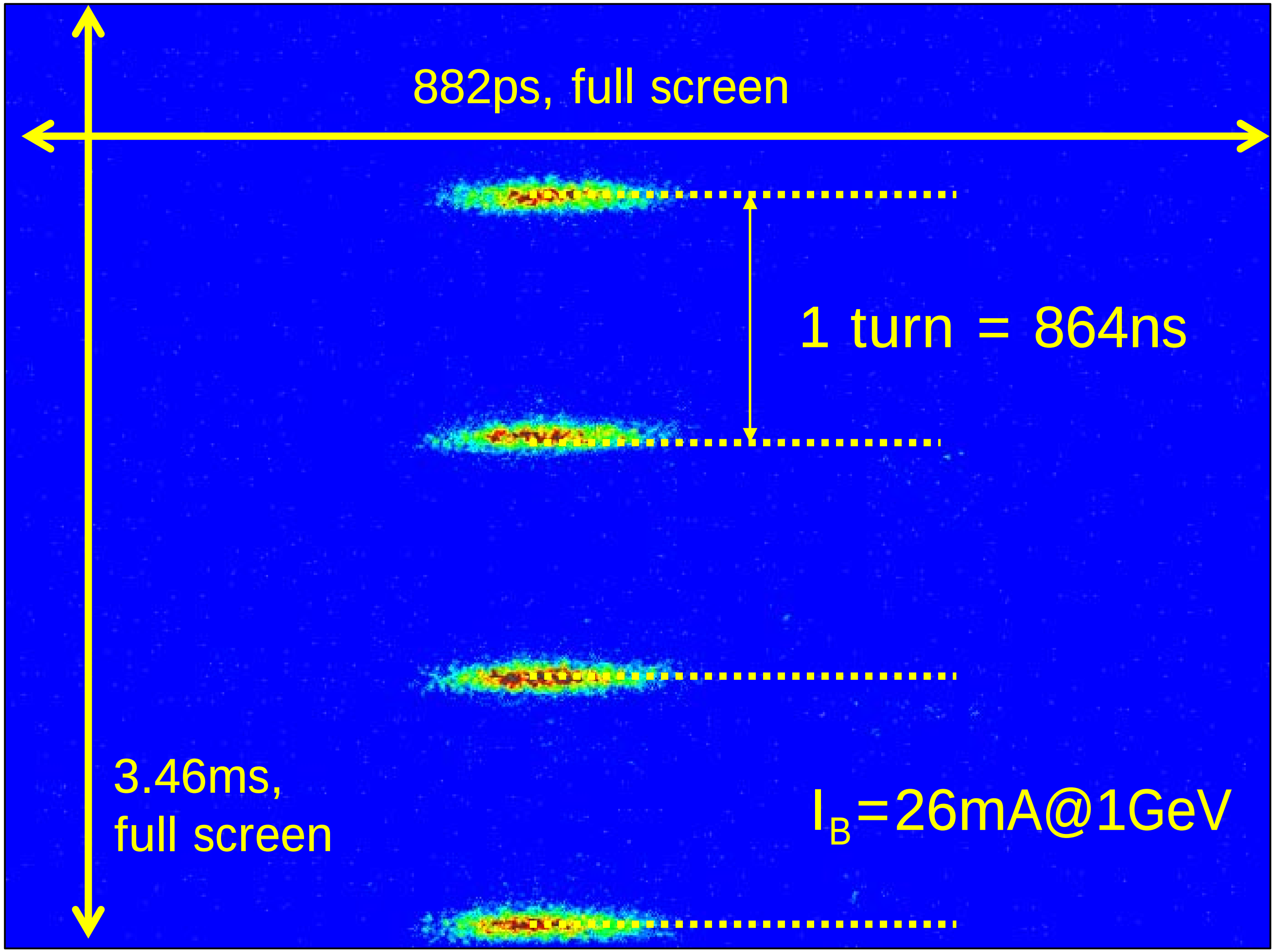
Single sweep acquisition [6]

one bunch;
sweep speed: 25ps/mm
(highest resolution in single sweep: 10ps/mm)



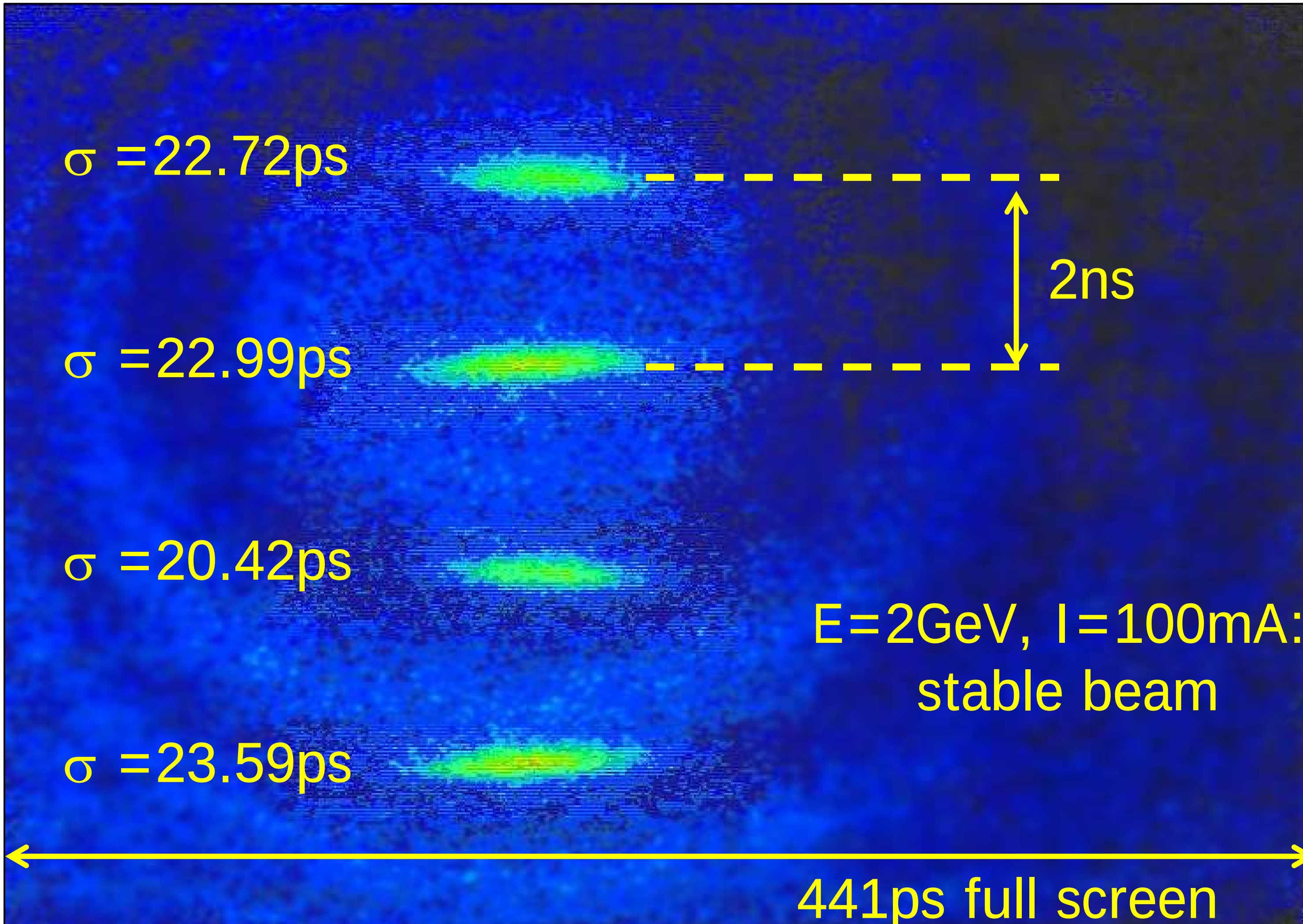
Double sweep with Synchroscan [6]

double sweep, single bunch over four turns



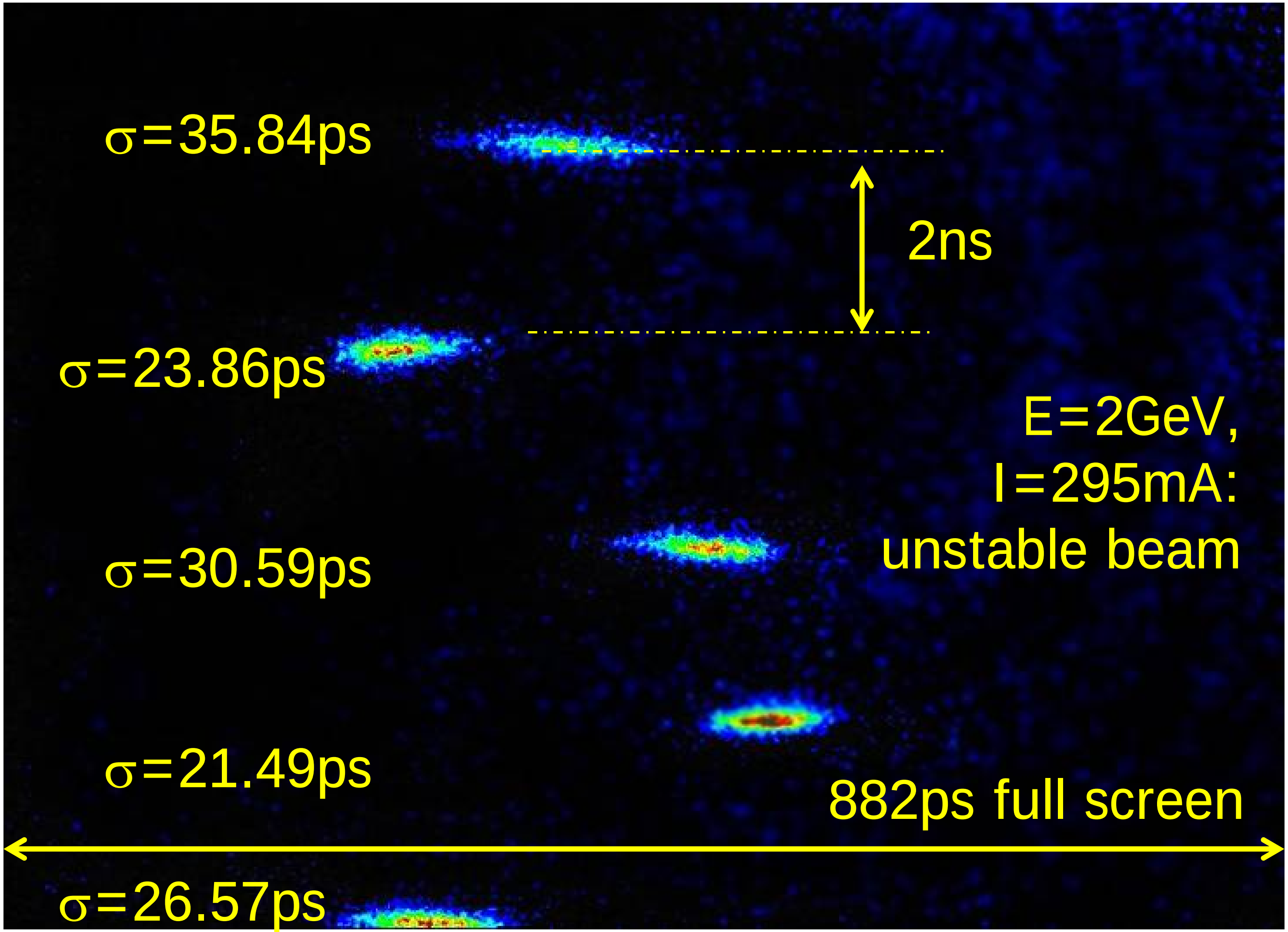
Double sweep with Synchroscan [6]

4 consecutive bunches @500MHz

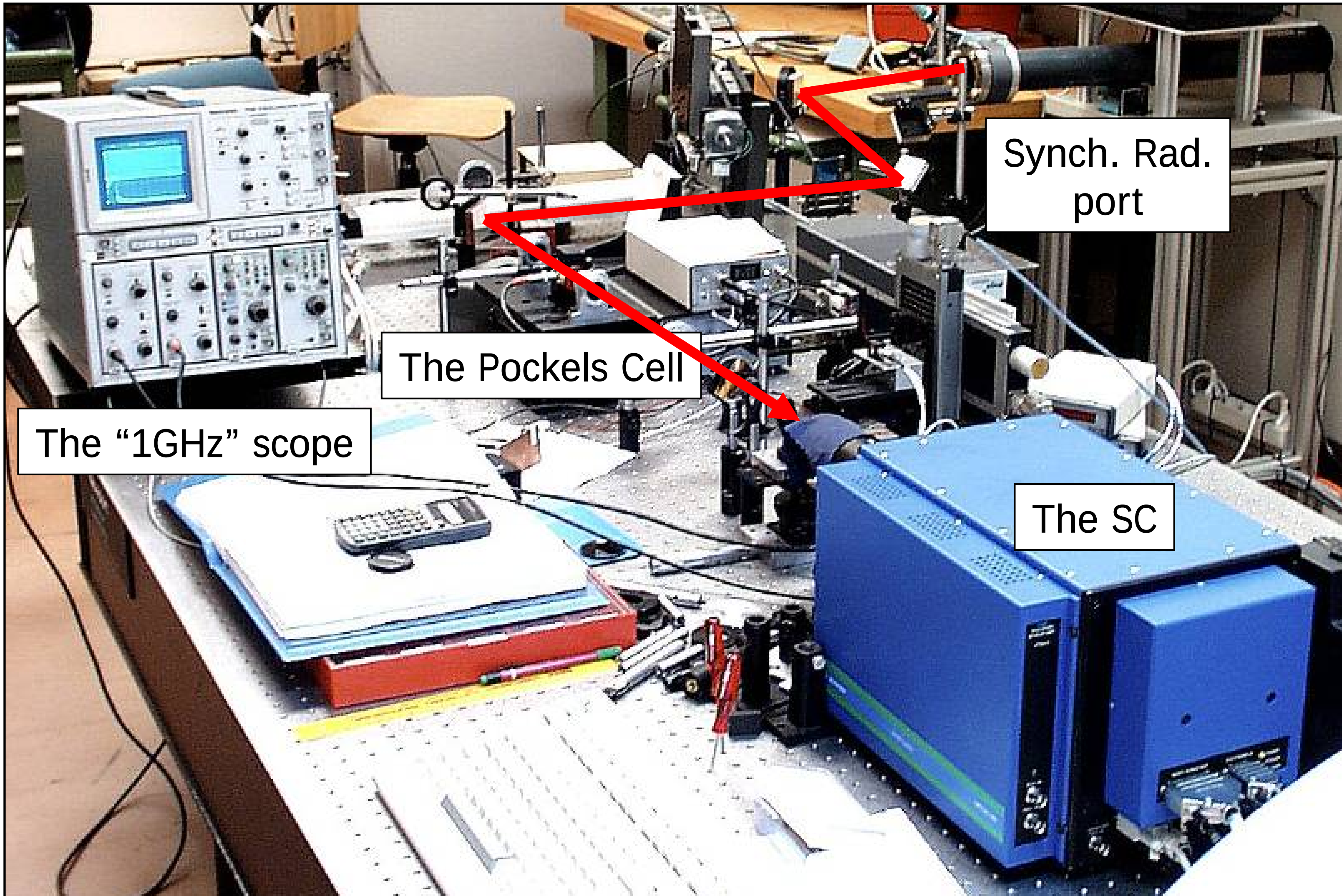


Double sweep with Synchroscan [6]

Multi Bunch filling, Single Shot Acquisition



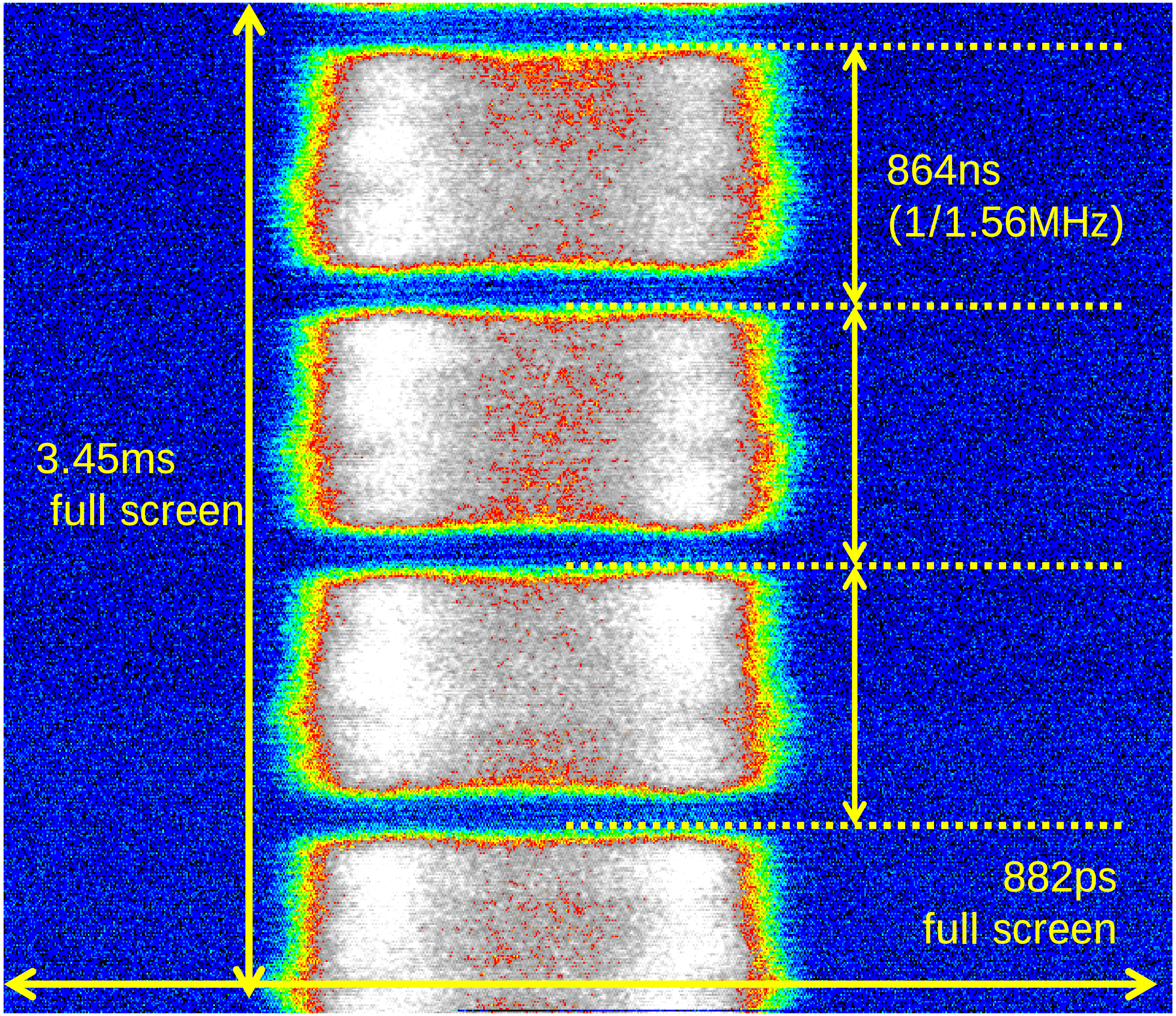
The Streak Camera:
how it's looks like...in the Elettra Optical lab



Double sweep with Synchroscan [6]

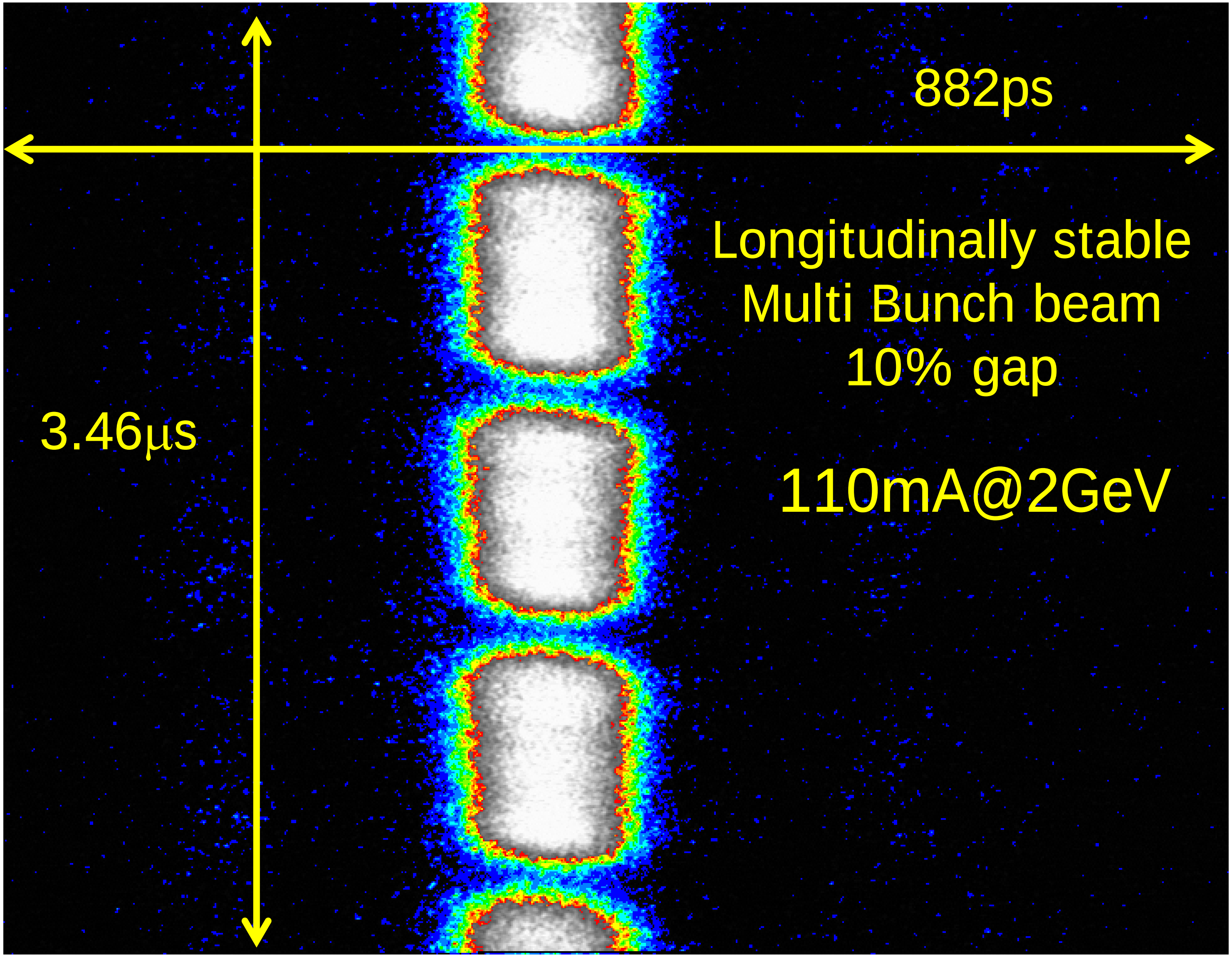
Accumulation Mode (5 averages)

