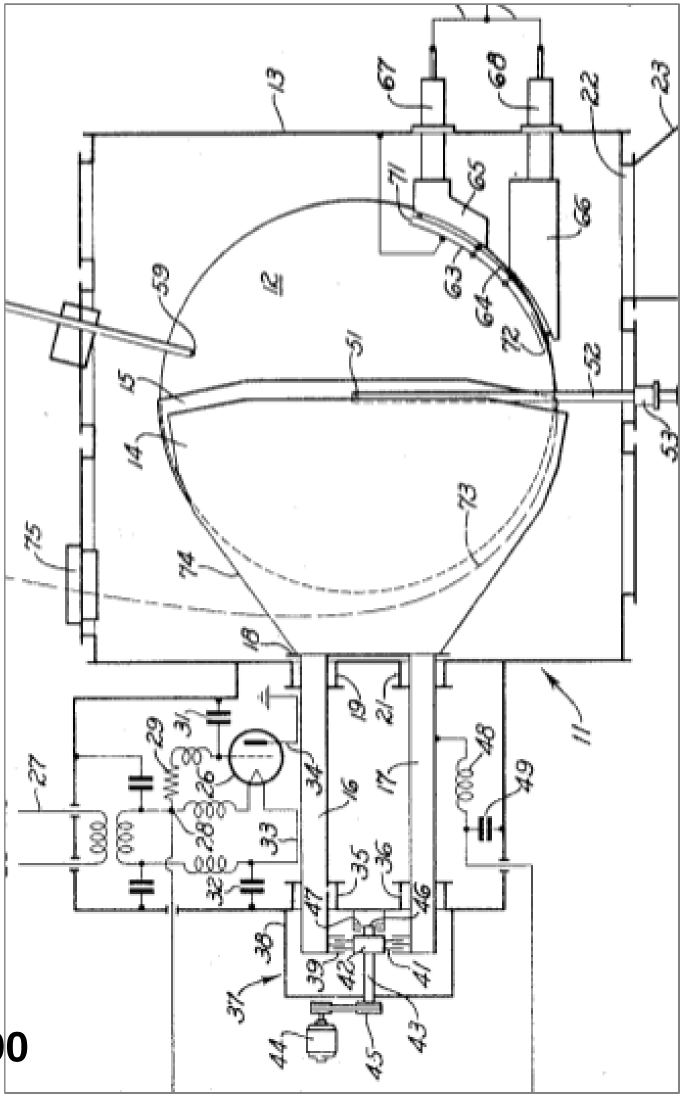
# SYNCHRO-CYCLOTRON

## 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,**

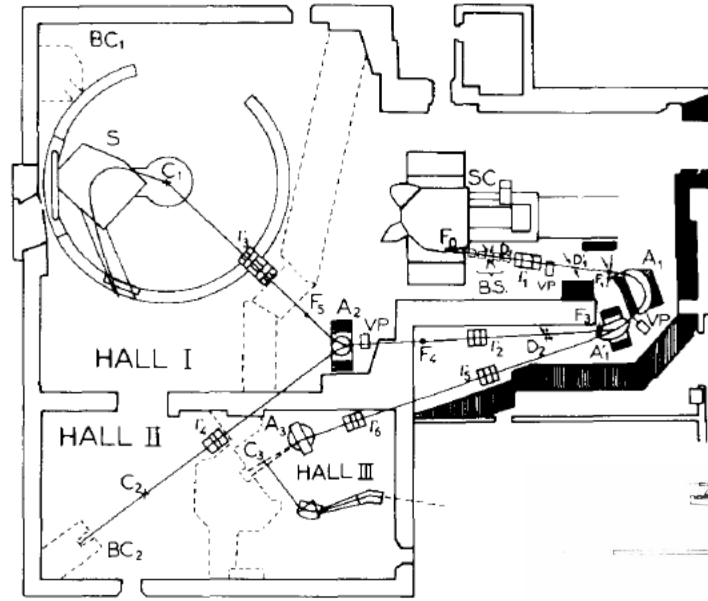
**- only ions with correct, accelerating, phase (a few 10s degrees of a 360 degree period) are “captured” by the voltage wave**

