The Large Hadron Collider

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Topics discussed in this Lecture

Single particle effects:

- Dynamic aperture
- Intrabeam scattering
- The beam-beam interaction

Coherent effects:

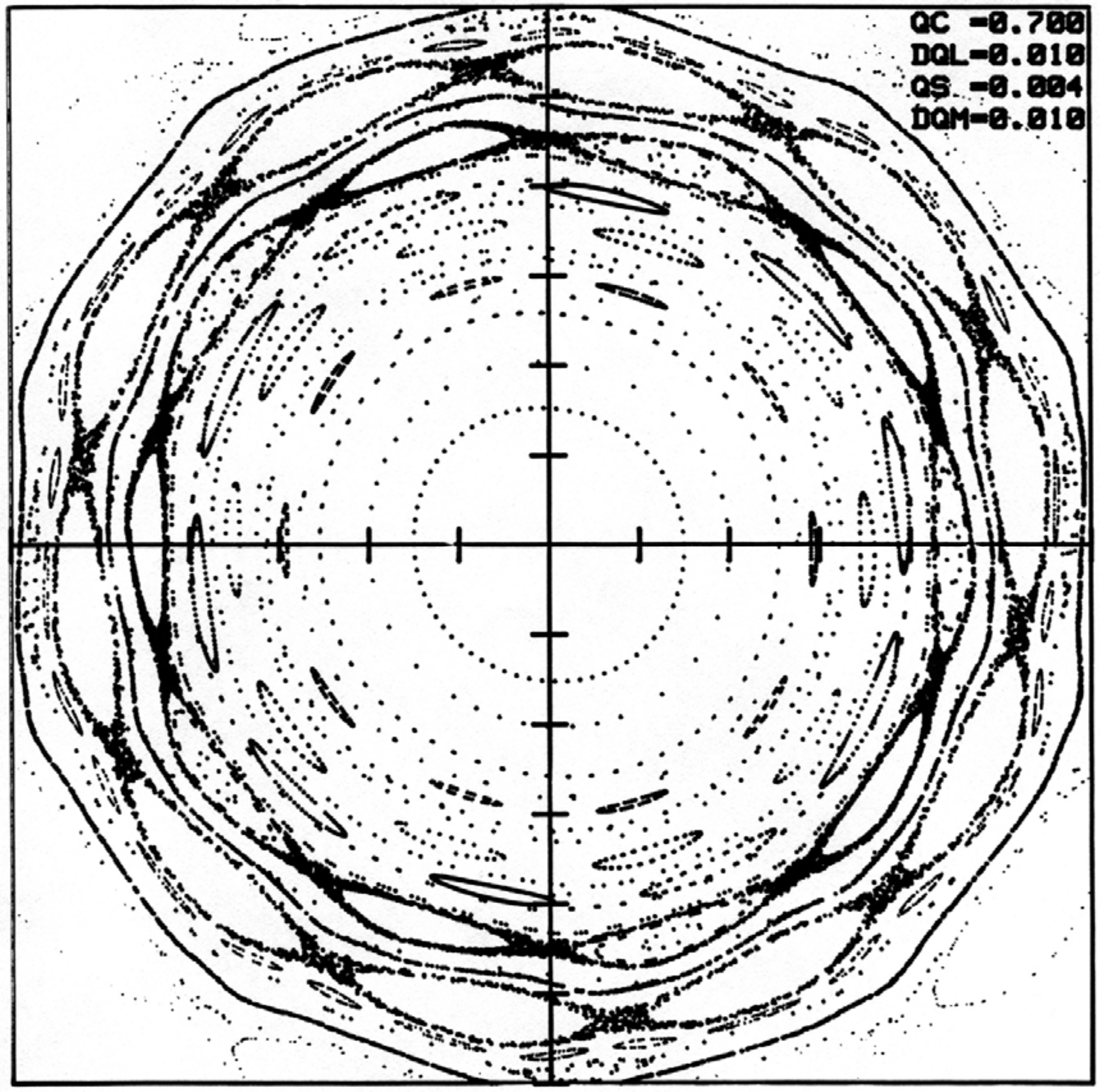
- Microwave instability
- Resistive wall
- Head-tail

Vacuum related

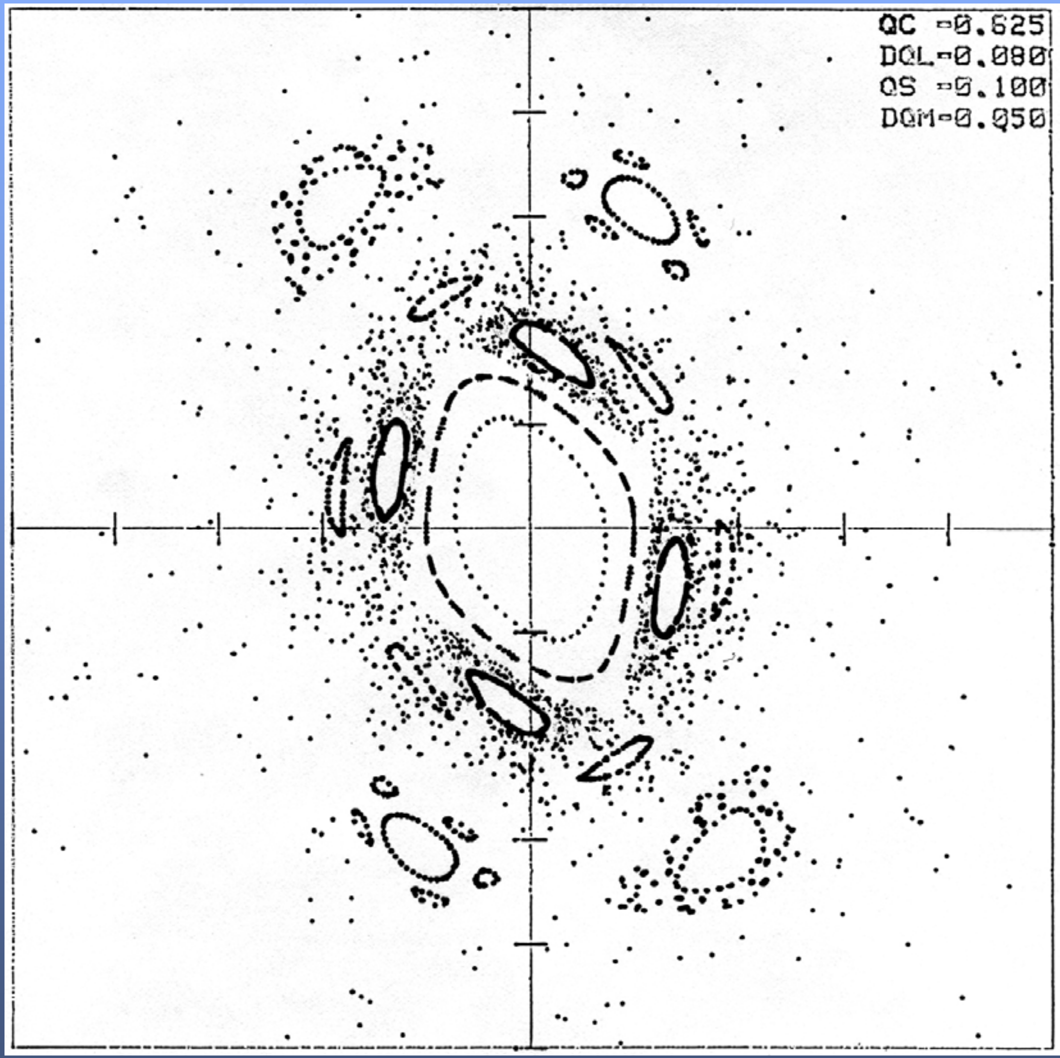
- Electron cloud

Dynamic Aperture

In superconducting magnets of the type used in the LHC, the field quality is determined by the precision of the positioning of the superconductor and not by the geometry of the iron yoke, so it can never be as good as in conventional magnets. It has been shown by experience in the different superconducting machines and by particle tracking that the aperture inside which particle orbits are stable is much smaller than the physical aperture of the beam pipe. This is called the dynamic aperture and is limited by a complex interplay between the unwanted higher field harmonics due to magnet imperfections. Sophisticated computer codes have been developed to track particle orbits around virtual machines with distributed random and systematic imperfections. And these results are used to define maximum systematic and random deviations of each field multipole.


