# ***WEAK FOCUSING SYNCHROTRON***

*A BRIEF INTRODUCTION*

- ORIGINS, PRINCIPLE
- PAST WF-SYNCHROTRONS
- WF SYNCHROTRON TODAY

# Bibliography


[] A. Sessler, E. Wilson, Engines of Discovery, World Scientific (2007)
[] M.S.~Livingston, The Development of High-Energy Accelerators, Dover Pub. Inc., NY (1966).
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[] JACoW http://www.jacow.org/
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http://www.esi-archamps.eu/Thematic-Schools/Discover-JUAS
[] USPAS archives
[] National Lab sites, US, EU
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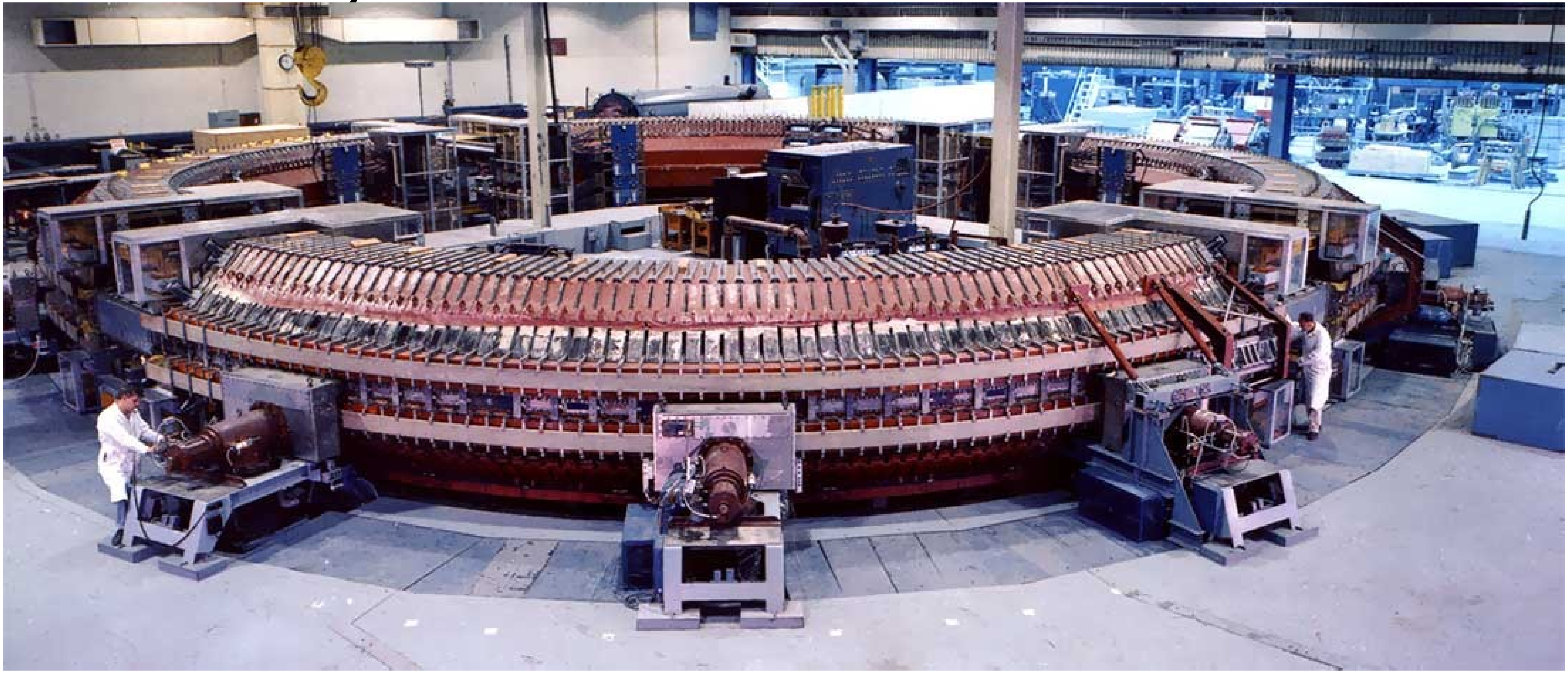
[] BNL's Flickr photo gallery
[] Wikipedia
[] G.~Leleux, Circular accelerators, INSTN lectures, SATURNE Laboratory, CEA Saclay (Juin 1978).

# Real life...

Today, rather

Yesterday...



# *Circular accelerator landscape, when longitudinal phase-stability was invented, 1944-45*

## - Cyclotron -

***Would eventually lead to***
PSI, 590 MeV, 1973, not far from the ~1 GeV limit of this beam guiding technology.
However: high power!

***Constant magnetic field, constant RF frequency***

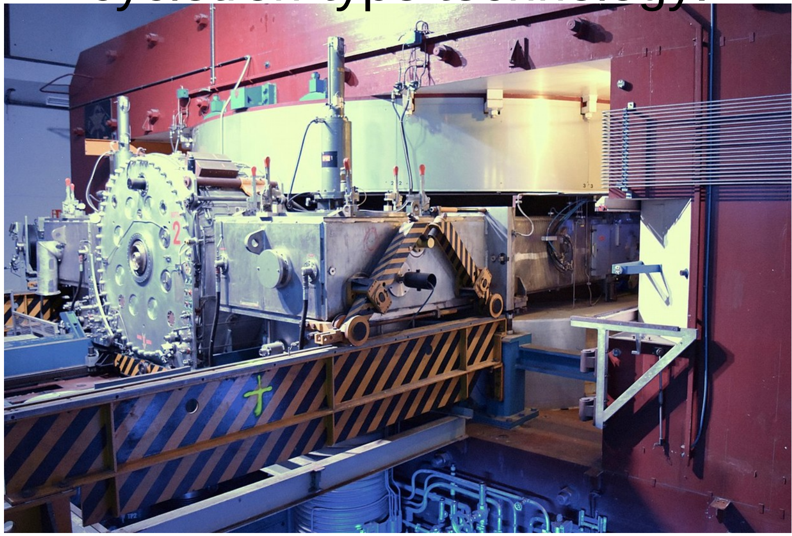
## - Betatron -

***Would eventually lead,***
late 1940s, to a 300 MeV beast (first one, and Kerst, in foreground)


***Pulsed magnetic field, induction (non-resonant) acceleration***

## - Cyclotron+phase stability: the synchro-cyclotron -

***Would lead to CERN's***
600 MeV; 184-inch 730MeV at Berkeley: highest energy, close to ~1 GeV limit of this cyclotron-type technology.



