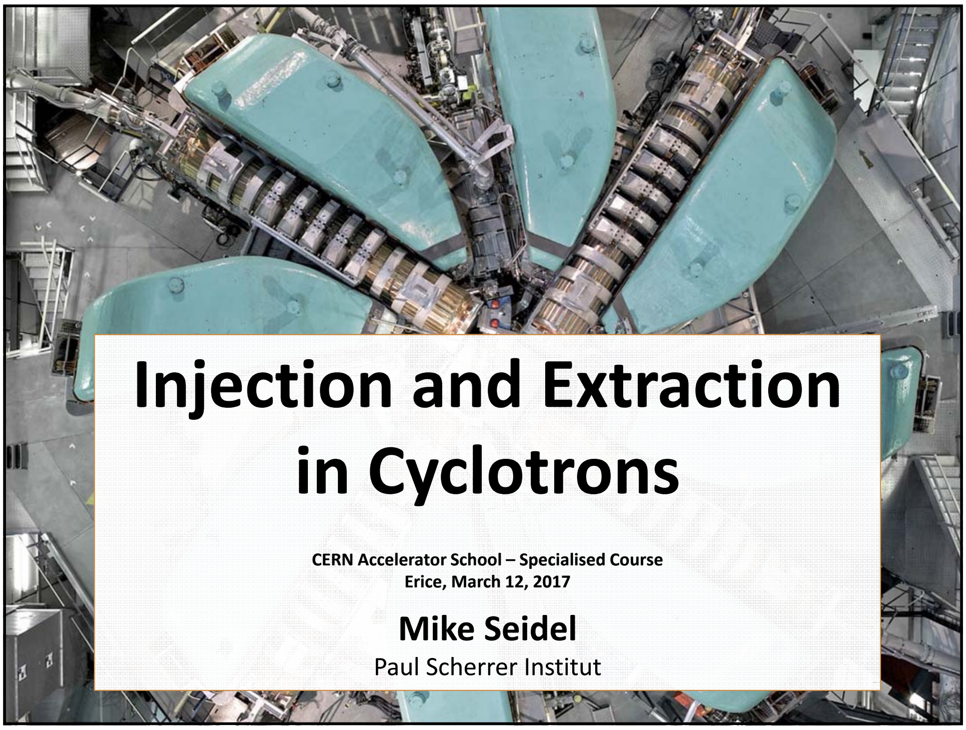

Injection and Extraction in Cyclotrons

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

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The Classical Cyclotron

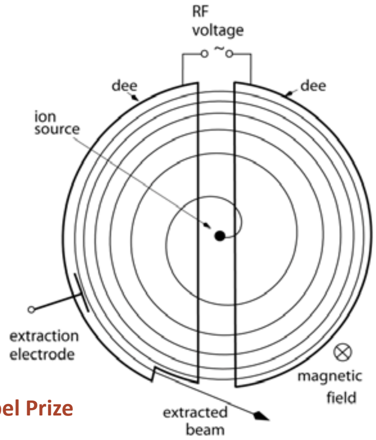
two capacitive electrodes „Dees“, two gaps per turn

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**

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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“

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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*:

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

cyclotron basics: stepwidth (nonrelativistic, B const)

relation between **energy and radius**

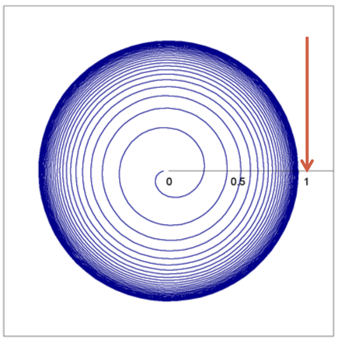
$$qRB_z = \sqrt{2mE_k}$$
$$\frac{dR}{R} = \frac{1}{2}\frac{dE_k}{E_k}$$

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 mv²/r

Lorentz force q$v\times B$

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

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

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

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

thus in radial plane:

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

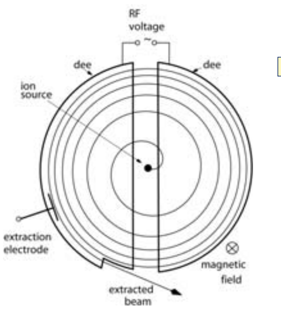
using isochronicity condition

in vertical plane: $\nu_z = \sqrt{-k}$

k<0 to obtain vertical focus.

