Cyclotrons

for high intensity beams

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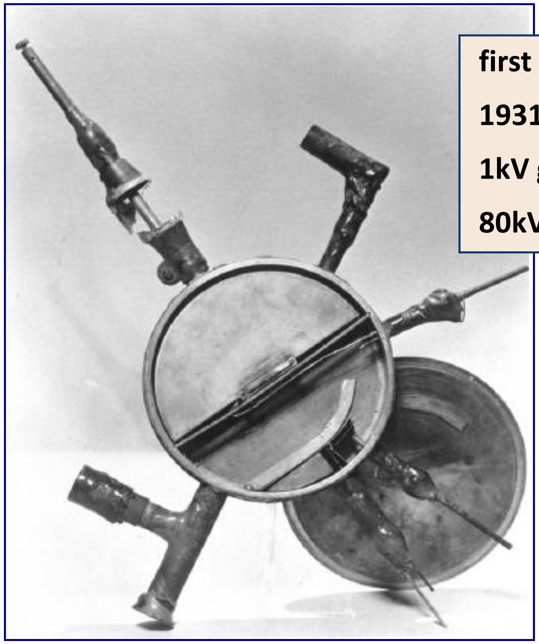
Cyclotrons - Outline

- classical cyclotron
  - **concept, classification of circular accelerators, relativistic relations, isochronicity, scalings**
- separated sector cyclotrons
  - **concept, focusing, space charge, injection/extraction, high intensity related aspects…**
- cyclotron subsystems
  - **RF, magnets, vacuum, diagnostics, electrostatic elements**
- examples of existing high intensity cyclotrons
  - **PSI-HIPA, RIKEN-SRC, TRIUMF**
- discussion of pro’s and con’s

Classical Cyclotron

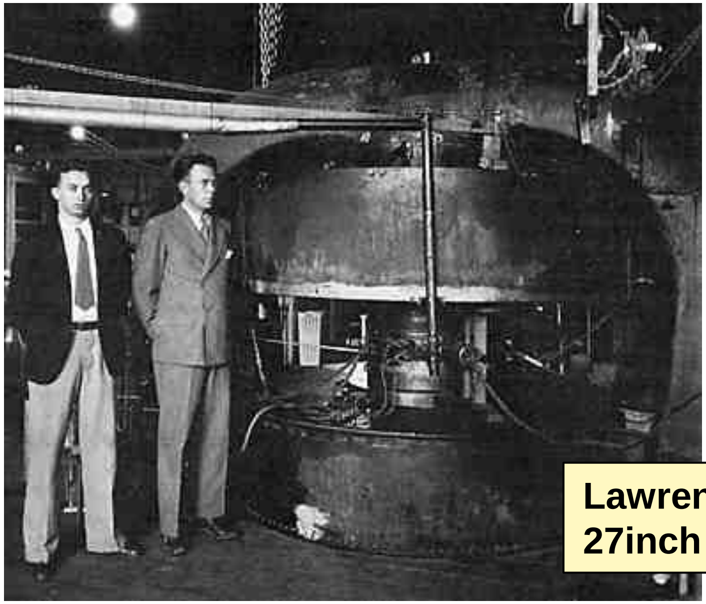


first cyclotron:

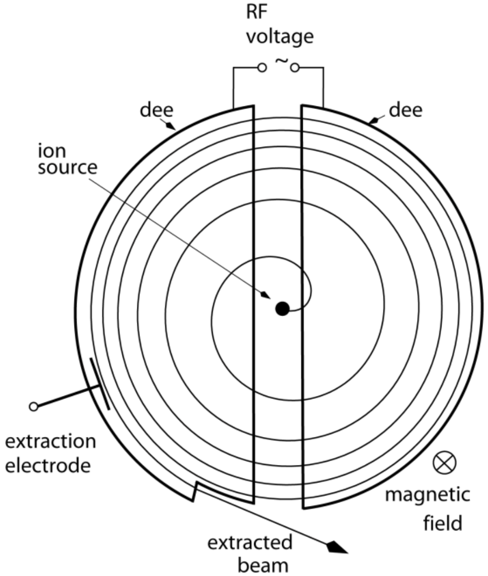
1931, Berkeley

1kV gap-voltage

80kV Protons



Lawrence & Livingston, 27inch Zyklotron



two capacitive electrodes „Dees", two gaps per turn

internal ion source

homogenous B field

constant revolution time

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

powerful concept:

- ➔ simplicity
- ➔ CW operation
- ➔ multiple usage of accelerating voltage

classification of circular accelerators

	bending radius	bending field vs. time	bending field vs. radius	RF frequency vs. time	operation mode (pulsed/CW)	comment
betatron	→	↗	↘		pulsed	induction
microtron	↗	→	→	→	CW	varying *h*
classical cyclotron	↗	→	→ / ↘ (dashed)	→	CW	simple, but limited E_k
isochronous cyclotron	↗	→	↗	→	CW	suited for high power!
synchro-cyclotron	↗	→	→ / ↘ (dashed)	↘	pulsed	higher E_k, but low P
FFAG	→ / ↗ (dashed)	→	↗	↗	pulsed	strong focusing!
a.g. synchrotron	→	↗		→ / ↗ (dashed)	pulsed	high E_k

basics – cyclotron frequency and *K* value

- **cyclotron frequency** (homogeneous) B-field:

$$\omega_c = \frac{eB}{\gamma m_0}$$

- **cyclotron *K*-value**:

→ *K* is the **kinetic energy reach** for protons **from bending strength** in non-relativistic approximation: $K = \frac{e^2}{2m_0}(B\rho)^2$

→ *K* can be used to rescale the energy reach of protons to other charge-to-mass ratios:

$$\frac{E_k}{A} = K\left(\frac{Q}{A}\right)^2$$

→ *K* in [MeV] is often used for naming cyclotrons

examples: K-130 cyclotron / Jyväskylä

cyclone C230 / IBA

basics – isochronicity and scalings

- magnetic rigidity:

$$B \cdot R = \frac{p}{e} = \beta\gamma \frac{m_0 c}{e}$$

- orbit radius from isochronicity:

$$R = \frac{c}{\omega_c}\beta = R_\infty \beta$$
$$= \frac{c}{\omega_c}\sqrt{1-\gamma^{-2}}$$

- since $R \propto \beta; \;\; B \cdot R \propto p \propto \beta\gamma$

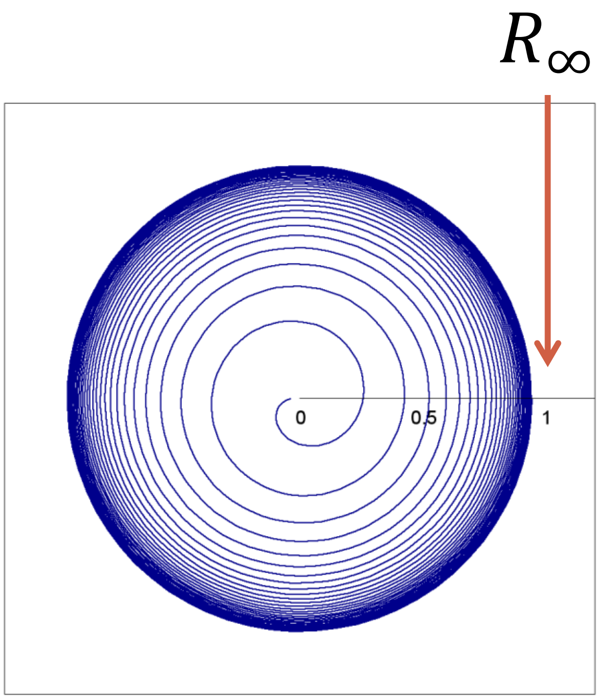
$$\rightarrow B \propto \gamma$$

- turn number:

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

energy gain per turn

radius increment per turn decreases with increasing energy because the revolution time must stay constant
→ extraction becomes more and more difficult at higher energies



basics – focusing in the classical cyclotron

- field index:

$$\zeta = \frac{R}{B_z}\frac{\partial B_z}{\partial R} \left(= \gamma^2 - 1\right) \text{ from isochronicity}$$

- betatron frequencies:

$$\left.\begin{aligned} \nu_r &= \frac{\omega_r}{\omega_c} = \sqrt{1+\zeta} \approx \gamma \\ \nu_z &= \frac{\omega_z}{\omega_c} = \sqrt{-\zeta} \end{aligned}\right\} \quad {\nu_r}^2 + {\nu_z}^2 = 1$$

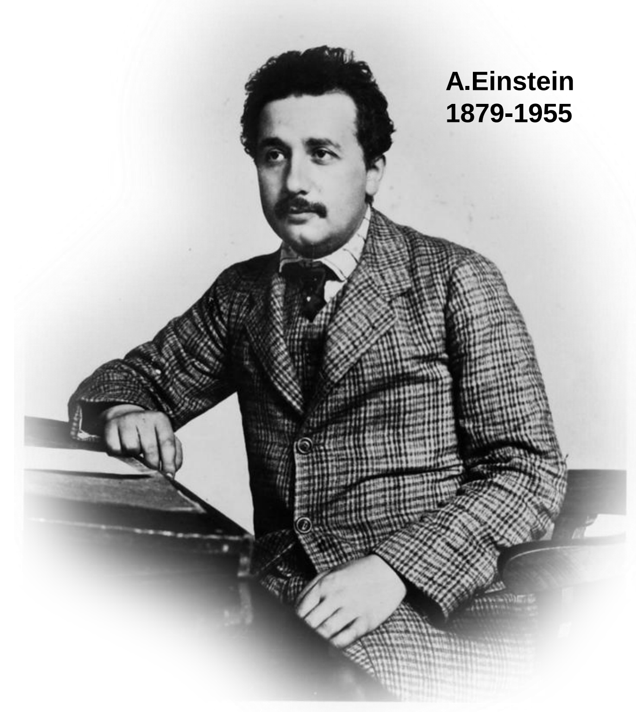
obtained from equations of motion and first order expansion of magnetic field B_z; note: curl**B**=0 provides relation between B_z and B_r

to obtain vertical focusing: $\frac{\partial B_z}{\partial R} < 0$

however, isochronicity requires: $B_z \propto \gamma$, i.e. $\frac{\partial B_z}{\partial R} > 0$

$\rightarrow$ kinetic energy of classical cyclotron is limited because of lack of vertical focusing

relativistic quantities in the context of cyclotrons



A.Einstein
1879-1955

energy

$$E = \gamma E_0$$

kinetic energy:

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

volocity

$$v = \beta c$$

revolution time:

$$\tau = \frac{2\pi R}{\beta c}$$

momentum

$$p = \beta\gamma m_0 c$$

bending strength:

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

useful for calculations – differential relations

$$\frac{d\beta}{\beta} = \frac{1}{\gamma(\gamma+1)} \frac{dE_k}{E_k}$$

energy

$$\frac{dE_k}{E_k} = \frac{\gamma+1}{\gamma} \frac{dp}{p}$$

volocity

momentum

$$\frac{dp}{p} = \gamma^2 \frac{d\beta}{\beta}$$

next: Sector Cyclotrons

the cyclotron concept suited for high intensity operation

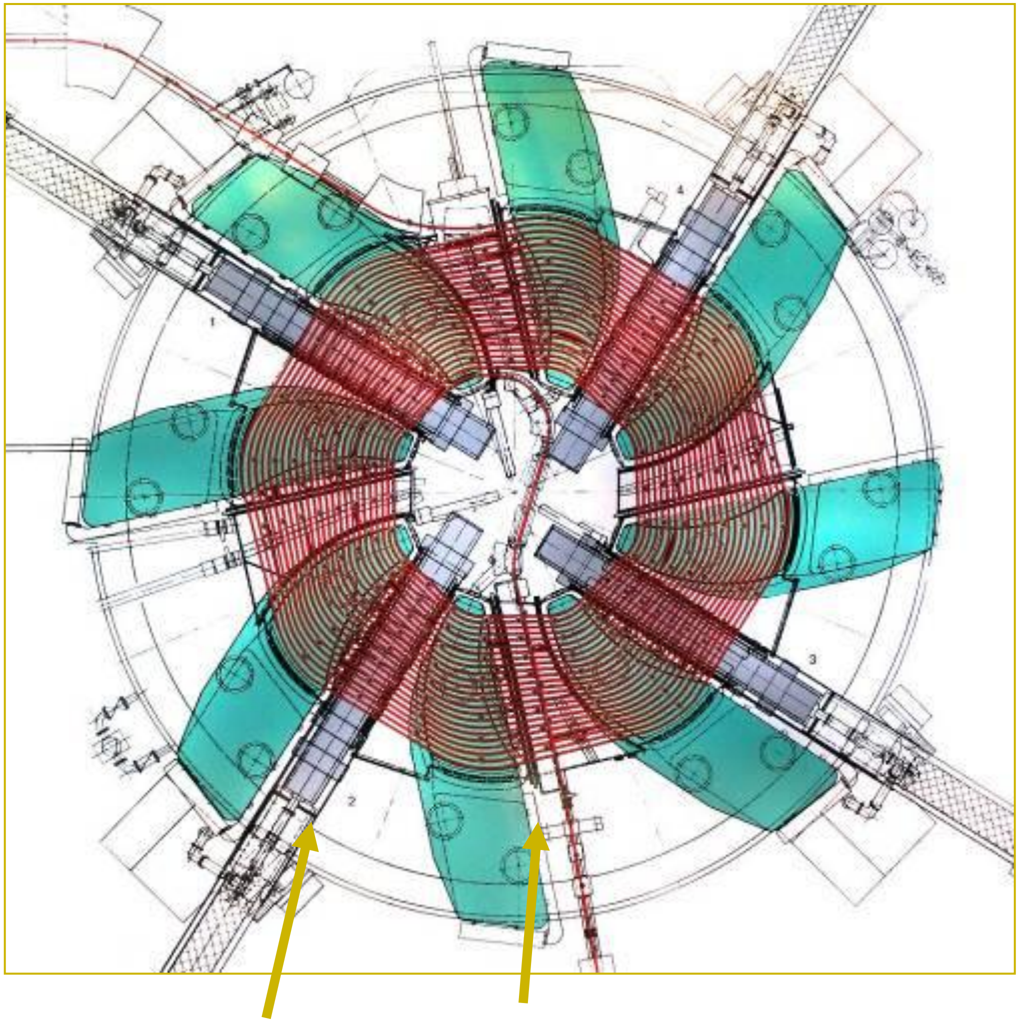
focusing, space charge, injection/extraction, high intensity related aspects…

today: Separated Sector Cyclotrons

- **edge+sector focusing**, i.e. spiral magnet boundaries, azimuthally varying B-field $\rightarrow$ next slide on focusing
- **modular layout,** larger cyclotrons possible, sector magnets, box resonators
- **external injection** required, i.e. pre-accelerator
- **radially wide vacuum chamber**; inflatable seals etc.
- detailed **field shaping for focusing and isochronisity** required

