Engines of Discovery

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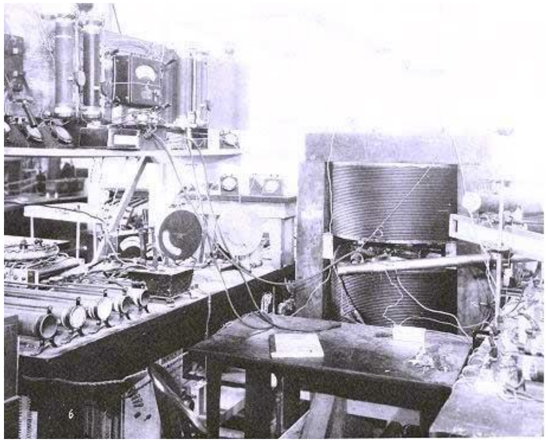


Berkley 1930
1 MeV

Geneva 200~~8~~9
14 TeV

Birth of Particle Physics and Accelerators

- 1909 Geiger/Marsden MeV α backscattering - Manchester
- 1919 Rutherford disintegrates Nitrogen - Manchester
- 1927 Rutherford demands accelerator development
  Particle accelerator studies - Cavendish
- 1929 Cockcroft and Walton start high voltage experiments
- 1932 The goal achieved: Cockcroft + Walton split Li nucleus

The Experimental Tube.

The experimental tube consisted of two glass tubes similar to those used in the tower of rectifiers, and is shown in fig. 5. A steel plate, A, was placed between the cylinders, and this formed the support for the electrodes, B. The thin sheets of metal used in the rectifiers would not have been sufficiently rigid to give the accurate alignment of the electrodes which is necessary in this case to direct the beam of ions down the axis of the tube. This metal plate had a 3 feet square piece of sheet metal, C, attached externally which acts as a stress distributor and which is maintained at half the total potential by a connection to the middle point of the tower of rectifiers. Protons were generated in a hydrogen discharge tube, D, placed above the apparatus. The discharge tube was of the Wien type described in the previous paper. The potential applied across the discharge tube was obtained from a 60 KV. transformer, E, fig. 6, the primary of this being supplied with alternating current at low potential. It was found that a much better proton current could be obtained from the discharge tube when the current sent through it was rectified by placing a small kenetron between it and the transformer.

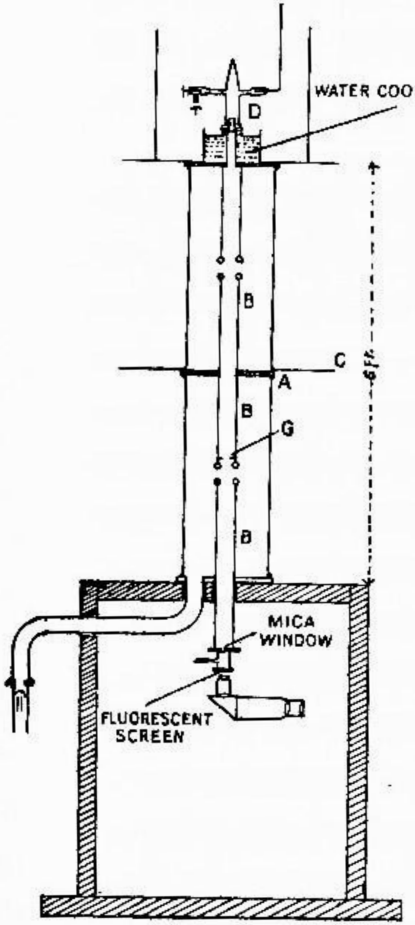
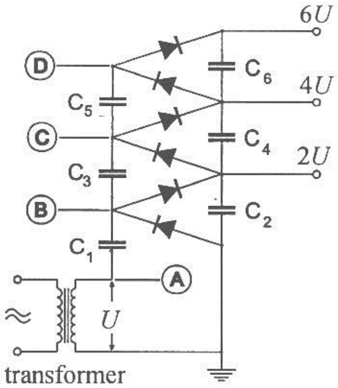
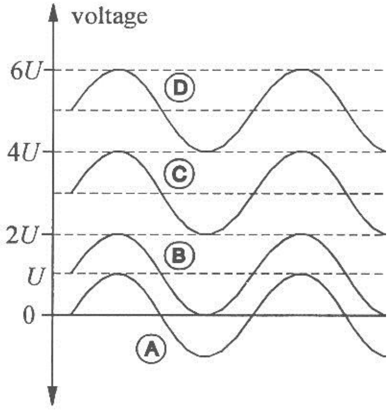


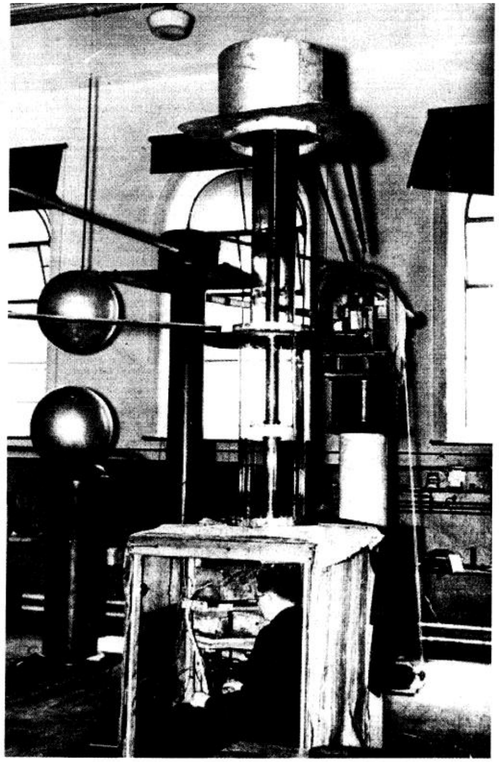
Fig. 5.

Cockcroft-Walton Generator

665 kV







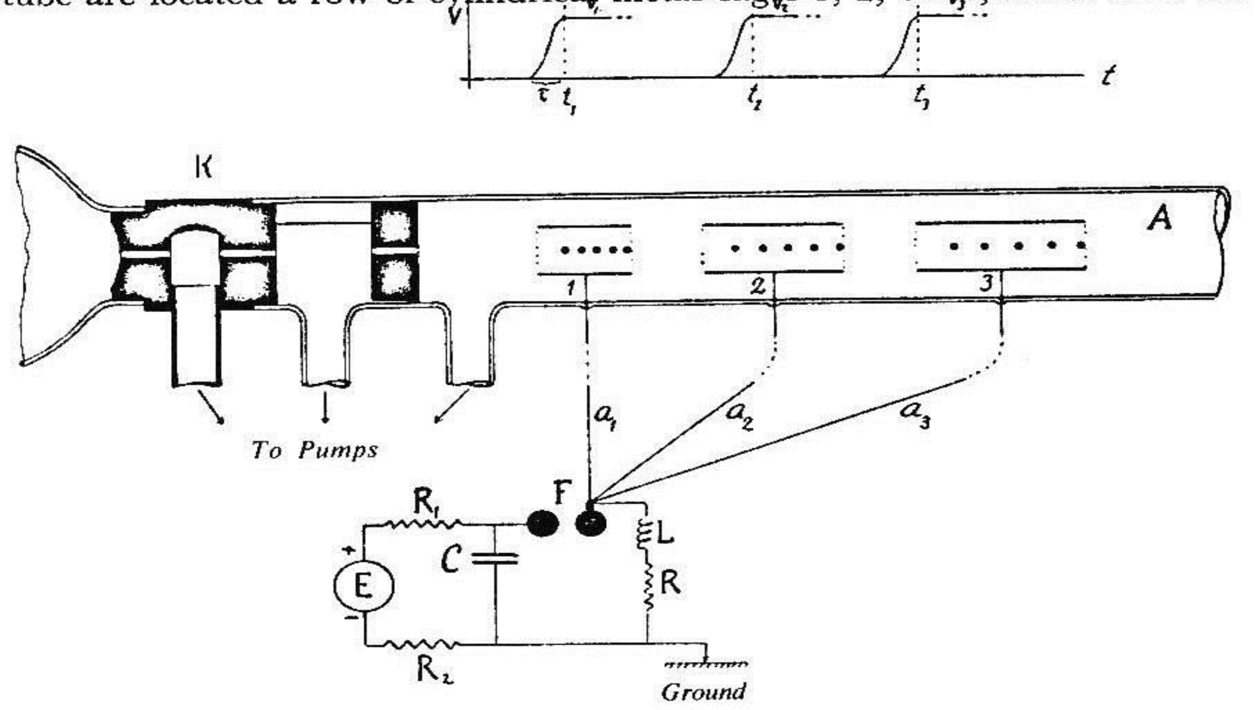
The Principle of a Method for the Production of Canal Rays of High Voltage

[Translation by F. W. Brasse of "Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl," *Arkiv för Matematik, Astronomi och Fysik, 18*: 1–4 (1924).*]

Ising – 1924

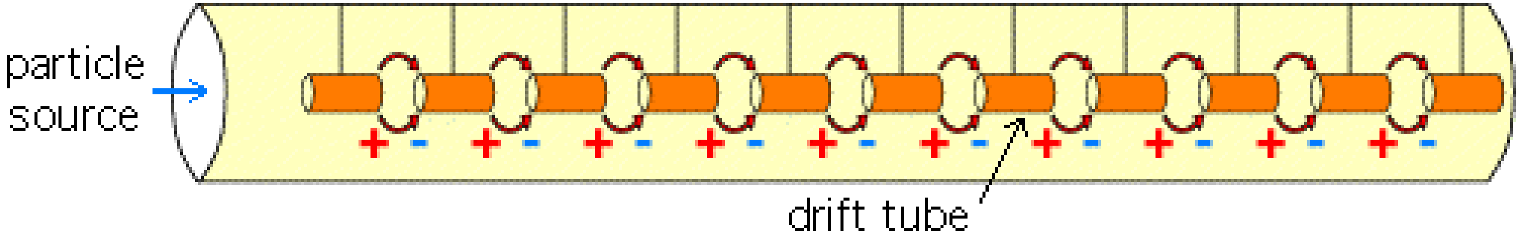
It is the purpose of the following lines to sketch a method which in principle permits the generation of canal rays (perhaps also cathode rays) of arbitrarily high voltage with the aid of available moderate potentials. This should be possible by requiring that the beam particles pass through the potential many times in its trajectory. The potential is transmitted as a charge wave along wires to various places along the particle's path with suitable time differences.

A suitable arrangement is shown schematically in Fig. 1. Canal rays enter from the discharge chamber at the left, through the grounded cathode *K* into the well-evacuated acceleration chamber tube *A* shown at the right. In this tube are located a row of cylindrical metal cages 1, 2, 3 . . . , whose ends are



Resonant Accelerator Concept

Wideroe - 1928

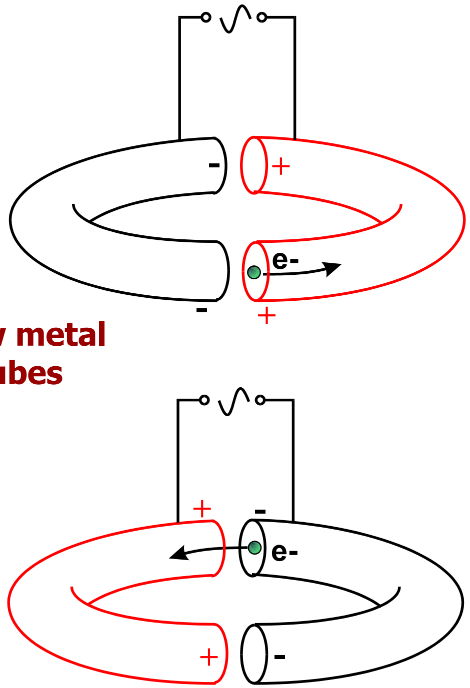


Alternating (radio frequency) fields allow higher voltages

- The acceleration occurs in the electric field between cylindrical *drift tubes*.
- The RF power must be *synchronised* with the motion of the electrons, so that acceleration occurs in every gap.

Linear Accelerator = LINAC

Recirculation Concept - Cyclotron

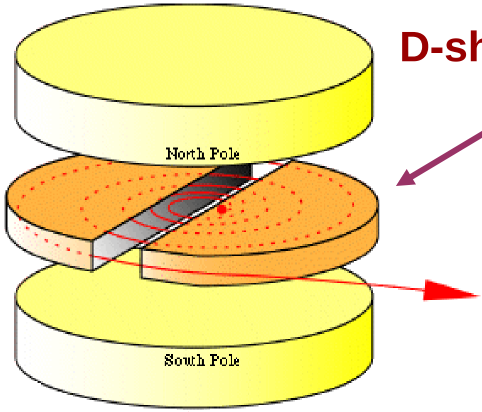


Radio frequency alternating voltage

Hollow metal drift tubes

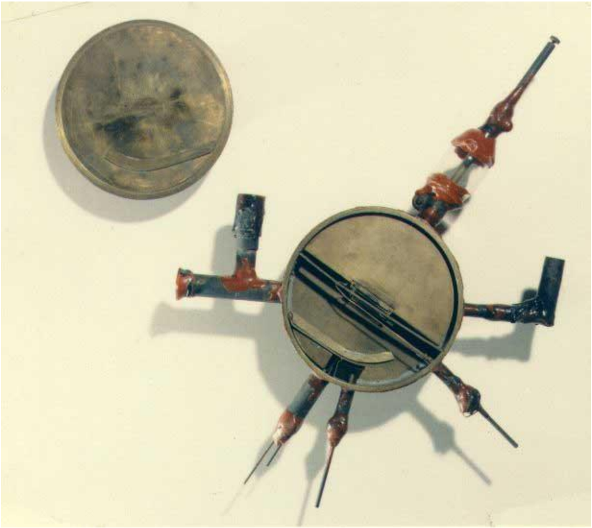
time $t = 0$

time $t = ½$ RF period

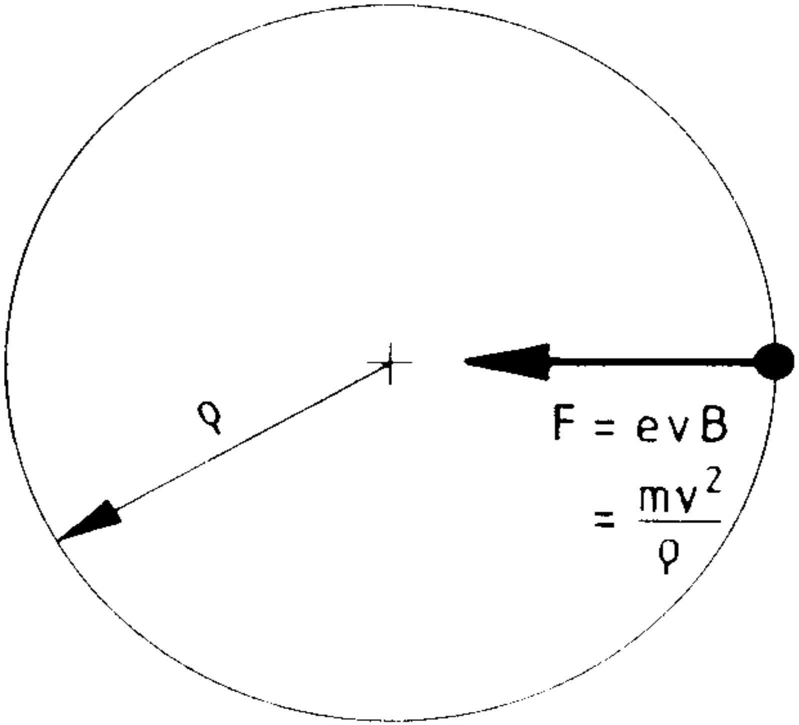


D-shaped RF cavities

Lawrence:
4” – 80 keV
11” - 1.2 MeV



- Orbit radius increases with momentum
- Orbital Frequency independent of momentum
- Particle motion and RF in phase



Equilibrium Orbit

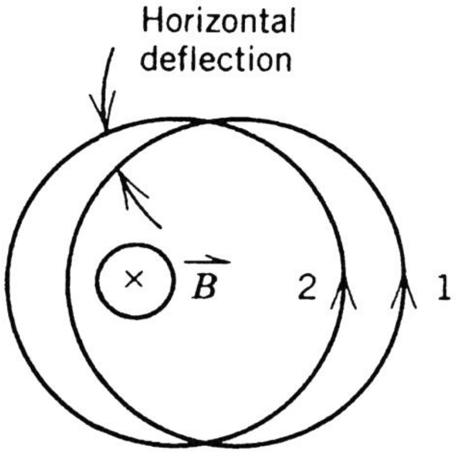
Constant revolution frequency

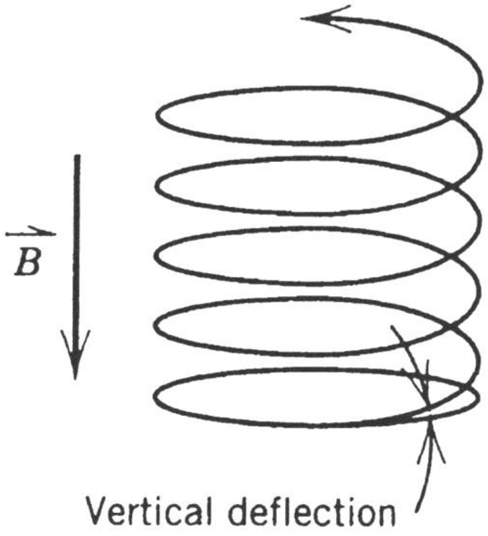
$$f_{rev} = \frac{v}{2\pi\rho} = \frac{v}{2\pi}\frac{eB}{mv} = \frac{eB}{2\pi m}$$

Magnetic rigidity

$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

Orbit Stability

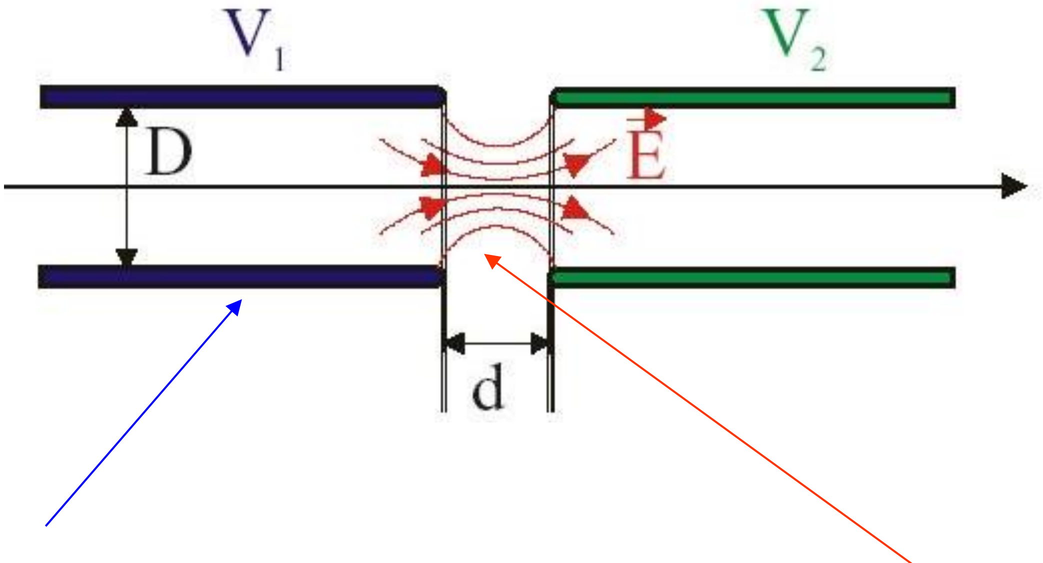




Slight Displacement from Equilibrium Orbit → Particle Lost

Vertical and Horizontal Focusing

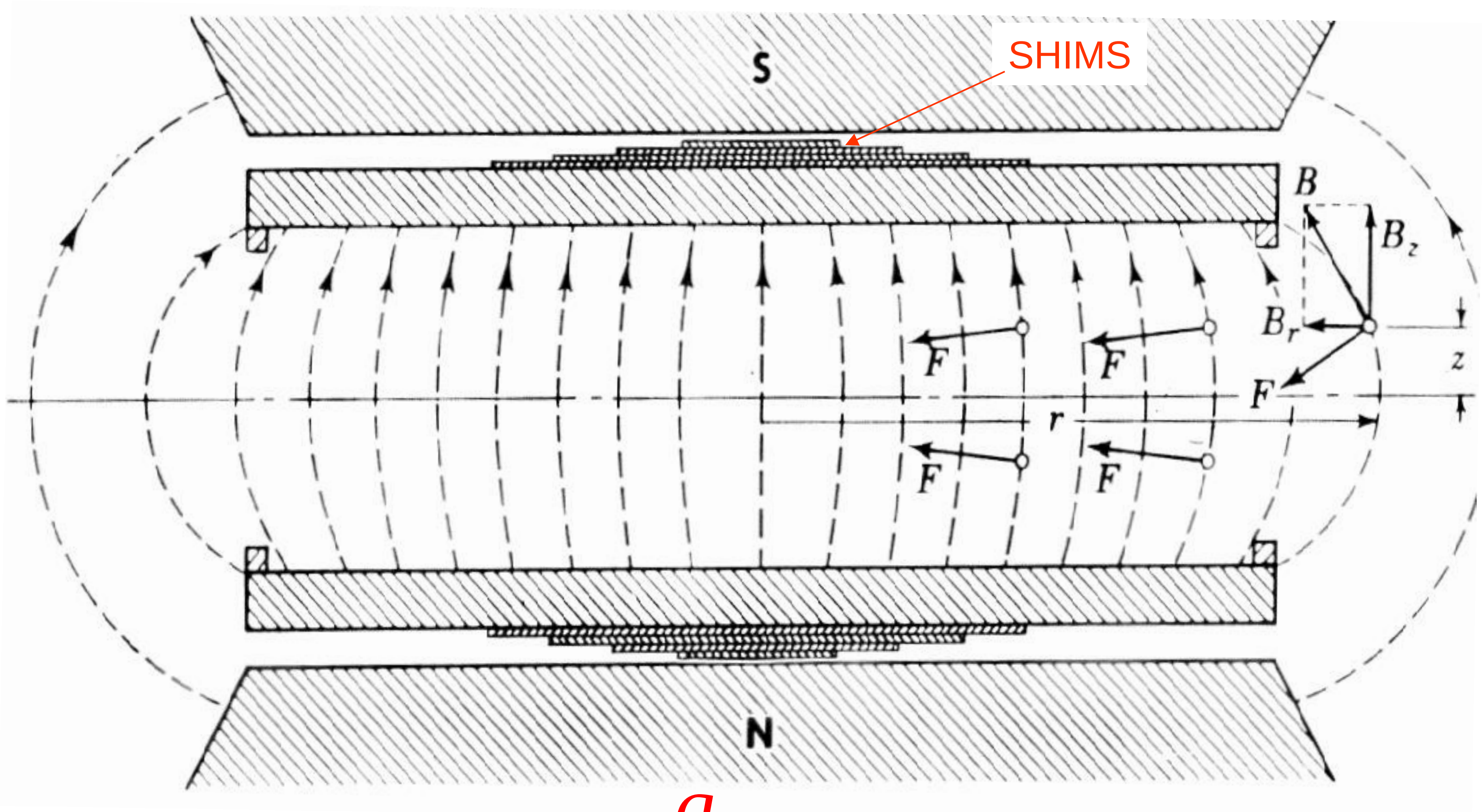
Vertical Orbit Stability in Lawrence’s Cyclotron



