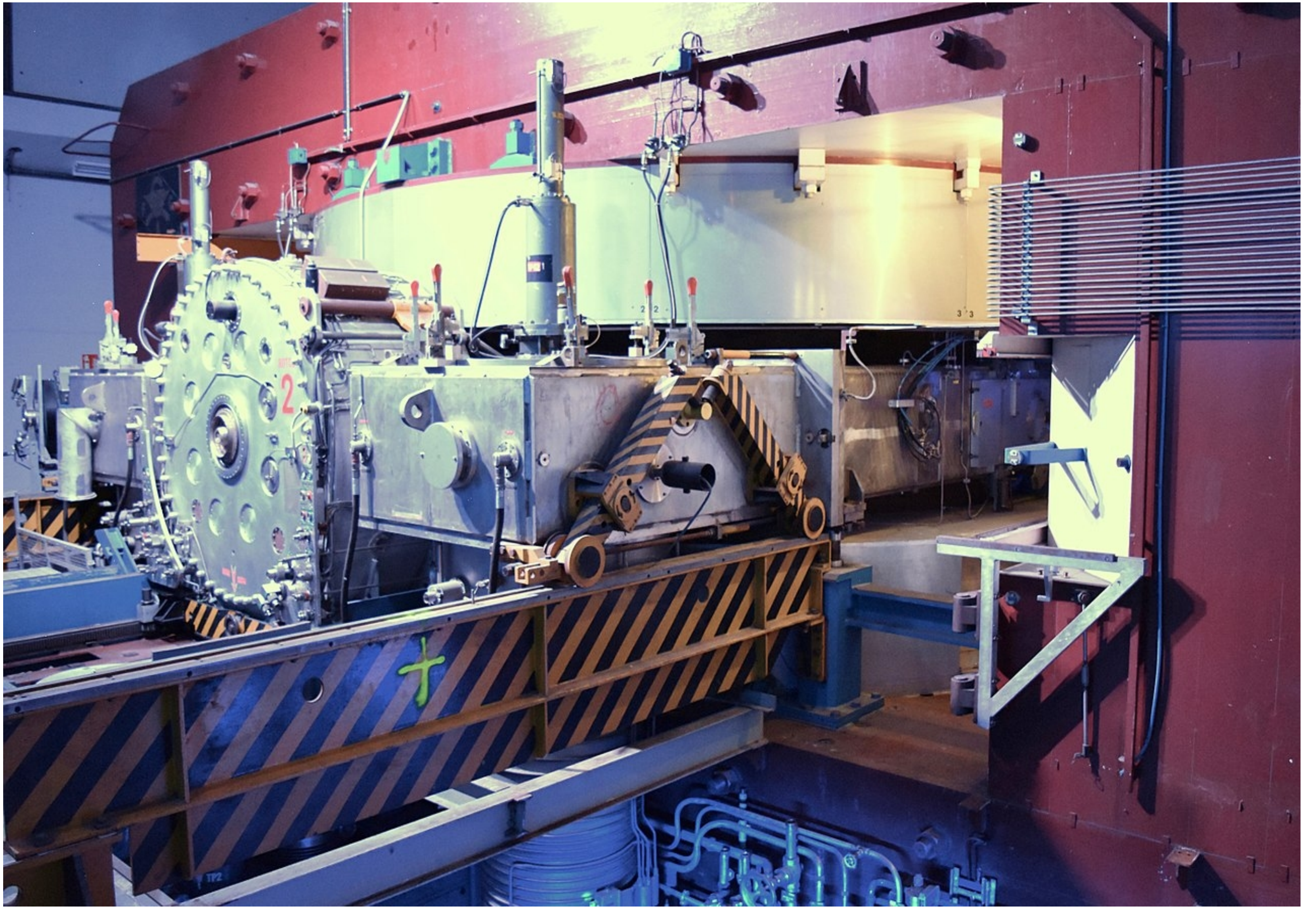
SYNCHRO-CYCLOTRON

A BRIEF INTRODUCTION

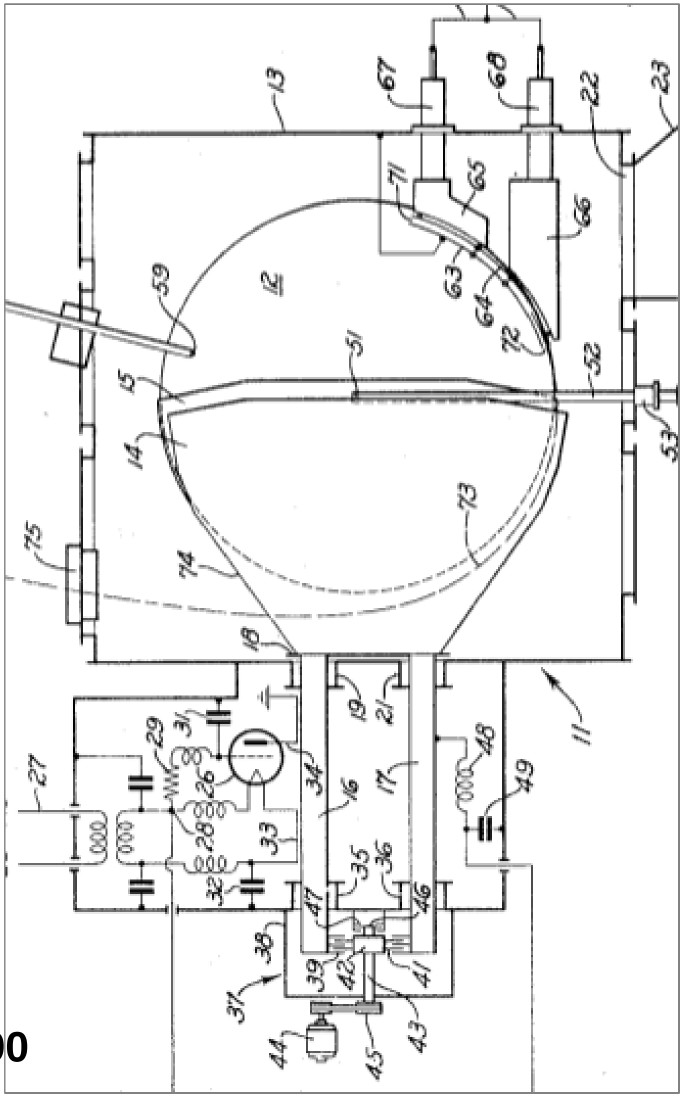
- ORIGINS, PRINCIPLE
- PAST SYNCHROCYCLOTRONS
- SYNCHROCYCLOTRON TODAY

In real life...
CERN 600 MeV SC



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

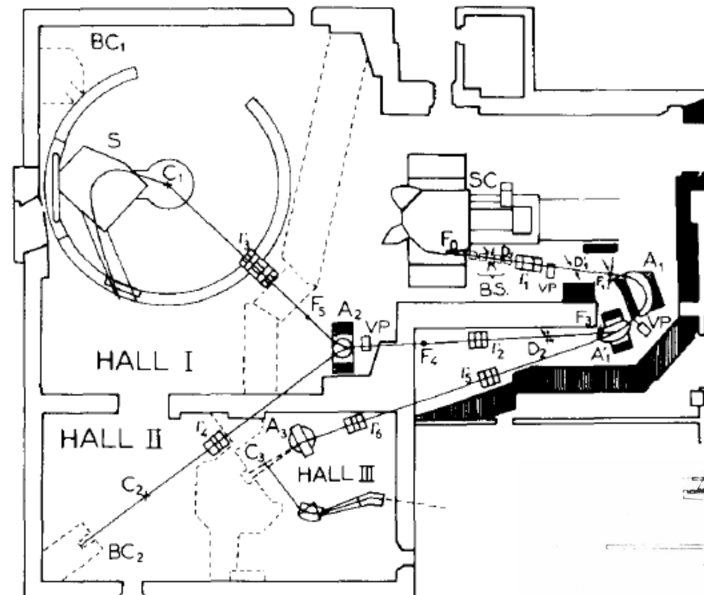