- strength: **CW acceleration**; higher energy up to 1GeV, high **extraction efficiency** possible:

  e.g. PSI: 99.98% = $(1 - 2\cdot 10^{-4})$



focusing in sector cyclotrons

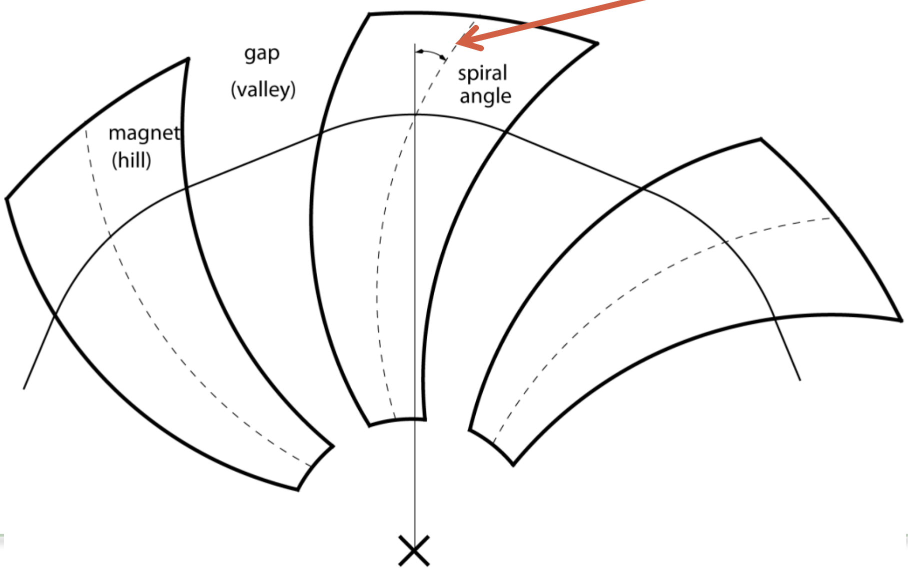
- hill / valley variation of magnetic field (Thomas focusing):

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

vertical betatron f.: $$\nu_z^2 = -\frac{R}{B_z}\frac{\partial B_z}{\partial R} + F$$

- with additional spiral angle of bending field:

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



radius increment per turn

- losses at extraction are typically limiting the intensity
- the electrode of an extraction element is placed between last two turns

$\rightarrow$ thus the radial stepwidth should be as large as possible

use orbit radius and turn number from previous slides:

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

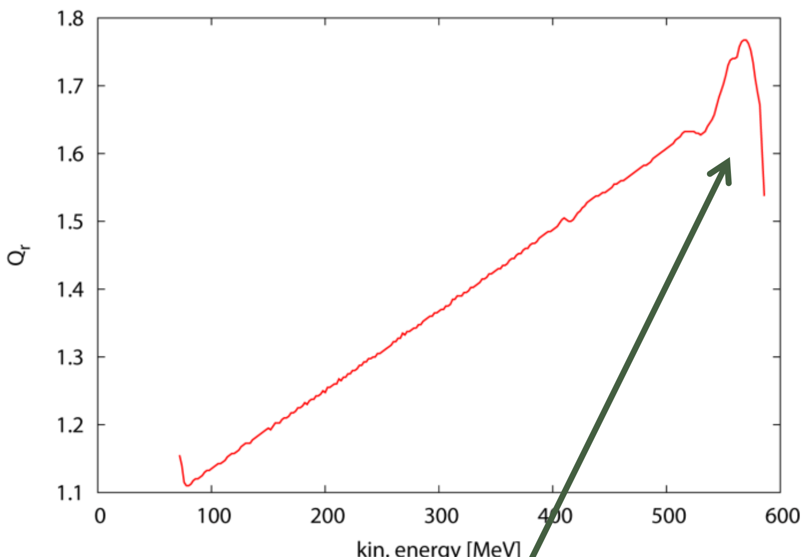
$$= \frac{R}{\gamma(\gamma^2-1)}\frac{U_t}{m_0c^2}$$ **with isochronicity**

$$= \frac{\gamma}{\gamma^2-1}\frac{R}{\zeta+1}\frac{U_t}{m_0c^2}$$ **more general; ζ - field index**

- ▶ **desirable: large radius**
- ▶ **desirable: large energy gain U_t (resonator voltages)**
- ▶ **field shaping at extraction radius helps**
- ▶ **note: strong decrease at relativistic energies (>1GeV not realistic for high intensity)**

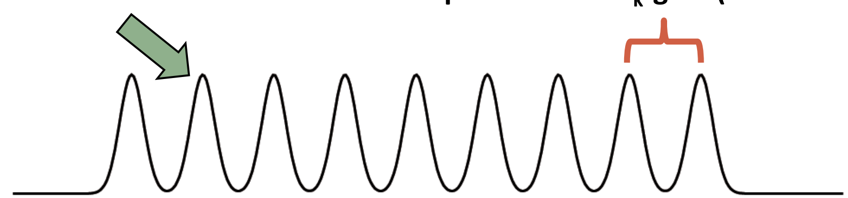
extraction with off-center orbits

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

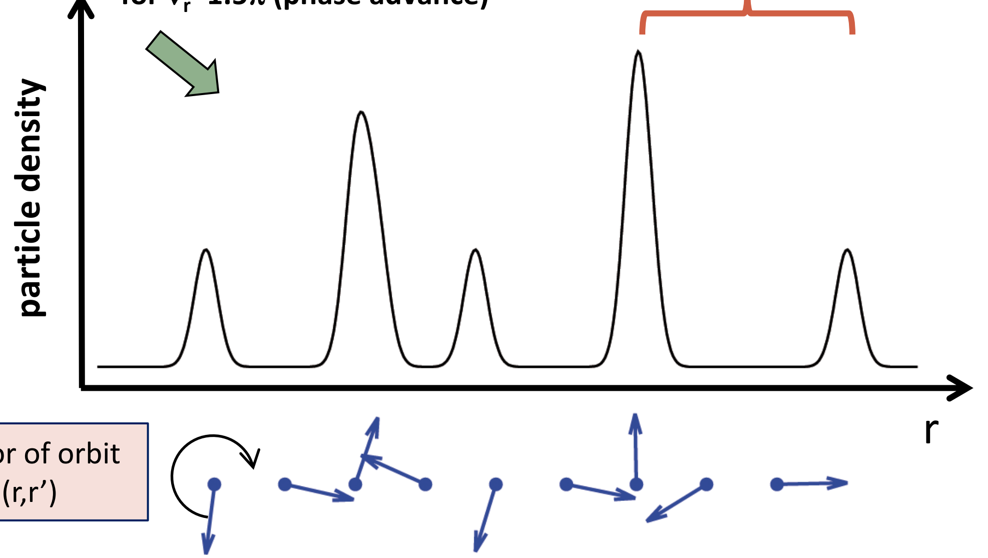


radial tune vs. energy
typically $\nu_r \approx \gamma$ during acceleration;
but decrease in outer fringe field

without orbit oscillations: stepwidth from E_k-gain (PSI: 6mm)

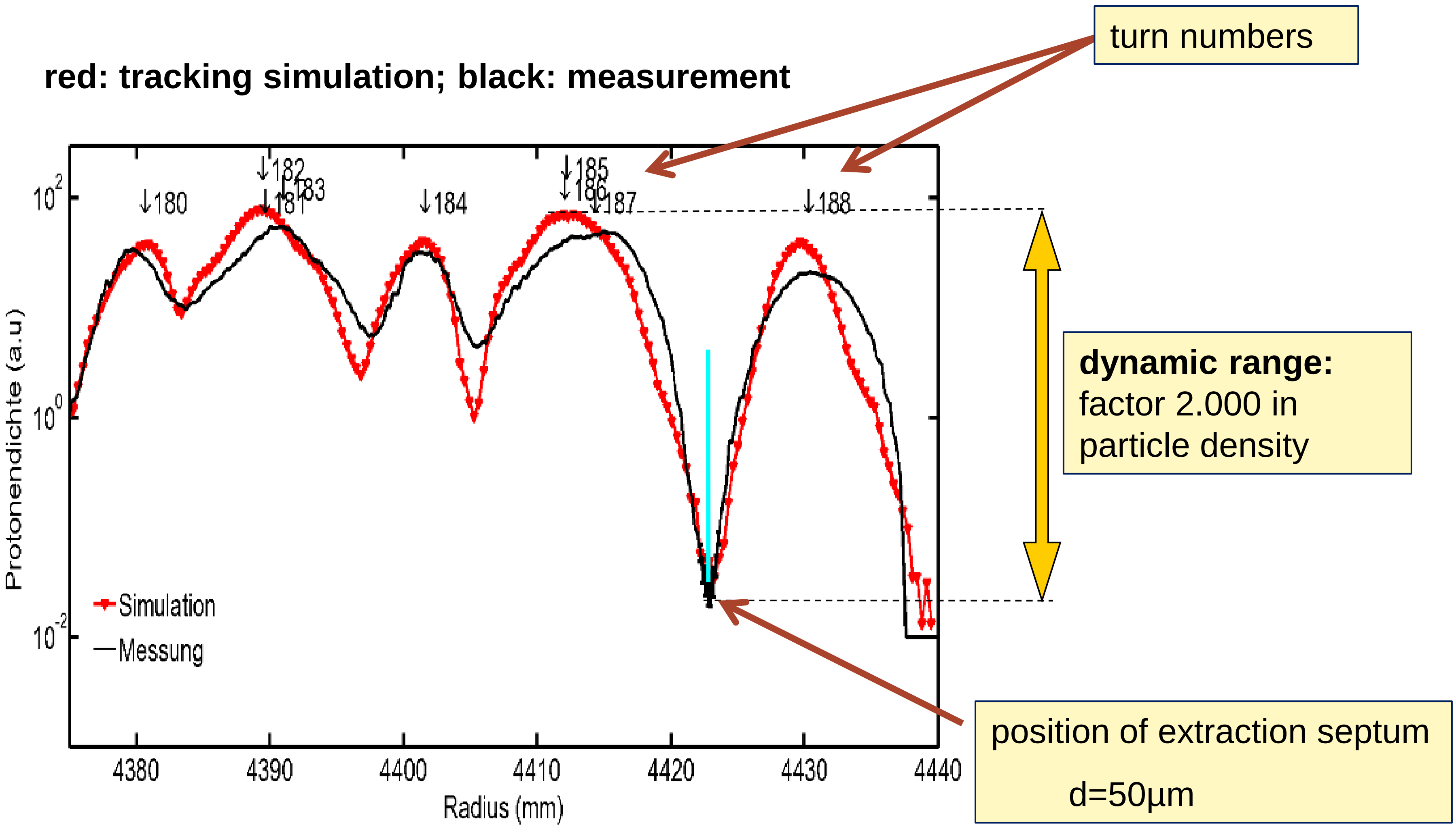


with orbit oscillations: extraction gap; up to 3 x stepwidth possible for ν_r=1.5π (phase advance)



extraction profile measured at PSI Ring Cyclotron

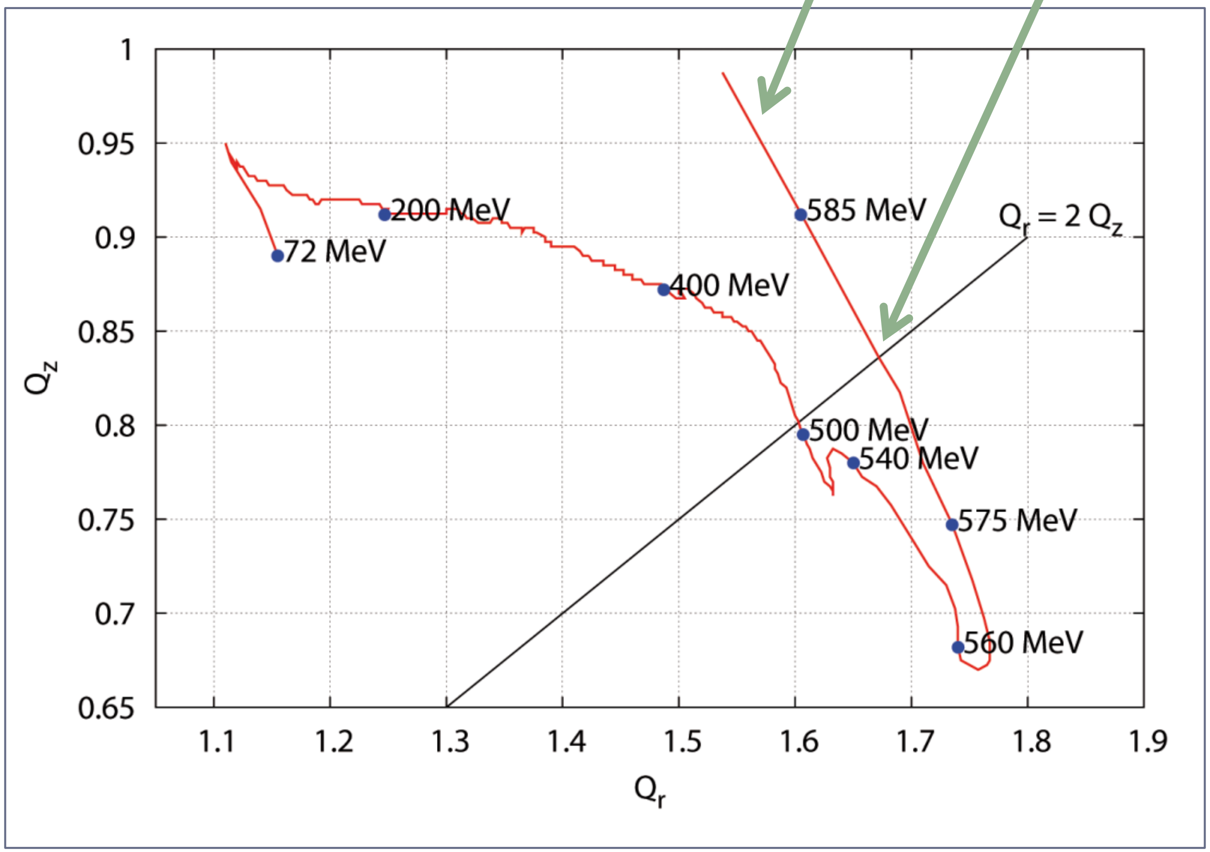
red: tracking simulation; black: measurement



PSI Ring Cyclotron – tune diagram

coupling resonance – pass quickly!