QC =0.700
DQL=0.010
QS =0.004
DQM=0.010

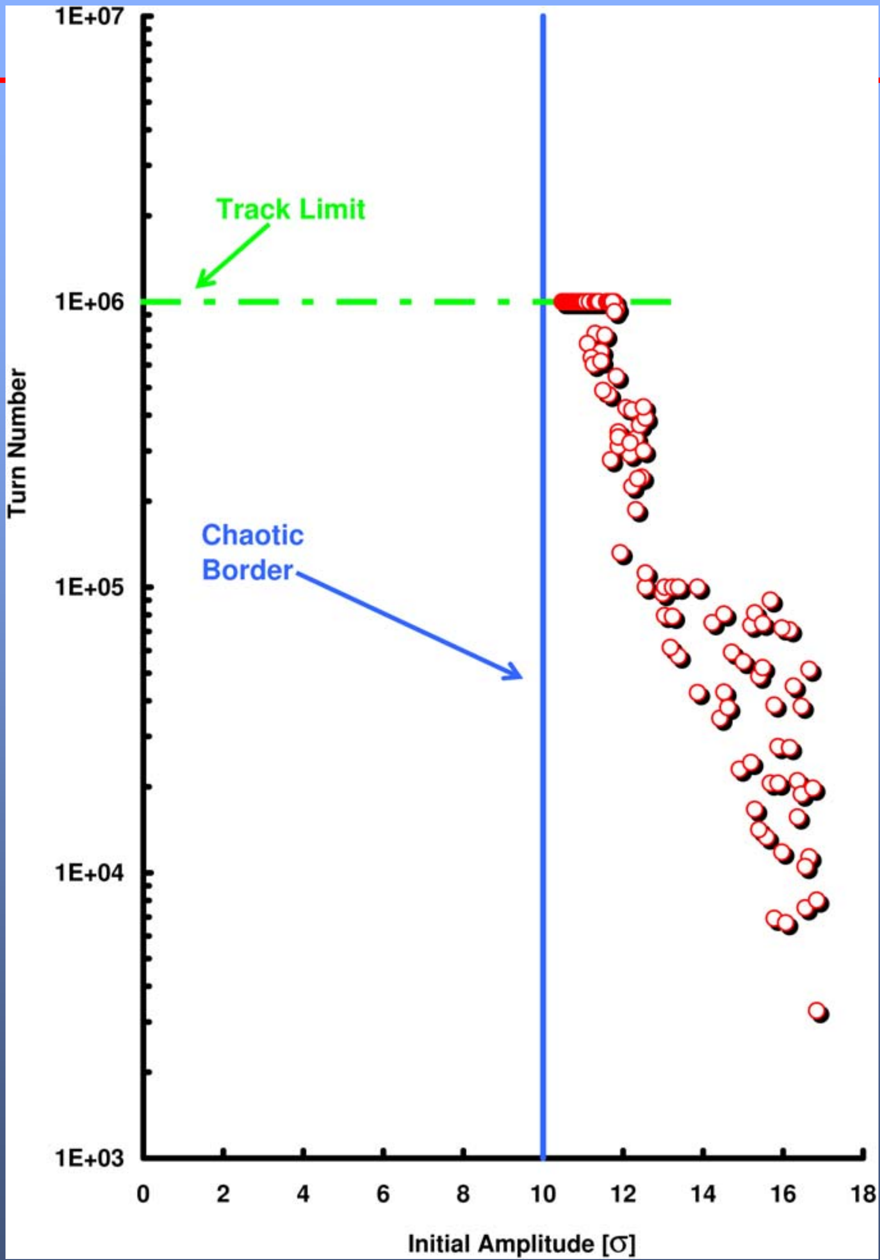
The Beam-Beam interaction



Dynamic Aperture

It was from this work that the control limits for the sextupole component of the dipole field were derived. Even with present day computers it is not possible to perform full scale simulation over a large number of virtual machines over 4x107 turns, which corresponds to 1 hour of storage time. The dynamic aperture obtained from tracking of existing machines is always too optimistic when compared to experiment by 20% or more. For the LHC, in order to insure a dynamic aperture of 6 sigms it has been decided that the tracked dynamic aperture over 106 turns should be a factor of 2 larger. These results have been used to supply the tables of allowed multipole errors to the magnet builders,

Since the dynamic aperture depends strongly on the horizontal and vertical tunes, the tracking studies are also used to find the best working points.



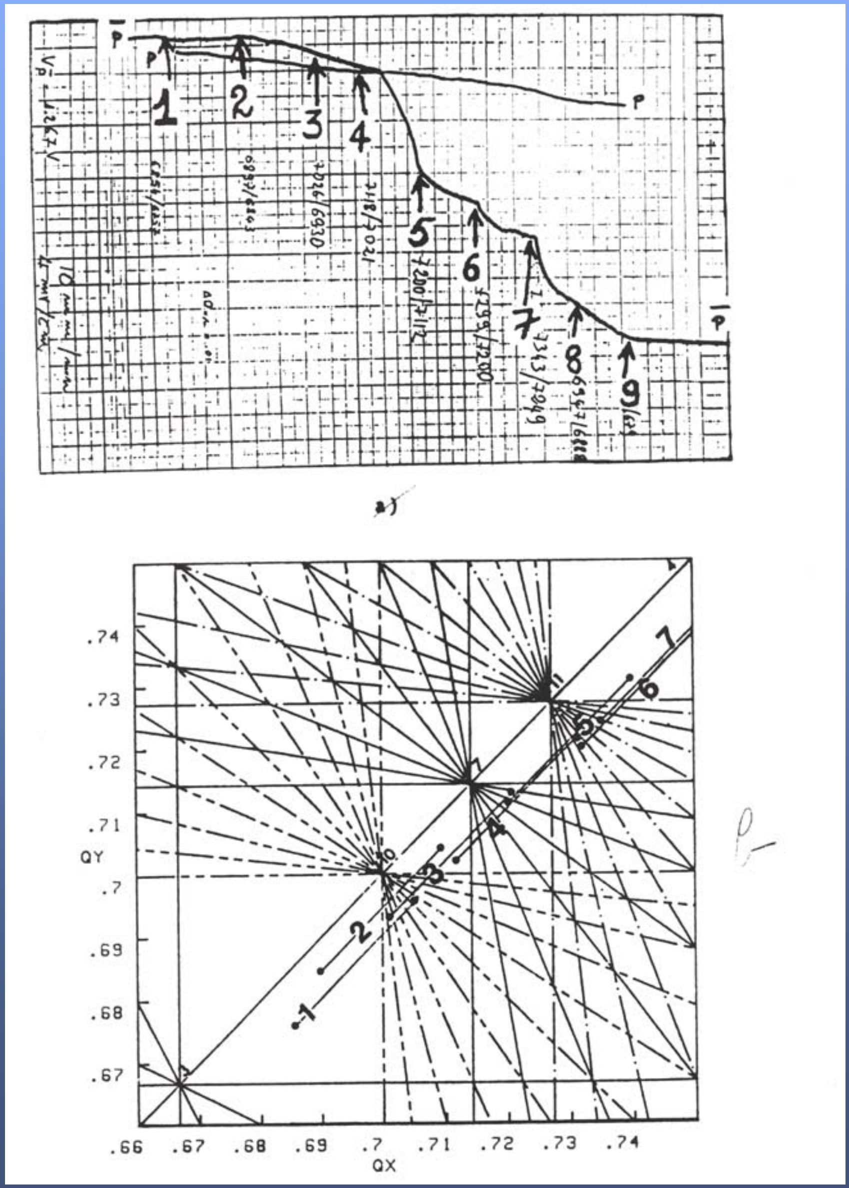
1E+07
1E+06
1E+05
1E+04
1E+03
Turn Number
Track Limit
Chaotic
Border
0
2
4
6
8
10
12
14
16
18
Initial Amplitude [σ]

Beam-Beam Interaction

When the beams are brought into collision, a much stronger nonlinearity than the magnet imperfections comes into play. It is called the beam-beam interaction and is caused by the force due to the electromagnetic field of one beam on the particles in the other beam. It produces two main effects.

The first is to cause a variation of the tune with amplitude. This means that the beam does not occupy a point on the Qh, Qv tune diagram but produces an extended “footprint” The second effect is that because of the periodic nature of the force (particles experience a delta function kick on each revolution) it excites nonlinear resonances which can strongly limit the beam lifetime.

