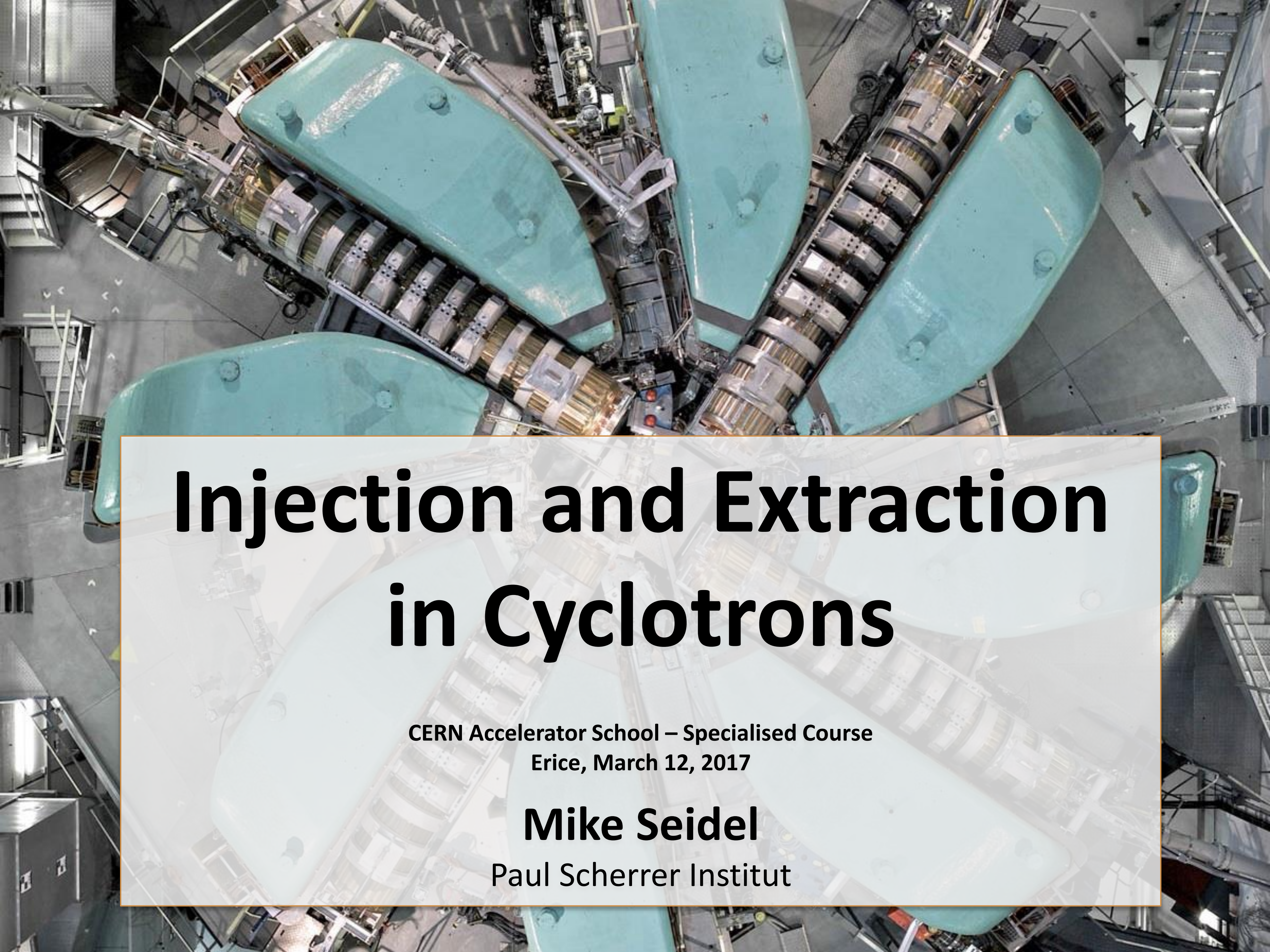


# Injection and Extraction in Cyclotrons

CERN Accelerator School – Specialised Course
Erice, March 12, 2017


**Mike Seidel**
Paul Scherrer Institut

# Outline

- Cyclotron Basics

  **scaling and isochronicity, focusing, turn separation, classical cyclotrons and derived types**

- Injection for Cyclotrons

  **internal source, electrostatic inflectors, horizontal injection, optics matching, bunching**

- Extraction for Cyclotrons

  **electrostatic septum, stepwidth calculation, charge exchange extraction**

# The Classical Cyclotron

two capacitive electrodes „Dees", two gaps per turn

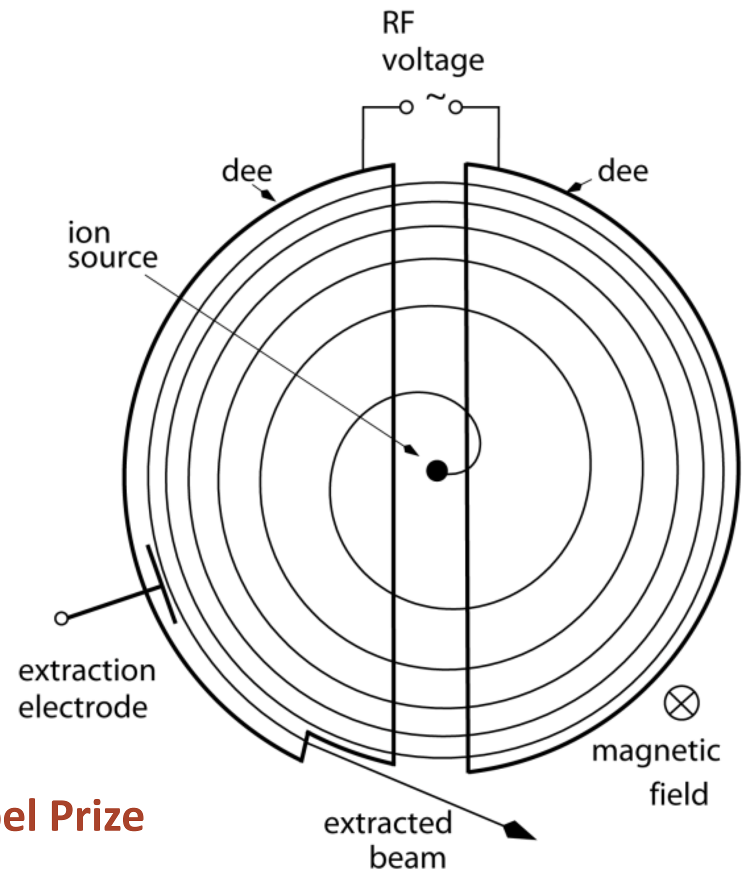
internal ion source

homogenous B field

**constant revolution time**

(for low energy, $\gamma \approx 1$)

$$\omega_c = \frac{eB_z}{\gamma m}$$




**invented 1930, Lawrence, Nobel Prize**

**powerful concept:**

- ➔ **simplicity, compactness**
- ➔ **continuous injection/extraction**
- ➔ **multiple usage of accelerating voltage**

# wide spectrum of cyclotrons …

compact and cost optimized for series production
e.g. medical nuclide production
→ Internal source, extraction or internal target

huge and complex for variable research purposes, e.g. R.I.B. production or high intensity
→ External source, injection

CYCLONE 30 (IBA) : $H^-$ 15 à 30 MeV

RIKEN s.c. Ring Cyclotron- „as big as a house“

# cyclotron basics: isochronicity and scalings

**continuous acceleration → revolution time should stay constant, though $E_k$, $R$ vary**

magnetic rigidity:

$$BR = \frac{1}{e}p = \beta\gamma\frac{m_0 c}{e}$$

orbit radius from isochronicity:

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

deduced scaling of *B*:

$$R \propto \beta; BR \propto \beta\gamma \longrightarrow B(R) \propto \gamma(R)$$

**thus, to keep the isochronous condition, *B* must be raised in proportion to γ(*R*); this contradicts the focusing requirements!**

**field index *k*:**

$$\begin{aligned} k &= \frac{R}{B}\frac{dB}{dR} \\ &= \frac{\beta}{\gamma}\frac{d\gamma}{d\beta} \\ &= \gamma^2 - 1 \end{aligned}$$

# cyclotron basics: stepwidth (nonrelativistic, B const)

relation between **energy and radius**

$$qRB_z = \sqrt{2mE_k}$$
$$\frac{dR}{R} = \frac{1}{2}\frac{dE_k}{E_k}$$

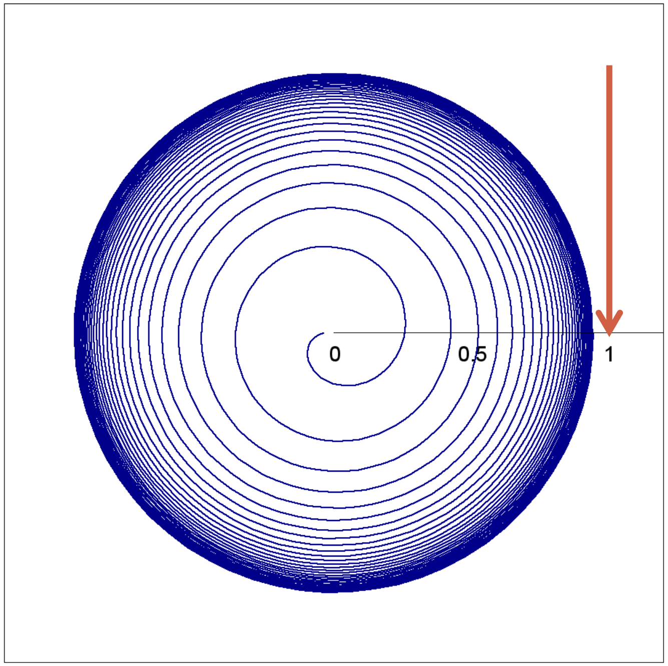
use: $\Delta E_k = \text{const}; B_z = \text{const}; E_k \propto R^2$

thus:

$$\Delta R \propto \frac{R}{E_k} \propto \frac{1}{R}$$

"cyclotron language"

$R_\infty = R/\beta$




radius increment per turn decreases with increasing radius
→ **extraction becomes more and more difficult at higher energies**

# focusing in a cyclotron

centrifugal force $mv^2/r$

Lorentz force $qv\times B$

$$m\ddot{r} = mr\dot{\theta}^2 - qr\dot{\theta}B_z$$

focusing: consider small deviations *x* from beam orbit *R* (*r = R+x*):

$$\begin{aligned} \ddot{x} + \frac{q}{m}vB_z(R+x) - \frac{v^2}{R+x} &= 0, \\ \ddot{x} + \omega_c^2(1+k)x &= 0. \end{aligned}$$

$$\text{using}: \quad \begin{aligned} \omega_c &= qB_z/m = v/R \\ r\dot{\theta} &\approx v \\ k &= \frac{R}{B}\frac{dB}{dR} \end{aligned}$$

**thus in radial plane:**

$$\begin{aligned} \omega_r &= \omega_c\sqrt{1+k} = \omega_c\nu_r \\ \nu_r &= \sqrt{1+k} \\ &\approx \gamma \end{aligned}$$

using isochronicity condition

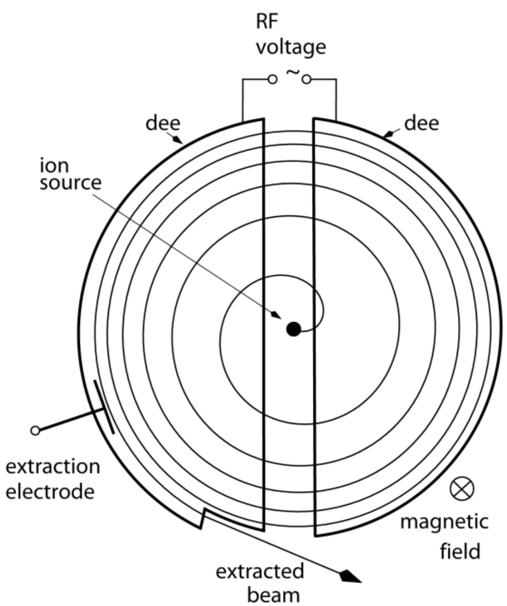
**in vertical plane:**

$$\nu_z = \sqrt{-k}$$

*k*<0 to obtain vertical focus.