Cross Section Thru Ds

Electrostatic Focusing Lens

Orbital Stability in a Cyclotron



$$\overline{F} = \frac{q}{c}\overline{v} \times \overline{B}$$

Betatron Oscillations

Horizontal

Vertical

$$B_z = B_{z_0}\left(\frac{R}{r}\right)^n$$

Field Index

Equilibrium Orbit

$$\gamma m \frac{d^2 y}{dt^2} = \frac{e}{c} v B_x$$

$$\frac{\gamma m v^2}{R} - \frac{e}{c} v B_{z_0} = 0$$

Centrifugal = Lorentz
on equilibrium orbit

$$\frac{\partial B_x}{\partial z} - \frac{\partial B_z}{\partial x} = 0$$

$$F_x = \frac{\gamma m v^2}{r} - \frac{e}{c} v B_z$$

Restoring Force

$$\gamma m \frac{d^2 y}{dt^2} = -n \frac{B_z}{R} \frac{e}{c} v = F_z$$

$$F_x = -\frac{\gamma m v^2}{R} \frac{x}{R} (1-n)$$

Simple Harmonic

$$\gamma m \frac{d^2 y}{dt^2} + n \gamma m \frac{v^2}{R^2} = 0$$

$$\omega_x = \frac{v}{R}\sqrt{1-n}$$

Stable Oscillations around
Equilibrium orbit

$$\omega_z = n \frac{v^2}{R^2}$$

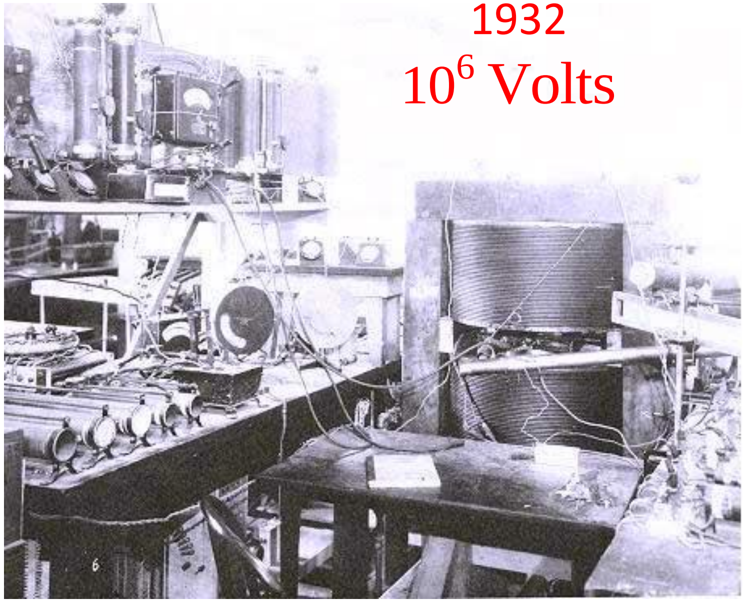
$$n < 1$$

Weak Focusing

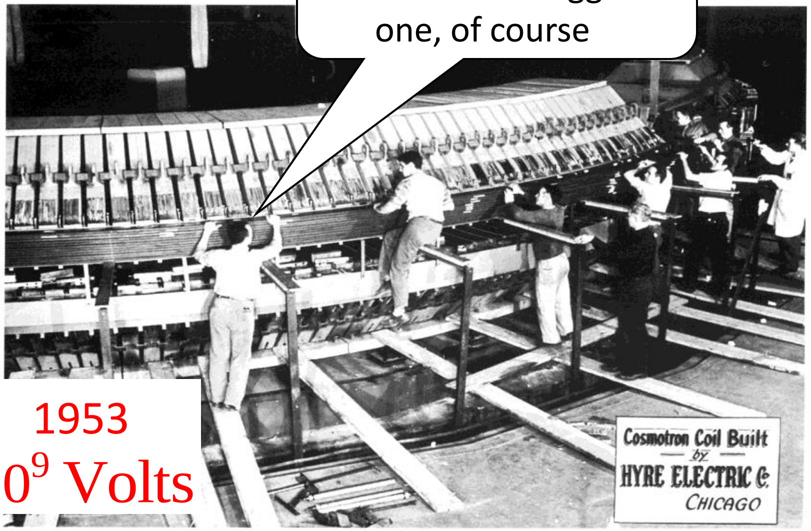
$$n > 0$$

This machine is just a model for a bigger one, of course

1931
10^4 Volts

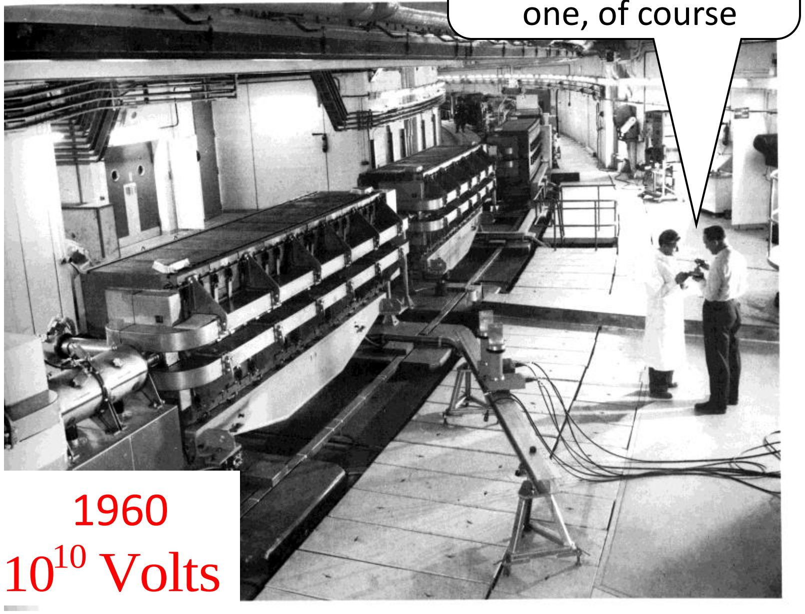


1932
10^6 Volts



This machine is just a model for a bigger one, of course

1953
10^9 Volts

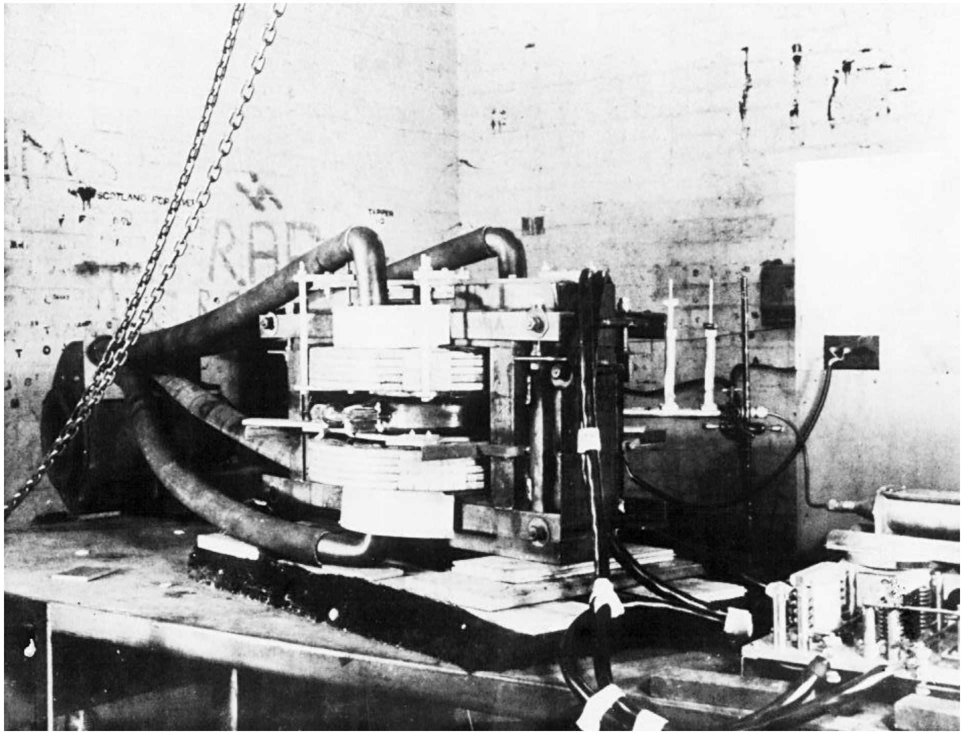


This machine is just a model for a bigger one, of course

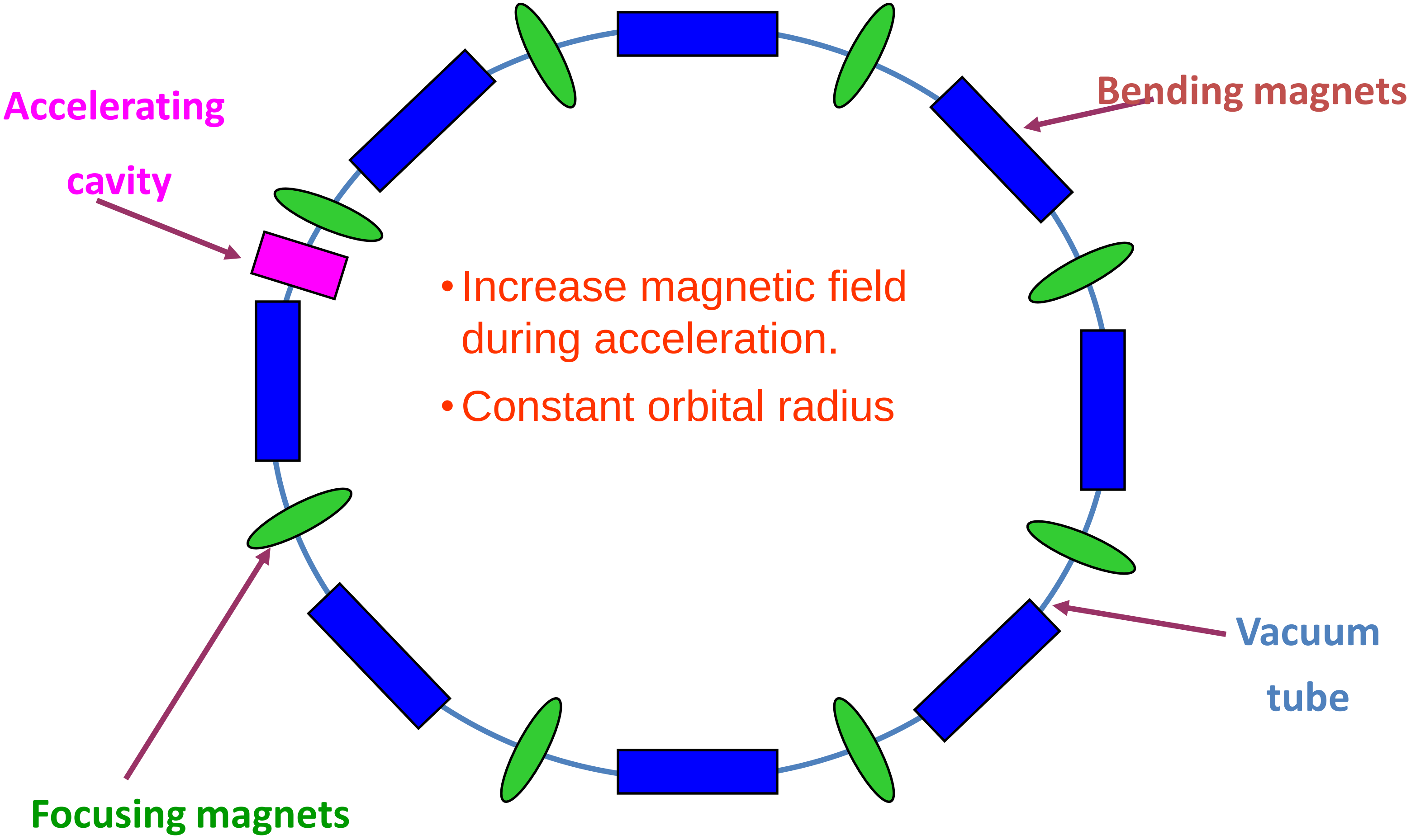
1960
10^{10} Volts

Invention of the Synchrotron

Marcus Oliphant
– later to become
Governor of South Australia

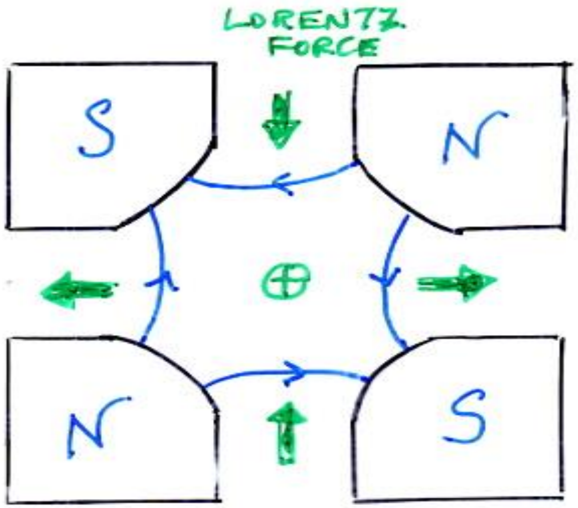


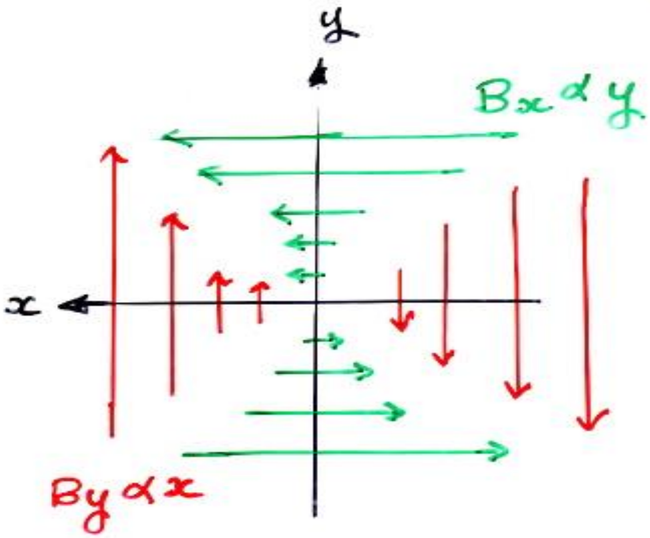
Synchrotron Ring Schematic



- Increase magnetic field during acceleration.
- Constant orbital radius

QUADRUPOLE





POLE FACES → EQUIPOTENTIAL SURFACE

FOR HYPERBOLIC POLE FACES.

MAGNETIC SCALAR POTENTIAL $\phi = kxy$

$$\bar{B} = -\bar{\nabla}\phi$$

IN DIAGRAM ABOVE

$B_x = -ky$ FOCUS

$B_y = -kx$ DEFOCUS

FIELD INDEX

WARM IRON MAGNETS $K = 12\ Tm^{-1}$

FOCUS 10 GeV ELECTRON

SUPERCONDUCTING MAGNETS $K = 75\ Tm^{-1}$

FOCUS 1 TeV PROTONS

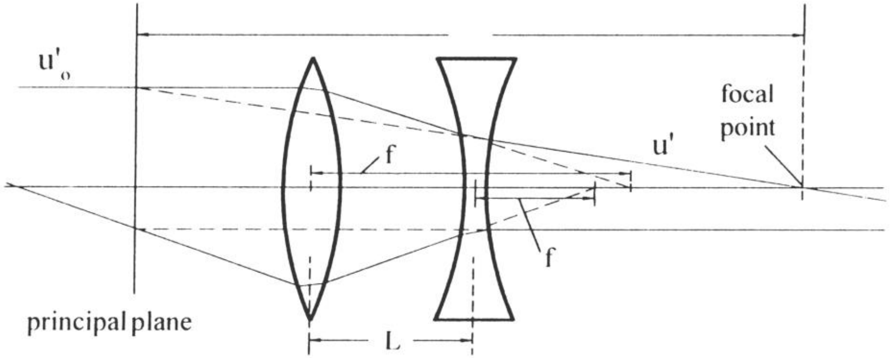
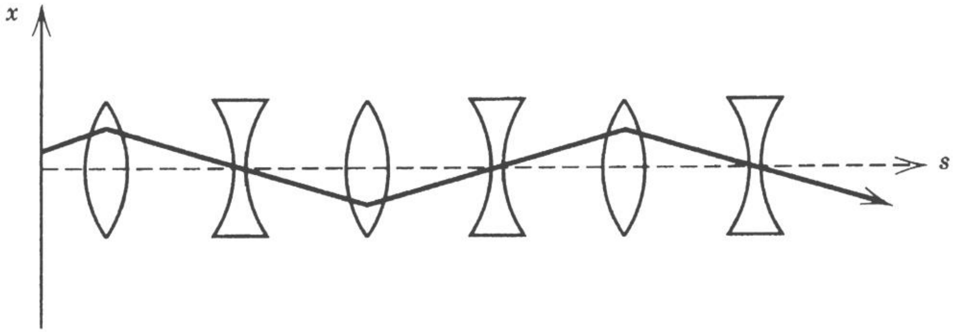


Fig. 4.14. Focusing in a quadrupole doublet

$$\begin{pmatrix}1 & 0\\ -\frac{1}{f} & 1\end{pmatrix}\begin{pmatrix}1 & L\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ +\frac{1}{f} & 1\end{pmatrix} = \begin{pmatrix}1+\frac{L}{f} & L\\ -\frac{L}{f^2} & 1-\frac{L}{f}\end{pmatrix}$$

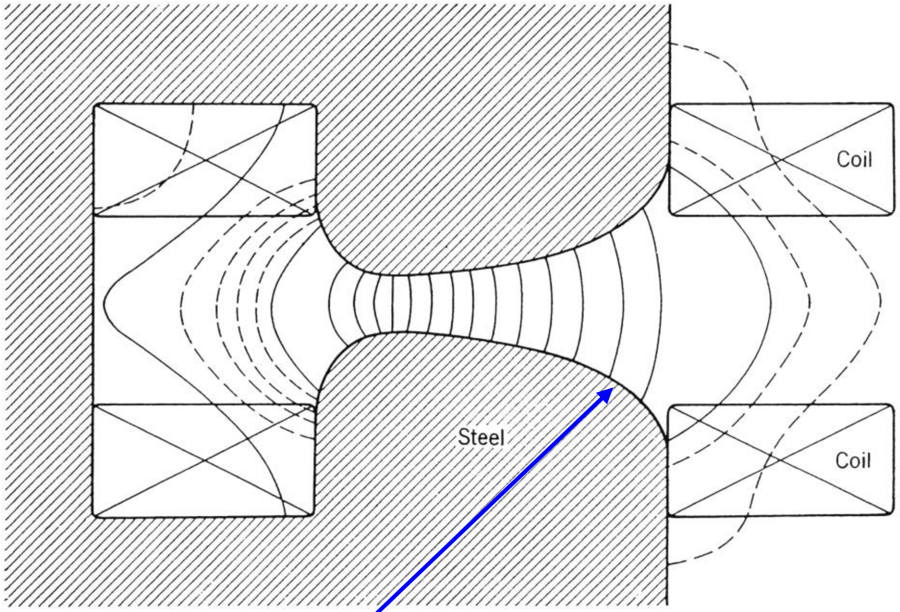
$$\approx \begin{pmatrix}1 & 0\\ -\frac{L}{f^2} & 1\end{pmatrix} \qquad L \ll f$$

