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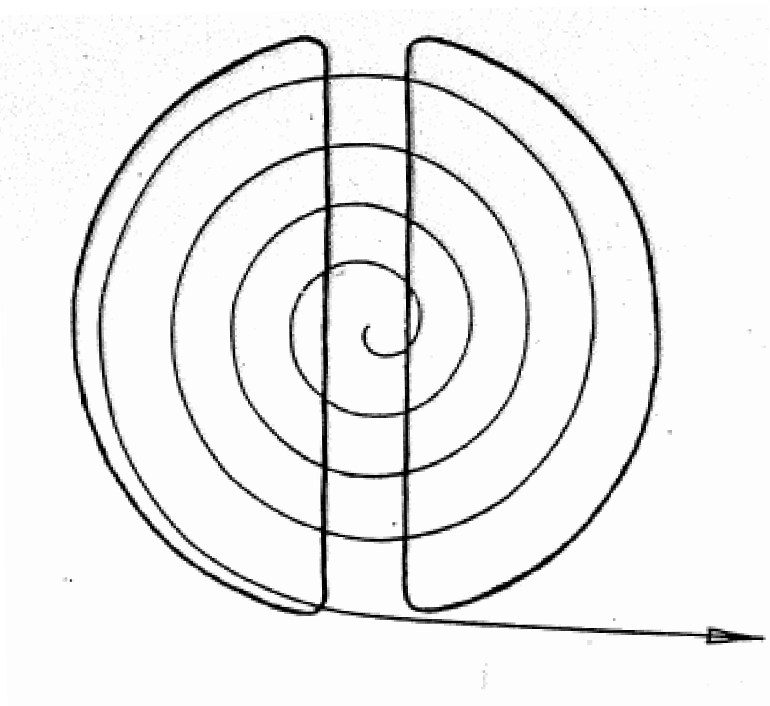
the Cyclotron Facilities at PSI

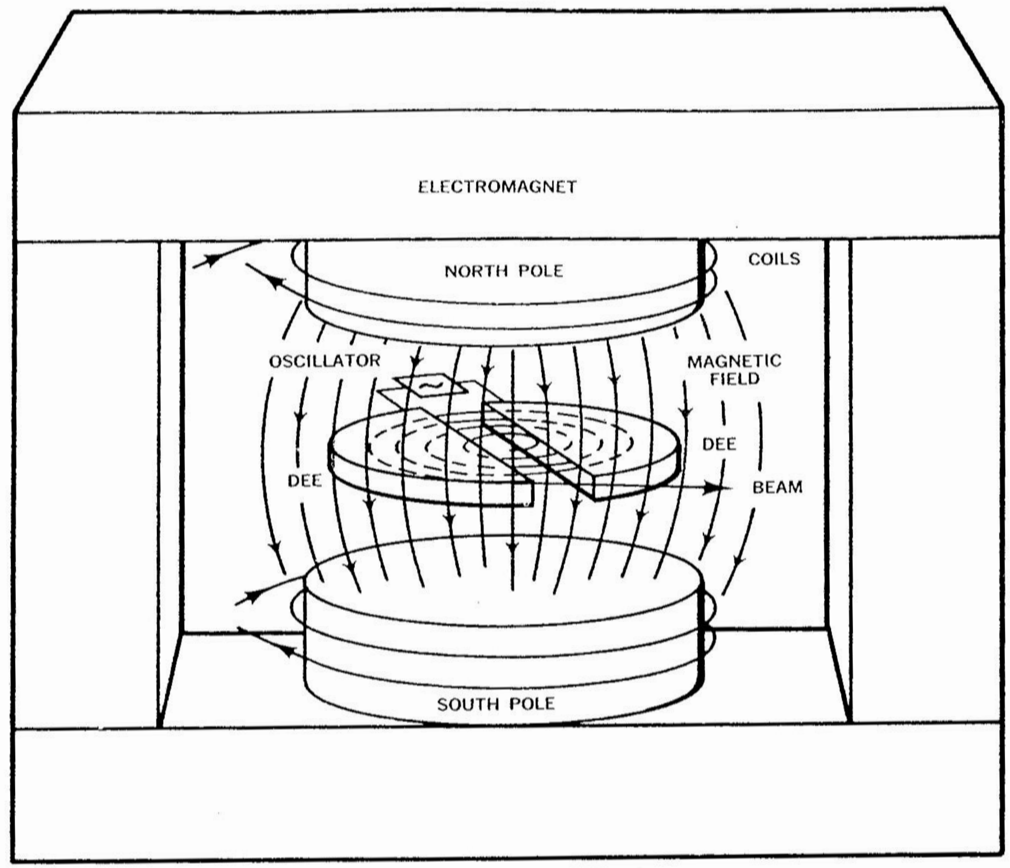
an overview

Werner Joho, PSI

original Cyclotrons



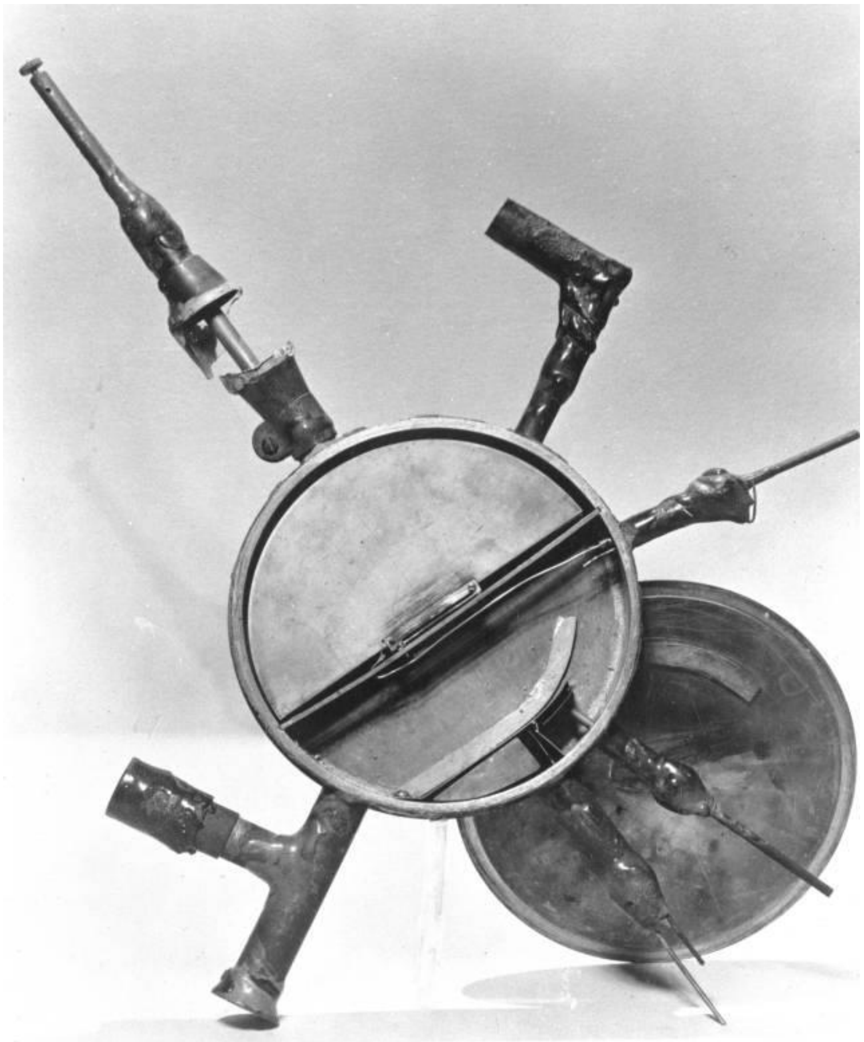
the cyclotron as seen by the inventor



the first classical cyclotrons

(the RF-system squezzed into the magnet gap)

The first Cyclotron 1931



invented by **E.O.Lawrence**,

constructed by M.S.Livingston

Berkeley, California

4 inch diameter

1 kV on the Dee

80 keV Protons

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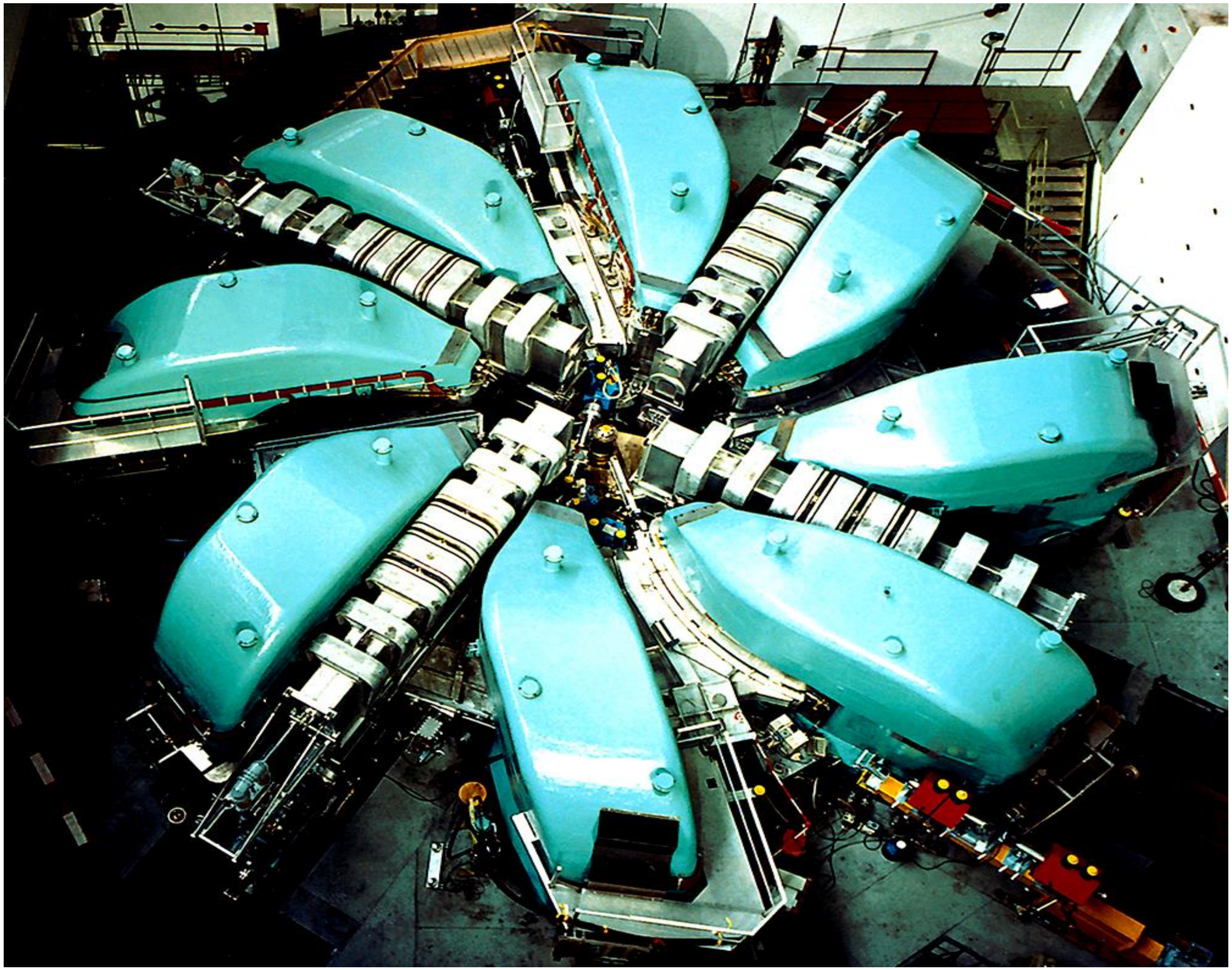
43 years later (1974)



Ring Cyclotron

590 MeV Protons

15 m Diameter

Hans Willax,

Jean Pierre Blaser,

Villigen, Switzerland

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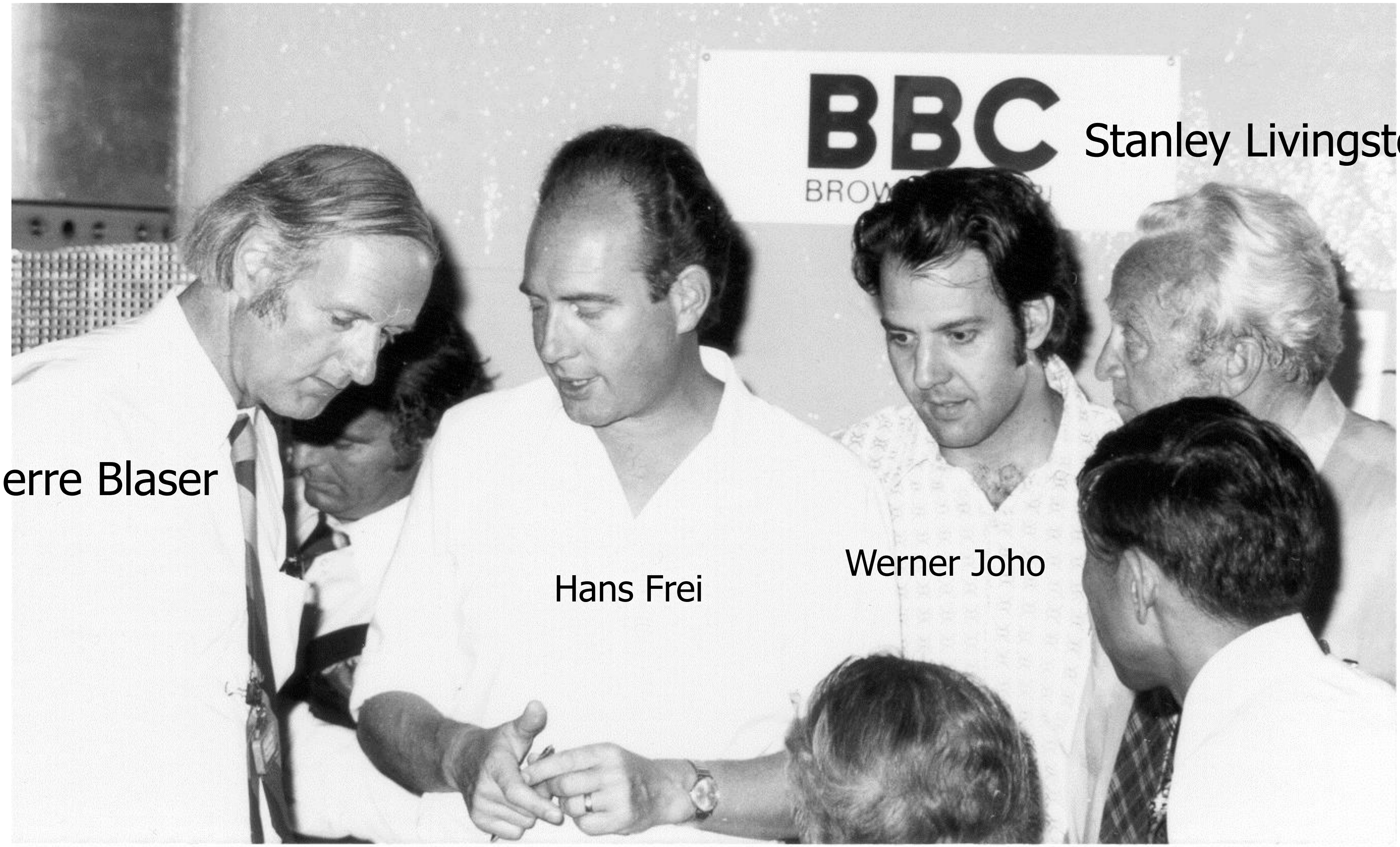
Int. Cyclotron Conference 1975 Zürich



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History of the Cyclotron

1929	Idea by E.O.Lawrence in Berkeley (inspired by R.Wideroe!)		
1931	4 inch cyclotron	80 keV	p
1932	10 inch cyclotron	1.2 MeV	p
1934	26 inch cyclotron	7 MeV	p
1939	60 inch cyclotron	16 MeV	d
1946	184 inch synchrocyclotron	200 MeV	d
		400 MeV	α

1938 Idea for sectored cyclotron (AVF) by Thomas

1962	88 inch sector cyclotron	K=160 MeV	ion
1974	SIN/PSI Ringcyclotron	590 MeV	p
1982	supercond.cyclotron MSU	K=500 MeV	ion

2008: ca. 90 indiv. cyclotrons, ca. 200(?) commercial cyclotrons

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the Livingston Plot

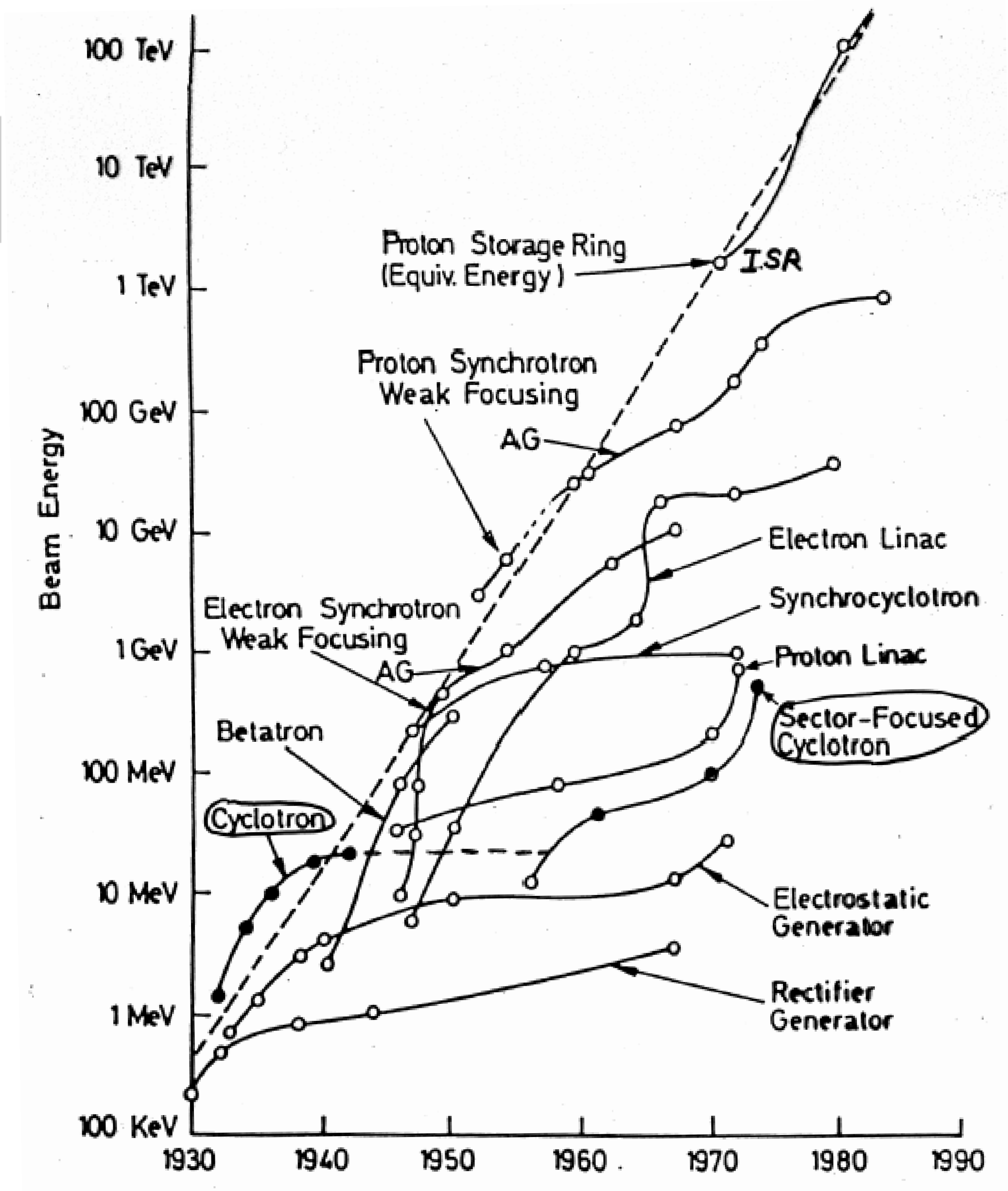
Energy Records for

Particle Accelerators

exponential increase of

maximum energy

Cyclotrons are the early leaders!



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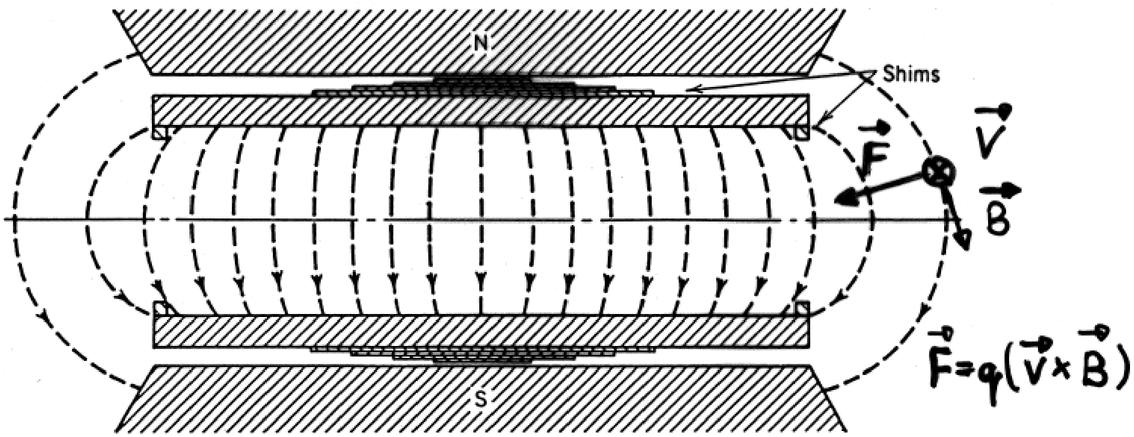
classical Cyclotron

In homogeneous magnetic field the circular orbits are vertically unstable

vertical stability with radially decreasing field B(r)



Definition of field index n with „logarithmic derivative"

$$\left(\frac{dB_0}{B_0}\right) \equiv -n \left(\frac{dr}{r}\right)$$

Focusing frequencies:

stable for $0 < n < 1$

$$Q_r = \sqrt{1-n}\,, \quad Q_y = \sqrt{n}\,,$$

$$Q_r^2 + Q_y^2 = 1$$

=> weak focusing, horizontally and vertically

Larmor Frequency

Revolution frequency ω_0 in homogeneous magnetic field:

ω_0 = v/R , p = mv = q B R (non rel.) :

$$\omega_0 = \frac{q}{m} B \qquad (= Larmor\ frequency)$$

ω_0 is independent of radius R and energy E !

