Particle Accelerators

Lyn Evans – *CERN/IC*

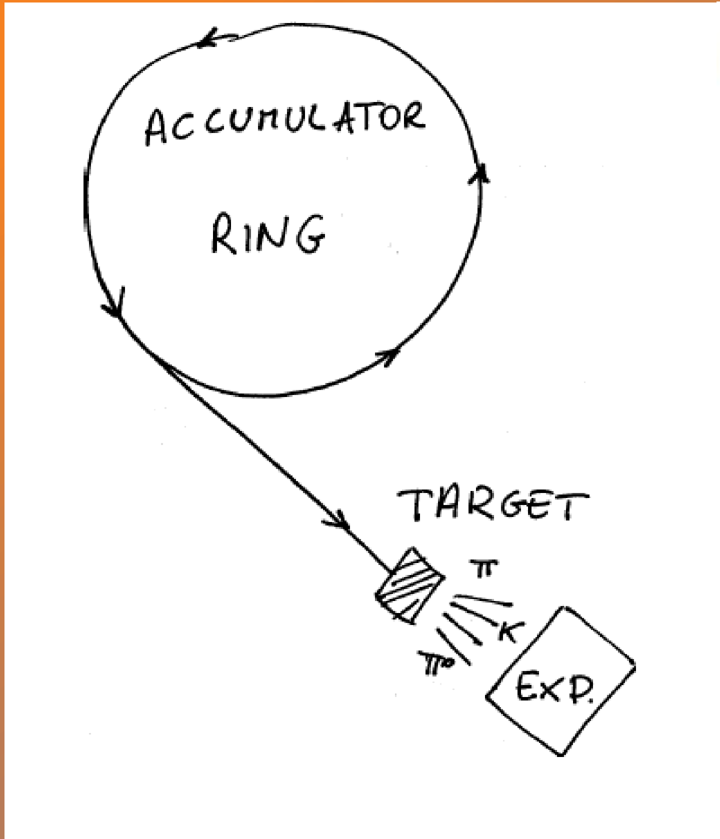
ASP2012 Kumasi Ghana 30th July 2012

The first circular accelerator
Lawrence and Livingston’s 80 keV cyclotron (1930)

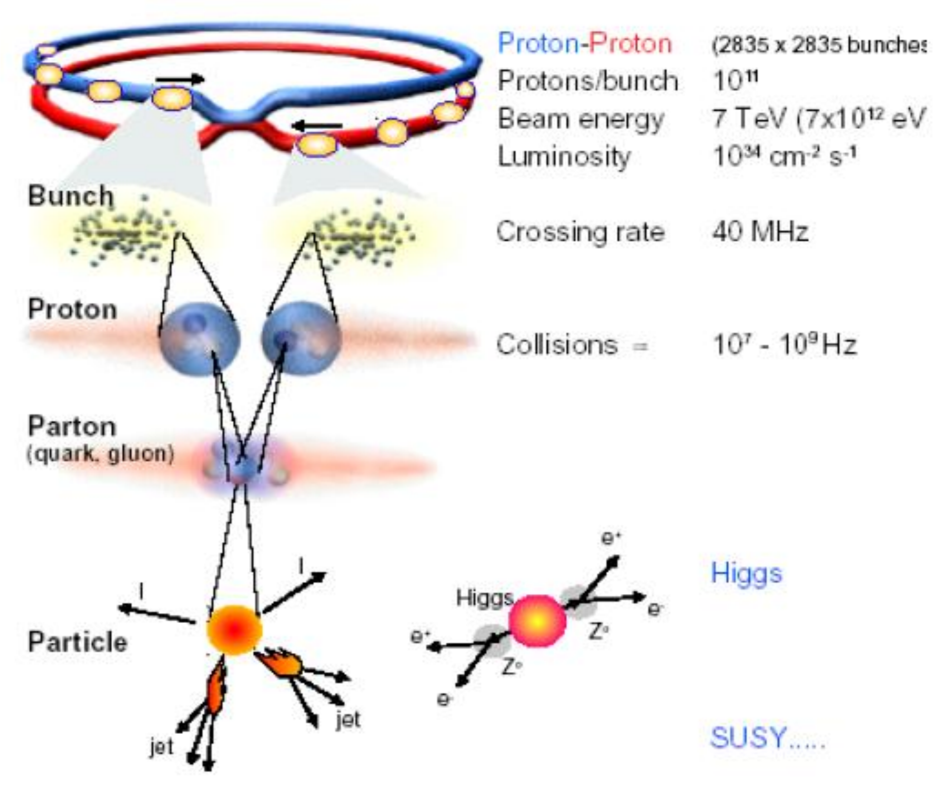
Ernest O. Lawrence

Different approaches fixed target vs collider

Fixed target



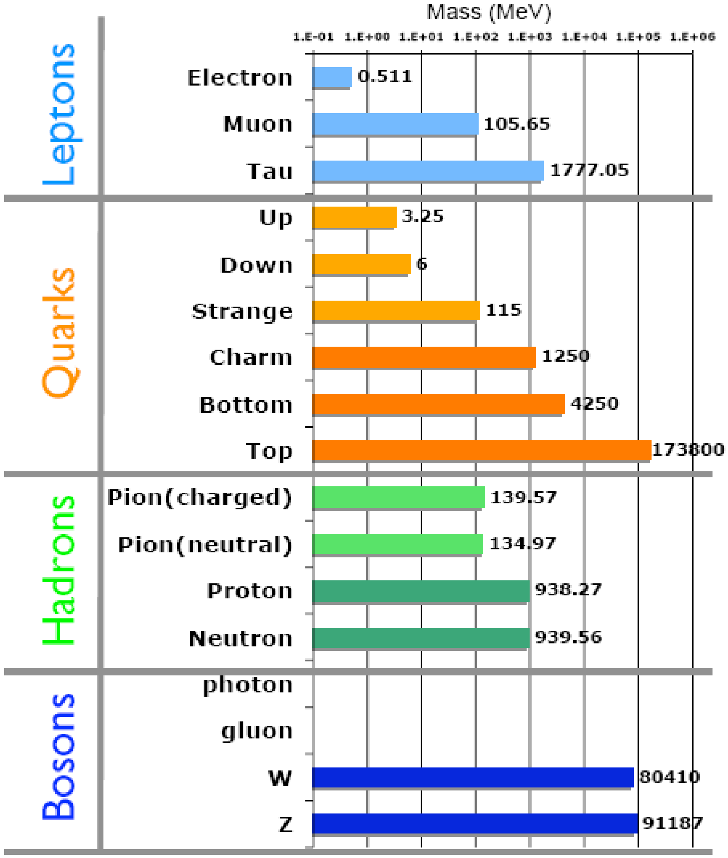
Storage ring/collider



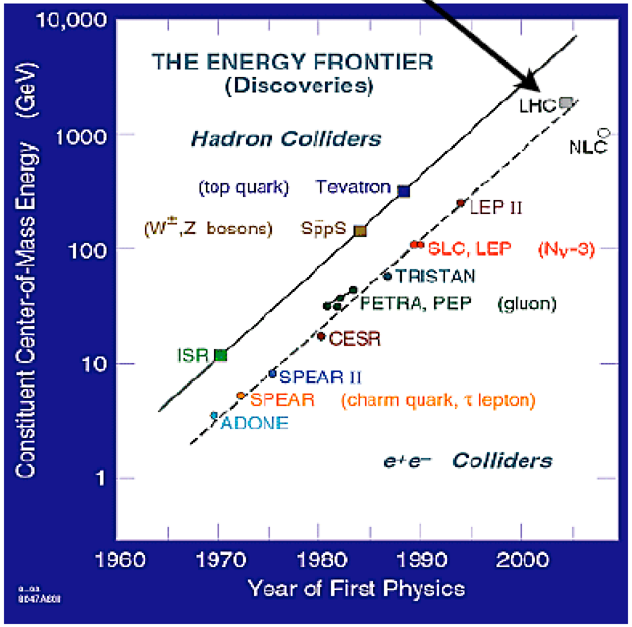
Proton-Proton	(2835 x 2835 bunches
Protons/bunch	10^{11}
Beam energy	7 TeV (7x10^{12} eV
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

History/energy line vs discovery



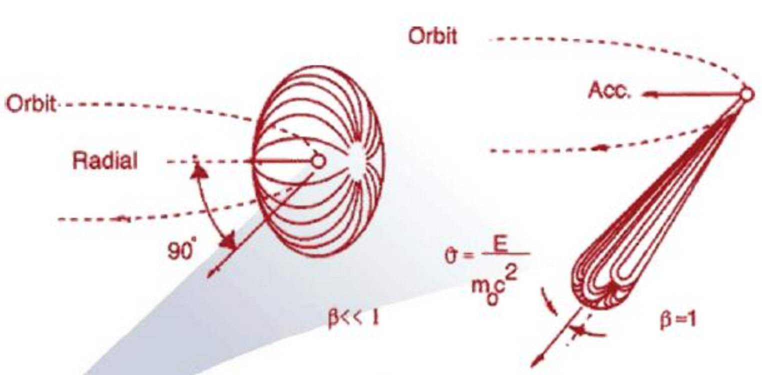
Higgs and super-symmetry ?
Or something else maybe



Behind the history plot is hidden the technological development required for each step

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either $\bar{p}$-p as Tevratron, p-p as LHC)

Synchrotron radiation



- Charged particle beams bent in a magnetic field undergo centripetal acceleration and emit e-m radiation
- When beams are relativistic, radiation is emitted in a narrow cone

- Radiated power

Free space impedance

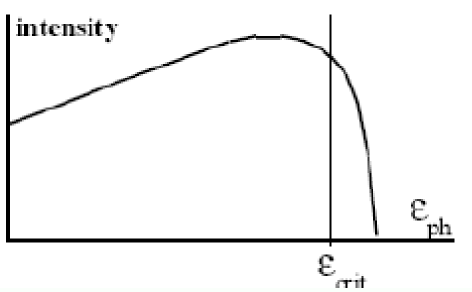
$$P_{syn} = \frac{Z_0\, e^2\, c\, \gamma^4}{3\, R} \boxed{N_b\, n_b\, f_{rev}}$$

~ beam current

Bending radius

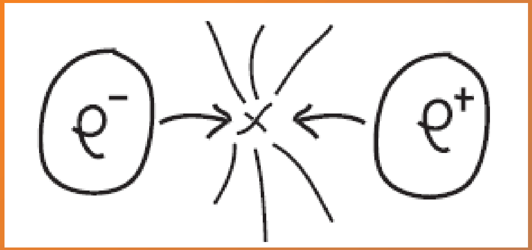
- Critical photon energy

$$u_c = \frac{3}{2} \hbar\, c \, \frac{\gamma^3}{R}$$



The proper particle for the propre scope

Electrons (and positrons) are (so far) point like particles: no internal structure



The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

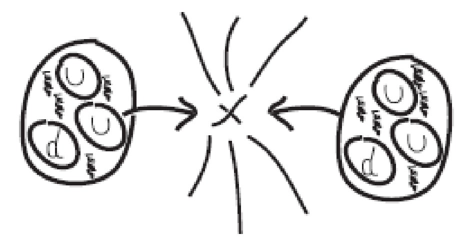
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Pros: the energy can be precisely tuned to scan for example, a mass region

Precision measurement (LEP)

Cons: above a certain energy is no more convenient to use electron because of too high synchrotron radiation (last lecture)

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

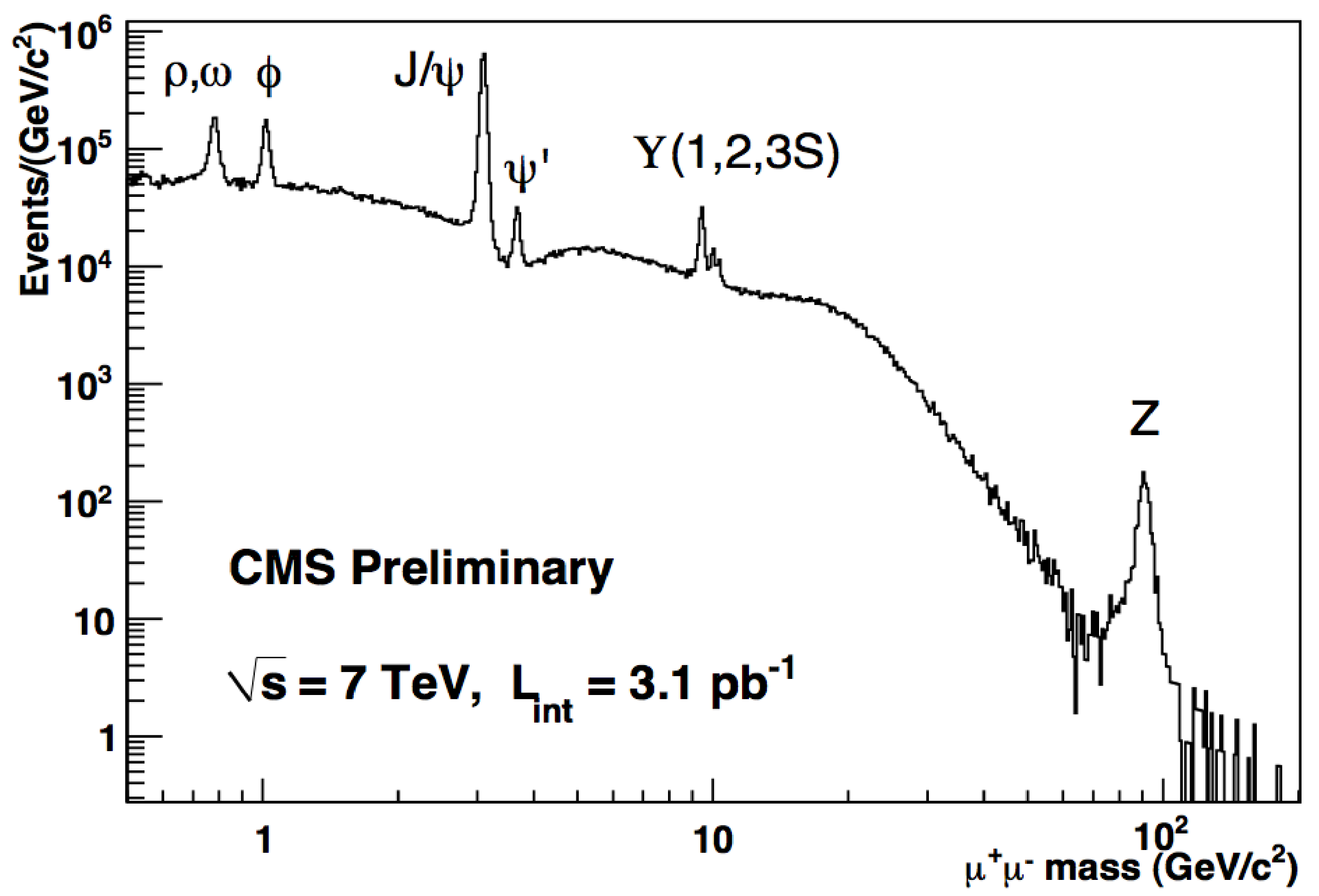
Ecoll < 2Eb

Pros: with a single energy possible to scan different processes at different energies

Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy

CMS Muon Pairs Mass



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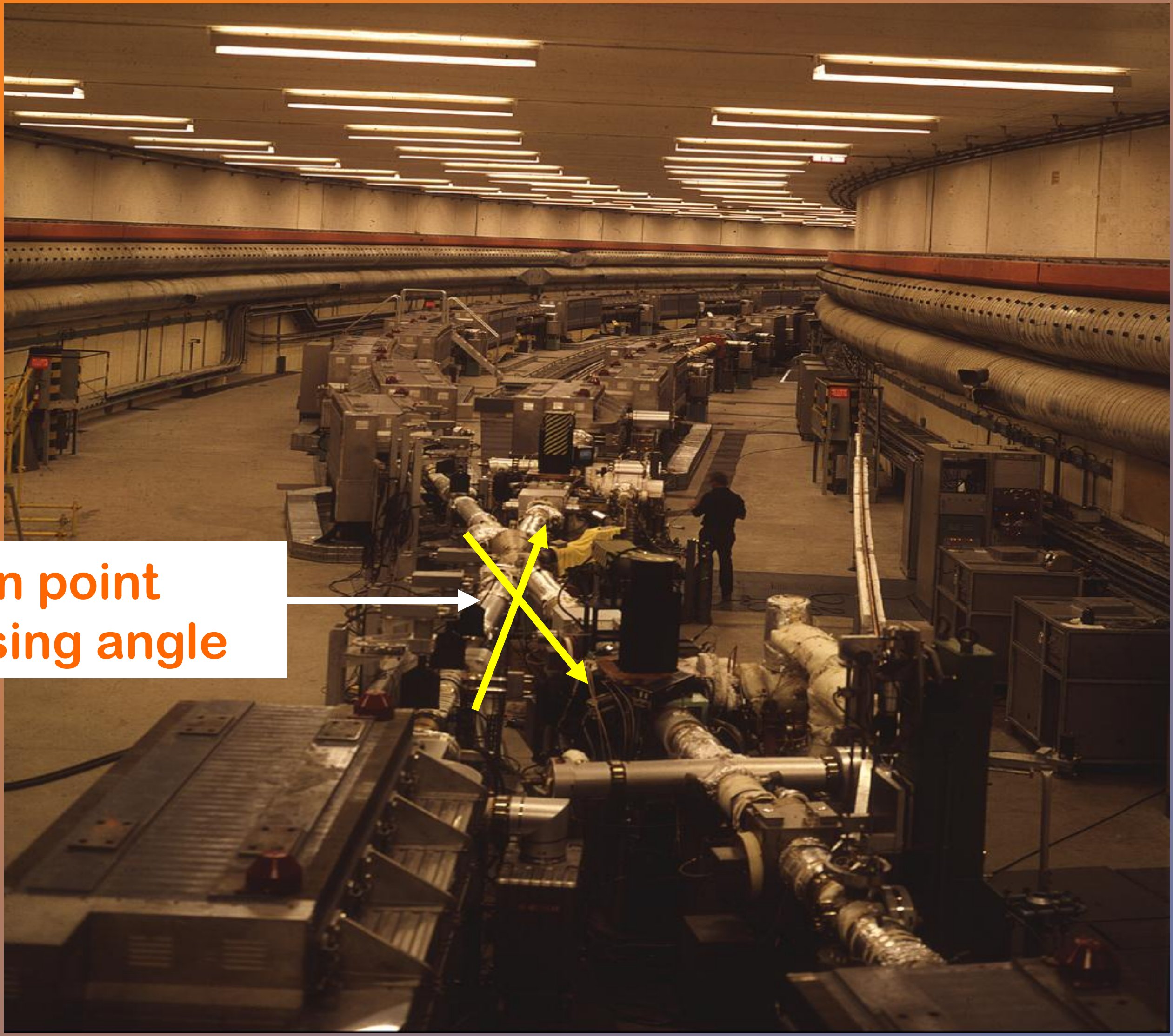
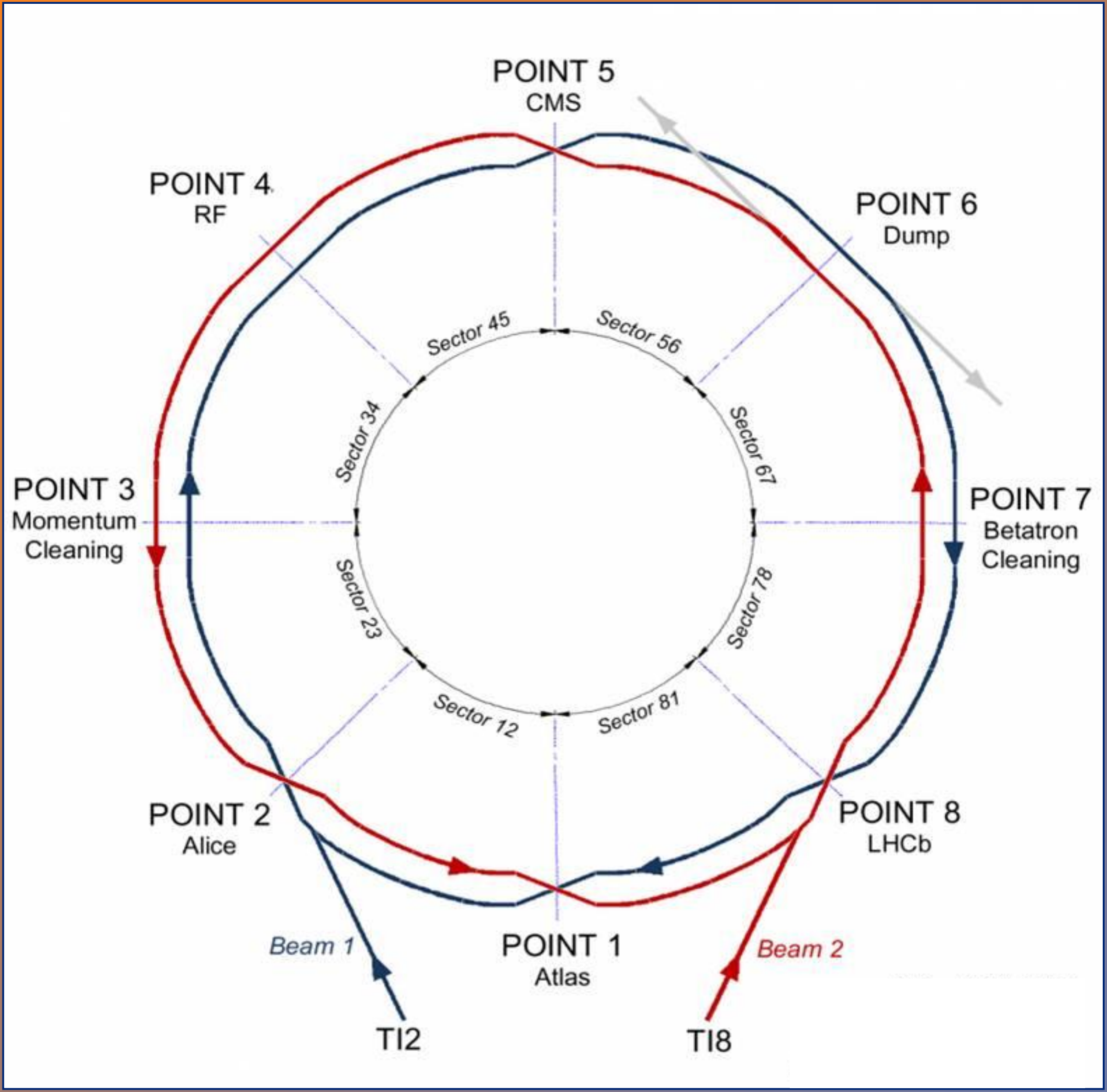
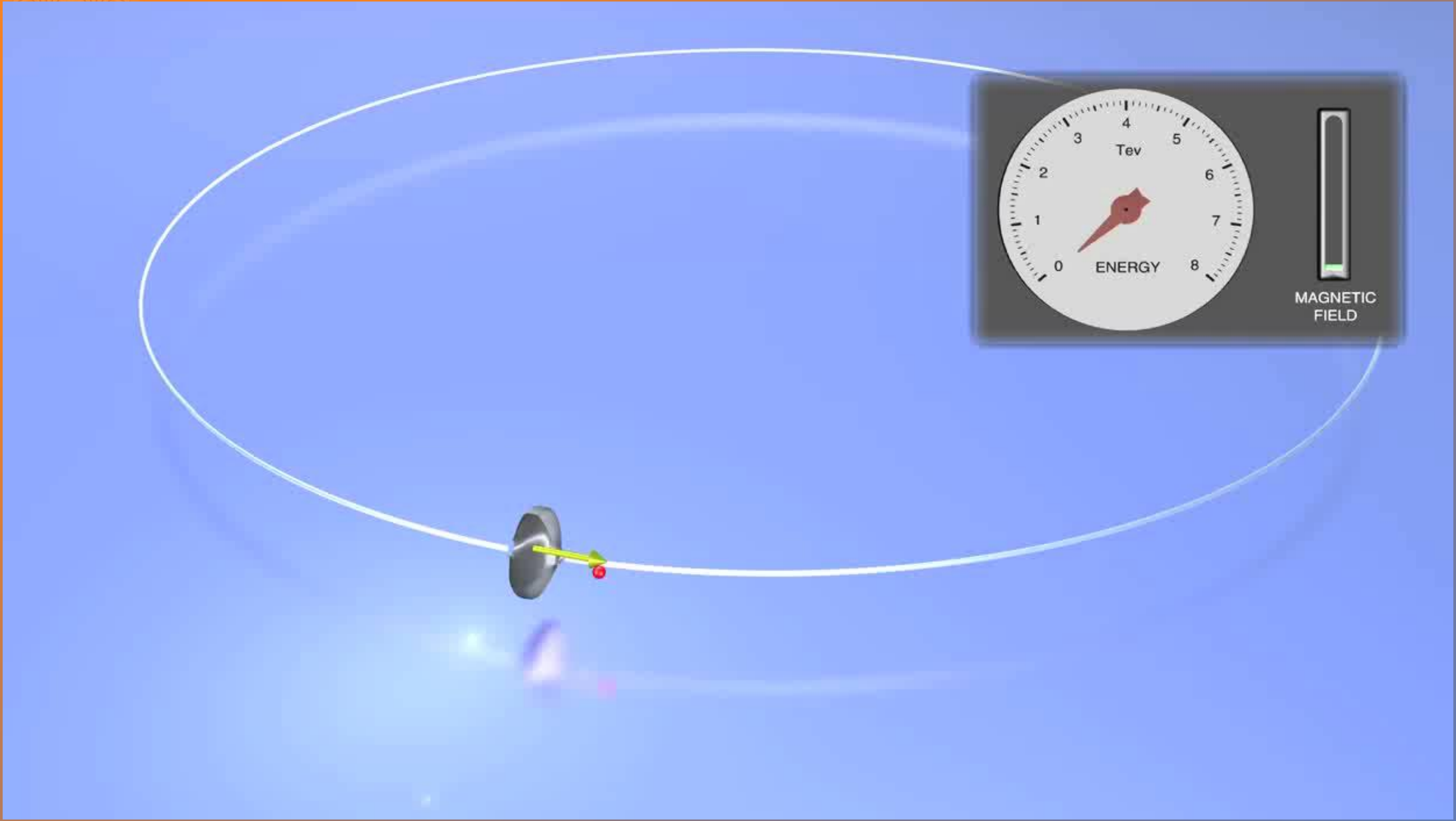


Interaction point with crossing angle

Colliding counter-rotating beams of hadrons



Acceleration principle



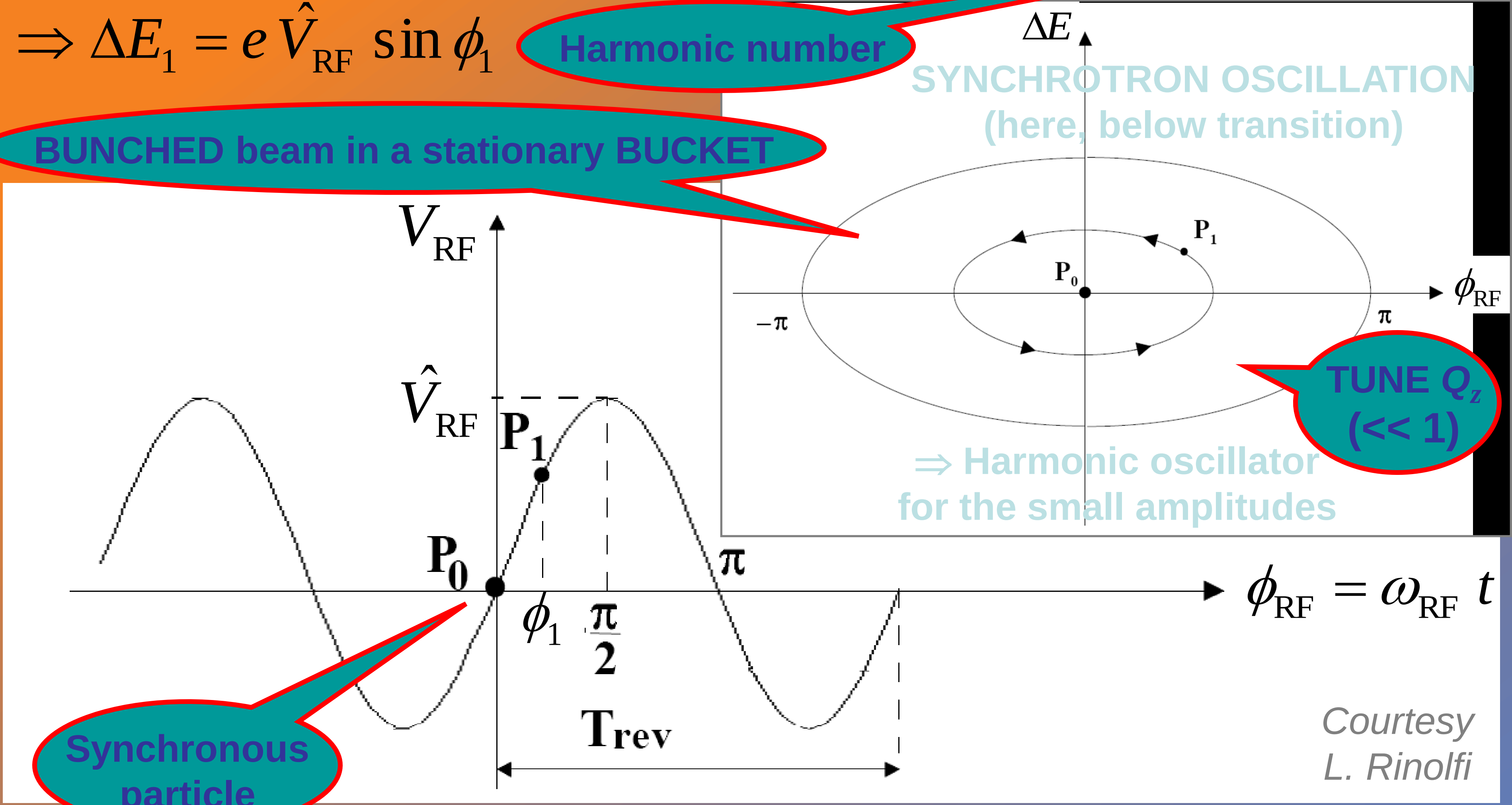
LONGITUDINAL BEAM DYNAMICS

- Sinusoidal voltage applied $V_{\mathrm{RF}} = \hat{V}_{\mathrm{RF}} \sin \phi_{\mathrm{RF}}(t)$ $\omega_{\mathrm{RF}} = h\,\omega_{\mathrm{rev}}$