**→ 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

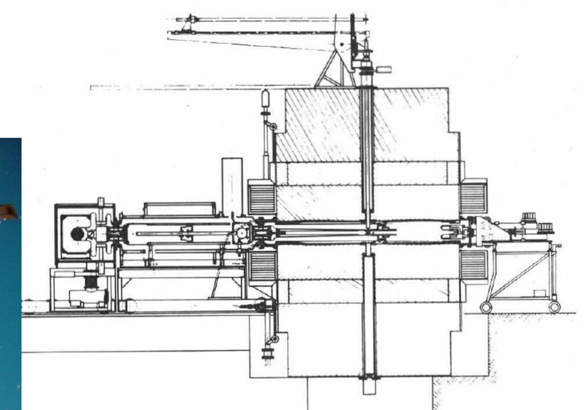


Fig.7. Side view

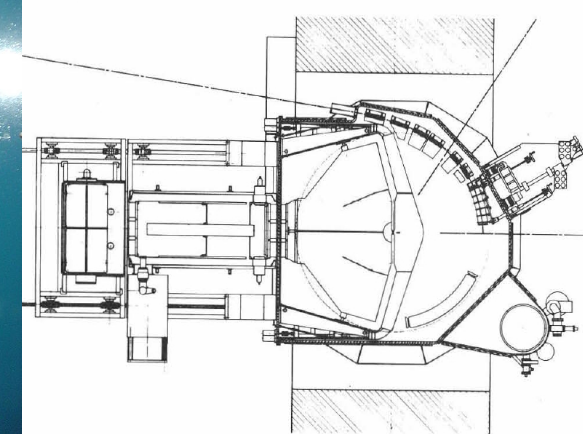


Fig.8. Top view

# 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.

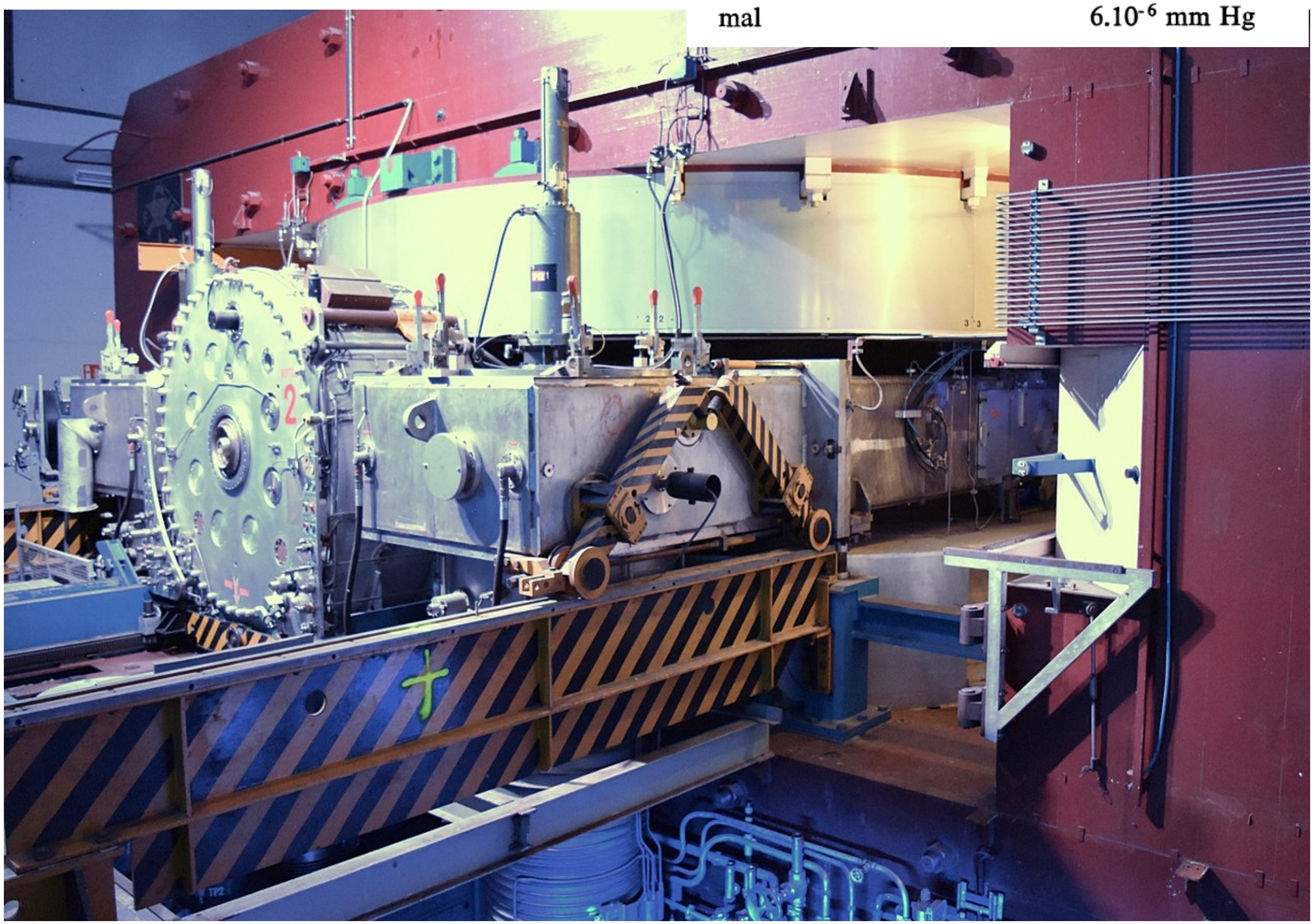
- 1964: started to concentrate on nuclear physics, leaving particle physics to the newer, 30 GeV, Proton Synchrotron.