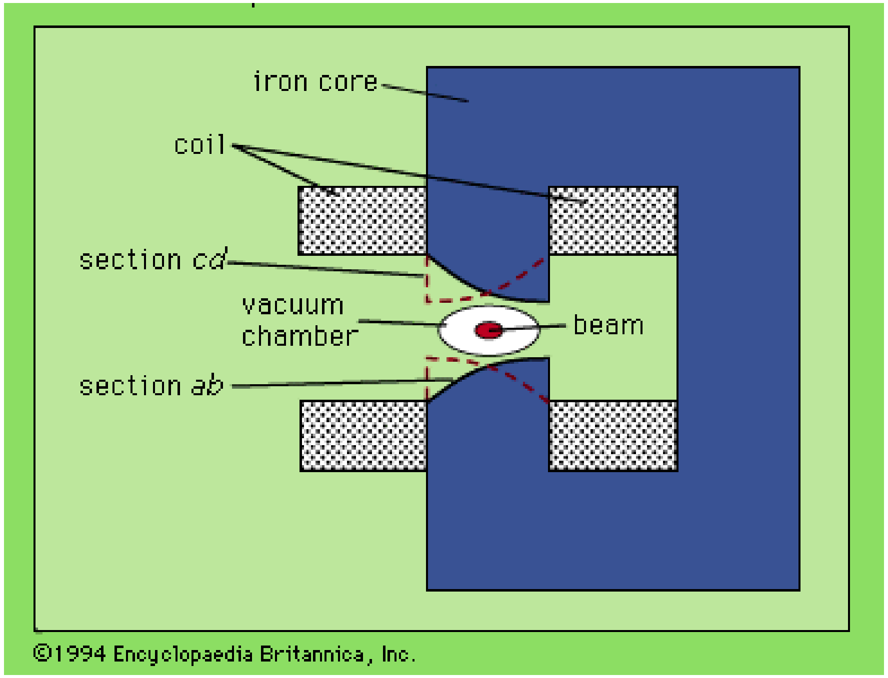
Net Focusing



- FODO Lattice
- Strong Focusing

Strong Focusing





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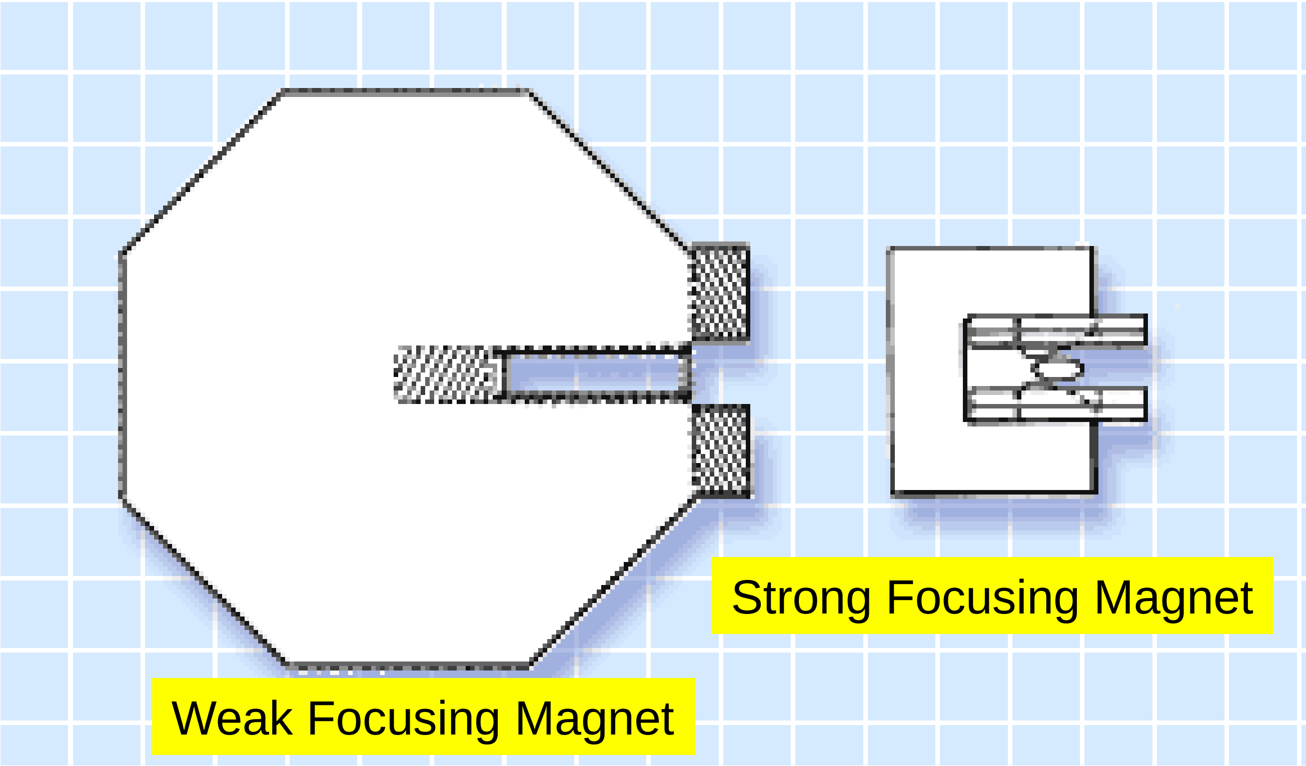
- Field Index set by Pole Face Shape
- Weak, n = 0.5
- Strong, n = 3500

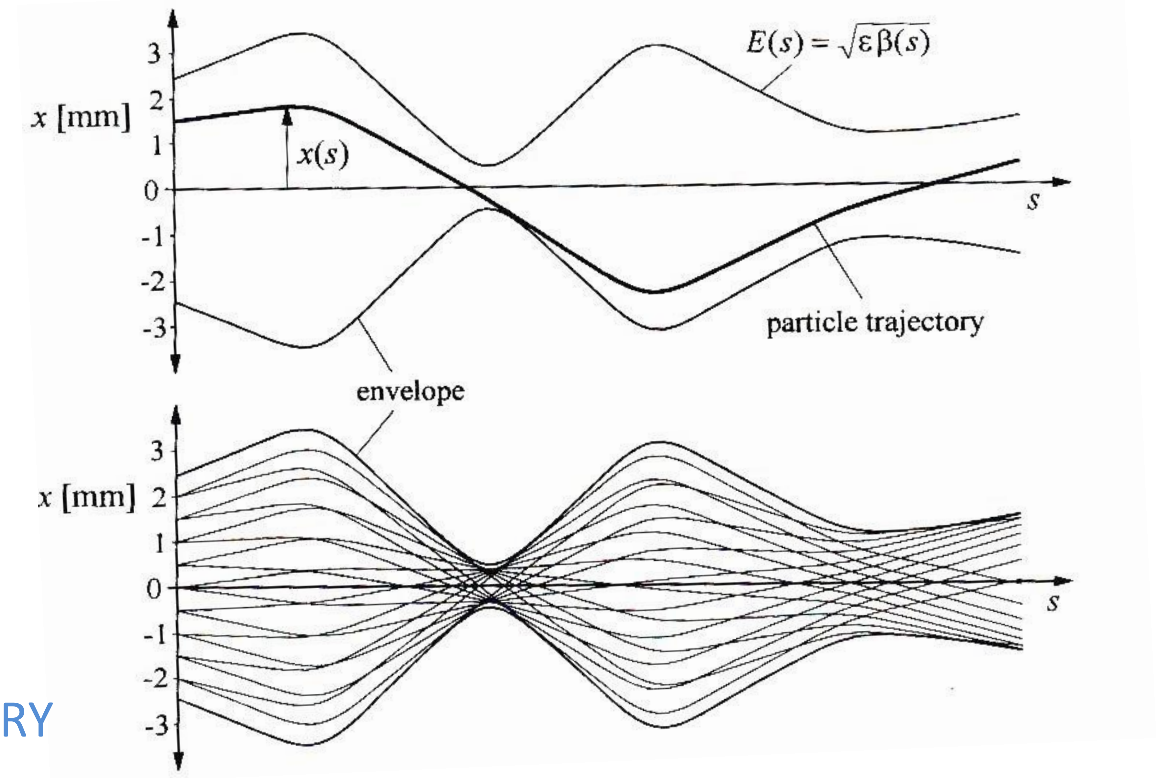
- Strong Focusing = Alternating Gradient
- “Combined Function” Magnet

Enormous Cost Saving



- Strong Focusing = Alternating Gradient
- Reduce amplitude of betatron oscillations
- Reduce diameter of vacuum pipe
- Reduce Aperture of Magnets

- 35 GeV (CERN PS, AGS) costs same as 7 GeV (NIMROD)



TRAJECTORY

$$\frac{d^2Y}{ds^2} + K(s)Y = 0$$

$$Y(s) = A\omega(s)\cos(\phi(s) + \delta)$$

$$Y(s) = \sqrt{\frac{\varepsilon}{\pi}\beta(s)}\cos(\phi(s) + \delta)$$

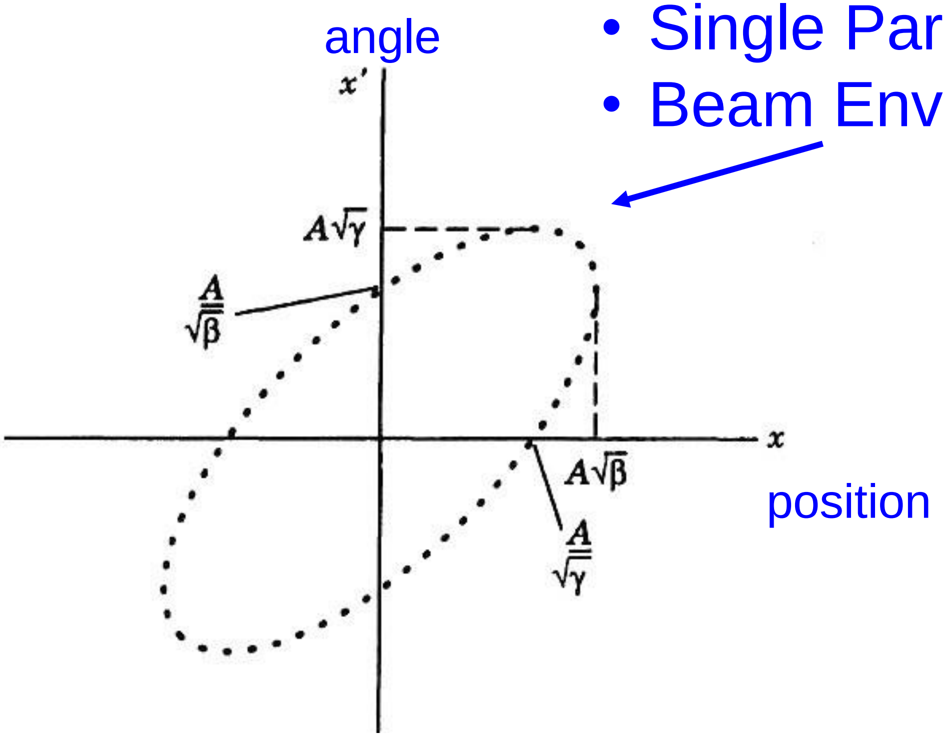
BEAM ENVELOPE

$$\frac{d^2\omega}{ds^2} + K(s)\omega = \frac{1}{\omega^3}$$

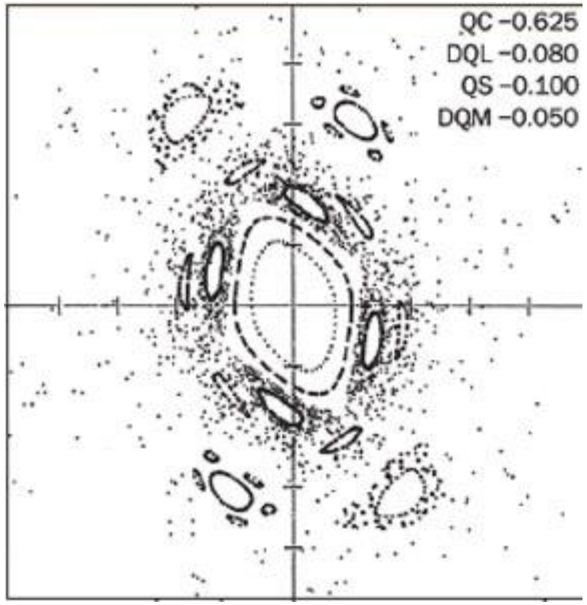
$$\beta(s) = \omega^2(s)$$

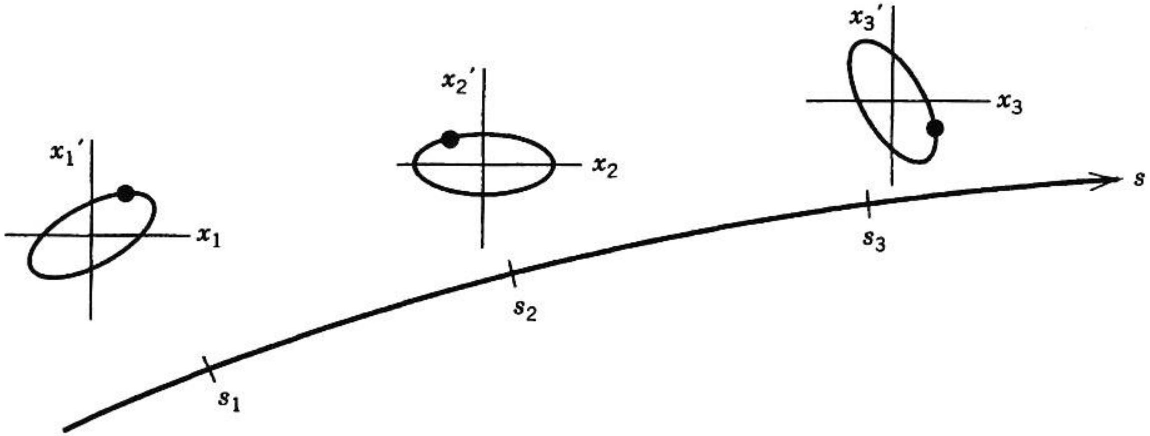
Amplitude of betatron oscillations

- Single Particle Phase Space
- Beam Envelope



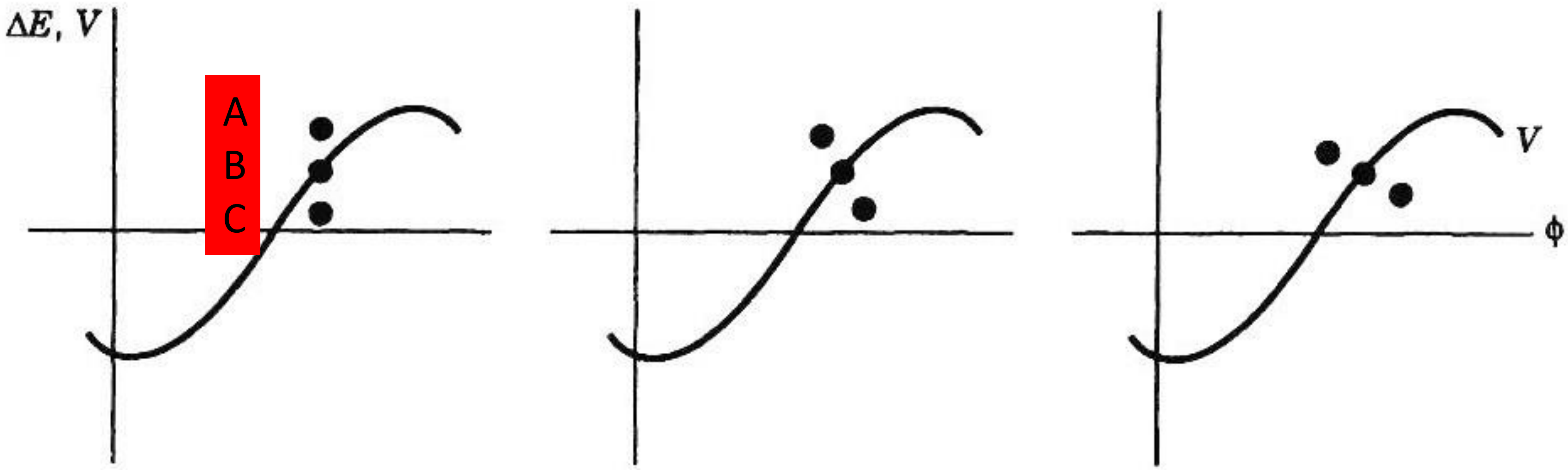
- Real Accelerator
- Non-linear





Shape of phase space changes along accelerator lattice
Area constant -> Liouville

Successive turns around accelerator lattice



- B is synchronous with RF phase
- A too energetic to be in phase
- B not energetic enough to be in phase

→ Closed Oscillations in Phase (non relativistic)

$$\left(E_s\right)_{n+1} = \left(E_s\right)_n + eV\sin\phi_s$$

Synchronous particle

$$\frac{\Delta\tau}{\tau} = \left(\frac{1}{\gamma_\tau^2} - \frac{1}{\gamma^2}\right)$$