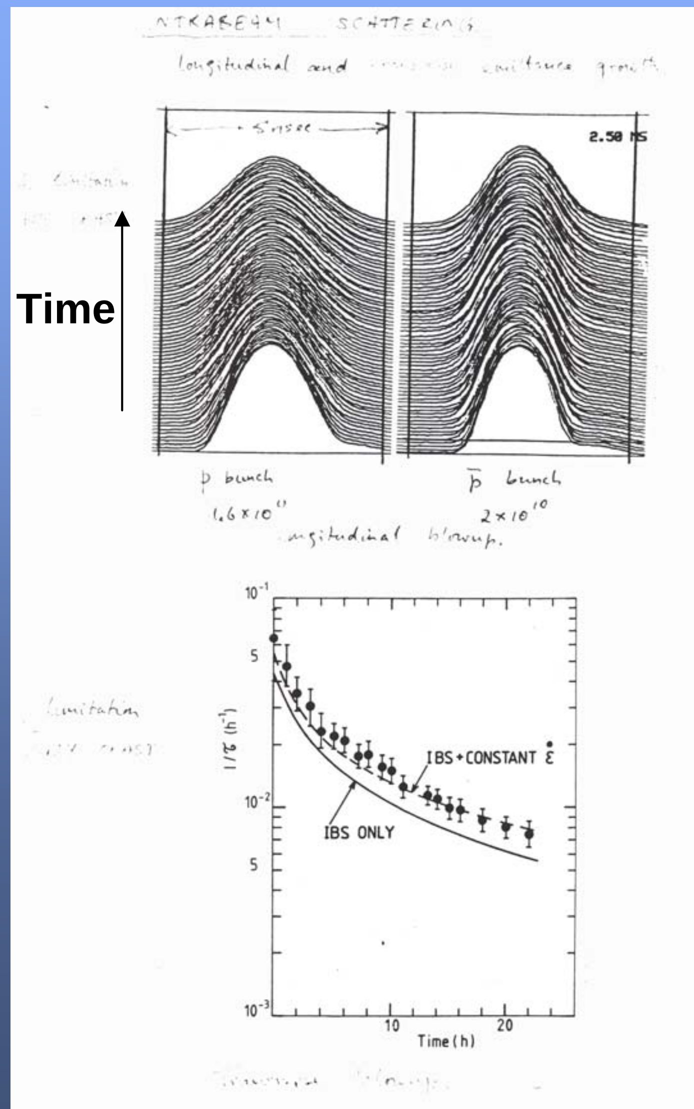
A beam-beam resonance scan at the SPS collider



Intrabeam Scattering

As particles perform their betatron and synchrotron oscillations, they exchange energy due to multiple Coulomb scattering. The correct frame of reference to understand the phenomenon is the rest frame of the beam. The transverse rms momenta σ'x,y are unchanged by this transformation whereas the longitudinal momentum σp is transformed into σp/g. In a highly relativistic beam like the LHC, the longitudinal plane is therefore very "cold" compared with the transverse planes and one would expect a damping of the transverse dimensions and an increase in the energy spread, which would be good for luminosity preservation. This indeed does occur in the vertical plane although the damping time is very long. Unfortunately, in the regions where the dispersion is not zero (most of the machine), a particle changes its energy by Coulomb scattering but does not change its position and therefore finds itself on the wrong orbit for its momentum. It can only make a betatron oscillation around its new equilibrium orbit, adding a heating term that completely swamps the slow damping in the radial plane.

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.

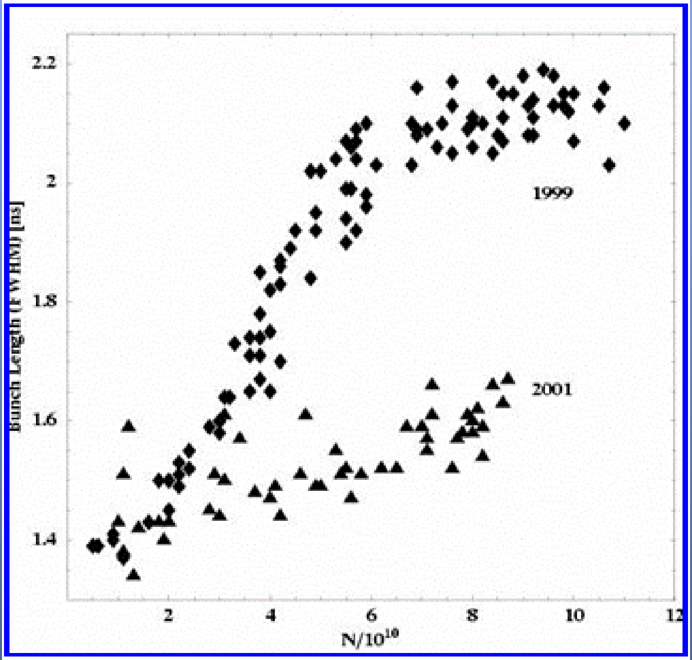


Coherent Instabilities

- The interaction of the beam with its environment can generate electromagnetic fields which react back on it and drive it unstable. The first remedial action is to design the vacuum chamber to reduce this coupling as much as possible.
- Coherent instabilities can be either longitudinal, driven by parasitic cavity-like objects or transverse, driven by deflecting modes in cavities or by the vacuum chamber itself.
- The first instability discussed is the longitudinal microwave instability in the LHC injector, the SPS, where a lot of work was needed to provide the beam for the LHC.

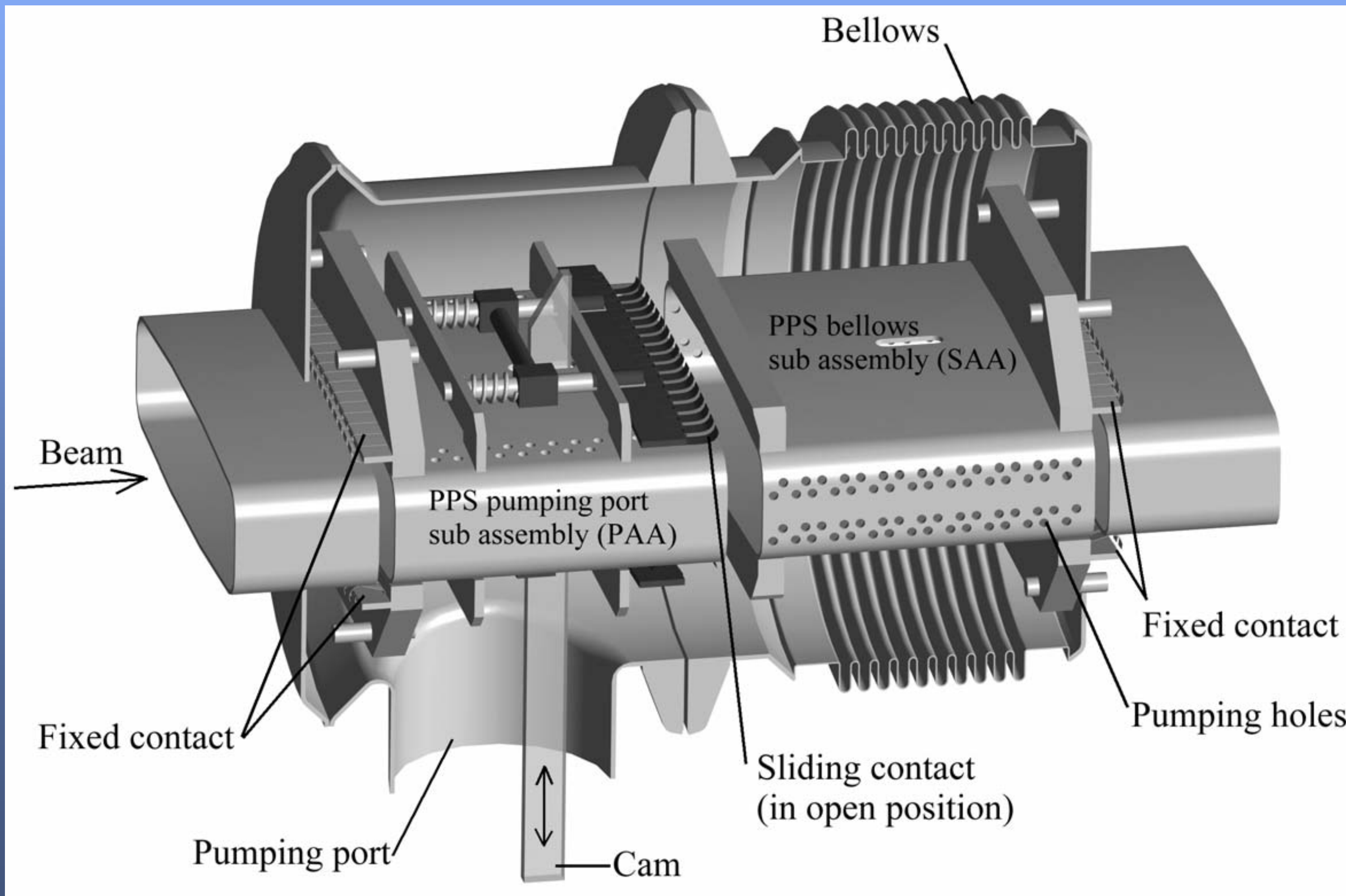
Anomalous bunch lengthening in the SPS

No emittance blow-up due to the microwave instability after the impedance reduction. A factor 7 difference in slope.