$\Rightarrow \Delta E_1 = e\,\hat{V}_{\mathrm{RF}} \sin \phi_1$

Harmonic number

BUNCHED beam in a stationary BUCKET



SYNCHROTRON OSCILLATION (here, below transition)

⇒ Harmonic oscillator for the small amplitudes

TUNE Q_z (<< 1)

Synchronous particle

Courtesy L. Rinolfi

LONGITUDINAL BEAM DYNAMICS

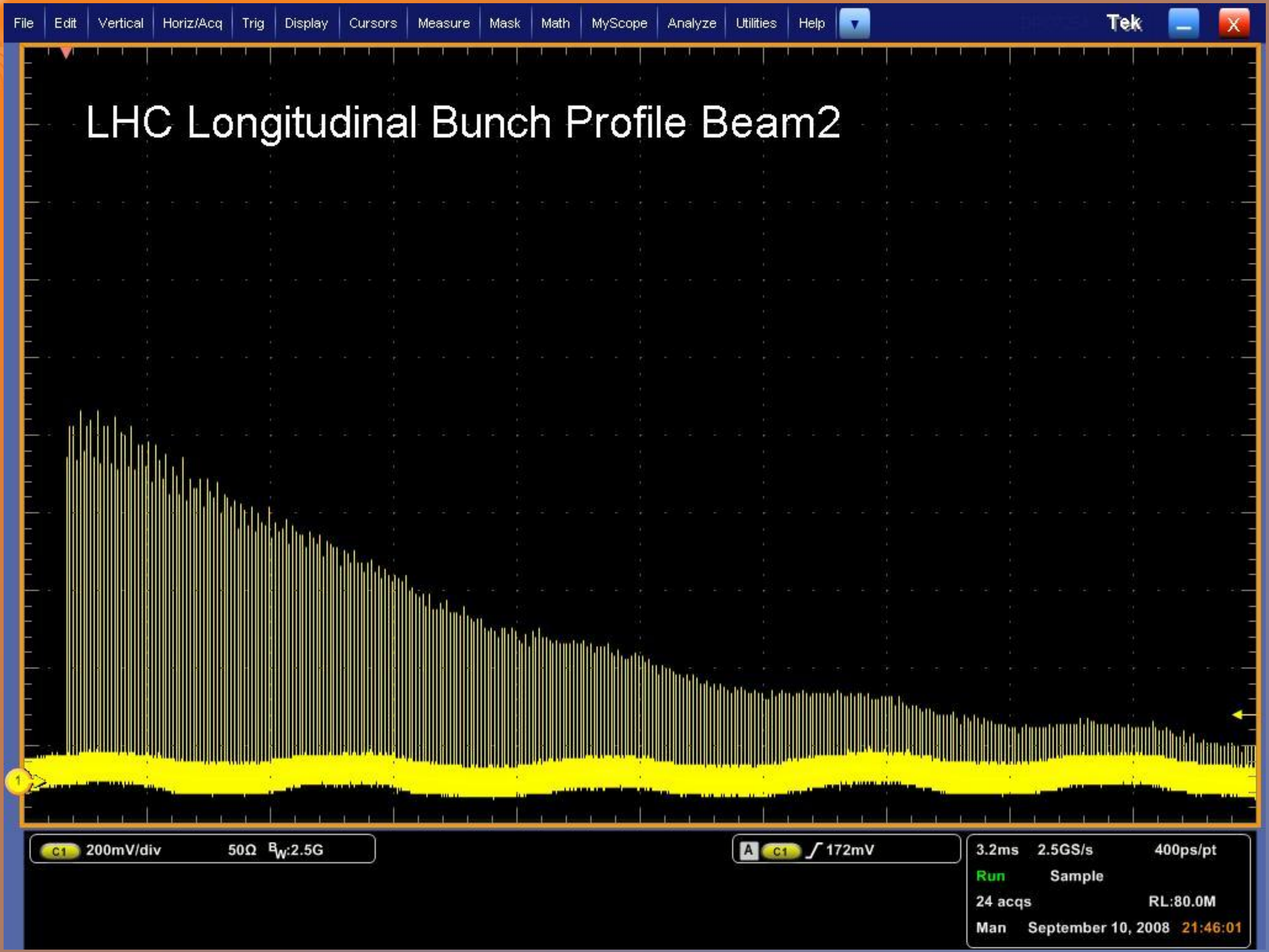
- TRANSITION ENERGY: The increase of energy has 2 contradictory effects

  - An increase of the particle's velocity
  - An increase of the length of the particle's trajectory

  According to the variations of these 2 parameters, the revolution frequency evolves differently

  - Below transition energy: The velocity increases faster than the length $\Rightarrow$ The revolution frequency increases
  - Above transition energy: It is the opposite case $\Rightarrow$ The revolution frequency decreases
  - At transition energy: The variation of the velocity is compensated by the variation of the trajectory $\Rightarrow$ A variation of energy does not modify the frequency

Few 100 turns



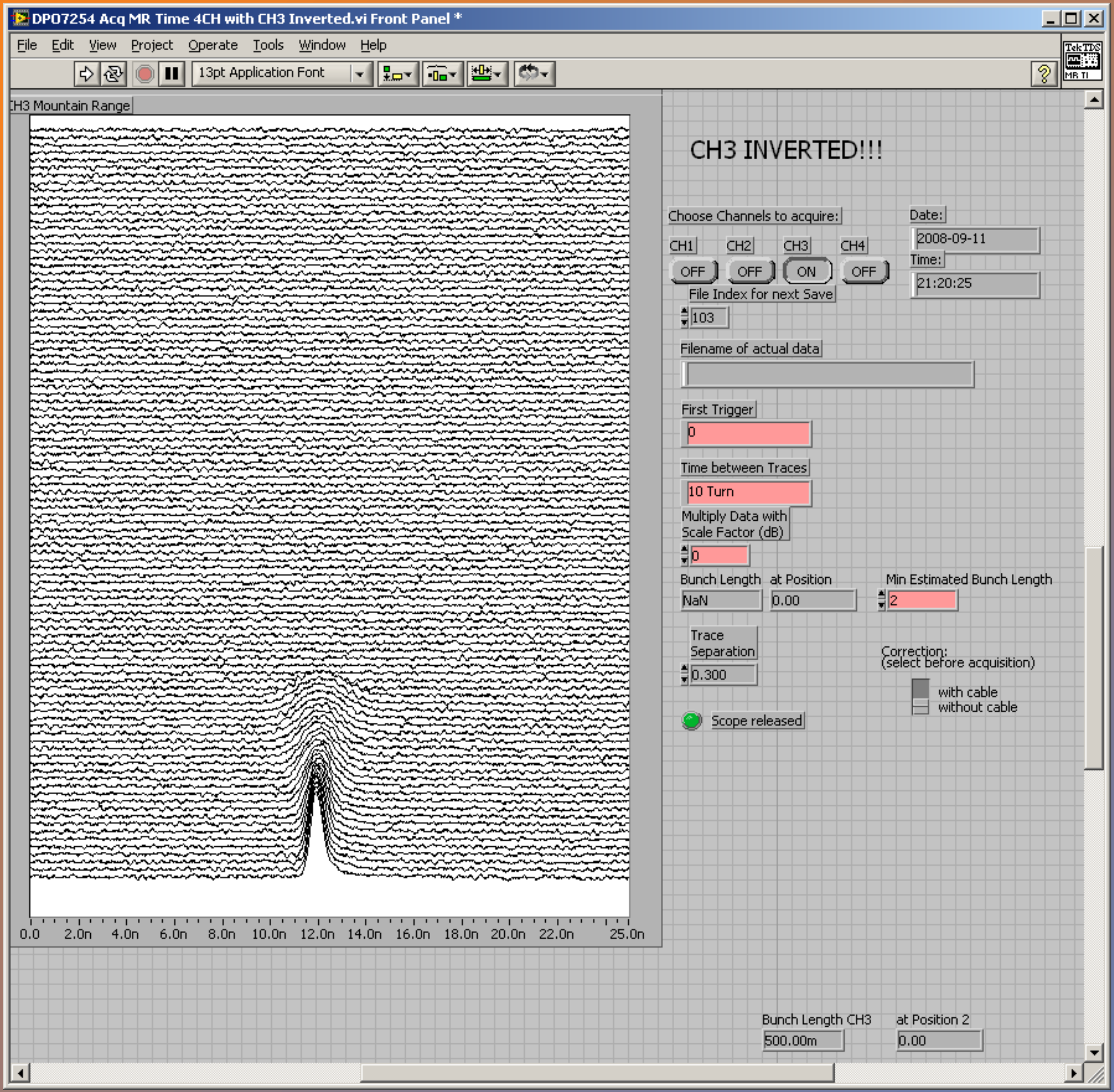
LHC Longitudinal Bunch Profile Beam2

C1 200mV/div 50Ω B_W:2.5G

A C1 ∫ 172mV

3.2ms 2.5GS/s 400ps/pt
Run Sample
24 acqs RL:80.0M
Man September 10, 2008 21:46:01

No RF, debunching in ~ 25*10 turns, i.e. roughly 25 mS



CH3 INVERTED!!!

Choose Channels to acquire:

CH1 OFF

CH2 OFF

CH3 ON

CH4 OFF

Date: 2008-09-11

Time: 21:20:25

File Index for next Save: 103

Filename of actual data:

First Trigger: 0

Time between Traces: 10 Turn

Multiply Data with Scale Factor (dB): 0

Bunch Length: NaN

at Position: 0.00

Min Estimated Bunch Length: 2

Trace Separation: 0.300

Correction: (select before acquisition)

with cable

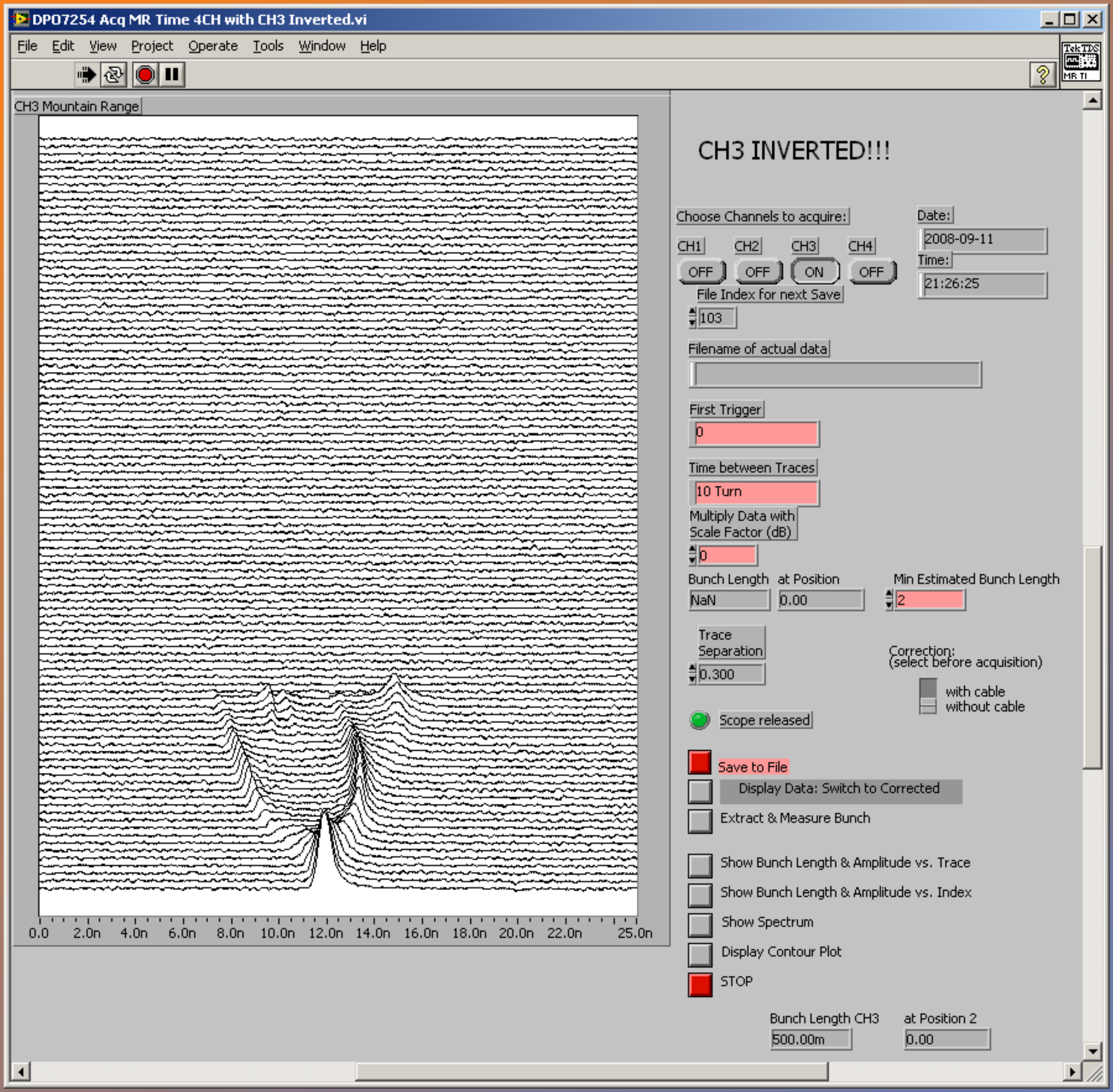
without cable

● Scope released

Bunch Length CH3: 500.00m

at Position 2: 0.00

First attempt at capture,
at exactly the wrong injection phase…



CH3 INVERTED!!!