Q_r decreases towards extraction
– enhance turn separation

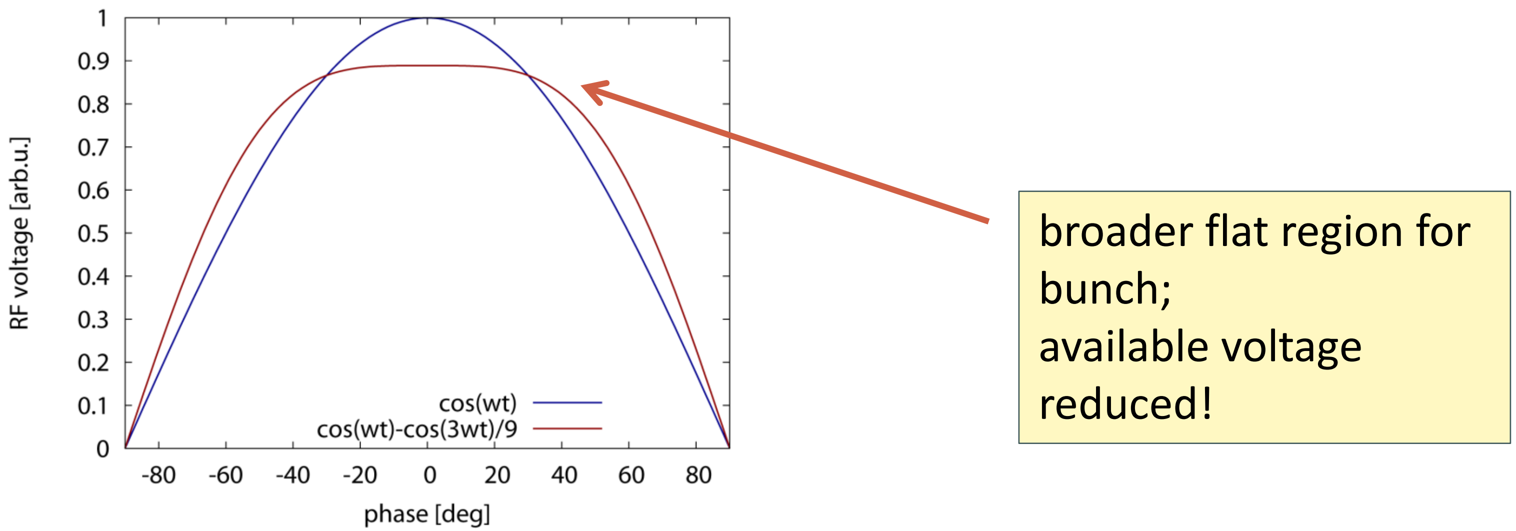


comments:

- 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

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: $U_{\text{tot}} = U_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$



longitudinal space charge

- with overlapping turns use current sheet model; shielding of vacuum chamber must be considered; after W.Joho, Cyclotron Conf. Caen (1981)
- non-relativistic approximation
- accumulated energy spread couples to transverse plane and broadens beam

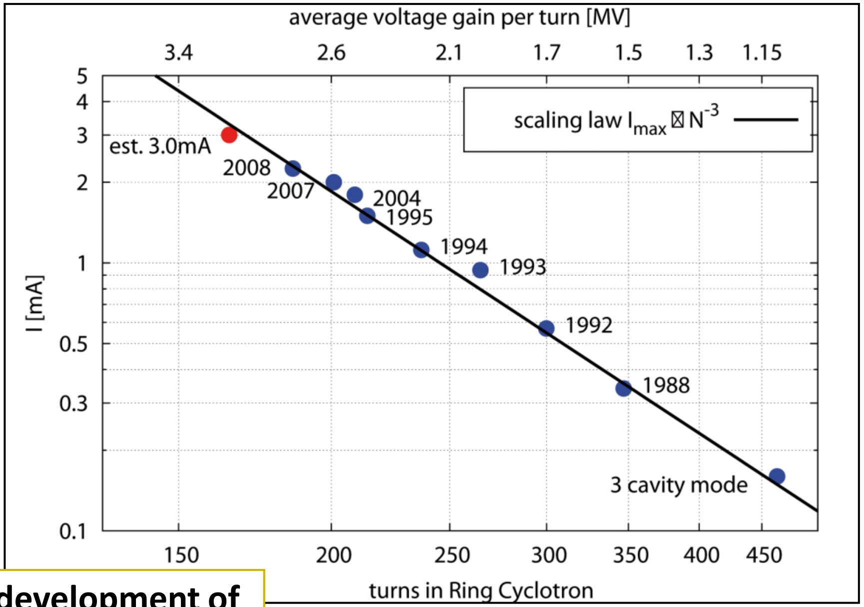
accumulated energy spread: $$\Delta E_k = \frac{16}{3}\frac{eZ_0}{\beta_{max}} \cdot I_{peak} \cdot {n_t}^2$$

number of turns

thus beam width scales as ${n_t}^2$

orbit separation scales as $U_t \propto {n_t}^{-1}$

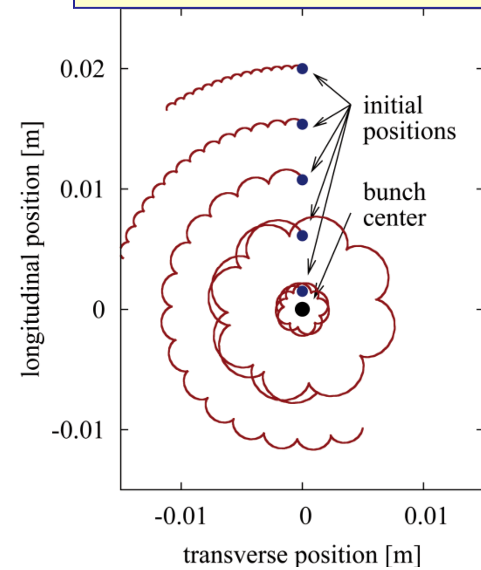
→ thus with constant losses at the extraction electrode the maximum attainable current scales as: $I_{max} \propto {n_t}^{-3}$



historical development of current and turn numbers in PSI Ring Cyclotron

different regime for very short bunches: formation of circular bunch

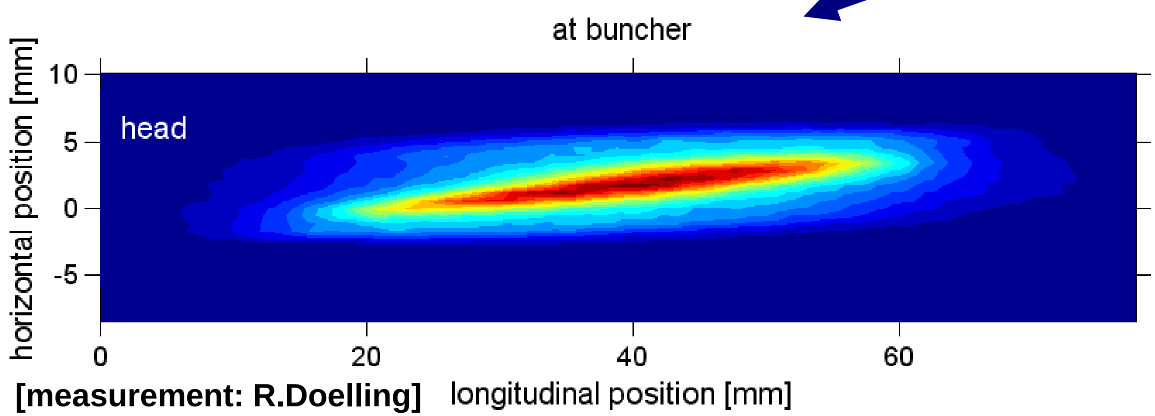
simplified model:
test charge in bunch field with vertically oriented bending field

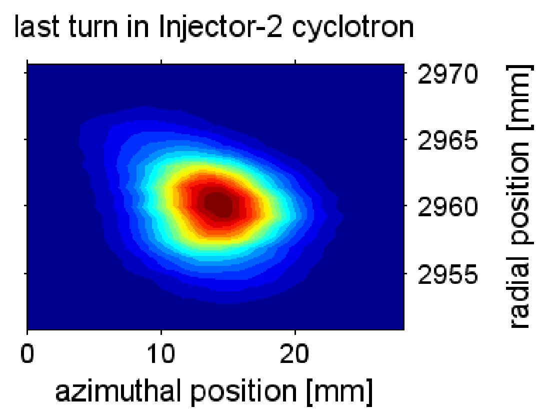


in theory
strong space charge within a bending field leads to rapid cycloidal motion around bunch center
[Chasman & Baltz (1984)]
→ bound motion; circular equilibrium beam destribution

in practice
time structure measurement in injector II cyclotron → circular bunch shape observed

blowup in ~20m drift



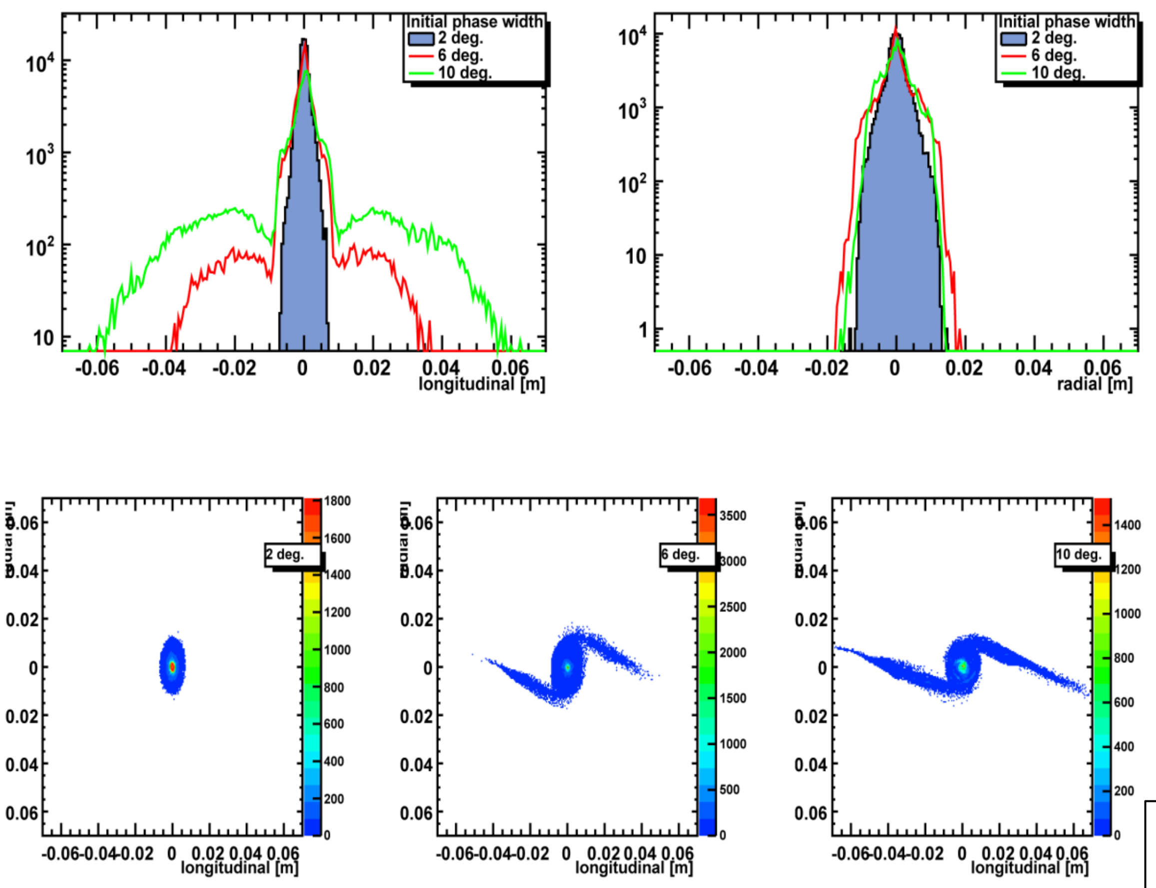


[measurement: R.Doelling]

circular beam in tracking study (Ring Cyclotron)

Plot: distribution after 100 turns, varying initial bunch length
→ short bunch stays compact, no tails!

- multiparticle simulations
- 10^5 macroparticles
- precise field-map
- bunch dimensions:
σ_z ~ 2, 6, 10 mm;
σ_{xy} ~ 10 mm



simulation:
J.Yang, CAEA/Beijing;
A.Adelmann, PSI

transverse space charge

with overlapping turns use current sheet model!