***Constant magnetic field, modulated RF frequency***

***None of these technologies has disappeared: cyclotrons, betatrons, synchro-cyclotrons, are still produced in number – no longer for high energy applications.***

# Genesis

- **Cyclotrons and betatrons appeared limited in energy by size of dipole magnet.**
- **At highest B, increase E meant increase $B \times 2\pi R$ in proportion,**
  **whereas unfortunately magnet volume goes like $R^3$.**

***"Largest cyclotron was already equivalent volume of metal of a battleship…***
***Doubling the energy meant a fleet..." [1]***

- **An idea which was in the air, instead: a thin ring of magnets based on a fixed-radius orbit as in the betatron**

**and pulse B to follow E increase → acceleration is cycled**

**If a separate oscillating voltage gap is arranged at some location(s) in the ring**
**(at the manner of the cyclotron volatge gap), it avoids the central yoke of the betatron.**

- **The energy gain per turn can be moderate, unlike cyclotron which needs high V to avoid isochronism, and as in the betatron.**

  **It just means hundreds of thousands of turns… not a problem!**
  **$\sim$1GeV / 10kV $\sim 10^5$ turns → $10^5$ C / c $\sim 3\times10^6 / 3\times10^8$ ~ tens of ms**

- **Focusing inherits directly from proven betatron or cyclotron technique, $0<n=-R/B\,dB/dR<1$ in all bending magnets, tapered gap opened (larger) outside & return yoke toward inside, "weak focusing" in nowaday's jargon.**
- **Oliphant, Memo to UK DAE, 1943: *"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field ... which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."***

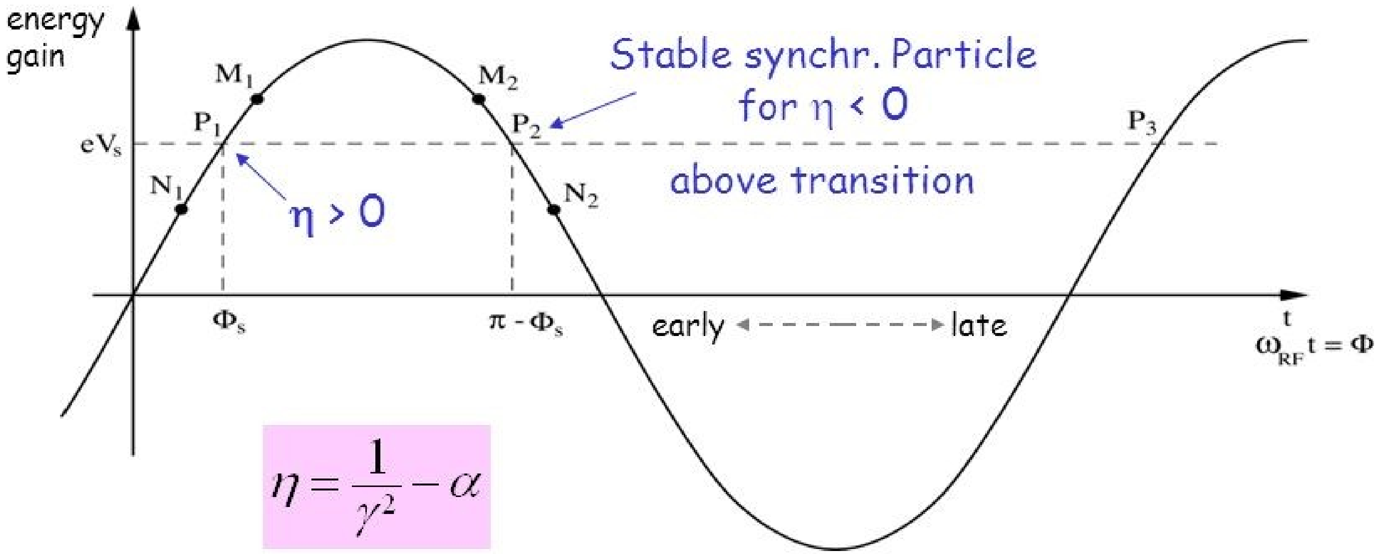
*[1] A Sessler, E. Wilson*

# 1944-Veksler; 1945-McMillan: discovery of the phase stability. That makes it possible!

## Phase Stability in a Synchrotron

From the definition of $\eta$ it is clear that an increase in momentum gives
- below transition ($\eta > 0$) a higher revolution frequency (increase in velocity dominates) while

- above transition ($\eta < 0$) a lower revolution frequency ($v \approx c$ and longer path) where the momentum compaction (generally > 0) dominates.




