PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

# Paul Scherrer Institut

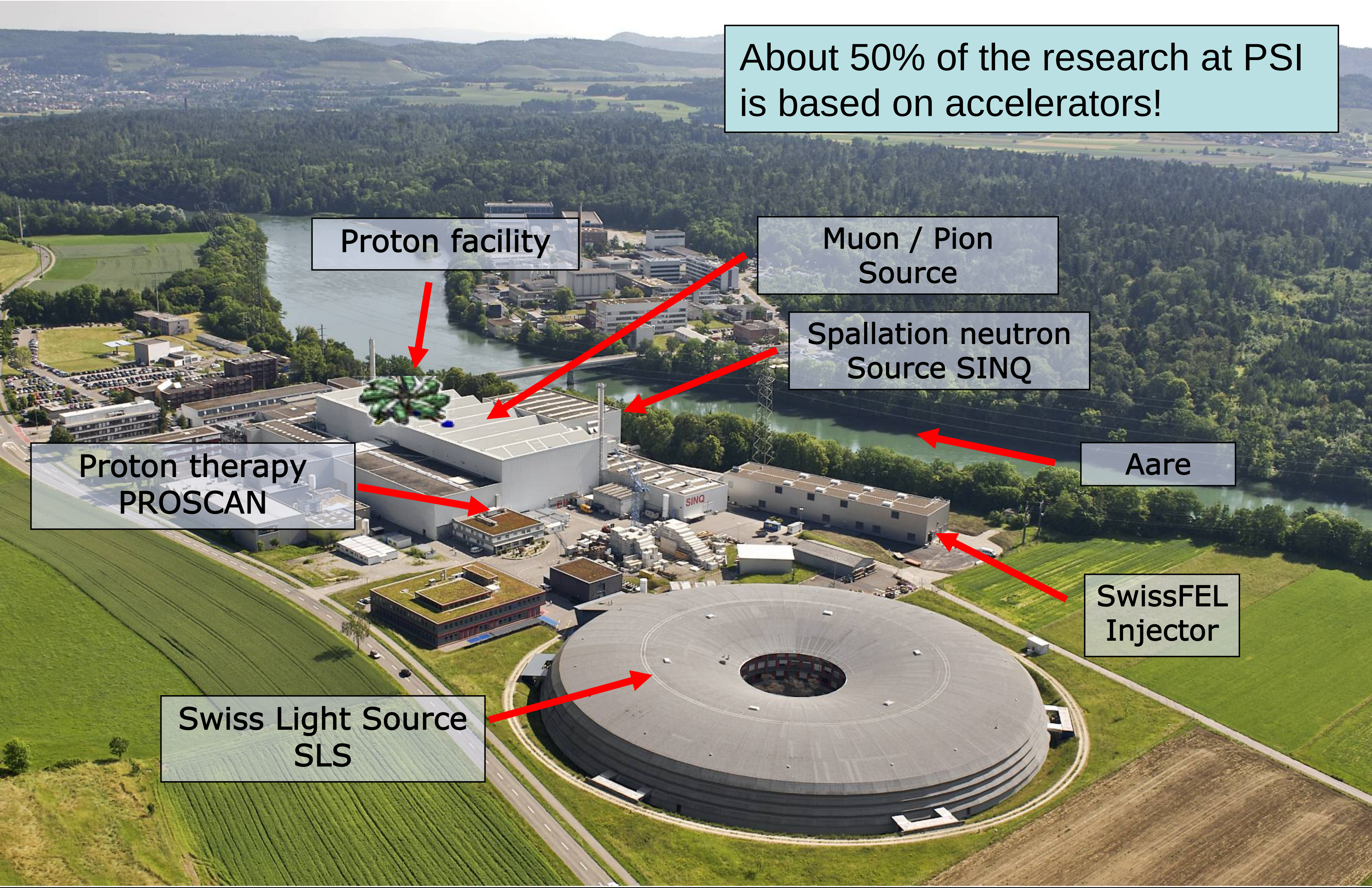
Joachim Grillenberger

## The High Intensity Proton Accelerator

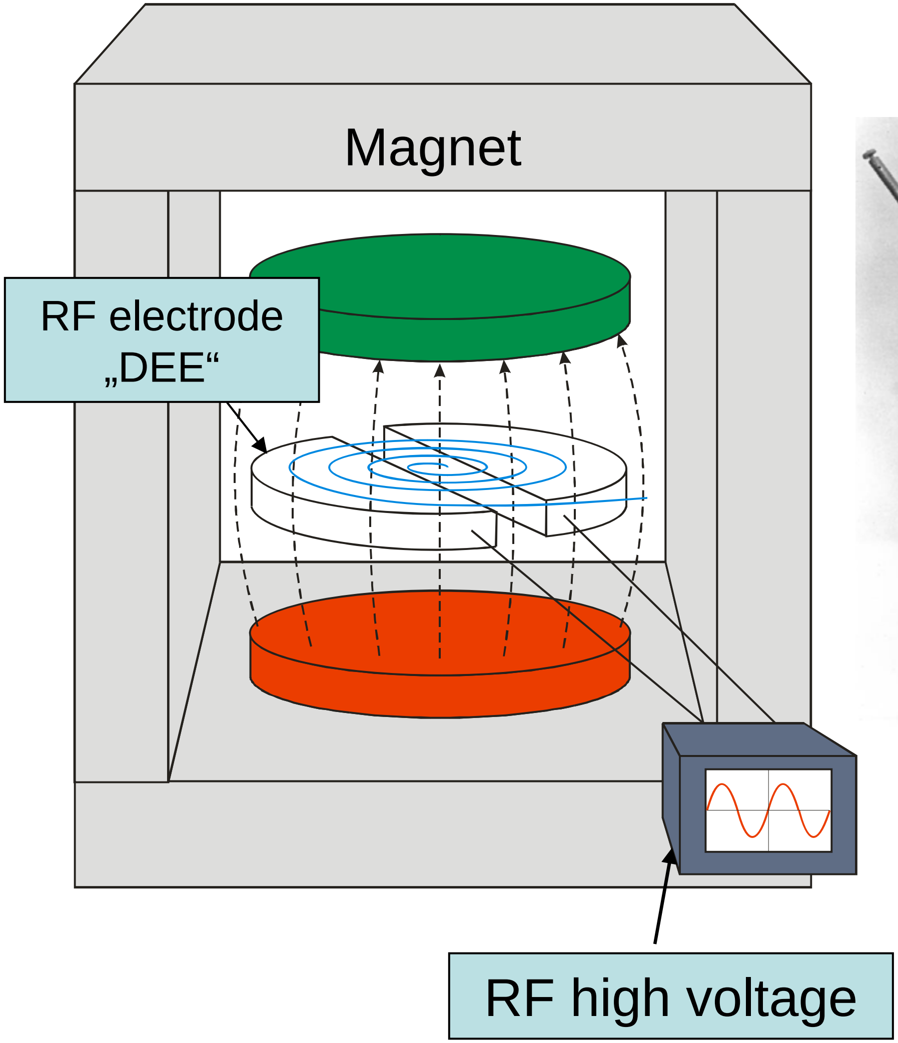
# Outline

- PSI accelerators
- The Cyclotron
- The Proton facility
  - Cockcroft Walton
  - Injector 2
  - Ring Cyclotron
- Neutron Imaging
- Outlook

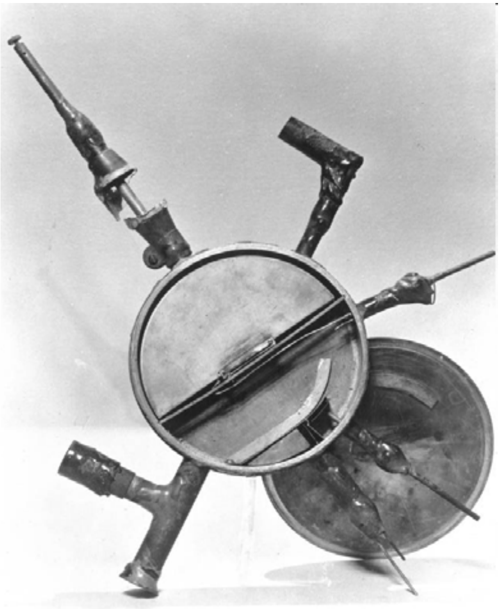
# PSI Accelerators



# Cyclotron 1930

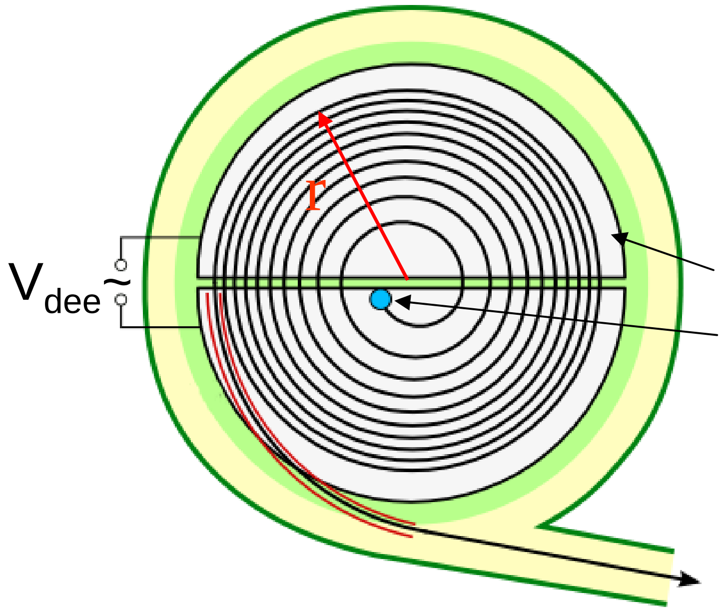



Ernest Lawrence (1901-1958)



$E_{proton}$= 80 keV

# Cyclotron




**1) At each electrode border:**

Energy gain: $\Delta E = qV_{dee}$

**2) Circular orbits**:

Centripetal force = Magnetic force $$\frac{mv^2}{r} = Bqv$$

=> $$T_{circle} = \frac{2\pi \cdot m}{Bq}$$

=> $T_{circle}$ independent from orbit radius $r$

speed $v$ **increases** with **orbit length** (~radius)

$m$ = mass

$v$ = speed

$r$ = orbit radius

$B$ = magnetic field

$q$ = charge

# Relativity in High-Energy Cyclotrons

Cyclotron essential: $T_{circle} = \frac{2\pi \cdot m}{Bq}$ => $T_{circle}$ constant for all radii

However, when $v \rightarrow c$: $m = \frac{m_0}{\sqrt{1 - v^2/c^2}} = \gamma \cdot m_0$

e.g: *10 MeV p:* *v/c=0.14* => *m=**1.01** $m_0$*

*250 MeV p:* *v/c=0.61* => *m=**1.27** $m_0$*

*590 MeV p:* *v/c=0.79* => *m=**1.63** m0*

=> $T_{circle}$ increases with radius => **particles lose pace with RF**.