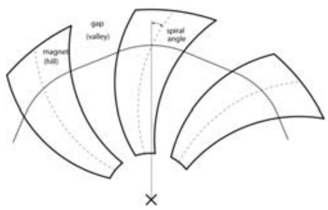
Classical vs Isochronous Cyclotron

classical cyclotron



- insufficient vertical focusing
- limited energy reach

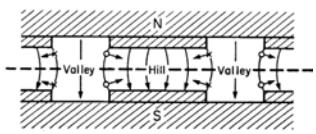
Sector/AVF cyclotron



flutter spiral angle

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

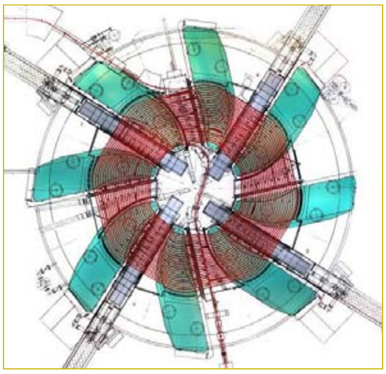
$$F^2 = \frac{\overline{B_z^2} - \overline{B_z}^2}{\overline{B_z}^2}$$



[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% = $(1 - 2{\cdot}10^{-4})$

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classification of cyclotron like accelerators

classical cyclotron
[B(θ) = const]

↓

Thomas cyclotron
[Azimuthally Varying Field, e.g. B(θ) ∝ b+cos(3θ), one pol]

complexity

↓

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

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

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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

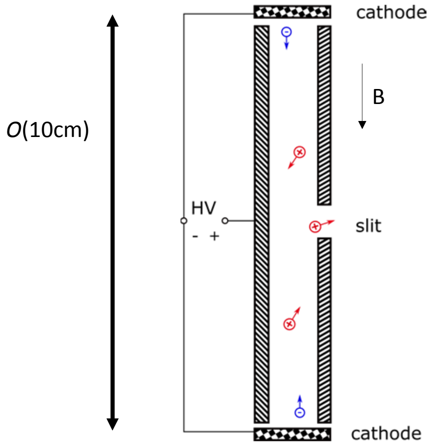
Internal Ion Source

Example: Cold Cathode, Penning Ionisation Gauge (PIG)

cylindrical „chimney“ with slit as extraction aperture for protons

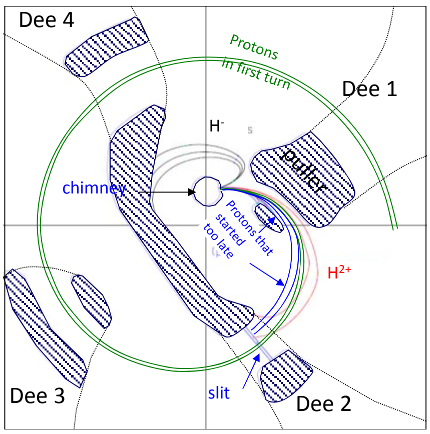
advantage:
- simple concept
- no heating required

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



internal ion source

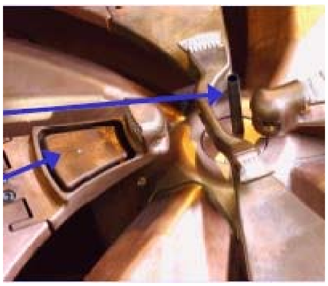
→ example COMET (Accel/Varian)



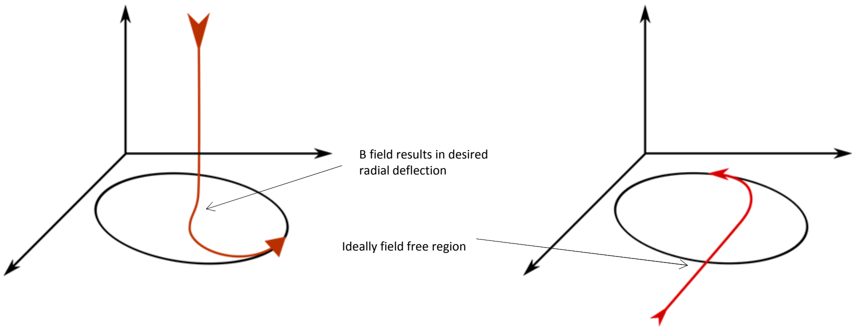
- Hydrogen is injected and ionized through chimney
- first acceleration by puller, connected to one Dee (80kV)

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

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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