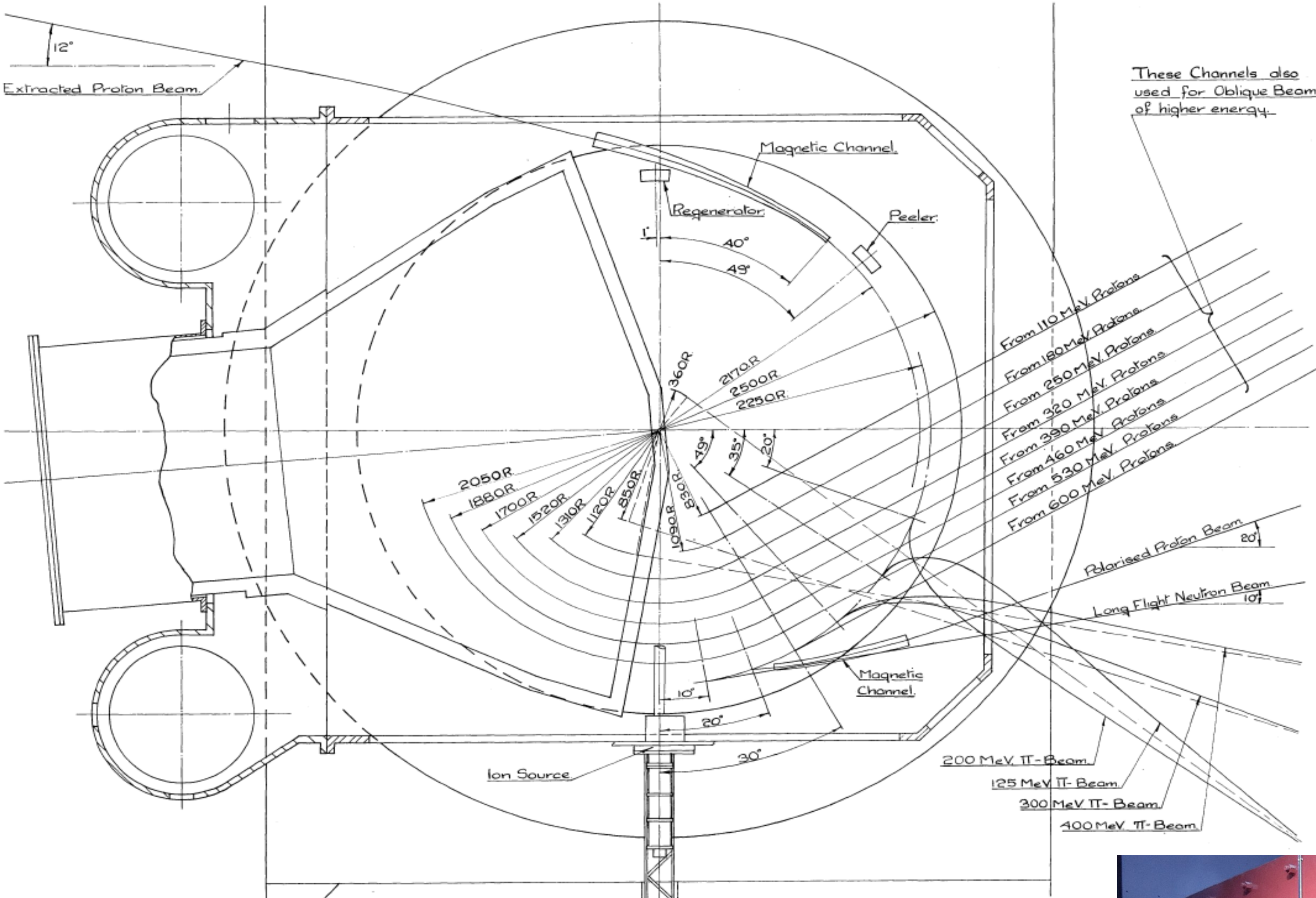
- 1967: start supplying beams for the radioactive-ion-beam facility ISOLDE (nuclear physics, astrophysics, Medical.)

