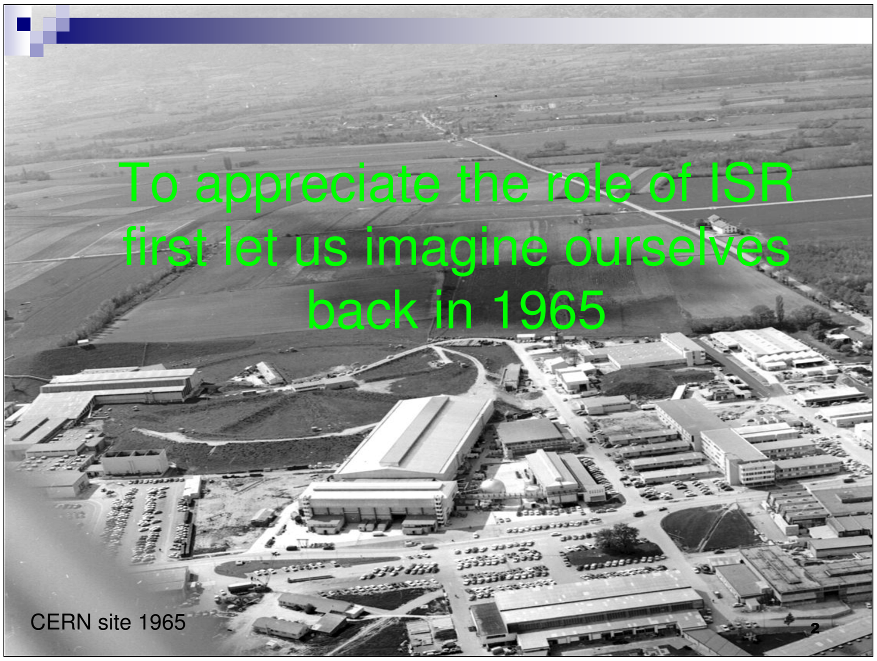
The Impact of the ISR on Accelerator Physics

P.J. Bryant

CERN, January 2011

1

Please read notes to explain and link slides.



To appreciate the role of ISR first let us imagine ourselves back in 1965.

1. Our team is highly experienced by 1960 standards. After all, it has just built the CERN PS.

2. The legacy of weak focusing machines is everywhere, but our team is well connected to the other laboratories in Europe and the US and in touch with all new ideas.

3. The community however is split between building a bigger PS and building the ISR, which explains a certain prudence in the air. After all, a failure would hold back funding for High Energy Physics for decades.

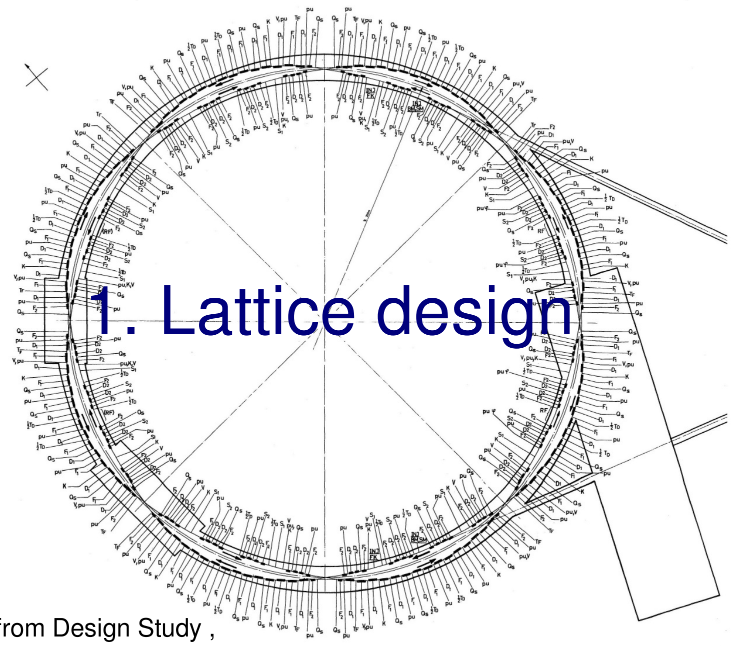
4. We now know that our team was standing at the start of rapid advance in accelerator technology, diagnostics and experimental physics – a veritable "explosion" that will change our understanding of accelerator physics from what appears now as "old fashioned" to something that looks very much as it looks today.

My aim is to :

• Illustrate that rapid expansion that was mainly concentrated in the years 1965 to 1977 and

• To underline the role of ISR in that rapid expansion.

1. Lattice design

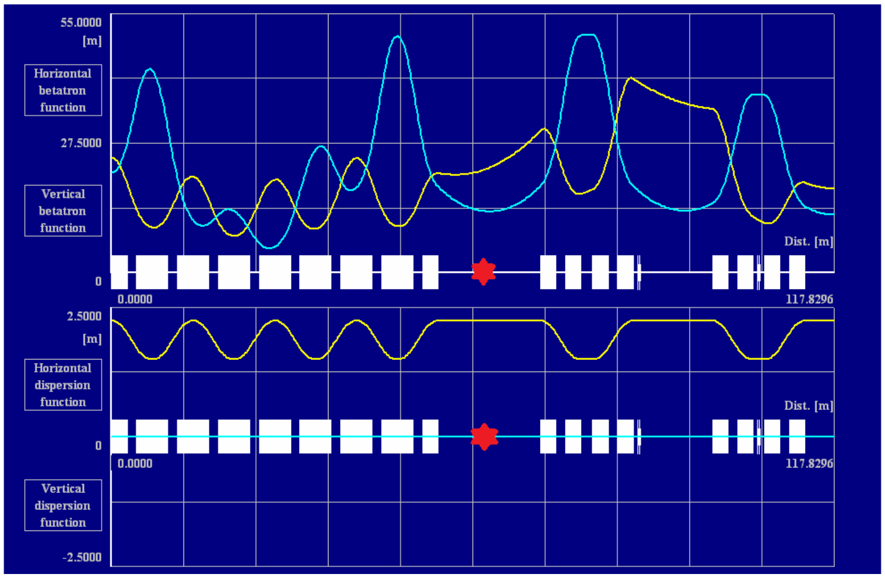


ISR layout from Design Study ,
CERN AR/Int. SG/64-9, (May 1964)

3

I start with **lattice design** because this is one of the more visual examples.

1.1 ISR lattice functions 1965



4

The original ISR lattice functions 1965 from the centre of an outer arc to the centre of an inner arc.

1. Note that the betatron amplitude functions are very rounded. This is due to the spread-out gradients in the combined-function magnets.

2. Note also there are no dispersion-free regions.

3. The lattice has been ‘manipulated’ globally to fit the interlaced geometry, to provide space for physics in the interaction regions.

4. The “split-F” structure provides local betatron minima at the crossing points, although these are not as low as would have been liked.

5. There is no LOCAL customisation of the lattice for specific tasks.

1.2 SCISR proposal 1977

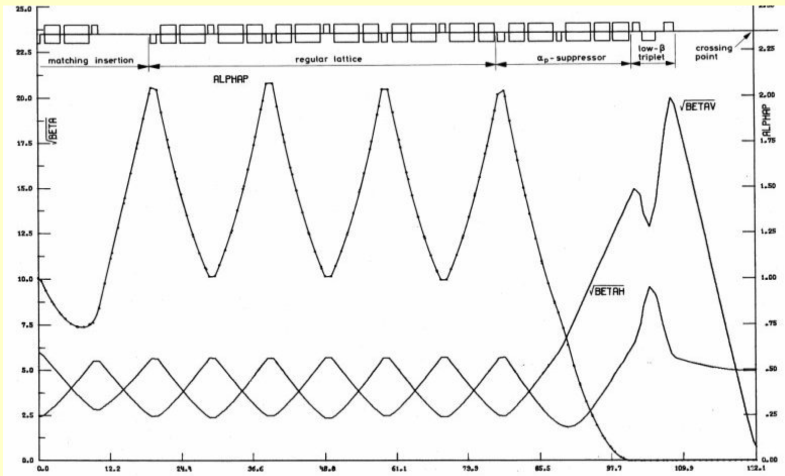


Fig. 1.9 Twiss parameters of the first half of an outer arc

5

We now compare with the ISR upgrade (SCISR) published in 1977.