# Relativity in High-Energy Cyclotrons

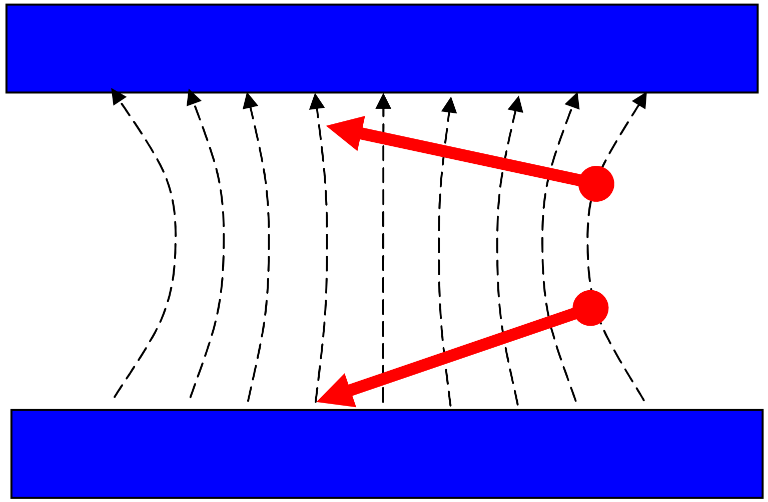
Remedies:

1) Synchro Cyclotron: decrease $f_{RF}$ during acceleration

But: pulsed beam (~1 kHz) => low duty cycle

2) increase *B* with radius: $B(r)=\gamma(r)B_0$

$$T_{circle} = \frac{2\pi \cdot m}{Bq}$$



When B **increases** with radius:

No **vertical stability**

# Relativity in High-Energy Cyclotrons

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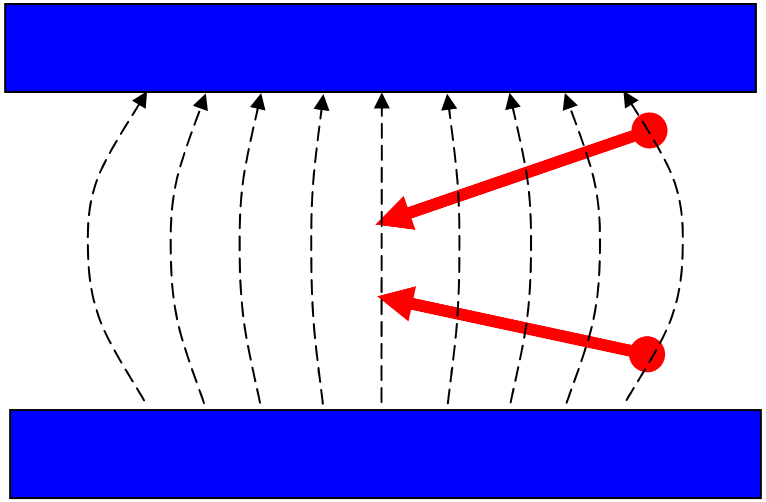


When B **decreases** with radius:

Automatic **vertical stability**

*Radial variation of field (field index):*

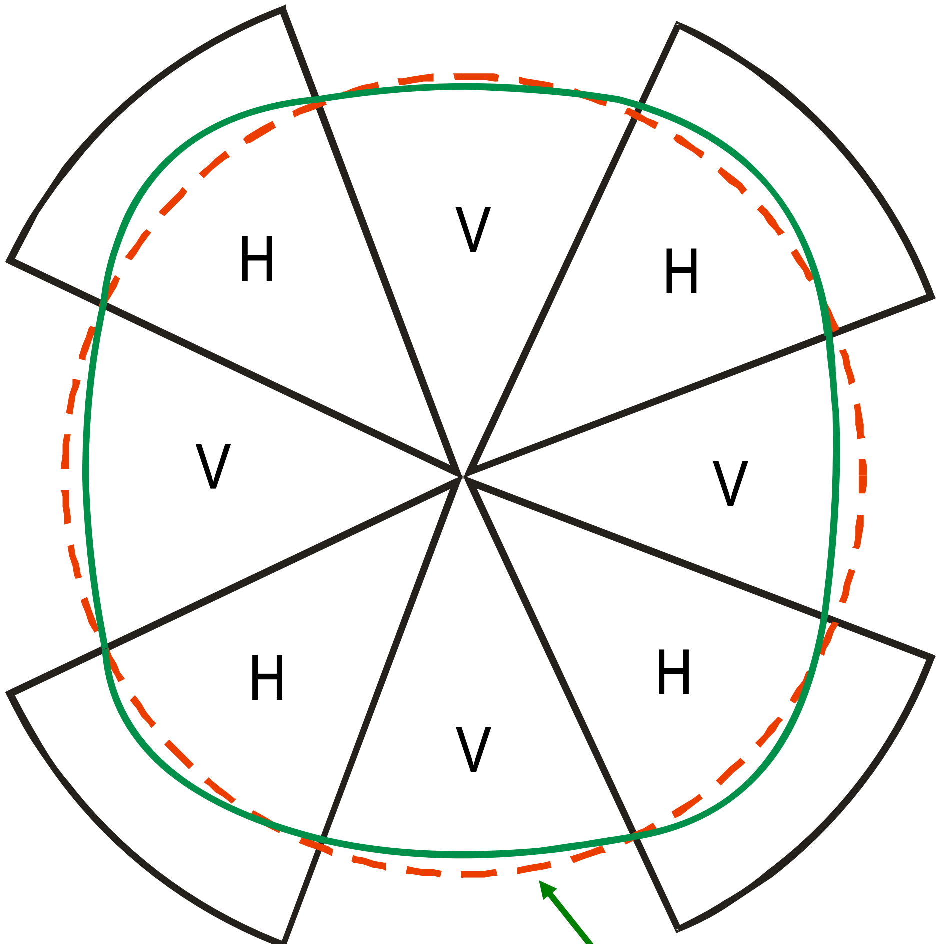
$$n(R) = -[R/B(R)]\ [dB(R)/dR]$$

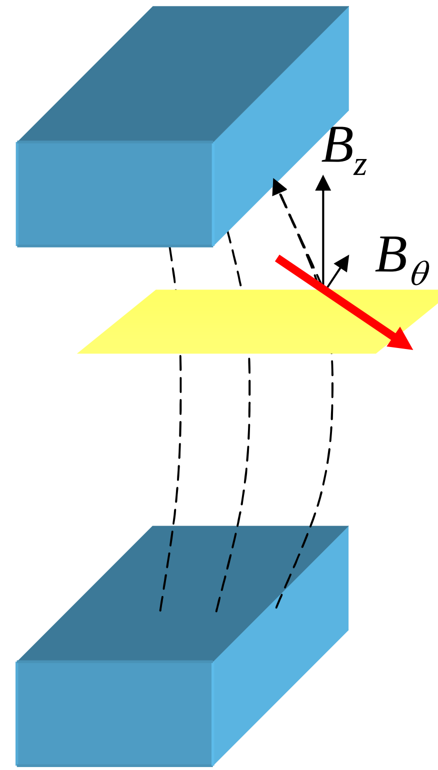
$$n>0\ :\ dB/dr<0$$

# Vertical Focusing (Thomas Cyclotron)

Hill:
stronger field

Valley:
weaker field



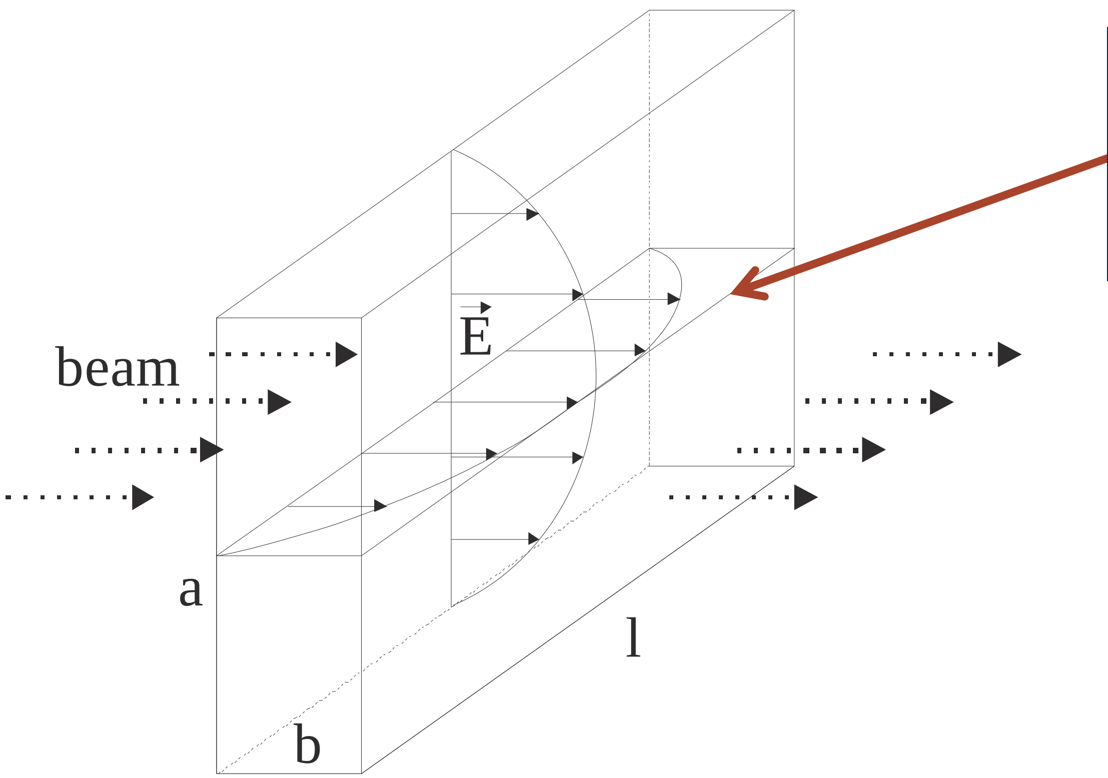

Net focusing effect from
vertical force $\boldsymbol{B_\theta \times v}$

Space for accelerating structures
and diagnostics!