$\Rightarrow$ Basis for classical Cyclotron (non rel.)

relativistic formula for all energies, with $E_{tot} = \gamma\, mc^2$ and $\omega_0 \equiv 2\pi\nu_0$

$$\nu_0 = \left(\frac{q}{2\pi m}\right)\frac{B}{\gamma}$$

$$\frac{q}{2\pi m} = 15.25\ \mathrm{MHz/T} \quad \text{for protons}$$

$$\frac{q}{2\pi m} = 28\ \mathrm{GHz/T} \quad \text{for electrons}$$

Isochronism

Acceleration of a particle with RF frequency ν_{RF} on harmonic h:

$$\nu_{RF} = h\,\nu_0$$

If this RF frequency stays constant during acceleration, we talk about an **isochronous cyclotron**. The condition for this is an average field which increases proportional to γ:

$$\Rightarrow B_0(R) \sim \gamma(R)$$

For an azimuthally symmetric field this leads to vertical instability. The way out is:

1) **magnetic sectors** give vertical focusing => $B(r,\vartheta)$, Thomas 1938

=> $B_0(R)$ = field averaged over the whole orbit

2) **synchro-cyclotron** with $\nu_{RF}(t)$ => pulsed beam, reduced intensity

Cyclotrons

classical Cyclotron — † — CW-beam — non relativistic energy limit

Synchro-cyclotron
- single pole (dying out!)
- FFAG with sectors

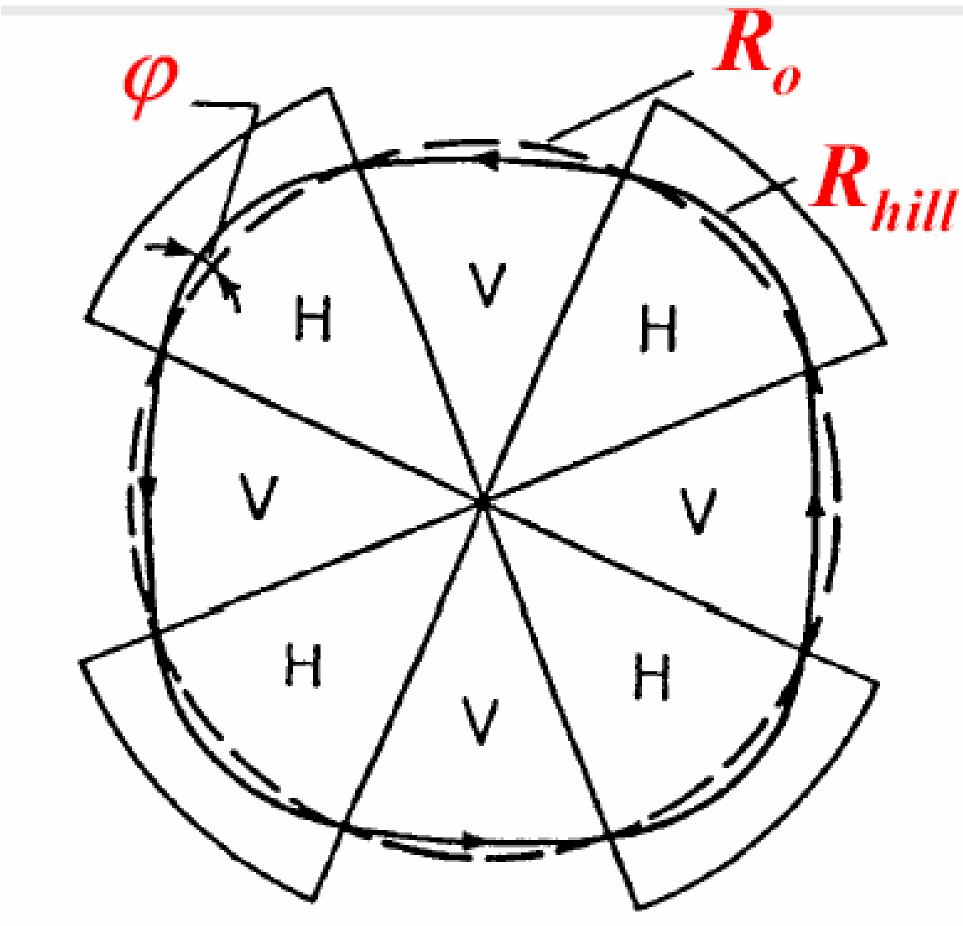
→ pulsed beam

Isochronous Cyclotron
- single pole with sectors
- Ring Cyclotron

→ CW-beam

- ASTOR concept → pulsed beam

Thomas Cyclotron (1938)



Sectors on the pole plates of an H-magnet

=> **vertical edge focusing**

between Hill (H) and Valley (V)

ΔB = B(Hill) - B(Valley)

focal length f_y through edge angle Ψ :

$$\frac{1}{f_y} = \frac{\Delta B}{(B\rho)} \tan\varphi, \quad (f_x = -f_y)$$

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Edge Focusing

horizontally:

the deflection of a particle with parallel

displacement x is delayed by the path length

$ds = x \tan \Psi$ => $x' = ds/R$

the effect is the same as a

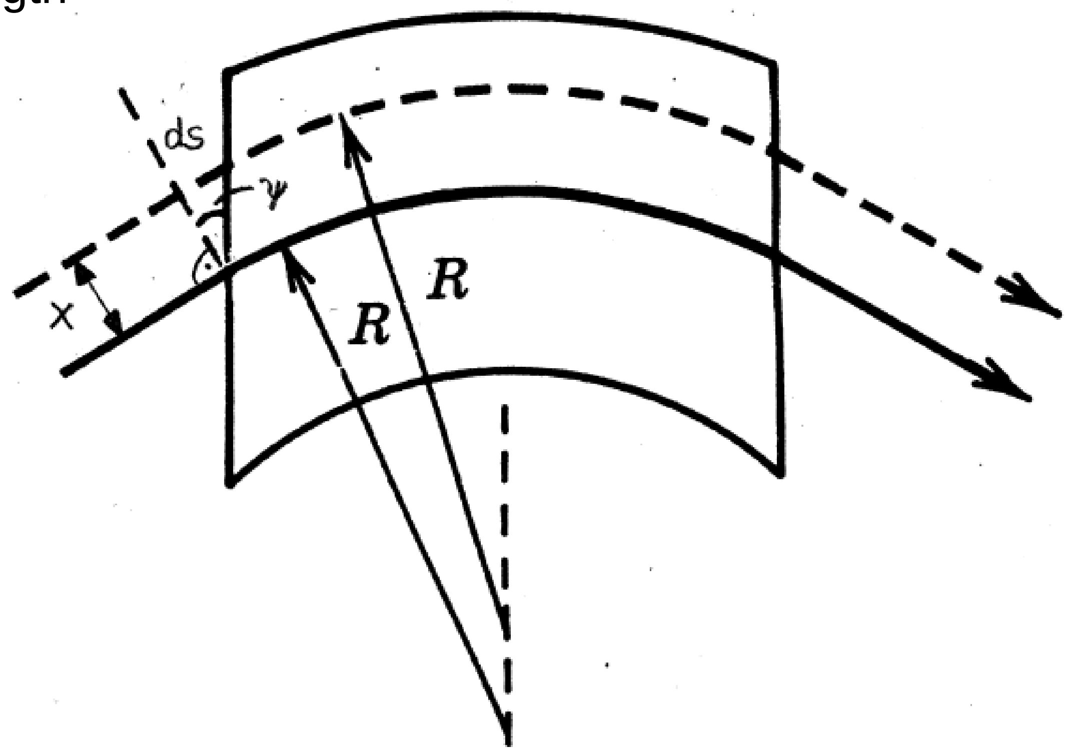
defocusing quadrupole

with strength: **$1/f_x = -(1/R) \tan \Psi$**

vertically:

focusing with $f_y = -f_x$

Sectormagnet with edge angle Ψ



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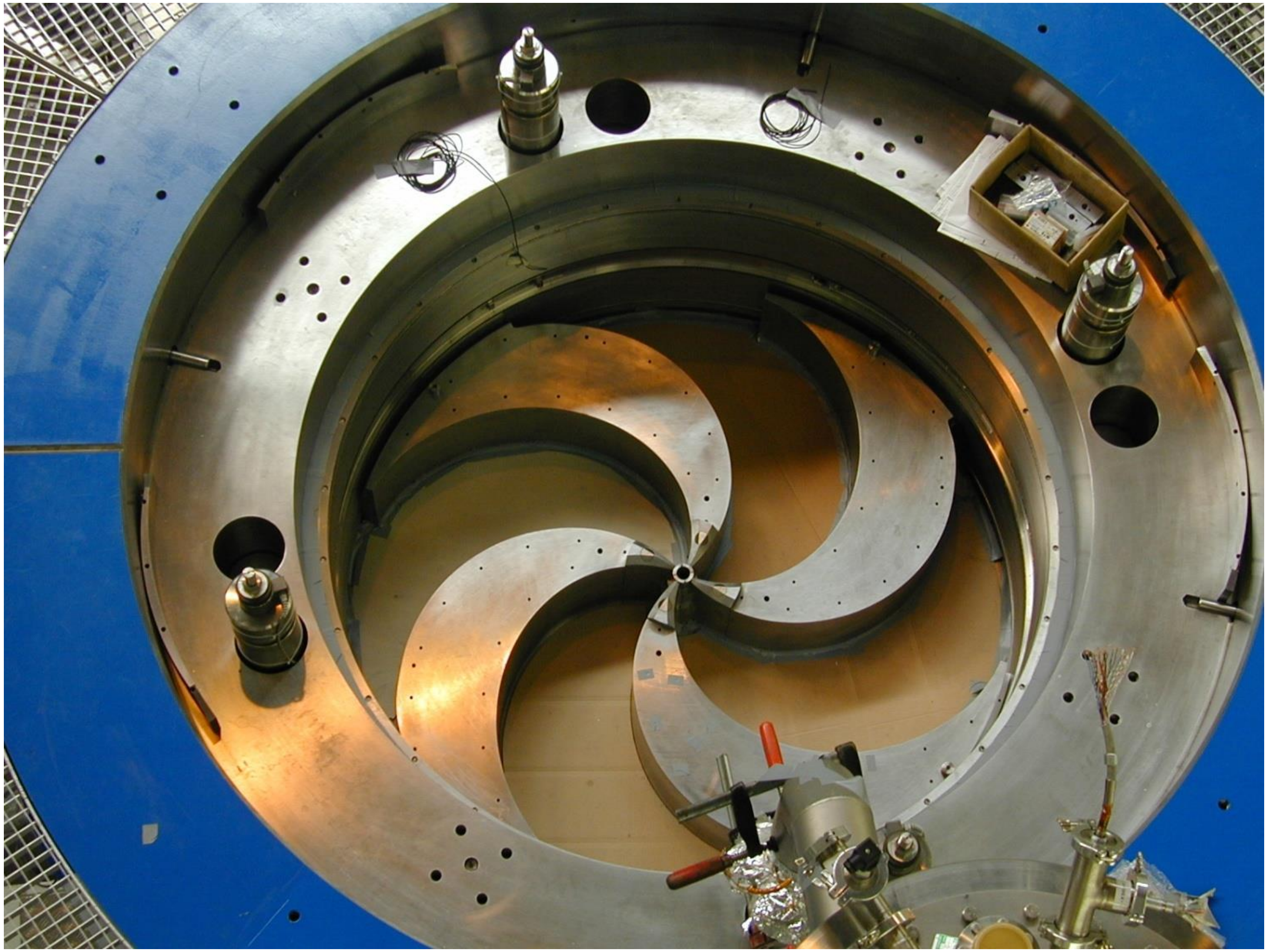
Comet Cyclotron, Spiral Sectors



250 MeV Protons for Therapy (ACCEL/ PSI)

superconducting Magnet with 4 Sectors

The spiral structure is responsible for the vertical beam focusing

0.5 m

Advantages of Ring Cyclotrons
(Hans Willax 1963)

magnetic field and RF system are decoupled

- many high voltage cavities
  - fast crossing of resonances,
  - good turn separation
- flattop cavity
  - monoenergetic beam
  - single turn extraction
- strong vertical focusing
  - small magnet gap
  - low power consumption
  - (magnet weight as low as for compact magnet!)
- straight sections
  - easy construction of extraction and injection elements (no kickers !)
  - lots of space for diagnostic and correction elements

low extraction losses

=> high intensity

requires injector!

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PSI has 3 Top-class Accelerators!

- **Ring-Cyclotron , 590 MeV Protons**

  => Neutrons, muons

- **Storage Ring , 2.4 GeV Electrons**

  => X-rays

- **compact-Cyclotron , 250 MeV Protons**

  => Cancer Therapy

Ring Cyclotron
590 MeV Protons

1.4 MW average Beam Power

(World Record!)

most intensive

Muon Beams

$5 \cdot 10^8\ \mu^+/s$, $10^8\ \mu^-/s$

Spallation-Neutron-Source

10^{14} n/s

equivalent to
medium Flux Reactor
(but without Uranium!)

Swiss Light Source (SLS)
2.4 GeV Electron Storage Ring

- constant beam current (400-402 mA)
  due to **top-up** injection every 2.5 min.

- extreme stable Photon Beams
  due to „**fast orbit feedback**“ (< 0.5 μm)

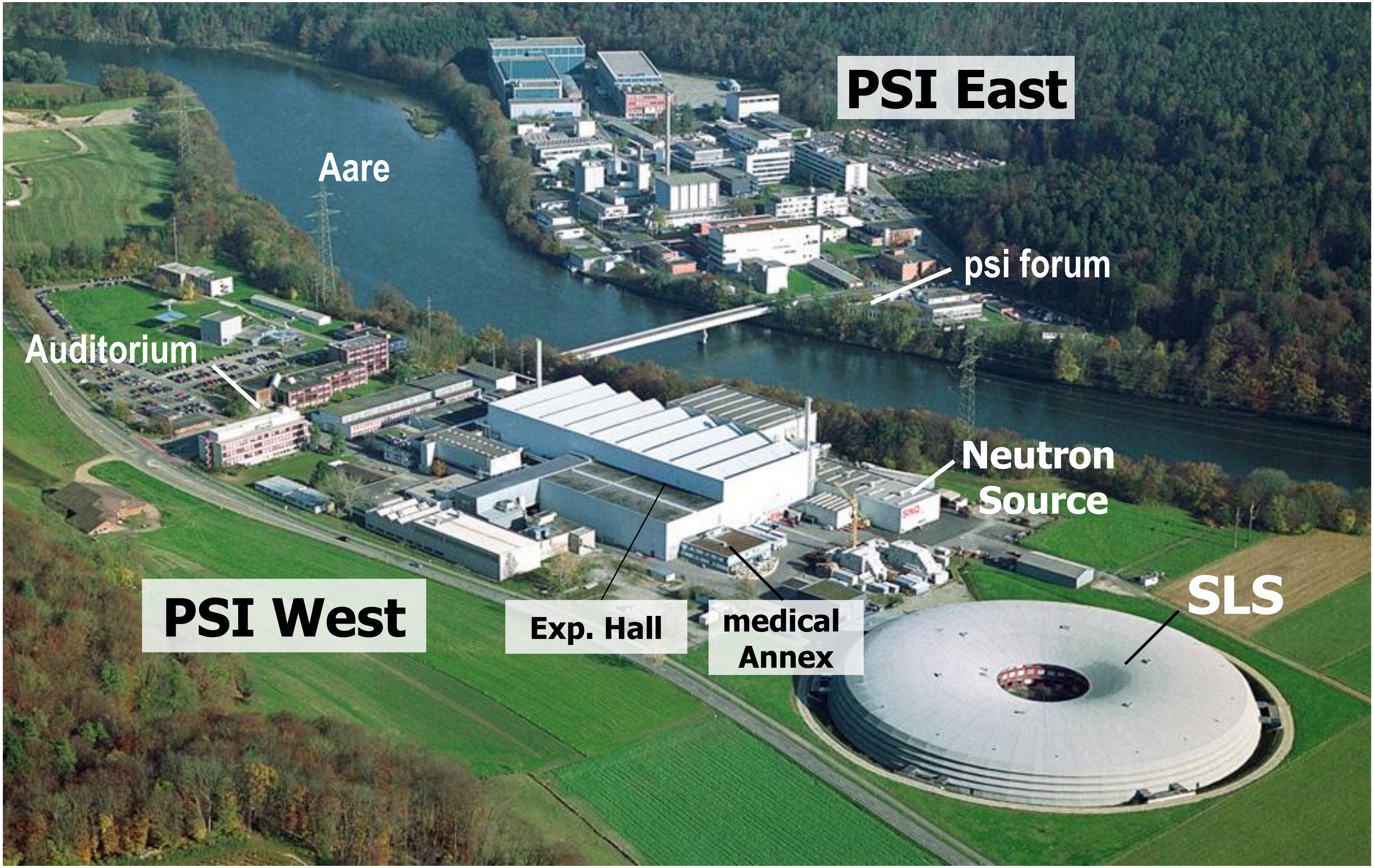
supraconducting Cyclotron 250 MeV Protons for Beam Therapy

Eye Tumours

2 rotating Gantries

3D-Spot Scanning

PSI Aerial View



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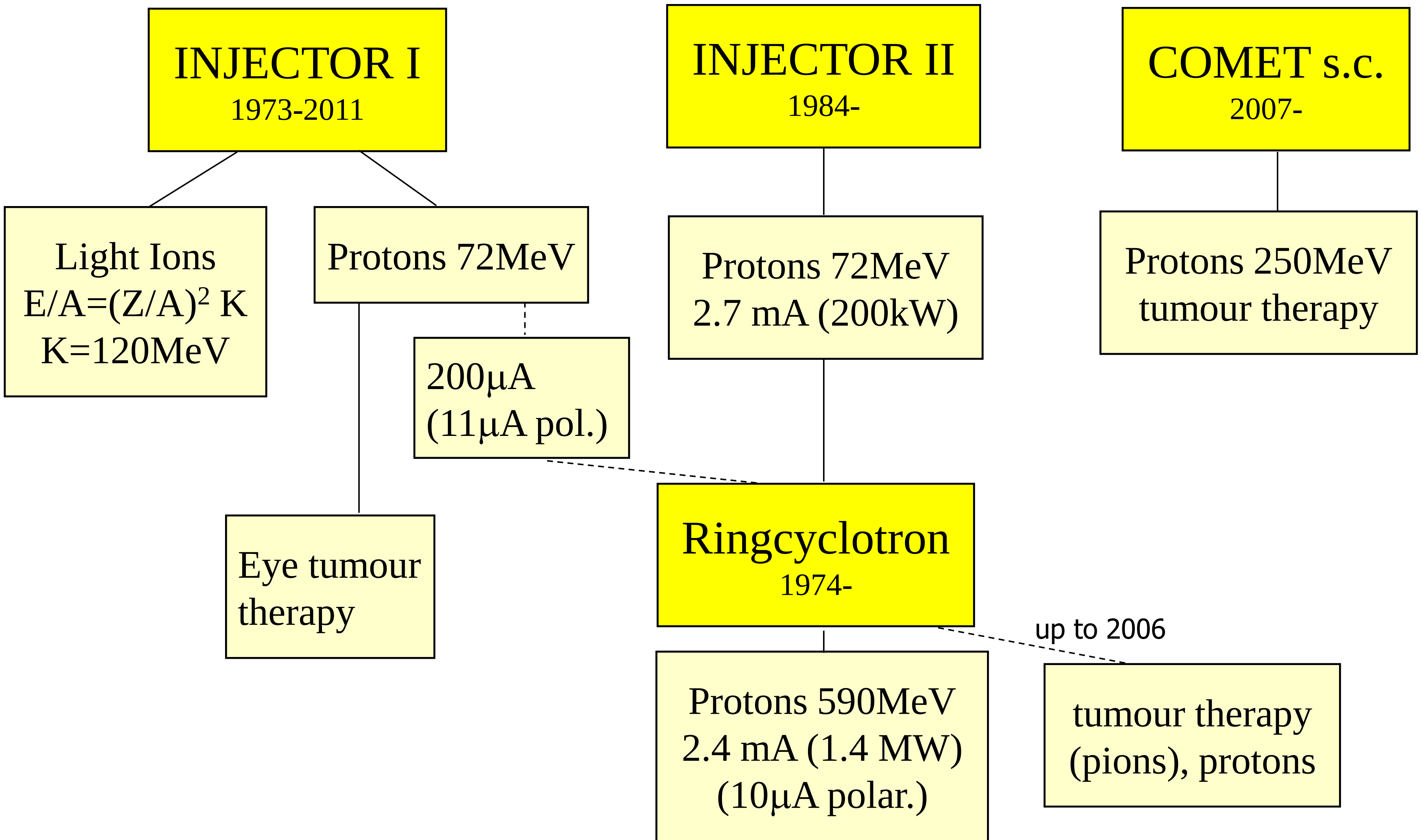
The PSI Cyclotrons



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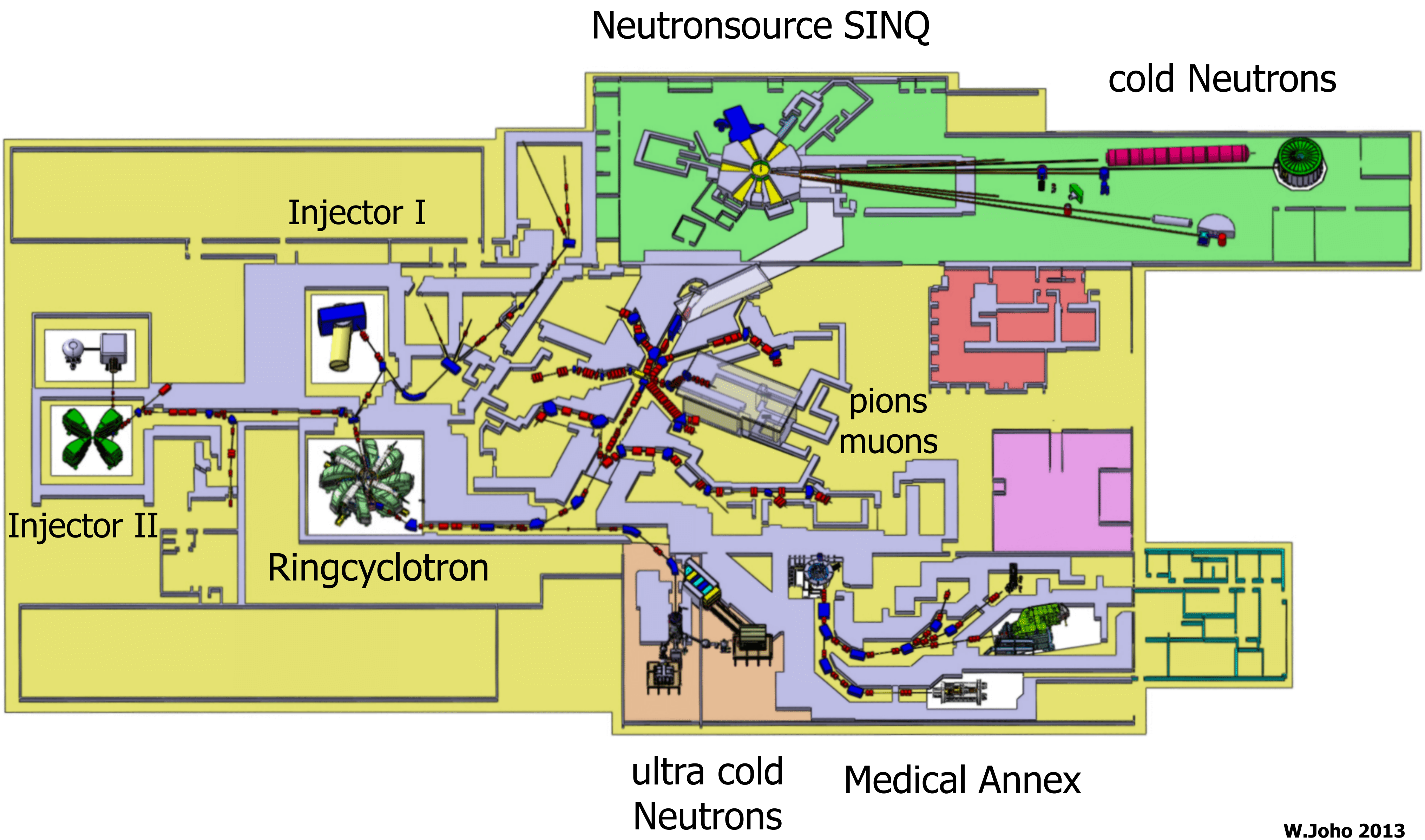
Experimental Hall



