WEAK FOCUSING SYNCHROTRON

A BRIEF INTRODUCTION

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

Circular accelerator landscape, when longitudinal phase-stability was invented

Cyclotron

PSI, 590 MeV, not far from the ~1 GeV limit of this beam guiding technology.
However: high power!

Constant magnetic field
Gap RF voltage, constant frequency

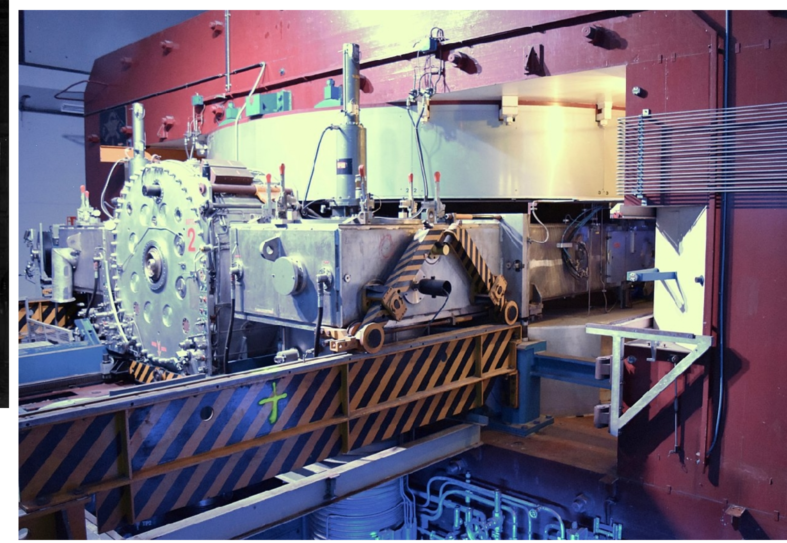
Betatron

Largest, late 1940s: 300 MeV
(first one, and Kerst, in foreground)

Pulsed magnetic field
Non-resonant (induction) acceleration

Synchro-cyclotron

CERN's 600 MeV, close to ~1 GeV limit of this cyclotron-type guiding technology.
Closed 1990



Constant magnetic field
Gap RF voltage, modulated frequency

None of these technologies has disappeared: cyclotrons, betatrons, synchro-cyclotrons, are still fabricated, but that's not 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 x 2πR 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 battleship 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!
  ~1GeV / 10kV ~ 10^5 turns → 10^5 C / c ~3x10^6 / 3x10^8 ~ tens of ms

- **Focusing inherits directly from proven betatron or cyclotron technique, 0<n=-R/BdB/dR<1 in all bendig magnets, "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."***

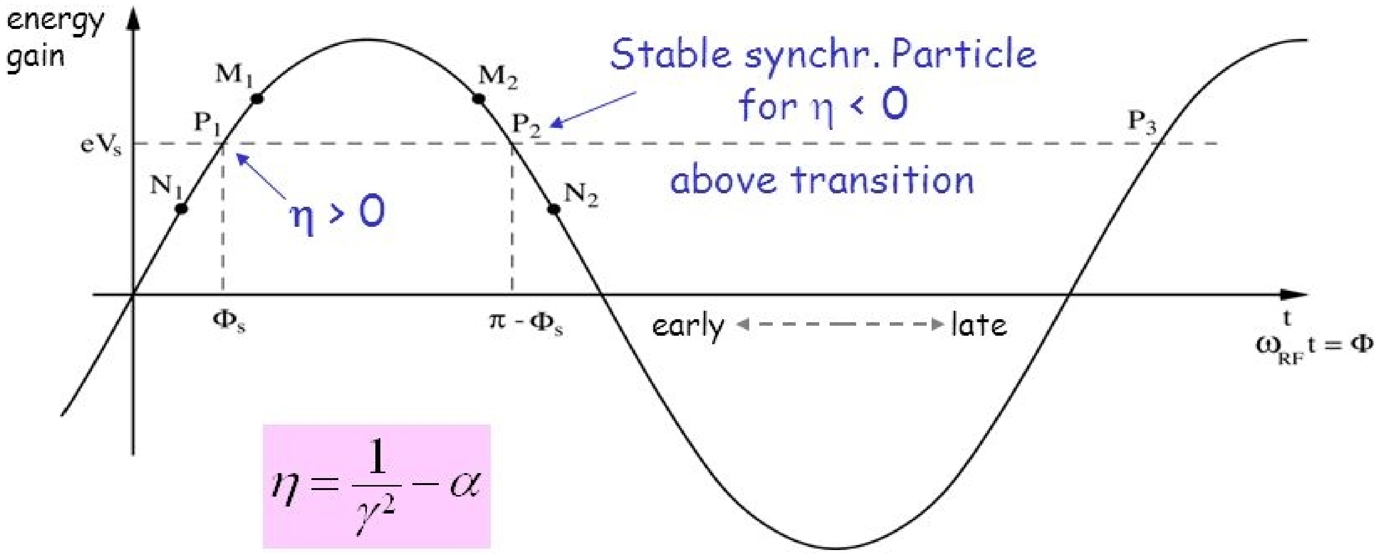
[1] A Sessler, E. Wilson

1994-Veksler; 1945-McMillan: discovery of the phase stability. That makes it possible!