# Components: Cyclotron resonators

cyclotron resonators are basically box resonators

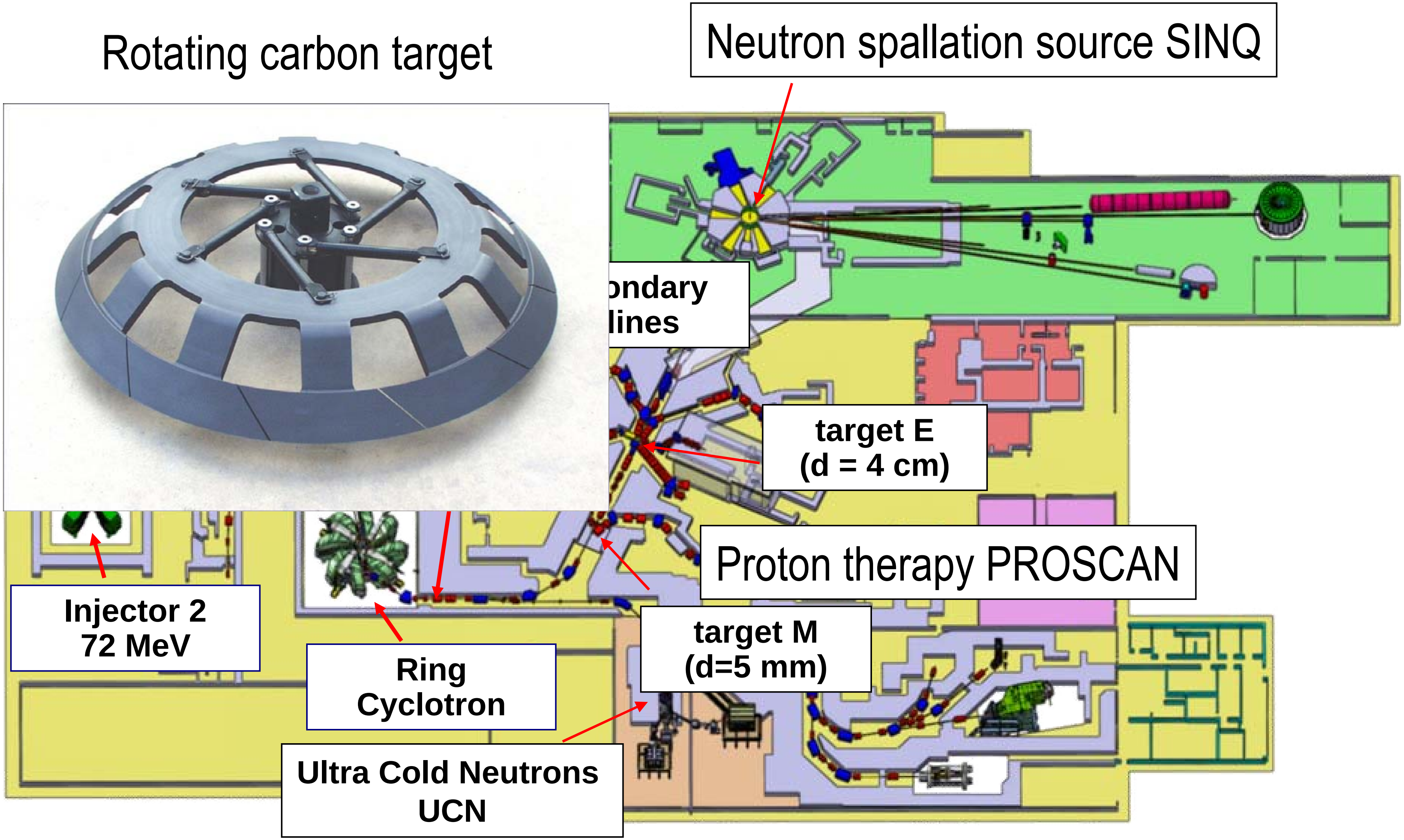
resonant frequency: $f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{l^2}}$




beam passes in center plane

accelerating voltage varies as sin(r)

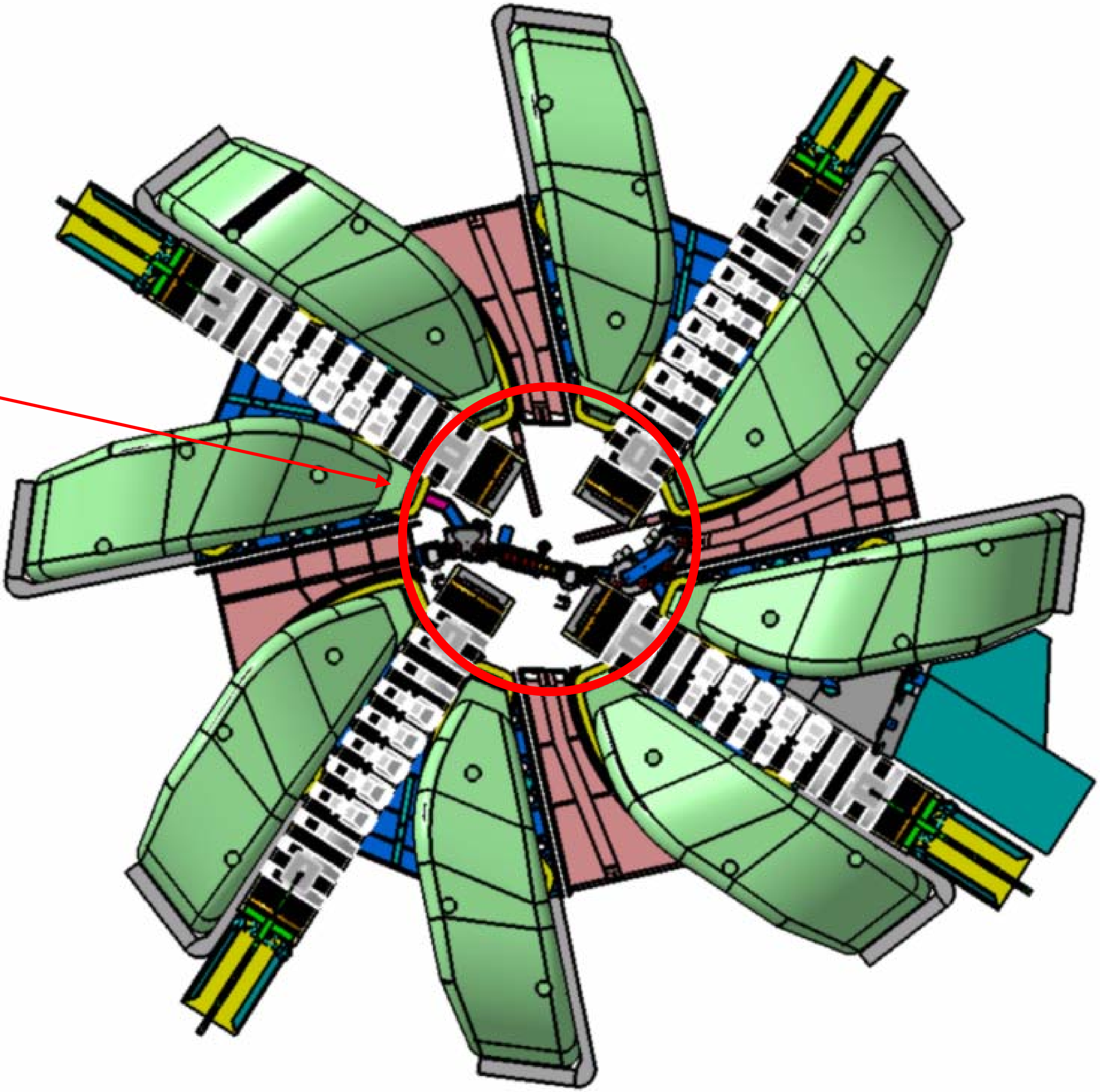
# Layout of the PSI proton facility



# Why Pre-Accelerators?

given injection radius
-> given injection energy

2.1 m -> 72 MeV



# Cockcroft-Walton Pre-Accelerator (1930)

$E_{max}$ = 870 keV
$I_{max}$ = 30 mA

High-Voltage platform
„Dome“ (810 kV)

Acceleration tube
Acrylic glass filled with $SF_6$

Voltage multiplier
„cascade“

Isolation transformers

# Electron Cyclotron Resonance (ECR) source

Microwave (2.4 GHz) ionizes hydrogen gas

Hydrogen inlet

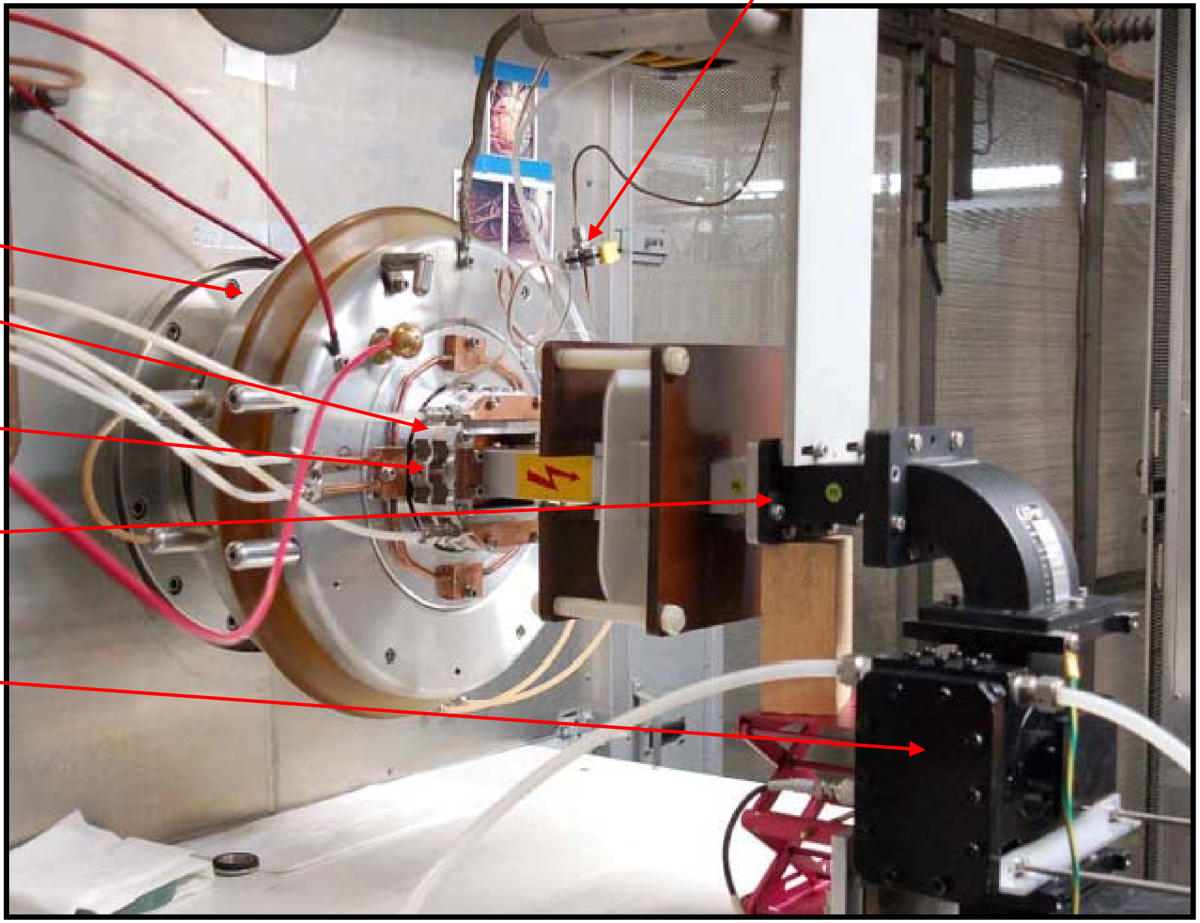
Electrostatic extraction system (60kV)