E=2GeV,
I=245mA
Multi bunch
20% gap
Longitudinally excited beam
Envelope of pk-pk oscillations can be observed



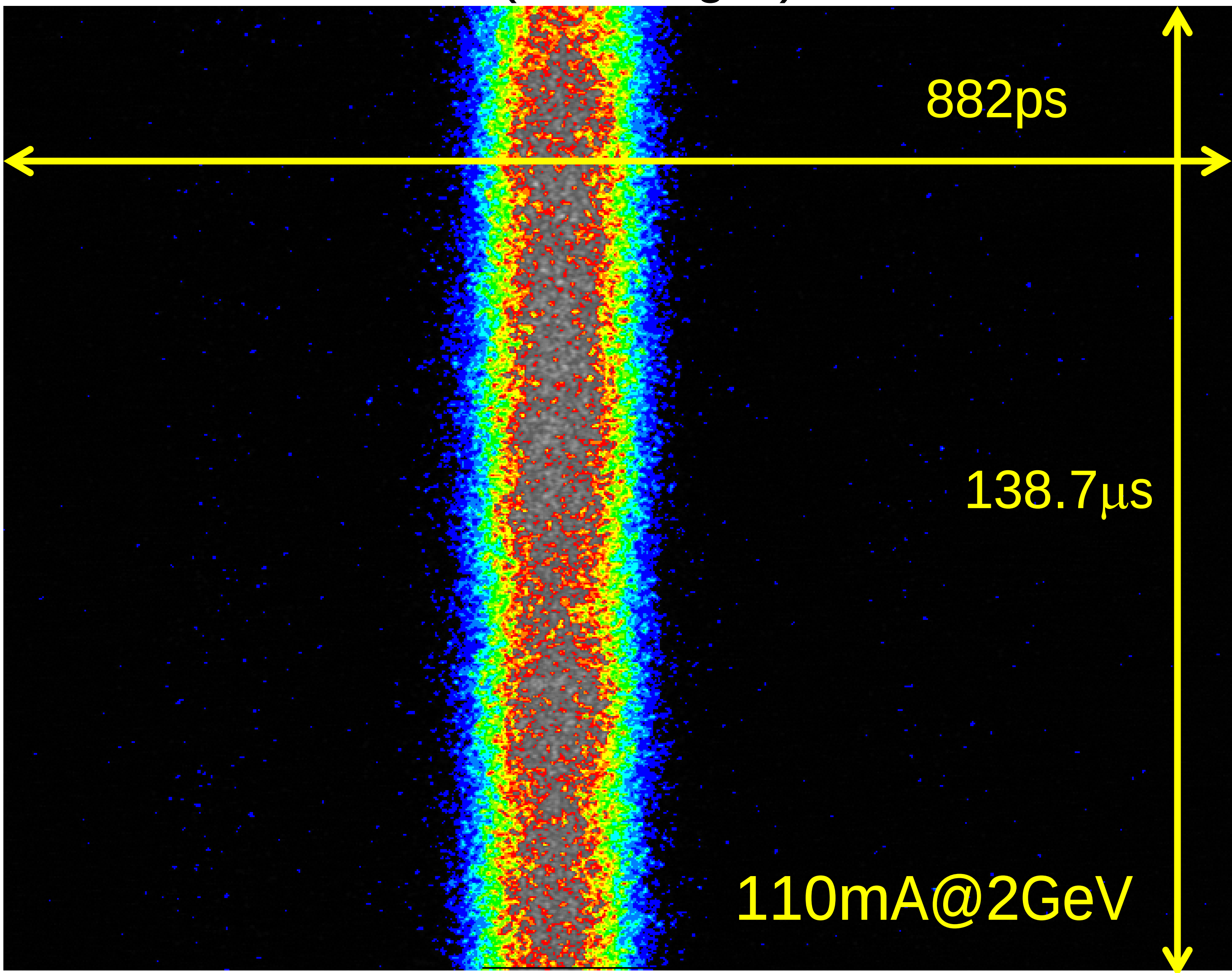
Double sweep with Synchroscan [6]

Accumulation Mode (5 averages)



Double sweep with Synchroscan [6]

Accumulation Mode (5 averages)



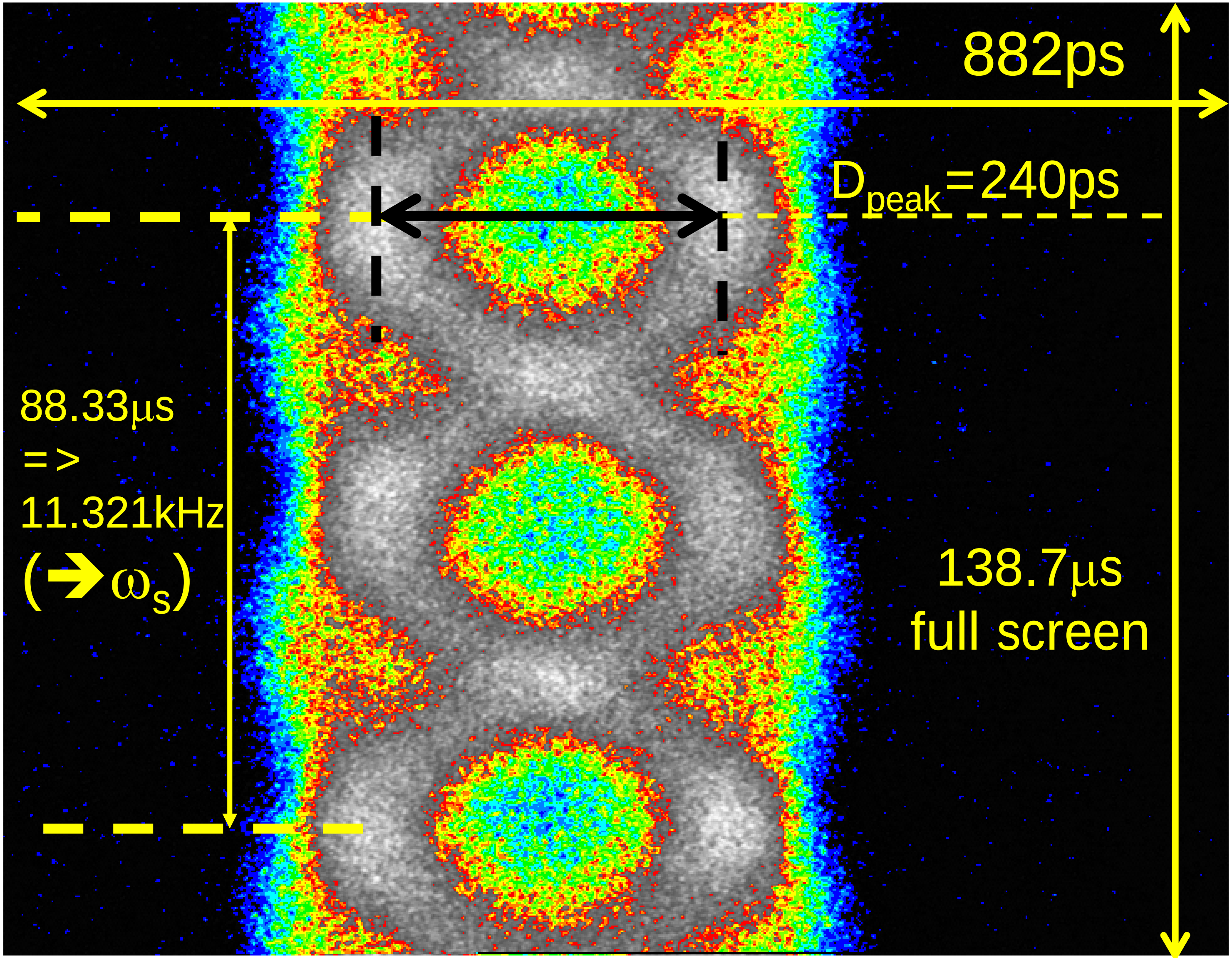
Longitudinally stable **Multi Bunch beam**

Gap no more observable due to longer vertical (slow) deflection

Double sweep with Synchroscan

coherent dipolar synchrotron oscillations

I_B=110mA
@2GeV



The Streak Camera insights

resolution limiting factors

- **streak tube design**: sweep speed / linearity / deflecting voltage
- **input radiation wavelength:** higher energy (shorter wavelenght) photons create a broader photo-electron bunch inside the streak tube;
- **dispersion:** photons of different energies broaden the streak image:

  0.05ps/nm@620nm Hamamatsu data

  0.1ps/nm@488nm measured at the ALS, Berkeley
- **space charge** effects on the photo-cathode, decreasing with accelerating voltage (typical **15keV**)

  use small pin-hole (50μm) / thin slit (30μm)
- the minimum achieved temporal resolution is **<300fs@800nm**

  FESCA 200 by HAMAMATSU
- weak signals? try averaging … **jitter of the trigger < SC resolution**

The Streak Camera insights [7]

SC characterization at Elettra with a fs laser

- We verified SC resolution vs. different parameters, like:

  - SC operation modes: synchroscan and single sweep

  - pinhole diameter (200,100 and 50mm) and slit (0÷3mm, used at 30μm)

  - input light intensity (N.D.=0, 0.5, 0.99; $I_{OUT}/I_{IN}=10^{-N.D.}$)

  - input light wavelength λ_0=810nm and 405nm (II harm.)

- sweep accuracy and linearity

  using an opt. delay line and measuring at different position over the full screen sweep

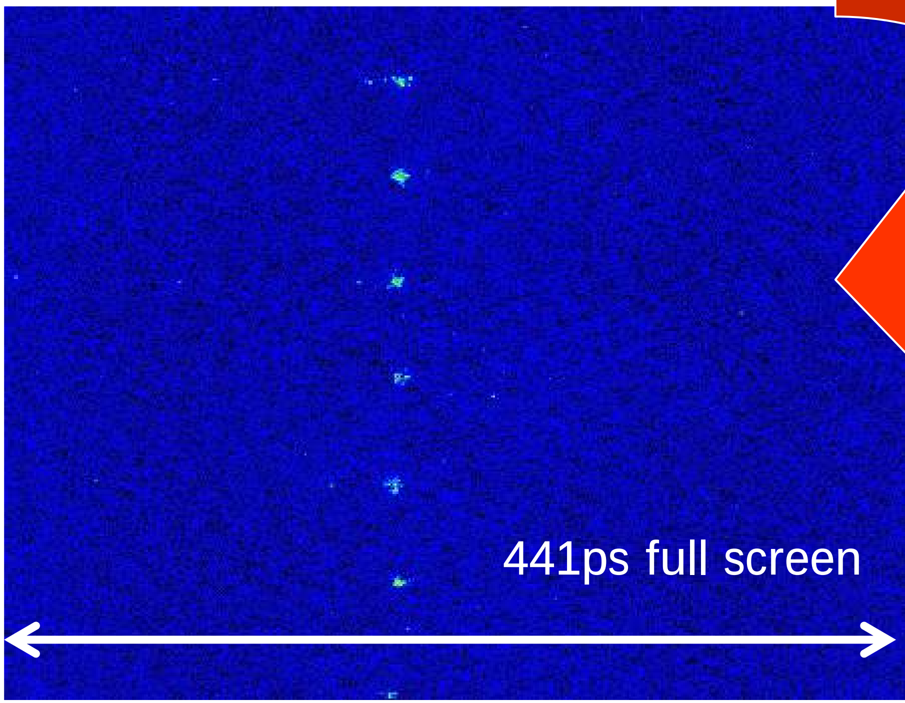
- jitter of the single sweep unit

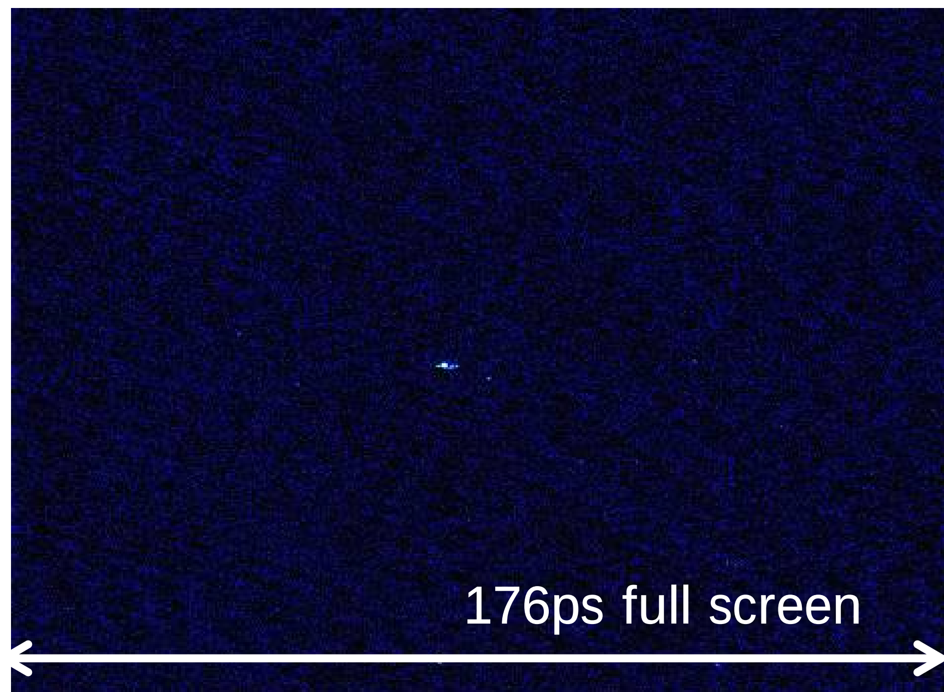
  by accumulation of many *single shot* acquisitions

The Streak Camera insights [7]

fs laser single-shot acquisitions

synchroscan | **single sweep**

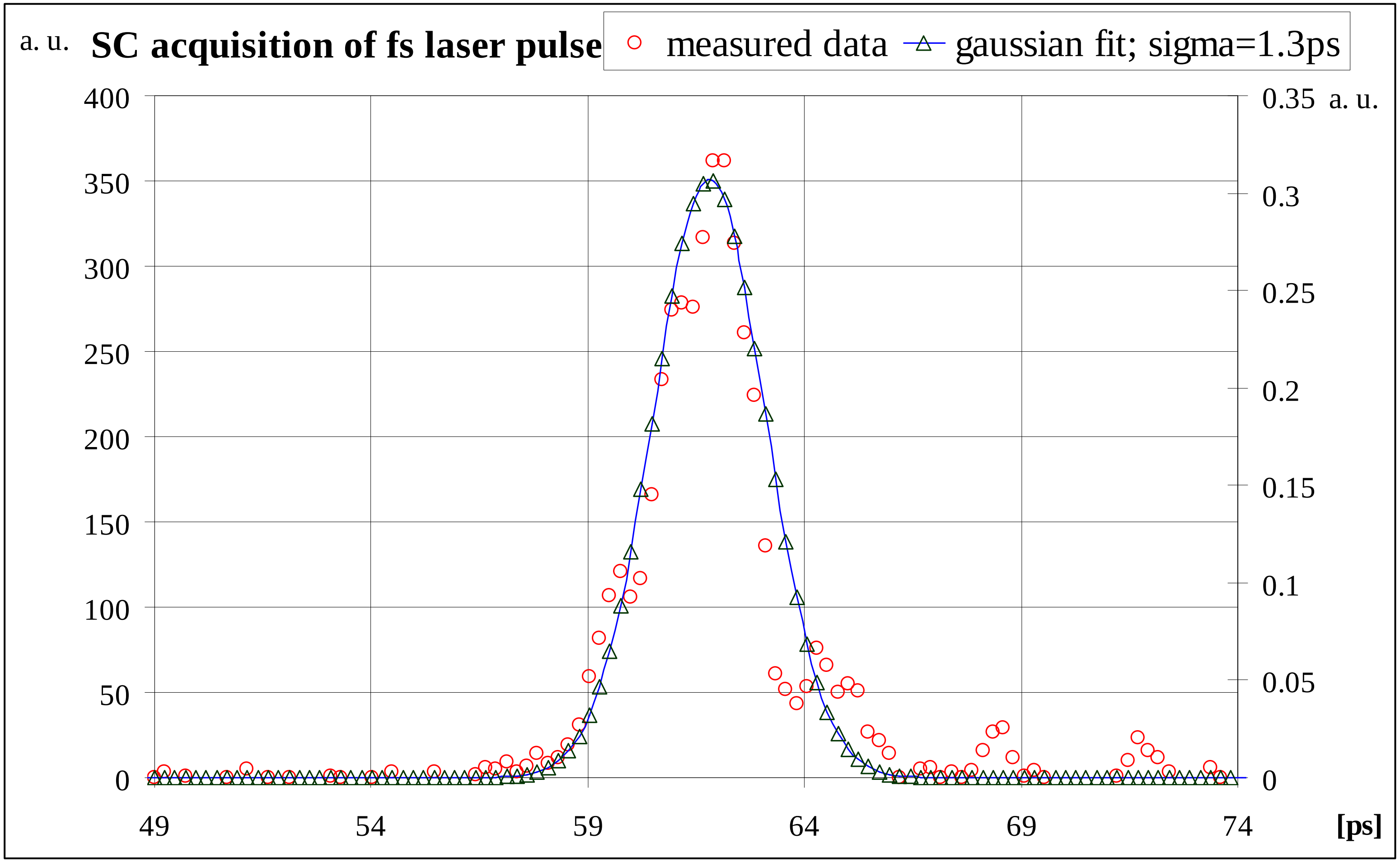




Single sweep fastest
deflection speed 10ps/mm

The Streak Camera insights [7]