Phase Stability in a Synchrotron

From the definition of η 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, 8 MeV proof-of-principle, operated by Goward in Woolwich, UK

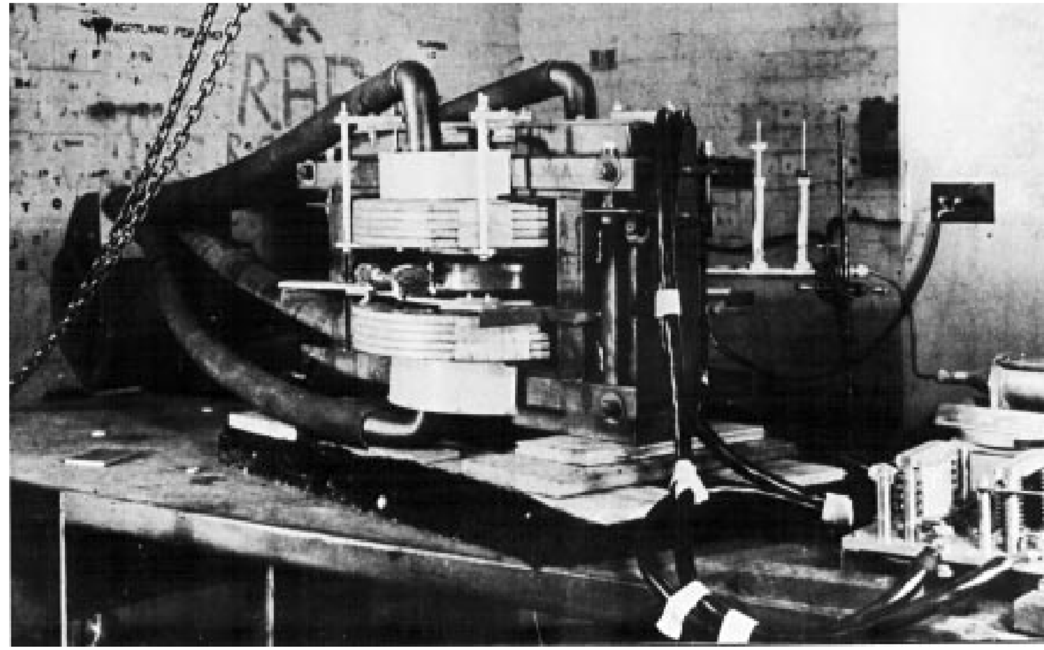


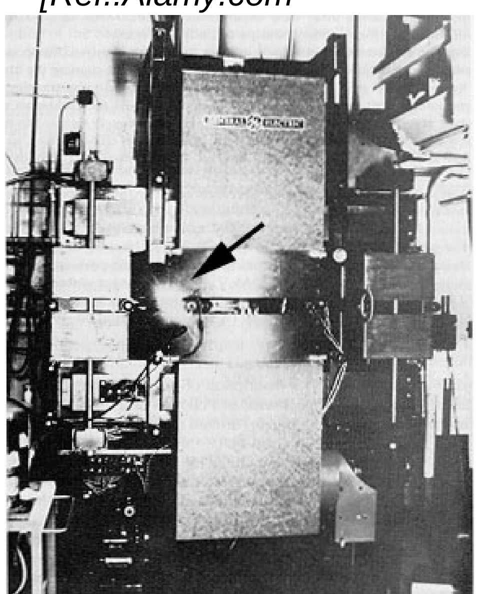
Fig. 4: The world's first synchrotron, installed at Malvern. The extra cooling system and RF feed to the resonator may be clearly seen.