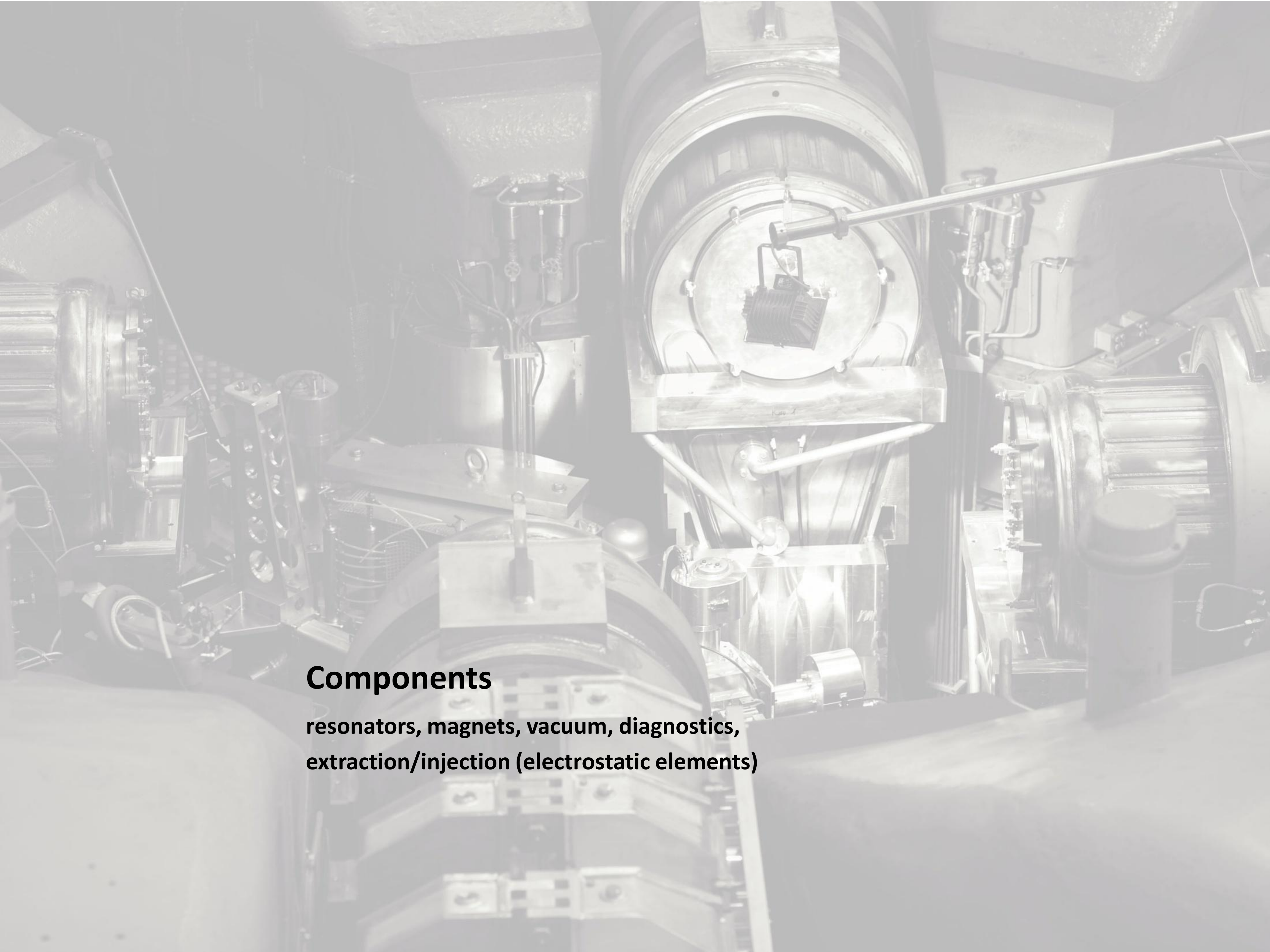
vertical force from space charge: $F_z = \frac{n_v e^2}{\varepsilon_0 \gamma^2} \cdot z$

particle density: $n_v = \frac{N}{\sqrt{(2\pi)^3}\sigma_y D_f R \cdot \Delta R}$

focusing force: $F_z = -m_0 \gamma {\omega_c}^2 {\nu_{z0}}^2 \cdot z$

→ equating space charge and focusing force delivers an intensity limit for loss of focusing!

tune shift from forces: $\Delta\nu_z \approx -\frac{2\pi r_p R^2 n_v}{\beta^2 \gamma^3 \nu_{z0}}$



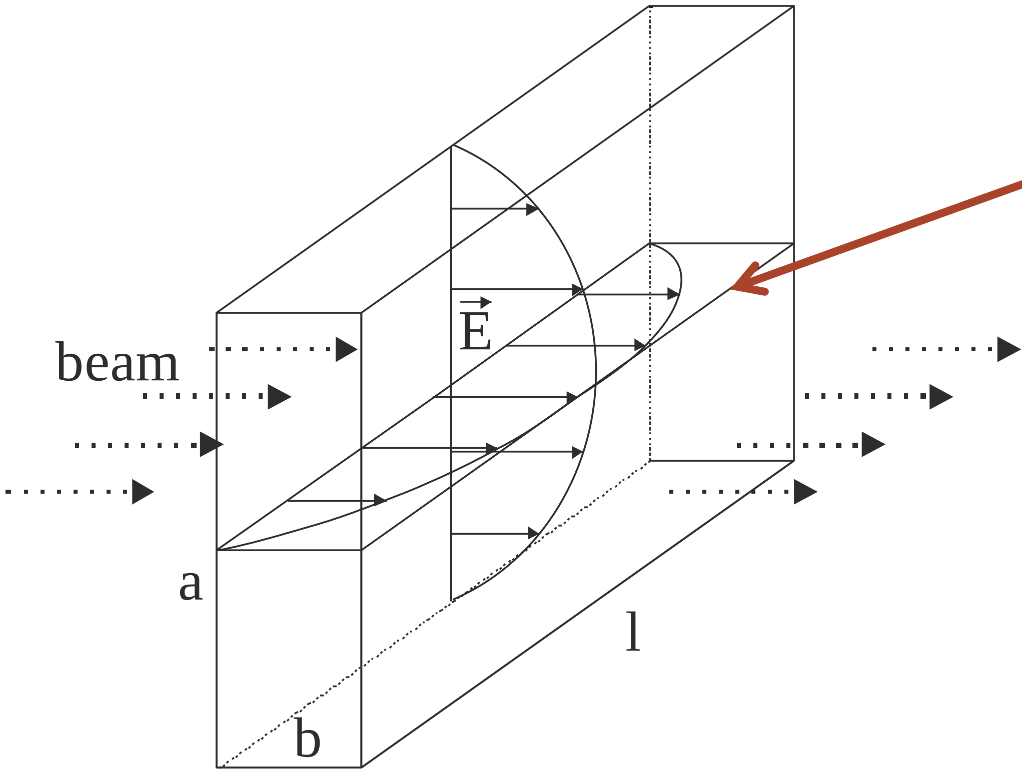
Components

resonators, magnets, vacuum, diagnostics, extraction/injection (electrostatic elements)

components: cyclotron resonators

cyclotron resonators are basically box resonators

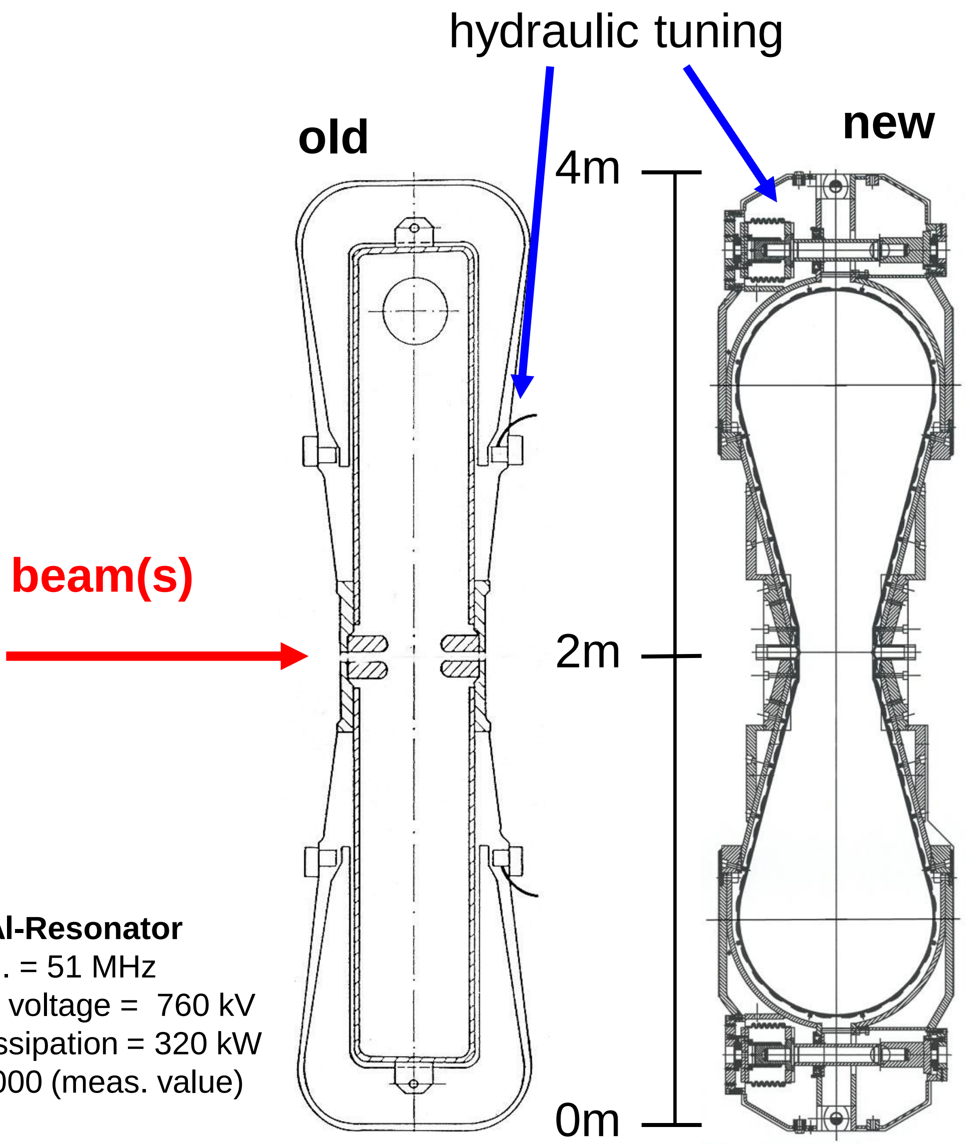
resonant frequency: $f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{l^2}}$



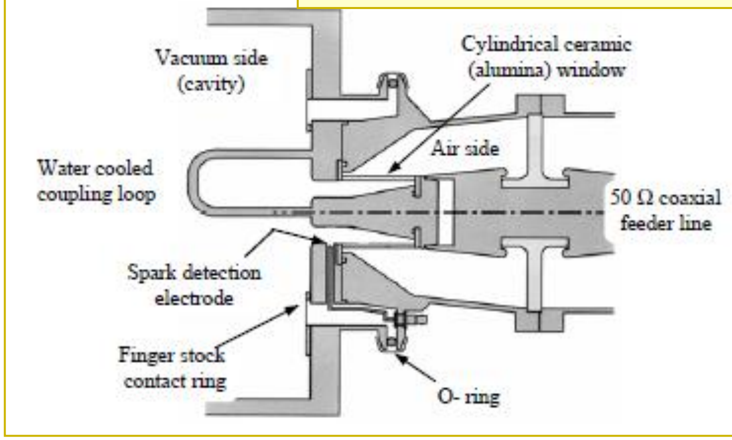
beam passes in center plane;

accelerating voltage varies as sin(r)

cross sections of PSI resonators



loop coupler @ 50MHz



original Al-Resonator
Oper. freq. = 51 MHz
Max. gap voltage = 760 kV
Power dissipation = 320 kW
Q0 = 32'000 (meas. value)

new Cu-Resonator
Oper. freq. = 51 MHz
Max. gap voltage > 1MV
Power dissipation = 500 kW
Q0 ≈ 48'000

copper resonator in operation at PSI’s Ring cyclotron

- **f = 50.6MHz**; **Q_0 = 4,8·10^4**; **U_{max}=1.2MV** (presently 0.85MV)
- wall plug to beam efficiency (RF Systems):
  32% [AC/DC: 90%, DC/RF: 64%, RF/Beam: 55%]
- transfer of up to **400kW power to the beam** per cavity

resonator inside

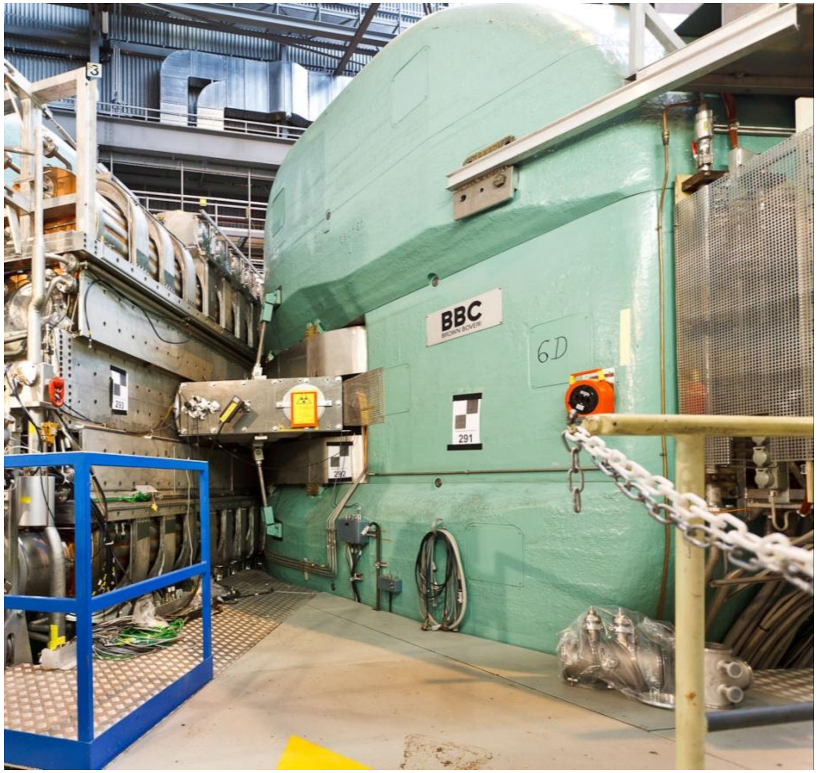
hydraulic tuning devices (5x)