Choose Channels to acquire:
CH1 OFF
CH2 OFF
CH3 ON
CH4 OFF

Date: 2008-09-11
Time: 21:26:25

File Index for next Save: 103

Filename of actual data:

First Trigger: 0

Time between Traces: 10 Turn

Multiply Data with Scale Factor (dB): 0

Bunch Length: NaN
at Position: 0.00
Min Estimated Bunch Length: 2

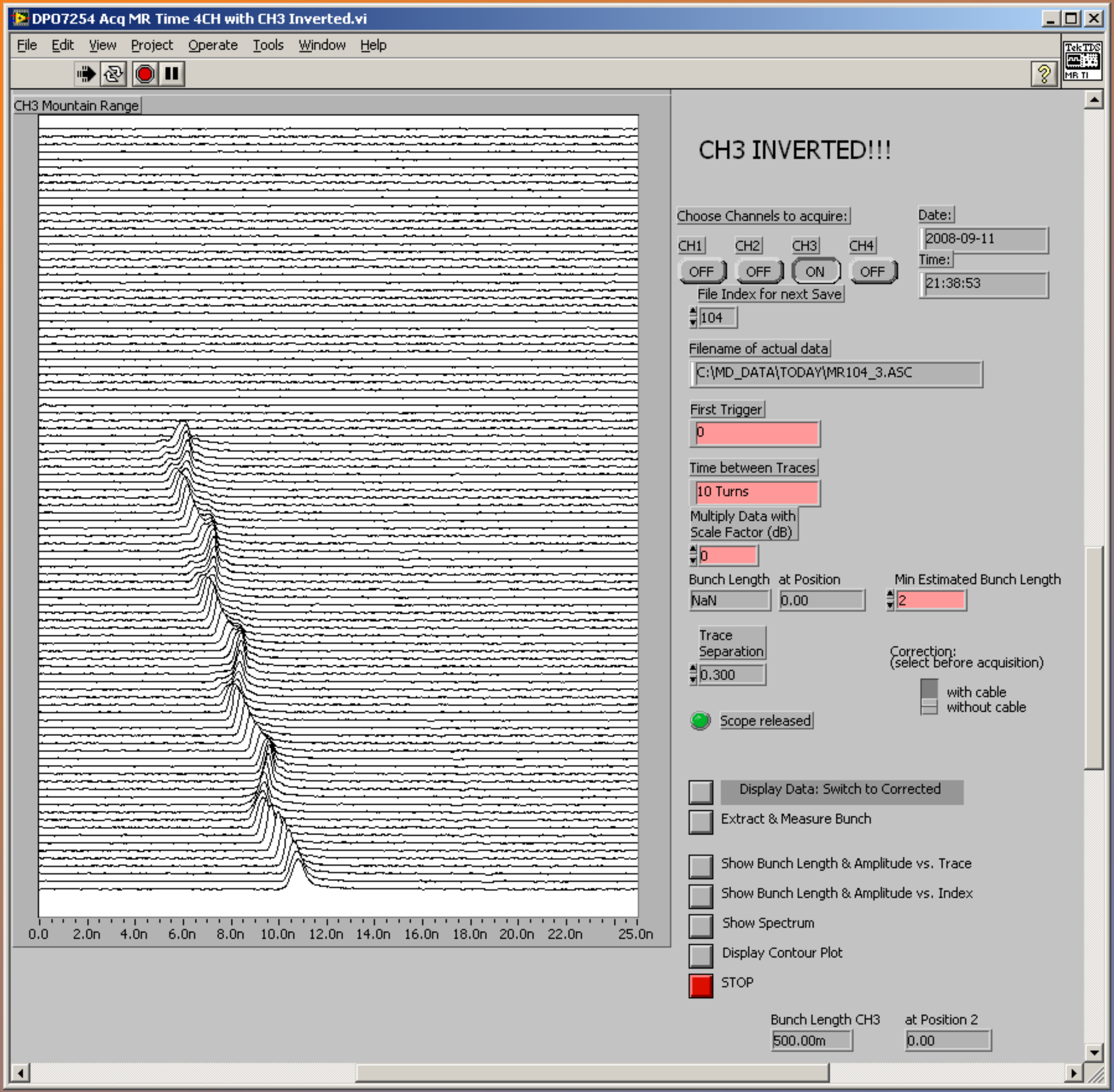
Trace Separation: 0.300

Correction: (select before acquisition)
● with cable
☐ without cable

● Scope released

Bunch Length CH3: 500.00m
at Position 2: 0.00

Capture with corrected injection phasing



CH3 INVERTED!!!

Choose Channels to acquire:
CH1 OFF
CH2 OFF
CH3 ON
CH4 OFF

Date: 2008-09-11
Time: 21:38:53

File Index for next Save: 104

Filename of actual data: C:\MD_DATA\TODAY\MR104_3.ASC

First Trigger: 0

Time between Traces: 10 Turns

Multiply Data with Scale Factor (dB): 0

Bunch Length: NaN
at Position: 0.00
Min Estimated Bunch Length: 2

Trace Separation: 0.300

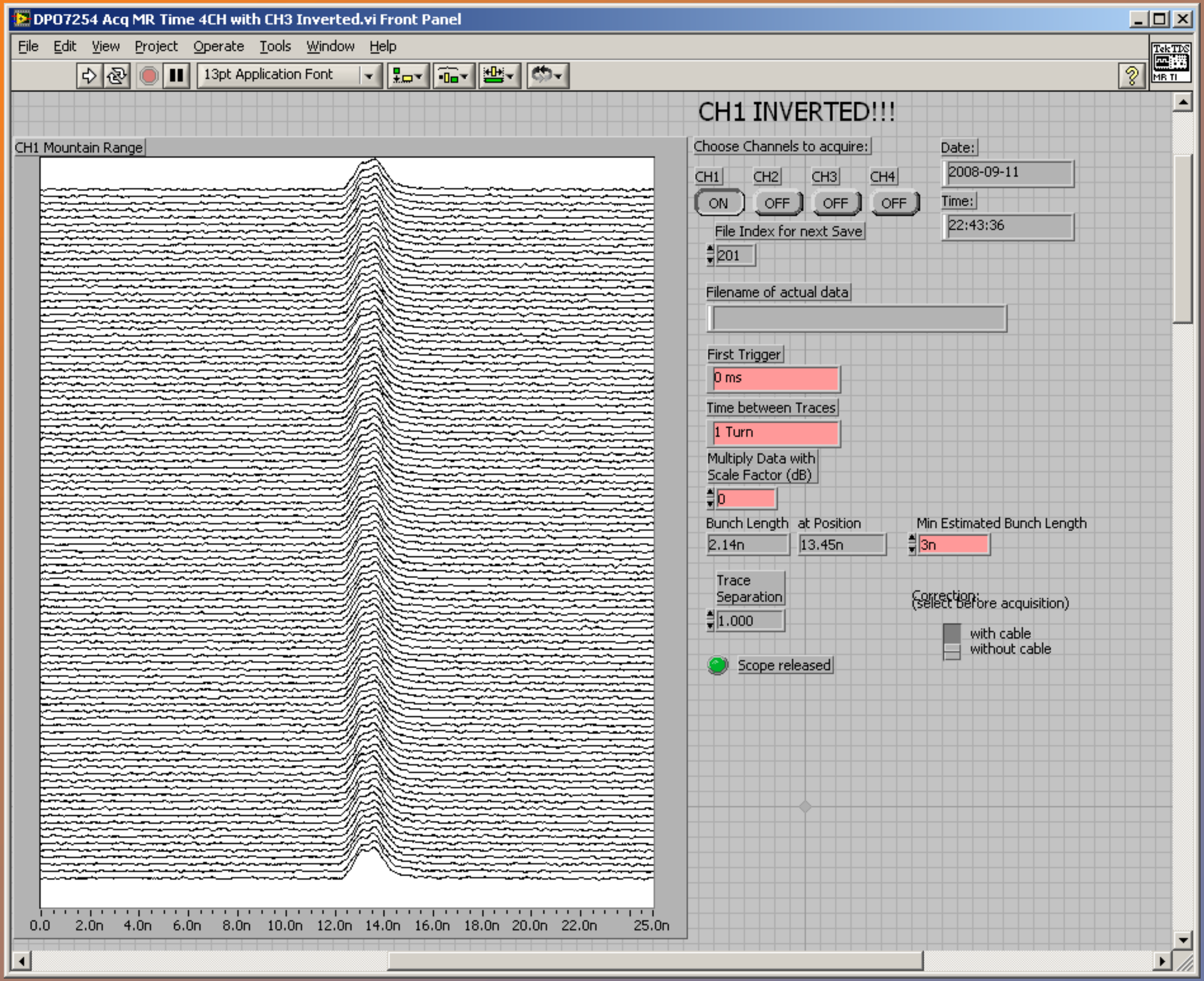
Correction:
(select before acquisition)
with cable
without cable

● Scope released

☐ Display Data: Switch to Corrected
☐ Extract & Measure Bunch
☐ Show Bunch Length & Amplitude vs. Trace
☐ Show Bunch Length & Amplitude vs. Index
☐ Show Spectrum
☐ Display Contour Plot
🟥 STOP

Bunch Length CH3: 500.00m
at Position 2: 0.00

Capture with optimum injection phasing, correct reference



DPO7254 Acq MR Time 4CH with CH3 Inverted.vi Front Panel

CH1 INVERTED!!!

Choose Channels to acquire:
CH1 ON
CH2 OFF
CH3 OFF
CH4 OFF

Date: 2008-09-11
Time: 22:43:36

File Index for next Save: 201

Filename of actual data:

First Trigger: 0 ms

Time between Traces: 1 Turn

Multiply Data with Scale Factor (dB): 0

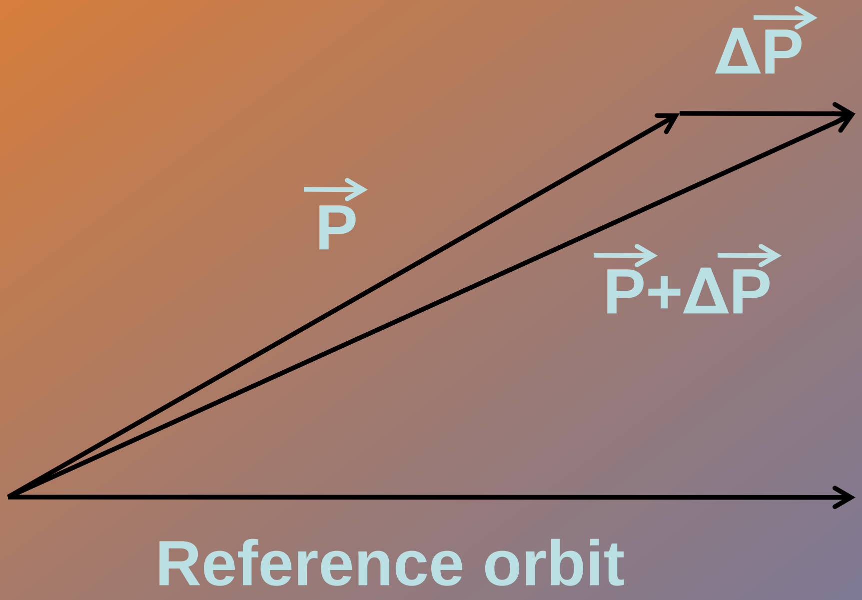
Bunch Length: 2.14n
at Position: 13.45n
Min Estimated Bunch Length: 3n

Trace Separation: 1.000

Correction: (select before acquisition)
with cable
without cable

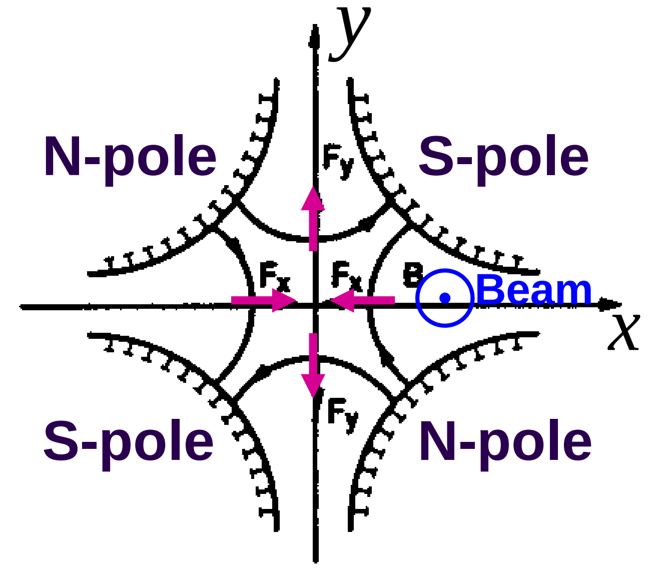
● Scope released

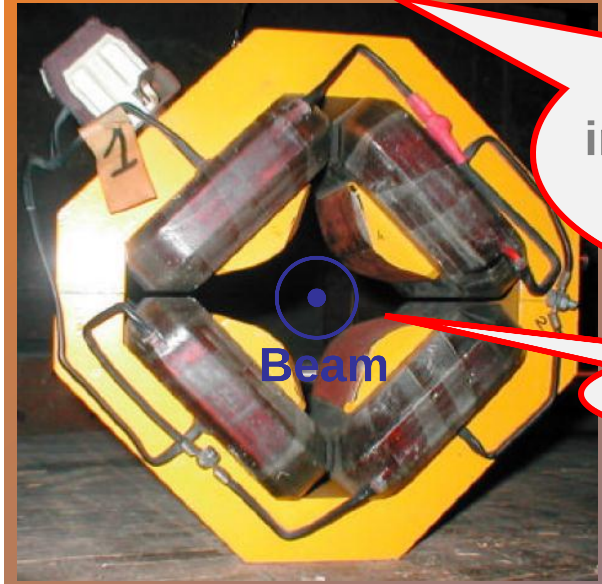
Adiabatic damping during acceleration



Transverse Beam Dynamics

QUADRUPOLE = Focusing magnet





In x (and Defocusing in y) ⇒ F-type. Permuting the N- and S- poles gives a D-type