The slide shows the lattice functions in the outer arc.

1. Immediately, one sees the arc is a tightly-packed, separate-function FODO structure, terminated by a dispersion suppressor and matched into a low-beta insertion, which is **exactly how the job would be done today**.

2. The dispersion suppressor was designed according to an elegant method from the ISR Theory Group.

3. Although low-beta insertions were not an ISR invention, the matching was based on an analytical solution for a variable-geometry triplet that came from ISR in 1973. I note this because **this is perhaps the most useful of all the analytical matching modules ever published**.

1.3 From global fitting to insertions

- The 1965 ISR lattice was designed and 'manipulated' globally. The so-called Terwilliger Scheme is an example of this.
- By 1974 the concept of a local insertion had been demonstrated by a convention steel low-β insertion, which consisted largely of borrowed quadrupoles from the PS, DESY and RAL. This was built in I7 and later moved to I1 (1976).

6

I already mentioned that the 1965 lattice was globally 'manipulated' to get the best fit to requirements.

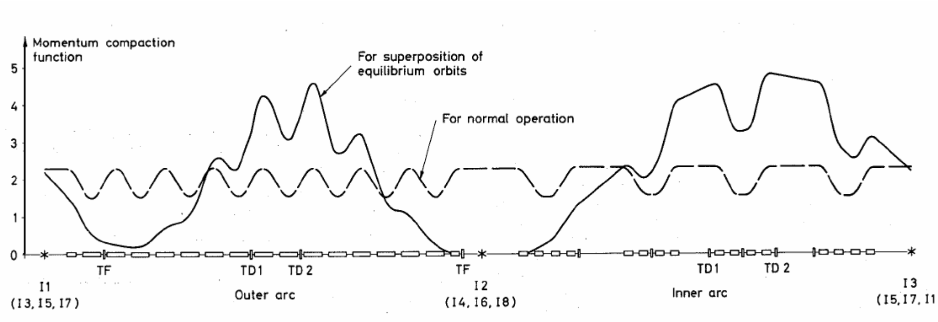
The Terwilliger Scheme is an example of this 'global manipulation.

This is to be compared to the more modern concept of insertions.

By 1974 the concept of a local insertion had been demonstrated by a **convention steel low-β insertion**, which consisted largely of borrowed quadrupoles from the PS, DESY and RAL. This was built in I7 and later moved to I1 (1976).

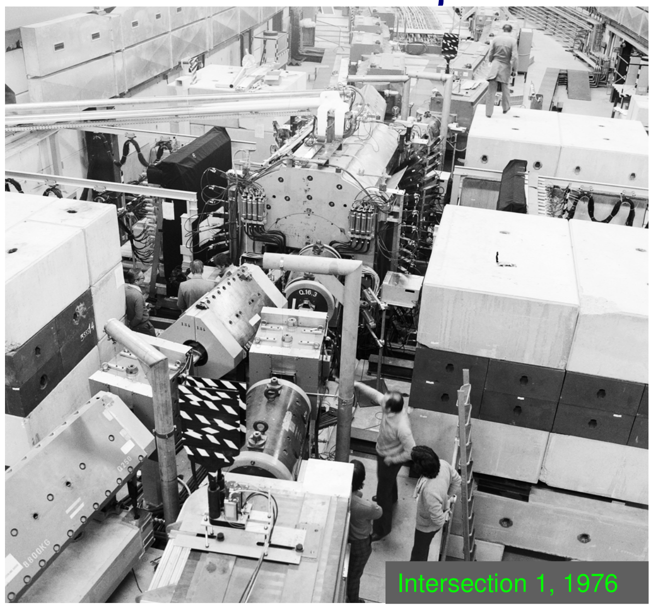
1.4 Terwilliger scheme

Although the Terwilliger Scheme is obsolete, I should like to mention this idea for making small interaction diamonds, since **to my knowledge the ISR is the only machine to have demonstrated this principle**.



7

1.5 Conventional low-β



8

Conventional low-beta (I7 then moved to I1)

The convention steel low-β insertion, which consisted largely of borrowed quadrupoles from the PS, DESY and RAL, was built in I7 (1974).

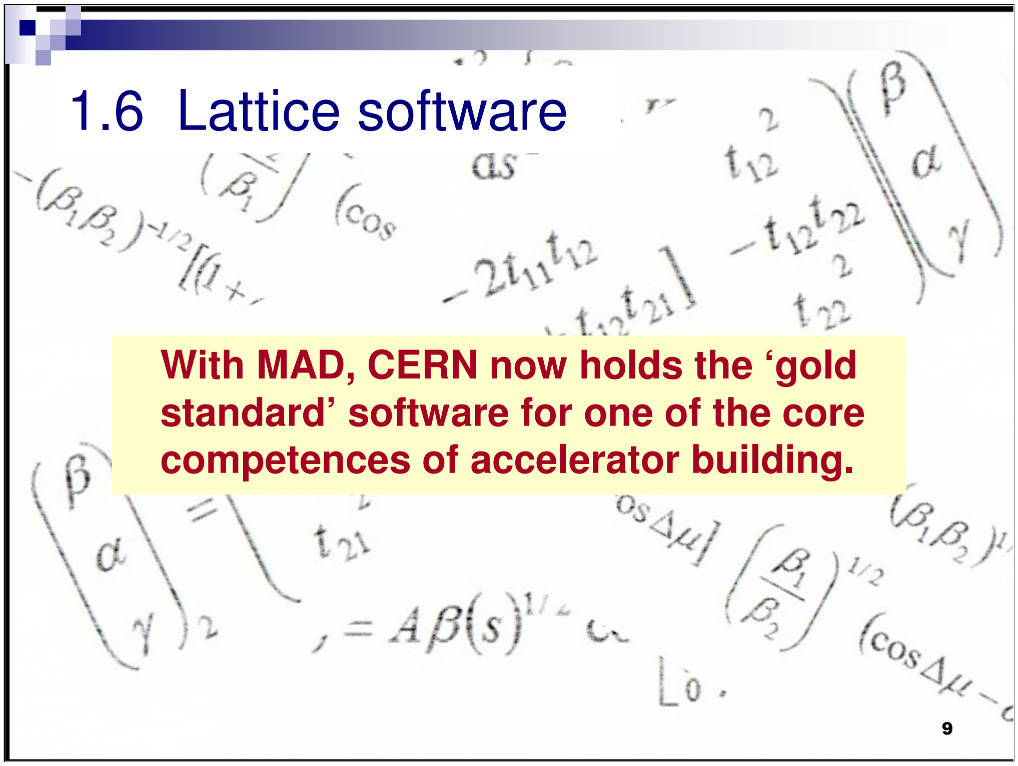
This ‘experiment’ was to test **the fear that the very marked super-periodicity of unity** would cause the high intensity ISR beams to be unstable or noisy. In reality, this did not prove to be an issue.

The ISR had no dispersion-free regions, the lattice functions were far from regular, so matching the low-beta was more of a challenge than a standard triplet scheme.

This insertion increased the luminosity by a smaller factor of 2.3.

It was later demounted and moved to Intersection 1 in 1976, where it was used in conjunction with a superconducting solenoid.

.