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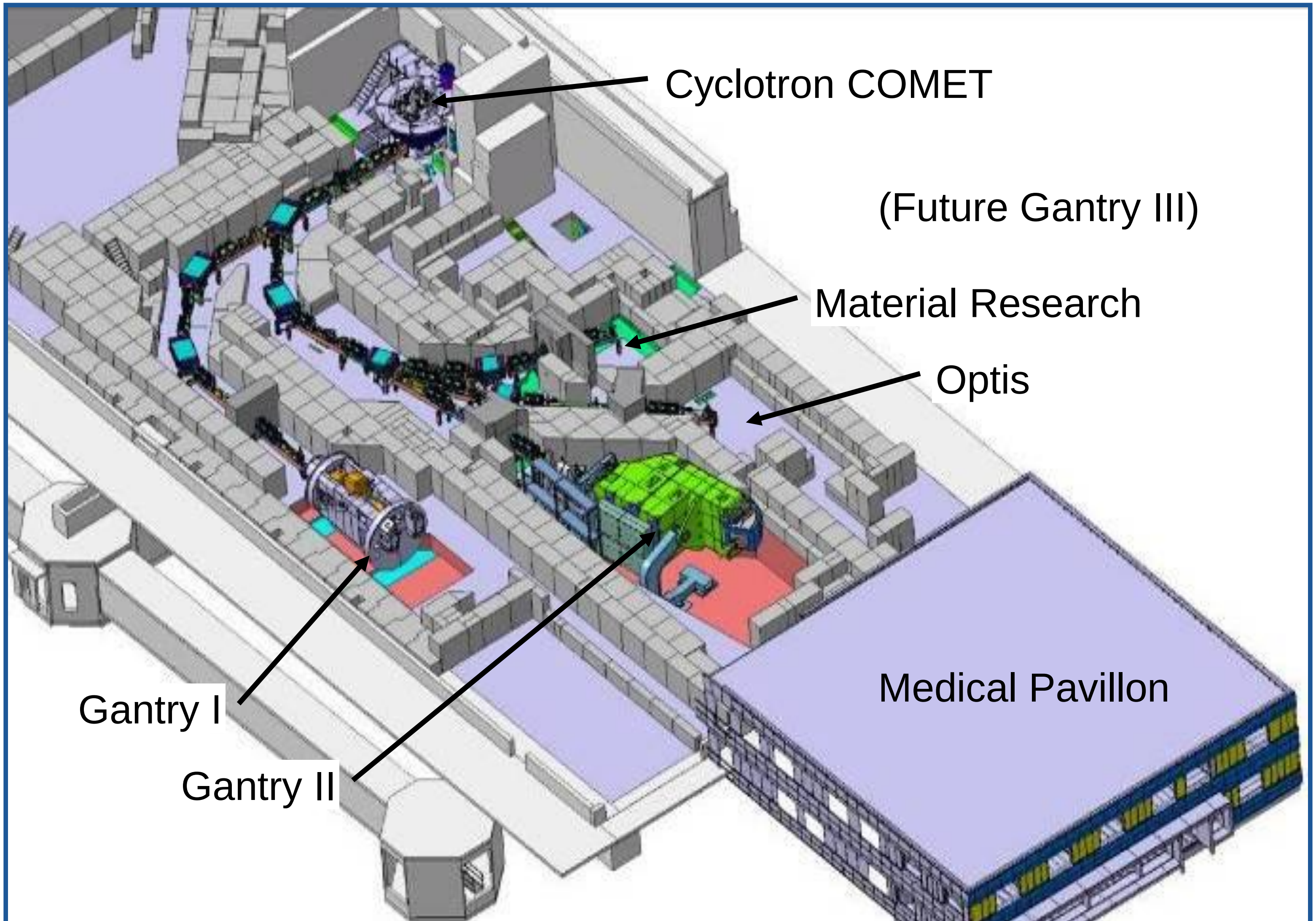
The PROSCAN Facility



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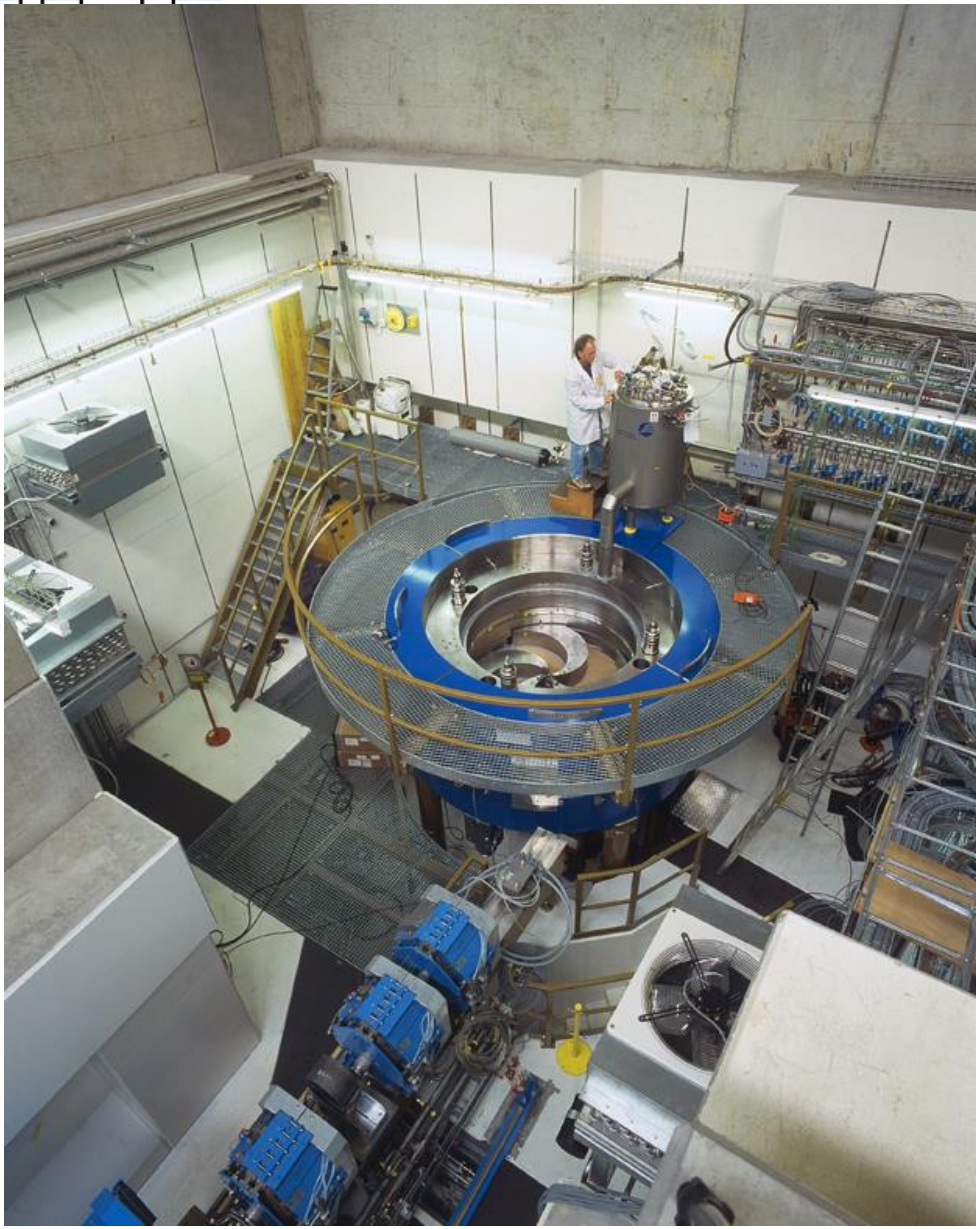


Comet Cyclotron

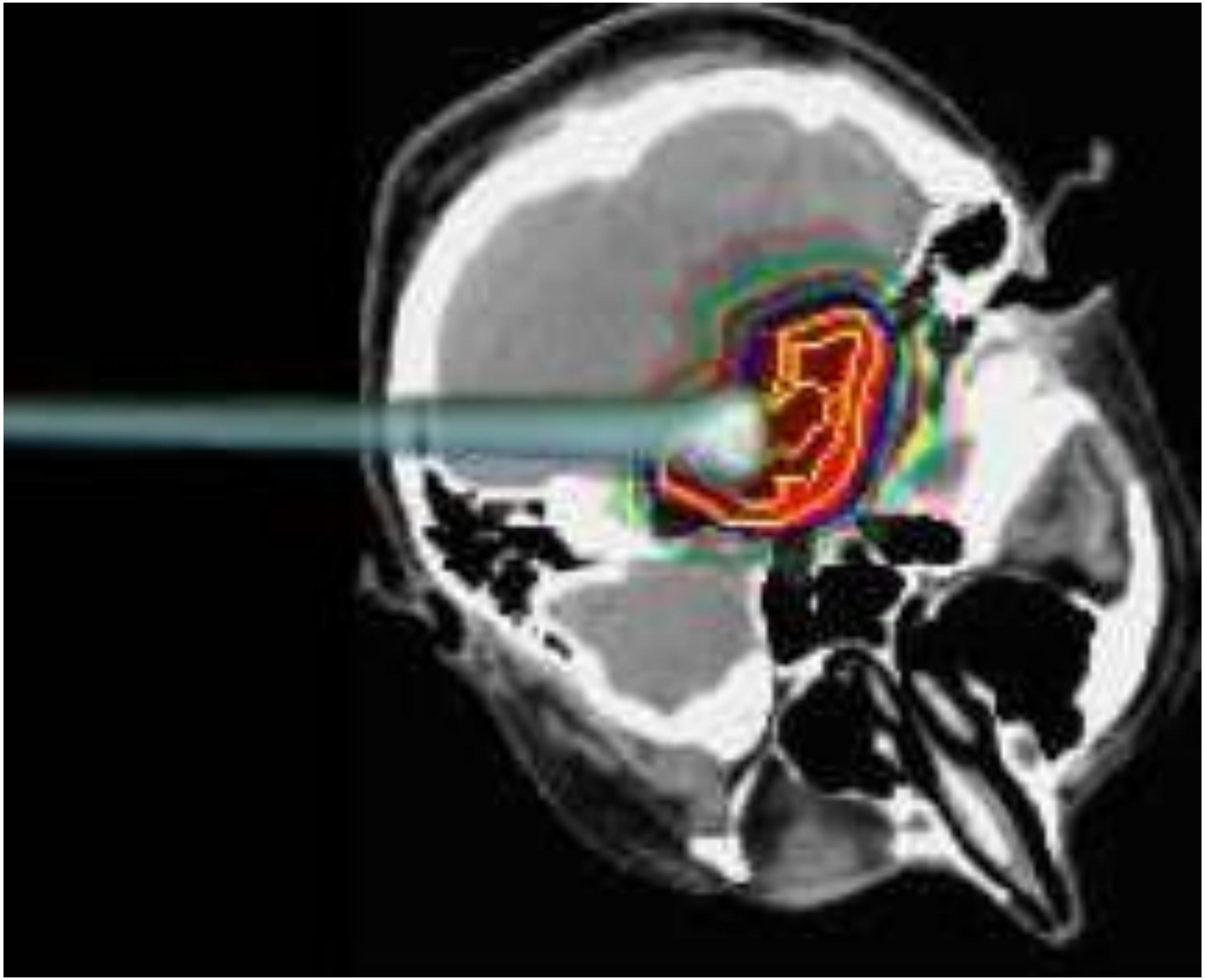
Radiation Therapy with 250 MeV Protons

superconducting Cyclotron:

Magnet, 3m Ø

Collaboration: ACCEL & PSI

Brain Tumour



Irradiation with

Protons by

Spot-Scanning

(E.Pedroni, PSI)

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Proton Therapy

Irradiation of Tumour from different Directions with Gantry

⇒ minimal Dose at Surface

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OPTIS, Eye Tumour Therapy with Protons

1984-2012

> 5‘500 Patients

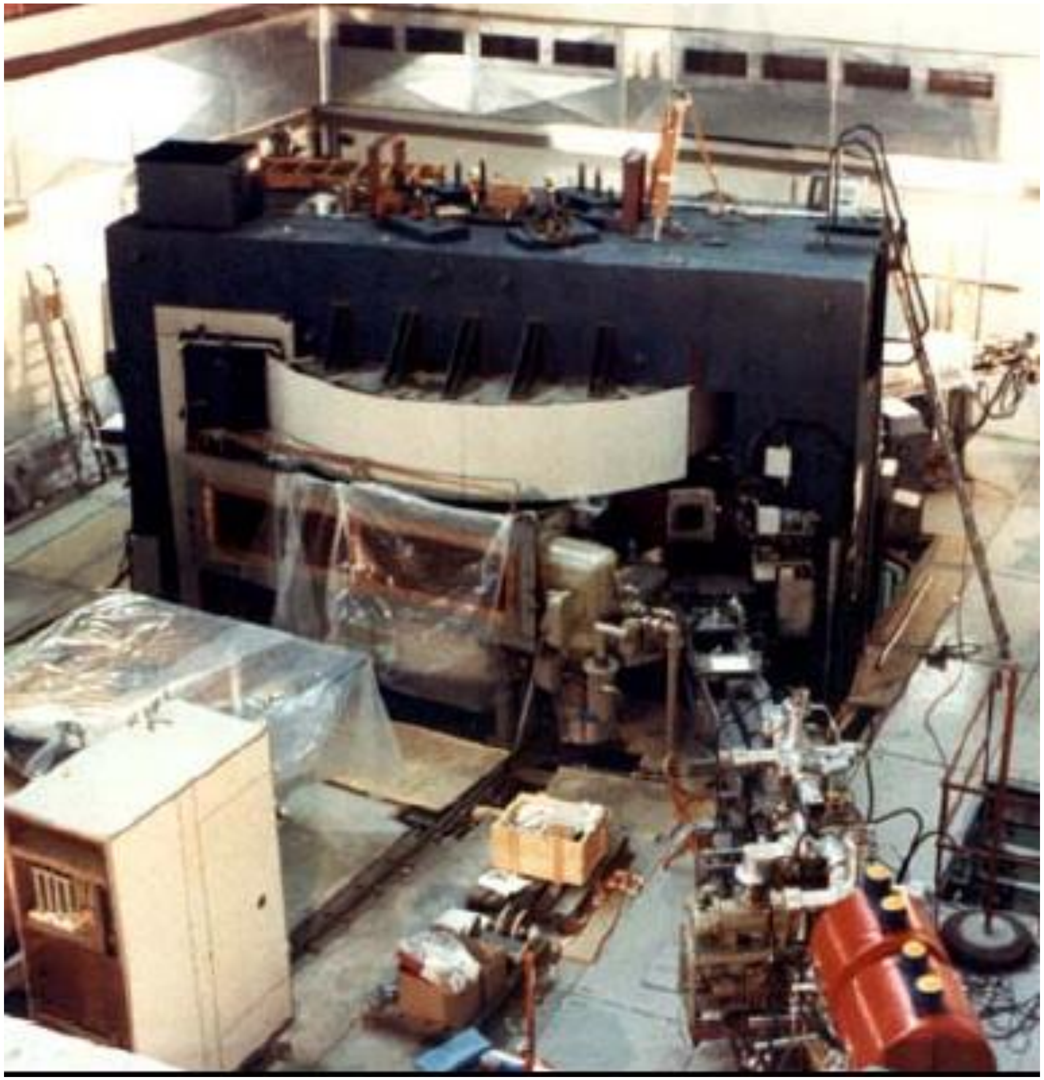
Tumour Control:

> 98%

(Collaboration with
Hospital Lausanne)

Irradiation on 4 Days

Injector I Cyclotron



Philipps (1973-2011)

72 MeV Protons:

100-200 μA

polarized: 10 μA

Ions, Energy/Nucleon:

$E/A=(Z/A)^2$ 120 MeV

e.g. Deuterons, α :

30 MeV/Nucleon

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Cockkroft-Walton Pre-accelerator

Voltage: 810 kV

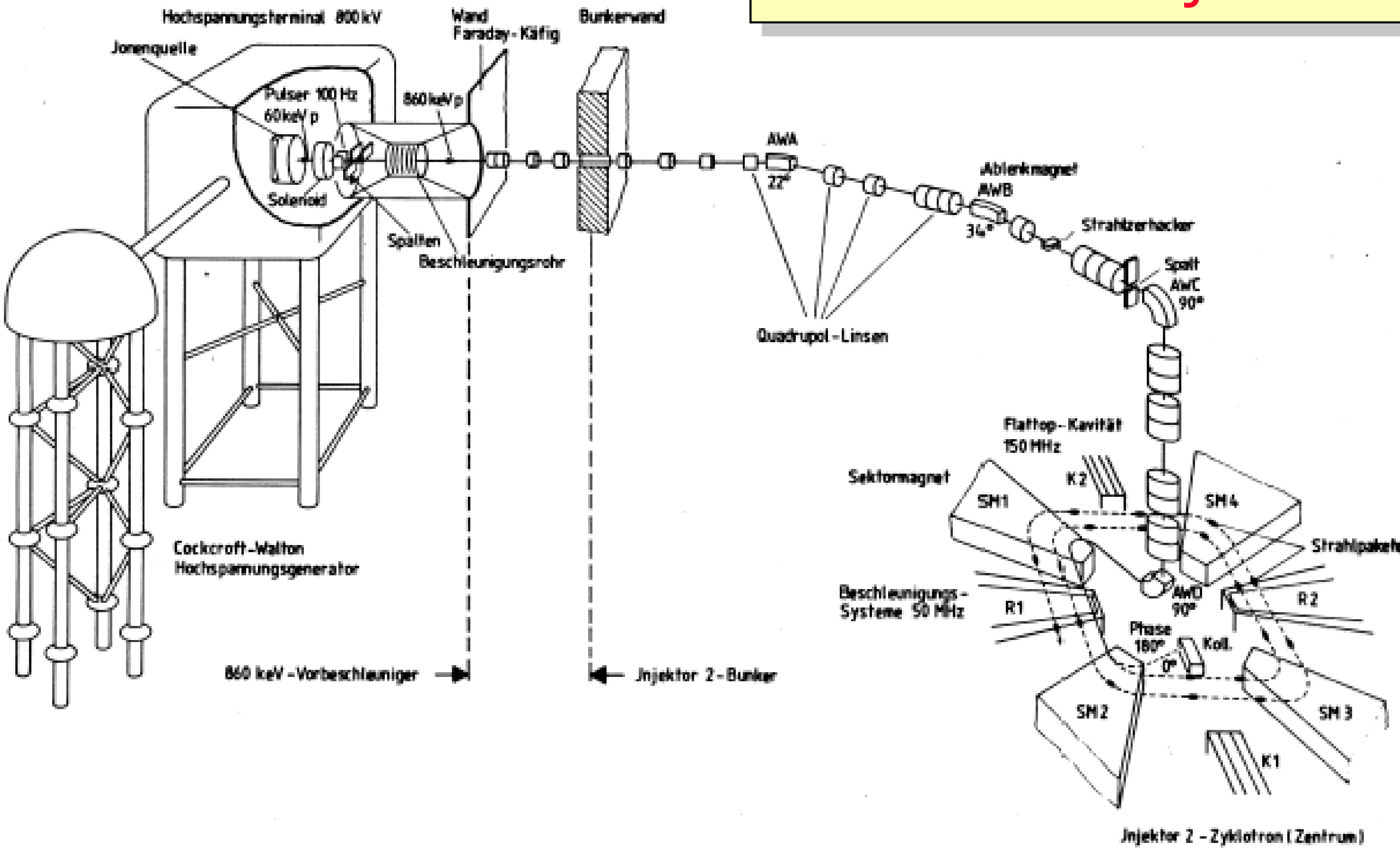
Acceleration Tube

Proton Source

inside Faraday

Cage on 60 kV

Injection of 870 keV Protons into Injector II



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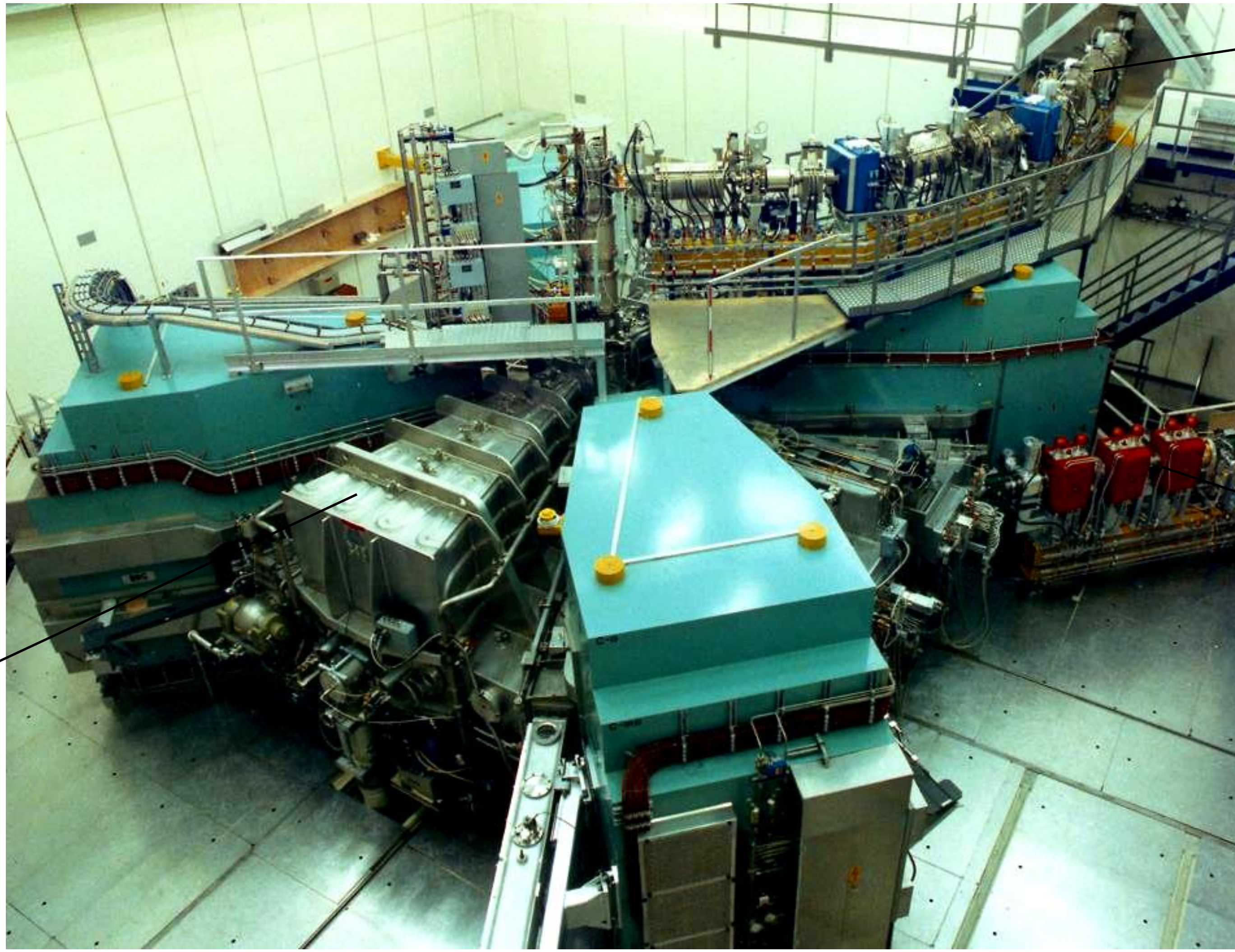
Injector II



Injection Line

870 keV

Extraction Line

72 MeV Protons

(after 100 turns)