→ much lower average current

- **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



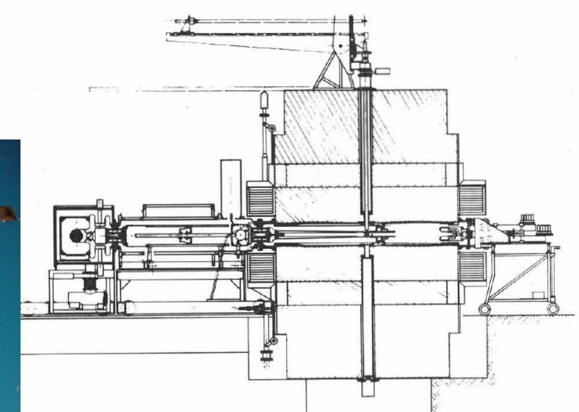


Fig.7. Side view

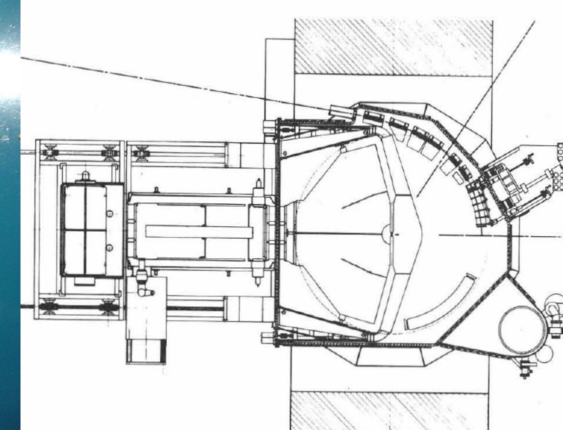


Fig.8. Top view

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.**