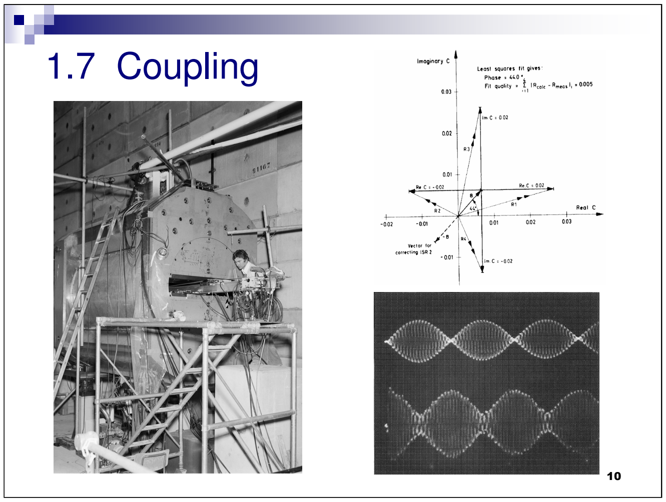
Lattice programs are the element behind lattice design and insertions.

In the 1960s, ISR and its transfer lines were designed with the SYNCH (LBL), AGS and BEATCH (CERN) programs.

AGS was developed through the life of ISR and finally replaced by MAD (Methodical Accelerator Design) by the ISR Theory Group and is now a ***de facto* world standard**.

CERN now holds the 'gold standard' software for one of the core competences of accelerator building, which I feel is very important for CERN

Thanks to the persistent efforts of the ISR Theory Group for improving this software.



Coupling is a lattice related topic in which ISR was a world leader in the 1970s.

An important step was the publication of the **'Complete Hamiltonian theory for sum and difference resonances in 3D fields' in 1976**, in which amongst other things driving terms and coupling coefficients are defined.

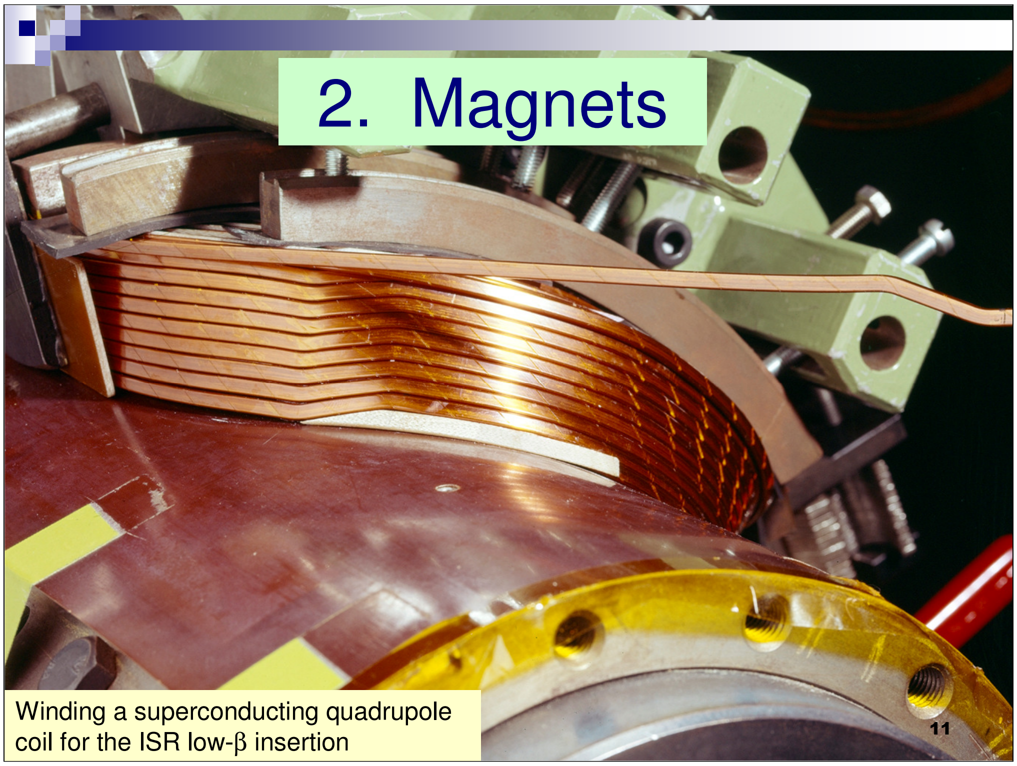
[Here we must acknowledge that Phil Morton from SLAC had independently reached many of the same results in an unfinished and unpublished note. A story that is similar to Rolf Wideröe who designed the betatron in his laboratory notebook and then put it into a draw and Lee Teng who did the same thing for his rotator for medical synchrotrons. However, in this case the reference work comes from ISR.]

Some coupling examples:

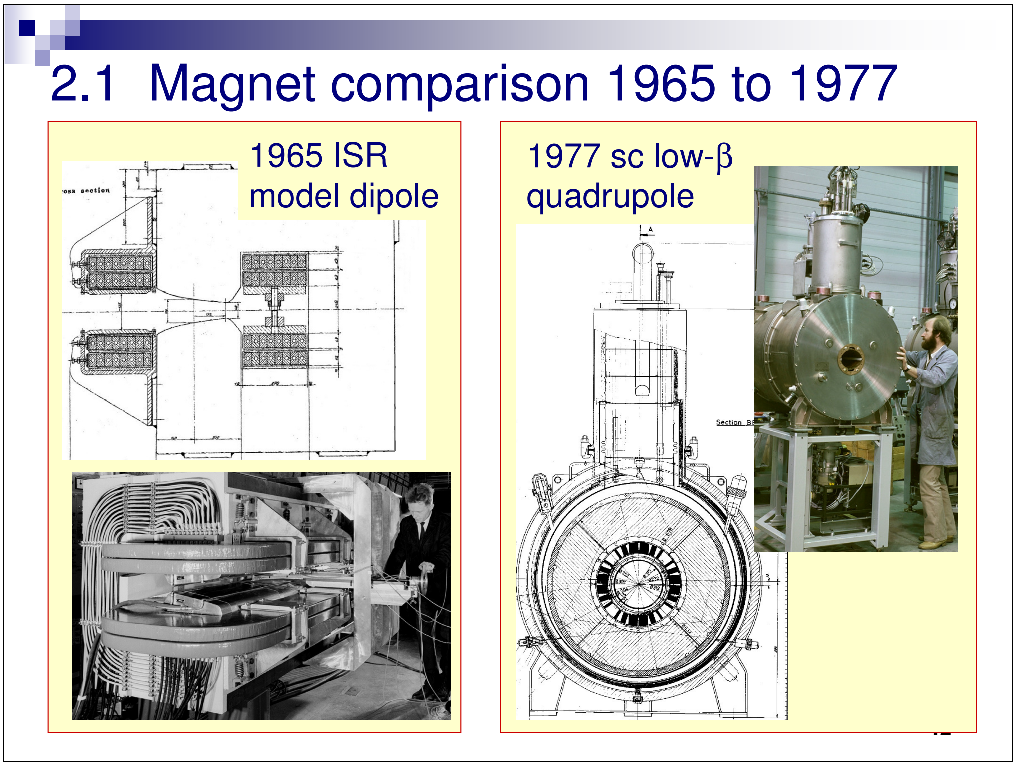
1. The I1 solenoid had horizontal slots in its end plates to accommodate the crossed beams. This new feature was described analytically and compensated in the ISR for the first time.

2. Since there are no dispersion-free regions in the ISR, the compensation scheme for the global coupling was of a unique design. This design also controls the vertical dispersion.

3. The ISR was also first to be equipped with an electronic coupling meter.



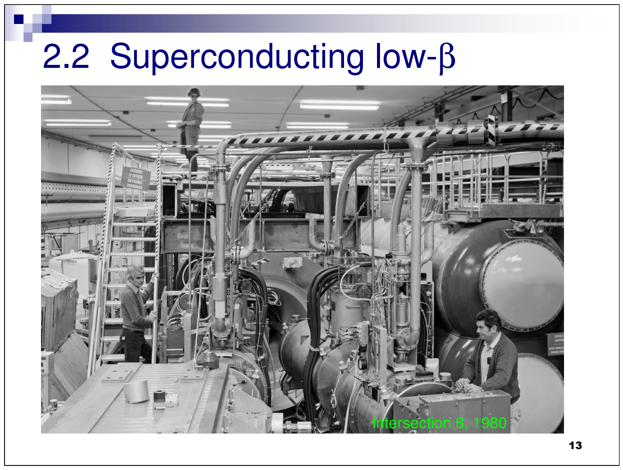
Again my main objective here is to illustrate the rapid advance in technology and particularly magnet technology..



