high intensity and high power aspects of cyclotrons

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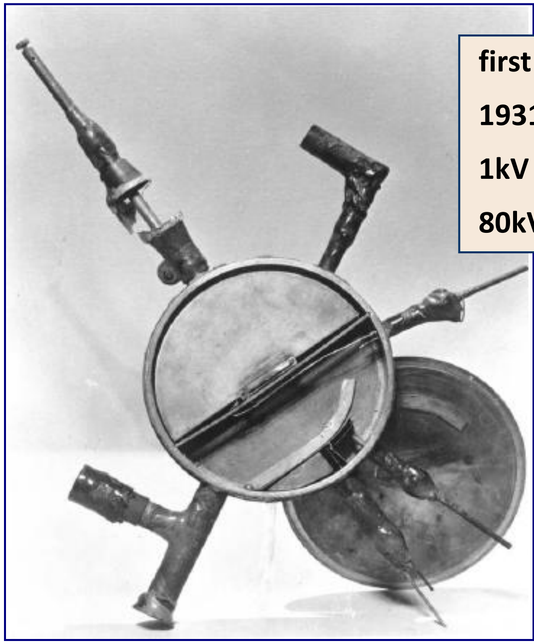
high intensity cyclotrons - Outline

- classical cyclotron – and its general suitability for high intensity beams
  - **advantages of cyclotron concept, classification of circular accelerators**
- beam dynamics - with emphasize on high intensity
  - **isochronicity and related scalings, classical extraction: pattern/stepwidth, transv./long. space charge, ion induced vacuum desorption, tracking codes**
- cyclotron subsystems - with relevance for high intensity
  - **extraction schemes, RF systems/power efficiency, vacuum issues, collimation issues**
- examples of high intensity cyclotrons
  - **TRIUMF, RIKEN SRC, ARRONAX, PSI Ring**
- discussion
  - **Pro's and Con's of cyclotrons**

Classical Cyclotron

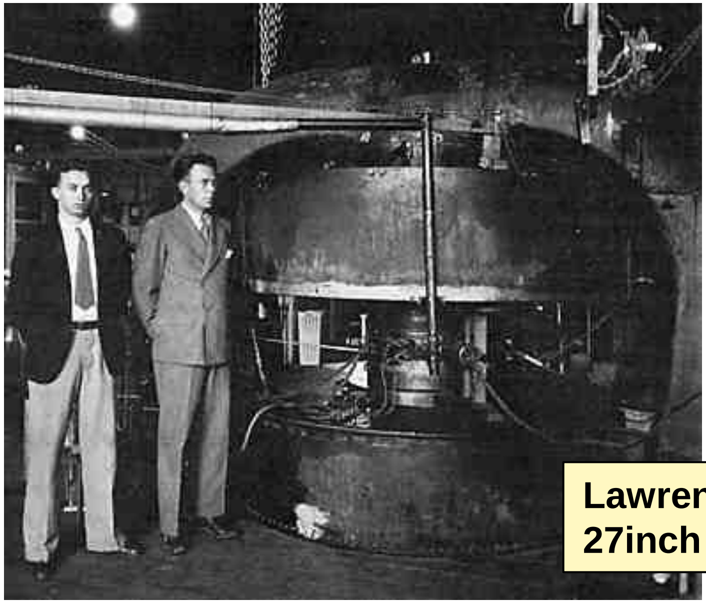


first cyclotron:

1931, Berkeley

1kV gap-voltage

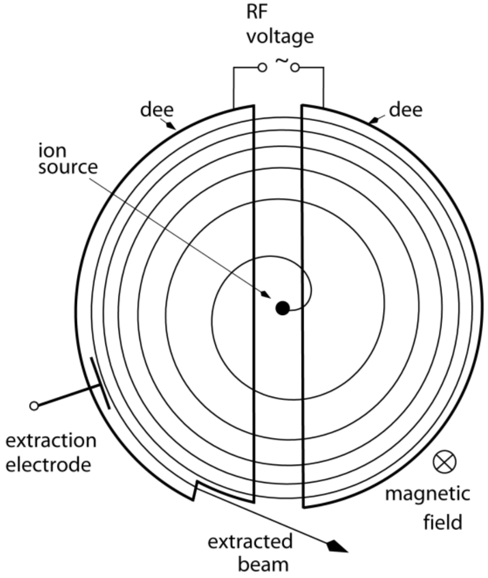
80kV Protons



Lawrence & Livingston, 27inch Zyklotron

powerful concept:

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



two capacitive electrodes „Dees“, two gaps per turn

internal ion source

homogenous B field

constant revolution time

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

classification of circular accelerators

	bending radius	bending field vs. time	bending field vs. radius	RF frequency vs. time	operation mode (pulsed/CW)	
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, strong focus

basic thoughts on the theme of this talk

- Why is the cyclotron suitable for high intensity beams?
  - CW operation is naturally possible
  - efficient and cost effective multi-turn (resonant) concept
  - cyclotrons are simple and compact
- Which aspects are critical?
  - most important: clean extraction! $\rightarrow$ activation
  - ions: vacuum induced losses; desorption; foil related issues
  - intensity limitations from space charge
  - technical difficulties: wide vacuum chamber; resonators and high power throughput; technical and personnel safety; complex tuning

- next: **beam dynamics**
  - isochronicity and related scalings
  - classical extraction: pattern/stepwidth
  - transv./long. space charge
  - ion induced vacuum desorption
  - tracking codes

isochronicity and scalings

magnetic rigidity:

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

orbit radius from isochronicity:

$$\begin{aligned} R &= \frac{c}{\omega_0}\beta = R_\infty \beta \\ &= \frac{c}{\omega_0}\sqrt{1-\gamma^{-2}} \end{aligned}$$

deduced scaling of *B*:

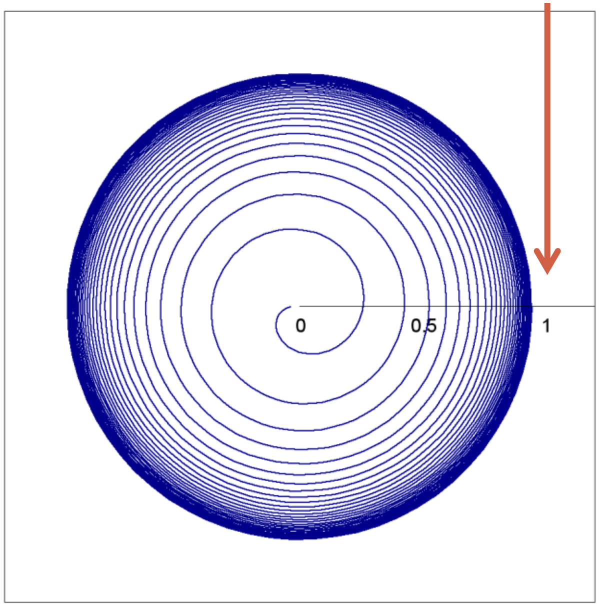
$$R \propto \beta; BR \propto \beta\gamma \longrightarrow B \propto \gamma$$

field index:

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

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

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



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 $k = R/B \cdot dB/dR$

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

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:

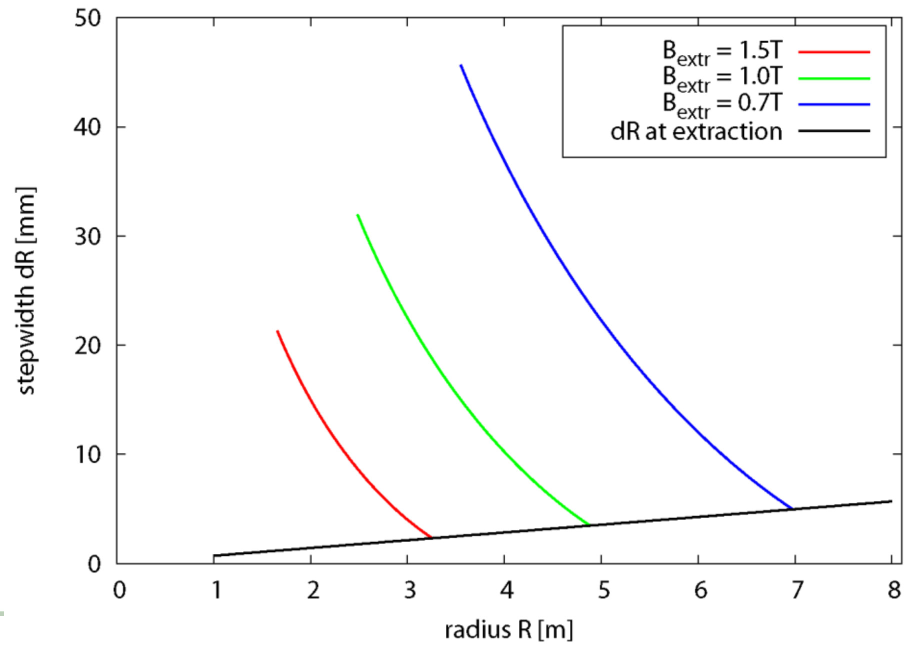
- limited energy (< 1GeV)
- large radius R_{extr}
- high energy gain U_t

non-relativistic approx., scaling during acceleration:

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

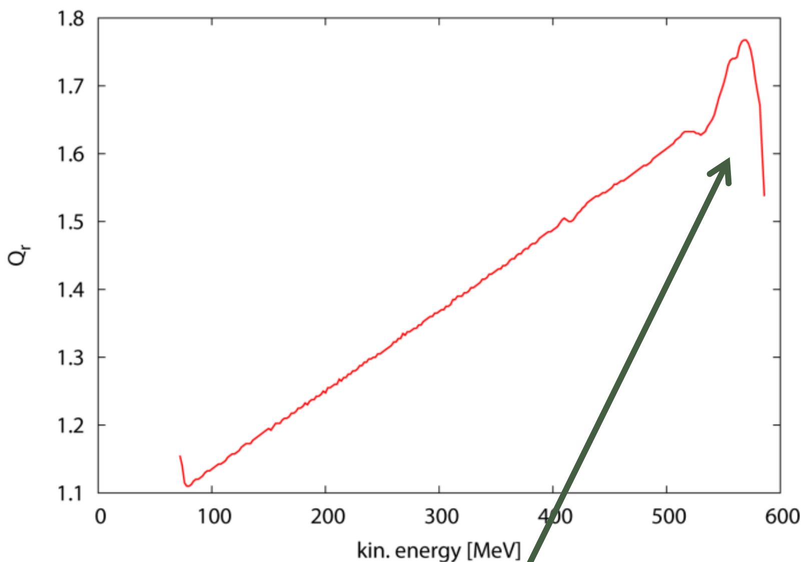
illustration:

- **stepwidth vs. radius** in cyclotrons of different sizes; 100MeV $\rightarrow$ 800MeV



extraction with off-center orbits

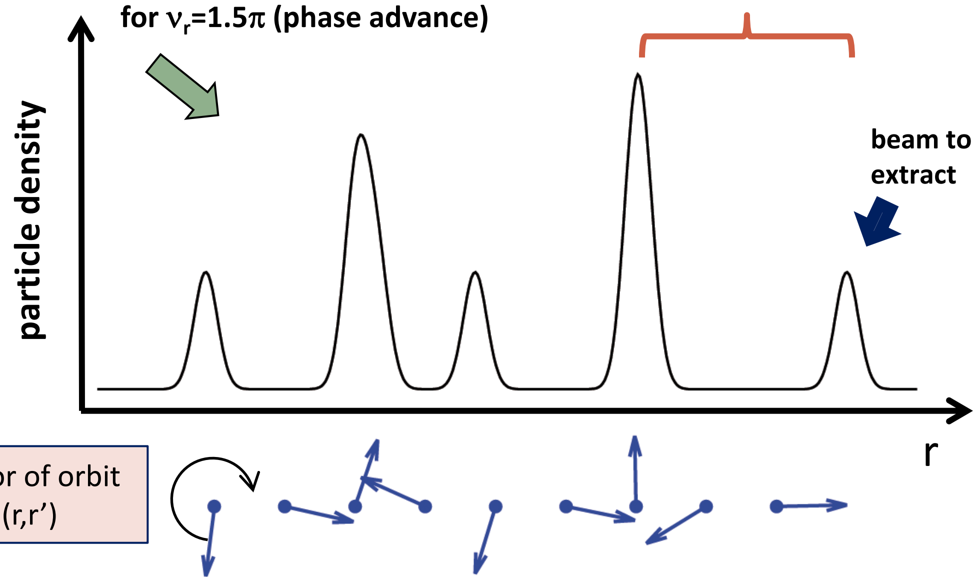
betatron oscillations around the “closed orbit” can be used to increase the radial stepwidth by a factor 3 !