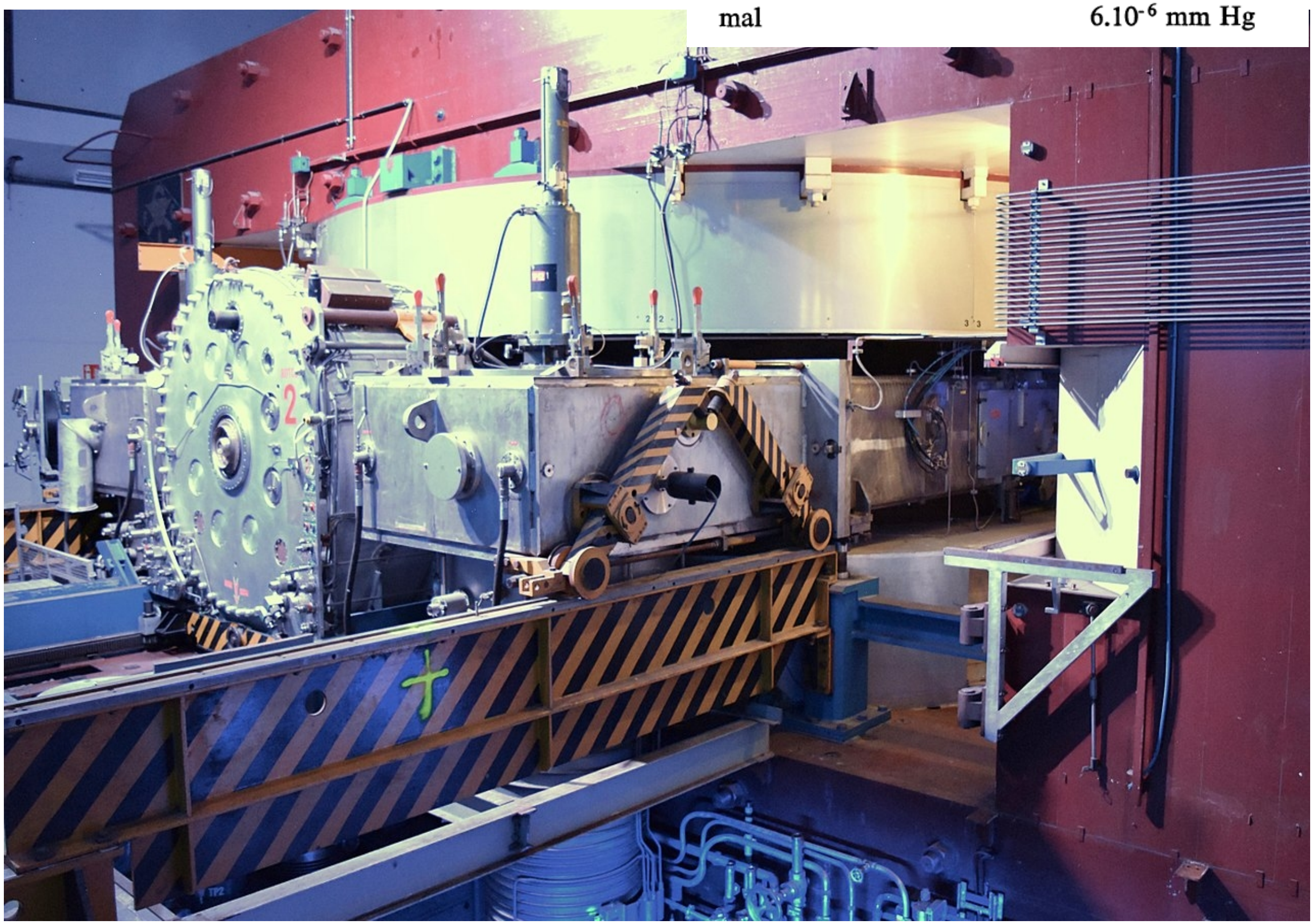
- **1964: started to concentrate on nuclear physics, leaving particle physics to the newer, 30 GeV, Proton Synchrotron.**

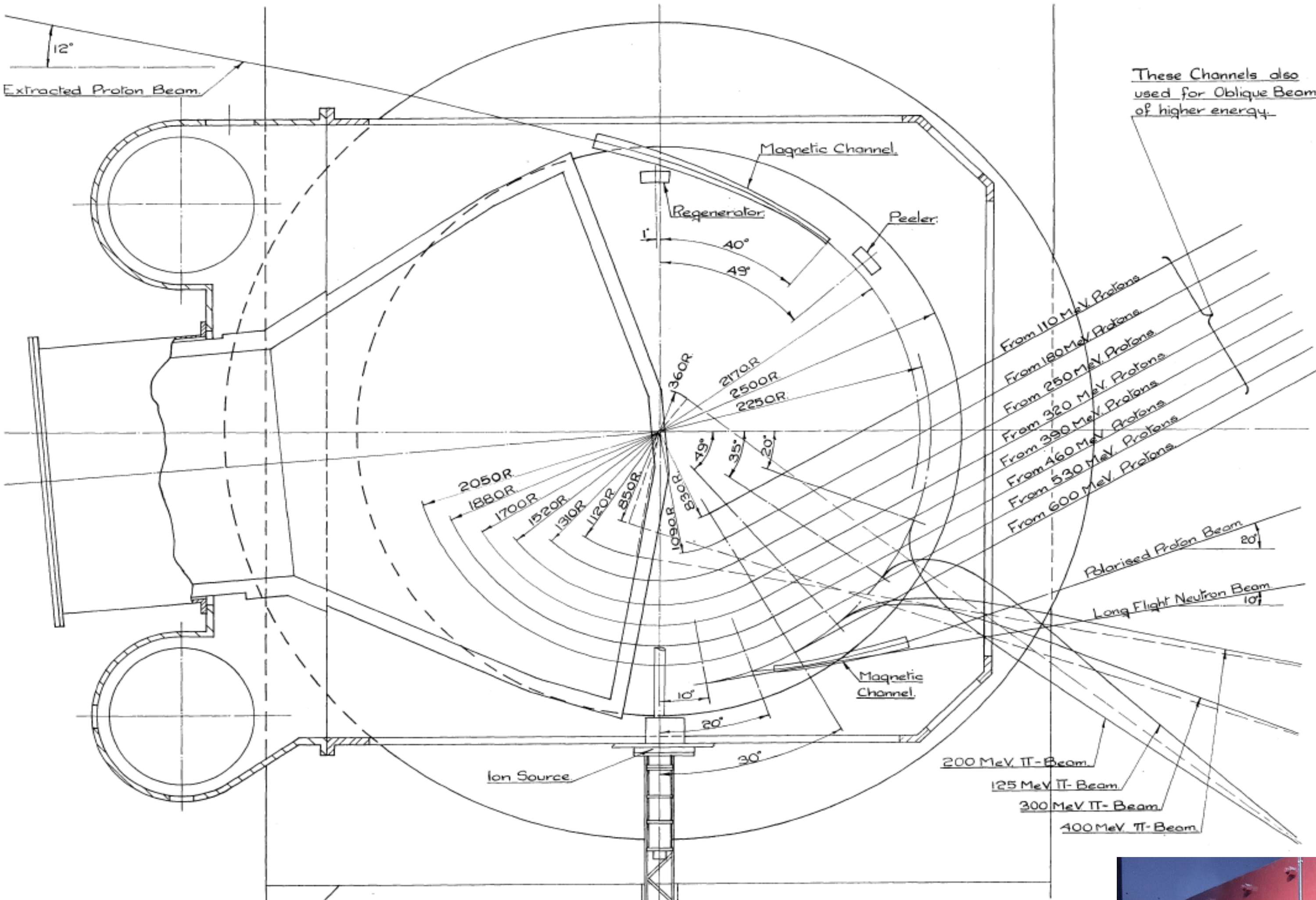
- **1967: start supplying beams for the radioactive-ion-beam facility ISOLDE (nuclear physics, astrophysics, Medical.)**