Linear force in x&y

$$\Rightarrow \quad x''(s)+K\,x(s)=0$$

: Equation of a harmonic oscillator

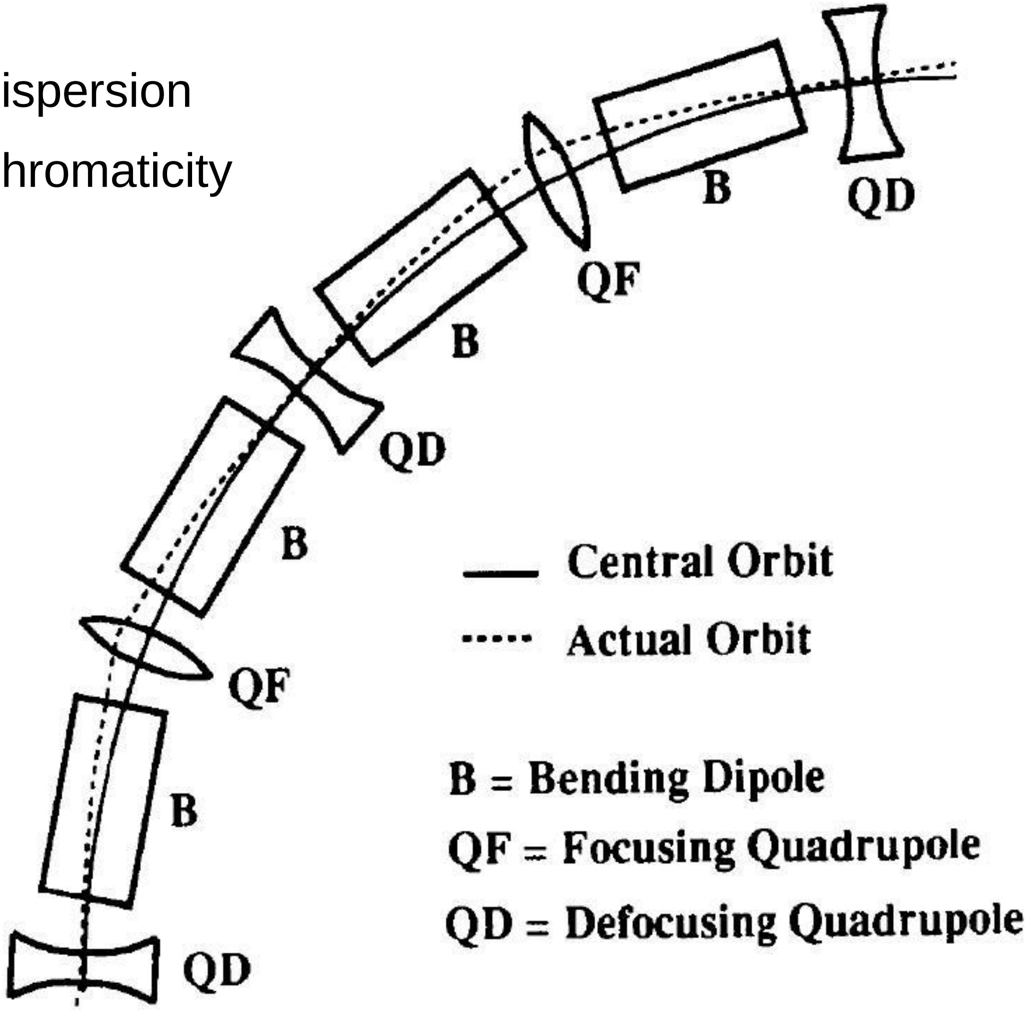
- From this equation, one can already anticipate the elliptical shape of the particle trajectory in the phase space (x, x') by integration

$$x'^2(s)+K\,x^2(s)=\mathrm{Constant}$$

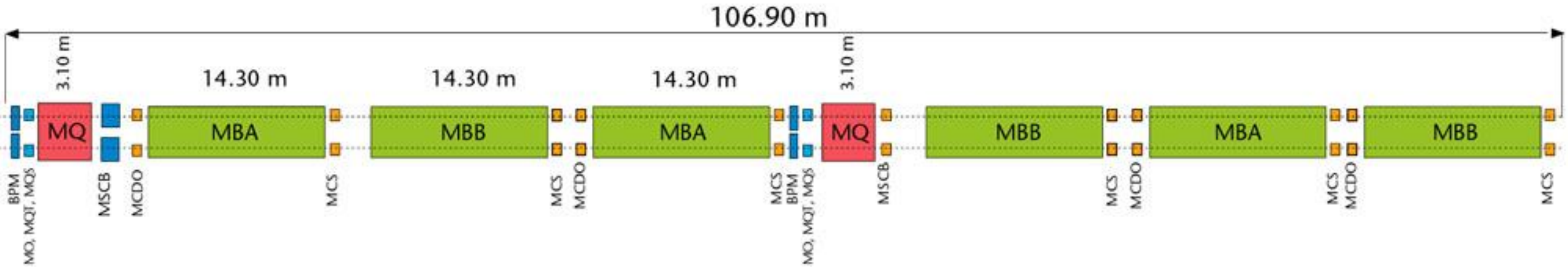
Alternating gradient focusing

Dispersion

Chromaticity



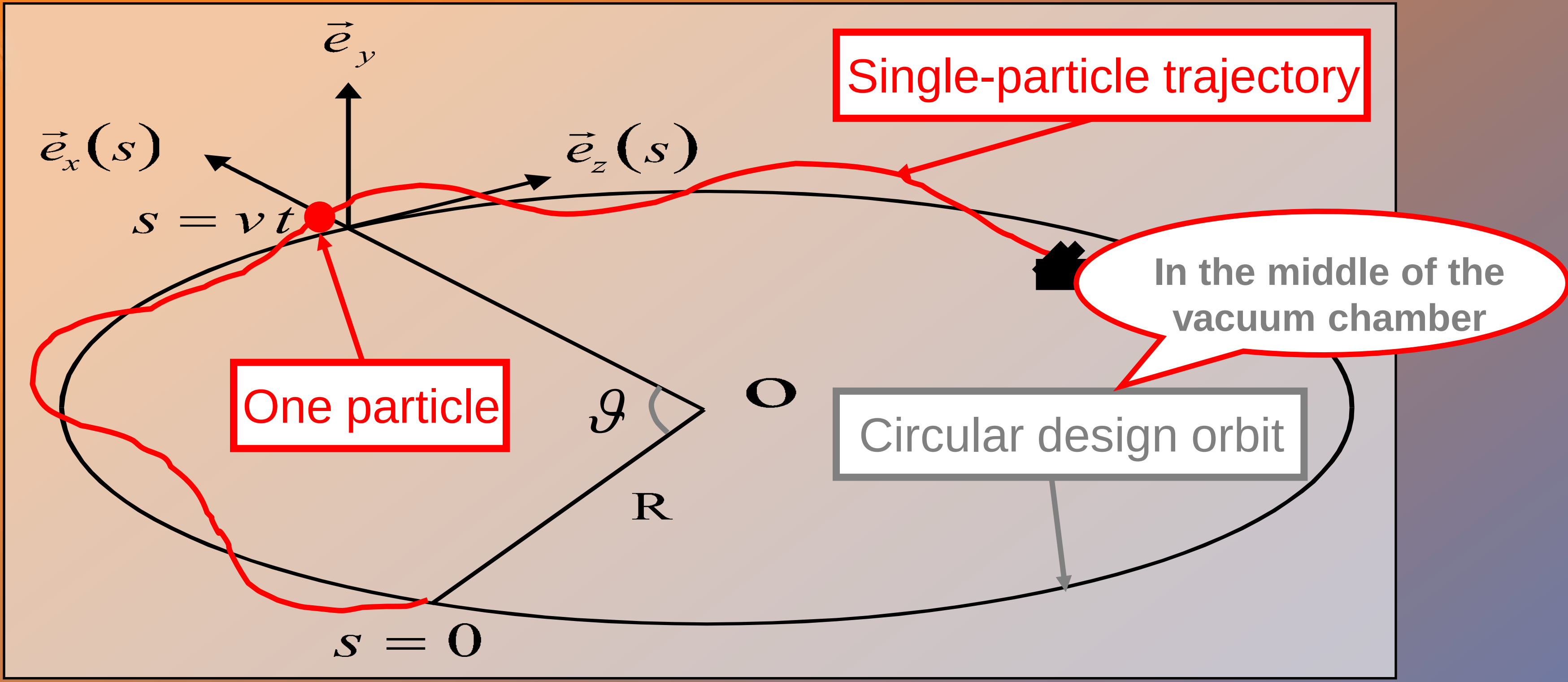
Schematic layout of one LHC cell (23 periods per arc)



MQ: Lattice Quadrupole
MO: Landau Octupole
MQT: Tuning Quadrupole
MQS: Skew Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type A
MBB: Dipole magnet Type B
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

HF226 - v10/99

Transverse Beam Dynamics



- The motion of a charged particle (proton) in a beam transport channel or a circular accelerator is governed by the LORENTZ FORCE

$$\vec{F} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

- The motion of particle beams under the influence of the Lorentz force is called BEAM OPTICS

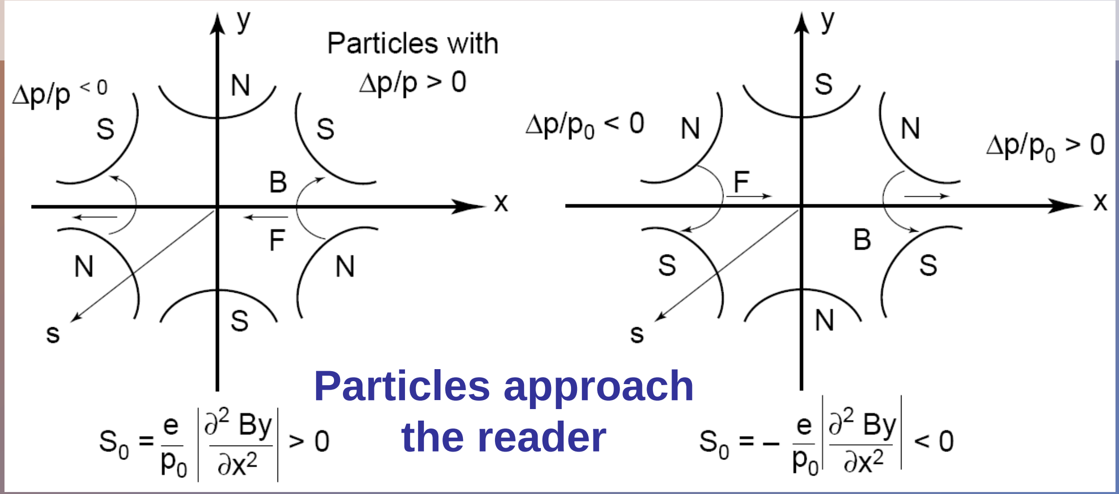
Transverse Beam Dynamics

- CHROMATICITY = Variation of the tune with the momentum

$$Q'_x = \frac{\Delta Q_x}{\Delta p / p_0}$$

- The control of the chromaticity (using a SEXTUPOLE magnet) is very important for 2 reasons
  - Avoid shifting the beam on resonances due to changes induced by chromatic effects (see later)
  - Prevent some transverse coherent (head-tail) instabilities (see also later)

SEXTUPOLE =
1st nonlinear magnet



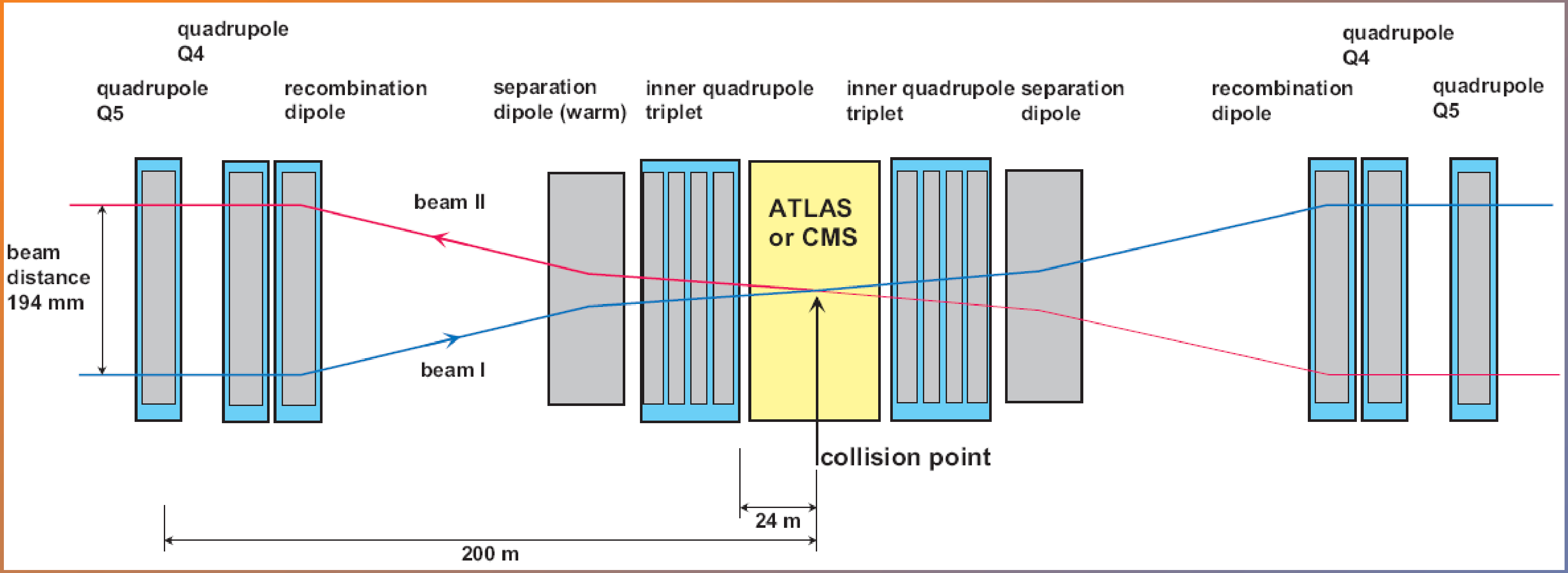
Particles approach the reader

Luminosity

$$L = \frac{N_b^2 \, n_b \, f_{rev} \, \gamma}{4 \, \pi \, \varepsilon_n \, \beta^*} F$$

$$F = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \, \sigma_z}{2 \, \sigma^*} \right)^2}}$$

Layout of high-luminosity collision region



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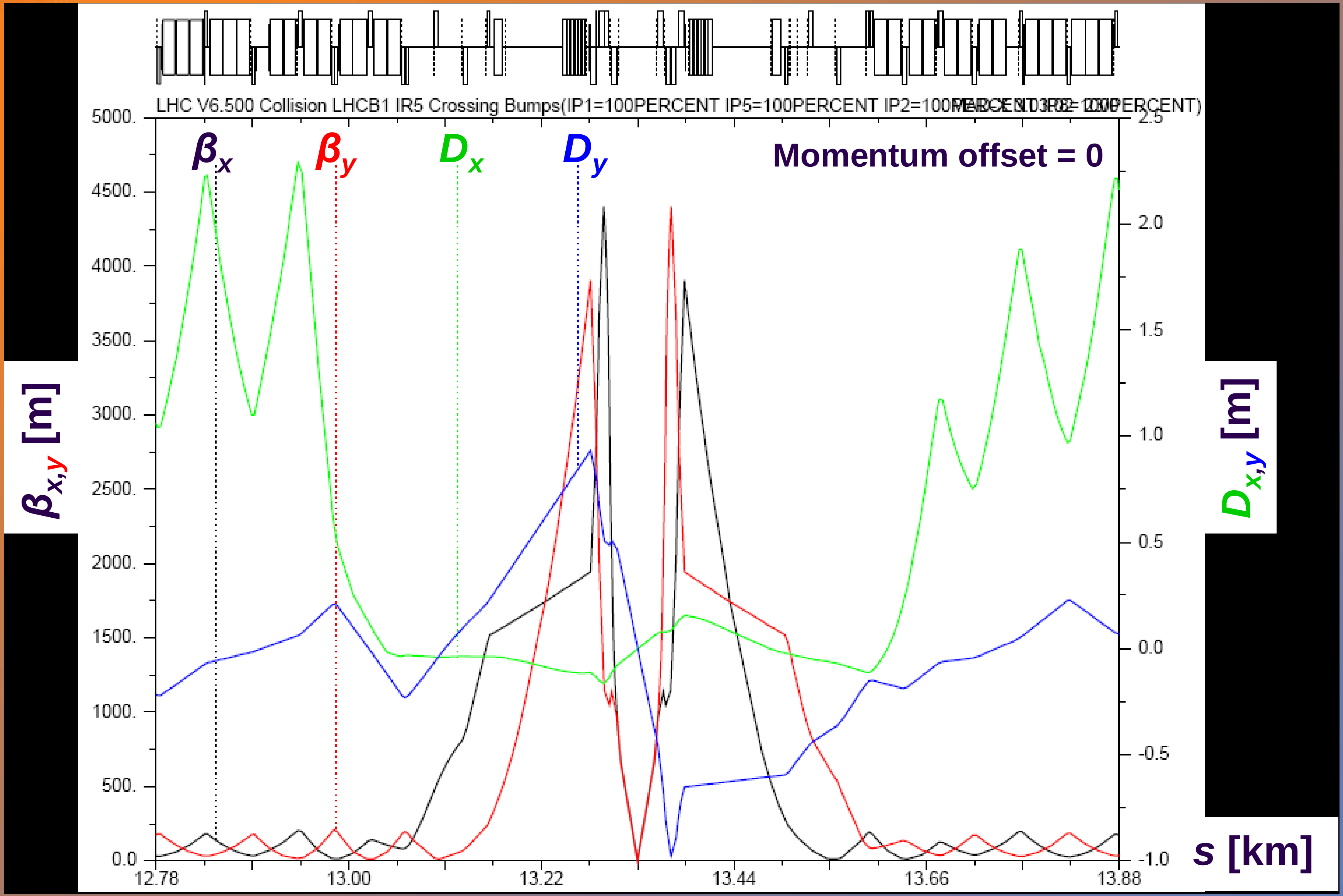
Transverse Beam Dynamics