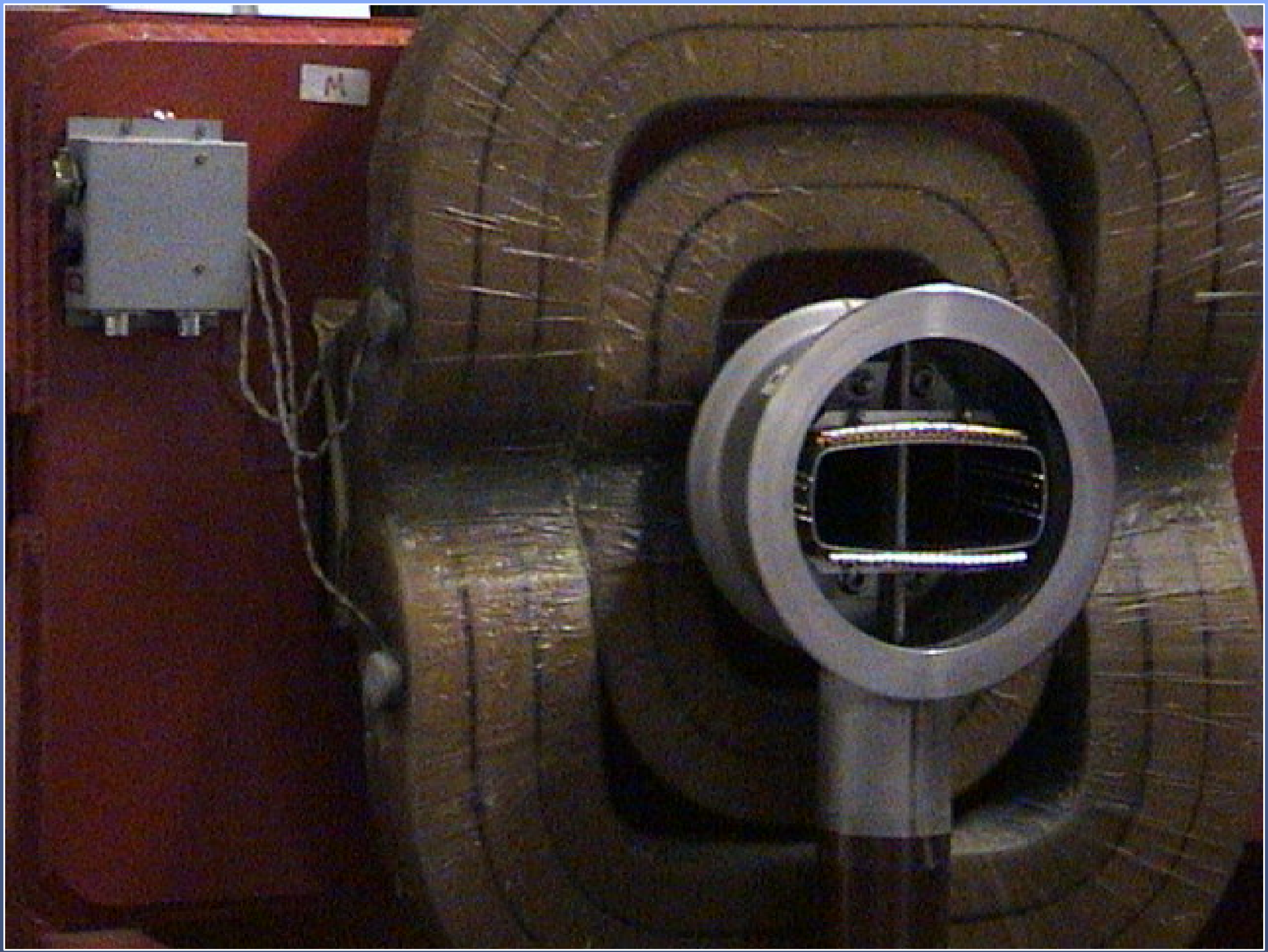


The bunch length is measured 600 ms after injection into SPS at 26 GeV/c, V=900 kV, bunch emittance 0.15 eVs

Pumping port shielding between 800 SPS dipoles

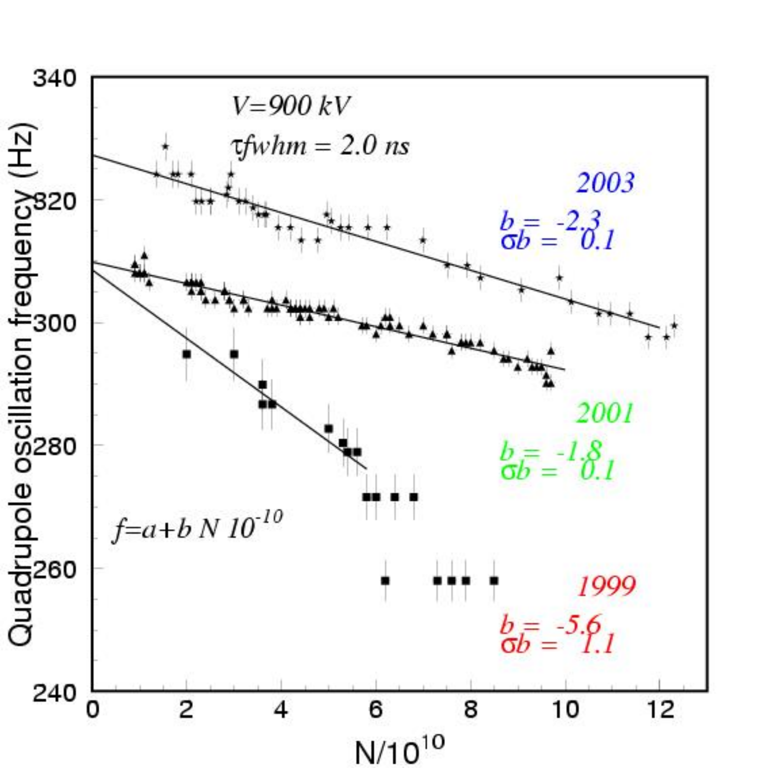


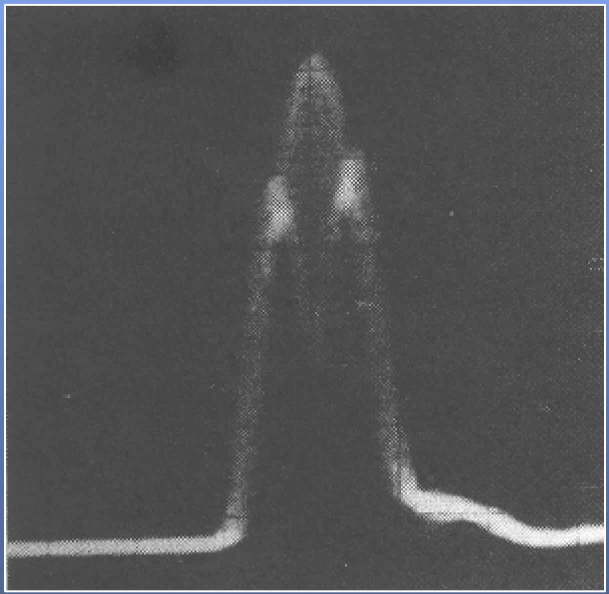
A moveable RF contact in the pumping port



Quadrupole mode frequency shift

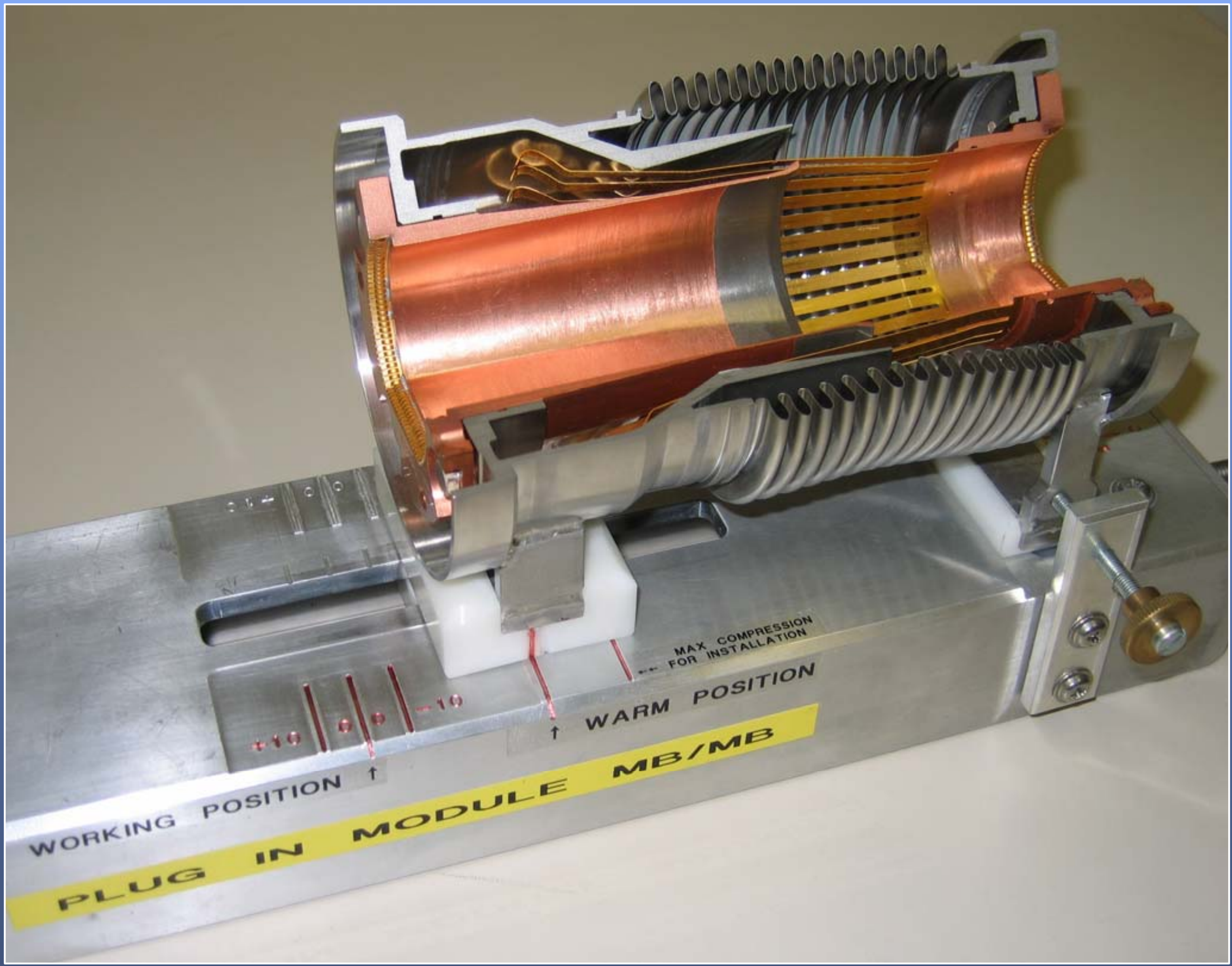
The change of quadrupole frequency shift (factor 2.5 from 1999 to 2001) agrees with that expected from impedance budget for Im{Z}/n (12 Ohms and 5 Ohms).





