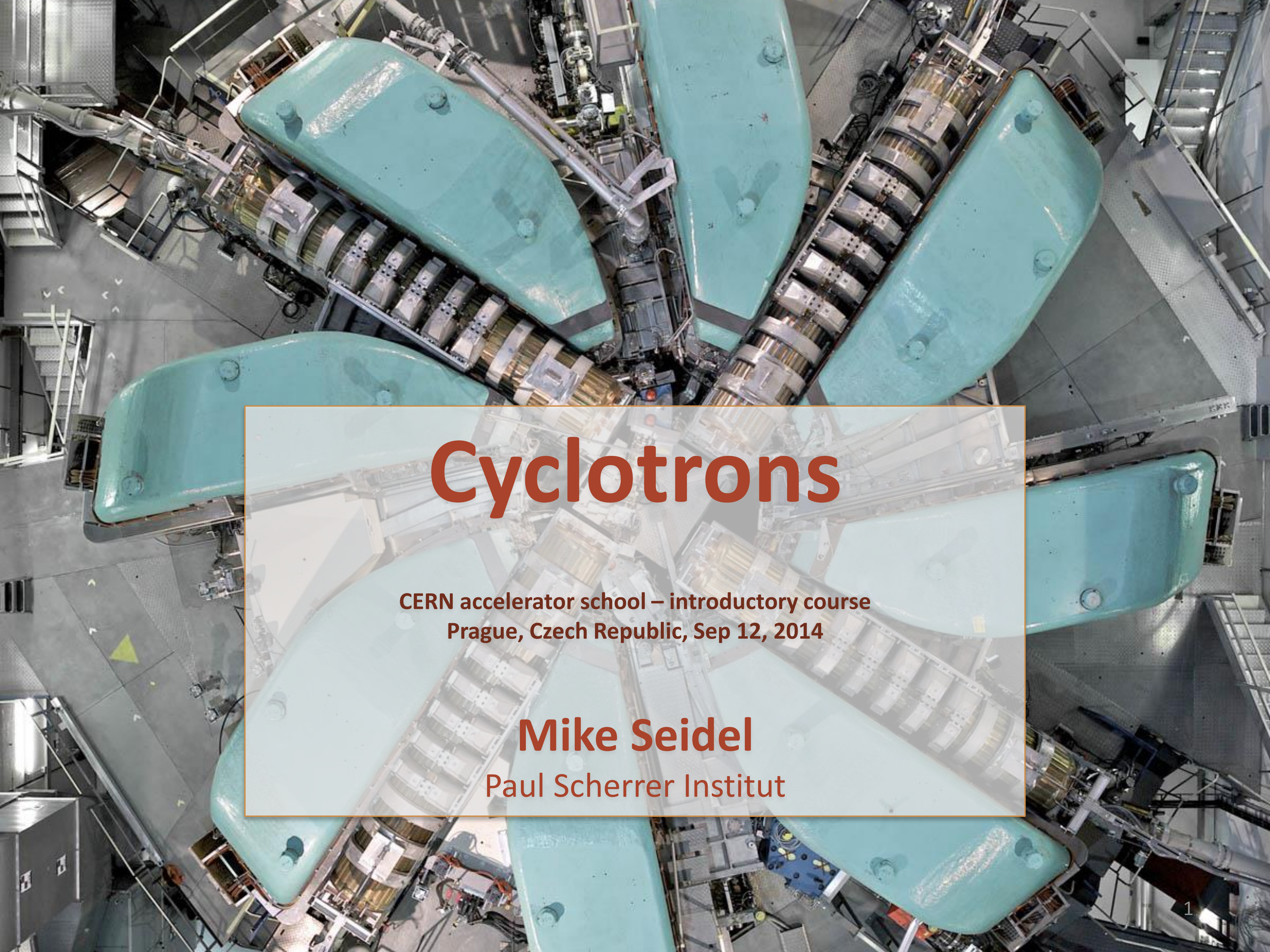


Cyclotrons

CERN accelerator school – introductory course
Prague, Czech Republic, Sep 12, 2014

Mike Seidel
Paul Scherrer Institut

Cyclotrons - Outline

- the classical cyclotron

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

- separated sector cyclotrons

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

- cyclotron subsystems

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

- applications and examples of existing cyclotrons

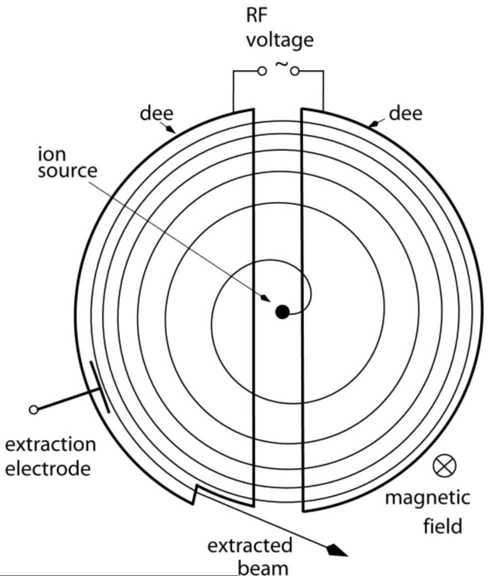
  TRIUMF, RIKEN SRC, PSI Ring, PSI medical cyclotron

- discussion

  Classification of circular accelerators

  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:

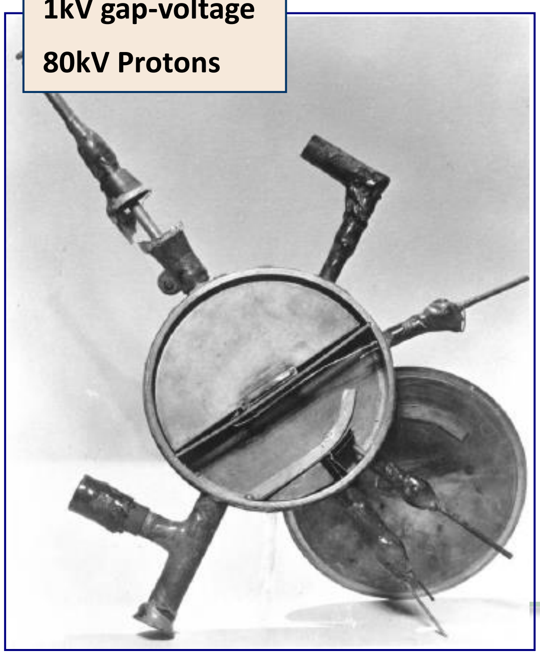
- ➔ **simplicity, compactness**
- ➔ **continuous injection/extraction**
- ➔ **multiple usage of accelerating voltage**

first cyclotron:

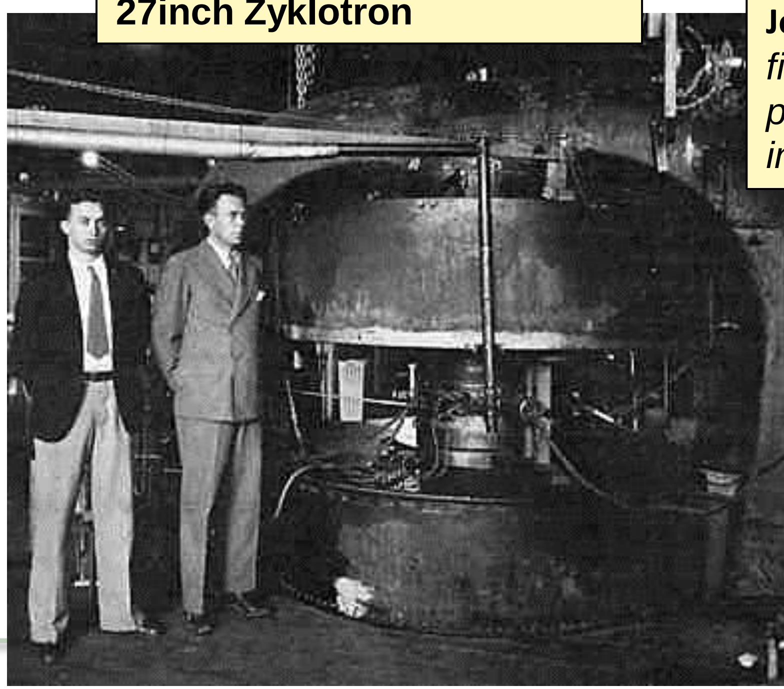
1931, Berkeley

1kV gap-voltage

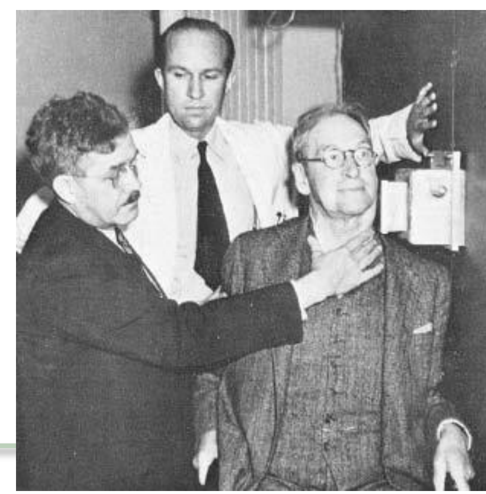
80kV Protons



E.Lawrence & S.Livingston, 27inch Zyklotron



John Lawrence (center), 1940'ies
first medical applications: treating patients with neutrons generated in the 60inch cyclotron



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:

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

→ *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:

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

orbit radius from isochronicity:

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

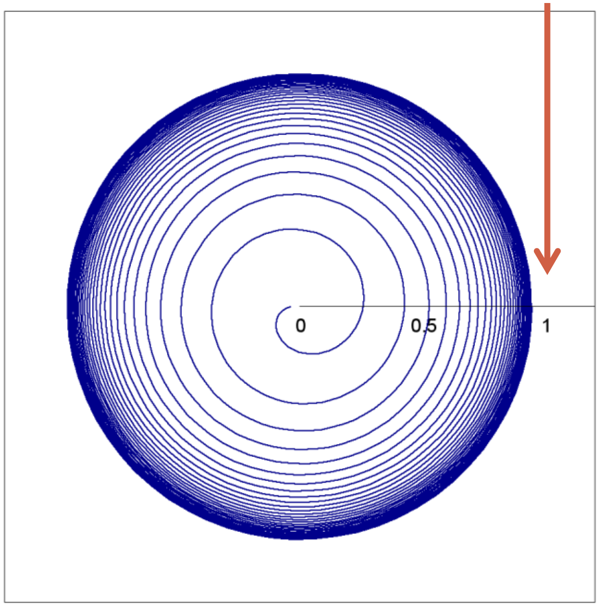
deduced scaling of *B*:

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

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:

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

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

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*):

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

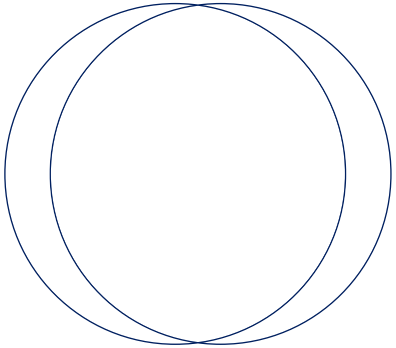
using: $\omega_\mathrm{c} = qB_z/m \approx v/R$, $r\dot{\varphi} \approx v$, $k = \frac{R}{B}\frac{dB}{dR}$

betatron tunes in cyclotrons

thus in radial plane:

$$\omega_r = \omega_c\sqrt{1+k} = \omega_c\nu_r$$
$$\nu_r = \sqrt{1+k}$$
$$\approx \gamma$$

