TRIUMF

Außenansicht auf einen Treiber für 50 Jahre Spitzenforschung: Das PSI-Zyklotron

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Festsymposium 50 Jahre HIPA

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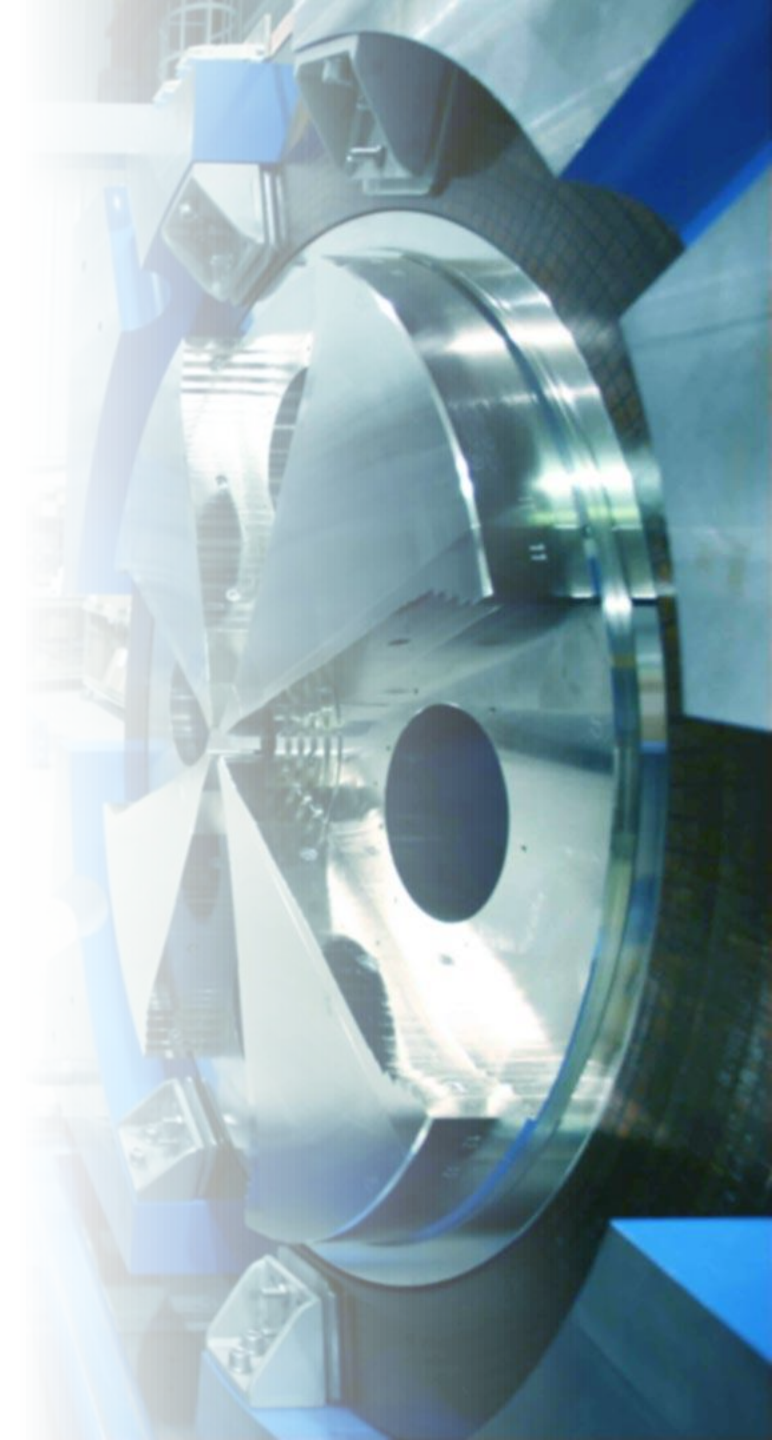
Discovery, accelerated

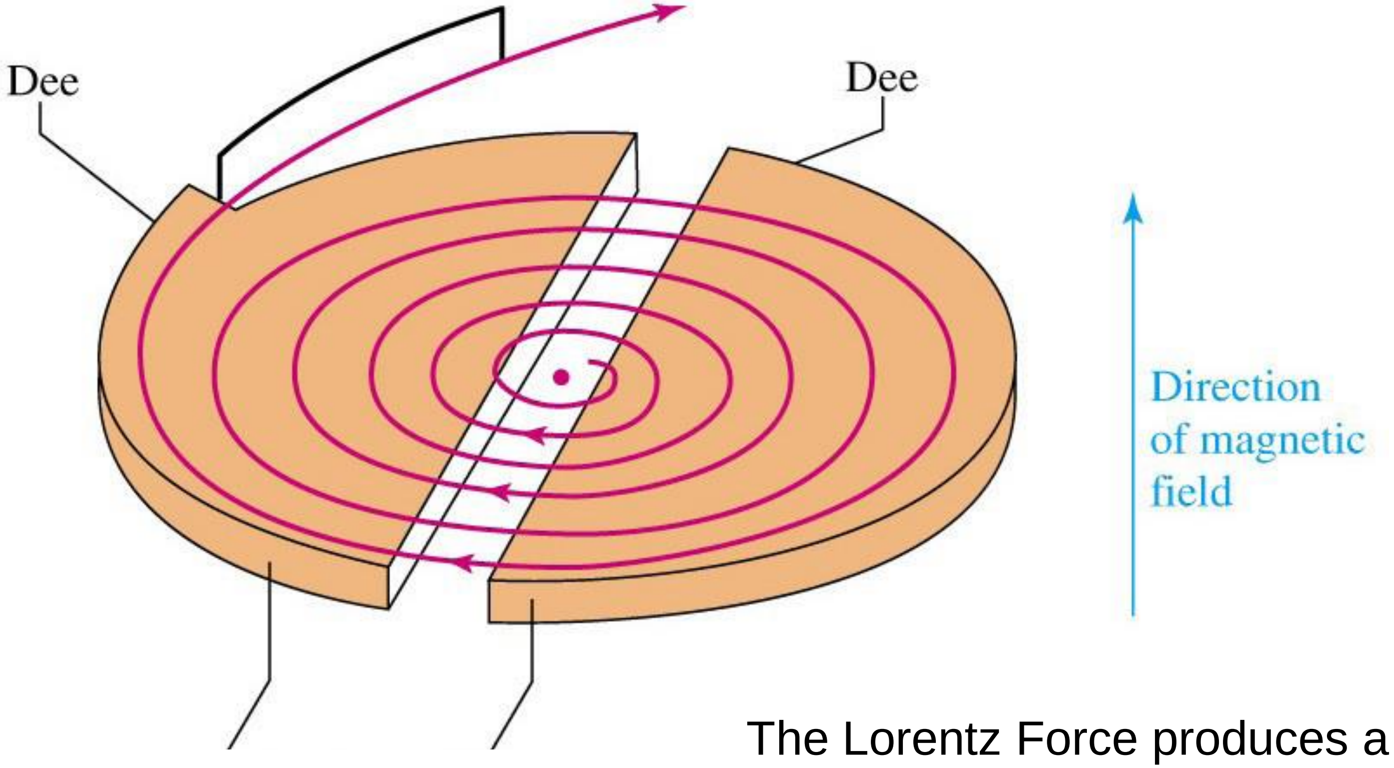
Outline

- The path towards the highest beam power cyclotron (and the competitor)
- How the High Intensity Proton Accelerator (HIPA) became one of the most powerful proton accelerators in the world
  an why it remains world leading!
- What has the cyclotron made possible at PSI?

Thanks to Mike Craddock, Rick Baartman, Mike Seidel and Werner Soho
for all the information that made this talk possible!



The cyclotron - principle



RF-amplifier

Ernest Lawrence at Berkeley considered in 1930 a circular version of the drift-tube linac!
Using a uniform and constant magnetic field and an accelerating gap between two D-shaped electrodes.

The particles are held to a spiral trajectory by a static magnetic field and accelerated by an RF-field.

→ Magnetic resonance, cyclotron motion

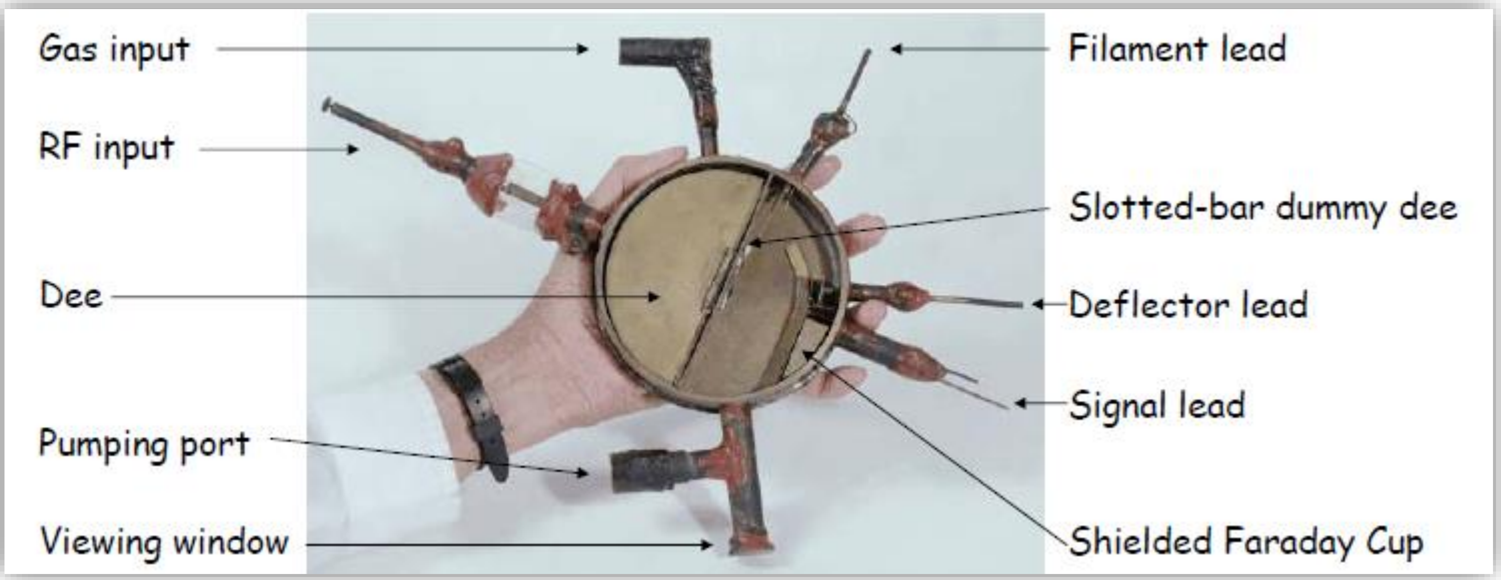
The Lorentz Force produces a circular track

$$\frac{mv^2}{r} = qvB \quad \Rightarrow \quad \frac{v}{r} = \omega_c = \frac{q}{m} B$$