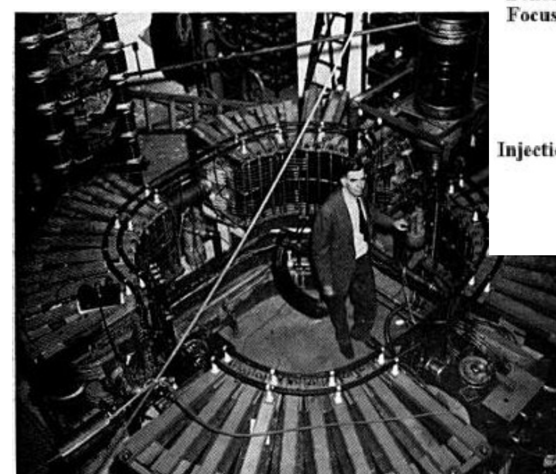
1947: First observation of synchrotron light (SR), not fully understood (spectrum etc.) - Julian Schwinger would develop a full theory of SR in a circular accelerator

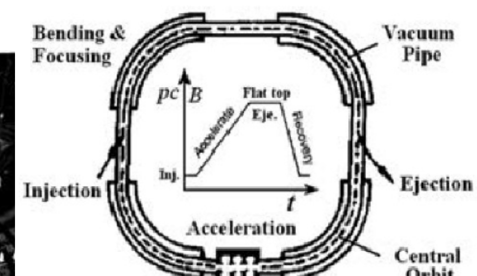
Vaccum chamber of GE synchrotron

[Ref.:Alamy.com

70 MeV synchrtron, GE







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

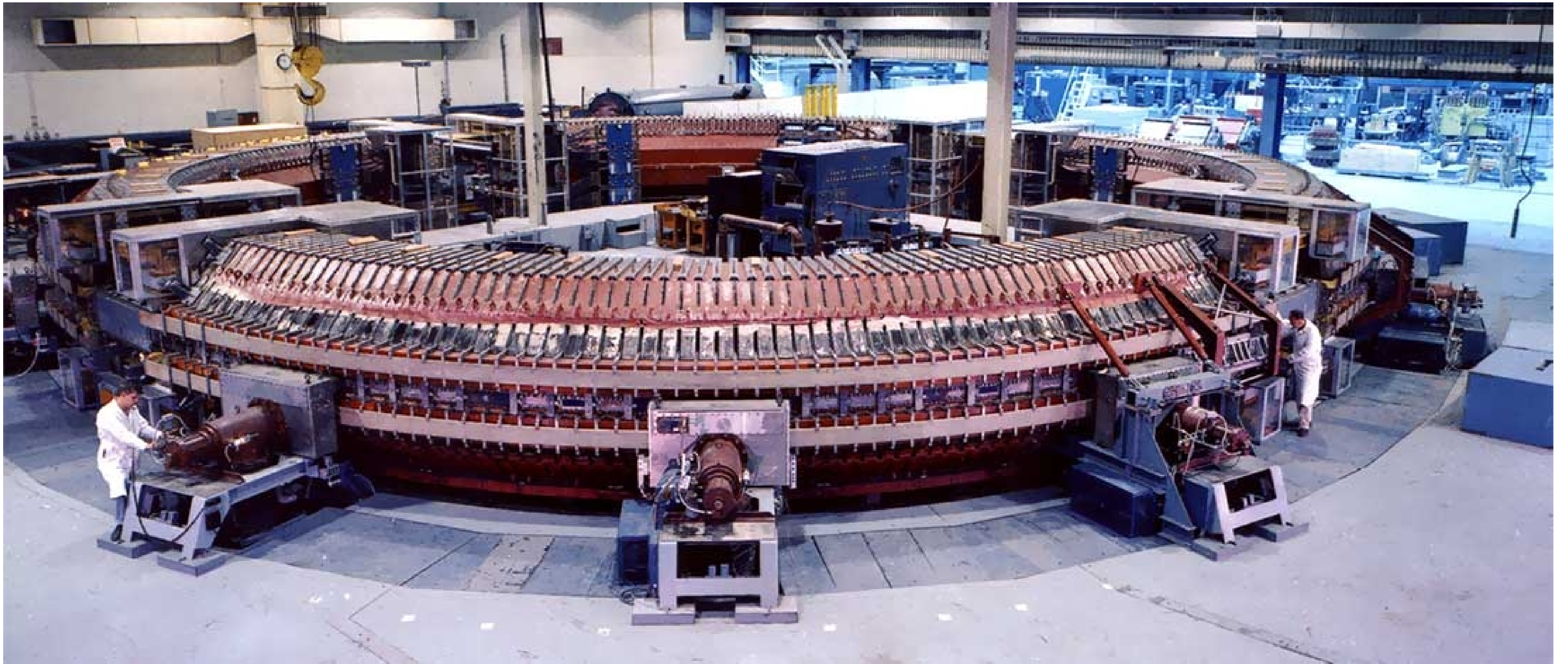
RACE FOR HIGH ENERGIES

Cosmotron (1952-1966) - The first >1 GeV ring, proton

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

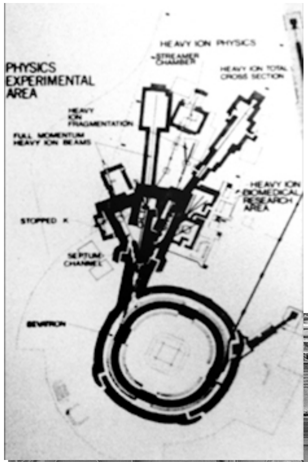
Reached its full design energy of 3.3 GeV in 1953.