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:

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

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 $k = \gamma^2 - 1 > 0$

classification of cyclotron like accelerators

classical cyclotron
[B(θ) = const]

Thomas cyclotron
[Azimuthally Varying Field, isochronous, one pol]

complexity

separated sector cyclotr.
[isochronous, 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

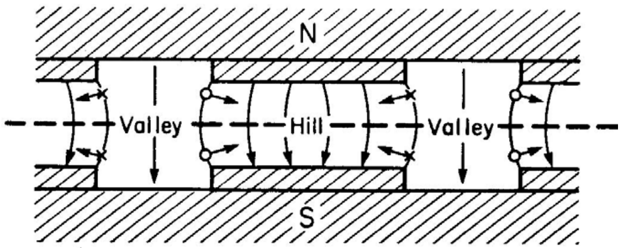
- next: **sector cyclotrons**
  - **AVF vs. separated sector cyclotron**
  - **focusing in sector cyclotrons**
  - **extraction: pattern/stepwidth**
  - **transv./long. space charge**

focusing in sector cyclotrons

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

Flutter factor:

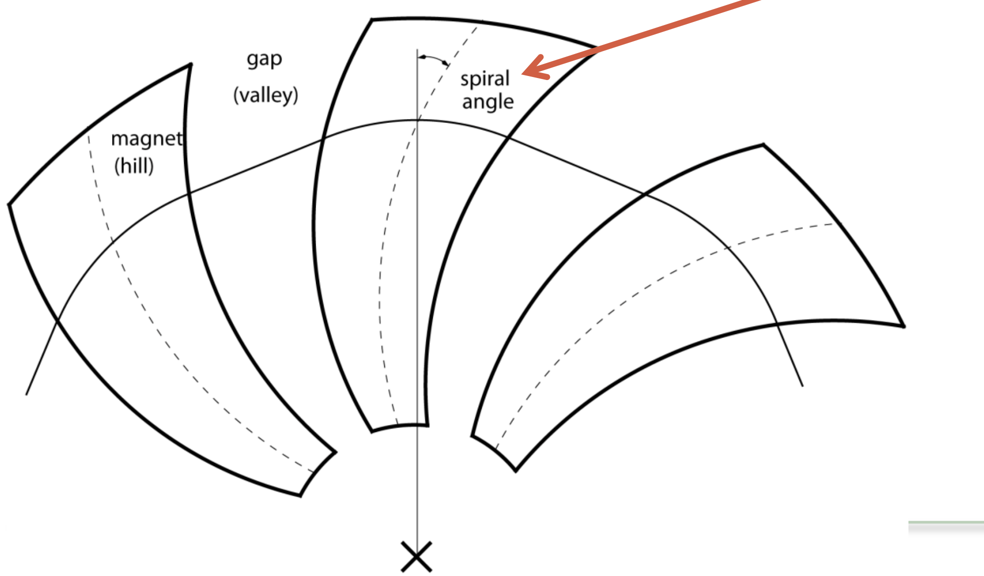
$$F^2 = \frac{\overline{B_z^2} - \overline{B_z}^2}{\overline{B_z}^2}$$



[illustration of focusing at edges]

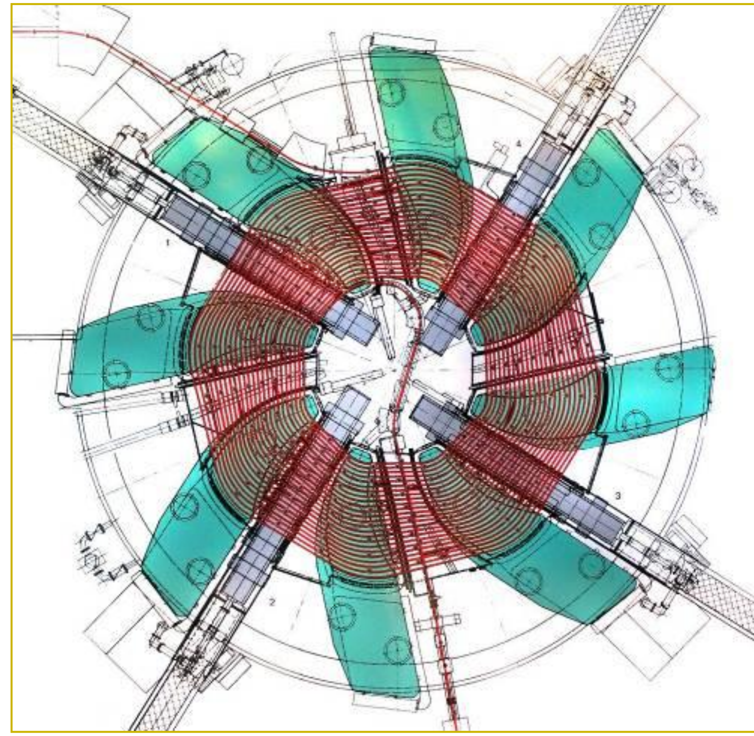
with flutter and additional spiral angle of bending field:

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



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
- **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% = $(1 - 2\cdot10^{-4})$

derivation of turn separation in a cyclotron

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

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

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

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

radius change per turn

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

[U_t = energy gain per turn]

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

} isochronicity not conserved (last turns)

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

} isochronicity conserved (general scaling)

turn separation - 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 at extraction:

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

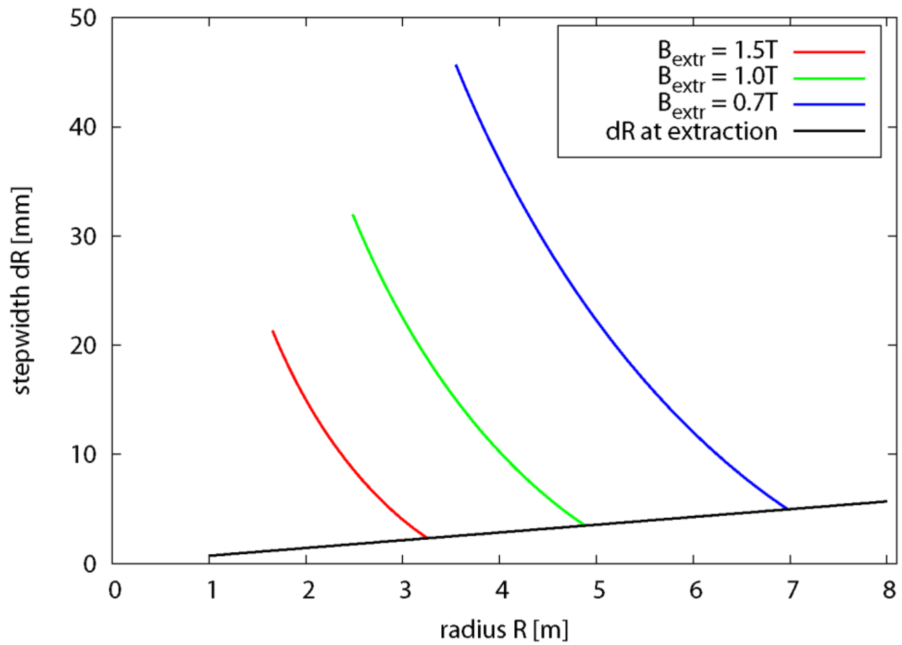
desirable:

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

scaling during acceleration:

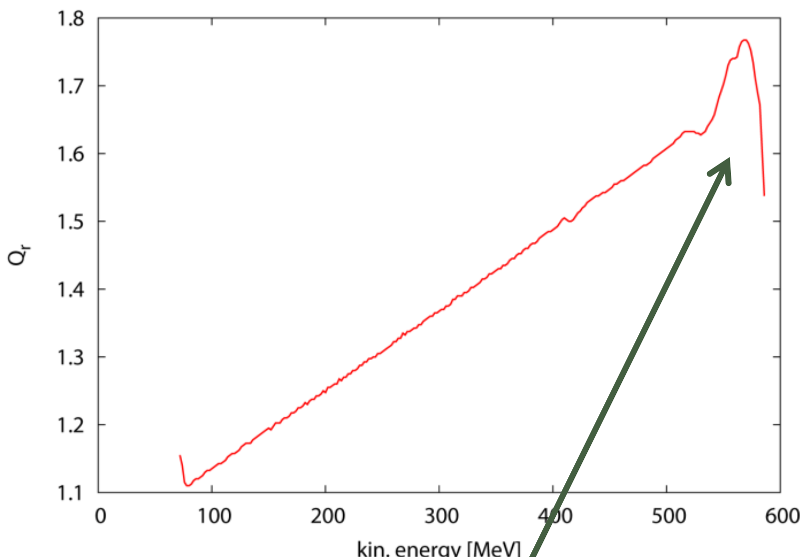
$$\frac{dR}{dn_t} \approx \frac{U_t}{m_0 c^2} \frac{R}{\beta^2} \rightarrow \Delta R(R) \propto \frac{1}{R}$$

