Four Decades of Colliders (From the ISR to LEP to the LHC)

IPAC10, Kyoto, Japan

27th May 2010

Steve Myers

Topics

- The ISR
- LEP
- LHC
- Future

Will not talk about

- sppbars
- Tevatron
- SLC
- RHIC

The ISR

- The almost forgotten, first ever hadron collider
- A real collider:
  - Accumulated and Collided enormous currents (57Amperes per beam) of enormous dimensions (more than 80mm,3.2 inches cross section)
  - Unbunched beams with 3% momentum spread
  - Aperture > 4% $\Delta p/p$

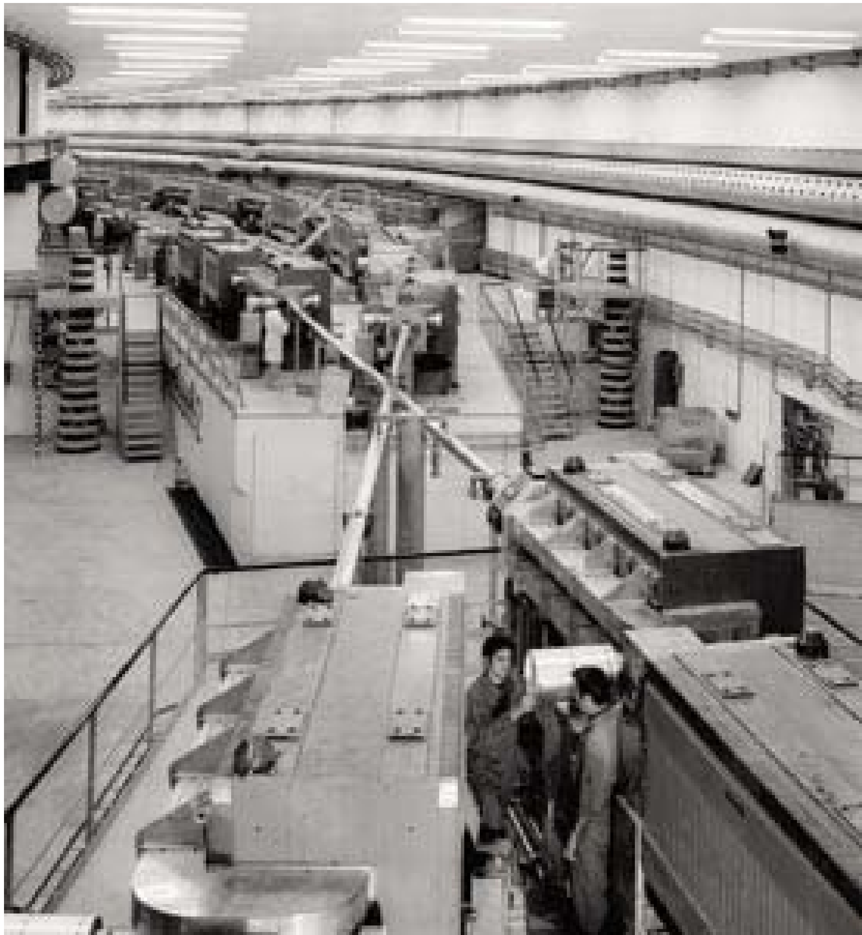
? Diagnostics?

- Enormous impact on Accelerator Physics but sadly little effect on particle physics

Accelerator Physics/Technology at ISR

- Stacking of protons
- Ultra high vacuum (clearing electrodes, electron cloud)
- High precision power supplies
- Low impedance machine
- Beam beam; pulsed beam-beam “overlap knock-out”
- Space charge compensation
- Collimation
- Luminosity scans (van der Meer scans)
- Phase displacement acceleration
- Schotty noise and scans
- Stochastic cooling
- Low beta insertions
- Proton-antiproton collisions
- Stacking and phase displacement of deuterons,...

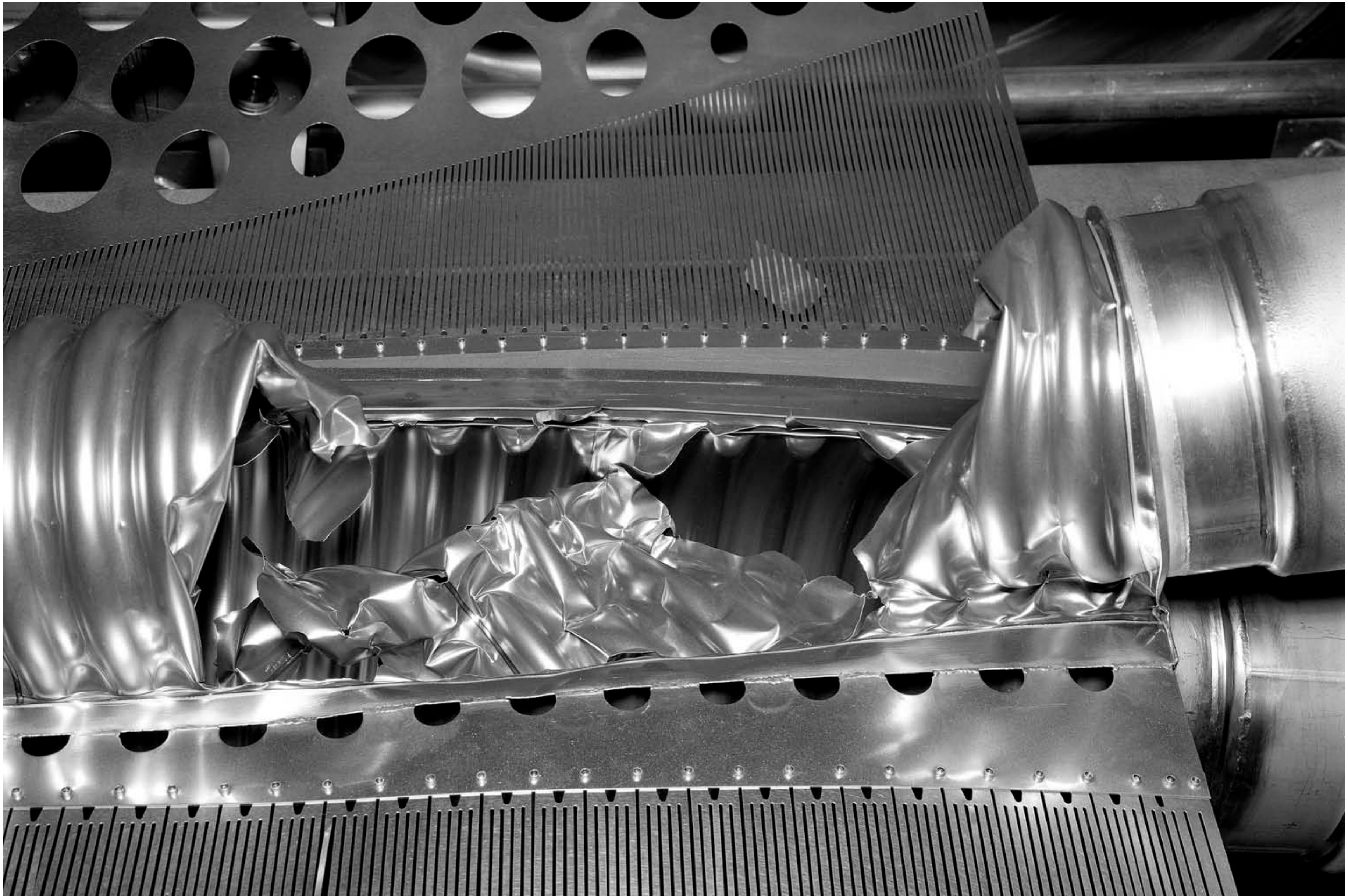
The first proton-proton collider, the CERN Intersecting Storage Rings (ISR), during the 1970's. One can see the "massive" rings and two of the intersection points.

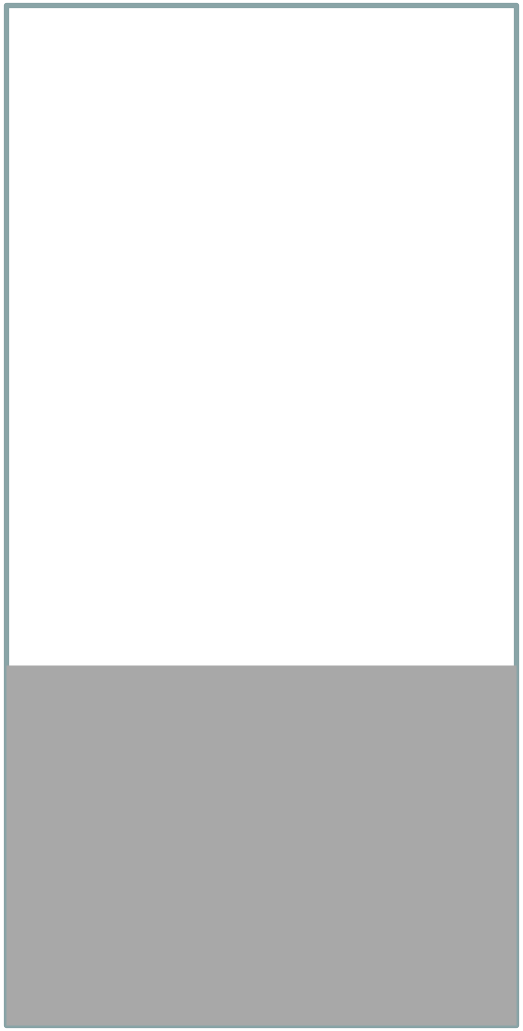


Where are the detectors around the collision points????

ISR Control Room (early 70s)

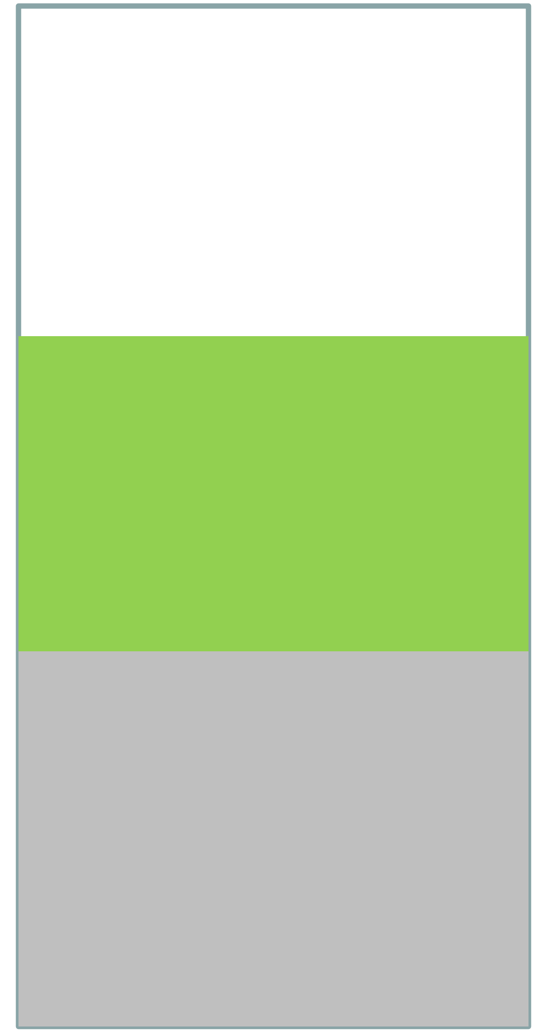
Imploded Thin Walled Vacuum Chamber





Stacking

Phase Displacement →



Space Charge Compensation

The required large tune spread resulted from the stability requirement from chromaticity and the large momentum spread needed for beam stacking. The minimum tune range of around .07 created difficulties to find a resonance free area in the tune