- LHC optics for the Interaction Point (IP) 5 (CMS) in collision



High-luminosity insertion
Preassembly of inner triplet

Interactions per bunch crossing

$$N_c = \frac{L\,\sigma_I}{\mathrm{n}_b\, f_{rev}}$$

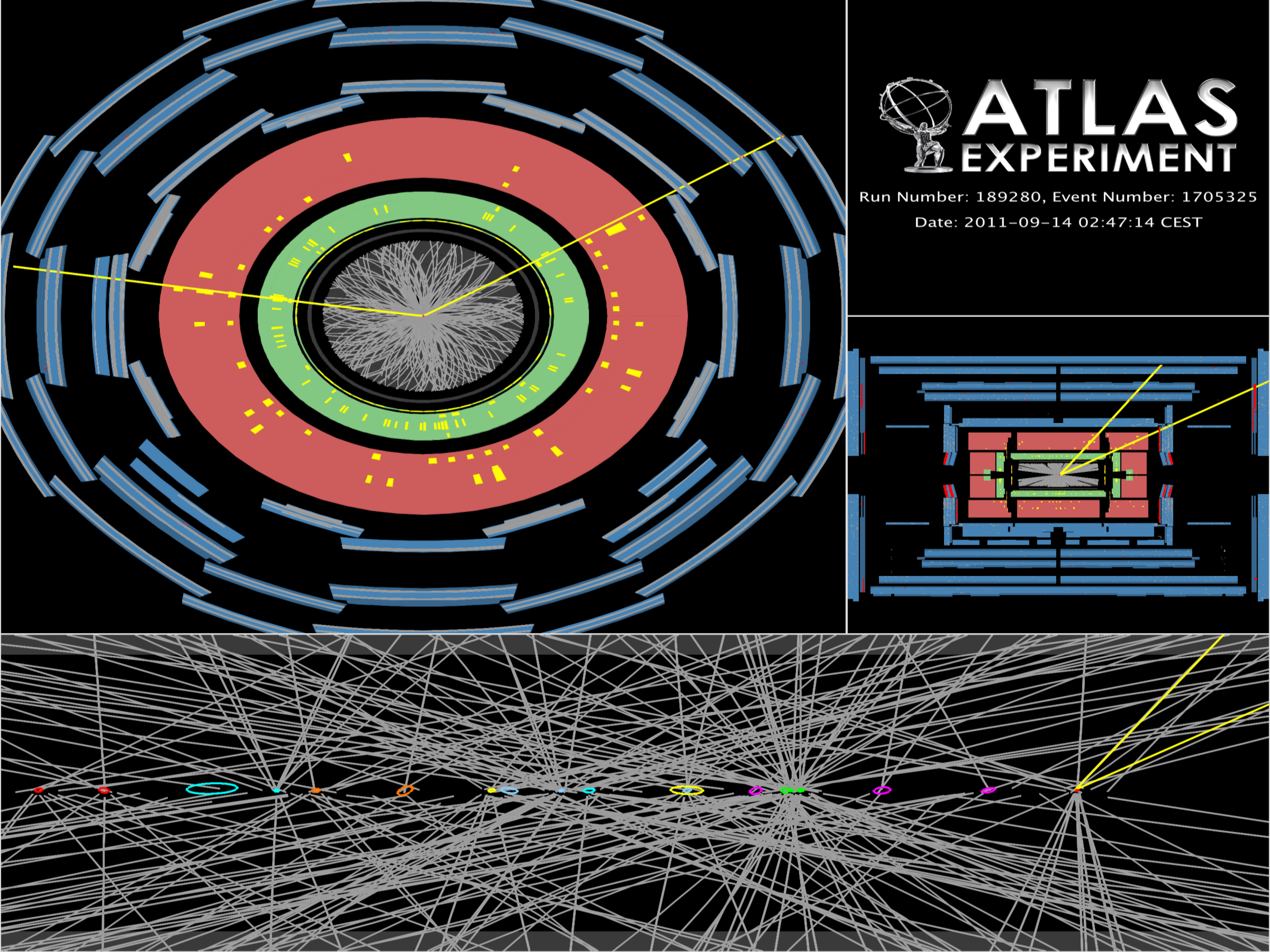
$$\sigma_T = \sigma_E + \sigma_I$$

$$\sigma_T = 100\ mb$$

$$\sigma_I = 60\ mb$$

$$Rate = L\sigma_I = 10^{34}.6.10^{-26} sec^{-1}$$

$$N_c = 19$$


ATLAS EXPERIMENT
Run Number: 189280, Event Number: 1705325
Date: 2011-09-14 02:47:14 CEST

Luminosity lifetime

$$\frac{1}{\tau_L} = \frac{1}{\tau_{IBS}} + \frac{2}{\tau_{gas}} + \frac{1}{\tau_{nuclear}}$$

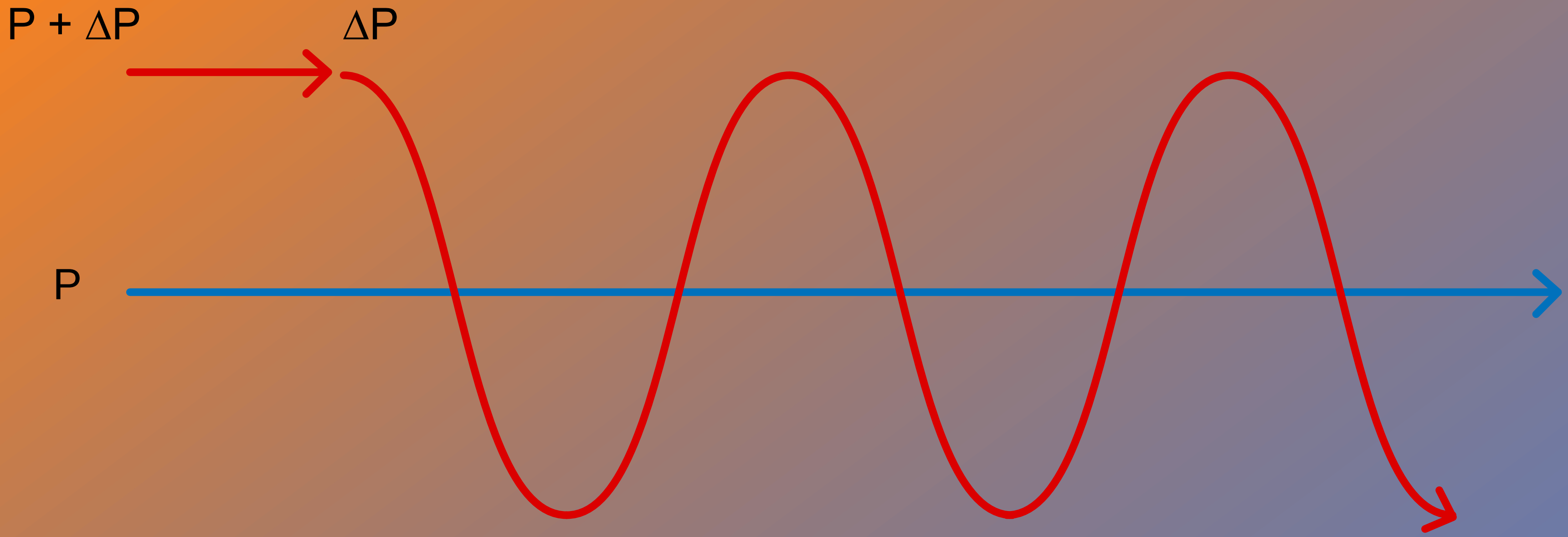
$$\tau_{nuclear} = \frac{N_{tot}}{L \sigma_T\, k}$$

Intrabeam scattering produces transverse emittance growth and dominates the luminosity lifetime at the beginning of a run.

However the main limitation of luminosity lifetime at high luminosity is the total cross section

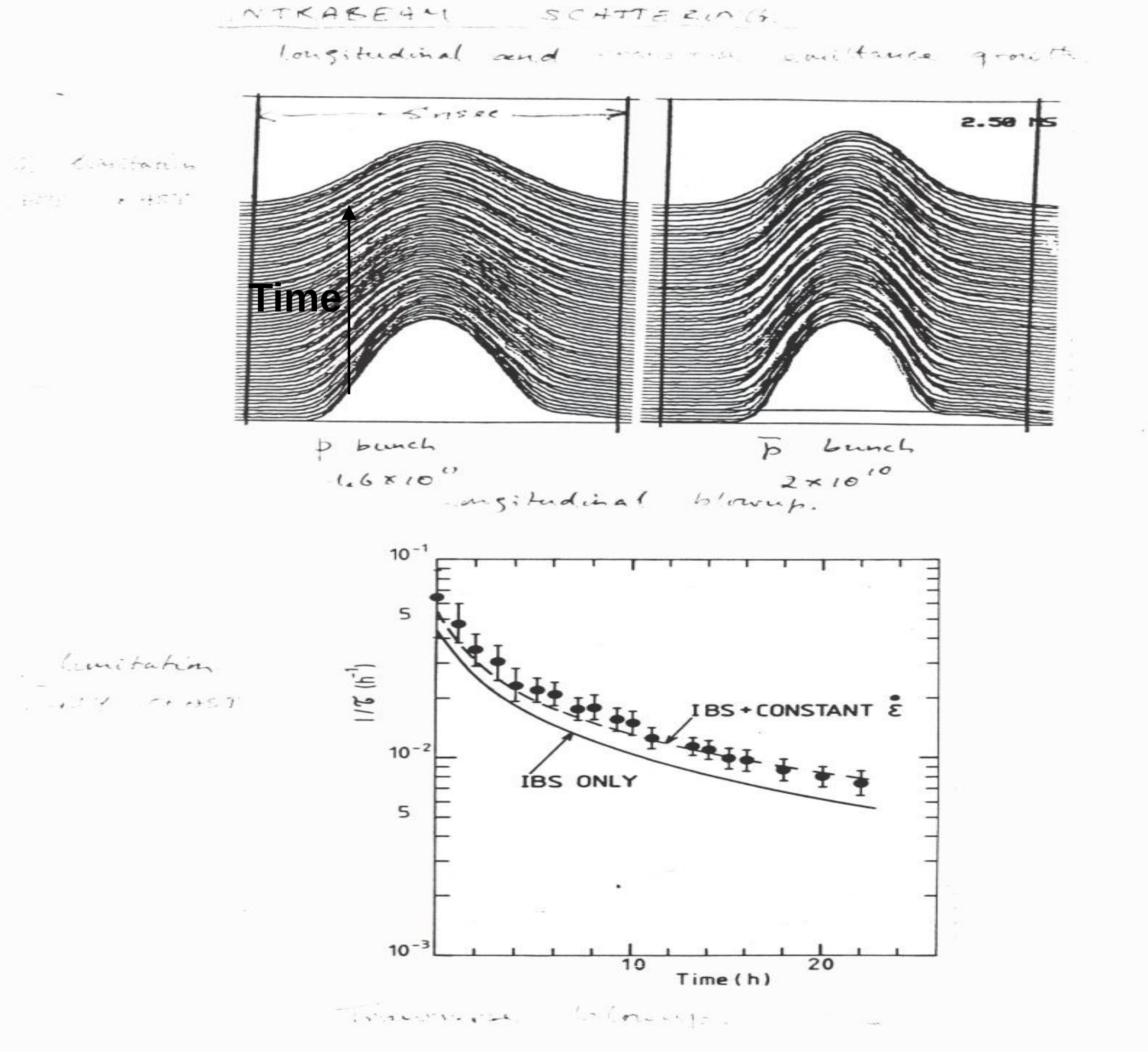
Intrabeam Scattering

Lab frame	$\sigma_{x'}$	$\sigma_{y'}$	σ_p
Rest frame	$\sigma_{x'}$	$\sigma_{y'}$	σ_p/γ



Intrabeam scattering in the SPS.

Top Bunch lengthening with time for a strong proton bunch (left) and a weak antiproton bunch (right) Bottom. IBS growth rate compared with theory.



