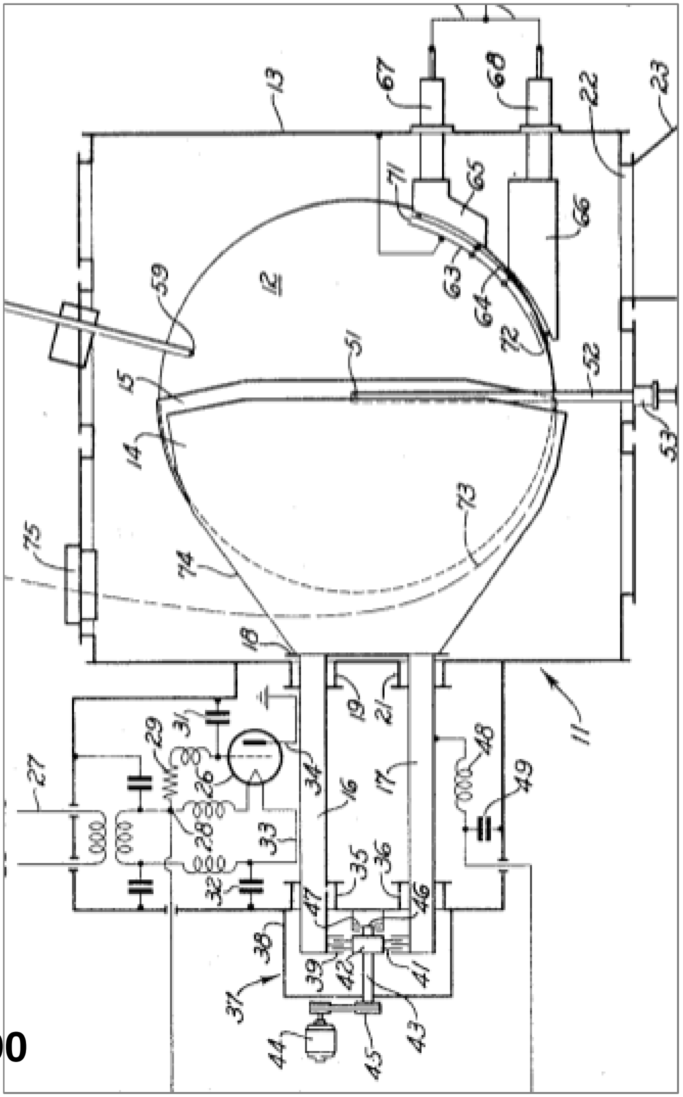
SYNCHRO-CYCLOTRON

A BRIEF INTRODUCTION

- ORIGINS, PRINCIPLE
- PAST SYNCHROCYCLOTRONS
- SYNCHROCYCLOTRON TODAY

McMillan's patent

A way to apply the brand new concept of “phase stability”, using existing technology - the cyclotron (weak focusing, dB/dr<0)



- The oscillating electric voltage is applied to a (unique) dee
- Its frequency decreases with increasing energy
- Thus voltage can be much lower compared to cyclotron, ~kVs : easier technology than ~100skV

→ many more turns needed ~10^5 vs. 100s– not a problem

- Yet, drawback:

- acceleration is to be cycled,

- only ions with correct, accelerating, phase (a few 10s degrees of a 360 degree period) are “captured” by the voltage wave

→ much lower average current

- The acceleration of the ions takes place twice per turn.
- At the outer edge, an electrostatic deflector extracts the ion beam.
- The first synchrocyclotron produced 195 MeV deuterons and 390 MeV α-particles.