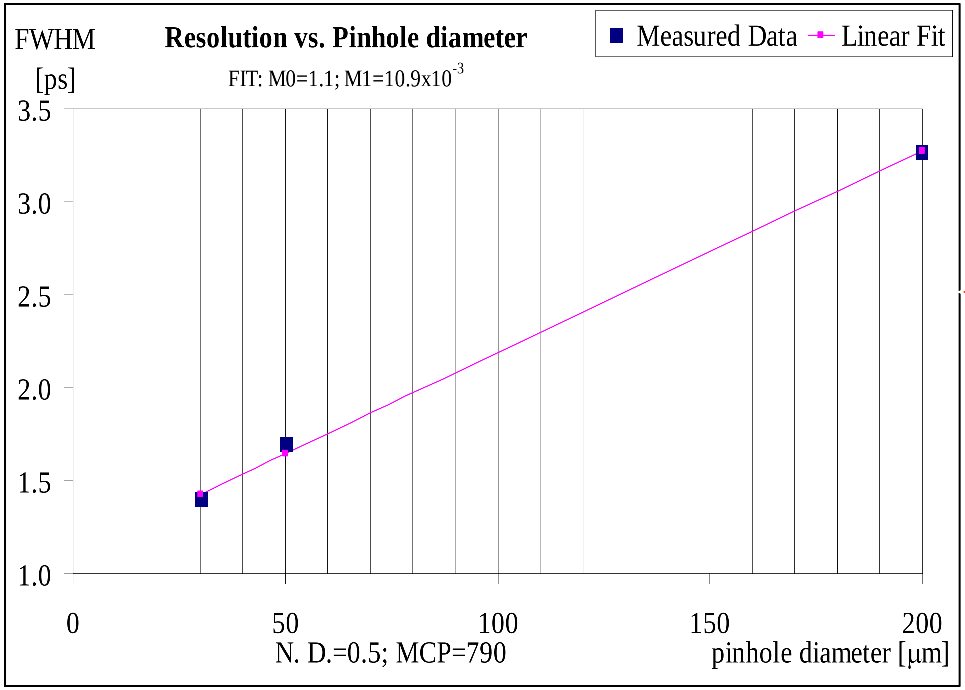
fs laser profile; pin-hole diameter=100μm



fs laser profile as acquired by SC in single sweep, single shot

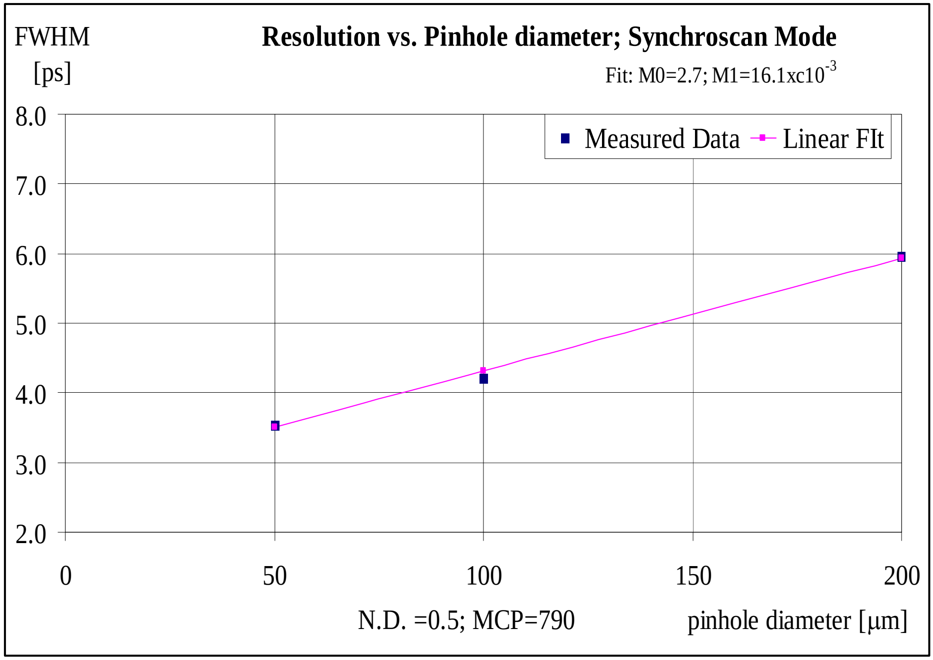
σ=1.3ps (Gaussian fit)

The Streak Camera insights [7]
resolution dependence vs. pinhole diameter



Single sweep mode

Pinhole diameter: 200μm, 50μm and 30μm (slit)



Double sweep /synchroscan

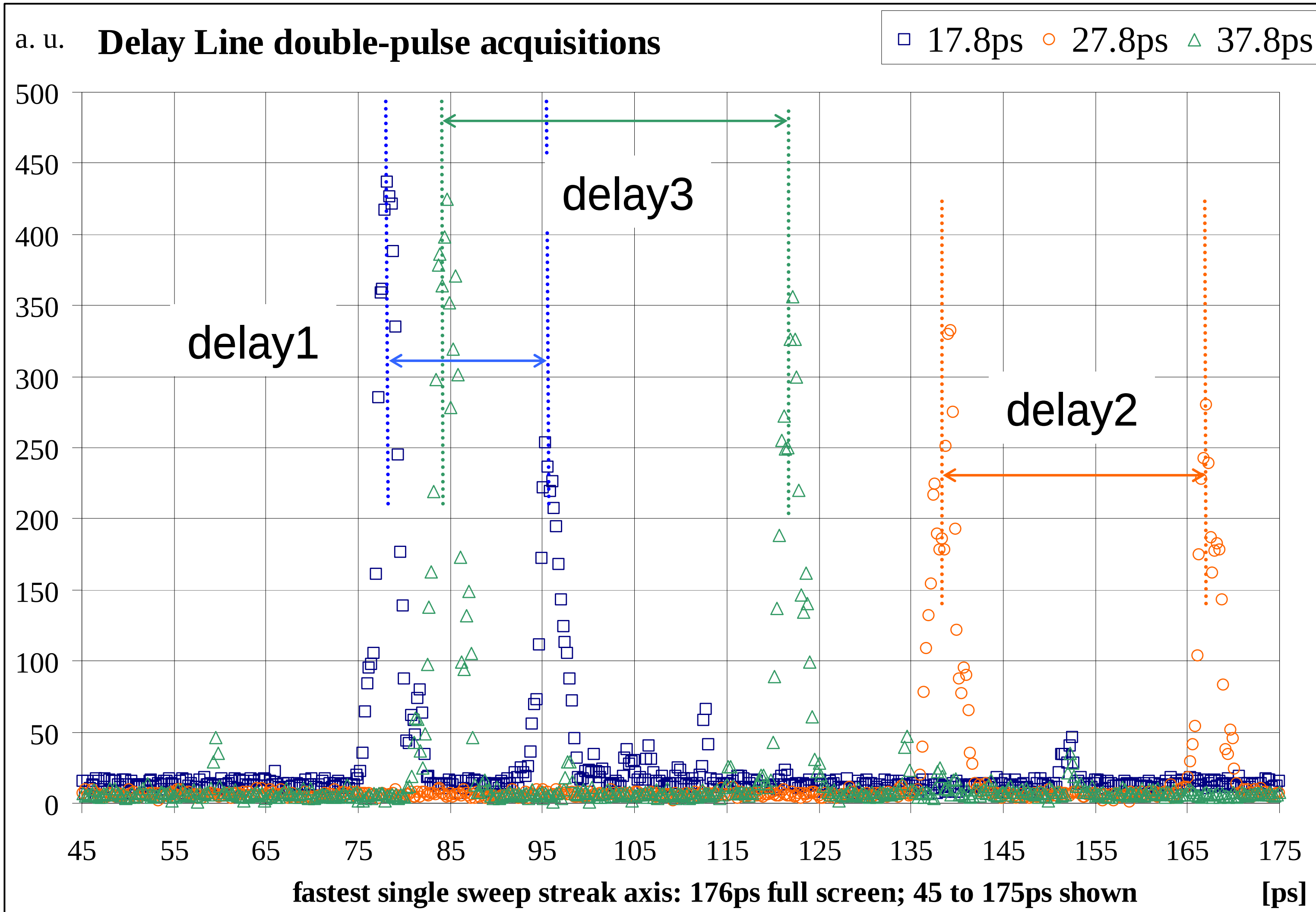
Pinhole diameter: 200μm, 50μm and 30μm (slit)

The Streak Camera insights [7]

measurement of sweep linearity

second pulse created with optical delay line and sum

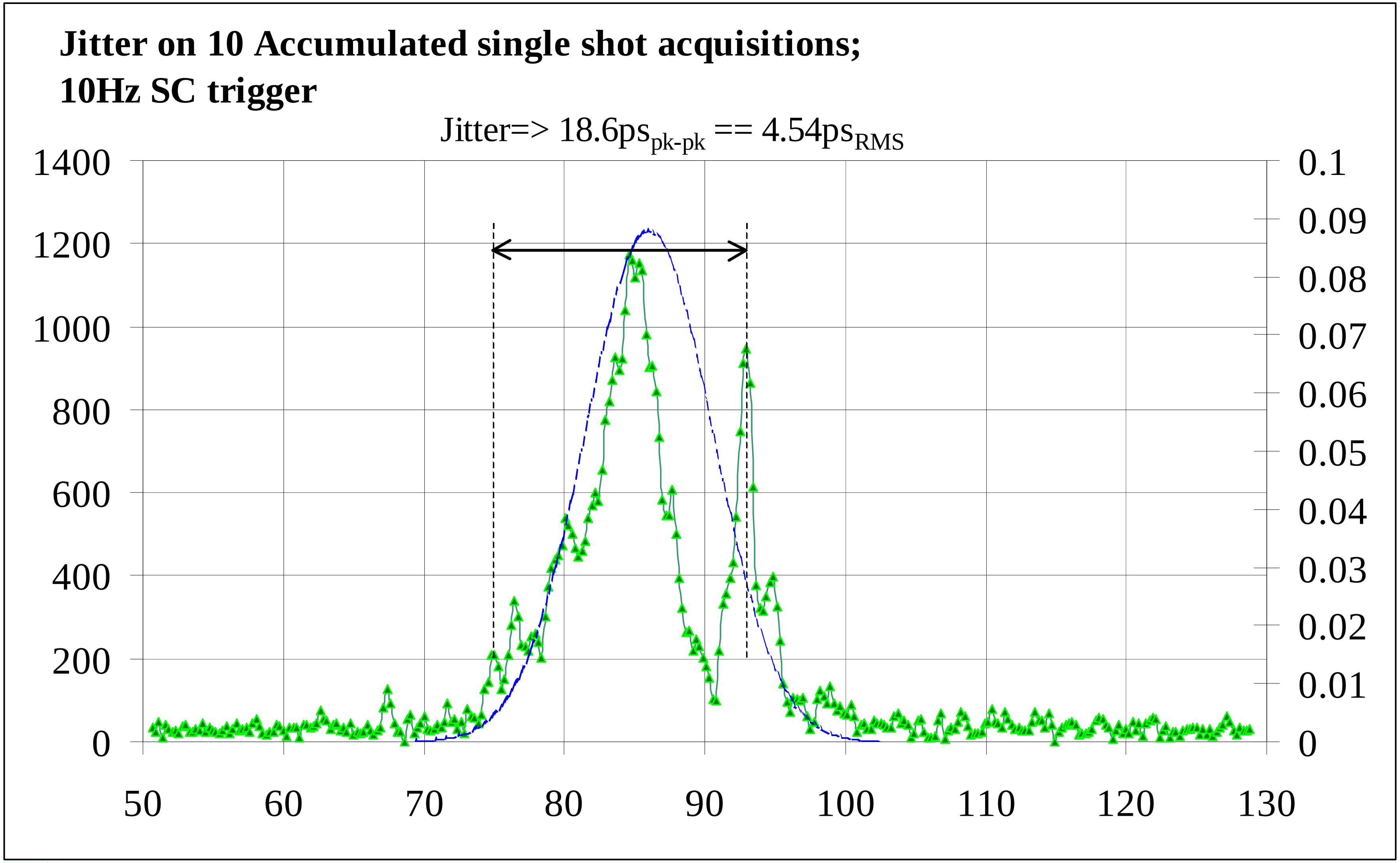
1mm ➔ 3.3ps **Optical Delay** changed in 1.5mm steps (x2, back and forth) ΔL=3mm/step ➔ 10ps/step



CAS THE CERN ACCELERATOR SCHOOL

The Streak Camera insights [7]

jitter measurement on SC trigger **4.5ps$_{RMS}$**

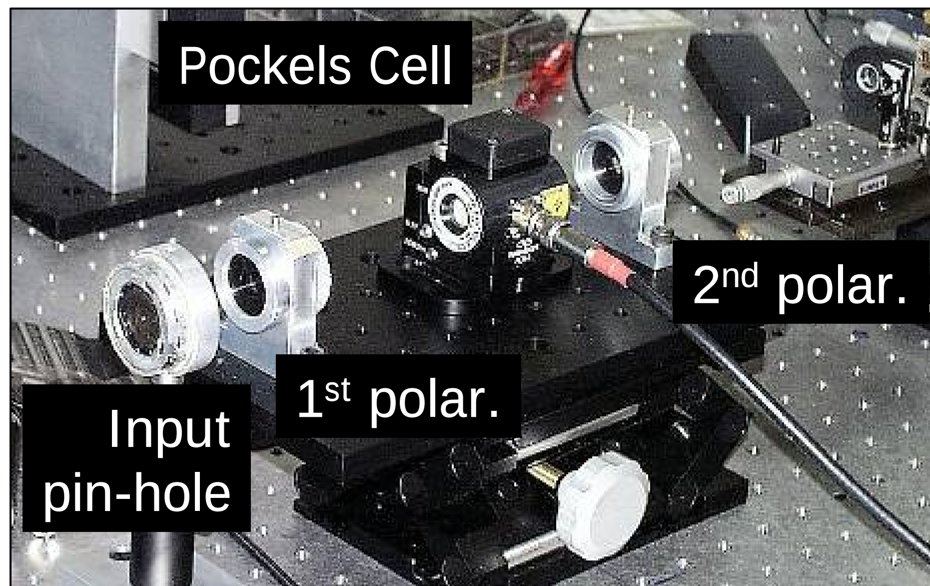


The Streak Camera insights [6]
improving your streak camera set-up

- for a SC acquisition, we may define the **Duty Cycle** DC_{SC} as the ratio between sweep duration (t_{SW}) and sweep (trigger) period (τ_T)
- Typically, the DC_{SC} is very low as the sweep has a very short duration and the time period in between sweeps is long (low rep. rate of SC sweeps) τ_T = 50ms ➔ sweep trigger @20Hz
  t_{SW} = 100ns (typical sweep duration)
  DC_{SC} = 2 x 10^{-6}
- With repetitive pulsed sources (f_{PULSES}=1-500MHz for ELETTRA) **most of the incident light pulses are not used (i.e. deflected)** by the streak camera and can **generate back ground noise**, eventually even damage the PC
- A fast opto-electronic (based on a Pockels Cell) shutter improves the quality of the image

The Streak Camera insights [6]
improving your streak camera set-up

- The Pockels Cell is based on a *Pockels effect*:* the refractive index of a medium exhibits a modification which is proportional to the strength of an applied electric field (→ **linear electro-optic effect**)
- By applying a high voltage (3kV) to a crystal the polarization rotates up to 90^o
- By putting the PC in between two linear polarizers whose axis have been previously aligned to be 90^o, then the whole set-up acts as a fast optical switch
- The pulse driving the HV PC driver has to be synchronized to the beam and to the SC trigger

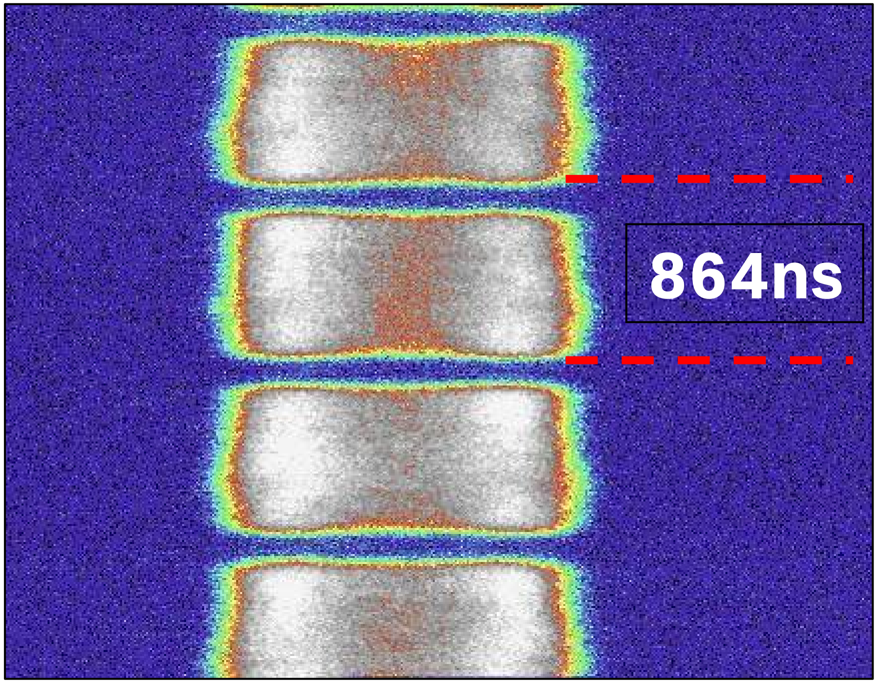


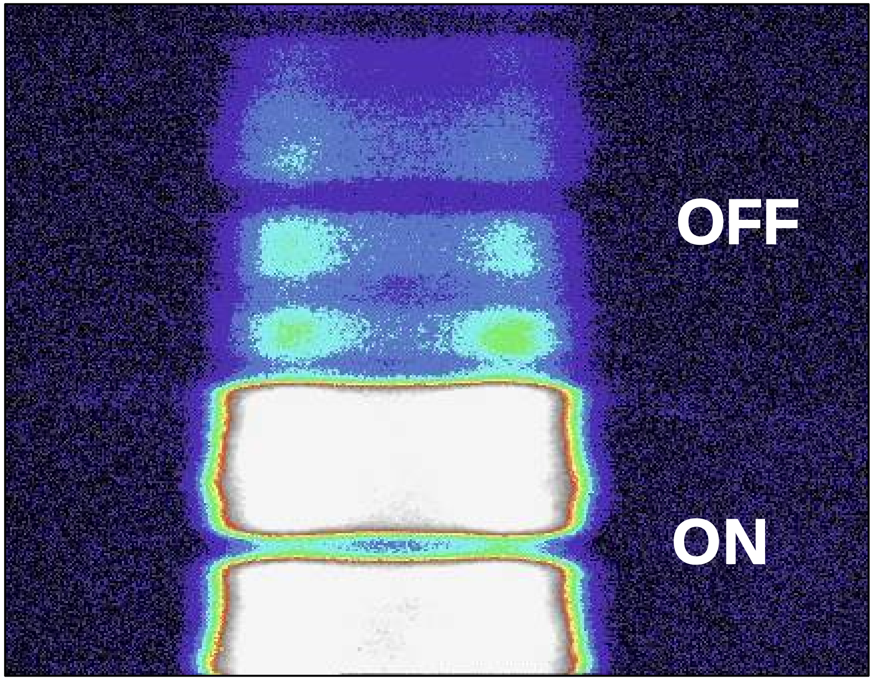
* http://www.rp-photonics.com

The Streak Camera insights [6]

Pockels cell based fast optical shutter

- Multi Bunch beam, 10% gap
- 4 turns; 864ns/turn
- ON-OFF switching time: <100ns

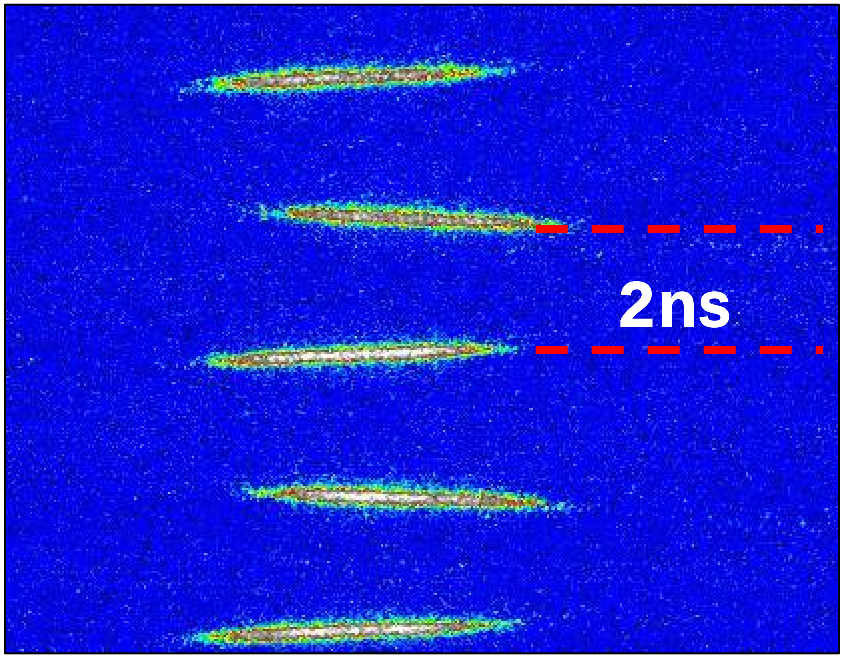


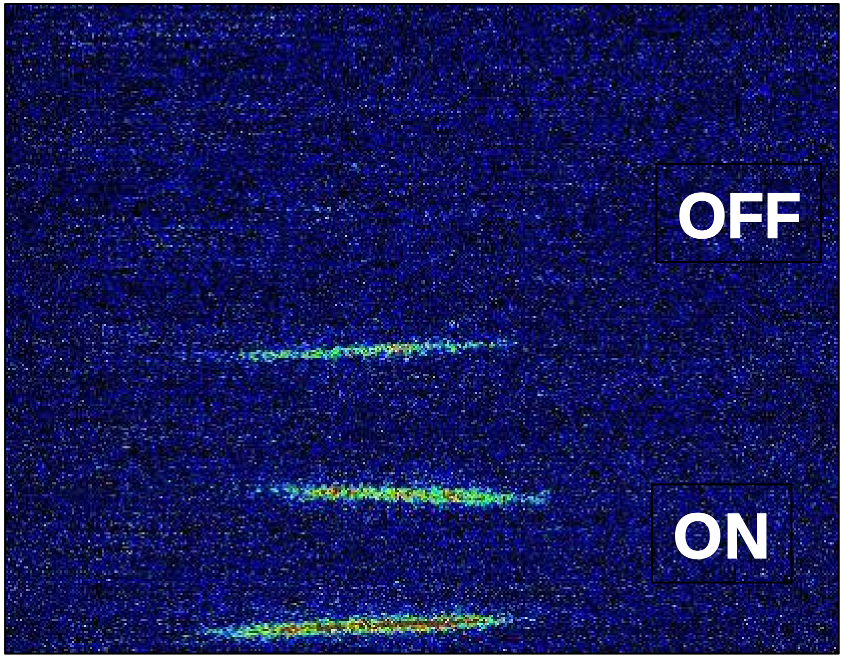


The Streak Camera insights [6]

Pockels cell based fast optical shutter

- Multi Bunch beam; 10% gap; 5 bunches
- ON-OFF switching time: <4ns!