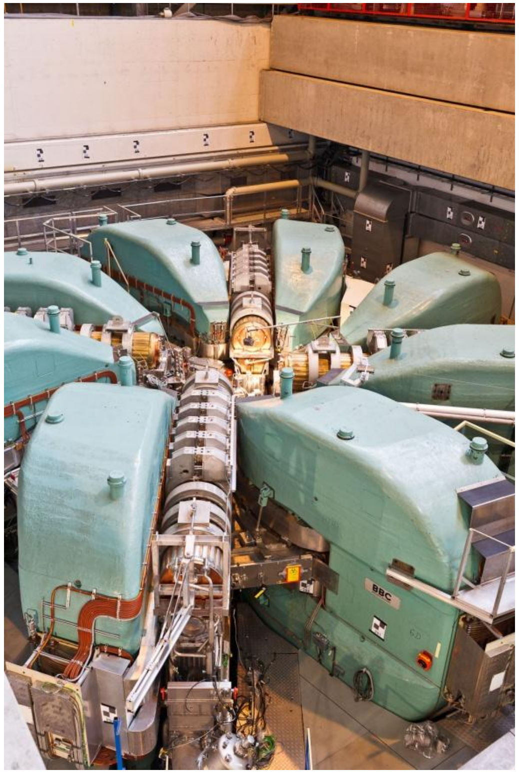
components: sector magnets

- cyclotron magnets typically cover a wide radial range $\rightarrow$ magnets are heavy and bulky, thus costly

PSI sector magnet

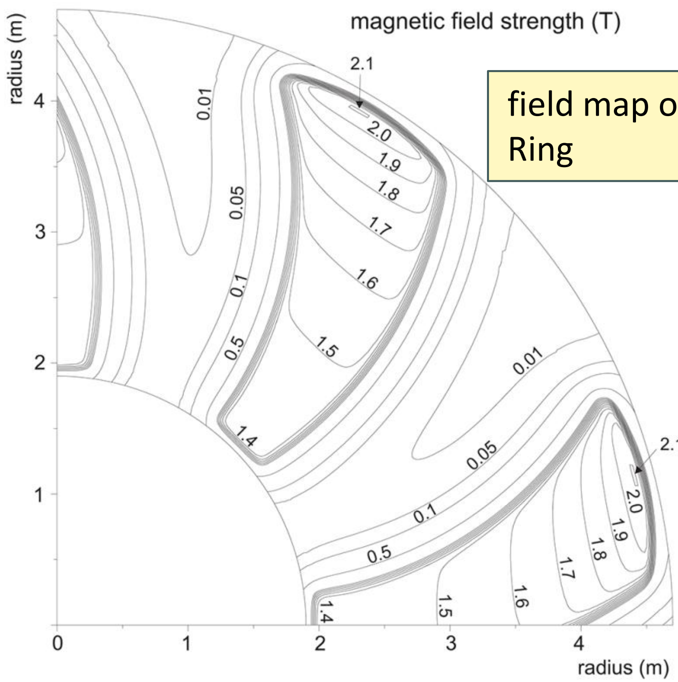
iron weight: 250 tons
coil weight: 28 tons
orbit radius: 2.1…4.5 m
spiral angle: 35 deg





components: sector magnets

- focusing and isochronicity need to be precisely controlled $\rightarrow$ sophisticated pole shaping including spiral bounds, many trim coil circuits
- modern cyclotrons use superconducting magnets; but for high intensity compactness is generally disadvantageous



field map of PSI Ring

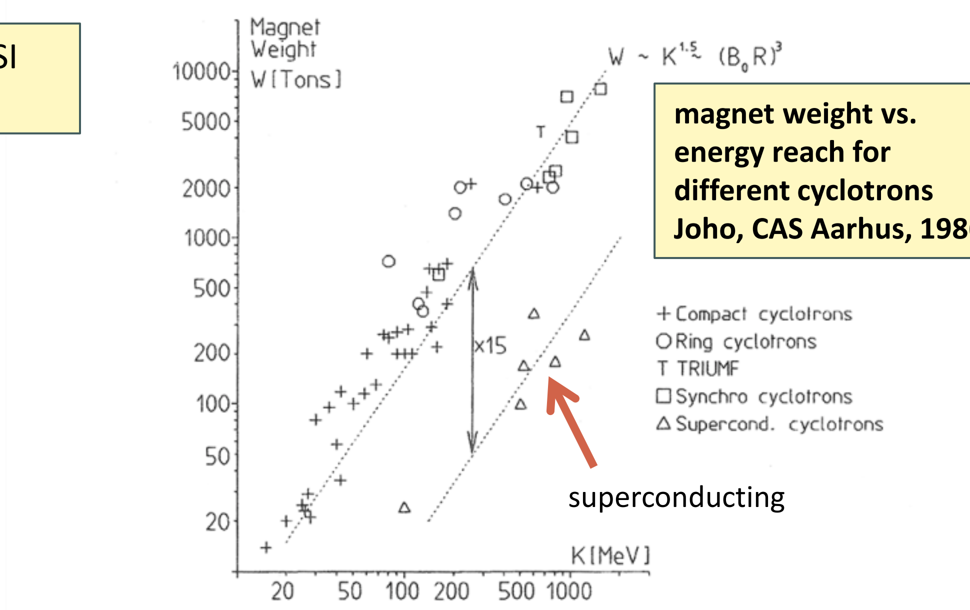


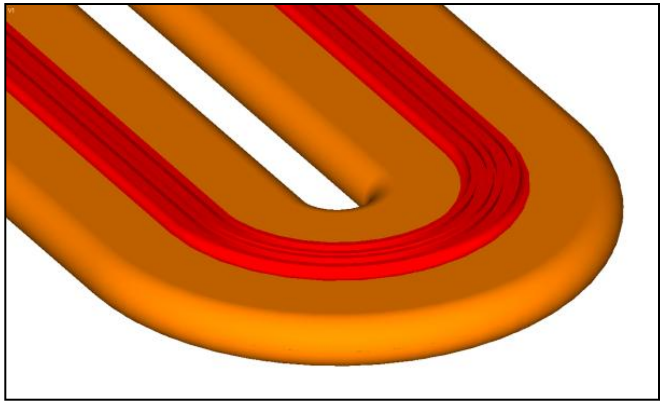
Fig. 6 Magnet weight W versus K-value for different cyclotrons and synchrocyclotrons.

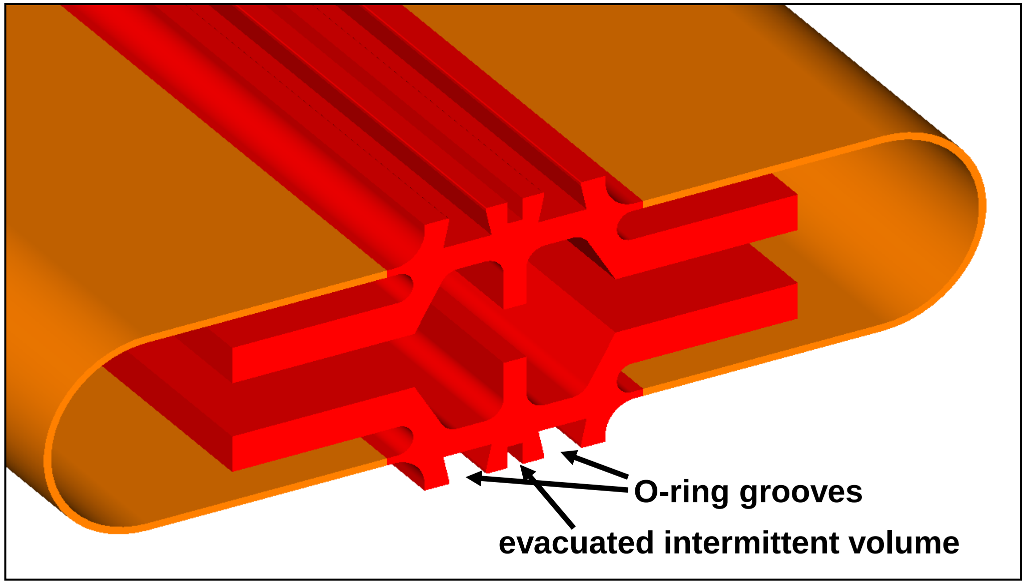
magnet weight vs. energy reach for different cyclotrons Joho, CAS Aarhus, 1986

cyclotron vacuum system

- pressure of 10^{-6} mbar is sufficient
- vacuum chamber with large radial width $\rightarrow$ difficult to achieve precisely matching sealing surfaces$\rightarrow$ noticeable leak rates must be accepted
- important design criterion is easy access and fast mountability
- use cryo pumps with high pumping speed and capacity

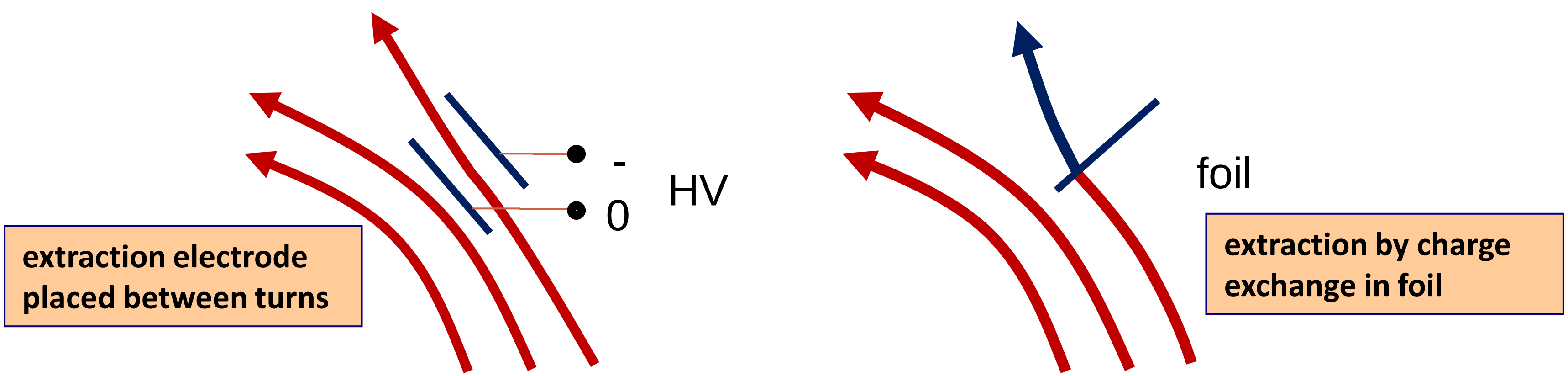
example: inflatable seals installed between resonators; length: 3.5m



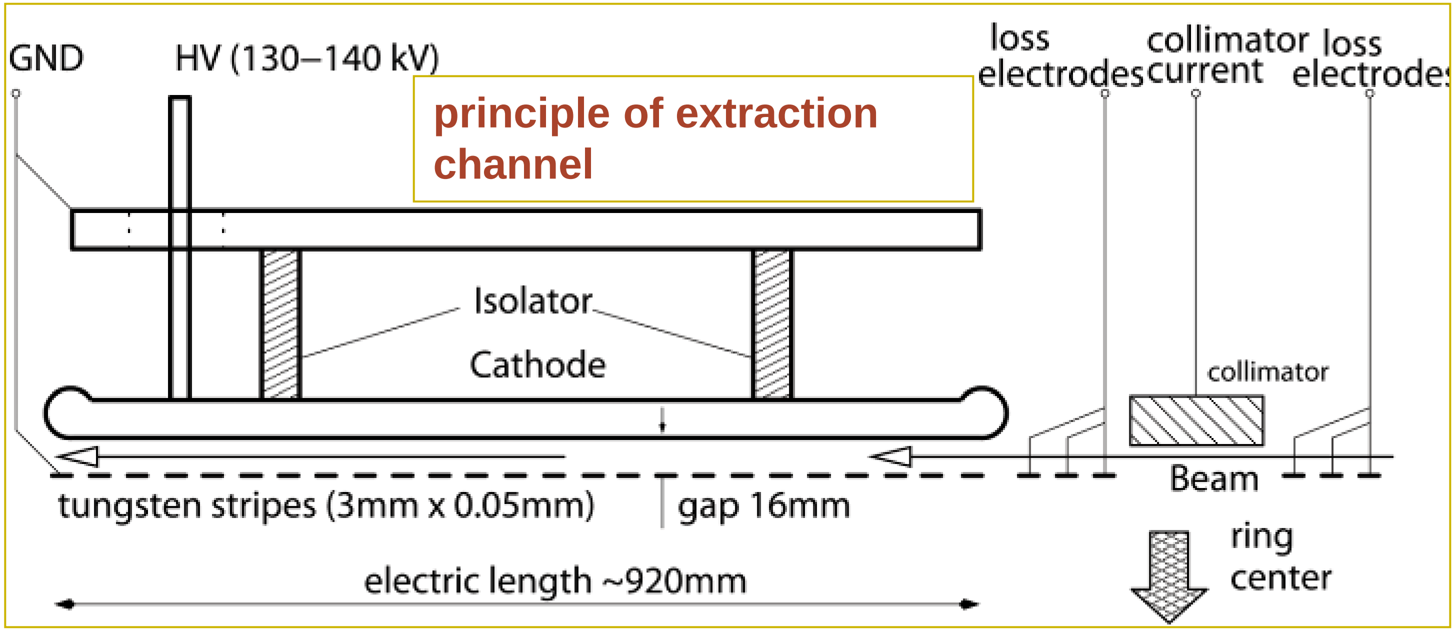


injection/extraction schemes

- deflecting element should affect just one turn, not neighboured turn → critical, cause of 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



parameters extraction chan.:

E_k= 590MeV

E = 8.8 MV/m

θ = 8.2 mrad

ρ = 115 m

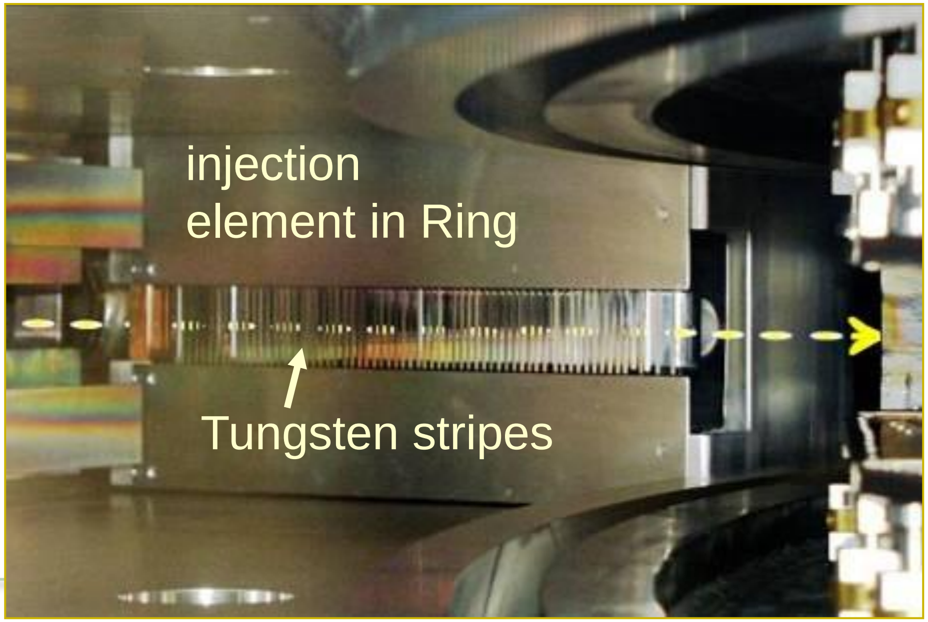
U = 144 kV

major loss mechanism is scattering in 50µm electrode!

electric rigidity:

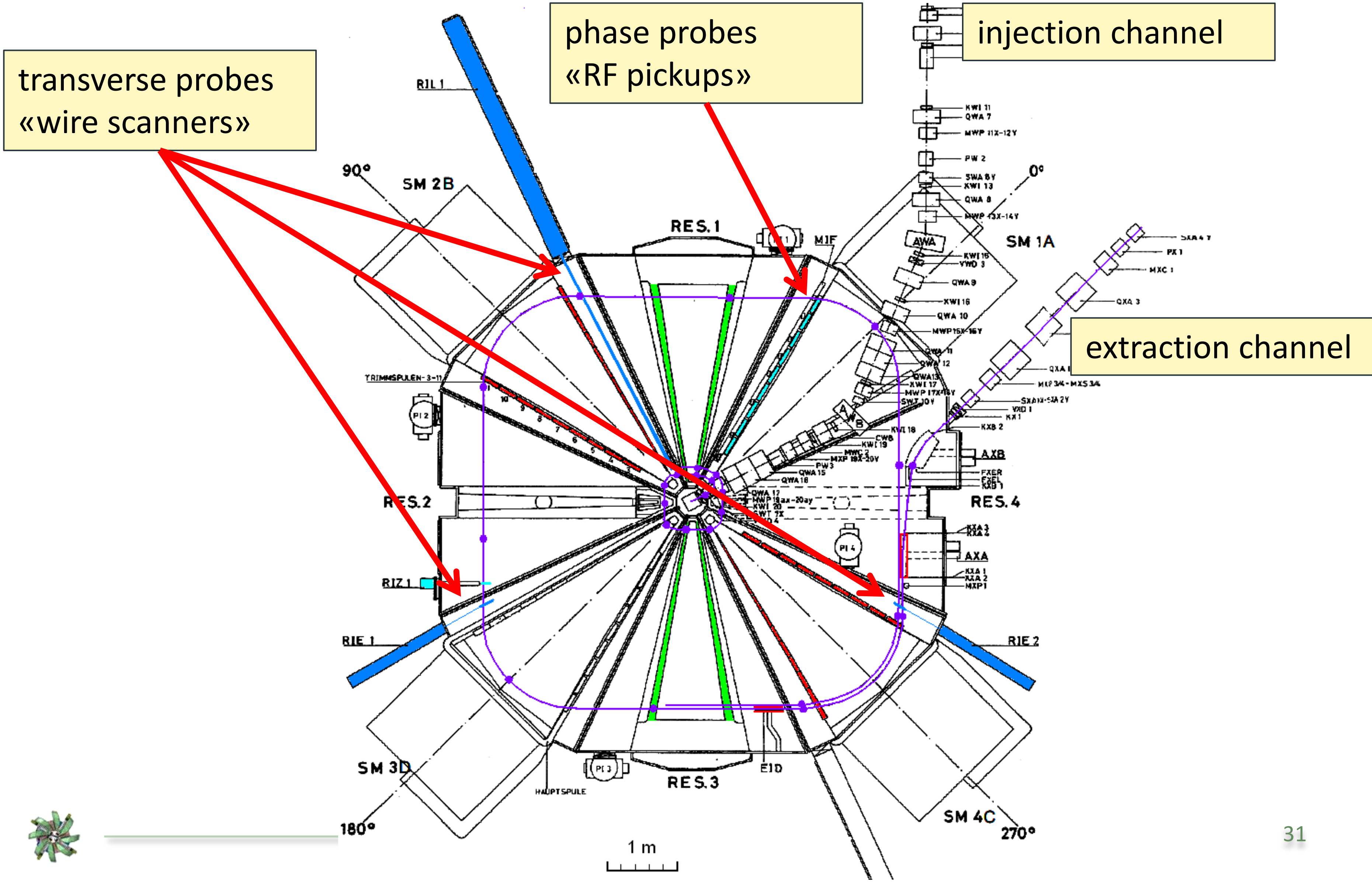
$$E\rho = \frac{\gamma+1}{\gamma}\frac{E_k}{q} \approx 2U_k$$

for small energy; U_k= accelerating voltage the particle has passed



cyclotron instrumentation

example: PSI 72MeV injector cyclotron



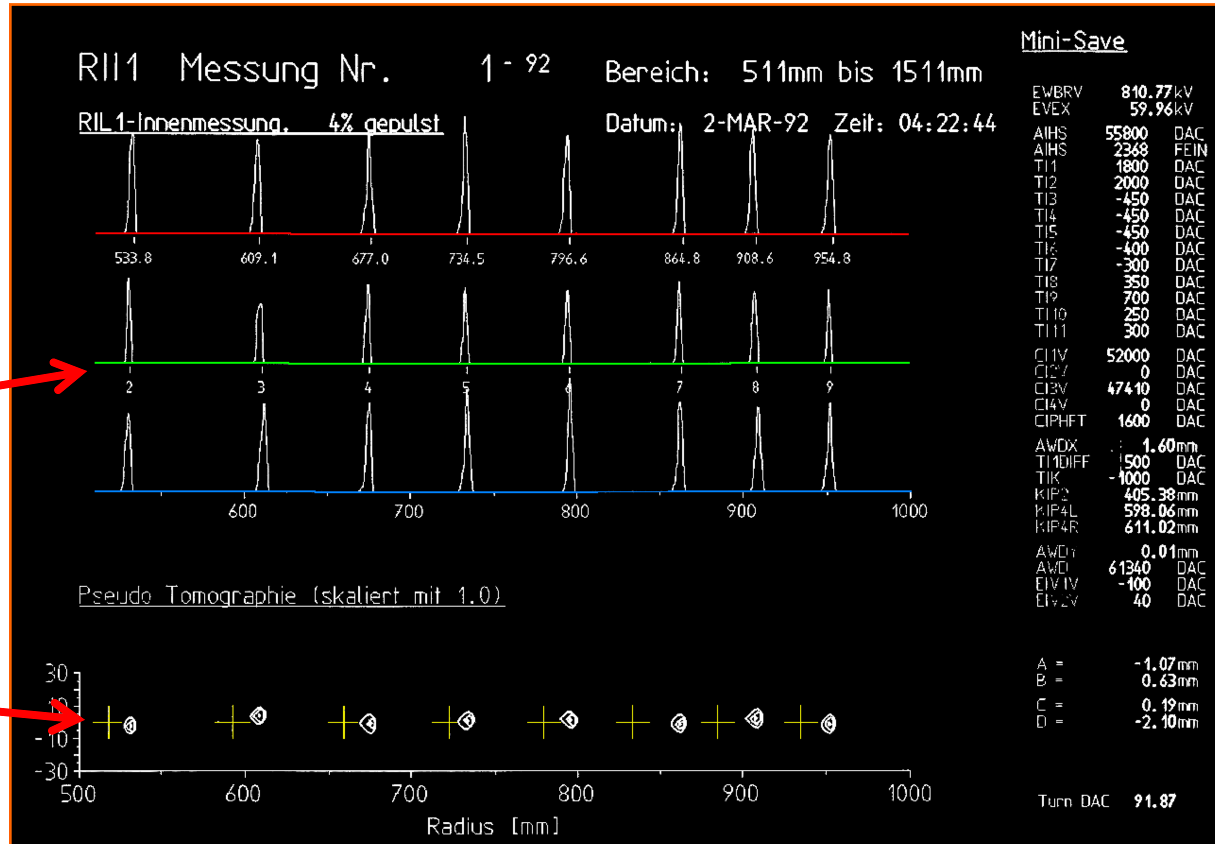
instrumentation: radial probe for turn counting / orbit analysis

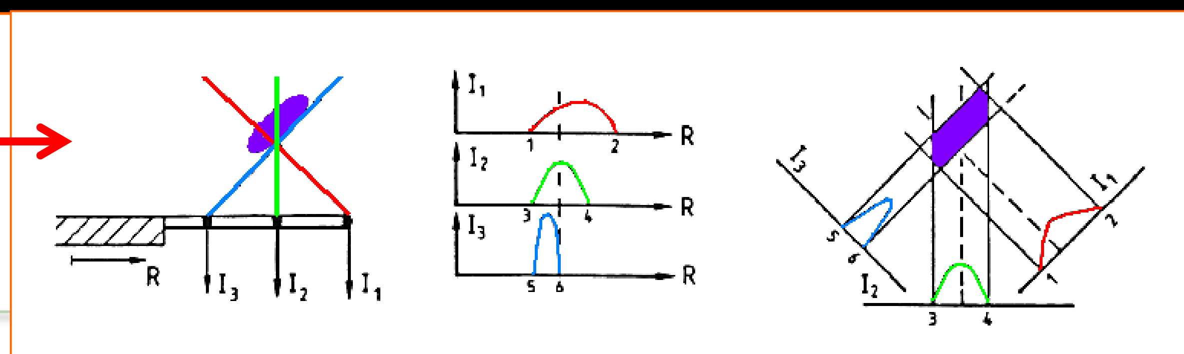
wire scanner with three tilted wires delivers radial beam profile and some vertical information

radial: positions of individual turns

vertical/radial orbit positions and stored reference orbit (crosses)