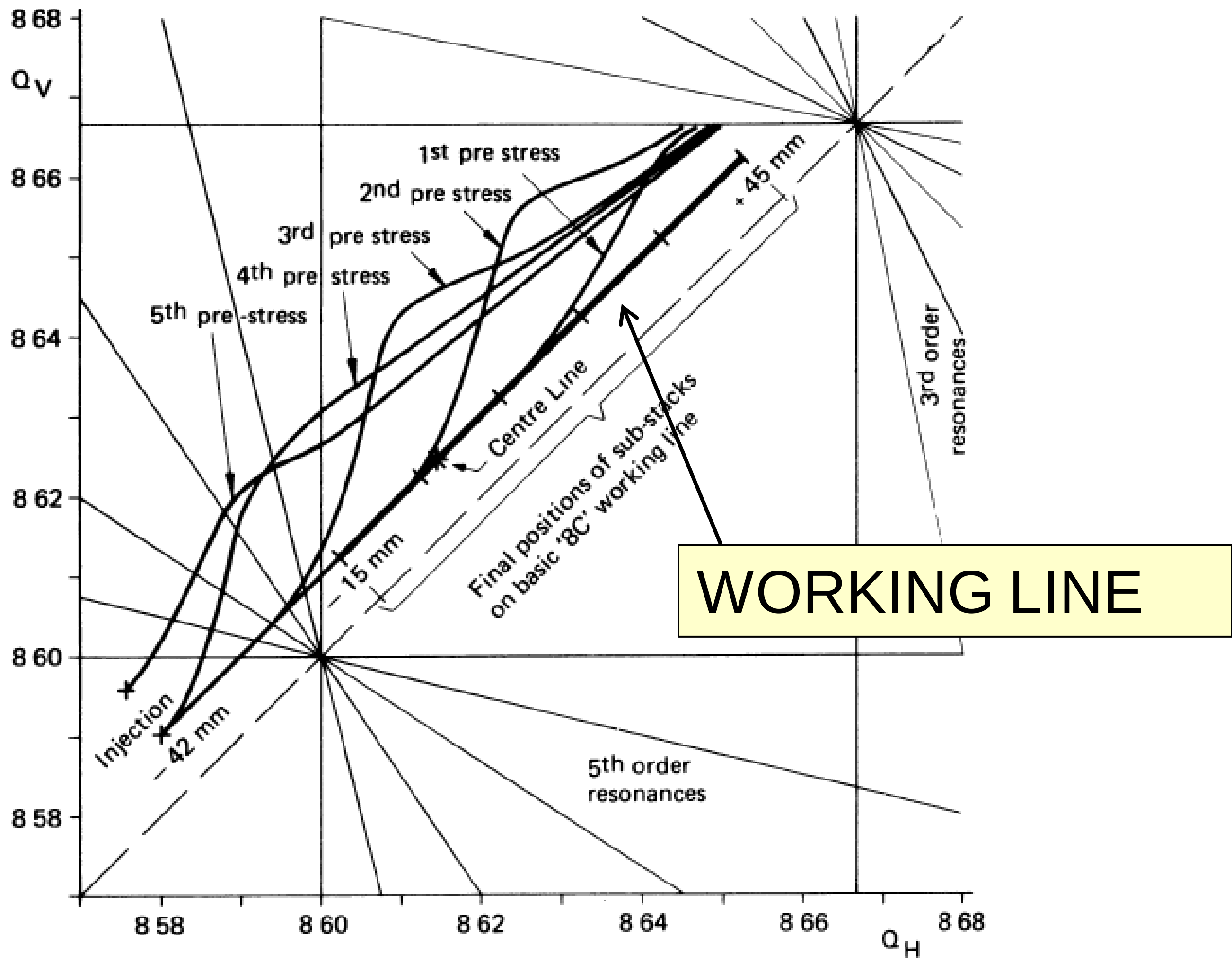


Fig 3 The family of pre-stressed working lines used at 22 GeV/c to stack 15 A in five steps of 3 A across the chamber from +45 mm to -15 mm (α_p average)

Phase Displacement Acceleration to 31.4GeV

- Since the ISR circumference was larger than the PS, the maximum energy was also higher (31.4 compared to 26.6GeV)
- Hence it was decided to attempt to increase the energy of the accumulated beam in the ISR.
- Clearly the small ISR RF system could not capture a beam with 3% momentum spread.
- So in our relative ignorance of the problems (space charge changing tunes, chromaticity, orbits, RF noise effects, absence of diagnostics...) we proposed to phase displace high intensity stacks of protons.
- Initially the progress was slow but, eventually, after some better understanding and a few break-throughs, 31.4GeV became the preferred high luminosity operational energy of the ISR.

Hurray!! Diagnostics; Schottky Scans

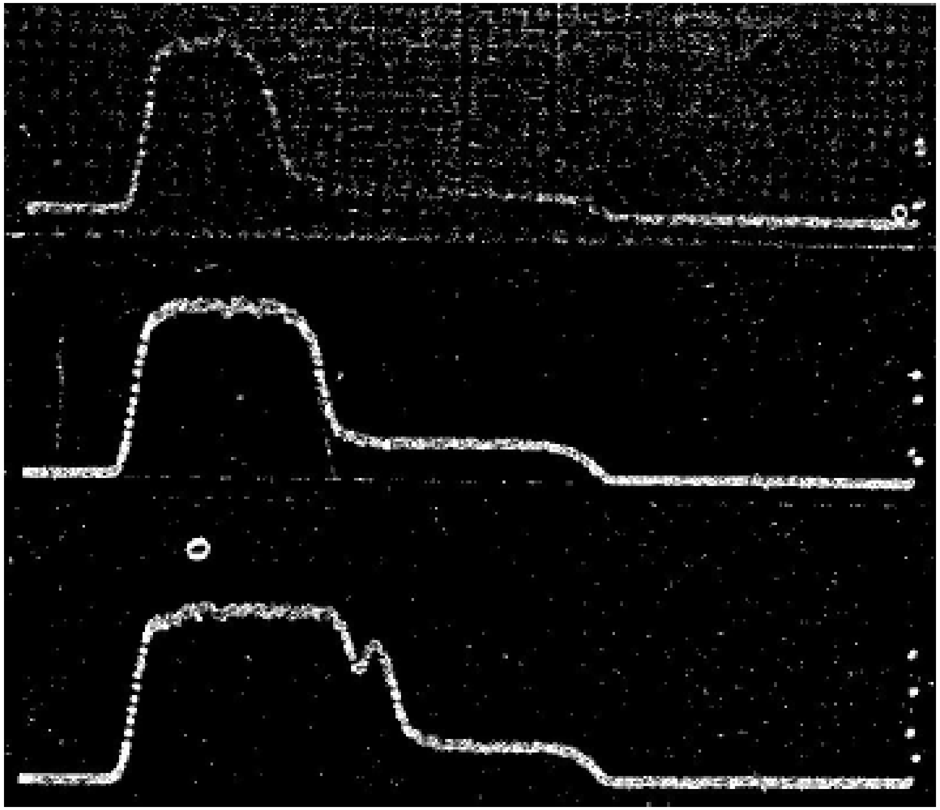
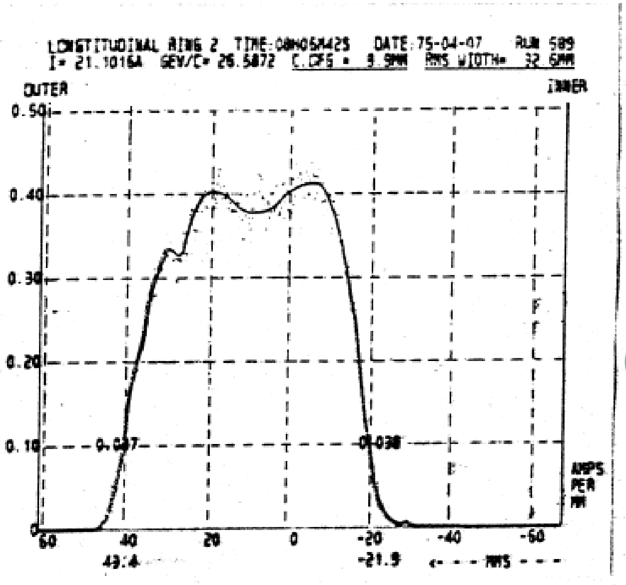
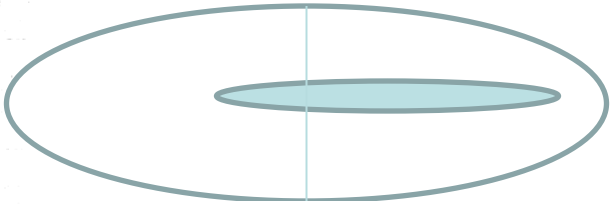


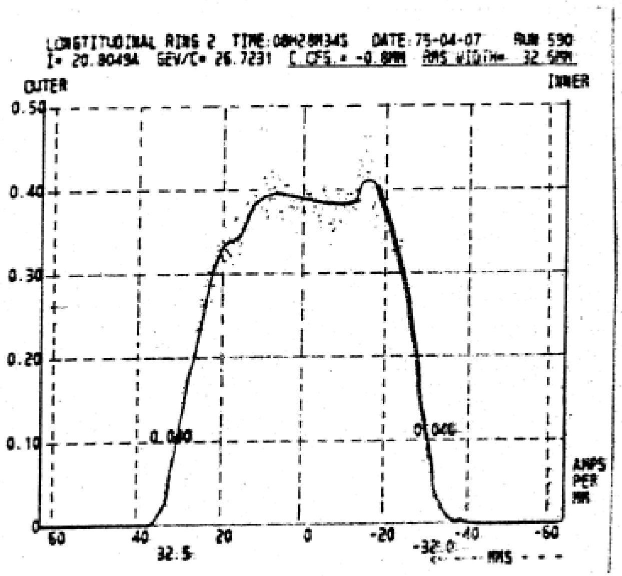
Fig. 9: Longitudinal Schottky scans of coasting proton beams of 10, 15, and 19 A [8]

Stack Centering



Before centering





After centering

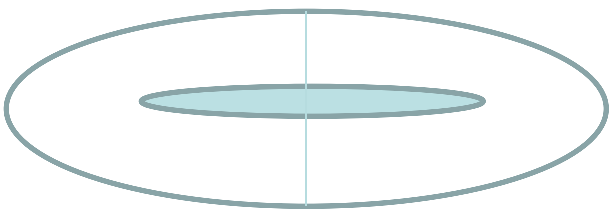
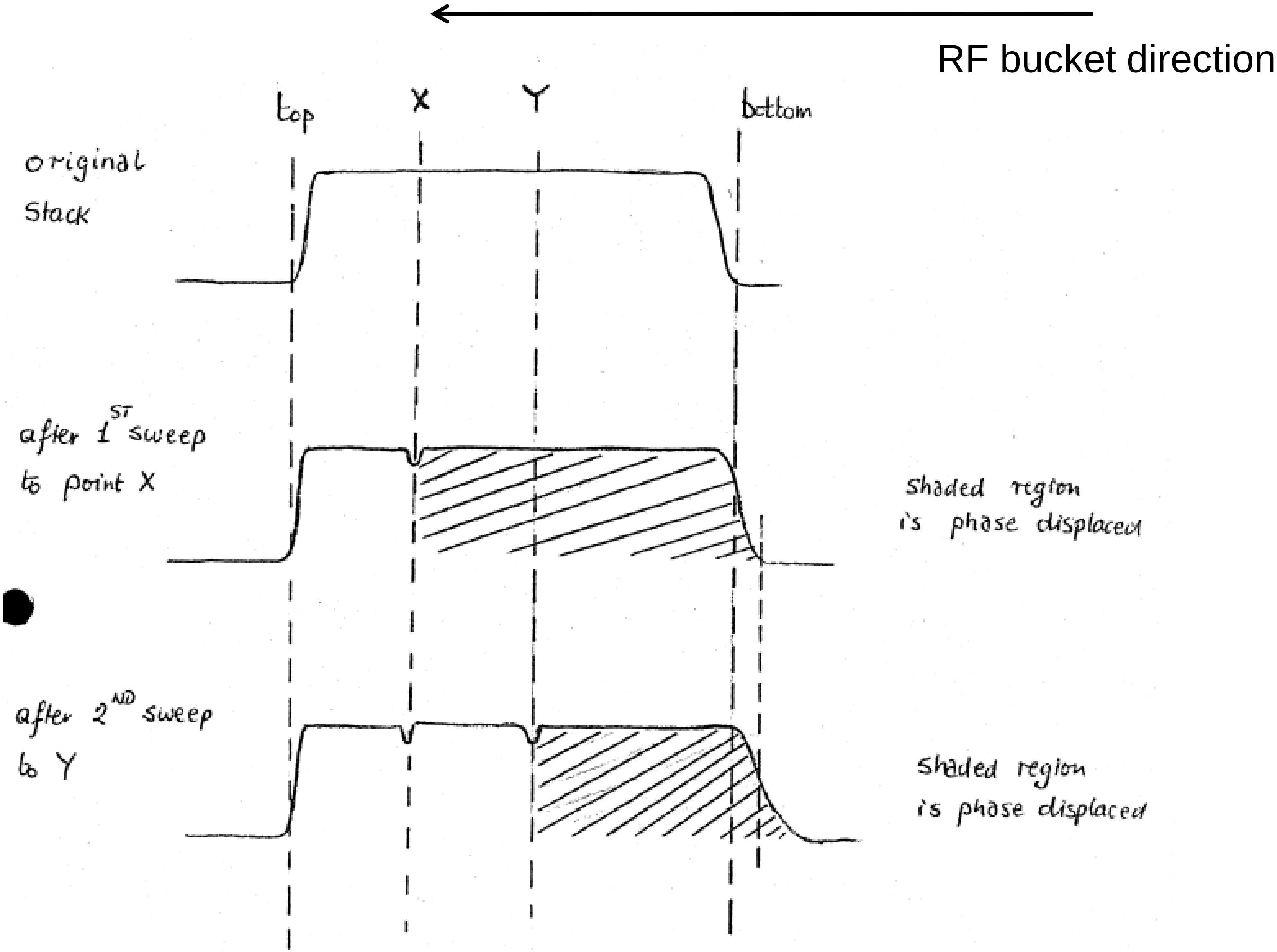