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

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)

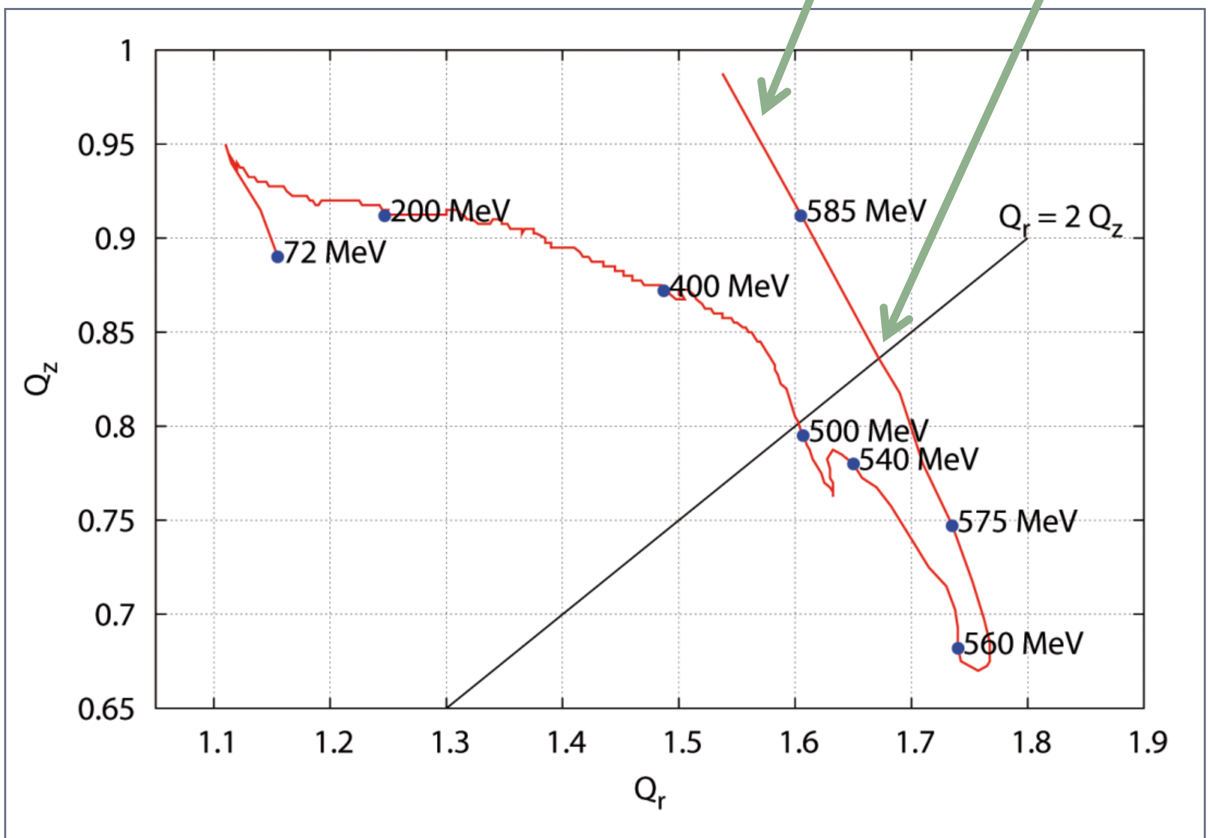


phase vector of orbit oscillations (r,r')

PSI Ring Cyclotron – tune diagram

coupling resonance – pass quickly!

Q_r decreases towards extraction
– enhance turn separation

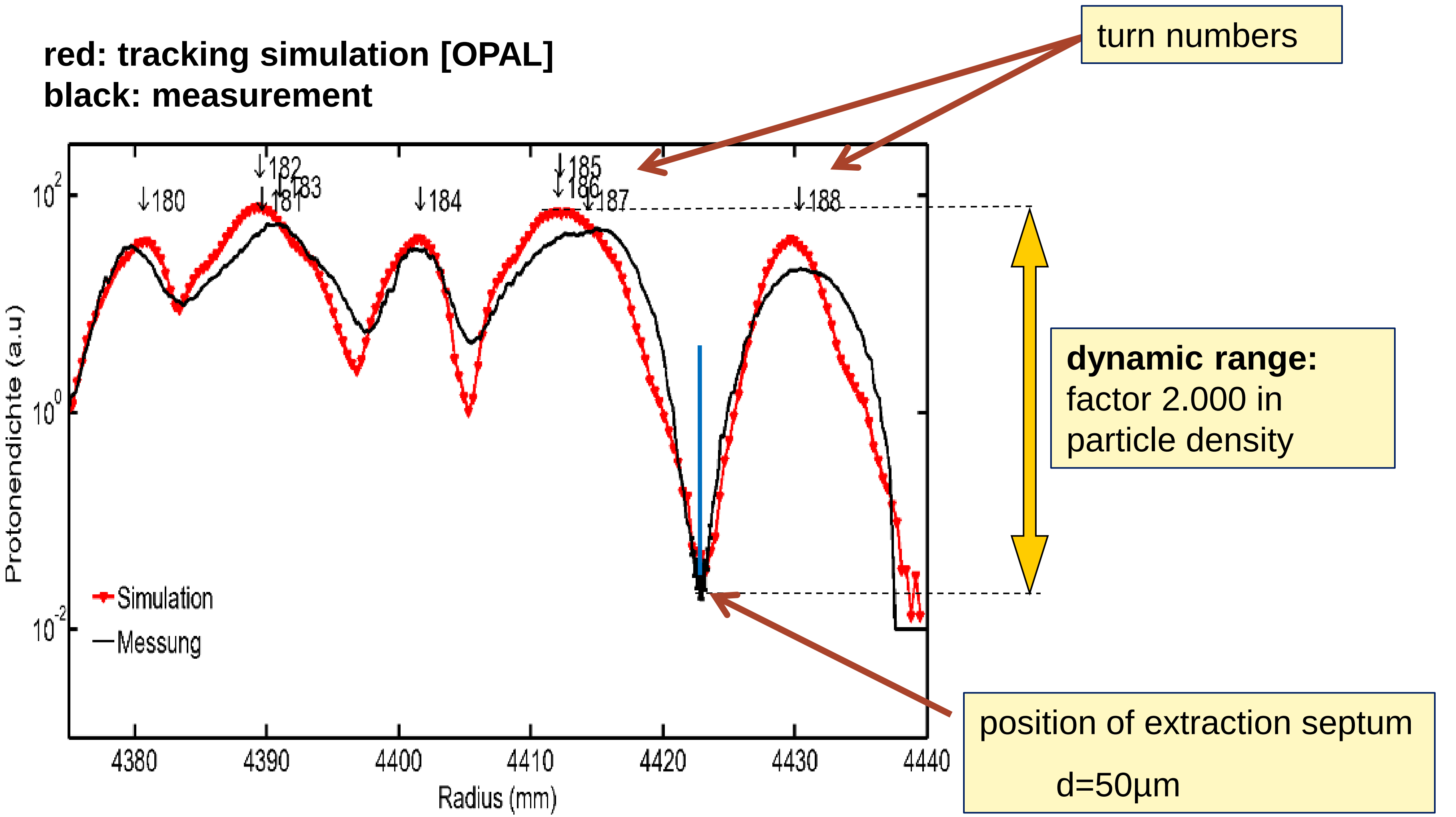


comments:

- 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

extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement



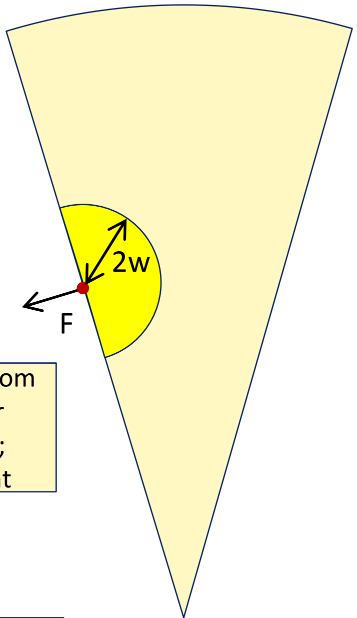
[Y.Bi et al]

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

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

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

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

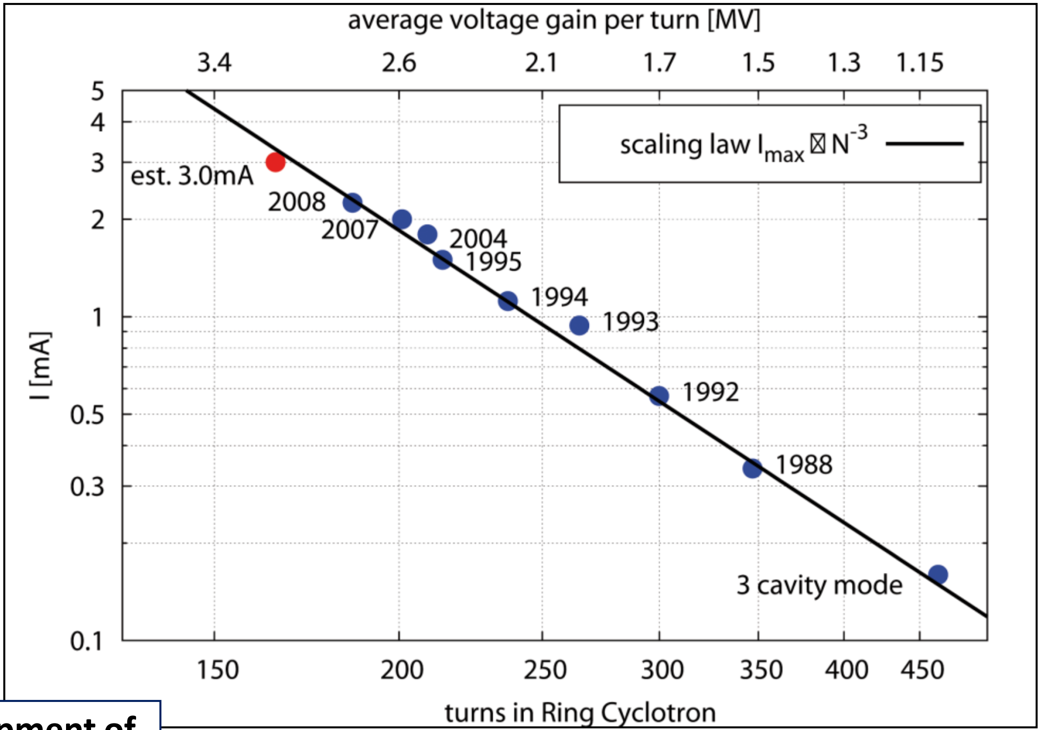
note: scaling with squared number of turns

- 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

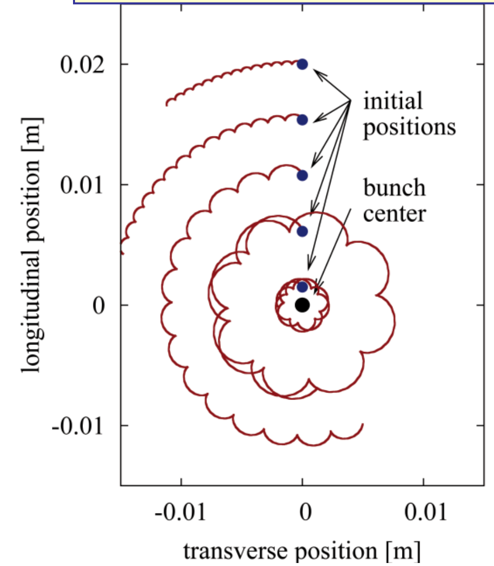
→ thus with constant losses at the extraction electrode the maximum attainable current scales as: $I_{\max} \propto n_t^{-3}$