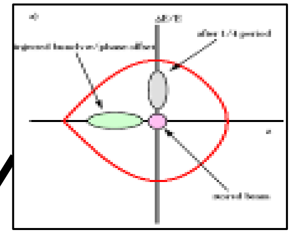
Examples of longitudinal diagnostics **[8]**

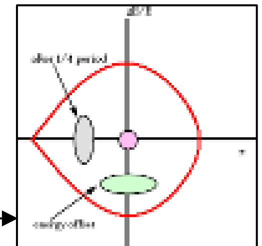
- **Injection transients in ALS** (1.5GeV e^- storage ring)
- Set-up: synchroscan streak camera triggered with injection
- Injection transient with:

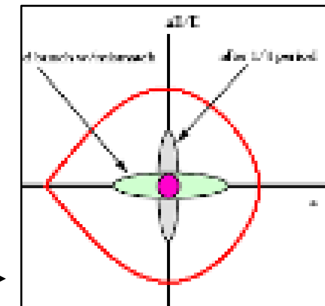
    energy offset

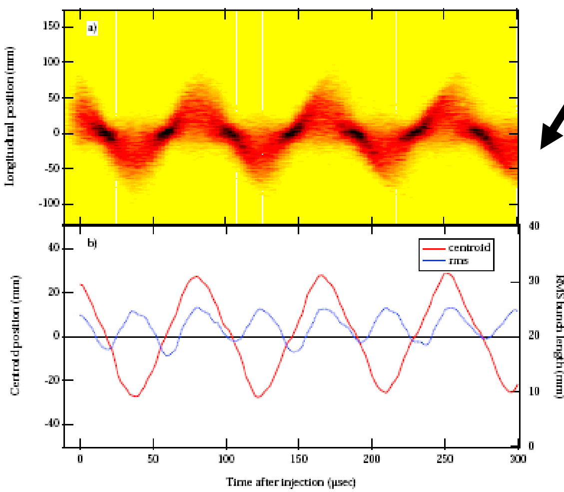
    phase offset

    phase mismatch

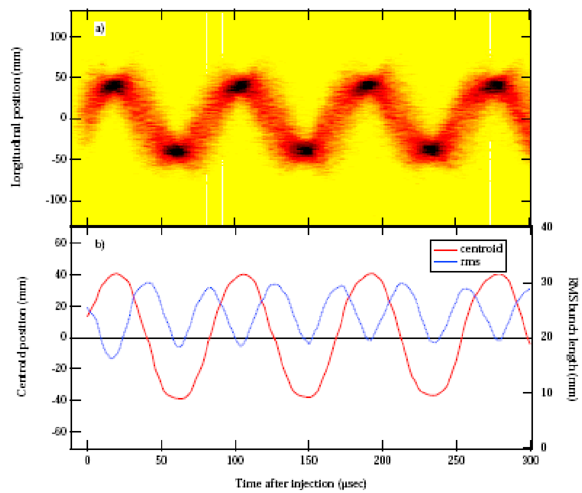




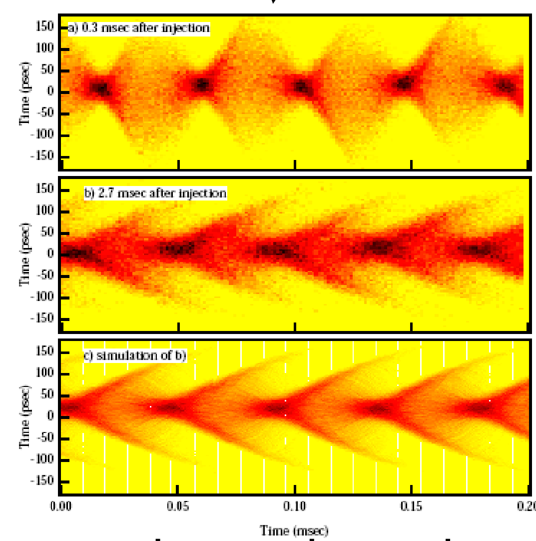




phase offset



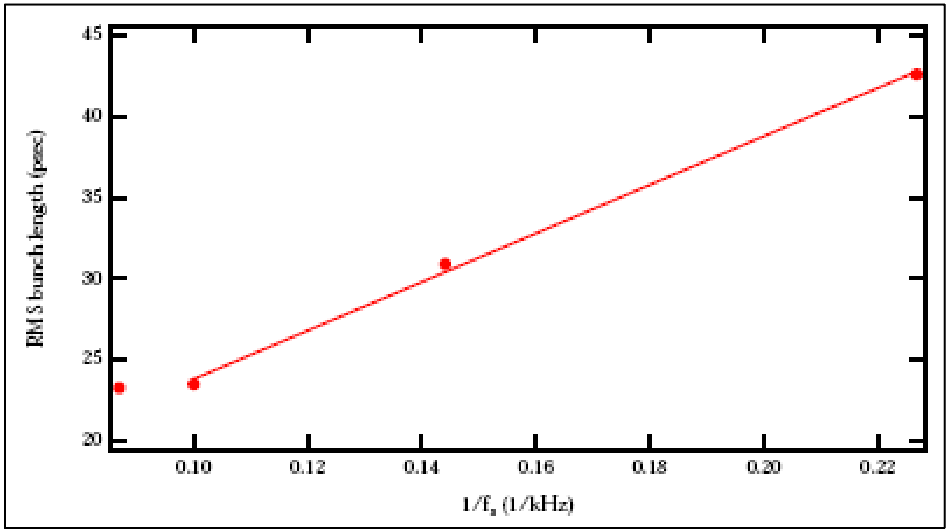
energy offset



phase mismatch

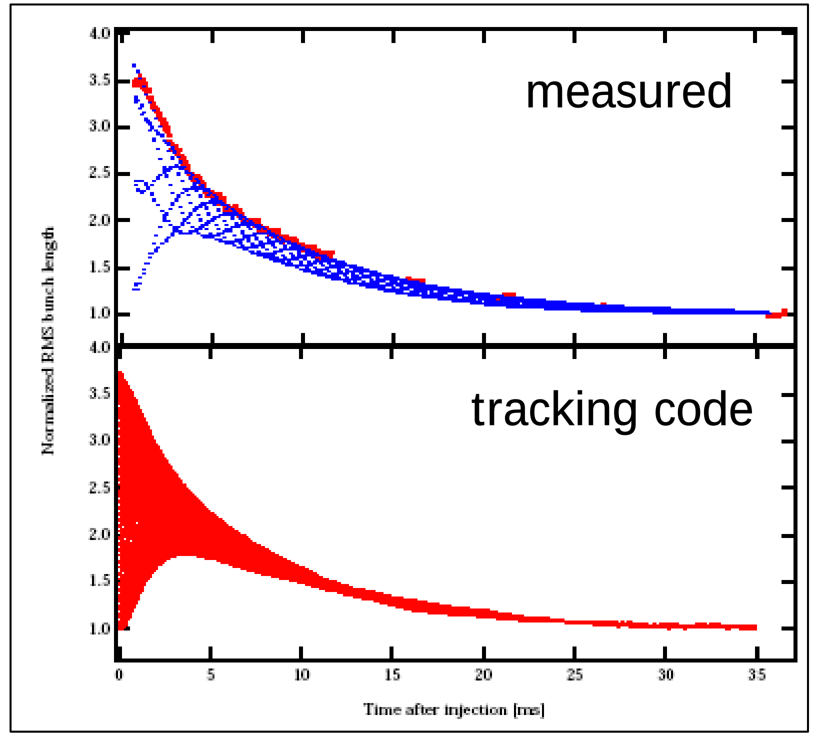
Examples of longitudinal diagnostics **[8]**

rms bunch length at minima of q-pole oscillations
vs. synchrotron frequency



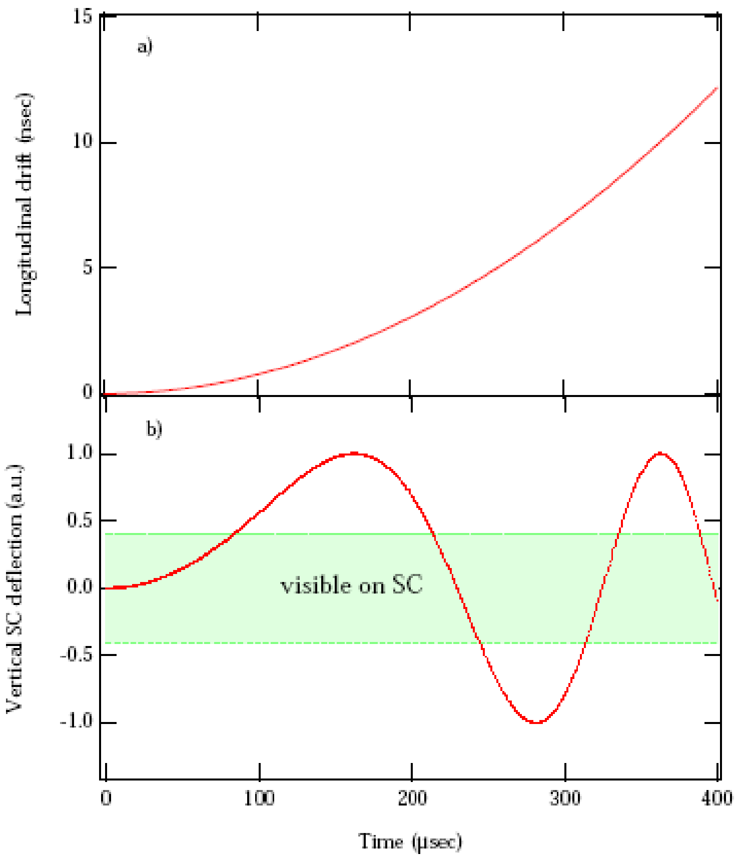
$$\sigma_{z,\min} = \frac{c\alpha}{2\pi f_s}\sigma_{\varepsilon 0}$$

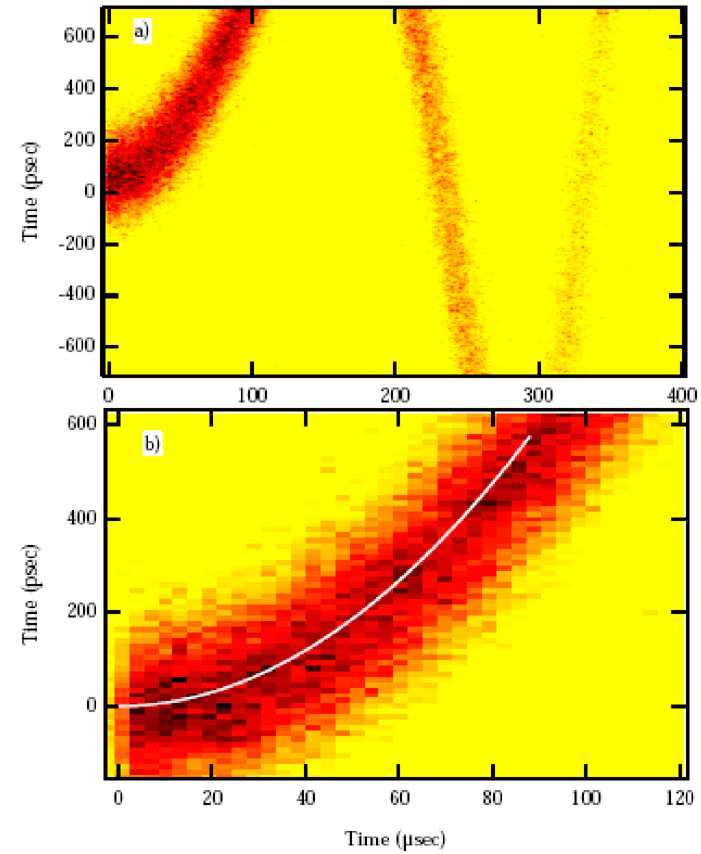
Measured peak rms bunch length over entire injection cycle



Examples of longitudinal diagnostics [8]

- Decaying with RF turned off:
  - no RF ➔ loose of E ➔ orbit spiral in-ward
  - ➔ orbit period T changes





$$\frac{\Delta T}{T_0} = \alpha \cdot \delta_{tot}$$

α moment compaction factor

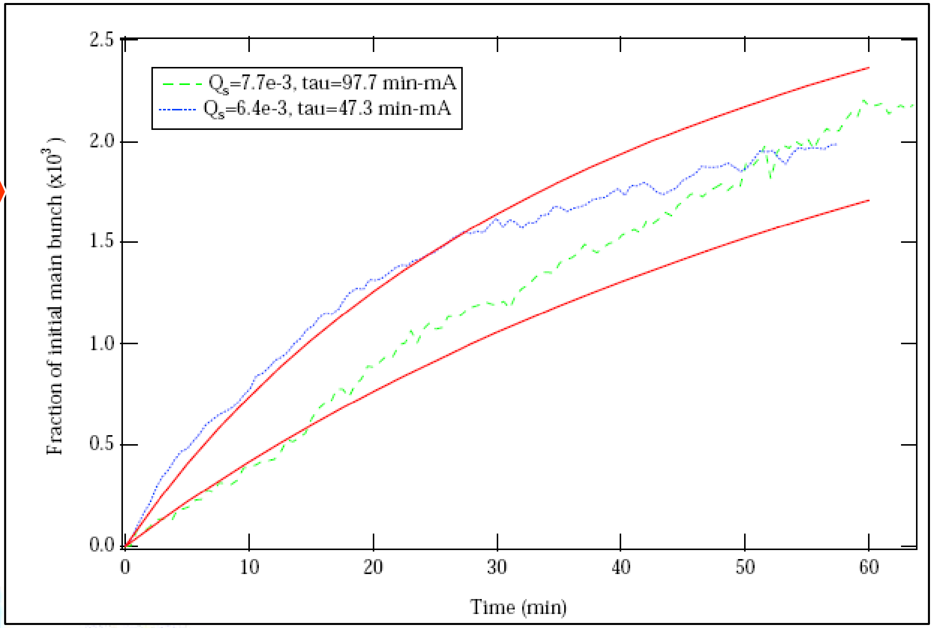
δ Fractional energy difference form injected energy

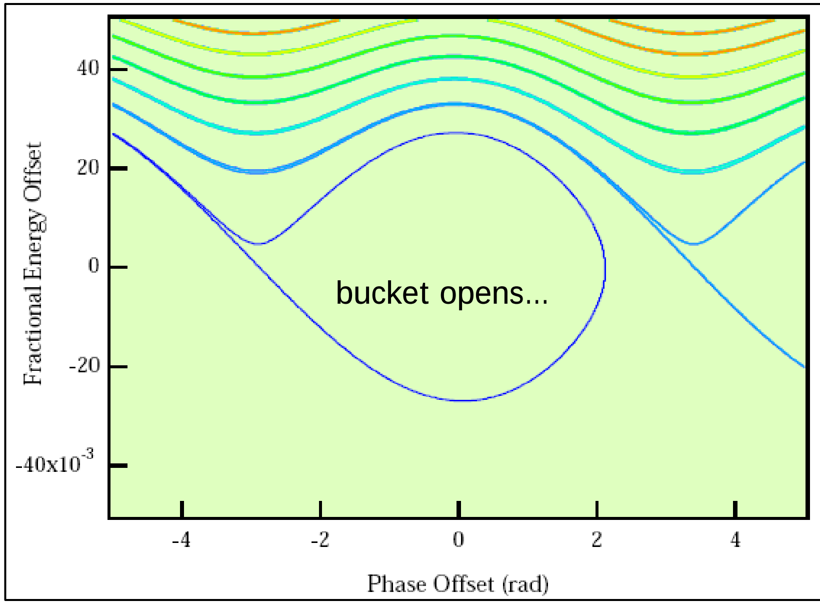
$\alpha>0$; $\delta<0$ ➔ ΔT decreases

Examples of longitudinal diagnostics **[9]**

- Nonlinear longitudinal dynamics studies at the ALS
- Diffusion bunch-to-bunch by radiation damping; low probability process
- May create parasitic bunches; affecting bunch purity
- Streak Camera measurements of single bunch and following parasites

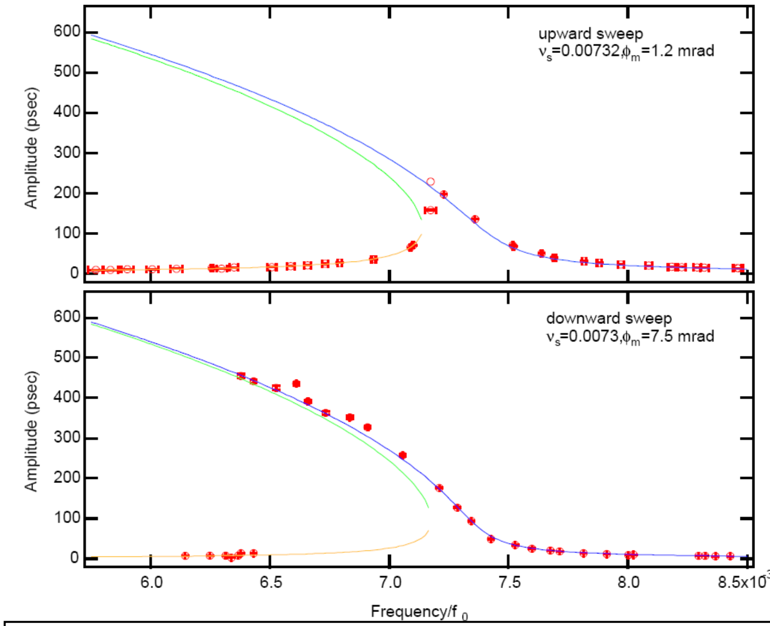
Measured charge in the parasite bunch relative to the main bunch for 2 different RF voltages. the solid lines for each data set are the calculated diffusion using the measured Touschek lifetime for each RF voltage.

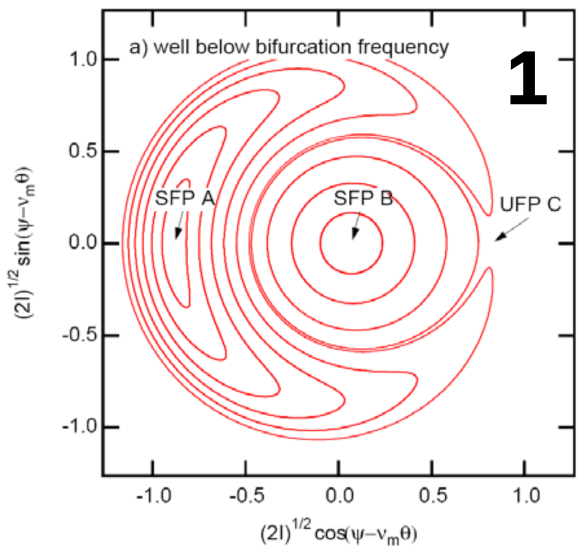


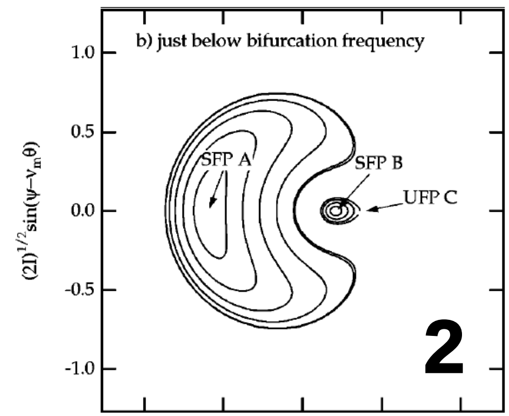


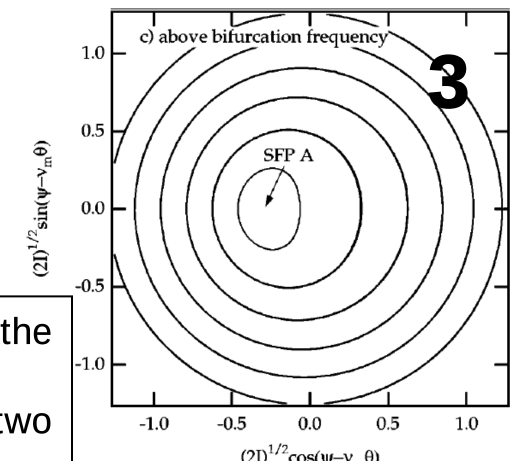
Observation of instabilities [9,10]

- Forced oscillations: driven by modulations bends / RF amp / RF phase
- Response of driven long oscillations
- Inter-island diffusion



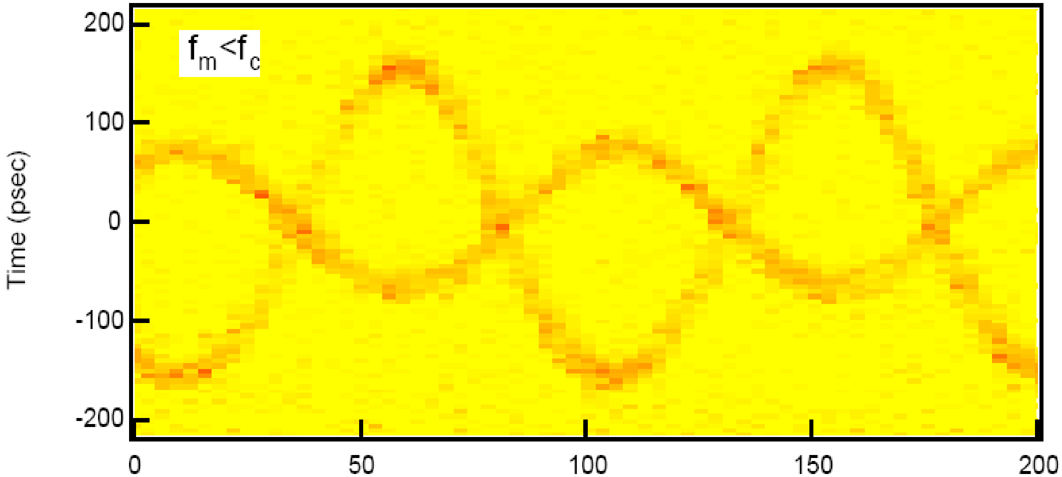






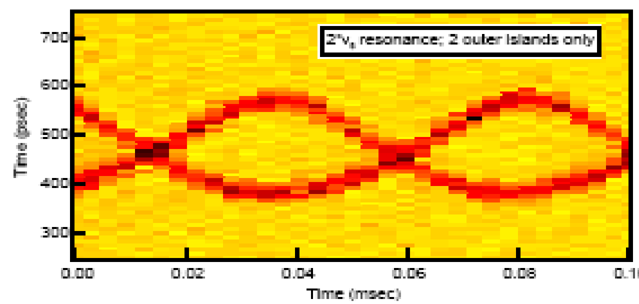
Poincare´ maps of the Hamiltonian in the resonant rotating reference frame for the case of three modulation frequencies.
In **1**, the modulation frequency is well below the bifurcation frequency and two separate stable islands appear.
In **2** the modulation frequency is just below the bifurcation frequency, and stable area *B* almost disappears.
Above the bifurcation frequency (**3**), only island *A* remains.
Note that islands *A* and *B* correspond to the negative and positive stable branches of the response curve shown in Fig. 1.