Resonator

50 MHz

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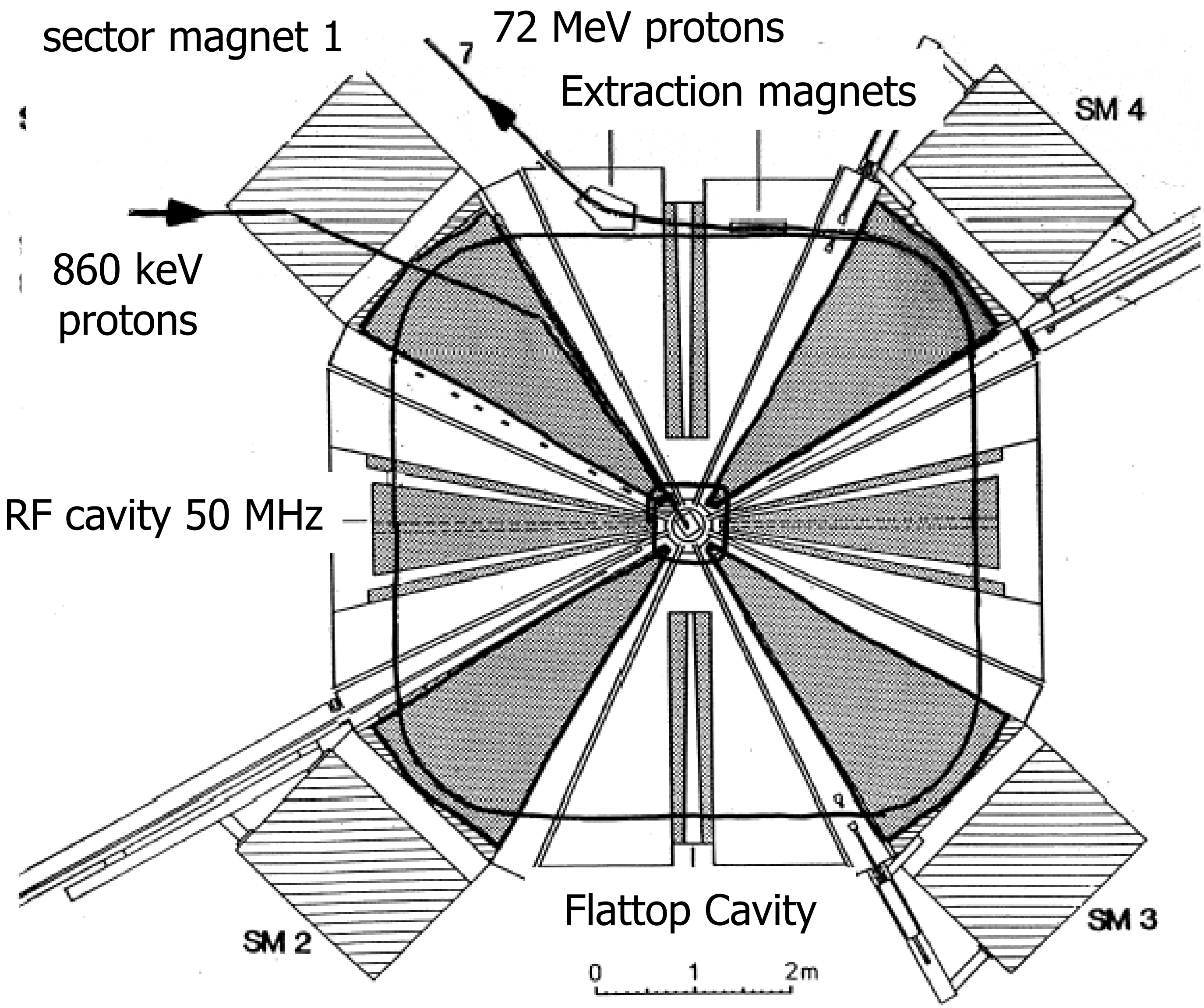
Layout Injector II



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Recipe for high Intensity

- continuos beam (cw)

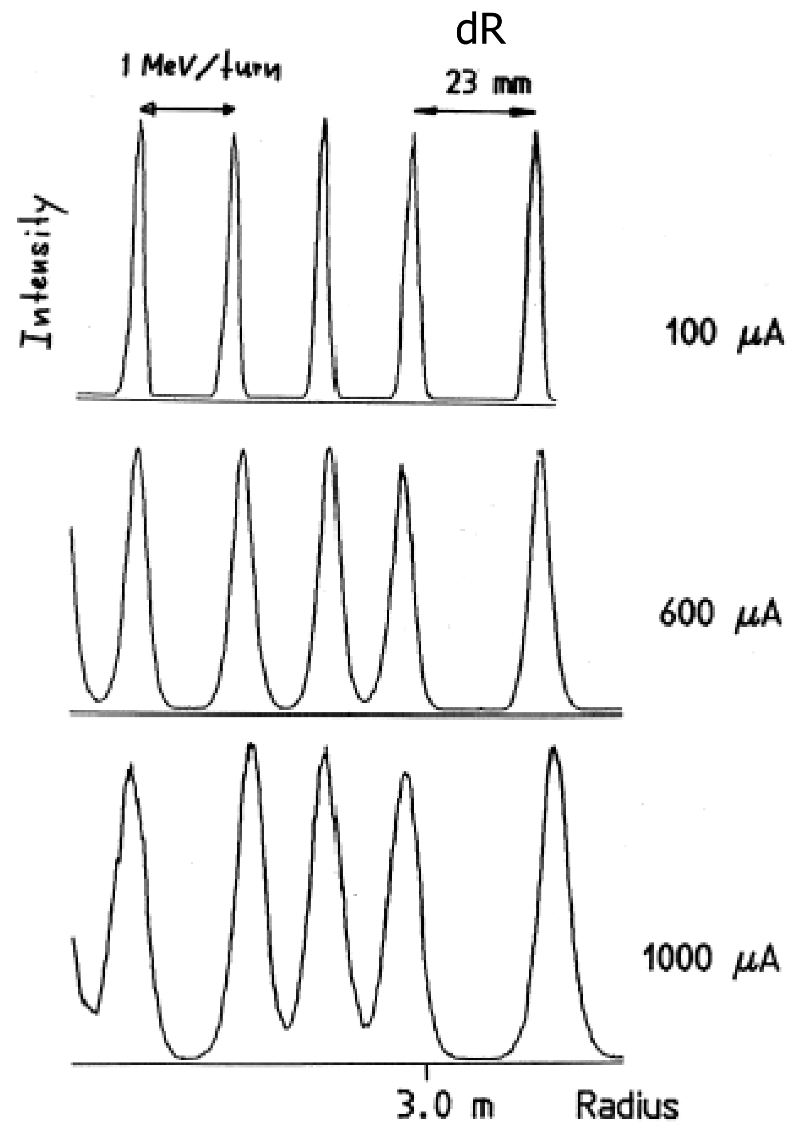
- very low extraction losses

  => separated turns with
  large turn separation dR
  at extraction

  => high energy gain per turn,
  powerful RF-system with
  high voltage cavities

  dR ~ Radius R
  => **large machine radius** !!

the last 5 turns in the Injector II



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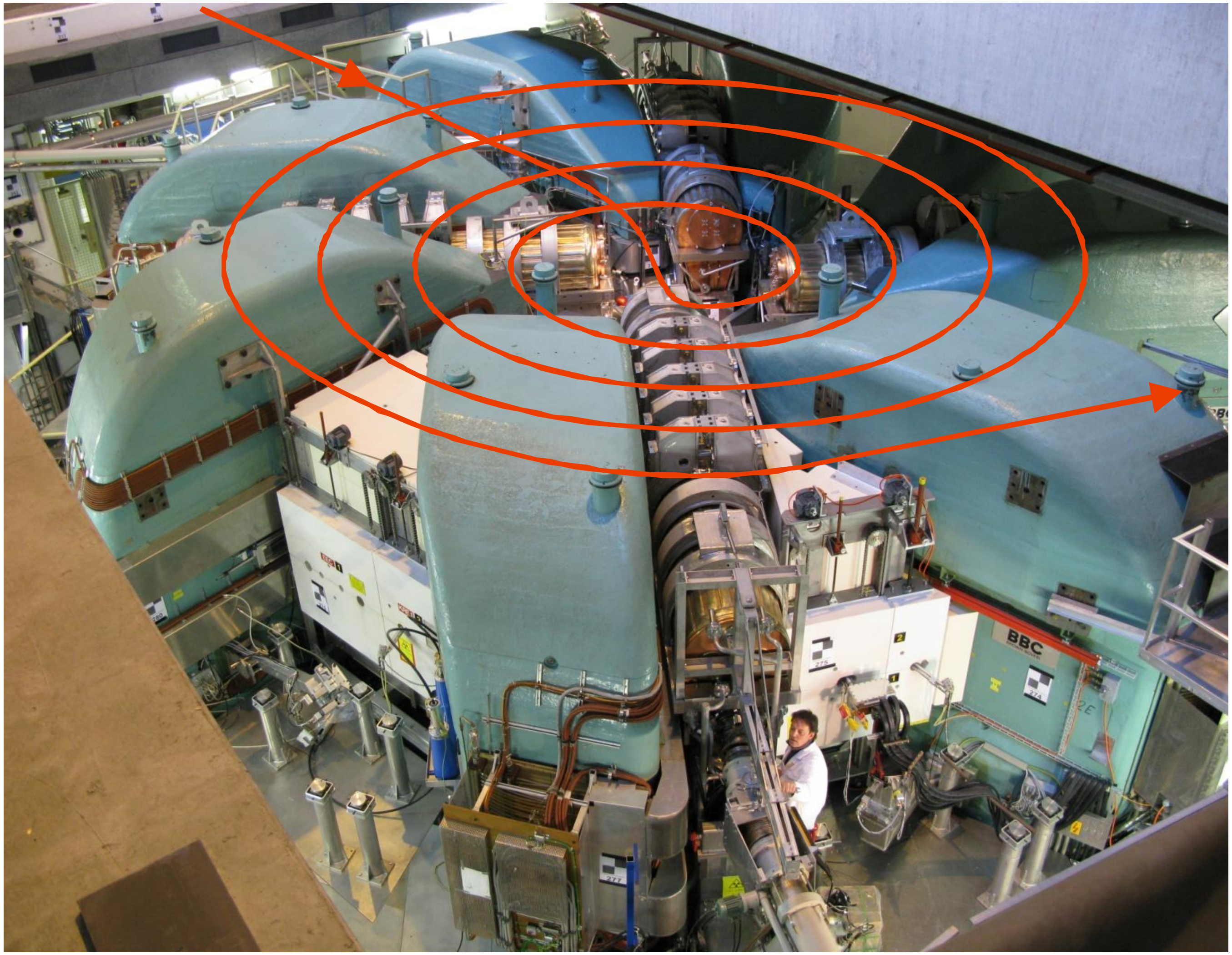
Ringcyclotron
4 new cavities 2008



590 MeV Protons

1.4 MW Beam Power

(World Record!)

8 Magnets à 250 t

4 Cavities à 900 kV

Extraction 99.99%

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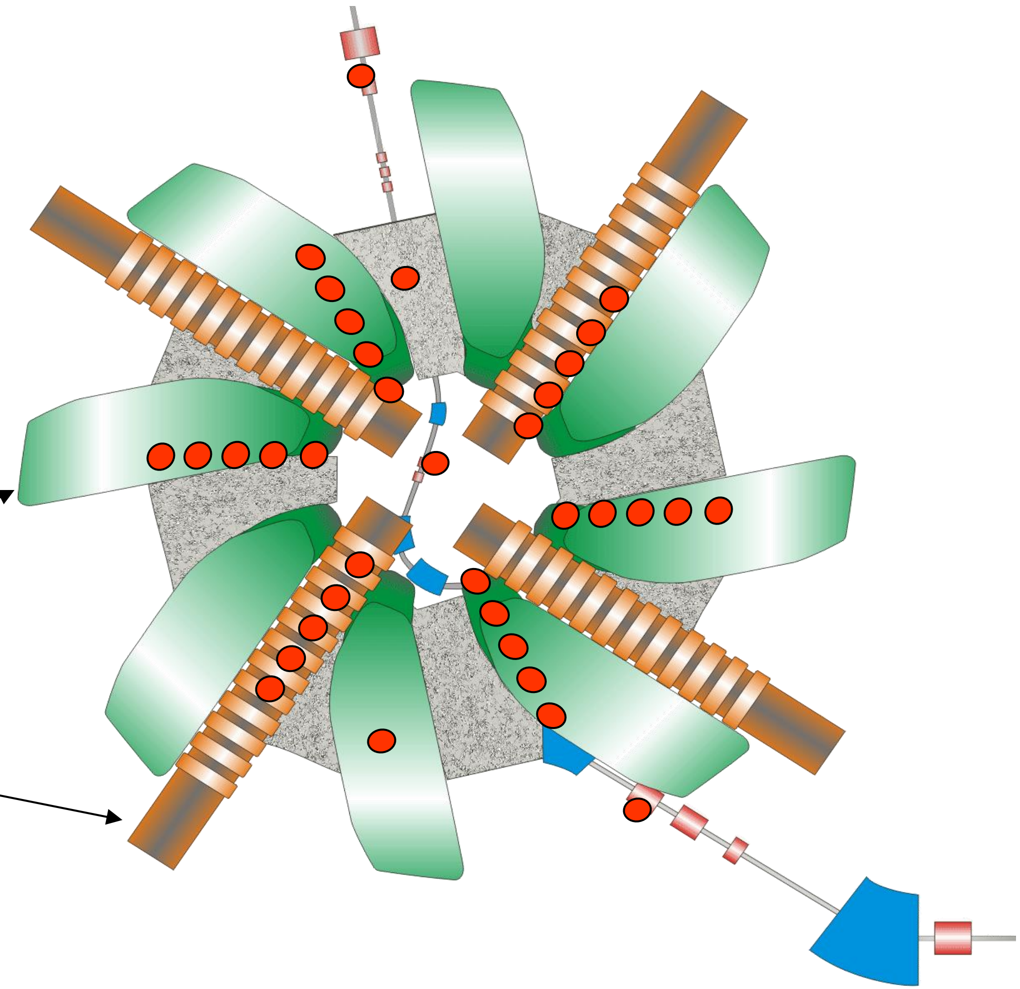
The PSI Ring-Cyclotron

8 Sektormagnets

4 Acceleration Cavities



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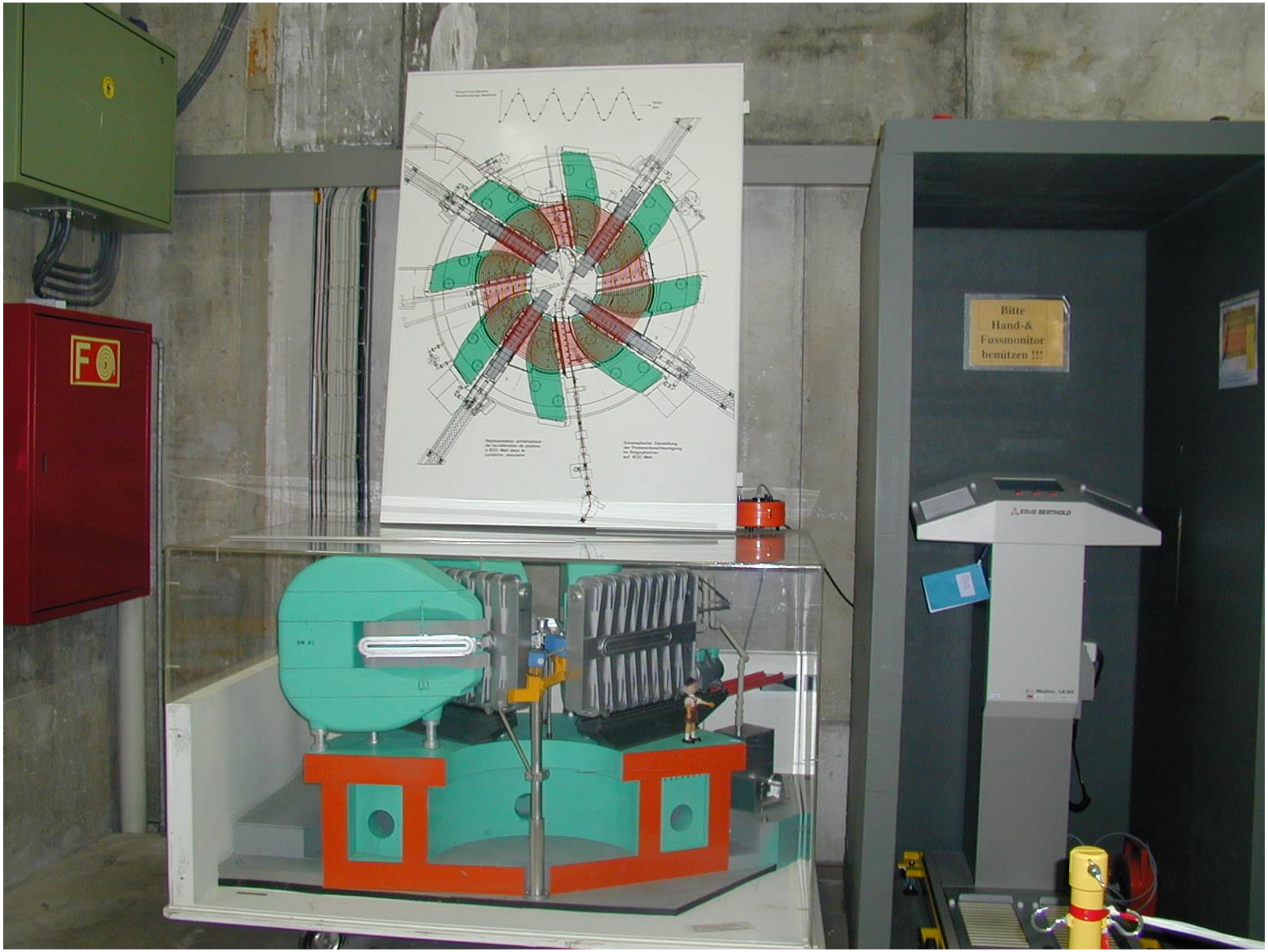
1:10 Model of Ringcyclotron



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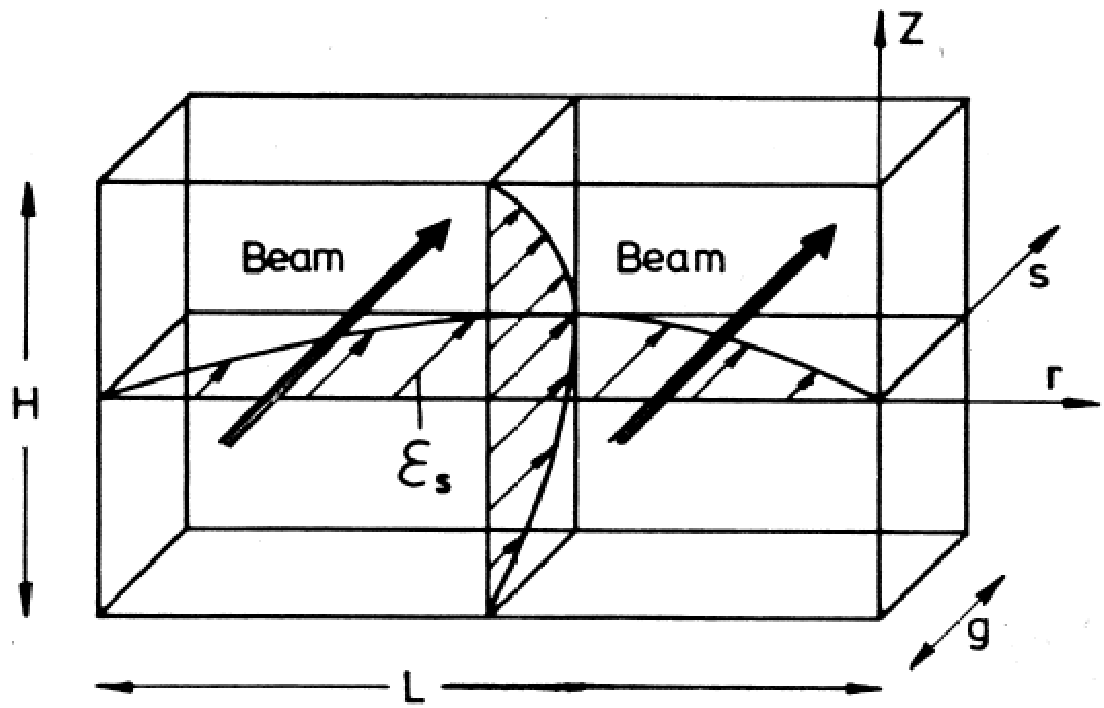
RF Cavity



Ring Cyclotron

590 MeV , 50.7 MHz

original version:

aluminum , V=720 kV

300 kW power loss

216 turns

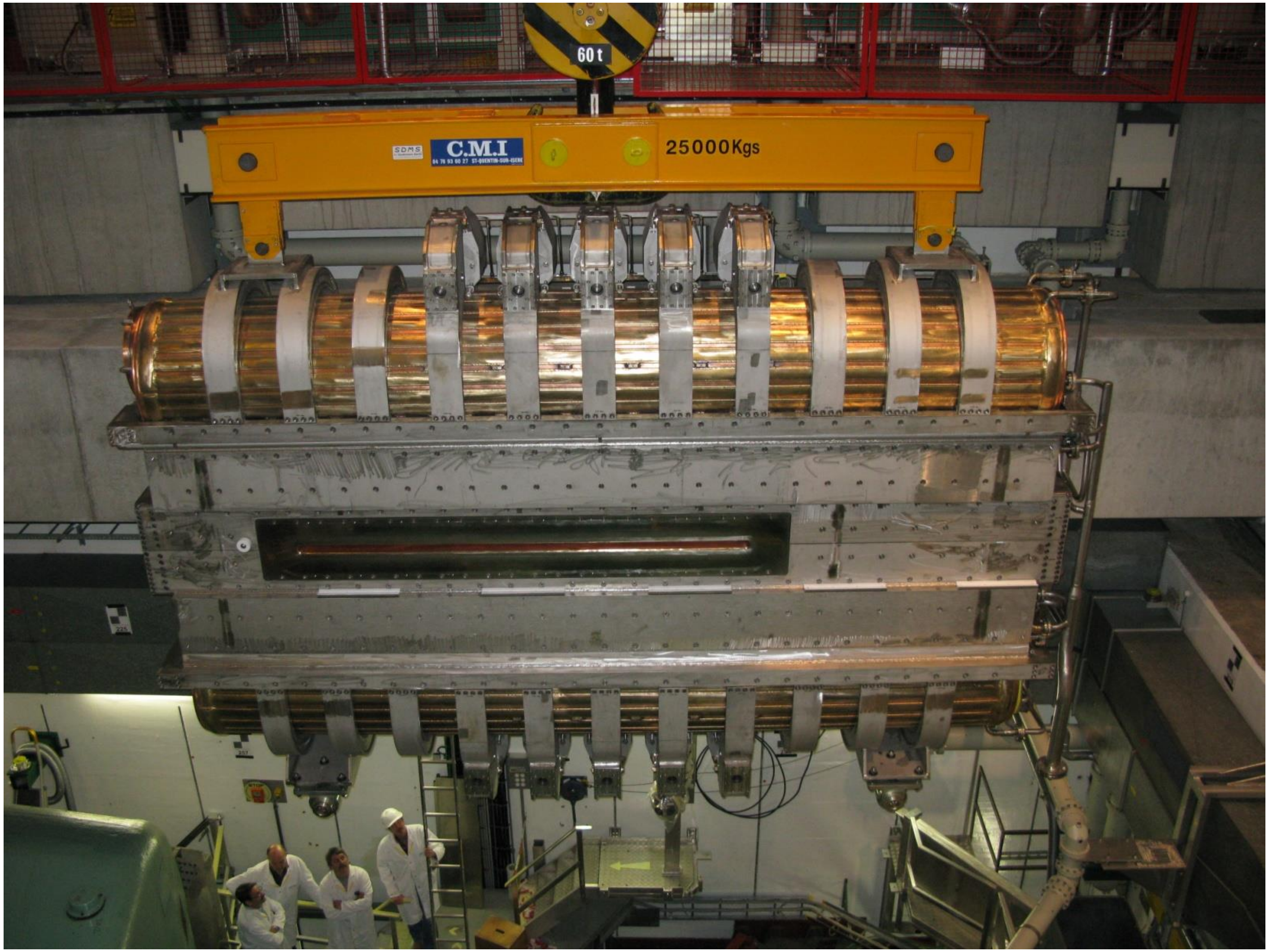
new cavity:

copper , limit=1 MV

at V = 850 kV: 250 kW power loss

185 turns

New Copper Cavity (5.6m long)



50 MHz, CW

Voltage limit 1 MV

(old cavity 0.72 MV)

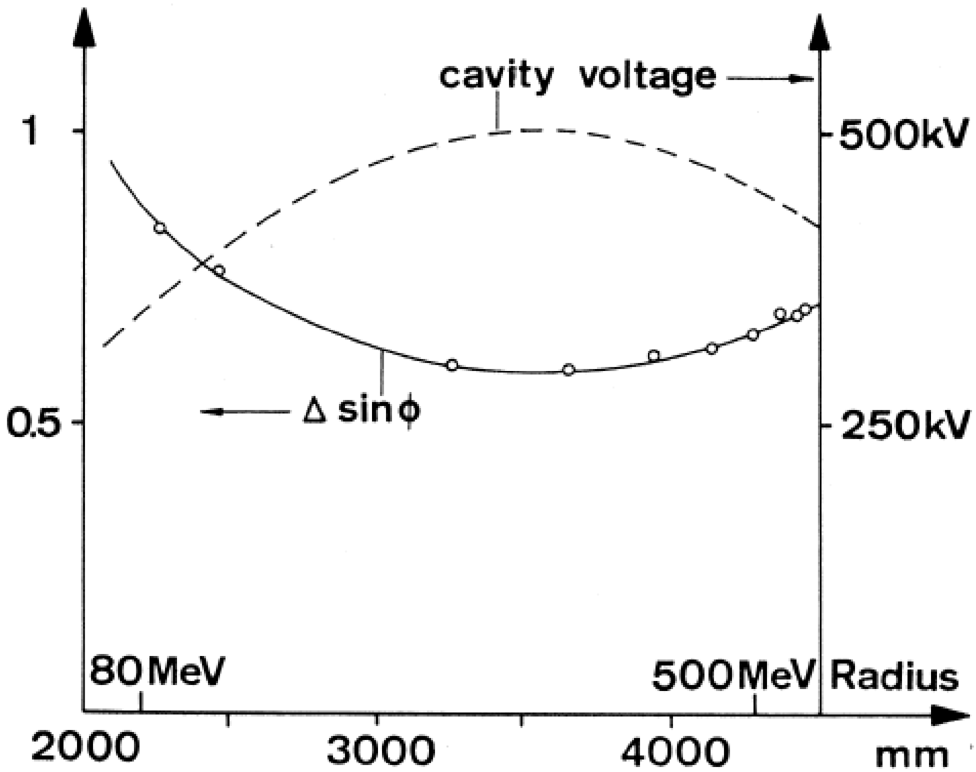
at 850 kV and 2.4 mA :

250 kW loss in cavity

350 kW goes to the beam

Beam limit 3 mA ?