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

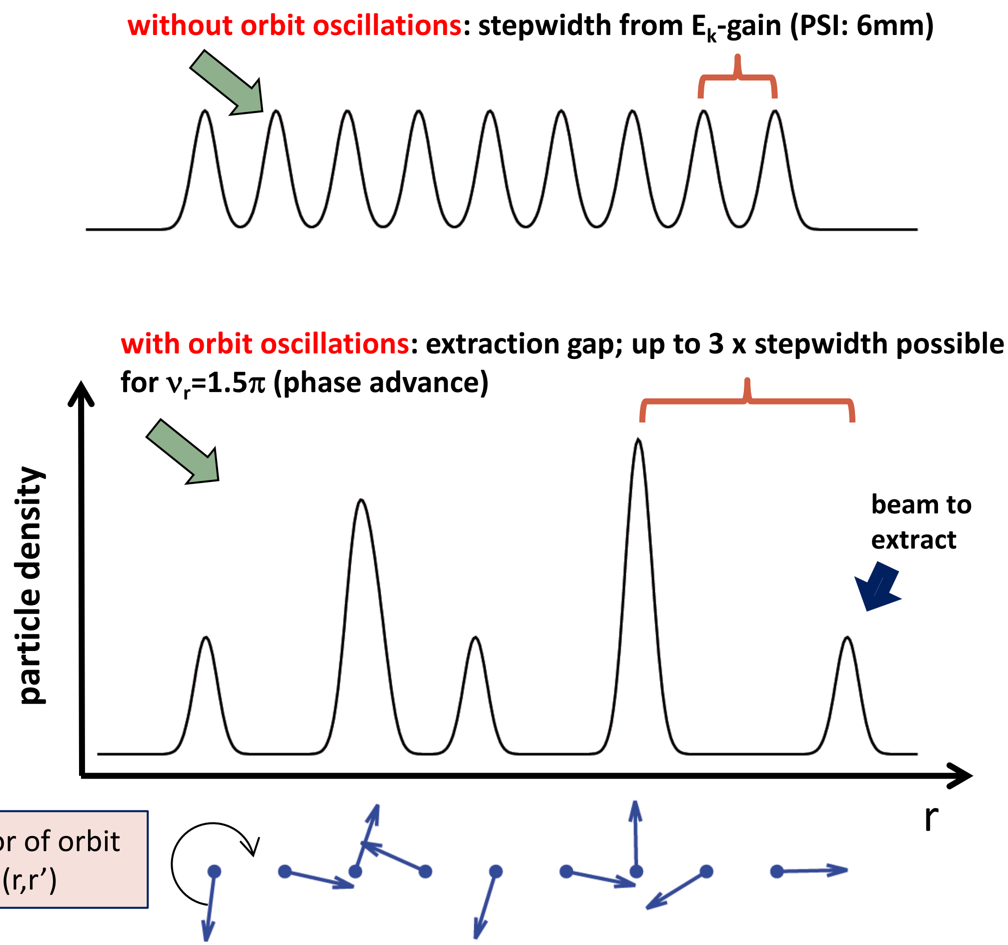


extraction with off-center orbits

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



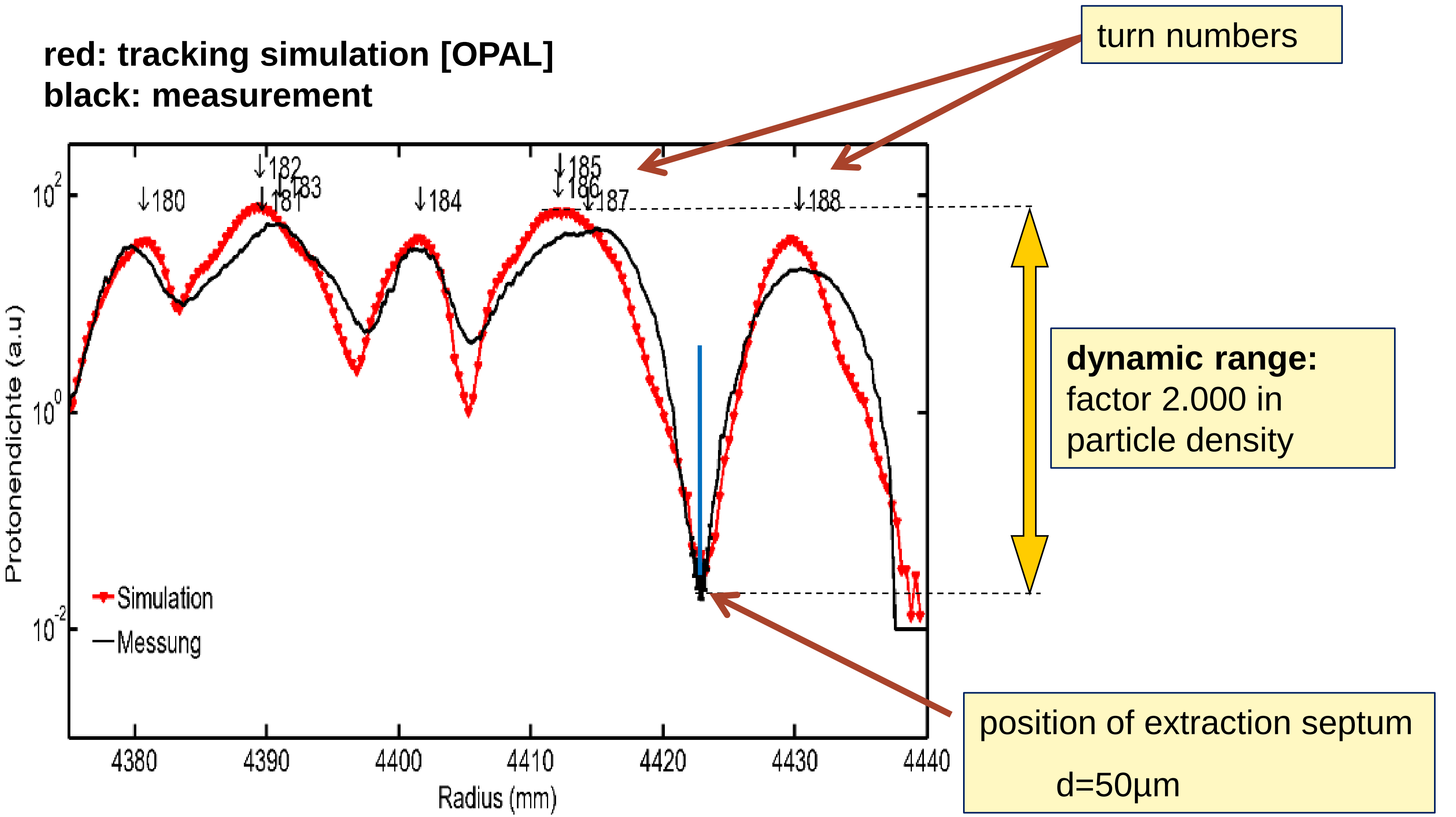
radial tune vs. energy (PSI Ring)
typically $\nu_r \approx \gamma$ during acceleration;
but decrease in outer fringe field



phase vector of orbit oscillations (r,r')

extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement



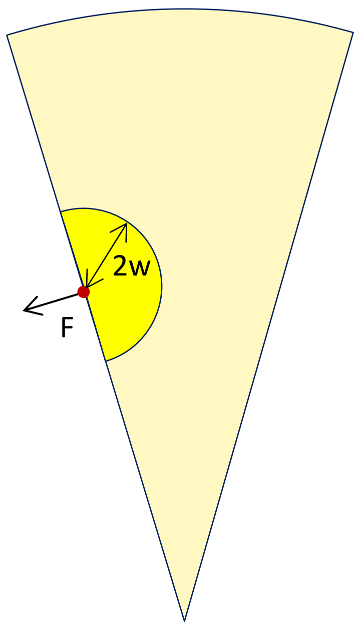
[Y.Bi et al]

longitudinal space charge

sector model (W.Joho, 1981):

→ accumulated energy spread transforms into transverse tails

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



two factors are proportional to the number of turns:

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

$$\Delta U_{sc} \quad = \quad \frac{8}{3} e I_p Z_0 \ln\left(4\frac{w}{a}\right) \cdot \frac{n_{\max}^2}{\beta_{\max}} \approx 2.800\Omega \cdot e I_p \cdot \frac{n_{\max}^2}{\beta_{\max}}$$

derivation see: [High Intensity Aspects of Cyclotrons, ECPM-2012, PSI]

in addition:

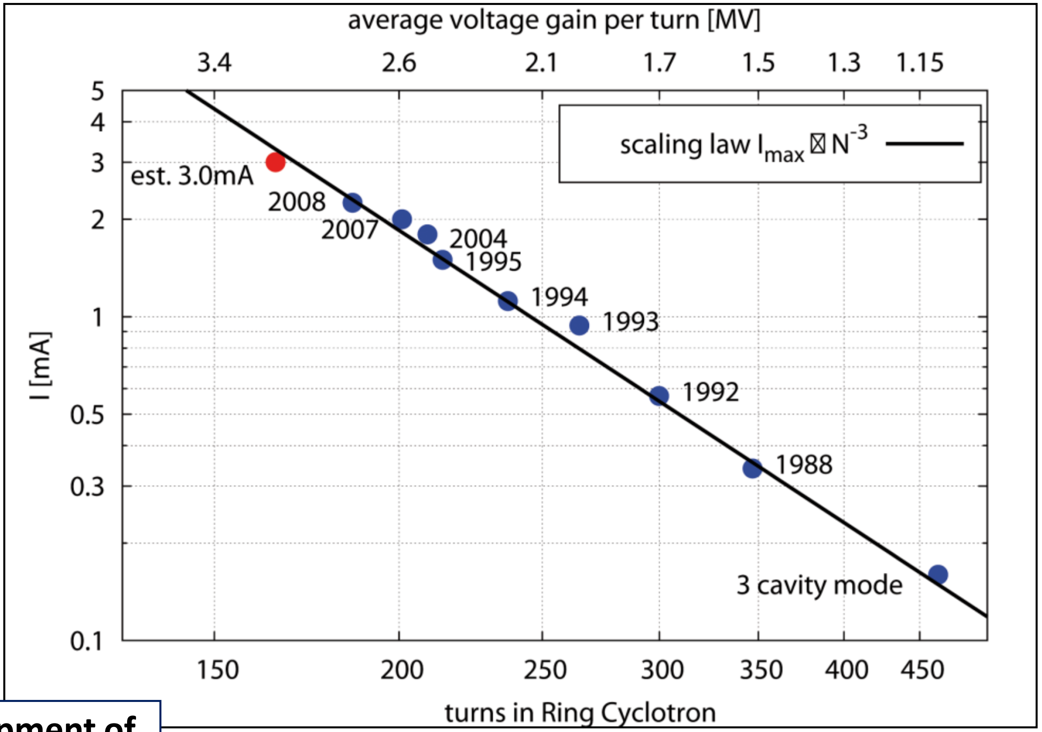
3) the inverse of turn separation at extraction: $\frac{1}{\Delta R_{\text{extr}}} \quad \propto \quad n_{\max}$

► thus the 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

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



historical development of current and turn numbers in PSI Ring Cyclotron

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:

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

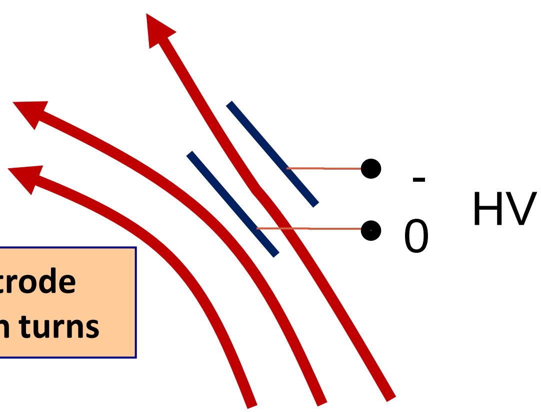
next: cyclotron subsystems

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

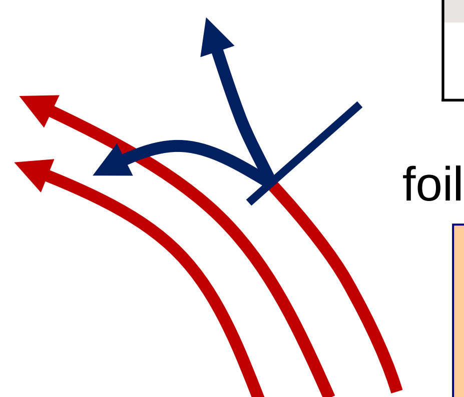
injection/extraction schemes

- 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

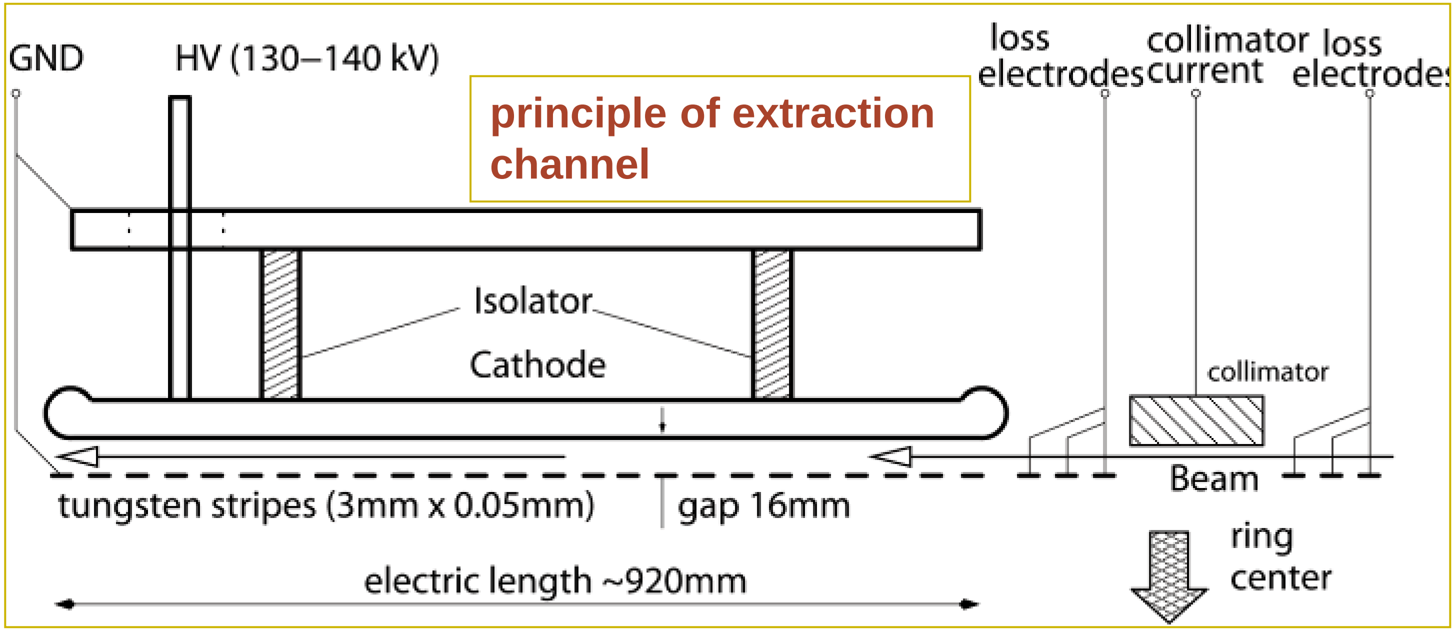


extraction electrode placed between turns



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

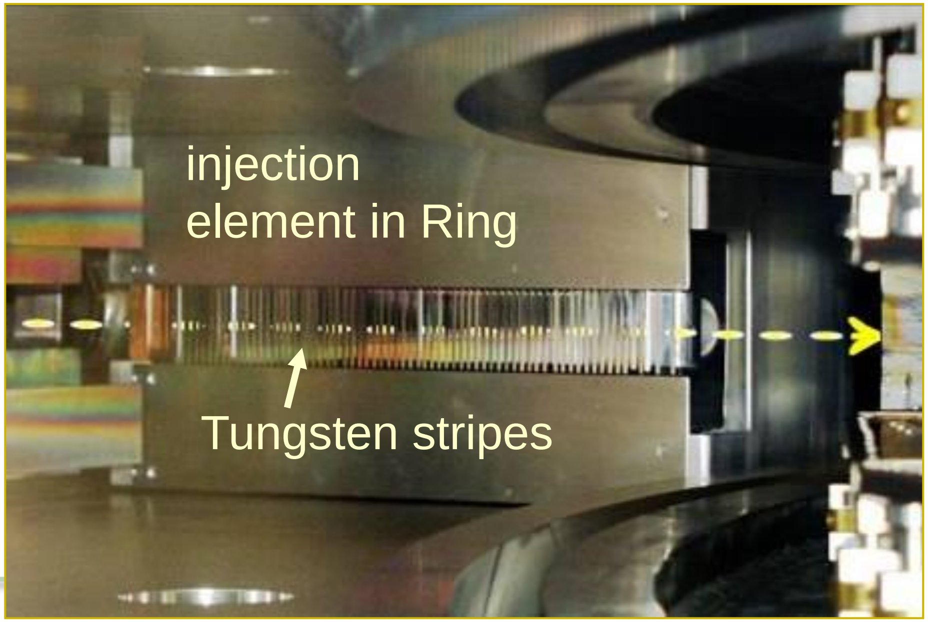
U = 144 kV

major loss mechanism is scattering in 50µm electrode!

electrostatic rigidity:

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

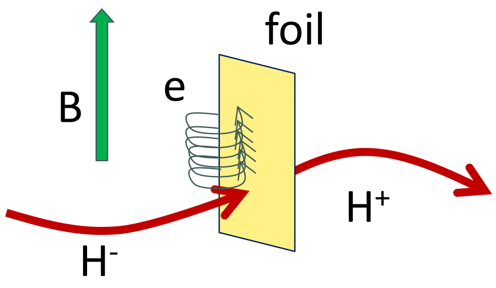
$$\theta = \frac{qlE}{E_k}\frac{\gamma}{\gamma+1}$$



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, rad.damage; conversion efficiencies, e.g. generation of neutrals, must be considered carefully

stripped electrons deposit energy in the foil



How much power is carried by the electrons?

$$E_e = \frac{m_e}{m_p} E_p = 5.4 \cdot 10^{-4} E_k^p$$

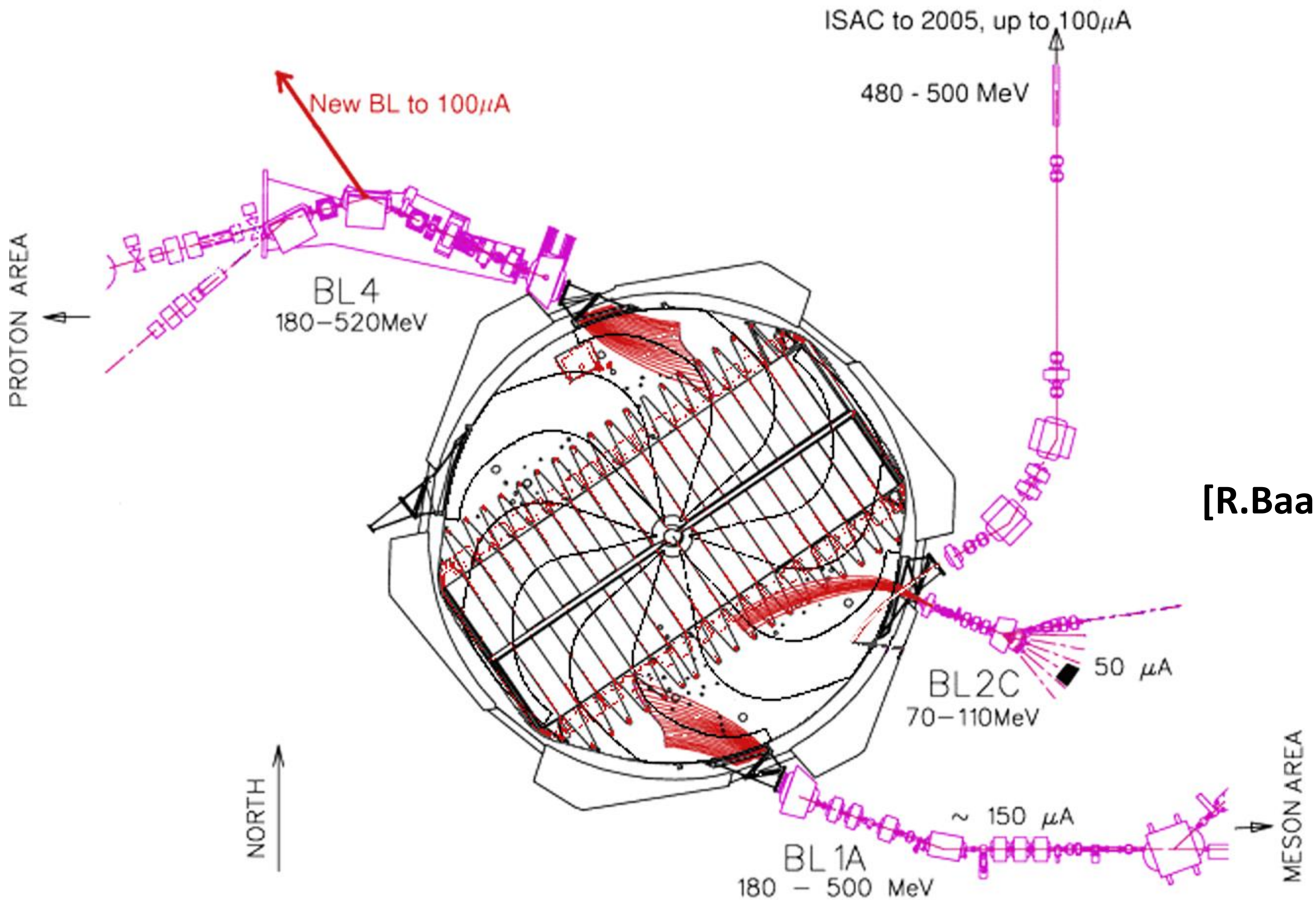
→ 1/2000 of beam power

Bending radius of electrons?

