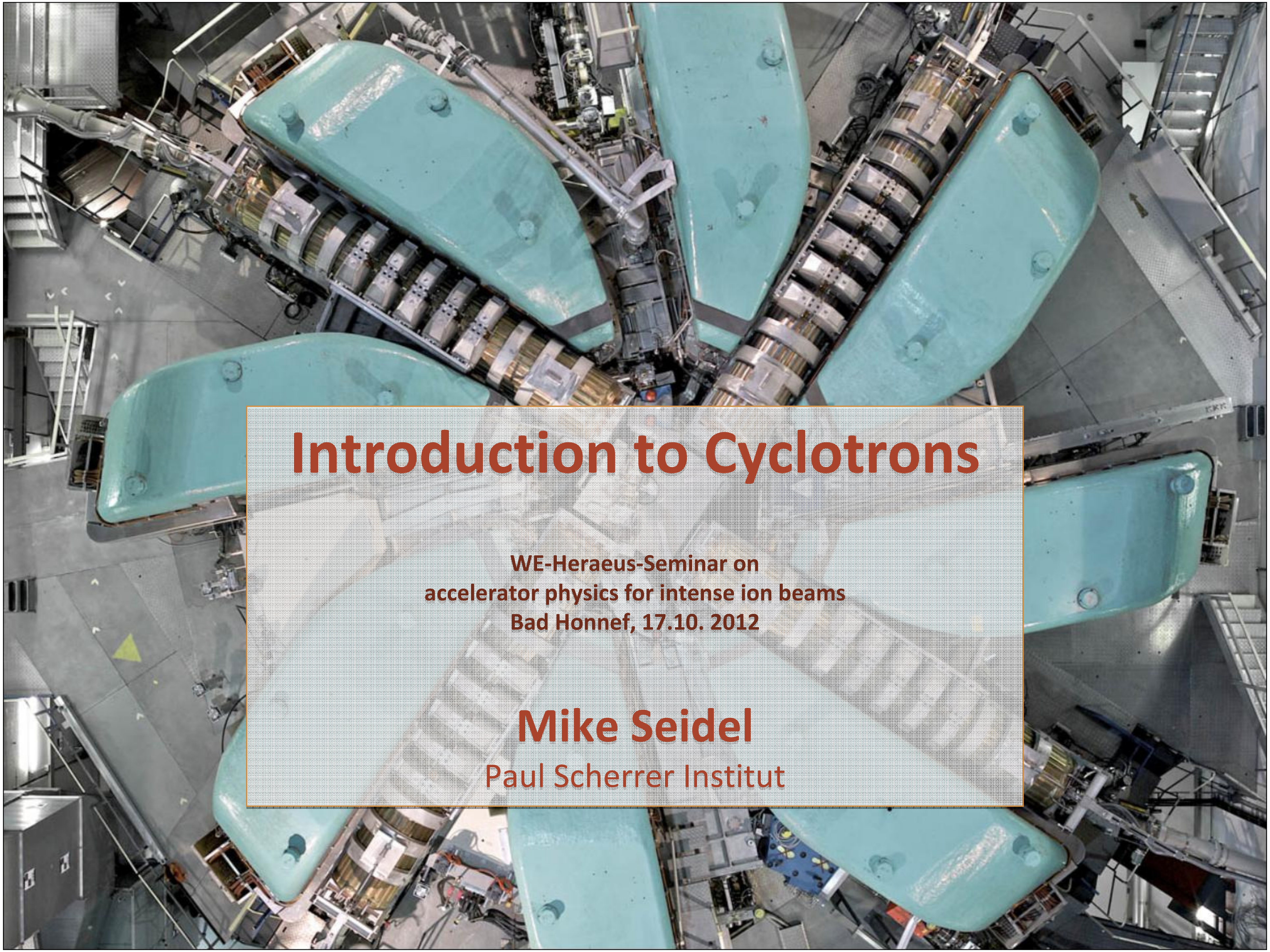


Introduction to Cyclotrons

WE-Heraeus-Seminar on
accelerator physics for intense ion beams
Bad Honnef, 17.10. 2012

Mike Seidel
Paul Scherrer Institut

Cyclotrons - Outline

- the classical cyclotron

  history of the cyclotron, basic concepts and scalings, classification of circular accelerators and cyclotron-like acceler.

- separated sector cyclotrons

  focusing in Thomas-cyclotrons, spiral angle, classical extraction: pattern/stepwidth, transv./long. space charge

- cyclotron subsystems

  extraction schemes, RF systems/resonators, magnets, vacuum issues, instrumentation

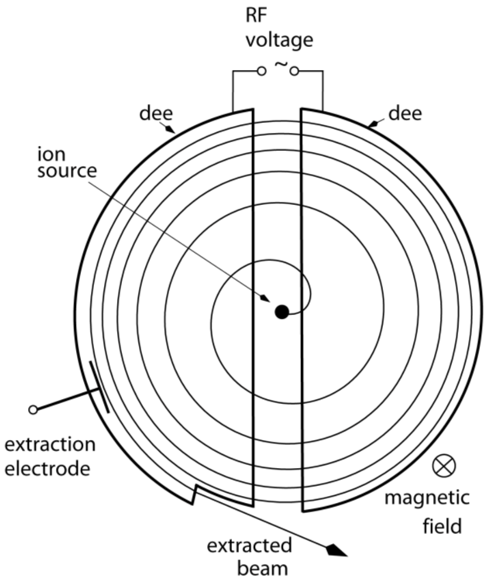
- applications and examples of existing cyclotrons

  TRIUMF, RIKEN SRC, PSI Ring, PSI medical cyclotron

- discussion

  Pro's and Con's of cyclotrons for different applications

The Classical Cyclotron



two capacitive electrodes „Dees“, two gaps per turn

internal ion source

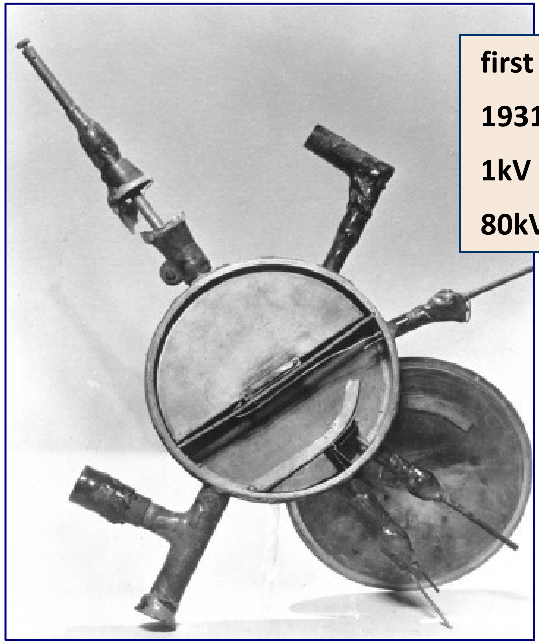
homogenous B field

constant revolution time

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

powerful concept:

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

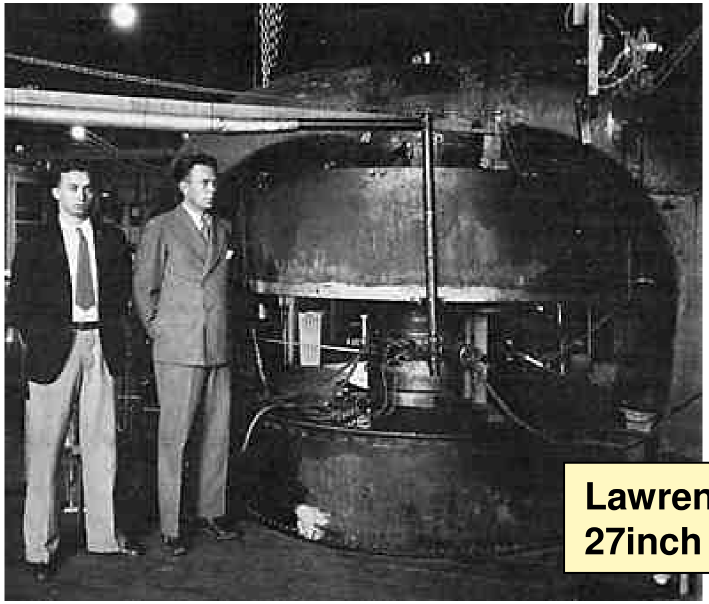


first cyclotron:

1931, Berkeley

1kV gap-voltage

80kV Protons



Lawrence & Livingston, 27inch Zyklotron

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

classical cyclotron - isochronicity and scalings

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

magnetic rigidity:

$$BR = \frac{p}{e} = \beta\gamma\frac{m_0 c^2}{e}$$

orbit radius from isochronicity:

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

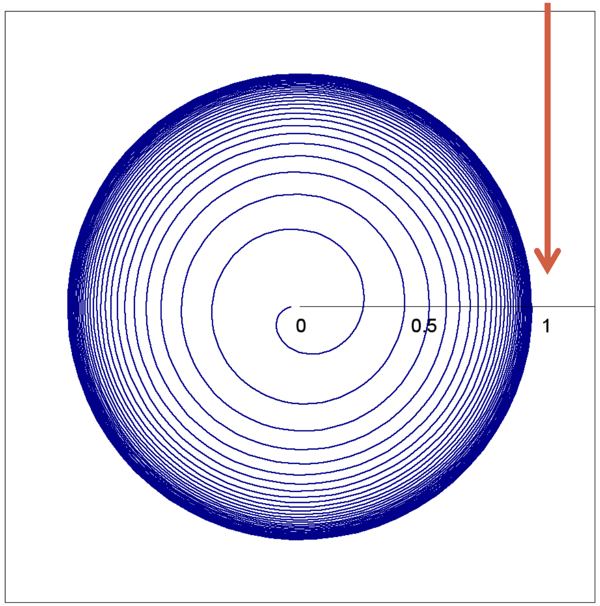
deduced scaling of *B*:

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

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

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

$$R_\infty = R/\beta$$



field index

the field index describes the (normalized) radial slope of the bending field:

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

from isochronous condition:
$B \propto \gamma$, $R \propto \beta$

relativistic quantities in the context of cyclotrons

A.Einstein
1879-1955

energy

$$E = \gamma E_0$$

kinetic energy:

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

velocity

$$v = \beta c$$

revolution time:

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

momentum

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

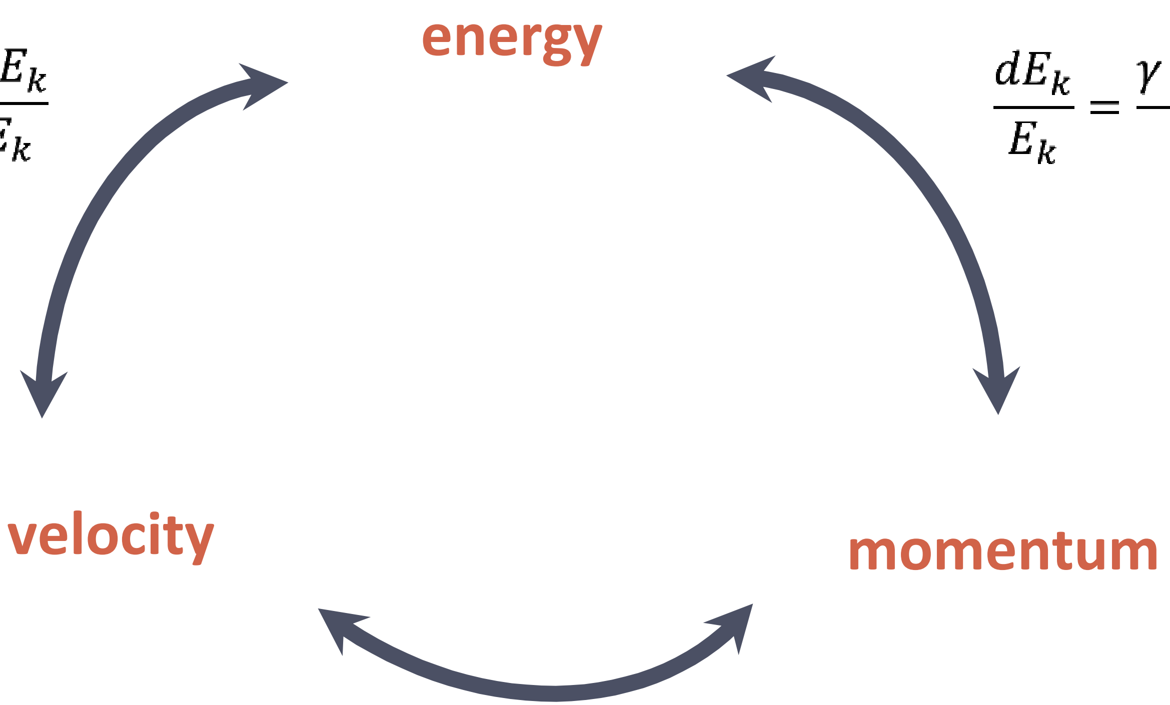
bending strength:

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

useful for calculations – differential relations

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

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



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

equation of motion in a classical cyclotron

centrifugal force mv^2/r

Lorentz force $qv\times B$

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

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

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

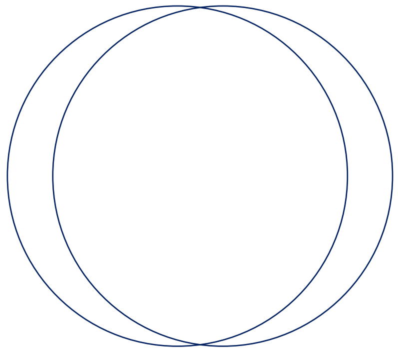
using: $\omega_{\mathrm{c}} = qB_z/m \approx v/R,\ r\dot{\varphi} \approx v, k = \frac{R}{B}\frac{dB}{dR}$

betatron tunes in cyclotrons

thus in radial plane:

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

note: simple case for *k = 0*: $\nu_r = 1$
(one circular orbit oscillates w.r.t the other)



using Maxwell to relate B_z and B_R:

$$\mathrm{rot}\,\vec{B} = \frac{dB_R}{dz} - \frac{dB_z}{dR} = 0$$

in vertical plane:

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

k<0 to obtain vertical focus.

thus: in classical cyclotron *k < 0* required;
however this violates isochronous condition *k* = γ^2-1 > *0*

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

separated sector cyclotron
[separated magnets, resonators]

synchro-cyclotron
[varying RF frequency]