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)]

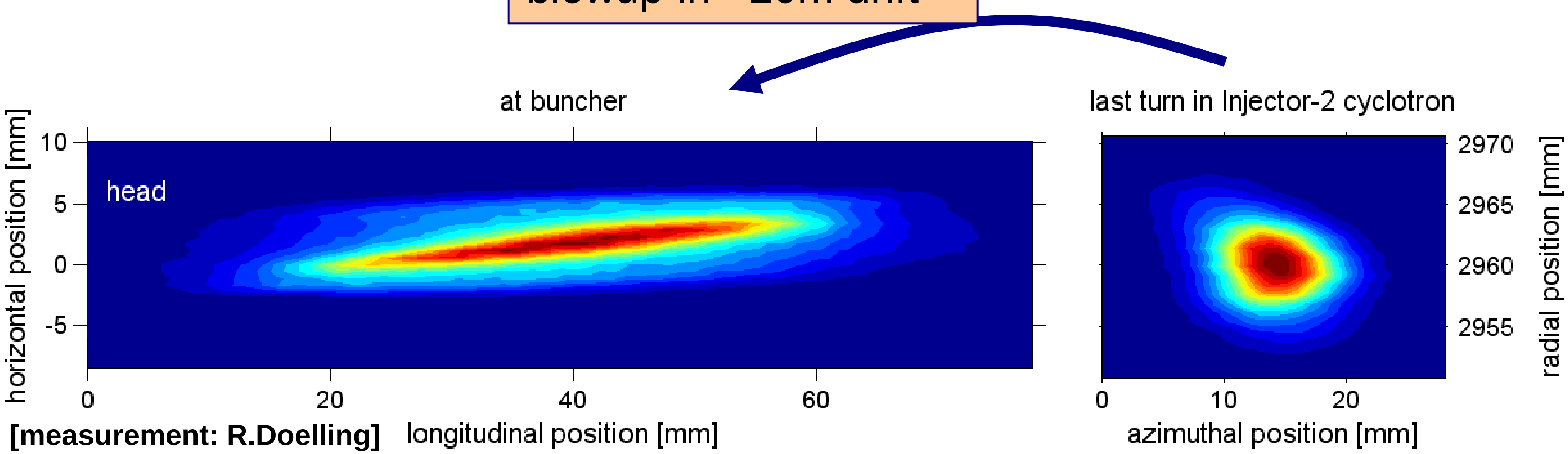
→ bound motion; circular equilibrium beam destribution

→ **see Ch.Baumgarten, Friday 13:30 on coupling theory**

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

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

tune shift from forces: $$\Delta\nu_y \approx -\sqrt{2\pi} \frac{r_p R}{e \beta c \nu_{y0} \sigma_z} \frac{m_0 c^2}{U_t} I_{avg}$$

intense ion beams in cyclotrons

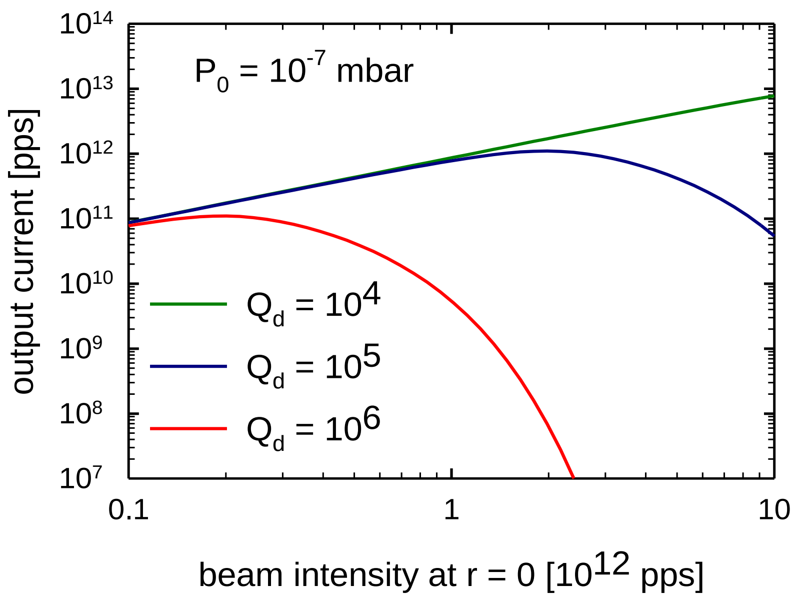
- ions in cyclotrons: e.g. GANIL, RIKEN, AGOR… but also synchrotrons: RHIC/BNL, FAIR/GSI, LHC chain/CERN…
- issues:
  - unwanted change of charge state
    (gas scattering, electro-magnetic stripping)
  - **ion induced gas desorption**
  - high energy density when stopped in material

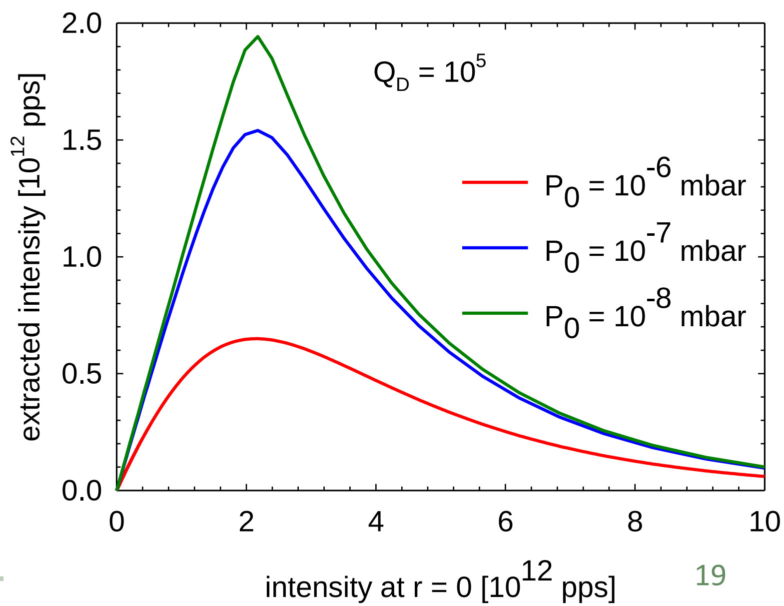
heavy ion acceleration

- neglect energy dependences
  $I_{out} = I_{in} \exp(-P/P_c)$
  $P = P_0 + Q_d (I_{in} - I_{out})/S_p$
    - Q_d: desorped molecules per lost ion
    - P_c: measure for charge exchange cross section
    - S_p: pumping speed (3000 l/s)
- $Q_d \approx 10^5$; $P_c \approx 2 \times 10^{-6}$ mbar
  - measurements GSI, KVI etc.
- Q_d/S_p dominating factor for transmission

compare electron rings:
- $Q_d(CO) \approx 10^{-4}$/photon
- $n_\gamma \approx 1$/meter/electron

[S.Brandenburg, KVI]

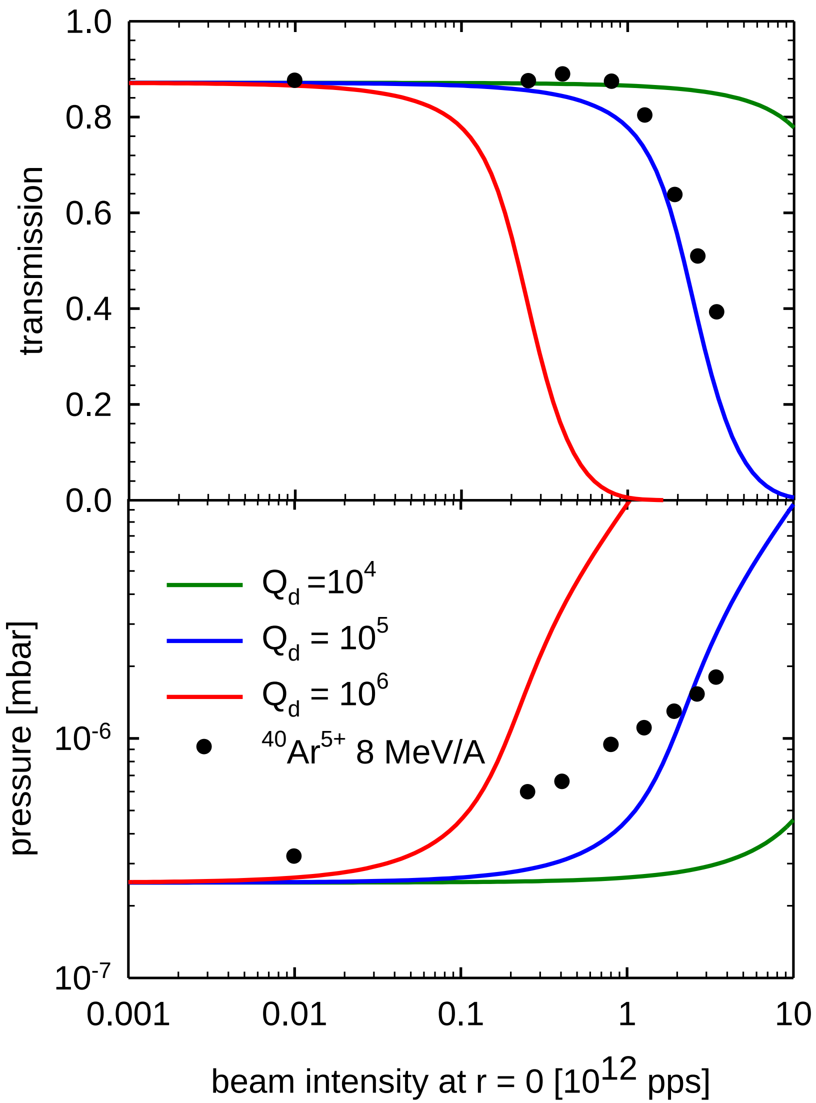




heavy ion acceleration

measurements at KVI, S.Brandenburg

- transmission of 40Ar^{5+} 8 MeV per nucleon
- base vacuum 3 x 10^{-7} mbar
- injected intensity up to 6 x 10^{12} pps
- beampower (for T = 1) 320 W



Beam dynamics modeling for high intensity beams in cyclotrons – general comments

Multiscale / Multiresolution

- Maxwell's equations in 3D or reduced set combined with particles; large and complex structures (field computations)
- many particles problem, n ~ 10^9 per bunch in case of PSI
- Spatial scales: 10^{-4} ... 10^4m → O(1E5) integration steps; advanced numerical methods; parallel computing
- neighboring bunches (Cyclotrons & FFAG)