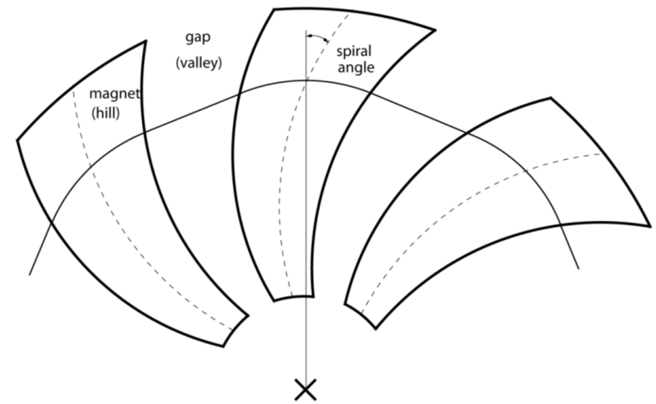
# Classical vs Isochronous Cyclotron

## classical cyclotron




- insufficient vertical focusing
- limited energy reach

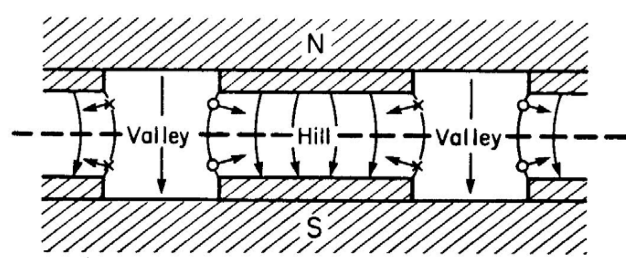
## Sector/AVF cyclotron




flutter    spiral angle

$$\nu_z^2 = -\frac{R}{B_z}\frac{dB_z}{dR} + F^2(1 + 2\tan^2\delta)$$

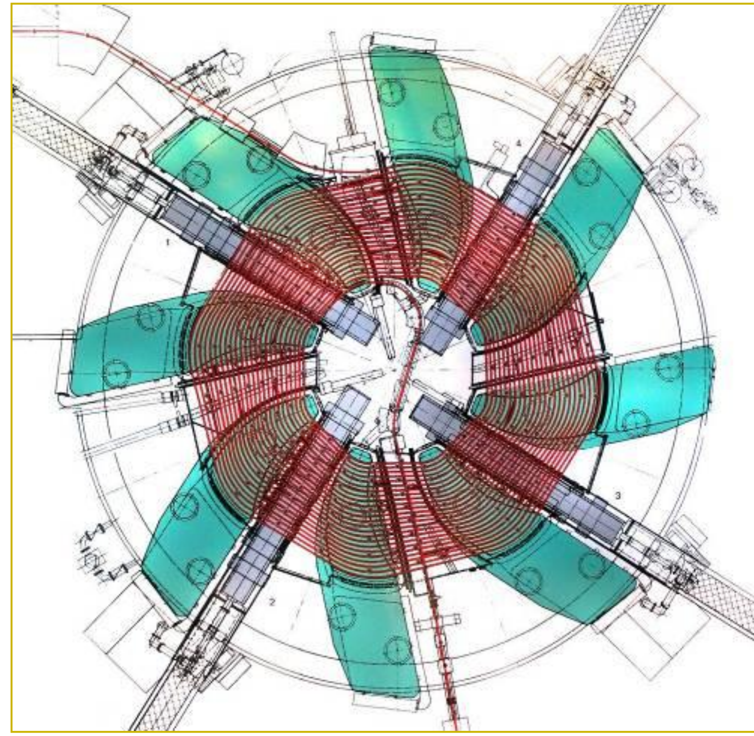
$$F^2 = \frac{\overline{B_z^2} - \overline{B_z}^2}{\overline{B_z}^2}$$




[illustration of focusing at edges]

# Azimuthally Varying Field vs. Separated Sector Cyclotrons


PSI/Varian comet: 250MeV sc. medical cyclotron



PSI Ring cyclotron

- **AVF = single pole with shaping**
- often **spiral poles** used
- **internal source** possible
- **D-type RF electrodes**, rel. low energy gain
- **compact**, cost effective
- depicted Varian cyclotron: 80% extraction efficiency; **not suited for high power**

- **modular layout,** larger cyclotrons possible, sector magnets, box resonators, stronger focusing, injection/extraction in straight sections
- **external injection** required, i.e. pre-accelerator
- **box-resonators** (high voltage gain)
- high **extraction efficiency** possible:
  e.g. PSI: 99.98% = $(1 - 2 \cdot 10^{-4})$

# classification of cyclotron like accelerators

**classical cyclotron**
[B(θ) = const]

↓

**Thomas cyclotron**
[Azimuthally Varying Field,
e.g. $B(\theta) \propto b+\cos(3\theta)$, one pol]

complexity

AVF concept – harmonic pole shaping,
electron model, Richardson et al (1950),
courtesy of Lawrence Berkeley National Laboratory

| separated sector cyclotron [separated magnets, resonators] | synchro-cyclotron [varying RF frequency] | Fixed Focus Alternating Gradient Accelerator FFAG [varying RF, strong focusing] |
|---|---|---|
| high intensity | high energy | compact machine |

# next: injection for cyclotrons

- internal source, axial injection, horizontal injection
- electrostatic inflector, electrostatic deflectors
- transverse matching, bunching
- space charge

# Injection – Overview

**Injection Techniques**

- **internal source**
- axial injection
  - mirrow inflector
  - **spiral inflector**
  - hyperbolic inflector
- radial injection
  - **electrostatic septum**
  - stripping injection

**Aspects to be considered**

- overall central region design
- radial centering
- matching of beam optics
- vertical centering
- bunching / long. capture
- minimize overall losses for high intensity application

# Internal Ion Source

## Example: Cold Cathode, Penning Ionisation Gauge (PIG)

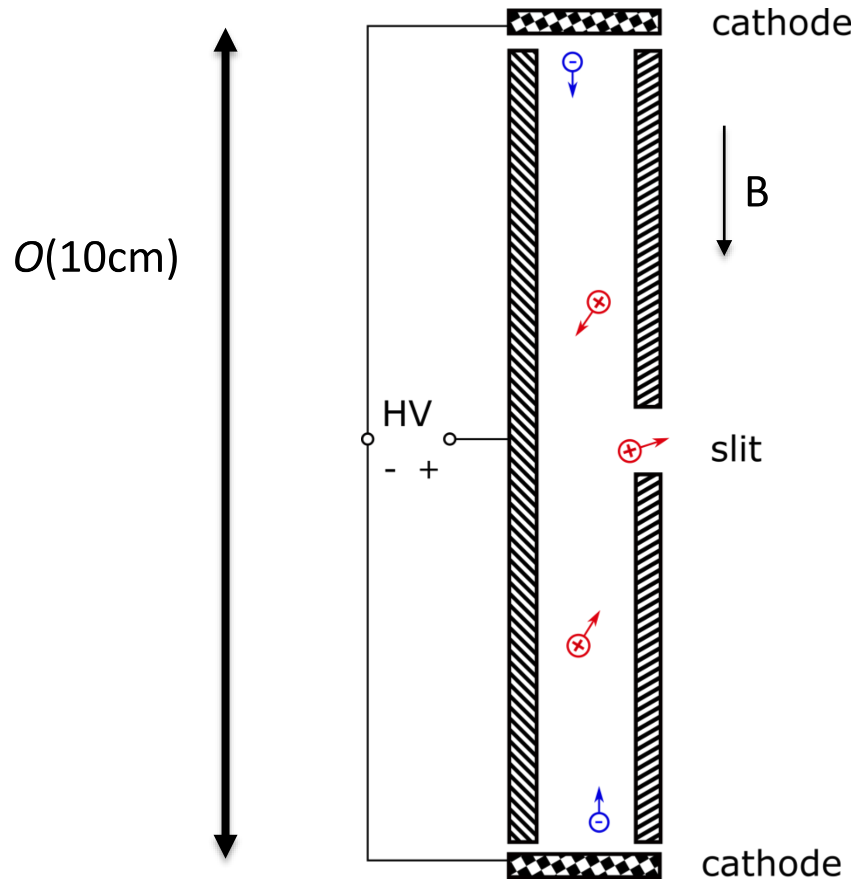
cylindrical „chimney“ with slit as extraction aperture for protons

**advantage:**

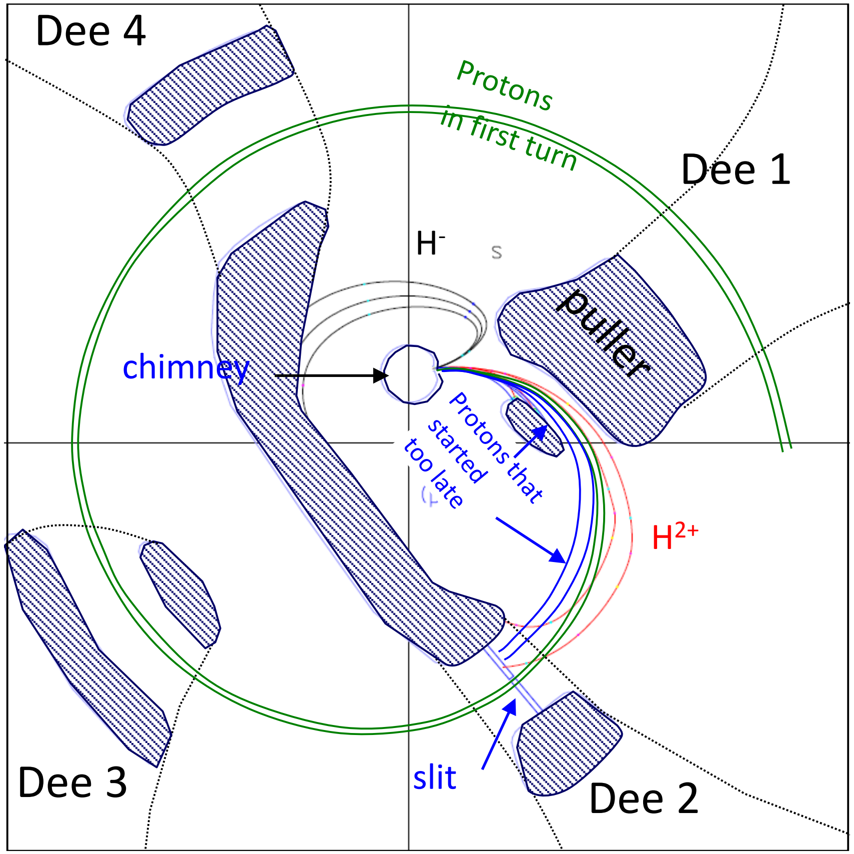
- simple concept
- no heating required

**critical:**

- reproducibility of captured current (geometry related sensitivity)
- current stability on short (ms) timescale



# internal ion source
## → example COMET (Accel/Varian)

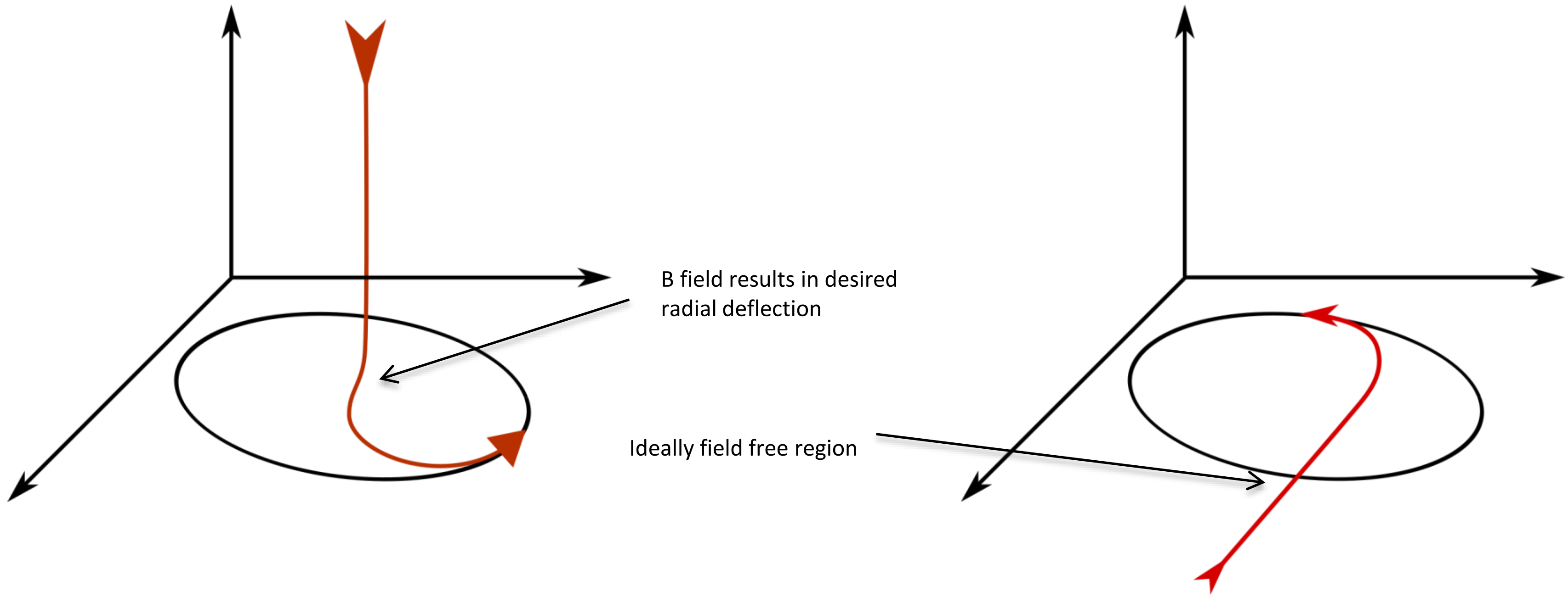



- Hydrogen is injected and ionized through chimney
- first acceleration by puller, connected to one Dee (80kV)