Cyclotron frequency

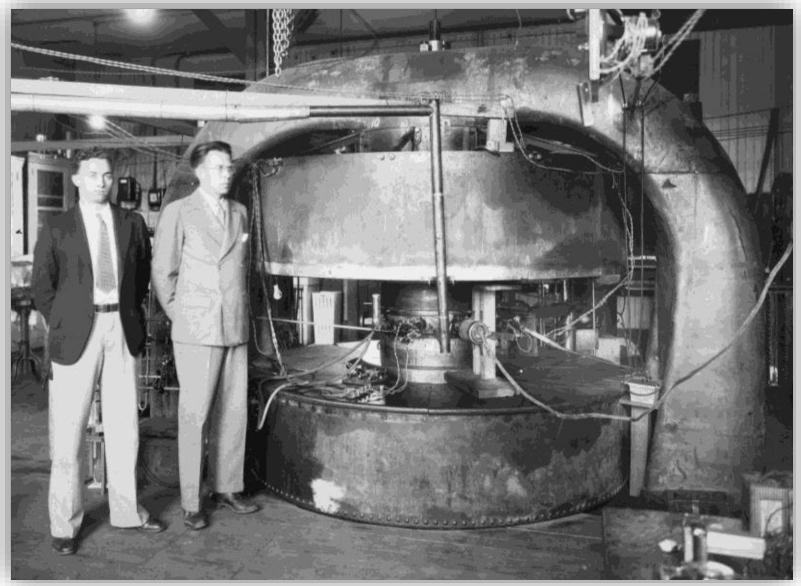
$$\omega_c = 2\pi \cdot f_c$$

Cyclotron history



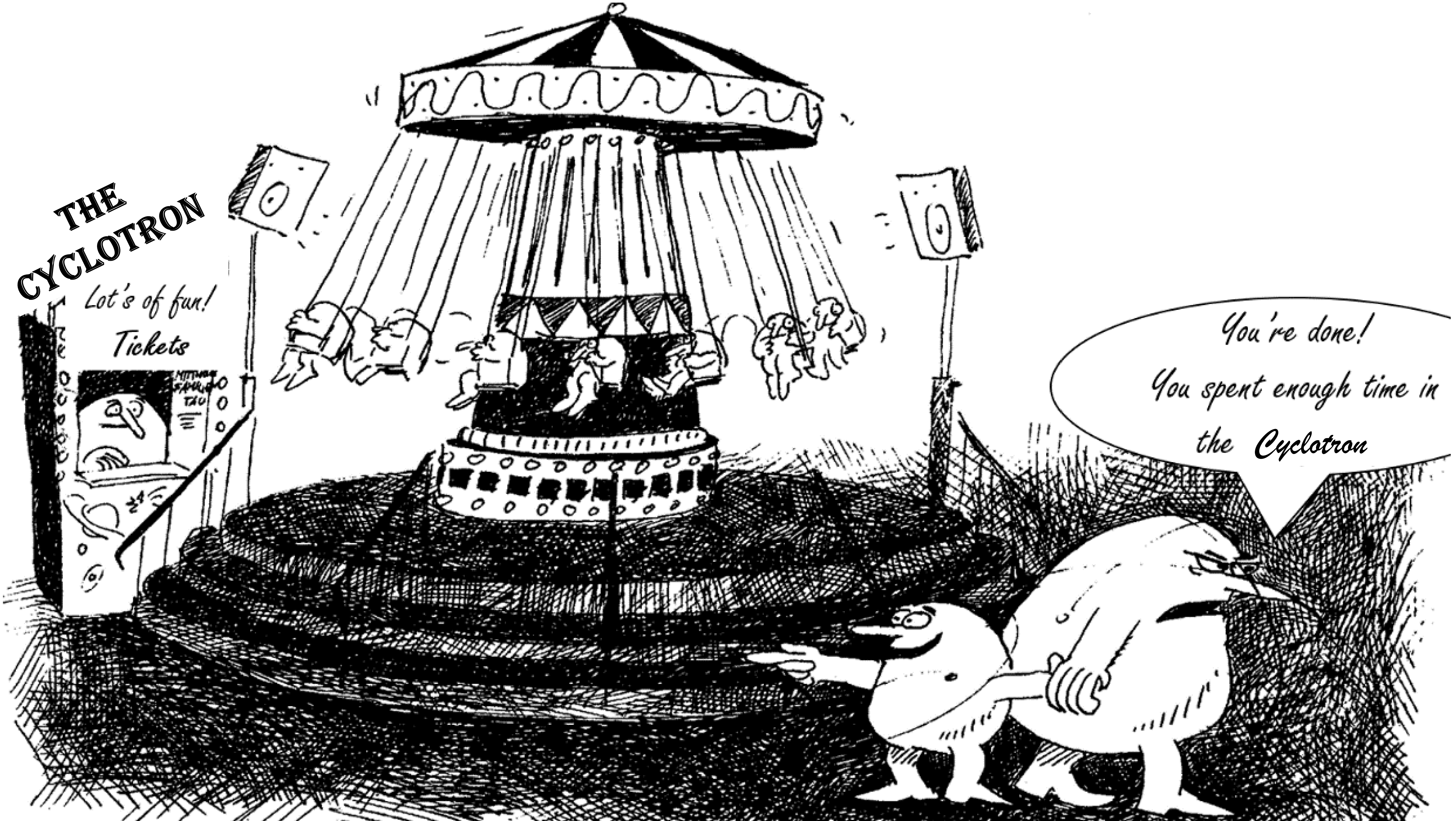
Lawrence and Livingston at the 27-inch cyclotron, Berkeley (1932).

The magnet was originally part of the resonant circuit of an RF current generator used in telecommunications.



In late 1930, Lawrence’s student, Stanley Livingston, built a “4-inch” version in brass.

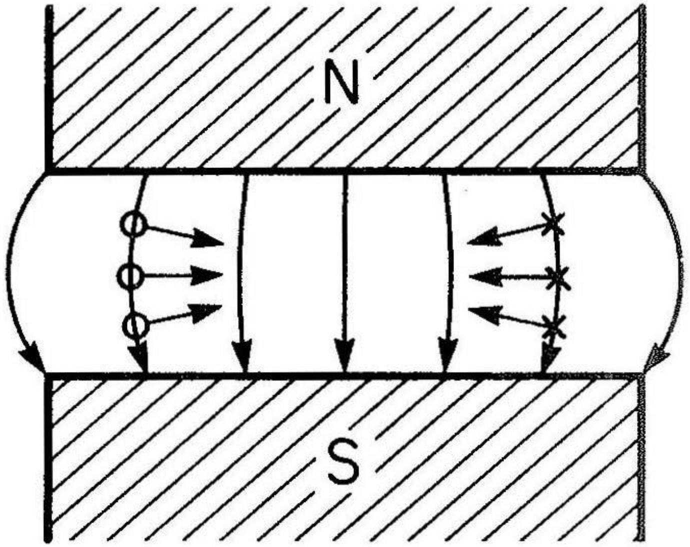
Clear evidence of magnetic field resonance was found in November, and in January 1931 they measured 80-keV protons. Ions were produced from the residual gas by a heated filament at the centre.


THE CYCLOTRON
Lot's of fun!
Tickets
You're done!
You spent enough time in the Cyclotron

Limits of the classical cyclotron

Relativistic mass effect require a stronger magnetic field at the outside to keep isochronicity!

$$\omega_c = \frac{q}{\gamma \cdot m_0} B_z(r(\gamma)) = \frac{qB_0 \cdot \gamma}{\gamma \cdot m_0} = \frac{qB_0}{m_0}$$



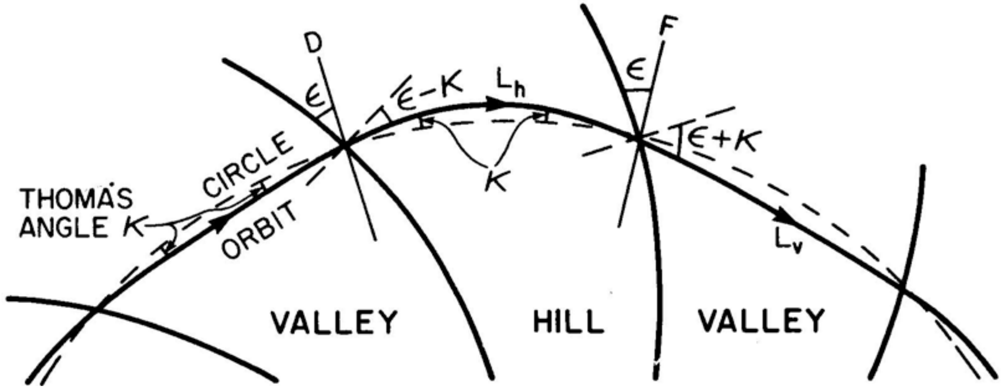
An outwardly-decreasing field
⇒ vertical focusing.
Positive axial focusing requires B decreasing with r.

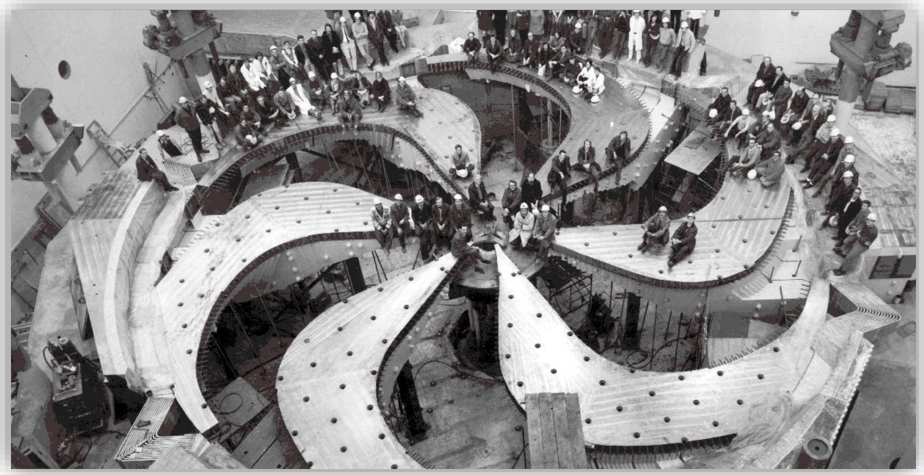
Solution to this problem: The use of edge focusing!