$$\eta = \frac{1}{\gamma^2} - \alpha$$

## 1946, Aug.: First synchrotron operation, 8 MeV proof-of-principle, by Goward in Woolwich, UK

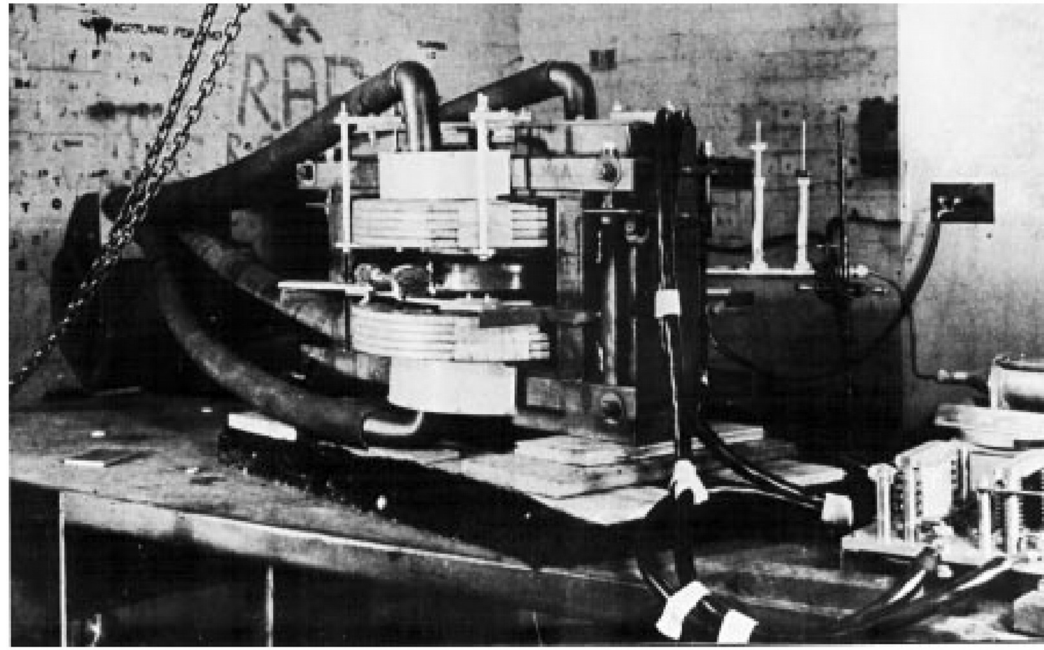


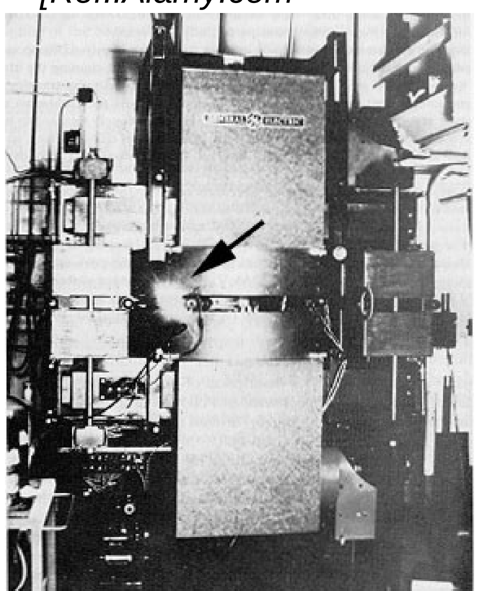
**Fig. 4:** The world's first synchrotron, installed at Malvern. The extra cooling system and RF feed to the resonator may be clearly seen.

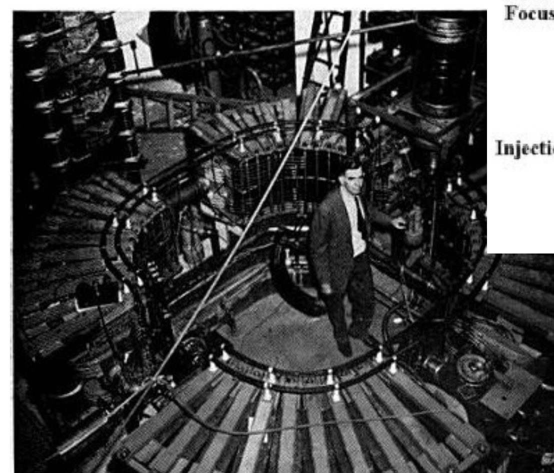
## 1947: First observation of synchrotron light (SR), not fully understood (spectrum etc.) - Julian Schwinger would develop a full theory of SR in a circular accelerator