**chimney = ion source**

**deflector electrode for intensity regulation**

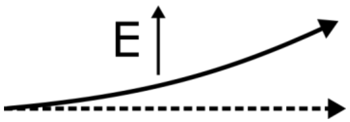
# external source: axial vs. horizontal injection




axial: suited for compact cyclotron with field covering entire plane

horizontal: suited for sector cyclotron with gaps between magnets

# Beam Deflection by Electric Field




momentum change: $\Delta p_\perp = \int F_\perp dt = \int \frac{F_\perp}{\beta c} ds, F = qE$

resulting angle: $\theta = \frac{\Delta p_\perp}{p} = \frac{qlE}{\gamma \beta^2 E_0}$

bending radius: $\rho = \frac{l}{\theta}$

electric rigidity: $E\rho = \frac{\gamma^2 - 1}{\gamma} \frac{E_0}{q} = \frac{\gamma + 1}{\gamma} \frac{E_k}{q}$

low energy at source: $E\rho \approx 2U_{\mathrm{acc}}$

| | |
|---|---|
| $E_0$ | rest energy |
| E | field strength deflector |
| $E_k$ | kinetic energy |
| ρ | bending radius |
| q | charge |
| l | length |
| $U_{acc}$ | acc.voltage (source) |

comparison electric and magnetic force on protons

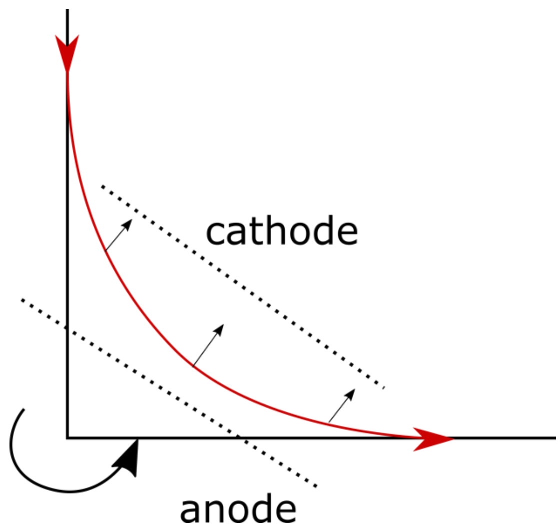
$$\vec{F_E} = e \cdot \vec{E}, \quad \vec{F_B} = e \cdot \vec{v} \times \vec{B}$$

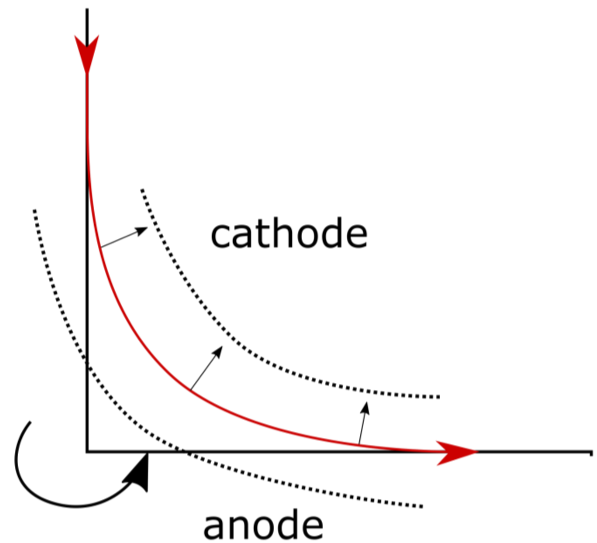
table: bending radius, varying $E_k$

**Bending radius in B and E:**

| $E_k$ | B = 1T | E = 10MV/m |
|---|---|---|
| 60 keV | 35 mm | 12 mm |
| 1 MeV | 140 mm | 200 mm |
| 1 GeV | 5.6 m | 150 m |

# electrostatic inflectors




mirror inflector: particle energy is variable, simple design

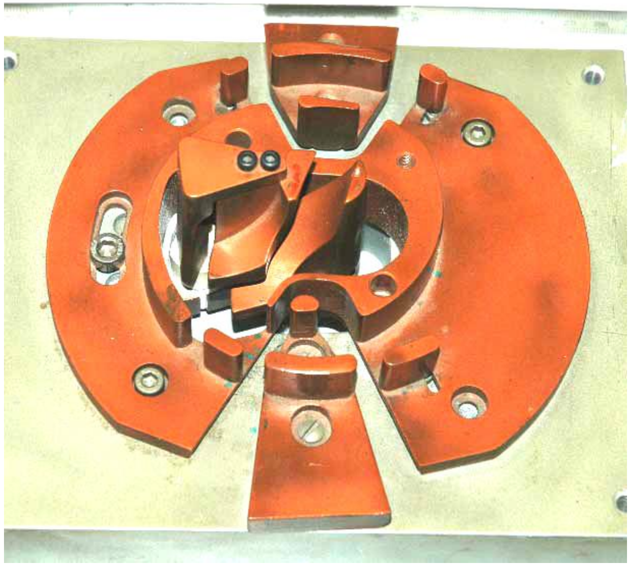
spiral inflector: force always perpendicular to velocity vector, no energy change

velocity vector rotates around vertical axis due to action of magnetic field;
other solutions exist, e.g. hyperbolic inflector or even magnetostatic inflector

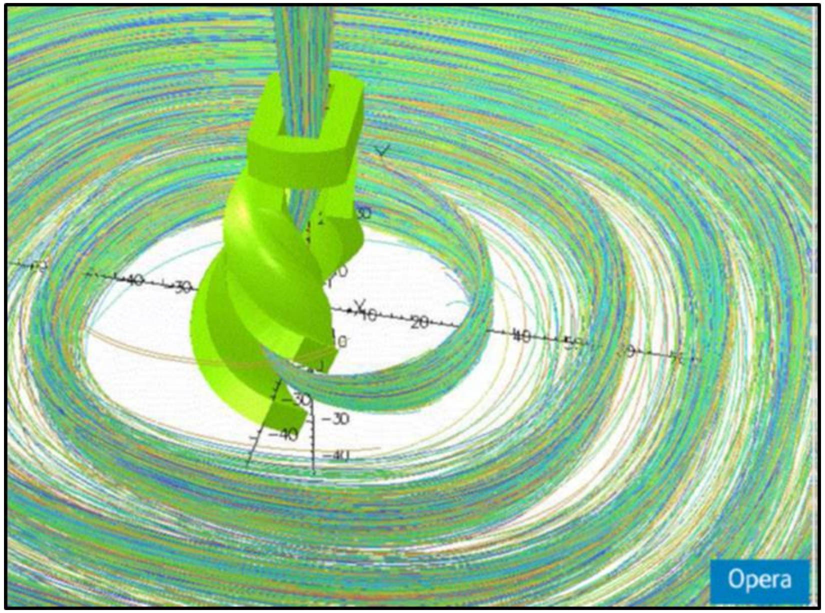
# injection schemes – spiral inflector

- an electrostatic component, basically a capacitor
- E-field arranged perpendicular to orbit, particles move on equipotential surfaces

simulation of orbits injected through a spiral inflector



[inflector IBA Cyclone 30 cyclotron]

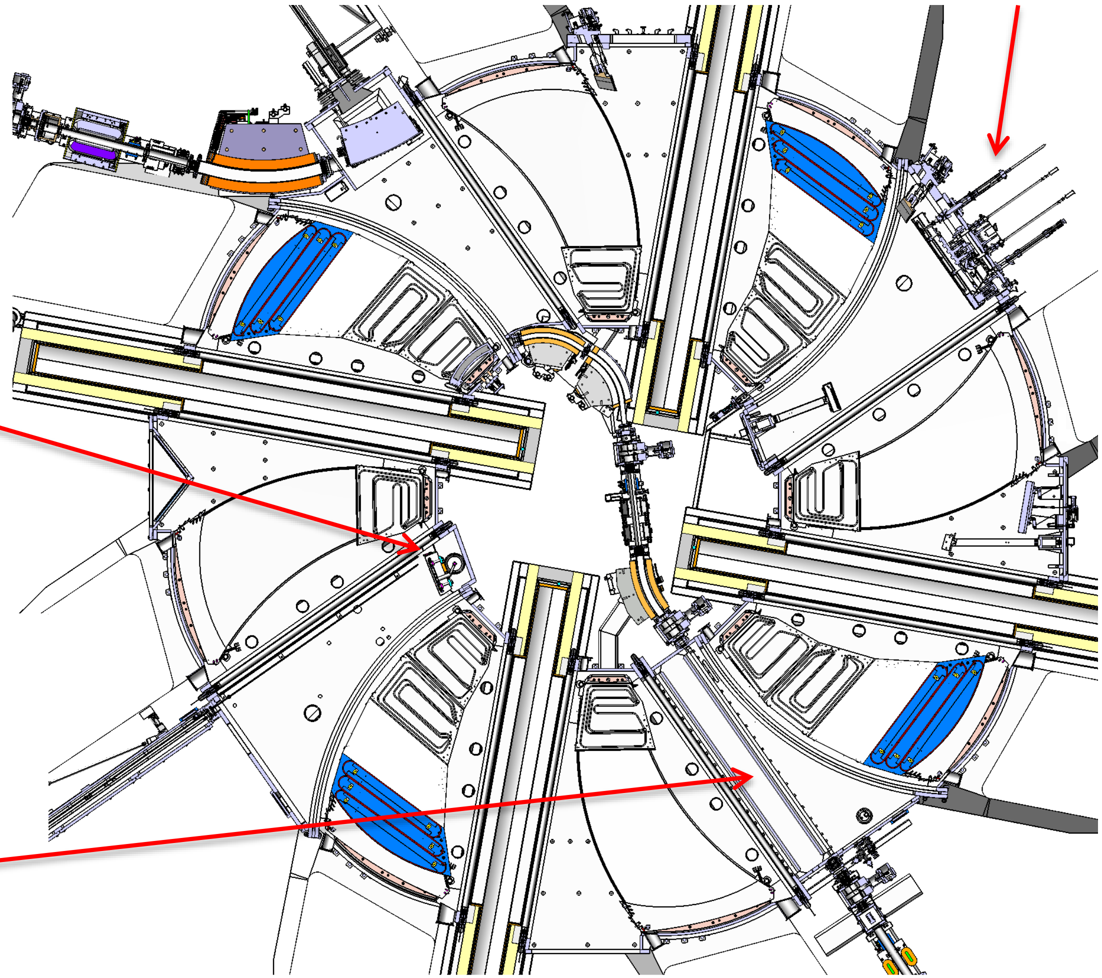



[courtesy: W.Kleeven (IBA)]