Orsay 1 kHz synchrocyclotron

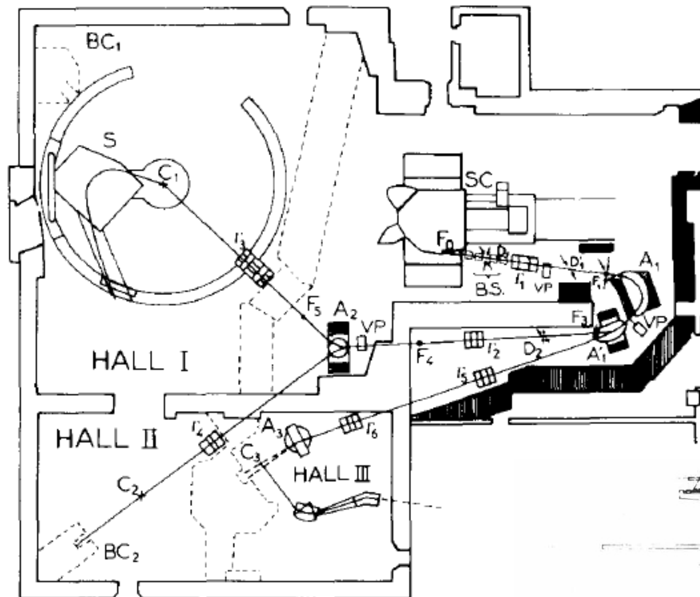
Mid. 1950s: a typical nuclear physics research installtion

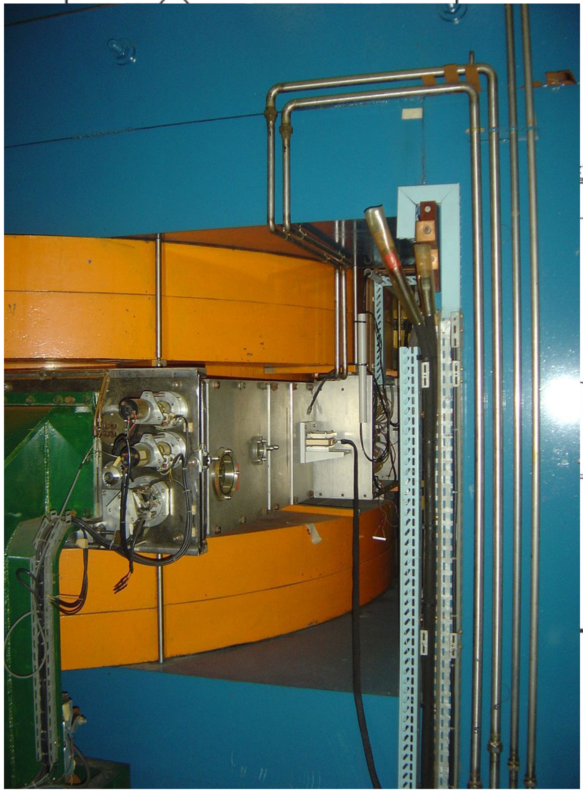
- 1958: first beam from the 157 MeV synchro-cyclotron

- 1975: shut-down for evolution to 200 MeV synchro-cylco

- 1993: installation converted to a hadrontherapy hospital, “IC-CPO” : Institut Curie-Centre de Protontherapie d'Orsay, one of the two in France

- 2010: synchro-cyclo stopped, proton-therapy persued with an IBA C250 cyclotron





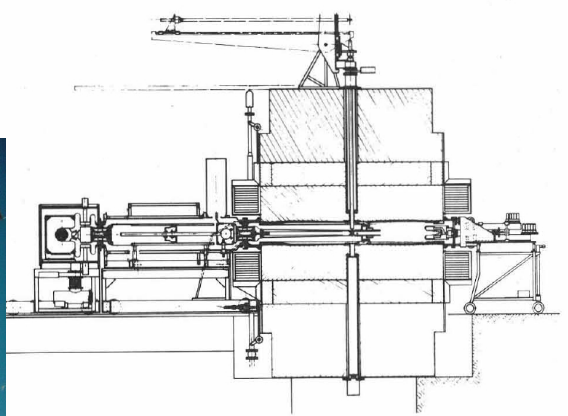


Fig.7. Side view

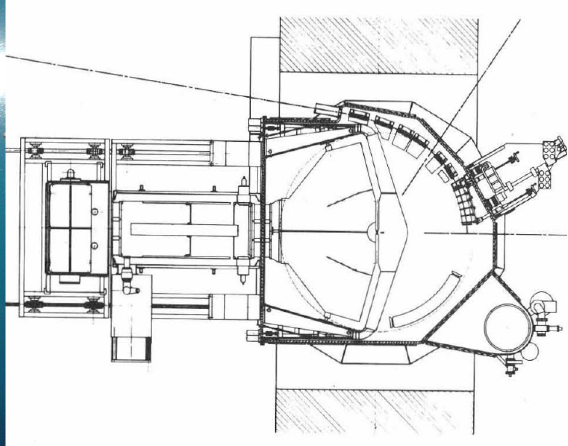


Fig.8. Top view

CERN Synchrocyclotron (SC)

- 1957: construction. CERN’s first accelerator, provided beams for CERN's first experiments in particle and nuclear physics, up to 600 MeV.