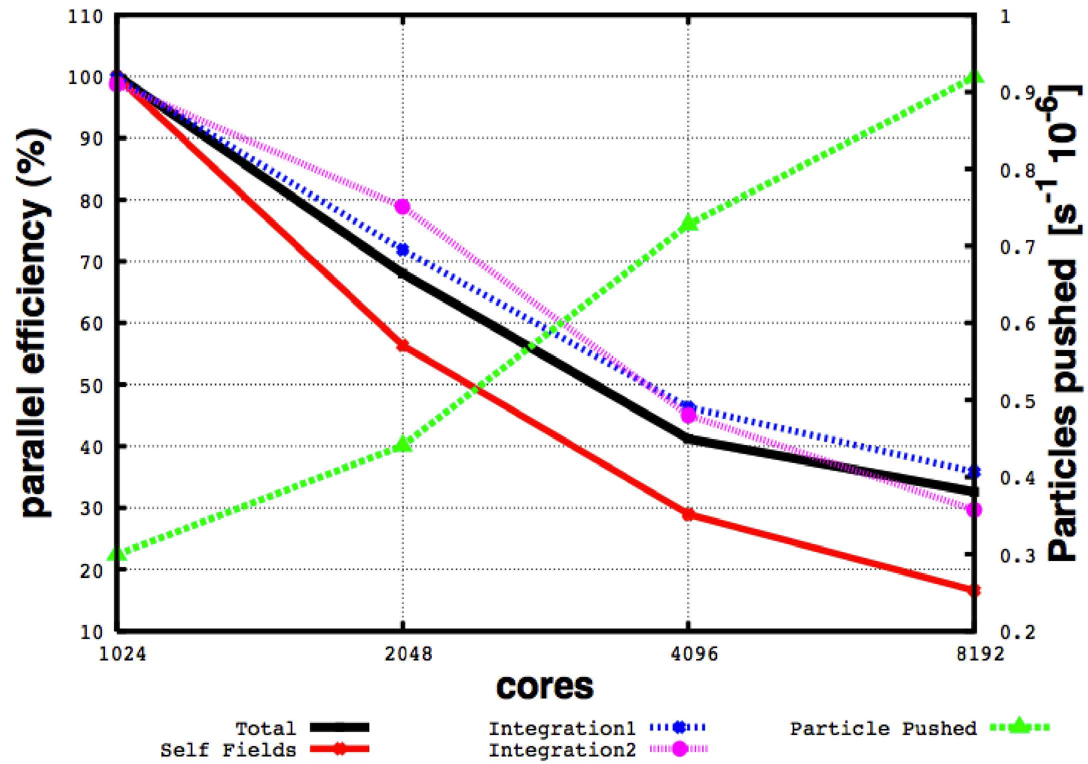
Multiphysics

- particle matter interaction, simulation of scattering
- field emission in resonators
- secondary particles

at PSI development of **OPAL** code with many extensions in recent years
see: **amas.web.psi.ch**

[A.Adelmann]

parallel computing - scalability



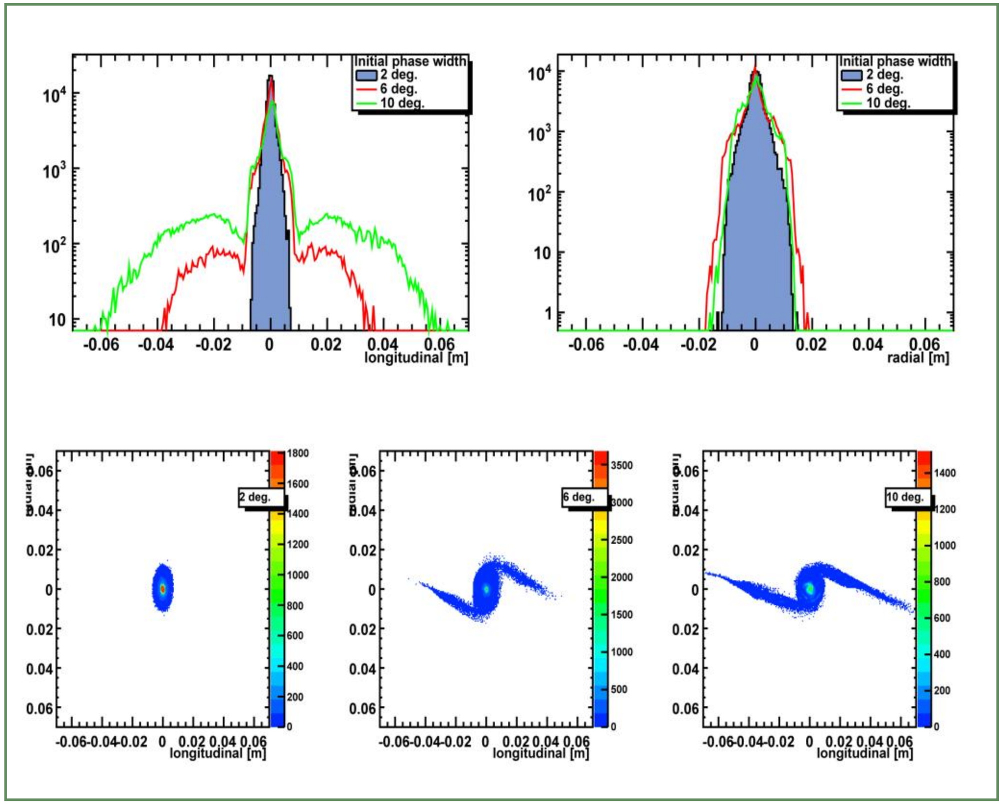
scaling test:
- **grid 1024x1024x1024**
- **particles 1E9**

[A.Adelmann]

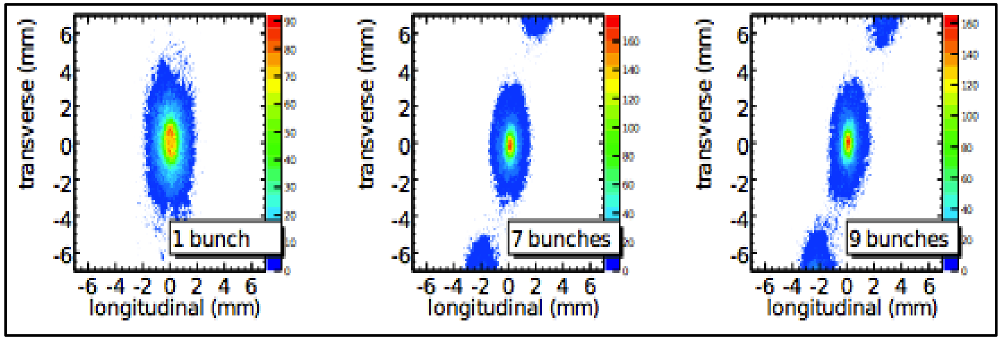
- **full 3D tracking run**
- **no parallel I/O considered in timing**
- **smallest number of cores = 1024 to run this problem**

real case:
- **5E6 32 cores, 108 turns 64x128x64 + I/O → 19 hours (modern cluster)**

examples of OPAL simulations in PSI Ring



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



tracking with 0, 6, 8 neighboring bunches;
considered bunch shows slight compression when taking neighbours into account [J.Yang, A.Adelmann]

next: **cyclotron subsystems**

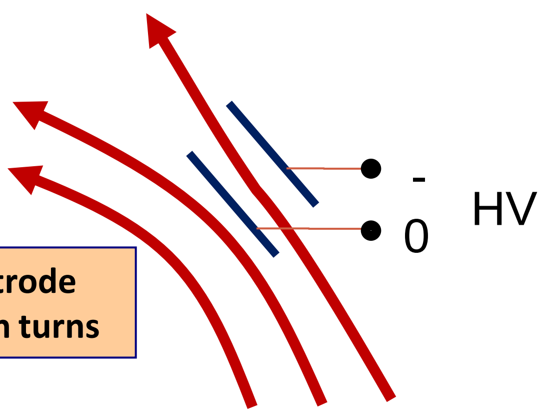
- with emphasize on high intensity

- **extraction schemes**
- **RF systems/power efficiency**
- **comments on vacuum**
- **collimation issues**

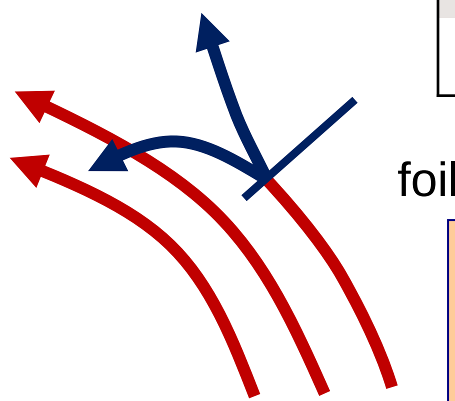
injection/extraction schemes

- 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

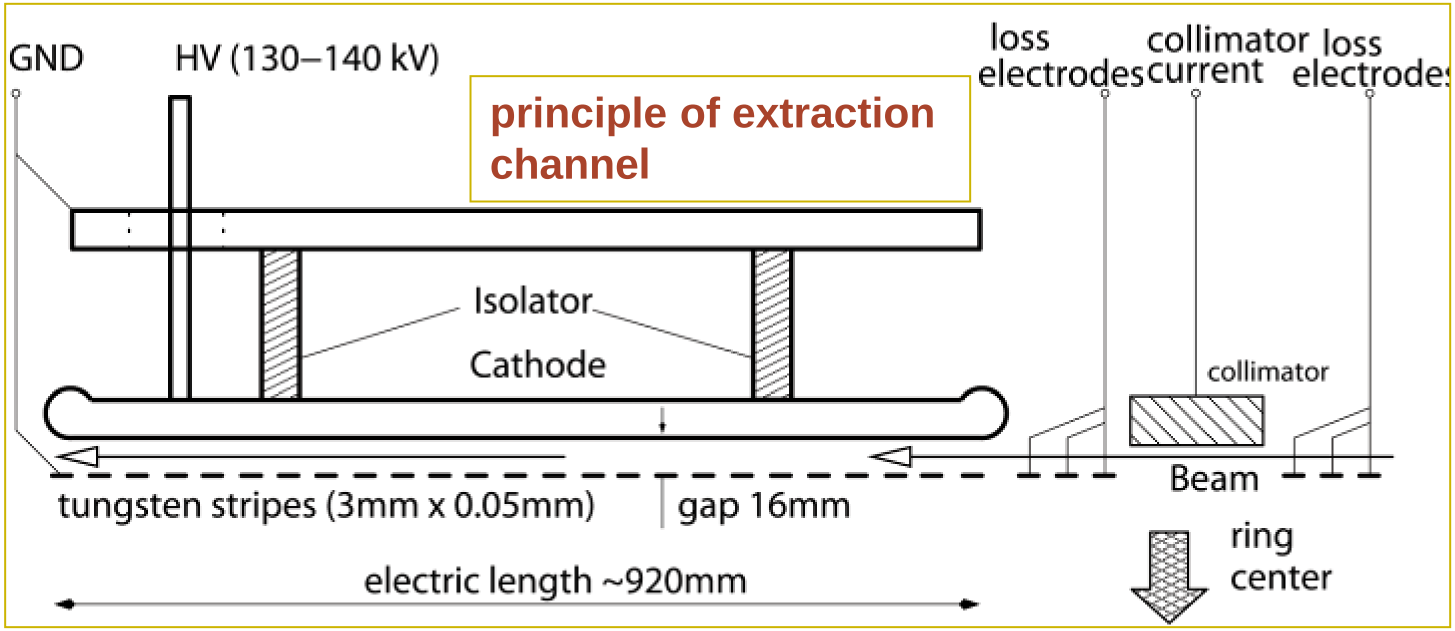


extraction electrode placed between turns



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

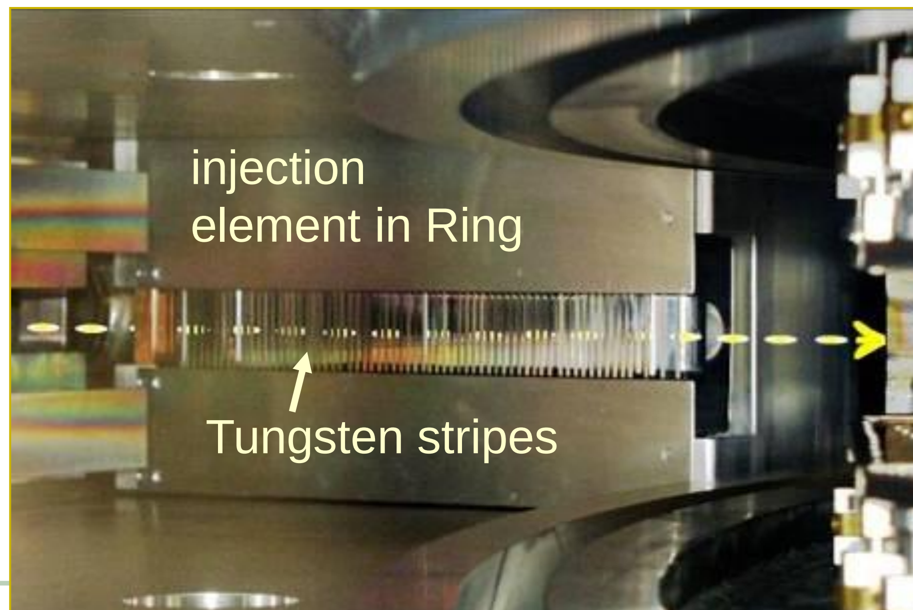
U = 144 kV

major loss mechanism is scattering in 50µm electrode!