# Horizontal Injection – Example PSI Ring Cyclotron

Injection element


extraction



**Injection path (72MeV)** in region of low field, passing along 3rd-harmonic (150MHz) resonator

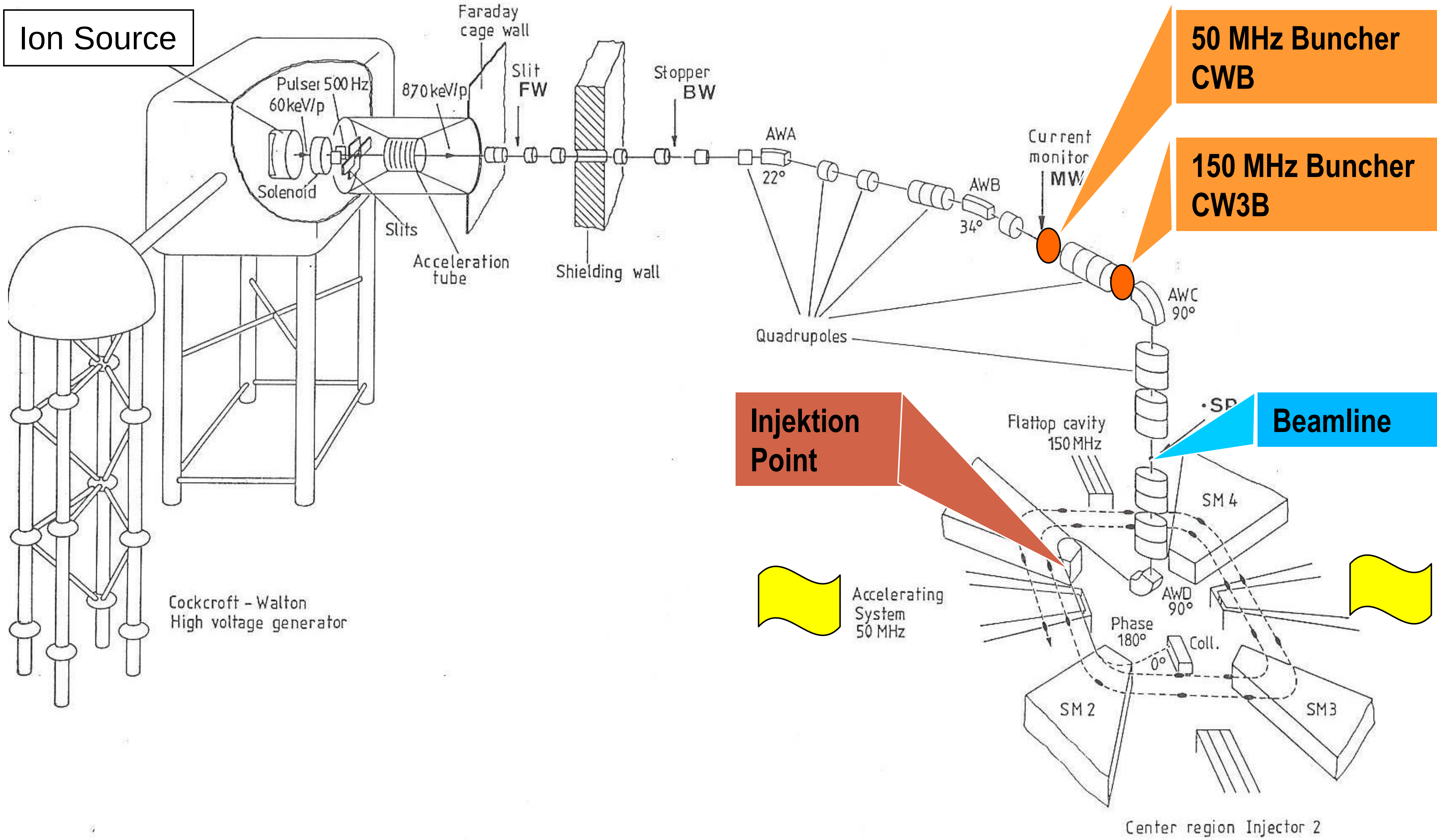
# Bunching for Cyclotrons

Ion sources deliver DC beam; for acceleration in an RF field the beam must be bunched; unbunched beam should be removed at low energy (≤5MeV) to avoid uncontrolled losses and activation

schemes applied in practice:

| | bunching in cyclotron | external buncher cavities | comment |
|---|---|---|---|
| internal source | **x** | | lowest cost and complication |
| external source | **x** | **x** | higher intensity, variety of ions |
| DC pre-accelerator Cockcroft-Walton | | **x** | low $\Delta$E, costly |
| Radio Freq. Quadrupole (RFQ) | | **x** | compact, costly |

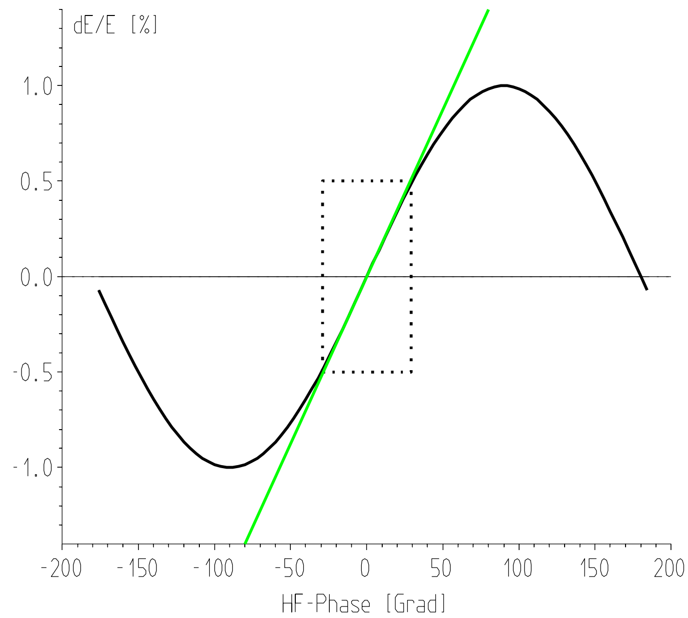
# Sketch of 870 keV Injektion Beam Line



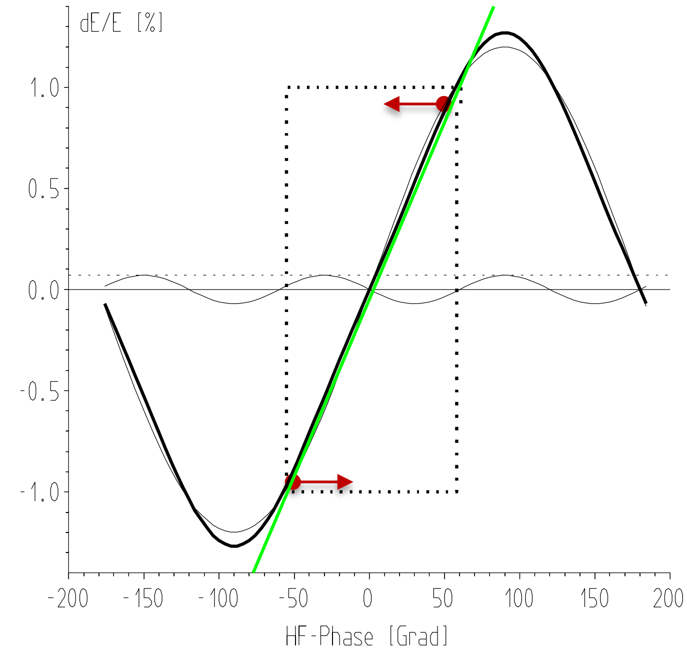
# 50 MHz and 50/150 MHz Harmonic Oscillation

→ by utilizing a harmonic buncher (3ω), a larger fraction of a DC beam can be captured in the cyclotron

only 50MHz buncher



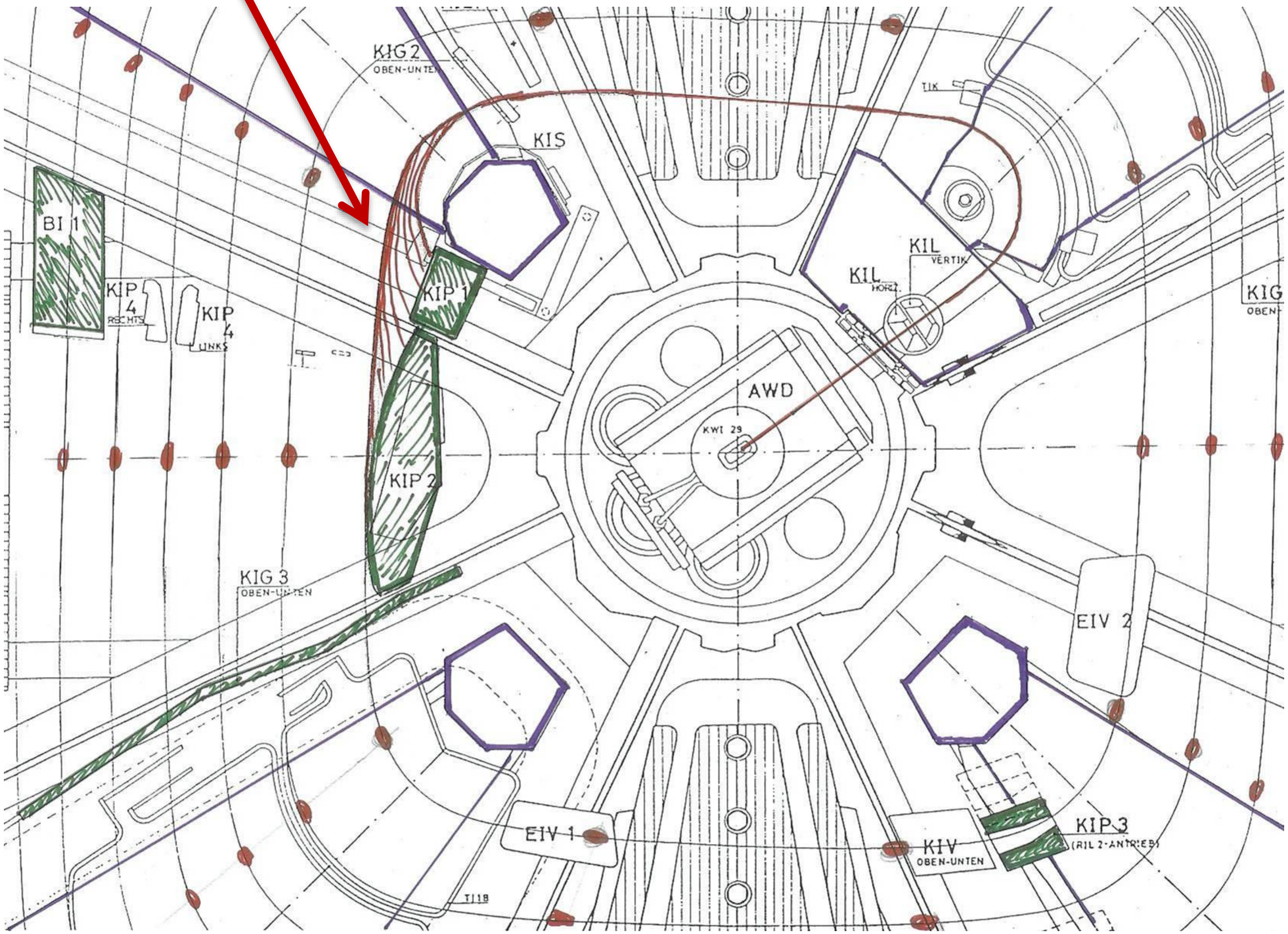

additional 150MHz buncher




[M.Humbel, PSI]