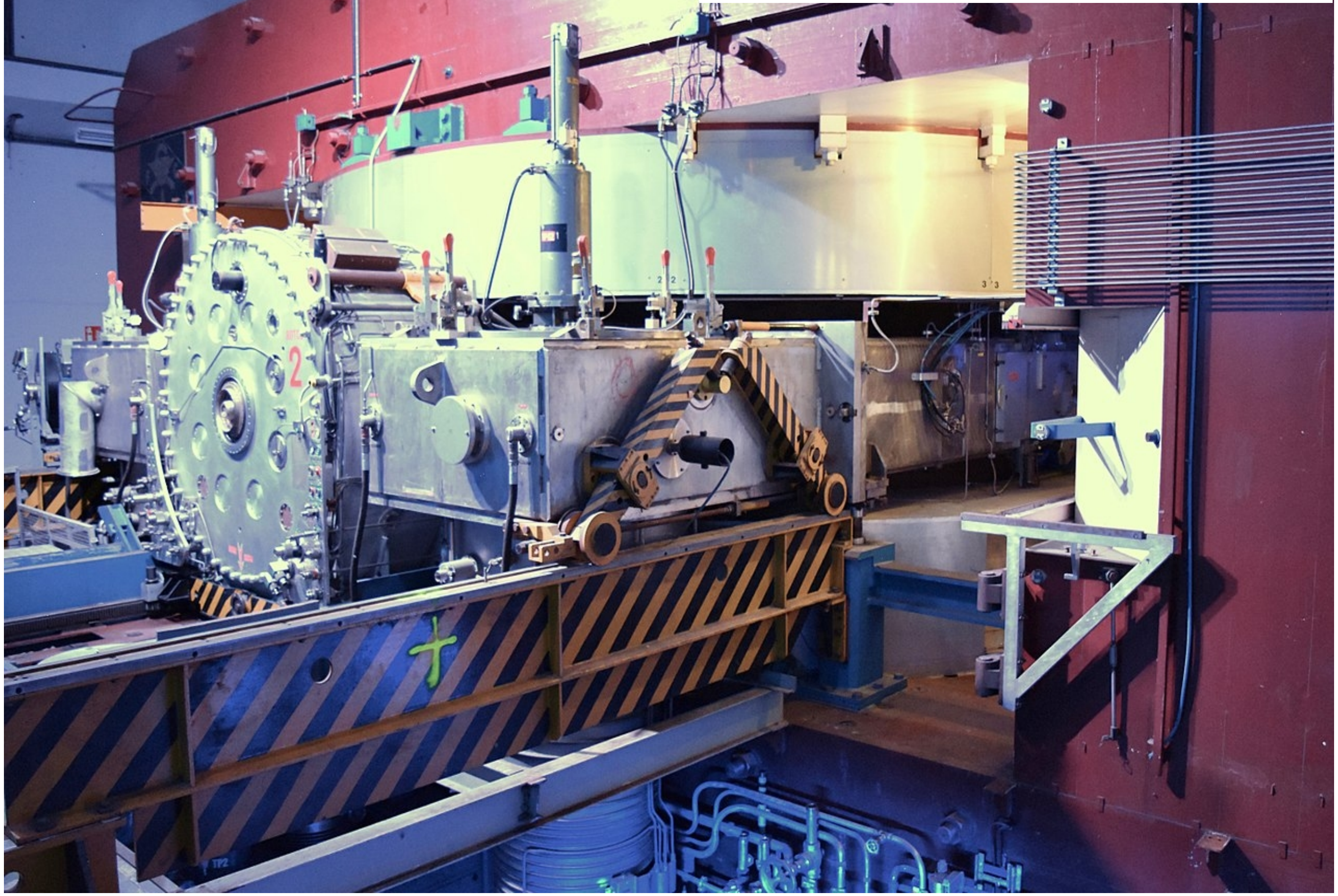
- 1964: started to concentrate on nuclear physics, leaving particle physics to the newer, 30 GeV, Proton Synchrotron.