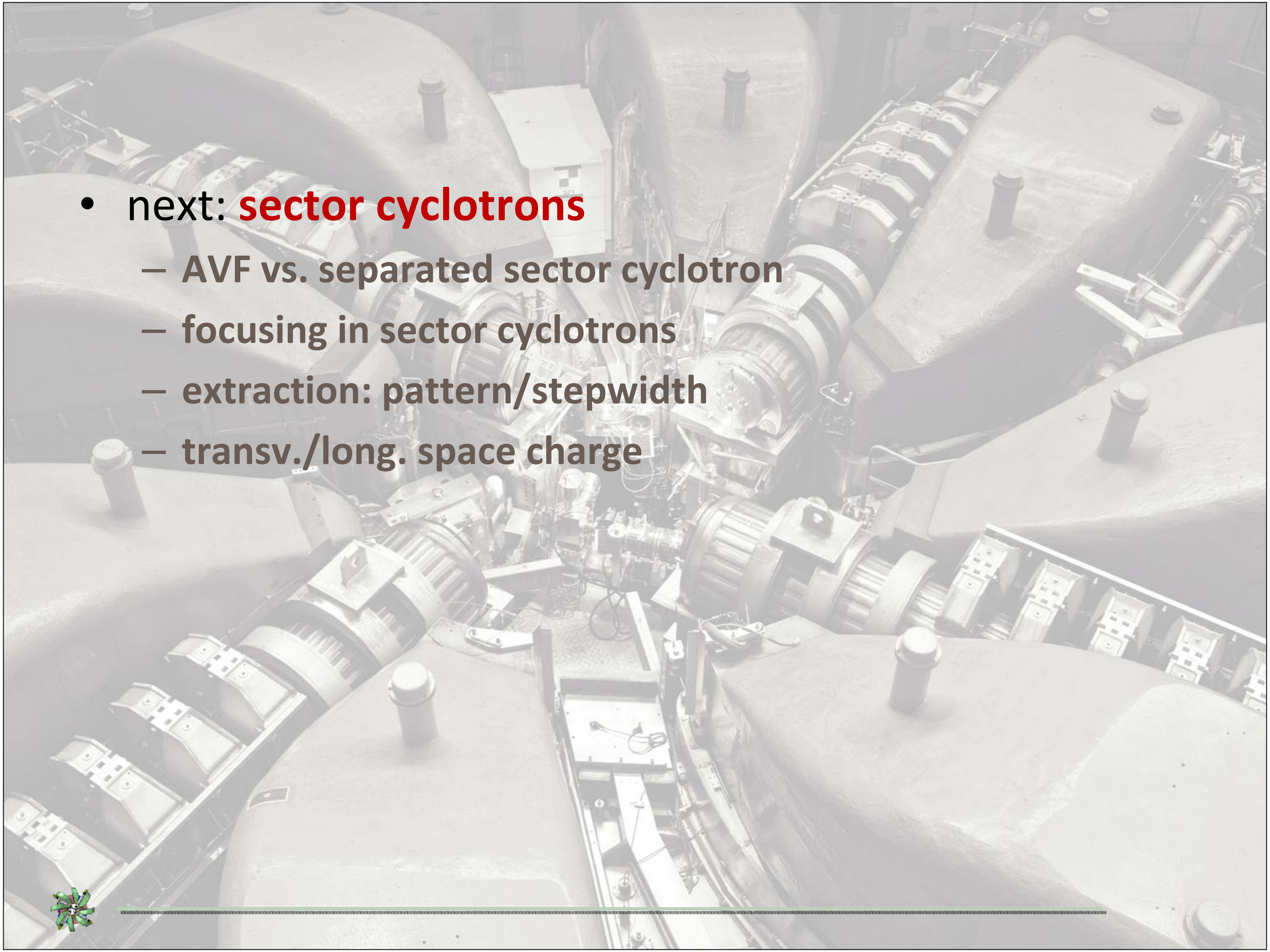
Fixed Focus Alternating Gradient Accelerator FFAG
[varying RF, strong focusing]

high intensity

high energy

compact machine


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



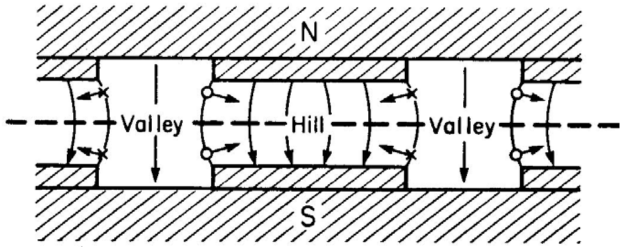
- next: **sector cyclotrons**
  - AVF vs. separated sector cyclotron
  - focusing in sector cyclotrons
  - extraction: pattern/stepwidth
  - transv./long. space charge

focusing in sector cyclotrons

hill / valley variation of magnetic field (Thomas focusing) makes it possible to design cyclotrons for higher energies

Flutter factor:

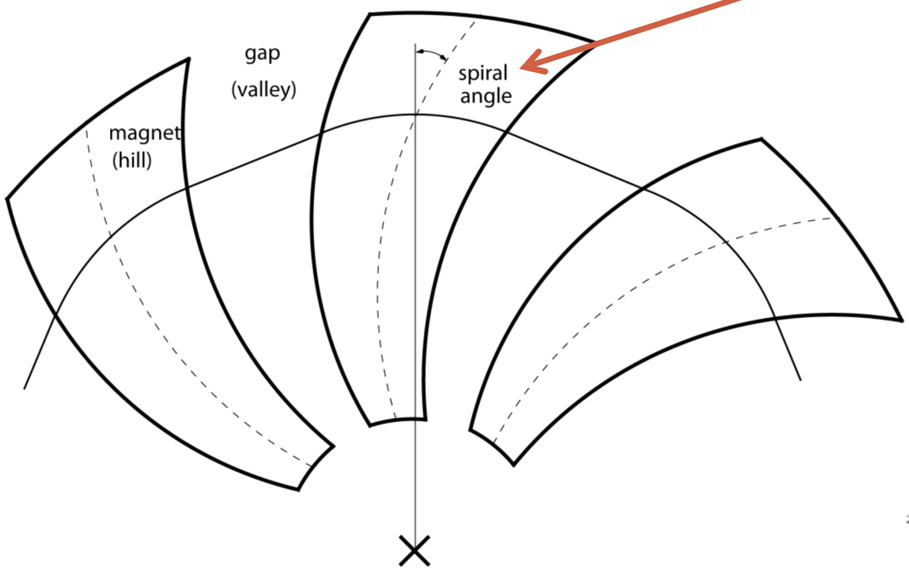
$$F^2 = \frac{\overline{B_z^2} - \overline{B_z}^2}{\overline{B_z}^2}$$



[illustration of focusing at edges]

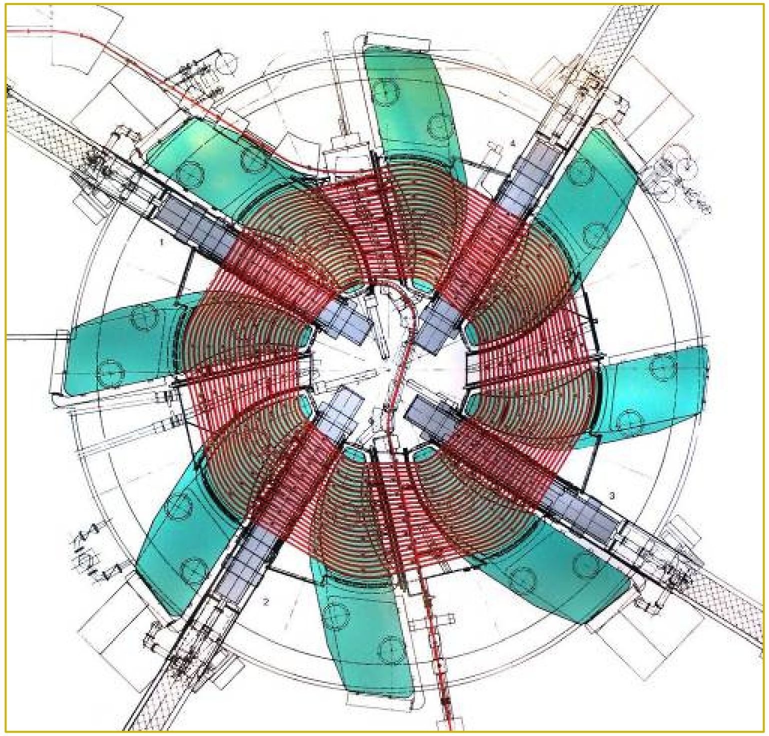
with flutter and additional spiral angle of bending field:

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



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
- **compact**, cost effective
- **internal source** possible
- **D-type RF electrodes**, relatively low energy gain
- 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% = $(1 - 2\cdot10^{-4})$

derivation of stepwidth / turn separation

$$BR = \sqrt{\gamma^2 - 1}\,\frac{m_0 c}{e} \quad \Rightarrow \quad \frac{dB}{B} + \frac{dR}{R} = \frac{\gamma\, d\gamma}{\gamma^2 - 1}$$

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

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

$$\frac{d\gamma}{dn_t} = \frac{U_t}{m_0 c^2}$$

radius change per turn

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

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

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

isochronicity not conserved (just few outer turns)

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

isochronicity conserved (general scaling)

stepwidth - discussion

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 for isochronous cyclotron:

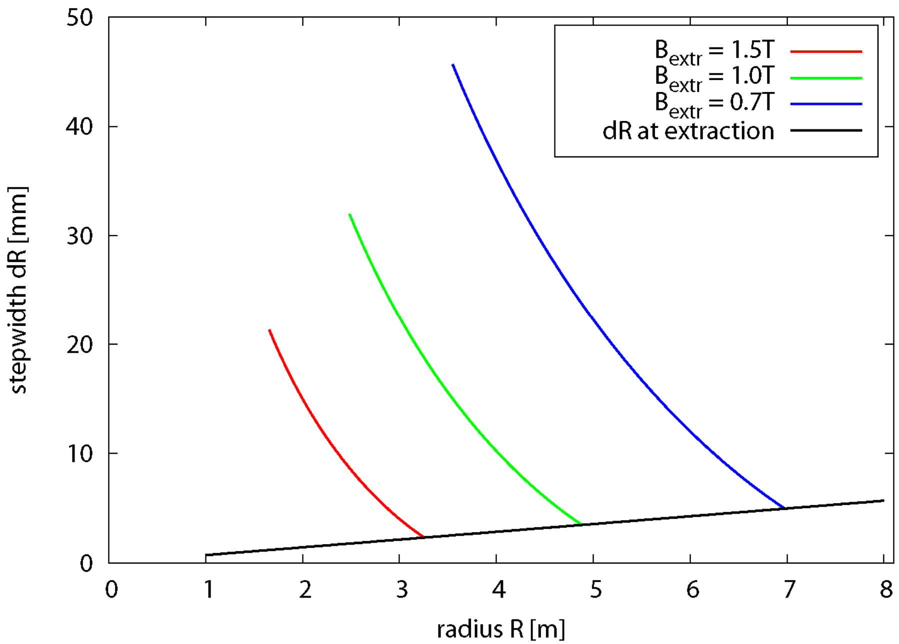
$$\Delta R(R_{\mathrm{extr}}) = \frac{U_t}{m_0 c^2} \frac{R_{\mathrm{extr}}}{(\gamma^2 - 1)\gamma}$$

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

non-relativistic approx., scaling during acceleration:

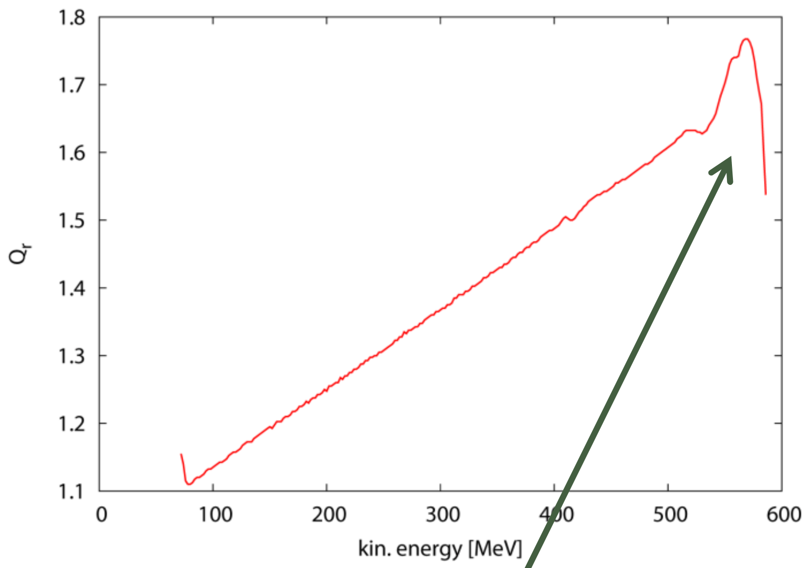
$$\frac{dR}{dn_t} \approx \frac{U_t}{m_0 c^2} \frac{R}{\beta^2} \rightarrow \Delta R(R) \propto \frac{1}{R}$$

illustration:
stepwidth vs. radius in cyclotrons of different sizes;
100MeV inj $\rightarrow$ 800MeV extr