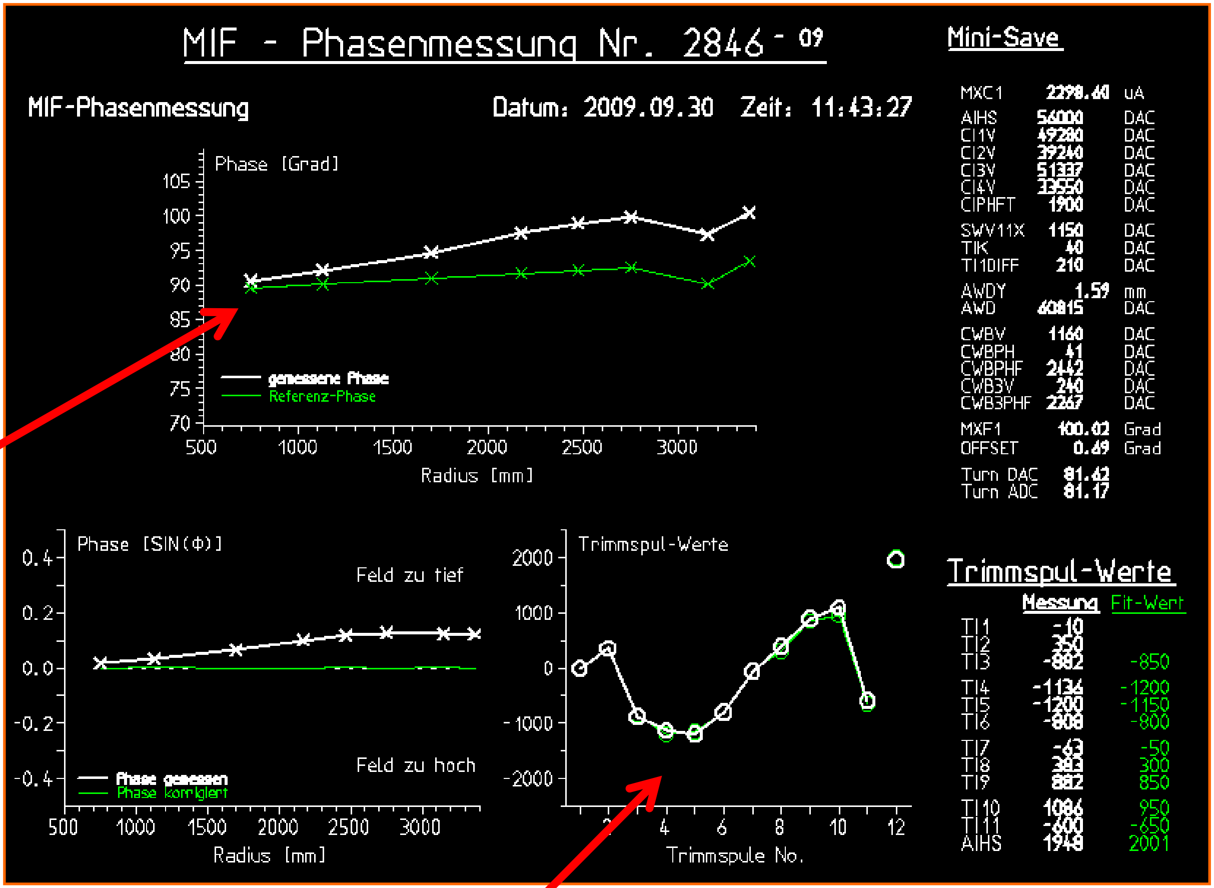
«pseudo tomography» with tilted wires





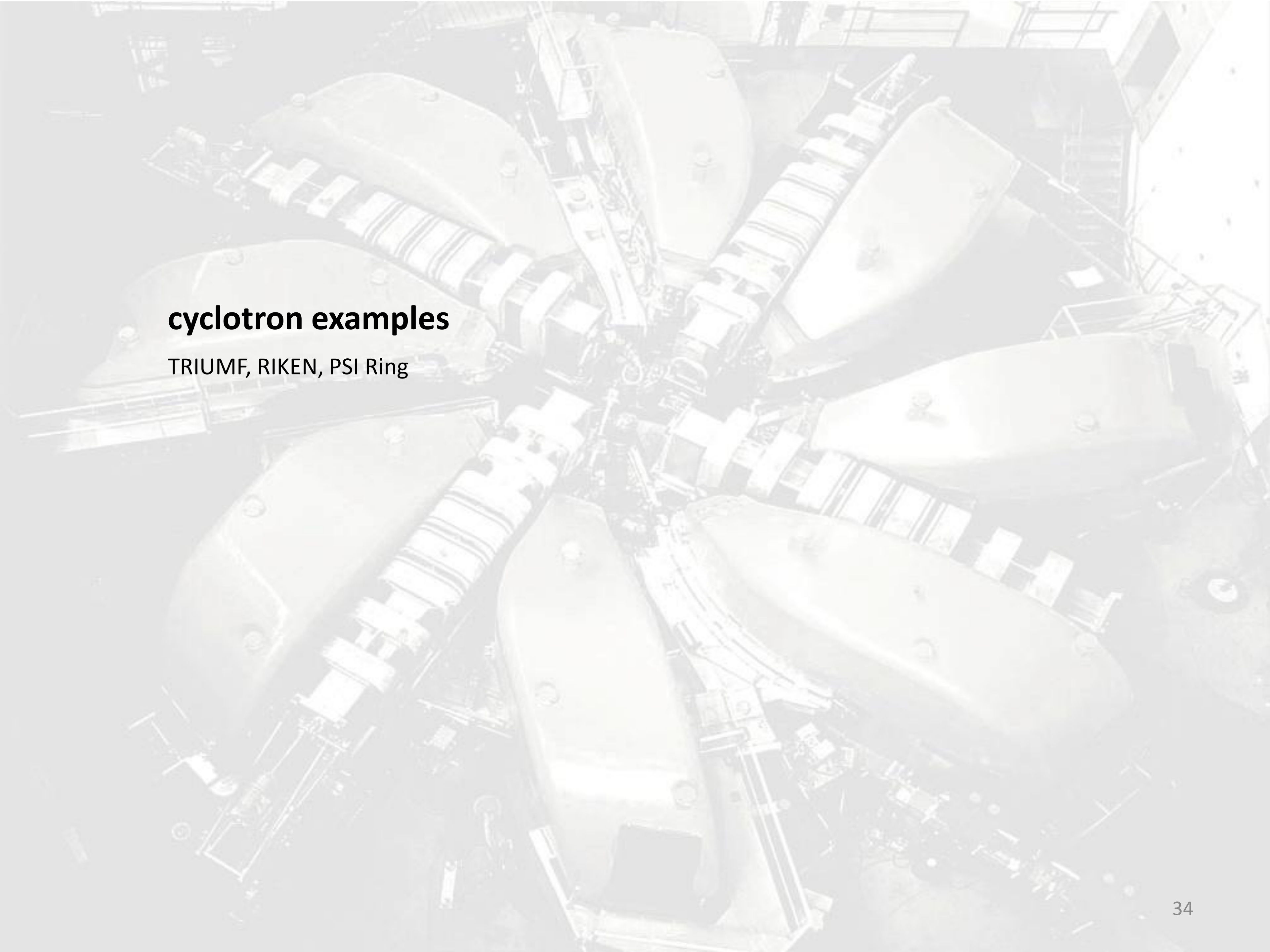
instrumentation: phase probes

phase probes are radially distributed RF pickups that detect the arrival time (phase) of bunches vs radius
→ adjustment of isochronicity



measured phase vs. radius;
green: reference phase for «good conditions»

trim coil settings (12 circuits across radius)
green: predicted from phase measurement

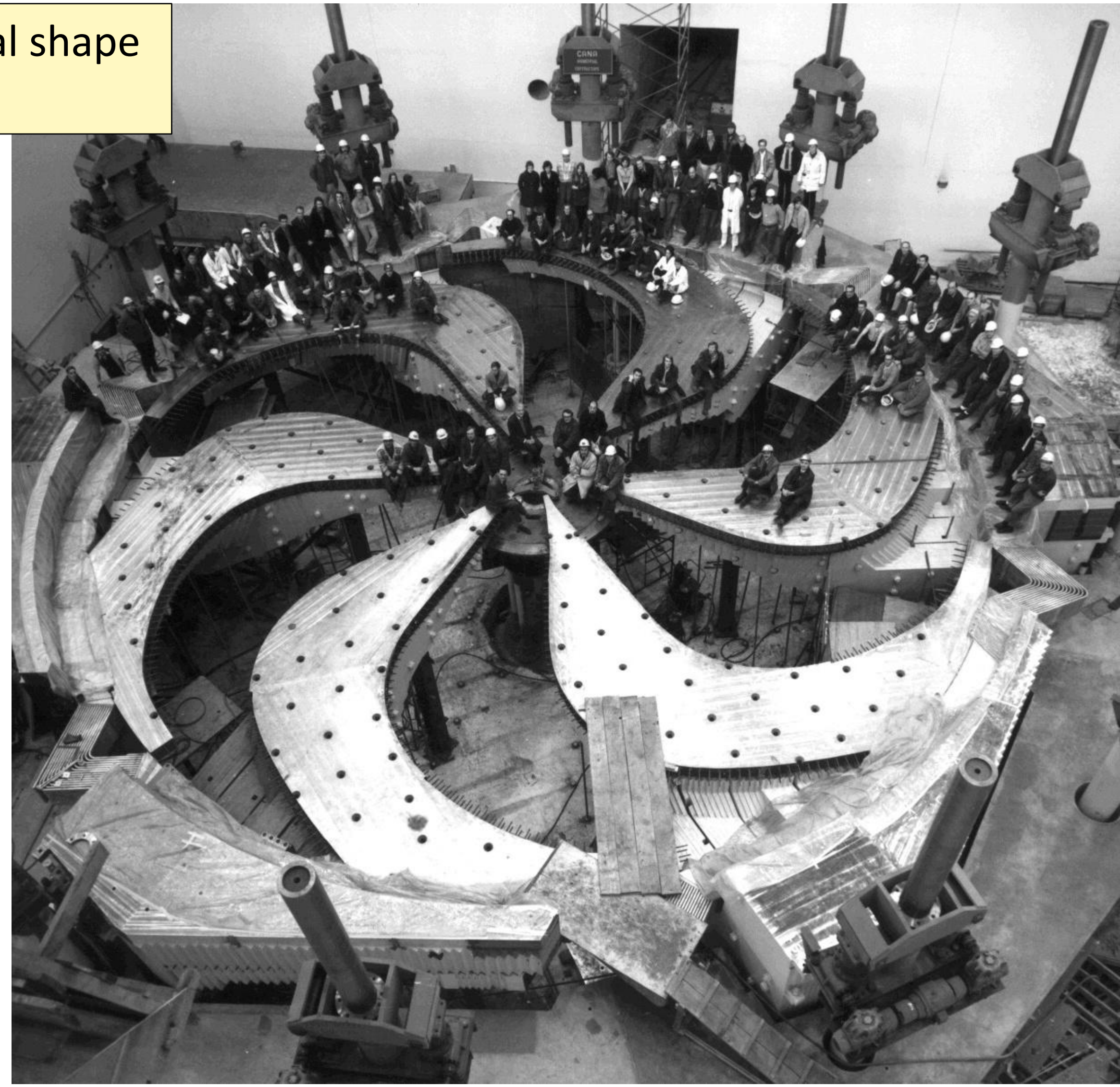


cyclotron examples

TRIUMF, RIKEN, PSI Ring

cyclotron examples: TRIUMF

photo: iron poles with spiral shape ($\delta_{\mathrm{max}} = 70°$)



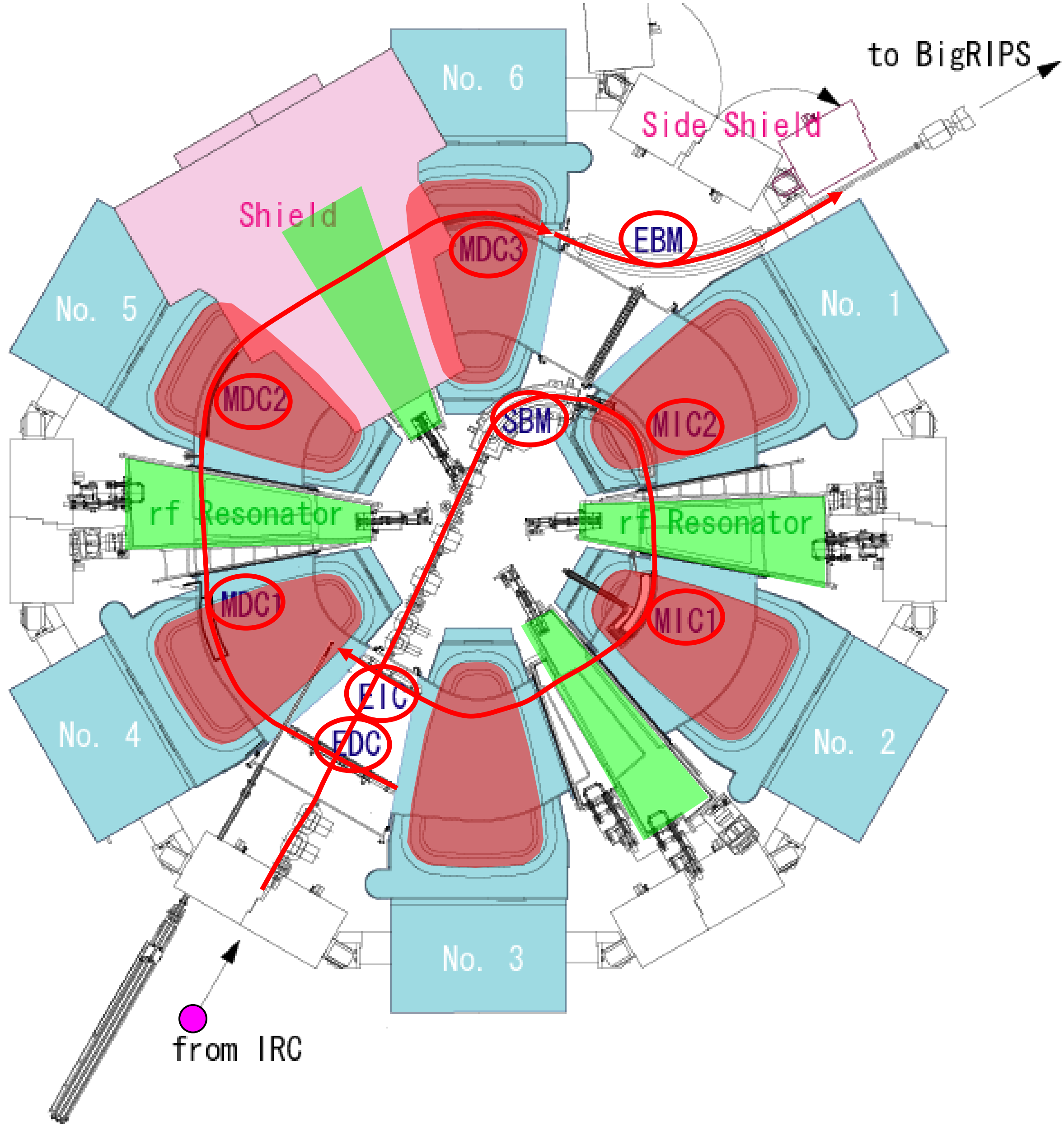
- p, 520MeV, up to 110kW beam power
- diameter: 18m (largest n.c. cyclotron worldwide)
- extraction by stripping H^- $\rightarrow$ variable energy; multiple extraction points possible

cyclotron examples: RIKEN (Jp) superconducting cyclotron

K = 2,600 MeV
Max. Field: 3.8T (235 MJ)
RF frequency: 18-38 MHz
Weight: 8,300 tons
Diameter: 19m
Height: 8m