As with the comparison of the ISR lattice with the SCISR upgrade, we see **a tremendous advance in magnet design** between the original ISR and the ISR low-beta insertion.

The superconducting magnet design shown here was not a futuristic sketch. Unlike the SCISR upgrade, the sc low-β insertion was approved, built and was a great success.

The commissioning of these projects spans just 11 years (1965 to 1977).



Superconducting low-beta insertion in I8.

<u>1. CERN made the important decision not to outsource the work</u> to other labs such as Rutherford, UK, but to accumulate in-house expertise in magnet building and cryogenics, **which was later to be immensely important for LEP and LHC**.

<u>2. CERN decided to build models and prototypes in-house and then to write a detailed engineering specification for tendering to industry for the series production</u>. In this approach, the magnetic design is the responsibility of CERN. The manufacturer is only responsible for respecting the tolerances, choices of materials and adherence to the various qualified procedures. **This philosophy was applied later in LHC**.

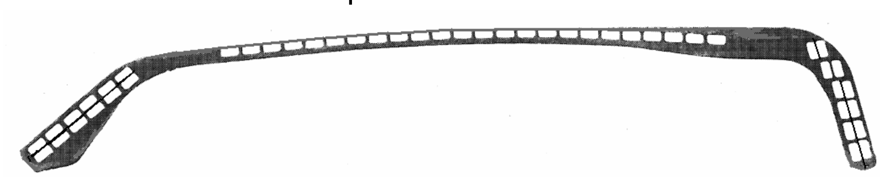
The low-β was a great success, increasing the luminosity in I8 by $\times$ 6.5.

This was the **first time that** industrially built sc quadrupoles had been operated in the lattice of a synchrotron that typically operated for 60 hours.

The record luminosity of 1.4×10^{32} cm^{-2} s^{-1} (Dec 1982) in the sc low-β and was not beaten until 1991 by CESR at Cornell with 1.7×10^{32} cm^{-2} s^{-1} .

2.3 Poleface windings

- The combined-function, C-type main magent of the ISR was not according to modern tastes, but it did have an extremely versatile set of poleface windings.
- The F- and D-blocks were each had 12 circuits and a 13th circuit to compensate stray field from the cables.
- Field shaping used a ‘practical’ system of so-called ‘half-multipoles’ that acted independently on the inner and outer halves of the aperture.



14

Poleface windings

Briefly, I should now like to go back to the original ISR magnet and mention the poleface windings. This feature did not develop into a *de facto* world standard, but it should be mentioned as I believe that it was the most versatile system of its type ever built.

Please note we will come back to the use of these windings later.

2.4 Physics detectors

- In 1965, ISR was regarded by some as "an expensive small-angle scattering experiment for the PS". There was no expertise for colliding beams.

- By the late 1970s, ISR was the test bed for a Superconducting Solenoid (I1), the Open Axial Field Magnet (I8) and an Air-cored Toroid (I6) – magnet configurations that might be used today.

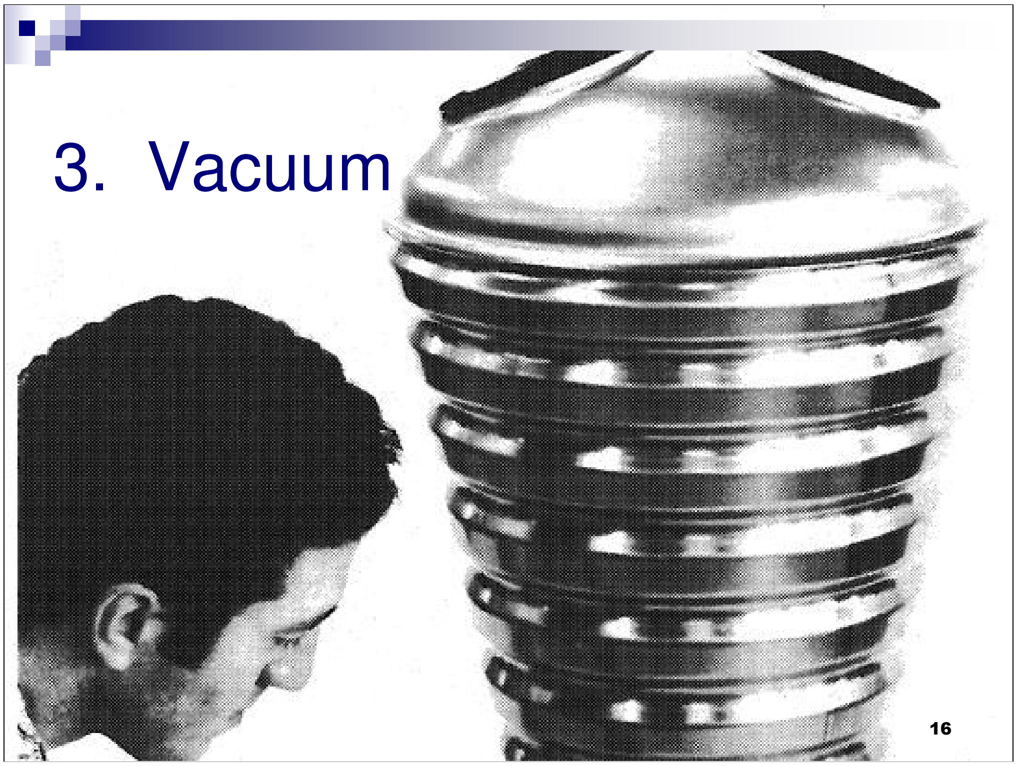
15

In this final section on magnets, I should like to look at physics detector magnets.

In 1965, colliding physics was more or less a blank page. In the official history of CERN, it was said that ISR was regarded by some as "an expensive small-angle scattering experiment for the PS".

By the late 1970s, detector magnets with 4π acceptance were being used and in one case the magnet was superconducting. This was effectively a jump to today's technologies in just a few years.

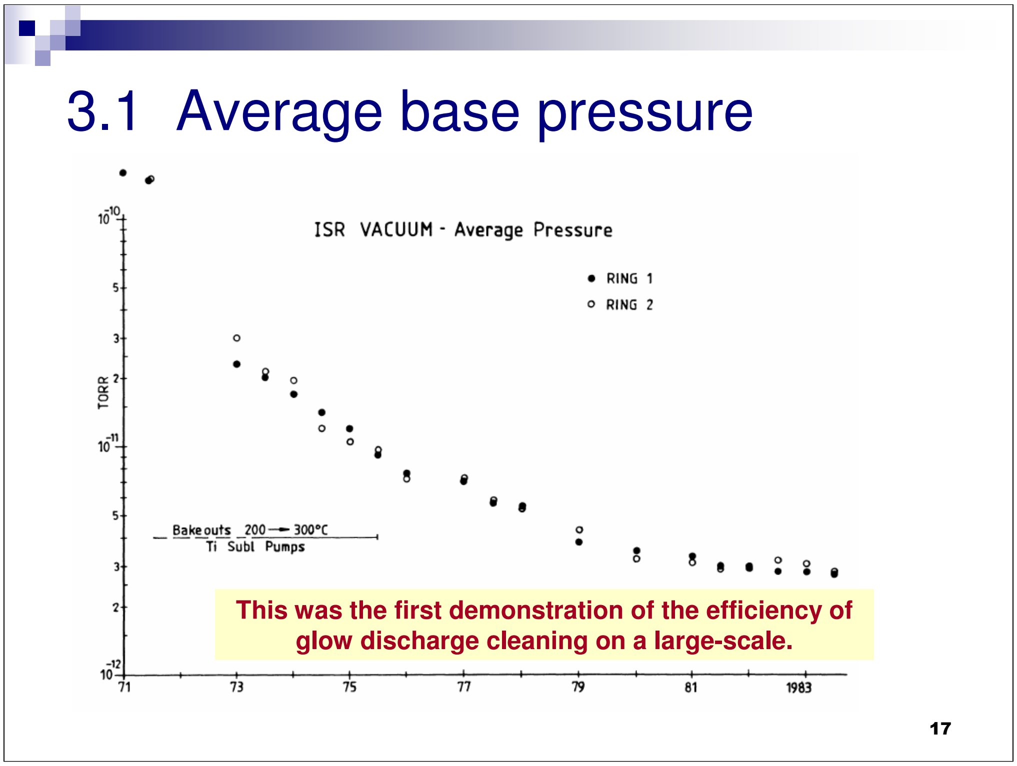
The OAFM is shown here because it is perhaps the least well known of the examples.