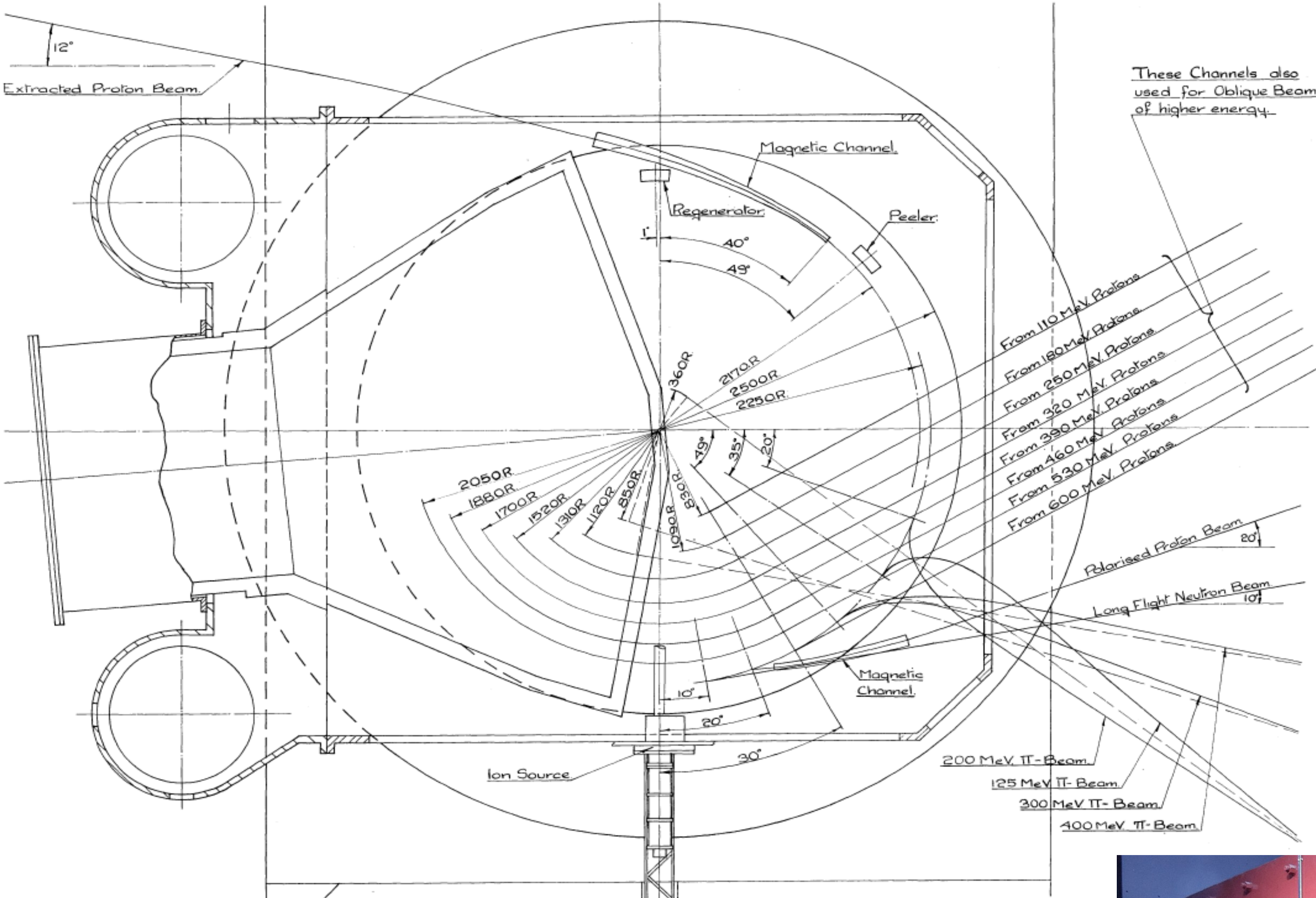
- 1967: start supplying beams for the radioactive-ion-beam facility ISOLDE (nuclear physics, astrophysics, Medical.)