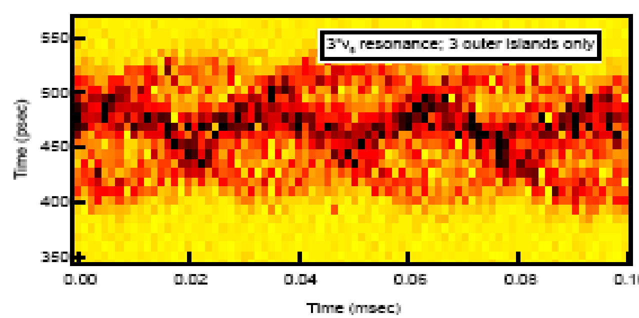
Observation of instabilities **[9, 10]**

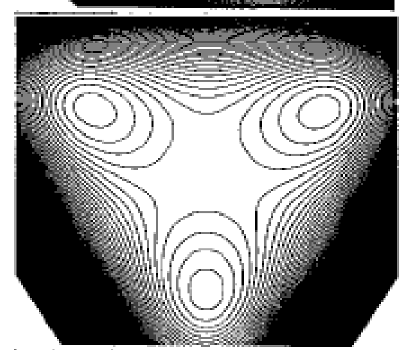


SC Image of the longitudinal profile when the modulation frequency is just below the bifurcation frequency.
The beam populates both stable phase space islands.

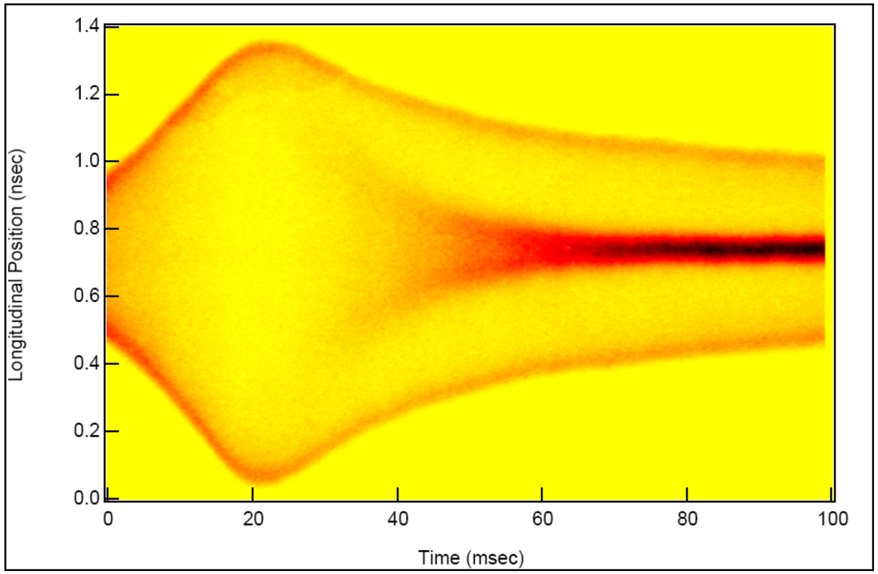
Measured SC image showing formation of two and three islands for excitation near 2**fs* and 3**fs*. The calculated phase space structure is also shown.





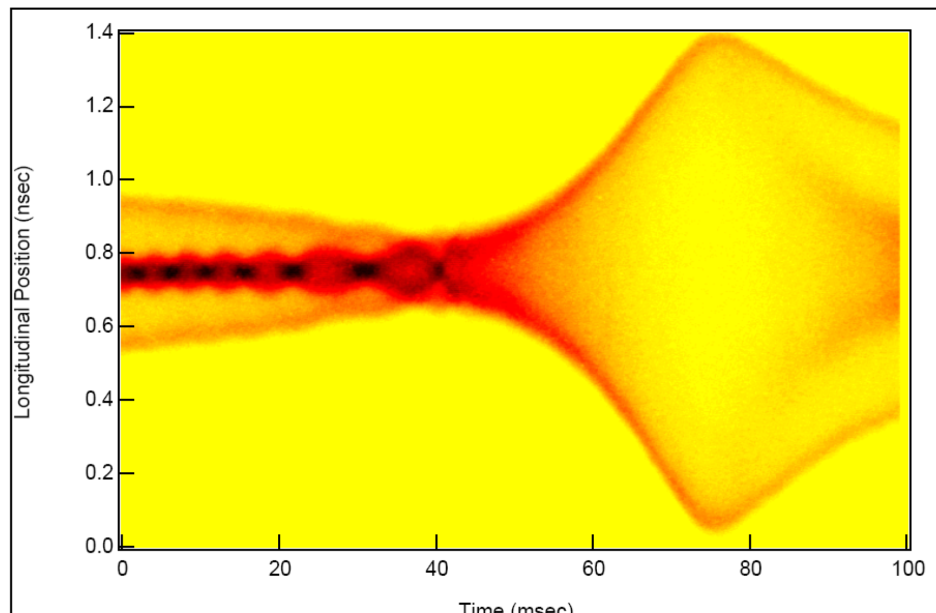


Observation of instabilities [11]

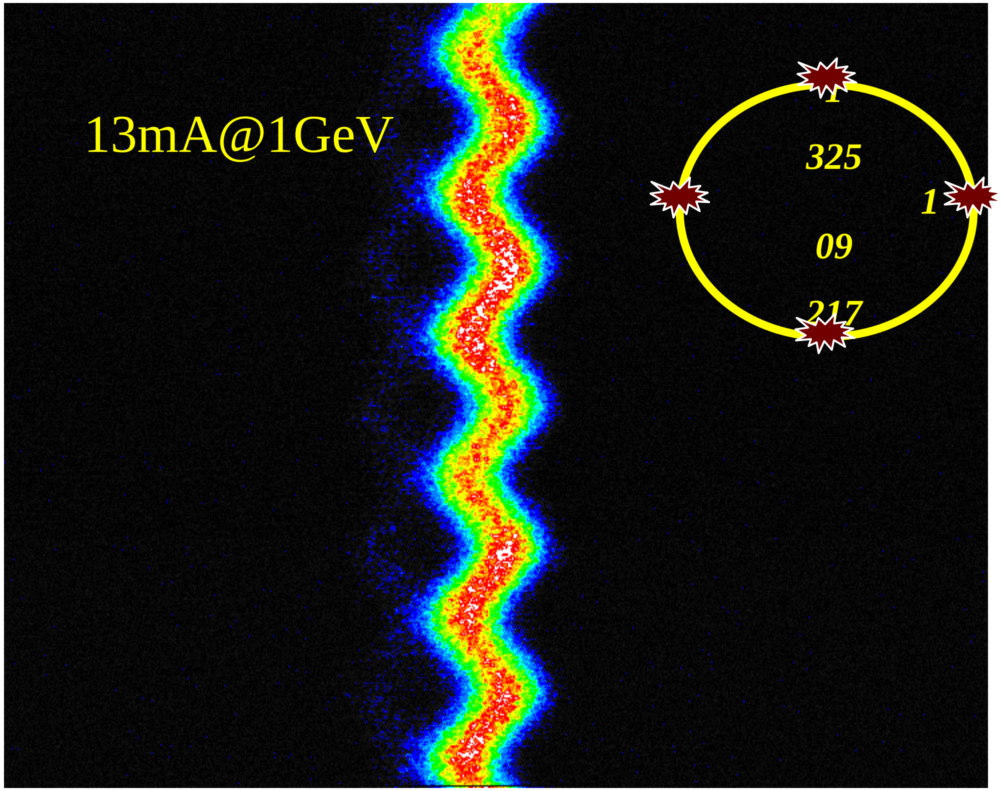


Saturation of an instability due to nonlinear effects.
Picture of a **Robinson instability**. Single bunch ≈mA.
Fundamental mode of the cavity is manually tuned above RF frequency to give Robinson instability

The effect is a saw-tooth like instability with a internal structure.
We see multiple fixed points being excited and populated with beam



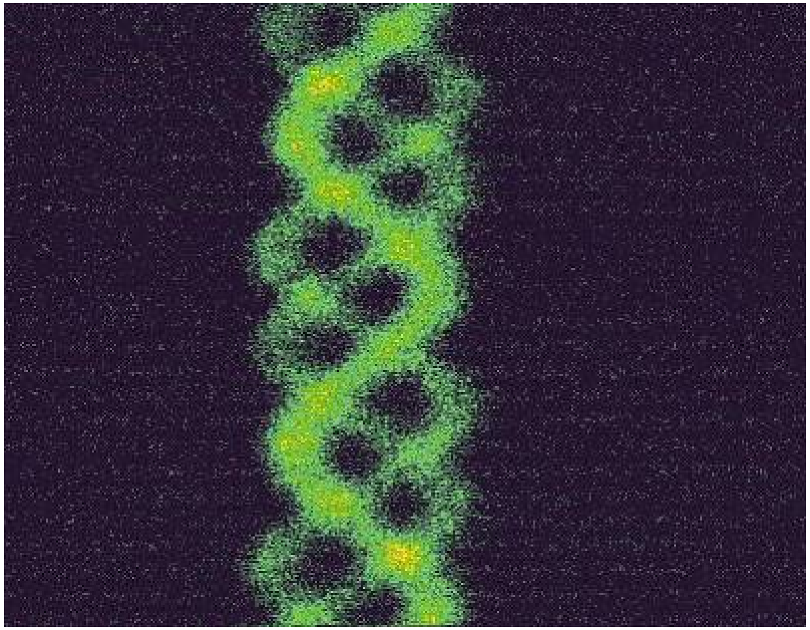
Observation of instabilities



SC Image taken at ELETTRA;
4 bunch beam 13mA@1GeV

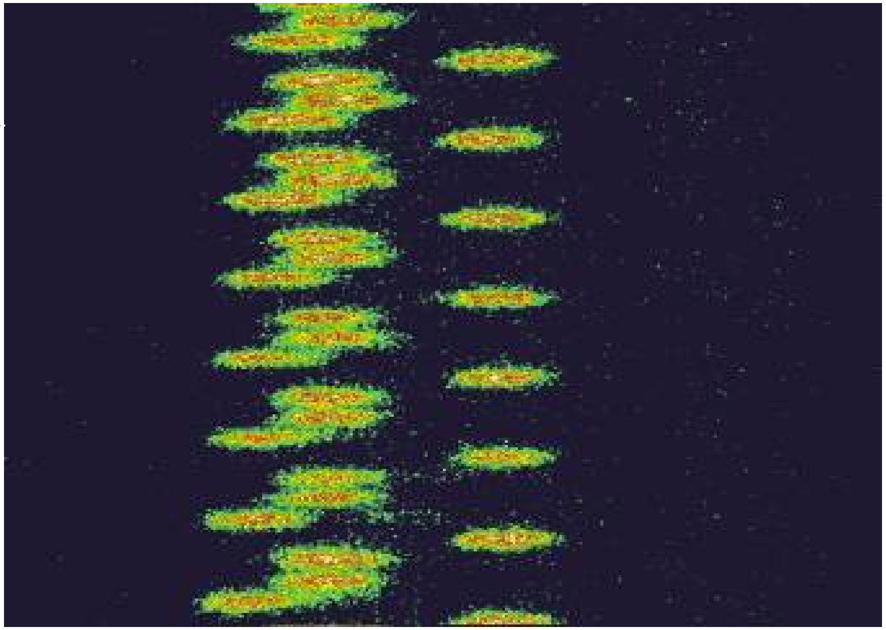
882ps x 65ms
in phase coherent
dipolar motion

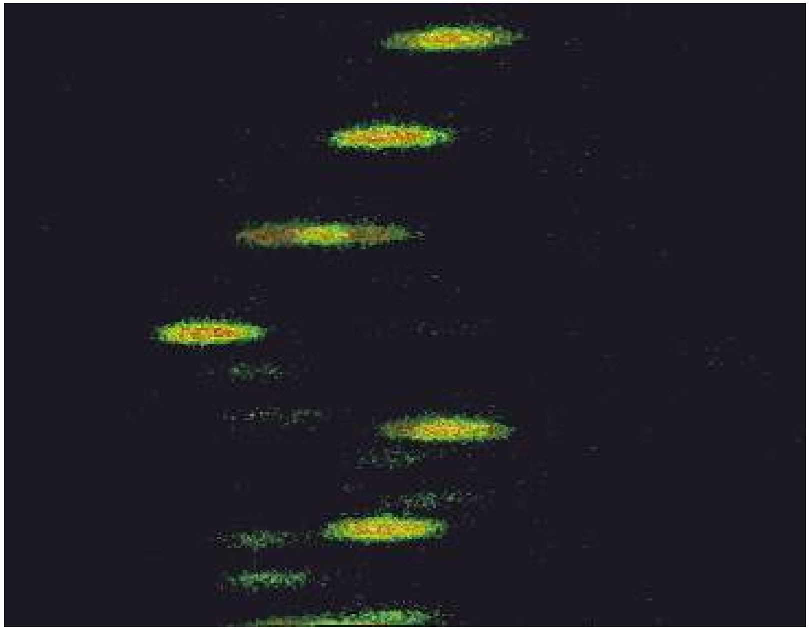
882ps x 37.5ms
3-phase
dipolar motion



Observation of instabilities

same beam as previous picture, but faster vertical scale:
2 bunches on the same phase; the other 2 on different phases

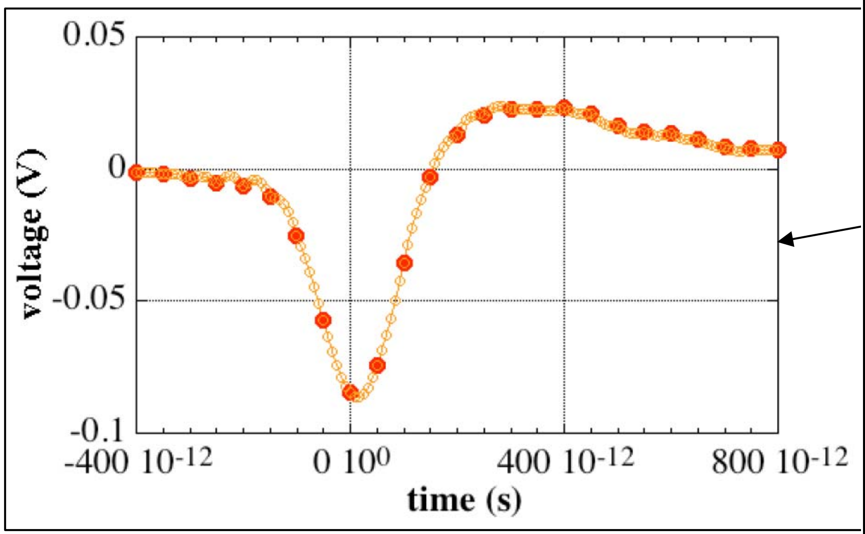


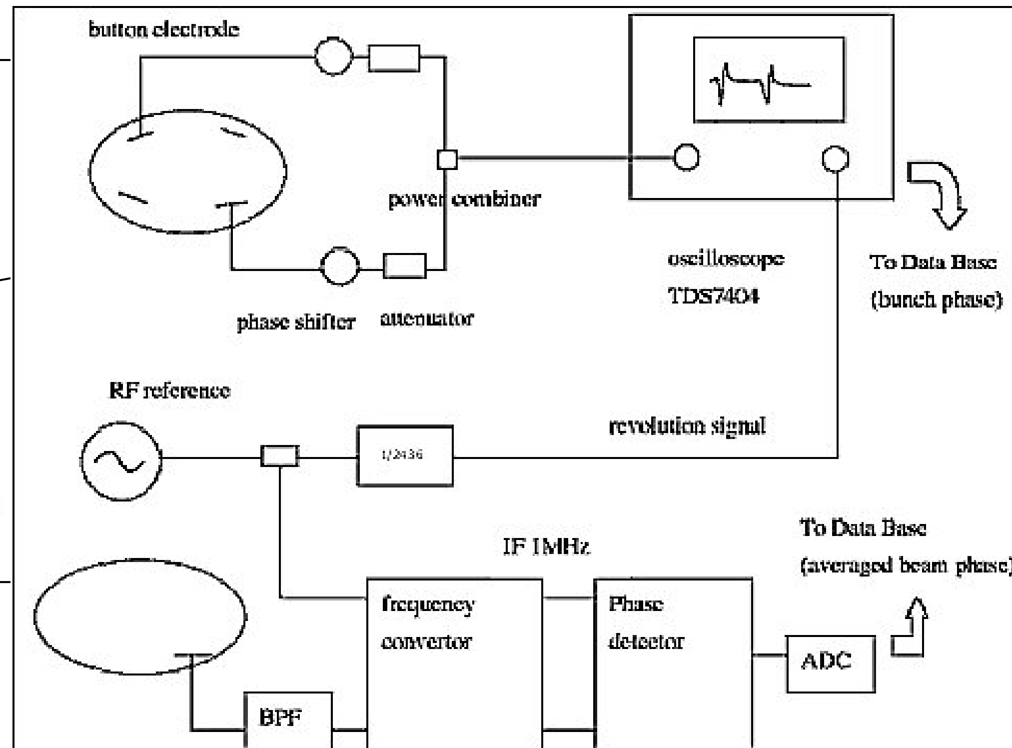


SC Image taken at ELETTRA;
4 bunch beam 32mA@1GeV
Each bunch is shifted

Examples of longitudinal diagnostics **[12]**

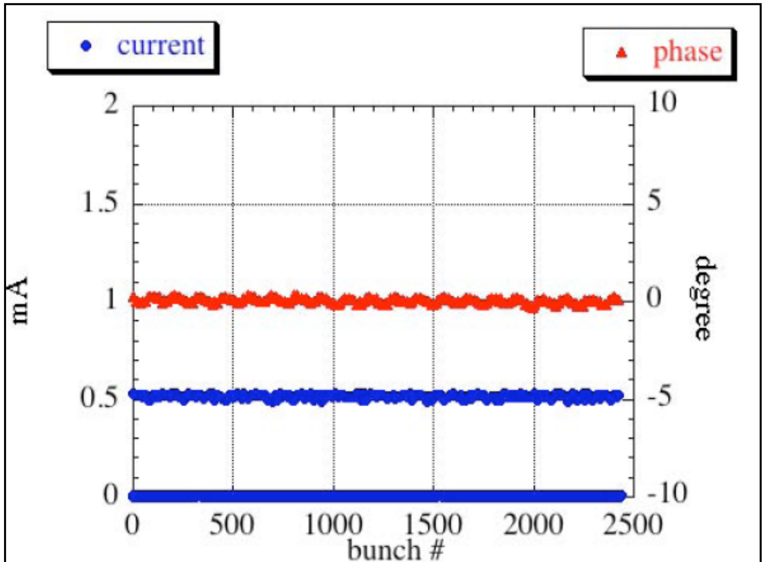
- Precise phase measurement of a specific bunch is required from the synchrotron radiation (SR) users (time resolved experiments)
- The timing of the SR light is affected by gap positions of insertion devices, filling pattern, bunch currents
- The bunch length of stored bunches is about 40ps
- The precision for the monitor system is <5ps (about 1^{o} of 508.58MHz RF)
- Two systems have been implemented...