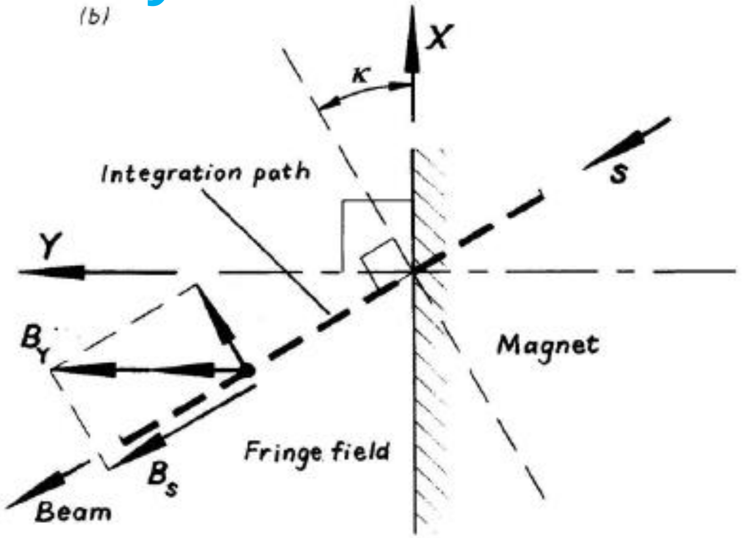
Edge focusing in the 520 MeV cyclotron

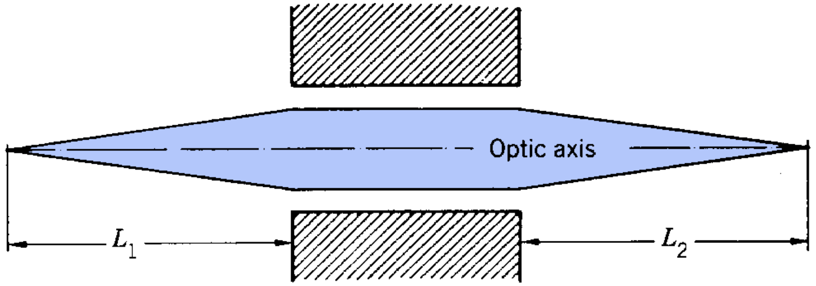
When a particle crosses a magnet end at an angle κ to the normal, longitudinal components of the fringe field B_y interact with velocity components v_x parallel to the edge, giving a vertical force!

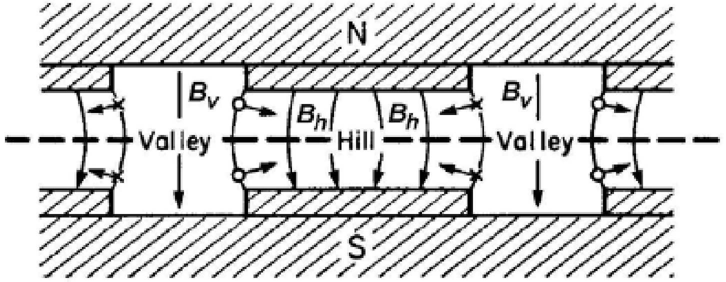
Kerst (1956) suggested using spiral sectors to increase the axial focusing