- 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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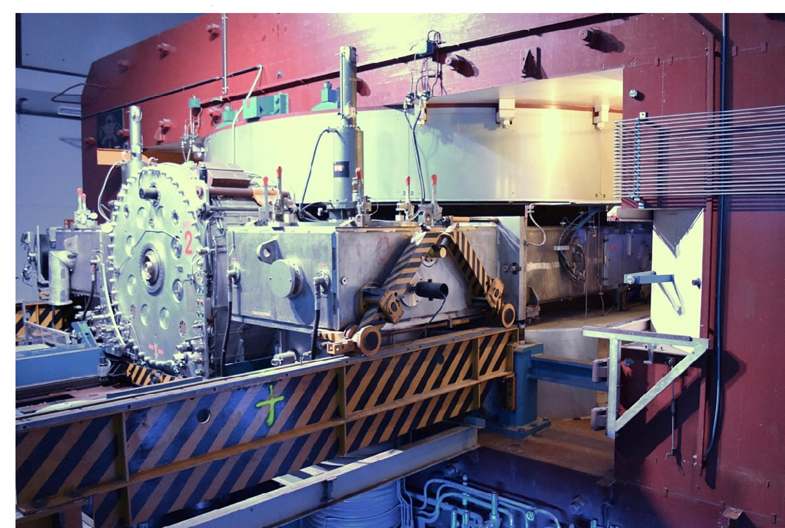


# Synchrocyclotron today

**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

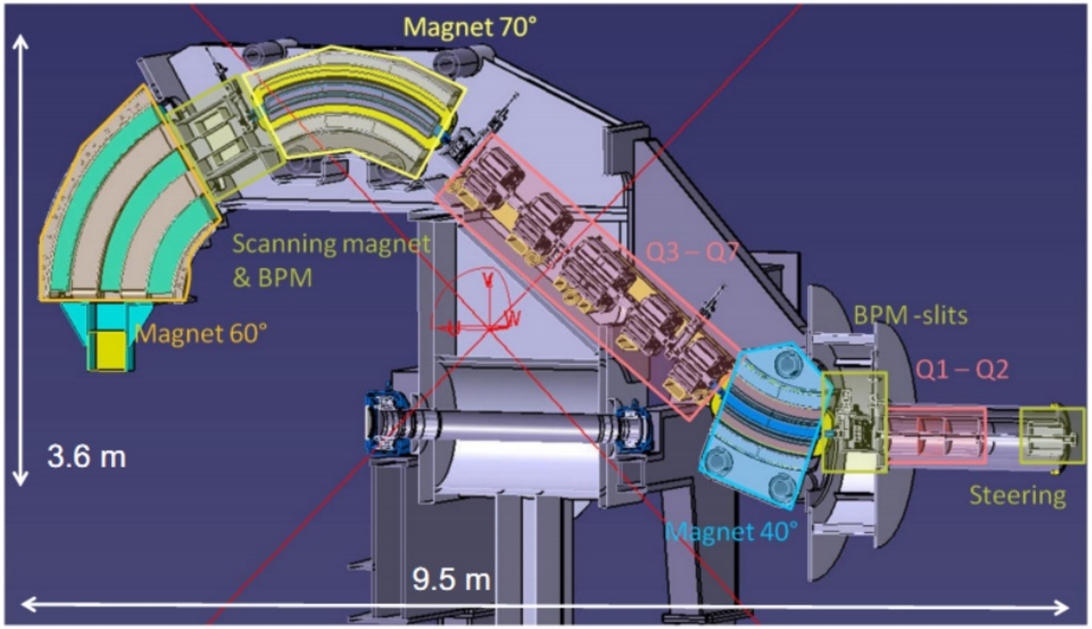
- **250 MeV protontherapy synchrocyclotron**