Plasma chamber (AlN cup)

Permanent magnets

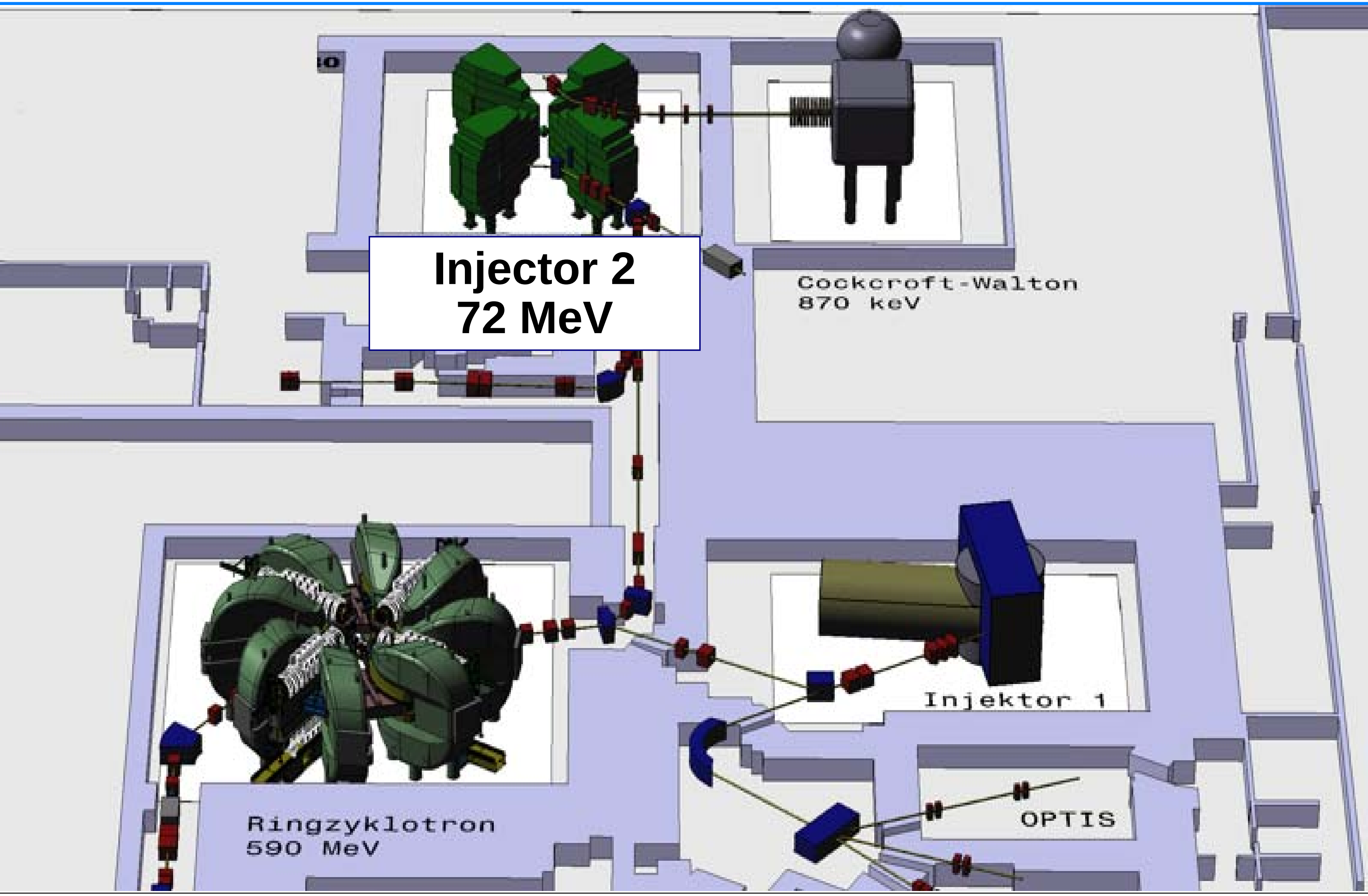
Wave guide

Magnetron



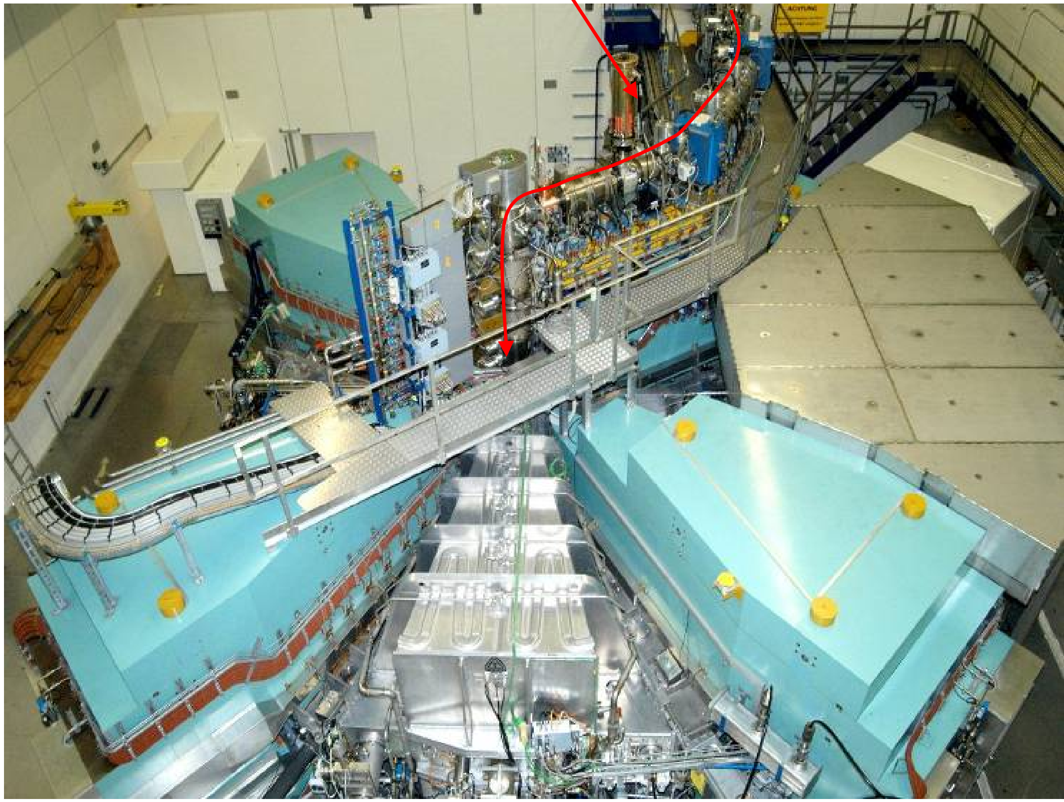
- Long service intervals
- High reliability
- High proton current and rate
- Small emittance
- Stable beam 10 – 15 mA

# Layout of the PSI proton facility



# Injector 2 Cyclotron

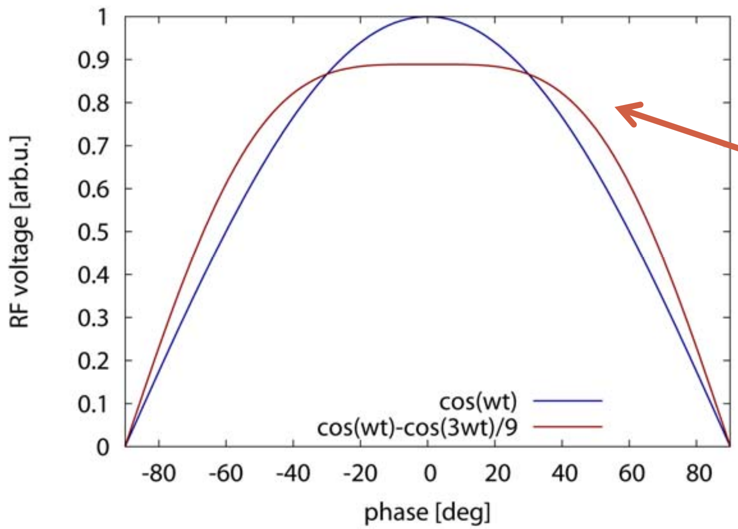
870 keV beamline



| | |
|---|---|
| - **4 sector Magnets:** | **0.33 – 0.36 T** |
| - **weight per magnet:** | **180 tons** |
| - **2 resonators:** | **50.63 MHz** |
| - **2 resonators:** | **150 MHz** |
| - **harmonic number:** | **10** |
| - **beam energy:** | **72 MeV** |
| - **max. beam current:** | **2.7 mA** |
| - **injection radius:** | **0.4 m** |
| - **extraction radius:** | **3.5 m** |

# Longitudinal dynamics – Flattop resonator

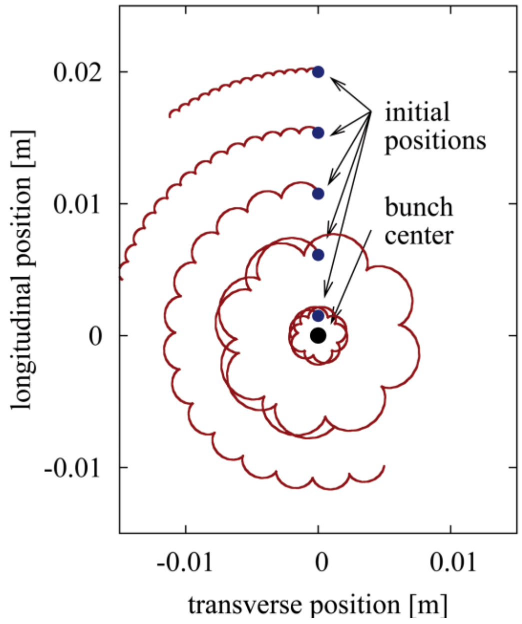
- variation of accelerating voltage over the bunch length **increases energy spread**
- thus a third harmonic flattop resonator is used to **compensate the curvature** of the resonator voltage w.r.t. time
- optimum condition: $U_{\mathrm{tot}} = U_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$