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

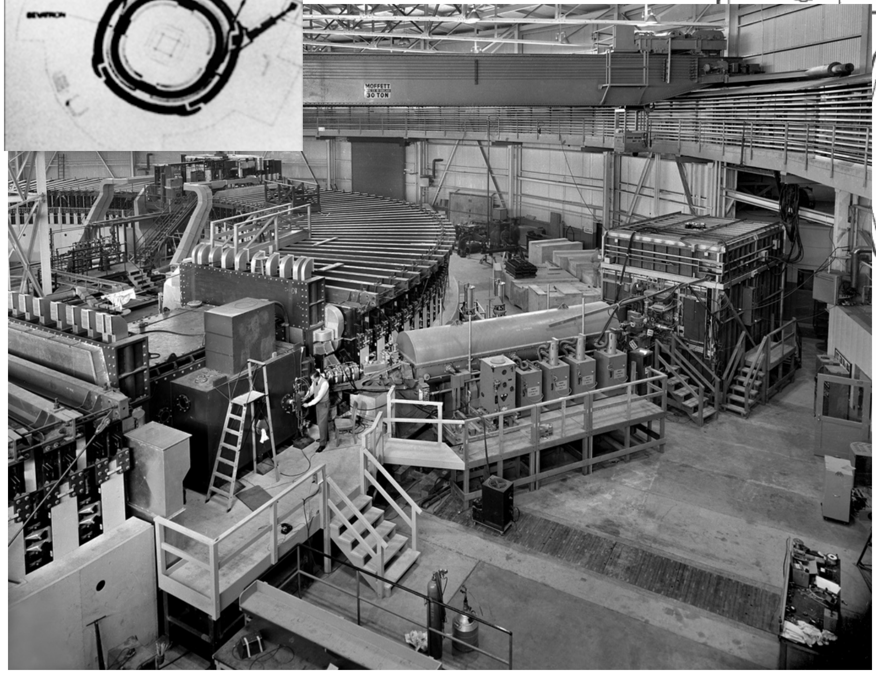


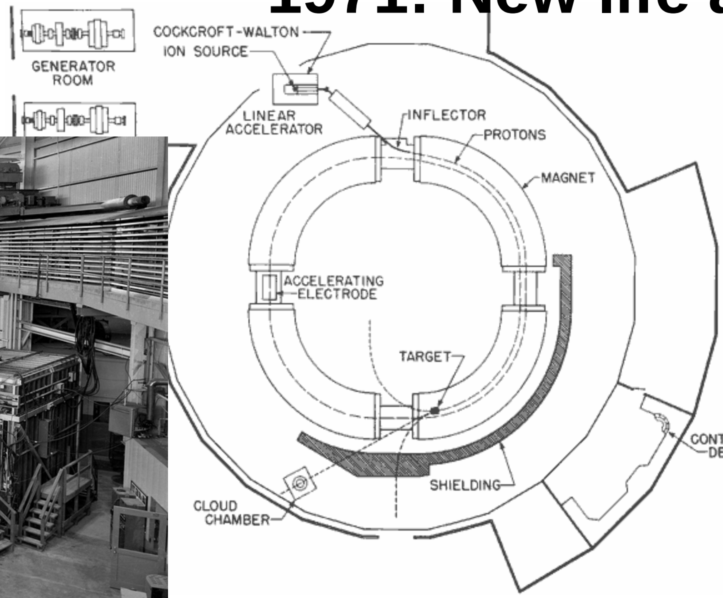
1954-1993: 6 GeV Bevatron, Berkley
1954: 1st ion-therapy treatment
1971: New life as "Bevalac", ions