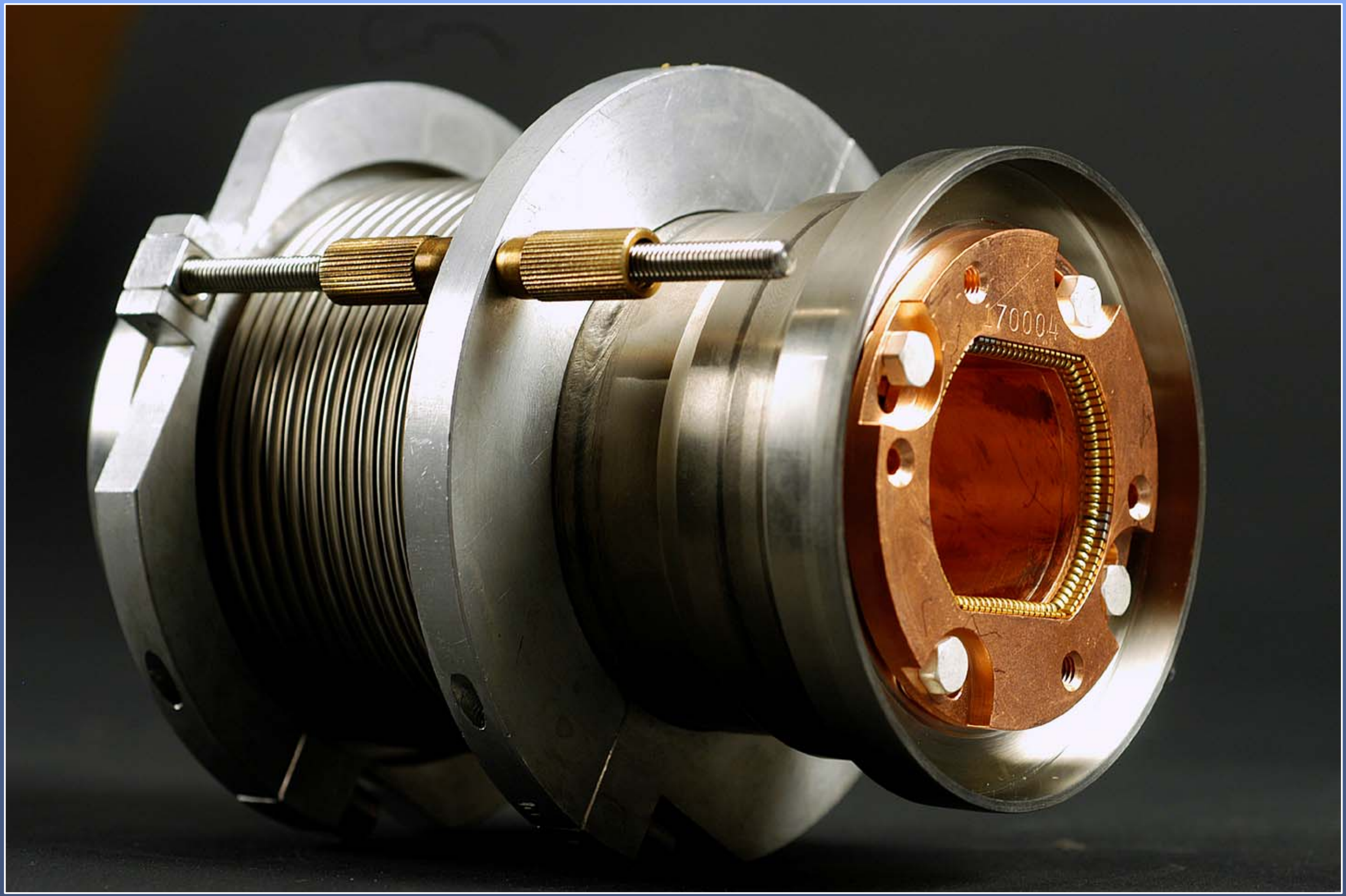
In 2003 the impedance increased slightly with the addition of new kickers

Arc plug-in module at warm temperature



Arc plug-in module at working temperature

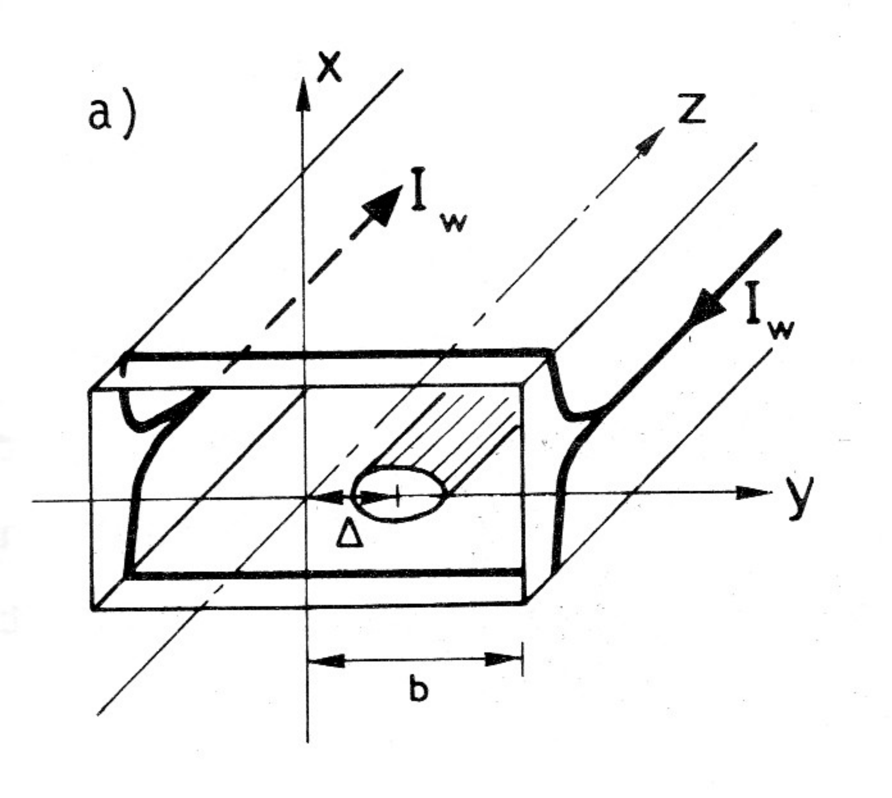
Module with installation compression tooling