Phase Compression / Phase Expansion due to Variation in Cavity Voltage



The radial variation of the cavity voltage produces a phase dependent magnetic field. This effects the revolution time and thus the phase of a particle.

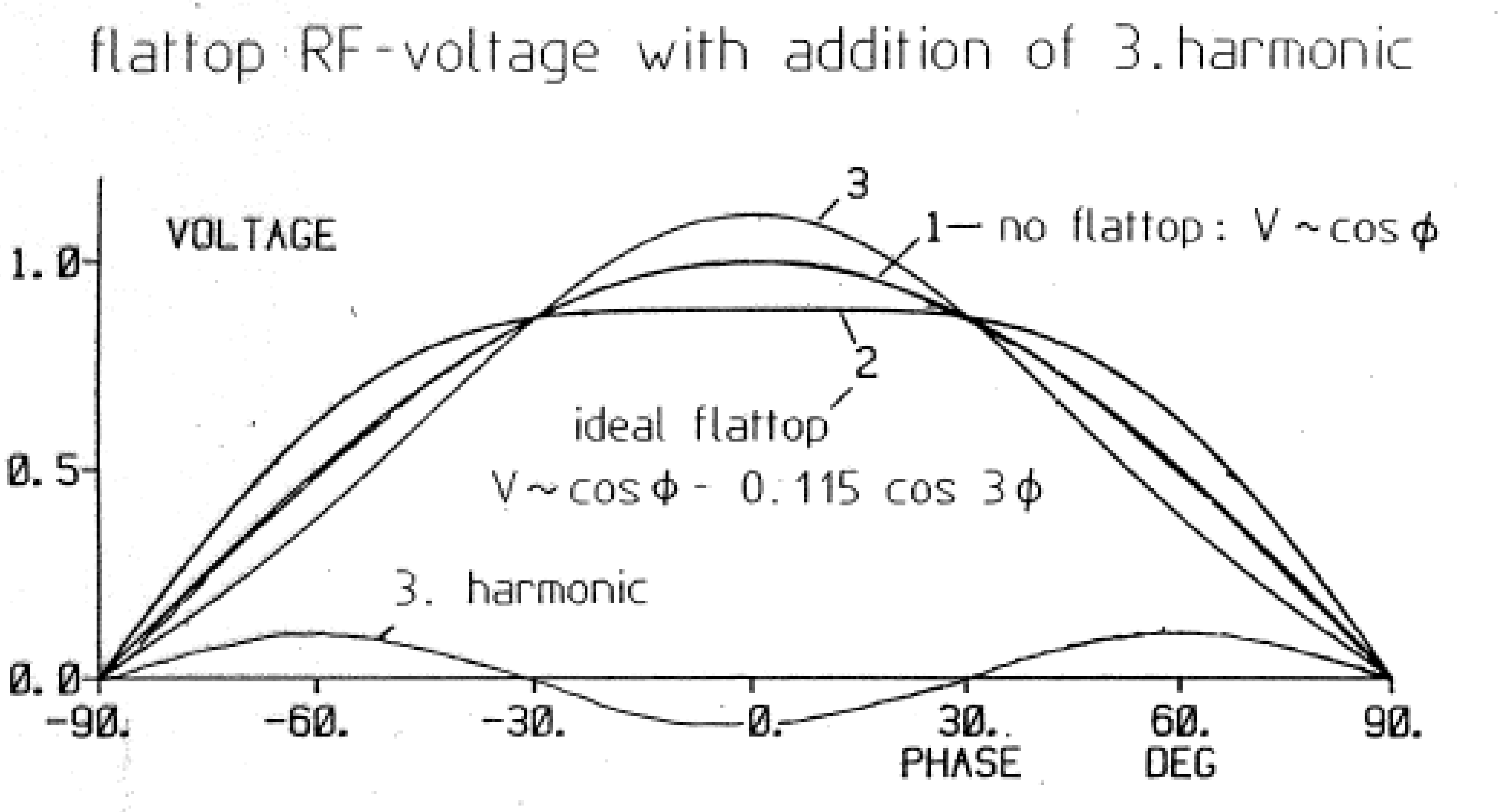
$$E_G(R)\,\Delta \sin\Phi(R) = const.$$

$\mathrm{E_G}$ = peak energy gain/turn

Φ = phase of particle

W.Joho, Particle Accelerators 1974, Vol.6, pp. 41-52

Flattop Voltage gives minimum energy spread



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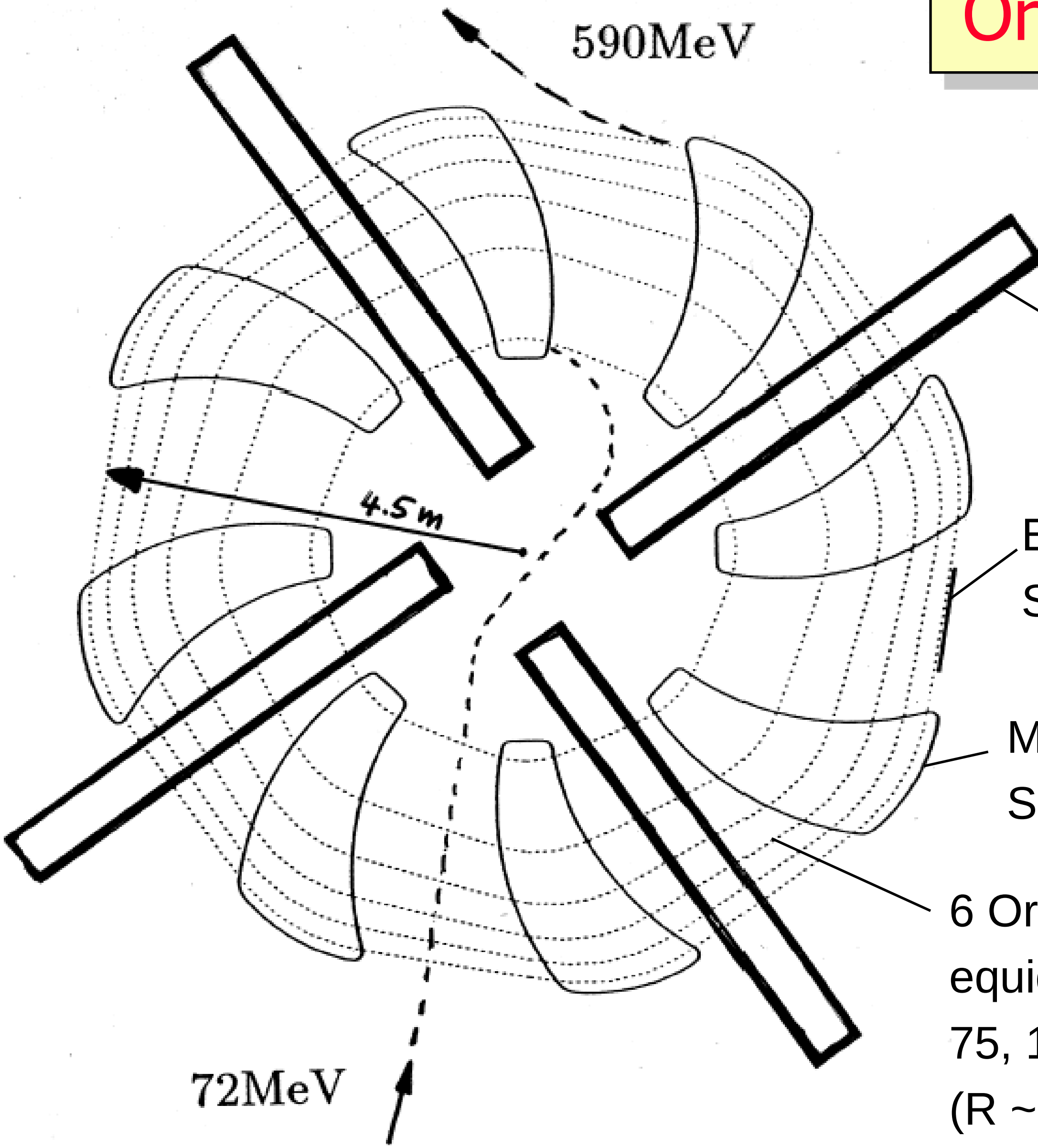
Orbits in Ring Cyclotron



RF Cavity

Extraction
Septum

Magnet
Sector

6 Orbits plotted at
equidistant energies:
75, 177, 279, 381, 483, 585 MeV
(R ~ β)

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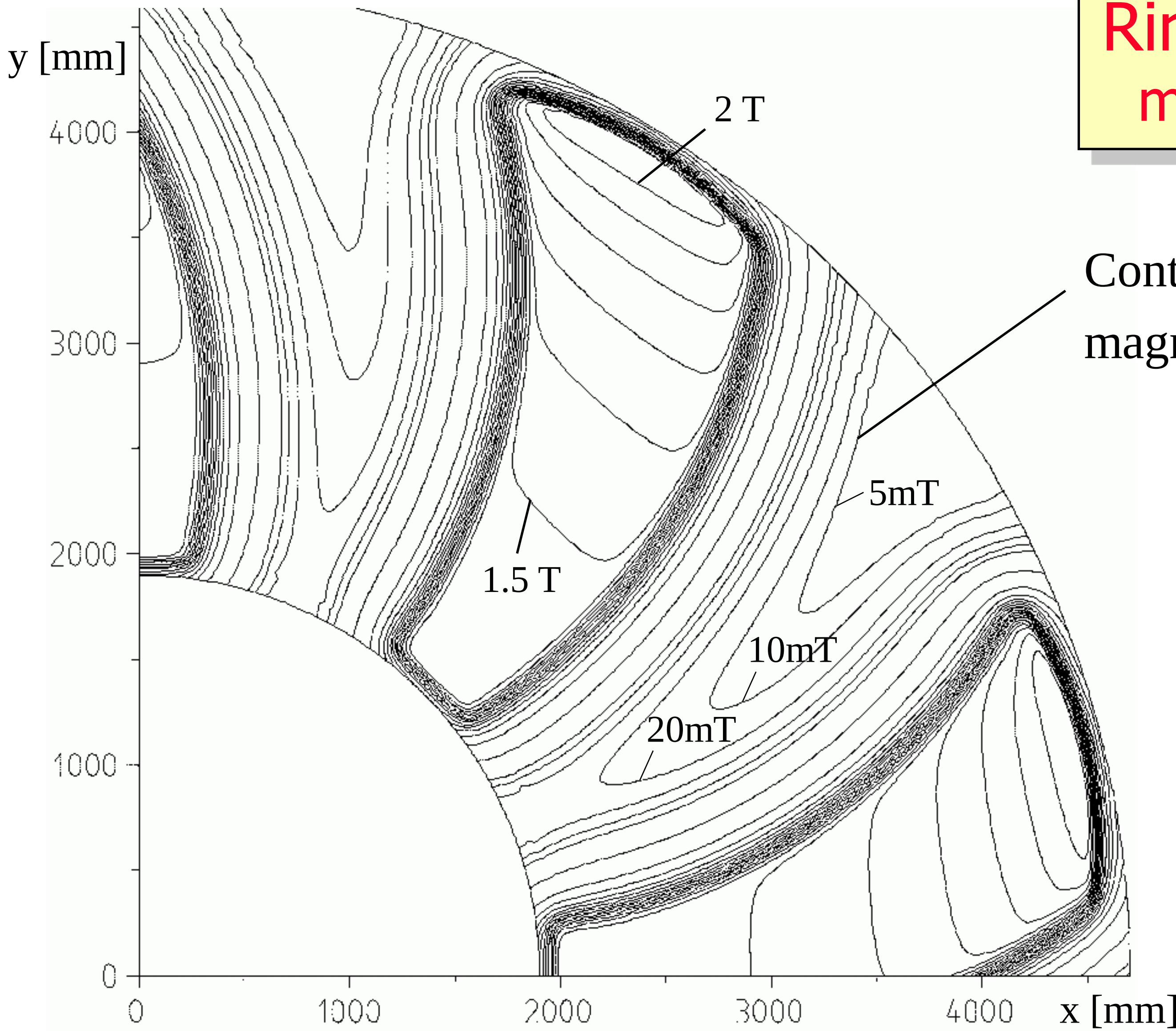
Ring Cyclotron magnetic field



Contour lines of the magnetic field

scaling of average field:

$B_0(R) \sim \gamma$

increases 55%

from 72-590 MeV

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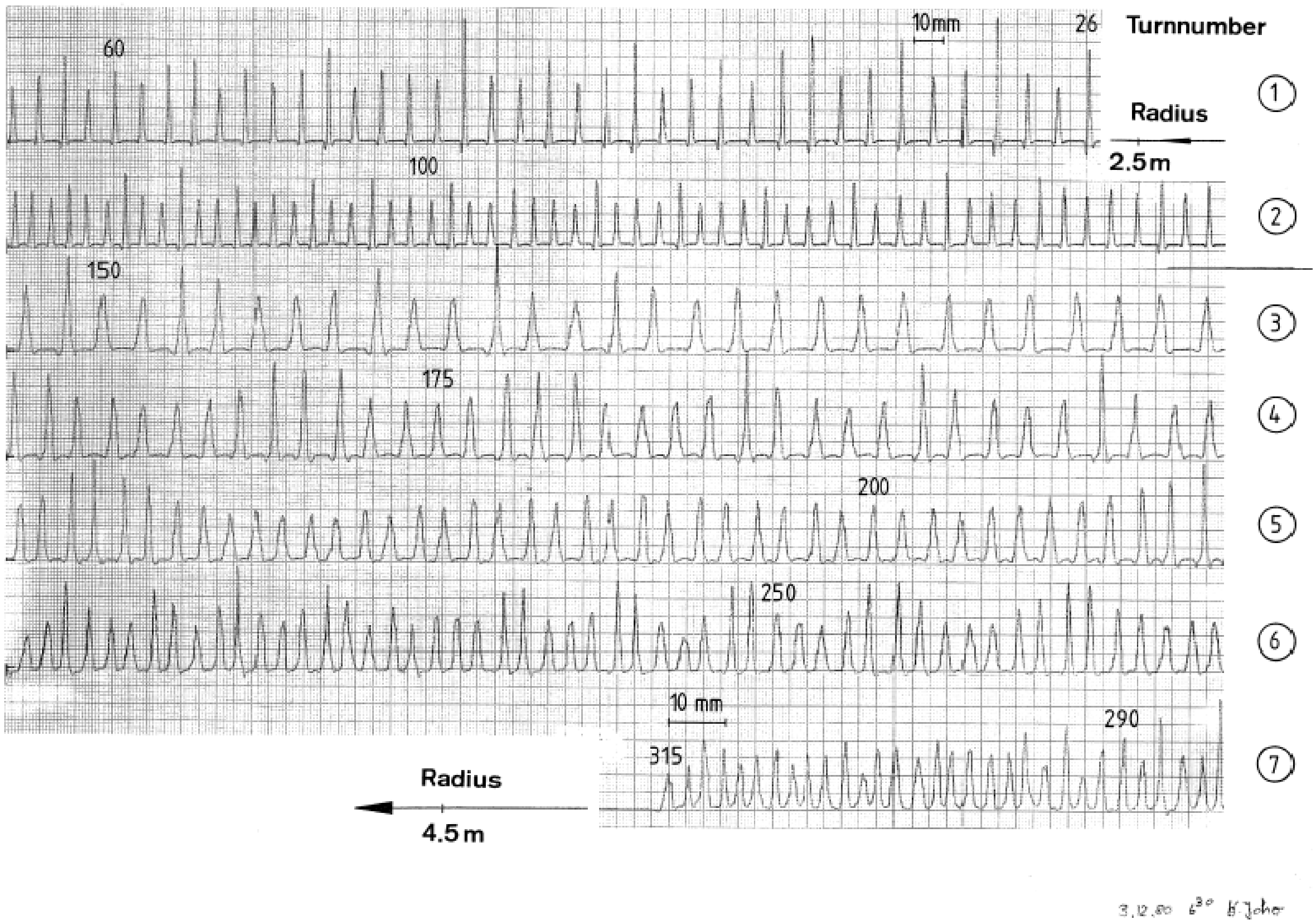
Ring Cyclotron (1980)

turns 26-315, 100-590 MeV



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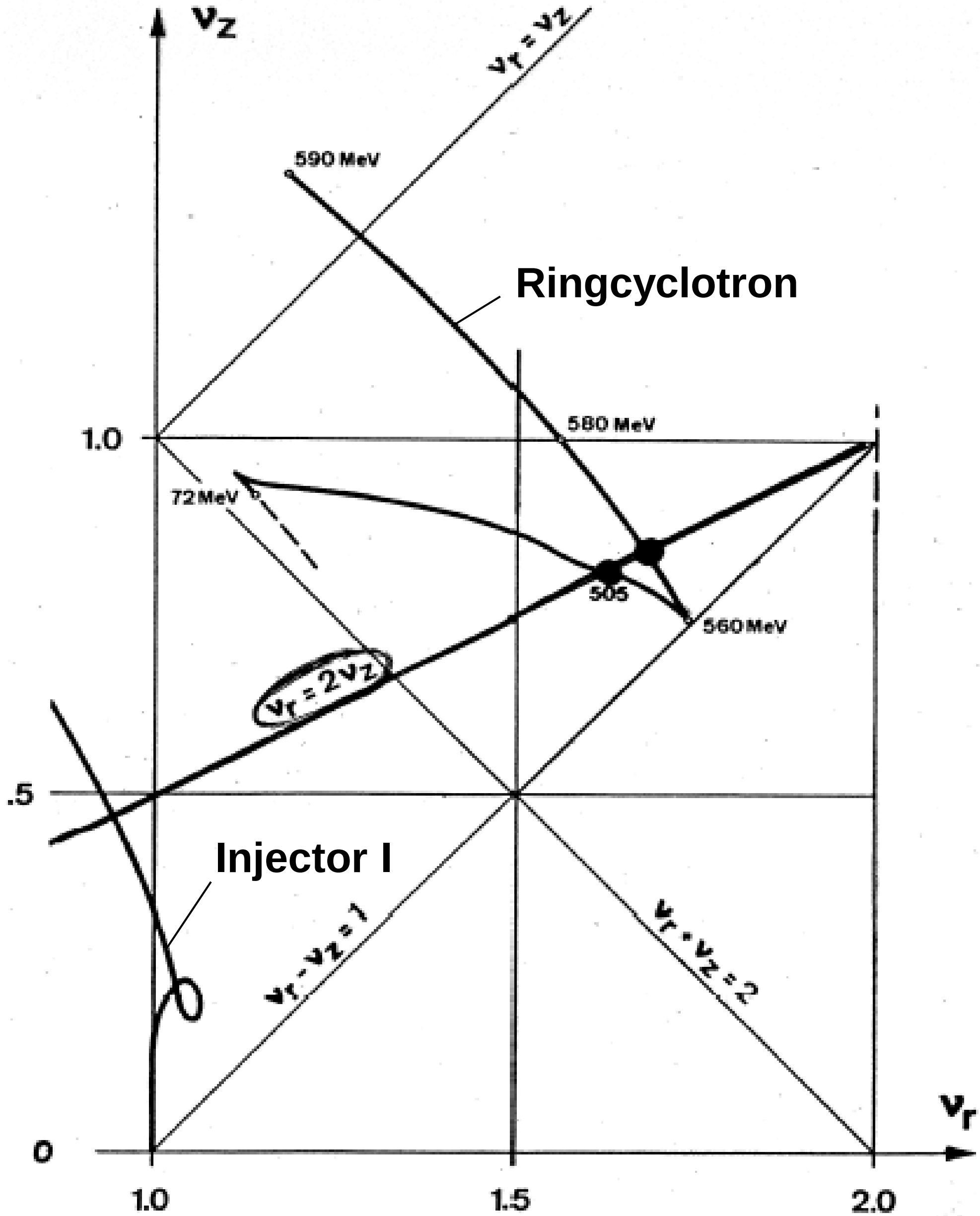

Resonance Diagram of focusing frequencies

In the Ring Cyclotron the coupling resonance $\nu_r = 2\nu_z$ is crossed twice before extraction

In the Injector I the resonance $\nu_r = 1$ is used to enhance the extraction efficiency