- 1990: SC closed, after 33 years of service.

10. Parameters of the Synchro-cyclotron

Maximum energy of the protons	600 MeV
Expected internal circulating beam (average in time)	1 μA
Exit radius (n = 0.2)	2.27 m
Flux density, at centre	1.88 Wb/m²
Flux density, at n = 0.2 (R = 2.27 m)	1.79 Wb/m²
Ampere-turns, normal	$1.2\ 10^6$ At
Ampere-turns, maximum	$1.35\ 10^6$ At
Coil power, normal	750 kW
Magnet weight	2500 T
Frequency range, theoretical	28.7 - 16.6 MHz
Repetition Frequency	55 Hz
Pressure in vacuum tank, ultimate	3.10^{-6} mm Hg
Pressure in vacuum tank, normal	6.10^{-6} mm Hg





A. Arrangement of internal targets, beam extraction system and ion source.

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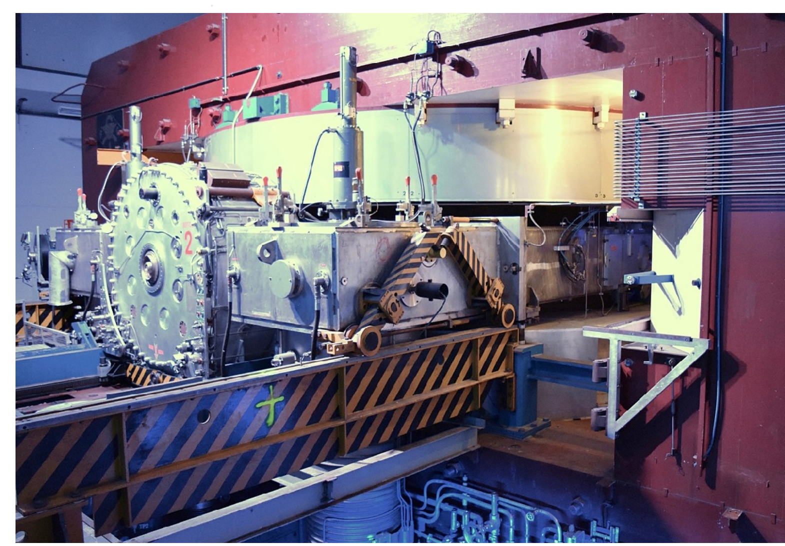


Synchrocyclotron today

Synchro-cyclotrons have been in many areas of science from the 1950s, include medicine, nuclear physics where high energy hadron beams were needed.

It is still present in hadrontherapy application today

- cryogeny makes it compact

- an easy and cheaper technology to get ion beams

FFAG technology is also part of the game

MEDICYC's S2C2

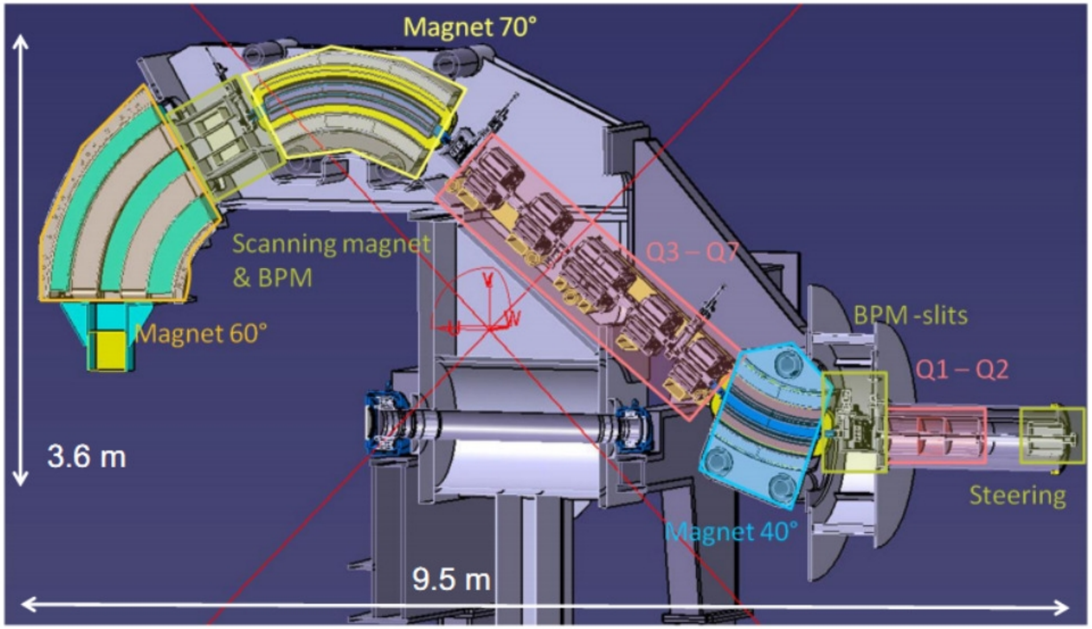
- 250 MeV protontherapy synchrocyclotron