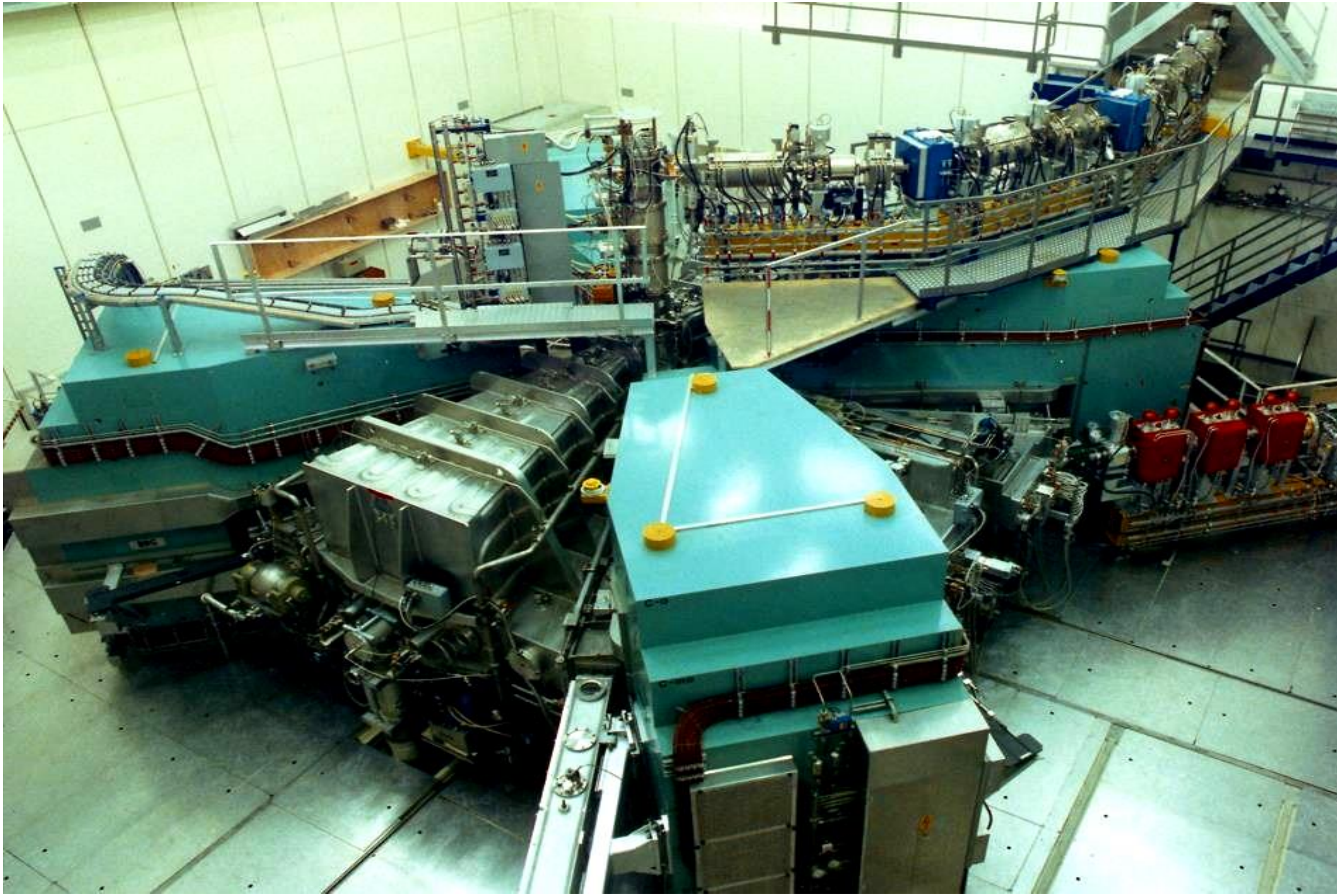
# Center Region of PSI Injector 2

collimation of low energy protons and intensity control




**0.86 → 72MeV**
**max 2.5mA, 180kW**

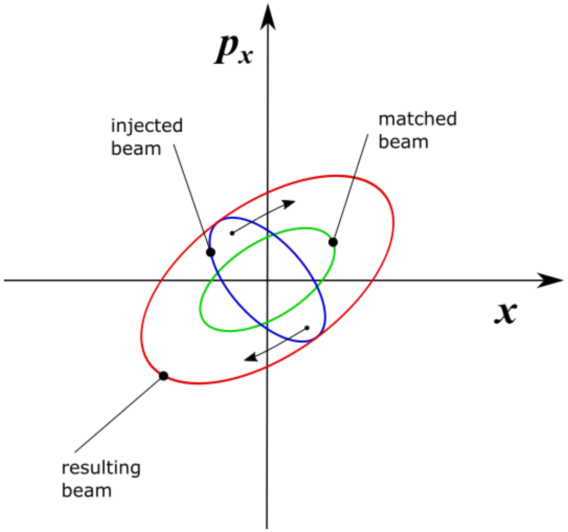
# PSI Injector 2 and Injection Beamline



To Beamdump BX2

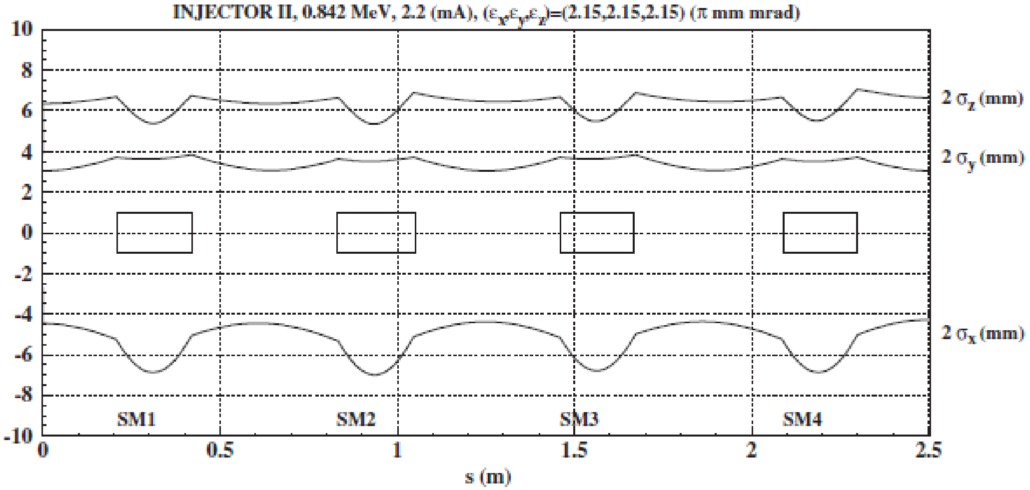
# Transverse Matching

- Similar to a synchrotron the envelope function β varies around the circumference; the beam at injection must be matched to avoid blow up and sub-optimal beam distributions




nonetheless of the short «storage» time of a beam in a cyclotron, the distribution starts to filament, if not properly matched

example: beam sizes around the circumference for Inj II cyclotron, PSI [Ch.Baumgarten, [7]]



# transverse space charge

especially at low energy space charge effects are critical for the injection of high intensity beams

vertical force from space charge: $F_y = \frac{n_v e^2}{\epsilon_0 \gamma^2} \cdot y, \; n_v = \frac{N}{(2\pi)^{\frac{3}{2}} \sigma_y D_f R \Delta R}$
[constant charge density, $D_f = I_{avg}/I_{peak}$]

thus, eqn. of motion: $\ddot{y} + \left( \omega_c^2 \nu_{y0}^2 - \frac{n_v e^2}{\epsilon_0 m_0 \gamma^3} \right) y = 0$

$\rightarrow$ tune shift results in **intensity limit** **(see [6])**!

tune shift from forces: $\Delta\nu_y \approx -n_v \frac{2\pi r_p R^2}{\beta^2 \gamma^3 \nu_{y0}}$

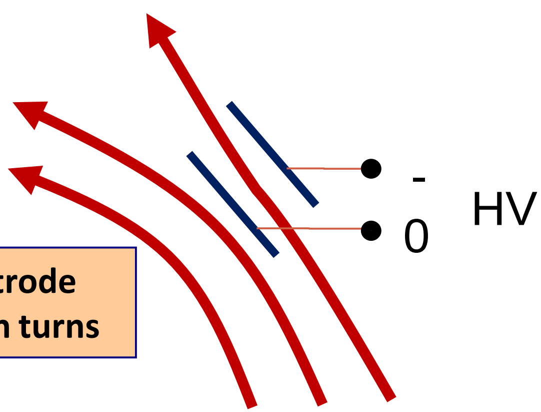
# next: extraction for cyclotrons

- **review of schemes: internal targets, electrostatic deflectors, stripping**
- **maximizing extraction efficiency: stepwidth, coherent oscillations, avoid tails**

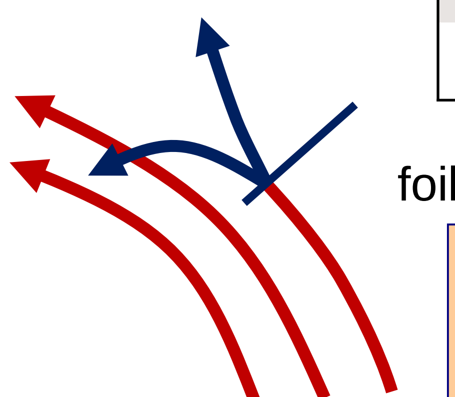
# electrostatic septum and charge exchange extraction

- simplest solution: use beam without extraction → **internal target;** use some mechanism to exchange target
- **electrostatic deflectors** with thin electrodes, deflecting element should affect just one turn, not neighboured turn → critical, cause of losses
- alternative: **charge exchange by stripping foil**; accelerate $H^-$ or $H_2^+$ to extract protons (problem: significant probability for unwanted loss of electron; Lorentz dissociation: B-field low, scattering: vacuum $10^{-8}$mbar)

| **binding** | **energies** |
|---|---|
| $H^-$ | $H_2^+$ |
| 0.75eV | 16eV |




**extraction electrode placed between turns**




**extraction by charge exchange in foil**
**eg.:** $H^- \rightarrow H^+$
$H_2^+ \rightarrow 2H^+$

# derivation of relativistic turn separation in a cyclotron

starting point: bending strength
→ compute total log.differential
→ use field index $k = R/B \cdot dB/dR$

$$BR = \sqrt{\gamma^2 - 1}\,\frac{m_0 c}{e}$$

$$\frac{dB}{B} + \frac{dR}{R} = \frac{\gamma\, d\gamma}{\gamma^2 - 1}$$

$$\frac{dR}{d\gamma} = \frac{\gamma R}{\gamma^2 - 1}\,\frac{1}{1+k}$$

slide 5

radius change per turn

$$\frac{dR}{dn_t} = \frac{dR}{d\gamma}\,\frac{d\gamma}{dn_t}$$

[$U_t$ = energy gain per turn]

$$= \frac{U_t}{m_0 c^2}\,\frac{\gamma R}{(\gamma^2 - 1)(1+k)}$$

isochronicity not conserved (last turns)

$$= \frac{U_t}{m_0 c^2}\,\frac{R}{(\gamma^2 - 1)\gamma}$$

isochronicity conserved (general scaling)

# discussion: scaling of turn separation

for clean extraction a large stepwidth (turn separation) is of utmost importance; in the PSI Ring most efforts were directed towards maximizing the turn separation

**general scaling at extraction:**

$$\Delta R(R_{\rm extr}) \;=\; \frac{U_t}{m_0 c^2}\frac{R_{\rm extr}}{(\gamma^2-1)\gamma}$$

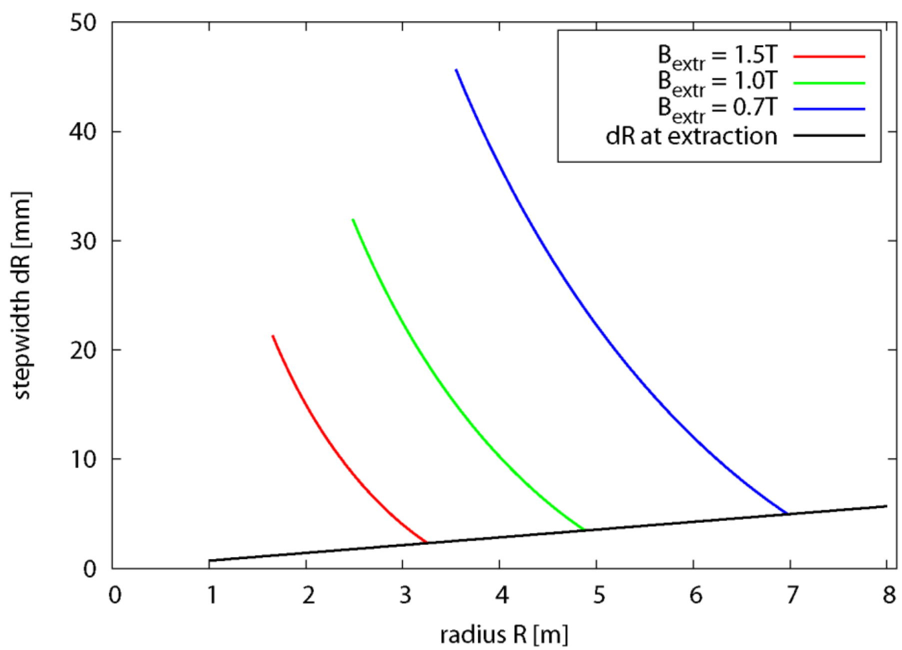
desirable:

- limited energy (< 1GeV)
- large radius $R_{extr}$
- high energy gain $U_t$

**scaling during acceleration:**

$$\frac{dR}{dn_t} \;\approx\; \frac{U_t}{m_0 c^2}\frac{R}{\beta^2} \rightarrow \Delta R(R) \propto \frac{1}{R}$$

illustration:
**stepwidth vs. radius** in cyclotrons of different sizes; 100MeV inj → 800MeV extr



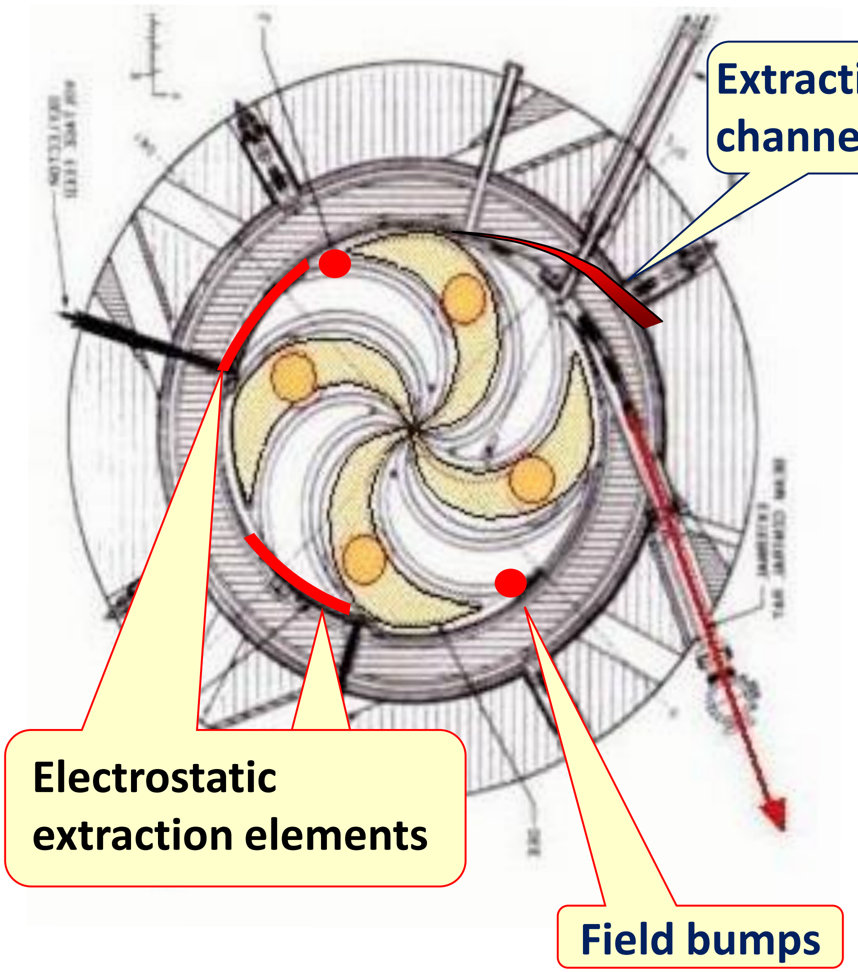
# methods to enhance turn separation

several techniques were invented to „artificially“ increase turn separation beyond the magnitude achieved by simple acceleration