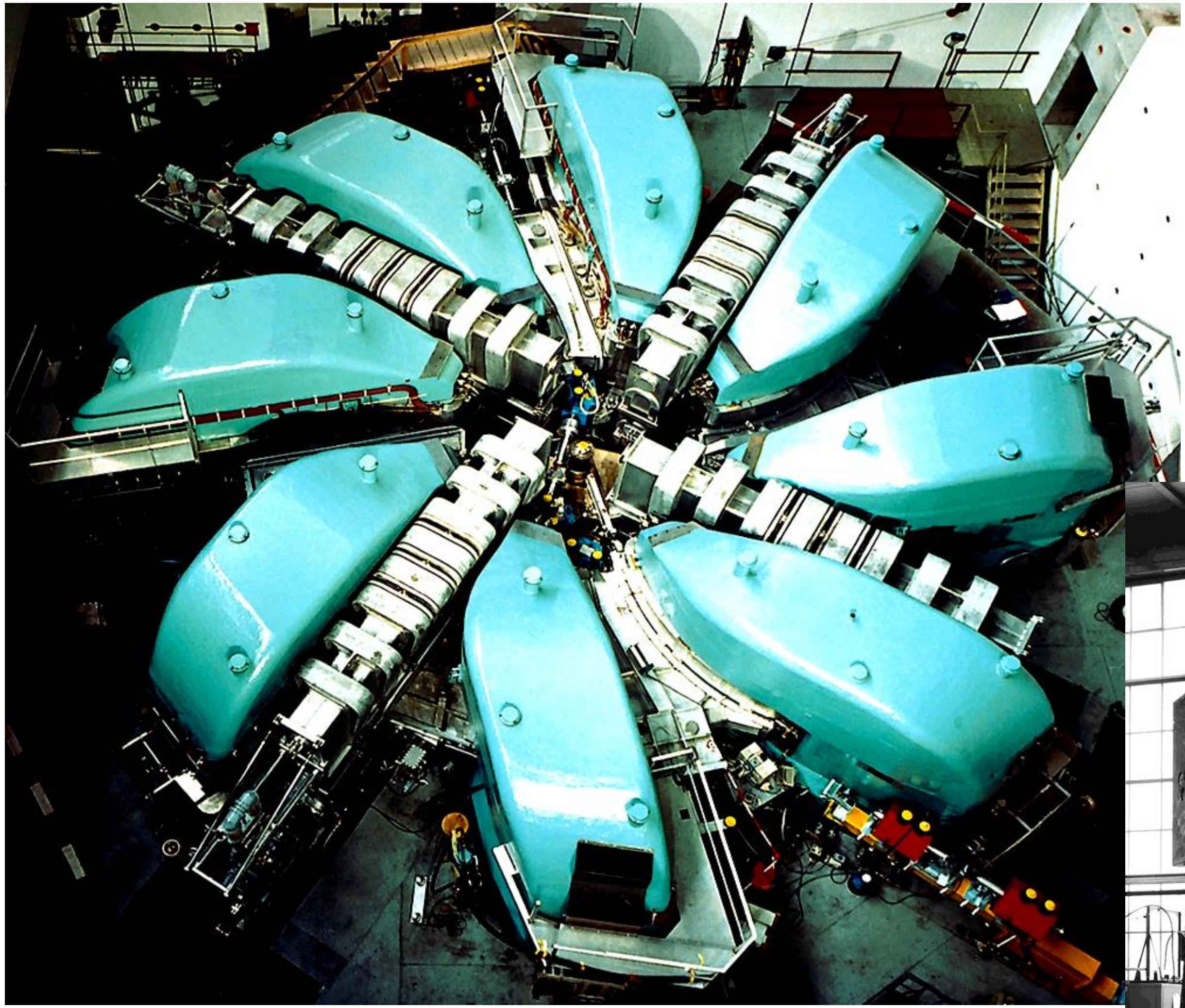


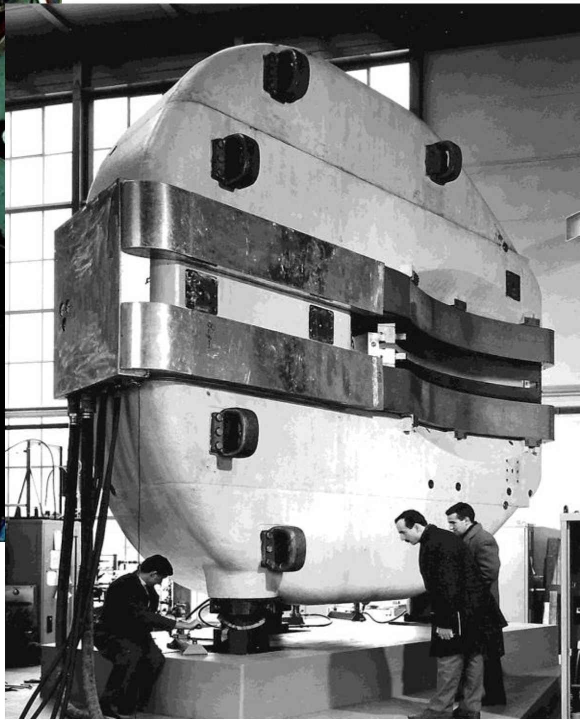




Discovery, accelerated

The Ring Cyclotron 1974





590 MeV Protons

- 8 Magnets (250 tons each)
- 4 RF-Cavities

15 m Diameter

Concept: Hans Willax

Director: J. P. Blaser

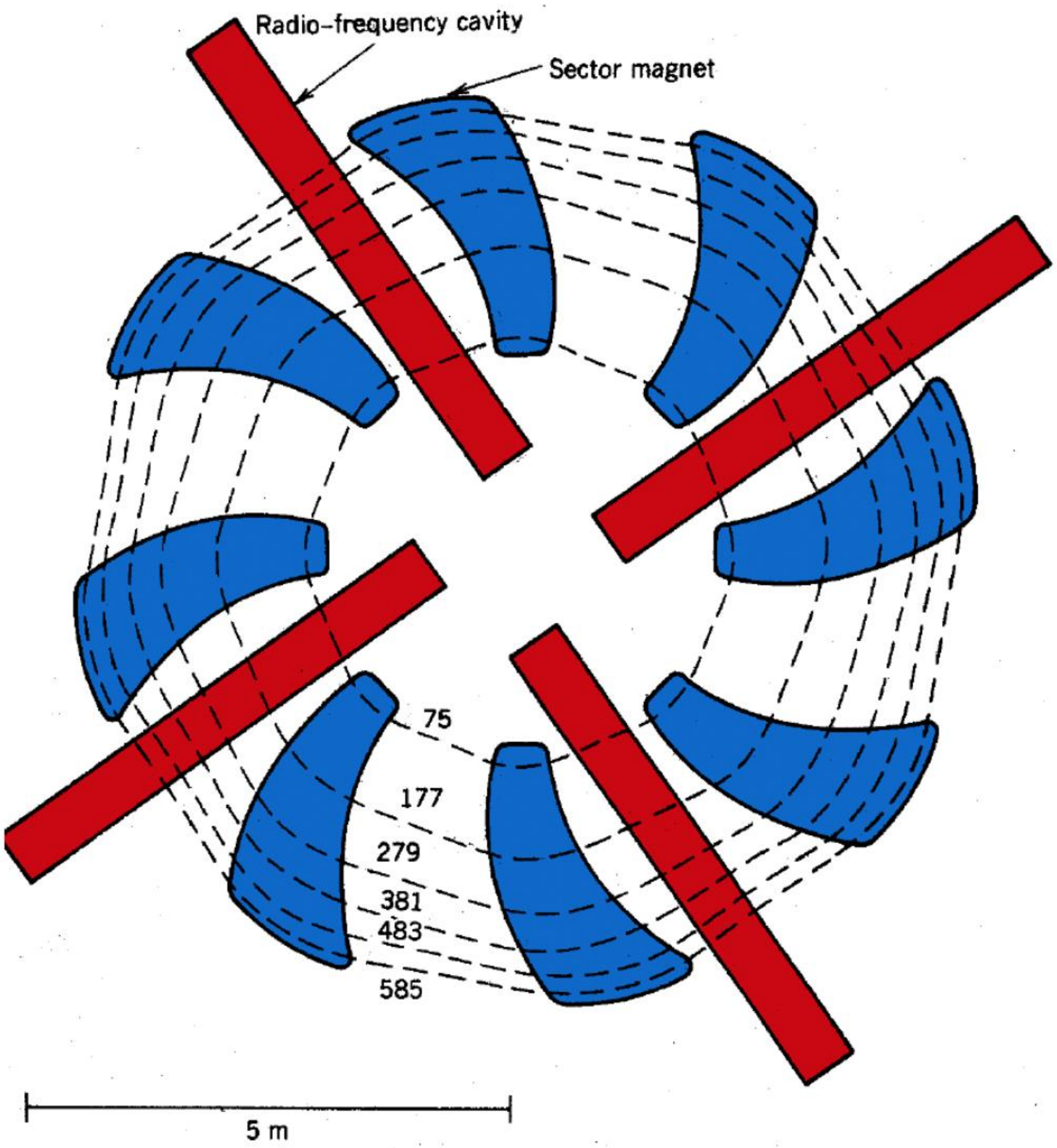
Advantages of ring cyclotrons:

- Magnet and RF systems are decoupled
- Many high voltage cavities → good separation between turns (good extraction)
- Small gaps possible (power consumption)
  also SC magnets can be used
- Space for diagnostics!!!

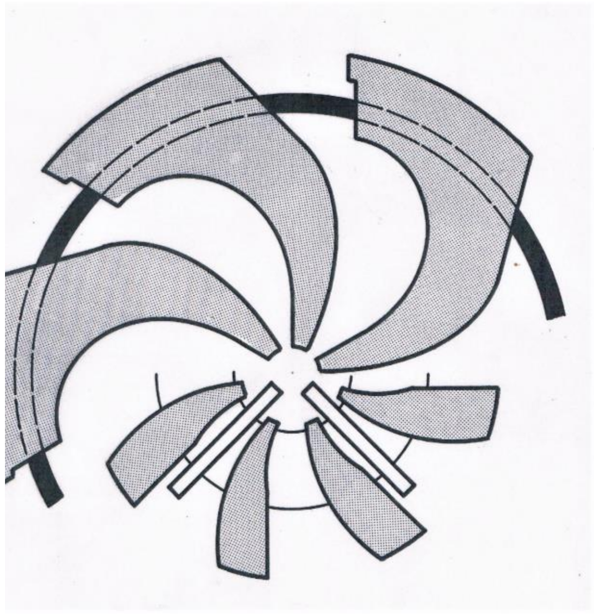
PSI ring cyclotron

Outer orbit is 4.5m compared with TRIUMF's 7.6m.

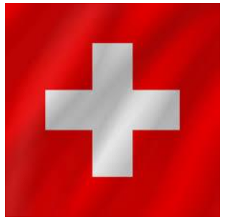
The TRIUMF 520 MeV cyclotron was put into operation in 1974 as well!



TRIUMF Cyclotron

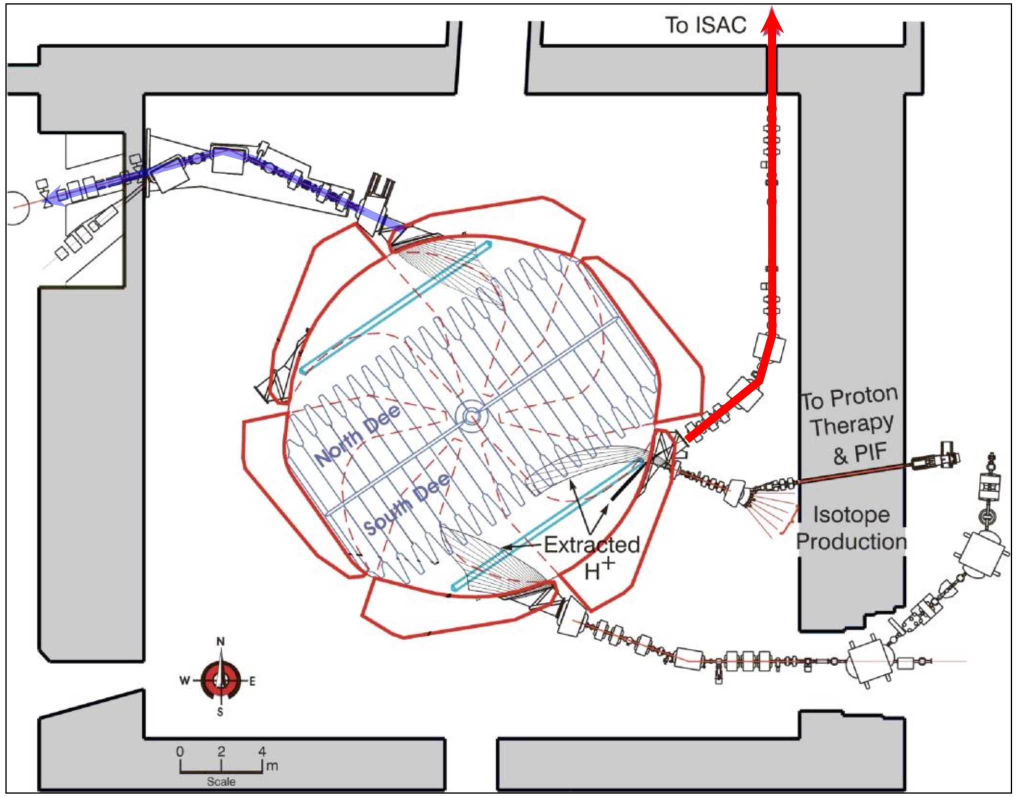


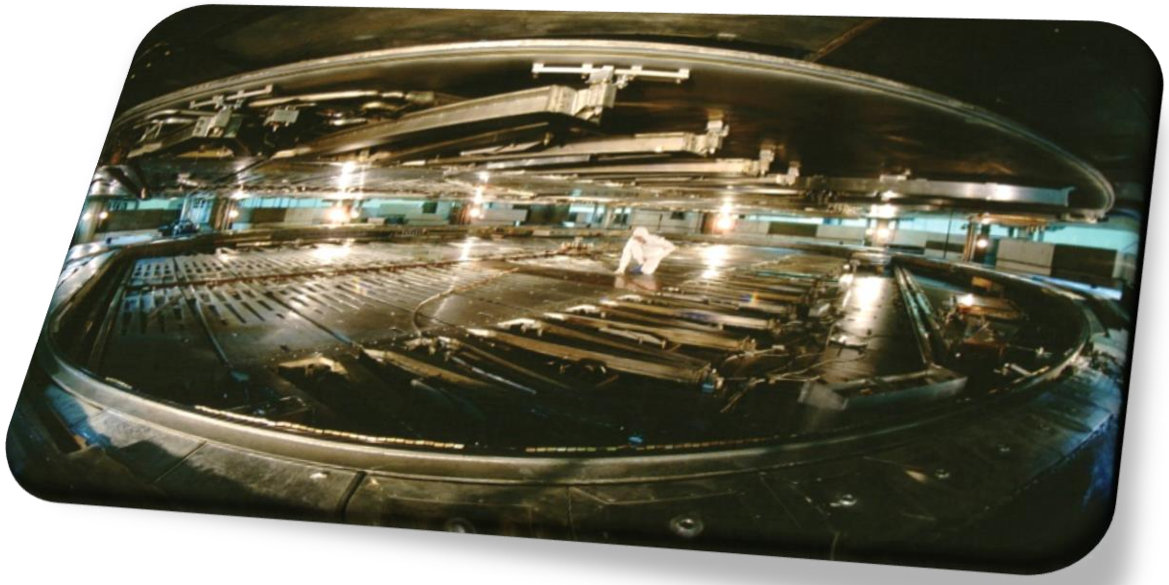
PSI Cyclotron

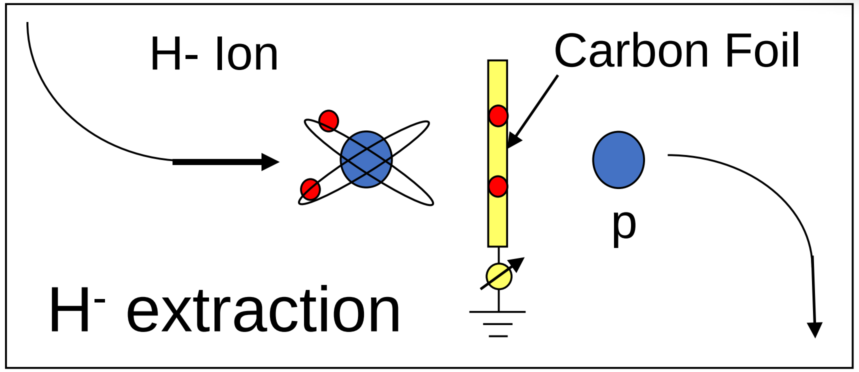


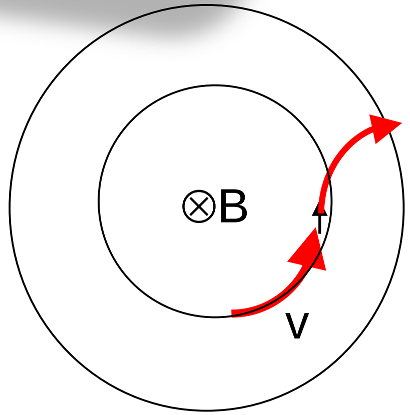
A competitor (and friend)!