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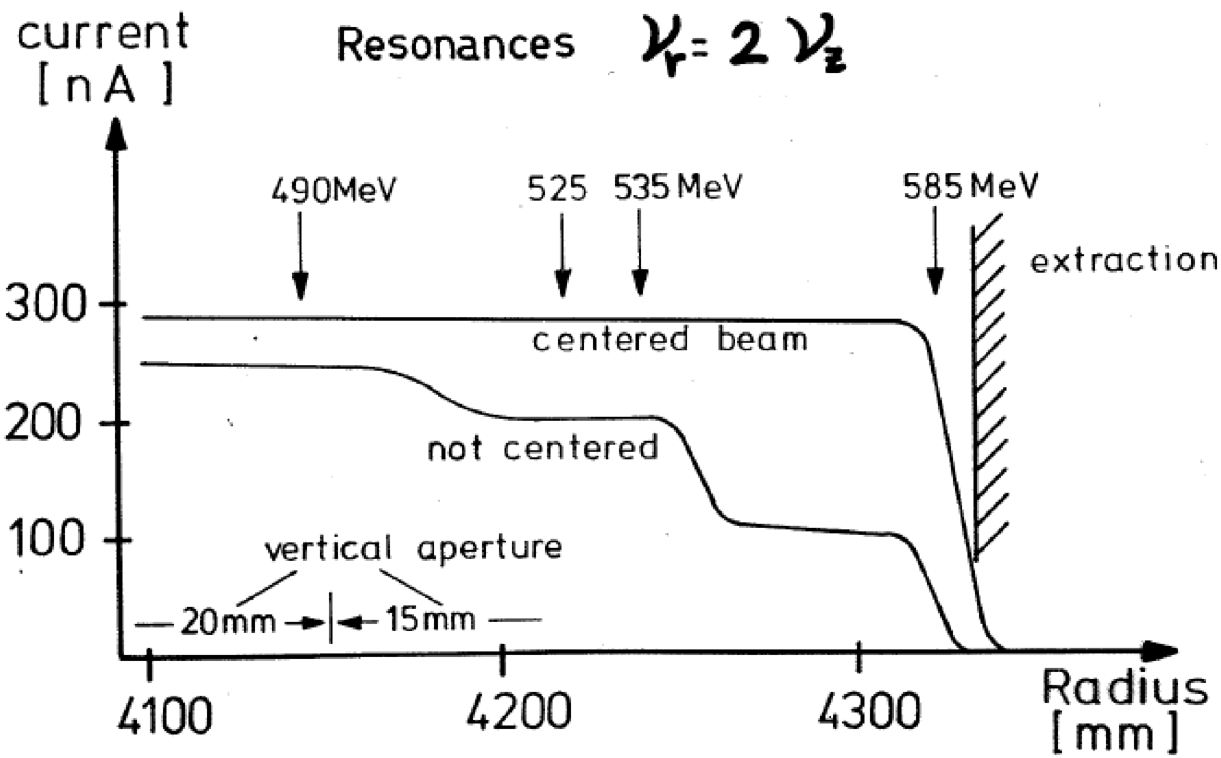
coupling resonance



Ring cyclotron 590 MeV p

a large horizontal oscillation is transformed into a large vertical one at the coupling resonance $\nu_r = 2\nu_z$

This can lead to beam losses

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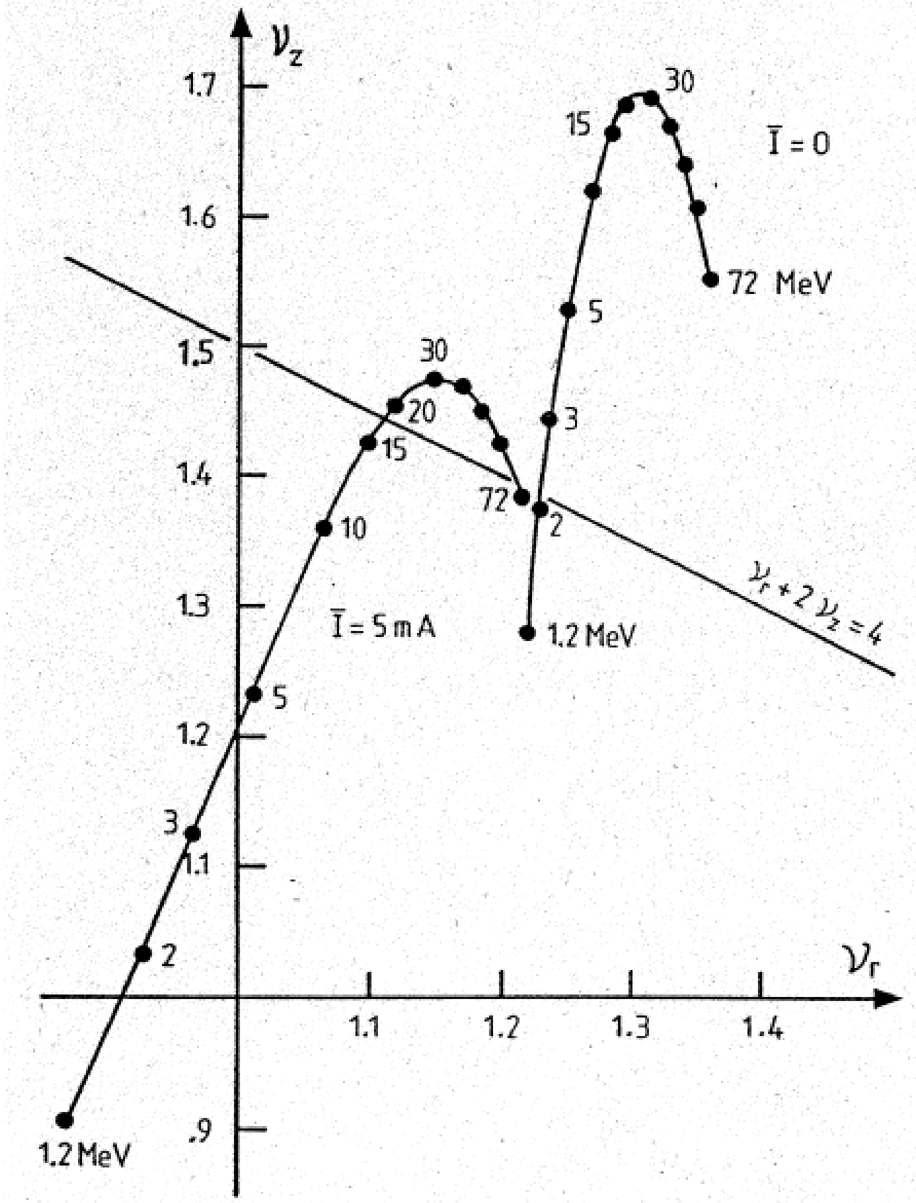
Focusing tunes Injector II

Due to the strong vertical focusing in a sector cyclotron the current limit due to the space charge tune shift is a few mA in Injector II

Resonances can be crossed very fast with high RF voltages



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radial scaling

In an isochronous cyclotron: ω_0 = const.

$R = v/\omega_0 \sim \beta$, ($\beta = v/c$)

absolute radius limit at v=c: $R_\infty = c/\omega_0$

$$R = \beta R_\infty$$

$$R_\infty[m] = h\,(\frac{47.7 MHz)}{\nu_{RF}})$$

Example: protons at PSI: ν_{RF} = 50.7 MHz , R_∞ = h· 0.94m

	E[MeV]	β_{max}	h	R_∞[m]	R_{max}[m]	B_0[T] (center)
Injektor I	72	0.37	3	2.83	1.05	1.1
Injektor II	72	0.37	10	9.40	3.5	0.33
Ring	590	0.79	6	5.65	4.5	0.55

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Extraction from a Cyclotron

The intensity limit of a Cyclotron is given by the beam losses.

Important is the radial distance dR/dn between the last two turns before extraction

=> large turn separation with:

- high RF voltage (intensity limit ~ V^3 !!)
- large machine radius R !

=> compact cyclotrons (supercond. !) have limited intensity

(1) $E = \frac{1}{2} m v^2 = \frac{1}{2} m \omega^2 R^2 \sim R^2$

(non relativistic)

(2) $E \approx n q \overline{V} \sim n$ (turn number),

$\overline{V}$ = average RF - voltage per turn

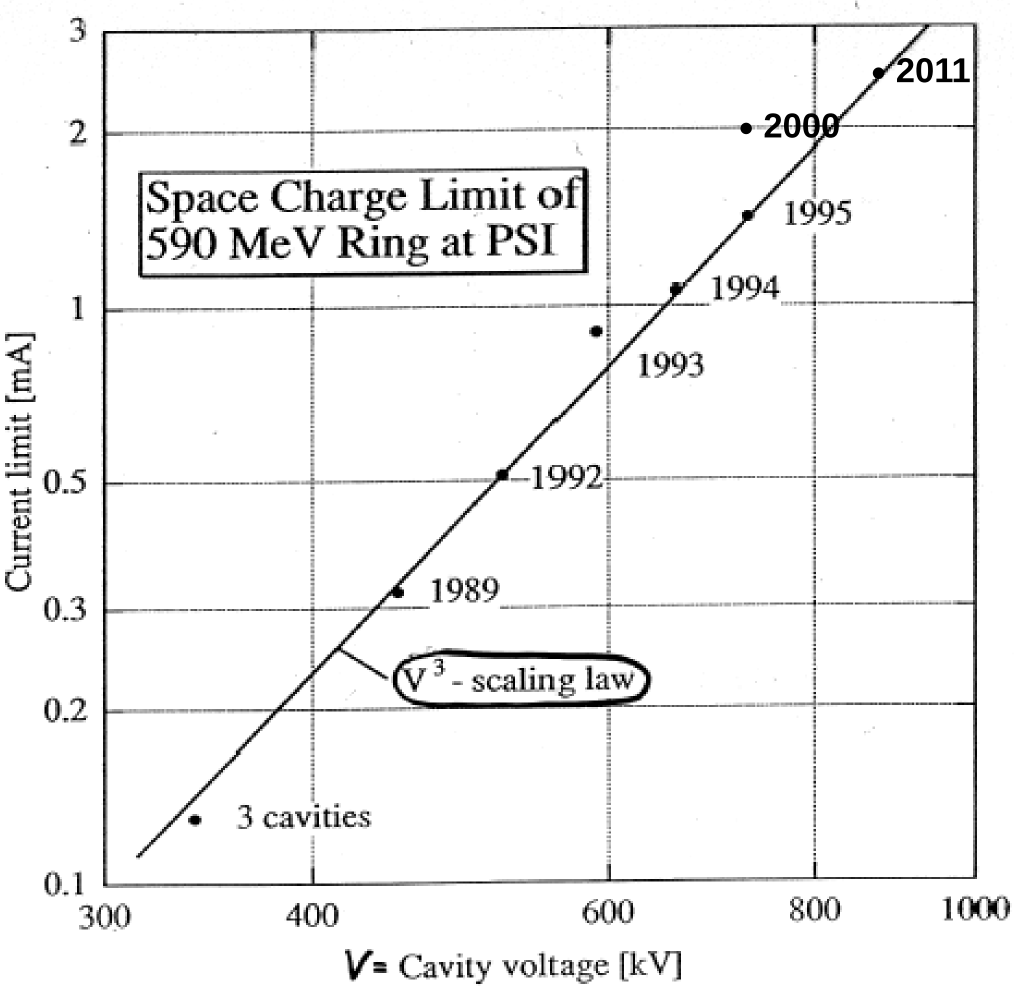
$$\Rightarrow \quad R \sim \sqrt{n}, \qquad \frac{dR}{dn} = \frac{R}{2n}$$

relativistic:

$$\frac{dR}{dn} = \frac{\gamma}{\gamma+1} R \frac{\overline{V}}{(E/e)} \frac{f^2}{Q_r^2}$$

$f \approx 1.1 - 1.2$ for ring cyclotrons

Current Limit in Ring Cyclotron



Longitudinal space charge forces

increase the energy spread

=> higher extraction losses

=> limit on beam current

Remedy:

higher voltage V on the RF cavities

=> lower turn number n (V·n = const.)

current limit ~ V^3 !

There are 3 effects, each giving a factor V(~1/n):

1) beam charge density ~ n
2) total path length in the cyclotron ~ n
3) turn separation ~ V

W.Joho, 9th Int. Cyclotron conference CAEN (1981)

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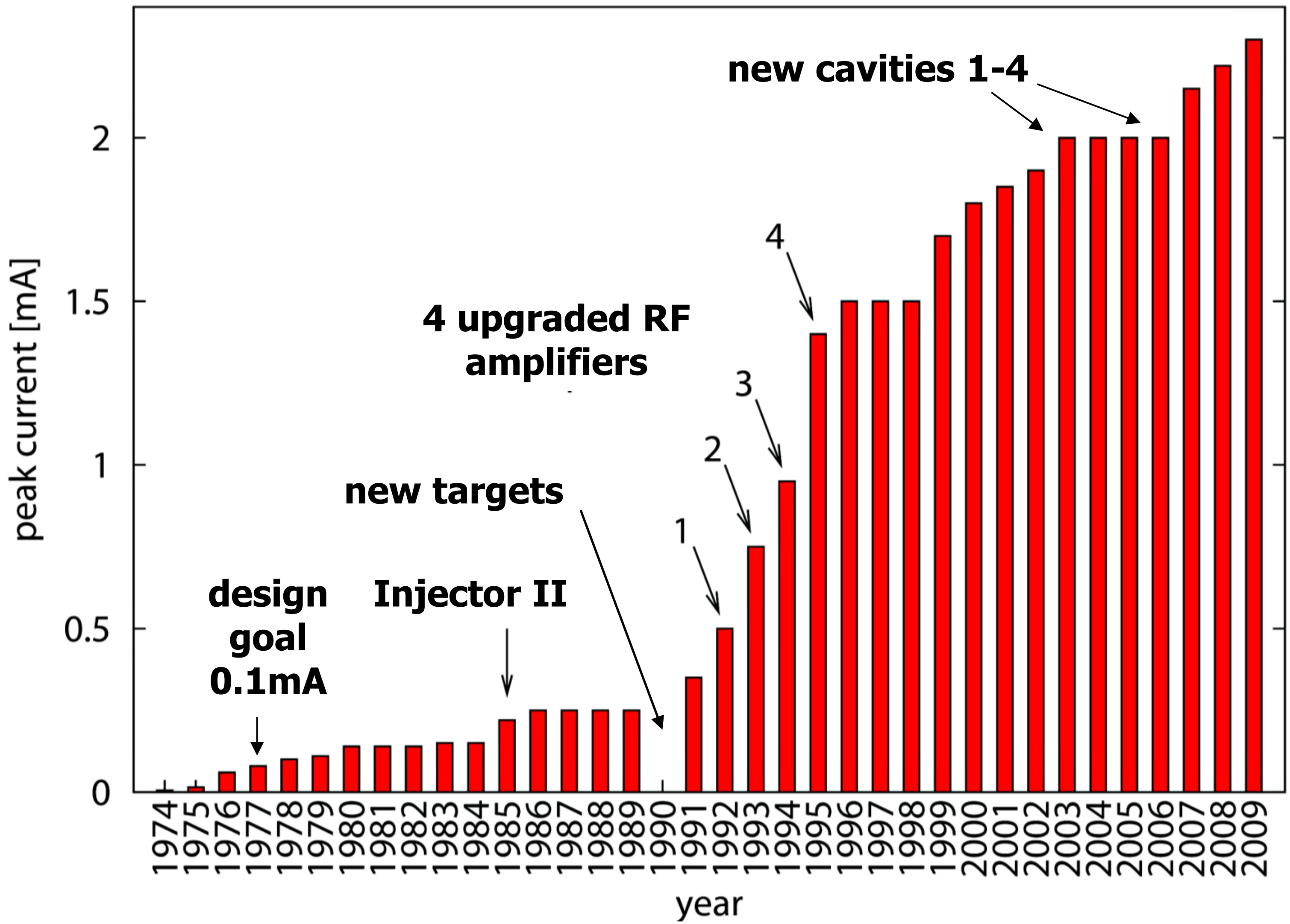
History of the Peak current in the 590 MeV Ring Cyclotron



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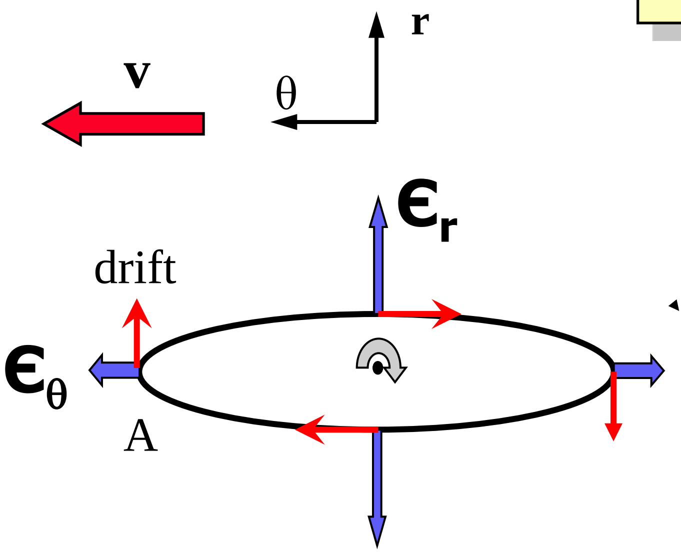
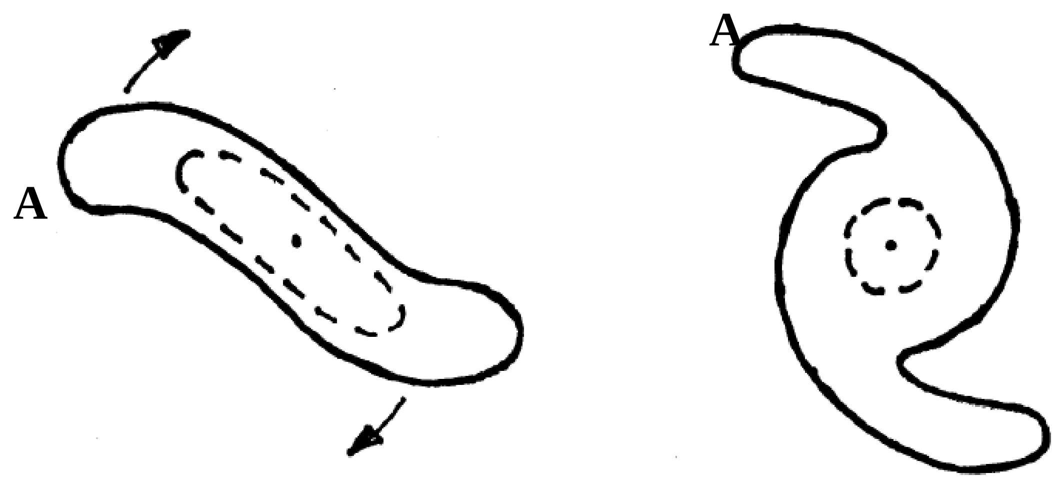
Longitudinal Space Charge in a Cyclotron Beam





Particle at position A:

=> gains additional energy from space charge forces

=> moves to higher radius due to isochronous condition

=> rotation of the bunch

=> nonlinearities produce spiral shaped halos

=> production of a rotating sphere („spaghetti effect")

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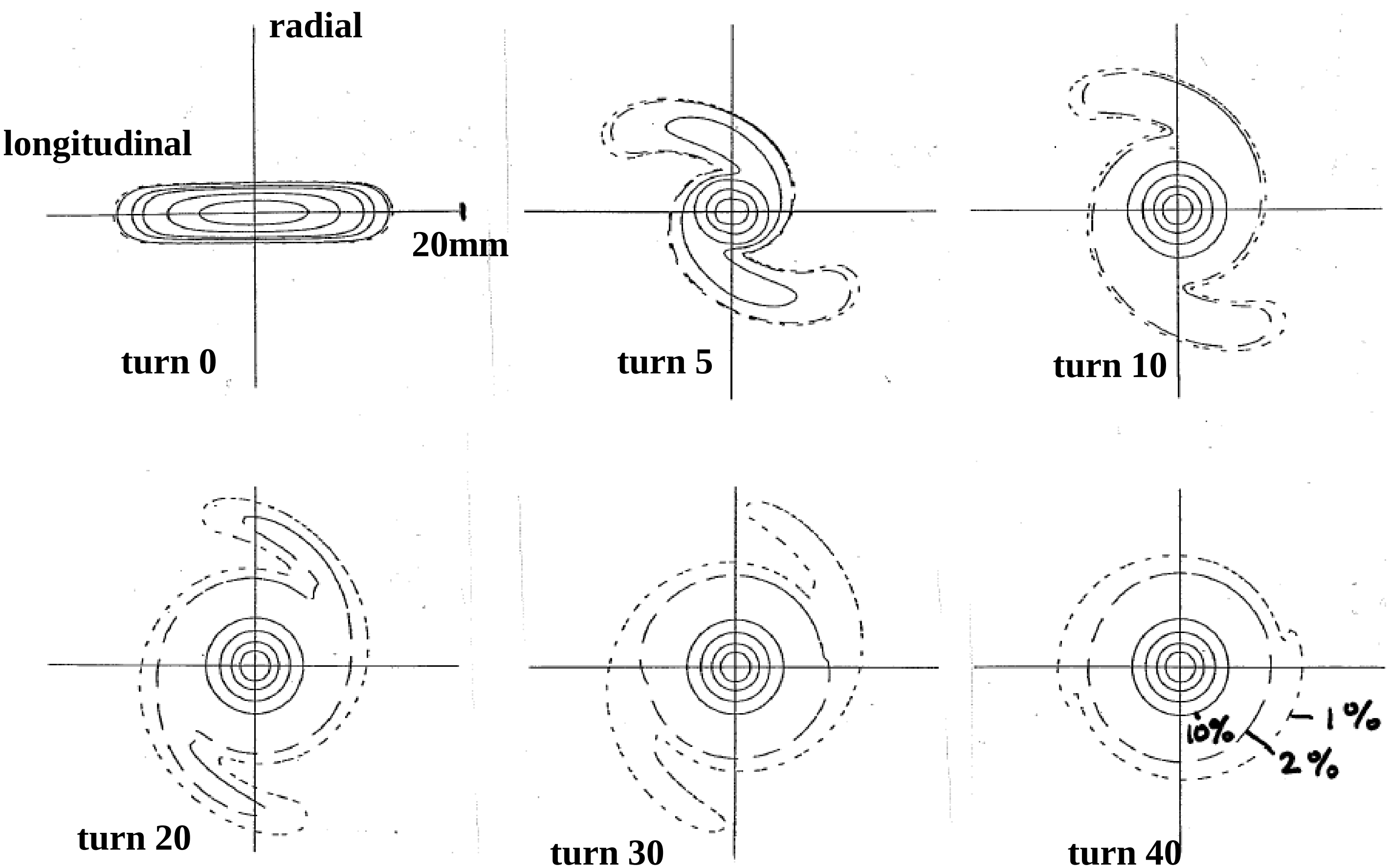
Longitudinal Space Charge in Cyclotron



Simulation of a 1mA beam, circulating in Injector II at 3 MeV for 40 turns without acceleration.

The core stabilizes faster than the halos; rotating sphere produces phase mixing (calculations by S.Adam)

Aristocracy ⇔ Democracy

Synchrotrons

Linacs

democratic:

a particle oscillates between head and tail

(phase focusing)

Cyclotrons

aristocratic :

a particle „born ahead“ stays ahead !