$$\rho^e = \frac{m_e}{m_p} \rho^p$$

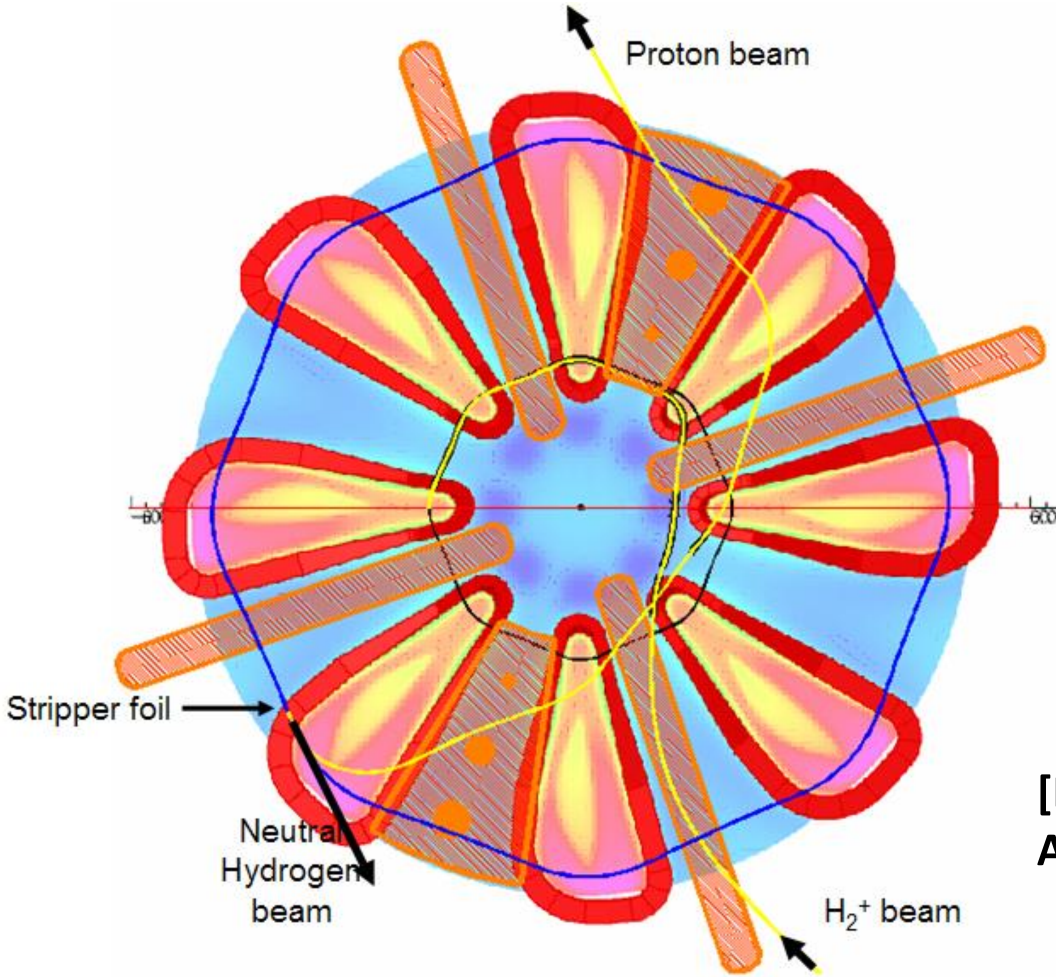
→ typically mm

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

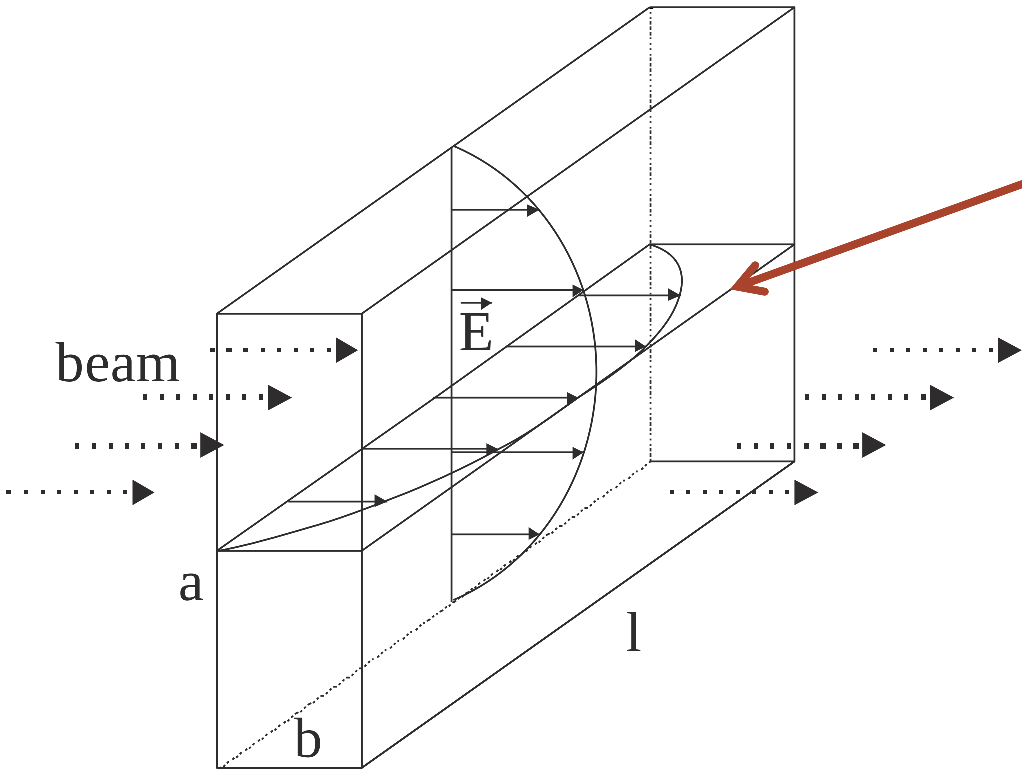
[L.Calabretta, A.Calanna et al]

components: cyclotron resonators

cyclotron resonators are basically box resonators

resonant frequency:

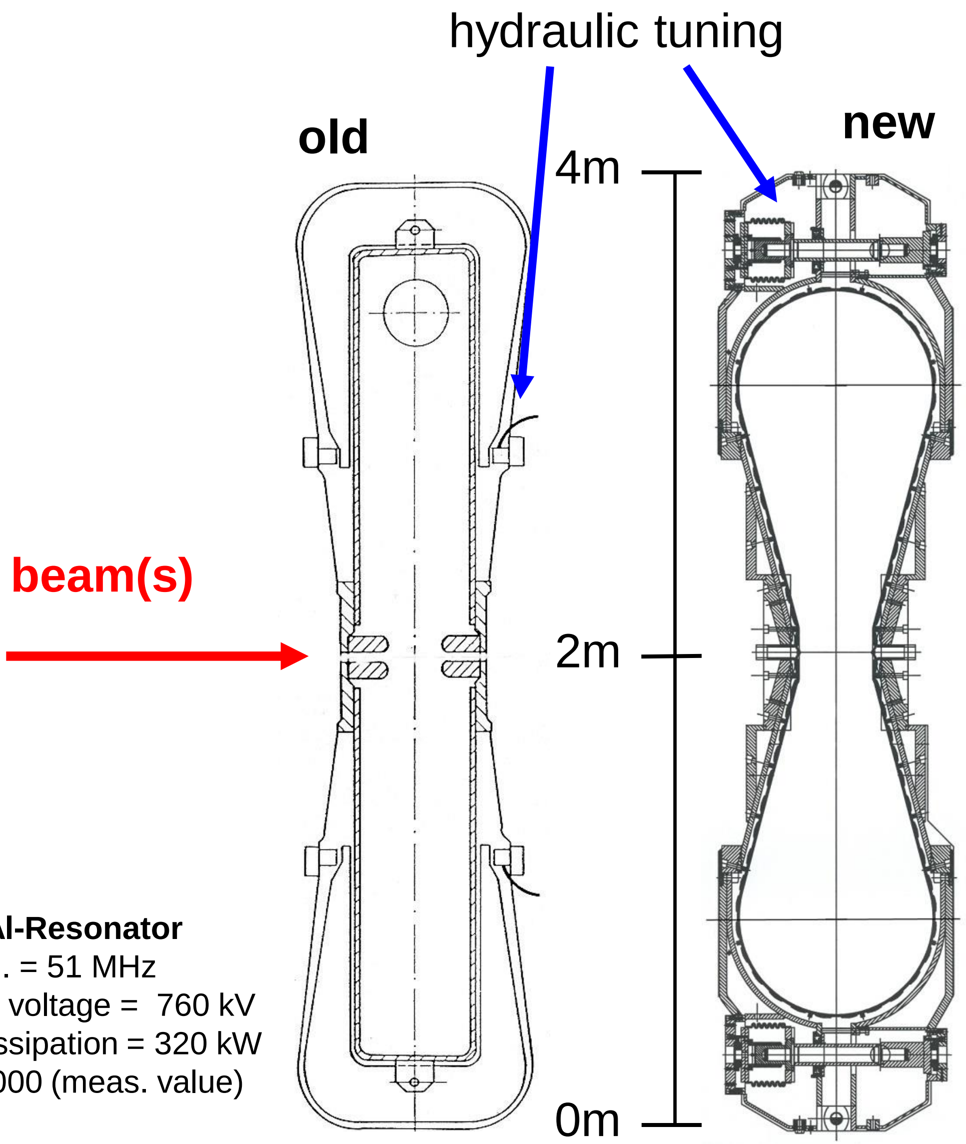
$$f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{l^2}}$$



beam passes in center plane;

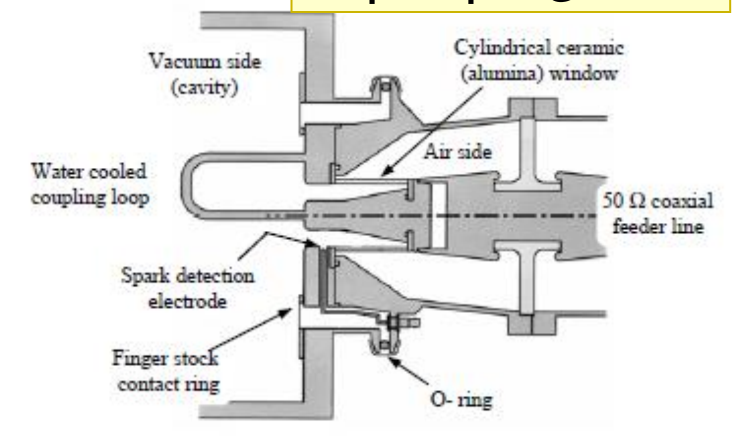
accelerating voltage varies as sin(r)