The original design criterion required 10^{-9} torr in the arcs (using ion pumps) and 10^{-10} torr in the crossing regions (using cryo-pumps), although it was noted that 10^{-11} torr would be more desirable.

The chamber itself was to be stainless steel bakeable to 300°C to 350°C, although initially it was only baked to 200°C.

This made the ISR the world's largest ultra-high vacuum (UHV) system, which was an enormous challenge for the technology at that time.



The early status (1971-72) of the vacuum was described in the first talk.

A staged programme to improve the vacuum system was already started in 1971 and progressed over several years. Baking at 300℃ and later at 350℃, instead of the initial 200℃ helped and some 500 additional titanium sublimation pumps were added.

The vacuum system was demounted arc by arc during shutdowns and cleaned using a new technique called **glow-discharge cleaning**. Later this was done in situ during bakeout by using the clearing electrodes to excite an argon discharge. Incredibly, a glow-discharged chamber could be opened to the air and left for many hours and still recover its ultra clean condition when pumped. **This was the first demonstration of the efficiency of glow discharge cleaning on a large-scale**

The focus on residual gas scattering background into the experiments moved to particle losses on nonlinear resonances and hours of working line studies.

3.2 Other vacuum aspects

- Beam-induced vacuum instability.
- Neutralisation tune shifts and e-p instabilities.
- All-welded vacuum systems (e.g. TT6).

18

It soon became clear that there were other ways through which the beam and vacuum could mutually destroy themselves.

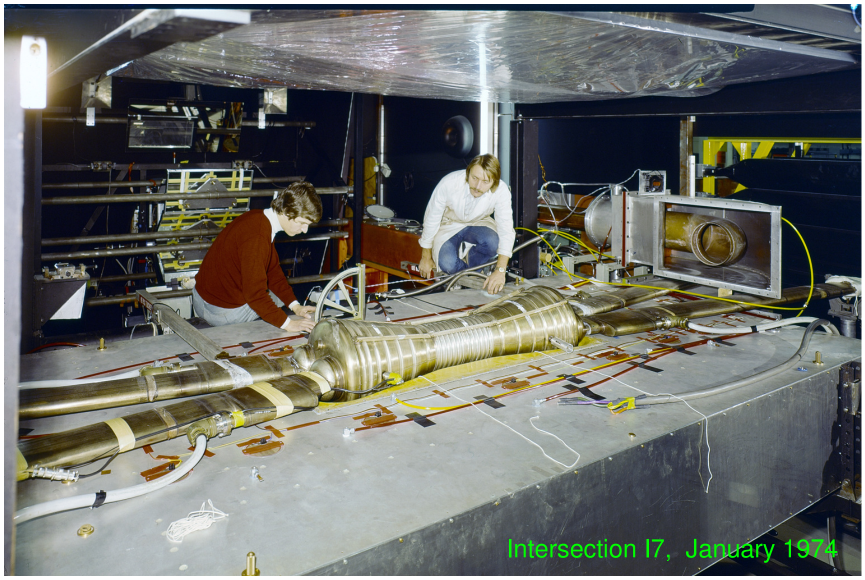
1. As the beam current increased, the residual gas was ionized and positive ions were repelled by the beam (potential 1-2kV) to crash into the chamber walls only to release adhered gas molecules (order of 10^4) that were in turn ionized by the beam to create a runaway effect that caused catastrophic beam loss.

2. Ionisation of the residual gas provides a source of electrons that can be trapped in the potential well of the beam causing tune shifts and eventually beam instability. Bunched beams can flush out pockets of neutralisation, but the only sure way is to install clearing electrodes. Additional electrodes were installed.

The ISR provided the perfect test bed for measurements and many papers were published on neutralisation tune shifts, e-p instabilities, electron removal by rf clearing and ion clearing in anti-proton beams.

Finally, the contrast of 1965 open-gap magnets, flanges etc. and the 'all-welded' and- closed-magnet- approach of TT6.

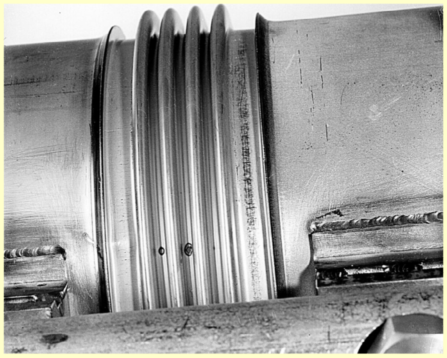
3.3 Thin-walled chambers



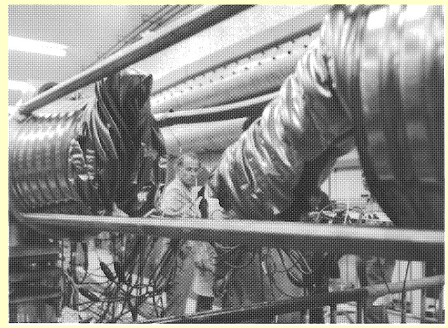
19

One pioneering activity in the ISR was the design and production of large, thin-walled vacuum chambers for the intersection regions. Typically the chamber walls were 0.4 mm to 0.28 mm thick and the materials used were stainless steel and titanium.

3.4 Accidents can happen



September 1972



Thin-walled (0.3 mm) Ti chamber implodes in Intersection 7, 1975

20

By 1973 the ISR had suffered two catastrophic events where the beam burnt holes in the vacuum chamber.

Bellows were particularly vulnerable because each convolution would radiate onto its neighbor so the heat could only escape by conduction through the thin metal.

In the case of a thin obstruction, the beam ‘locks on’ returning every 10-20 turns depositing more energy.

This led to collimation rings being inserted in the flanges to protect the adjacent bellows.

Thin-walled chambers were also known to fail causing dirt to enter the system and requiring extensive cleaning while leaving a twisted sculpture.

This is the ISR control room. We have to admit that the appearance was rather plain.

Again there is a rapid change in attitude. **In 1965 nobody trusted the computer** and there were panels of manual controls. Some were physically locked by key to prevent access.

By the mid-term of the ISR, there was a highly sophisticated control system. Manual interventions were discouraged and only automated procedures under computer control and high-level functions were used.

4.1 Closed-orbit correction

- One of the first operations to be carried out in any machine is the correction of the closed orbit.
- The algorithm MICADO (1971) was developed for the ISR.
- **MICADO was written into the program COCO and after some years of development became a *de facto* standard for many laboratories.**

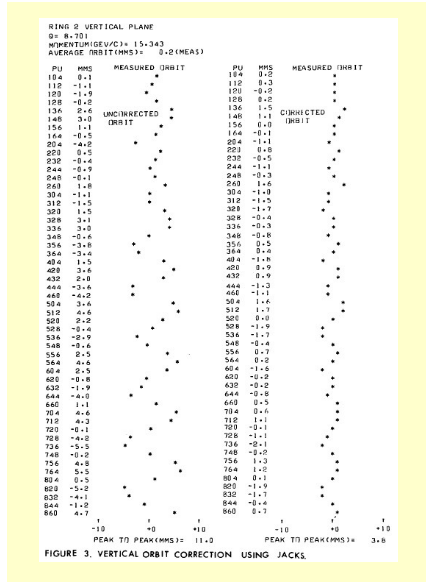


FIGURE 3. VERTICAL ORBIT CORRECTION USING JACKS.