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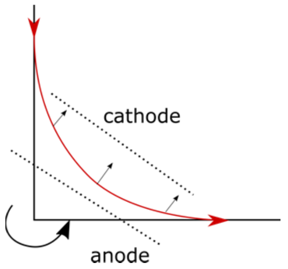
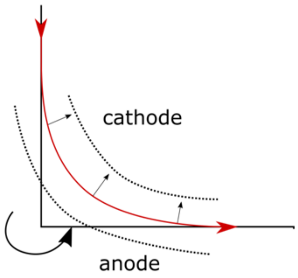
electrostatic inflectors





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

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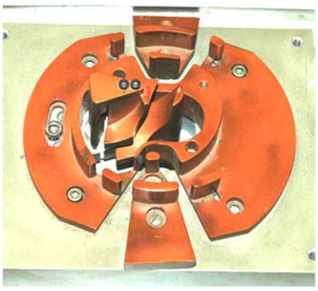
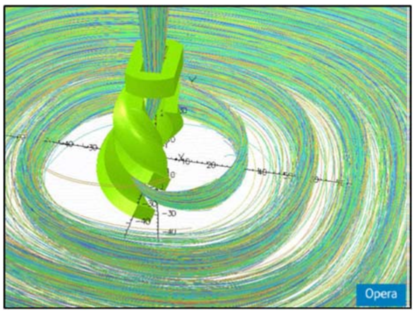
injection schemes – spiral inflector

- 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)]

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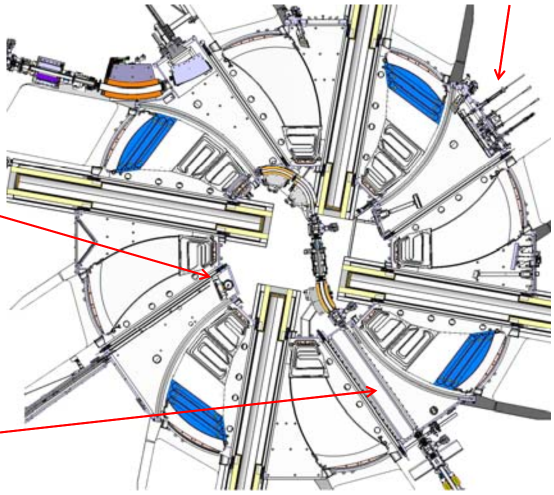
Horizontal Injection – Example PSI Ring Cyclotron

Injection element

extraction



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

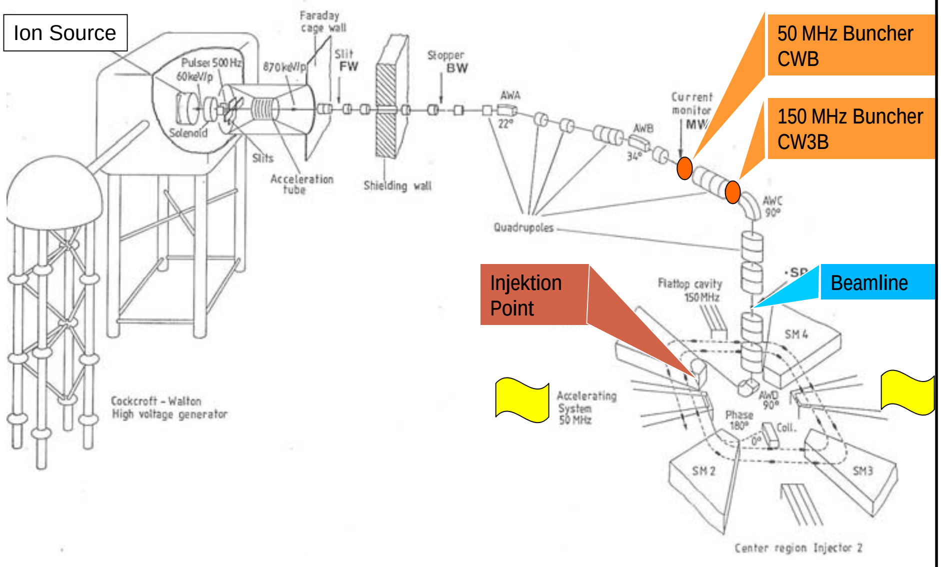
Bunching for Cyclotrons

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 ΔE, costly
Radio Freq. Quadrupole (RFQ)		x	compact, costly