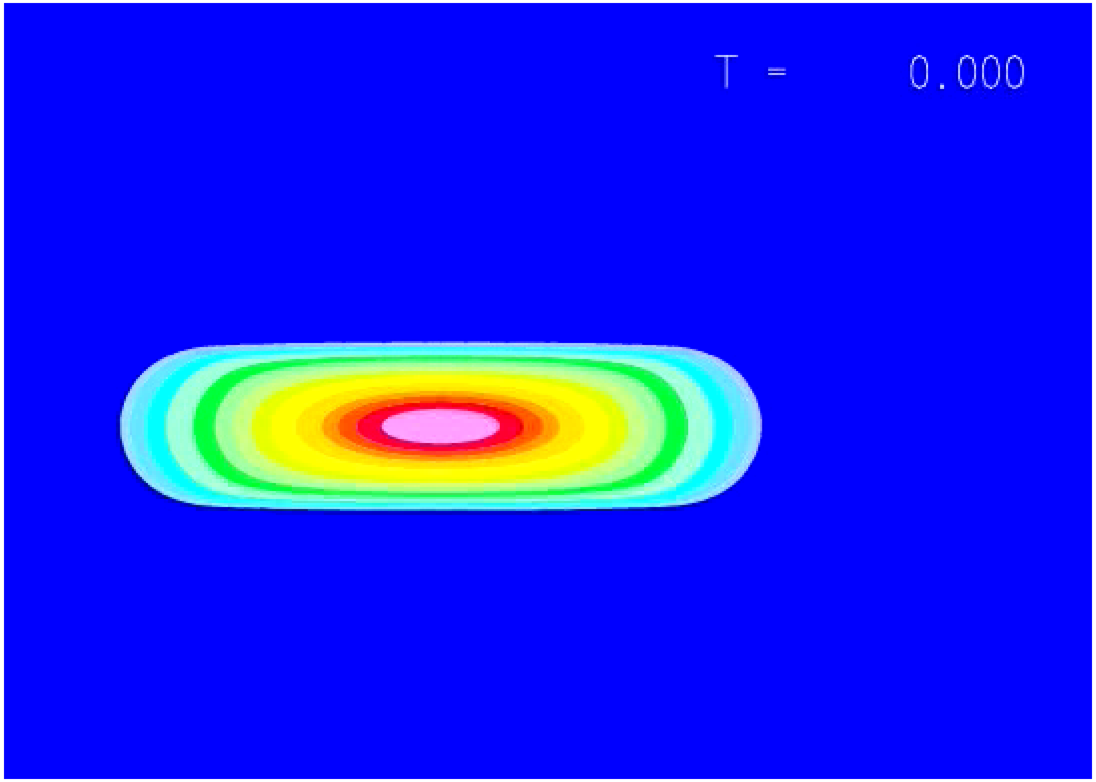



broader flat region for bunch
available voltage reduced!

# Space charge dominated acceleration

**simplified model:**
**test charge in bunch field with**
**vertically oriented bending field**



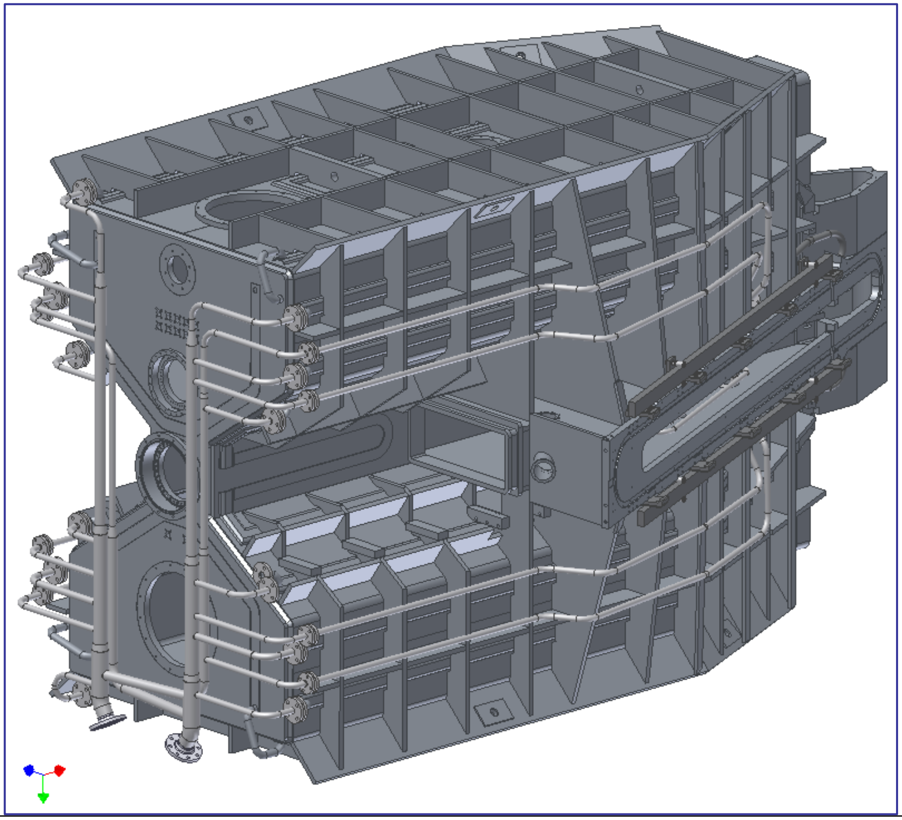
# New 50.63 MHz resonators for Injector 2