at Nice, France

- First beam 2015

- IBA developed it with, and first implemented at, the anti-cancer protontherapy center MEDICYC, Nice.

- Compact gantry, attached to the S2C2



FFAG synchrocyclotron

See detailed introduction to the FFAG session

BETATRON

A BRIEF INTRODUCTION

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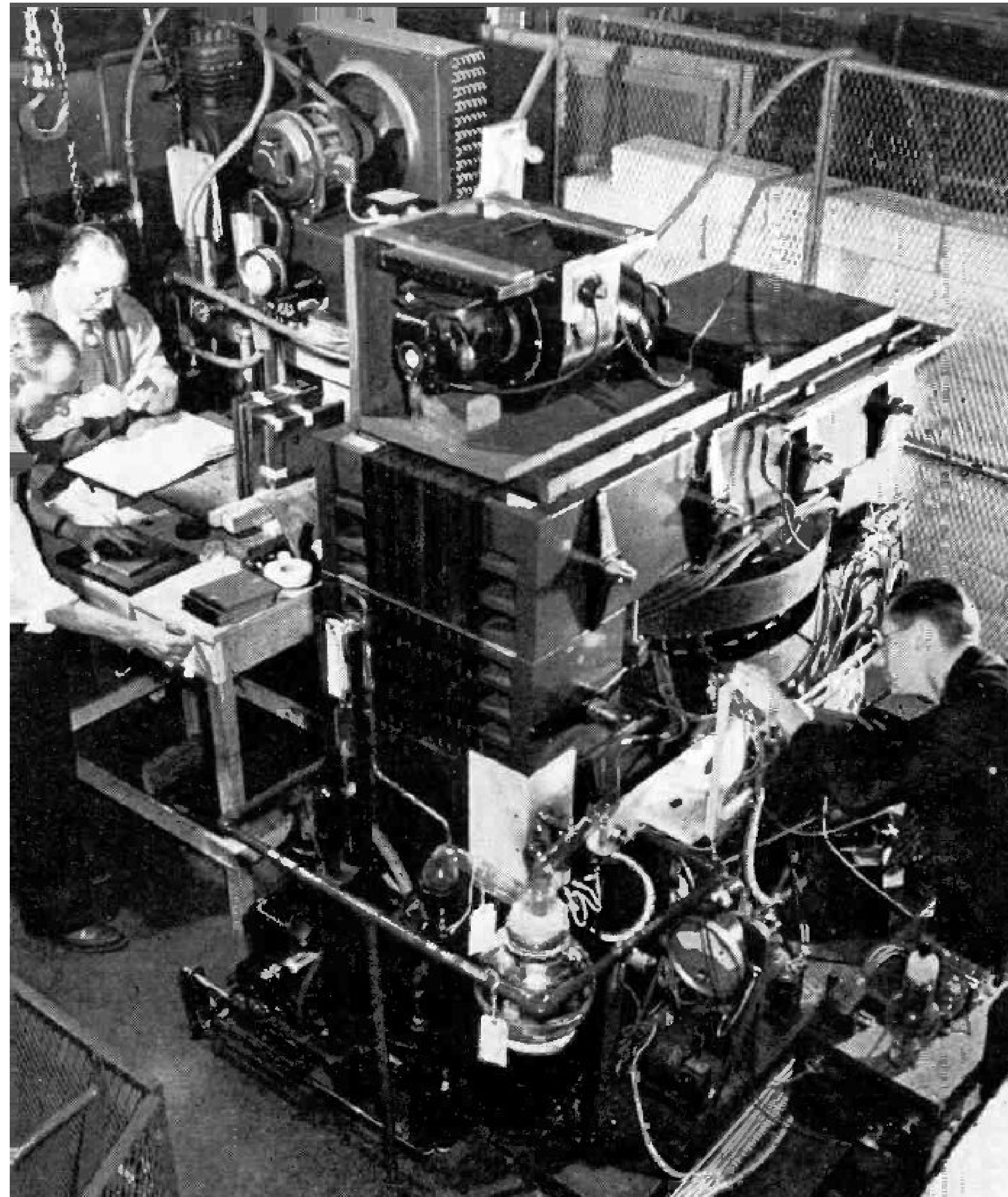
- BETATRON TODAY