- **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

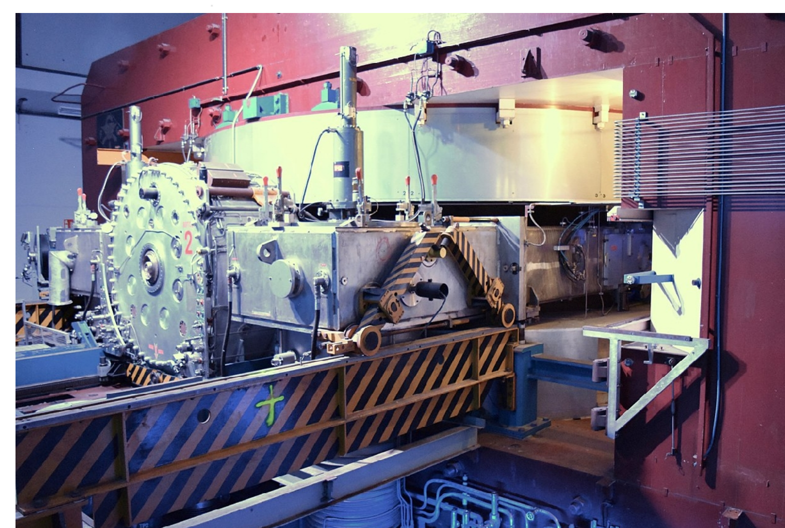




A. Arrangement of internal targets, beam extraction system and ion source.

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



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

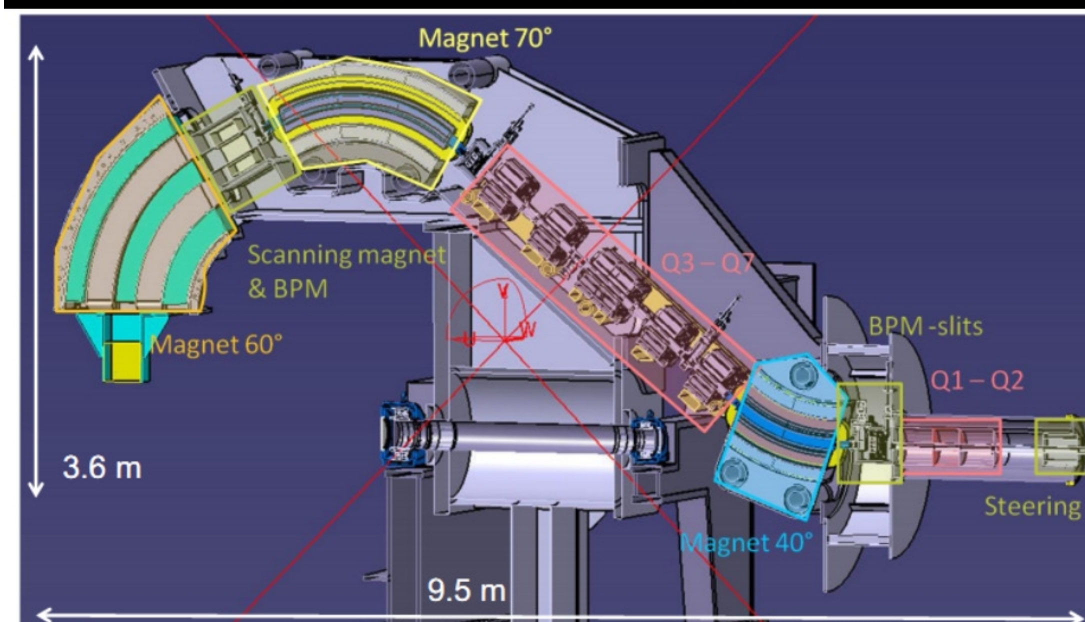
- **250 MeV protontherapy synchrocyclotron**