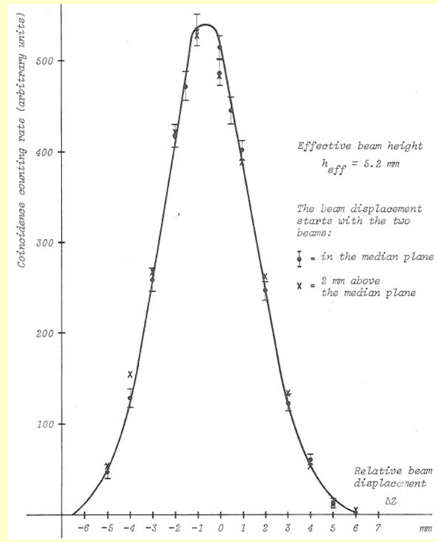
22

The most advanced versions of COCO now have feedback loops and can be found in synchrotron light machines.

4.2 Luminosity calibration method

- Invented in 1968 specially for the ISR colliding beam geometry, **this method is still used in LHC**.
- The 'effective' beam height is measured by scanning the two beams vertically through each other while monitoring the count rate (LUMS program).
- The luminosity is given by,

$$L = 10^{29} \frac{I_1[\mathrm{A}]\, I_2[\mathrm{A}]}{h_{\mathrm{effective}}[\mathrm{mm}]} [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$



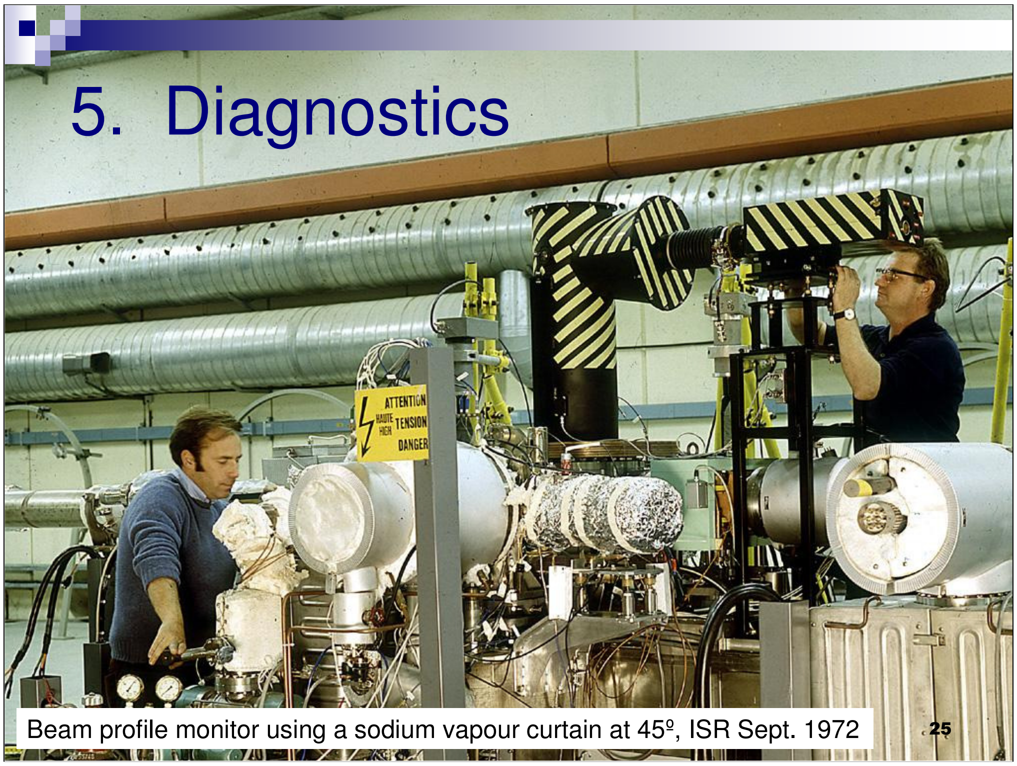
Annual Report 1971

23

The closed-orbit bumps used to move the beams were corrected for the coherent beam tune shift and hysteresis in the magnets.

4.3 Other particles

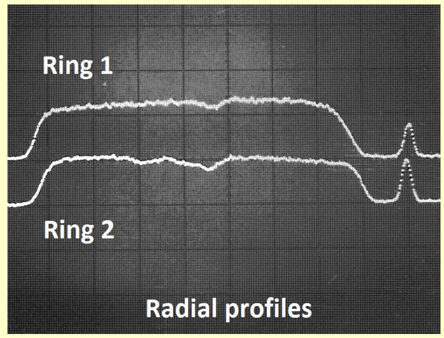
- ISR was also able to store deuterons and alpha particles as soon as they became available from the PS, leading to a number of runs with *p-d, d-d, p-α* and *α-α* collisions from 1976 onwards.
- For CERN's antiproton programme, a new beam line, TT6 was built from the PS to Ring 2. The first *p-pbar* runs took place in 1981.
- ISR's final runs in 1984 were dedicated to a 3.5 GeV/c antiproton beam to colliding with a gas-jet target.



Beam profile monitor using a sodium vapour curtain at 45 degrees.

5.1 Schottky signals

- **If one subject has to be singled out, then it would be the discovery of Schottky noise and the proposal for stochastic damping.**
- Longitudinal Schottky scans showed the √(current density) in the stack as a function of the momentum (transverse position), without perturbing the stack.
- Transverse Schottky scans showed the √(current density) times the rms of the betatron amplitudes as a function betatron frequency, or “tune”.

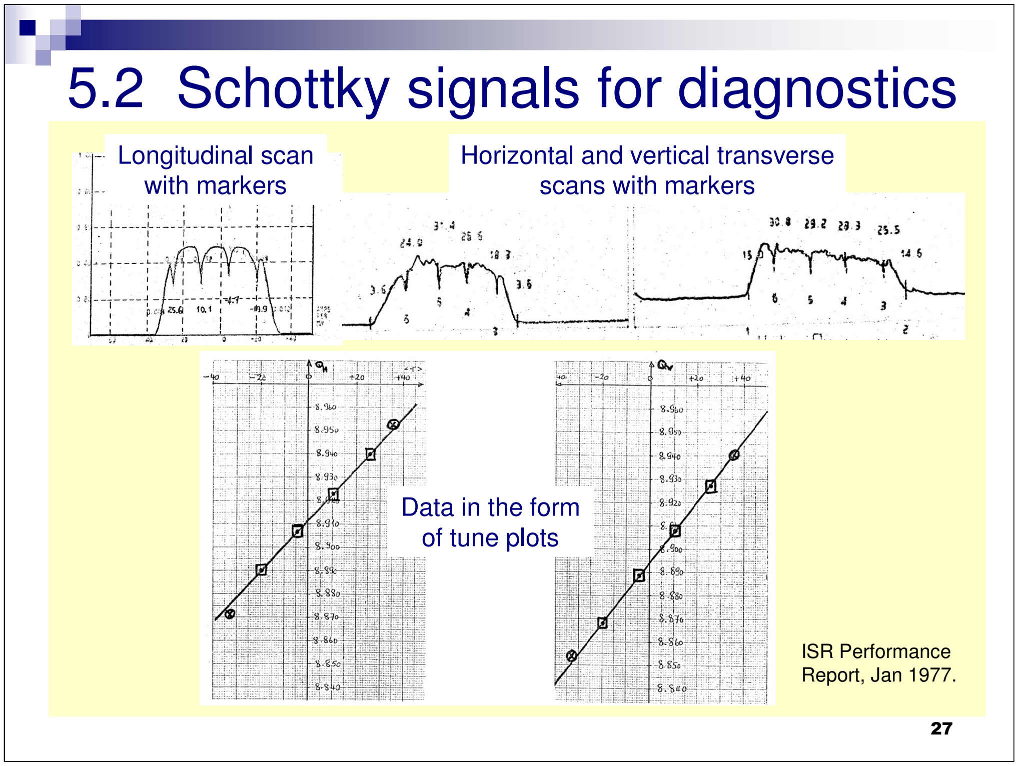


Annual Report 1971

26

In 1972, Simon van der Meer wrote a report about Schottky noise and the possibility of stochastic damping based on work he had done in 1968. The idea had seemed too far-fetched in 1968, but this changed in 1972 when longitudinal and transverse Schottky signals were found at the ISR.