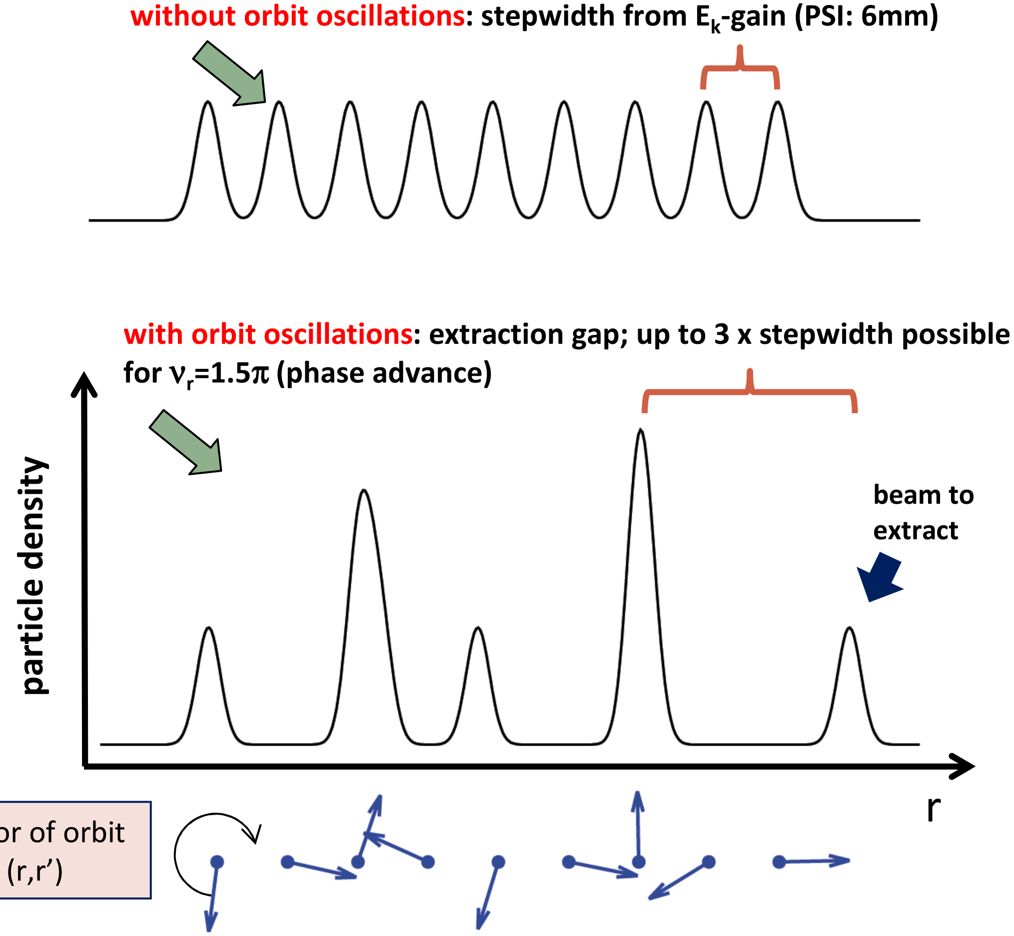


extraction with off-center orbits

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



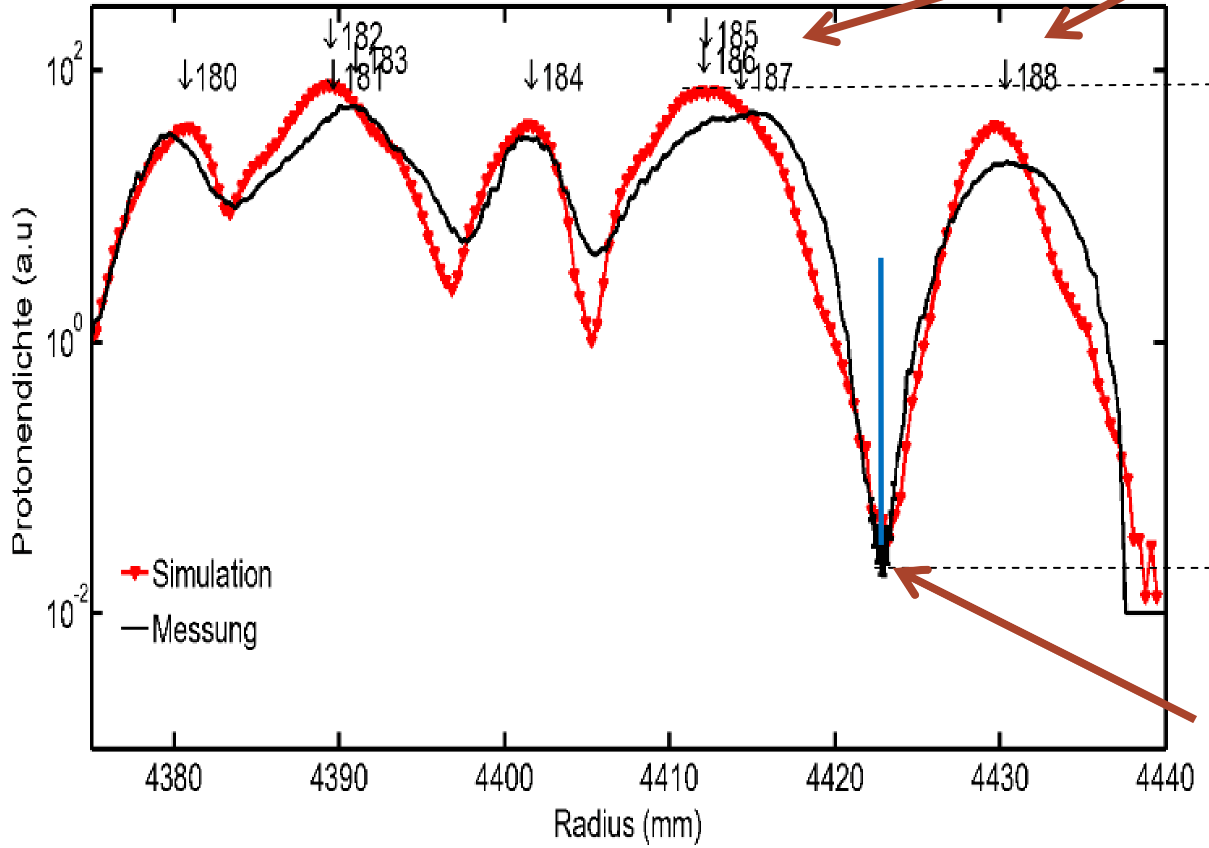
radial tune vs. energy (PSI Ring)
typically $\nu_r \approx \gamma$ during acceleration;
but decrease in outer fringe field



phase vector of orbit oscillations (r,r')

extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement



turn numbers

dynamic range:
factor 2.000 in
particle density

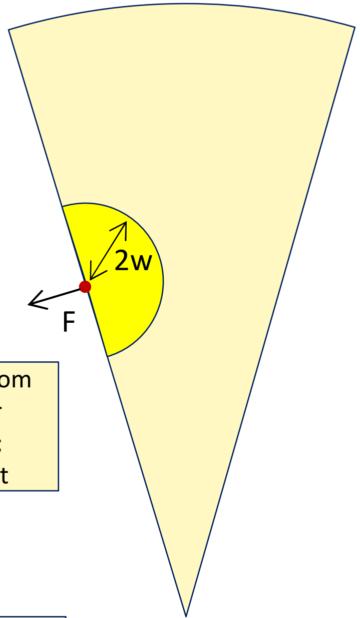
position of extraction septum

d=50µm

[Y.Bi et al]

longitudinal space charge

sector model (W.Joho, 1981):
aim: compute **total energy spread** after acceleration process generated by longitudinal electric field
- consider rotating sectors of charge
- uniform charge distribution (overlapping turns)
- test particle "sees" only fraction of sector due to shielding of vacuum chamber with gap height 2*w*



$$E_\theta \approx \frac{\rho}{\varepsilon_0} \cdot \frac{a \ln\left(4\frac{w}{a}\right)}{\pi}$$

geometry factor from integration over "visible" charge; 2a = beam height

$$\rho = \frac{Q}{\Delta R \cdot 2\pi R \cdot D_f \cdot 2a} = \frac{I_p}{\beta c \cdot \Delta R \cdot 2a}$$

peak current = constant

$$\frac{dU_{sc}}{dn} = 2\pi e R E_\theta = \frac{e R_\infty I_p Z_0 \ln\left(4\frac{w}{a}\right)}{\Delta R}$$

accumulated energy spread per turn

turn separation → varies through acceleration

longitudinal space charge (cont.)

relation turn number / radius:

$$E_k \propto n_t \propto v^2 \propto R^2$$

non-relativistic !

$$R(n_t) = \sqrt{\frac{n_t}{n_{\max}}} R_{\max}$$

$$\frac{\Delta R}{\Delta n_t} = \frac{R_{\max}}{2\sqrt{n_t n_{\max}}}$$

next: integration over turns

front vs. trailing particle

$$\Delta U_{sc} = 2 \cdot \int_{n_t=0}^{n_{\max}} \frac{dU_{sc}}{dn} dn_t$$

$$= \frac{4eR_\infty I_p Z_0 \ln\left(4\frac{w}{a}\right)\sqrt{n_{\max}}}{R_{\max}} \int_{n_t=0}^{n_{\max}} \sqrt{n_t} dn_t$$

$$= \frac{8}{3} e I_p Z_0 \ln\left(4\frac{w}{a}\right) \cdot \frac{n_{\max}^2}{\beta_{\max}}$$

for w/a = 4

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

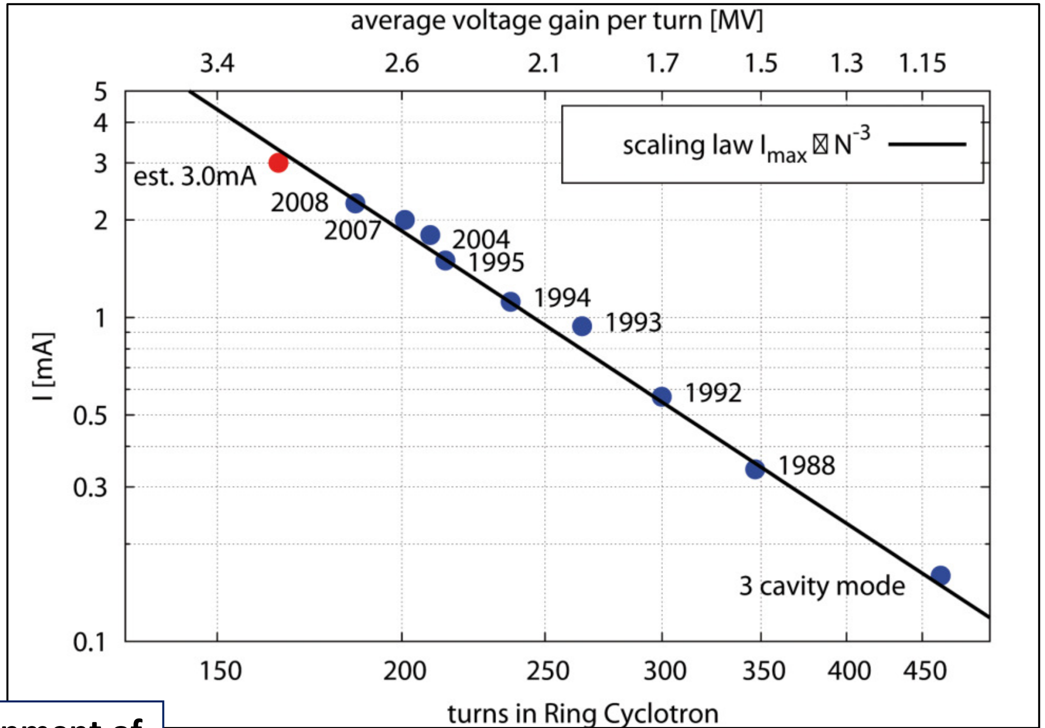
note: scaling with squared number of turns

- energy spread is converted to transverse tails → losses at extraction
- in addition: turn separation at extraction element scales with n_{max}^{-1}; thus attainable current at constant losses scales as n_{max}^{-3}

longitudinal space charge; evidence for third power law

- at PSI the maximum attainable current indeed scales with the third power of the turn number
- maximum energy gain per turn is of utmost importance in this type of high intensity cyclotron

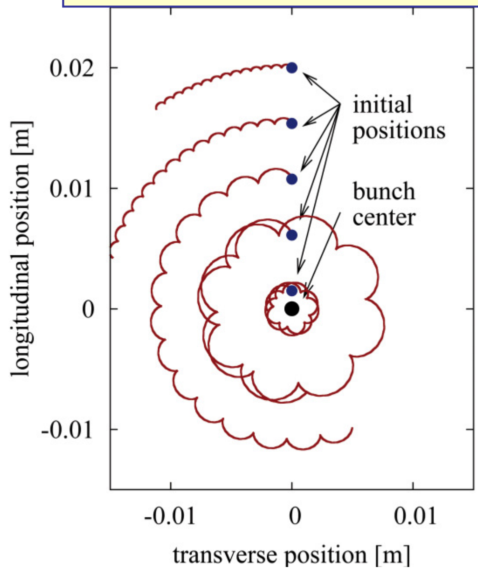
→ thus with constant losses at the extraction electrode the maximum attainable current scales as: $I_{max} \propto n_t^{-3}$



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



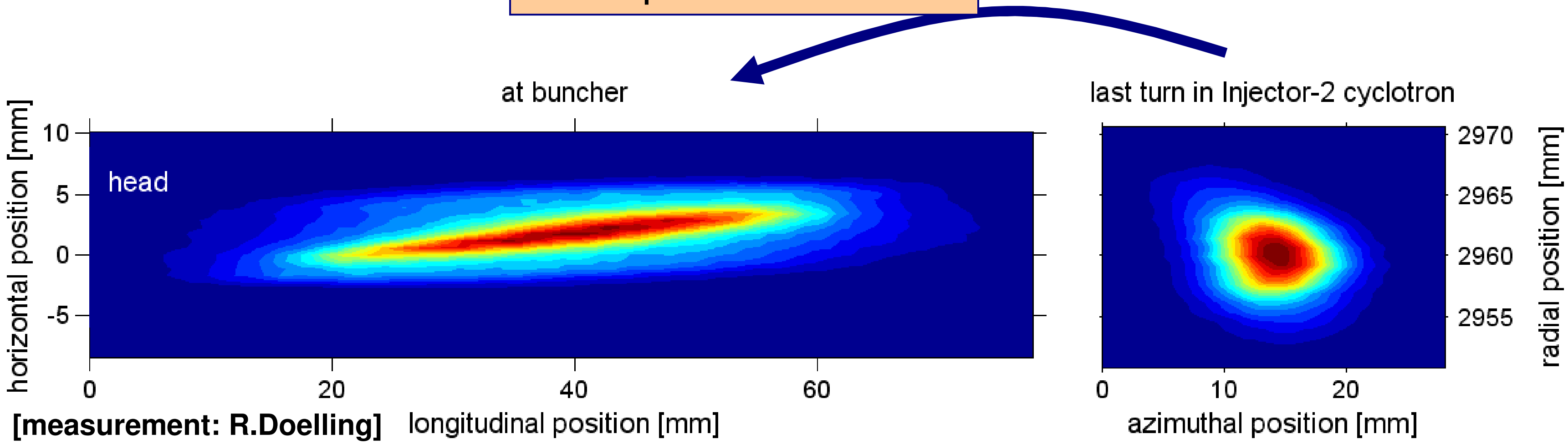
in theory

strong space charge within a bending field leads to rapid cycloidal motion around bunch center
[Chasman & Baltz (1984)]
→bound motion; circular equilibrium beam destribution
→see Ch.Baumgarten, ECPM 2012

in practice

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

blowup in ~20m drift



[measurement: R.Doelling]

transverse space charge

with overlapping turns use current sheet model!

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, $D_f = I_{avg}/I_{peak}$]

focusing force: $F_y = -\gamma m_0 \omega_c^2 \nu_{y0}^2 \cdot y$

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

$\rightarrow$ equating space charge and focusing force delivers an **intensity limit for loss of focusing**!

tune shift from forces:

$$\Delta\nu_y \approx -n_v \frac{2\pi r_p R^2}{\beta^2 \gamma^3 \nu_{y0}} \approx -\sqrt{2\pi} \frac{r_p R}{e\beta c \nu_{y0} \sigma_z} \frac{m_0 c^2}{U_t} I_{avg}$$

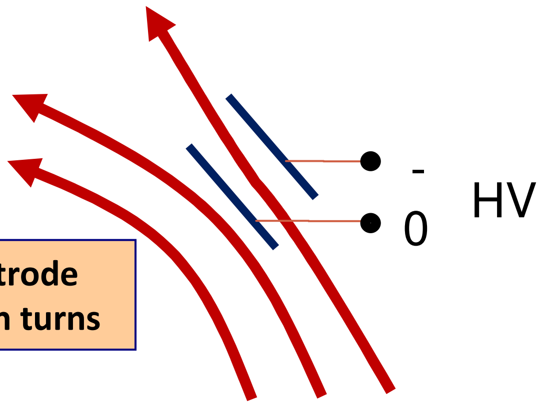
next: cyclotron subsystems

- extraction schemes
- RF systems/power efficiency
- cyclotron magnets
- comments on vacuum
- specific instrumentation