cross sections of PSI resonators



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

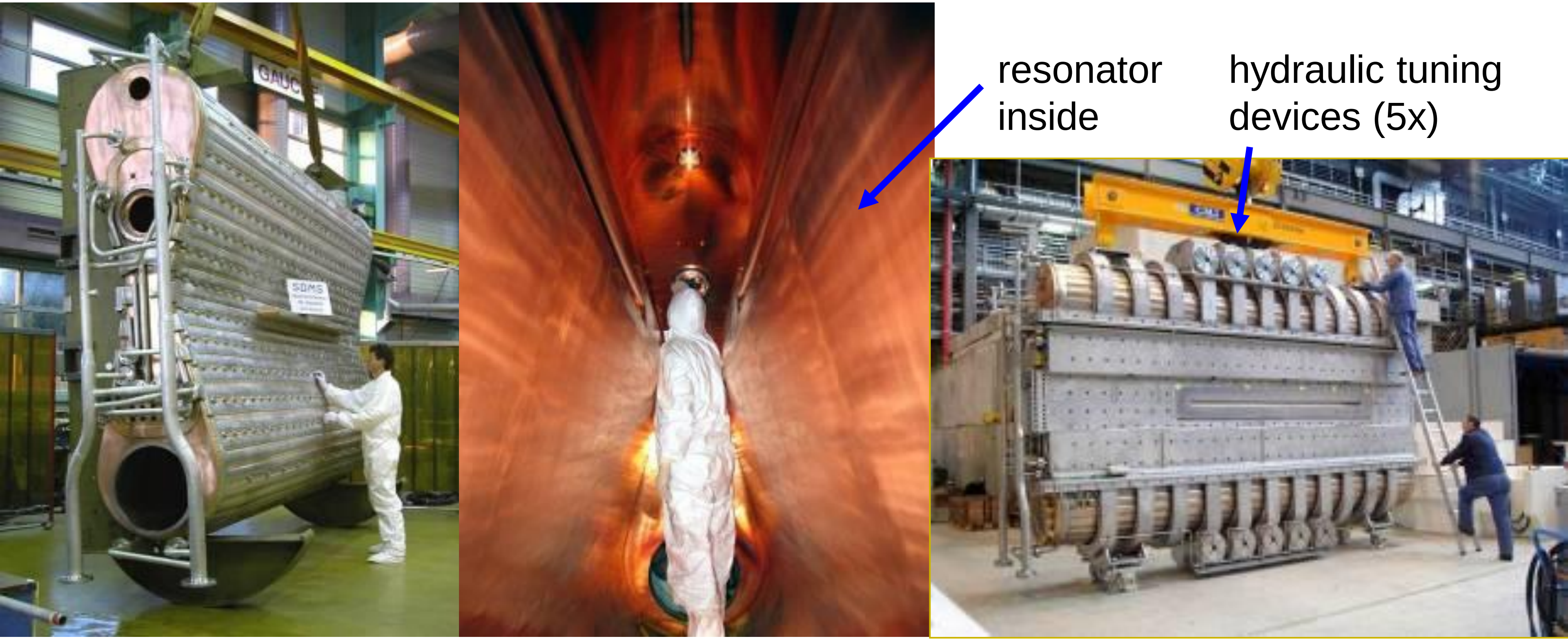
loop coupler @ 50MHz



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%**

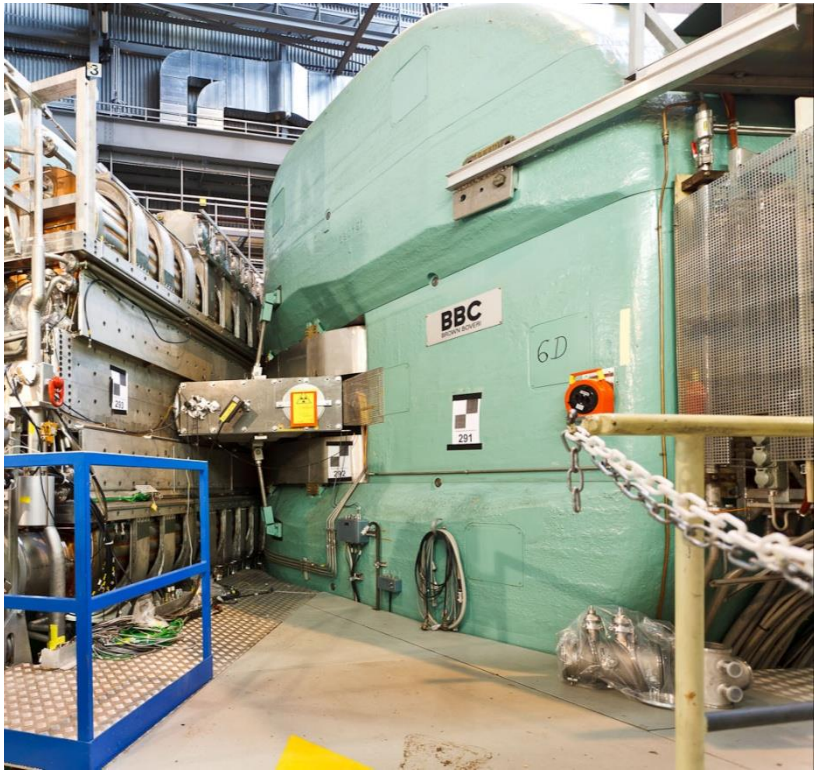


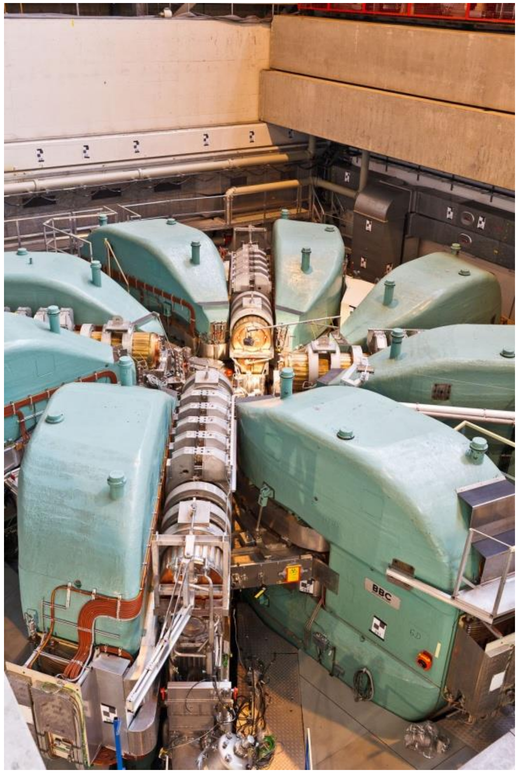
components: sector magnets

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

PSI sector magnet

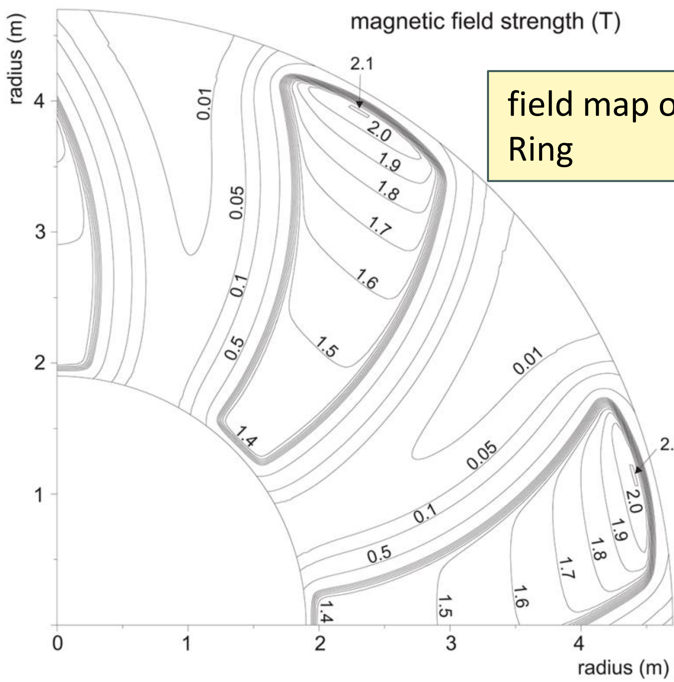
iron weight: 250 tons
coil weight: 28 tons
orbit radius: 2.1…4.5 m
spiral angle: 35 deg





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



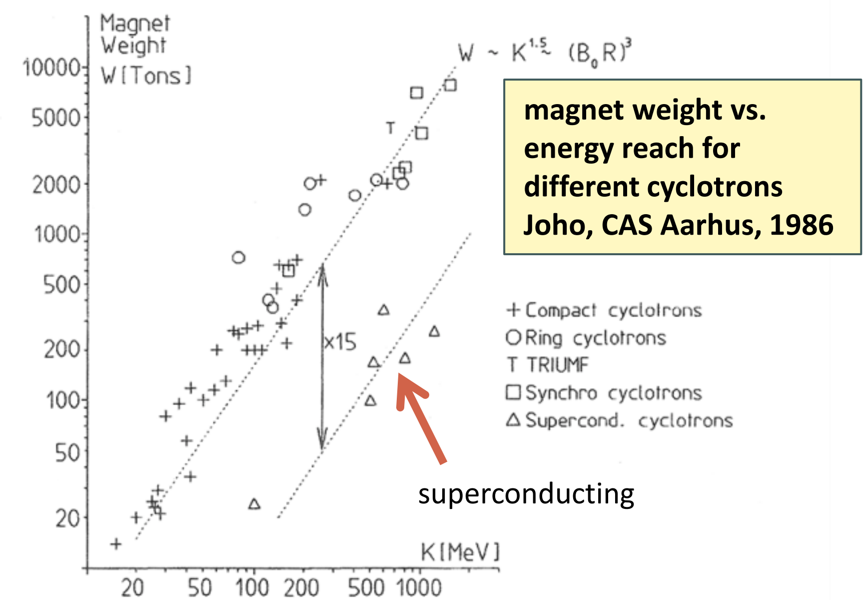


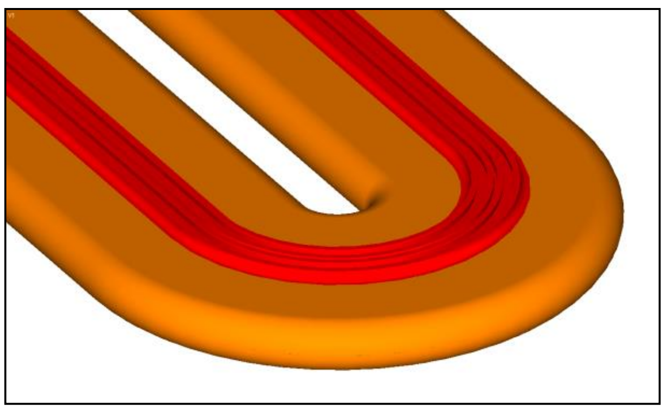
Fig. 6 Magnet weight W versus K-value for different cyclotrons and synchrocyclotrons.