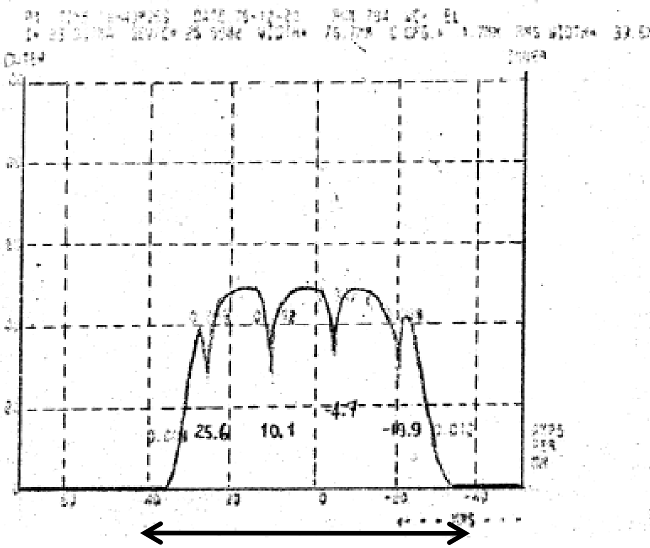
Table II

Run	I_1 amps	I_2 amps	before displacement $\frac{di_1}{at}$ ppm/min	$\frac{di_2}{at}$ ppm/min	after displacement $\frac{di_1}{at}$ ppm/min	$\frac{di_2}{at}$ ppm/min
593	24.0	24.0	60	10	0.8	0.8
594	24.0	24.0	10	10	0.8	0.8

In each of the runs, after the stacks centring, the loss rates remained at unusually low values throughout the run (3 → 4 ppm/min after 20 hours).

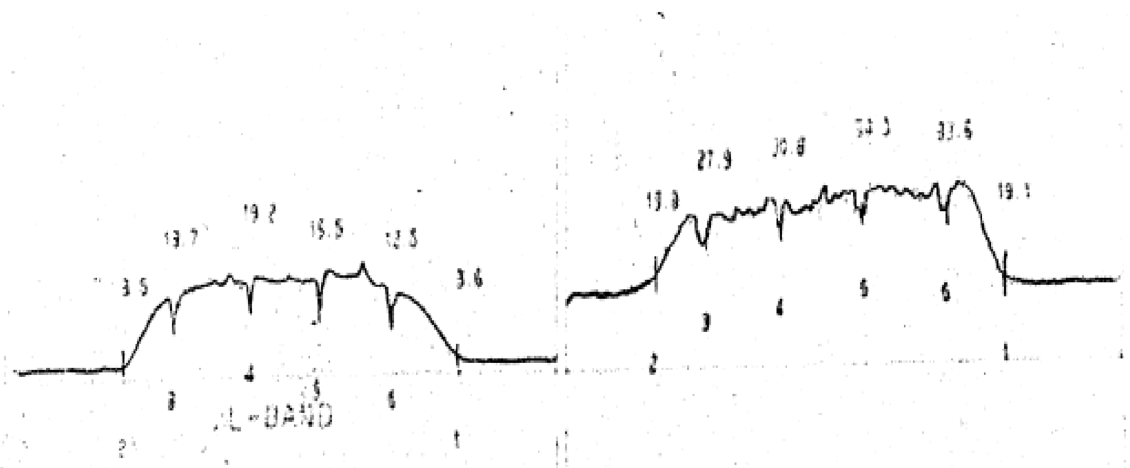
Putting Marks in the Stacks



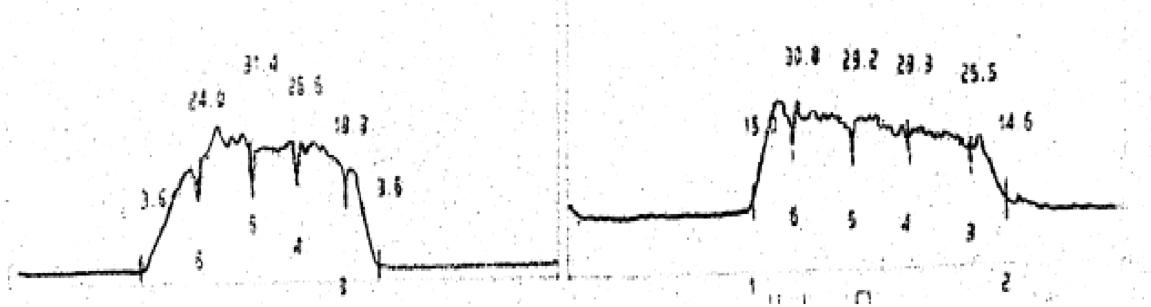


Longitudinal Schottky

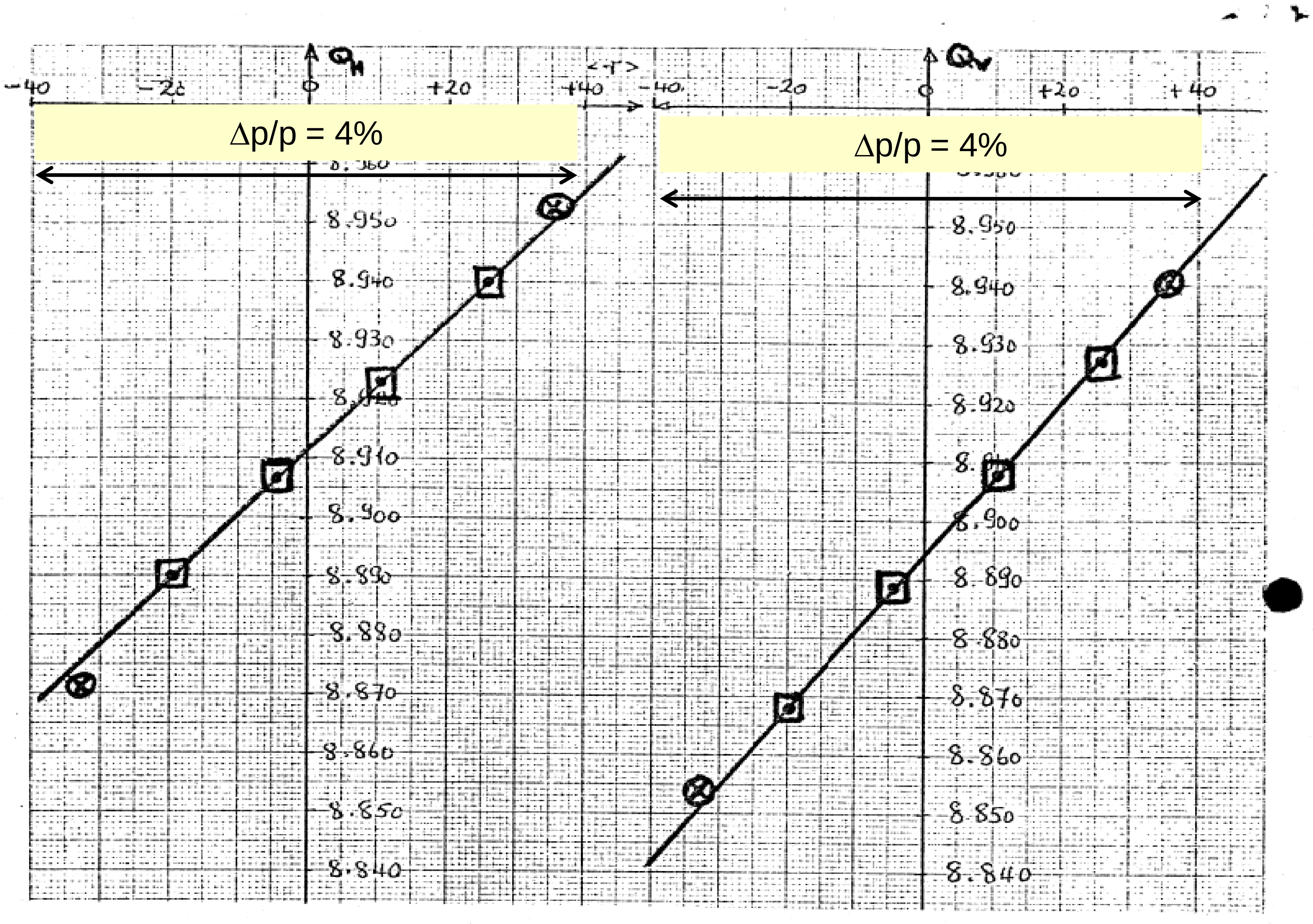
$\Delta p/p = 4\%$



Transverse Schottky



Measurement of the Working Line



New Working Line

- As the intensities increased we needed more tune spread for stability (0.07 was no longer enough: needed around .09)
- Tried a WL (5C) crossing 5th order resonances-disaster
- The most resonance free region is close to the integer (not a very easy place to operate)
- Over time cured many of the problems (orbit stability, transverse stability,..) BUT always had a large blow-up of the emittance "at the top"

Overlap Knock out

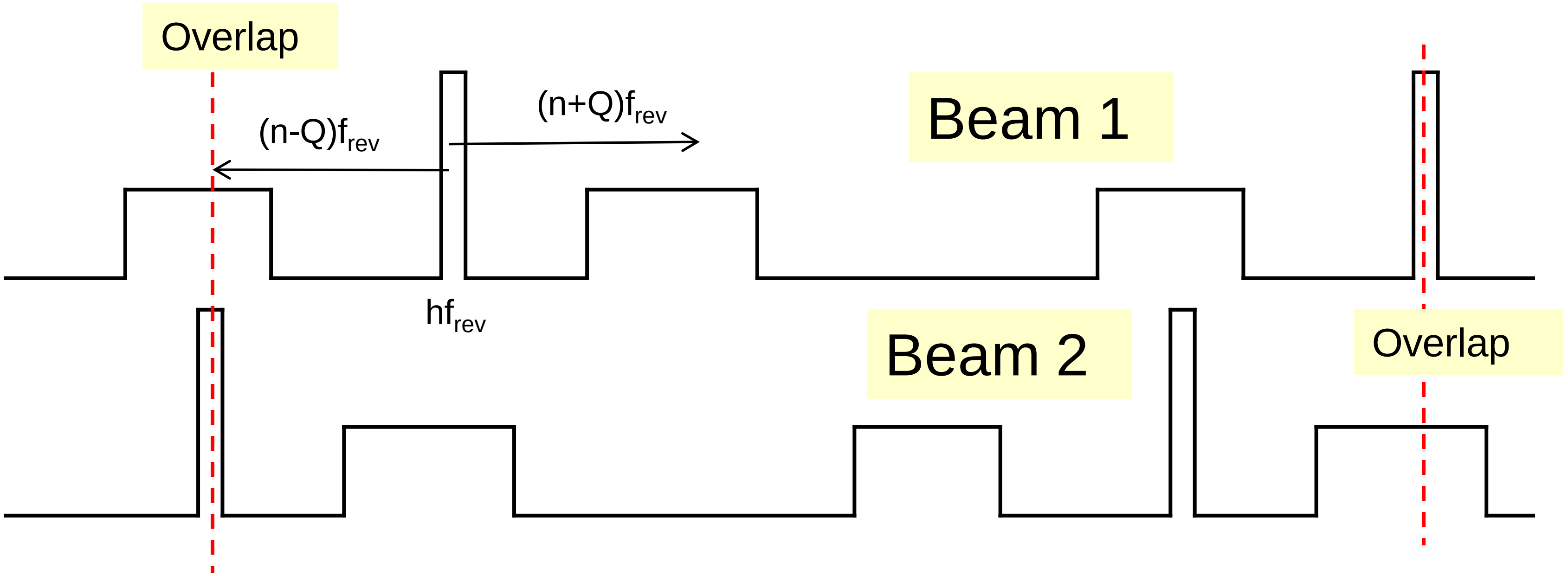
Transversely the beam looked like a lacrosse stick

In the ISR we had to worry about **4 beams**: 2 beams per ring. The bunched beam at injection and during acceleration and the debunched already accumulated beam