Change in transit time around lattice

$$\left(E_s\right)_{n+1} = \left(E_s\right)_n + eV\sin\phi_s$$

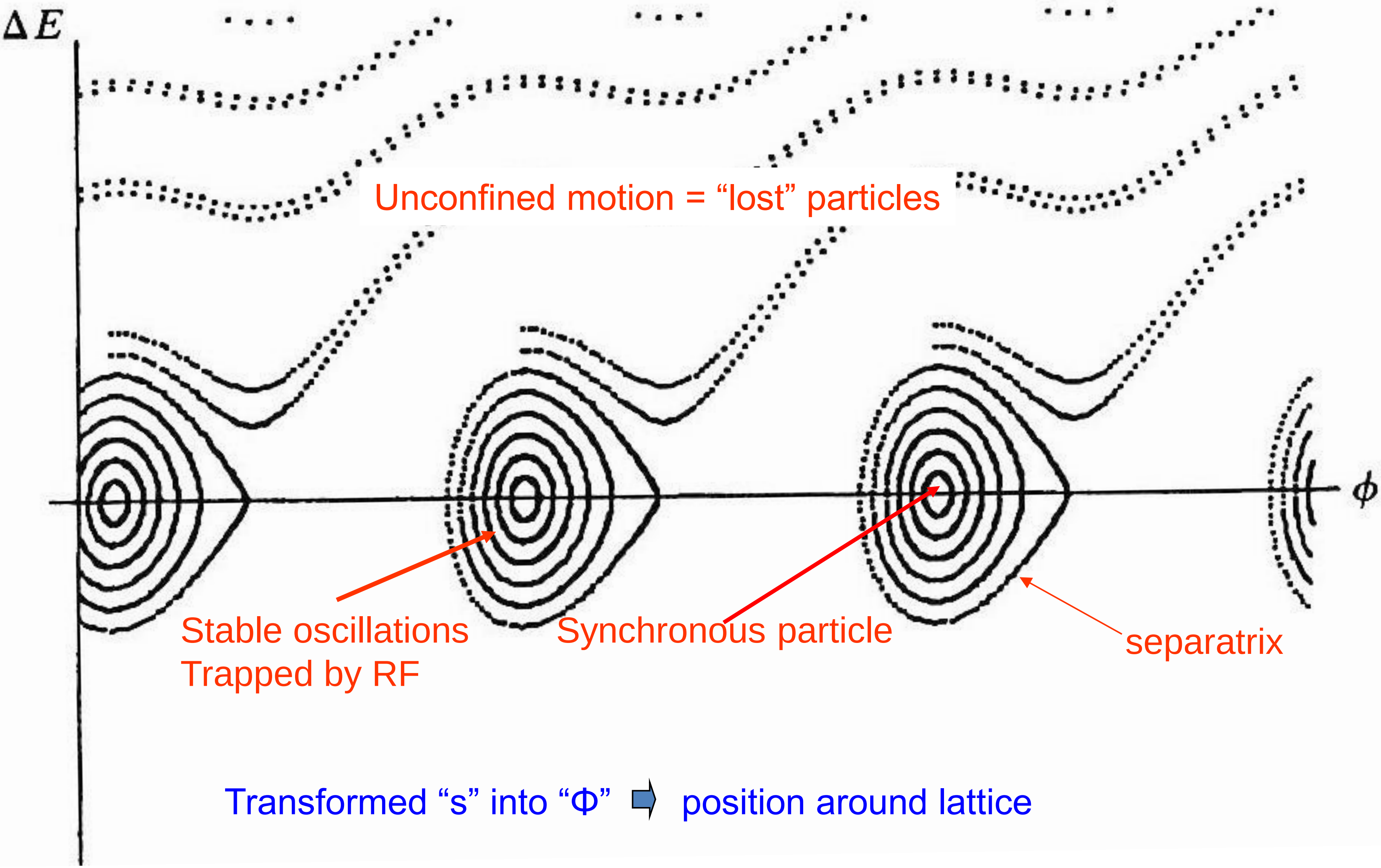
Synchronous Particle

$$\phi_{n+1} = \phi_n + \frac{\eta\omega\tau c^2}{v^2 E_s}\Delta E_{n+1}$$

Non-Synchronous Particle

$$\Delta E_{n+1} = \Delta E_n + eV\left(\sin\phi - \sin\phi_s\right)$$

- Symplectic Mapping
- Preserves Phase Space



Unconfined motion = “lost” particles

Stable oscillations
Trapped by RF

Synchronous particle

separatrix

Transformed “s” into “Φ” ⇨ position around lattice

Particle orbits in energy-phase

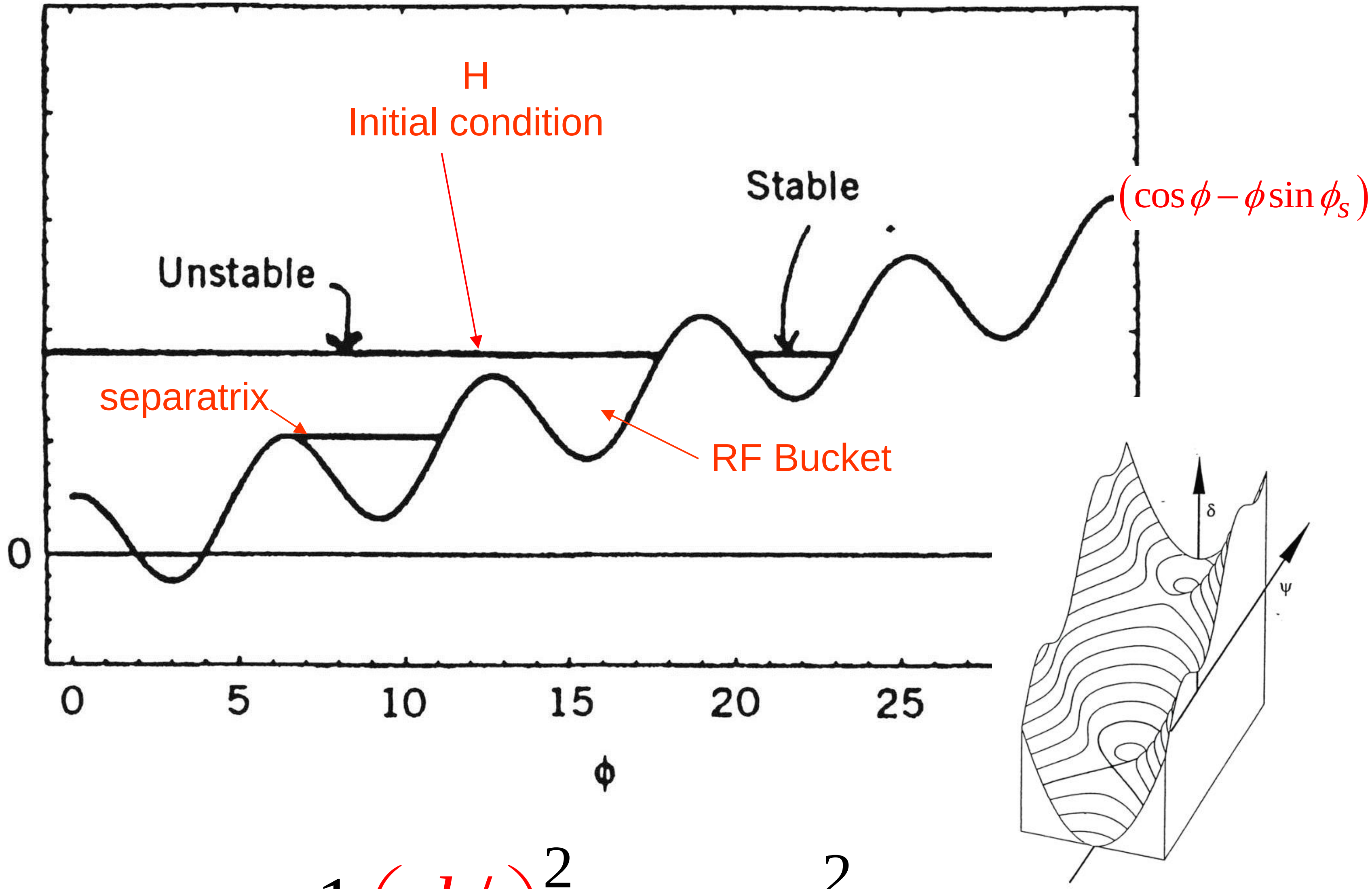
$$\left(E_s\right)_{n+1} = \left(E_s\right)_n + eV\sin\phi_s$$

$$\frac{d\phi}{dn} = \frac{\eta\omega\tau c^2}{v^2 E_s}\Delta E$$

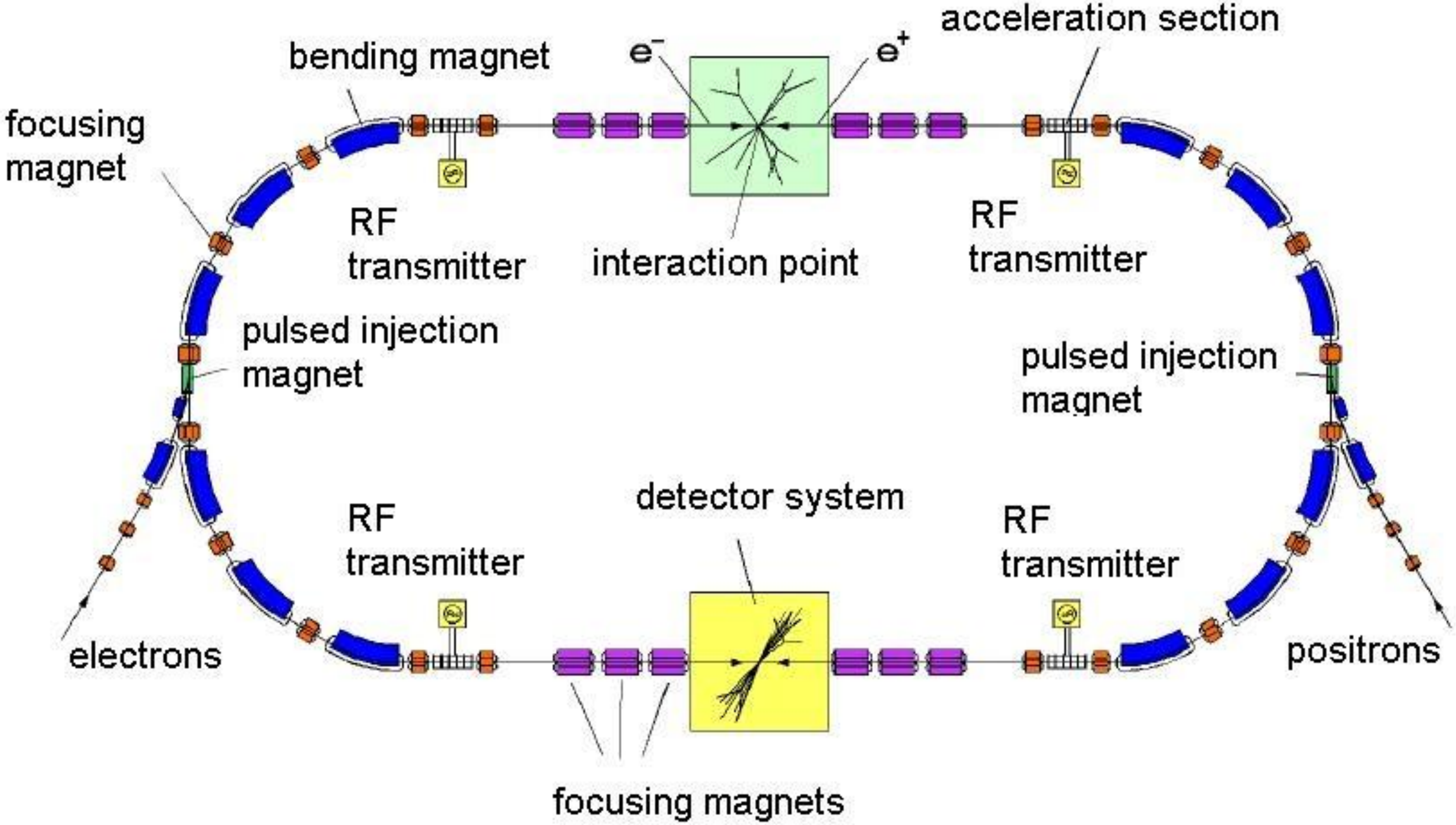
$$\frac{d\Delta E}{dn} = eV\left(\sin\phi - \sin\phi_s\right)$$

Non-linear equations

Describing deviation in phase and energy from synchronous orbit



$$\text{constant} = \mathrm{H} = \frac{1}{2}\left(\frac{d\phi}{dn}\right)^2 + \frac{\eta\omega\tau c^2}{v^2 E_s}\left(\cos\phi - \phi\sin\phi_s\right)$$

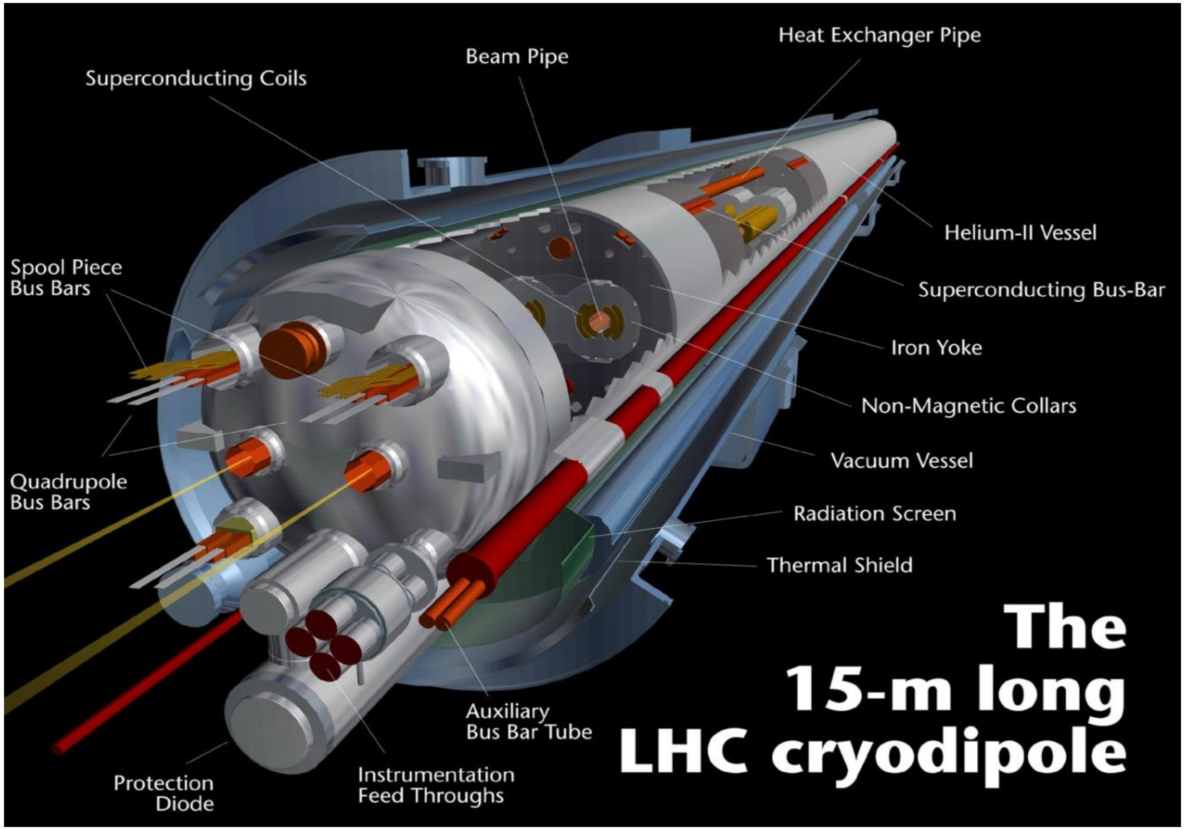

acceleration section
bending magnet
e^-
e^+
focusing magnet
RF transmitter
interaction point
RF transmitter
pulsed injection magnet
pulsed injection magnet
detector system
RF transmitter
RF transmitter
electrons
positrons
focusing magnets

CERN Seen from the Air

- Tunnels of CERN accelerator complex superimposed on a map of Geneva.
- Accelerator is 50 m underground
- 25 km in circumference

Superconducting Magnet

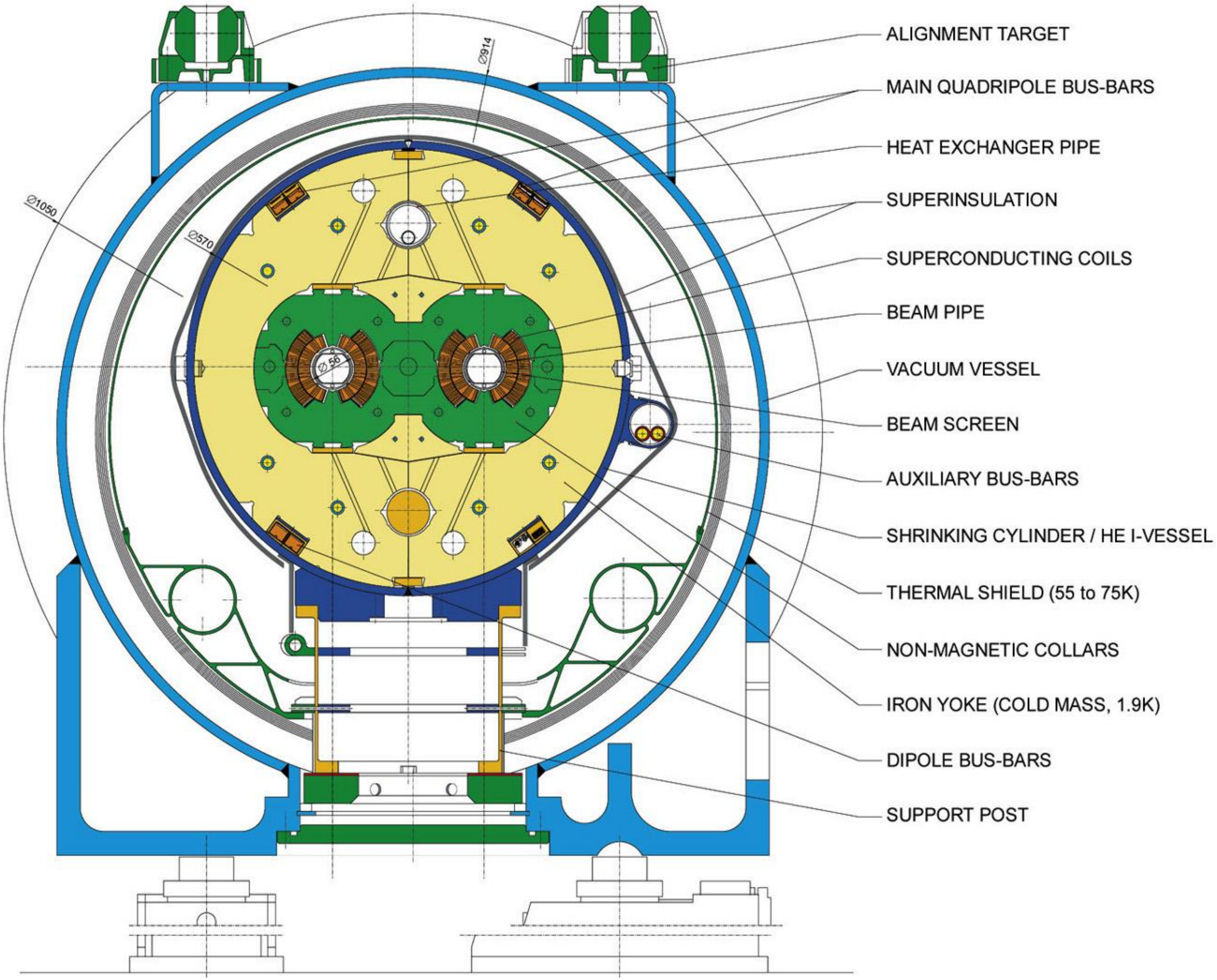
8 Tesla



- In order to accelerate protons to high energy, must bend them in circular accelerator
- 7 TeV momentum needs intense magnetic field