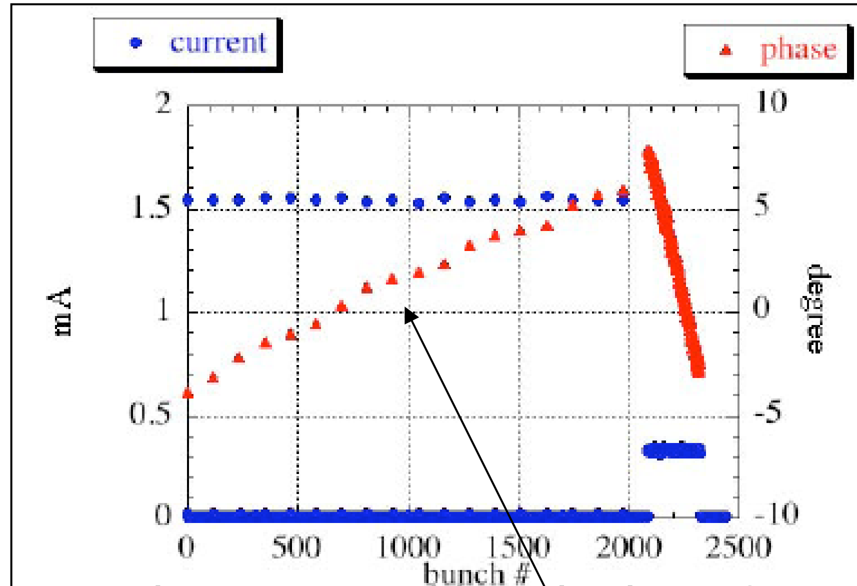


The analogue bandwidth of the scope TDS7404B is 4GHz and the sampling rate is 20Gs/s.

Examples of longitudinal diagnostics **[12]**

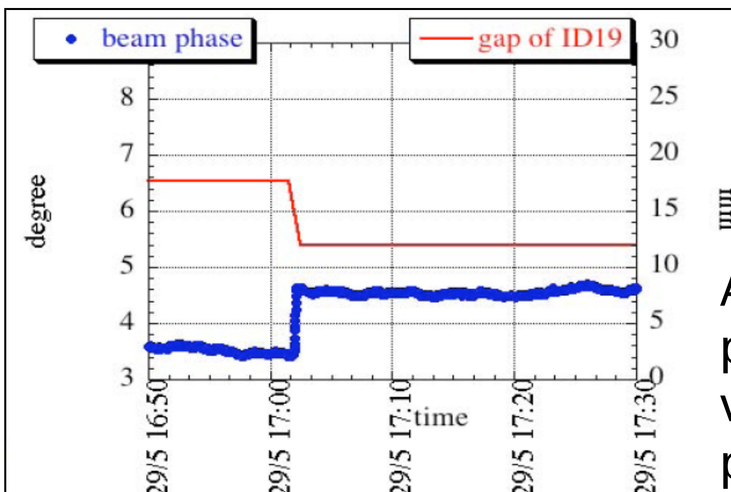


Bunch current and phase for 203 equally spaced bunches



Bunch current and bunch phase for a filling pattern of 18 singles and 232 bunch trains

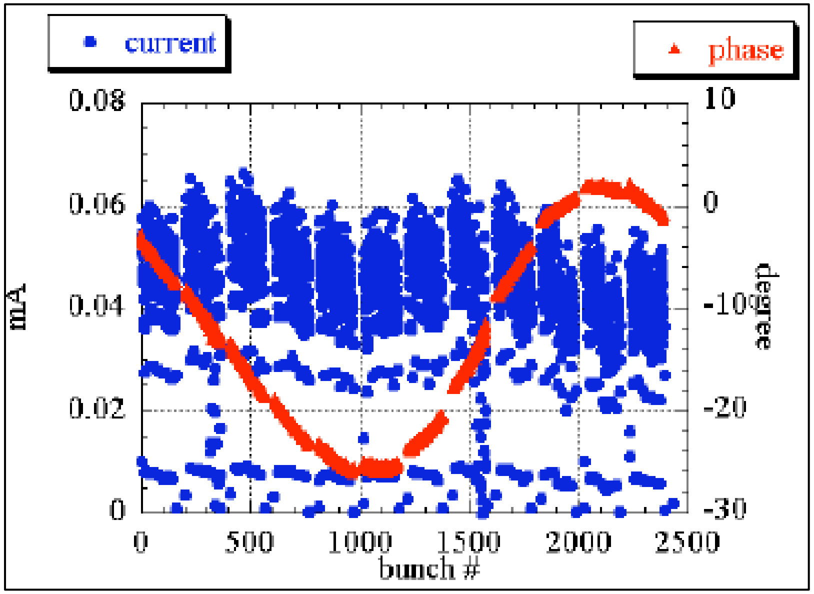
Effect of beam loading reducing Vacc



Average beam phase vs. ID gap position

Examples of longitudinal diagnostics **[12]**

- An attempt was tried to store the beam with the energy of 4GeV instead of nominal energy of 8GeV.
- In this case the damping time becomes long and longitudinal instabilities are observed.
- To overcome this instability, a modulation of accelerating voltage was applied; where acceleration voltage of 3MV was produced with nominal RF frequency while 1MV was applied with nominal RF frequency plus one revolution frequency.
- The RF voltage is modulated in one turn and the synchrotron frequency is changed according to the bunch address. By applying this RF modulation it was possible to accumulate up to 100mA

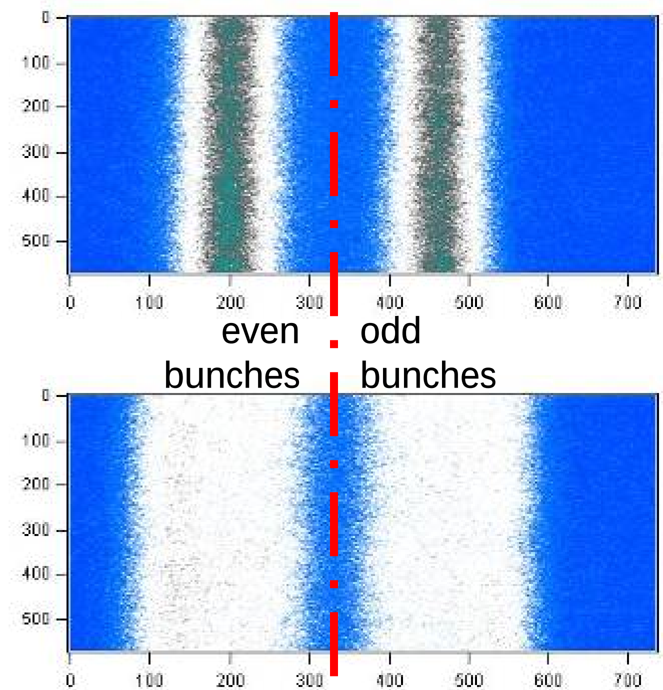


Longitudinal manipulation [13]

- An idle (passive mode) 3rd harmonic cavity (3HC) has been installed and fully characterized at Elettra
- The harmonic voltage generated by the beam passing through the cavity depends on the frequency detuning

$$V_{harm} \approx I_b \cdot \frac{R}{Q} \cdot \frac{\omega_{res}}{\delta_\omega}$$

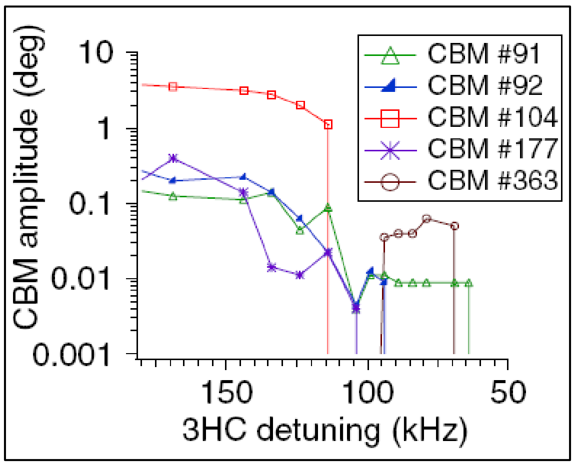
- The following effects have been observed and studied:
  - Landau Damping / CBM reduction / Lifetime improvements
  - Phase shift
  - Bunch lengthening / overstretching
  - Bunch shortening
- 3HC flattens the potential in the main RF bucket causing an increase in the bunch length with a consequent reduction of the intra-beam scattering ➔ an improvement in the Touschek lifetime
- Also, the non-linearity of the RF waveform helps in fighting the coupled bunch instabilities (CBM) by means of *Landau damping: s*ynchrotron frequency dependence on the amplitude; spread in synchrotron frequencies within bunches



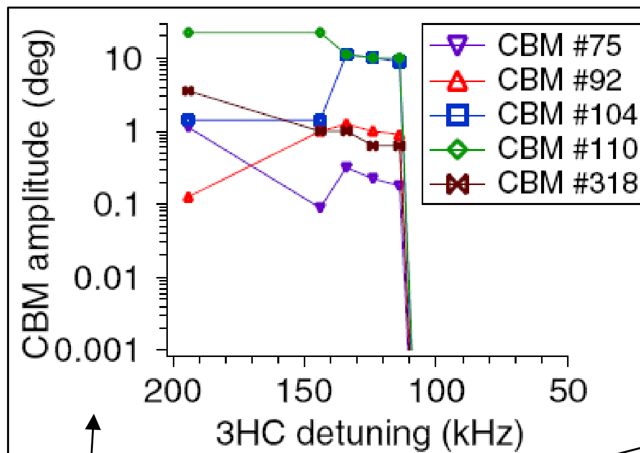
3HC effect on a Multi Bunch beam (uniform filling) at detuning frequencies of 200kHz (upper) and 60kHz (lower)

Longitudinal manipulation[13]

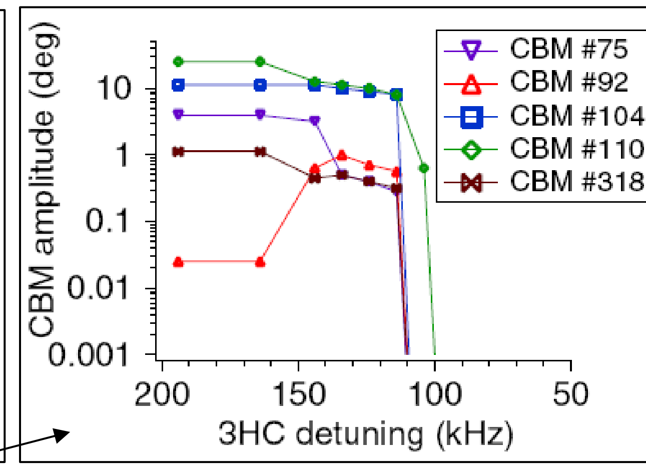
- With 3HC detuned (away from the 3rd harmonic), a large gap leads to some Landau damping
- When 3HC gets closer to the 3rd harmonic the Landau damping effect due to 3HC is dominant over the one from the "large gap"
- For I_{beam} =315mA and E =2.0GeV



CBMs amplitude versus 3HC tuning for a 70% SR filling



CBMs amplitude versus 3HC tuning for a 90% SR filling



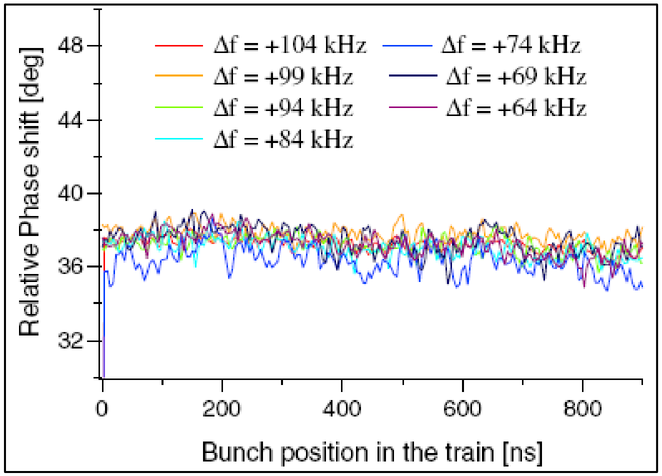
CBMs amplitude versus 3HC tuning for a uniform filling

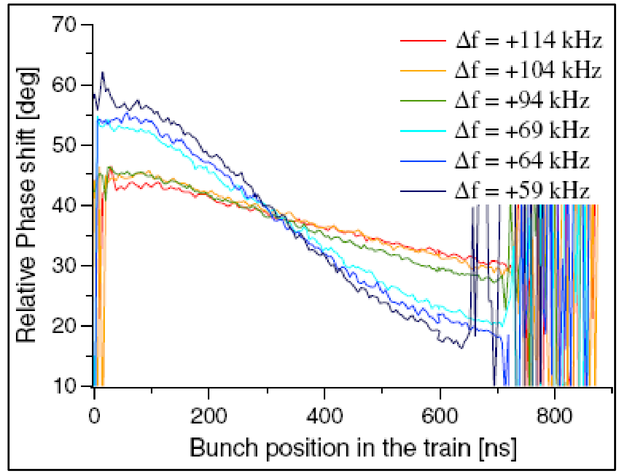
For uniform filling, the Landau damping is provided only by 3HC, while in the case of fractional filling the gap too contributes to the damping, while not allowing a completely stable beam, unless 3HC is activated

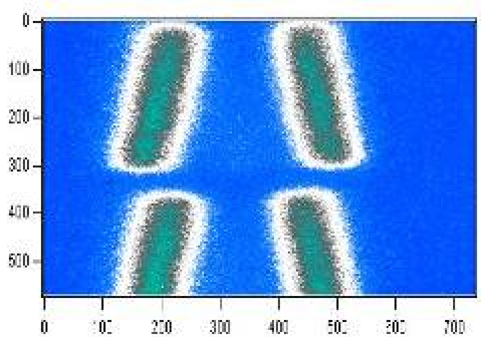
Longitudinal manipulation [13]

- Phase shift head-tail introduced by the gap:

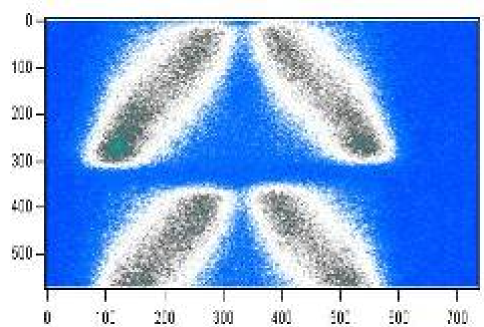
uniform filling **80 % gap**





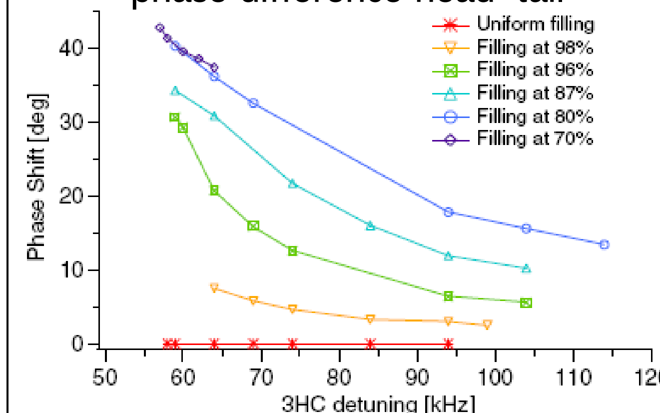


δω=100kHz



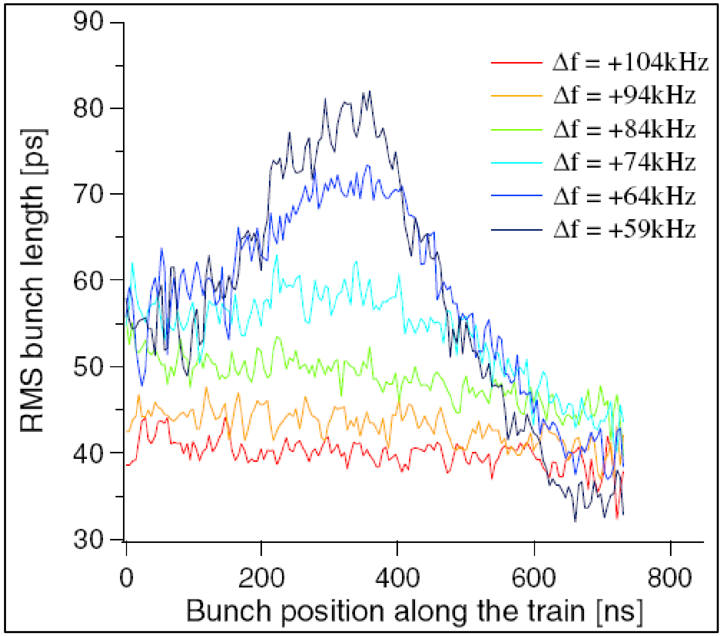
δω=60kHz

The larger the gap, the larger is the phase difference head–tail

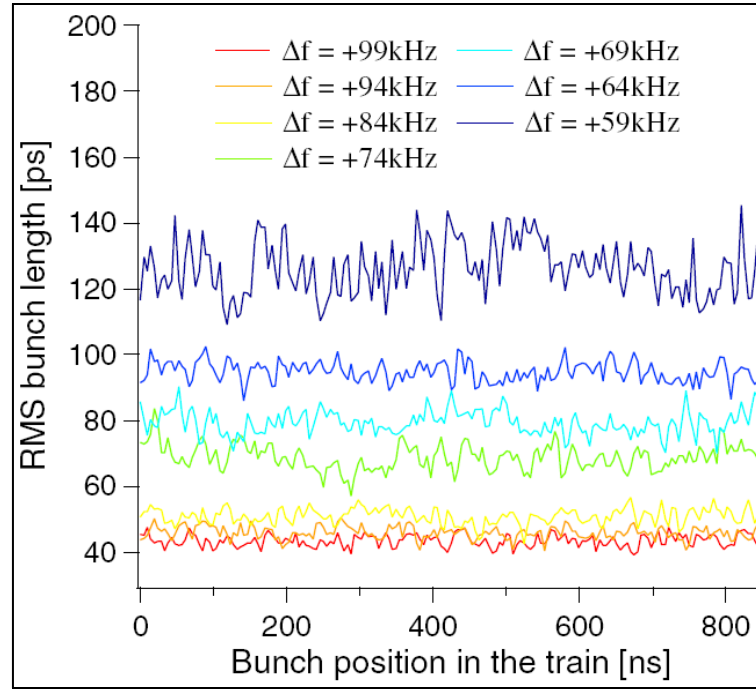


Longitudinal manipulation [13]

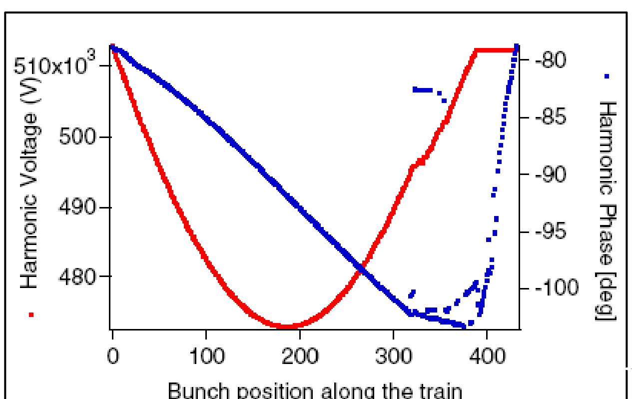
- Bunch lengthening vs. fractional filling



RMS bunch length along the bunch train for several 3HC tuning with a filling of 90%



RMS bunch length along the bunch train for several 3HC tuning with a uniform filling

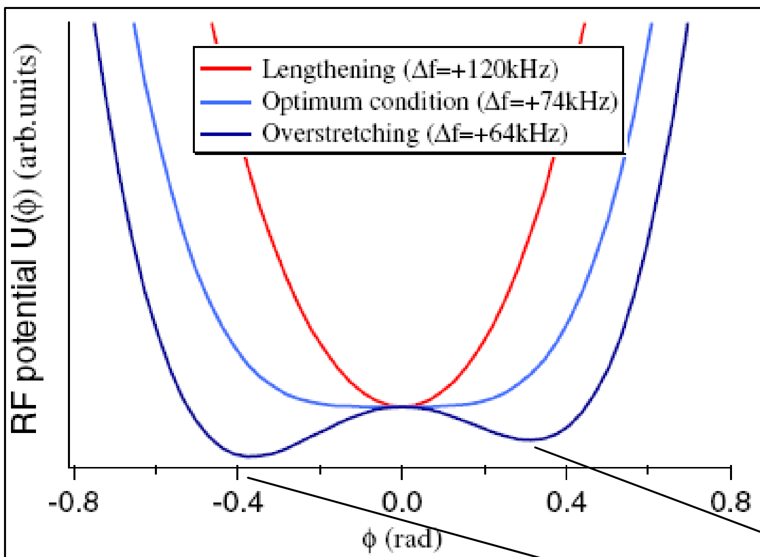


ESRF code results of the harmonic voltage (red) and phase (blue) modulation along the bunch train after the transient beam loading, obtained for a beam current of 315 mA, a 90% filling (3HC detuning=81 kHz)

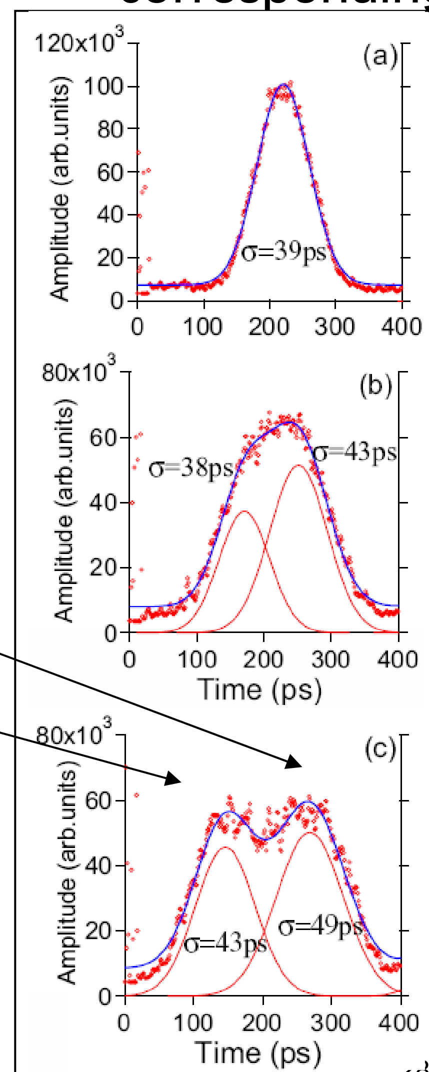
Longitudinal manipulation [13]

- Bunch over-stretching

The streak camera data acquired at different 3HC detuning with the corresponding best fitting curve.