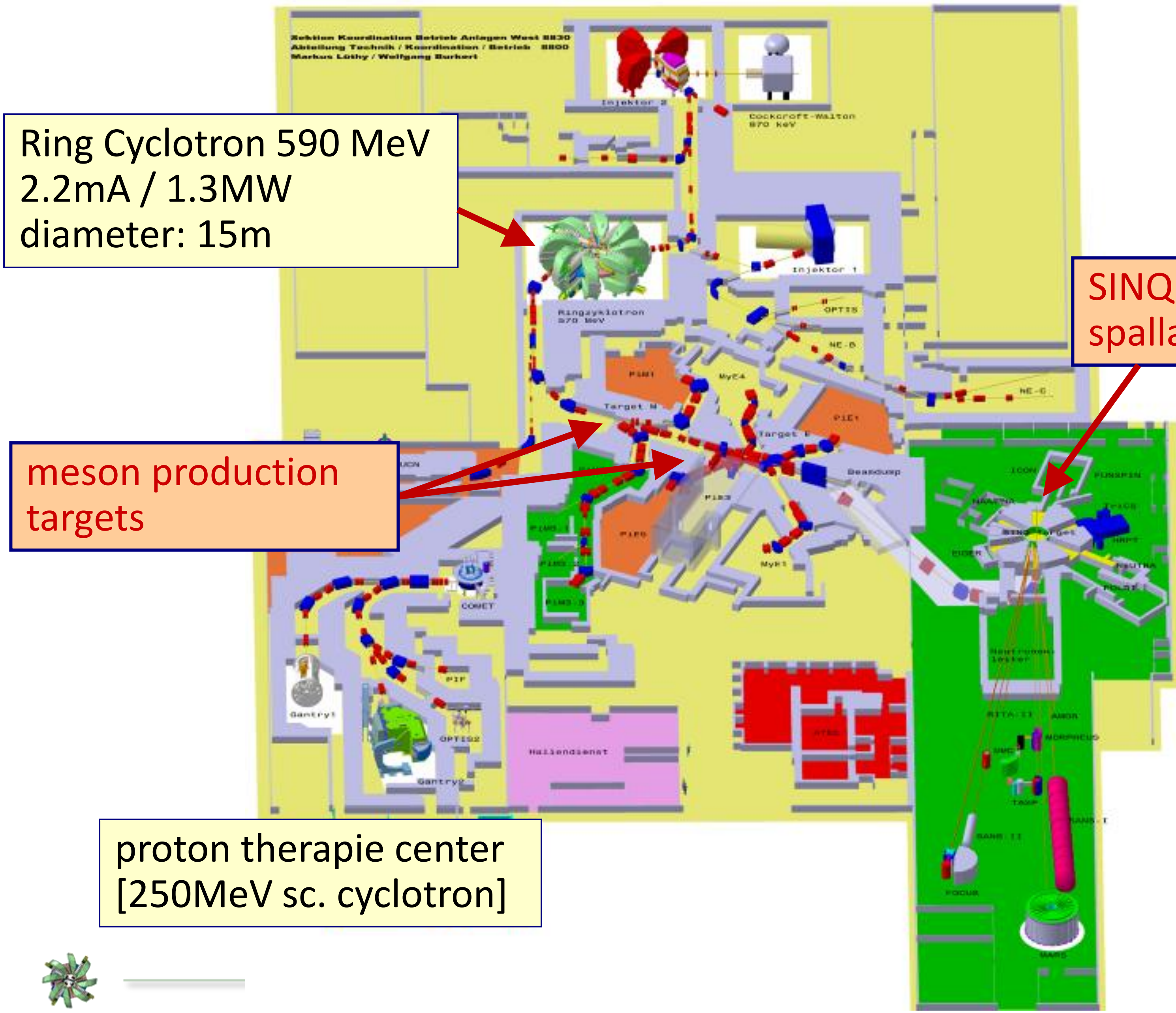
superconducting
Sector Magnets :6
RF Resonator :4
Injection elements.
Extraction elements.

utilization:
broad spectrum of
ions up to Uranium



RIKEN SRC in the vault

examples: PSI High Intensity Proton Accelerator

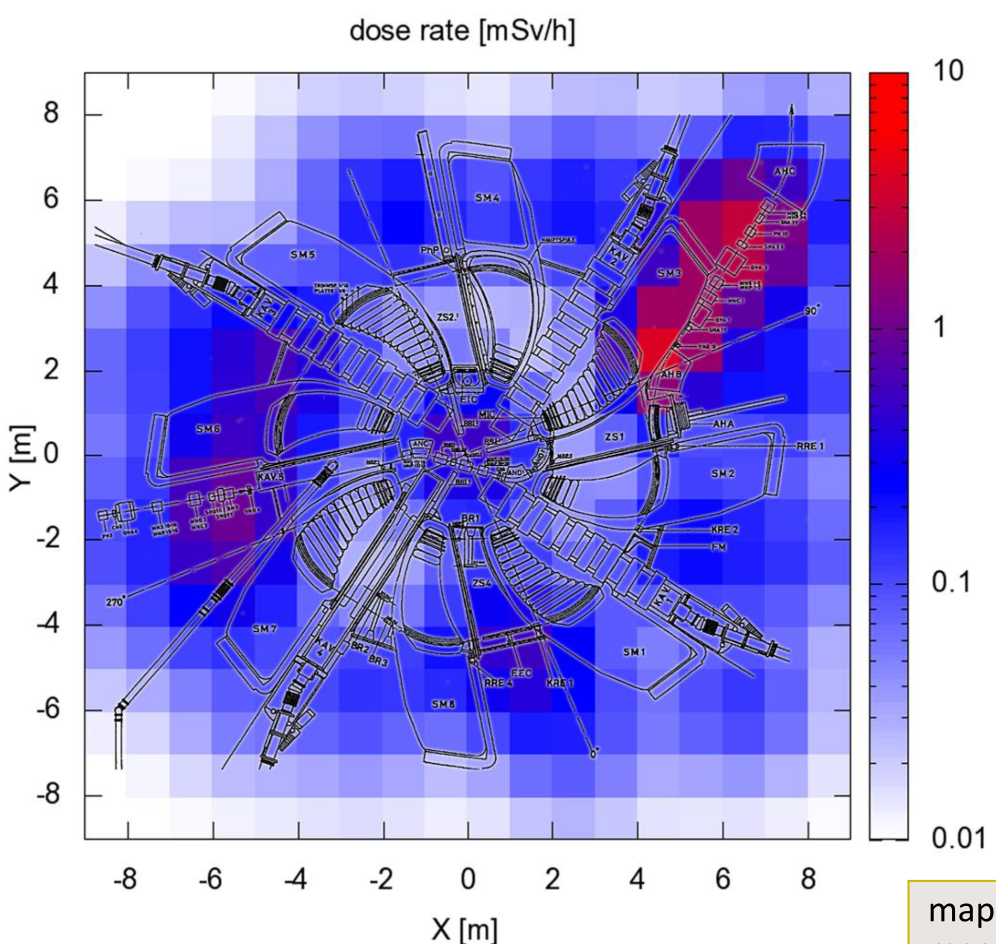


dimensions:

120 x 220m^2

losses and resulting activation in PSI Ring

- maximum intensity is limited by losses (typ. 200-400nA) and **activation**
- losses at extraction dominate the activation
- thus efforts at optimizing performance are concentrated on the extraction
  → largest possible turn separation; design of electrostatic septum



map interpolated from ~30 measured locations

activation level allows for necessary service/repair work

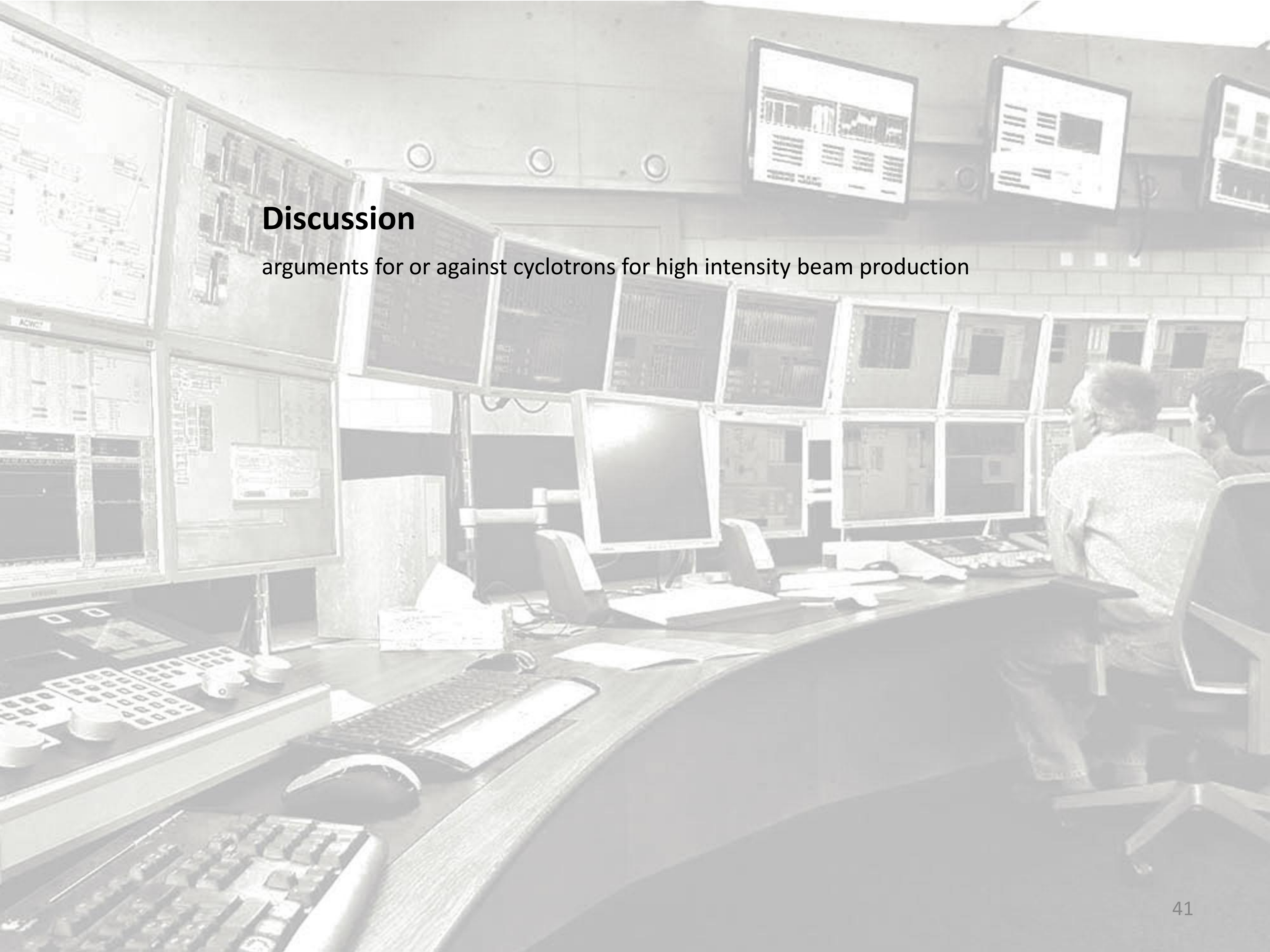
- personnel dose for typical repair mission 50-300μSv
- optimization by adapted local shielding measures; shielded service boxes for exchange of activated components
- detailed planning of shutdown work

example (2010):
personnel dose for 3 month shutdown:

47mSv, 186 persons
max per person: 2.9mSv

comparison of cyclotrons

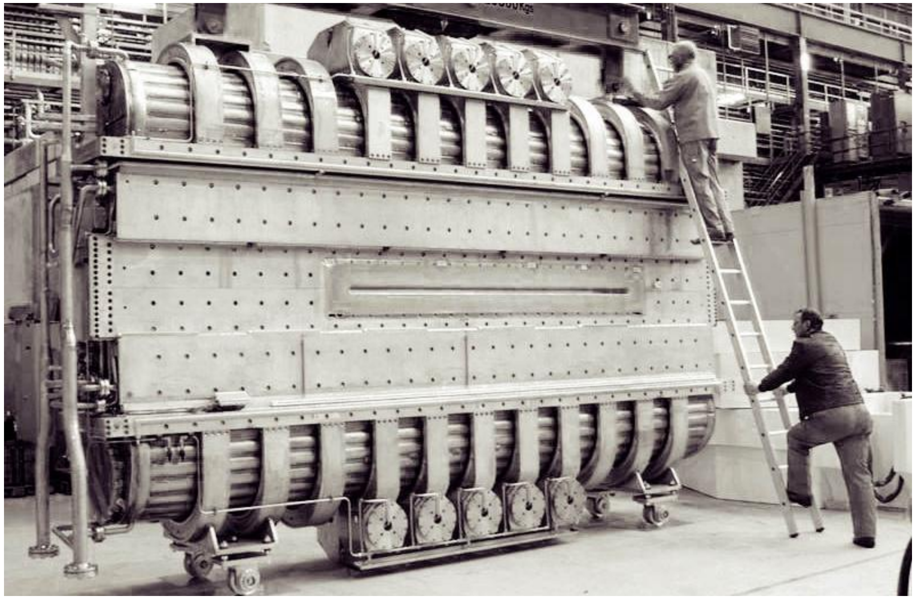
	TRIUMF	RIKEN SRC (supercond.)	PSI Ring	PSI medical (supercond.)
particles	H- $\rightarrow$ p	ions	p	p
K [MeV]	520	2600	592	250
magnets (poles)	(6)	6	8	(4)
peak field strength [T]	0.6	3.8	2.1	3.8
R_{inj}/R_{extr} [m]	0.25/3.8…7.9	3.6/5.4	2.4/4.5	-/0.8
P_{max} [kW]	110	1 (86Kr)	1300	0.25
extraction efficiency (tot. transmission)	0.9995 (0.70)	(0.63)	0.9998	0.80
extraction method	stripping foil	electrostatic deflector	electrostatic deflector	electrostatic deflector
comment	variable energy	ions, flexible	high intensity	compact



Discussion

arguments for or against cyclotrons for high intensity beam production

pro and contra cyclotron



pro:
- compact and simple design
- efficient power transfer
- only few resonators and amplifiers needed

con:
- injection/extraction critical
- energy limited to 1GeV
- complicated bending magnets
- elaborate tuning required

other:
- naturally CW operation

thank your for your attention !