electrostatic rigidity:

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

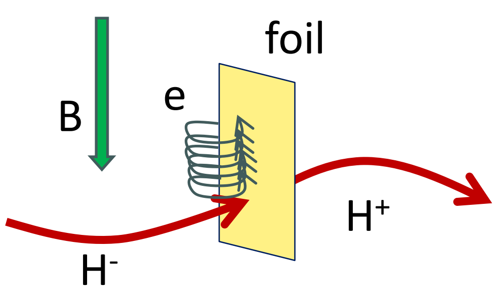
$$\theta = \frac{qlE}{E_k}\frac{\gamma}{\gamma+1}$$



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*

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

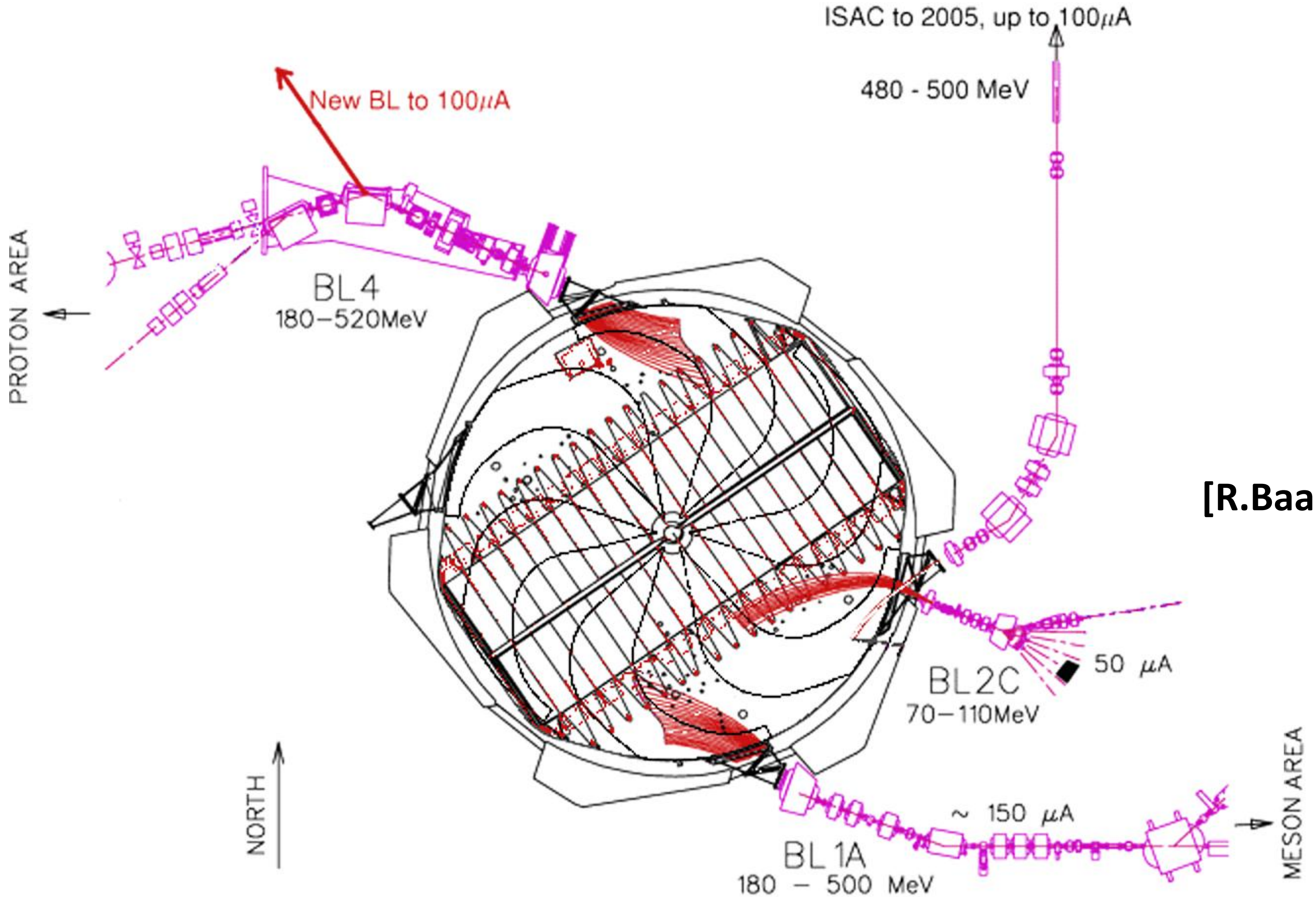
$$\rightarrow E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

Bending radius of electrons?

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

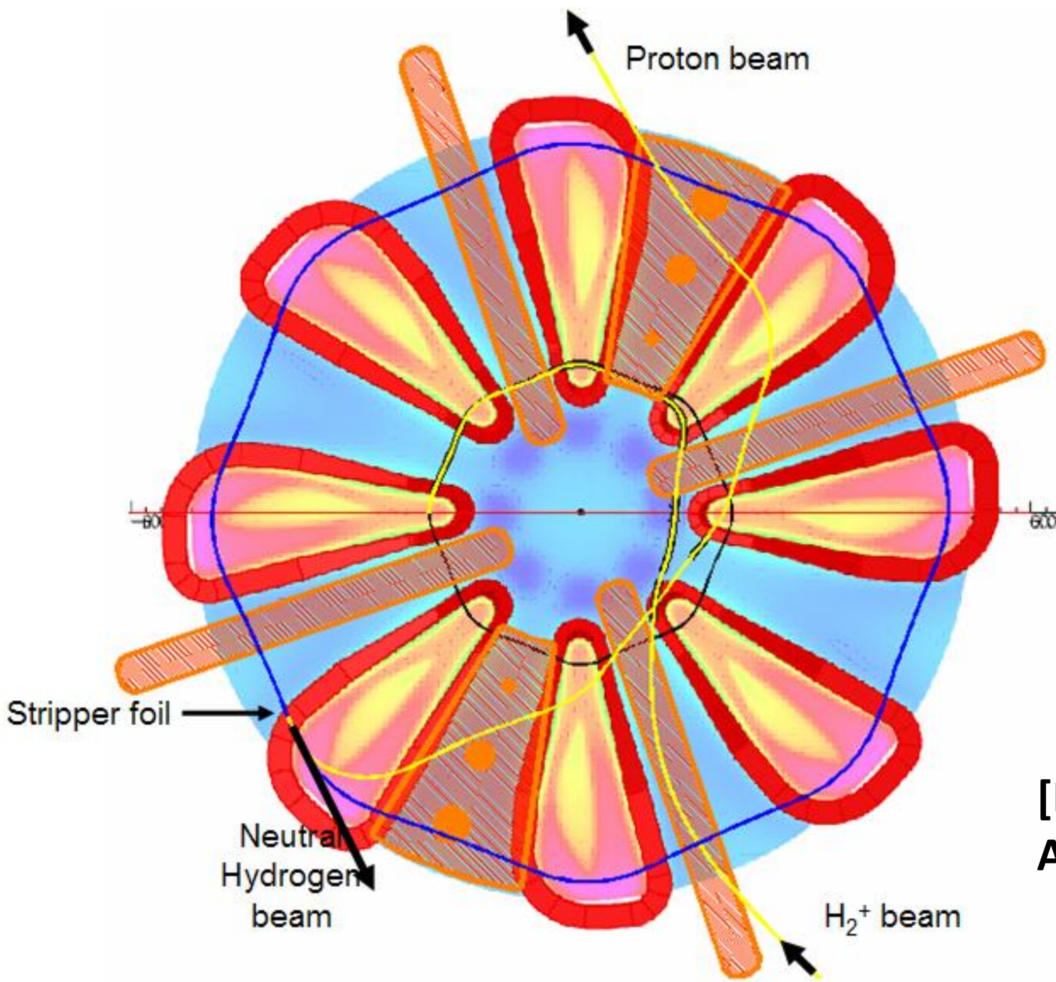
→ typically mm

example: multiple H^- stripping extraction at TRIUMF



[R.Baartman]

example: H_2^+ stripping extraction in planned Daedalus cyclotron



purpose: pulsed high power beam for neutrino production

- 800MeV
- 5MW

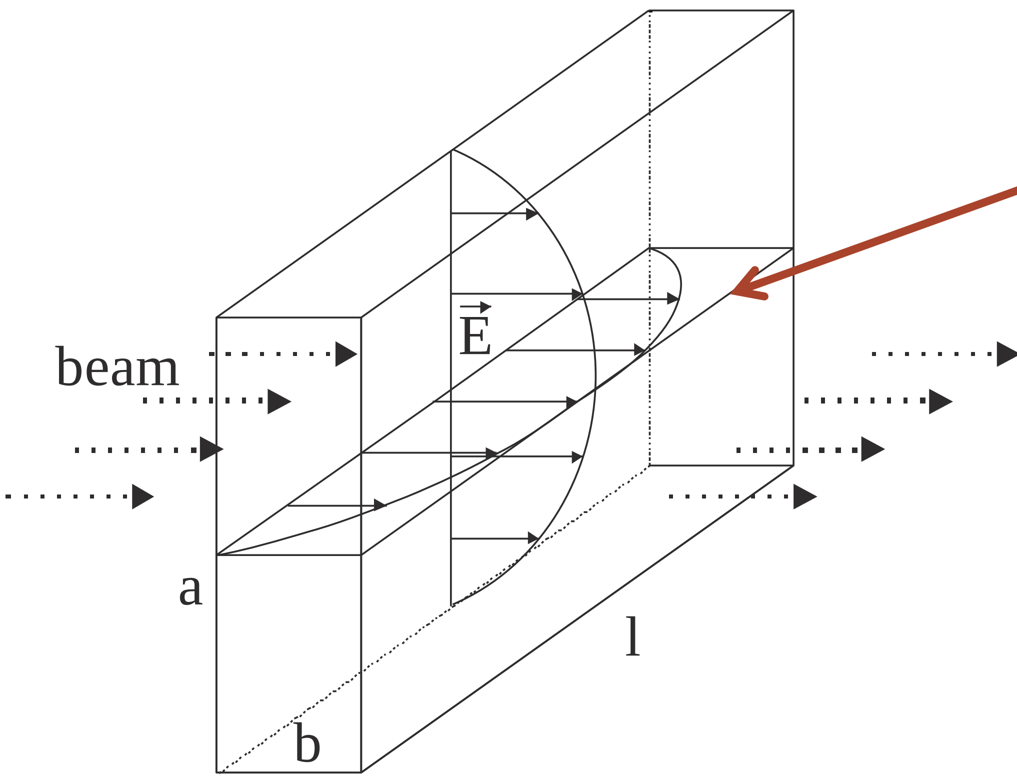
see talks in ECPM program!