NTRABEAM SCATTERING.

longitudinal and [illegible] emittance growth

2. Limitation [illegible] + IBS

p bunch 1.6×10^{11}

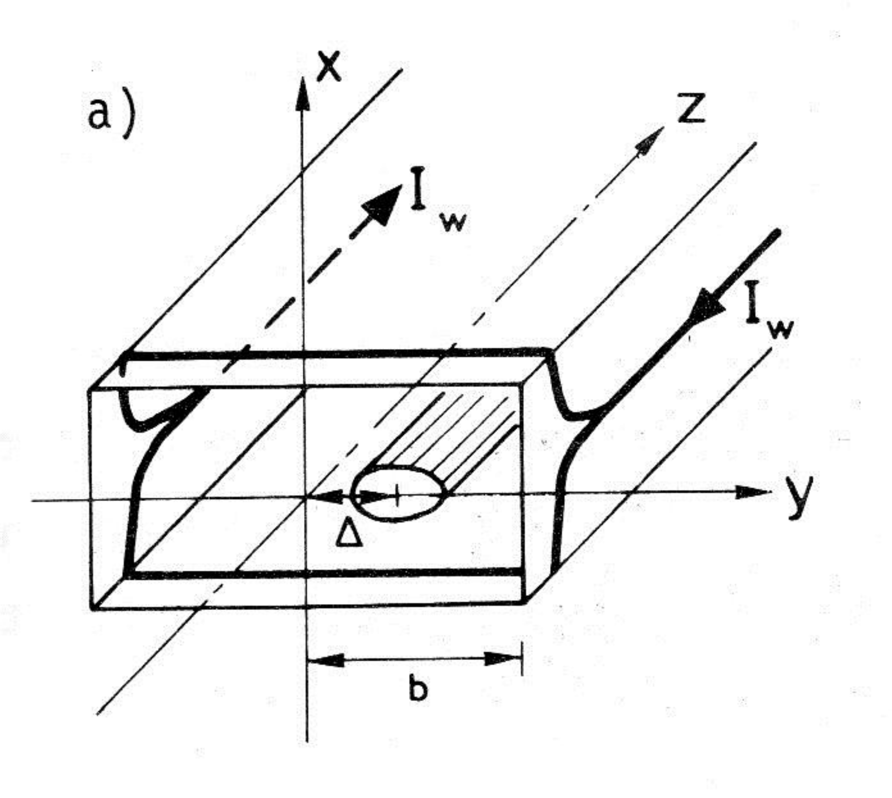
$\bar{p}$ bunch 2×10^{10}

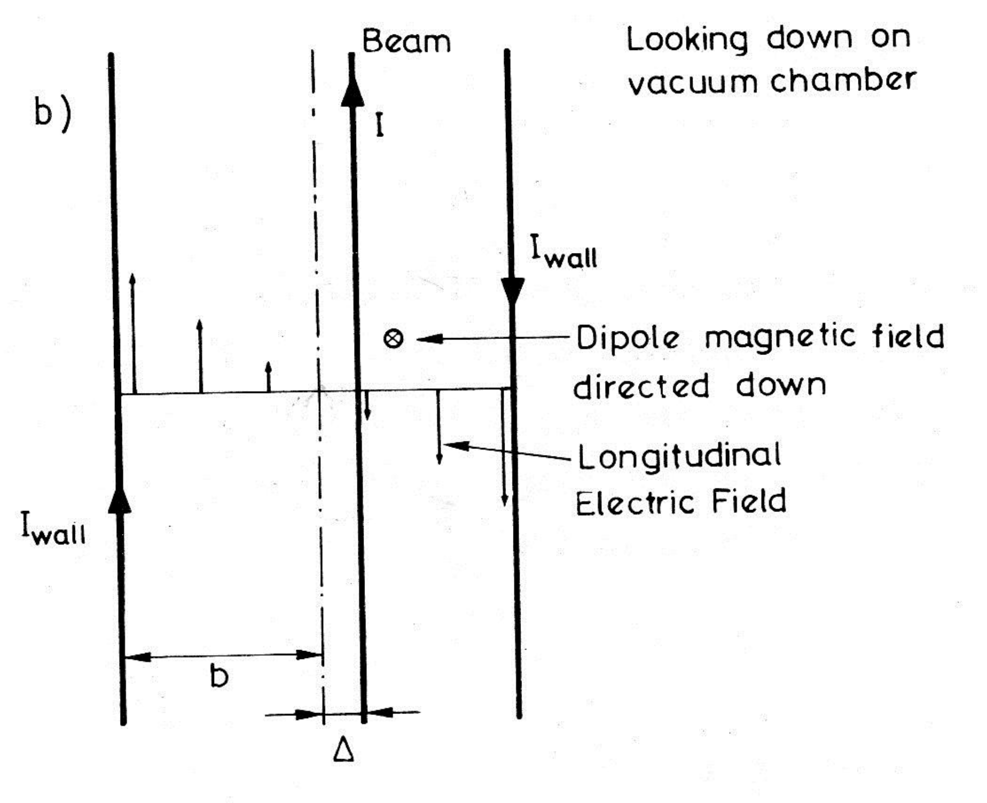
longitudinal blowup.

limitation [illegible] + IBST

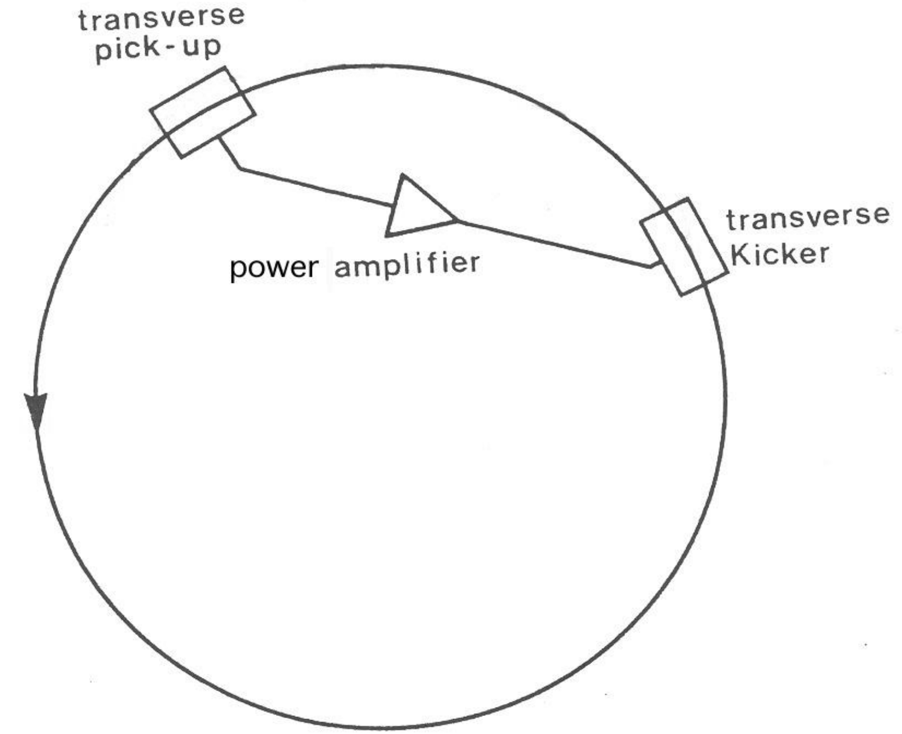
Transverse blowup.

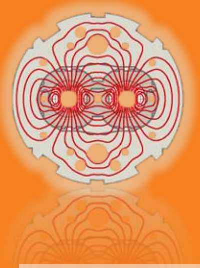
Instability driven by the chamber wall





Transverse Feedback with One-Turn Delay





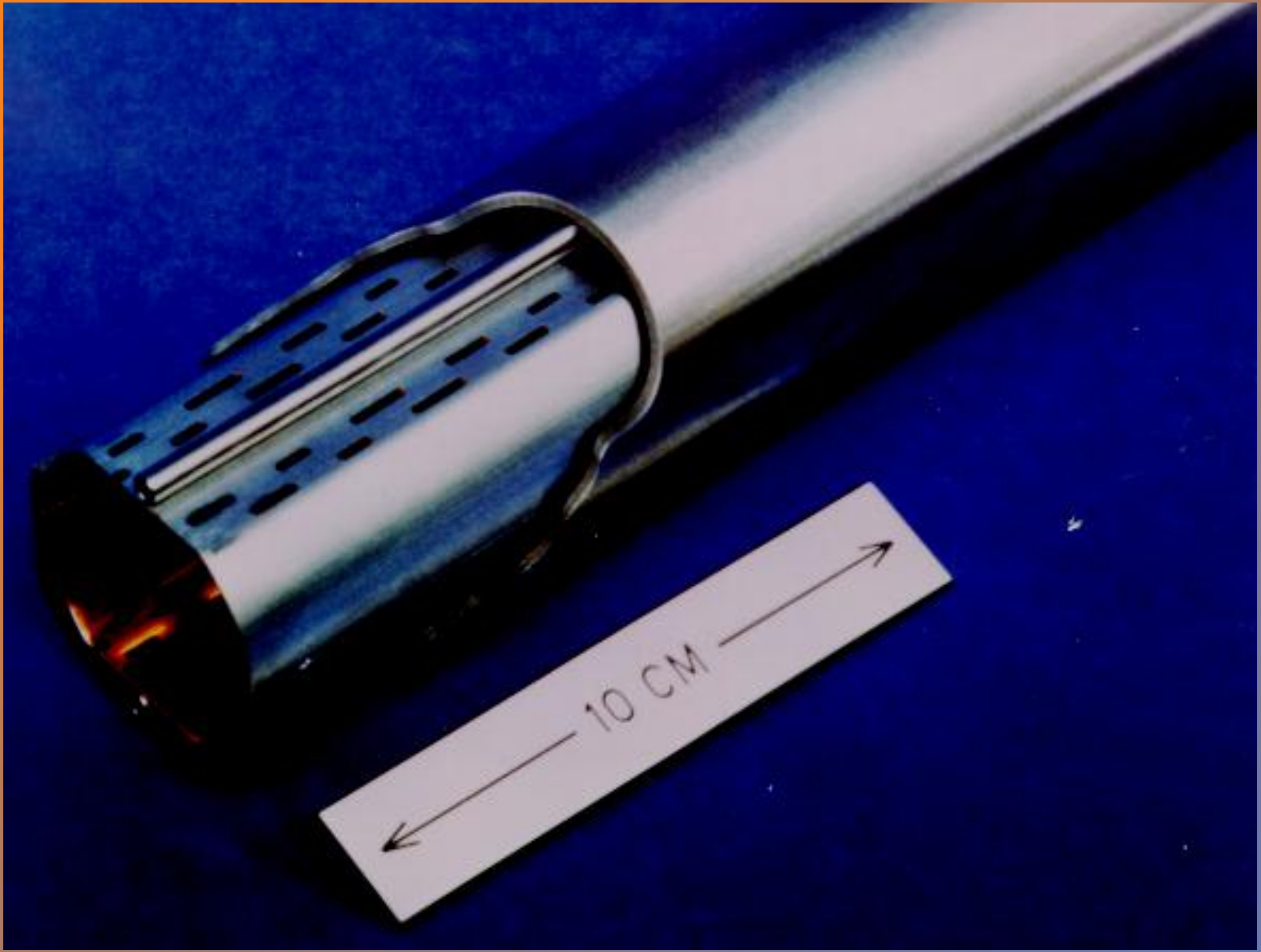
Vacuum System

The LHC presents several original requirements compared with classical vacuum systems. It has to ensure adequate beam lifetime in a cryogenic system where heat input to the 1.9 K helium circuit must be minimized and where significant quantities of gas can be condensed on the vacuum chamber. The main heat sources are:

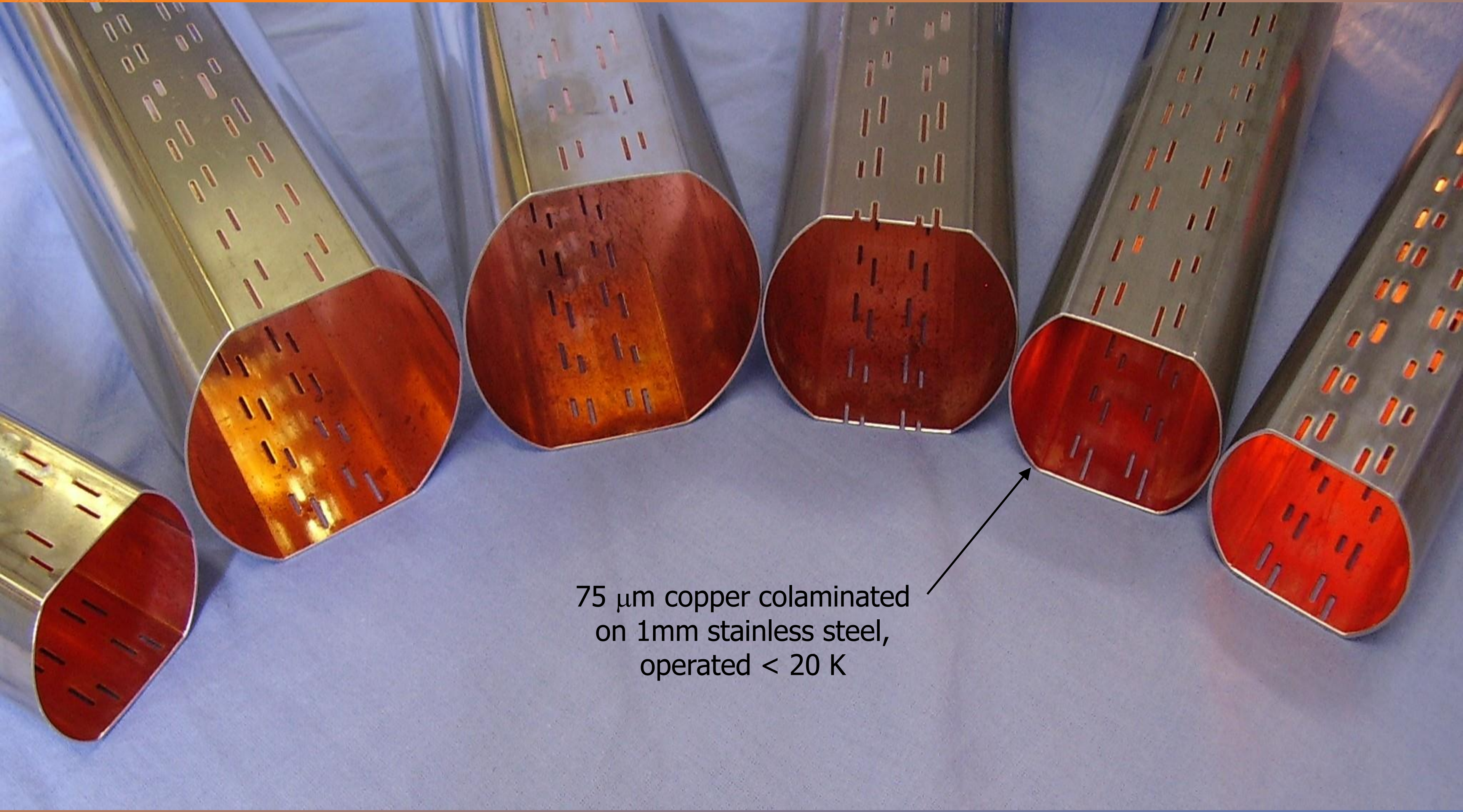
- Synchrotron light radiated by the beam at high energy (0.2 W.M-1 per beam, with a critical energy of about 44 eV;
- Image currents (0.2 W.M-1 per beam);
- Energy dissipated by the development of electron clouds.
- Energy loss by nuclear scattering (30 mW.M-1 per beam).

In order to remove the heat from all these processes but the last with high thermodynamic efficiency, the 1.9 K cold bore of the magnets is shielded with a beam screen cooled to between 5 and 20 K. This beam screen is perforated with about 4% of the surface area to allow the cold bore of the magnets at 1.9 K to act as a distributed cryopump, allowing gas to be condensed on the cold bore surface protected against desorption by bombardment with synchrotron radiation photons.