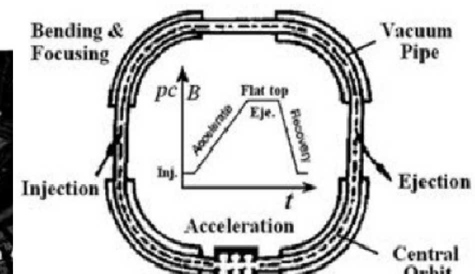
***Vaccum chamber of GE synchrotron***

*[Ref.:Alamy.com*


***70 MeV synchrtron, GE***








***The first "racetrack" sybnchrotron with straight sections, 300 MeV electron, University of Michigan, 1949.***

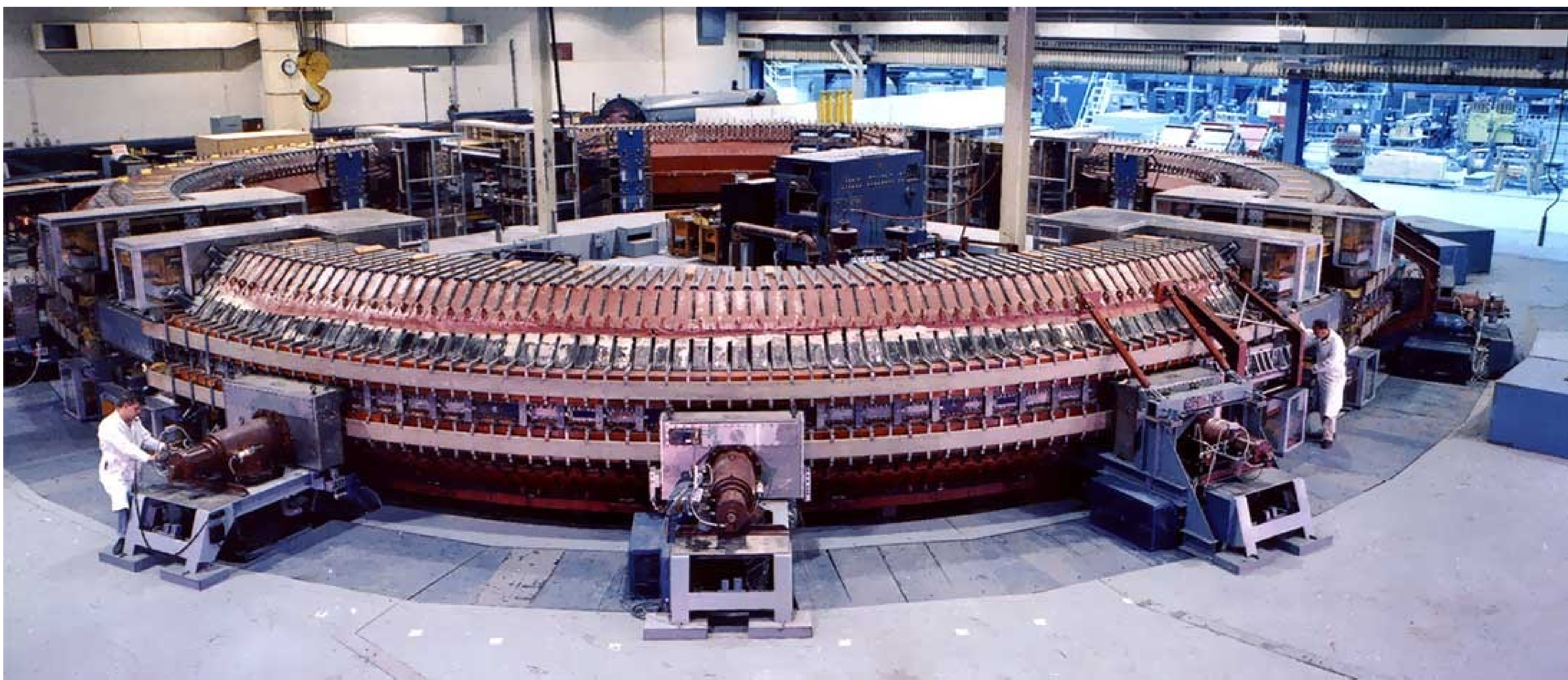
# RACE FOR HIGH ENERGIES

## Cosmotron (1953-1966) - The first >1 GeV ring, proton

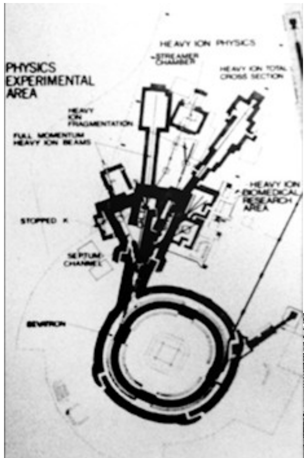
**April 1948, the US Atomic Energy Commission approves a plan for a proton synchrotron to be built at Brookhaven.**

**Reached its full design energy of 3.3 GeV in 1953. Gap aperture : 1.2m x 0.22m**

**The first synchrotron to provide an external beam of particles for experimentation outside the accelerator.**

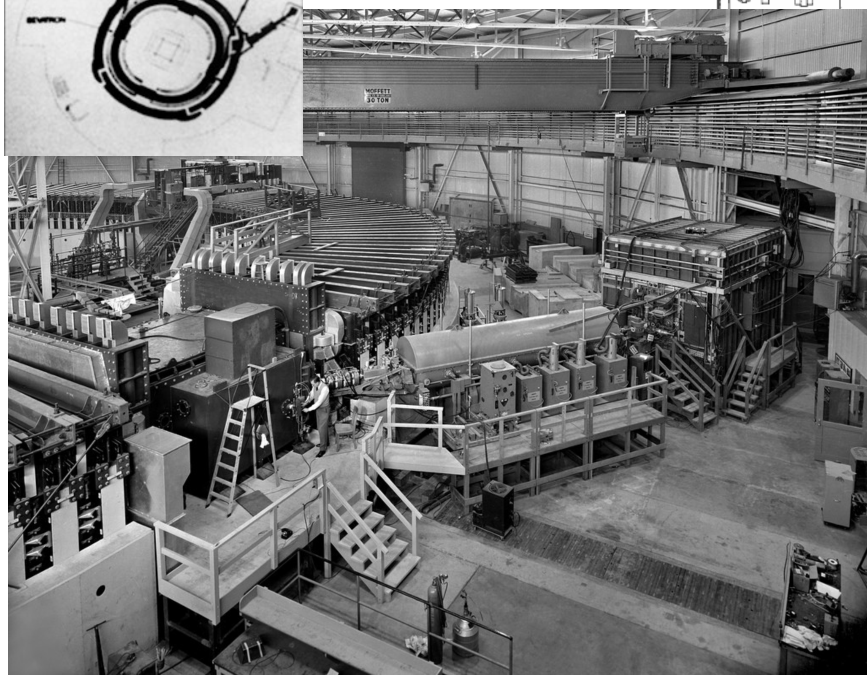


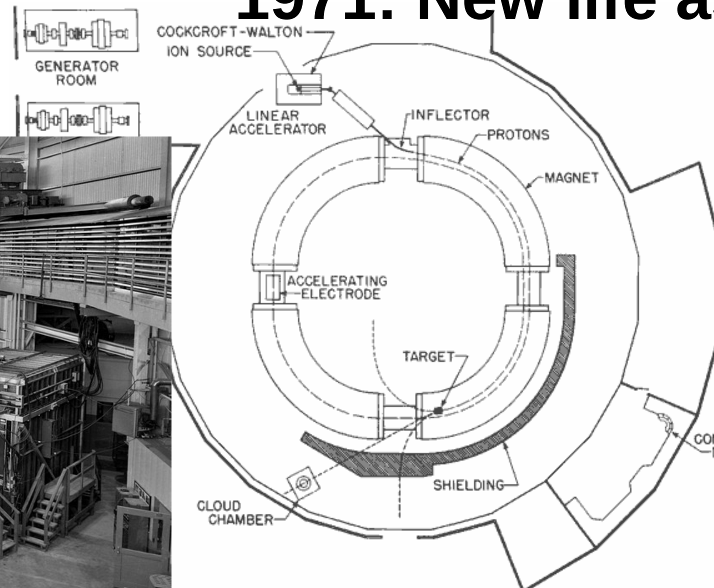
# 1954-1993: 6 GeV Bevatron, Berkeley.
# 1954: 1st ion-therapy treatment.
# 1971: New life as “Bevalac”, ions