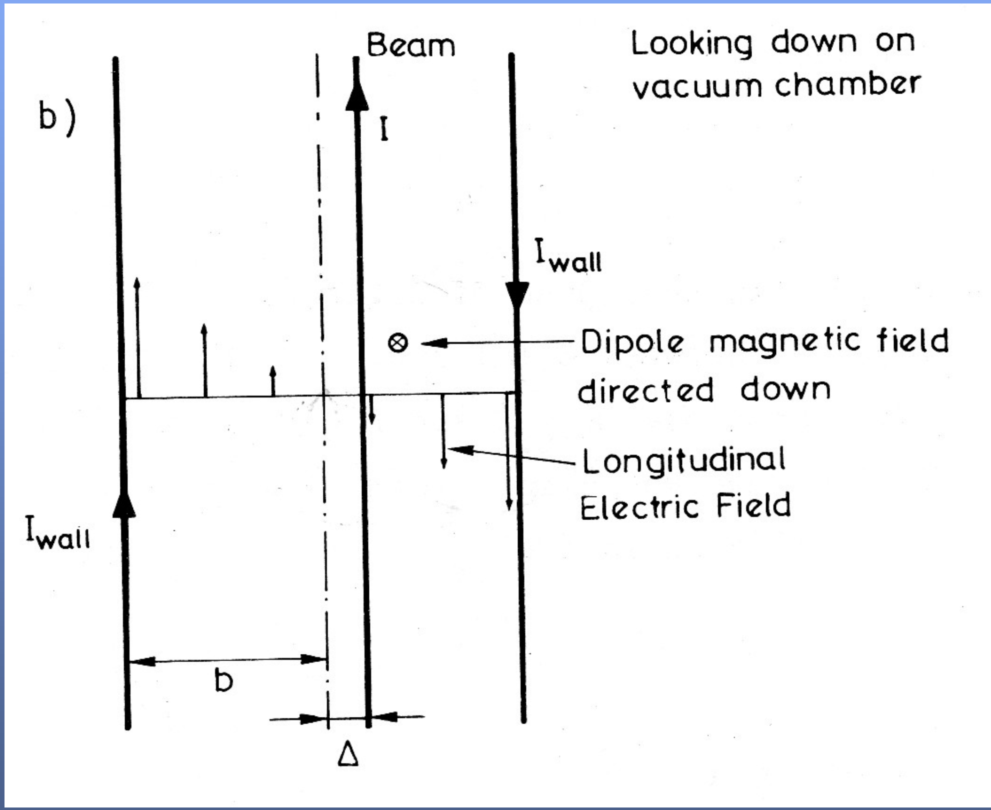


Instabilities in the LHC

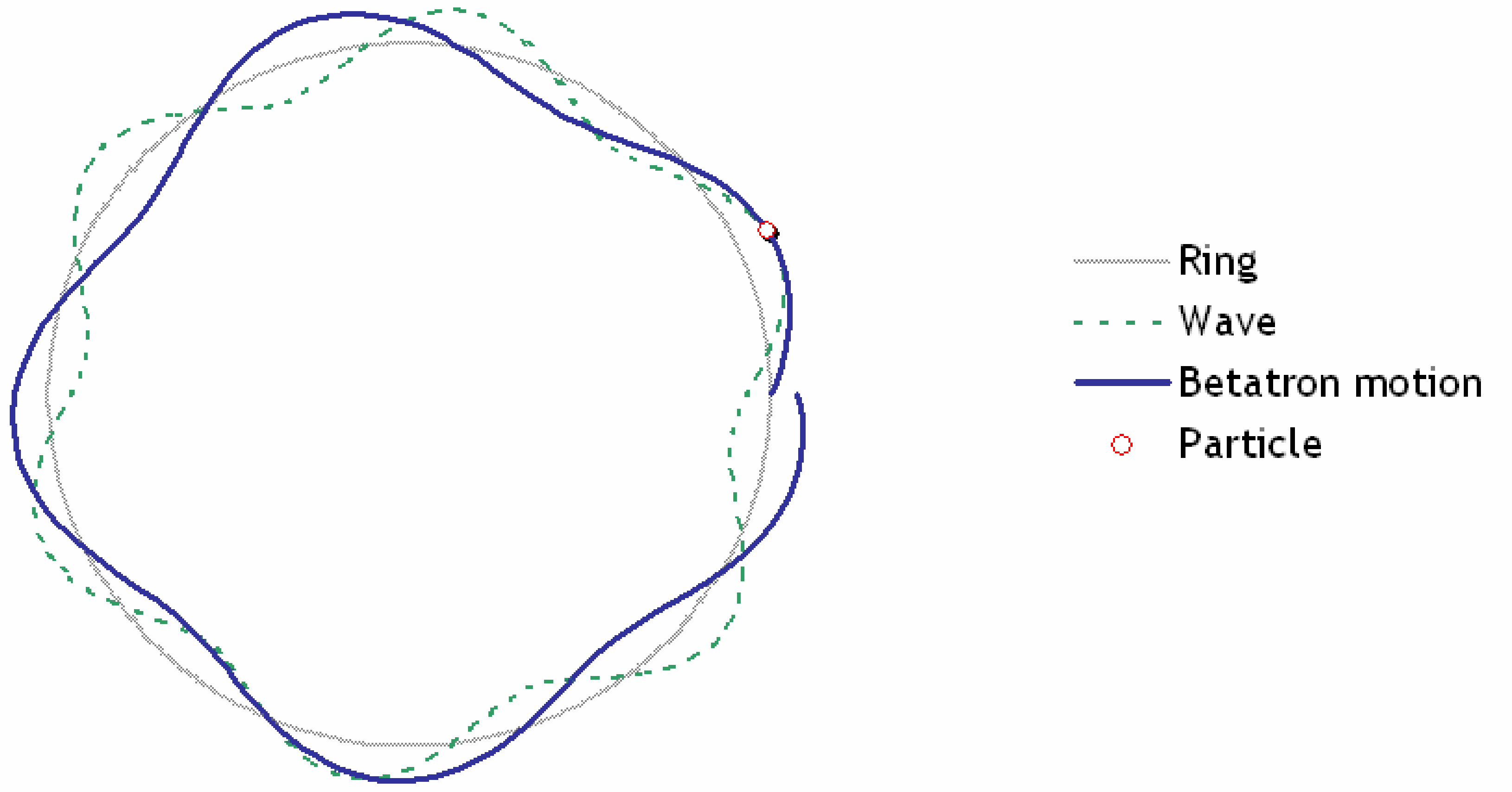
- The LHC has been designed to avoid instabilities of the type observed in the SPS. However, one cannot avoid the chamber wall which can drive the beam unstable as well as other equipment such as collimators, which are in close proximity to the beam.
- The first instability to be damped is the transverse resistive wall instability.

Instability driven by the chamber wall





The Slow Wave



The Unstable Modes

- The waves that can remain synchronous with the beam have frequencies

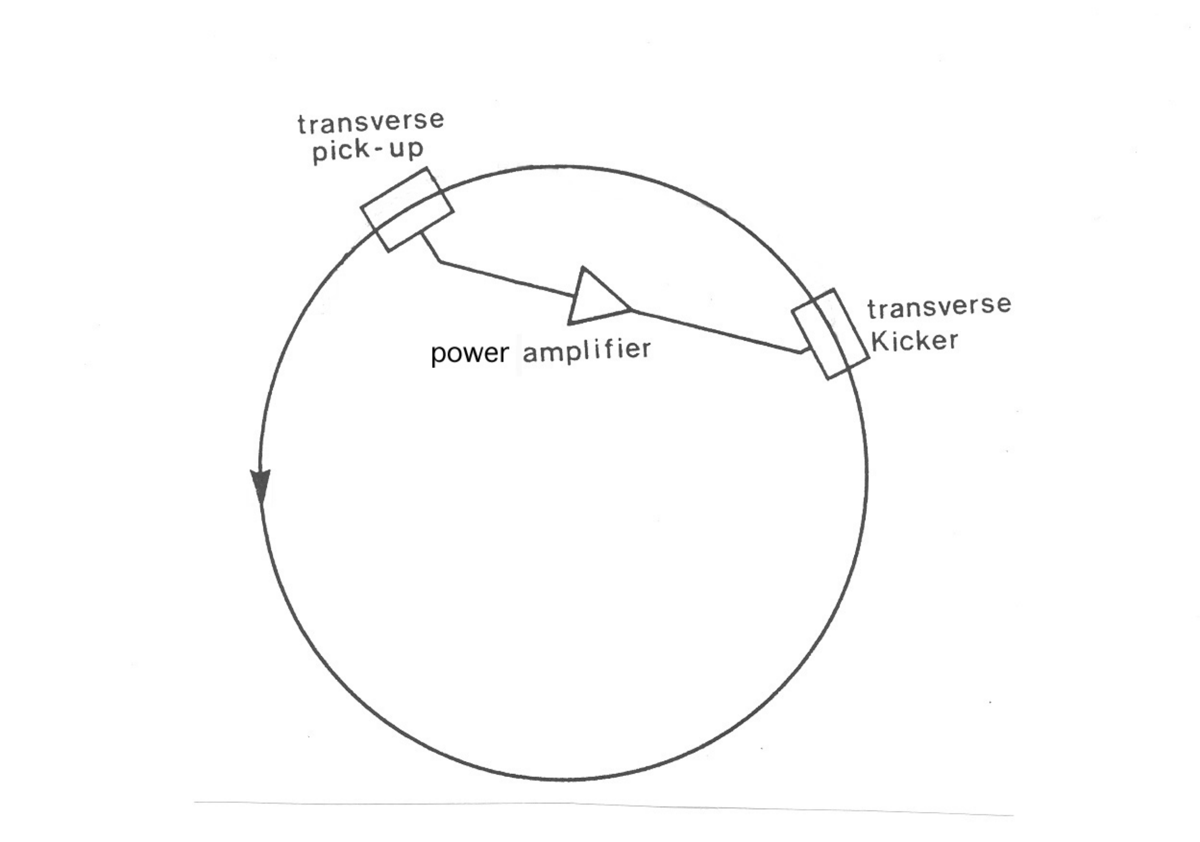
  $$f_n = (n \pm Q)\, f_r$$

  where *n* is the mode number and *fr* is the revolution frequency (11 kHz)