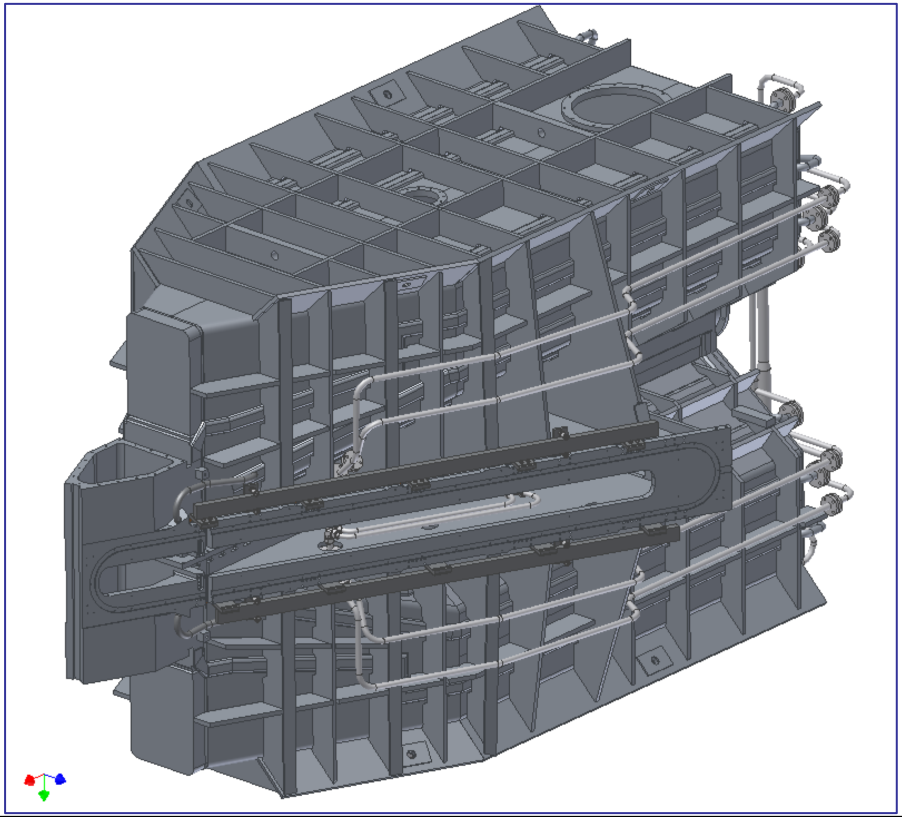
$U_{max}$ = 500 kV

Material: Aluminum

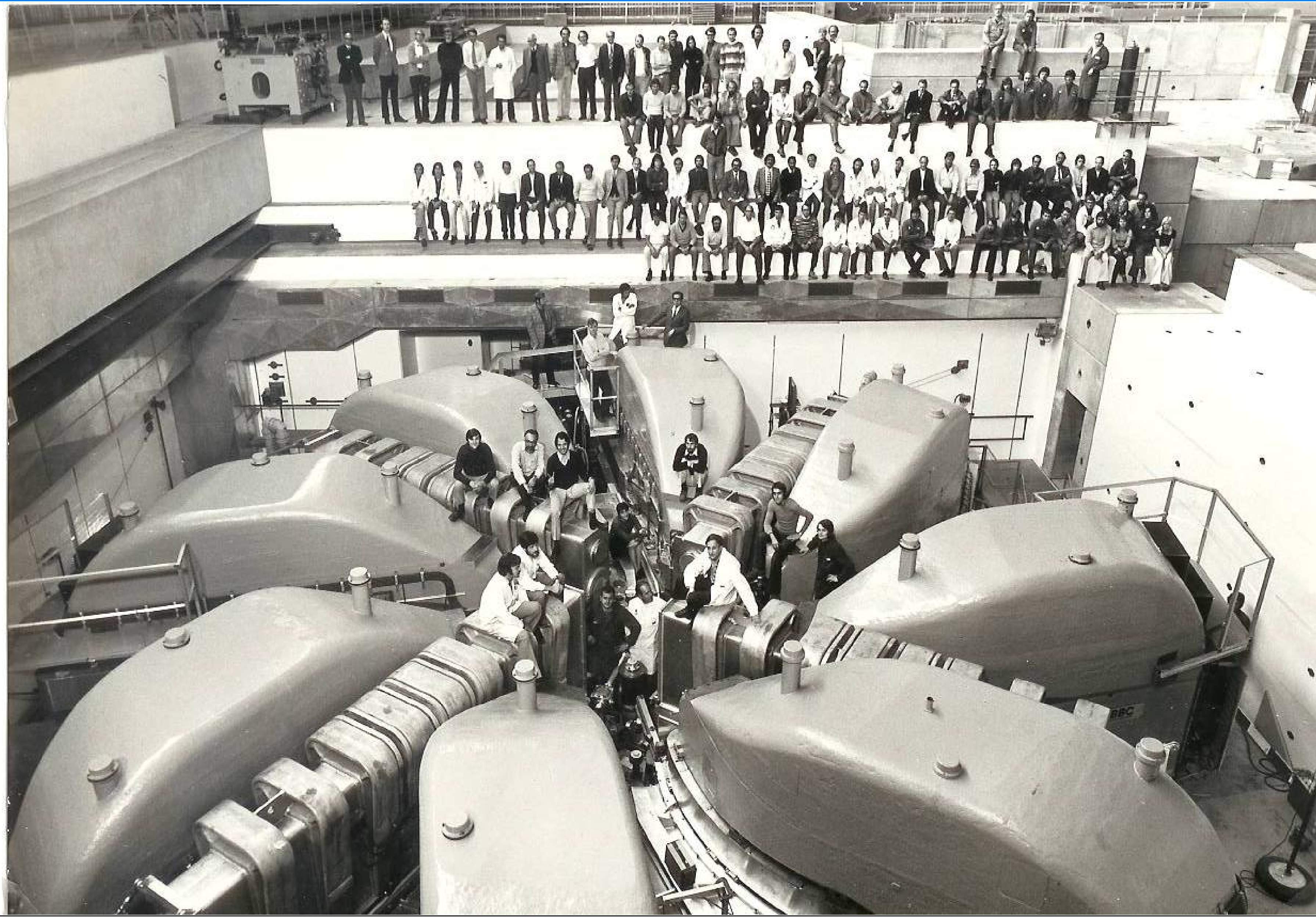
replace two 150 MHz flat-top cavities

Reduced number of turns -> better turn separation

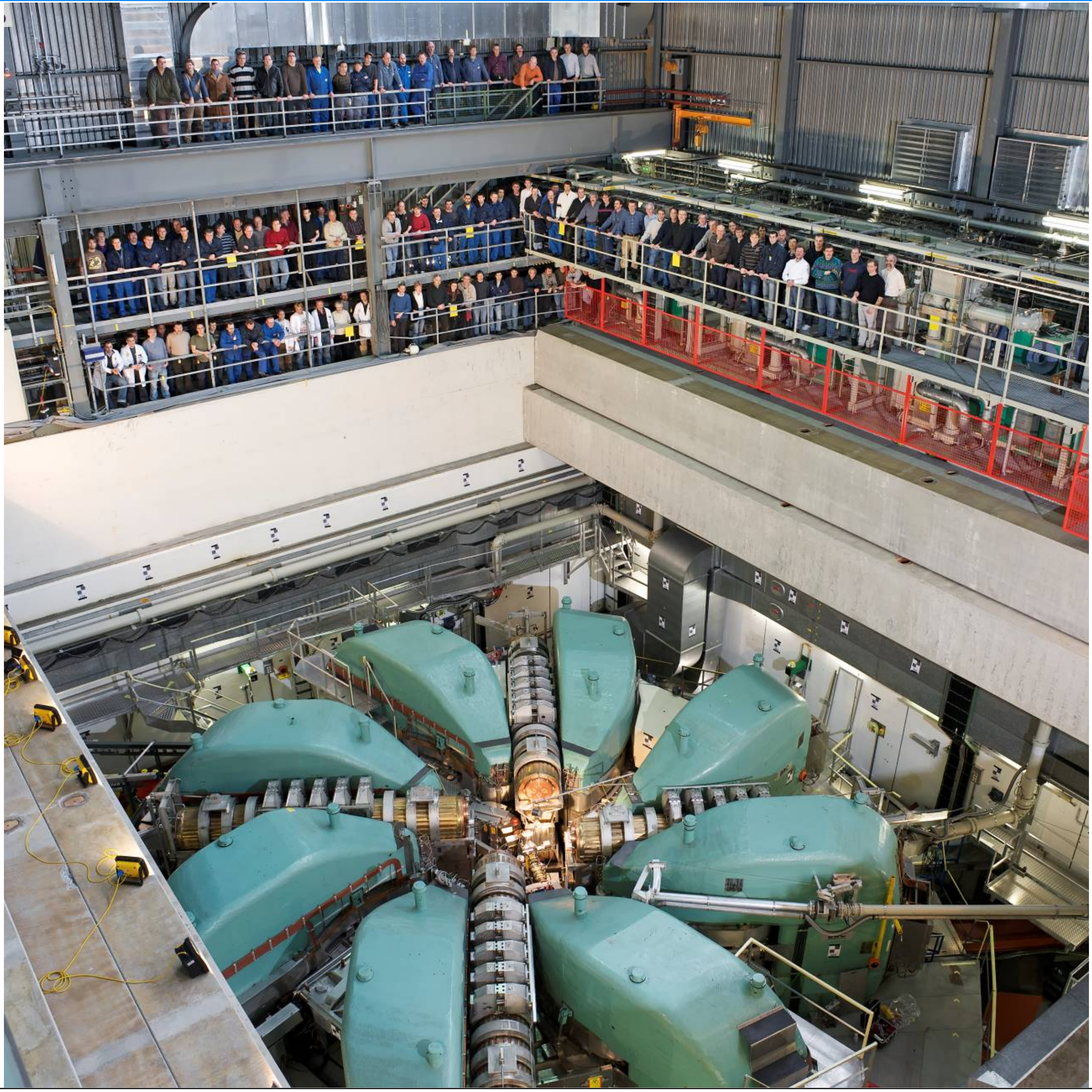




# Ring Cyclotron in September 1974

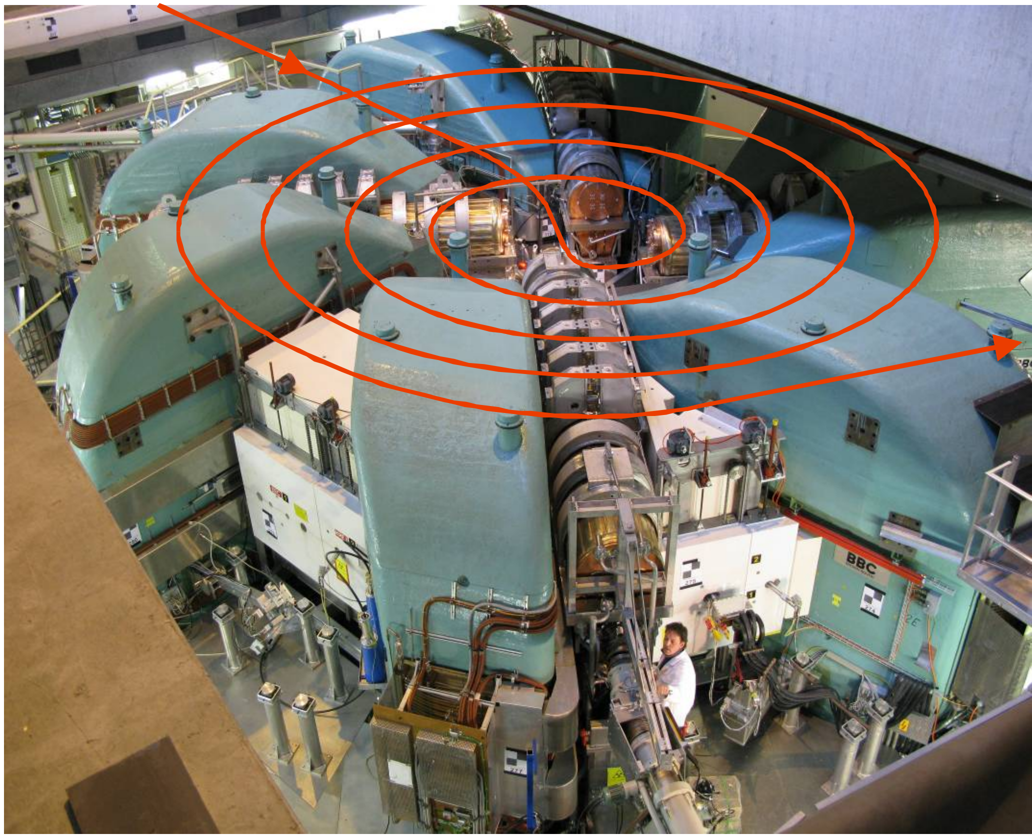


# Ringcyclotron in 2010



# 590 MeV Ring Cyclotron

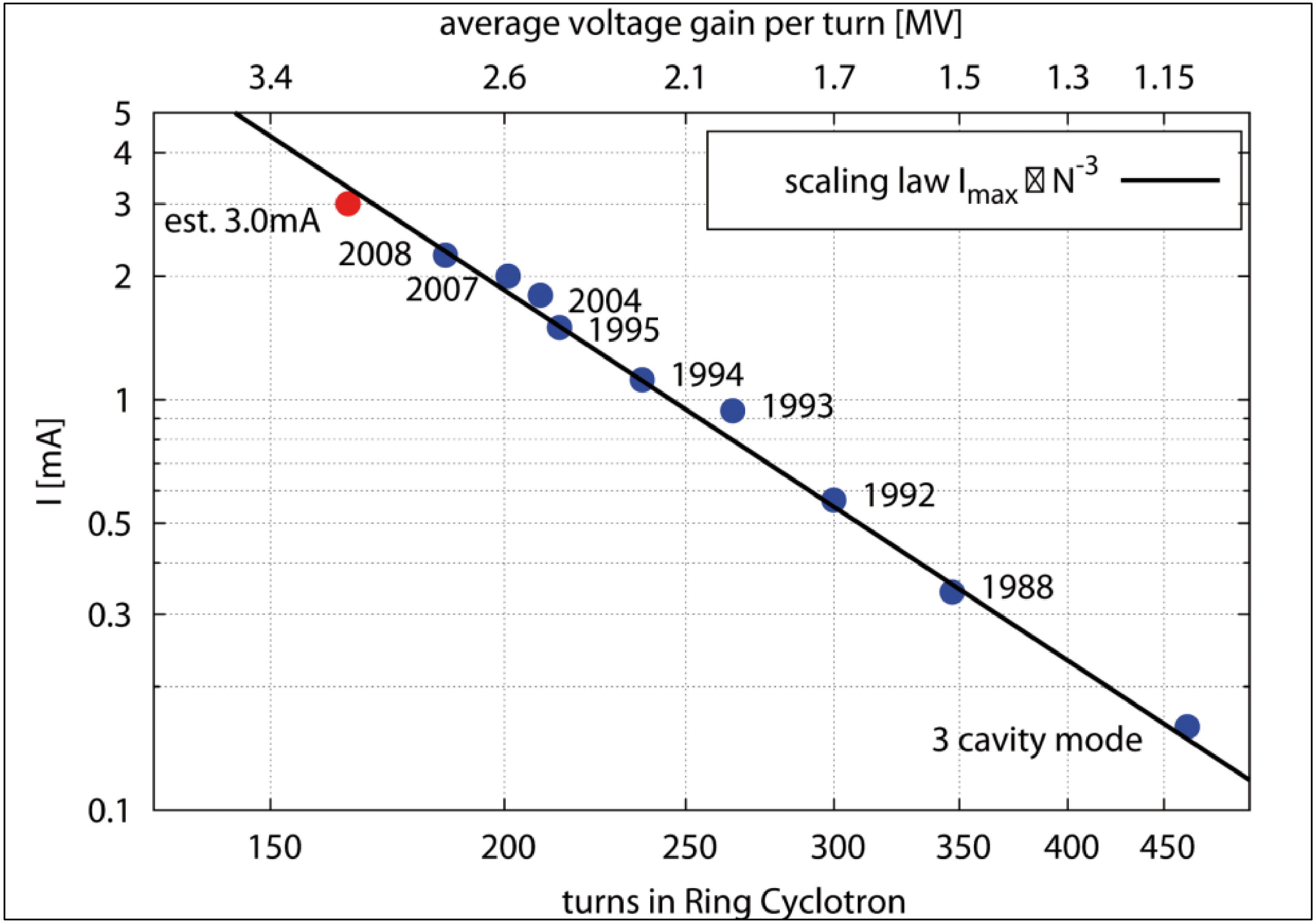
| | |
|---|---|
| - **8 sector Magnets:** | **0.6 – 0.9 T** |
| - **weight per magnet:** | **250 tons** |
| - **4 cavities 50.63 MHz:** | **850 kV** |
| - **1 flat-top resonator:** | **150 MHz** |
| - **harmonic number:** | **6** |
| - **beam energy:** | **590 MeV** |
| - **beam current (now):** | **2.4 mA** |
| - **injection radius:** | **2.1 m** |
| - **extraction radius:** | **4.5 m** |
| - **sprial angle** | **35°** |
| - **relative losses:** | **$\sim 2 \cdot 10^{-4}$** |




Beam power: 1.4 MW

Losses limit the maximum current!