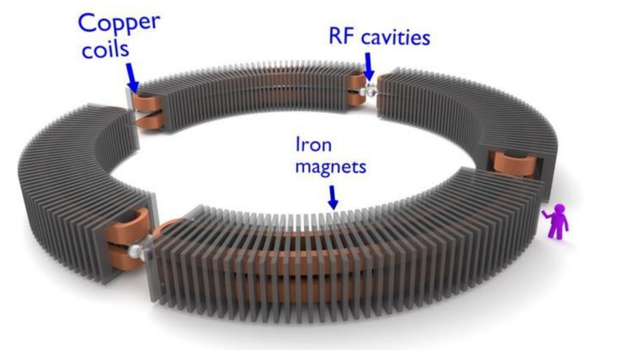


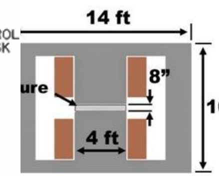

**Beam goes to experimental areas**

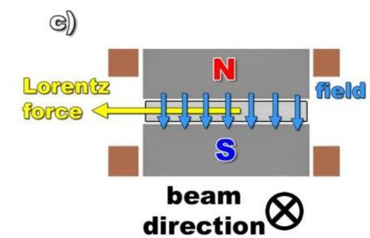
**Construction**





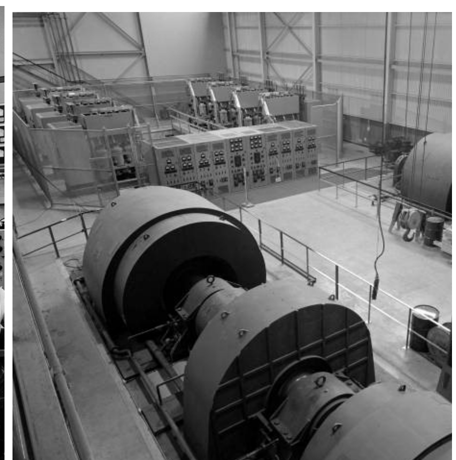



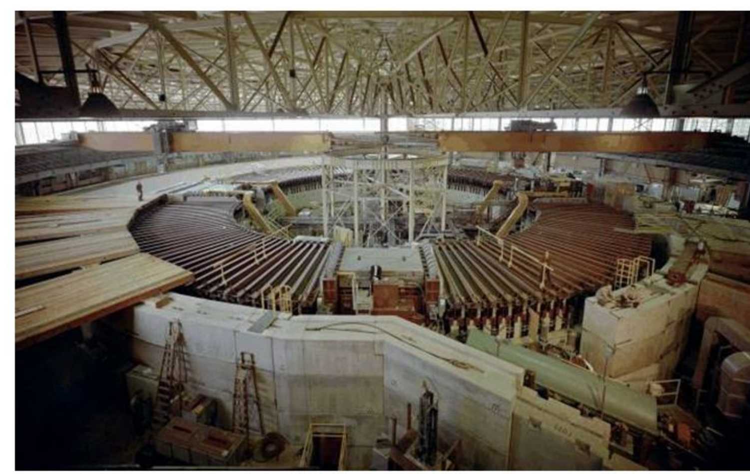




**Control room**

**Power supplies**





Overview of the Berkeley Bevatron during its construction in the early 1950s. One can just see the man on the left. **Gap was 4.3mx1.2m**

# In spite of the discovery of “strong focusing”, 1952,

***which meant, much smaller magnets (gap /10),***

**- weak focusing remained the preferred choice for the cautious accelerator scientists,**

**- and the Cosmotron, Bevatron, were followed by:**

**Synchrophasotron in Dubna (10GeV, 1957),**

**Saturne in France (3 GeV, 1958),**

**ZGS at Argonne (12GeV, 1963!-1979),**

**and Nimrod in the UK (8 GeV, 1964!-1978).**

# SATURNE 1, Saclay (1958-1970) 3 GeV

SATURNE 1, at Saclay, inaugurated in October 1958.


**Plans for polarized proton at SATURNE 1 motivated Froissart-Stora theory on the effect of depolarizing resonances, late 1950s.**