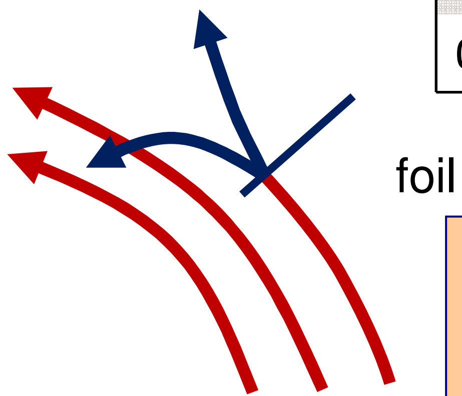
injection/extraction schemes

- 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; Lorentz dissociation: B-field low, scattering: vacuum 10^{-8}mbar)

binding	**energies**
H^-	H_2^+
0.75eV	15eV

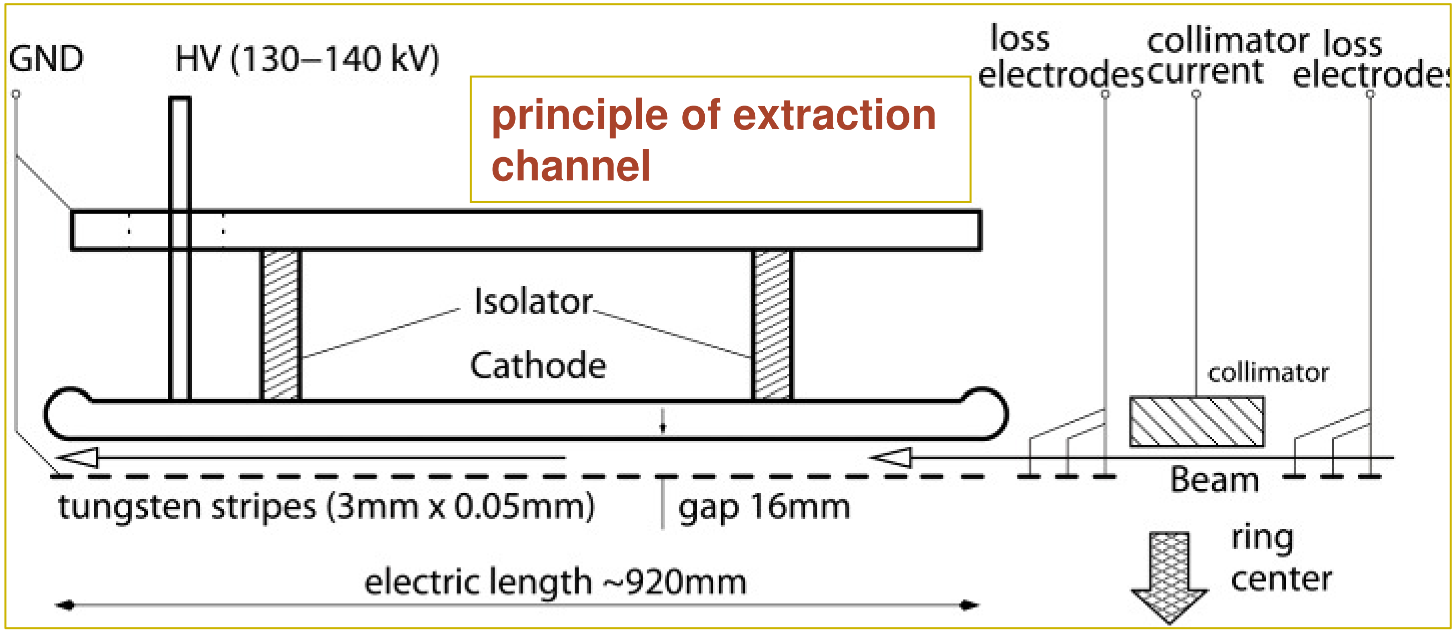


extraction electrode placed between turns



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

injection/extraction with electrostatic elements



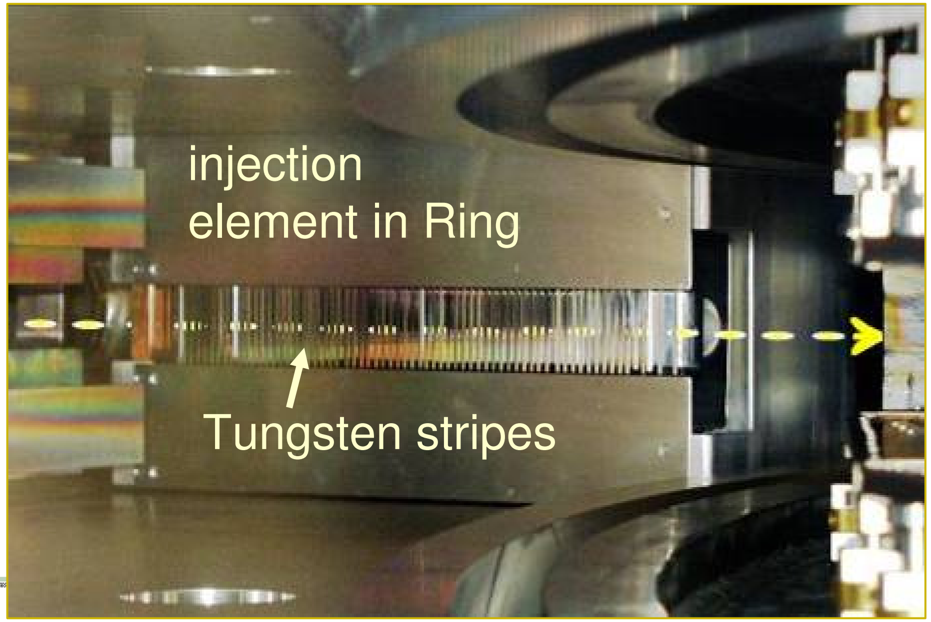
parameters extraction chan.:
E_k= 590MeV
E = 8.8 MV/m
θ = 8.2 mrad
ρ = 115 m
U = 144 kV

major loss mechanism is scattering in 50μm electrode!

electrostatic rigidity:

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

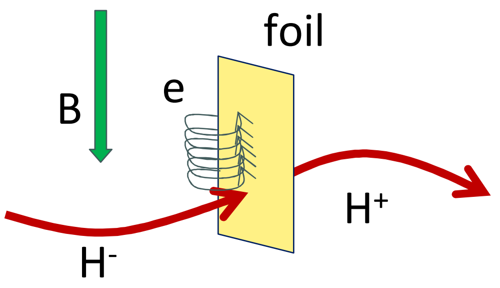
$$\theta = \frac{qlE}{E_k}\frac{\gamma}{\gamma+1}$$



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 γ are equal for *p* and *e*

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

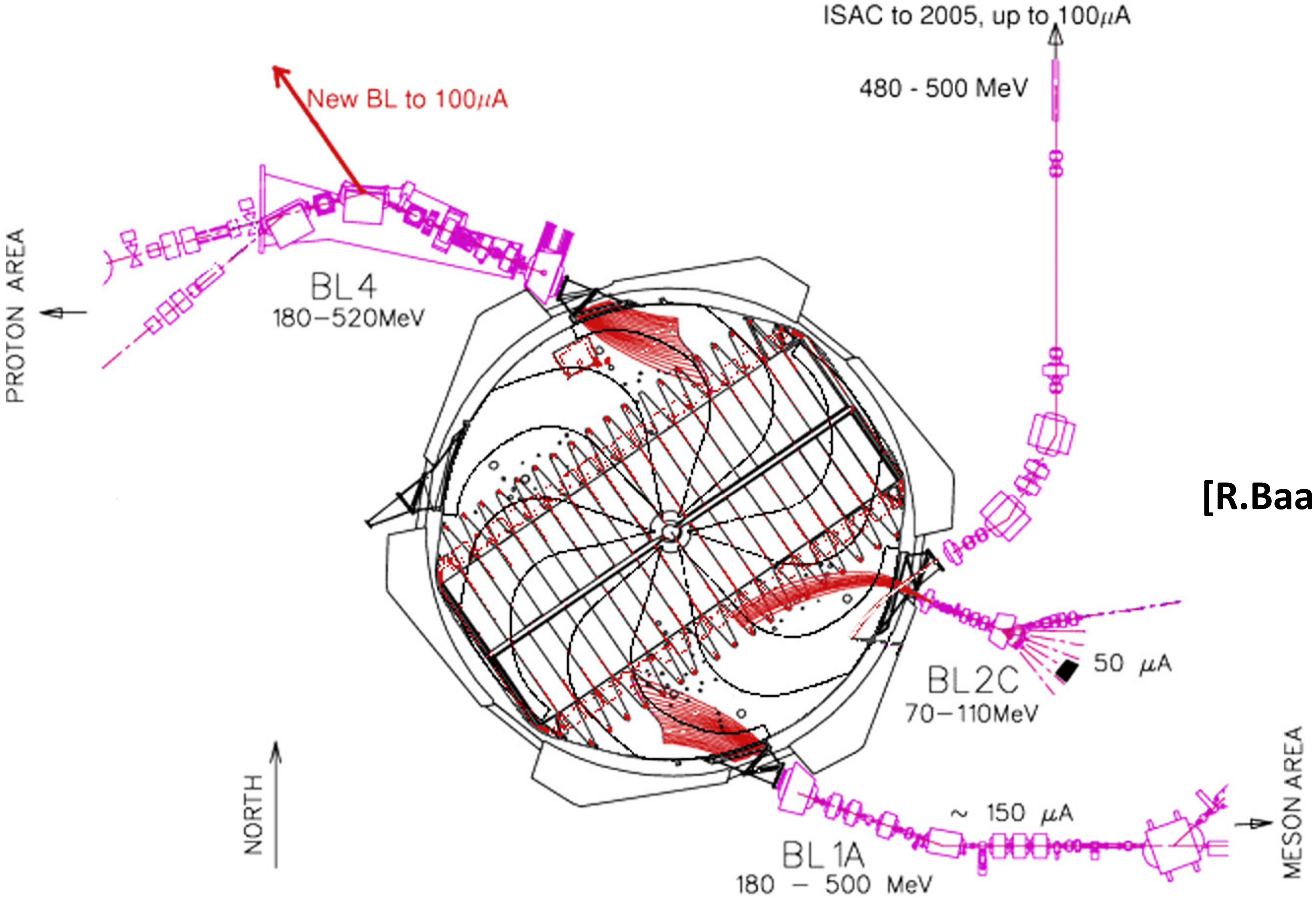
$$\rightarrow E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

Bending radius of electrons?

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

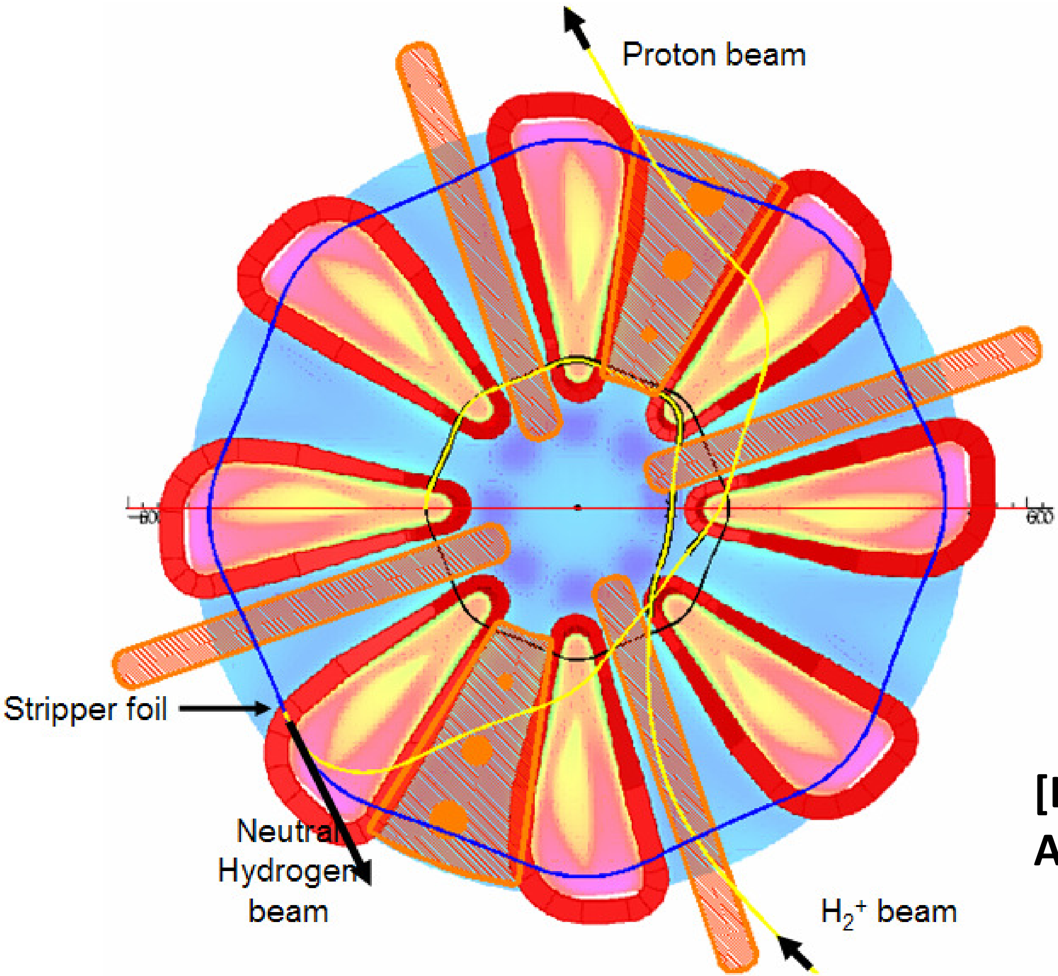
→ typically mm

example: multiple H^- stripping extraction at TRIUMF



[R.Baartman]

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



purpose: pulsed high power beam for neutrino production
- 800MeV
- 5MW

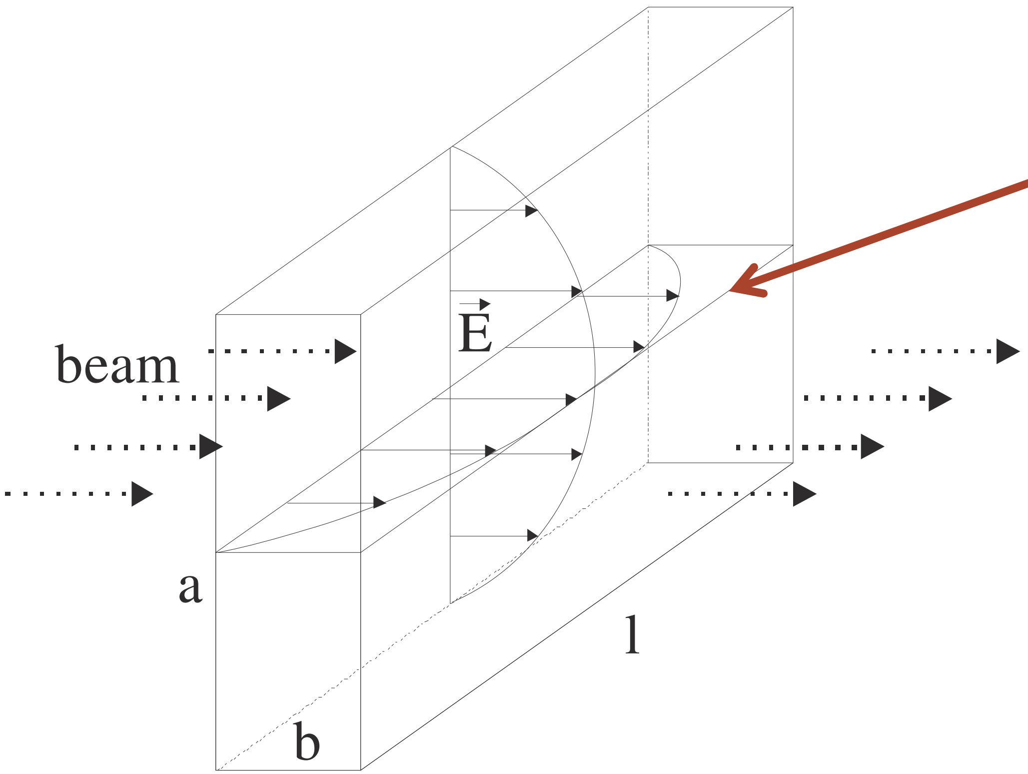
[L.Calabretta, A.Calanna et al]

components: cyclotron resonators

cyclotron resonators are basically box resonators

resonant frequency:

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

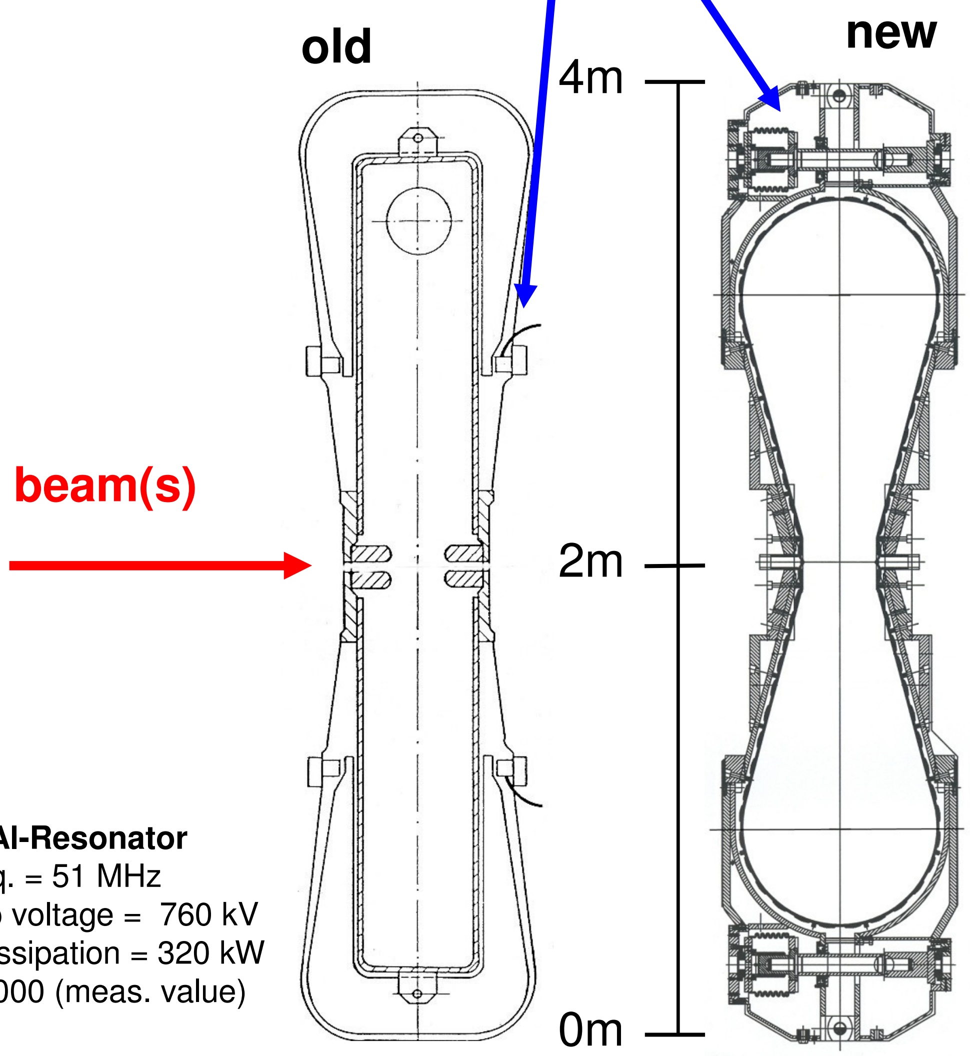


beam passes in center plane;

accelerating voltage varies as sin(r)

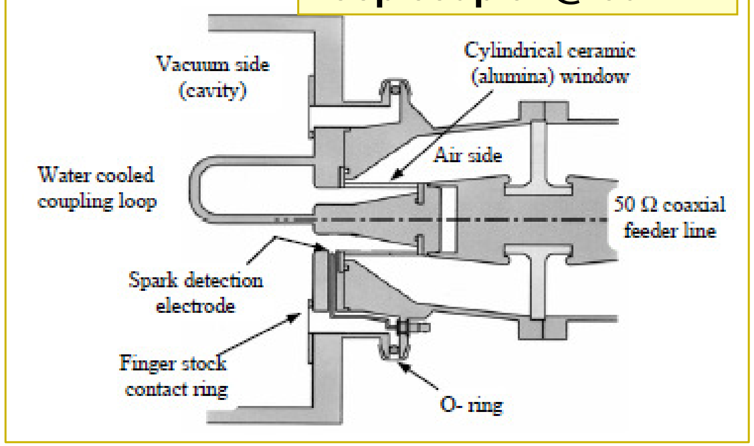
cross sections of PSI resonators

hydraulic tuning



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

loop coupler @ 50MHz



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

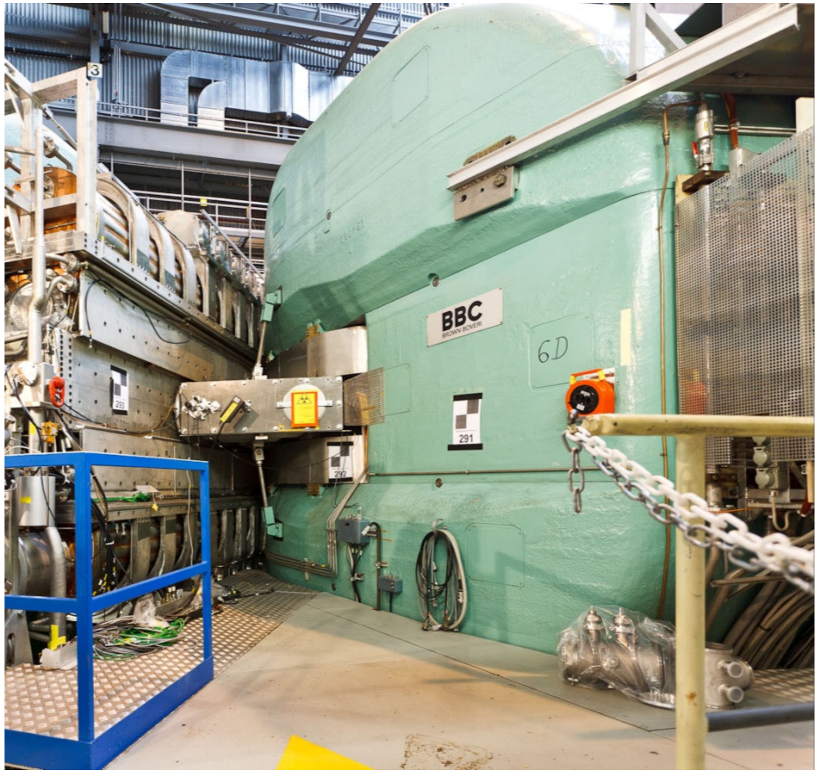
- **f = 50.6MHz**; **Q_0 = 4,8·10^4**; **U_{max}=1.2MV** (presently 0.85MV)
- transfer of up to **400kW power to the beam** per cavity
- Wall Plug to Beam Efficiency (RF Systems): **32%**

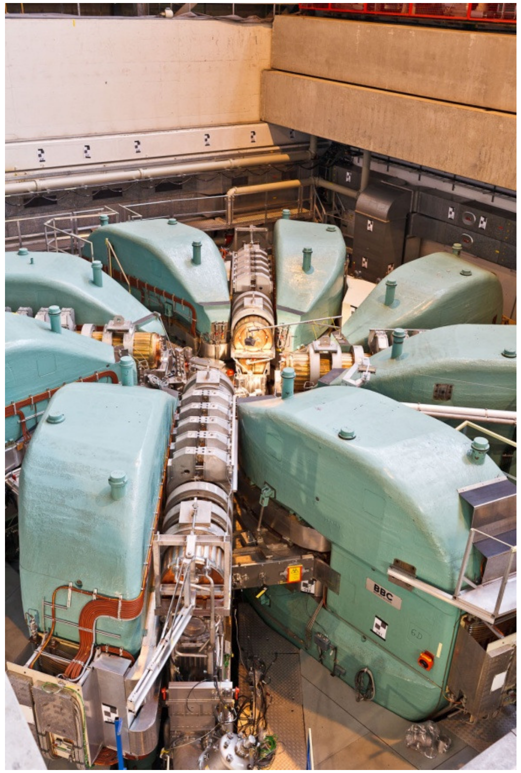
components: sector magnets

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

PSI sector magnet

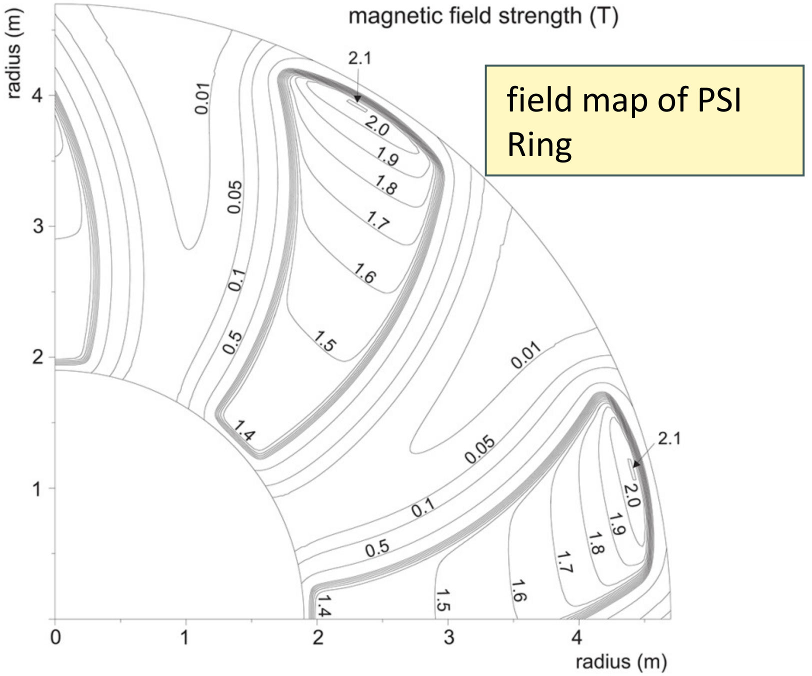
iron weight: 250 tons
coil weight: 28 tons
orbit radius: 2.1…4.5 m
spiral angle: 35 deg





components: sector magnets

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



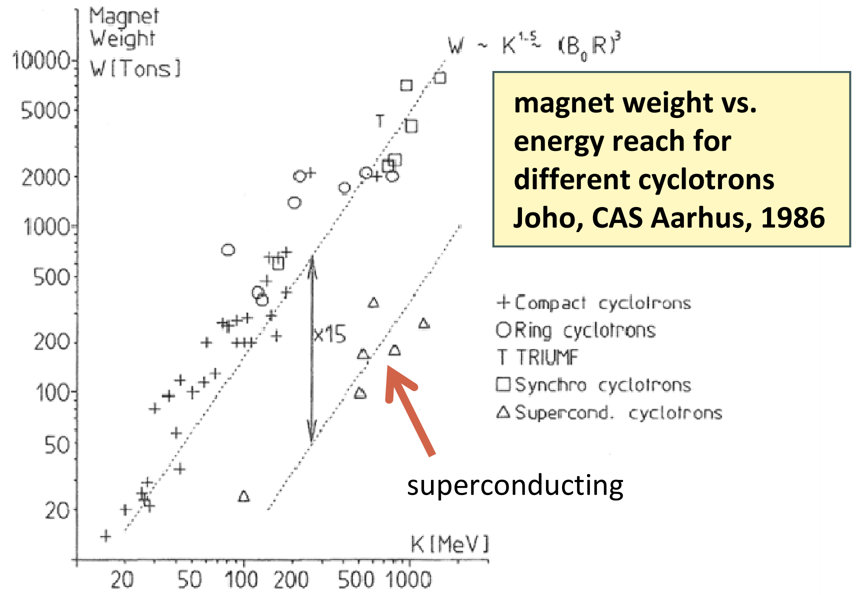


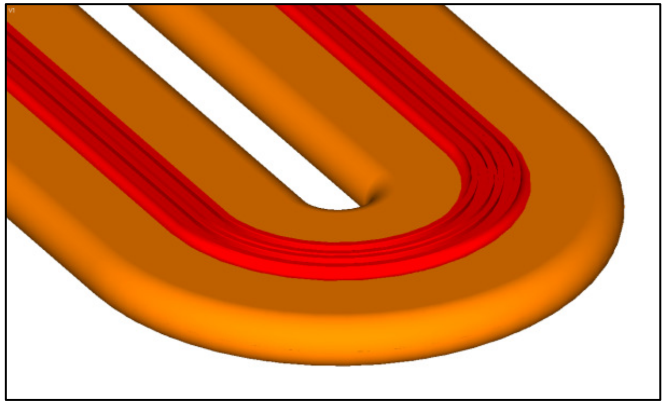
Fig. 6 Magnet weight W versus K-value for different cyclotrons and synchrocyclotrons.

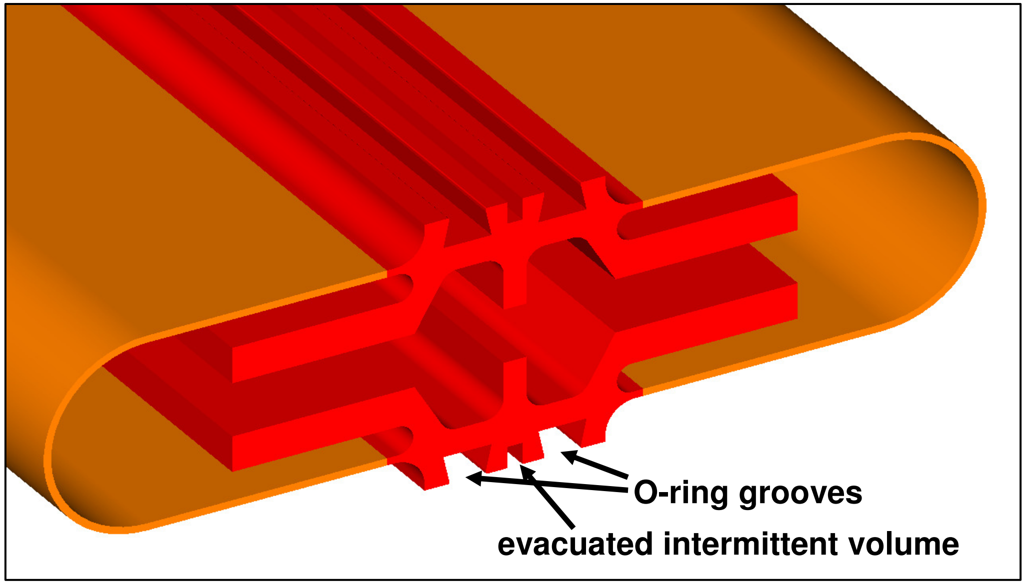
cyclotron vacuum system

- vacuum chamber with large radial width → difficult to achieve precisely matching sealing surfaces→ noticeable leak rates must be accepted
- use cryo pumps with high pumping speed and capacity
- ≈10^{-6}mbar for p, ≈10^{-8}mbar for ions (instability! e.g. AGOR at KVI)
- design criterion is easy access and fast mountability (activation)