# Beampower history




W. Joho, Cyclotron Conference Caen 1981

# Losses in Ring Cyclotron

Scaling Law by W. Joho: $I_{max} \propto N^{-3}$

| | | |
|---|---|---|
| charge density | $\propto$ | N |
| acceleration time | $\propto$ | N |
| 1/turn separation | $\propto$ | N |

→ fast acceleration

Cu-Resonators (max. 1 MV instead of 750 keV)

Now: N = 186 instead of 200

$I_{max}$ = 2.4 mA

# Components: High Power Resonators

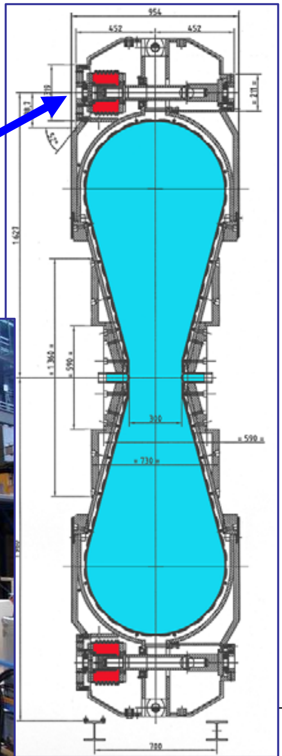
f = 50.63 MHz
$U_{max}$ = 1.2 MV (presently 0.85 MV→185 turns in cyclotron, goal for 3 mA: 165 turns)
400 kW power transfer to the beam per cavity

- less wall losses
- higher gap voltage
- better cooling distribution

deformation from air pressure ~20 mm
hydraulic tuning devices in feedback loop → regulation precision ~10μm


resonator inside

hydraulic tuning devices (5x)



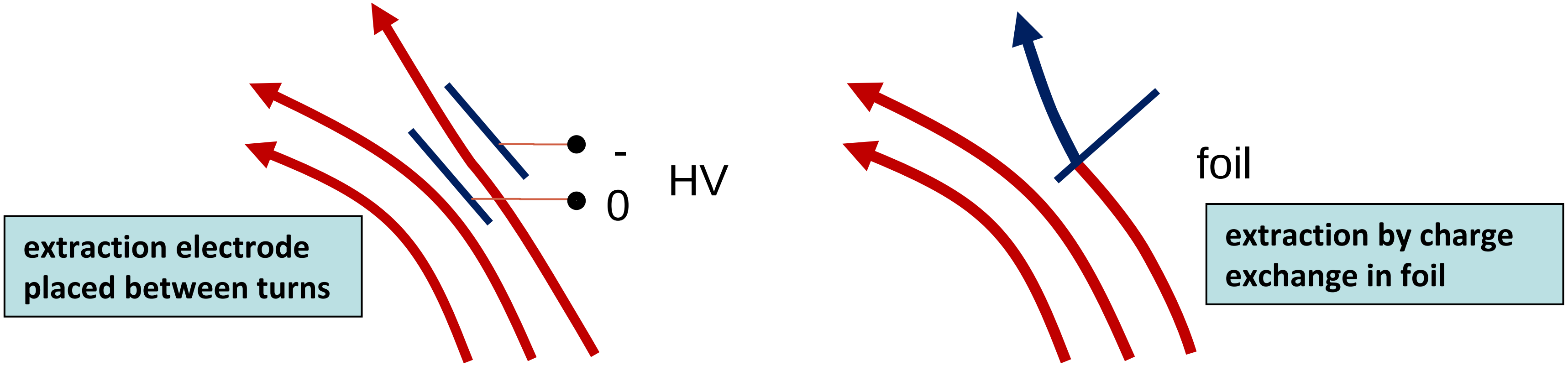
# Extraction schemes

- deflecting element should affect just one turn, not neighboured turn

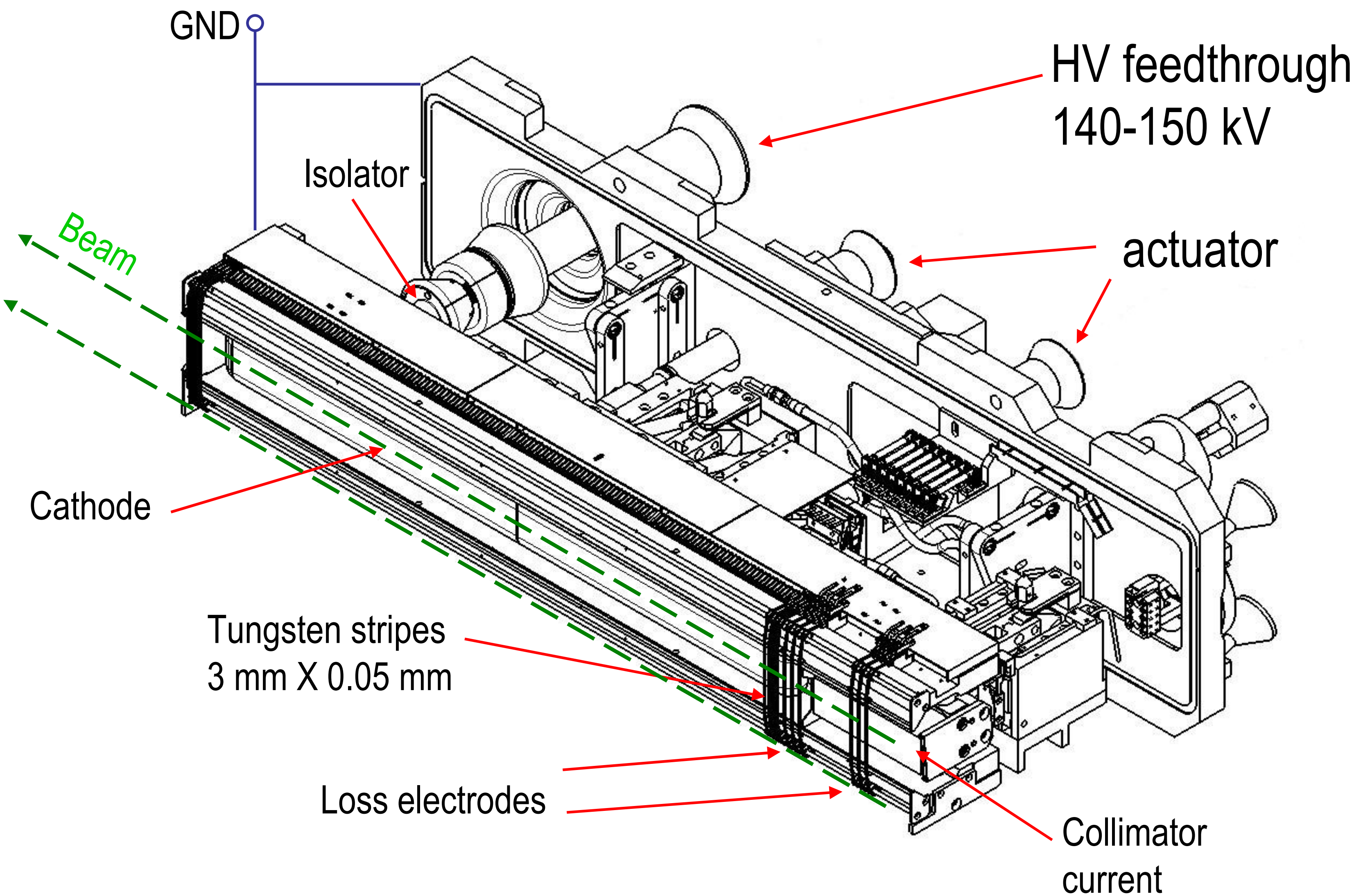
$\rightarrow$ critical, cause for losses

- often used: electrostatic deflectors with thin electrodes
- alternative: charge exchange, stripping foil; accelerate $H^-$ or $H_2^+$ to extract protons

  problem: significant probability for unwanted loss of electron



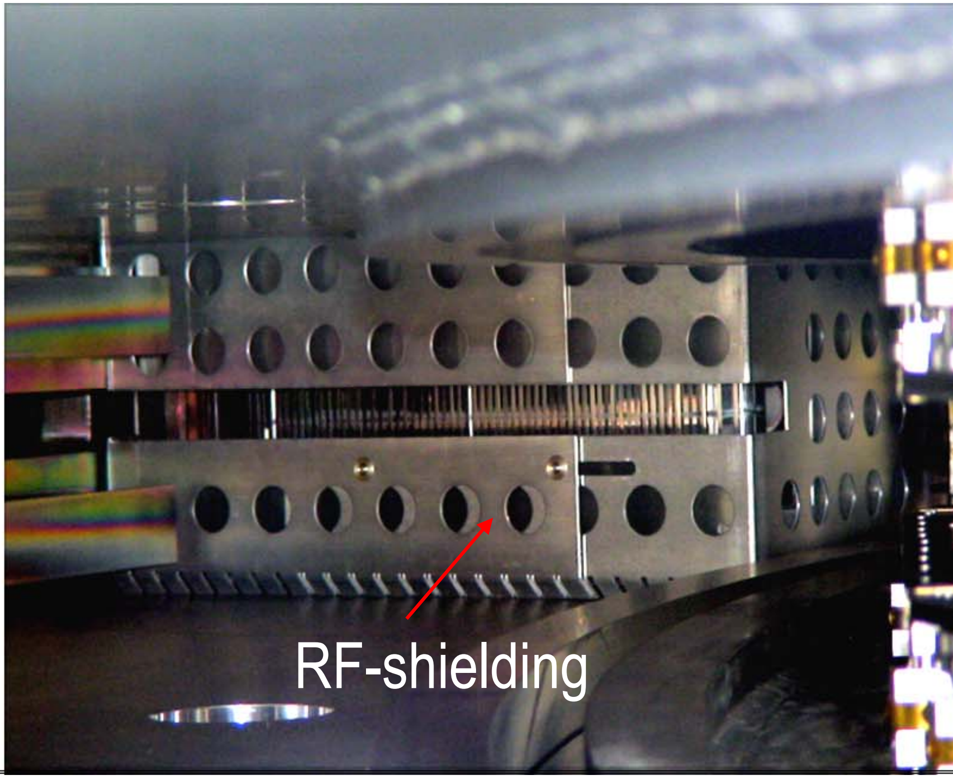
# Injection / Extraction with electrostatic elements