This discovery opened new vistas for non-invasive beam diagnostics and active cooling systems for reducing the size and momentum-spread of a beam.

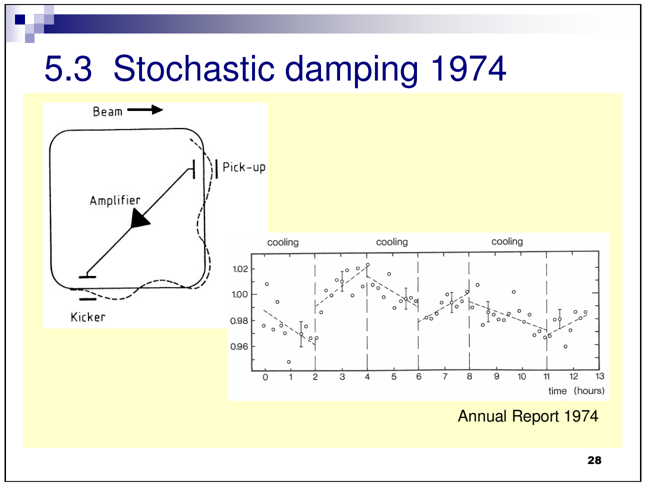


Artificial markers are created by phase displacement of the stack to create small regions of low beam density.

Stack edges and losses on resonances form natural markers.

Four to five artificial markers could be created in a physics stack.

Longitudinal scan on left and H and V trans scans middle and right.



Since small statistiscal fluctuations could be detected in beams it was thinkable that small fluctuations could also be corrected.

The possibility of damping the betatron oscillations was experimentally demonstrated in the ISR.

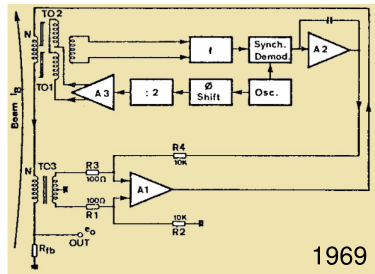
Towards the end of ISR's life, stochastic cooling was routinely used to cool antiproton beams in order to increase the luminosity in antiproton-proton collisions.

Furthermore, stochastic cooling was the decisive factor in the conversion of the SPS to a p-pbar collider and hence in the discovery in 1983 of the W and Z bosons. Carlo Rubbia together with Simon van der Meer shared the Nobel Prize in Physics in 1984.

Stochastic cooling was also used in the Tevatron at Fermilab, CERN's low-energy antiproton programmes, as well as similar programmes at GSI in Germany and at Brookhaven in the US.

5.4 Direct current beam monitor

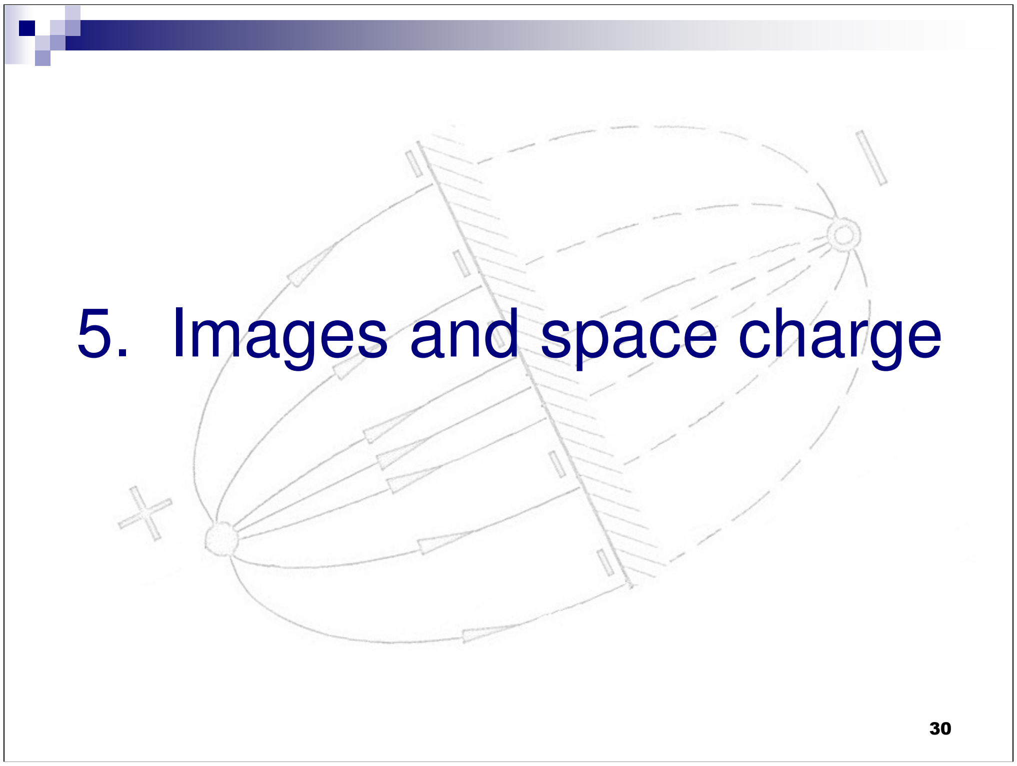
- The ISR was also the home of the zero-flux, direct-current transformer (1969).
- **This device became another *de facto* world standard**.



Beam current monitors of this type developed at CERN in 1981 and 1990 became national primary standards in Germany, certified and operated by the PTB (Physikalisch-Technische Bundesanstalt) in Berlin.

29

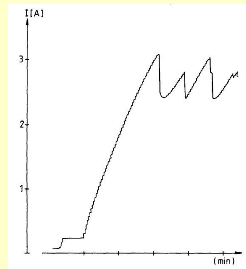
No replacement technology has yet been found.

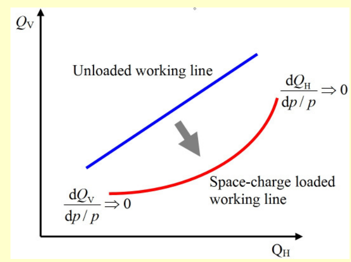


I am not considering the wider beam-chamber interaction because of time limitations.

5.1 'Brickwall' instability

- Shortly after the start of the ISR, a coherent transverse instability, dubbed the 'brick wall', limited the beam current.
- One explanation invoked dust 'jumping' into the beam, once the beam potential had reached a certain value.
- However, studies of the shape of the working line in the tune diagram revealed the culprit to be image space-charge tune shifts.
- **From these beginnings, the ISR spawned tens of papers on incoherent and coherent space-charge tune shifts on central and off-axis orbits in variously shaped chambers and the correction of these effects.**





31

Shortly after the start of the ISR a coherent transverse instability was observed that limited the beam intensity. This phenomenon was dubbed the 'brick wall' instability.

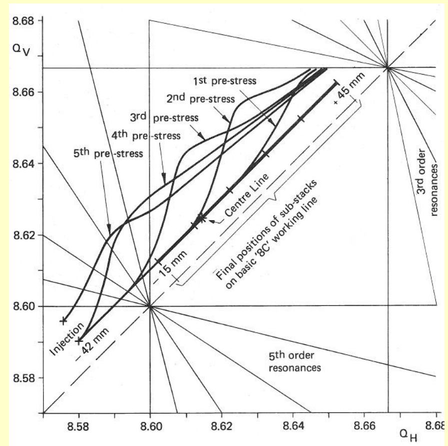
The intensity would increase while stacking to around 3 A where there would be a sudden loss of 10% to 15% of the beam after which stacking would resume only to have a repeat beam loss at around the 3 A level. This gave a 'sawtooth' pattern on the accumulated current that appeared to be knocking against a 'brickwall'.