[L.Calabretta, A.Calanna et al]

components: cyclotron resonators

cyclotron resonators are basically box resonators
resonant frequency:

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

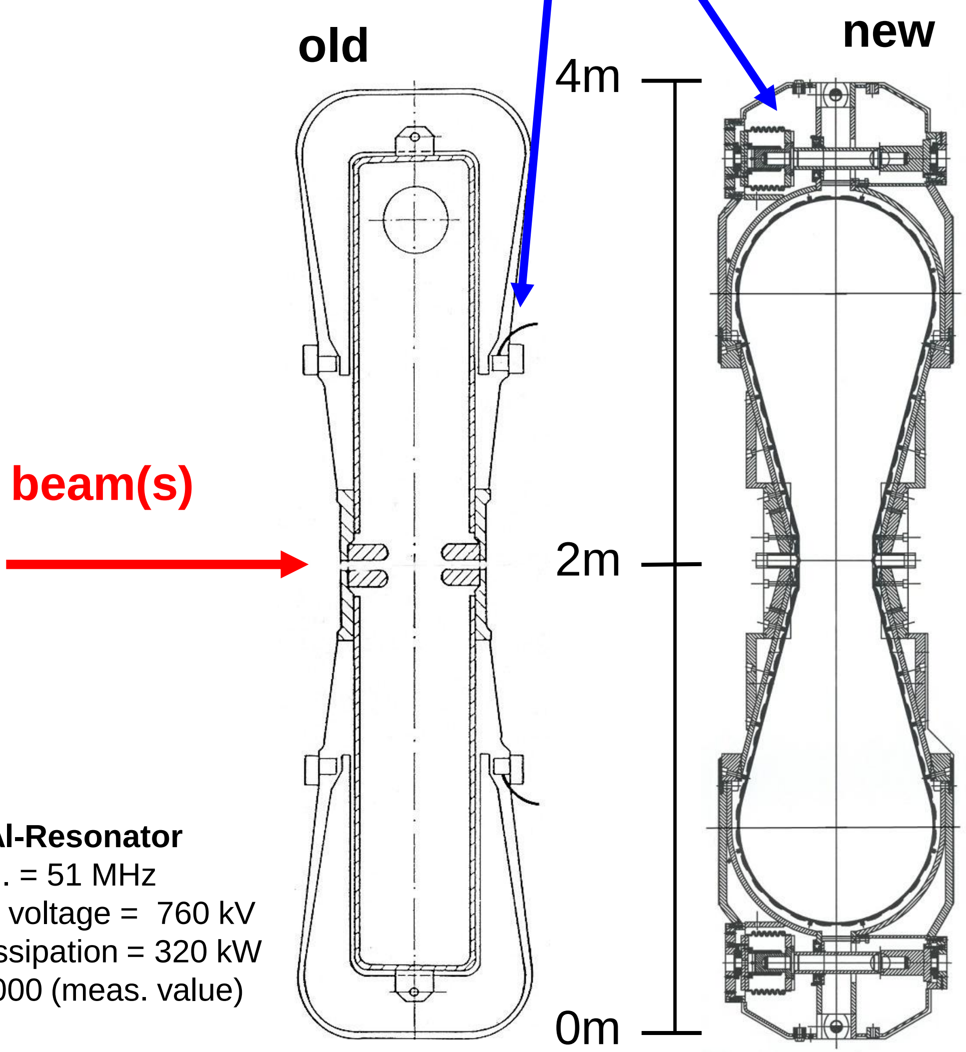


beam passes in center plane;

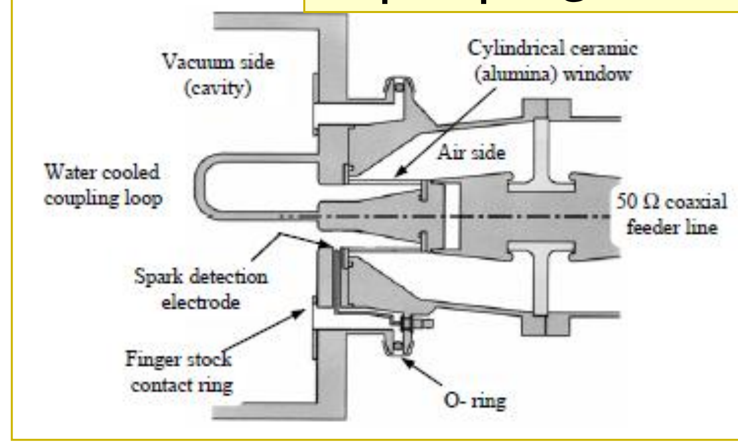
accelerating voltage varies as sin(r)

cross sections of PSI resonators

hydraulic tuning



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

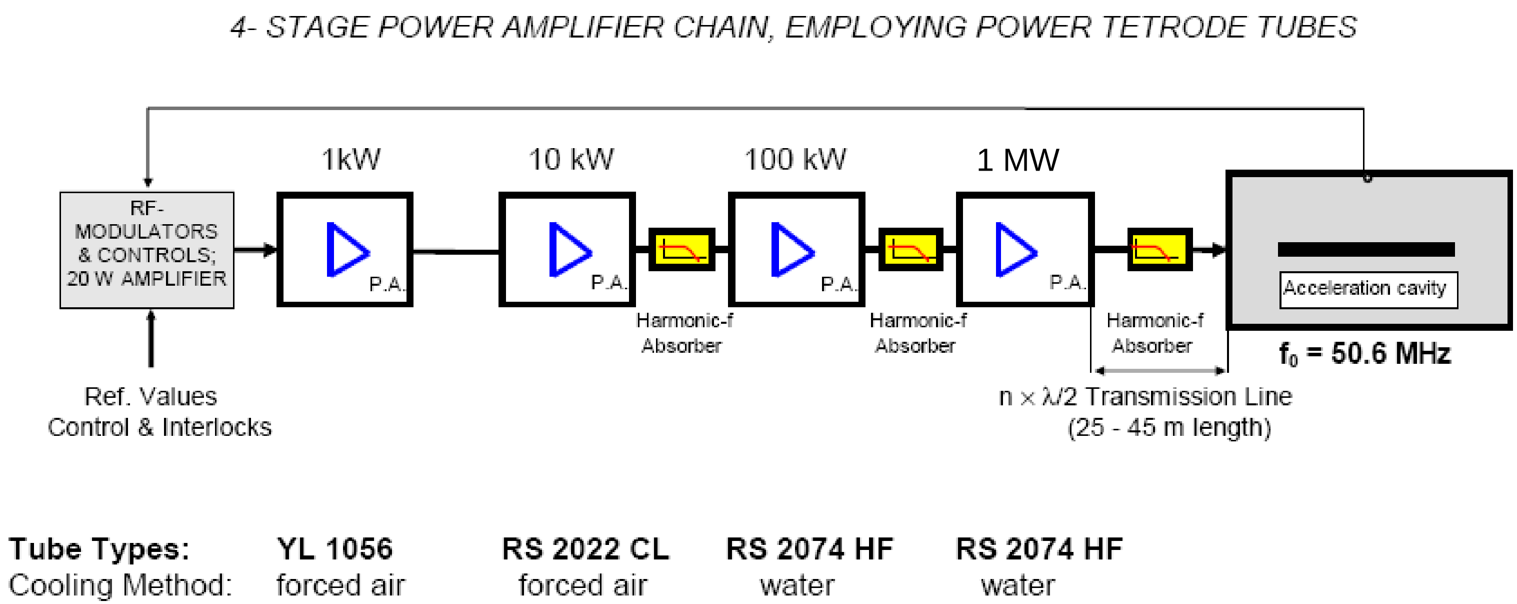
copper resonator in operation at PSI's Ring cyclotron

- **f = 50.6MHz**; **Q_0 = 4,8·10^4**; **U_{max}=1.2MV** (presently 0.85MV)
- transfer of up to **400kW power to the beam** per cavity

resonator inside

hydraulic tuning devices (5x)

50 MHz 1 MW amplifier chain for Ring cyclotron



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

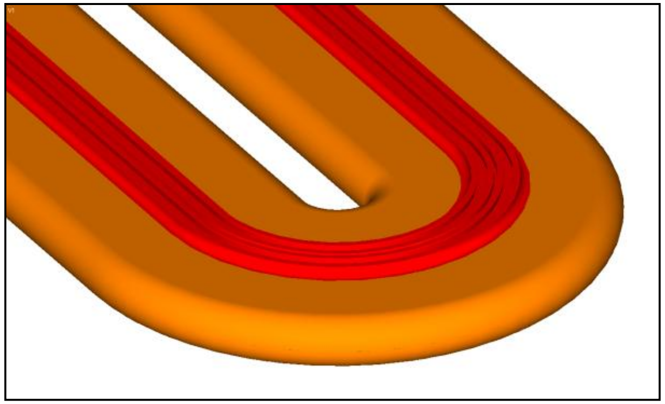
[L.Stingelin et al]

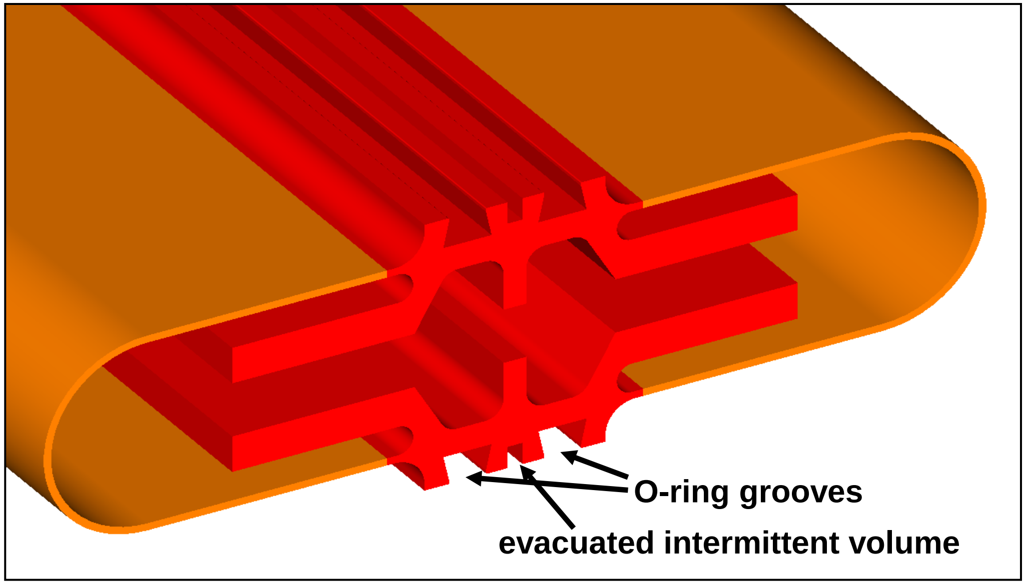
cyclotron vacuum system

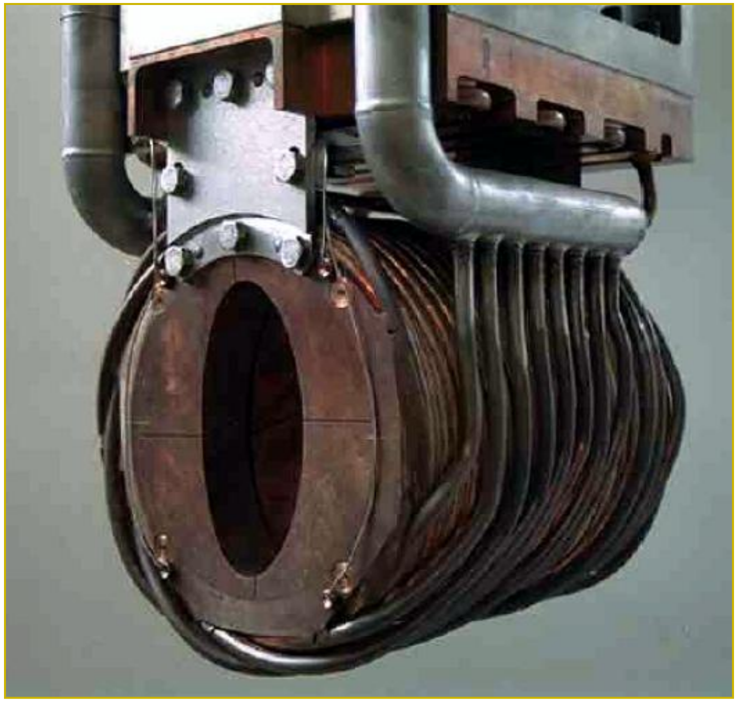
- vacuum chamber with large radial width → difficult to achieve precisely matching sealing surfaces→ noticeable leak rates must be accepted
- use cryo pumps with high pumping speed and capacity
- ≈10^{-6}mbar for p, ≈10^{-8}mbar for ions
- design criterion is easy access and fast mountability (activation)