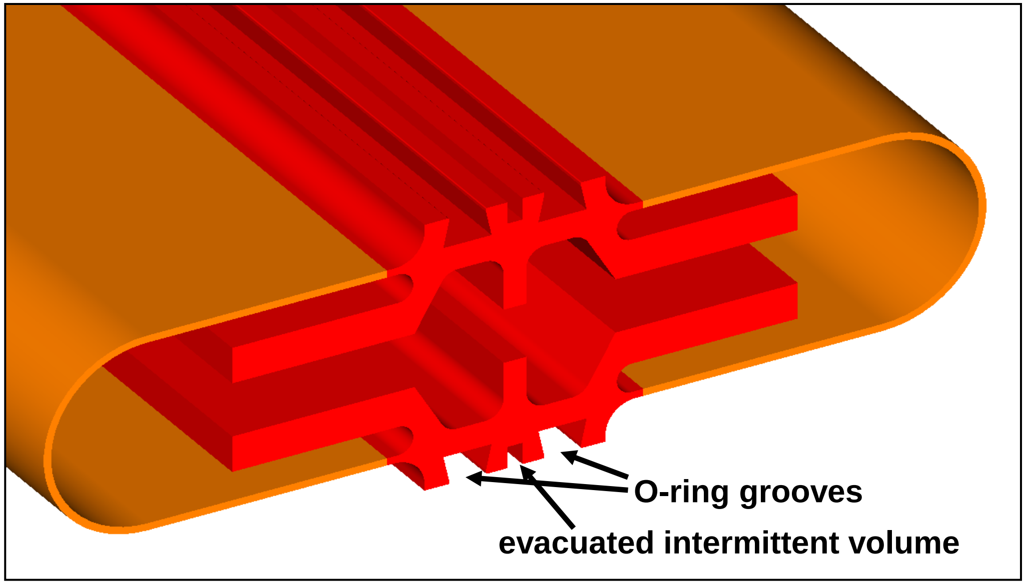
cyclotron vacuum system

- 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

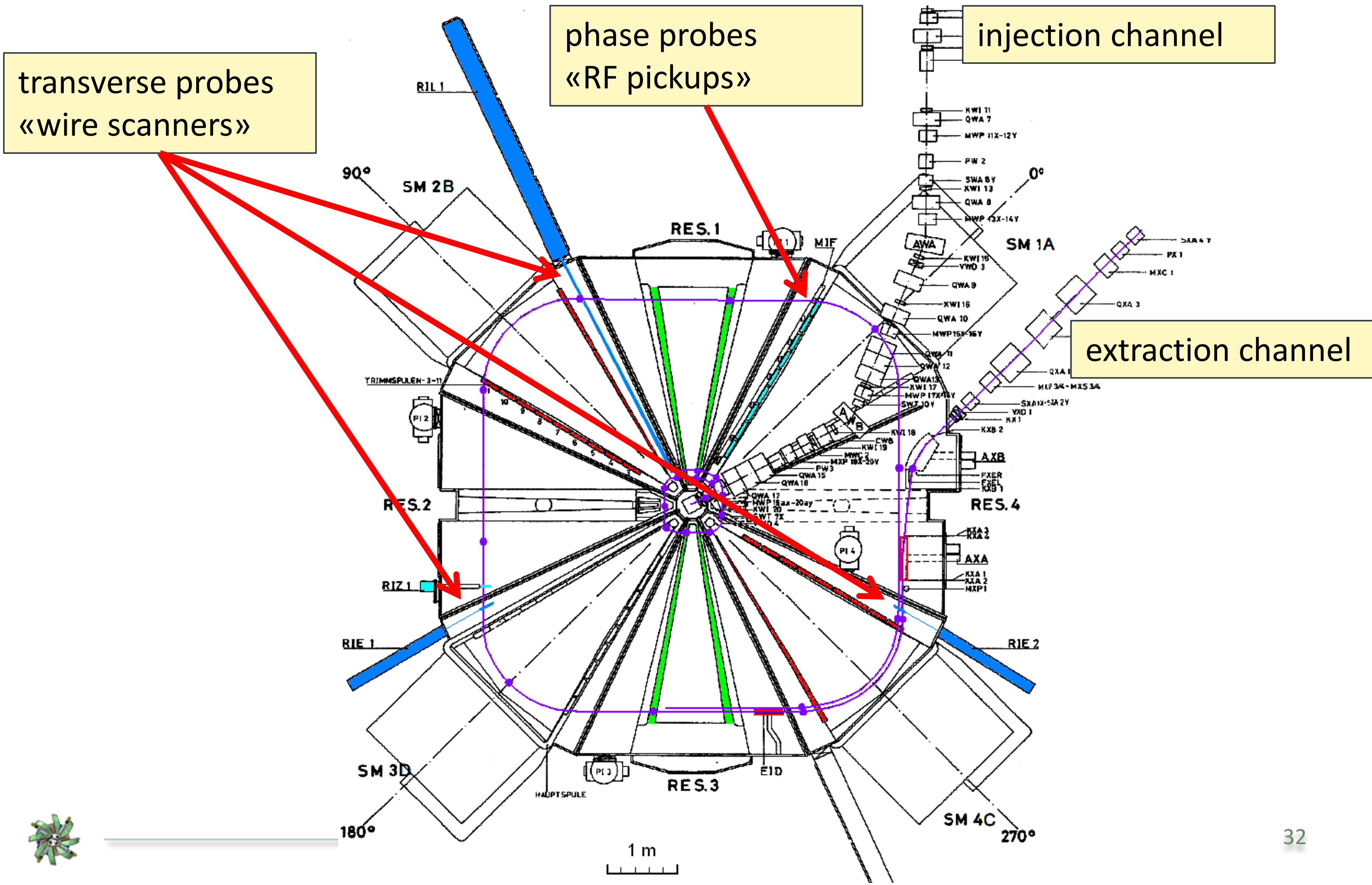
length: 3.5m





cyclotron instrumentation

example: PSI 72MeV injector cyclotron



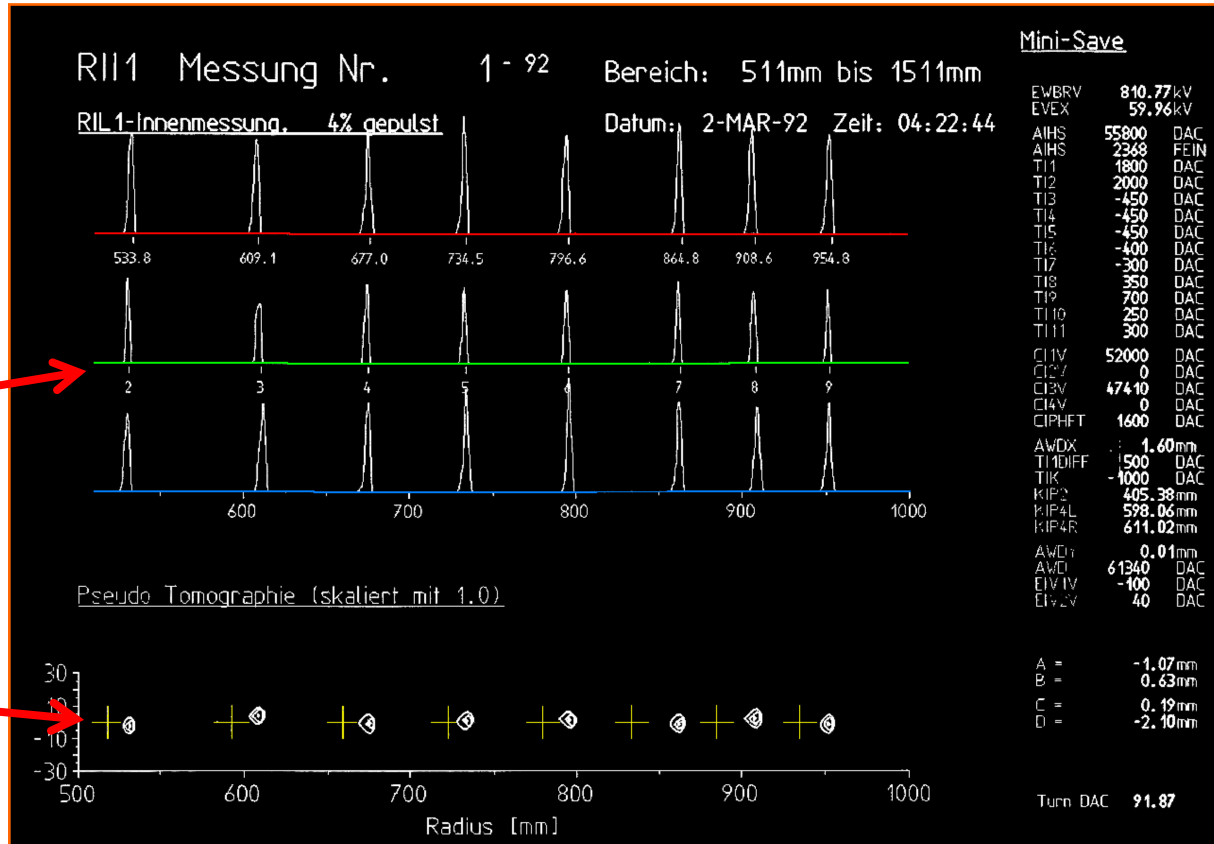
instrumentation: radial probe for turn counting / orbit analysis

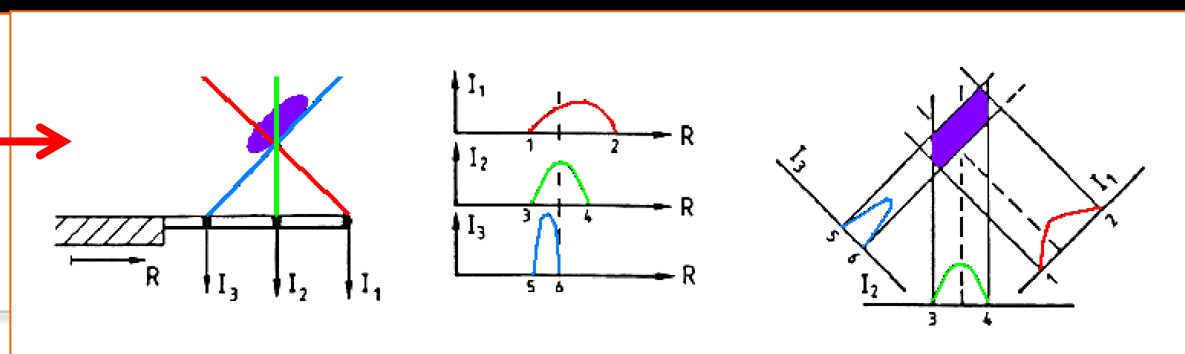
wire scanner with three tilted wires delivers radial beam profile and some vertical information

radial: positions of individual turns

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

«pseudo tomography» with tilted wires





next: cyclotron examples

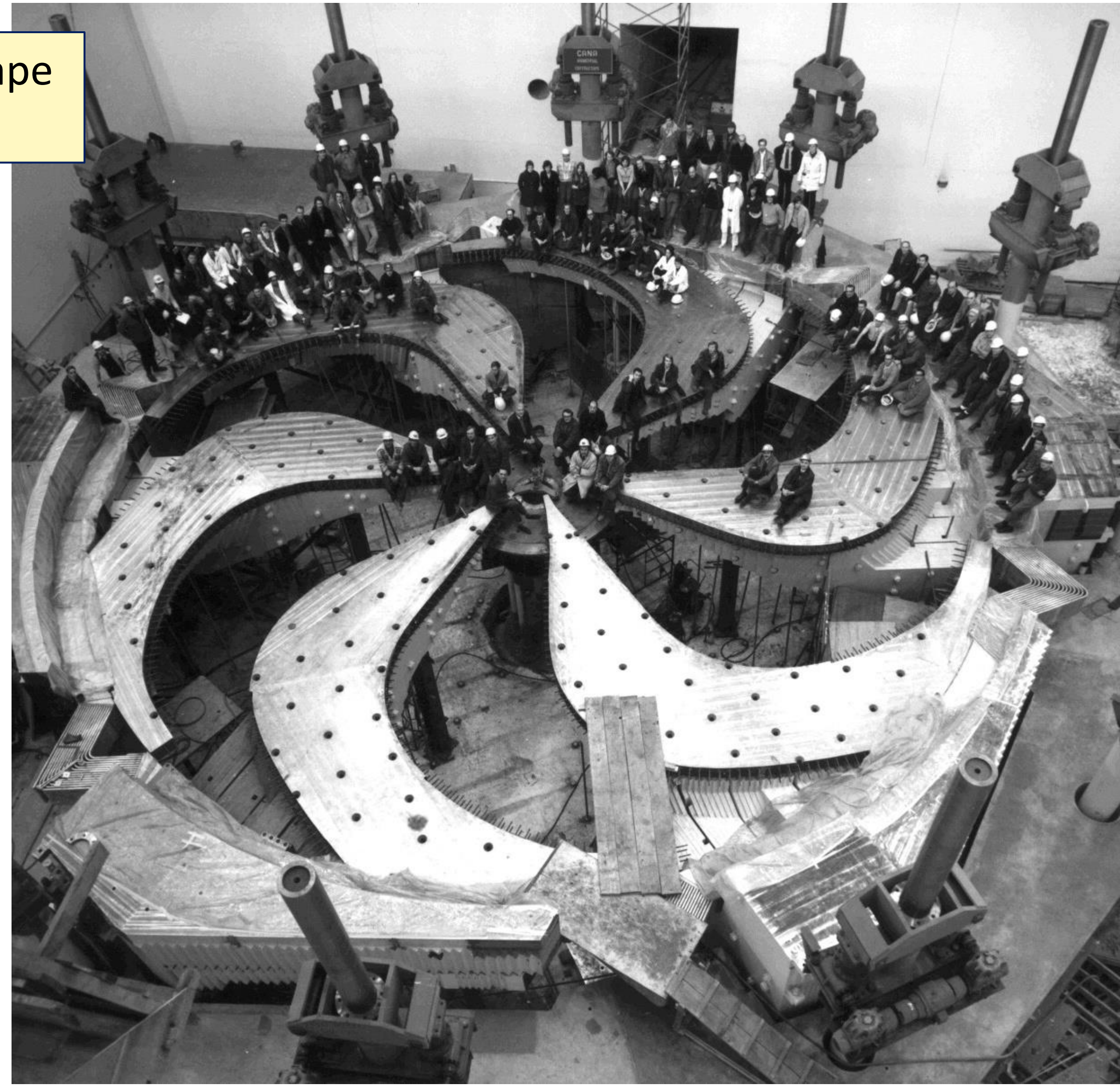
- **TRIUMF, RIKEN SRC, PSI-HIPA, PSI-Comet**