One explanation invoked dust 'jumping' into the beam once the beam potential reached a certain value. However, studies of the shape of the working line in the tune diagram and the action of space-charge loading revealed that the stabilization expected from the tune spread was being destroyed by the image space-charge tune shifts.

From these beginnings, the ISR spawned tens of papers on incoherent and coherent space-charge tune shifts on central and off axis orbits in variously shaped chambers and the correction of these effects.

5.2 Stabilising the 'brickwall'

- A series of pre-stressed lines was created to correct the space-charge loading every 3A. Example shows '8C' line for 15 A.
- Once longitudinal Schottky scans were operational the true current density could be measured at any time, the tune shifts calculated and the necessary poleface winding currents applied by a semi-automated procedure called QCOM.
- **QCOM was unique and highly successful.**
- **The highest current recorded in a single ring was 57 A at 26 GeV/c and physics beams were typically 30-40 A at 31.4 GeV/c.**



Annual report 1972

32

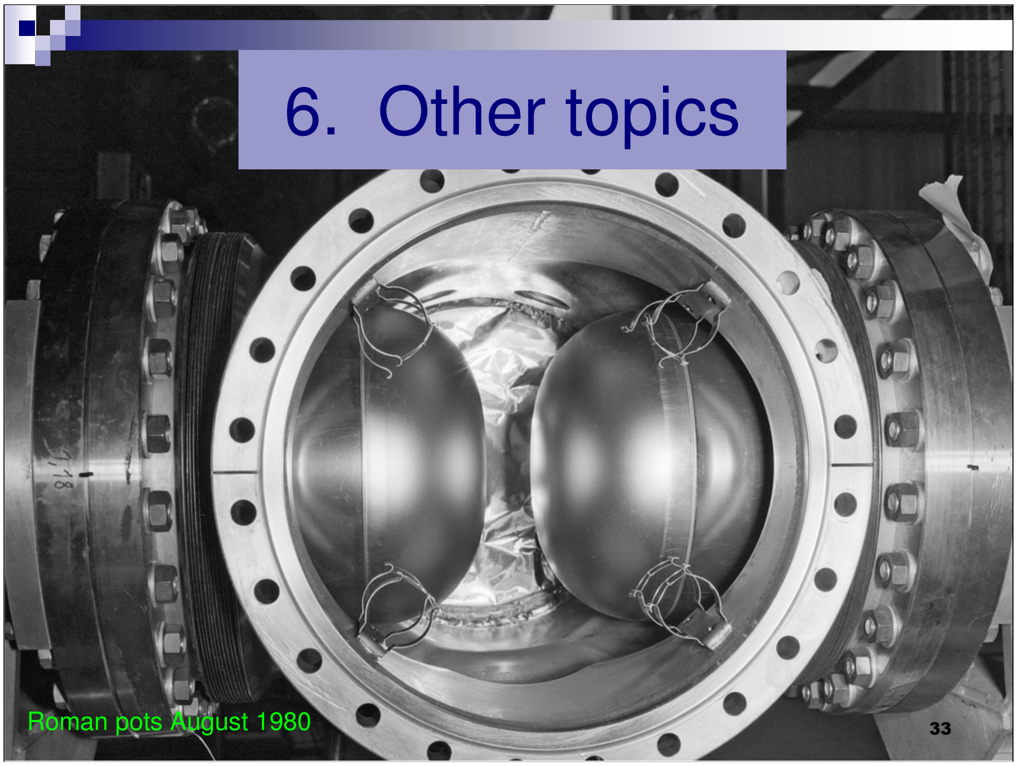
The example shows the line '8C' for 15 A applied in 5 steps of 3 A.

The final stack sits with uniform tune spread in a region with no resonances below 8th order.

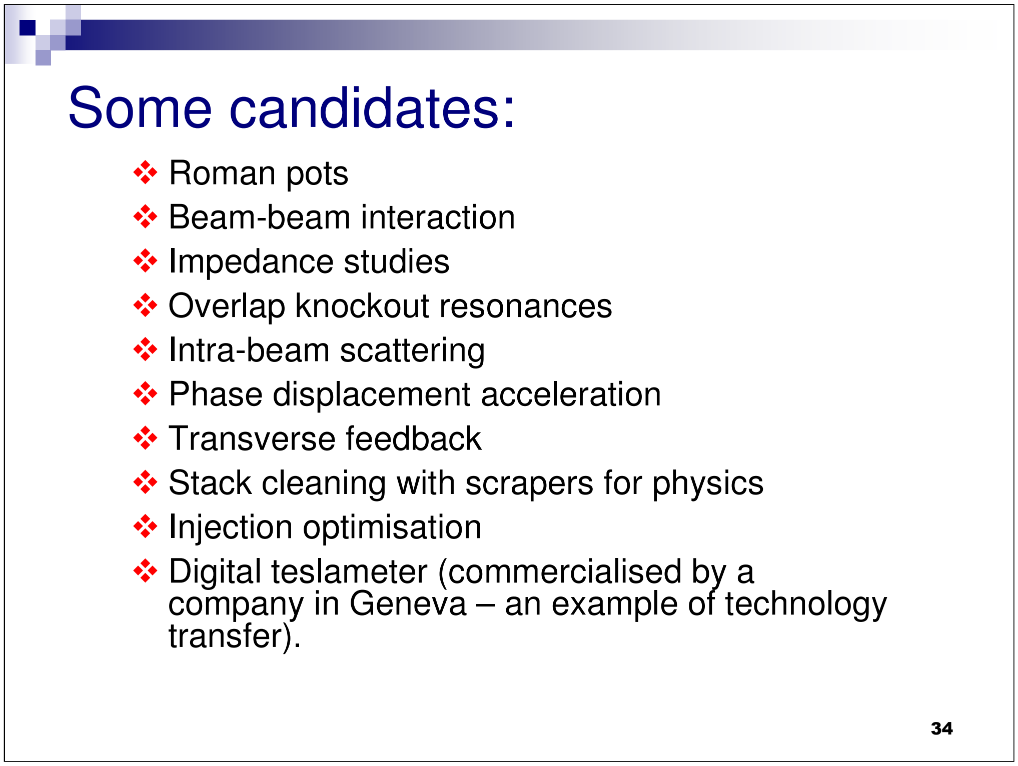
Once longitudinal Schottky scans became operational, the true current density could be measured at any time, the tune shifts with radial position calculated and the necessary poleface winding currents calculated and applied.

Typically, these corrections would be performed every 3 A by a semi-automated procedure called QCOM.

This procedure was unique and so successful that currents of many tens of amperes could be safely accumulated. The maximum current recorded in a single ring was 57 A at 26 GeV/c and physics beams were typically 30-40 A at 31.4 GeV/c.



This photograph shows the Roman Pots.



The roman pots shown in the previous slide.

The beam itself is the strongest source of resonance excitation and ISR had exceedingly high beam intensities/luminosities so the reaction was strong. These results were compared with those from electron-positron machines and helped to guide the design of future colliders.

For most of these subjects ISR was an ideal test bed, BUT it is difficult to pick out single discoveries from the 'sea' of papers.

I just note one example of technology transfer – the digital teslameter – a temperature controlled hand-held Hall probe device.

Conclusions

- The timing of ISR was such that the world-wide community was poised to advance to what we would now recognize as ‘modern’ accelerators.
- No doubt some of the advances described would have taken placed had CERN built a ‘Super PS’ rather than ISR, but much of what has been described depends strongly on the particular attributes of the ISR.
  - Schottky noise exists in a bunched beam for example, but it is less likely to be discovered so quickly.
  - The exceptionally large momentum spread pushed the studies of tune shifts, coupling and chromaticity schemes into more detail.
  - The colliding beam geometry was essential for beam-beam studies.
  - Colliding beam physics would have been seriously held back without a test stand for experimentation.

ISR the right machine at the right time!

35

I have missed out many subjects, but I hope I have imparted the idea of a rapid expansion and that ISR was a major player in that expansion.

Thank you.