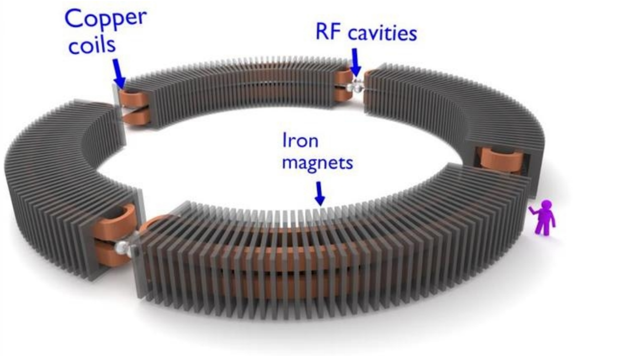
Beam goes to experimental areas

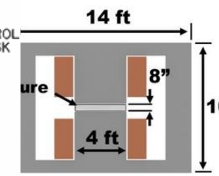


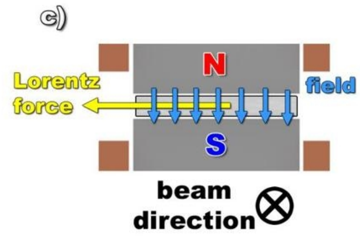
Construction





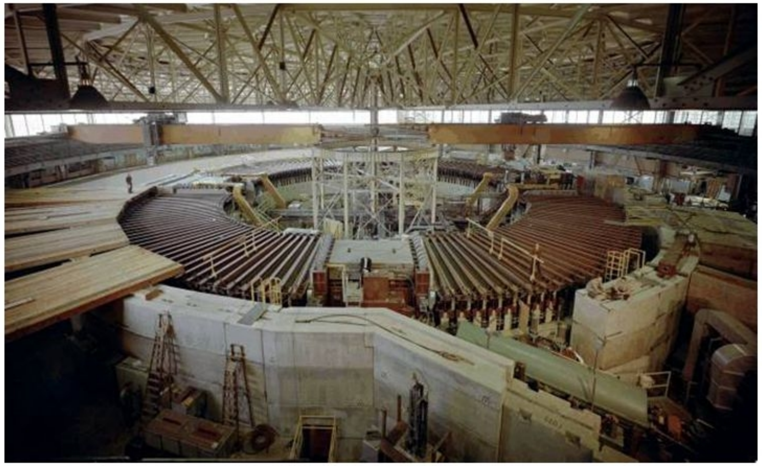






Control room

Power supplies



Overview of the Berkeley Bevatron during its construction in the early 1950s. One can just see the man on the left.

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

- meaning much smaller magnets,

- weak focusing remained the preferred choice of the cautious,

- and the Cosmotron was followed by:

ZGS at Argonne,

Synchrophasatron in Dubna,

Saturne in France

and Nimrod in the UK.

SATURNE 1, Saclay (1958-1970) 3 GeV

SATURNE 1, at Saclay, inaugurated in October 1958.

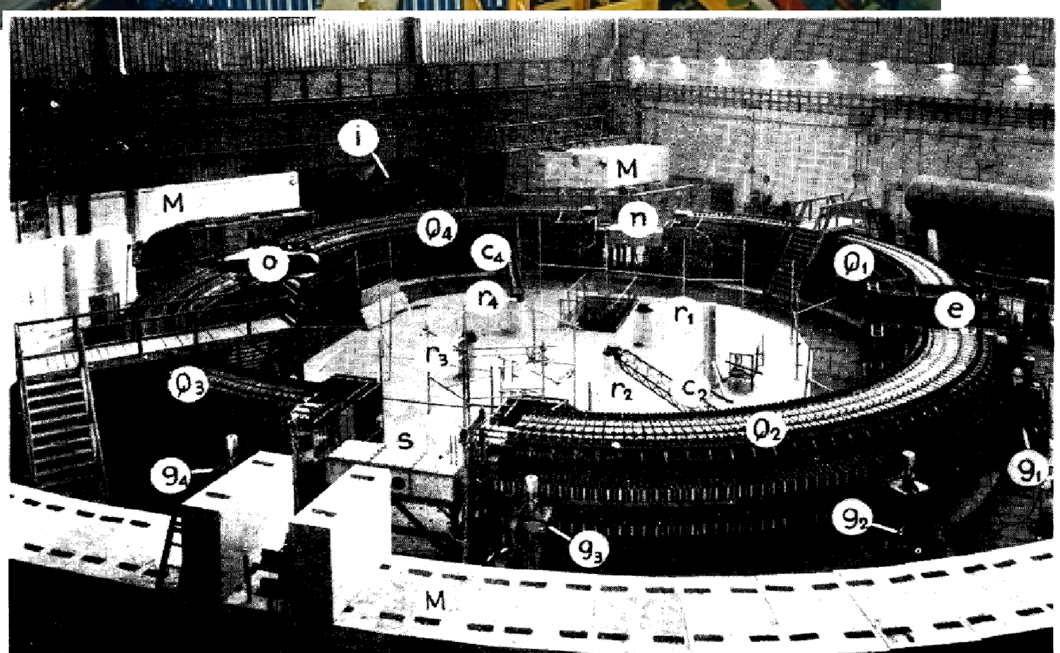
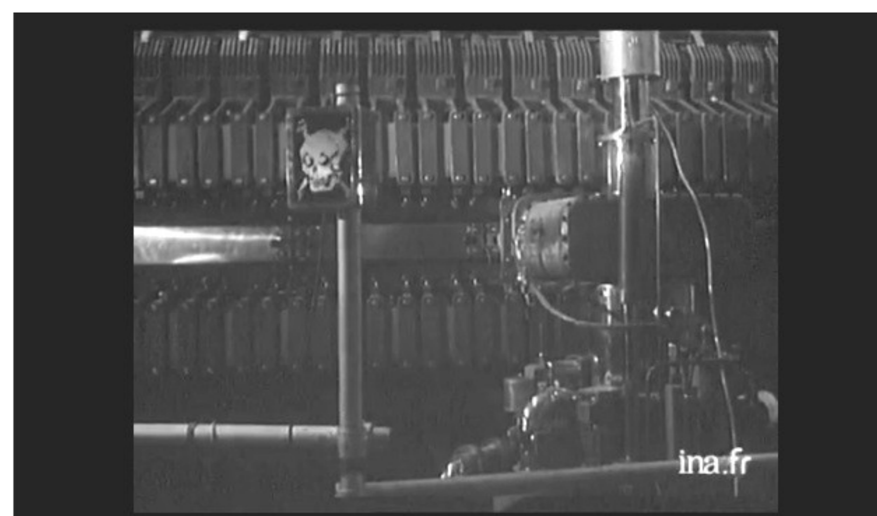