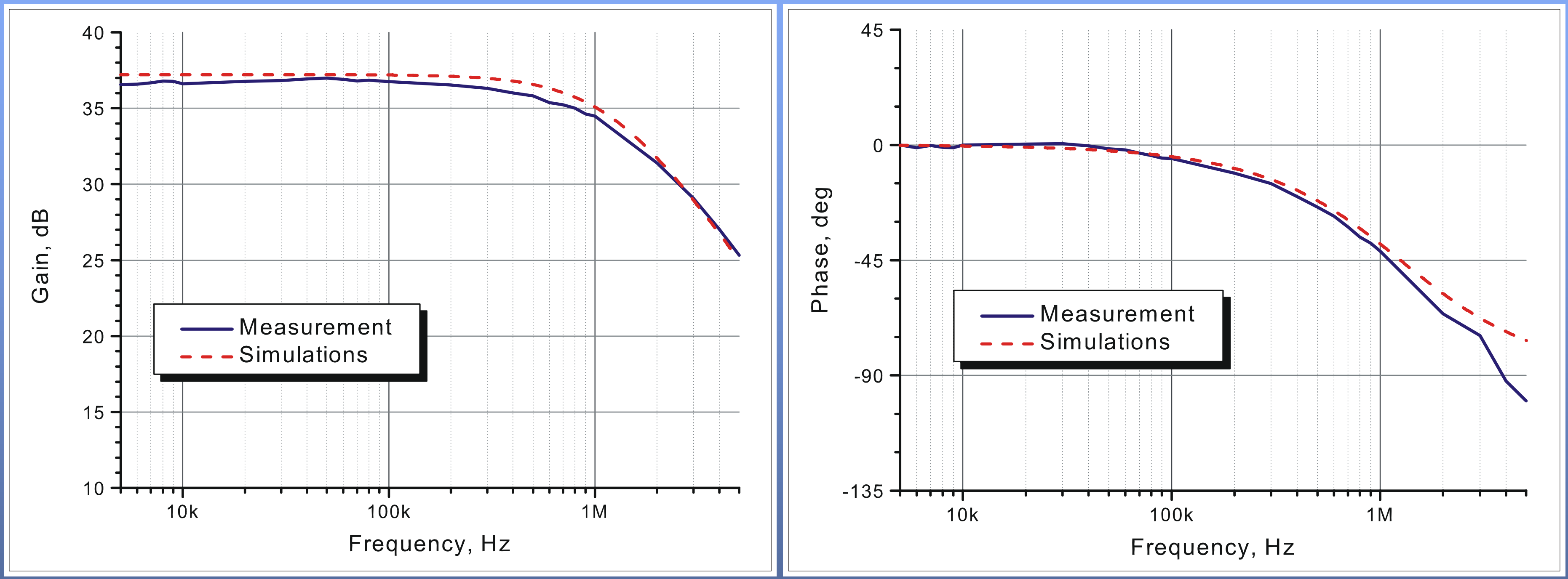
  Only the slow waves ((n-Q) with n>Q) are unstable. The fast (n + Q) waves are damped as well as those with n < Q.

  The risetime of the first unstable mode (n = 60, Q = 59.3) at 8 kHz Is about 30ms (300 turns). Between 8 kHz and 20 MHz, the 2000 or so unstable modes are damped by active feedback.

Transverse Feedback with One-Turn Delay



Damper response



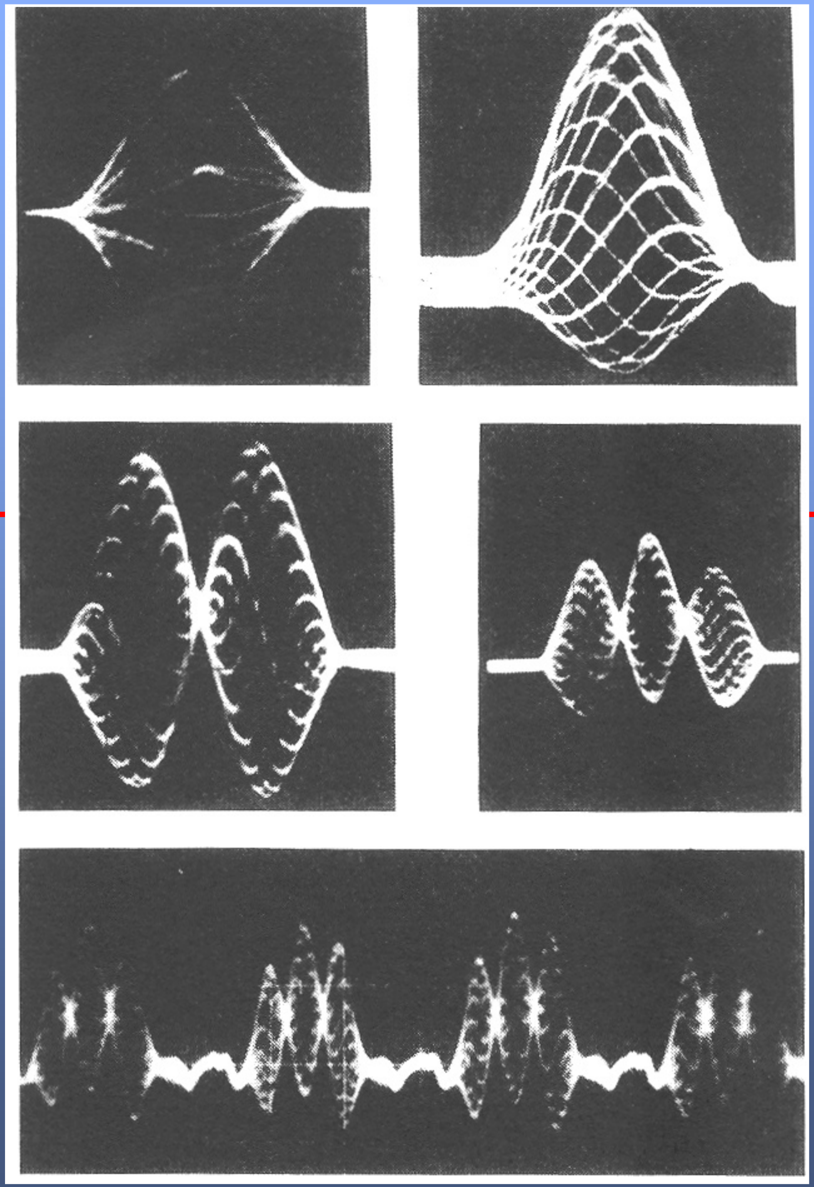
±7.5 kV was obtained as per specification to >1MHz for injection damping. Small signal gain is obtained to 20MHz for instability control.

Head-Tail Instability

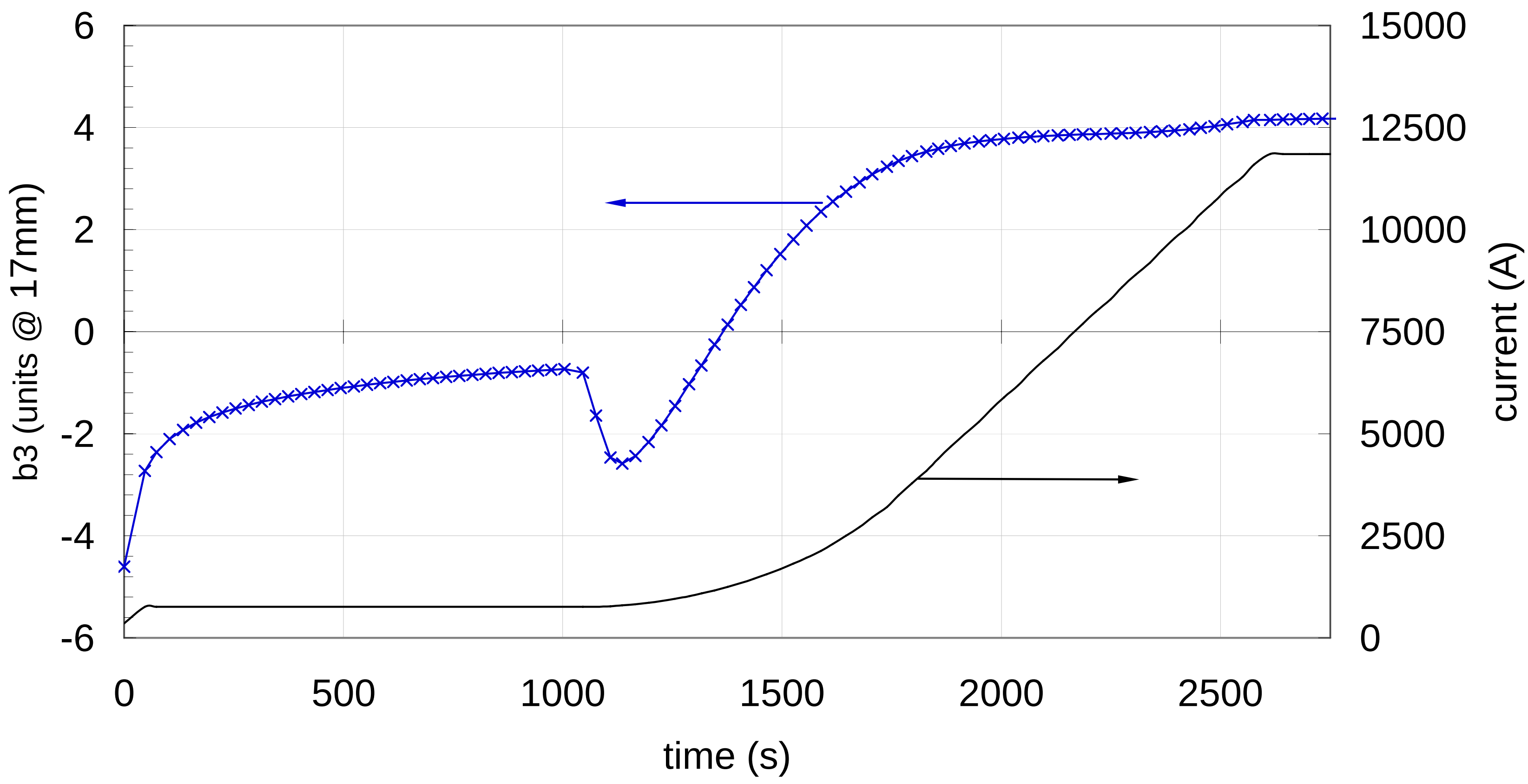
The head-tail instability, first observed in Adone in 1969, is driven by the interaction of a single bunch with its environment in the presence of synchrotron oscillations.