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999



LHC 2002

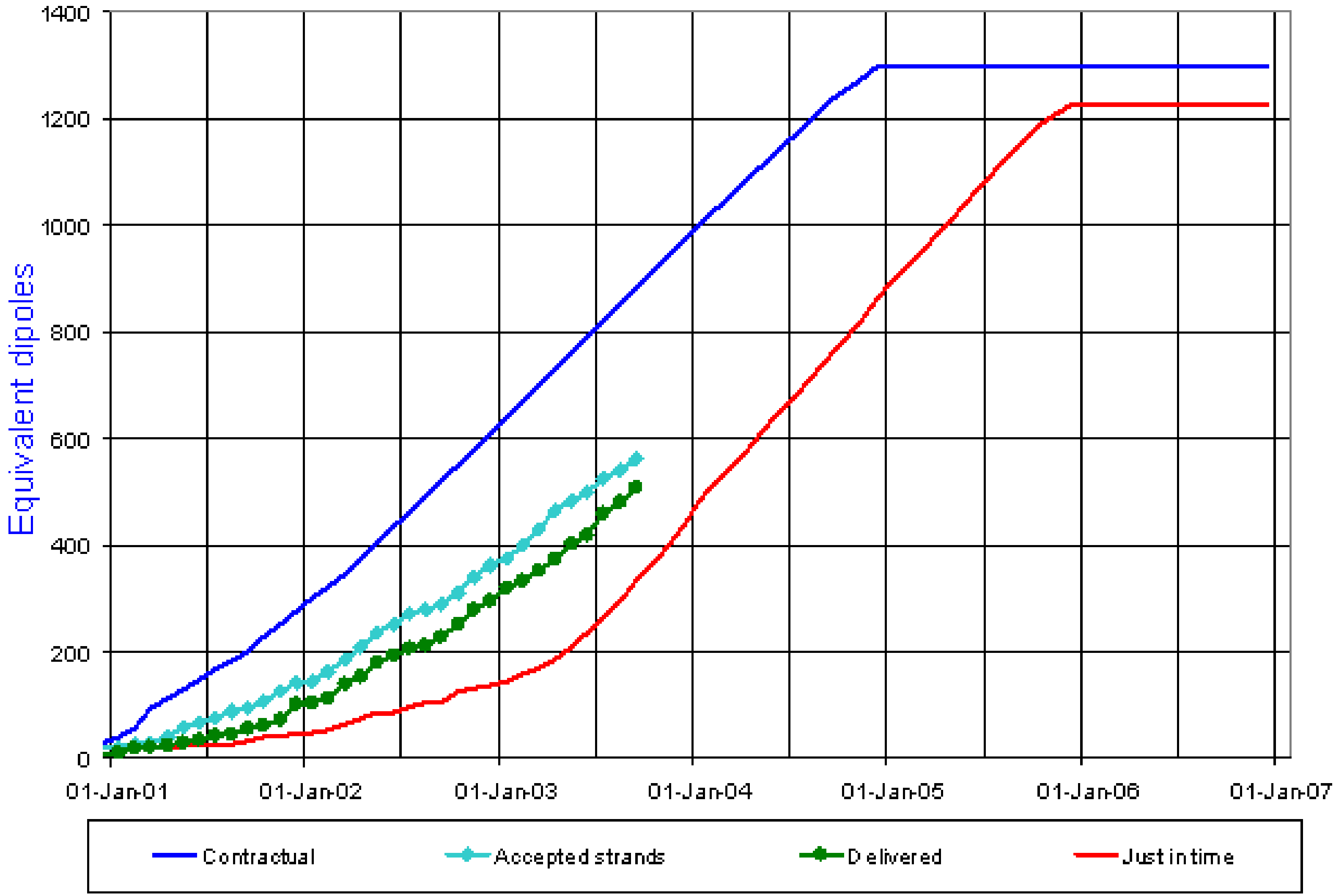
LHC 2003

Dipole Cold Masses

LHC Progress Dashboard

Accelerator Technology Division

Superconducting cable 1

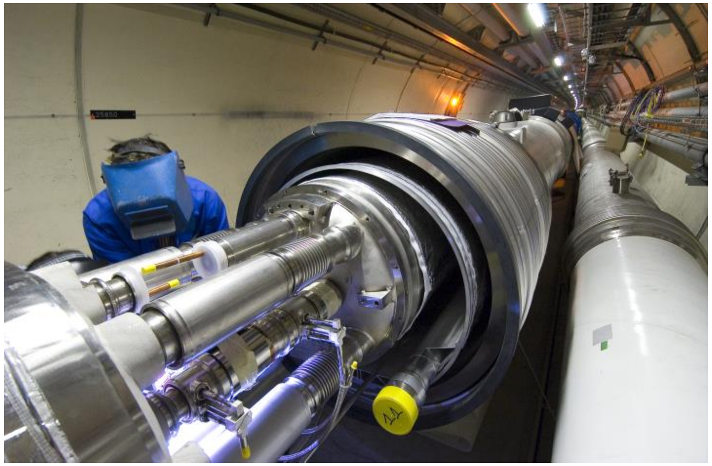


Updated 30 Sep 2003

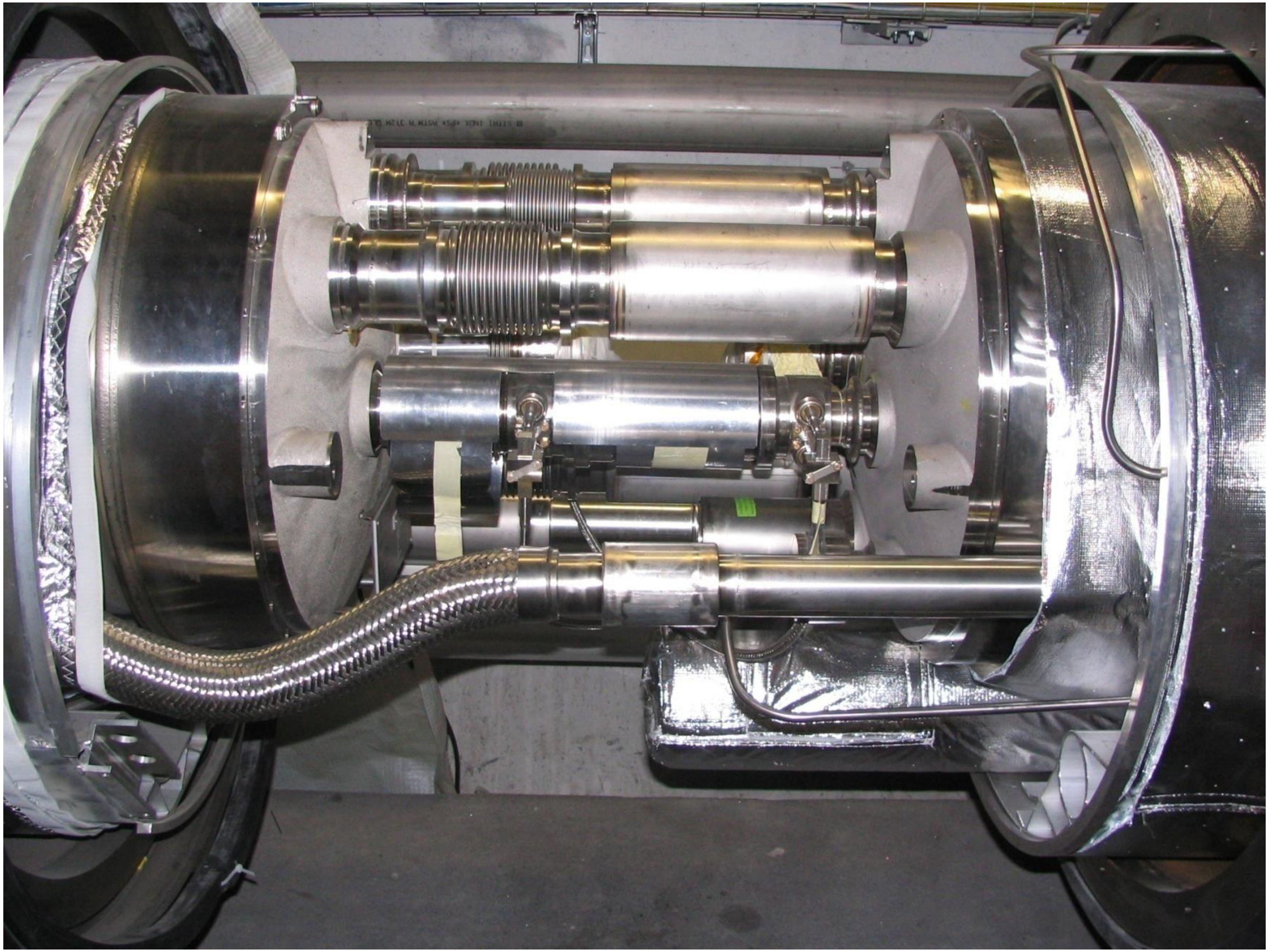
Data provided by A. Verweij AT-MAS

Infrastructure completed in 2003

Underground

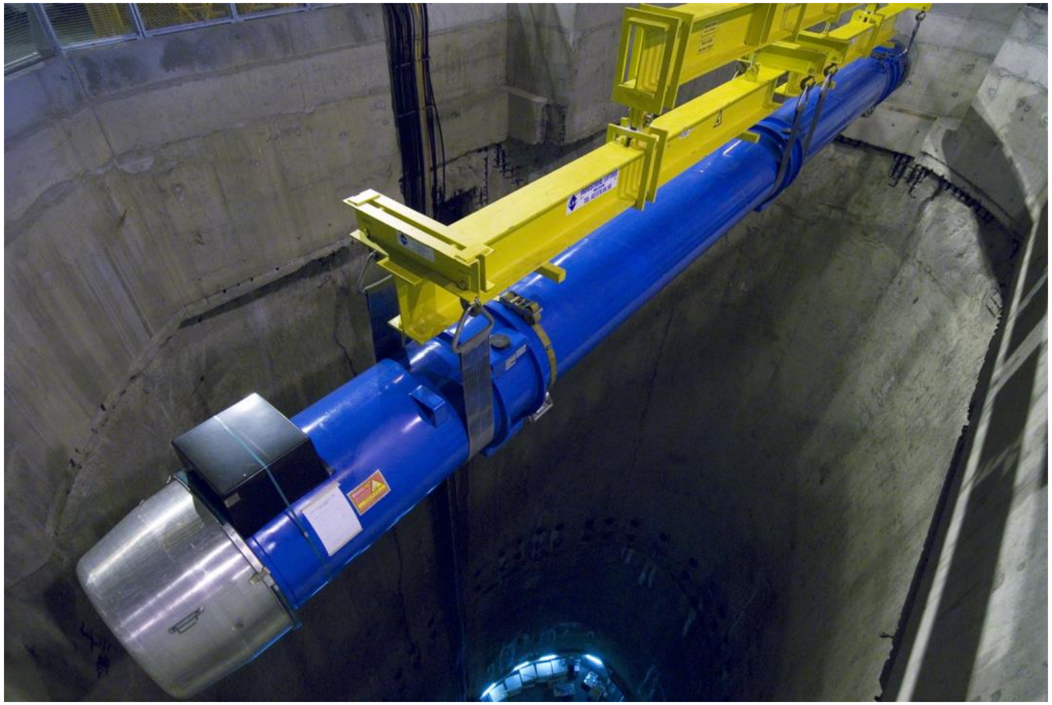


Dipole-dipole interconnect



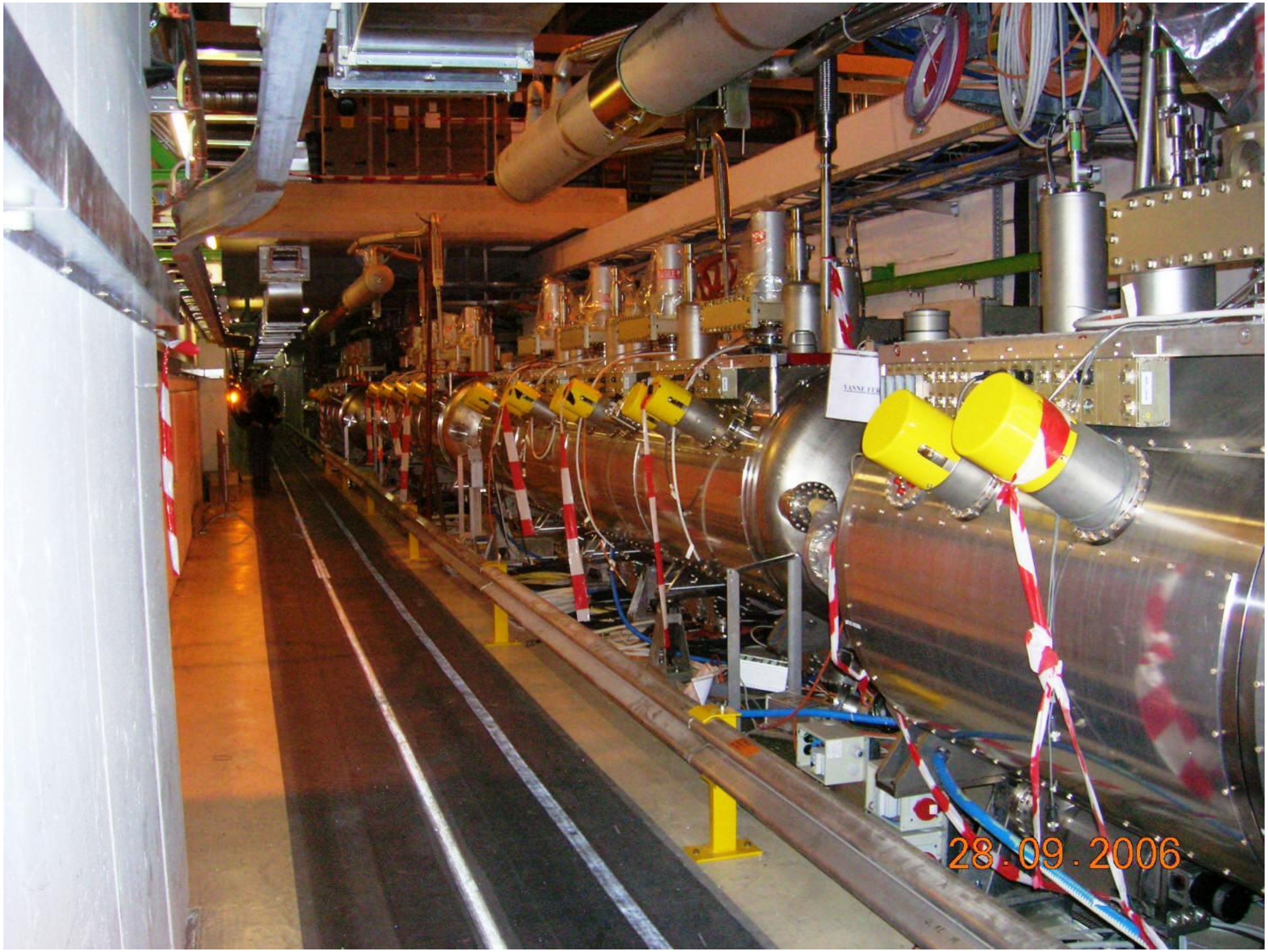
March 2006

Descent of the Last Magnet, 26 April 2007



300 m underground at 2 km/h!