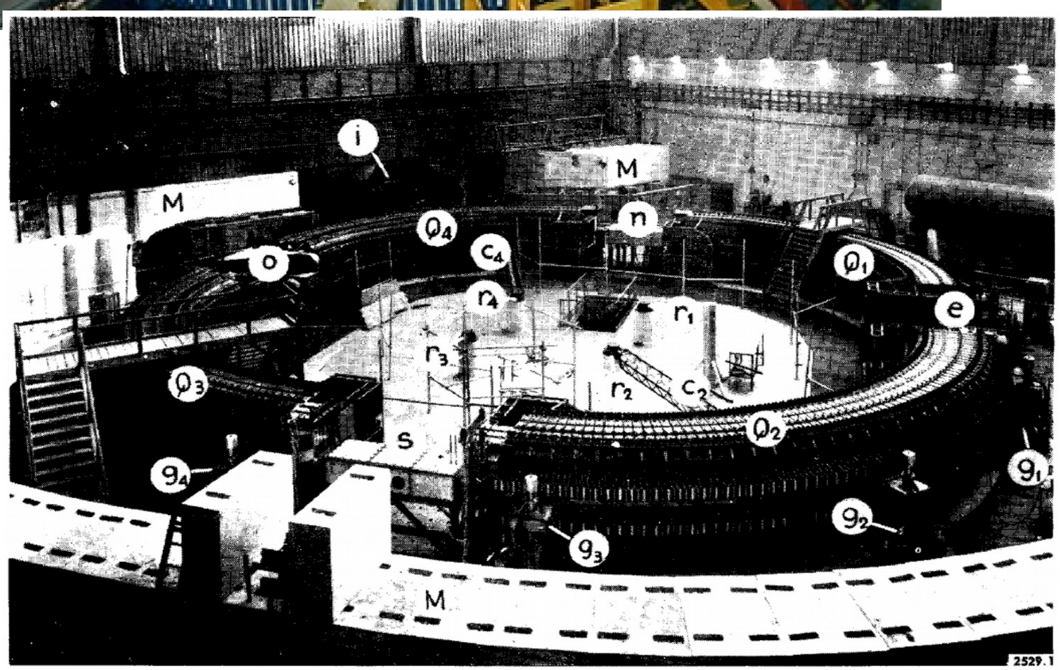
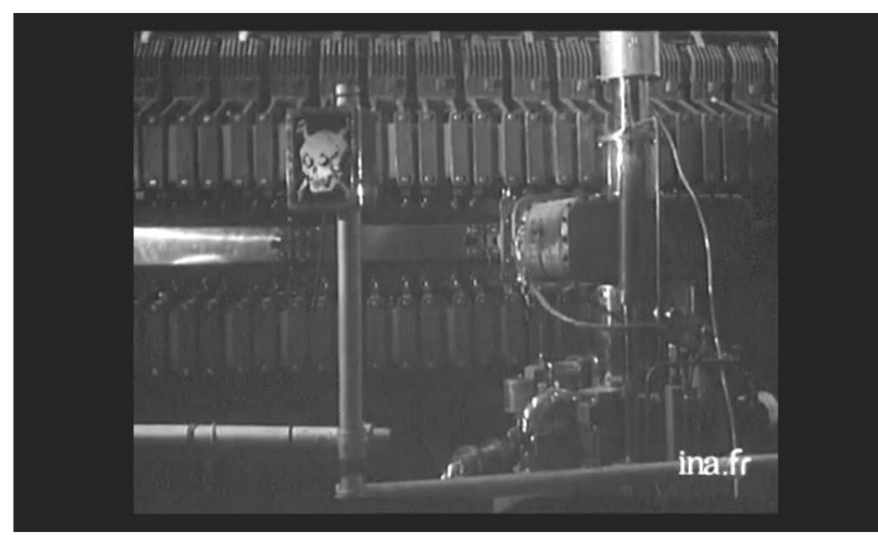



Figure 1. Vue générale de Saturne.



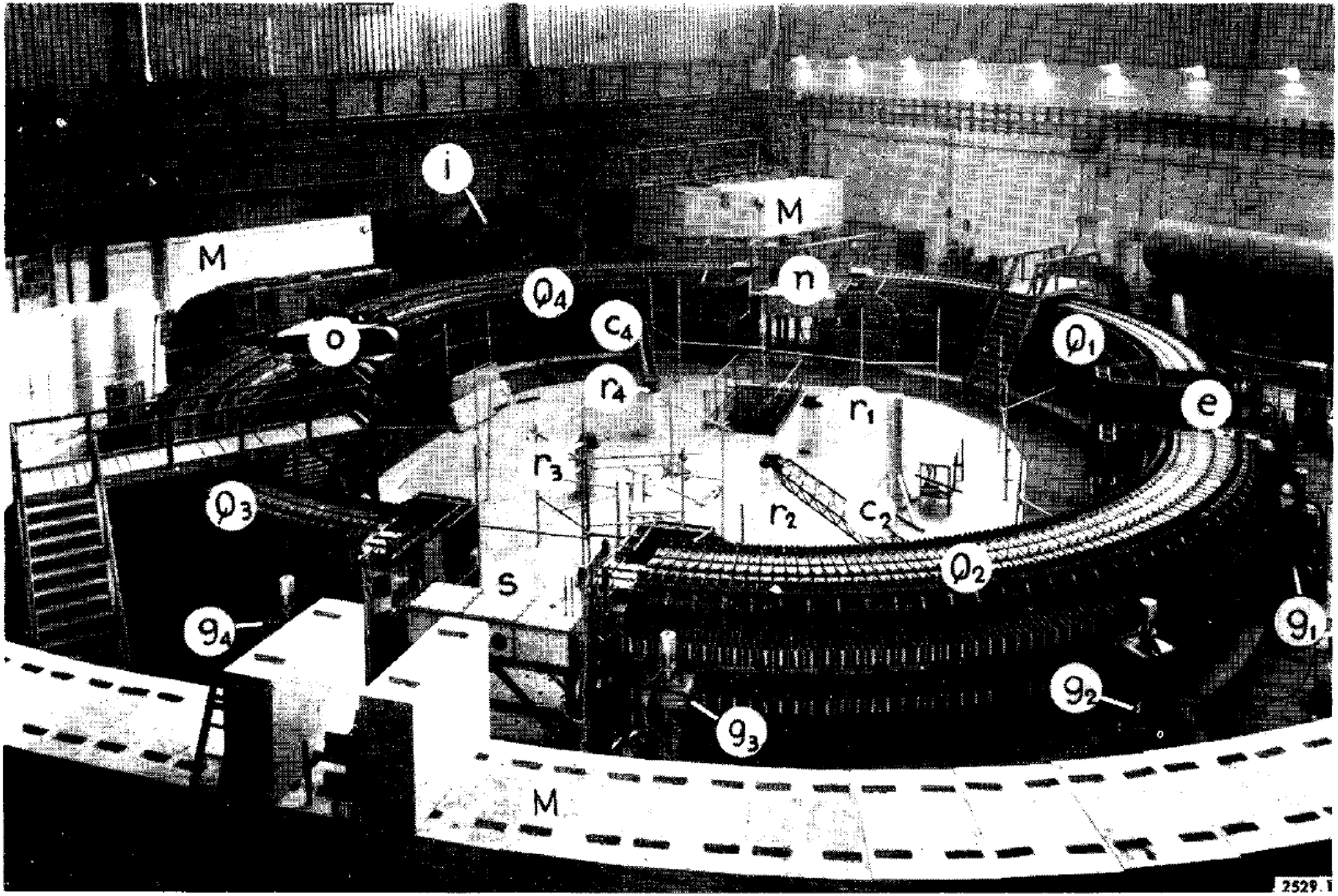
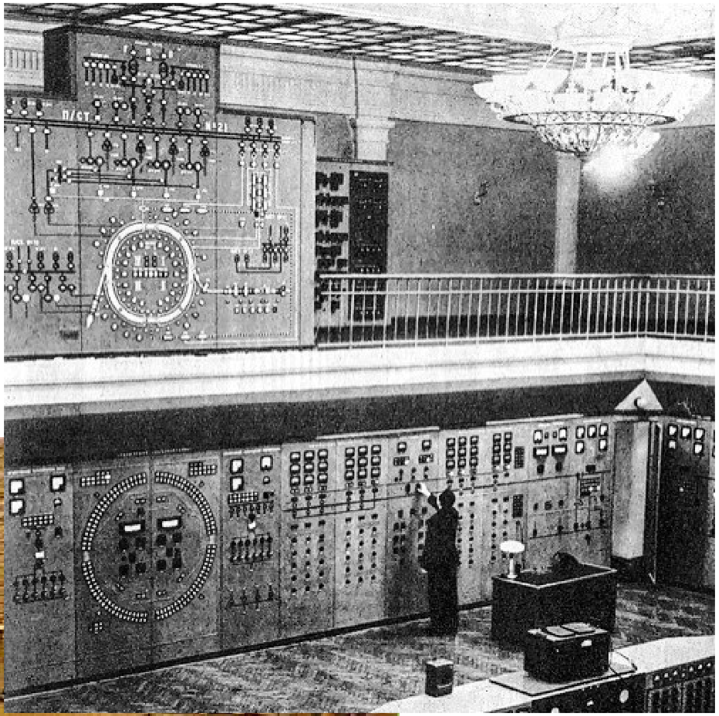