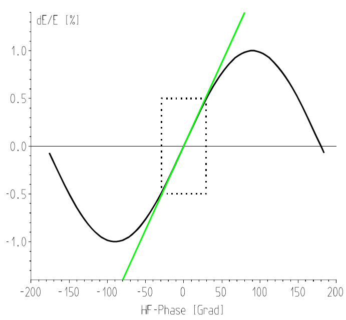
Sketch of 870 keV Injektion Beam Line



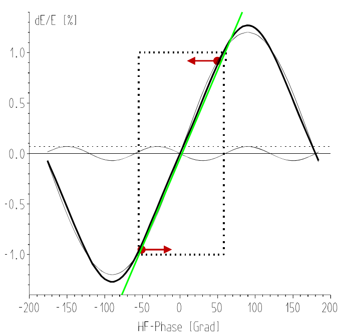
50 MHz and 50/150 MHz Harmonic Oscillation

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

only 50MHz buncher



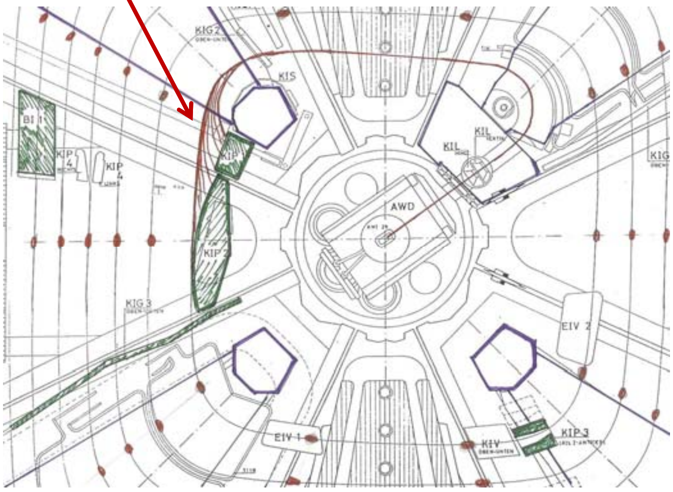
additional 150MHz buncher



[M.Humbel, PSI]