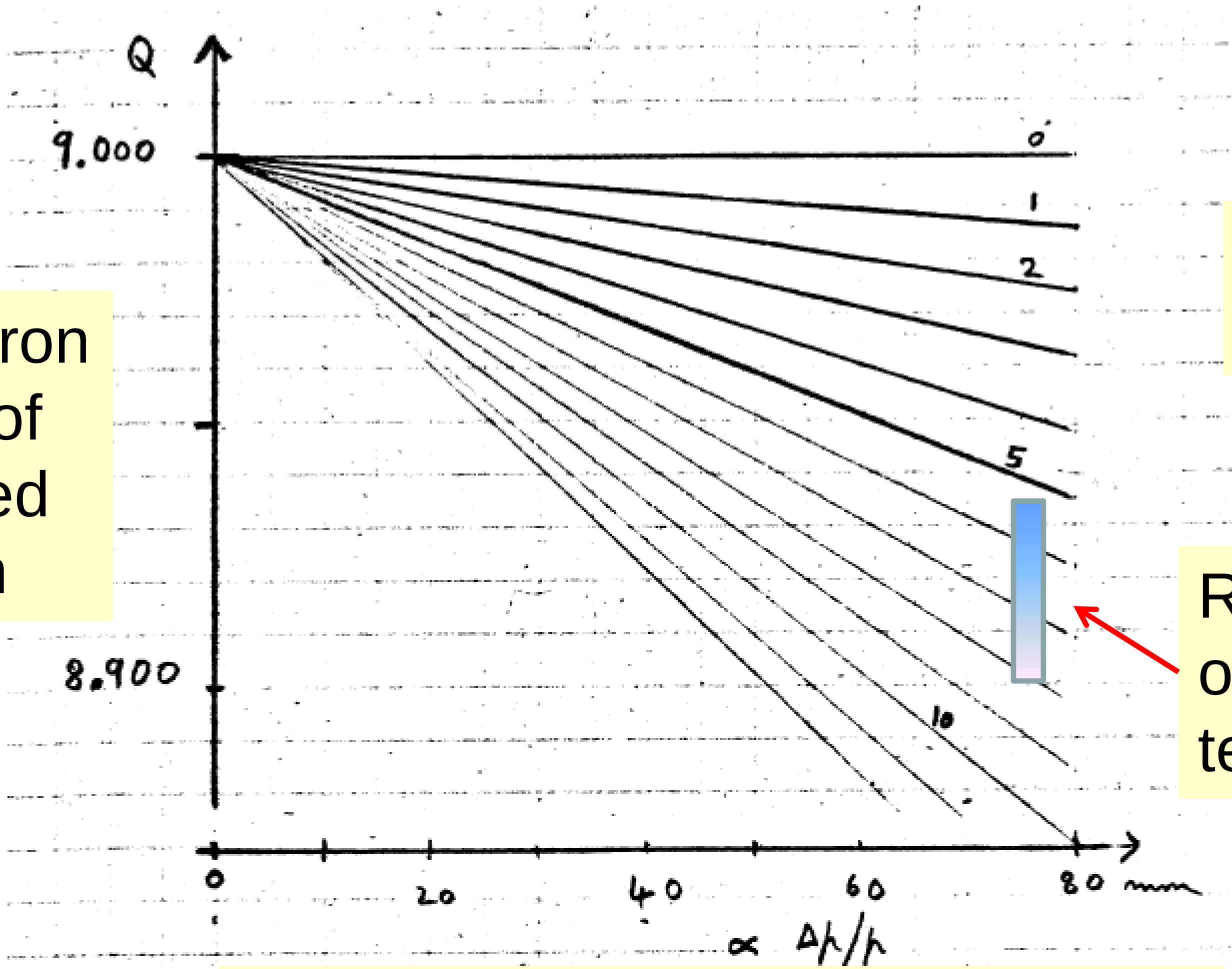
For beams that have significantly different revolution frequencies (caused by different $\Delta p/p$ or different charge/mass ratios)

Overlap Knock out

is an effect where the longitudinal harmonics of the bunch spectrum have components which are equal (“overlap”) to the transverse betatron frequencies and thereby can excite the beam at its transverse resonant frequency (“RF knock-out”)



Frequency Overlap Conditions (resonance)



Harmonic of fbunch

Betatron tune of excited beam

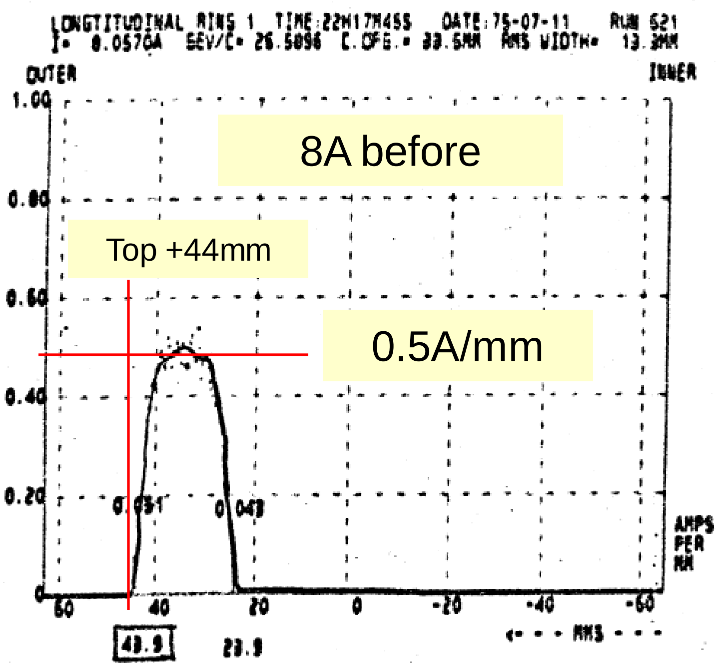
Region of overlap for test

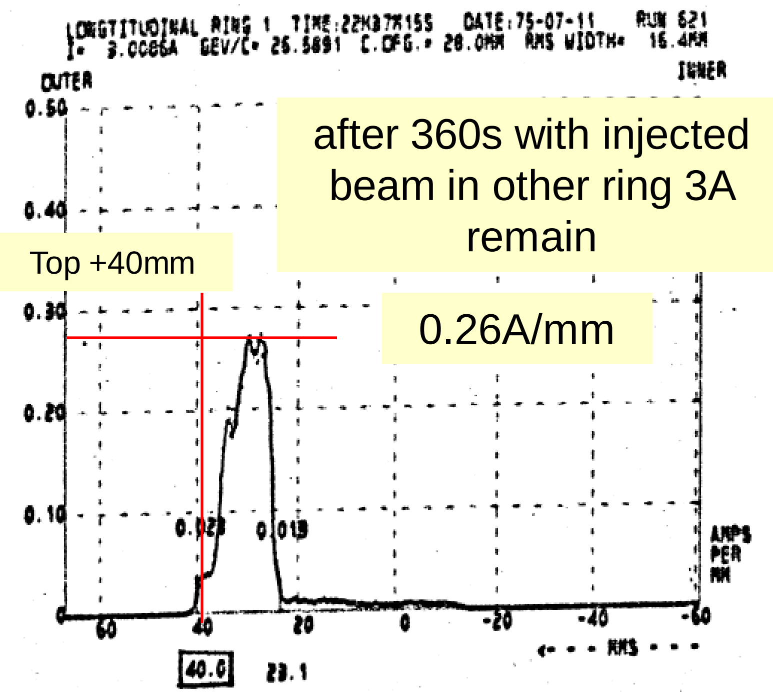
$\Delta p/p$ difference between beams

Effect of Two Ring Overlap Knock-out

2.1.4 Magnitude of the current loss during typical stacking

In order to simulate the conditions which occur during normal stacking a stack of 8.0 A was made in Ring 2 and subjected for 360 s to a bunched pulse of 80 mA in Ring 1 on injection orbit with 16 kV RF and ± 4 mm bad bumps. During the 360 s the stack was aperture restricted vertically by the underside scraper. The longitudinal Schottky scans before and after are shown in Fig. 13. It can be seen that around 5 A was lost in this short time! The top 4 mm of the stack was completely lost and the average density of the rest of the stack severely reduced. This is reasonably consistent with the vertical blow-up plus current loss observed during normal stacking.





Cures for 2 Beam OLKO

- Reduce the higher harmonics of the bunch spectrum by bunch lengthening (lower RF voltage)
- Use separations in the interaction regions so that the vector sum of beam beam kicks over one turn is minimized

These cures allowed long term operation on the new WL

Type of OLKO	**Resonance condition**	**Coupling mechanism**
single beam dipolar	$\Delta p/p$ between beams	coupling impedance
two beam dipolar	$\Delta p/p$; charge/mass ratio	beam beam
two beam quadrupolar	$\Delta p/p$; charge/mass ratio	beam beam
etc..		

Stochastic Cooling at ISR

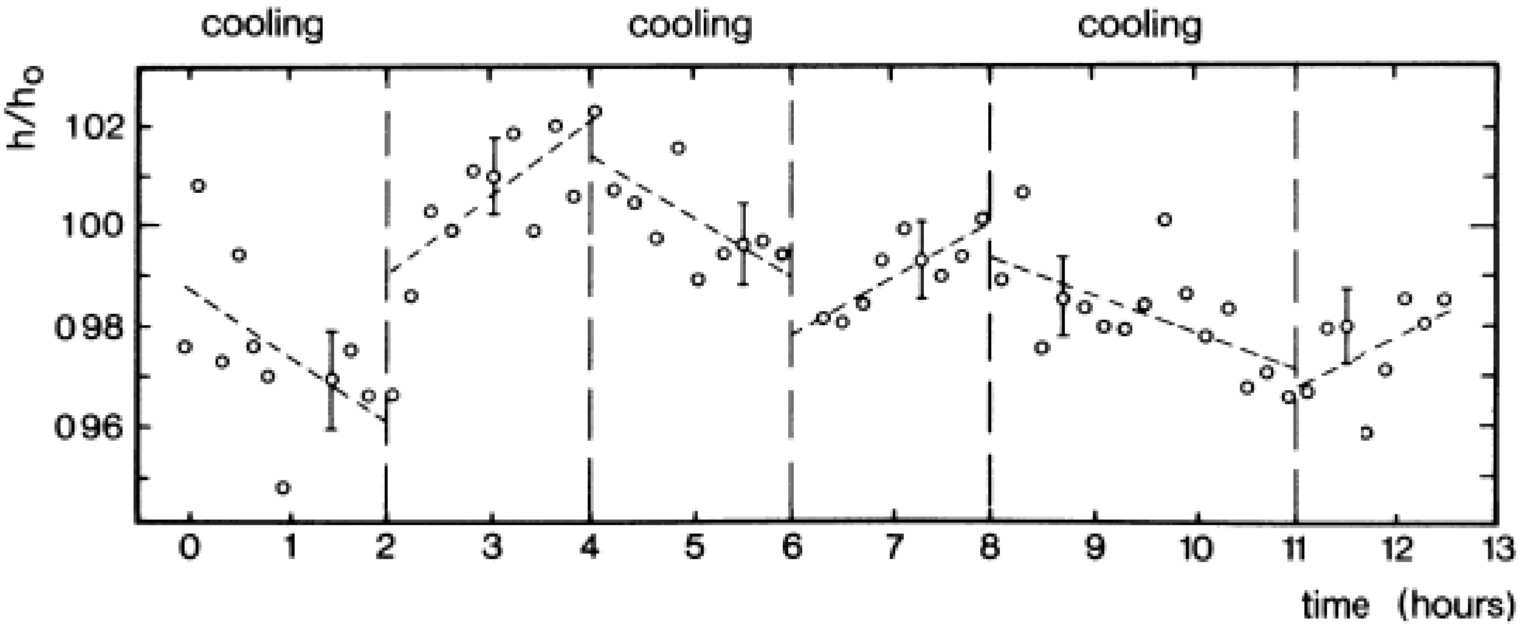


Fig 8 Observation of stochastic cooling in the ISR through measurements of the effective beam height (h/h_0), as a function of time, decreasing when cooling is applied and increasing when not applied The cooling equipment, installed in only one ring, detects and corrects statistical fluctuations of average beam position Luminosity is inversely proportional to the effective beam height