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**



There is more !
FFAG synchrocyclotron

1950s: FFAG optics adds strong focusing → better transverse confinement

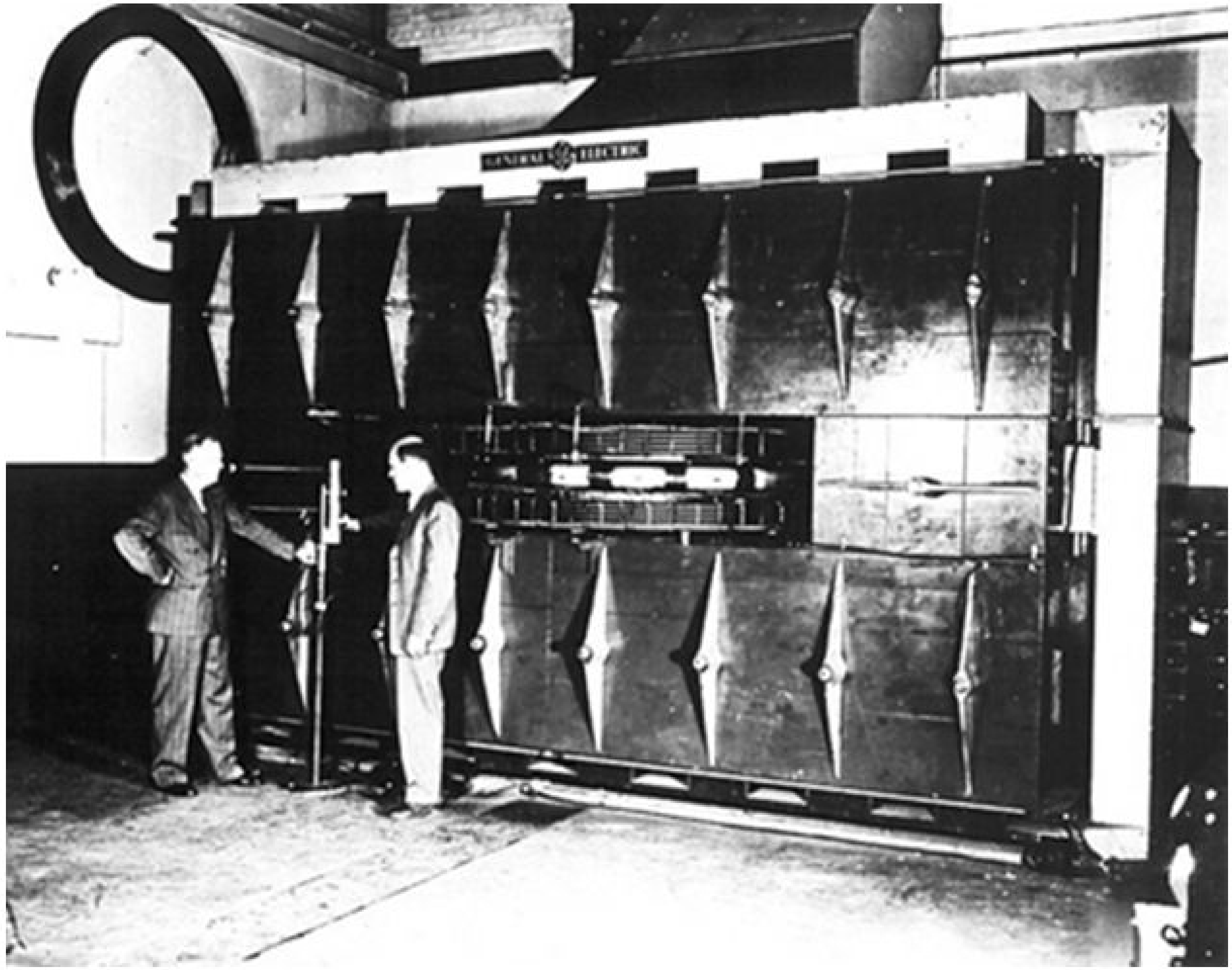
Detailed introduction at the FFAG session

BETATRON

A BRIEF INTRODUCTION

- ORIGINS, PRINCIPLE
- PAST BETATRONS
- BETATRON TODAY

In real life...



A picture of the 100 MeV betatron (completed in the early 1940s) at the G.E. Research Laboratory in Schenectady after Kerst had returned to the University of Illinois.

http://slideplayer.com/slide/5939802/

First successful functioning by Kerst, university of Illinois, 1940

"The acceleration by magnetic induction"
Phys. Rev., 60, 47-53 (1941)

[Reprinted from RADIOLOGY, Vol. 40, No. 2, Pages 115–119, February, 1943.]

The Betatron[1]