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

length: 3.5m

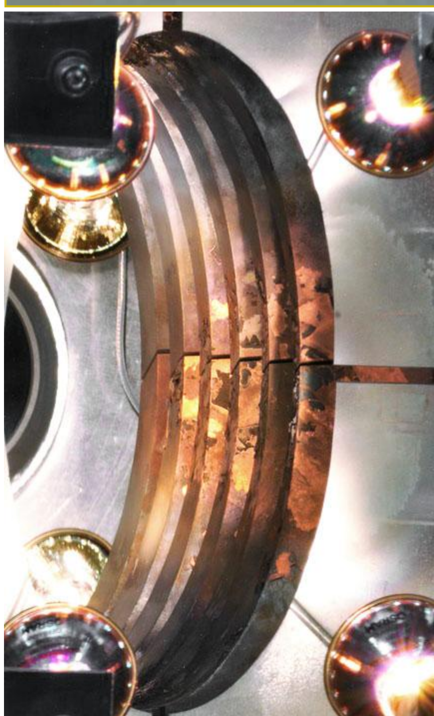


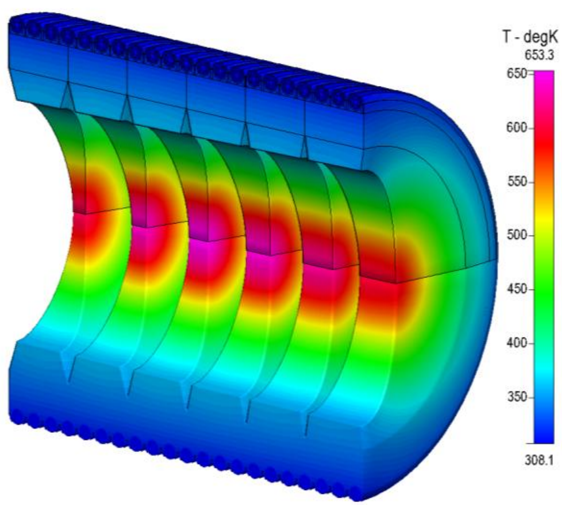




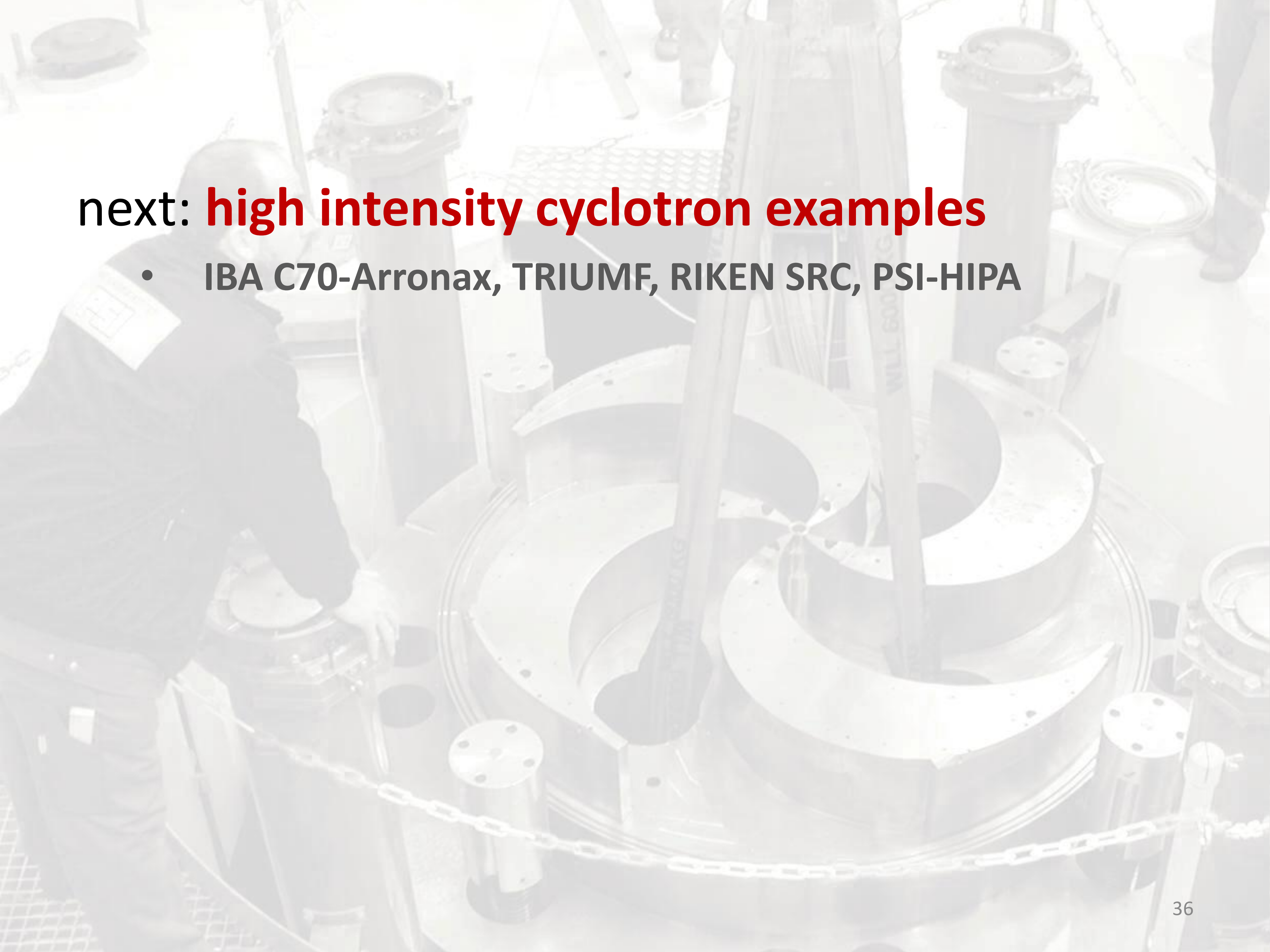
collimator for high intensity beam
(sitting in beam transport line at PSI)

aspects:
- high power deposition; cooling at limit
- high radiation dose; estimated 20-40dpA; measured dose rate on axis: 500Sv/h (!)
- material properties and rad.damage? (λ, $\sigma_{0.2}$)
- activation in water circuits (^3H, ^7Be)
- instrumentation (T, I_{loss})
- long term reliability





[D.Kiselev, Y.Lee et al]



next: high intensity cyclotron examples

- **IBA C70-Arronax, TRIUMF, RIKEN SRC, PSI-HIPA**

parameters of some cyclotrons

	TRIUMF	**RIKEN SRC (supercond.)**	**PSI Ring**	**IBA C70 ARRONAX**
particles	$H^- \rightarrow p$	ions	p	$H^- \rightarrow p$, ions
K [MeV]	520	2600	592	70
magnets (poles)	(6)	6	8	(4)
peak field strength [T]	0.6	3.8	2.1	1.6
R_{inj}/R_{extr} [m]	0.25/3.8…7.9	3.6/5.4	2.4/4.5	0.03/1.16
P_{max} [kW]	110	6.2 (^{18}O)	1400	52
extraction efficiency (tot. transmission)	0.9995 (0.70)	(0.63)	0.9998	(0.8)
extraction method	stripping foil	electrostatic deflector	electrostatic deflector	stripping foil
comment	variable energy	ions, flexible	high intensity	compact, flexible

IBA C70 ARRONAX

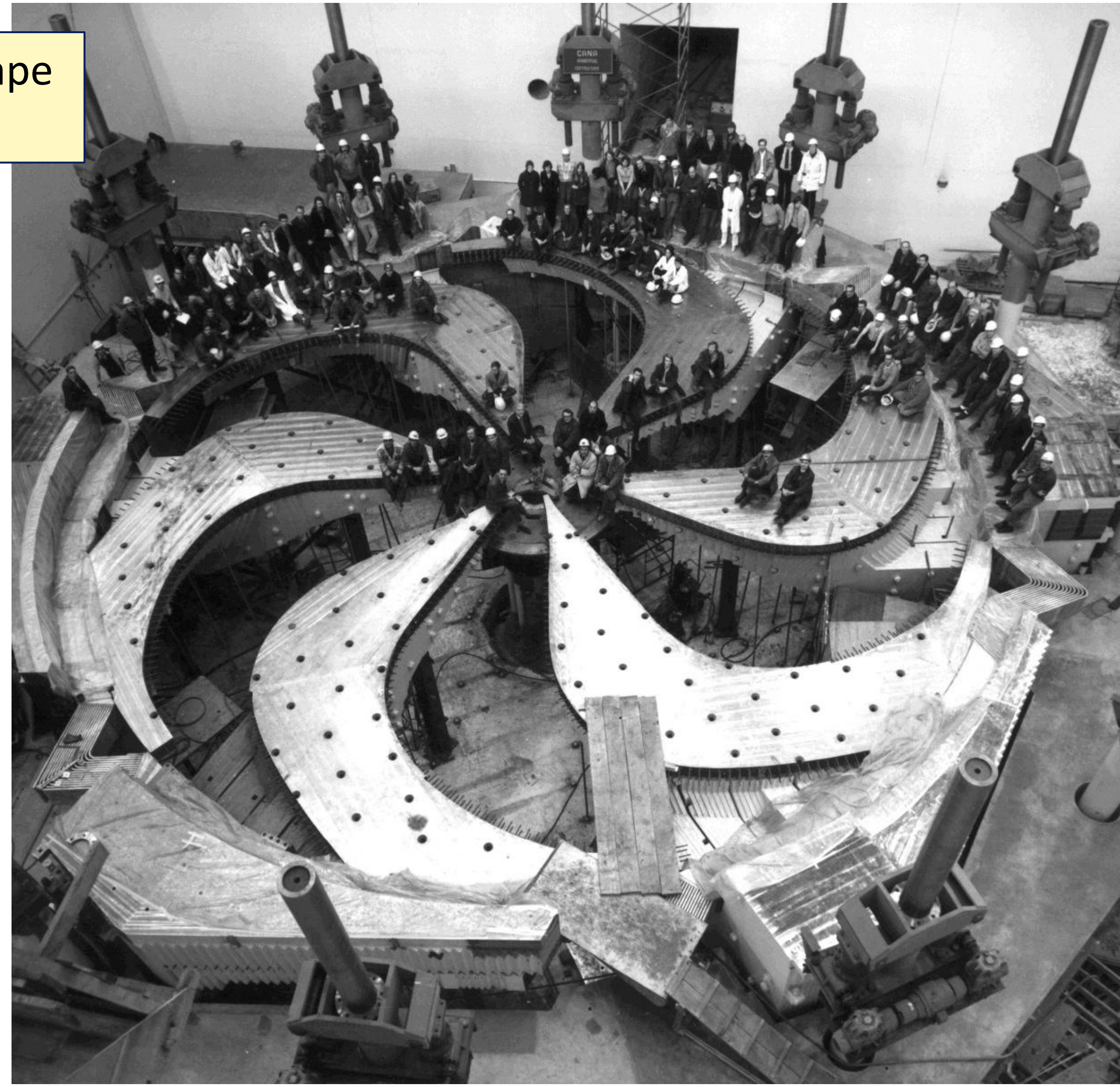
multi-purpose, compact cyclotron with 50kW beam power

- H^- for high intensity, 70MeV variable energy
- multiple ion species; two independent extraction systems
- application: isotope production, nuclear medicine in Nantes, France