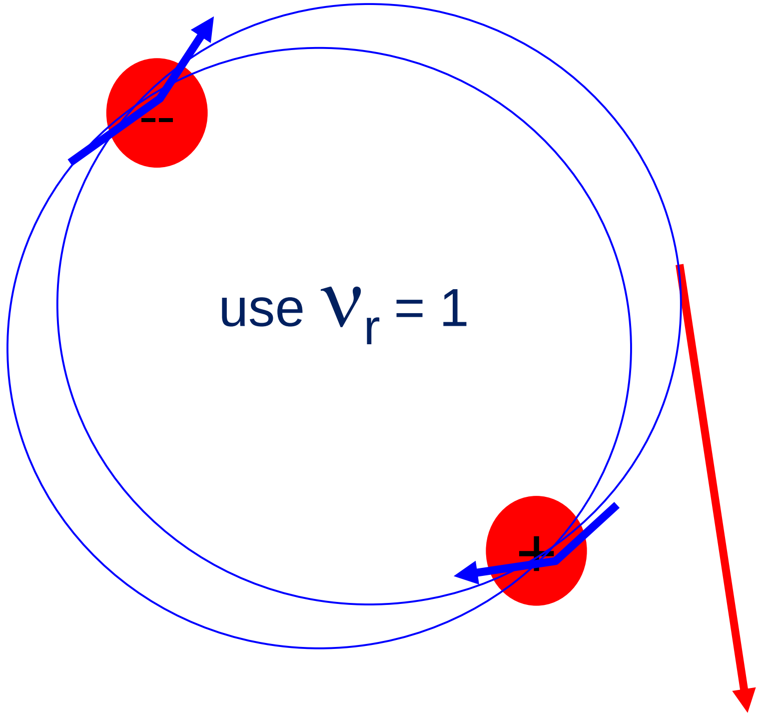
| | |
|---|---|
| **„brute force“** | resonant orbit distortion is excited by harmonic coils beyond a certain radius |
| **precessional extraction** | resonant excitation at $\nu_r$=1 plus steep $\nu_r$ slope in fringe field |
| **regenerative extraction** | using coherent excitation at half integer resonance by gradient bump |

taken from Kleeven [1]

# Resonant Extraction (Varian/Accel cyclotron)



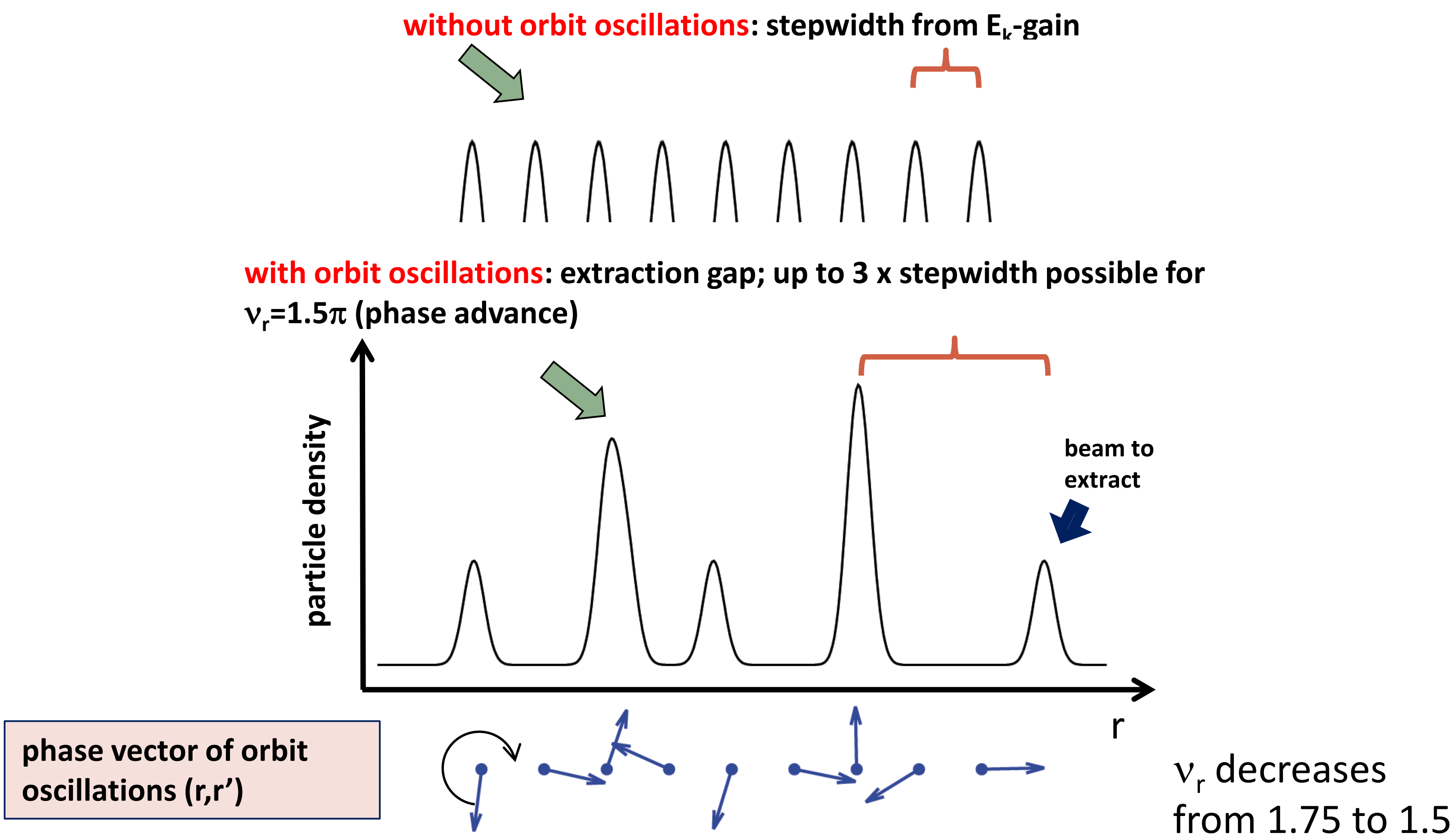

extraction efficiency:
up to 80%




[M.Schippers, PSI]

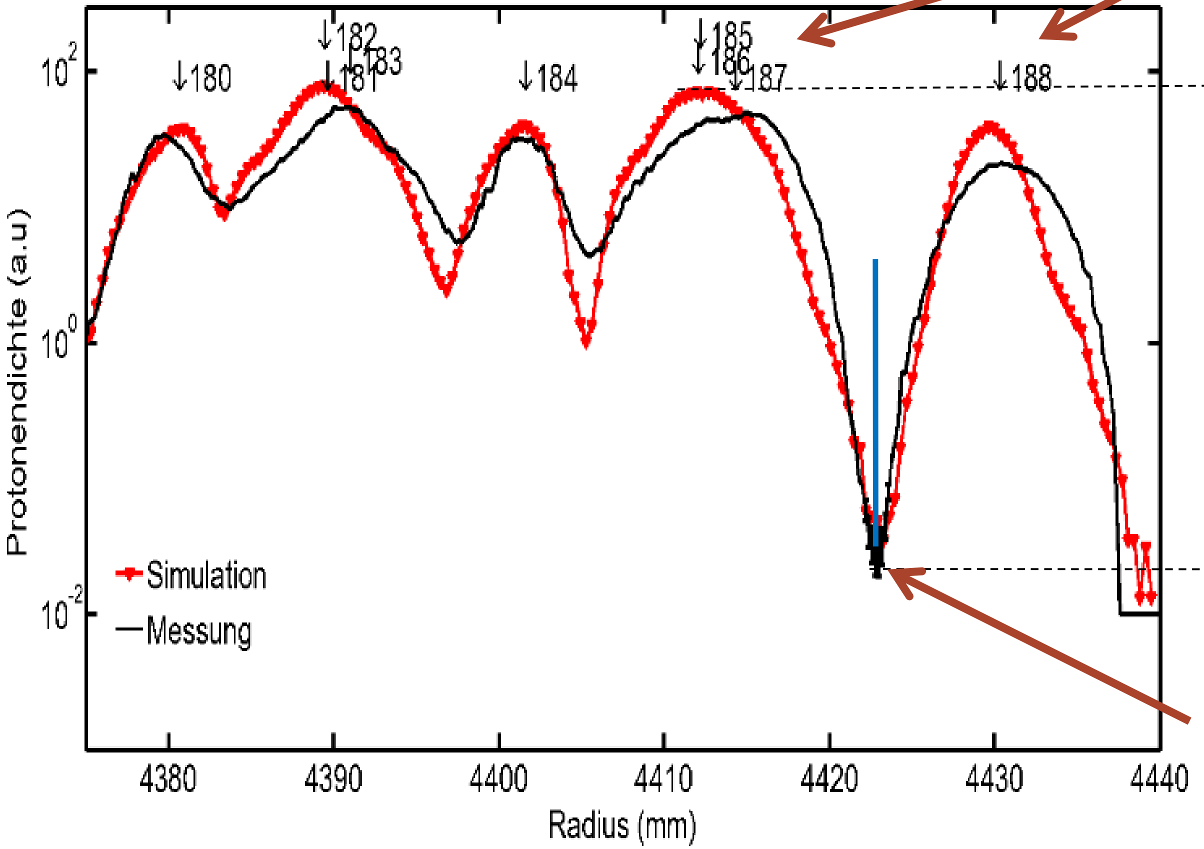
# extraction with coherent oscillations (PSI)

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



# extraction profile measured at PSI Ring Cyclotron

**red: tracking simulation [OPAL]**
**black: measurement**




turn numbers

from simulation

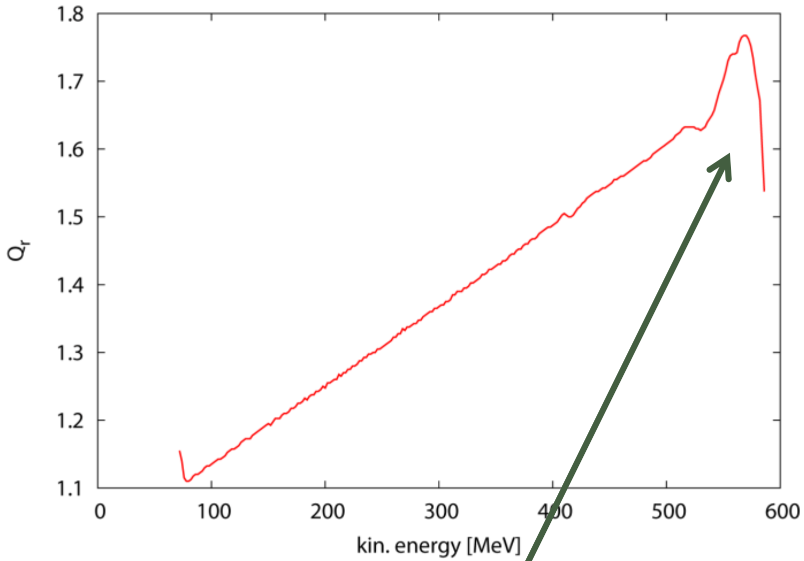
**dynamic range:**
factor 2.000 in
particle density

position of extraction septum

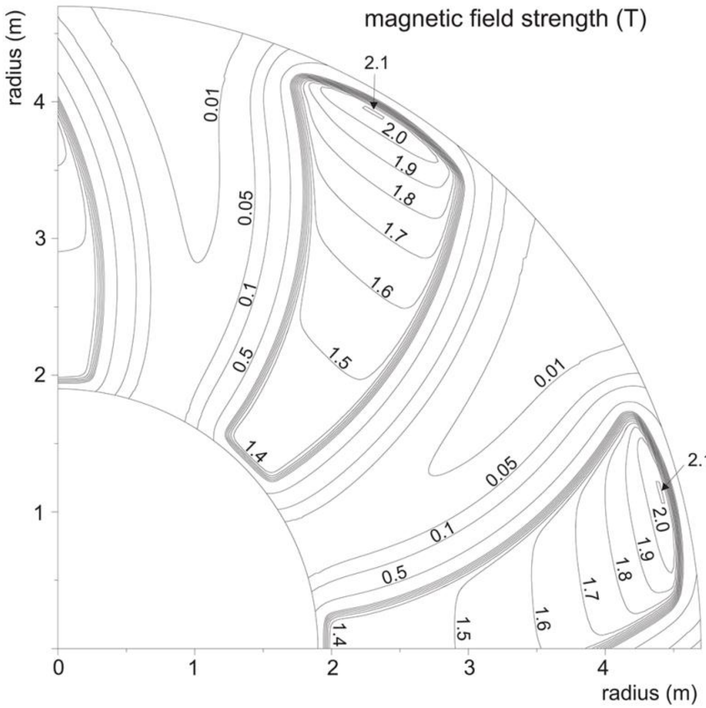
d=50µm

[Y.Bi et al]