D. W. KERST, Ph.D.
University of Illinois, Physics Department

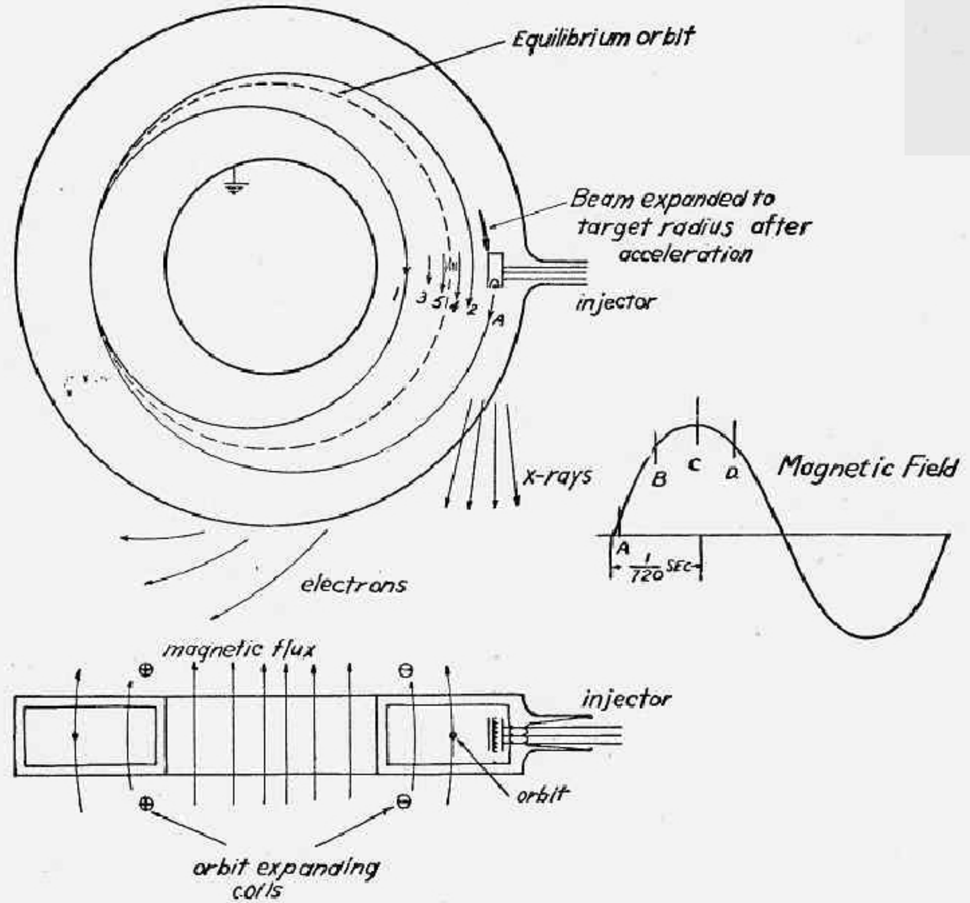


Fig. 1. The doughnut-shaped vacuum tube. Electrons are injected at time *A* in the magnetic cycle and directed against the target by the orbit expanding coils at time *C*.

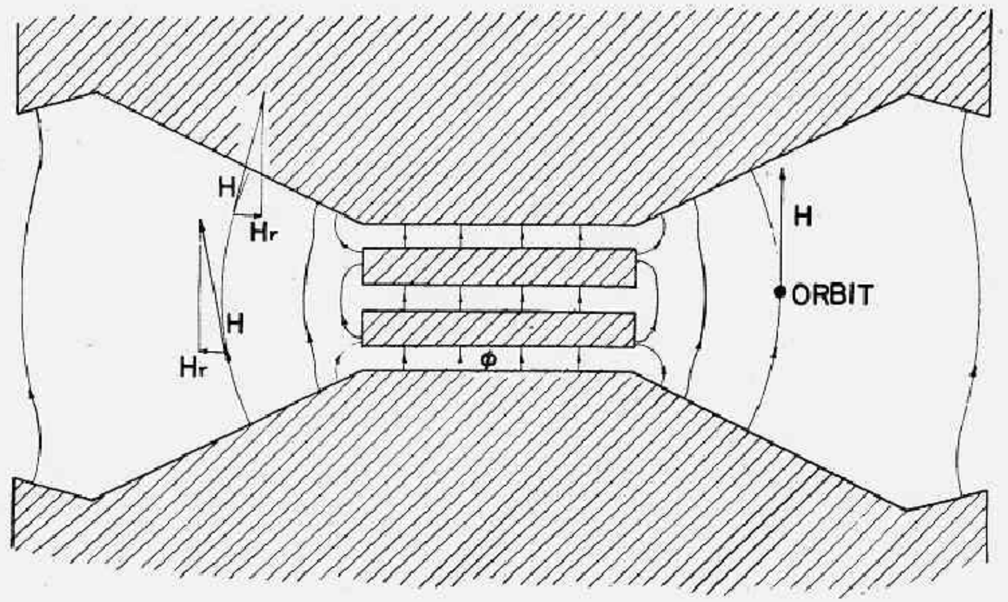
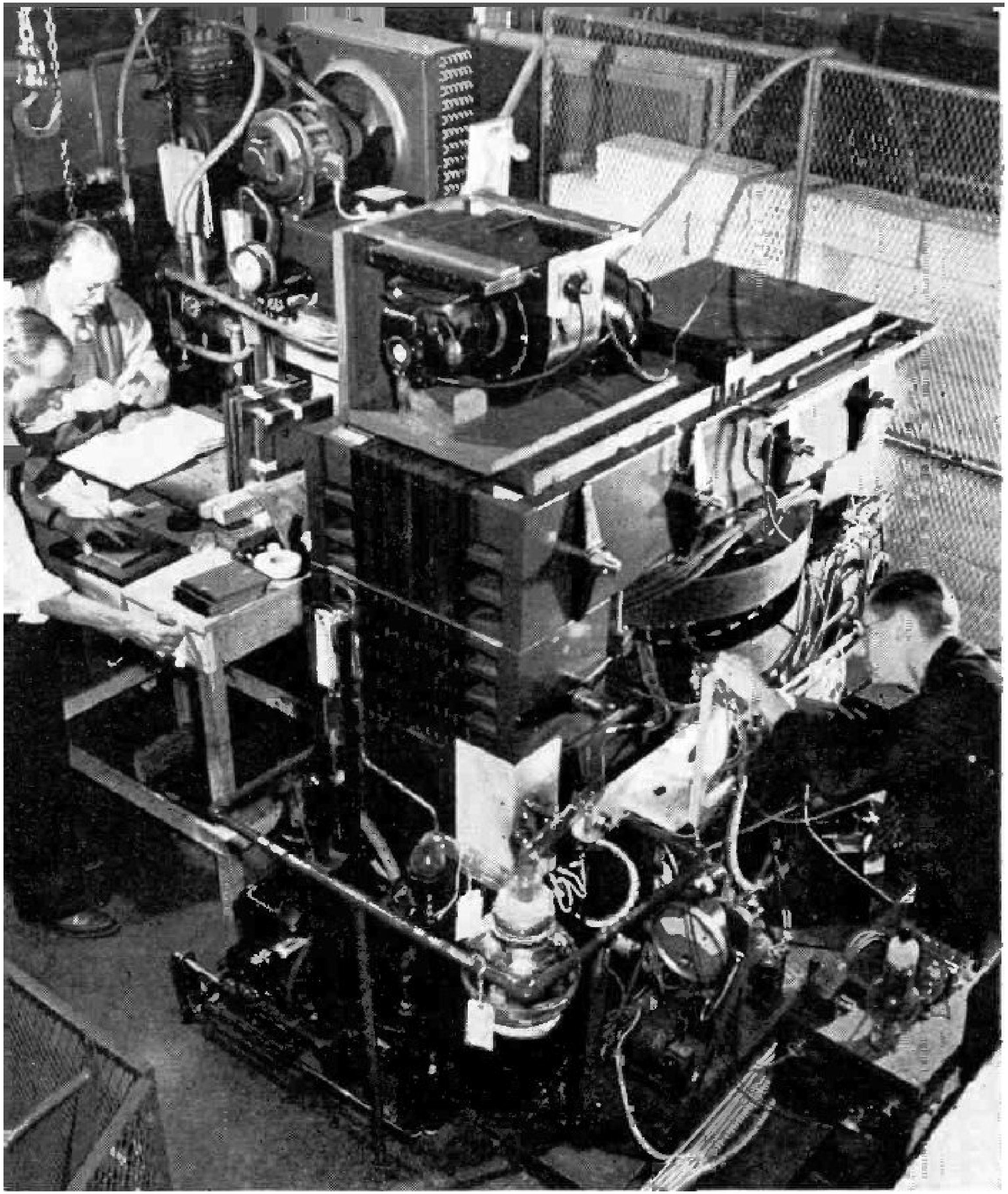