# Electrostatic Elements

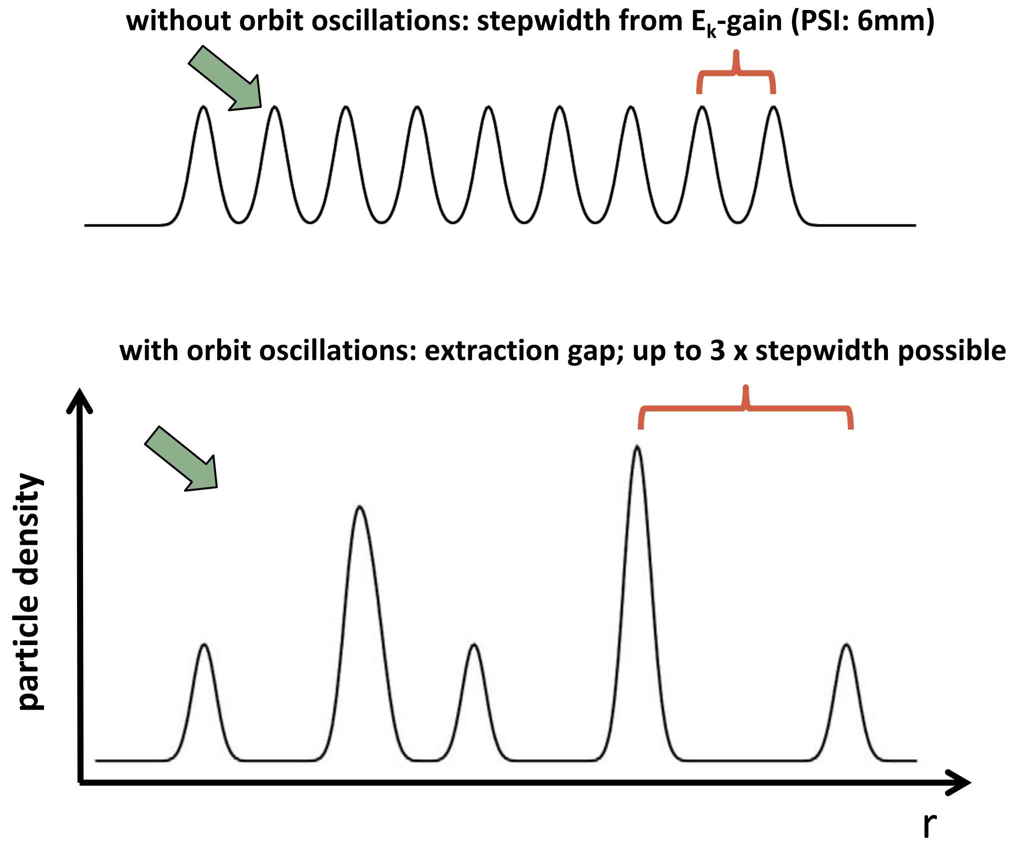
Extraction Channel EEC
145 kV

Injection Channel EIC
130 kV

# Extraction with off-center orbits

betatron oscillations around the “closed orbit” can be used to increase the radial stepwidth by a factor 3 !



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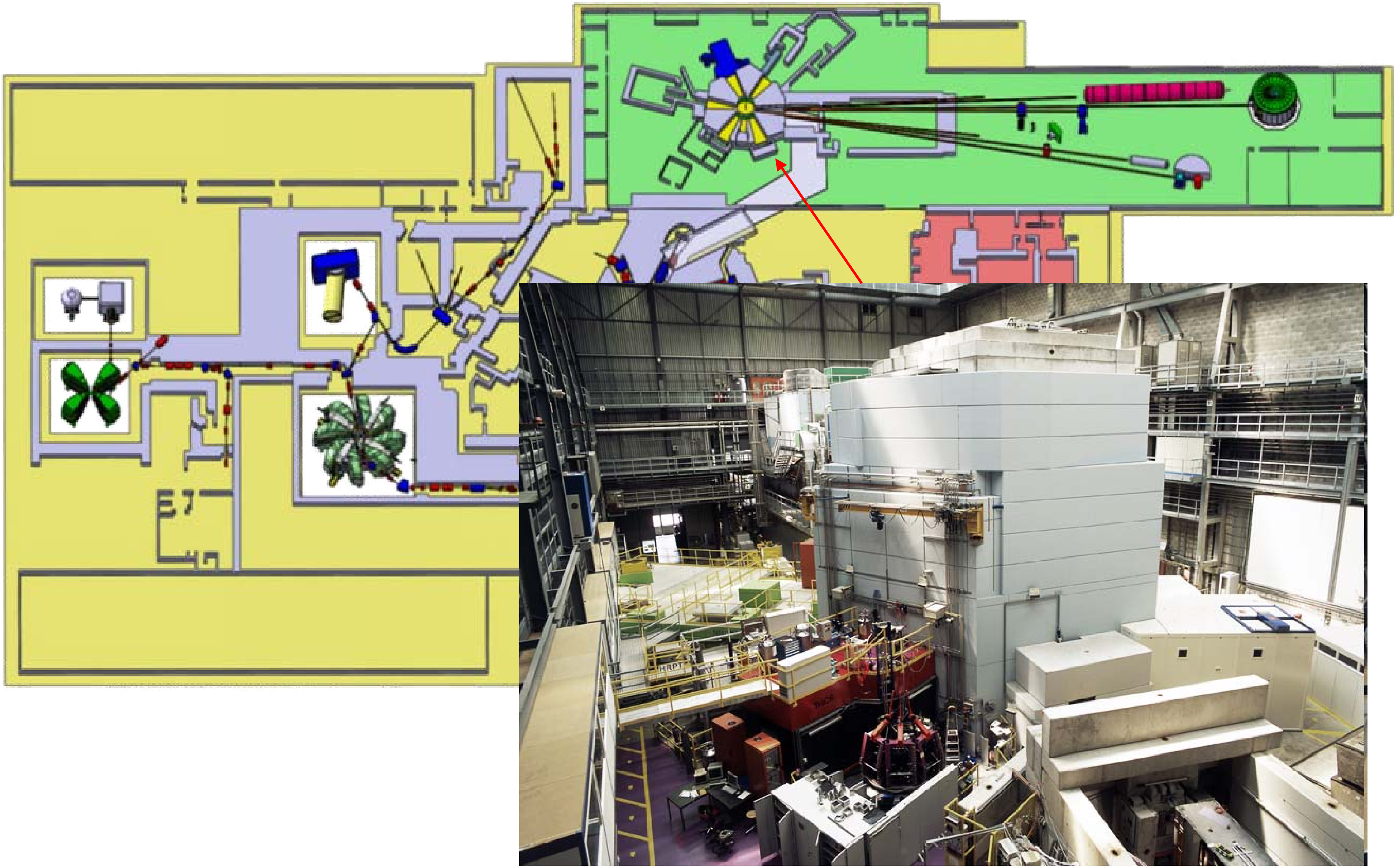
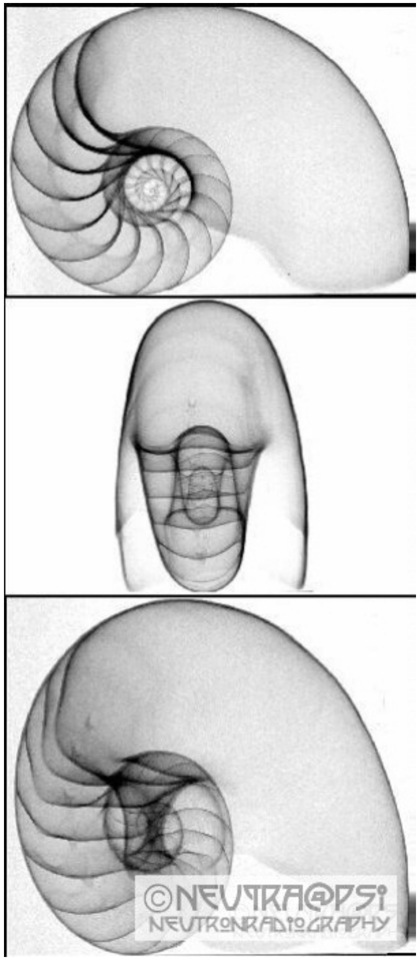
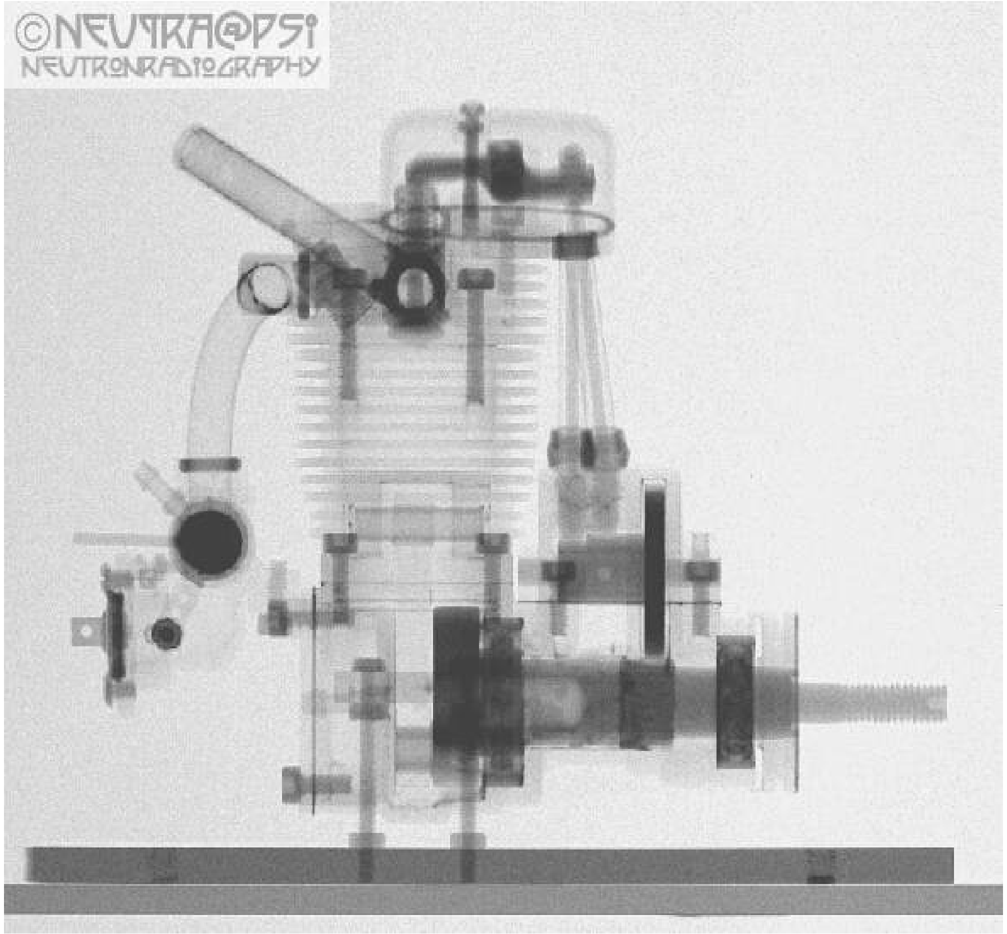
# Neutron Spallation Source SINQ



# Neutron Imaging



# Neutron imaging

# Thank you for your attention