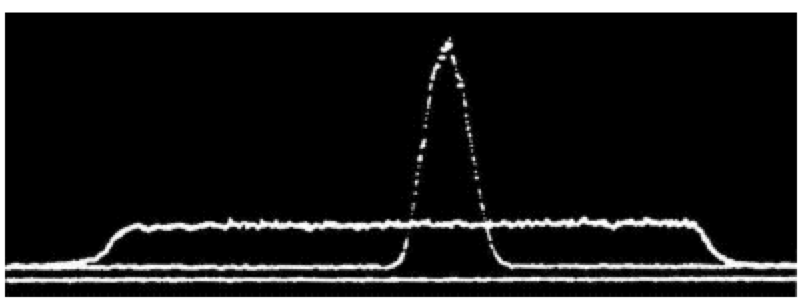


Fig. 12: Distribution of protons as a function of momentum before (wide rectangle) and after cooling (narrow peak) in ICE

Vacuum Evolution

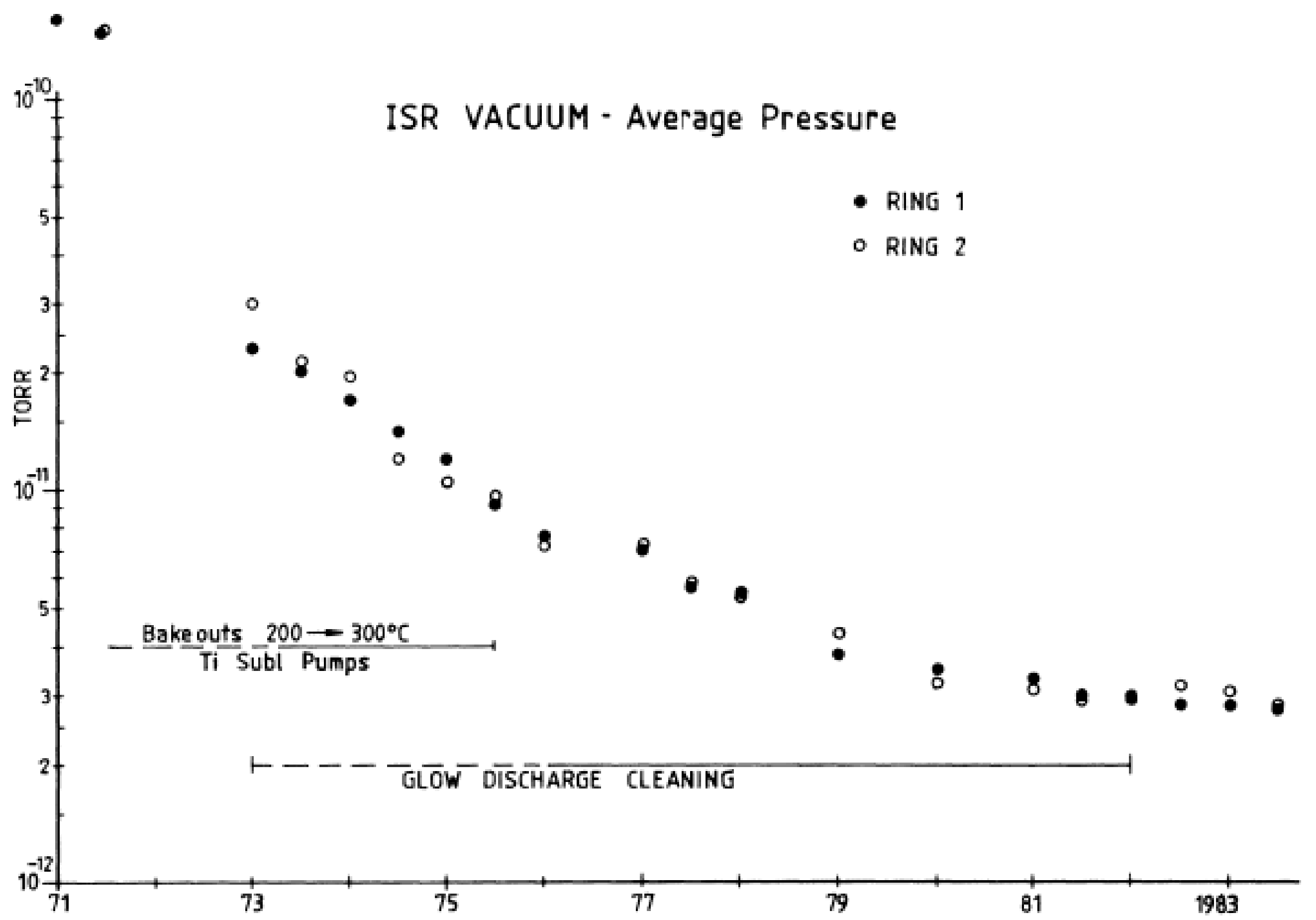


Fig 5 The average pressure of the ISR vacuum for the years 1971-83

Luminosity Evolution

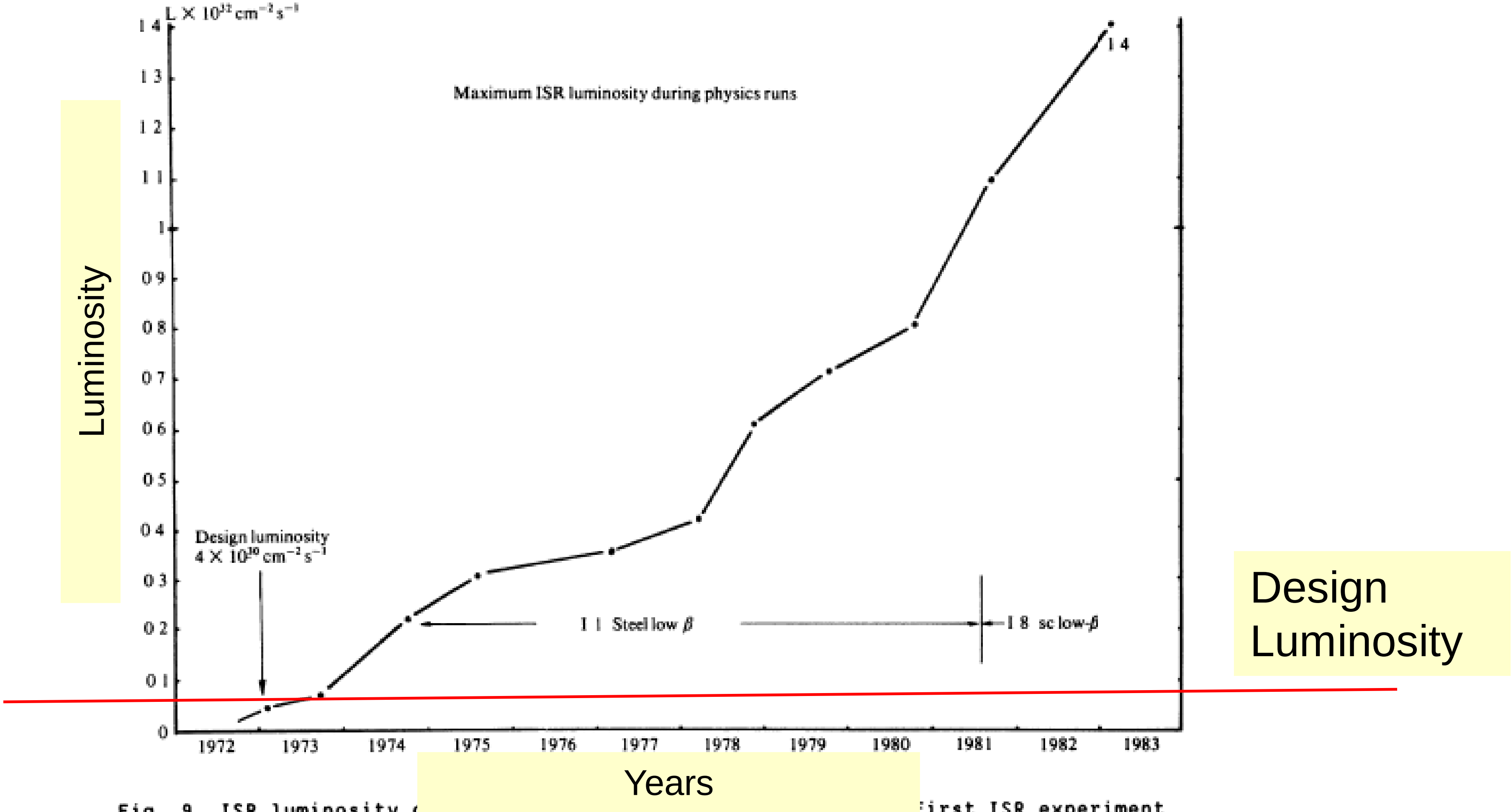


Fig 9 ISR luminosity during physics runs. September 1971 -- first ISR experiment to be completed, R101; maximum luminosity = 1 3 × 10^{29} cm^{-2} s^{-1}. December 1982 -- Highest luminosity achieved for physics (R807) = 1 4 × 10^{32} cm^{-2} s^{-1}

What is the Legacy of ISR?

How to build collider detectors

The need for good diagnostics

Schottky, stochastic cooling, phase displacement ICE, AA LEAR; (ppbar in SPS)

Accelerator experience and people

Computer control of colliders

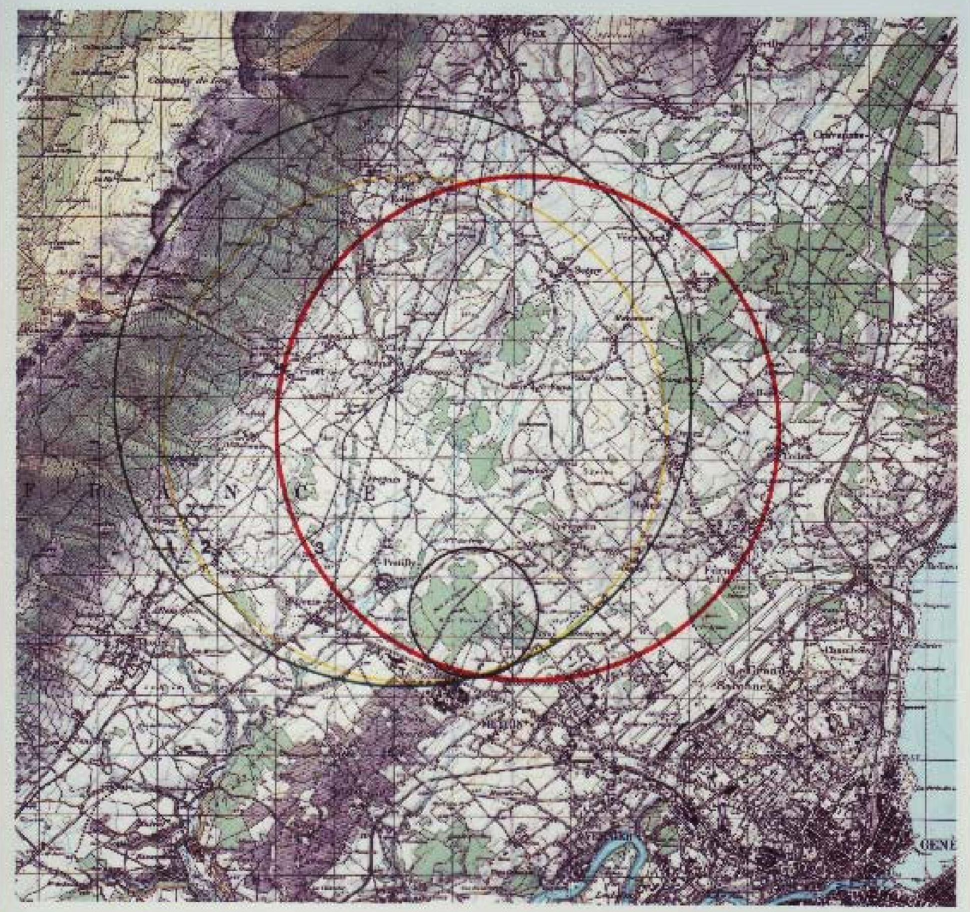
Collimation and background control

Luminosity calibration by Van der Meer scans

Impedance and transverse instabilities

Optics calculations and measurements

LEP Collider



1 LEP de 30 km

2 LEP de 26,6 km – Variante

3 LEP de 26,6 km – Solution retenue

V.4 Tracés des variantes de l'implantation du tunnel du LEP

B/315.