**Figure 1. Vue générale de Saturne.**

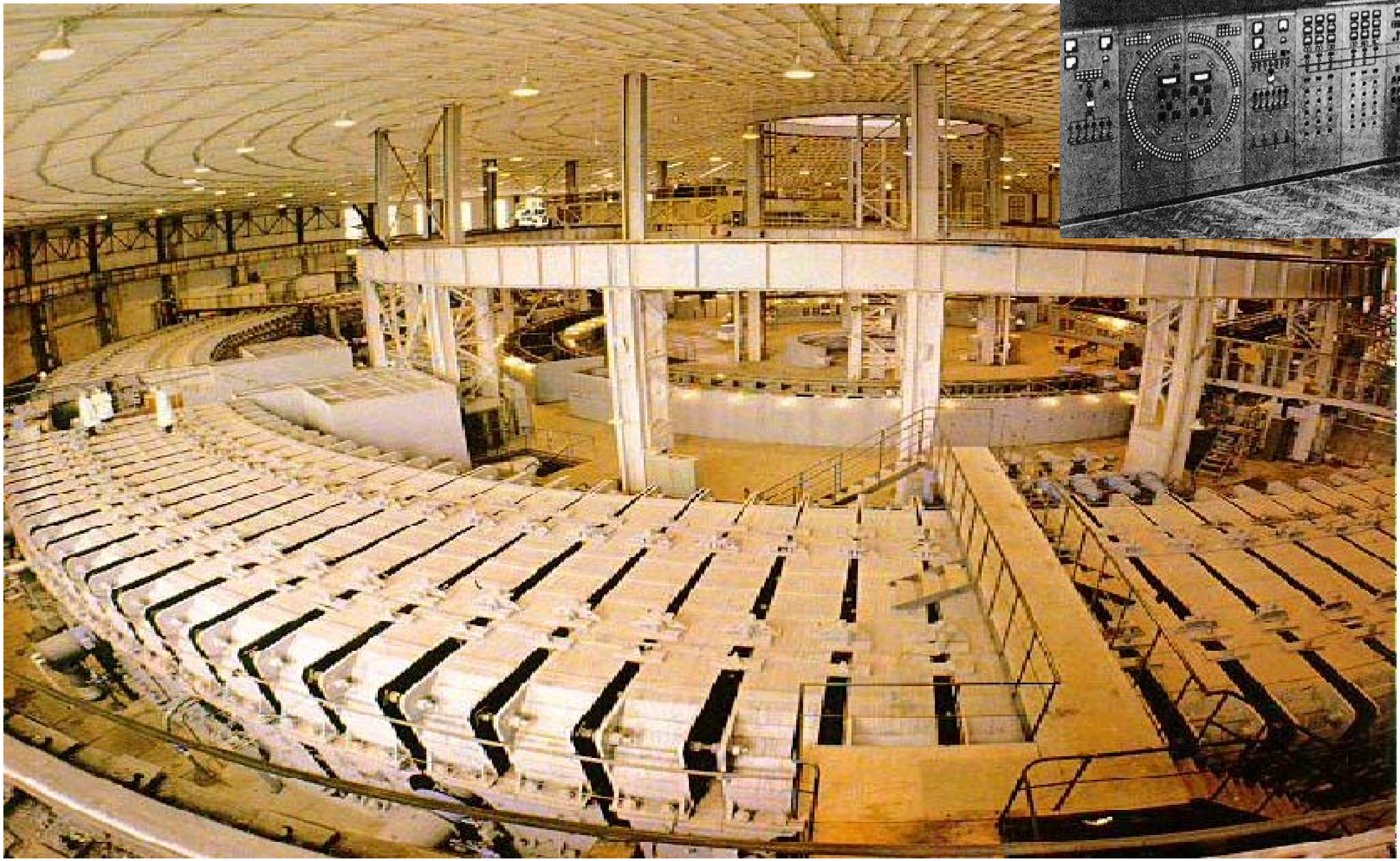
$Q_1$, $Q_2$, $Q_3$, $Q_4$ = Quadrants de l'aimant. n = Section droite nord contenant l'inflecteur d'injection. e = Section droite est contenant les électrodes de détection du faisceau. s = Section droite sud dans laquelle seront montés les dispositifs d'éjection du faisceau. o = Section droite ouest contenant la cavité HF d'accélération. J = Générateur électrostatique d'injection. $g_1$ à $g_4$ = Quatre des douze groupes de pompage de la chambre à vide. $r_1$ à $r_4$ = Références matérialisant les centres des quatre quadrants. Ces références et une référence centrale ont servi à mettre les blocs de l'aimant en position. Deux compas de mesure $c_2$ et $c_4$ sont encore en place. M = Différentes parties du mur de protection.