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

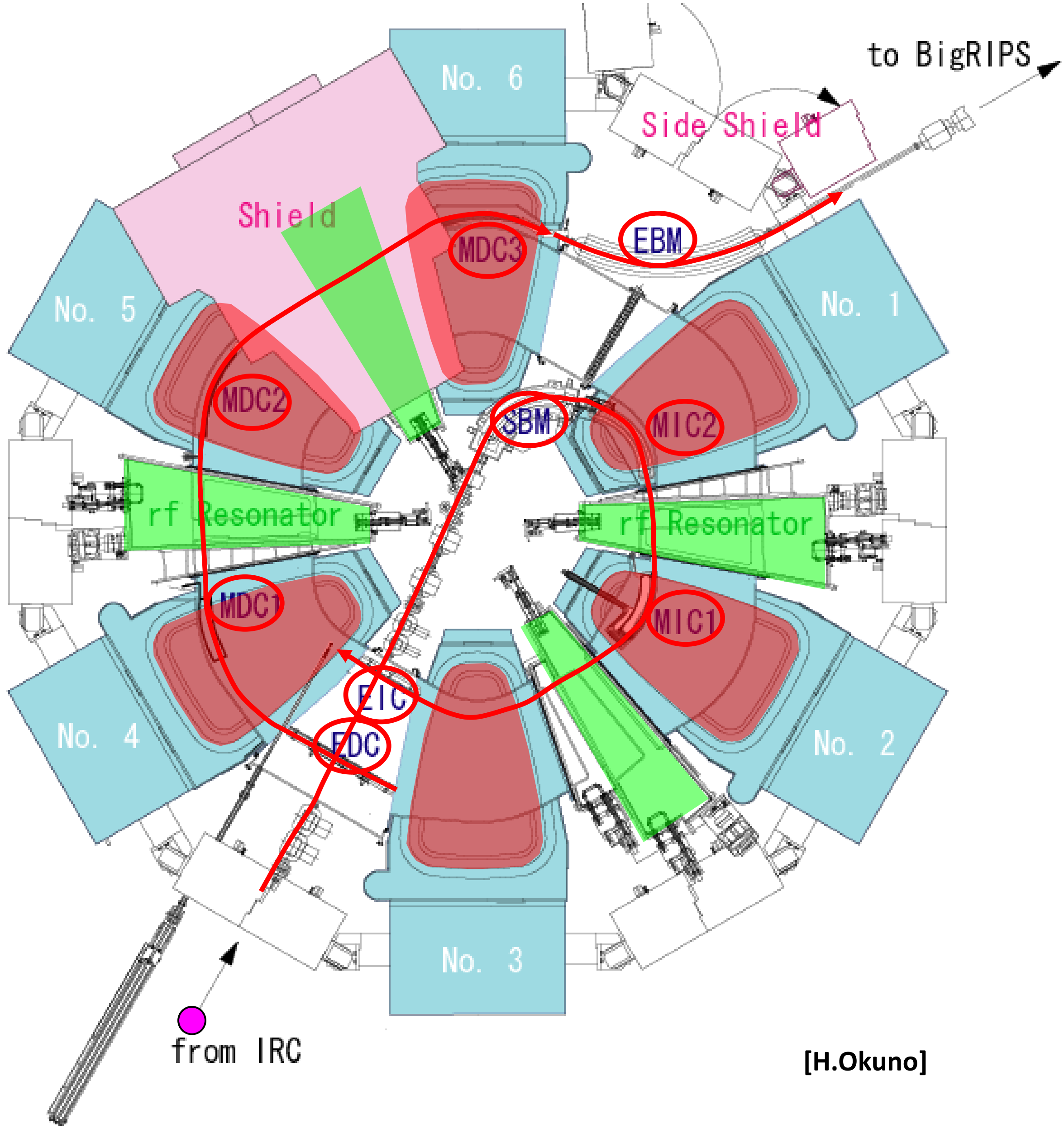


example: RIKEN (Jp) superconducting cyclotron

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.

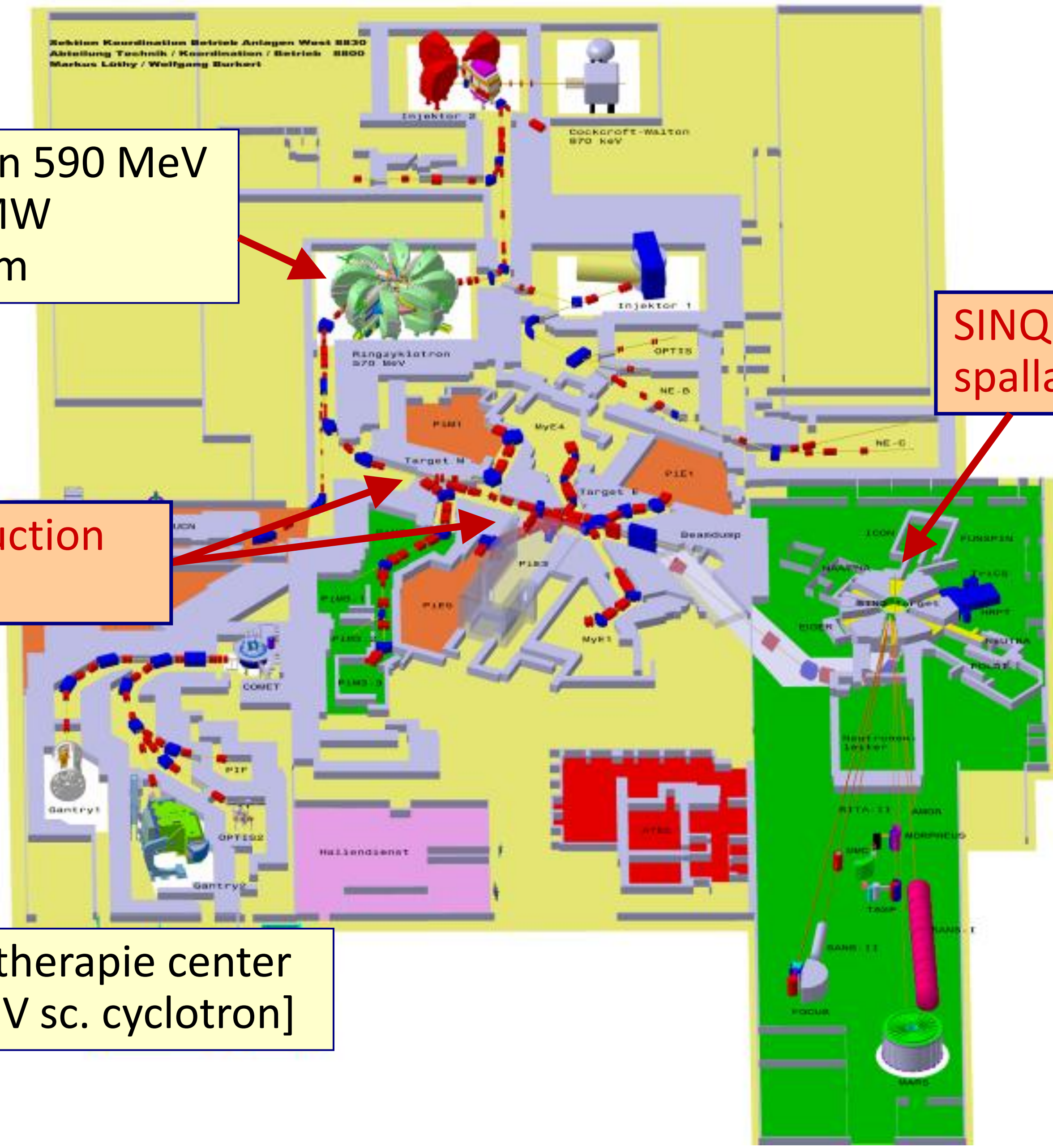
utilization:
broad spectrum of
ions up to Uranium



[H.Okuno]

RIKEN SRC in the vault

examples: PSI High Intensity Proton Accelerator



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

SINQ
spallation source

meson production
targets

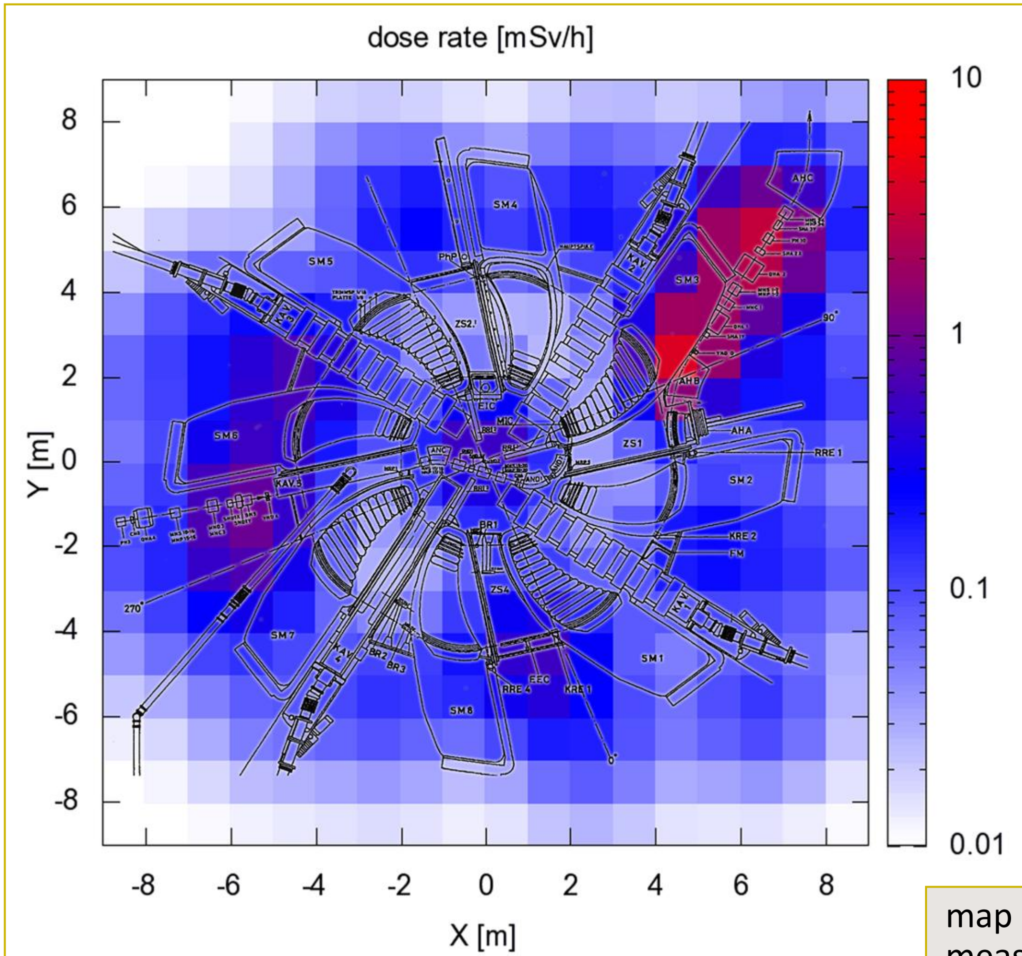
proton therapie center
[250MeV sc. cyclotron]

dimensions:

120 x 220m^2

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:

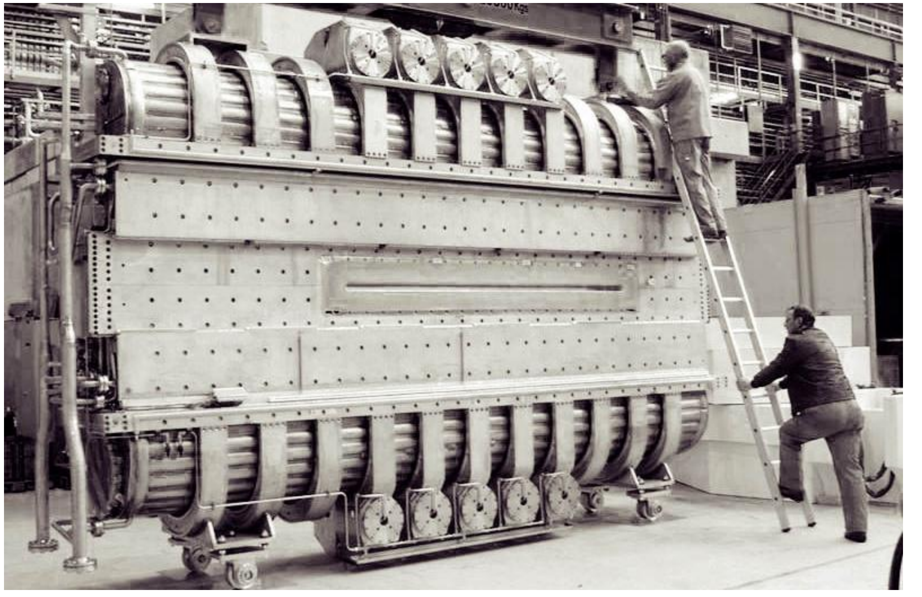
47mSv, 186 persons

max per person: 2.9mSv

finally: **discussion**

- **pro- and con`s of cyclotrons for high intensity beam acceleration**

pro and contra cyclotron



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

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

alternative: sc. linac
- no energy limit
- small losses
- but high cost and low efficiency

some literature w.r.t. high intensity 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; comp. 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, Experimental Investigation of Impact-Induced Molecular Desorption by 4.2 MeV/u Pb ions, PAC 2001, 2165 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 !