Fig. 2. Curvature of lines of force between the poles of the betatron. There is a radial component to the magnetic field everywhere except in the central plane. The radial component of magnetic field always forces electrons back toward this plane.

What it looked like in the 1940s :

Ref. Wikipedia



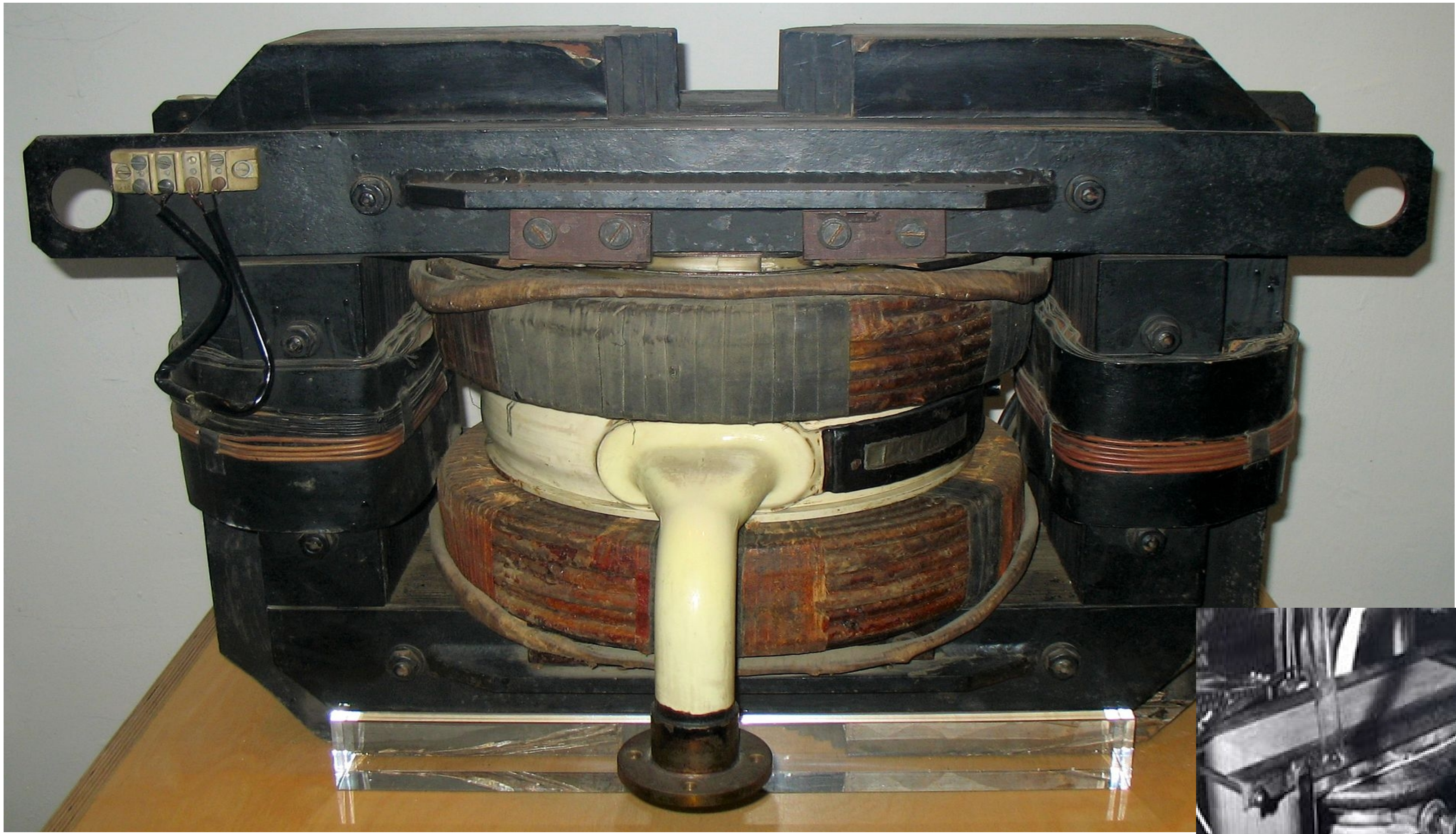
Early betatron (not the first one) at University of Illinois.

A 4-ton dipole magnet device.