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

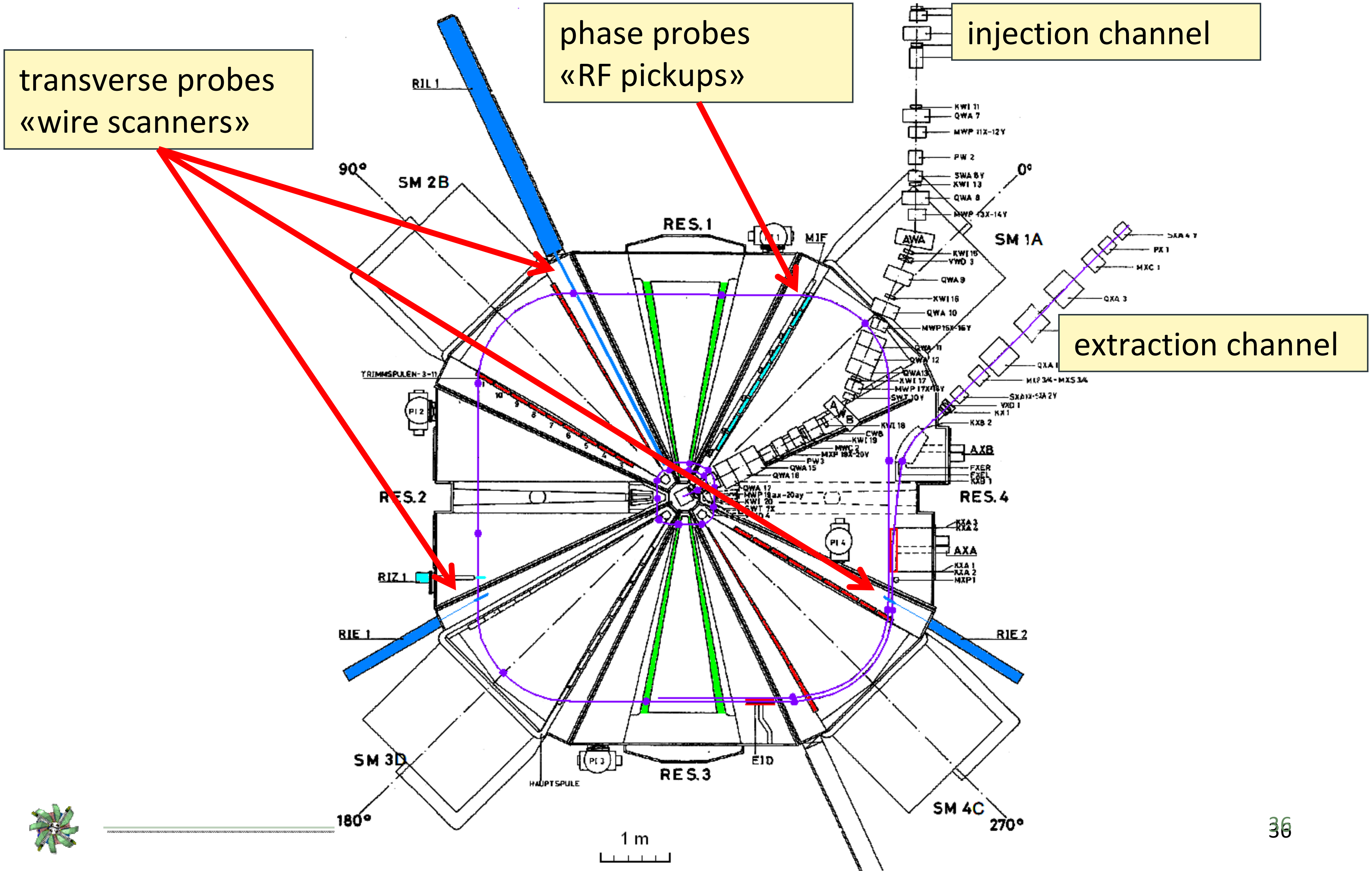
length: 3.5m





cyclotron instrumentation

example: PSI 72MeV injector cyclotron



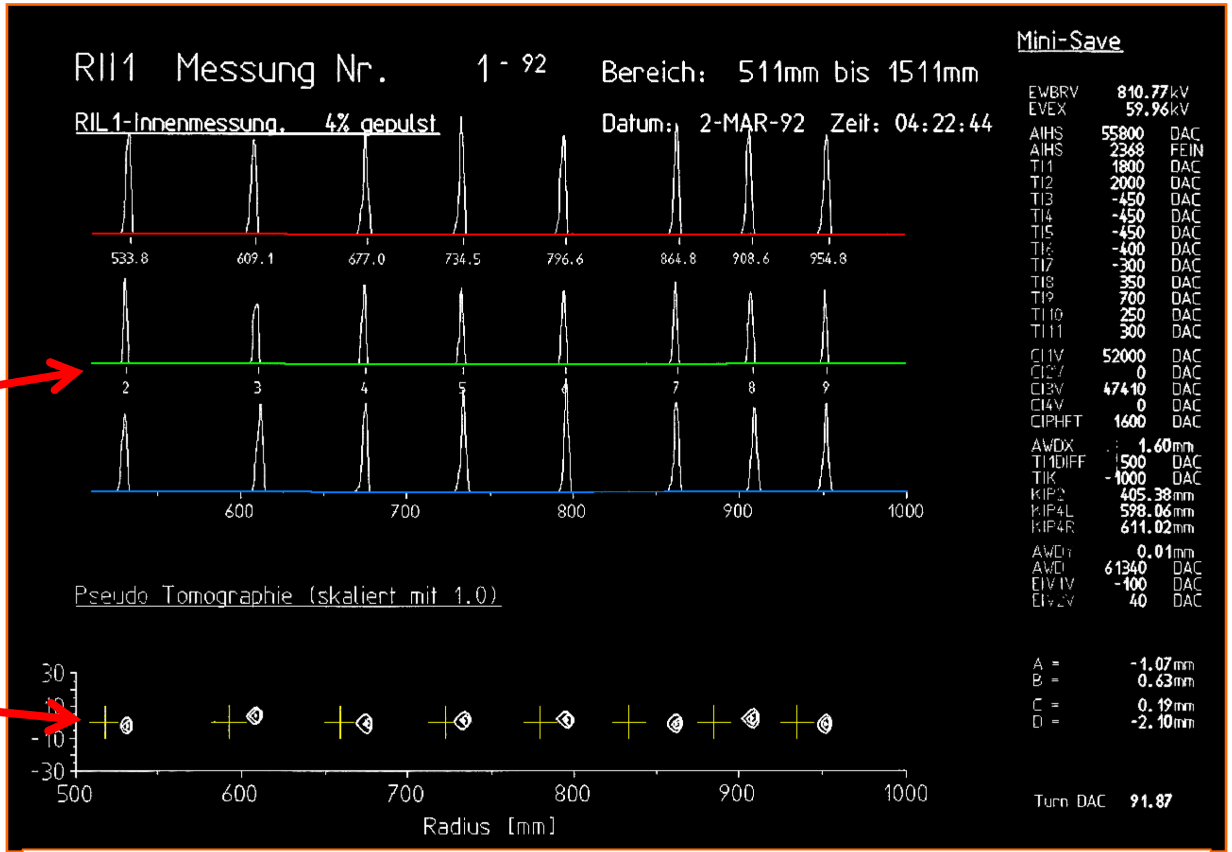
instrumentation: radial probe for turn counting / orbit analysis

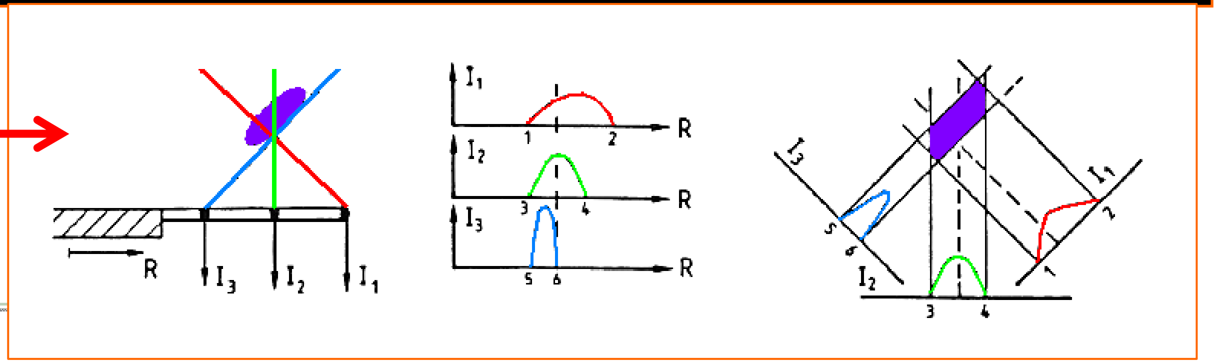
wire scanner with three tilted wires delivers radial beam profile and some vertical information

radial: positions of individual turns

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

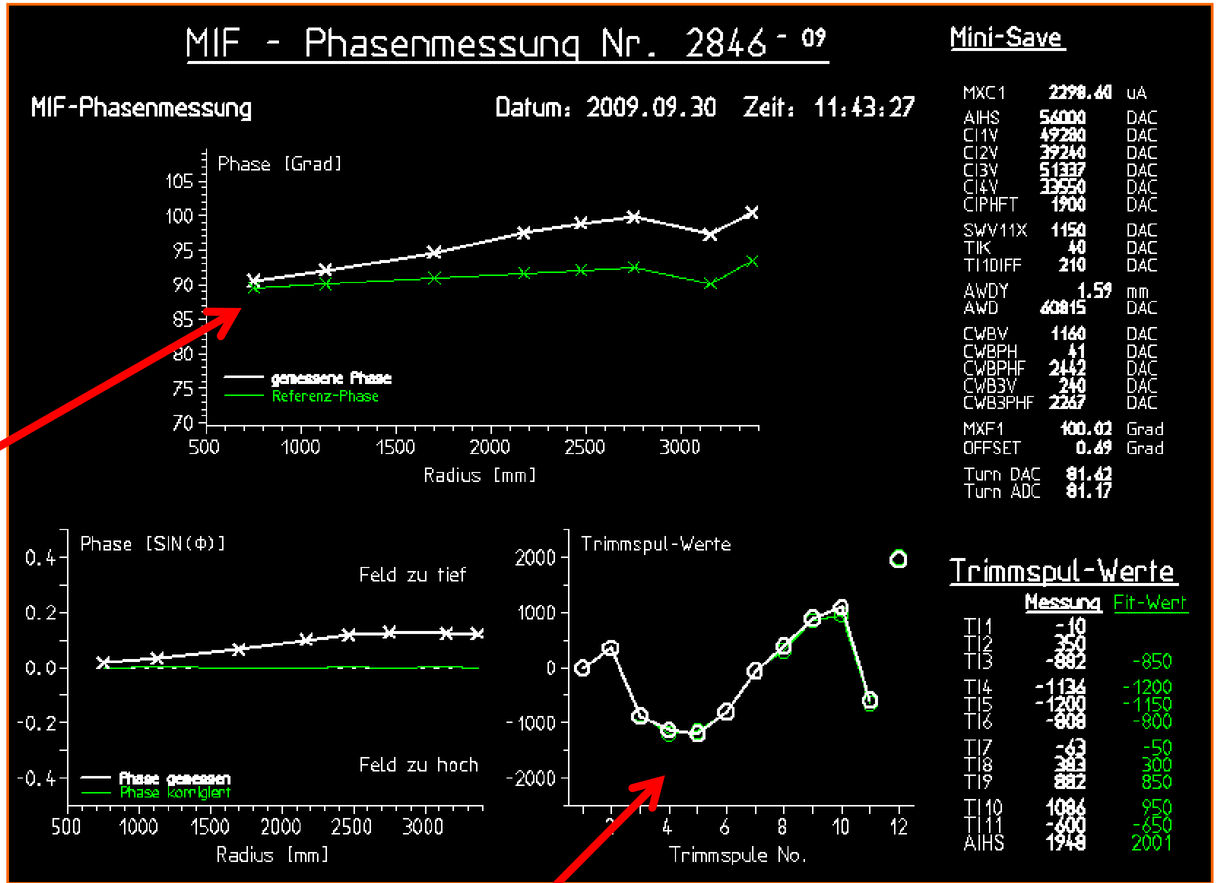
«pseudo tomography» with tilted wires





instrumentation: phase probes

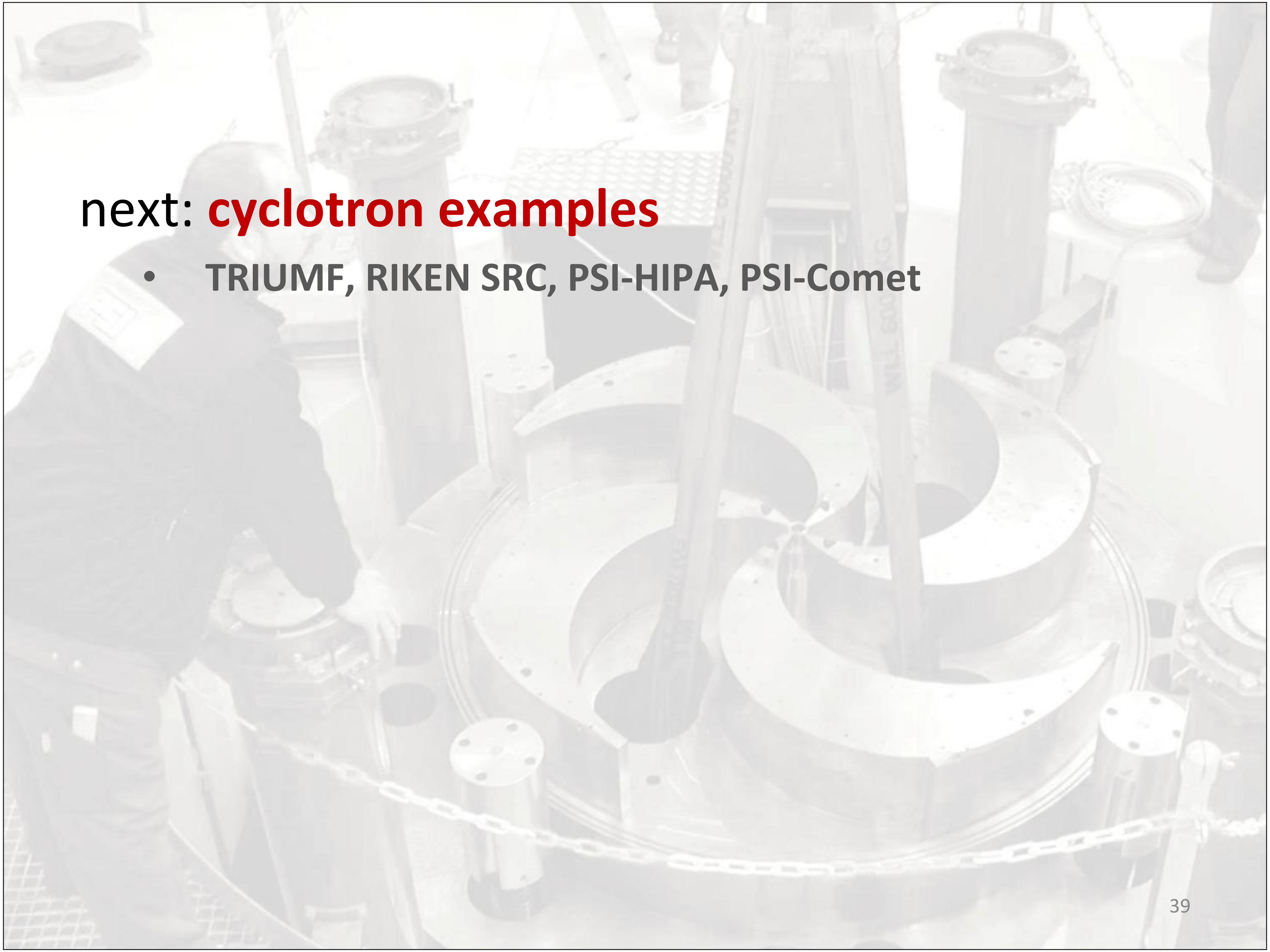
phase probes are radially distributed RF pickups that detect the arrival time (phase) of bunches vs radius
$\longrightarrow$ adjustment of isochronicity