# The 10 GeV Synchrophasotron (1957-2003)
# JINR, Dubna



**Accelerated protons and Deutons**

**Constructed under the supervision of Vladimir Veksler**



# THE FALL

**...was essentially a matter of dipole magnet aperture:**

**- the Cosmotron aperture was 1.2 by 0.22 m**

**which had great consequences anyway – as the photos show,**

**- given B$\times$gap = μNI, larger gap means larger NI**
**→ great I, big coils, big yokes, big vacuum chambers, big pumps...**

**and – finally ! resulted from the application of "strong focusing" discovered in 1952.**

# WEAK FOCUSING SYNCHROTRONS NOWADAYS

## Medical application essentially

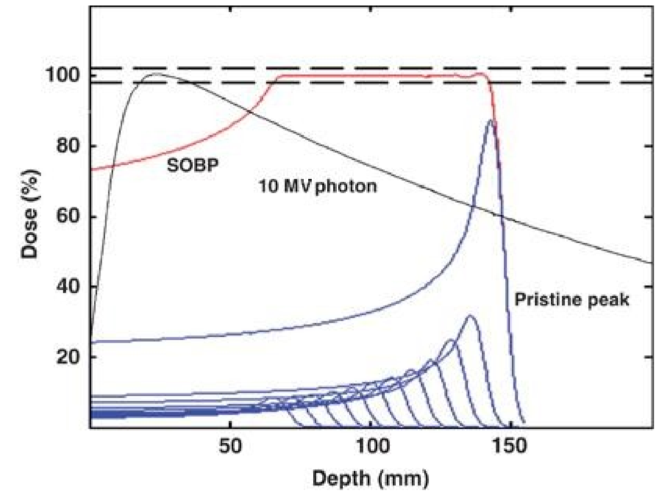
**A technically cool (dipole is easy, just 1 type of magnet x 4),**

**and cost-friendly,**

**way to get proton beams in the cancer-therapy range of energy**
**→ up to 250MeV for 35 cm Bragg peak penetration in water.**

# The Proton Treatment Center at Loma Linda University Medical Center.


**The first hospital-based proton facility.**
**Construction 1988-1990.**
**1 of ~40 proton centers worldwide**

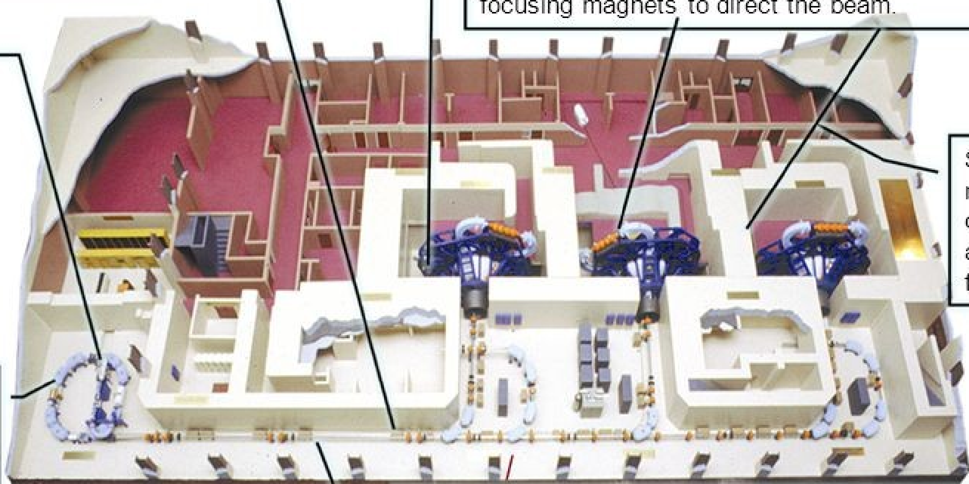



## Facility Layout

**Stationary Beam:**
Has two branches:
•Eye Tumors
•Head and Neck Tumors

**The Gantries:**
Resembling giant ferris wheels can rotate around the patient and direct the proton beam to a precise point. Each gantry weights about 90 tons and stands 3 stories tall. It supports the bending and focusing magnets to direct the beam.

**The Injector:**
Protons are stripped out of the nucleus of hydrogen atoms and sent to the accelerator.



Steel-reinforced concrete walls are up to 15 feet thick.

**Synchrotron: (Accelerator)**
A ring of magnets, 20 ft. in diameter, through which protons circulate in a vacuum tube.

**Beam Transport System:**
Carries the beam from the accelerator to one of four treatment rooms. This system consists of several bending and focusing magnets which guide the beam around corners and focus it to the desired location.