Summary of LEP Performance

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b (GeV/c^2)	k_b	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

Modes of Operation

Year	Optics	Comments	Bunch scheme
1989	60/60	LEP commissioned	4 on 4
1990	60/60		4 on 4
1991	60/60	90/90 optics tested	4 on 4
1992	90/90	Pretzel commissioned	4 on 4 / Pretzel
1993	90/60		Pretzel
1994	90/60		Pretzel
1995	90/60	tests at 65-68 GeV	Bunch trains
1996	90/60	108/90 tested	4 on 4
1997	90/60	108/60 and 102/90 tested	4 on 4
1998	102/90		4 on 4
1999	102/90		4 on 4

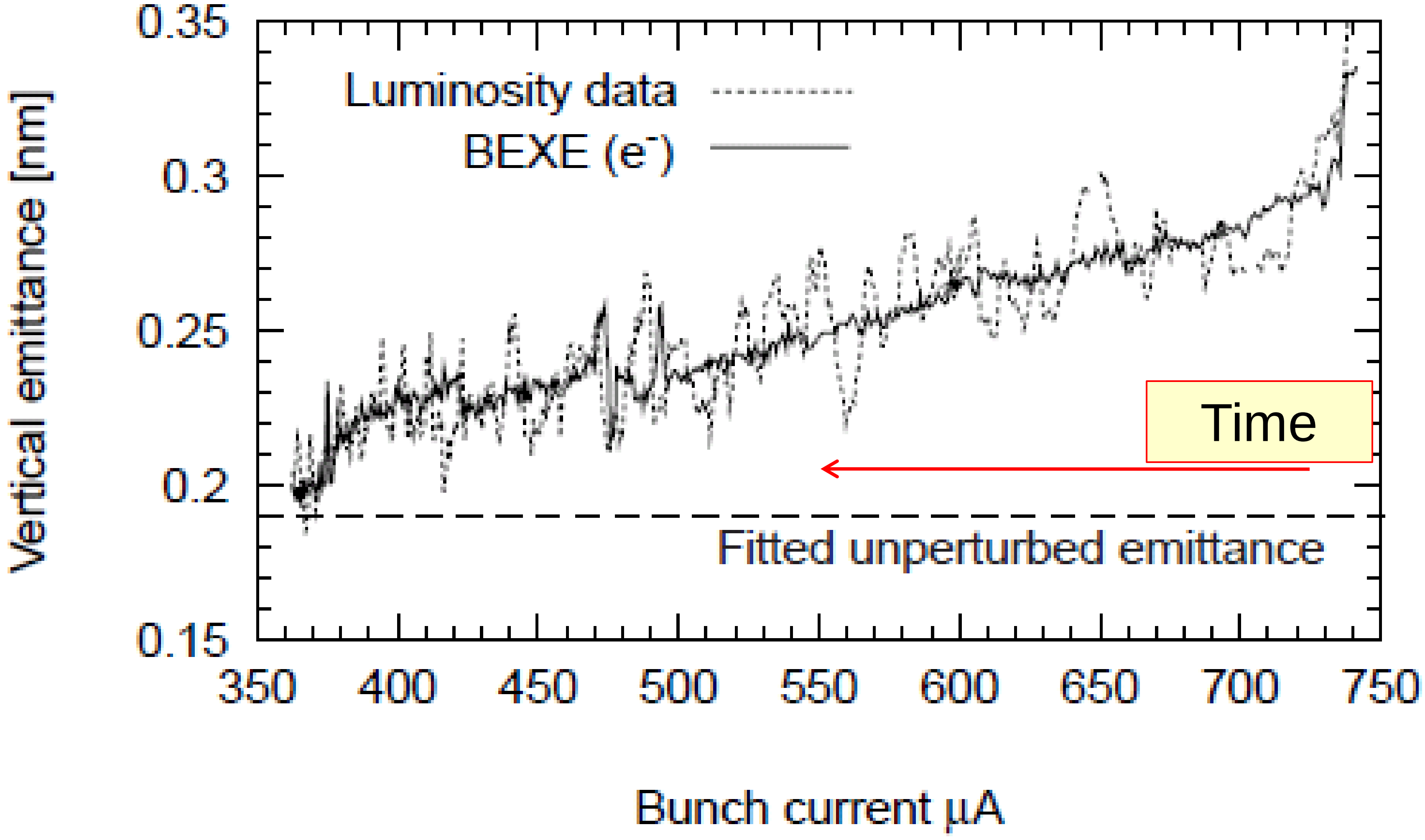
Every Year was Different

LEP: Design and Reality

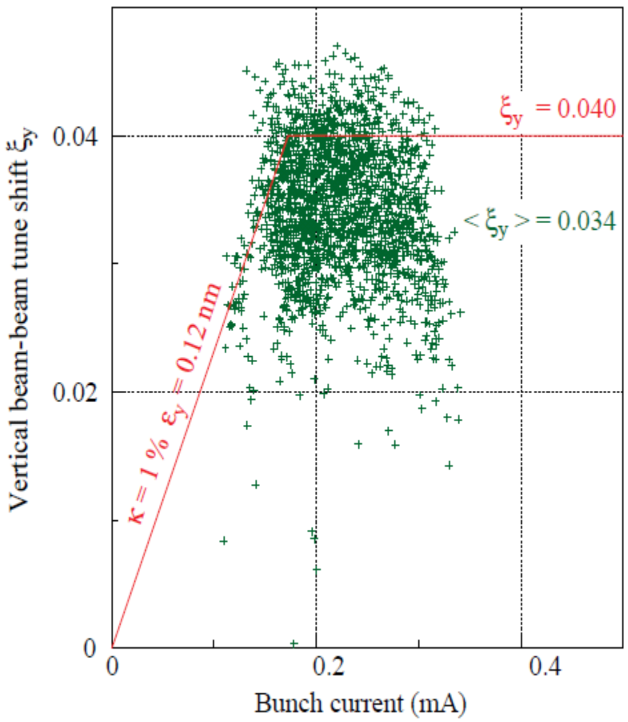
Parameter	**Design** (55 / 95 GeV)	**Achieved** (46 / 98 GeV)	
Bunch current	0.75 mA	1.00 mA	
Total beam current	6.0 mA	8.4 / 6.2 mA	
Vertical beam-beam parameter	0.03	0.045 / 0.083	
Emittance ratio	4.0 %	0.4 %	x 10
Maximum luminosity	**16 / 27** **10^{30} $cm^{-2}s^{-1}$**	**23 / 100** **10^{30} $cm^{-2}s^{-1}$**	x 1.4 / 3.7
IP beta function b_x	1.75 m	1.25 m	
IP beta function b_y	7.0 cm	4.0 cm	

Reality better than design (result of many years work)!

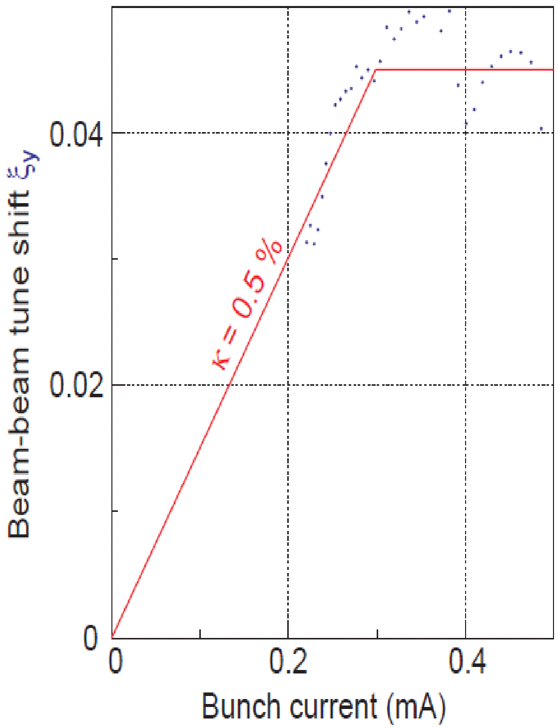
The Beam Beam Effect



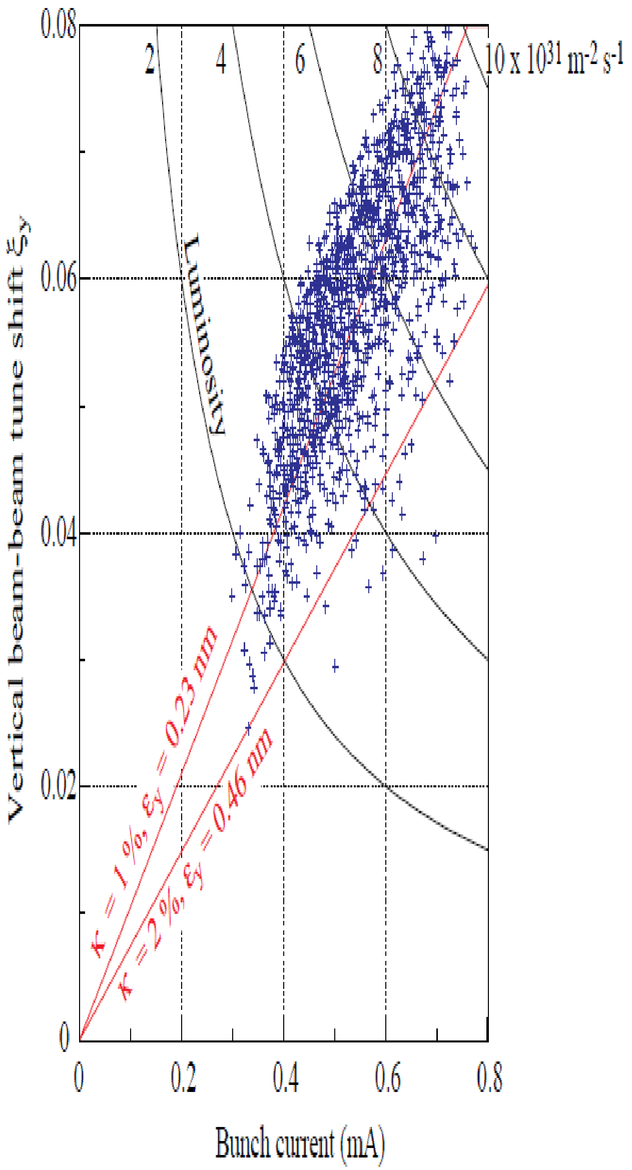
Beam-Beam Behaviour



45 GeV



65 GeV



98 GeV

The Unforeseen and Unexpected

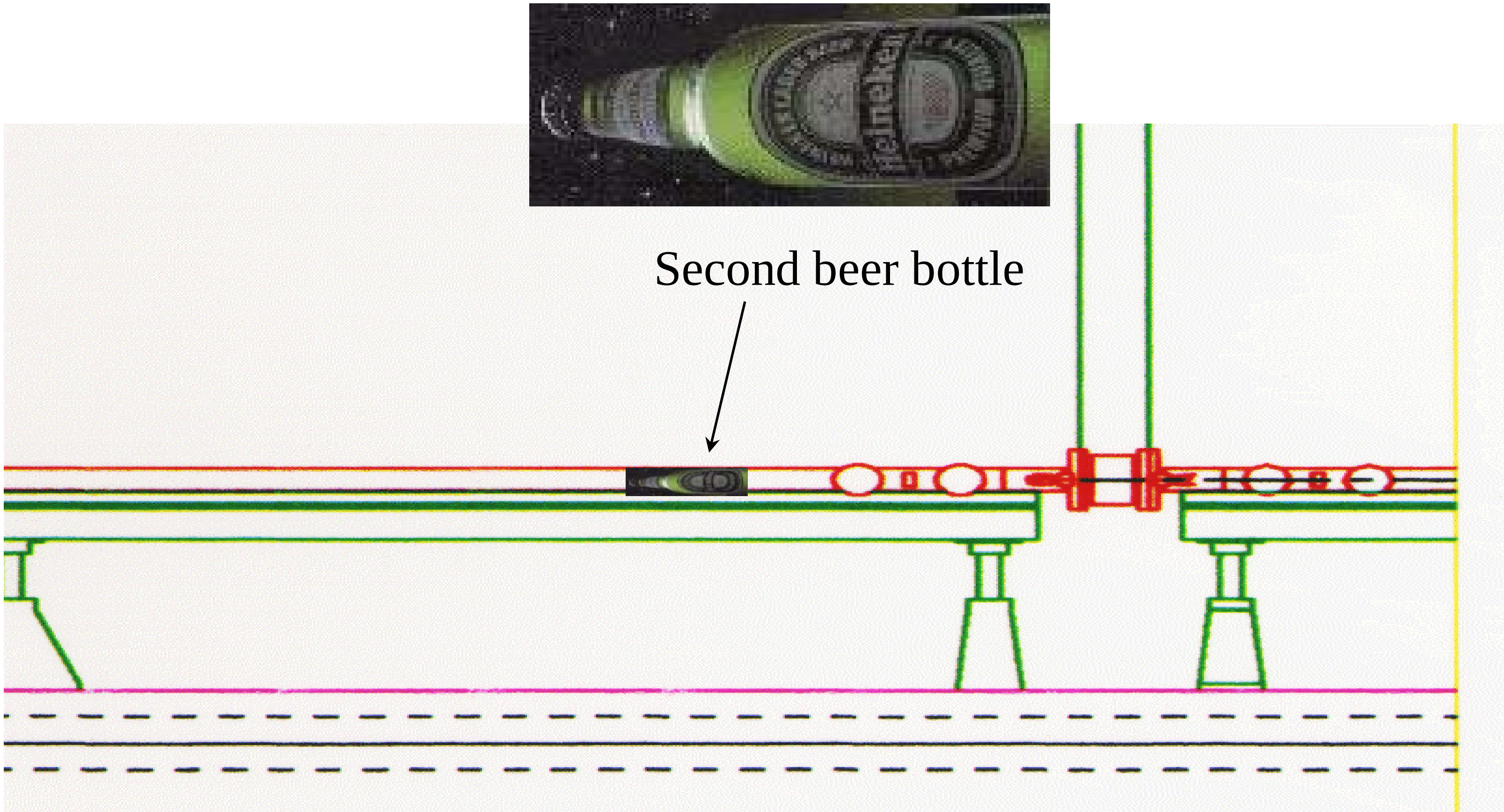
The sun and the moon (beam energy)

The TGV influence on the energy calibration

The beer bottles found in the vacuum chamber

The electrocution of animals: deers rats,...