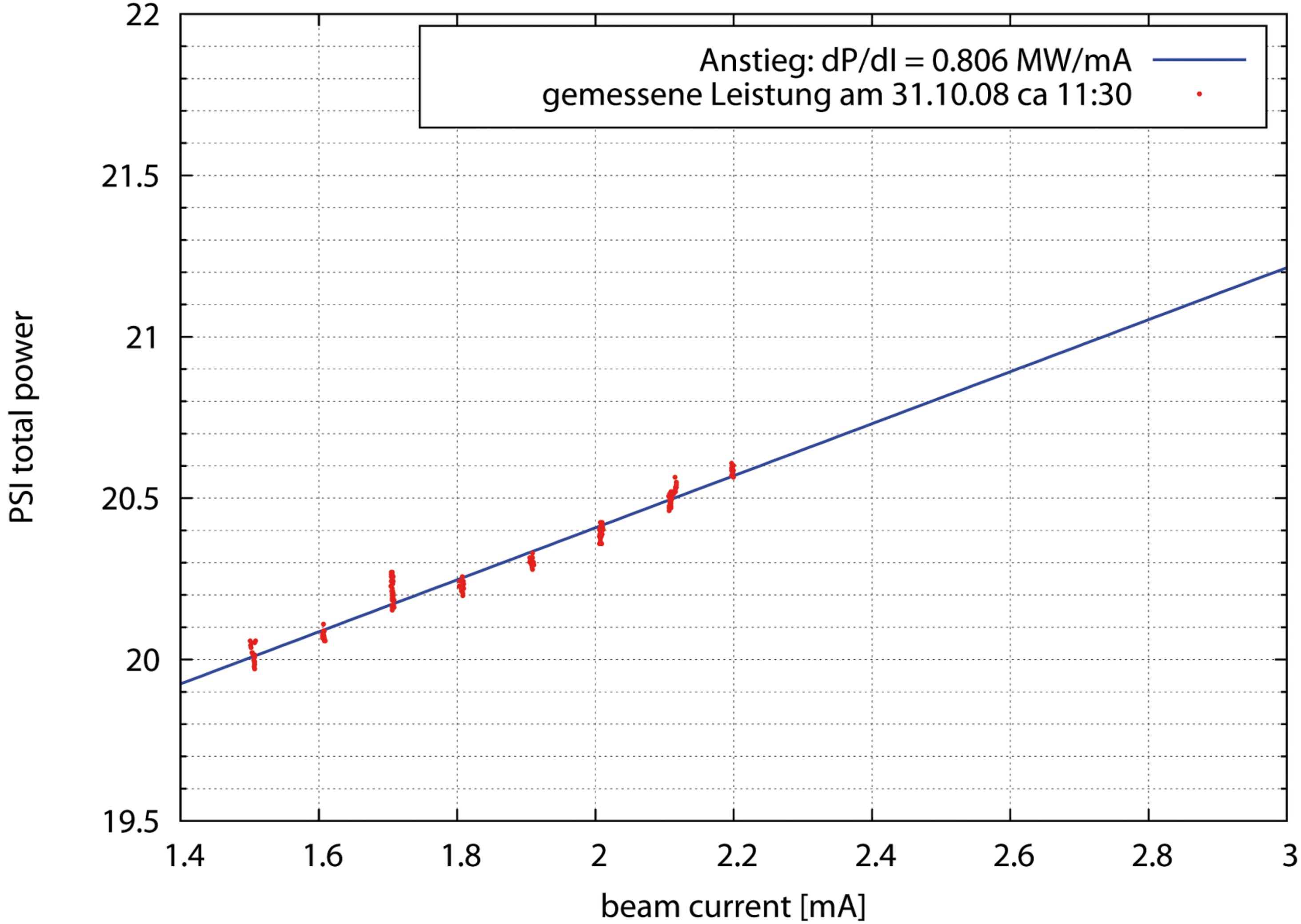
(isochronism)

but **at high intensity**

a cyclotron becomes **democratic** !!

(space charge mixes phases)

RF efficiency in Ring Cyclotron



beam current needs 0.806 MW/mA

beam power =0.59 MW/mA

=> RF efficiency=73% (M.Seidel)

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Graphite Target Wheel

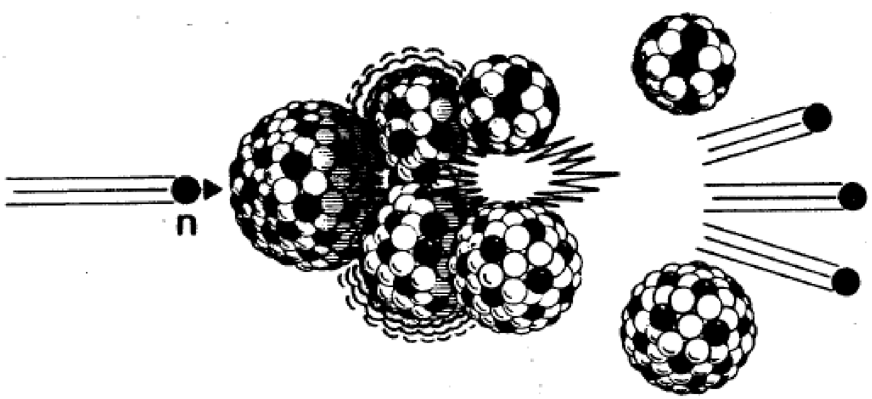
1.3 MW
Proton Beam

creates Pions
and Muons

„slow“ Neutrons for Material Research

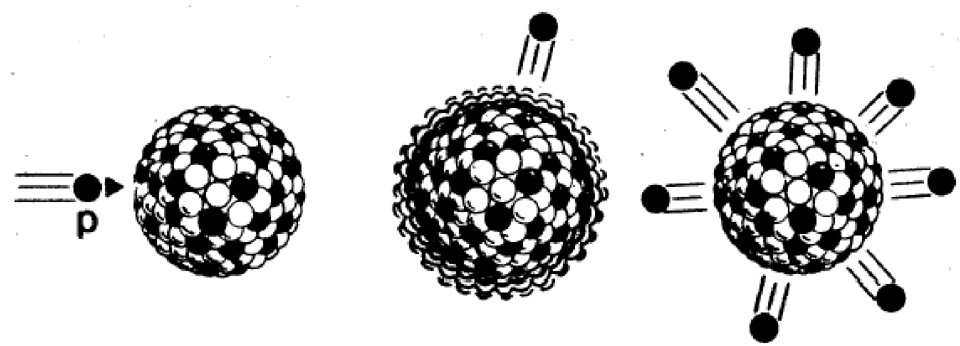
- Production of fast Neutrons
- slowing down in Moderator

1. **Fission** of Uranium (U^{235}) in a Reactor



2. **Spallation** of heavy Nuclei (e.g. lead) by Bombardment with Protons from an Accelerator

=> safe and fast turning off !



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Spallation Neutrons

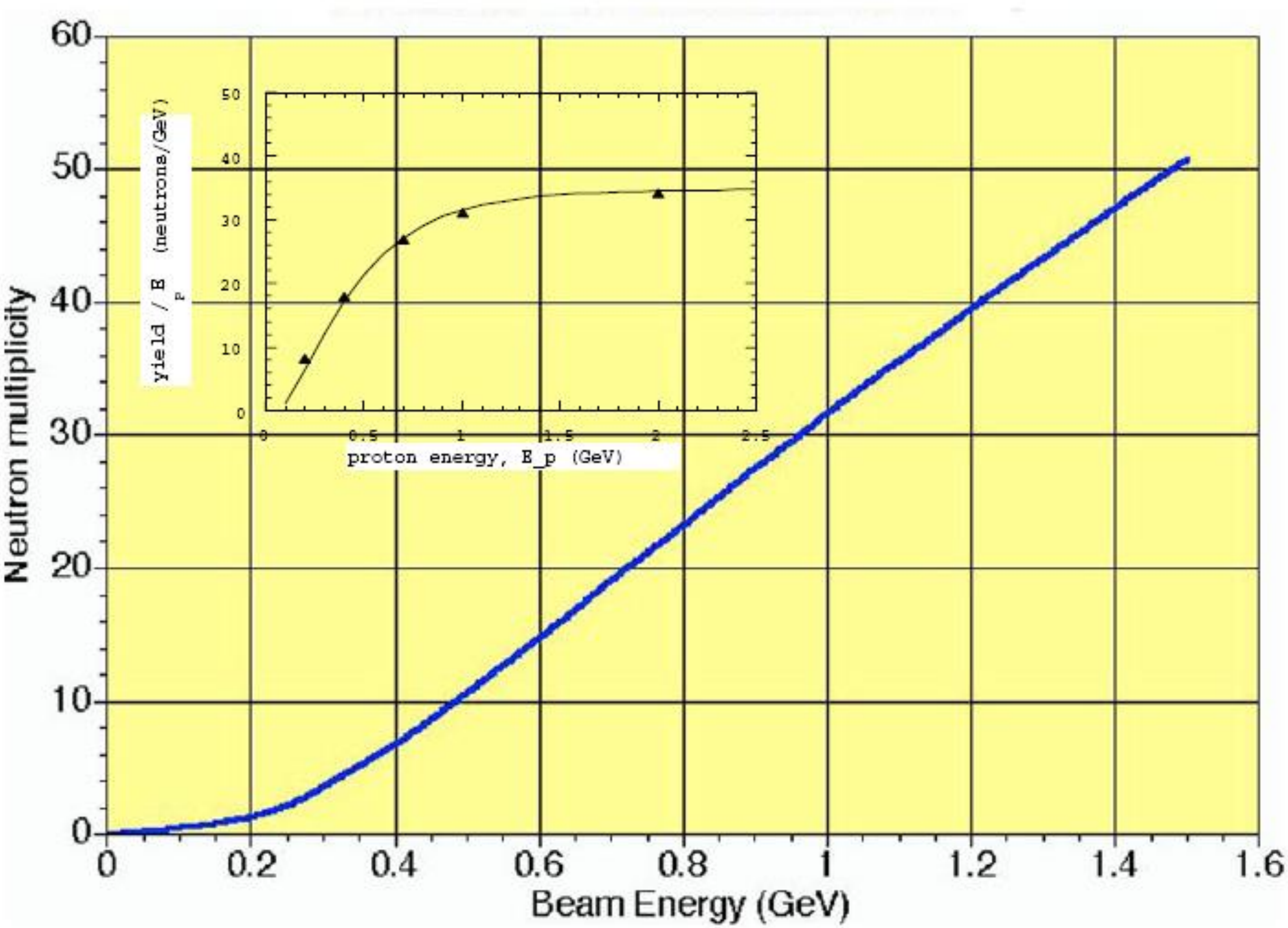


Figure 1. Calculated neutron multiplicity on lead as a function of proton energy[5]; the insert shows a calculated energy-normalised yield.

for beam energy > 1GeV

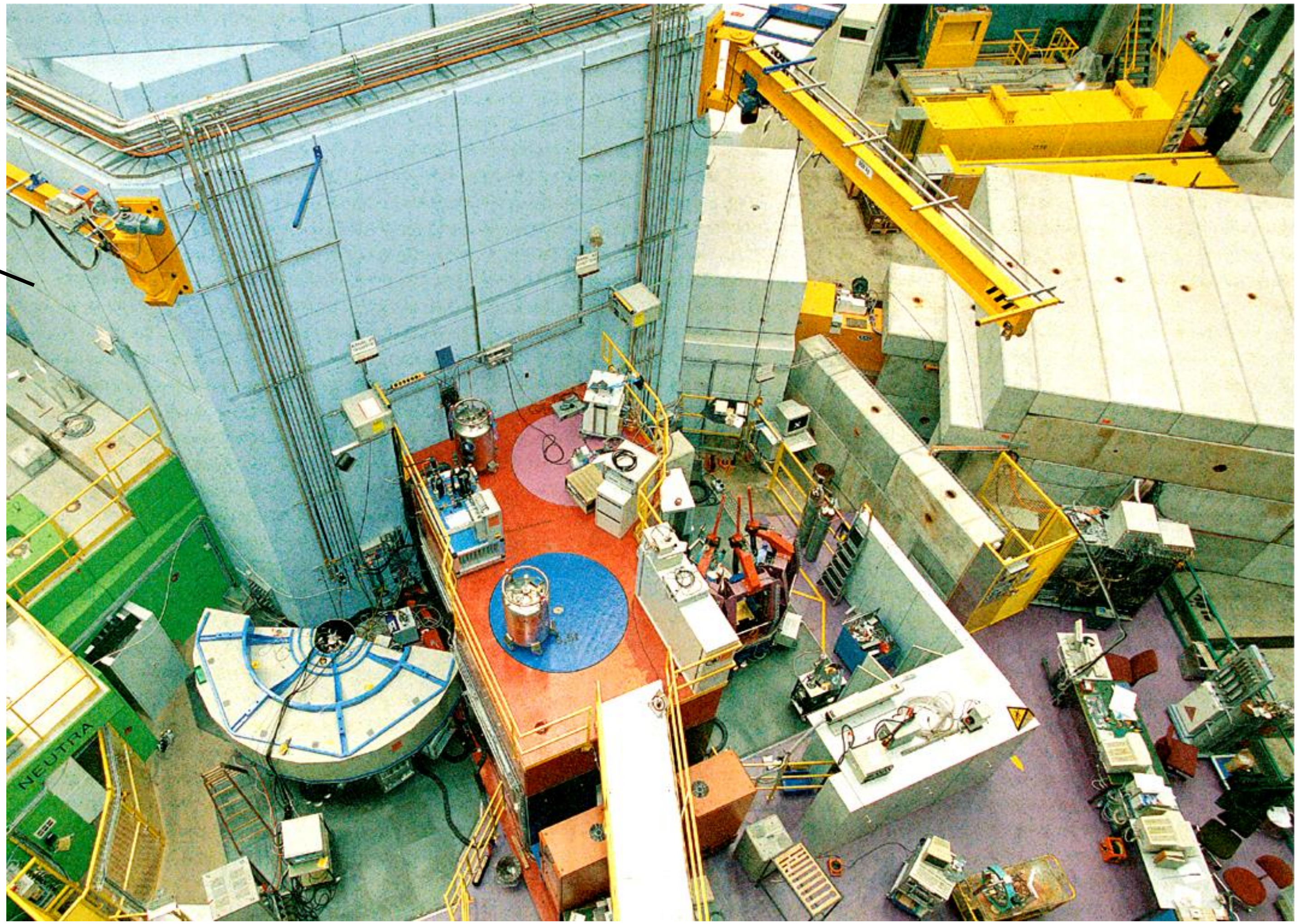
=> production of neutrons

prop. to **beam power**

SINQ
Neutron Spallation Source

Shielding

7 m Concrete



Guide for
cold Neutrons

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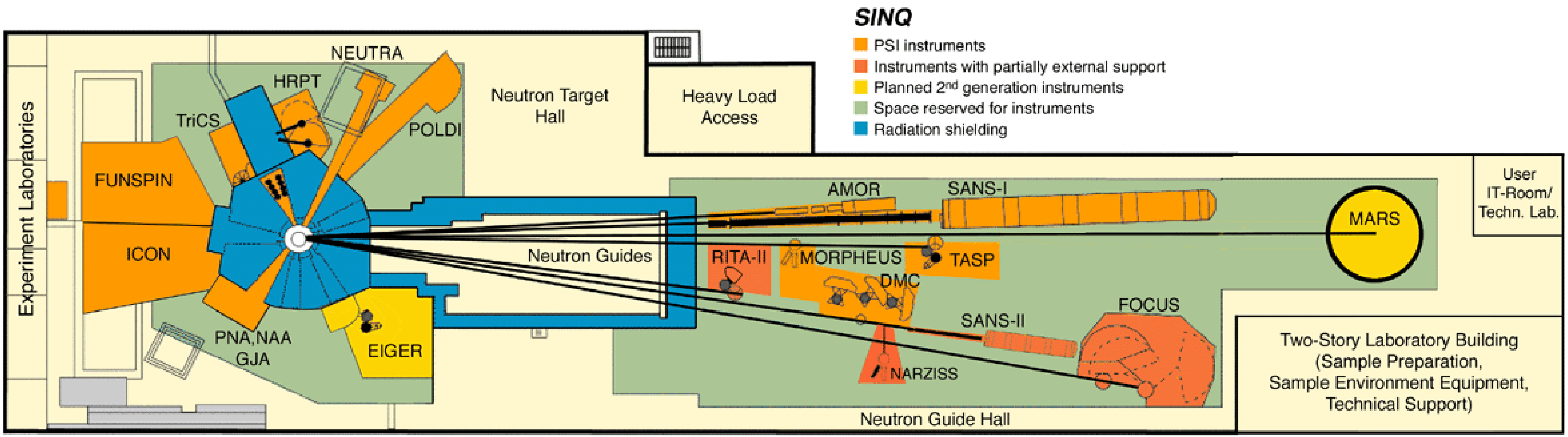
cold Neutrons

Proton (590 MeV) => Lead Nucleus => ca. 10 Neutrons

=> Moderation to < 0.025 eV => Diffraction on Material Probes



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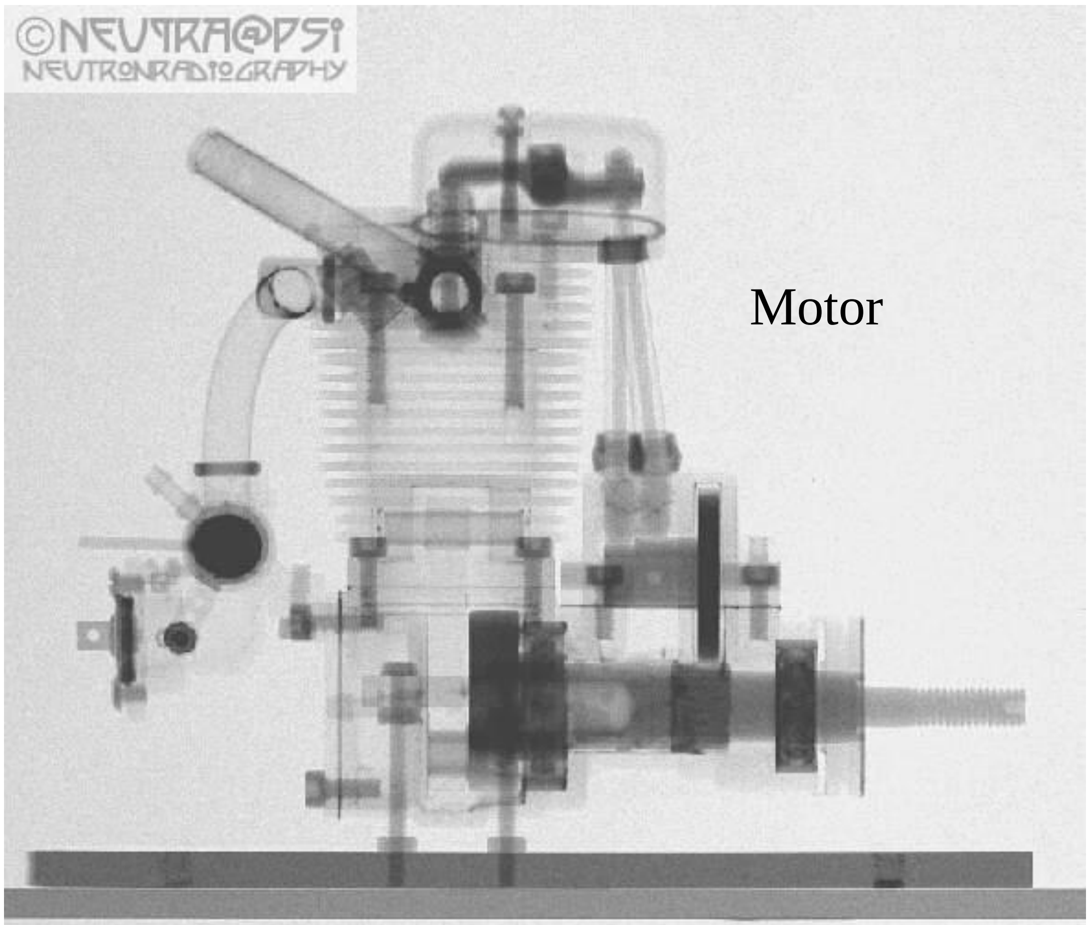
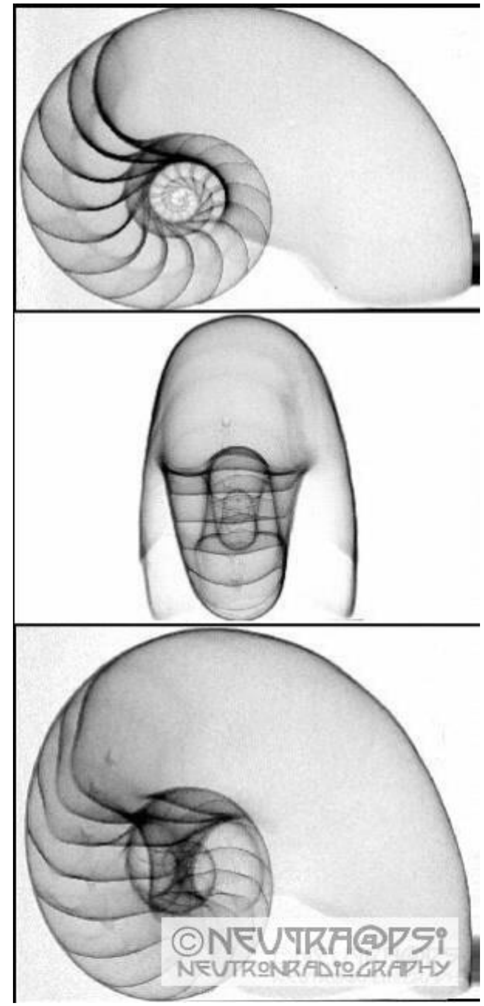
Radiography with Neutrons

=> the interior of big objects becomes visible





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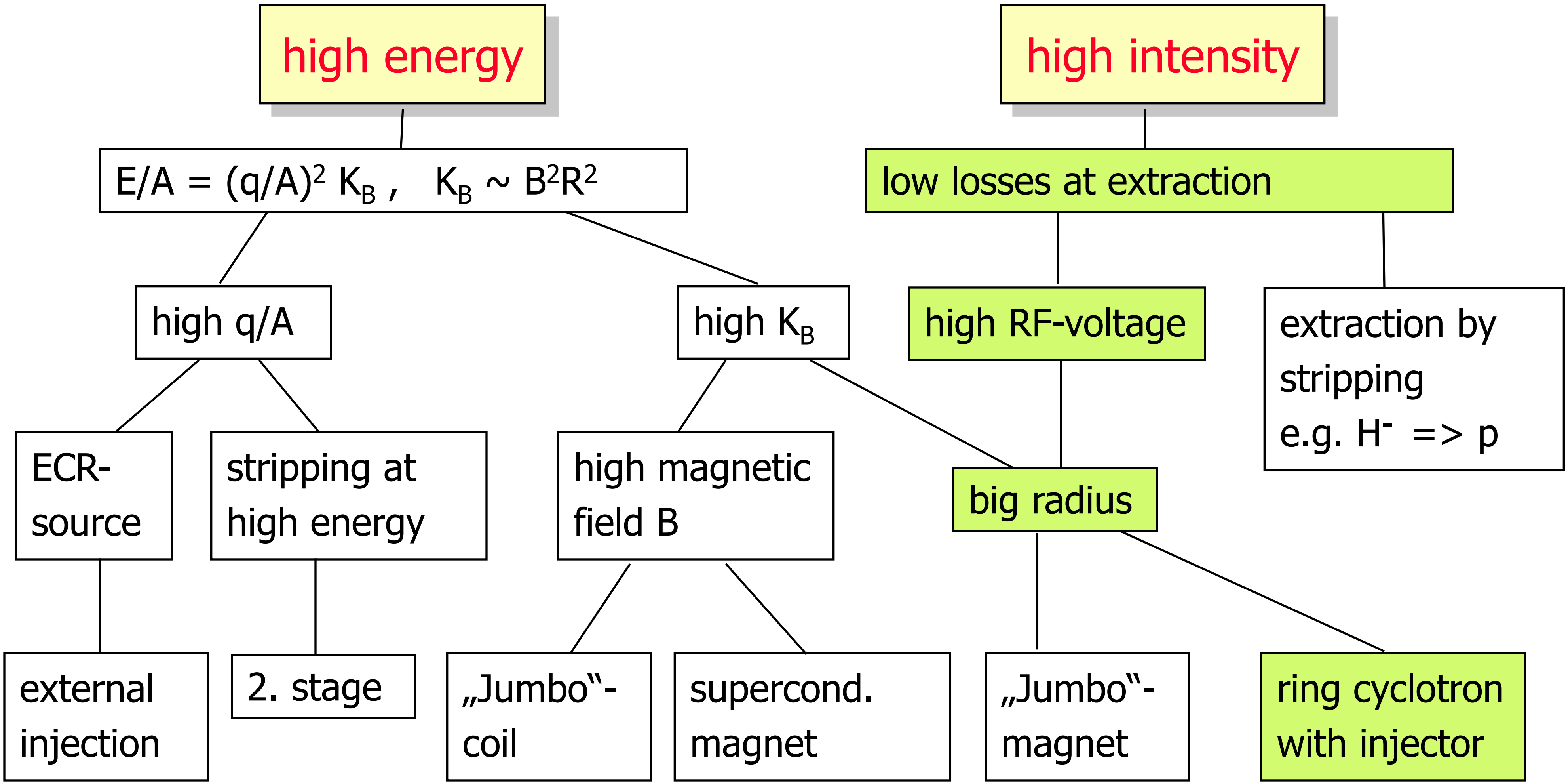
Strategy for Cyclotrons