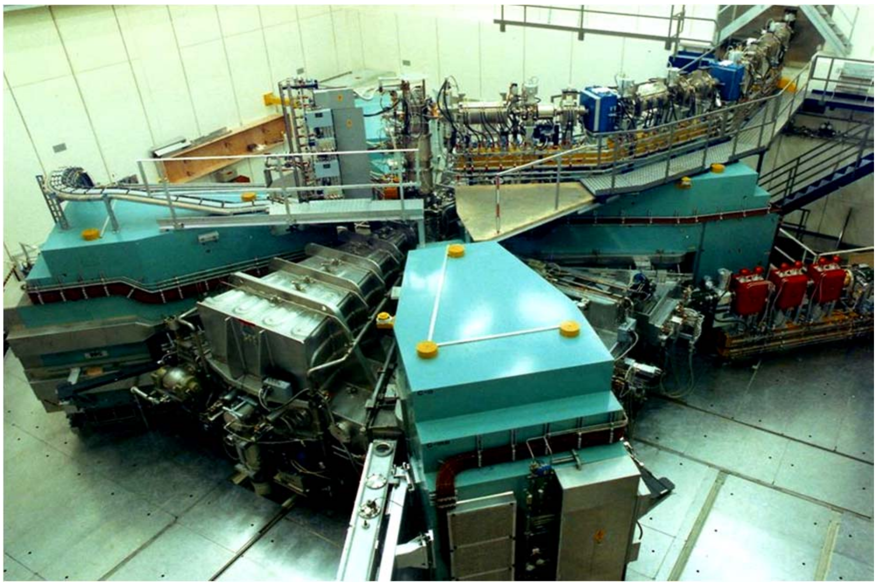
Center Region of PSI Injector 2

collimation of low energy
protons and intensity control



0.86 → 72MeV
max 2.5mA, 180kW

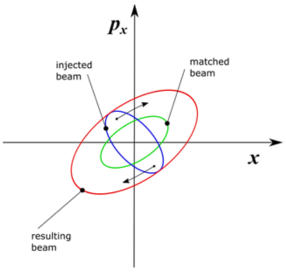
PSI Injector 2 and Injection Beamline



To Beamdump BX2

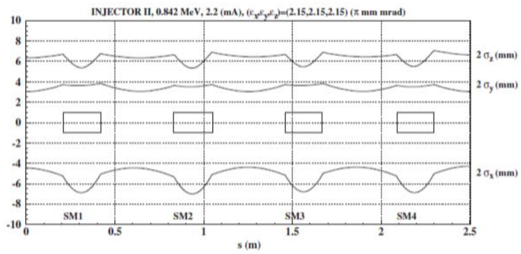
Transverse Matching

- 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

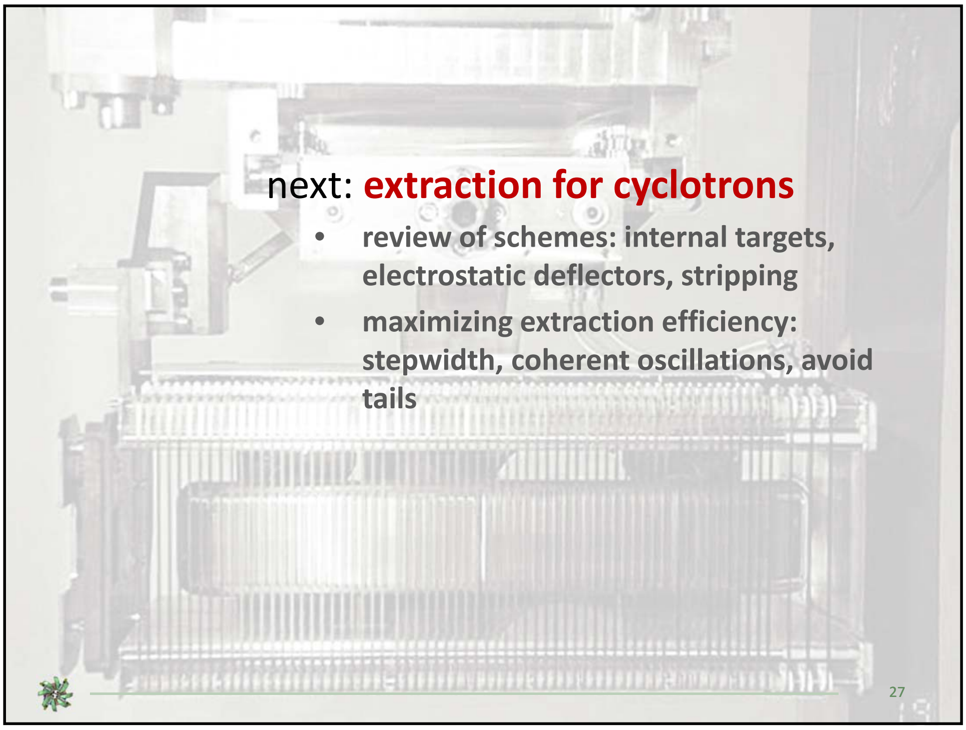
vertical force from space charge: $F_y = \frac{n_v e^2}{\epsilon_0 \gamma^2} \cdot y,\; n_v = \frac{N}{(2\pi)^{\frac{3}{2}} \sigma_y D_f R \Delta R}$
[constant charge density, $D_f = I_{avg}/I_{peak}$]

thus, eqn. of motion:

$$\ddot{y} + \left(\omega_c^2 \nu_{y0}^2 - \frac{n_v e^2}{\epsilon_0 m_0 \gamma^3} \right) y = 0$$

→ 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

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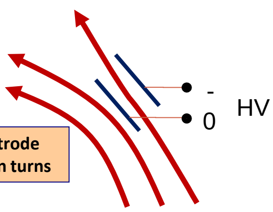
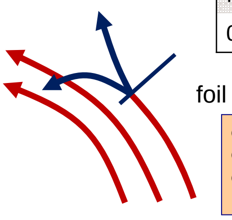
electrostatic septum and charge exchange extraction

- 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.: $H^- \rightarrow H^+$
$H_2^+ \rightarrow 2H^+$

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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

$[U_t$ = energy gain per turn$]$

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

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

} 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:

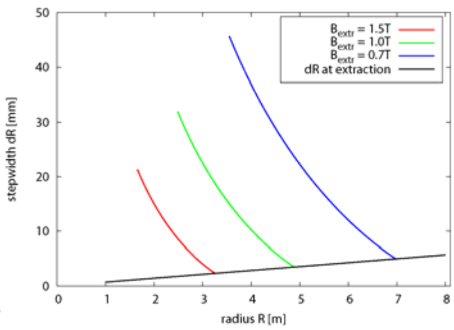
$$\Delta R(R_{\rm extr}) = \frac{U_t}{m_0 c^2}\frac{R_{\rm extr}}{(\gamma^2 - 1)\gamma}$$