# vertical tune in Ring cyclotron supports extraction




**radial tune vs. energy (PSI Ring)**
typically $\nu_r \approx \gamma$ during acceleration;
but decrease in outer fringe field

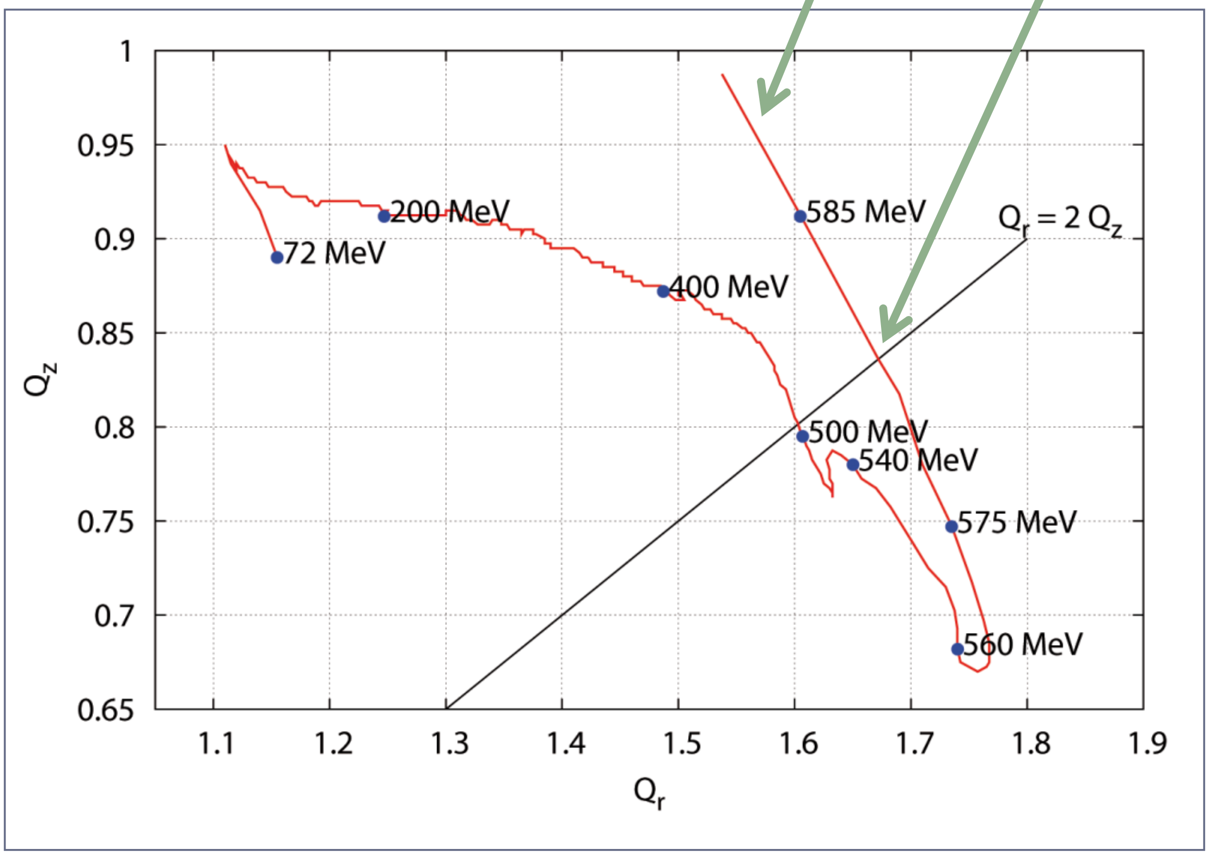



field map showing increase and steep decline of field with radius

# PSI Ring Cyclotron – tune diagram

coupling resonance – pass quickly!

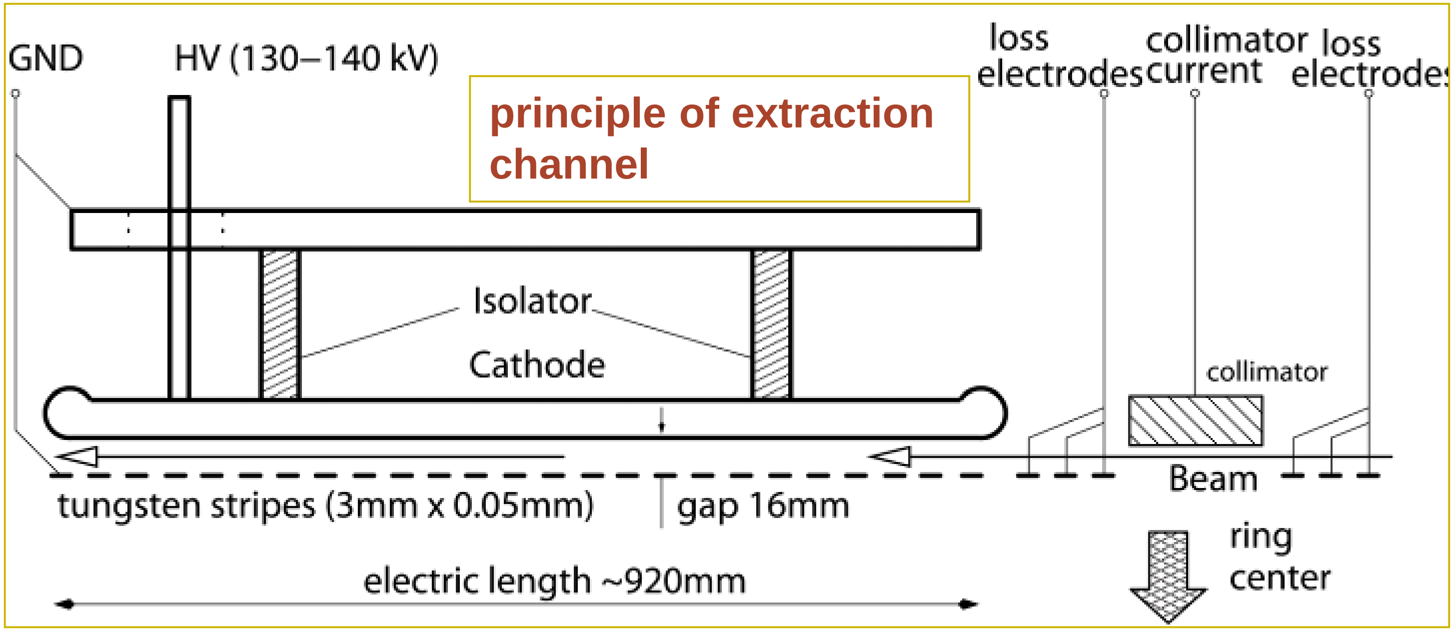
$Q_r$ decreases towards extraction
– enhance turn separation




**comments:**

- running on the coupling resonance would transfer the large radial betatron amplitude into vertical oscillations, which must be avoided
- special care has to be taken with fine-tuning the bending field in the extraction region

# injection/extraction with electrostatic elements




**parameters extraction chan.:**

$E_k$= 590MeV

E = 8.8 MV/m

θ = 8.2 mrad

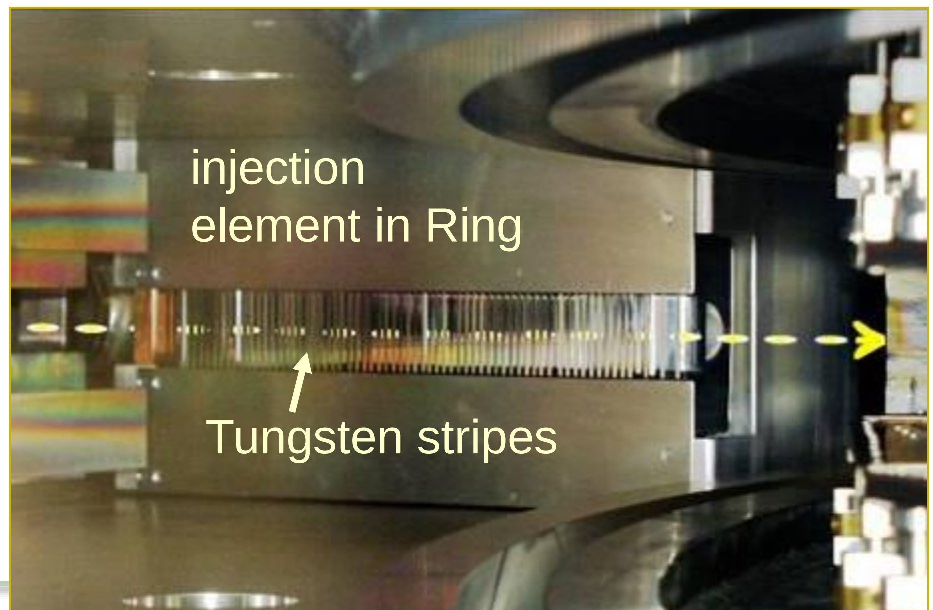
ρ = 115 m

U = 144 kV

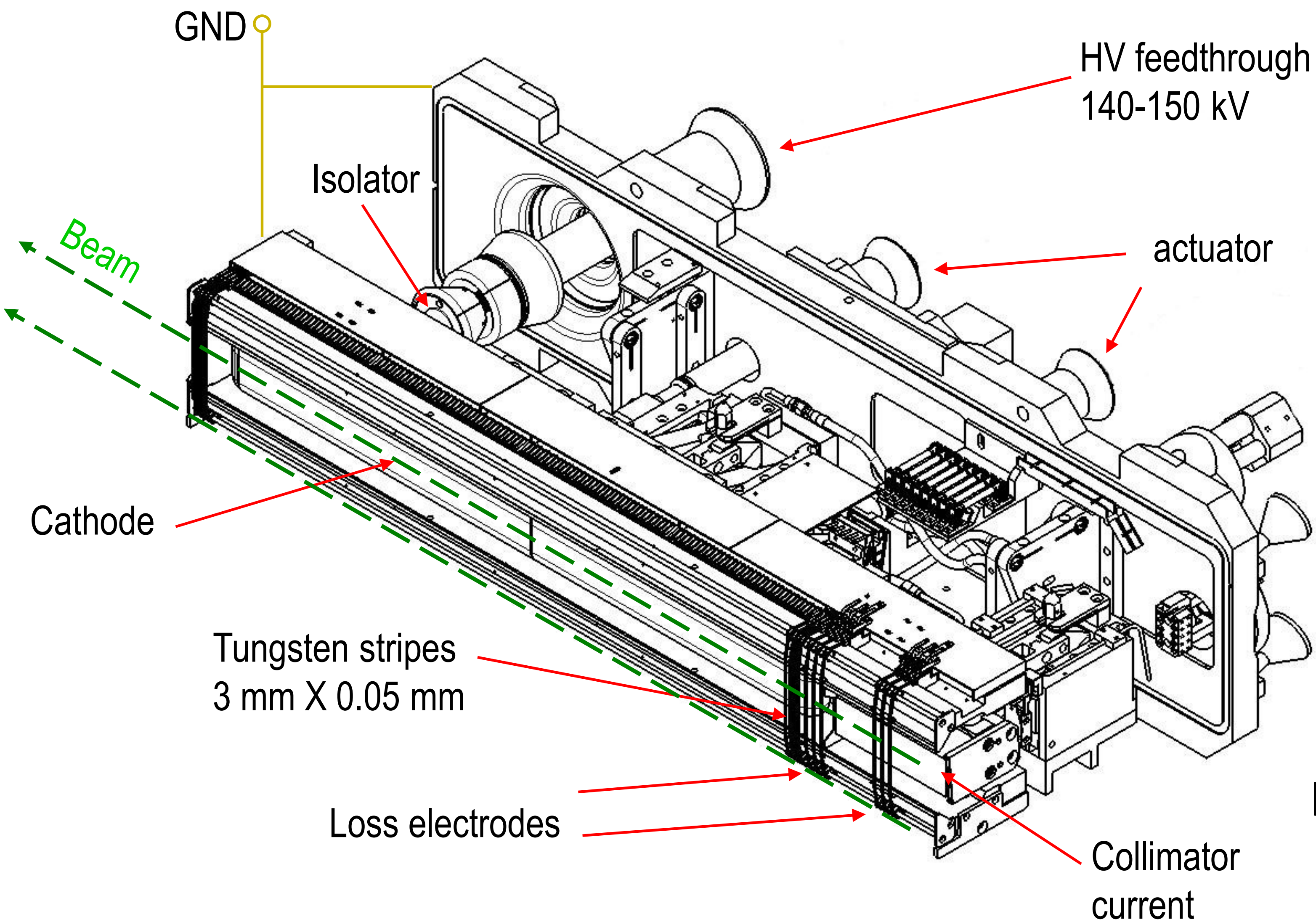
**major loss mechanism is scattering in 50µm electrode!**