**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

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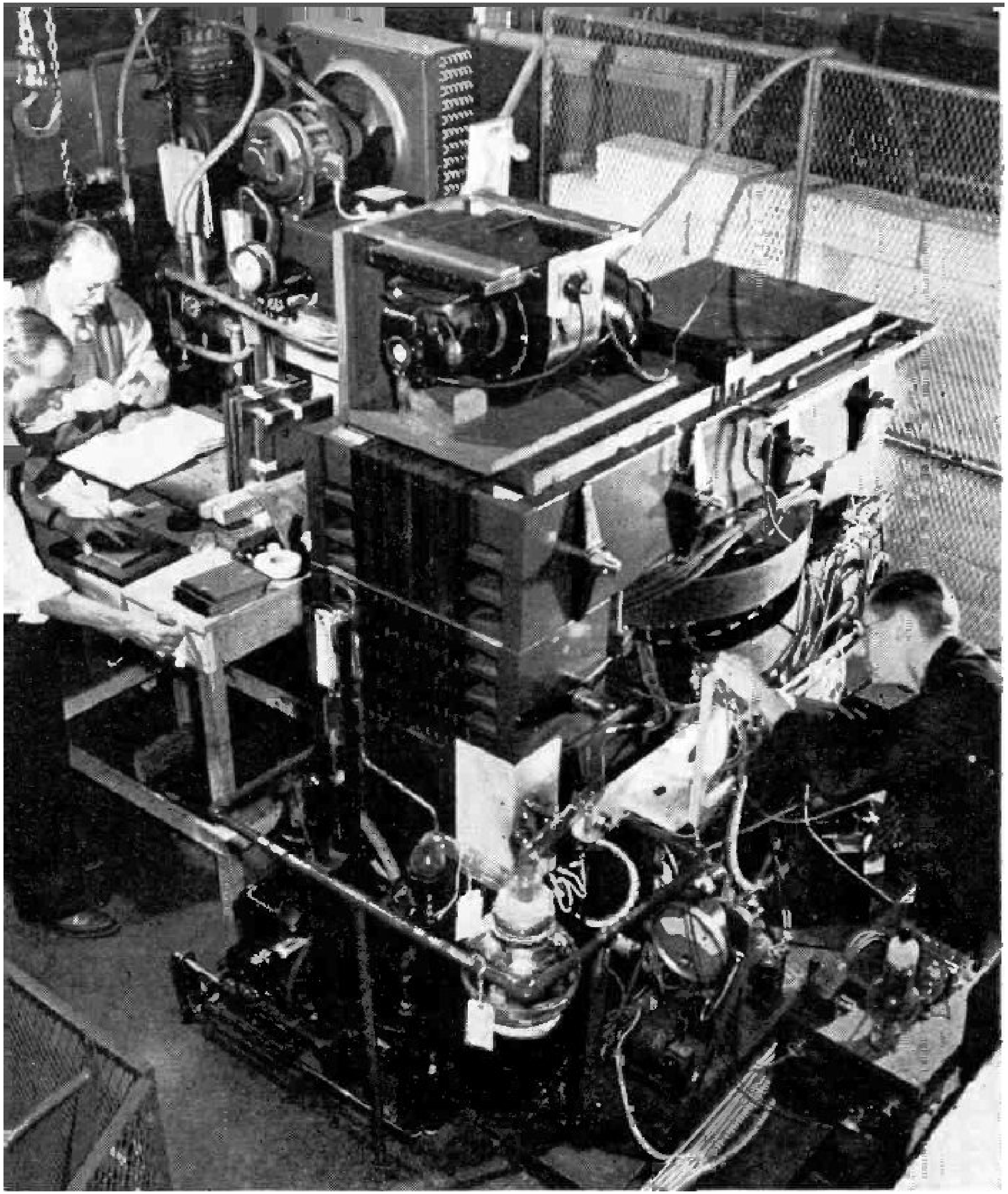
# What it looked like in the 1940s :

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

- 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.

- 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

# 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...**