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



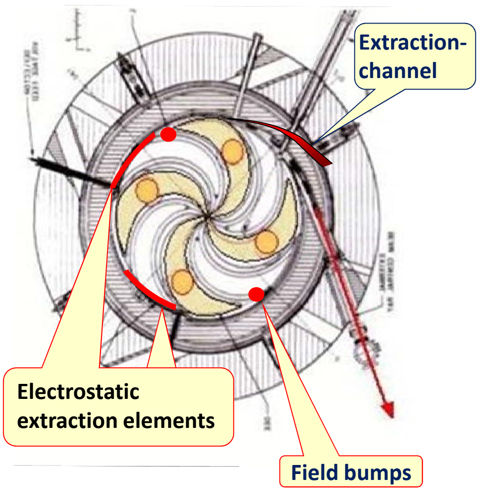
methods to enhance turn separation

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

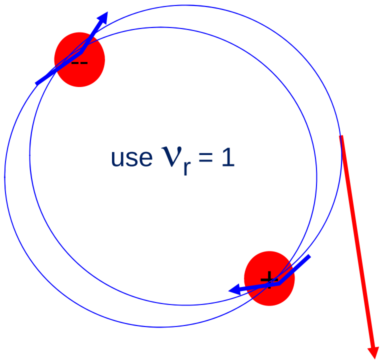
„brute force"	resonant orbit distortion is excited by harmonic coils beyond a certain radius
precessional extraction	resonant excitation at ν_r=1 plus steep ν_r slope in fringe field
regenerative extraction	using coherent excitation at half integer resonance by gradient bump

taken from Kleeven [1]

Resonant Extraction (Varian/Accel cyclotron)



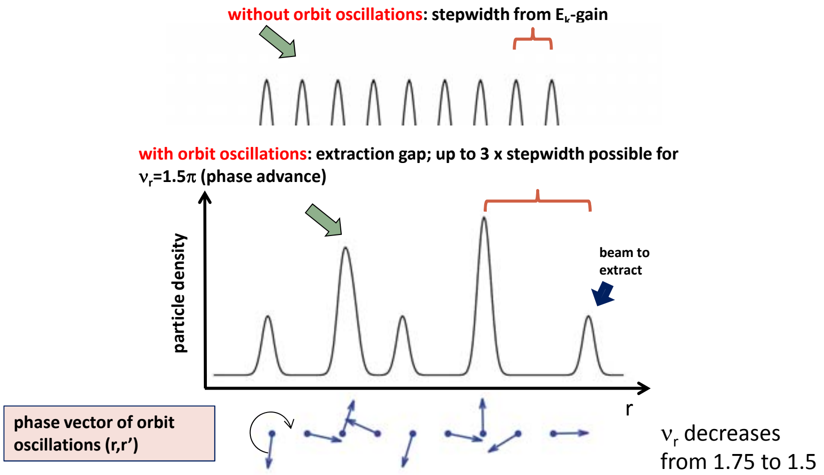
extraction efficiency: up to 80%



[M.Schippers, PSI]

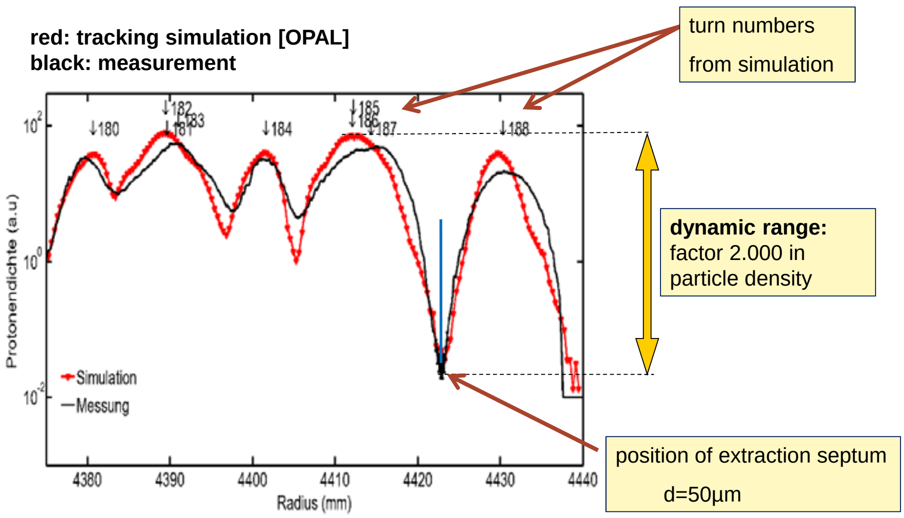
extraction with coherent oscillations (PSI)