10 metres to the right

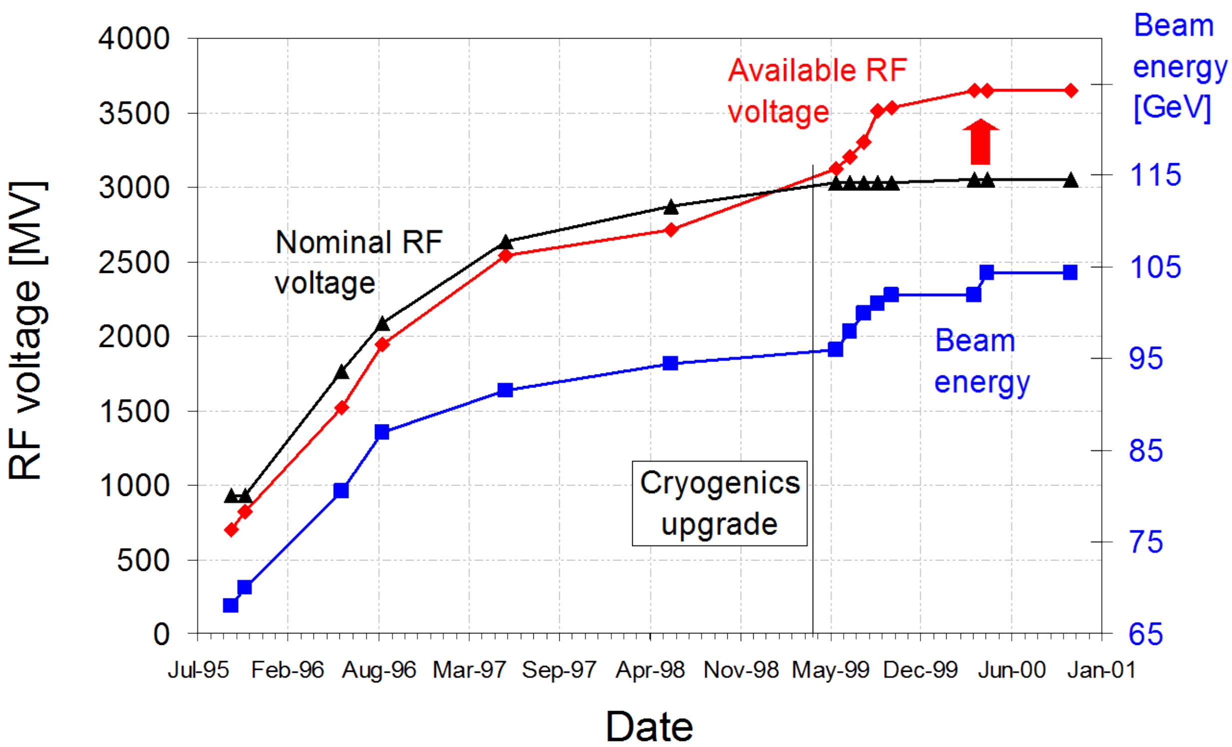


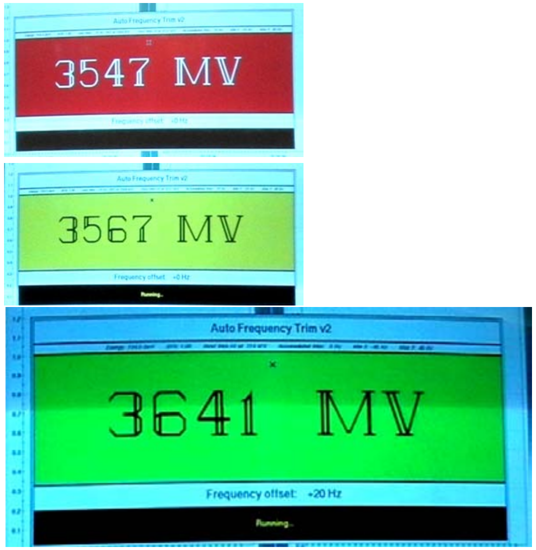
Unsociable sabotage: both bottles were empty!!

1996: Heineken Beam Stopper

UK advertising at the time:

Heineken; the beer that gets to places no other beer can!





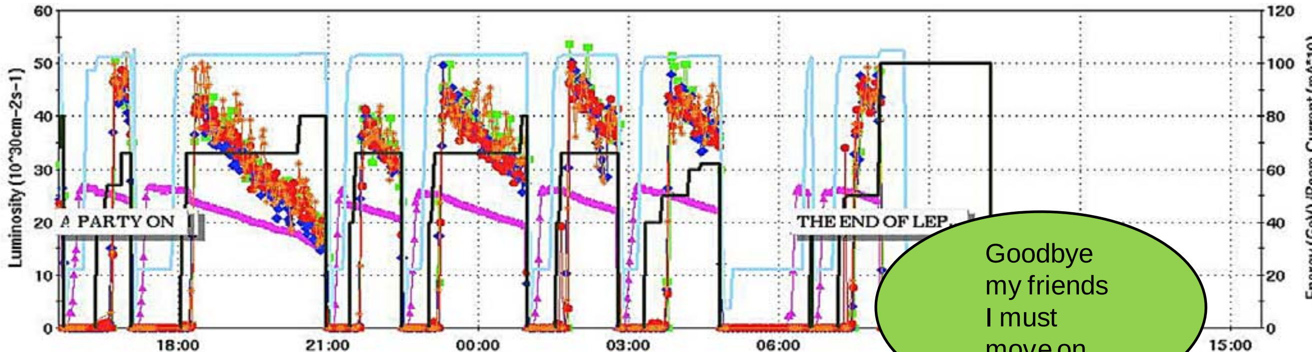
Beam energy (year)	Average accelerating field [MV/m]
96 GeV (1999)	6.1
100 GeV (1999)	6.9
104 GeV (2000)	7.5

Design:

6 MV/m

The last beam in LEP (2000); A sad occasion

I had to prepare the dismantling with my LEP colleagues AArrggHH!



In the photo:

- Roger Bailey,
- Ralph Assmann,
- Paul Collier,
- Mike Lamont,
- Steve Myers
- Andy Butterworth

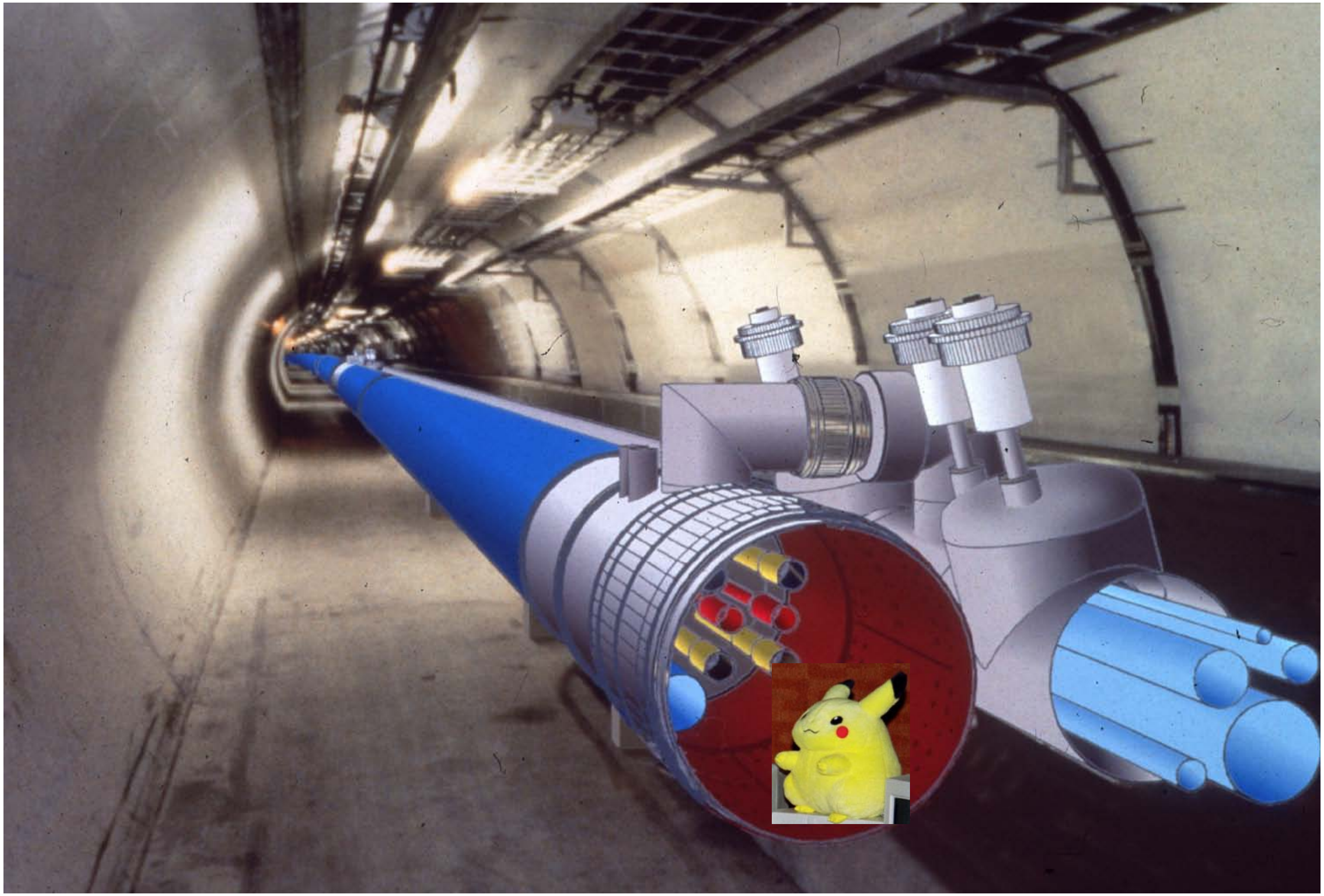
What is the Legacy of LEP?

The physics data (luminosity, energy, energy calibration).

The experience in running large accelerators.
- Technical requirements to control a large-scale facility.
- Operational procedures for high efficiency.
- Orbit optimization in long machines.
- Alignment, ground motion and emittance stability in deep tunnels.
- Designing and running a large SC RF system.
- Impedance and TMCI in long machines.
- Optics designs from 60/60 to 102/90 and 102/45.