RF Modules

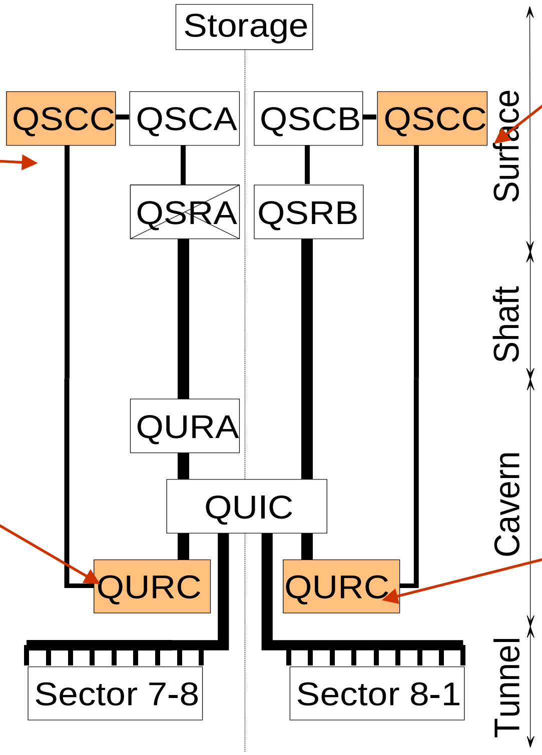


28.09.2006

Refrigeration Units at 1.8 K

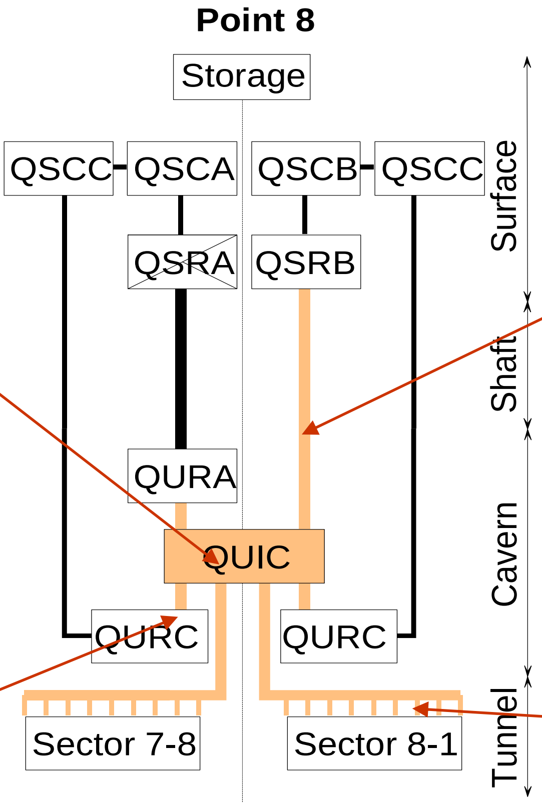
Air Liquide

Point 8



IHI Linde

Cryogenic Distribution



Point 8

Storage

QSCC

QSCA

QSCB

QSCC

~~QSRA~~

QSRB

QURA

QUIC

QURC

QURC

Sector 7-8

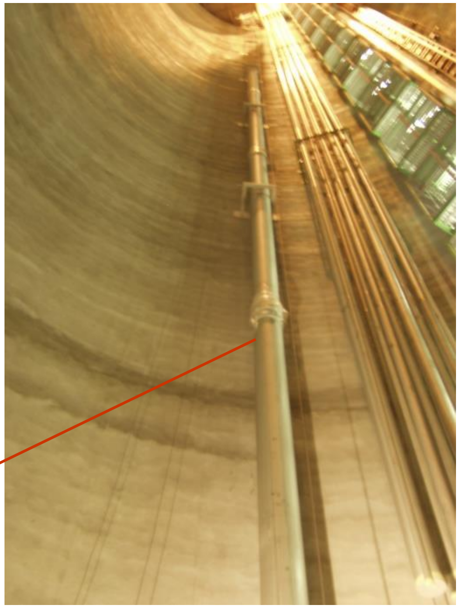
Sector 8-1

Surface

Shaft

Cavern

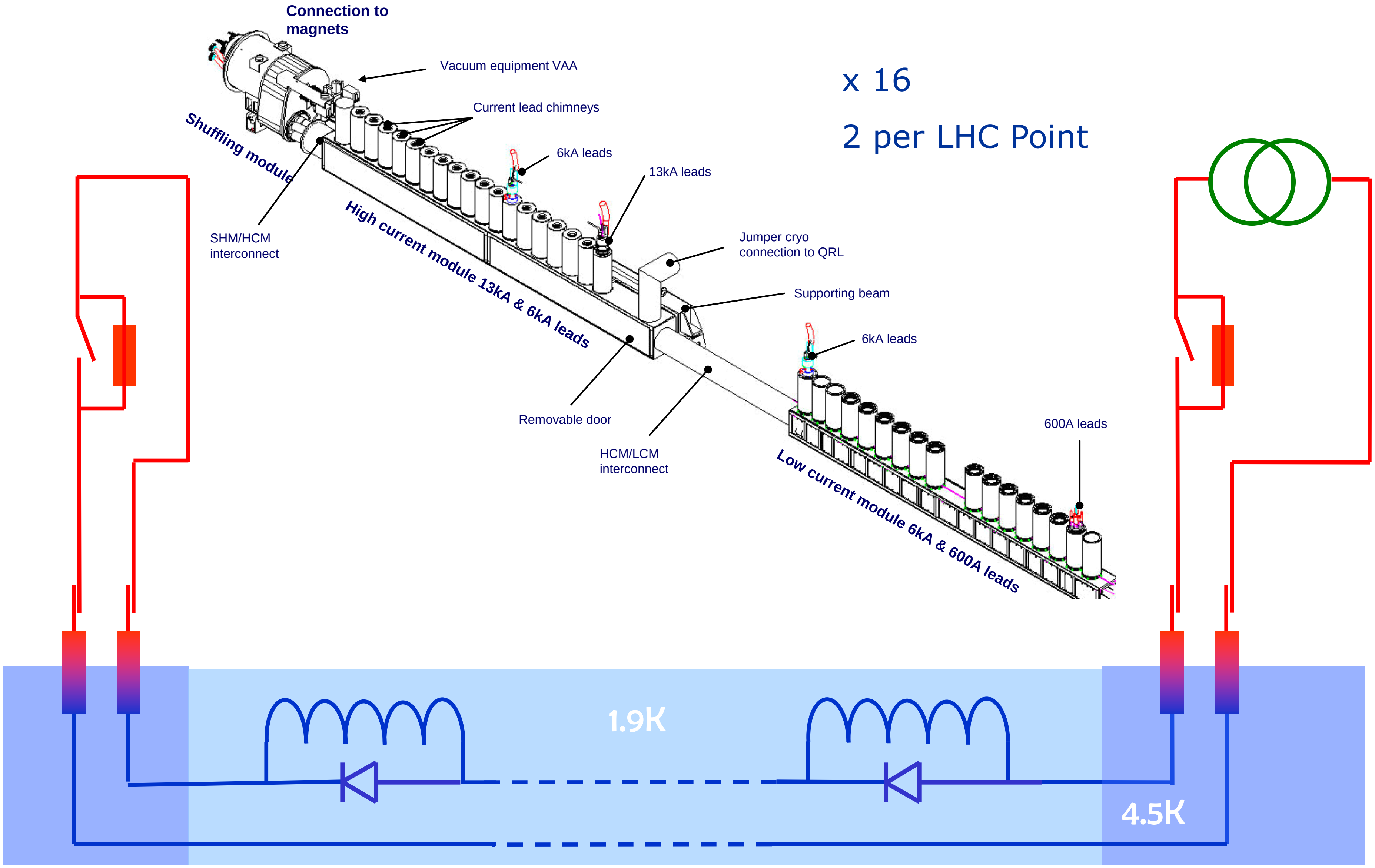
Tunnel



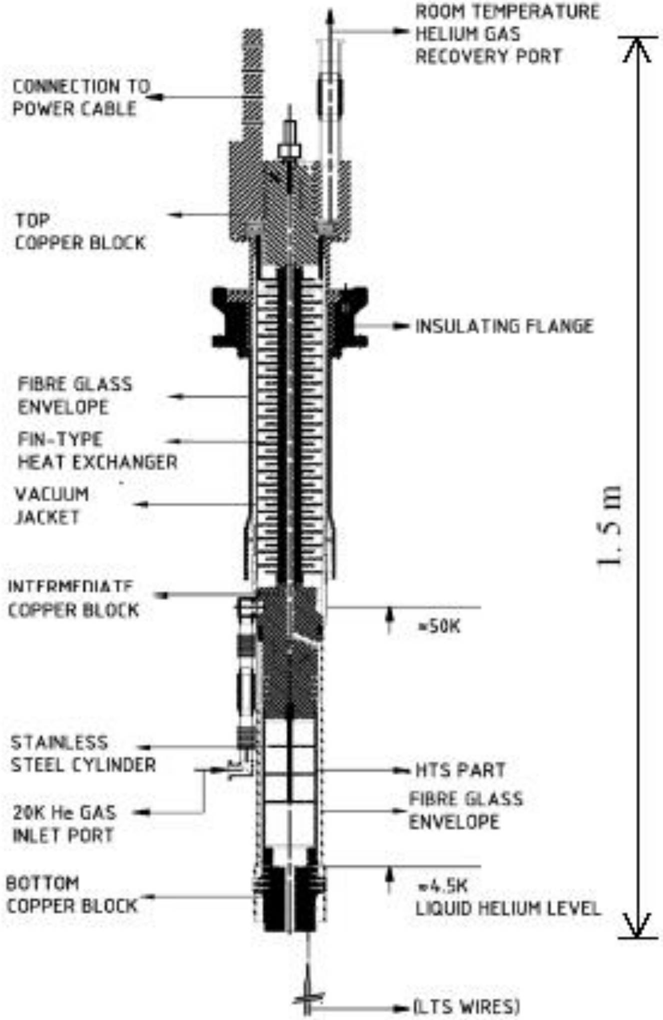
DFBA Electrical Feed Box

x 16

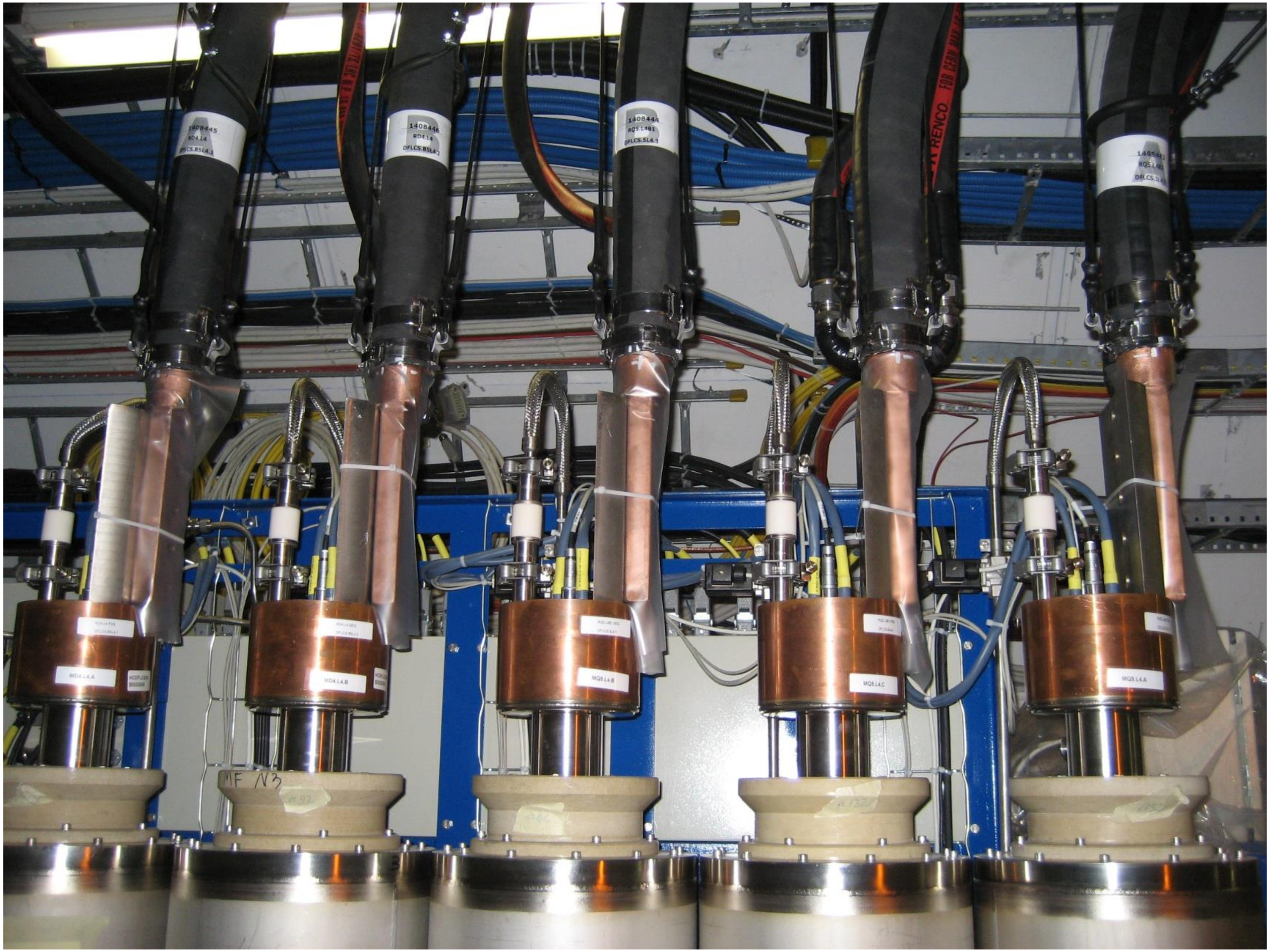
2 per LHC Point

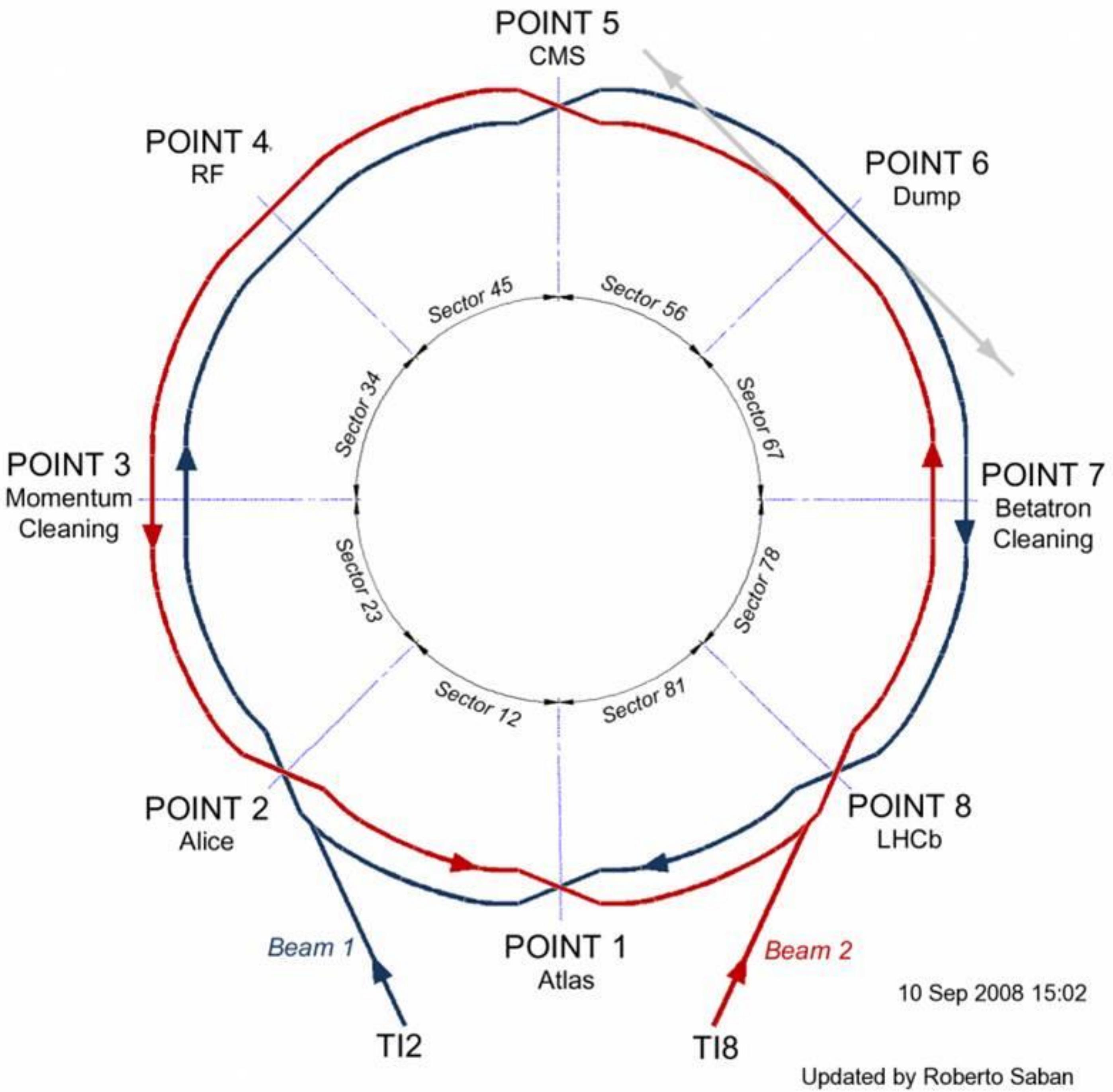


13 kA HTS Current Leads



6 kA current leads with water-cooled cables

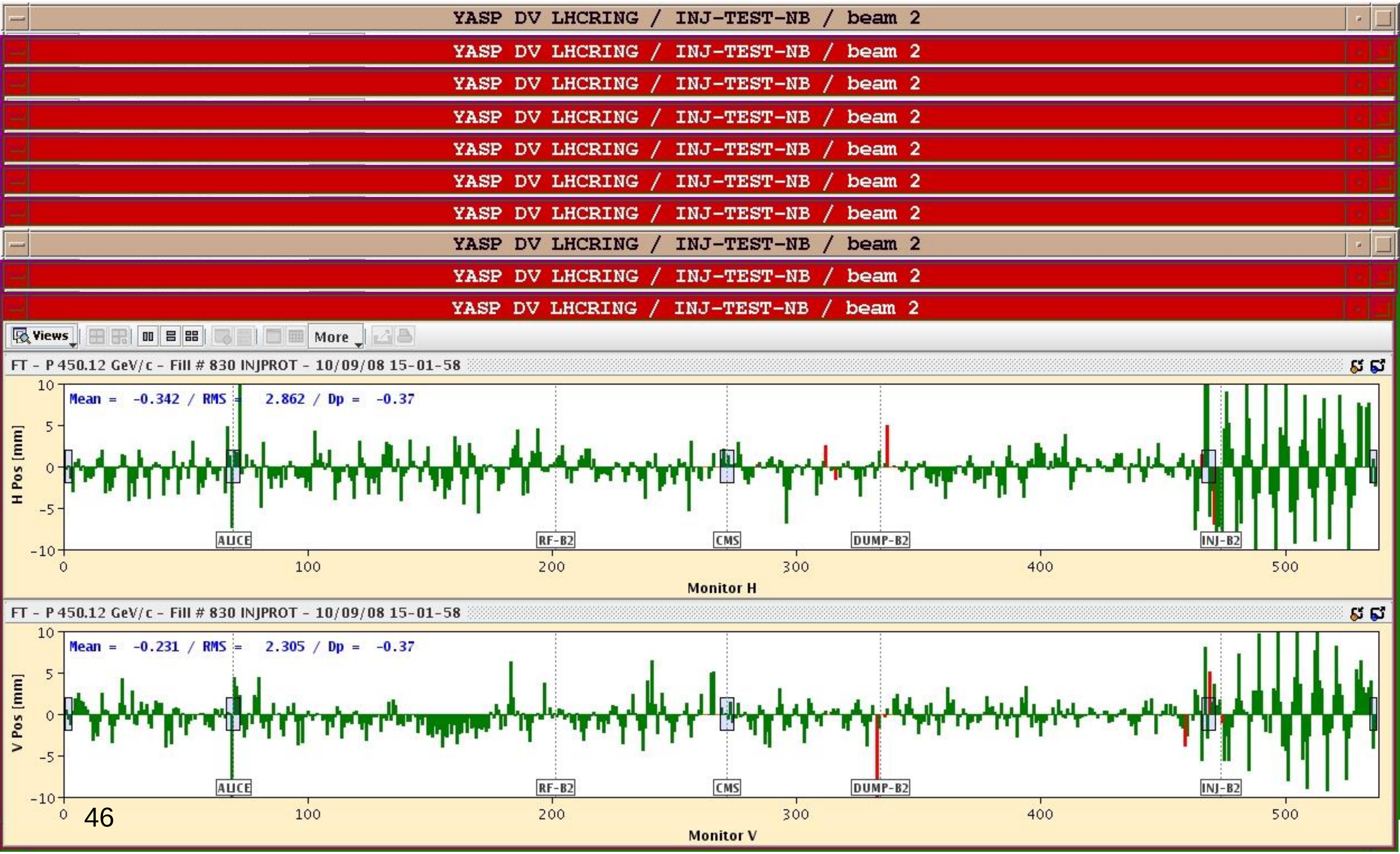




10 Sep 2008 15:02

Updated by Roberto Saban

Beam 2 first beam – D-Day



YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2
YASP DV LHCRING / INJ-TEST-NB / beam 2

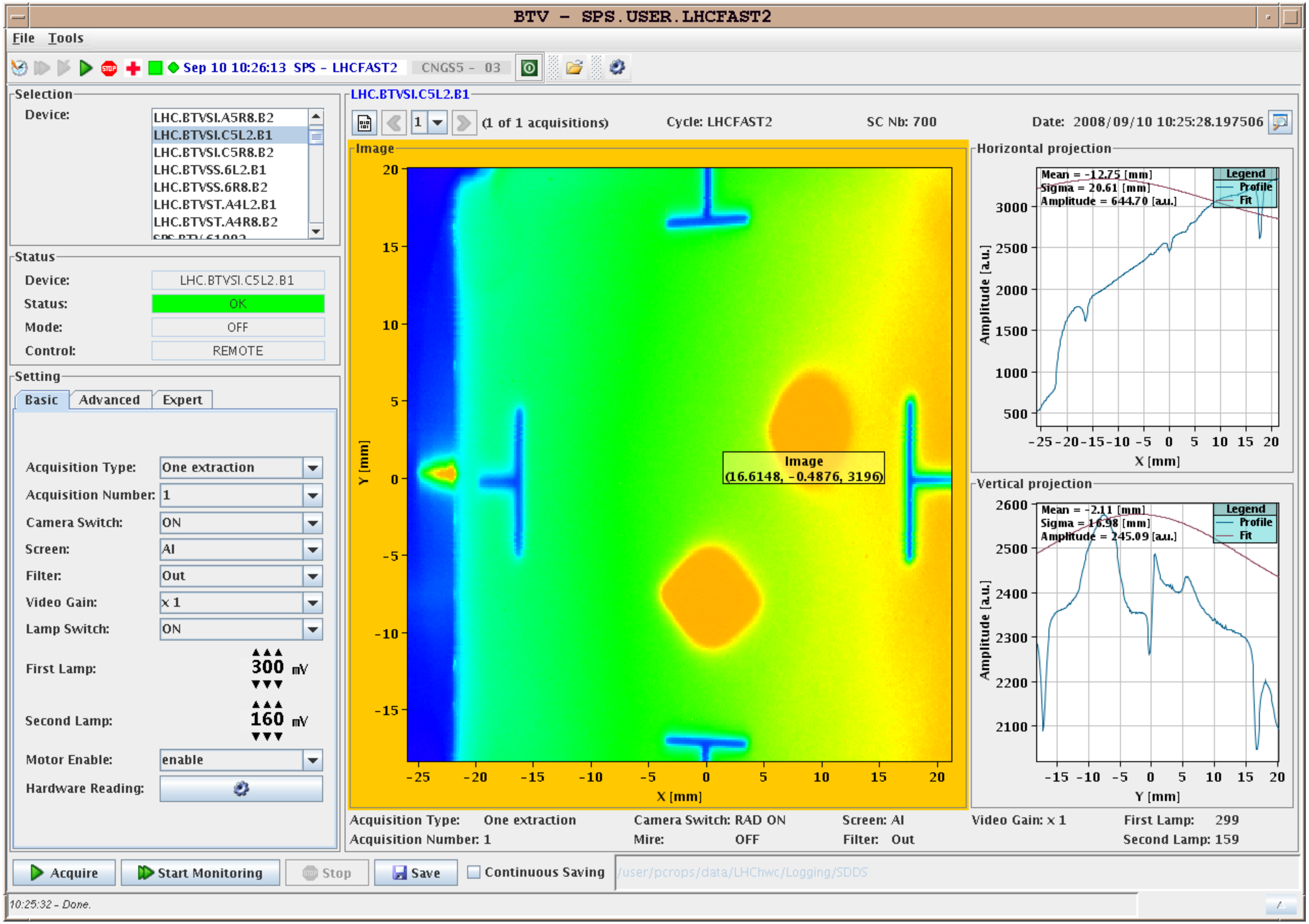
FT – P 450.12 GeV/c – Fill # 830 INJPROT – 10/09/08 15-01-58

Mean = -0.342 / RMS = 2.862 / Dp = -0.37

FT – P 450.12 GeV/c – Fill # 830 INJPROT – 10/09/08 15-01-58

Mean = -0.231 / RMS = 2.305 / Dp = -0.37

Beam on turns 1 and 2



BTV – SPS.USER.LHCFAST2

Sep 10 10:26:13 SPS – LHCFAST2 CNGS5 – 03

Selection

Device: LHC.BTVSI.A5R8.B2
LHC.BTVSI.C5L2.B1
LHC.BTVSI.C5R8.B2
LHC.BTVSS.6L2.B1
LHC.BTVSS.6R8.B2
LHC.BTVST.A4L2.B1
LHC.BTVST.A4R8.B2

Status

Device: LHC.BTVSI.C5L2.B1
Status: OK
Mode: OFF
Control: REMOTE

Setting

Acquisition Type: One extraction
Acquisition Number: 1
Camera Switch: ON
Screen: Al
Filter: Out
Video Gain: x 1
Lamp Switch: ON
First Lamp: 300 mV
Second Lamp: 160 mV
Motor Enable: enable
Hardware Reading:

LHC.BTVSI.C5L2.B1

1 (1 of 1 acquisitions) Cycle: LHCFAST2 SC Nb: 700 Date: 2008/09/10 10:25:28.197506

Image (16.6148, -0.4876, 3196)

Horizontal projection:
Mean = -12.75 [mm]
Sigma = 20.61 [mm]
Amplitude = 644.70 [a.u.]

Vertical projection:
Mean = -2.11 [mm]
Sigma = 16.98 [mm]
Amplitude = 245.09 [a.u.]

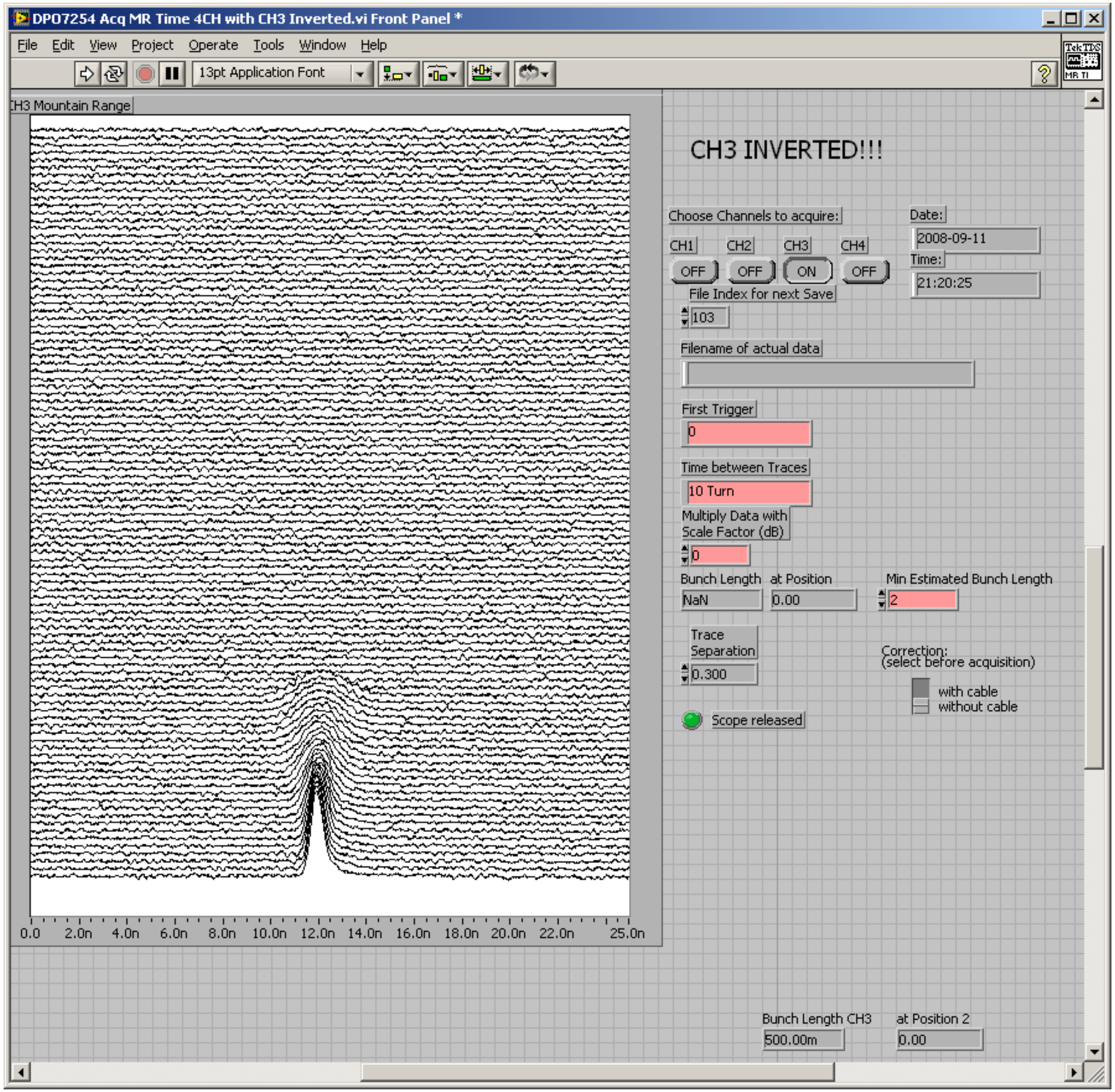
Acquisition Type: One extraction
Acquisition Number: 1
Camera Switch: RAD ON
Mire: OFF
Screen: Al
Filter: Out
Video Gain: x 1
First Lamp: 299
Second Lamp: 159

☐ Continuous Saving /user/pcrops/data/LHChwc/Logging/SDDS

10:25:32 - Done.