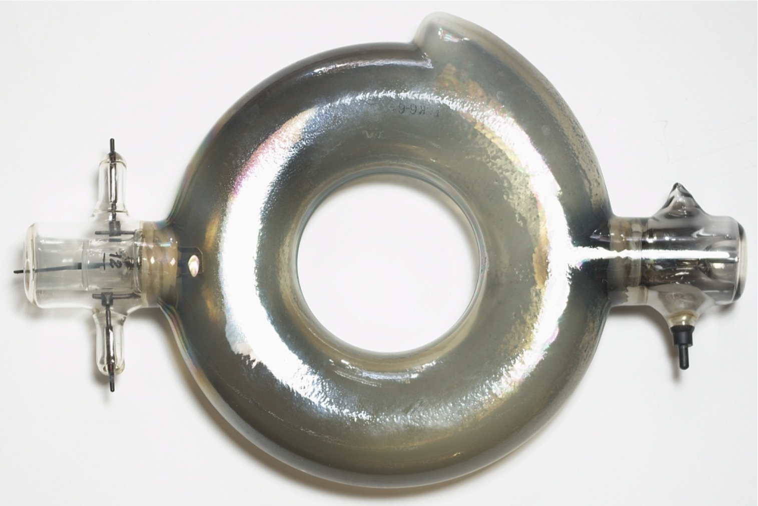
Kerst working on it.

Another early specimen

6 MeV betatron, Germany, 1942.



1920s : The betatron method was invented to accelerate beta-rays (today's electron beams !) to produce bursts of X-rays
- constant-radius orbit, the $B_{induc}=2B_{guide}$ rule, at the primary coil,
- the secondary coil – the beam - is in a vacuum tight donut.



SVETLANA RBK6-6E Betatron 6 MeV. Manufacturing date around 1991. In-situ radiotherapy and radiographic non destructive testing: containers, ship hulls, weapons [Ref.: http://lampes-et tubes.info/xr/xr033.php?l=d]

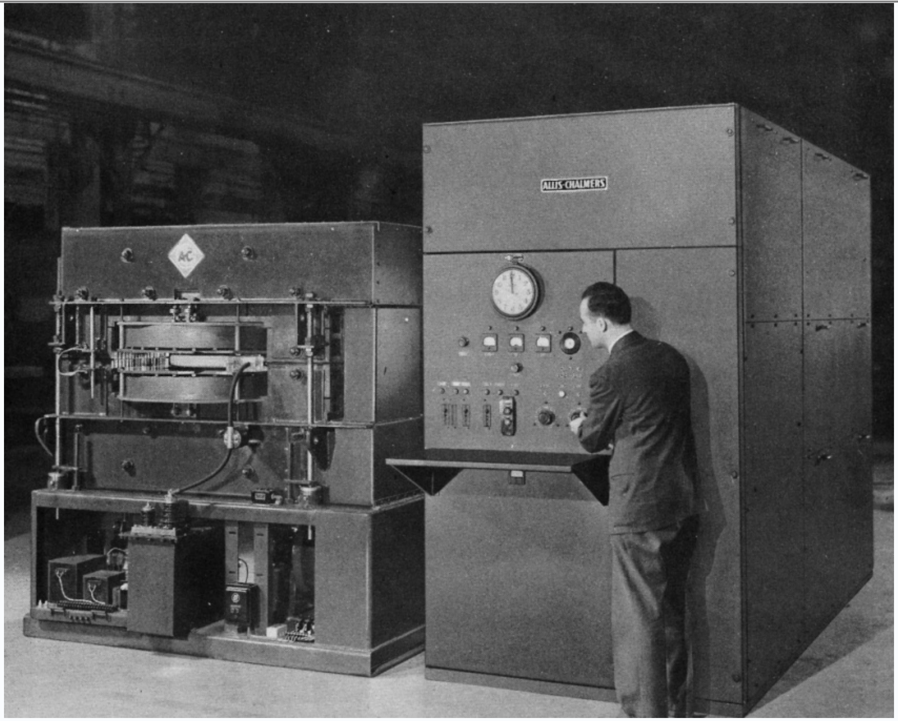
- **1940 : that's when a complete theory of transverse stability would be formalized (Kerst & Serber).**
  It allowed bringing moving to realisation:

- **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 key aspects the precursor of synchrotrons:



20 MeV betatron and control equipment
[Ref.:lampes-et-tubes.info/xr/xr033.php?l=d]

- 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...

- 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, 100 mA for particle physics,
  Limitations were magnet size, synchrotron radiation [1]

The betatron would be outperformed in an interval of a few years,

- by linac in the medical application,

- by synchrotrons for higher electron energies demanded by nucleus and particle physics

HOW ABOUT IONS ?

The betatron concept does not present an interest for ions:

- at low energy, v<<c, number of turns over a betatron cycle is very small → energy increase is low

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.

Conclusion 1/2

- Betatrons are produced nowadays

essentially as light (portable)

compact X-ray sources for

material analysis, a few MeV energy range.

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

- FFAG focusing was extended to the betatron in the 1950s, for the high energy acceptance of “zero-chromaticity” FFAG optics

  Induction acceleration in FFAG applied in the 2000s for high power electron beams (Japan R&D) → 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...

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).

[] CERN Accelertor School archives

[] JACoW http://www.jacow.org/

[] Joint Universities Accelerator School lectures
http://www.esi-archamps.eu/Thematic-Schools/Discover-JUAS

[] USPAS archives

[] National Lab sites, US, EU

[] CERN documentation web sites

[] BNL's Flickr photo gallery

[] Wikipedia

[] G.~Leleux, Circular accelerators, INSTN lectures, SATURNE Laboratory, CEA Saclay (Juin 1978).