Don’t screw up on the readiness of the beam instrumentation and the controls for the initial commissioning

And the tunnel



The Continuing Legacy of LEP in the LHC

LCC Mandate February 14, 2001

Use the experience and expertise gained in LEP to Prepare beam commissioning and operation of the LHC collider

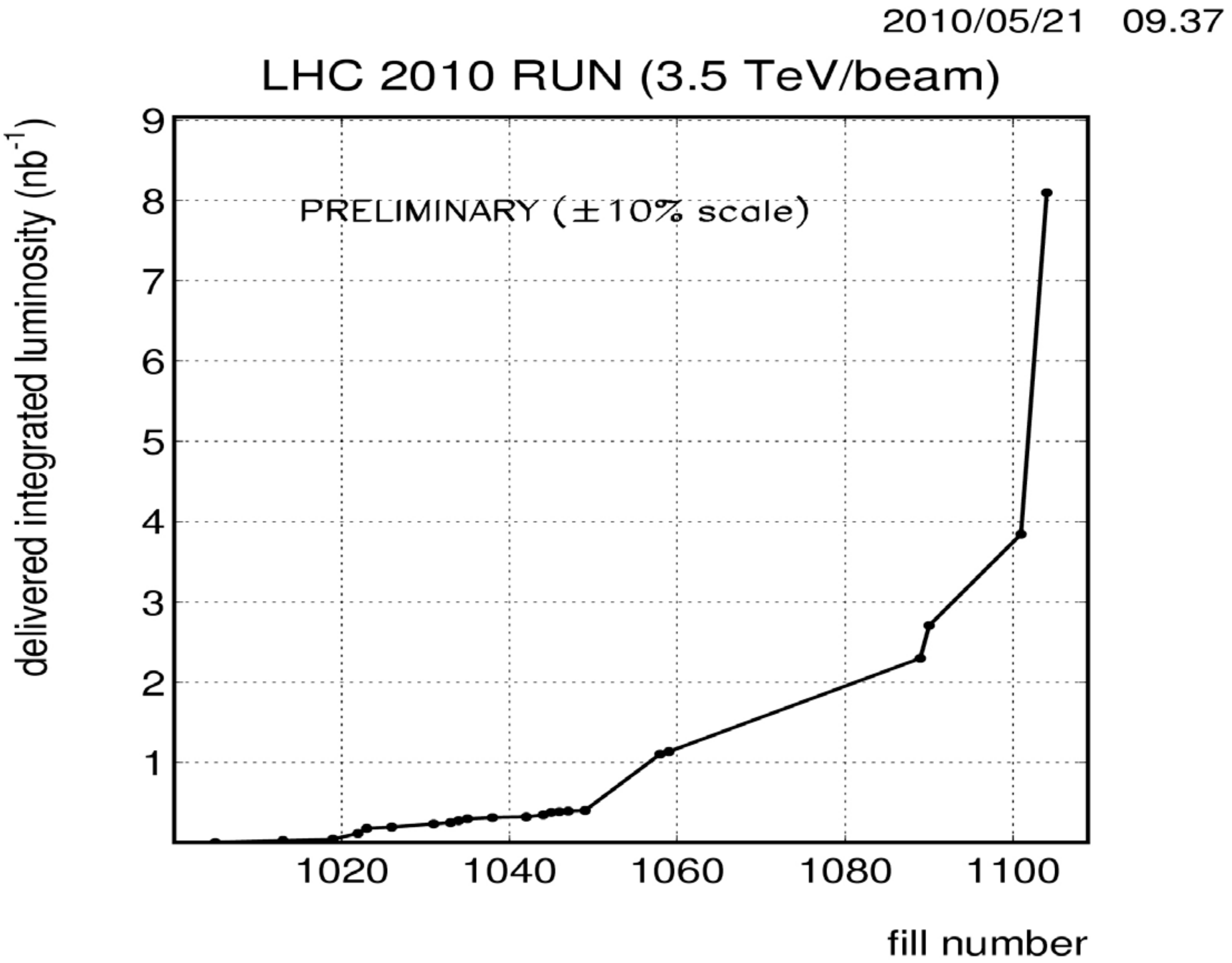
- Evaluate and maximise the performance of the injectors.
- Organise and evaluate experience with other relevant machines
- Prepare a detailed scenario and create a competent and appropriately experienced and trained team for initial commissioning.
- Examine and specify special software requirements pertaining to machine commissioning and operation.
- Plan and examine the results of MD experiments pertaining to the machine and its injectors
- Proposals of design changes to equipment groups on topics pertaining to commissioning, operation or performance of the machine.

LHC Commissioning Committee (LCC 1)

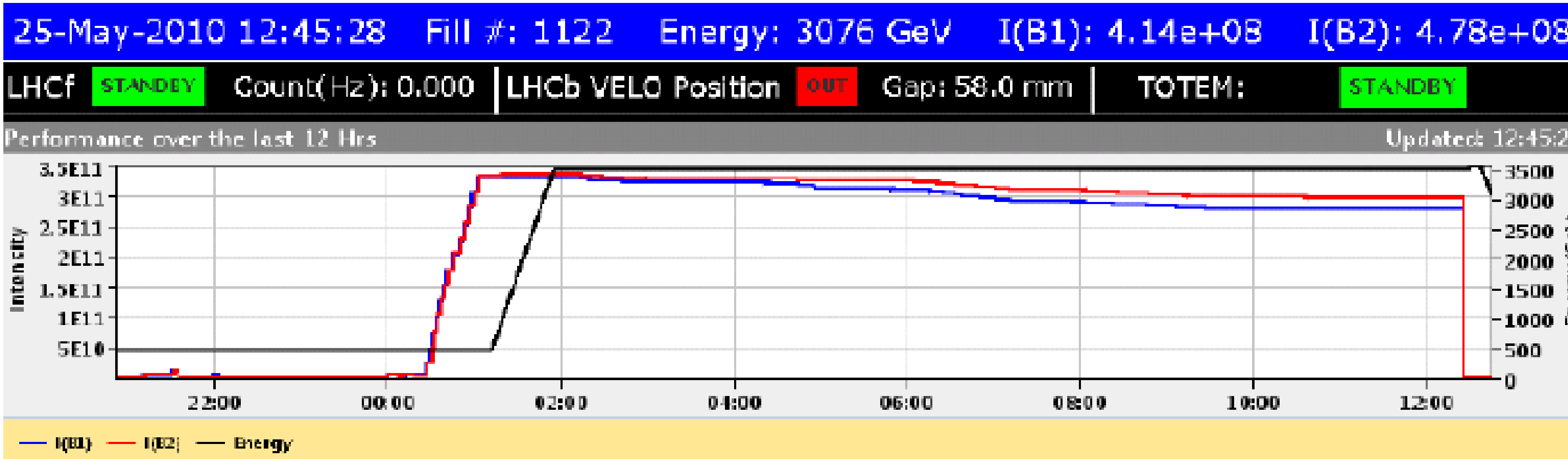
BAILEY Roger, CLAUDET Serge, CORNELIS Karl, FAUGERAS Paul, FERNQVIST Gunnar, JEANNERET Jean-Bernard, KOUTCHOUK Jean-Pierre, LAMONT Mike, LINNECAR Trevor, MERTENS Volker, MYERS Steve (Chair), POOLE John, PROUDLOCK Paul, ROY Ghislain, RUGGIERO Francesco, SABAN Roberto, SASSOWSKY Manfred, SCANDALE Walter, SCHMICKLER Hermann, SCHMIDT Rudiger, TSESMELIS Emmanuel, WENINGER Jorg

Present Status of the LHC Machine

Integrated Luminosity versus Time



Breaking news: Doubled luminosity with 13 bunches per beam



13 bunches of 2e10

Lumi = $1.5 \times 10^{29} cm^{-2} s^{-1}$

Four Decades of Colliders (From the ISR to LEP to the LHC)

I will briefly describe CERN's colliders starting with th ... ugh LEP,
and finishing with the LHC. The common threa ... ed in terms of
people and techniques. I will start by des ... ible impact on
accelerator physics of the almost fo ... hadron collider, the ISR. I
will then present the constructi ... of operation of LEP. Finally I will
also provide the latest r ... eration in the LHC as well as the plans
for the near and fa

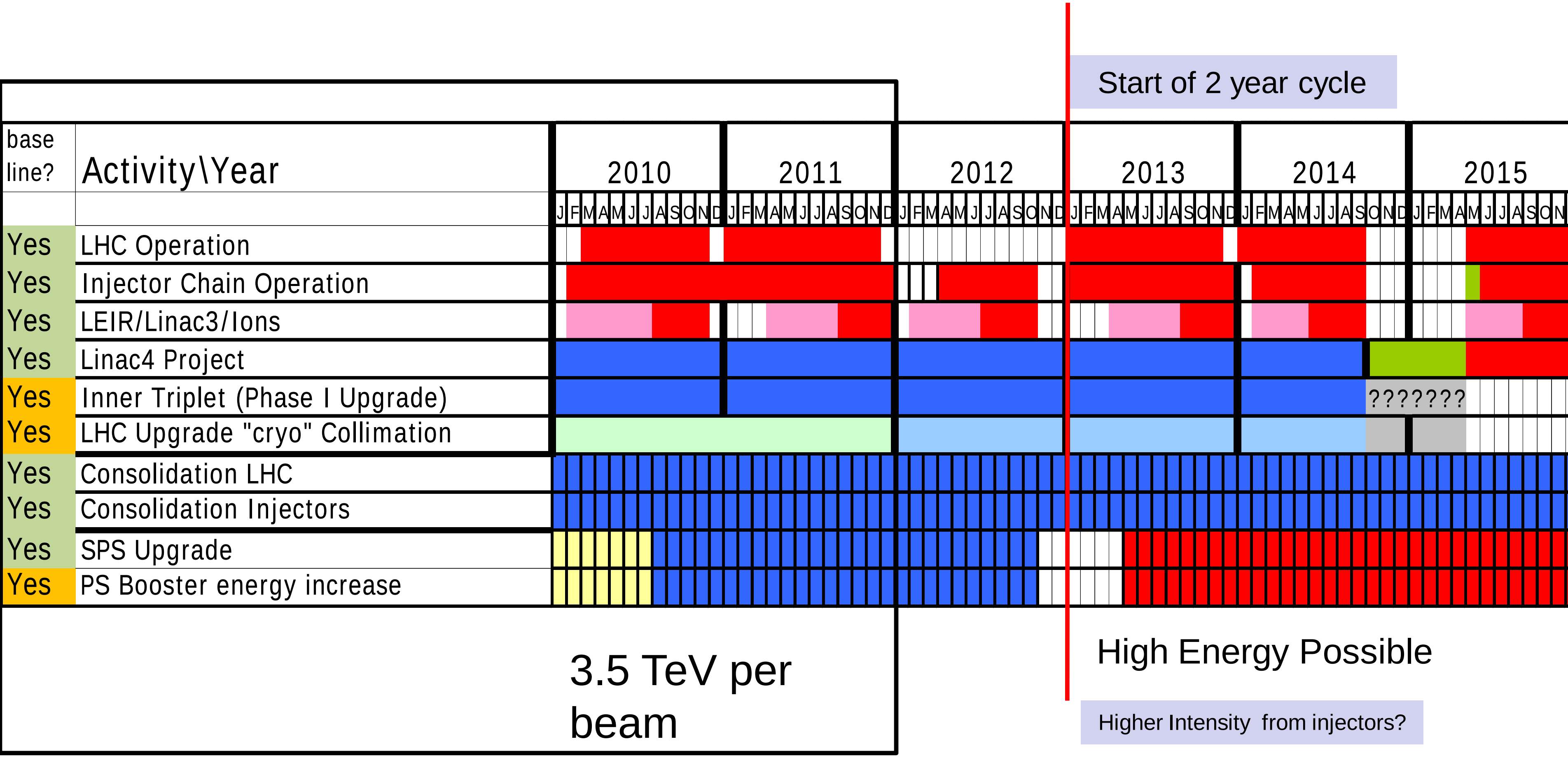
And… The next decades

IPAC10, Kyoto, Japan

27th May 2010

Steve Myers

Time lines



Long Term Plan has been prepared for LHC running until (at least) 2030

Luminosity Upgrade (~ 2020-2021)

Goal is 5-6x10^{34}cm^{-2}s^{-1}

- very low β values at the interaction point by the possible use of new sc NB3Sn quadrupoles
  R&D has started (US and CERN)
- crab cavities (Following the experience of KEKB) collaboration started (KEK-CERN)

Long luminosity lifetime

- by "levelling" i.e.optimization of the collision region parameters as a function of the decaying beam current during the course of the physics fill.
  - reducing the β*, the crossing angle, the bunch length, and the crab parameters

The present idea is that this upgrade in luminosity will be time synchronized with upgrades of the LHC detectors.

Energy Upgrade (Just started!)

The first set of parameters looks very interesting. New design approach needed

- synchrotron excitation and damping become significant.
- at 16.5Tev the damping time is ~ 1hour
- the equilibrium transverse emittance would become vanishingly small (but, intra beam scattering etc)
- luminosity levelling for free
- ? Beam-beam produce e+e- behaviour or pp
- Launched large scale computer simulations, taking into account all known effects in order to answer some of the previous questions.

First set of parameters indicate that we can have high luminosity without enormous stored beam energy

It is clear that such an upgrade is not for the immediate future but a reasonable aim is to be ready to install new machine by the end of the life of the present LHC sometime in 2030

All we need to do now is develop 20Tesla dipoles with good field quality!

And in parallel

1—3 TeV Linear Collider (Jean-Pierre Delahaye)

Conclusions

"Four decades" is a short time when you're having fun

The threads through colliders

1. The generations of dedicated people
2. Diagnostics, diagnostics, diagnostics
3. The *"§**&*# beam-beam effect

Thank you for listening