The lowest head-tail made is stabilised by reversing the sign of the natural chromaticity. Higher head-tail modes can be unstable for positive chromaticity but can be easily controlled by Landau damping.

The first 3 head-tail modes observed in the PS Booster



Sextupole component in main dipole during ramp

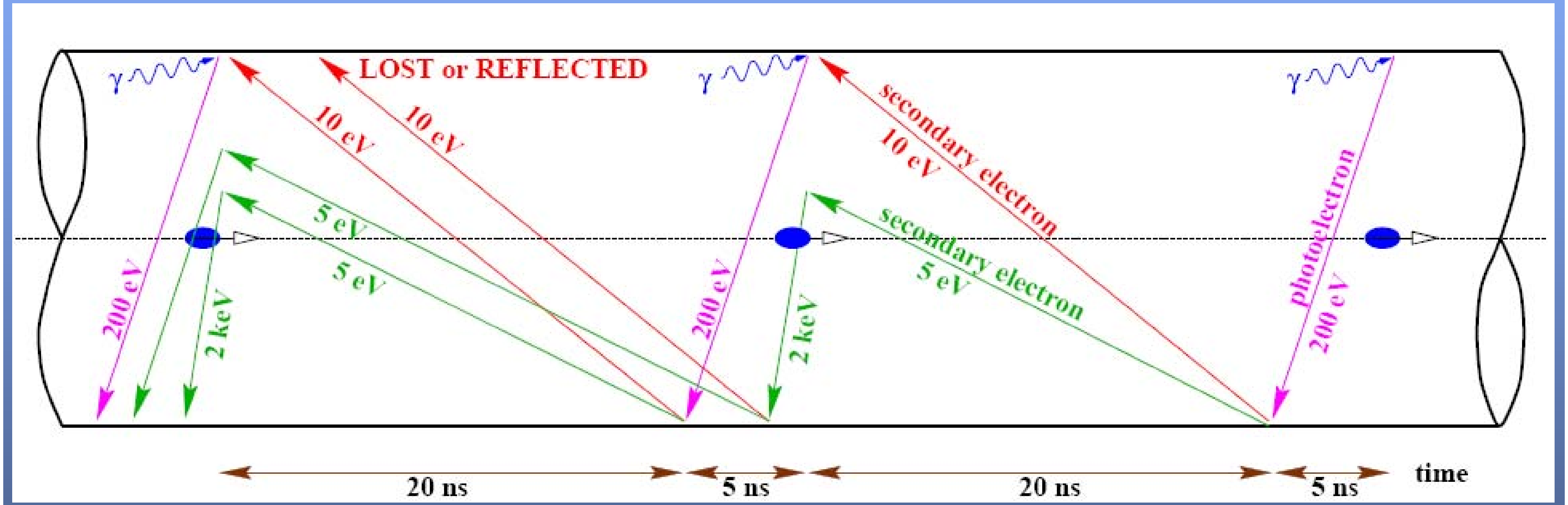


Landau Damping

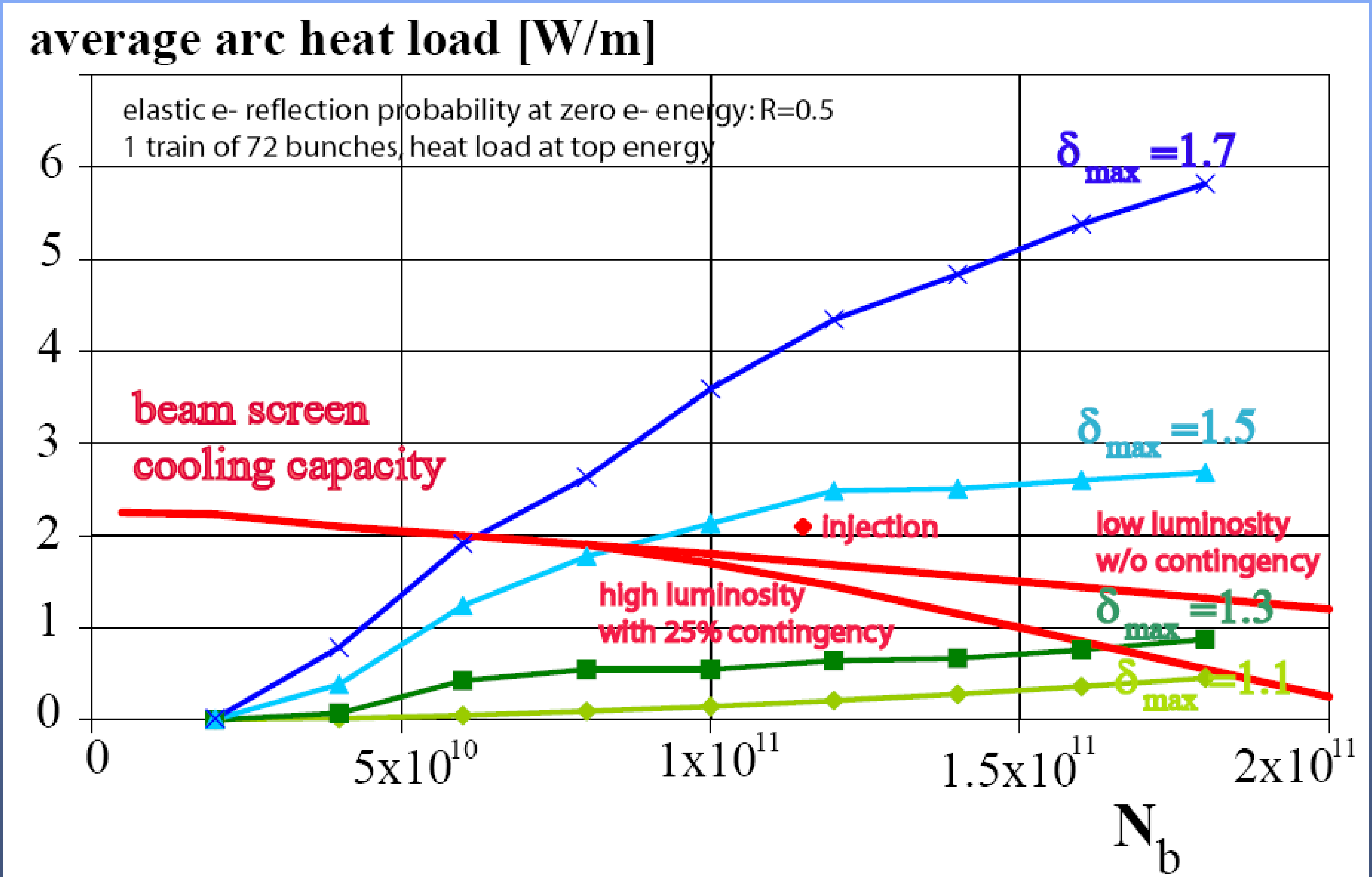
The LHC lattice contains two families, each of 84 octupoles. This produces an amplitude-dependent tune spread that will stabilise the beam at 7 TeV without transverse feedback.

During collision, the beam-beam effect will also produce a strong non linearity which will help to stabilise the beams.

The electron cloud effect



Simulated heat load as a function of SEY



Conclusions

- The LHC design has integrated more than 30 years of accumulated knowledge of the behaviour of beams in hadron storage rings. The various correction systems will be adequate to stabilise the beams up to and beyond design luminosity.
- The one new effect is the electron cloud which may be the limiting factor in pushing the luminosity well above the design value. This will depend on the efficiency of scrubbing that can be achieved.
- And, of course, there can always be surprises…