Potential well distortion in lengthening mode, at optimum condition (flattened) and in over-stretching regime, calculated for I_{beam}=315mA



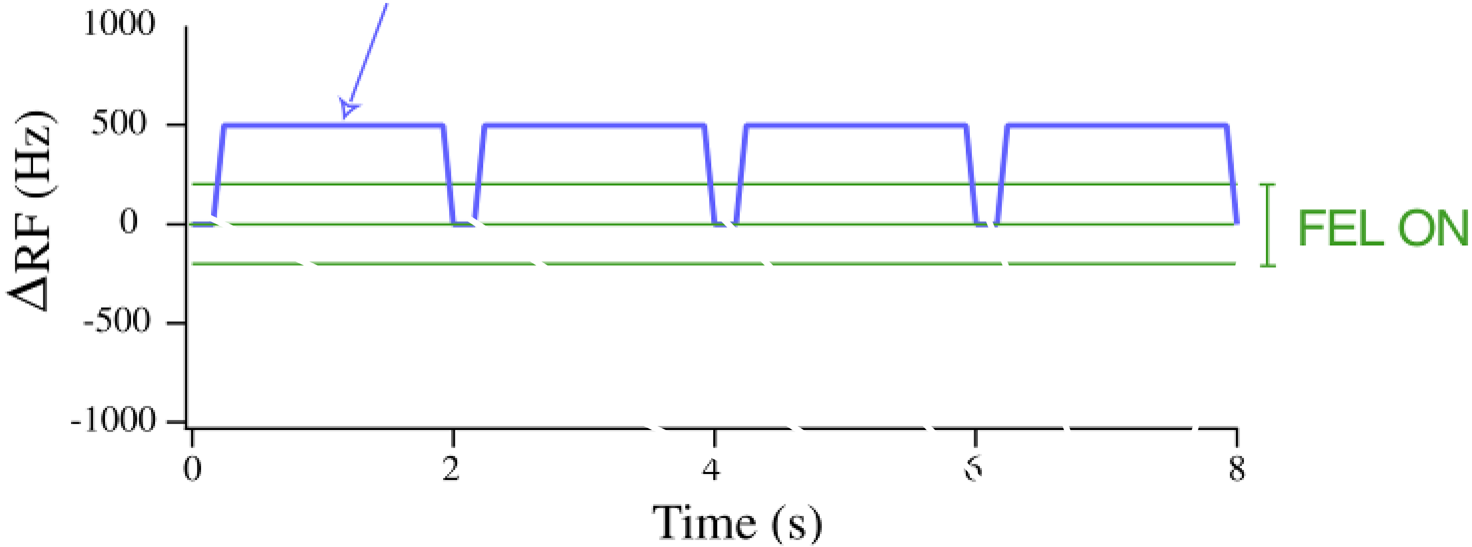
At **114 kHz** the bunch profile is still well fitted by a single Gaussian

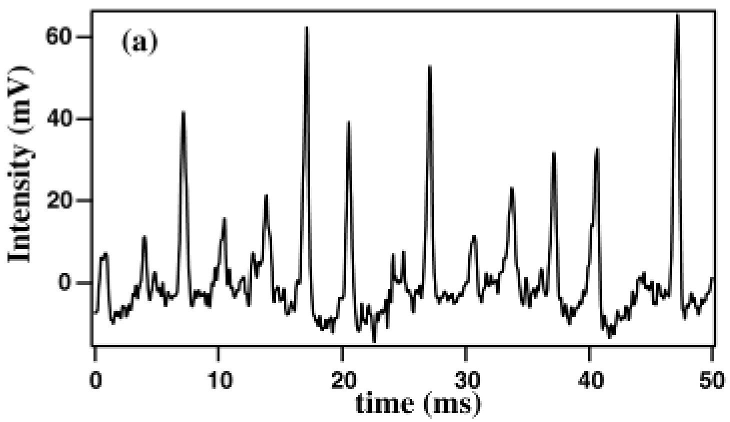
At **74 kHz** corresponding to a flattened potential, the bunch profile should be flat, so that the sum of 2 Gaussians provides the best data fitting

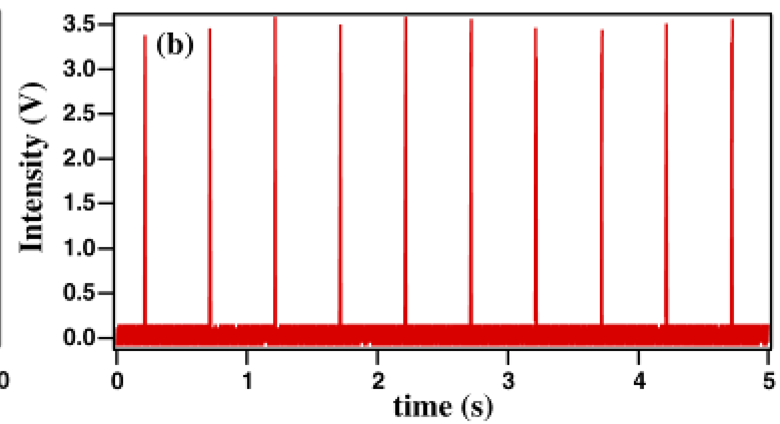
At **64 kHz** and the bunch profile appears strongly overstretched, with two well-separated stable peaks

Examples of longitudinal diagnostics

- Storage Ring FEL measurements





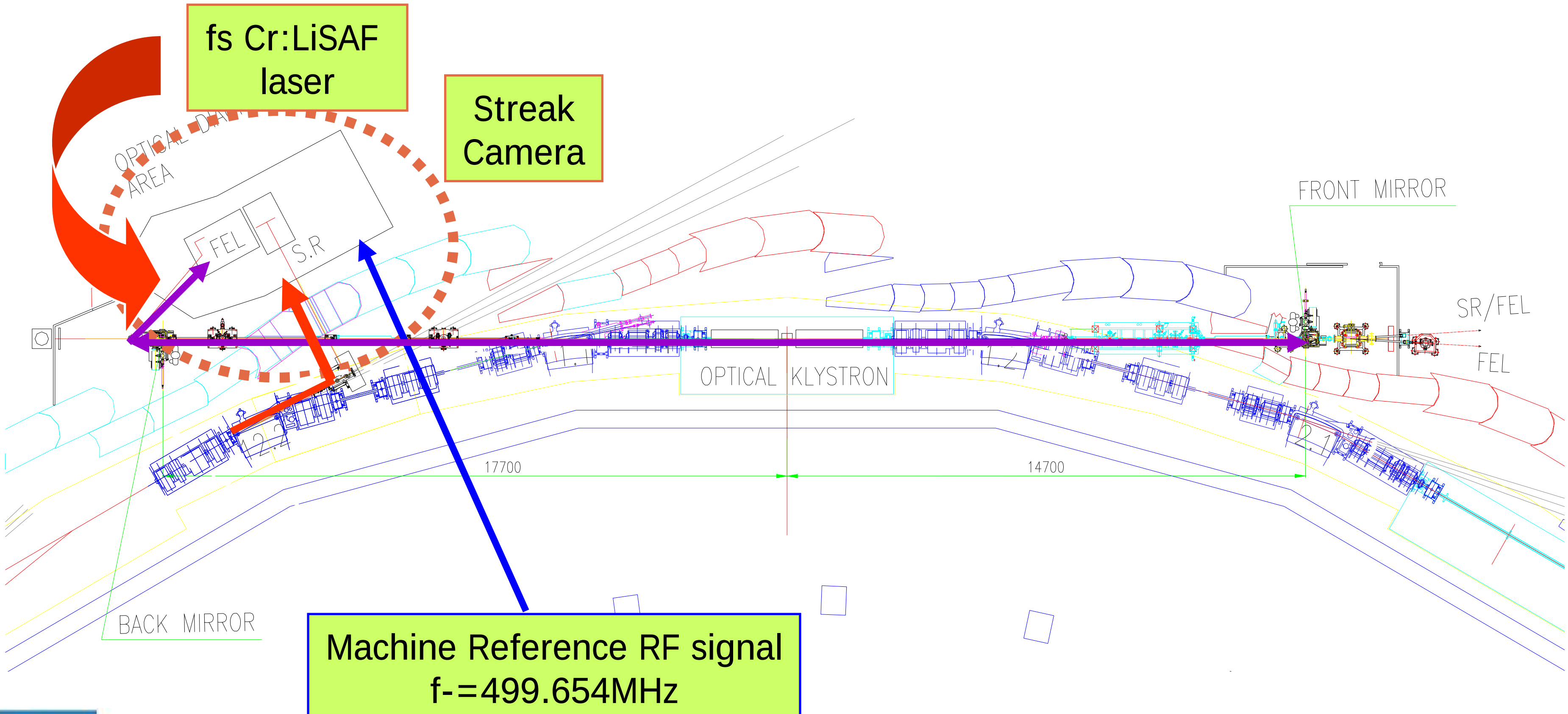


Free running **Q-Switch**

courtesy: G. De Ninno

Examples of longitudinal diagnostics

- Lay out of section 1 of the ELETTRA Storage Ring with diagnostics Optical Laboratory
- Three sources have been made available at the same location:
  - Synchrotron Radiation from Bending magnet **B12.2**
  - SR FEL
  - fs Cr:LiSAF laser

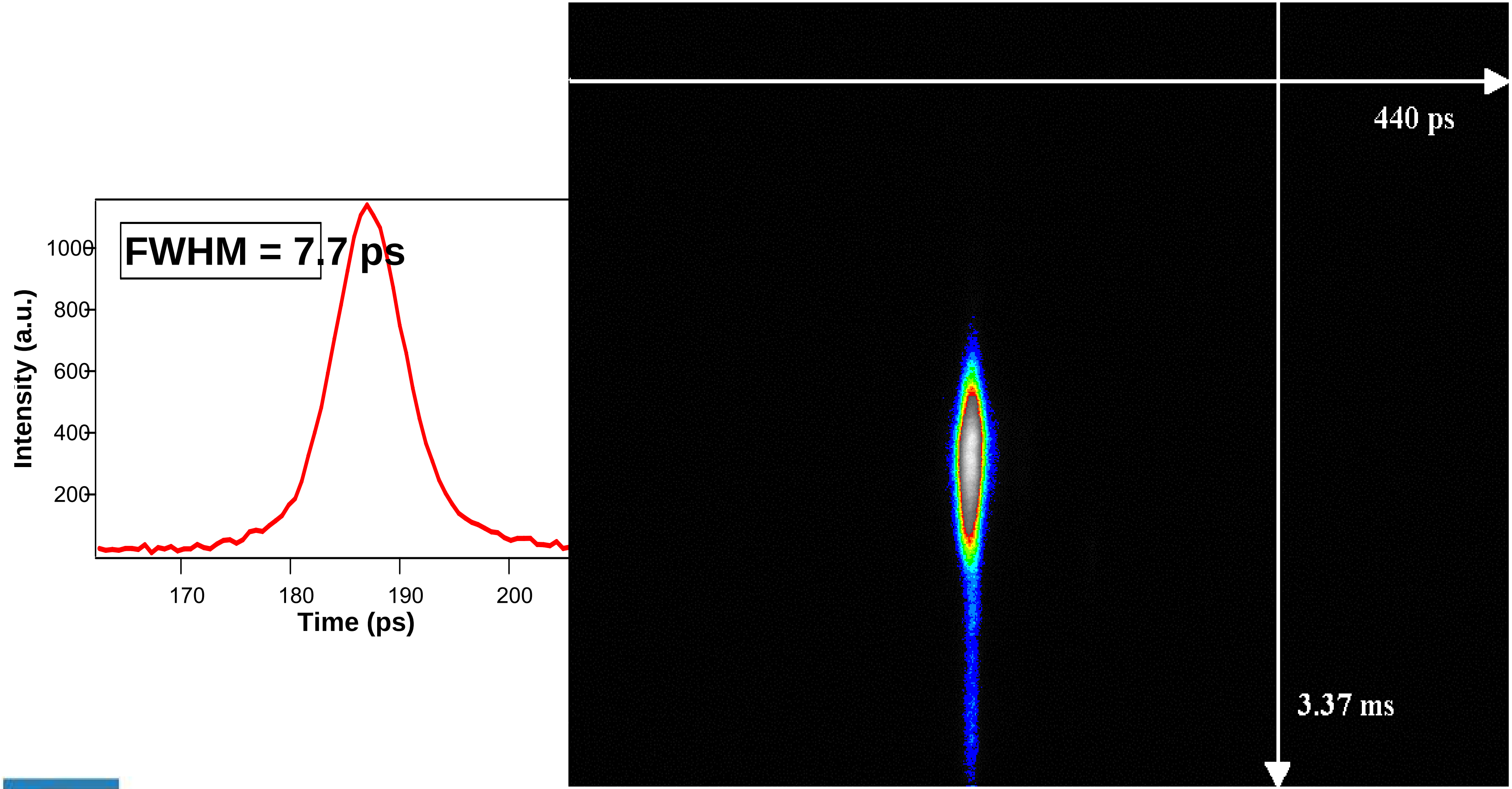


Examples of longitudinal diagnostics **[14]**

- Cr:LiSAF laser in Optical laboratory hutch; Streak Camera in foreground

Examples of longitudinal diagnostics

- UV FEL streak camera acquisition:
  λ=196nm, length=7.7ps FWHM



Examples of longitudinal diagnostics [14]

- Fs laser synchronization to the Storage ring: table of frequencies

f_{RF}=499.654MHz

Multi Bunch
1 bunch / 2ns

÷5

$f_{REP1}=f_{RF}\div 5 = 99.9308\text{MHz}$

$t_{LASER} = 10.006\text{ns} \Rightarrow$
1 laser pulse / 5 bunches

Coincidence laser on same bunch: every 5 revolutions (864/10 = 86.4ns)

4-Bunch SR-FEL
1 bunch / 216ns

÷6

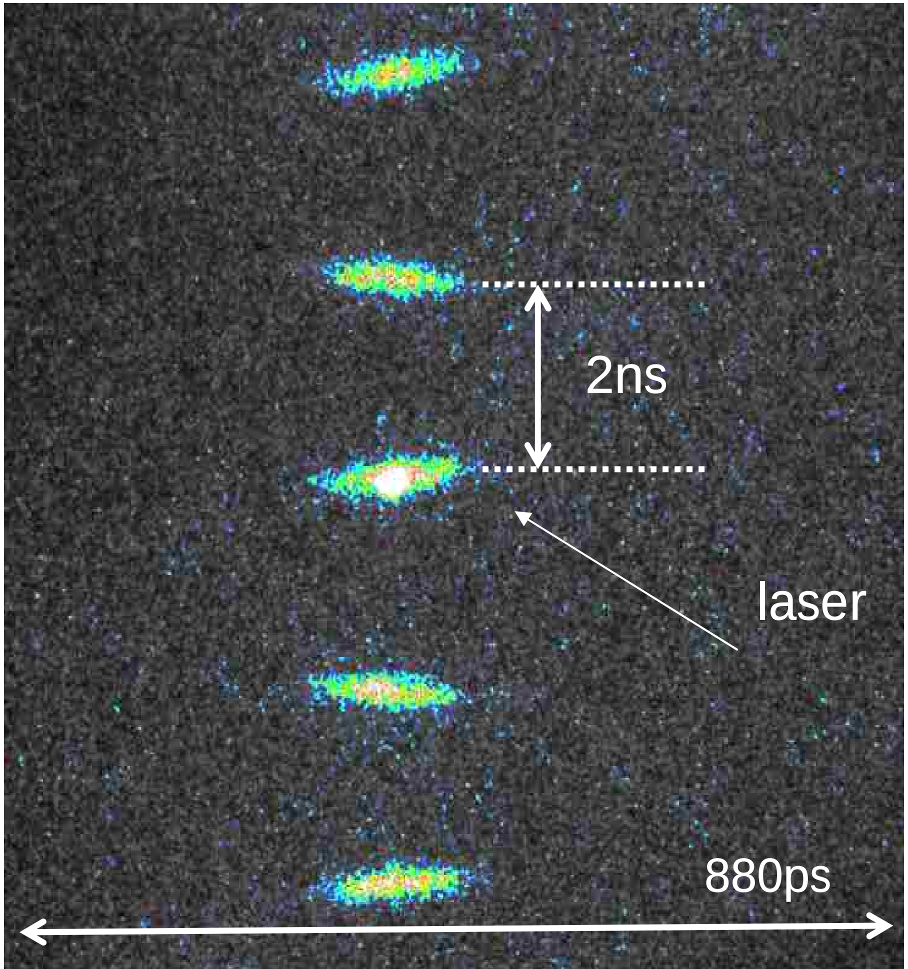
$f_{REP2} = f_{RF}\div 6 = 83.2756\text{MHz}$

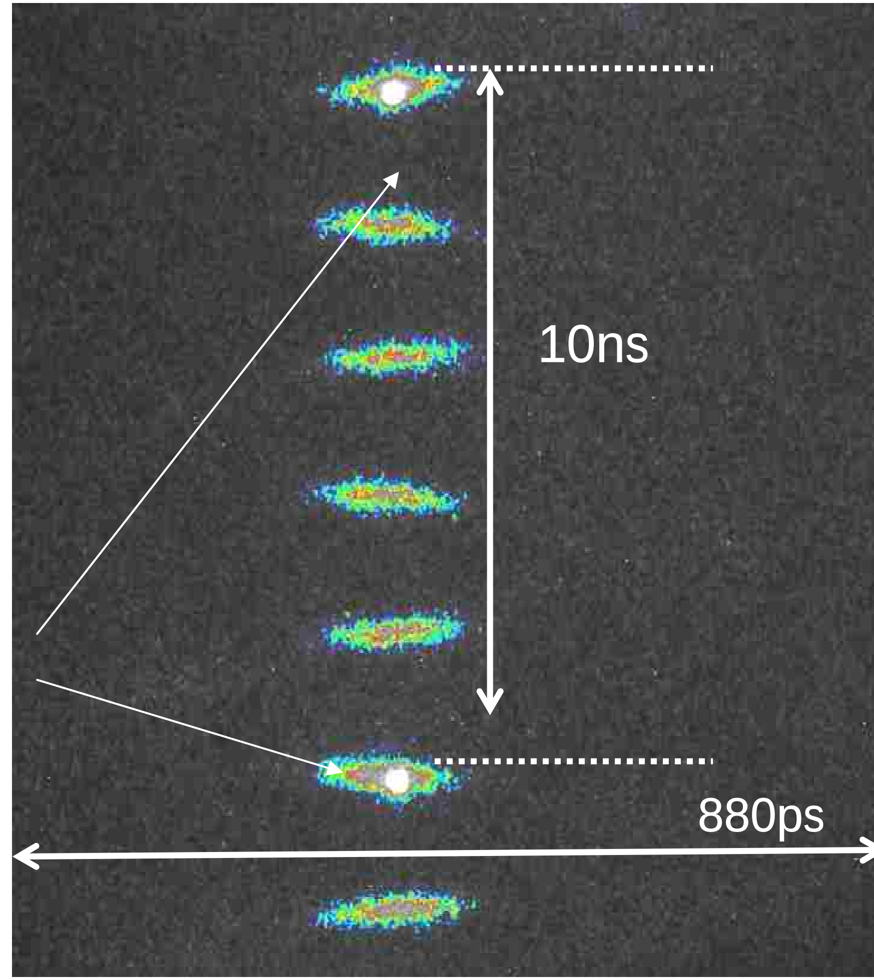
$t_{LASER} = 12.006\text{ns} \Rightarrow$
18 laser pulses / bunch (4B)
(12ns*18=216ns)