Figure 1. Vue générale de Saturne.

Plans for polarized proton at SATURNE 1 motivated Froissart-Stora theory on the effect of depolarizing resonances.



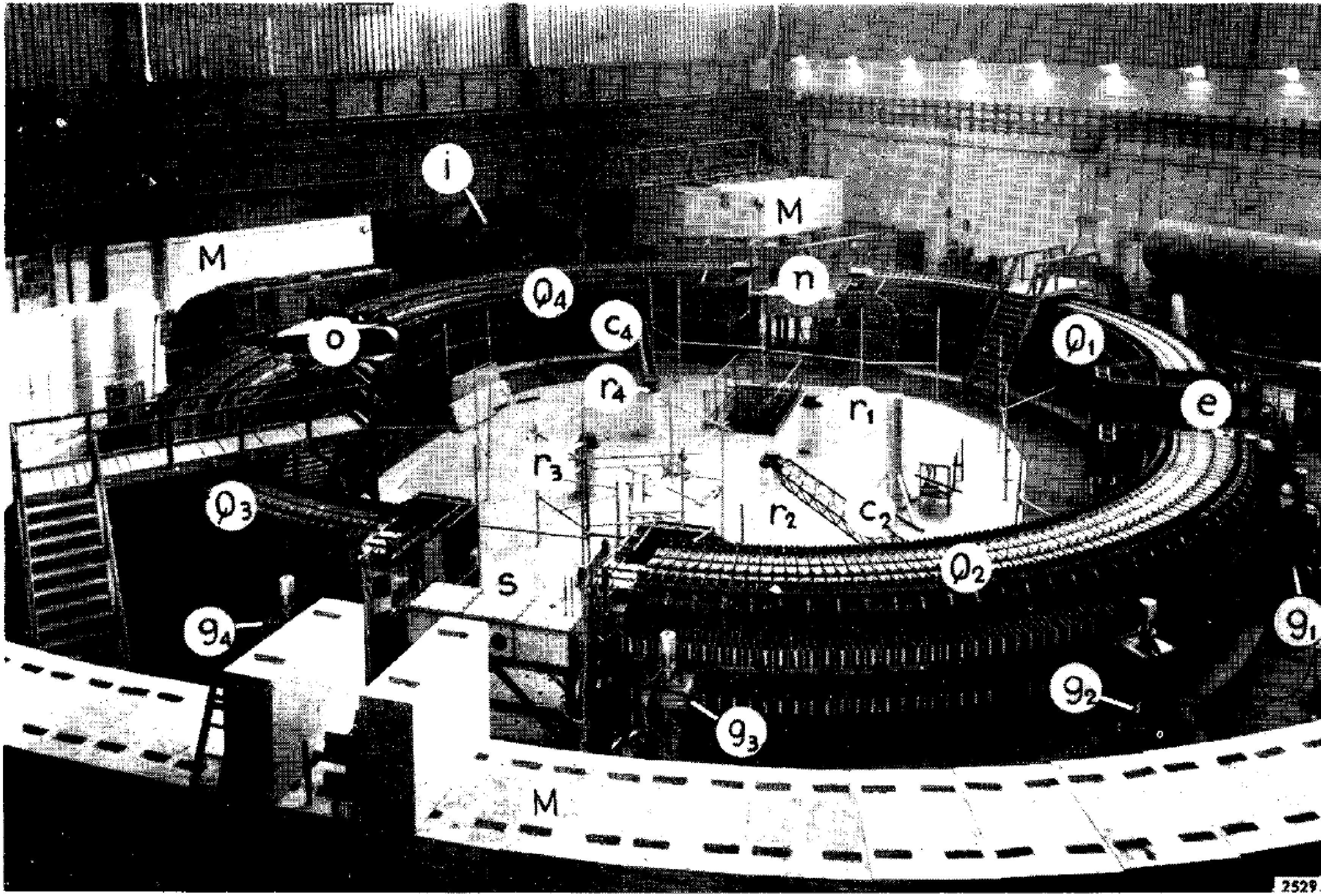
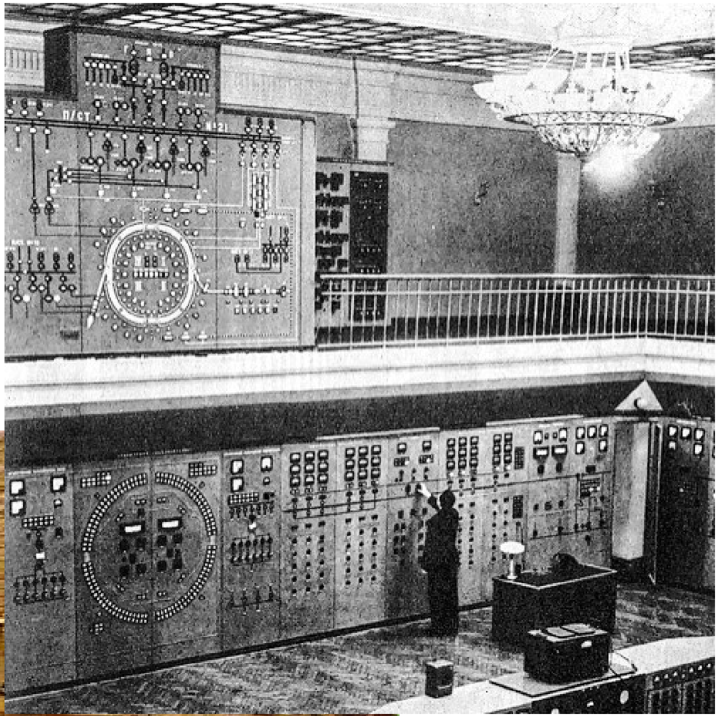