**electrostatic rigidity:**

$$E\rho \quad = \quad \frac{\gamma+1}{\gamma}\frac{E_k}{q}$$



# Electrostatic Elements for High Energy/High Intensity



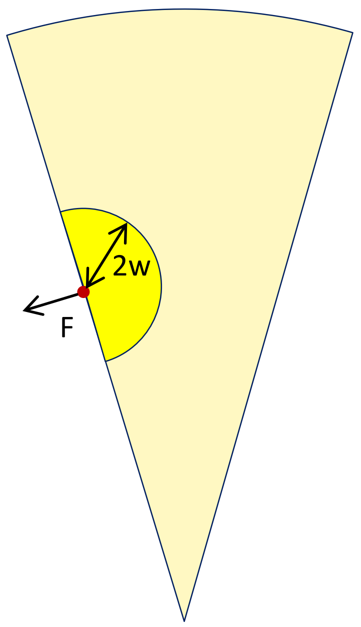

[D.Götz, PSI]

# longitudinal space charge (tails at extraction)

**sector model**:

$\rightarrow$ accumulated energy spread transforms into transverse tails

- consider rotating uniform sectors of charge (overlapping turns)
- test particle "sees" only fraction of sector due to shielding of vacuum chamber with gap height 2*w*




two factors are proportional to the number of turns:

1) the charge density in the sector
2) the time span the force acts

$$\Delta U_{sc} \quad \approx \quad 2.800\Omega \cdot eI_p \cdot \frac{n_{\mathrm{max}}^2}{\beta_{\mathrm{max}}}$$

**derivation see [4]: Joho 1981**

in addition:

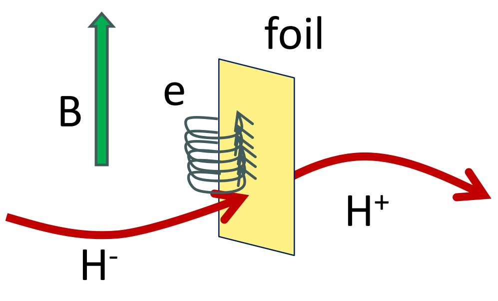
3) the inverse of turn separation at extraction: $\frac{1}{\Delta R_{\mathrm{extr}}} \quad \propto \quad n_{\mathrm{max}}$

$\rightarrow$ the attainable current at constant losses scales as $n_{max}^{-3}$

# extraction foil

- thin foil, for example carbon, removes the electron(s) with high probability
- new charge state of ion brings it on a new trajectory → separation from circulating beam
- lifetime of foil is critical due to heating, fatigue effects, radiation damage
- conversion efficiencies, e.g. generation of neutrals, must be considered carefully

electrons removed from the ions spiral in the magnetic field and may deposit energy in the foil




**How much power is carried by the electrons?**

→ velocity and thus $\gamma$ are equal for *p* and *e*

$$E_k = (\gamma - 1) E_0$$

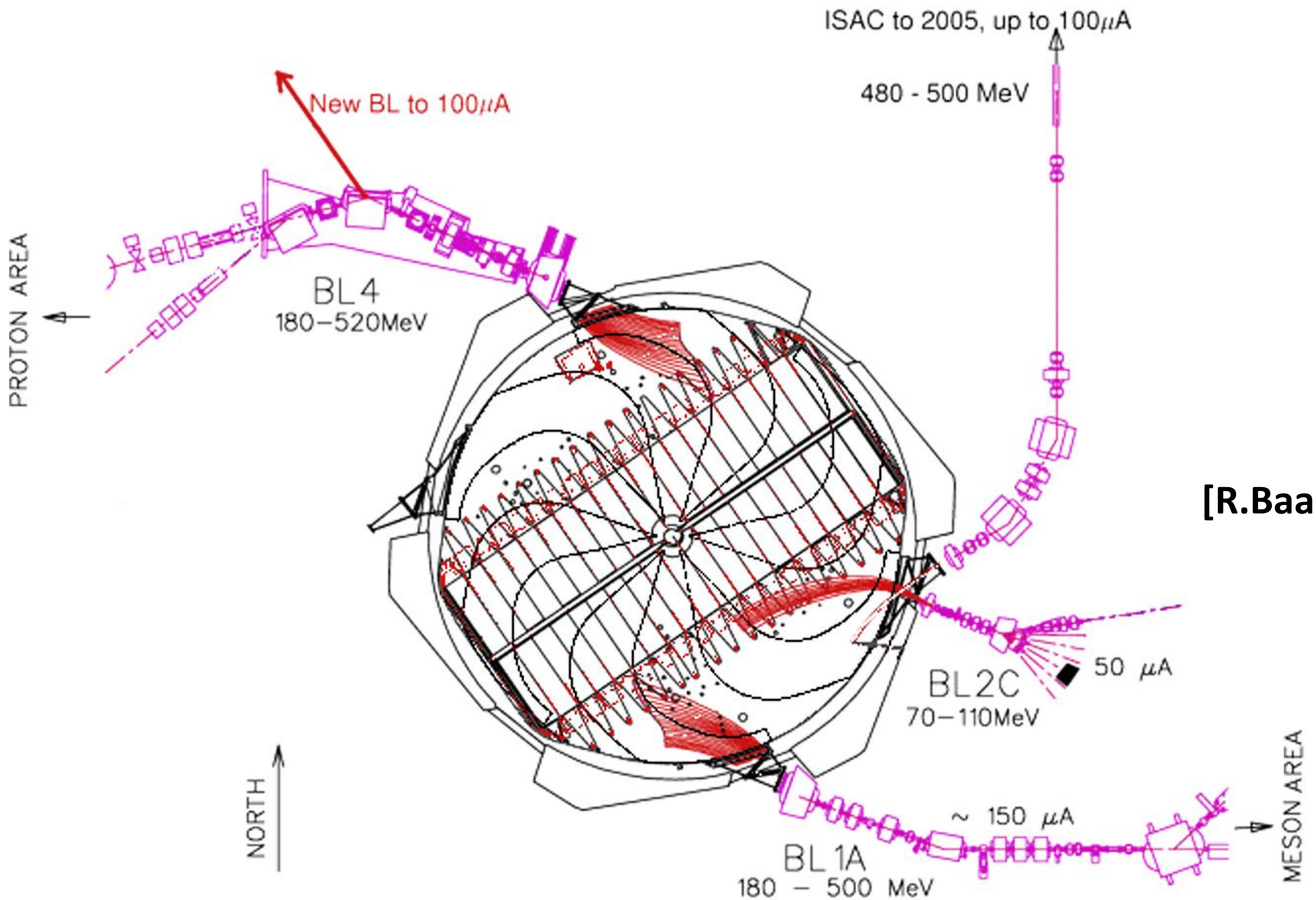
$$\rightarrow E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

**Bending radius of electrons?**

$$\rho^e = \frac{E_0^e}{E_0^p} \rho^p$$

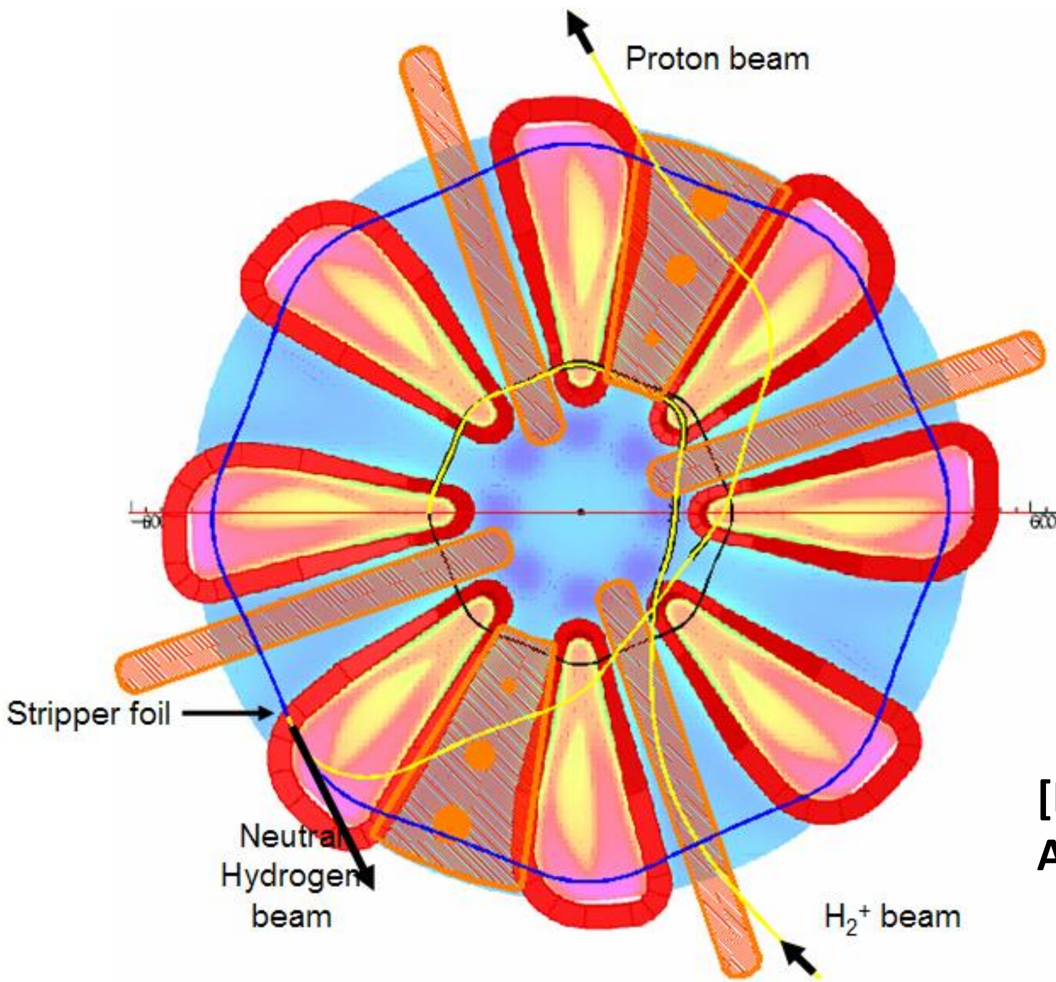
→ typically mm

# example: multiple $H^-$ stripping extraction at TRIUMF




[R.Baartman]

# example: $H_2^+$ stripping extraction in proposed Daedalus cyclotron [neutrino source]




purpose: pulsed high power beam for neutrino production, goals:

- 800MeV kin. energy
- 5MW avg. beam power

**[L.Calabretta, A.Calanna et al]**

# Summary: Injection & Extraction for Cyclotrons

**injection**

**internal source**

**axial injection:**
electrost. inflector

**horizontal injection:**
electrost. septum

**stripping injection**

compact cyclotron

size
cost
function

separated sector cycl.

**extraction**

**internal target**

**electrostatic element**
coherent oscillations
resonant extraction

**stripping extraction**
$H^-$, $H_2^+$, various ions

**beam physics aspects**:

central region design, beam centering, transverse matching, bunching, beam blowup/tails & loss minimization & activation, space charge

# literature w.r.t. cyclotron injection/extraction



| | | |
|---|---|---|
| [1] | comprehensive review of inj./extr. concepts | W.Kleeven (IBA), Injection and Extraction for Cyclotrons https://cds.cern.ch/record/1005057/files/p271.pdf |
| [2] | many examples and calculations for compact machines | P.Heikkinen (Jyväsyla), Injection and Extraction for Cyclotrons http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/26/001/26001643.pdf |
| [3] | calculations and matching on spiral inflectors | W.Kleeven & R.Baartman, 2x paper on spiral inflectors, Particle Accelerators 41 (1993), pages 41 and 55 |
| [4] | extraction for very high intensity | W.Joho, High Intensity Problems in Cyclotrons, Proc. 5th intl. Conf. on Cyclotrons and their Applications, Caen, 337-347 (1981) http://accelconf.web.cern.ch/AccelConf/c81/papers/ei-03.pdf |
| [5] | OPAL simulations; extraction profile | Y.Bi, A. Adelmann, et al. Phys. Rev. STAB Vol. 14, 054402 (2011) http://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.14.054402 |
| [6] | Intensity limitation | R.Baartman, Space Charge limit in separate Turn Cyclotrons, *Intl. Cycl. Conf. (2013)* http://accelconf.web.cern.ch/AccelConf/CYCLOTRONS2013/papers/we2pb01.pdf |
| [7] | formation of round bunches and matching approach | Ch.Baumgarten, transverse-longitudinal coupling by space charge in cyclotrons http://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.14.114201 |

# Thank you for your attention !