The 520 MeV cyclotron at TRIUMF – an IEEE major engineering milestone!









- Proton beam energy can be varied between 70 and 480 MeV.
- Low magnetic field (0.3-0.5 T) required!
  At higher energies, the Lorentz electric field lowers the potential barriers of the weakly bound electron in the H^- → significant beam losses

- Largest normal conducting Cyclotron in the world:
  D = 18 m, magnet weight: 4000 t, Coil current ~18500 A
- 5500 hours of beam delivery per year

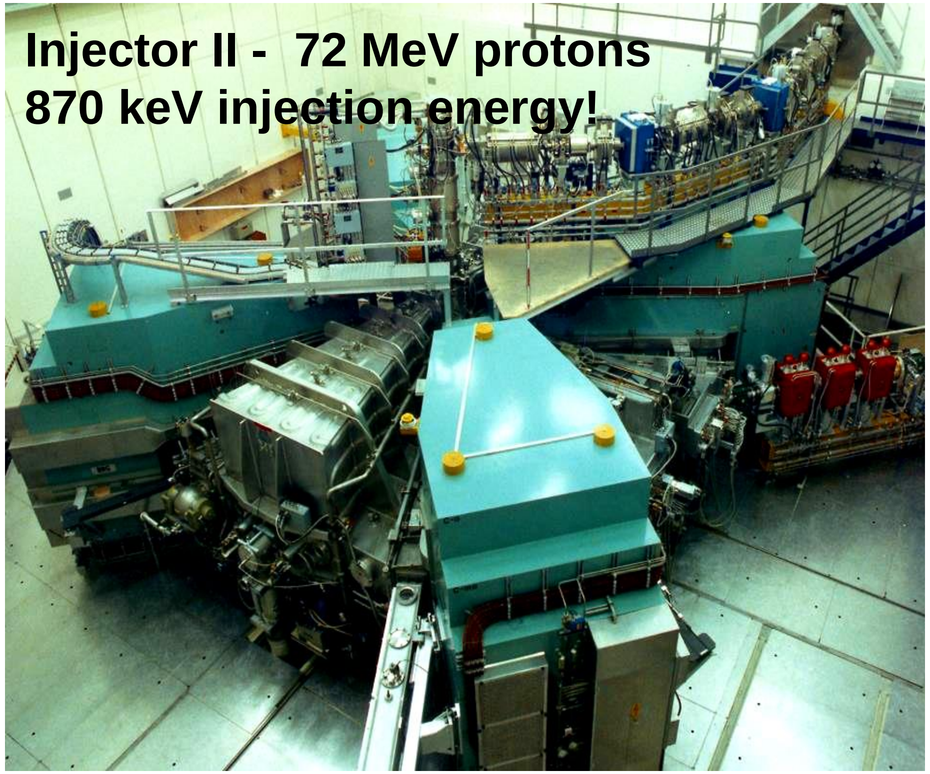
However, we are proud of the leader in cyclotron beam intensity – PSI!

Ring Cyclotron September 1973

The High Intensity Proton Accelerator (HIPA)

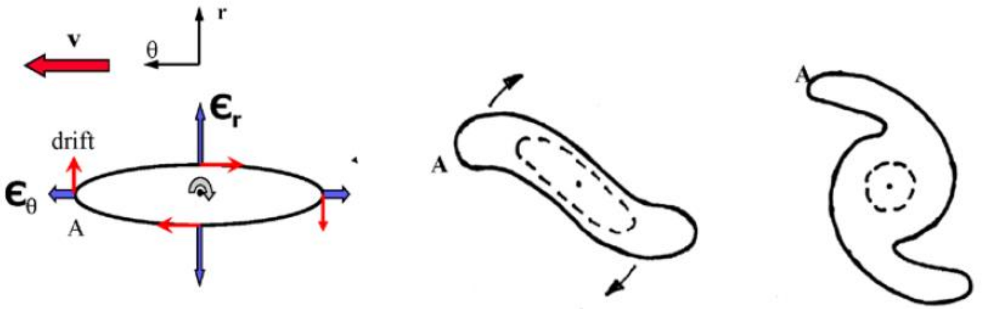
The path to high intensities

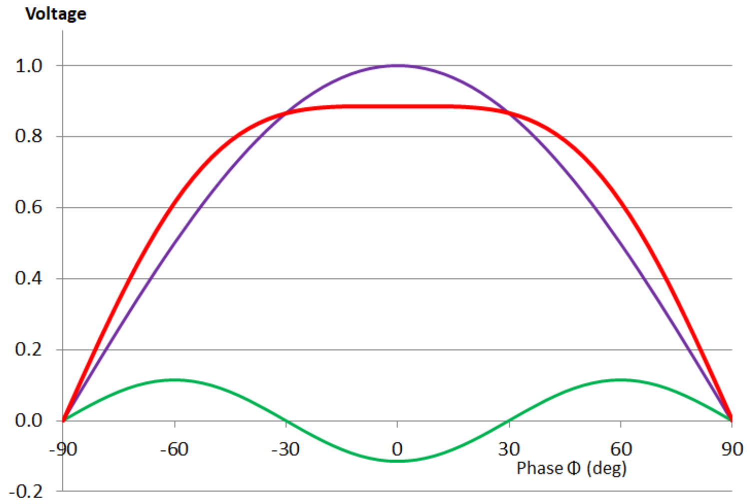
- The HIPA reaches 2.4 mA beam intensity and 1.4 MW average Beam Power which is **World Record!**
  - most intensive Muon Beams: $5 \cdot 10^8$ µ+/s , 10^8 µ-/s
  - Spallation-Neutron-Source 10^{14} n/s (medium flux reactor equivalent)
- Why can the TRIUMF cyclotron only deliver 300-400 µA?
  - High intensity → requires a powerful injector and higher injection energy of the beam from the source.
  - 870 keV at PSI versus 300 keV at TRIUMF
- **Current limits in a Sector/Ring Cyclotron?**
  - Longitudinal space charge forces increase the energy spread => higher extraction losses
  - Can be mitigated by high voltage on the RF cavities → lower turn number, current limit ~ V^3 (Joho's rule)



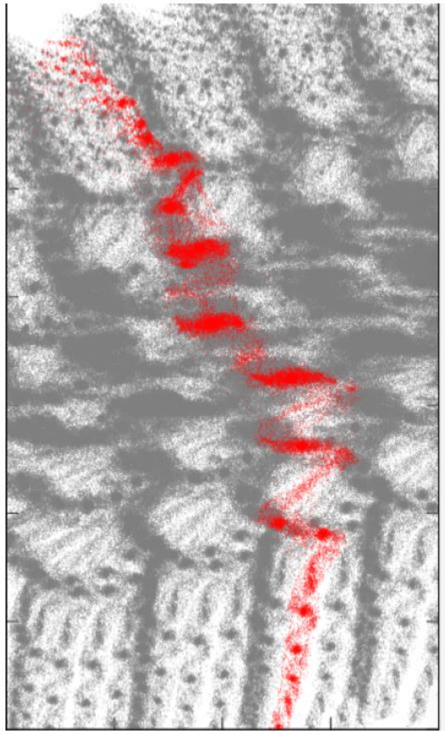
Beam dynamics discoveries @ PSI

- Joho's model (1981) showed how disc-like bunches develop spiral arms (space charge effect), and led to his cubic law for beam current I ~ V^3.
- Reduction of space charge forces by cavity voltage flattop – added higher harmonics (150 MHz)