Courtesy R. Bailey

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



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

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

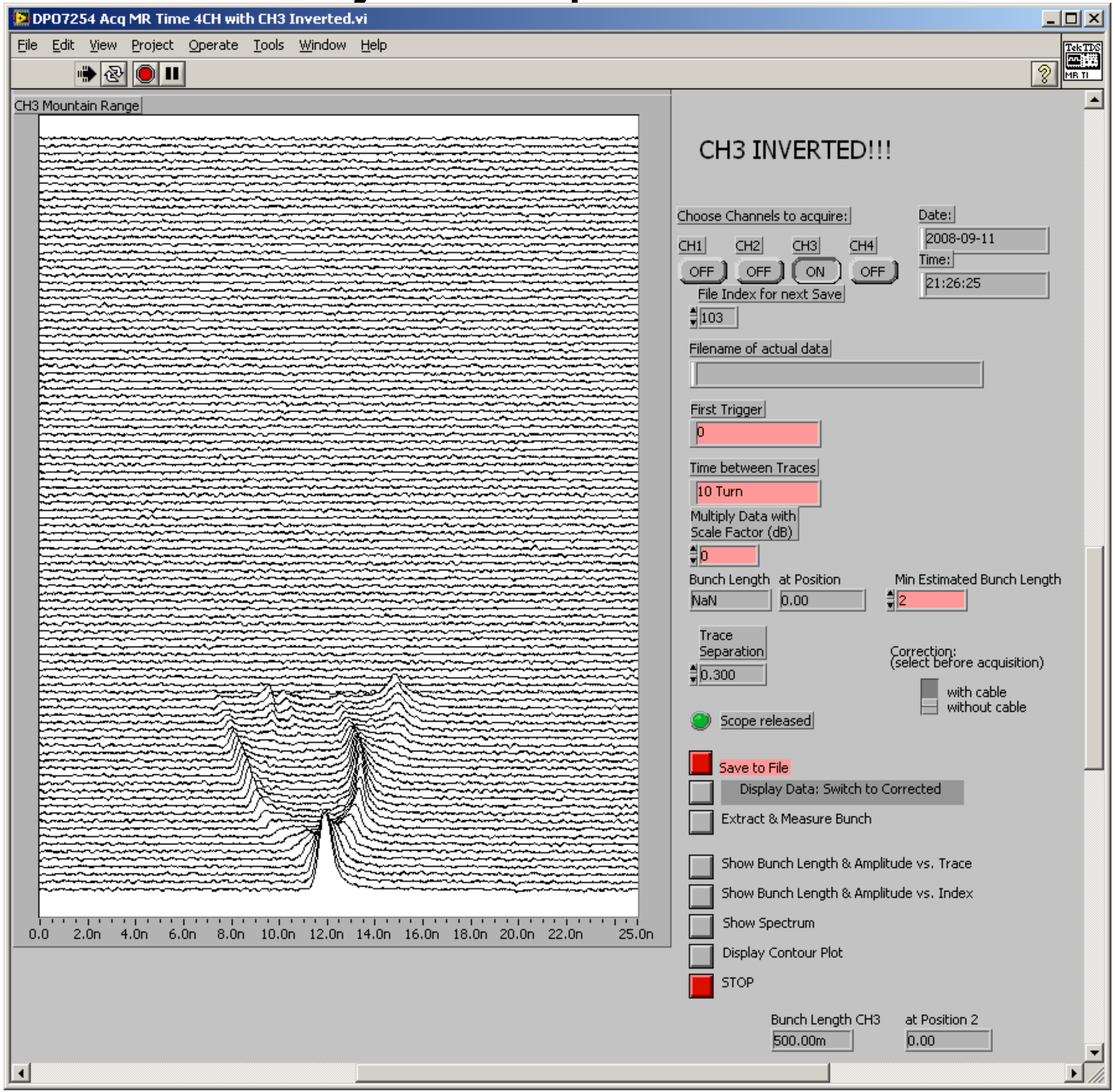
● Scope released

Bunch Length CH3: 500.00m

at Position 2: 0.00

Courtesy E. Ciapala

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

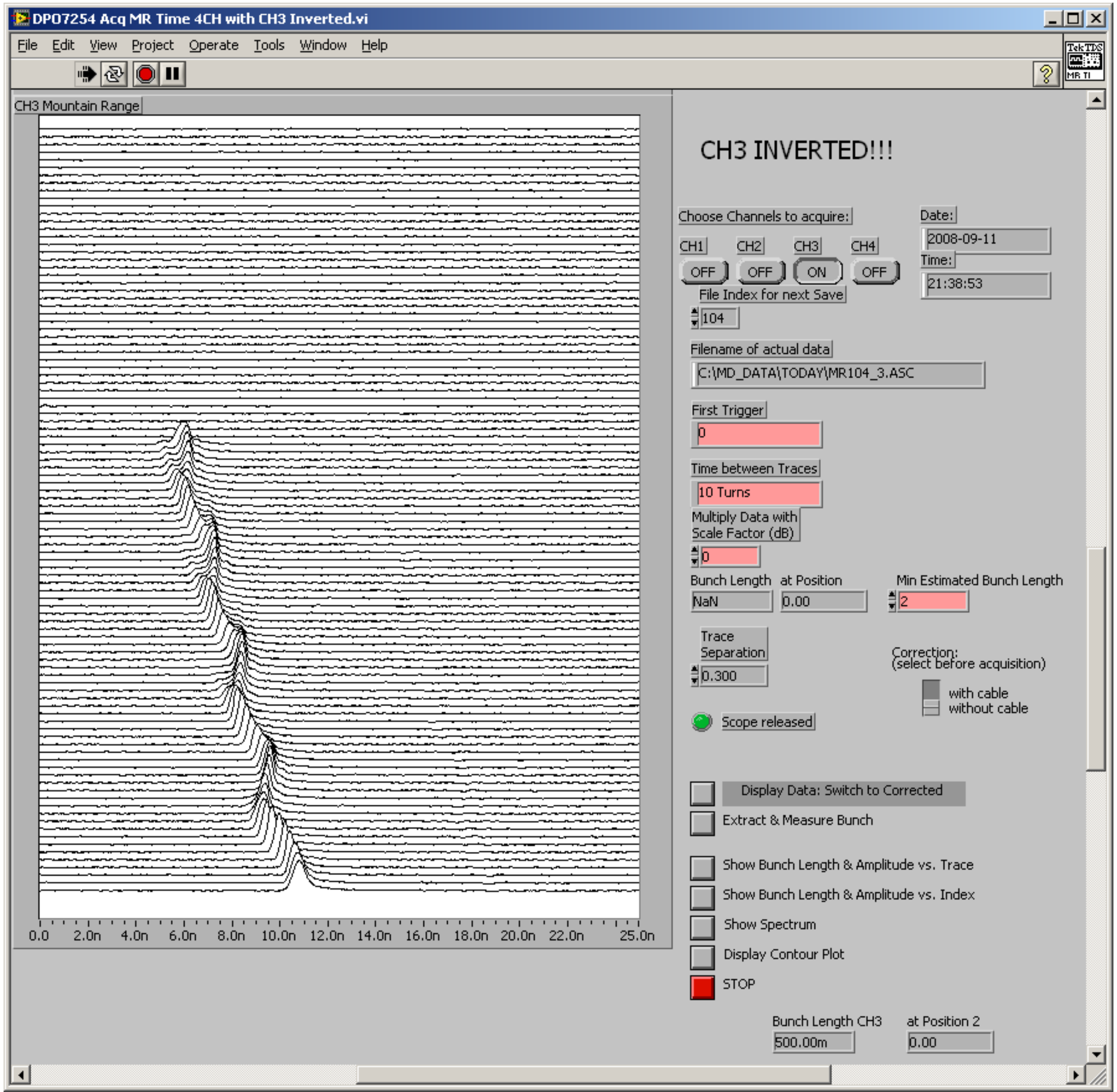
Correction: (select before acquisition)
with cable
without cable

● Scope released

Bunch Length CH3: 500.00m
at Position 2: 0.00

Courtesy E. Ciapala

Capture with corrected injection phasing



DPO7254 Acq MR Time 4CH with CH3 Inverted.vi

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

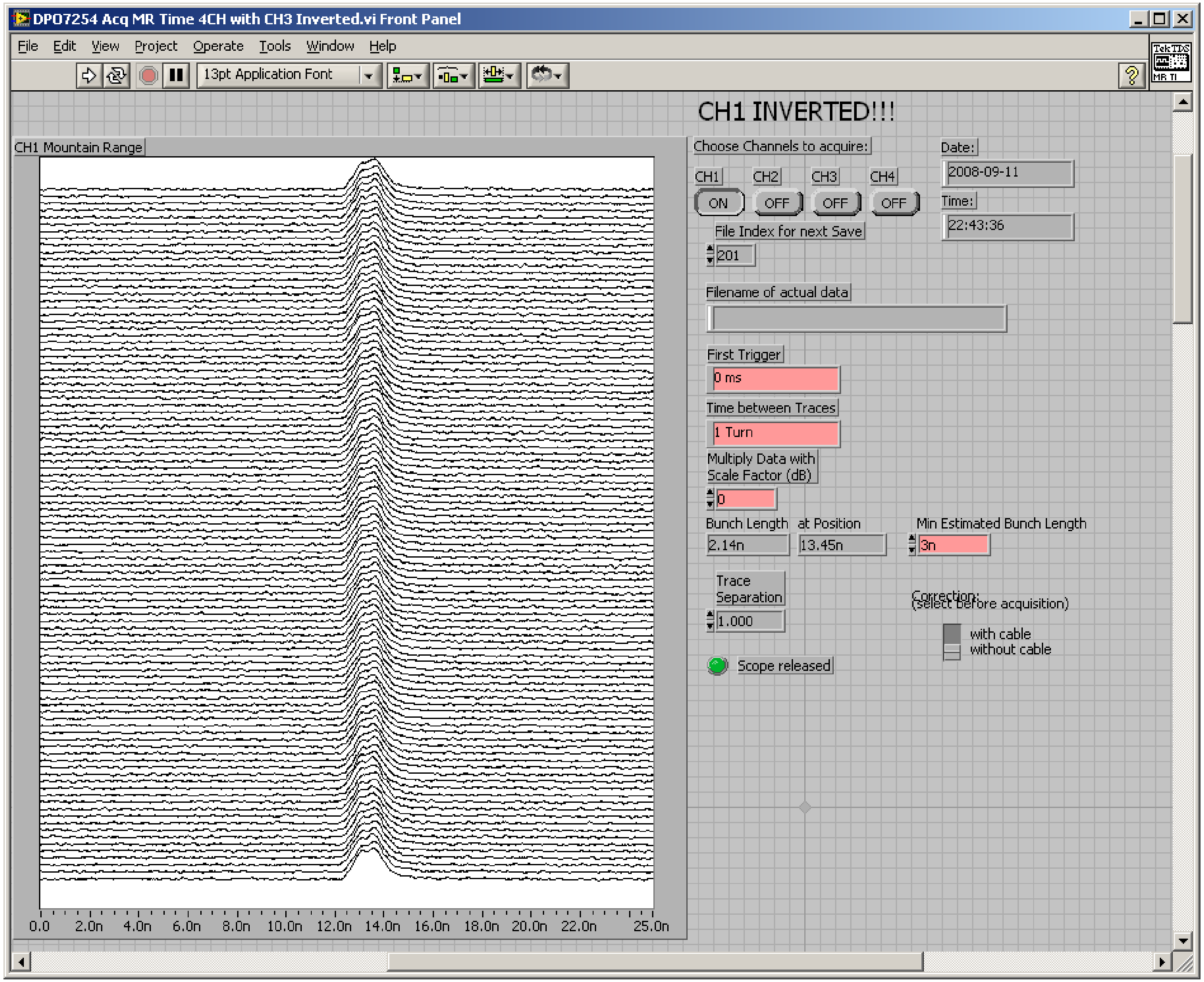
Correction:
(select before acquisition)
with cable
without cable

● Scope released

Bunch Length CH3: 500.00m
at Position 2: 0.00

Courtesy E. Ciapala

Capture with optimum injection phasing, correct reference



CH1 INVERTED!!!

Choose Channels to acquire:

CH1	CH2	CH3	CH4
ON	OFF	OFF	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	at Position	Min Estimated Bunch Length
2.14n	13.45n	3n

Trace Separation: 1.000

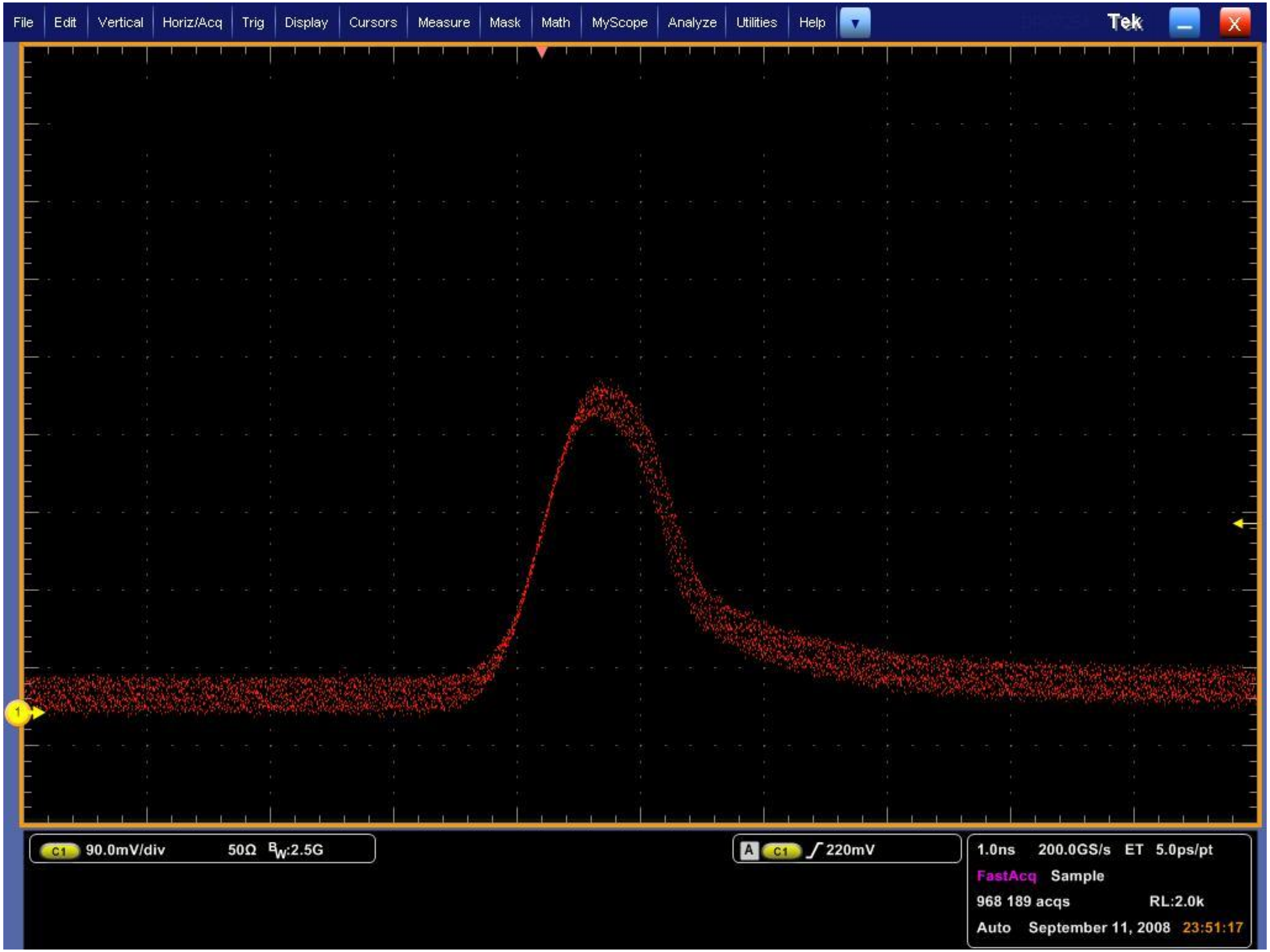
Correction: (select before acquisition)

with cable
without cable

● Scope released

Courtesy E. Ciapala

LHC longitudinal bunch profile Beam 2



C1 90.0mV/div 50Ω BW:2.5G

A C1 ∫ 220mV

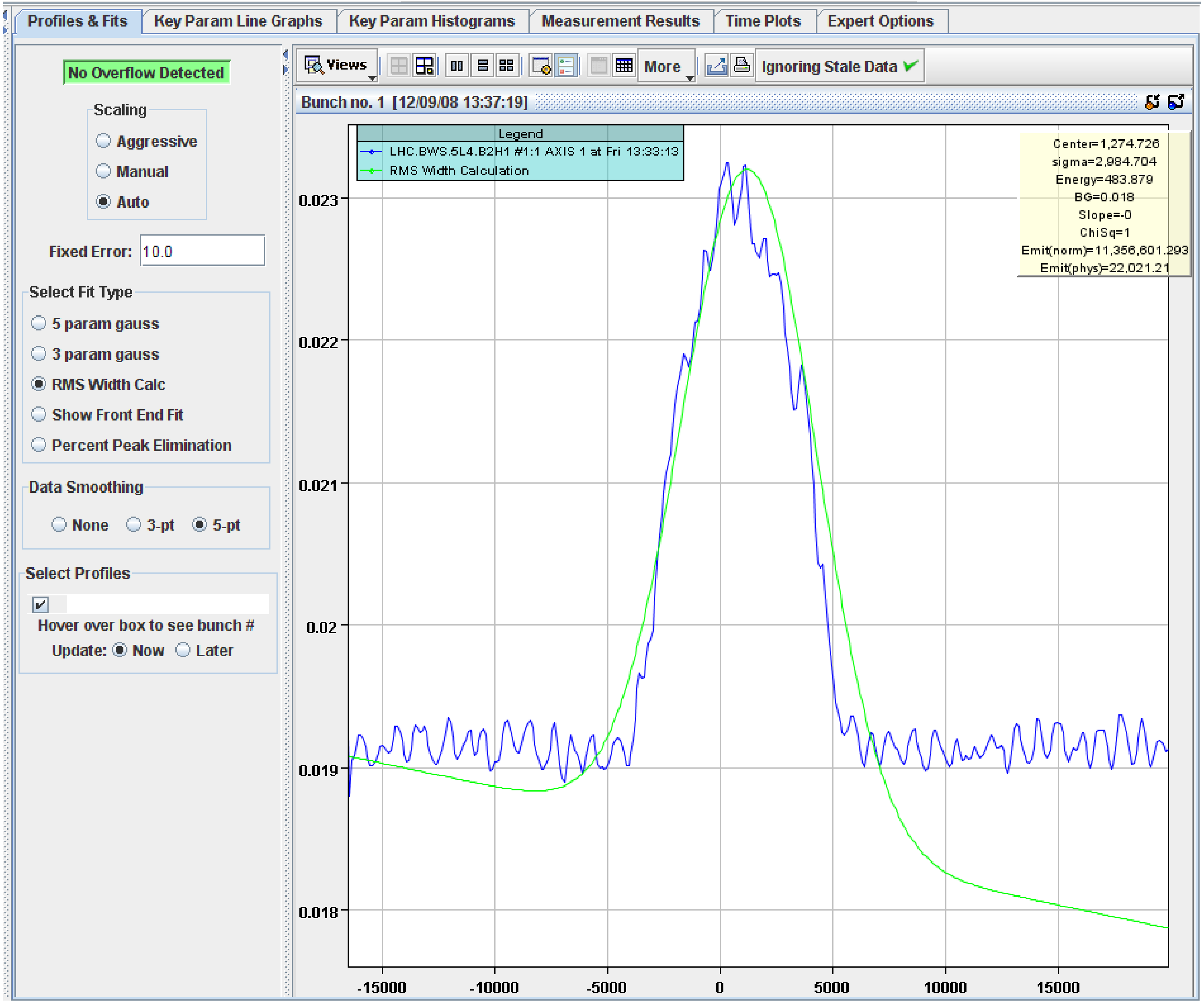
1.0ns 200.0GS/s ET 5.0ps/pt

FastAcq Sample

968 189 acqs RL:2.0k

Auto September 11, 2008 23:51:17

H wire scan



No Overflow Detected

Scaling
○ Aggressive
○ Manual
● Auto

Fixed Error: 10.0

Select Fit Type
○ 5 param gauss
○ 3 param gauss
● RMS Width Calc
○ Show Front End Fit
○ Percent Peak Elimination

Data Smoothing
○ None ○ 3-pt ● 5-pt

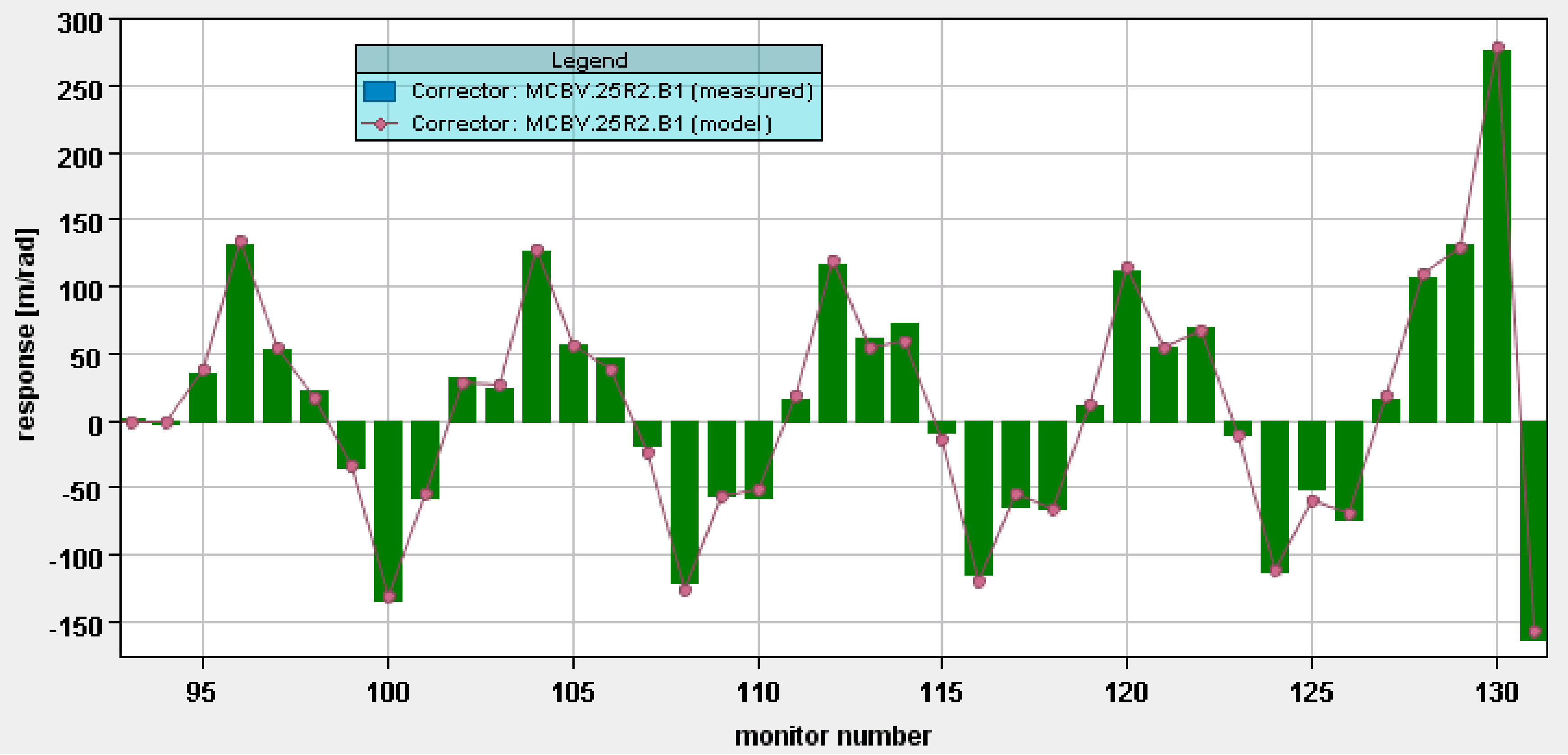
Select Profiles
☑
Hover over box to see bunch #
Update: ● Now ○ Later