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

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

38



next: **cyclotron examples**

- **TRIUMF, RIKEN SRC, PSI-HIPA, PSI-Comet**

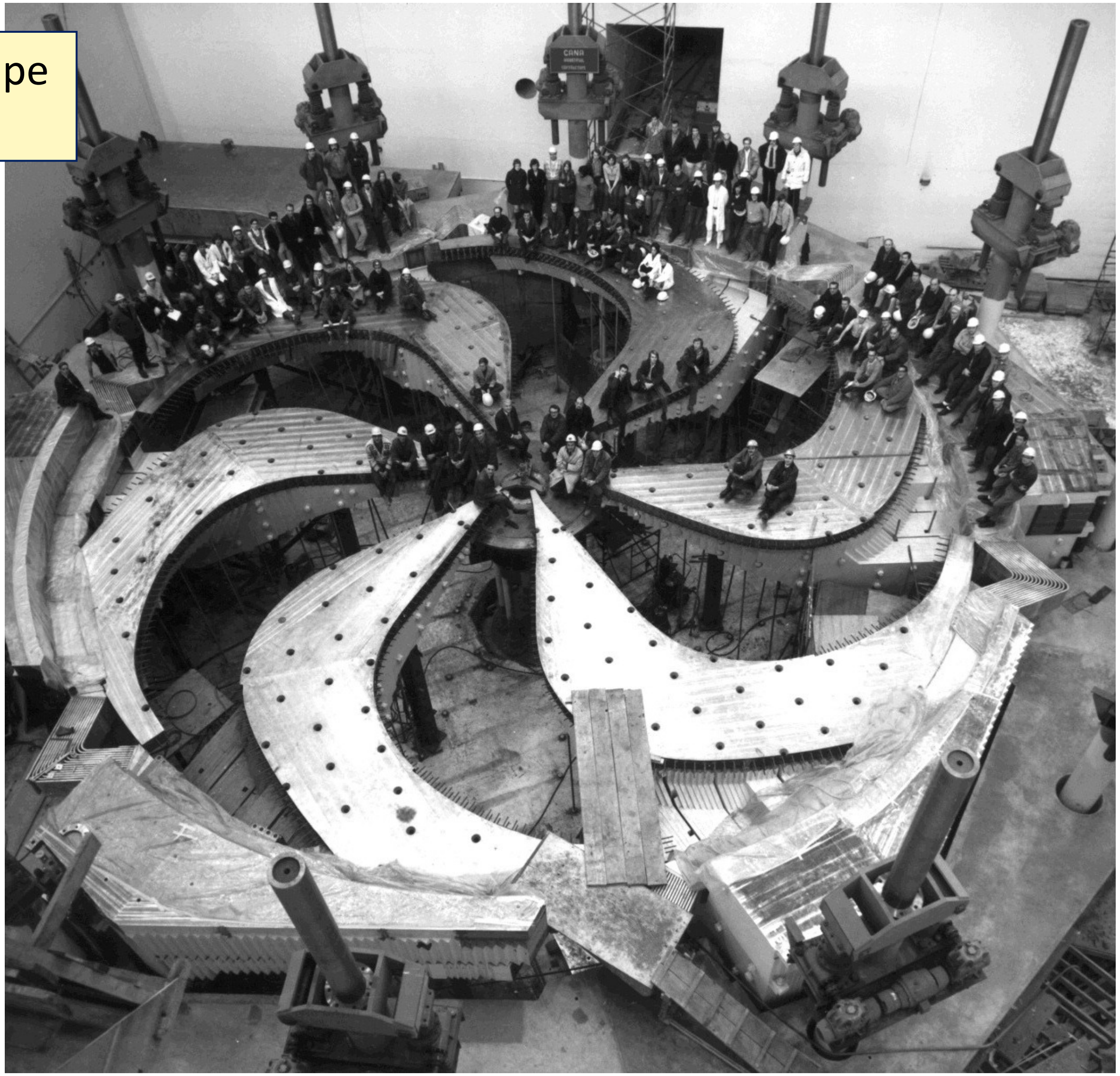
comparison of cyclotrons

	TRIUMF	RIKEN SRC (supercond.)	PSI Ring	PSI medical (supercond.)
particles	H- → 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

cyclotron examples: TRIUMF

photo: iron poles with spiral shape (δ_{max}=70deg)

- 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

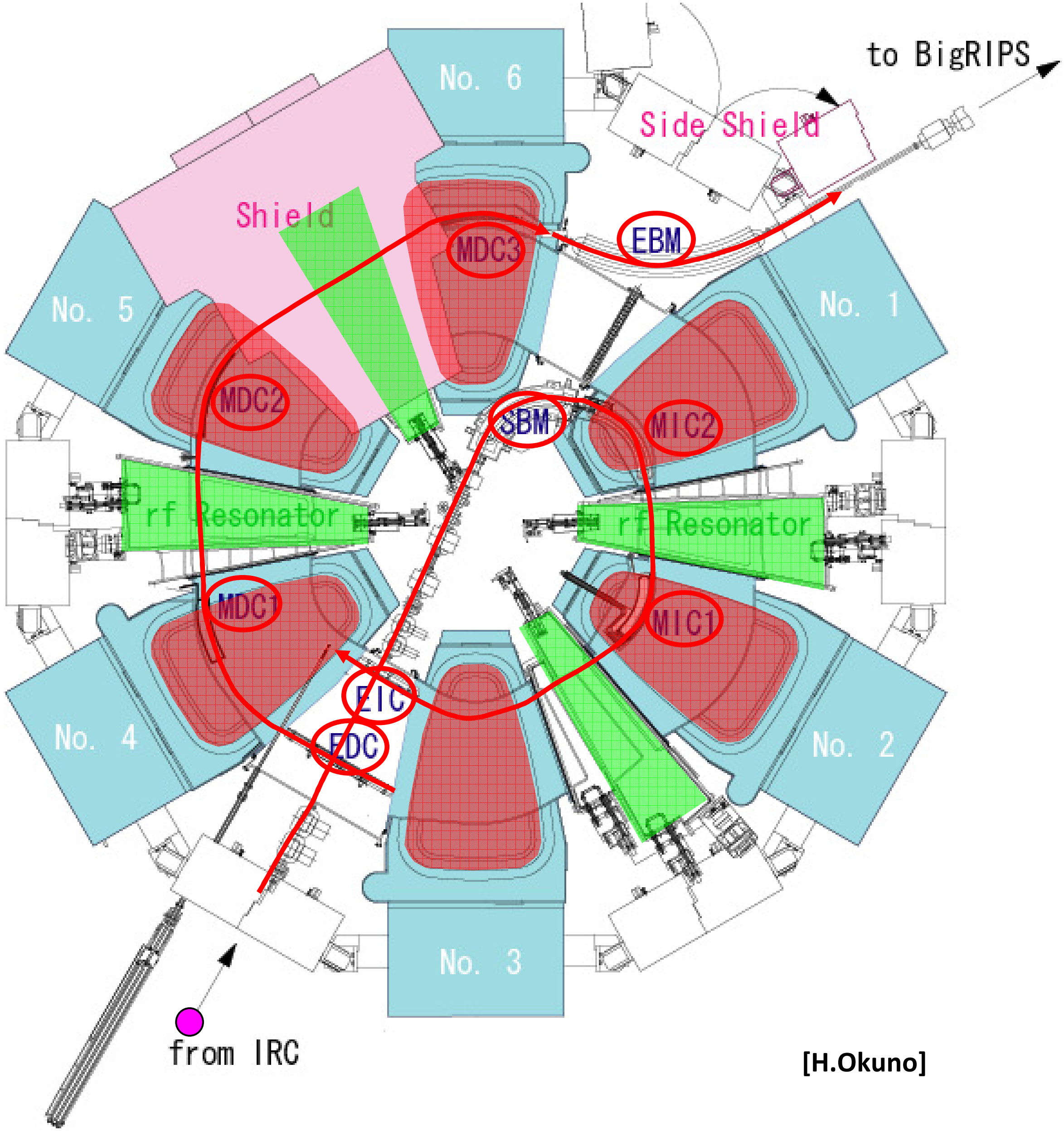


example: RIKEN (Jp) superconducting cyclotron

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

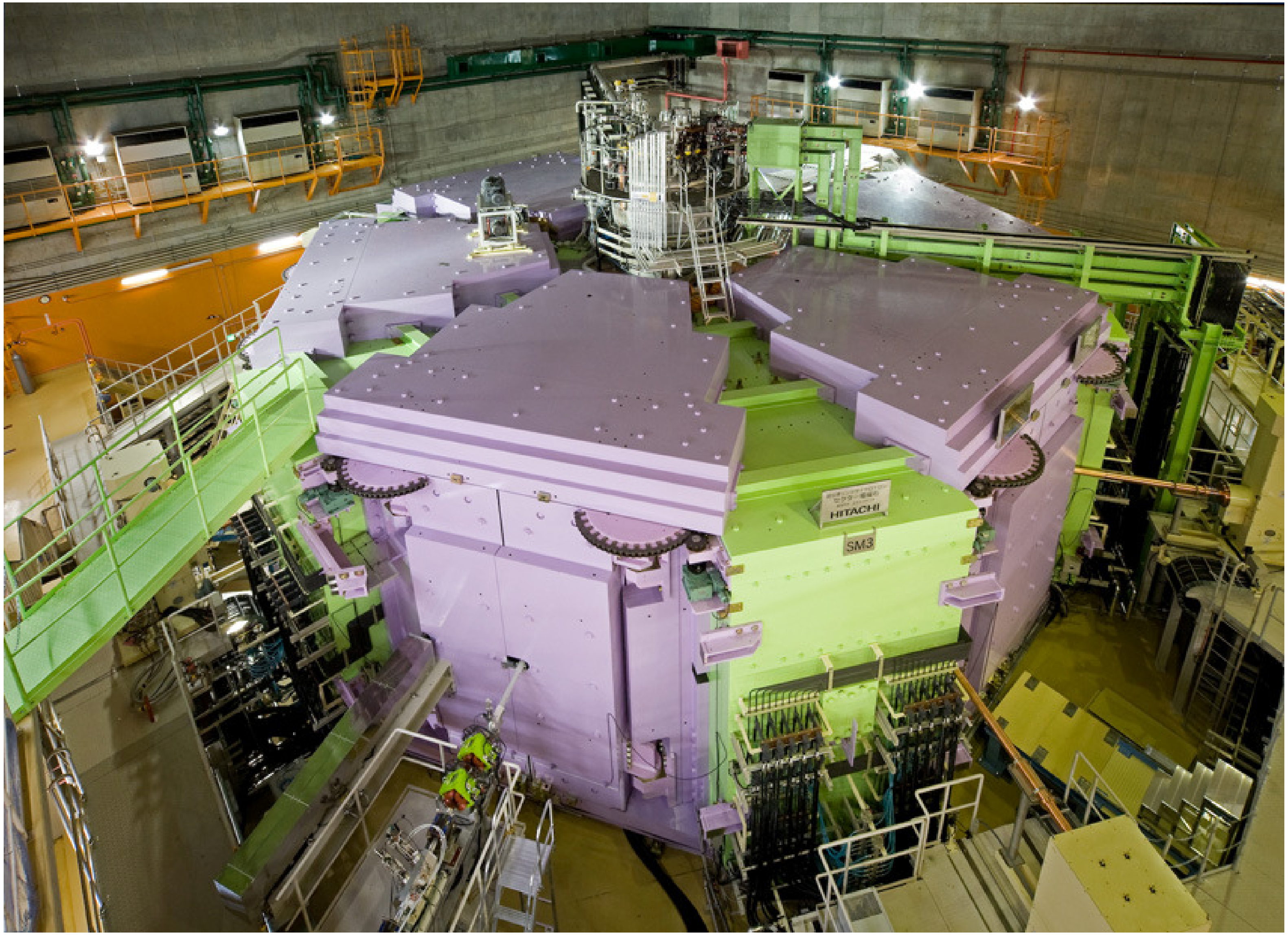
superconducting
Sector Magnets :6
RF Resonator :4
Injection elements.
Extraction elements.

utilization:
broad spectrum of
ions up to Uranium



[H.Okuno]

RIKEN SRC in the vault



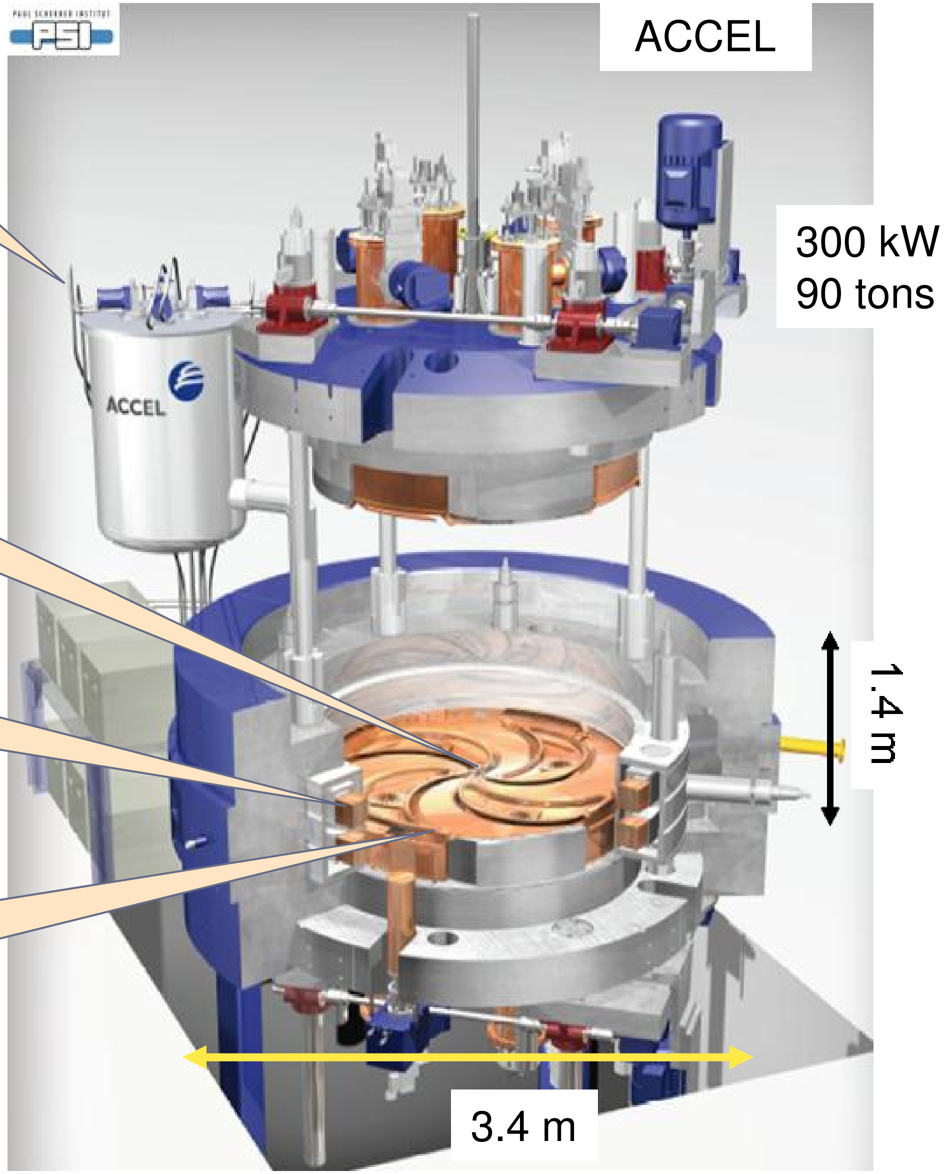
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