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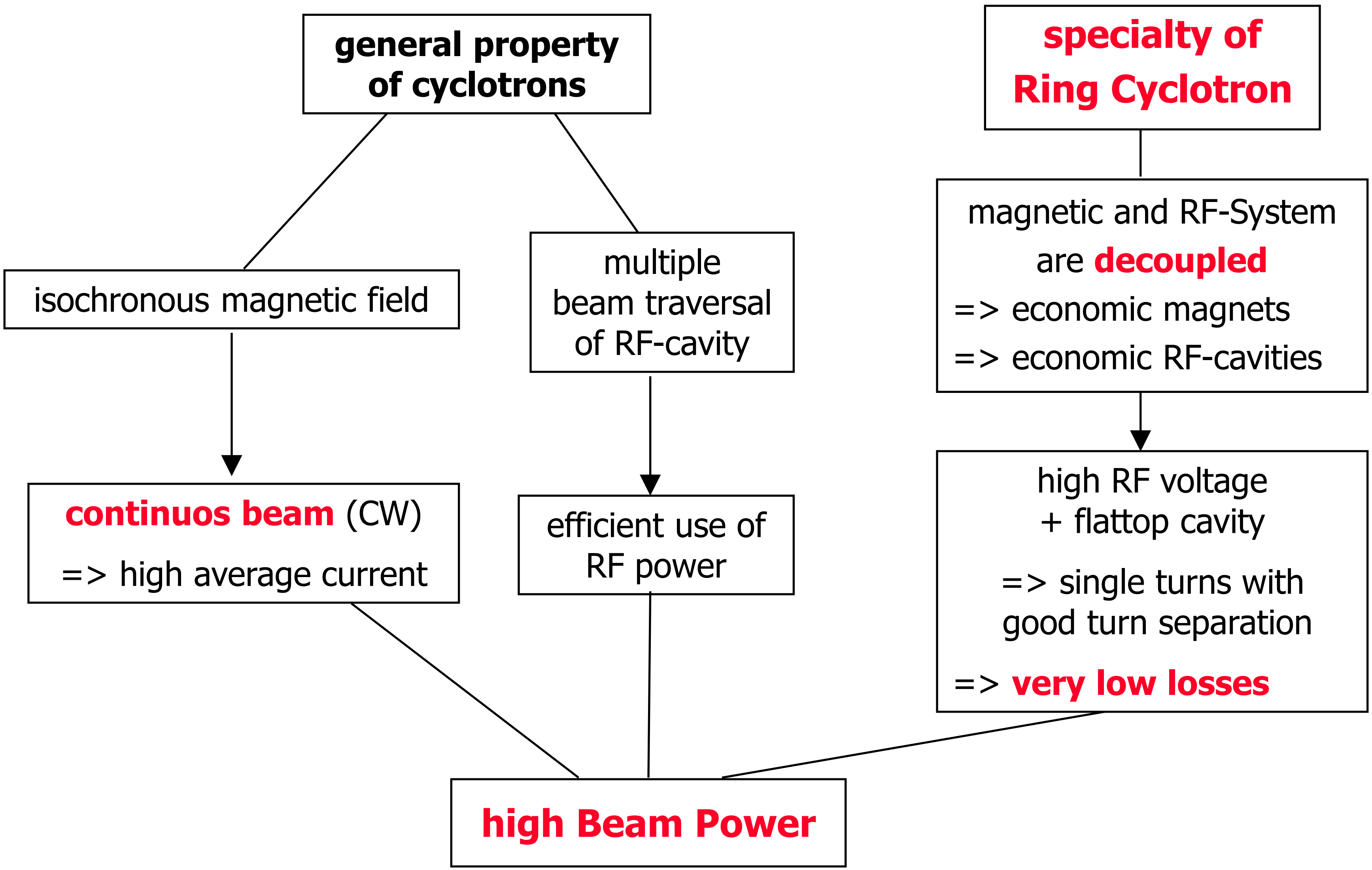
why is the PSI Ring Cyclotron such an efficient accelerator ?



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Model of the last turns in the 590 MeV Ring Cyclotron

- the turn separation is proportional to the orbit radius **R** and the cavity voltage **V**

=> concept of a large ring cyclotron with many high voltage cavities

- Flattop cavity gives mono-energetic beam

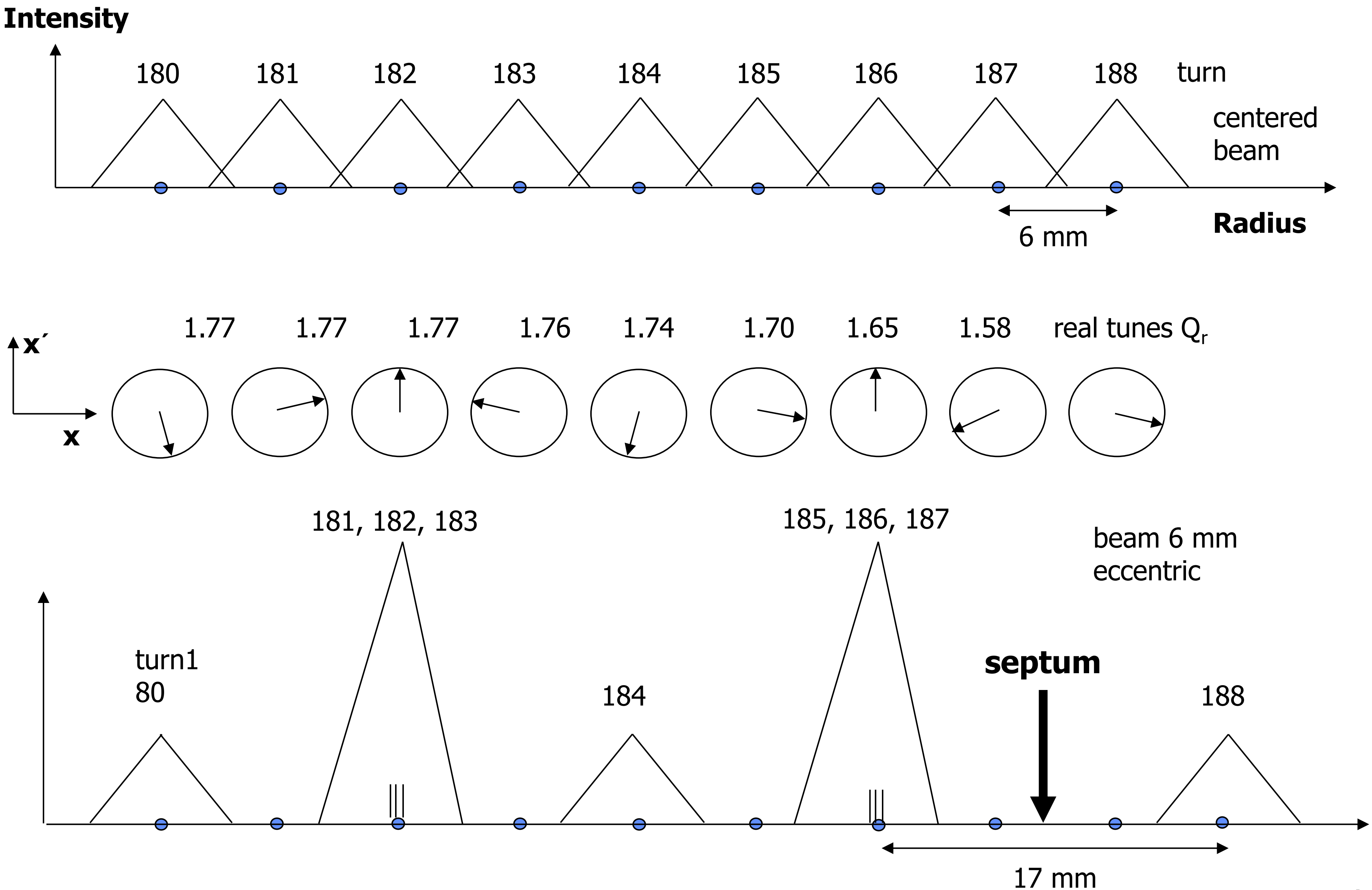
=> leads to single turn extraction

=> an eccentrically injected beam is still eccentric at extraction.

=> This can be used to increase the radial separation between the last two turns.

- In our simple model we assume an average turn separation of 6mm at extraction (energy gain 3 MeV/turn)

the last turns in the Ring Cyclotron, model with real tune Q_r



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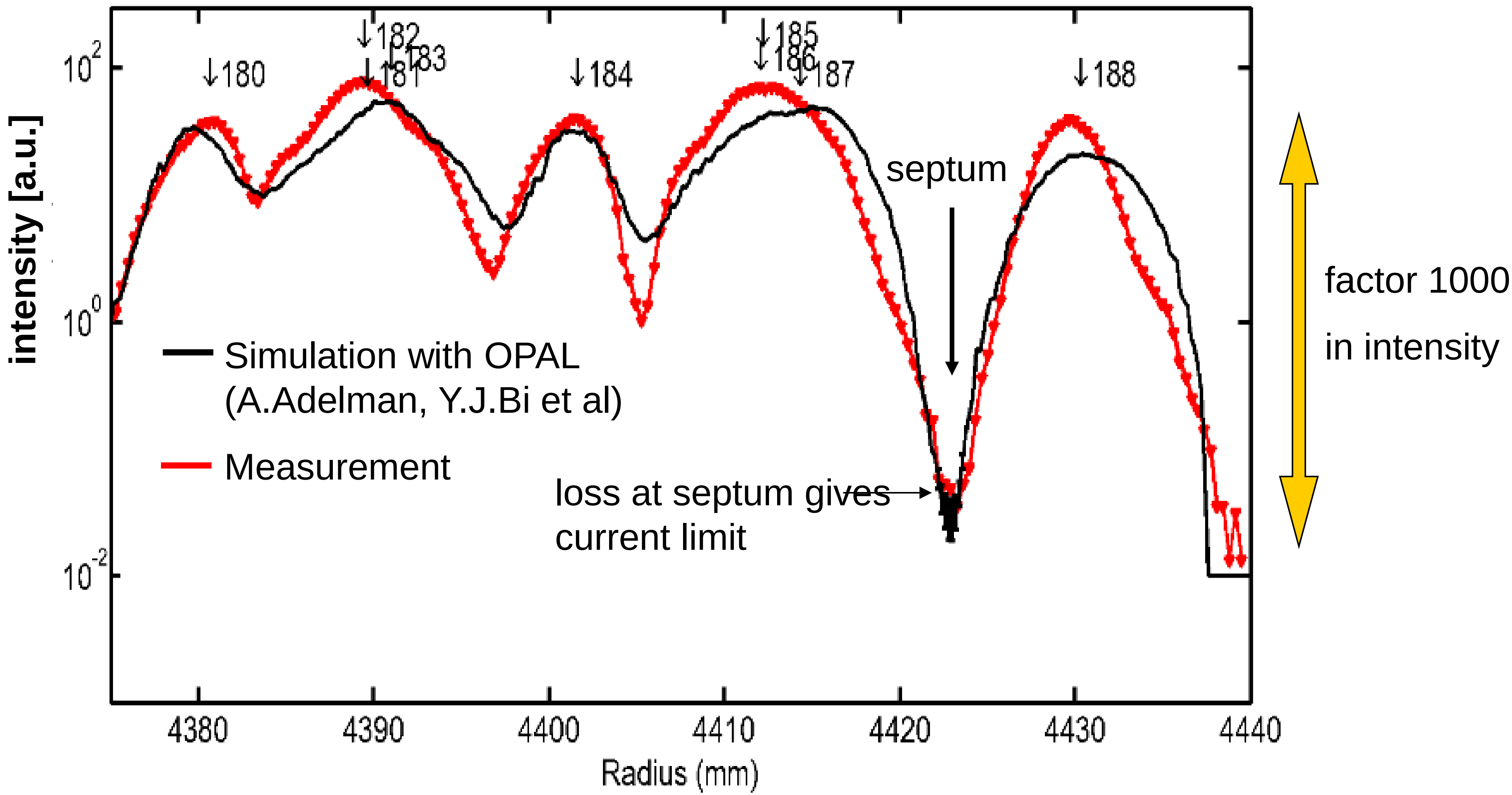
590 MeV Ring Cyclotron
last 9 of 188 turns for a 2 mA beam



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Success Factors for PSI Ring Cyclotron

1	Magnets and RF-System are decoupled		
2	4 high voltage cavities	→	**I max ~ V^3**
3	large Radius R	→	high turn separation dR/dn ~ R·V
			fast acceleration into fringe field, where Qr drops: dR/dn ~ $1/Qr^2$
4	excellent beam from Injector	→	separated turns
5	Flattop Cavity	→	high phase acceptance ΔΦ
6	eccentric Injection	→	Qr at extraction 1.75 => 1.5
			wins factor 3 in dR/dn: 6 => 17mm
7	straight electrostatic Septum with 0.1mm strips	→	Losses at extraction ≈ 10^{-4}
			↓
8	Continuous Beam (CW)	→	**1.4 MW Beam Power**

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Reduction of Extraction losses

Cavity Voltage [kV]	Beam	Flattop Cavity	Losses [%]	Losses [µA]	Imax [µA]
500	Orig. Design	no	5	**5**	100
450	centered	no	1.2	0.5	40
450	eccentric	no	0.25	0.5	200
450	eccentric	yes	0.1	0.5	500
850	eccentric	no	0.06	0.5	800
850	eccentric	yes	0.02	0.5	2'400

Improvement by	Factor	
Beam Quality	~ 3	
eccentric Injection	~ 5	
Flattop Cavity	~ 3	
Cavity Voltage	~ 5	(≈ V^3 law)
total	**240**	

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Properties of Cyclotrons

versatile

all Ions from p to U

Energies:

p: up to 600 MeV
=> limit ≈ 10 GeV ?

Ions: up to 500 MeV/n

CW-Beams

=> high Intensity (few mA)

=> polarized Ions (few μA)

Coincidence Experiments with

high Event Rates

continuos Beam allows easy

Tuning of Accelerator

excellent Beam Quality

in all 6 Dimensions

transv.: π 1 mm mrad (norm.)

$\Delta E/E \approx 10^{-3}$

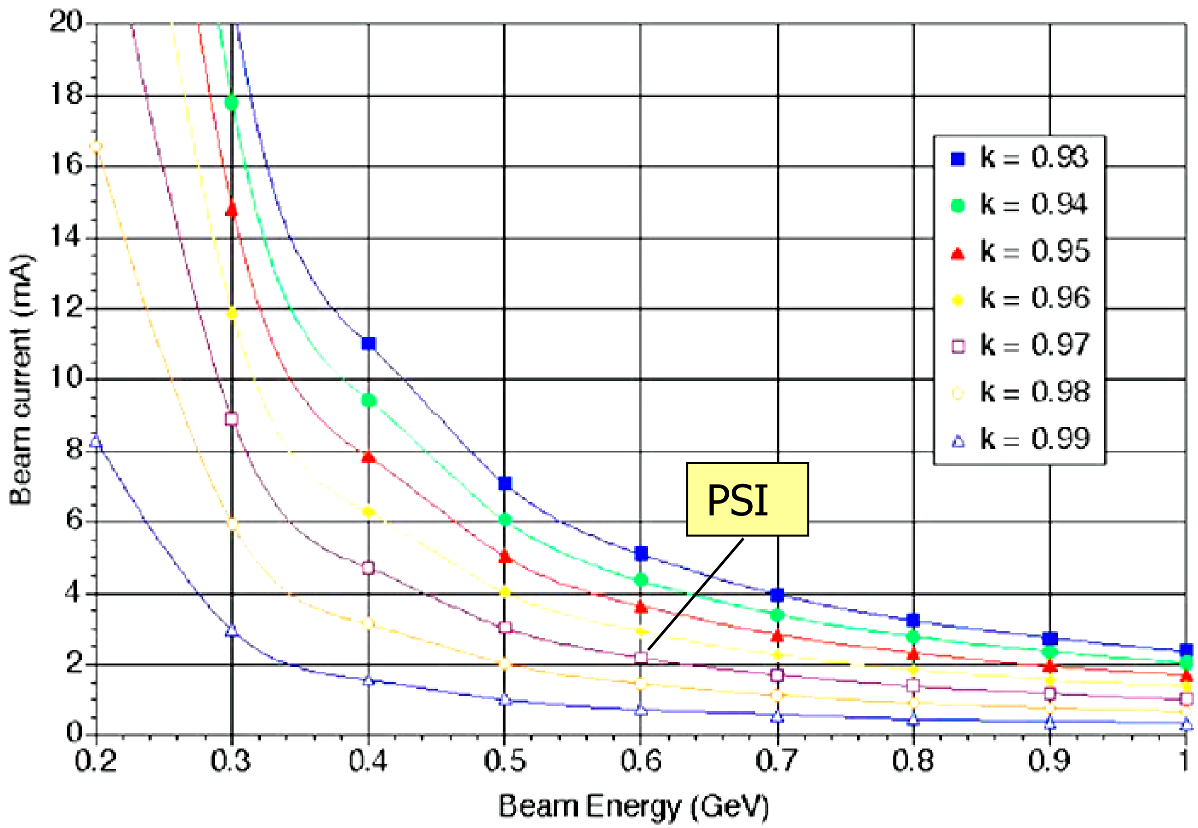
$\Delta t \approx 0.3$ ns

Pulse Selection at low Energy
gives flexible microscopic Time
Structure for Time of Flight
Experiments

Cyclotrons are still attractive !

- Commercial Cyclotrons for
  Radiation Therapy and Isotope Production
- Acceleration of Radioactive Beams
- Injectors for Ion Storage Rings
- Intense Neutron Sources, replacing Reactors
- Energy Amplifier Concept (Carlo Rubbia)
- Transmutation of Nuclear Waste

Energy Amplifier Concept (C.Rubbia)



Beam current needed to produce 80 MW_{th} with protons for different criticality factors k (ref. Ansaldo 2001)

example: 600 MeV PSI Cyclotron

in future with 3 mA => **1.8 MW**

=> production of neutrons in subcritical reactor **(e.g. k=0.97)**

=> 110 MW_{th} => **40 MW_{el}**

=> power plant with 1 GW_{el} needs 35 mA protons at 1 GeV => s.c. Linac

- **inherently safe**
- **use of Thorium (big reserves)**
- **no production of Plutonium for weapons**

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reduction of lifetime of nuclear waste !

chem. separation of long lived actinides

⬇

high intensity protonen beam
≈ 40 MW (30*PSI) , ca. 2050 ?

⬇

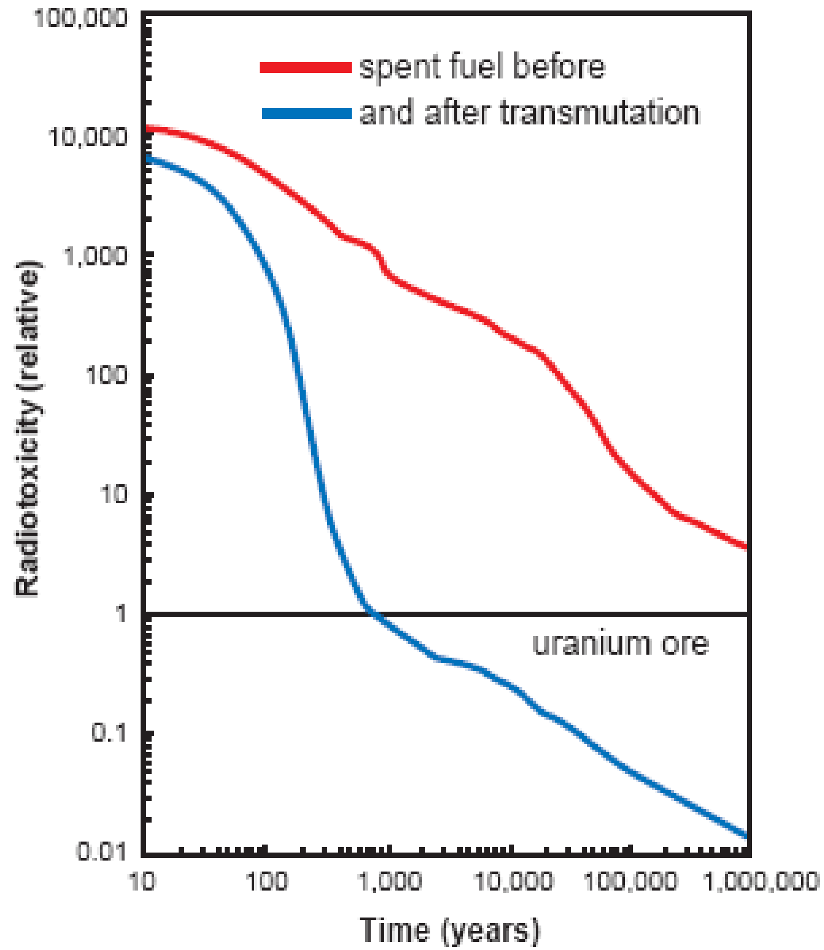
production of neutrons

⬇

transmutation of aktinides

⬇

Reduction from 1 Mill. years to 400 years



European Roadmap for Accelerator Driven Systems … ENEA Italien 2001

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some personal References

W.Joho, Particle Accelerators 1974, Vol.6, pp. 41-52

W.Joho "High Intensity Problems in Cyclotrons" Proc. 9th Int. Conf. on Cyclotrons, 1981, Caen, France, Les editions de physique, Paris (1981) p. 337

W.Joho, M.Olivo, Th.Stammbach, H.Willax "The SIN Accelerators, …"

US Particle Accelerator Conference, 1977 Chicago, IEEE NS-24, 1618 (1977)

W.Joho "Modern Trends in Cyclotrons, CERN Accelerator School, 1986 Aarhus, Denmark, CERN 87-10, 260 (1987)

J.Stetson, S.Adam, M.Humbel, W.Joho, Th.Stammbach "The Commissioning of PSI Injector II for High Intensity, High Quality Beams" Proc. 13th Int. Conf. on Cyclotrons, Vancouver 1992

More information on the PSI Accelerator Facilities can be found in: www.psi.ch

More talks by the author are found in www.google.ch with "Werner Joho PSI" or directly in

http://gfa.web.psi.ch/publications/presentations/WernerJoho/

History of SIN: Geschichte des SIN, Andreas Pritzker, Munda Verlag 2013

professional career of Werner Joho

1958 – 1962 physics student at ETH Zurich

1962 – 1990 Cyclotron group ETH => PSI , leader Beam Dynamics

1990 – 2003 Synchrotron Light Source (SLS) , Project leader Booster

after 2003 Consulting (PSI, Barcelona, Taiwan, Beijing, Vancouver)

external stays:

1963 CERN , Geneva, computer codes for cyclotron orbits

1964 Michigan State University, graduate studies

1971 – 1973 TRIUMF Vancouver , Canada, Injection Line
lectures on thermodynamics at University UBC

1990 Berkeley, California, Light Source ALS

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Ring Cyclotron September 1973

1 Hans Willax

2 Miguel Olivo

3 Thomas Stammbach

4 Werner Joho

5 Christa Markovits

Confidence in success !

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First 600 MeV Protons on Target 25.2.1974

Richard Reimann
Manfred Daum

Thomas Stammbach

Werner Joho

Paul Rudolf

Hans Willax

Urs Schryber

Jean Pierre Blaser

Francesco Resmini

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