Figure 1. Vue générale de Saturne.

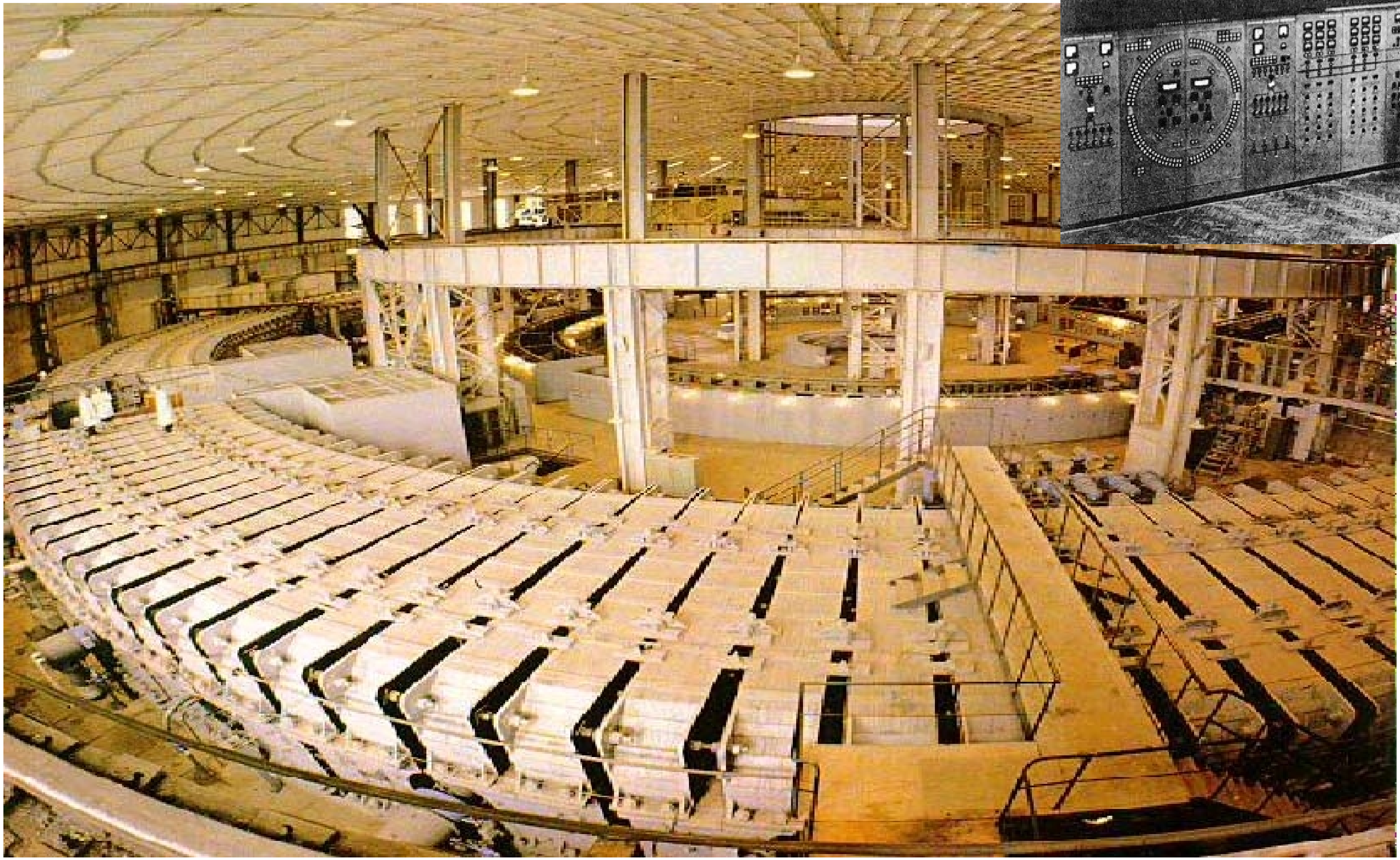
Q_1, Q_2, Q_3, Q_4 = Quadrants de l'aimant. n = Section droite nord contenant l'inflecteur d'injection. e = Section droite est contenant les électrodes de détection du faisceau. s = Section droite sud dans laquelle seront montés les dispositifs d'éjection du faisceau. o = Section droite ouest contenant 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 $B \times gap = \mu NI$, 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