What it looked like in the 1940s :

Ref. Wikipedia



Early betatron at University of Illinois, a 4-ton dipole magnet device.

Kerst working on it.

- **1920s : The betatron method was devised to accelerate beta-rays (today's electron beams !) to produce bursts of X-rays**

- constant-radius orbit, the $B_{induc}=2B_{guide}$ "Wideroe rule", was advanced in that period,

- **1940 : that's when a complete theory of transverse stability would be formalized (Kerst & Serber).**

It allowed bringing the concept to realisation:

- **1940: production of X-rays from a 2.3~MeV e-beam (100 millicurie radium source equivalent): a breakthrough in medecine, material radioscopy.**

- **Kerst-Serber's betatron implements 3 technologies of that time:**

- the ring method as used in cyclotrons, and pole shaping (dB/dr<0) focusing in a similar way

- induction acceleration, already known for many years

- vacuum

- The betatron is not a resonant accelerator, however, it is in important aspects the precursor of synchrotrons:
- the first constant-orbit ring, field and momentum rising together, magnetic field pulsed for that reason, acceleration cycled as a corollary,
- no problem to digest relativistic effects
- its understanding yielded the theory of “betatron motion” and its jargon as betatron frequency, betatron amplitude, betatron resonance...
- interestingly, the first proof-of-principle synchrotron used an existing betatron magnetic structure

- The 1940-1950 period saw increase to ultimate energy:
  Kerst's 300 MeV machine, for particle physics.
Limitations were magnet size, *synchrotron radiation*

- The betatron would rapidly, in an interval of a few years, be outperformed
- by linac in the medical application,
- synchrotrons for higher electron energies ever needed by nucleus and particle physics

The betatron concept does not present an interest for ions:

- at low energy, v<<c, an ion would only get little energy increase over the short duration of a betatron pulse.

On the other hand large proton or deuteron rigidity, BR = p/q,

- means large magnet size (proton BR is for instance 2.4 Tm at 250 MeV, 5.7 Tm at 1 GeV, R respectively 1.6 m, 3.8 m for Bmax = 1.5 T),

- whereas magnet core volume increase as R^3 in corellation with return flux.

A 6 MeV betatron (Germany, 1942)

Conclusion 1/2

[5] ADVANCED INSPECTION SYSTEMS. JME Portable 6 MeV. X-RAY BETATRON. Microprocessor model: PXB-6 M. Jun 15, 2010.

- **Betatrons are produced nowadays essentially as light (portable) compact X-ray sources for material analysis, a few MeV energy range.**

- **Betatron acceleration also found extention to acceleration in electron-FFAG (Japan R&D), for high power electron beams**

→ food sterilization, radiography

- **Note: strictly speaking, ramping field in synchrotron magnets causes inductive accelerating E-field. It is in principle a small effect...**

Conclusion 2/2
A parenthesis: induction acceleration

- **The betatron method is one way to use it**

- **There are others, not to mention the induction linac... for instance in the recent past:**

  - induction acceleration in a synchrotron (KEK)

→ was proposed for long-bunch at LHC, early 2000s...