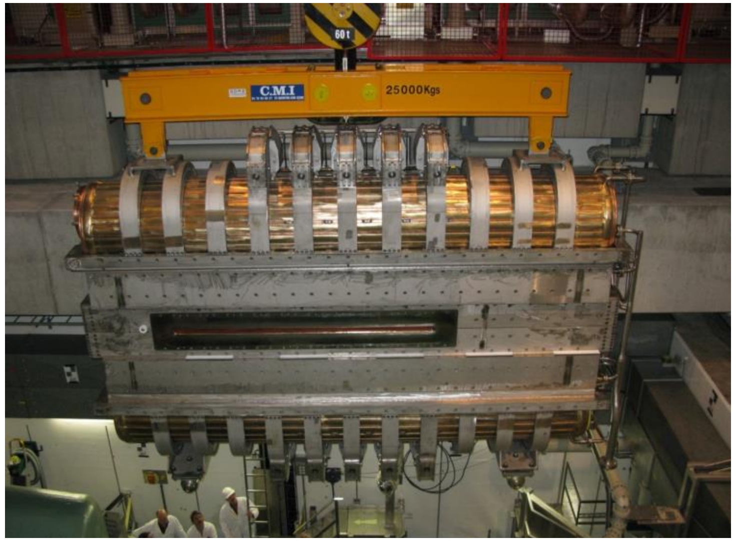


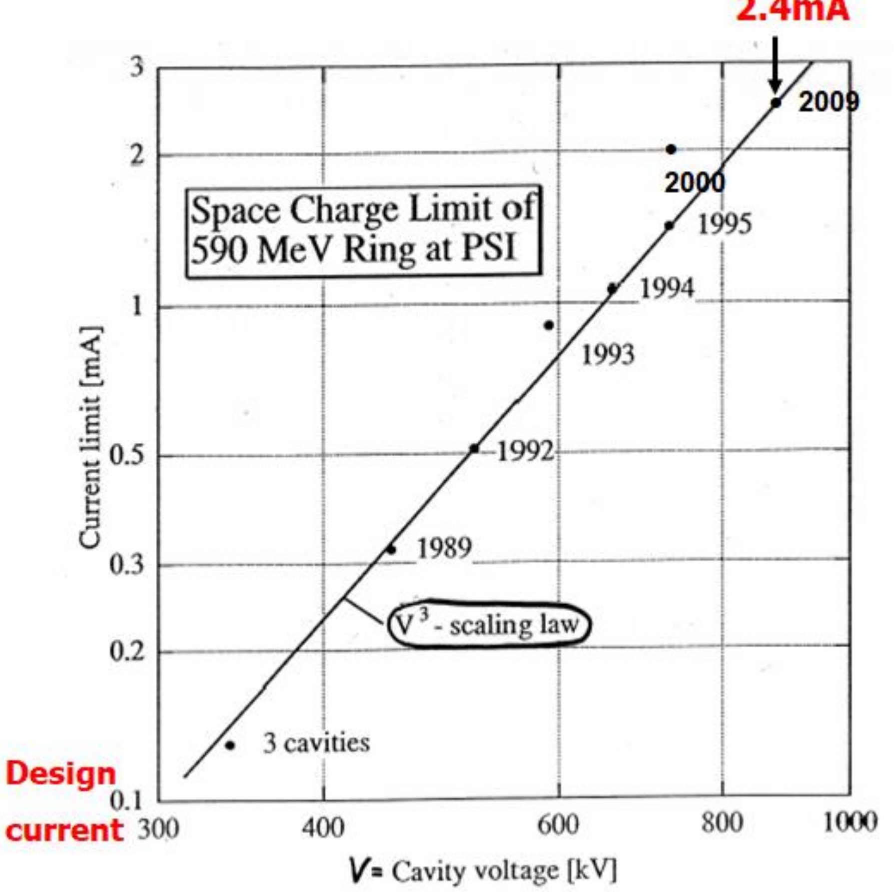
- We observe this in the simulation of high intensity beams in the TRIUMF 520 MeV cyclotron. Equations that describe the behaviour are identical to those that describe the cloud motion of Jupiter!

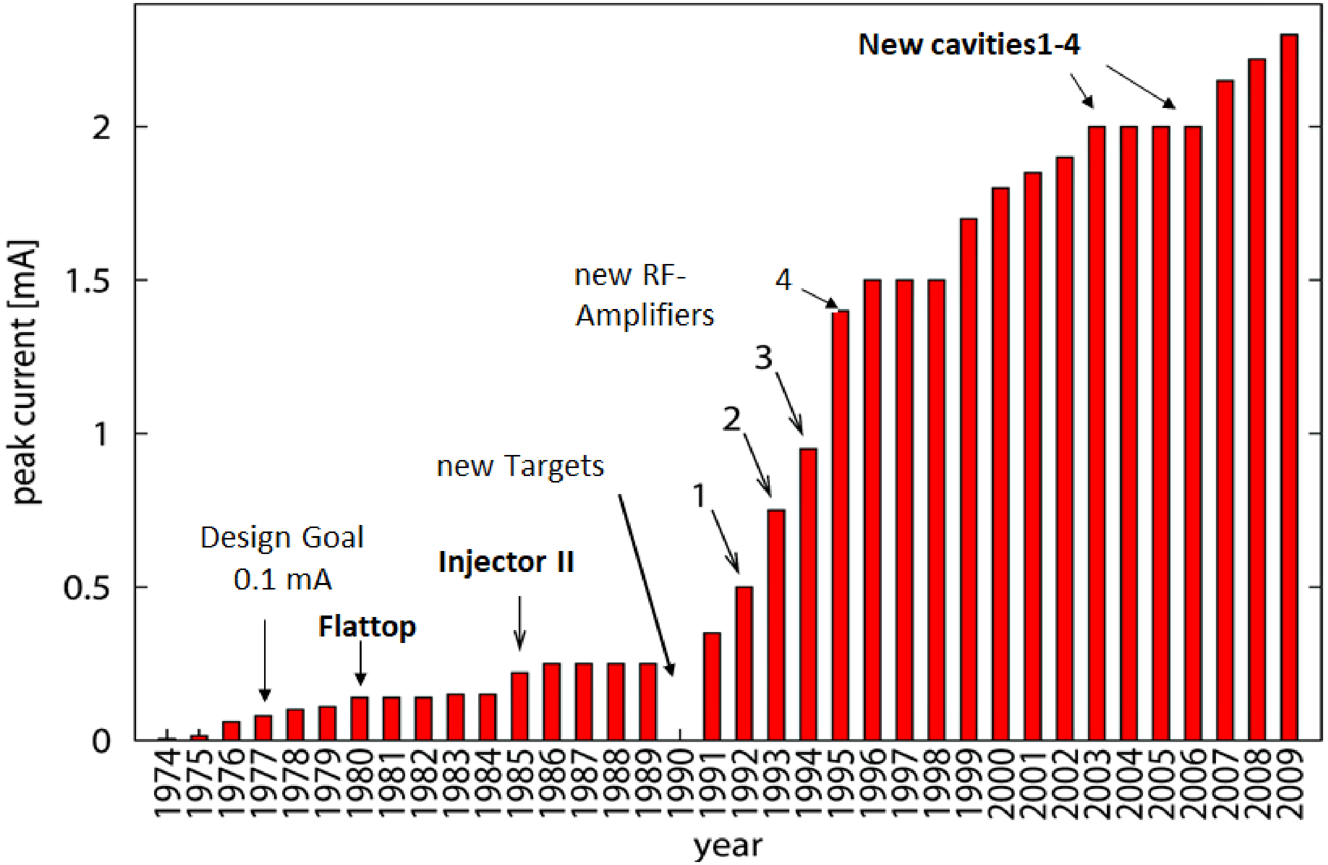


New Copper Cavity 50 MHz

- Voltage limit ~ 1MV, better cooling and better breakdown characteristic
- 60% of RF power go into the beam only 40% losses in the cavity
- **Replacing the 500-kV cavities by 1-MV ones has raised beam power by a factor of 8.**



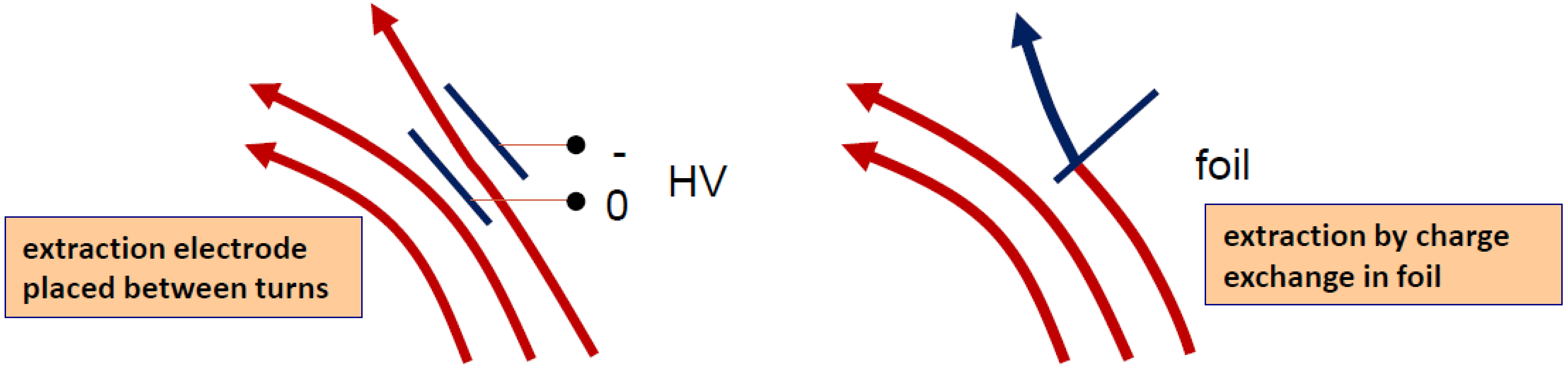




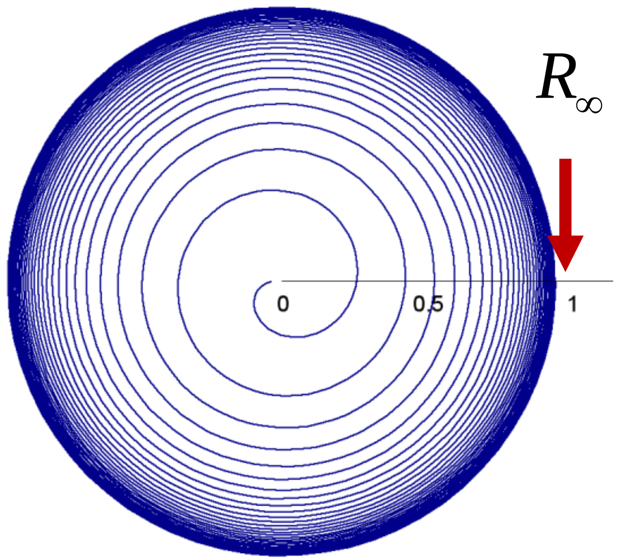
Extraction – beam path separation

- For protons the stripping extraction cannot be applied → use of a deflecting element
- Deflecting element should affect just one turn, not neighboured turn otherwise it will be the cause of losses!
- Often used are electrostatic deflectors with thin electrodes → can be damaged by heating of lost beam particles! Requires
  >99.9% extraction efficiency, difficult to reach.

Single turn extraction



How to get sufficient turn separation for extraction?