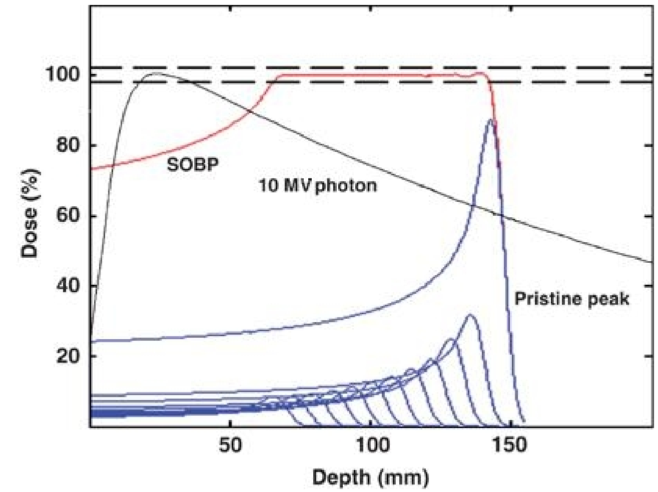
A technically cool (dipole is easy, just 1 type of magnet x 4),

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

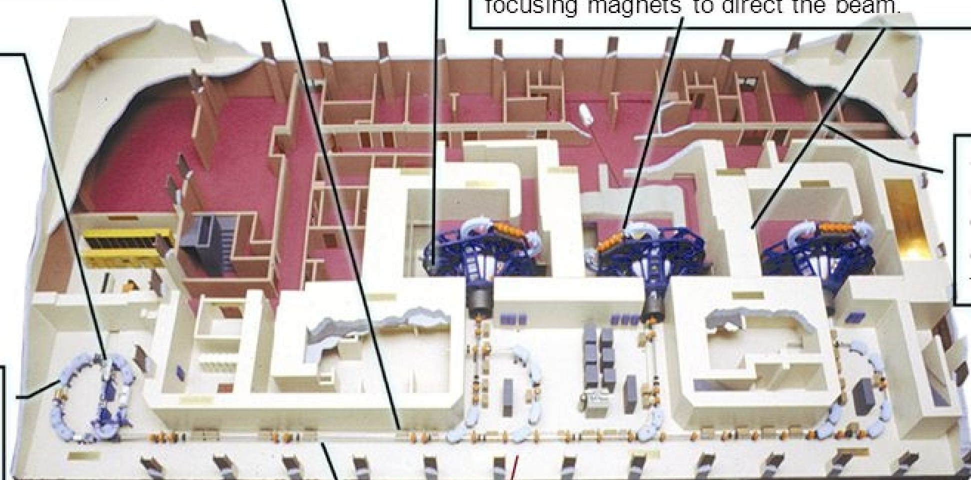


Facility Layout

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.