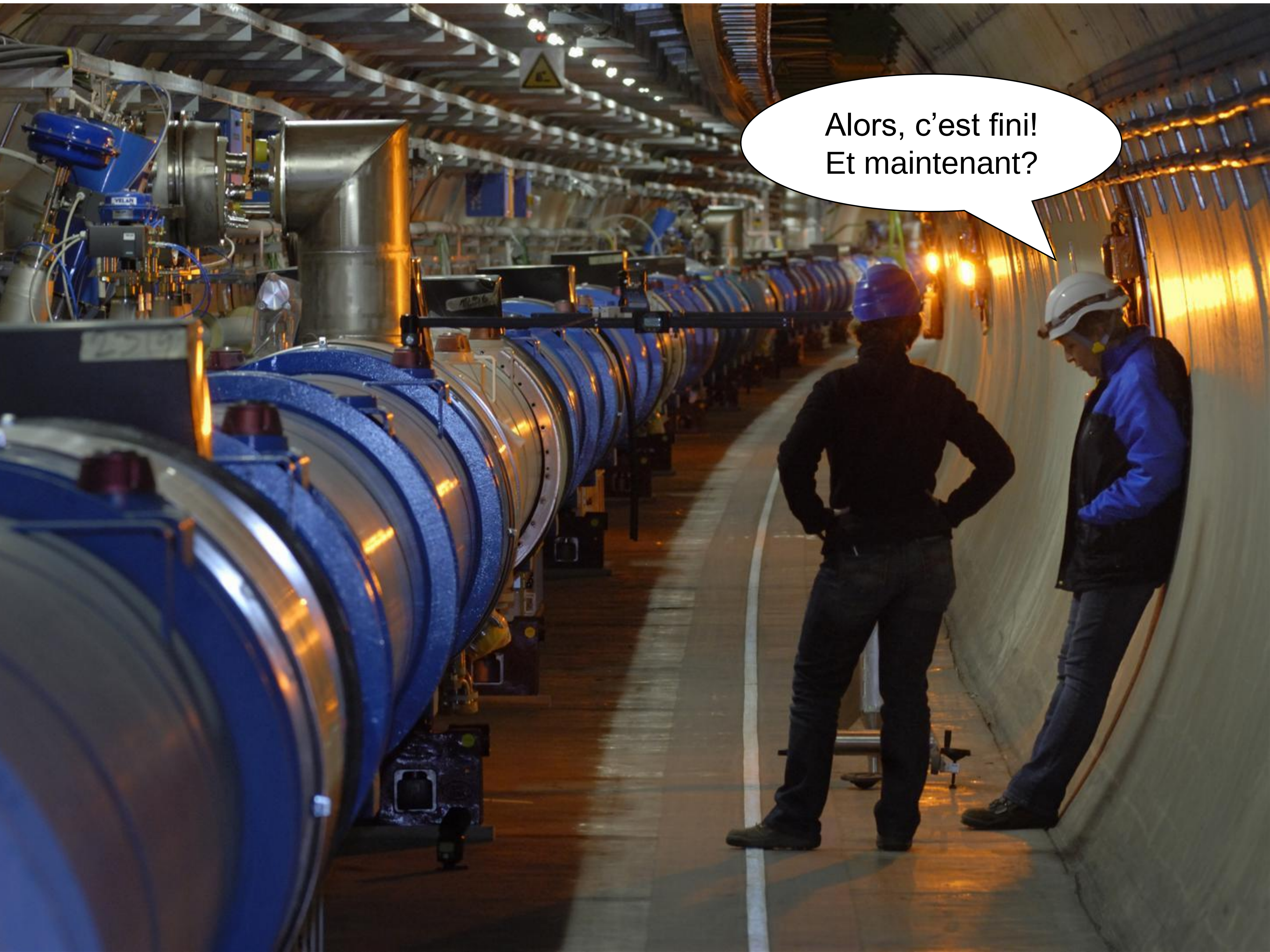
Bunch no. 1 [12/09/08 13:37:19]

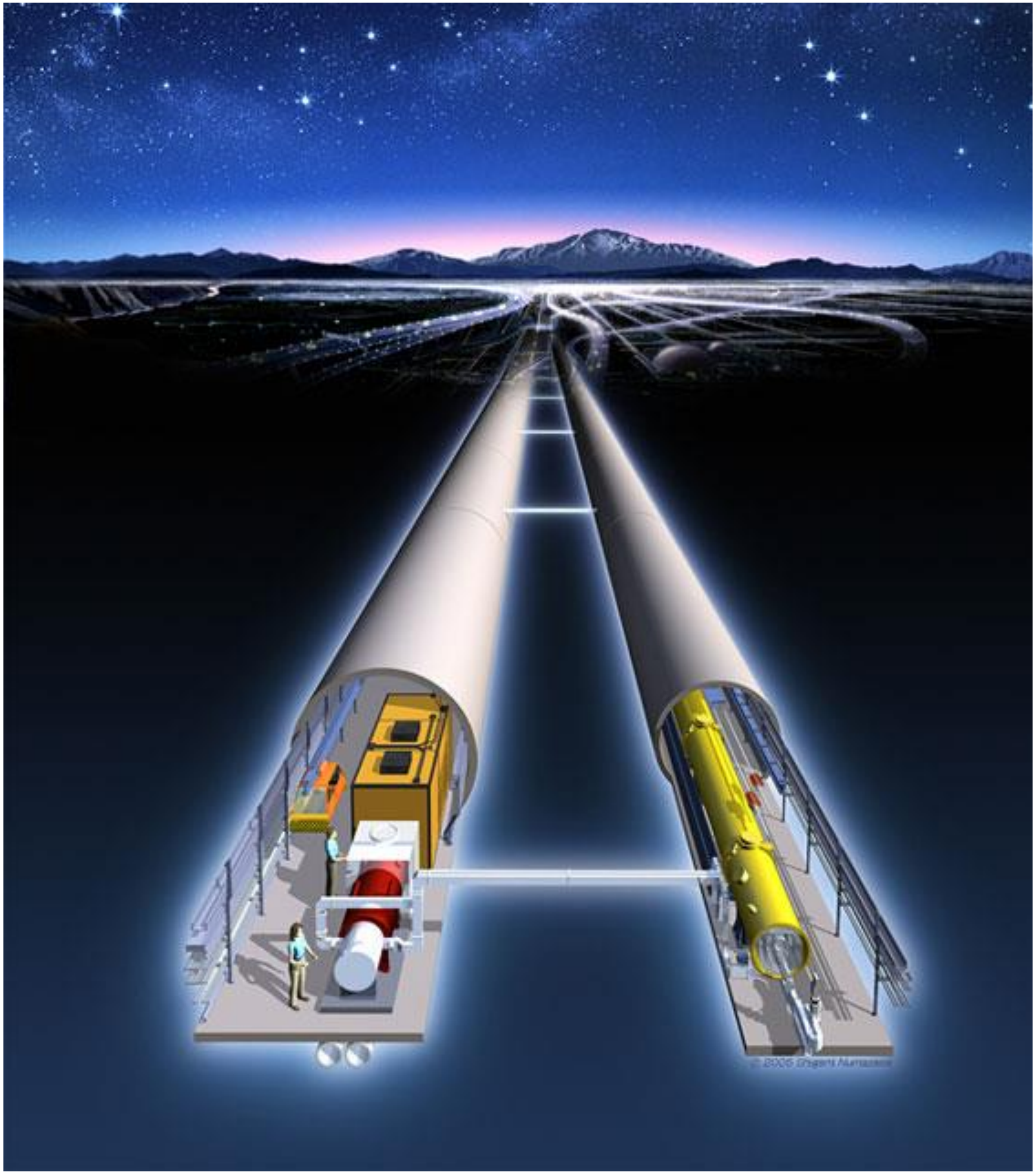
LHC.BWS.5L4.B2H1 #1:1 AXIS 1 at Fri 13:33:13
RMS Width Calculation

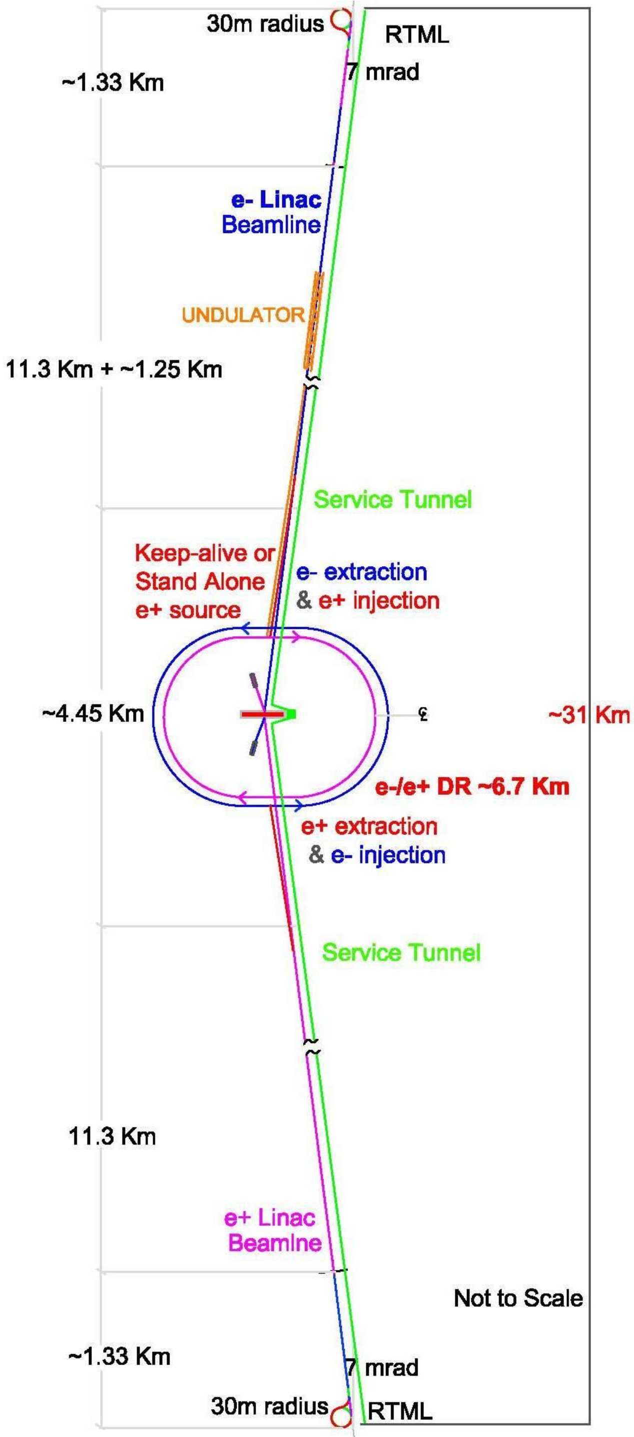
Center=1,274.726
sigma=2,984.704
Energy=483.879
BG=0.018
Slope=-0
ChiSq=1
Emit(norm)=11,356,601.293
Emit(phys)=22,021.21

Kick response compared with theoretical optics

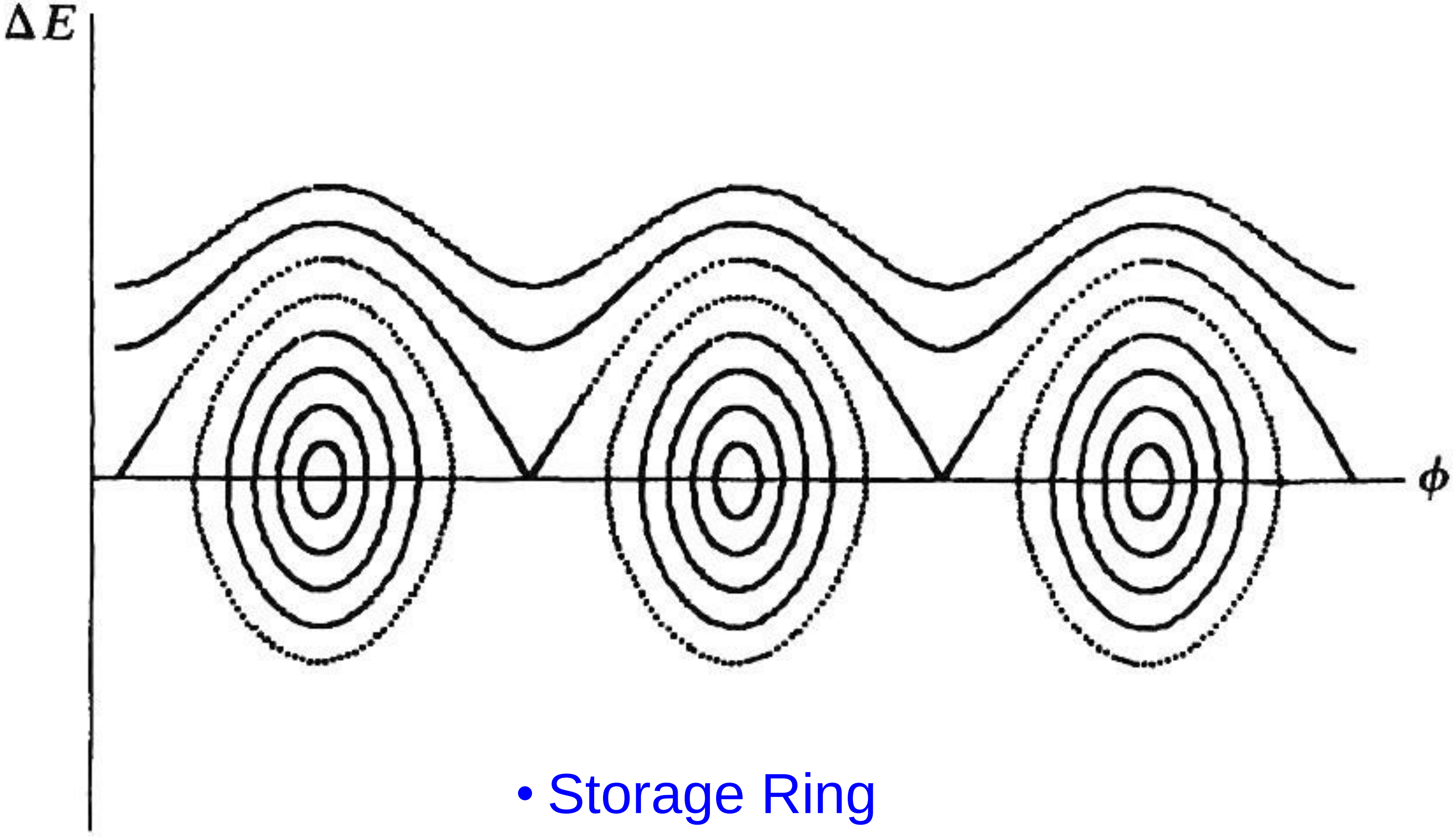



Alors, c’est fini!
Et maintenant?

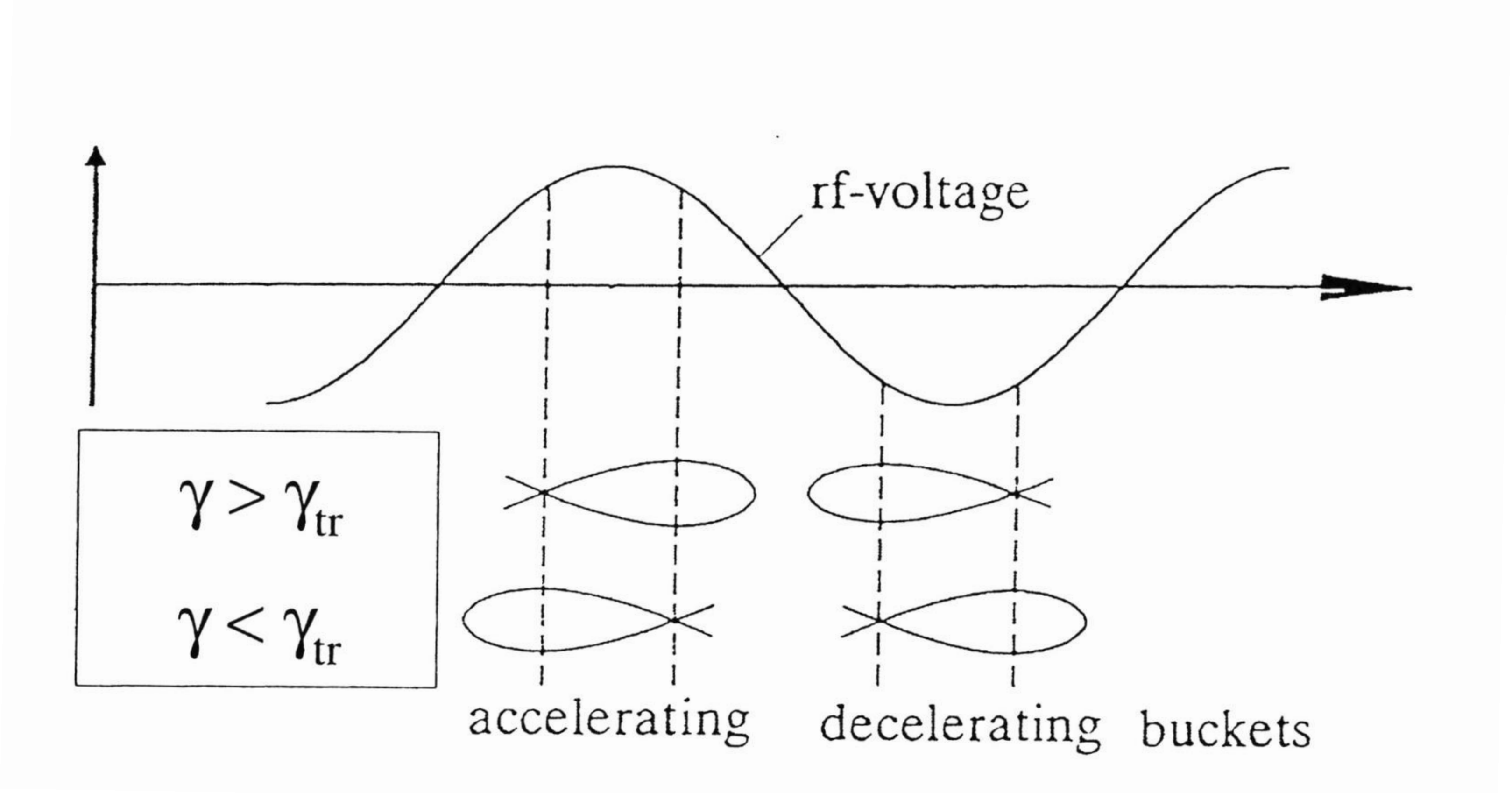



30m radius
RTML
~1.33 Km
7 mrad
e- Linac
Beamline
UNDULATOR
11.3 Km + ~1.25 Km
Service Tunnel
Keep-alive or
Stand Alone
e+ source
e- extraction
& e+ injection
~4.45 Km
℄
~31 Km
e-/e+ DR ~6.7 Km
e+ extraction
& e- injection
Service Tunnel
11.3 Km
e+ Linac
Beamlne
Not to Scale
~1.33 Km
7 mrad
30m radius
RTML

終



- Storage Ring
- Stable phase = 0°
- No acceleration



Synchrotron (phase) oscillations

$$\frac{d^2\Delta\phi}{dn^2} + \left(\frac{-\eta\omega\tau c^2 eV}{v^2 E_s}\cos\phi_s\right)\Delta\phi = 0$$

$$\frac{d^2\Delta\phi}{dn^2} + \left(2\pi\nu_s\right)\Delta\phi = 0$$

$\eta < 0 \quad ; \quad (\gamma < \gamma_t) \quad ; \quad \cos\phi_s > 0$

$\eta > 0 \quad ; \quad (\gamma > \gamma_t) \quad ; \quad \cos\phi_s < 0$