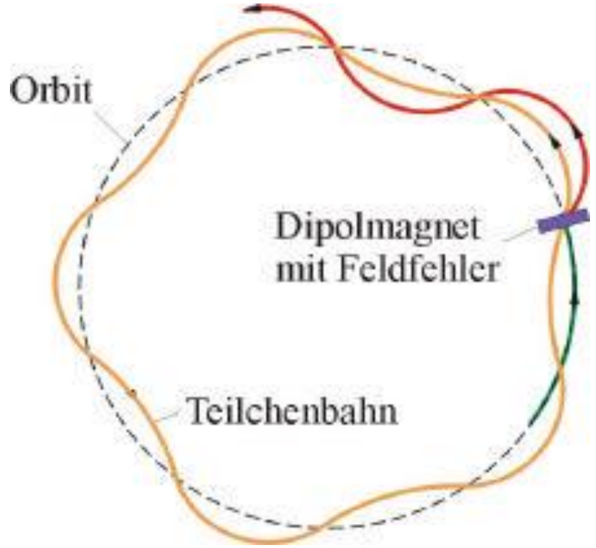


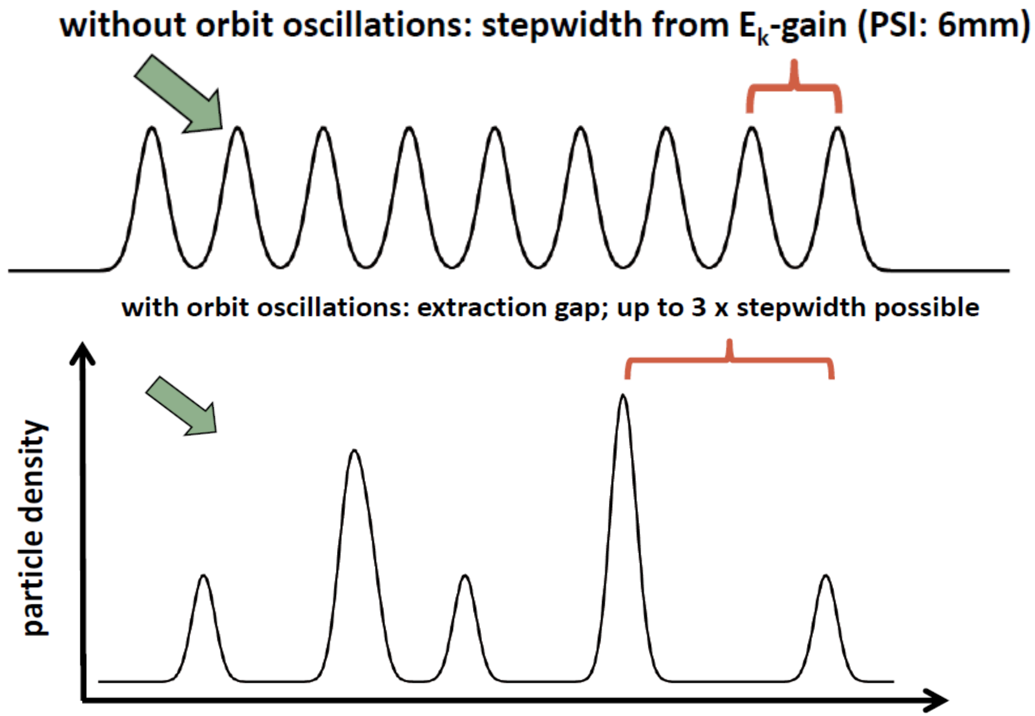
- Radius increment per turn decreases with increasing energy (R ~ momentum and isochronicity)

$$R = \frac{p}{qB} = \frac{m\beta c}{qB} = \frac{\beta c}{\omega_c} = R_\infty \beta$$

→ extraction becomes more and more difficult at higher energies

- Solution: Extraction with off-center orbits using strong betatron (transverse) oscillation.



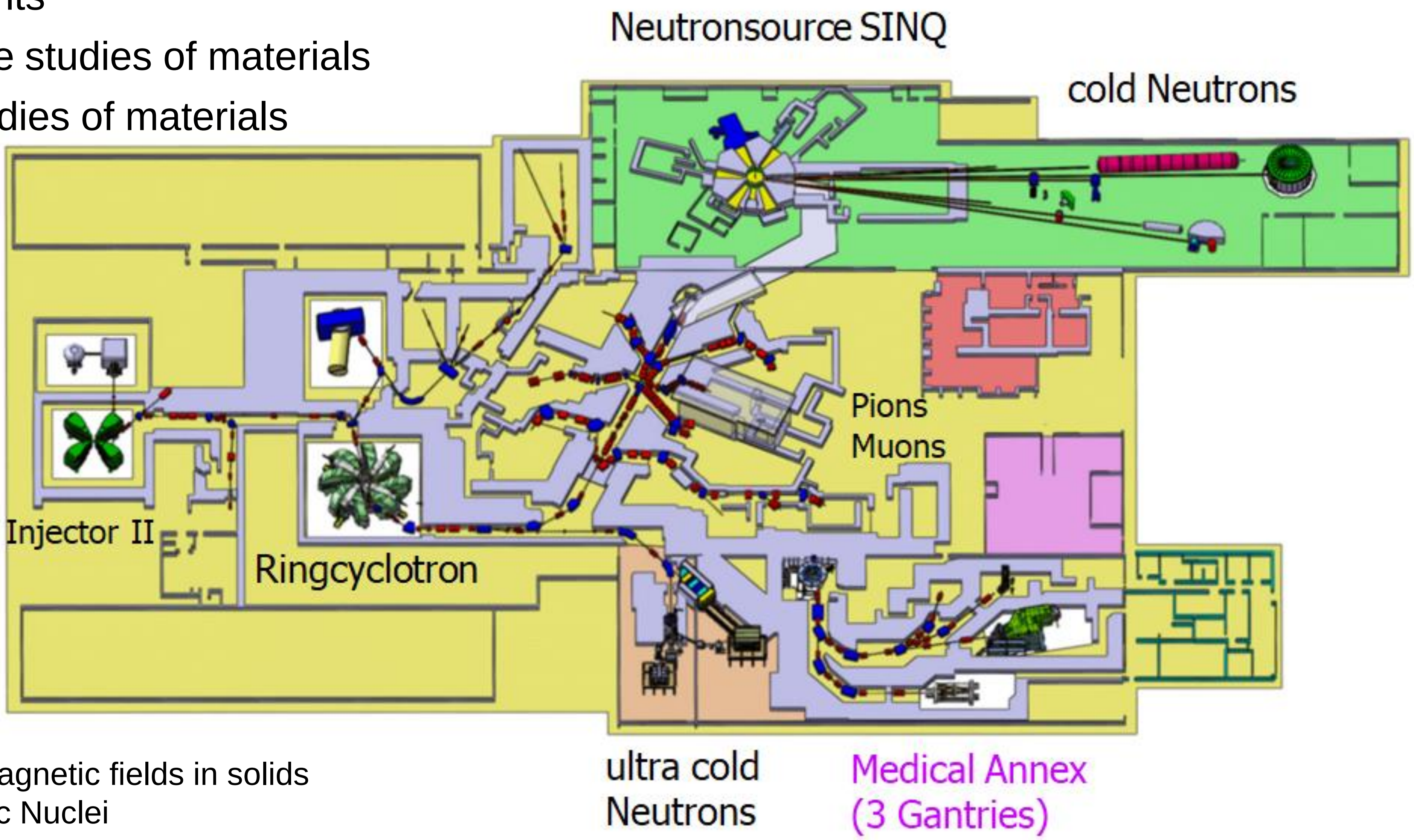


What has the cyclotron made possible at PSI?

World leading programs in

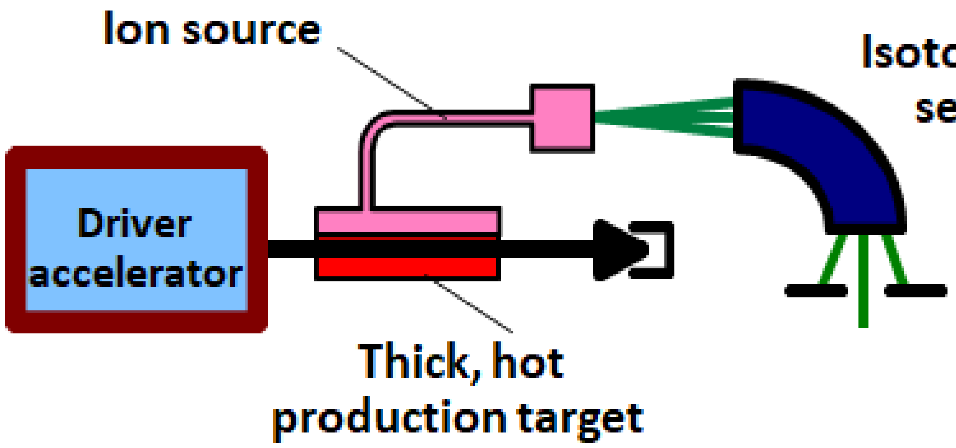
- Subatomic physics, fundamental symmetries – precision measurements
- Muon Spin Resonance studies of materials
- Spallation neutron studies of materials
- Proton irradiation, Ultra-Cold Neutrons
- Cancer therapy with pions and protons
- 2 complementary Probes for material research:

Muons (μSR) → internal magnetic fields in solids
Neutrons (SINQ) → Atomic Nuclei

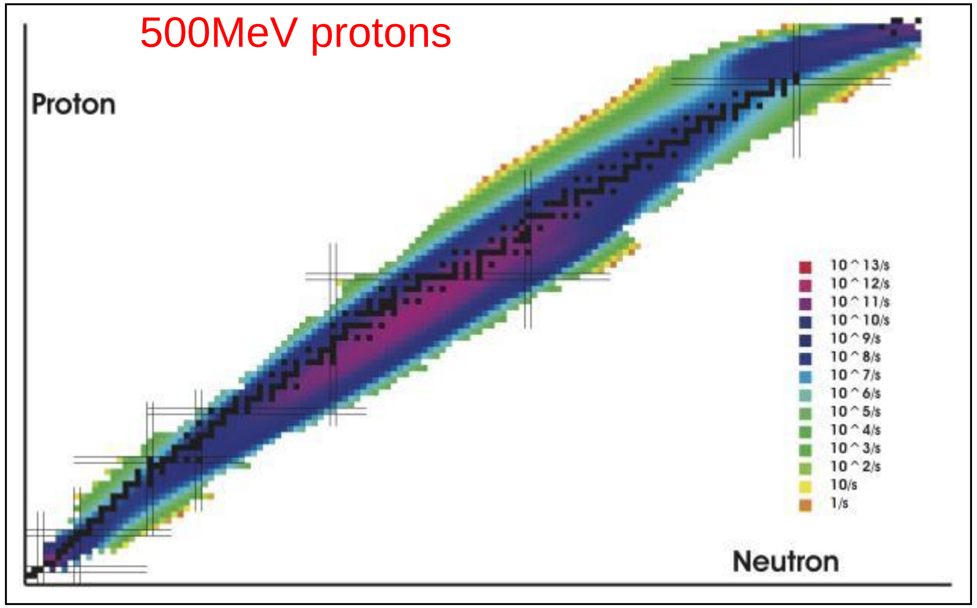


Rare isotope production example TRIUMF

Ion Separation OnLine (ISOL)