Proton source

superconducting
coils
=> 2.4 - 3.8 T

4 RF-cavities
~100 kV on 4 Dees

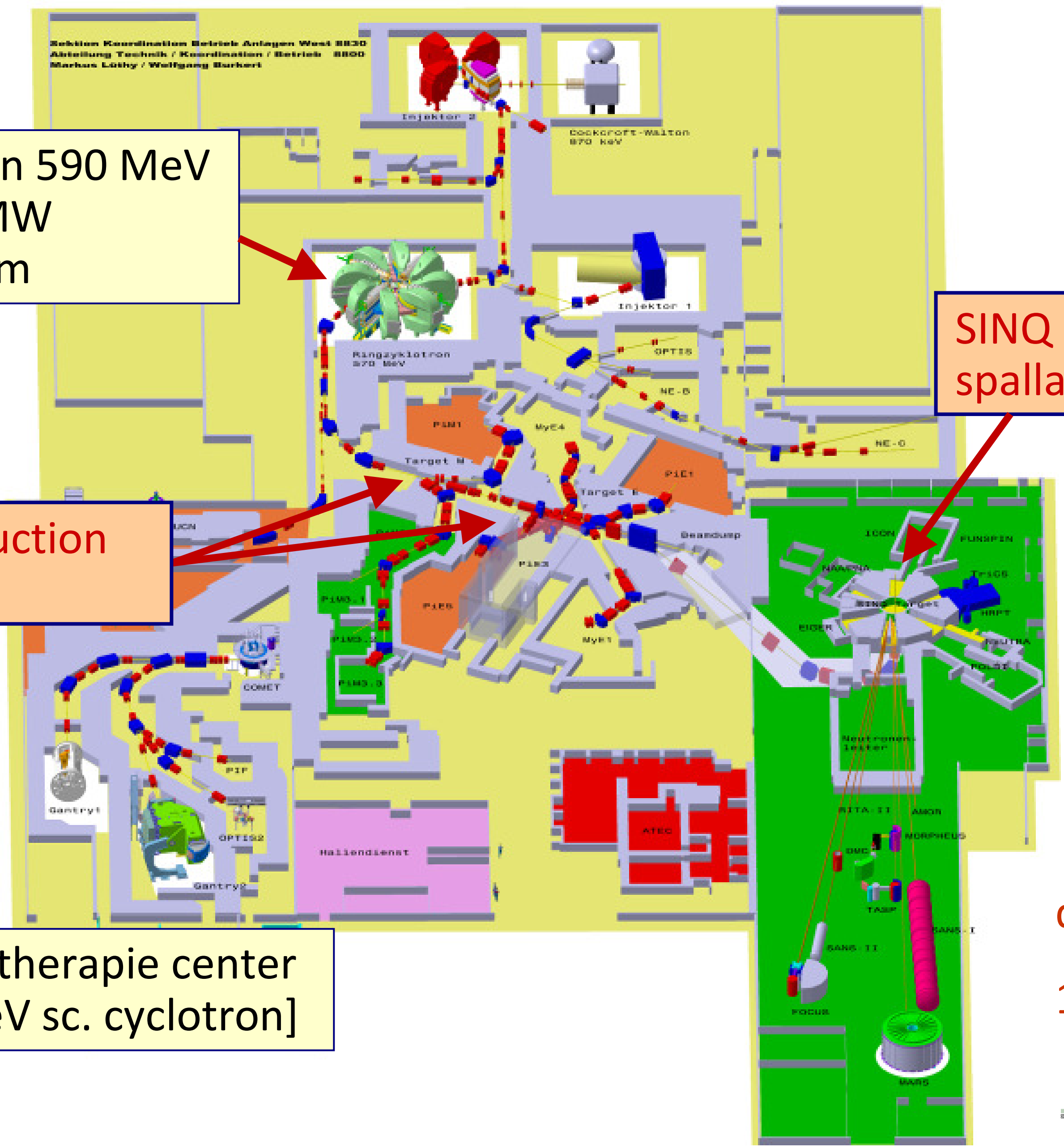


examples: PSI High Intensity Proton Accelerator

Ring Cyclotron 590 MeV
2.2mA / 1.3MW
diameter: 15m

SINQ
spallation source

meson production
targets



proton therapie center
[250MeV sc. cyclotron]

dimensions:

120 x 220m^2

finally: **discussion**

- **comparison of circular accelerators**
- **suitability of cyclotrons**
- **some literature**

classification of circular accelerators

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

pro and contra cyclotron

limitations of cyclotrons	typical utilization of cyclotrons
• energy limitation ~1GeV due to relativistic effects • relatively weak focusing is critical for space charge effects (10mA ?) • tuning is difficult; field shape; many turns; limited diagnostics • wide vacuum vessel (radius variation)	• medical applications ≤250MeV; intensity range well covered • isotope production → several 10MeV • acceleration of heavy ions (RIKEN) • very high intensity proton beams (PSI:1.4MW)

some literature w.r.t. cyclotrons

comprehensive overview on cyclotrons	L.M.Onishchenko, Cyclotrons: A Survey, Physics of Particles and Nuclei 39, 950 (2008) **http://www.springerlink.com/content/k61mg262vng17411/fulltext.pdf**
scaling of PSI concept to 10MW	Th.Stammbach et al, The feasibility of high power cyclotrons, Nuclear Instruments and Methods in Physics Research B 113 (1996) 1-7
space charge effects and scalings	W.Joho, High Intensity Problems in Cyclotrons, Proc. 5th intl. Conf. on Cyclotrons and their Applications, Caen, 337-347 (1981)
long. space charge; comparison to analytical result	E.Pozdeyev, A fast code for simulation of the longitudinal space charge effect in isochronous cyclotrons, cyclotrons (2001) http://accelconf.web.cern.ch/AccelConf/c01/cyc2001/paper/P4-11.pdf
H_2^+ concept for high power	L.Calabretta et al, A multi megawatt cyclotron complex to search for cp violation in the neutrino sector, cyclotrons (2010); upcoming NIM paper! http://accelconf.web.cern.ch/AccelConf/Cyclotrons2010/papers/tua1cio01.pdf
Ion induced desorption	E.Mahner et al, Review of heavy-ion induced desorption studies for particle accelerators, PRST-AB 11 (104801) http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/WPAH036.PDF
OPAL simulations; documentation	J.Yang, A. Adelmann, et al. Phys. Rev. STAB Vol. 13 Issue 6 (2010) http://amas.web.psi.ch


thank your for your
attention !

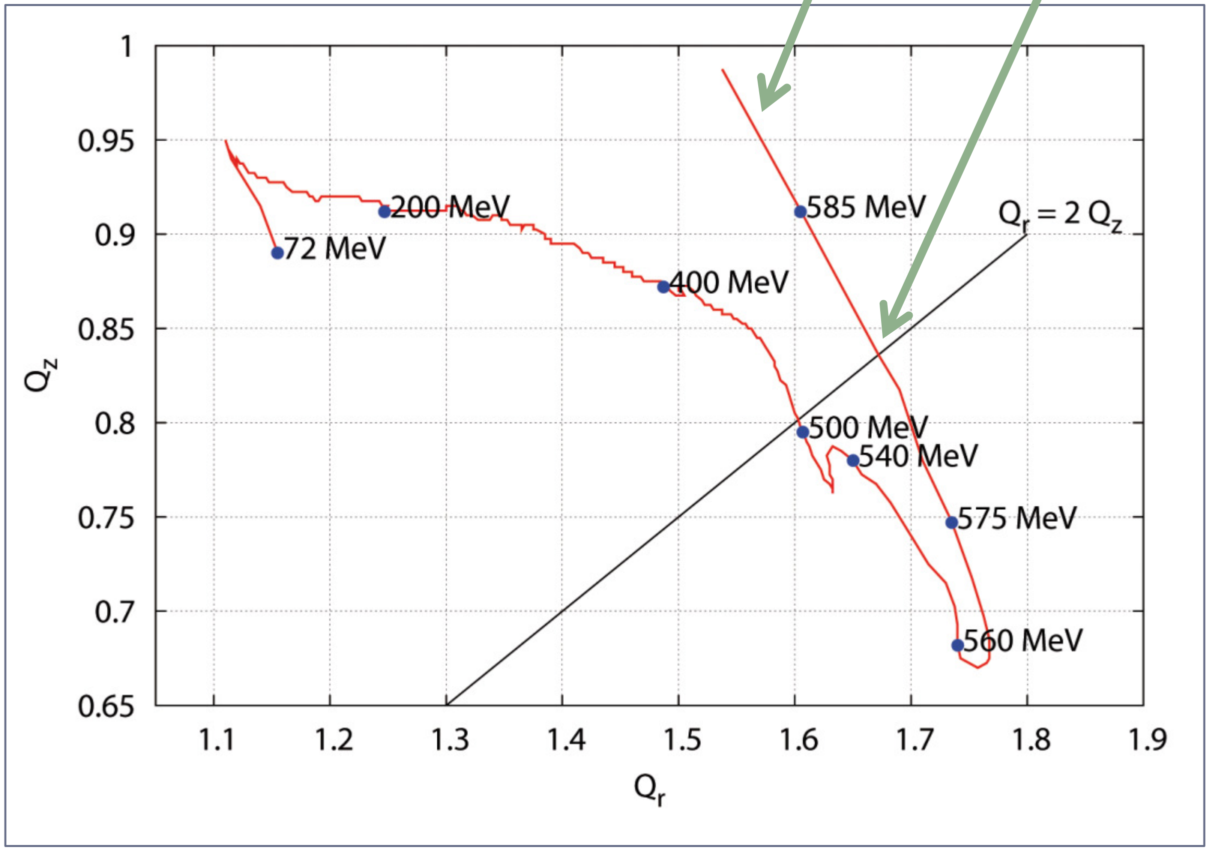
cyclotrons – spare transparencies

- tune diagram of PSI Ring cyclotron
- vacuum – estimate of required pressure
- measured activation levels
- 50MHz amplifier chain

PSI Ring Cyclotron – tune diagram

coupling resonance – pass quickly!

Q_r decreases towards extraction – enhance turn separation



comments:

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

Losses – required vacuum quality for protons

- losses are caused by inelastic scattering at residual gas molecules, use inelastic reaction cross section to estimate losses, convert to mean free path
- compute pressure for 10^{-5} relative loss

common gases :
(norm.cond.)

$$
\begin{aligned}
\lambda_{\mathrm{inel}}(\mathrm{air}) &= 747\mathrm{m} \\
\lambda_{\mathrm{inel}}(\mathrm{CO}) &= 753\mathrm{m} \\
\lambda_{\mathrm{inel}}(\mathrm{H_2}) &= 6110\mathrm{m} \\
\lambda_{\mathrm{inel}}(\mathrm{Ar}) &= 704\mathrm{m}
\end{aligned}
$$

mean free path:

$$
\begin{aligned}
\lambda_{\mathrm{inel}} &= \frac{A}{\rho N_A} \frac{1}{\sigma_{\mathrm{inel}}} \\
\lambda_{\mathrm{eff}} &= \left(\frac{1}{P_0} \sum \frac{P_i}{\lambda^i_{\mathrm{inel}}} \right)^{-1}
\end{aligned}
$$

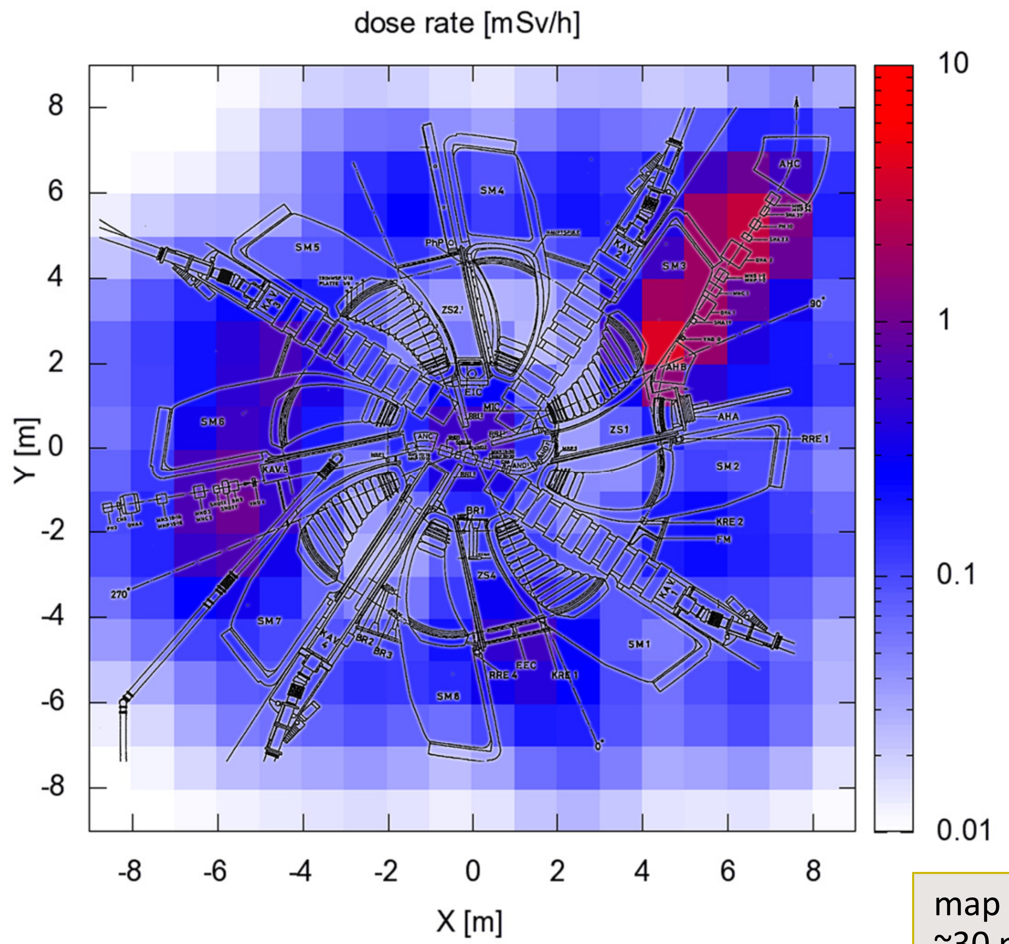
beam loss:

$$
\frac{N_0 - N(l)}{N_0} = 1 - \exp(-l/\lambda_{\mathrm{eff}}) \approx l/\lambda_{\mathrm{eff}}
$$

pressure for loss < 10^{-5}: P_i(air) > 0.01 mbar → **easily achievable, vacuum no problem!**

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
  $\rightarrow$ **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):

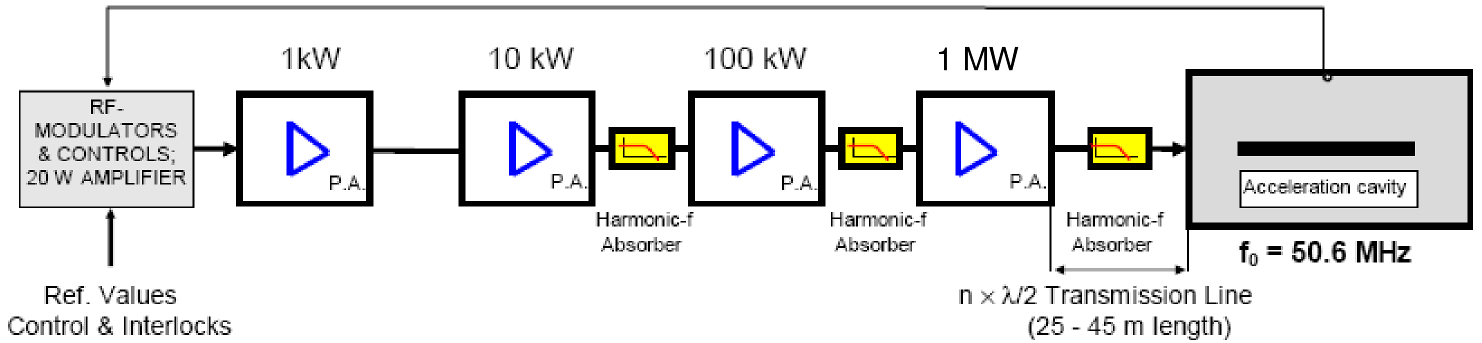
personnel dose for 3 month shutdown:

47mSv, 186 persons

max per person: 2.9mSv

50 MHz 1 MW amplifier chain for Ring cyclotron

4- STAGE POWER AMPLIFIER CHAIN, EMPLOYING POWER TETRODE TUBES



Tube Types:	**YL 1056**	**RS 2022 CL**	**RS 2074 HF**	**RS 2074 HF**
Cooling Method:	forced air	forced air	water	water

Wall Plug to Beam Efficiency (RF Systems): **32%**
[AC/DC: 90%, DC/RF: 64%, RF/Beam: 55%]

[L.Stingelin et al]