LHC Beam Screen

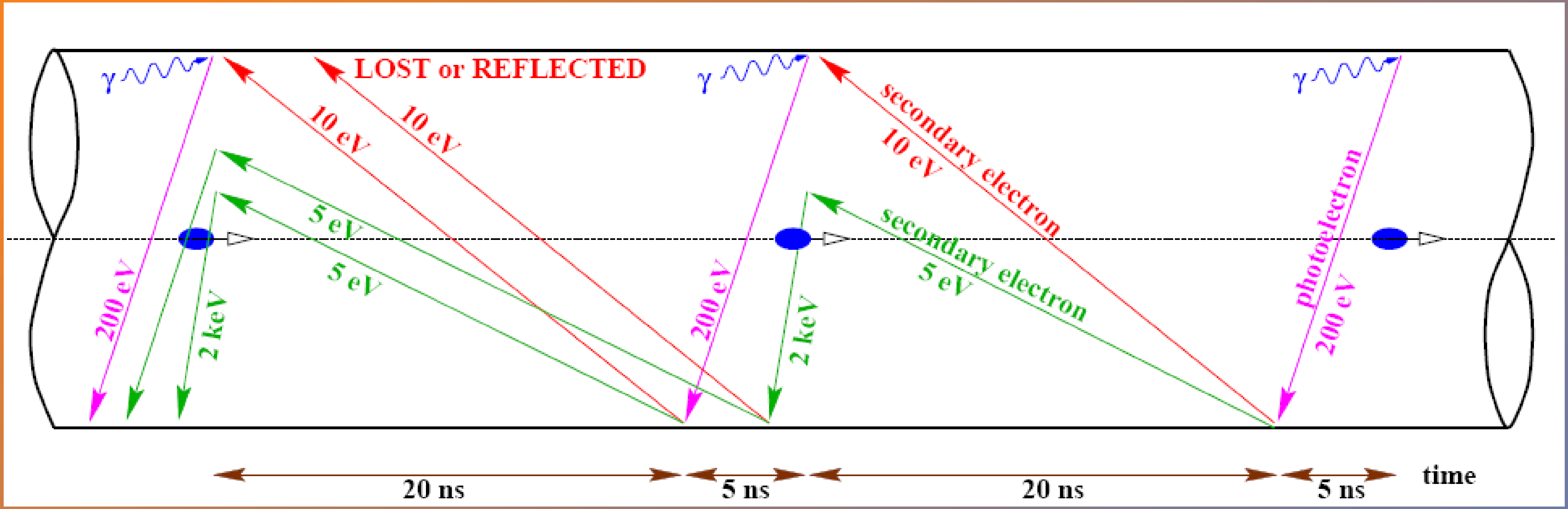


Copper-coated beam screens

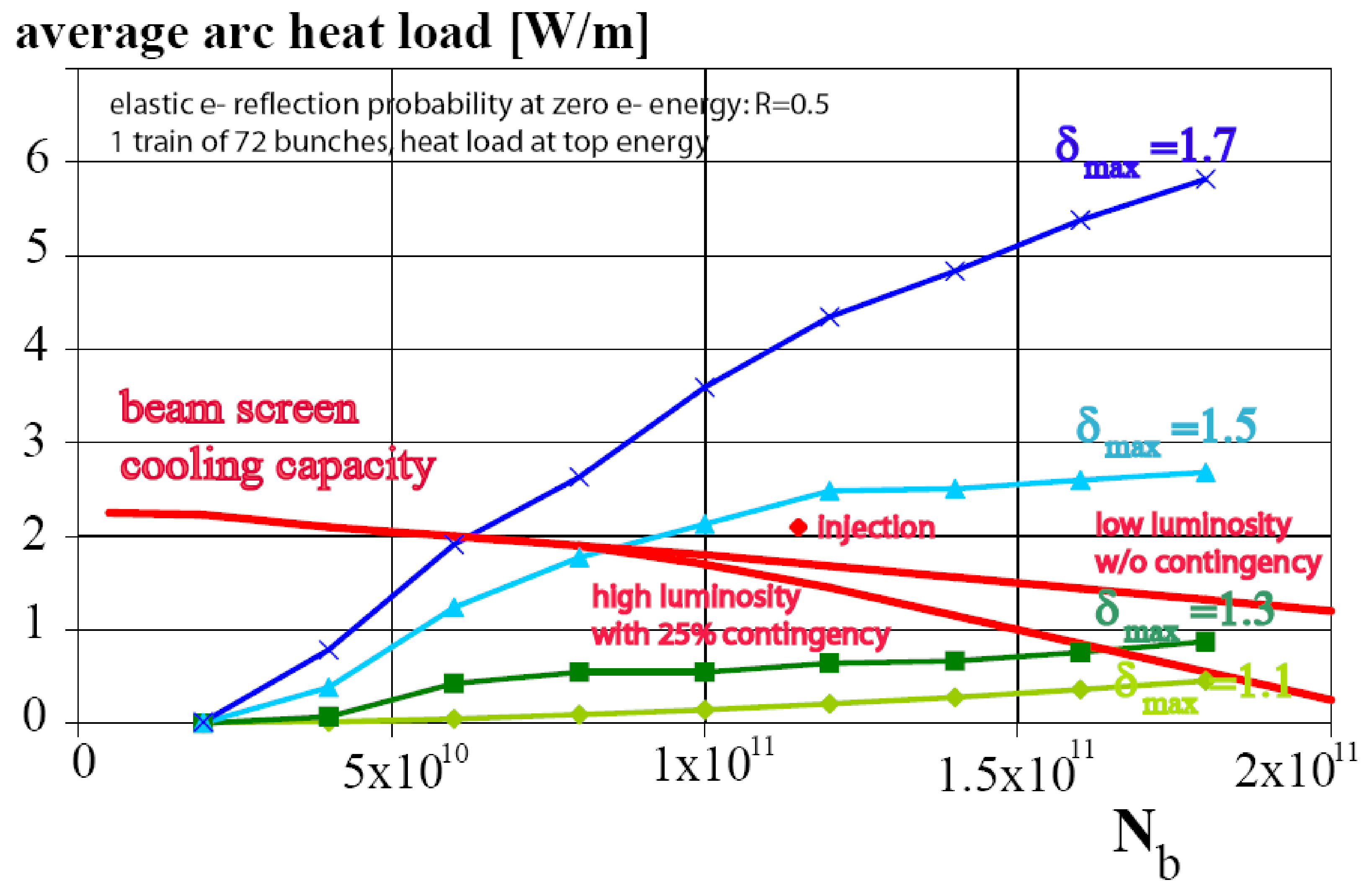


75 μm copper colaminated
on 1mm stainless steel,
operated < 20 K

The electron cloud effect

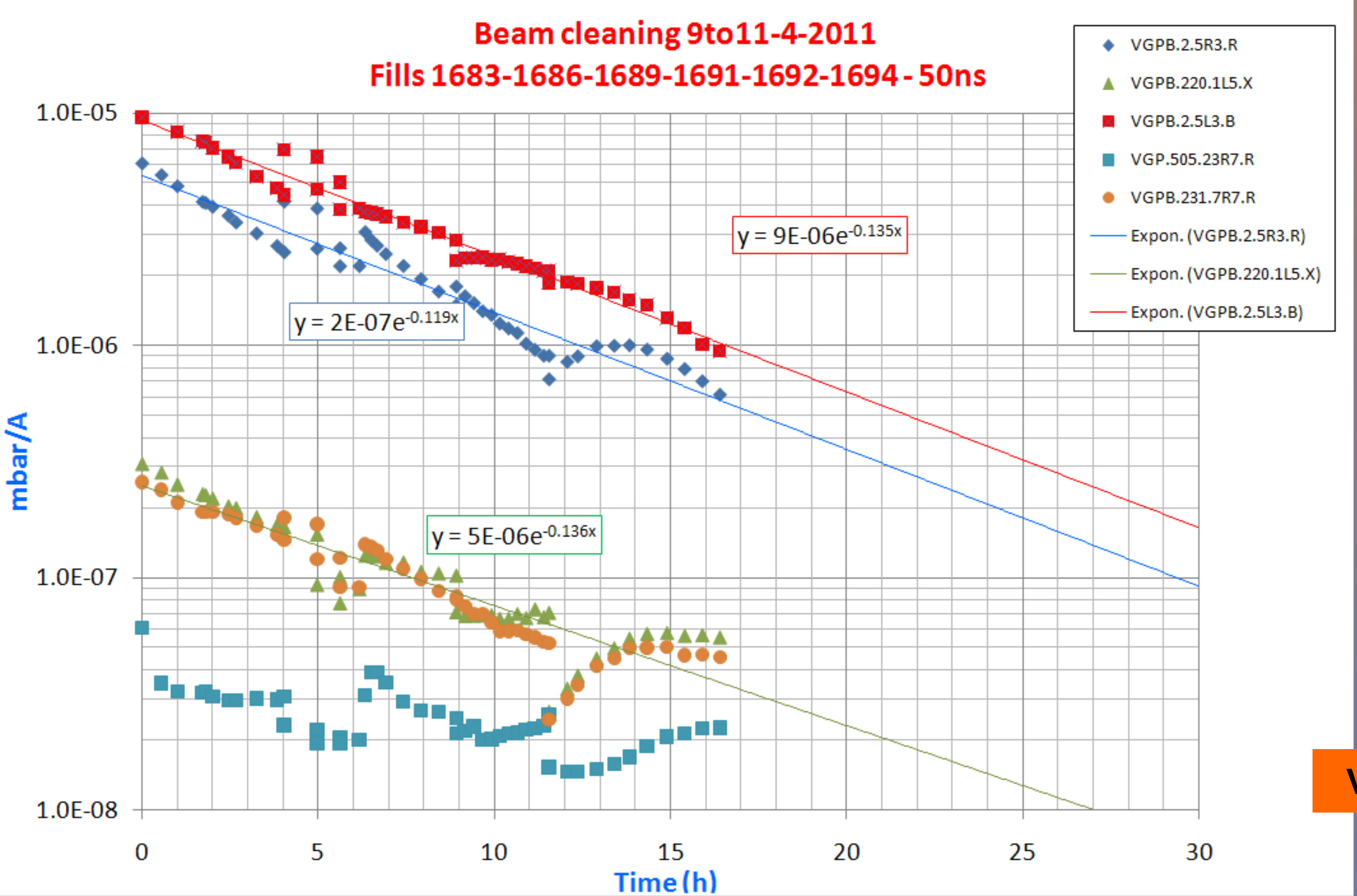


Simulated heat load as a function of SEY



Vacuum pressure evolution with 50 ns

Reduction of one decade in about 17h (periods with constant number of bunches)



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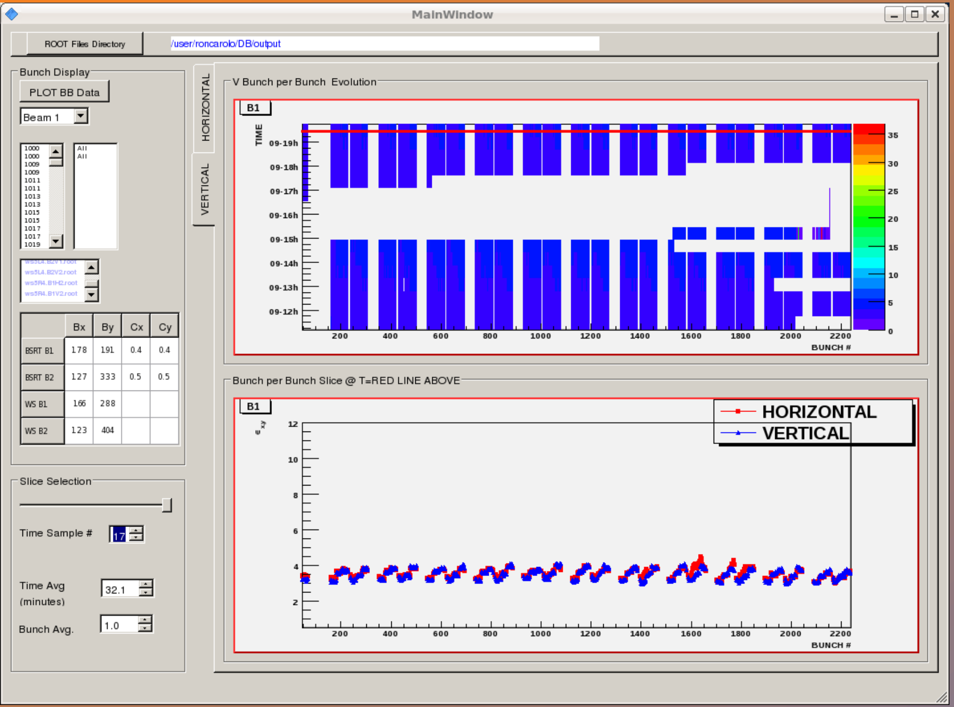
Emittance preservation

Limited blow-up observed after some hours at injection (injected emittances are in the range 2.5-3 mm), even with 800 and >1000 bunches. **Clear improvement due to reduced activity in the arcs. Low chromaticity (~4)**

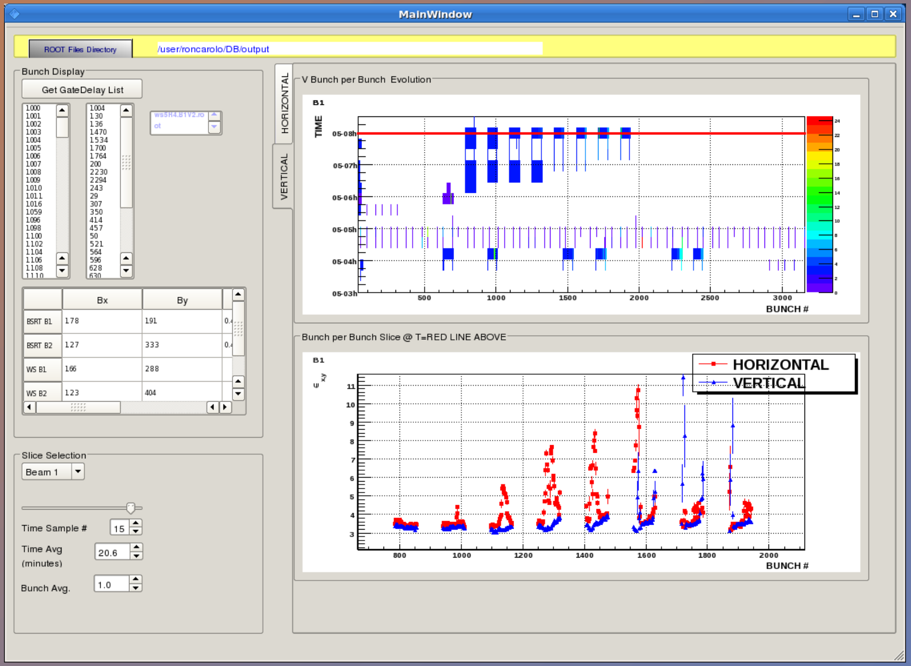


	Bx	By	Cx	Cy
BSRT B1	178	191	0.4	0.4
BSRT B2	127	333	0.5	0.5
WS B1	166	288		
WS B2	123	404		

Time Sample # 17

Time Avg (minutes) 32.1

Bunch Avg. 1.0



	Bx	By
BSRT B1	178	191
BSRT B2	127	333
WS B1	166	288
WS B2	123	404

Beam 1

Time Sample # 15

Time Avg (minutes) 20.6

Bunch Avg. 1.0

Day 3 – 800 bunches

We started like that…

Day 1 – 300 bunches