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



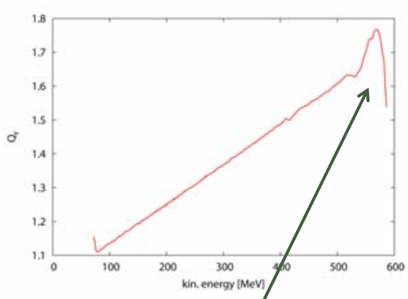
extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement

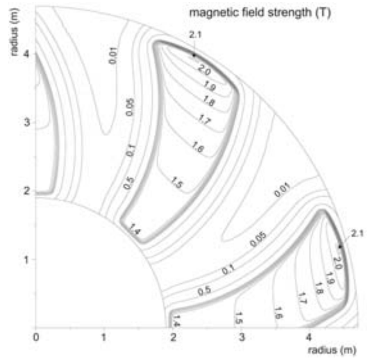


[Y.Bi et al]

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

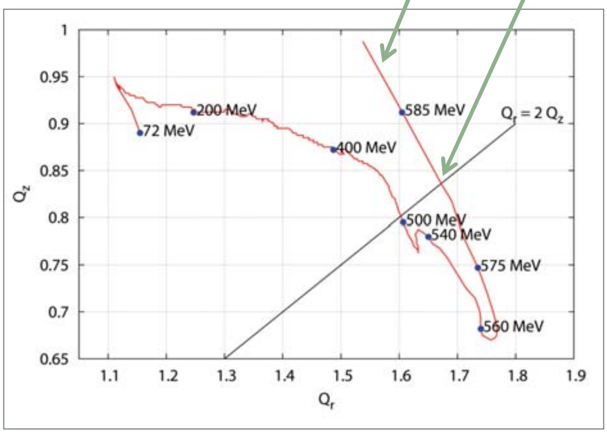


field map showing increase and steep decline of field with radius

PSI Ring Cyclotron – tune diagram

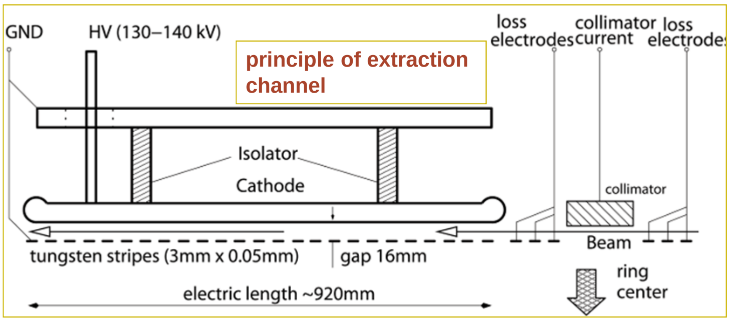
coupling resonance – pass quickly!

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

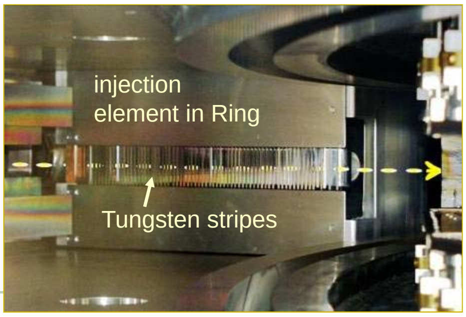


parameters extraction chan.:
E_k= 590MeV
E = 8.8 MV/m
θ = 8.2 mrad
ρ = 115 m
U = 144 kV

major loss mechanism is scattering in 50µm electrode!

electrostatic rigidity:

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



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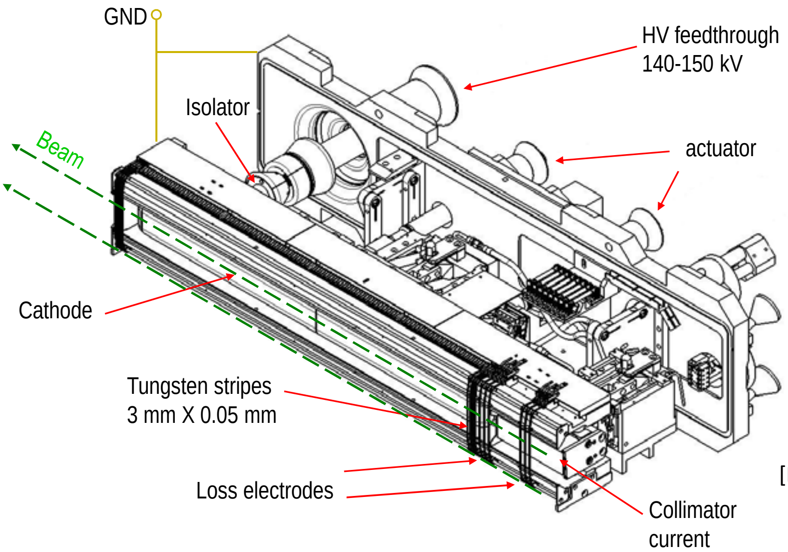
Electrostatic Elements for High Energy/High Intensity



[D.Götz, PSI]

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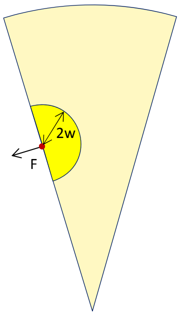
longitudinal space charge (tails at extraction)

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

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

derivation see [4]: Joho 1981

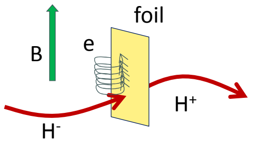
in addition:
3) the inverse of turn separation at extraction: $\frac{1}{\Delta R_{\mathrm{extr}}} \propto n_{\max}$

$\rightarrow$ 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?
$\rightarrow$ velocity and thus γ are equal for *p* and *e*

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

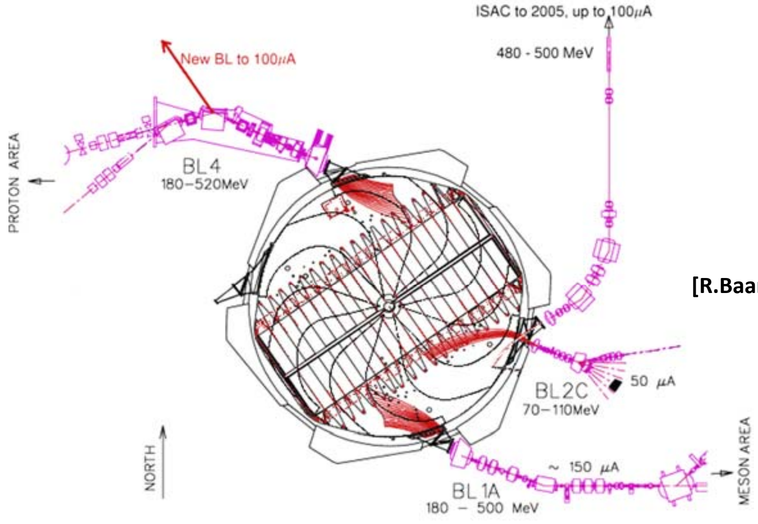
$$\rightarrow E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

Bending radius of electrons?

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

$\rightarrow$ typically mm

example: multiple H⁻ stripping extraction at TRIUMF



[R.Baartman]

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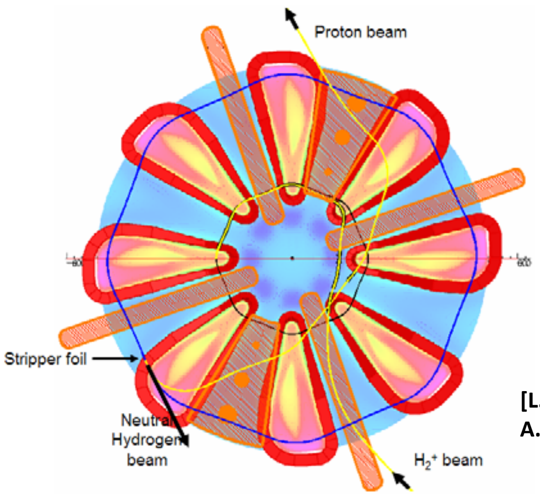
example: H_2^+ stripping extraction in proposed Daedalus cyclotron [neutrino source]



purpose: pulsed high power beam for neutrino production, goals:
- 800MeV kin. energy
- 5MW avg. beam power

[L.Calabretta, A.Calanna et al]

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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

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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

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Thank you for your attention !