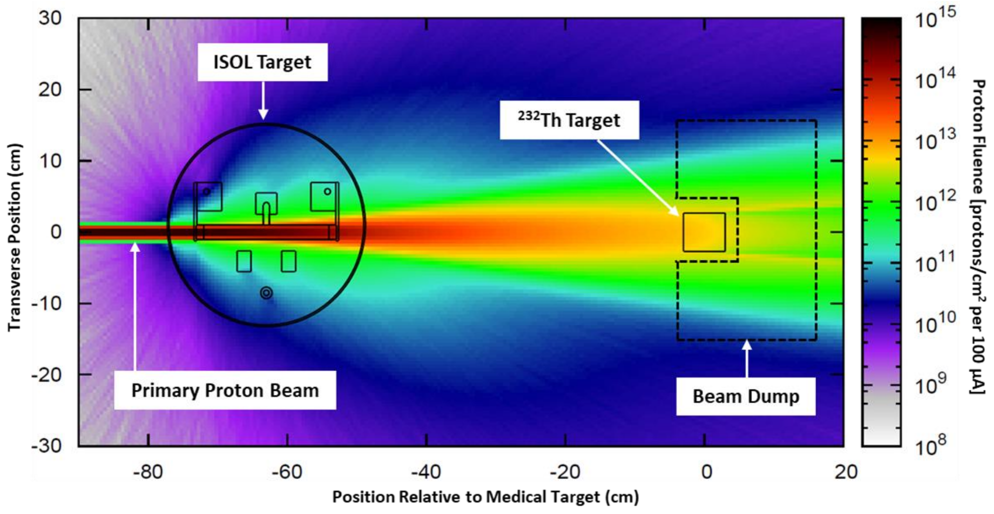


TRIUMF
ISOLDE (CERN)
GANIL



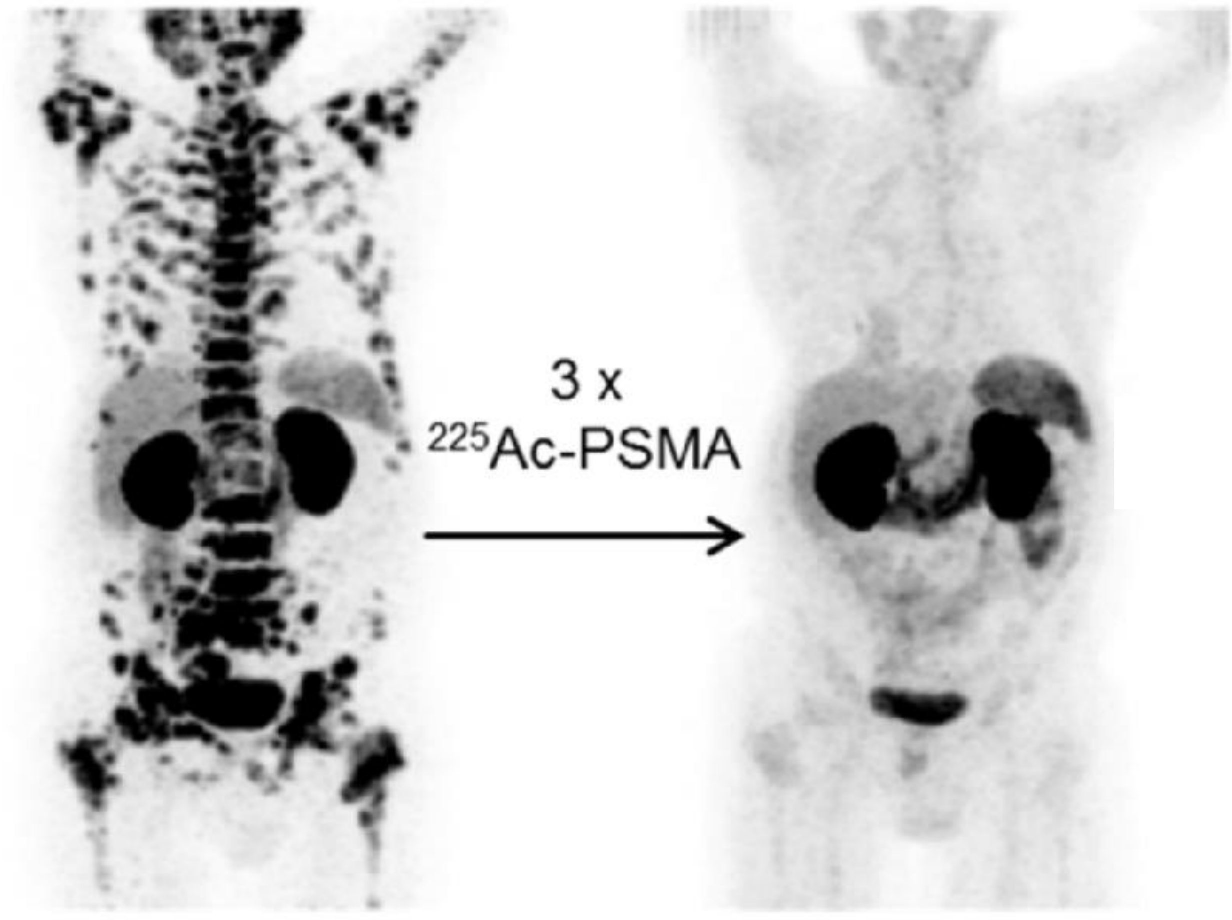
Symbiotic production of medical radionuclides

- Place symbiotic medical target in-between ISOL target and beam dump
- Pneumatic target delivery system from ARIEL hot cell complex to proton target station
- up to 100 mCi of ^{225}Ac from ^{232}Th spallation



Other example is ISOLDE MEDICIS

The future: Clinical Medical isotopes



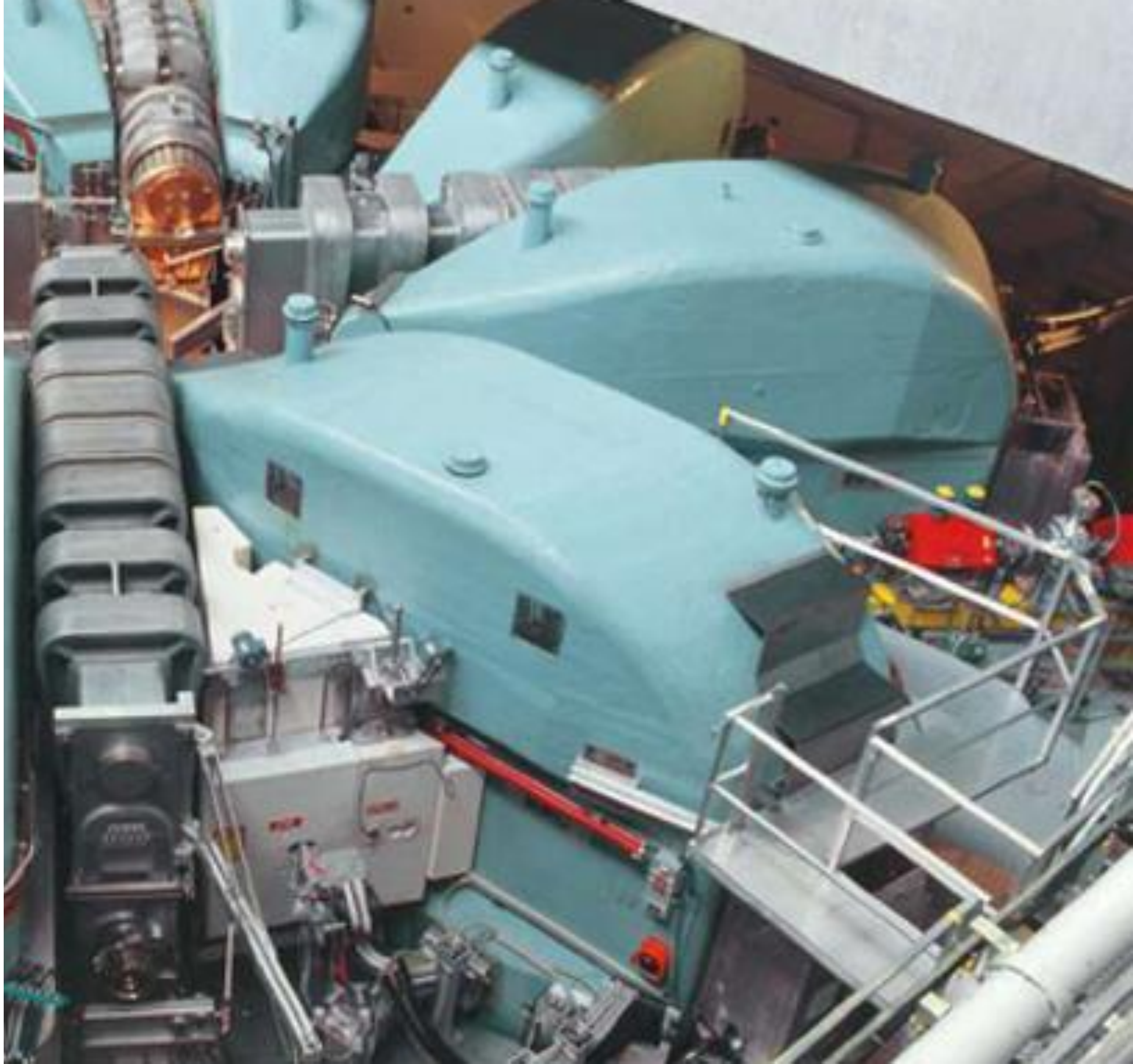
Kratochwil *et al., J. Nuc. Med.* 2016;57(12):1941–1944.

They make IMPACT!

- Patient (prostate cancer) had received several other treatment - all failed
- In many clinical trials now
- Primary 225Ac sources:
  - ^{229}Th/^{225}Ac generator ($t_{1/2}$ ~ 7880 y) sourced via legacy stockpile, ORNL, ITU
  - ^{226}Ra irradiation
  - ^{232}Th spallation with p beams (500 MeV)

- Not enough Ac-225 worldwide available for all clinical trial and treatments for different cancer sites!!!

In conclusion! The future is bright!



First 590 MeV protons on meson-targets 24.2.1974
the start of a great success story

Thomas Stammbach | Werner Joho | **Hans Willax** | Urs Schryber | **Jean-Pierre Blaser**

How shall I summarize the external view on the game-changing machine at PSI?

Fascination

and

Admiration!

Congratulations

on the 50th Anniversary of the PSI HIPA

from Nigel Smith, Executive Director and CEO and a lot of good friends at TRIUMF!