Coincidence laser on same bunch: at each turn

Examples of longitudinal diagnostics **[14]**

- Streak camera synchroscan acquisitions
  Multi Bunch beam + laser

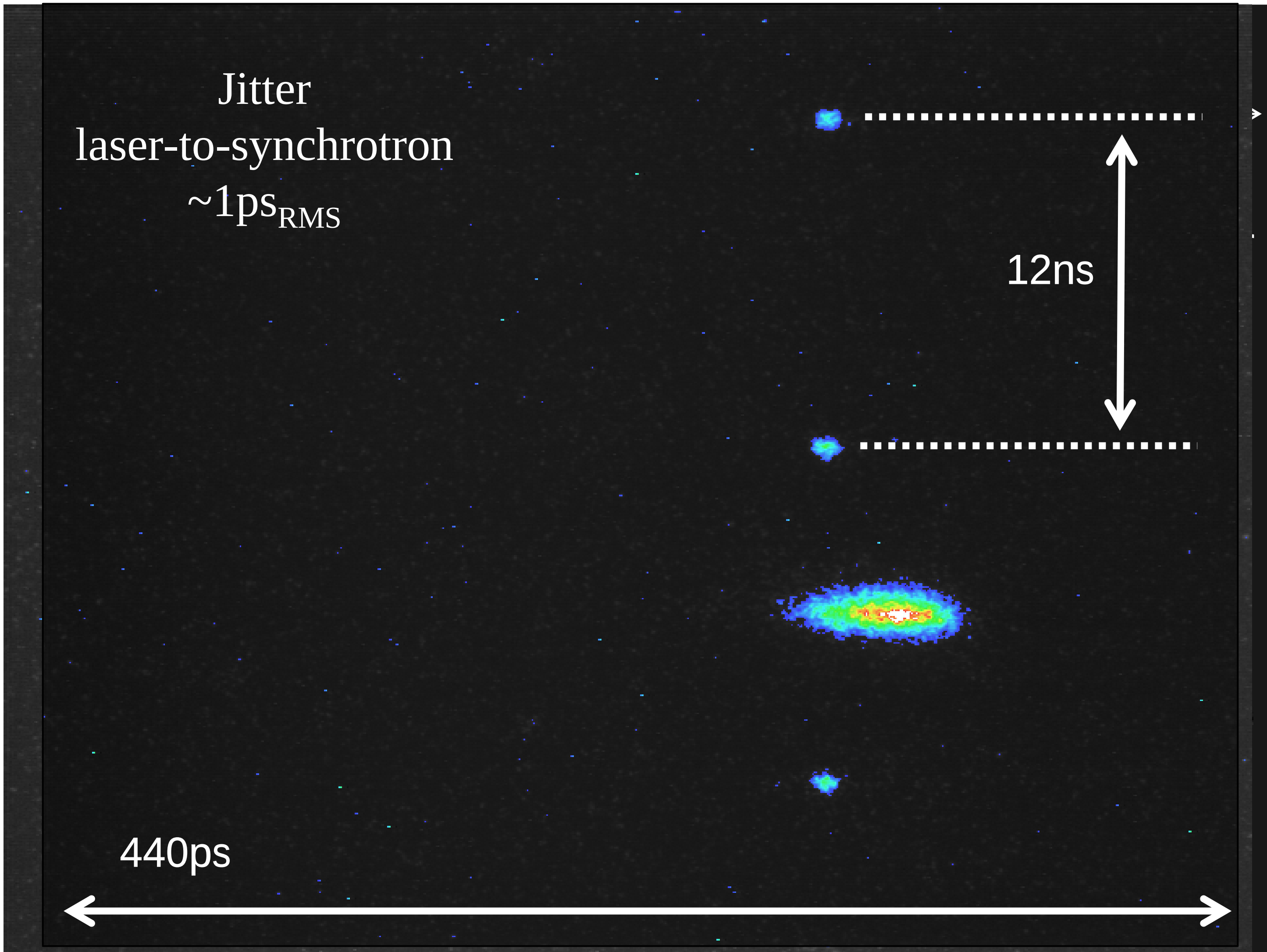




$$f_{REP1} = f_{RF} \div 5 = 99.9308\,\mathrm{MHz}$$

Examples of longitudinal diagnostics **[14]**

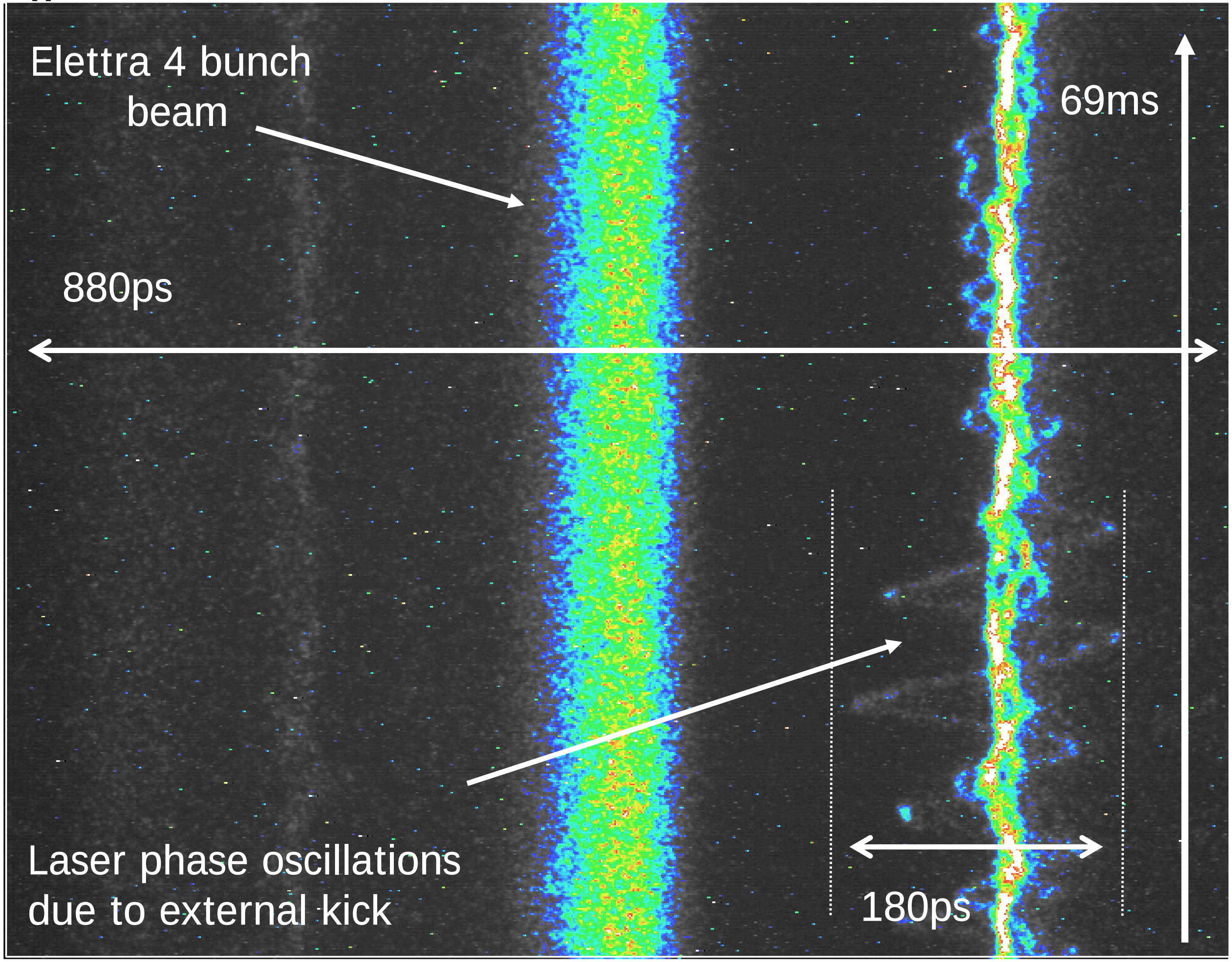
- 4 bunch beam: SR-FEL mode; electron bunches spacing => 216ns



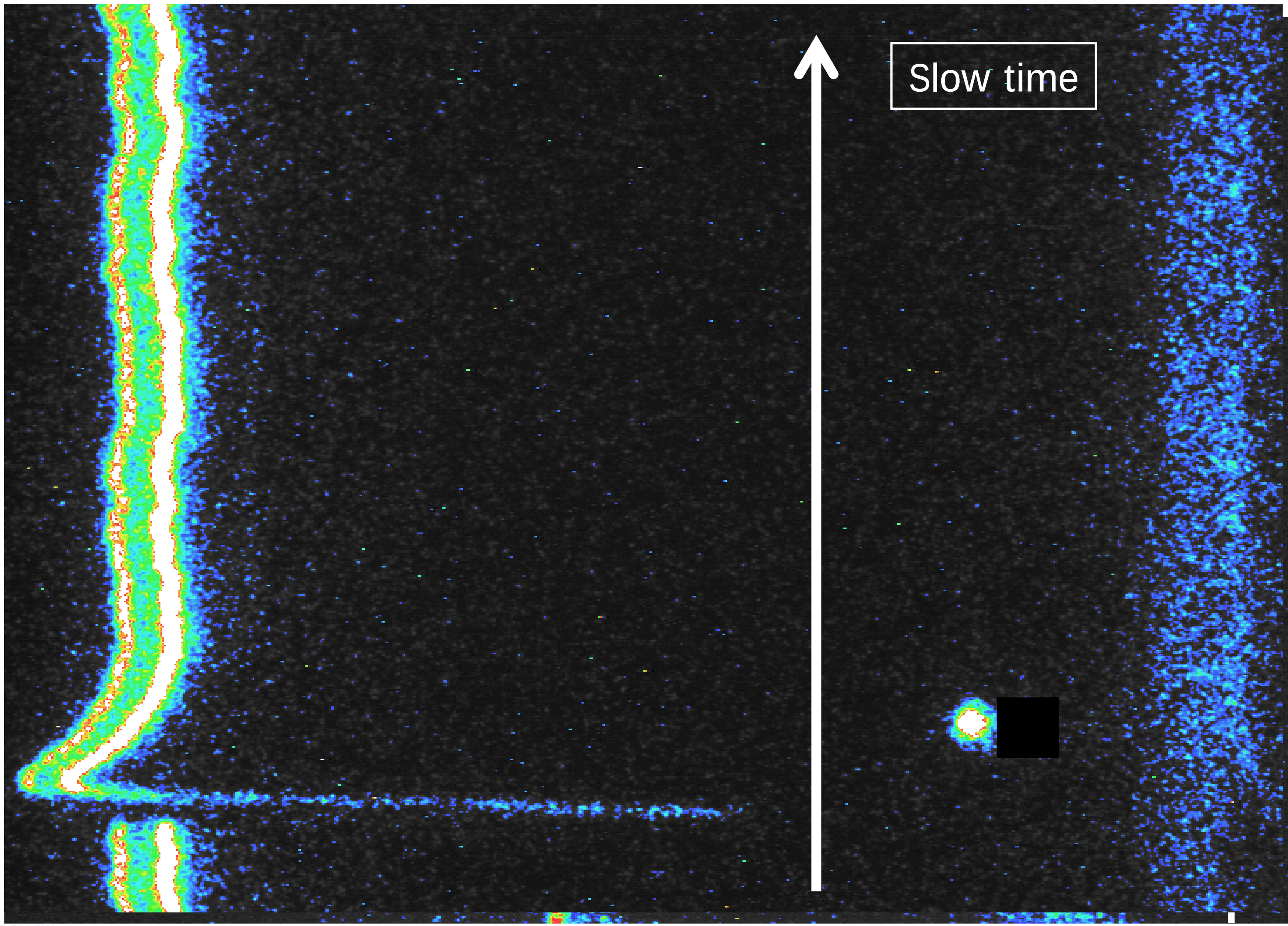
$f_{REP2} = f_{RF} \div 6 = 83.2756MHz$

Examples of longitudinal diagnostics **[14]**

- Storage Ring FEL measurements

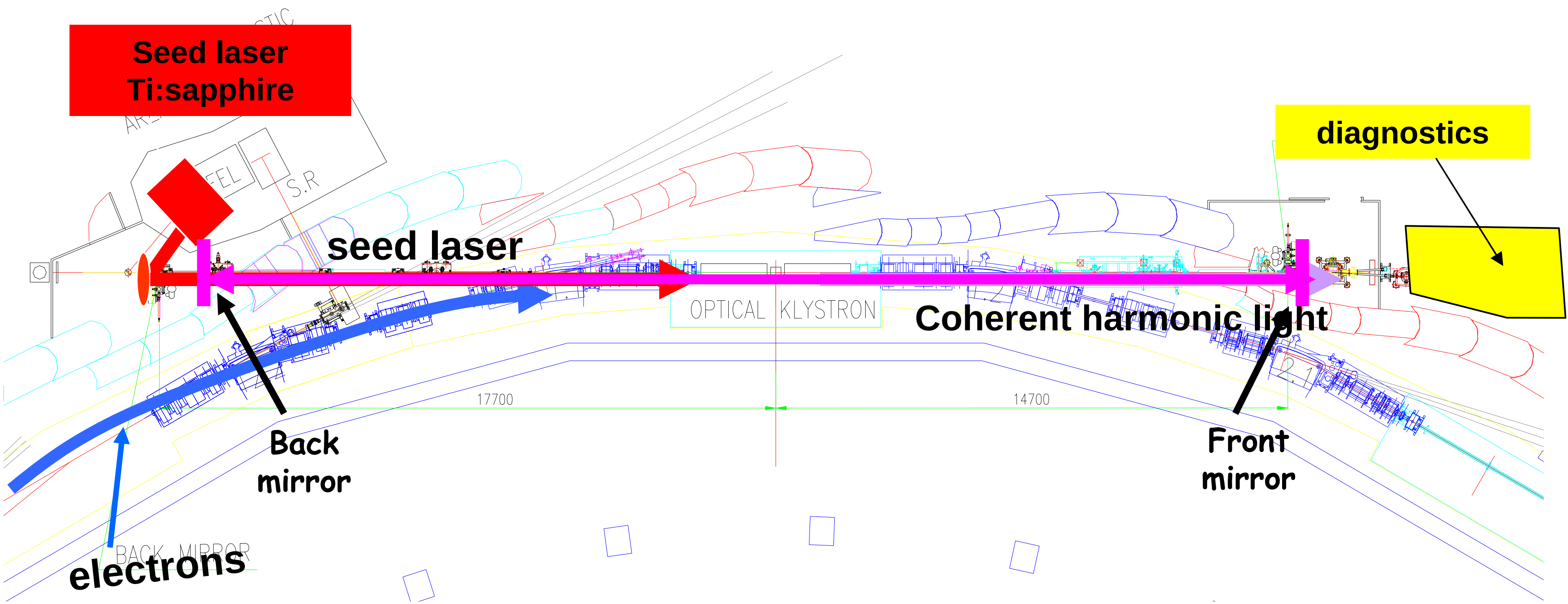


Examples of longitudinal diagnostics **[14]**



Examples of longitudinal diagnostics [15]

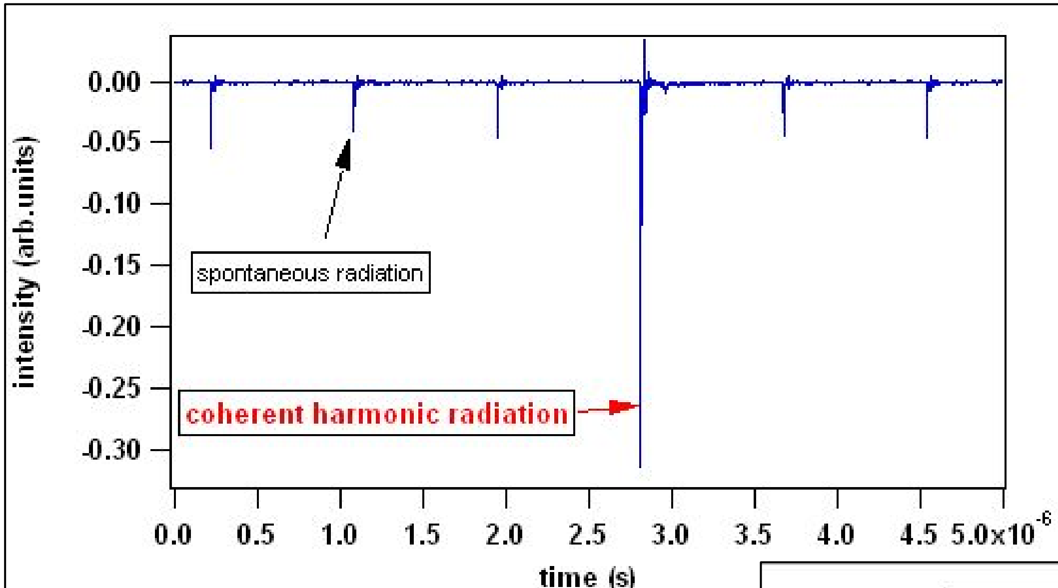
- Storage Ring FEL harmonic seeding



Cortesy of G Deninno

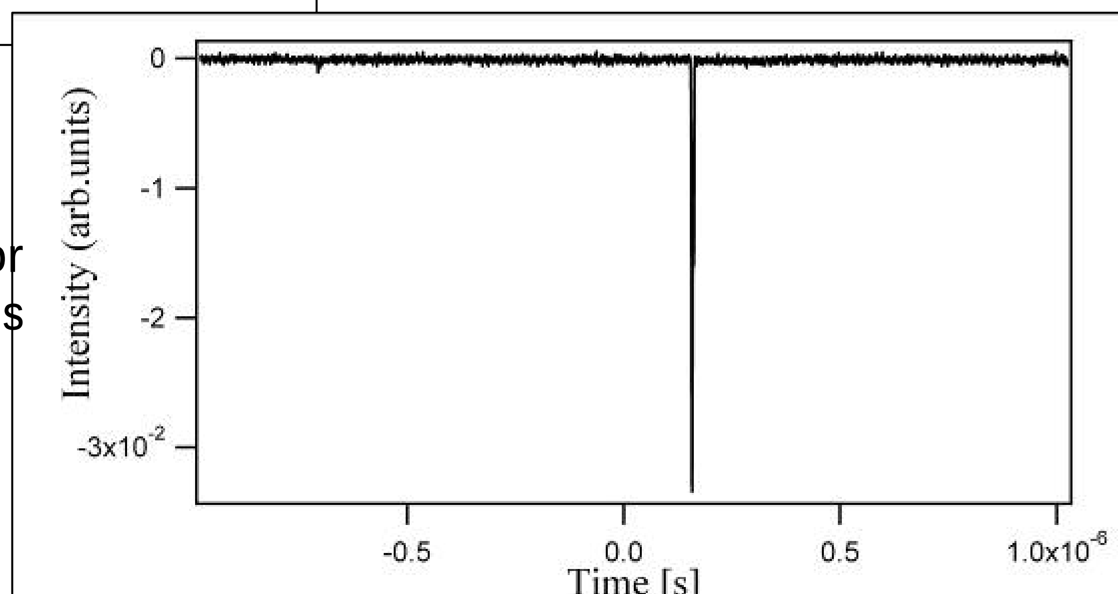
Examples of longitudinal diagnostics **[15]**

- Harmonic generation on the Storage Ring FEL



Integrated signal of the monochromatized radiation at 260 nm acquired with a photo-multiplier tube.
The enhanced peak is the coherent signal generated by the seeded electron bunch, small peaks represent the spontaneous (i.e., un-seeded) radiation

Seeded signal is a factor about **50** above spontaneous emission



References

[1] K. Scheidt “**Review of Streak Cameras for accelerators: feature, applications and results**” in EPAC ‘00 Proceedings, June 2000, Vienna, A

[2] Hamamatsu Photonics; http://www.sales.hamamatsu.com

[3] Photek Ltd; tech. note at: http://www.photek.com

[4] Optronis Gmbh; http://www.optronis.com/

[5] M. Ferianis et al. “**Bunch length Measurements at Elettra**” in DIPAC ‘97 Proceedings, 1997 Frascati ITA

[6] M. Ferianis “**The Elettra Streak Camera: system set-up and first results**” in DIPAC ’99 Proceedings, May‘99 Chester UK

[7] M. Ferianis and M. Danailov “**Streak Camera Characterization Using a Femtosecond Ti:Sapphire Laser**” in BIW’02 Proceedings, May 2002, *Brookhaven National Laboratory, Upton, NY*

[8] J.M. Byrd S. De Santis “**Longitudinal injection transients in an electron storage ring**” Paper LBNL-47593, 2000. http://repositories.cdlib.org/lbnl/LBNL-47593

[9] J. M. Byrd et al. “**Nonlinear longitudinal dynamics studies at the ALS**” in Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

[10] J. M. Byrd et al. “**Nonlinear effects of phase modulation in an electron storage ring**” PHY REV E VOLUME 57, NUMBER 4 APRIL 1998

[11] J. Byrd private communication, Apr 2008

[12] T. Ohshima, A. Yamashita “**Beam phase measurement of stored bunch**” in Proceedings of the 2006 European Particle Accelerator Conference, 2006 Edinburgh, Scotland

[13] G. Penco and M. Svandrlik “**Experimental studies on transient beam loading effects in the presence of a superconducting third harmonic cavity**” in PRST-ACCELERATORS AND BEAMS 9, 044401 (2006)

[14] M. Ferianis et al. “**Synchronization of Elettra Storage ring Light Sources with an ultrafastT CR:LISAF laser**” in Advanced Laser Technologies 2004 (Proceedings Volume), Proceedings of SPIE Volume: **5850.**

[15] C. Spezzani et al. “**Sub-picosecond coherent VUV source on the Elettra storage ring**” submitted to NIM