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

cyclotron examples: TRIUMF / Vancouver

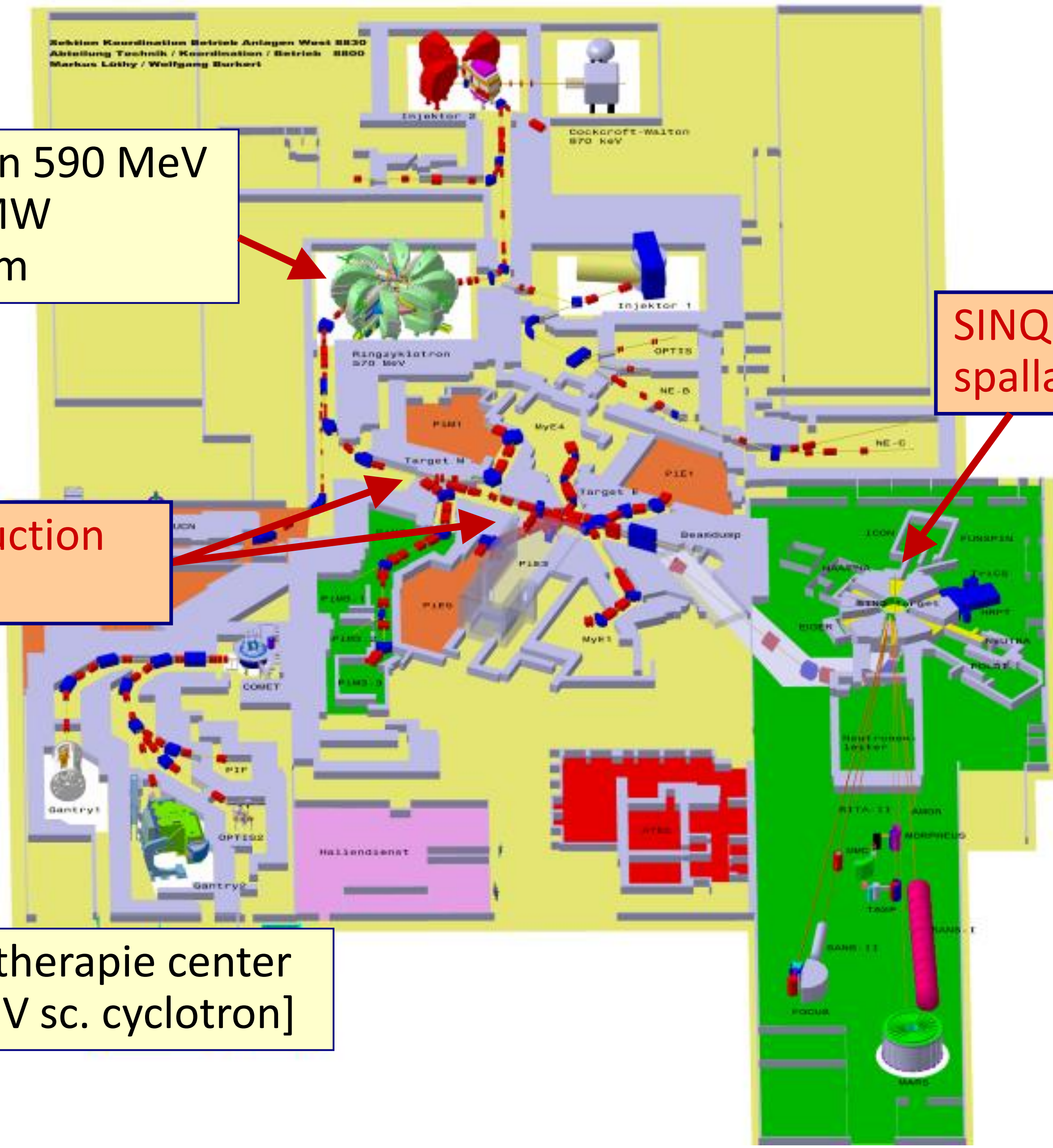
photo: iron poles with spiral shape (δ_{max}=70deg)



- 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

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:

$120 \times 220 m^2$

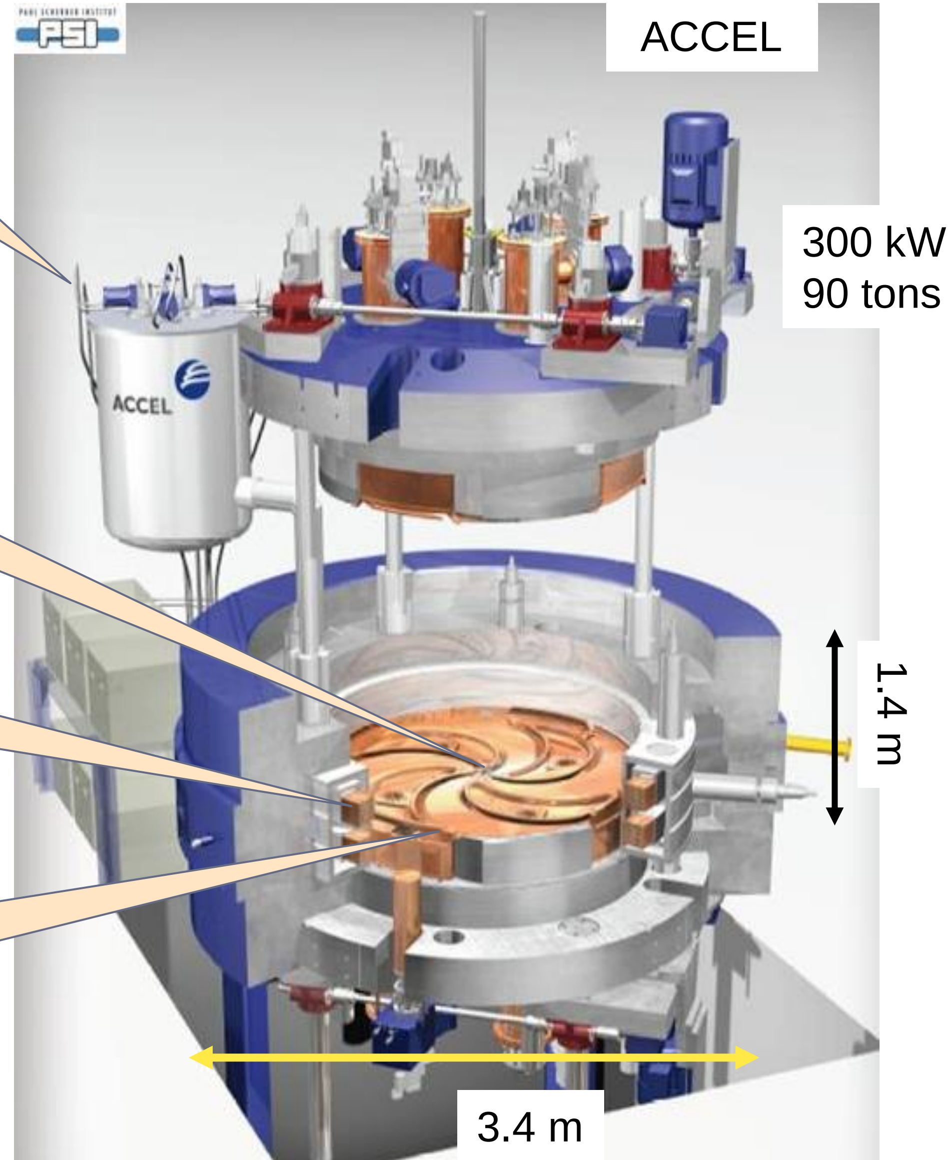
250 MeV proton cyclotron (ACCEL/Varian)

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



compact cyclotrons for Isotope production

CYCLONE 30 (IBA) : H^- 15 à 30 MeV

vertical setup (!)

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	→	↗	↘		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

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 $\leq$250MeV; intensity range well covered • isotope production $\rightarrow$ several 10MeV • acceleration of heavy ions (e.g. RIKEN) • very high intensity proton beams (PSI:1.4MW, TRIUMF: 100kW, ADS Concepts)

cyclotron conferences – a valuable source of knowledge

Select Conferences

ALL ☑	
ABDW	ERL'13, HB'12, ERL'11, HB'10, Ecloud'10, ERL'09, HB'08, Factories'08, ERL'07, HB'06, FLS'06
APAC	'07, '04, '01, '98
BIW	'12, '10, '08
COOL	'13, '11, '09, '07
CYCLOTRONS	'13, '10, '07, '04, '01, '98, '95, '92, '89, '86, '84, '81, '78, '75, '72, '69, '66, '63, '59
DIPAC	'11, '09, '07, '05, '03, '01, '99
ECRIS	'12, '10, '08
EPAC	'08, '06, '04, '02, '00, '98, '96, '94, '92, '90, '88
FEL	'13, '12, '11, '10, '09, '08, '07, '06, '05, '04
HIAT	'12, '09
IBIC	'13, '12
ICALEPCS	'13, '11, '09, '07, '05, '03, '01, '99
ICAP	'12, '09, '06
IPAC	'13, '12, '11, '10
LINAC	'12, '10, '08, '06, '04, '02, '00, '98, '96, '92, '90, '88, '84, '81, '76, '72, '66
NA-PAC	'13
PAC	'11, '09, '07, '05, '03, '01, '99, '97, '95, '93, '91, '89, '87, '85, '83, '81, '79, '77, '75, '73, '71, '69, '67, '65
PCaPAC	'12, '10, '08
RuPAC	'12, '10, '08, '06, '04
SRF	'11, '09, '07, '05, '03, '01, '99, '97, '95, '93, '91, '89, '87, '84, '80

first
1959

cyclotron conferences
every three years

old cyclotron conferences are digitized for JACOW (effort of M.Craddock!)
cyclotrons 2016: organized by PSI in Zürich

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) http://accelconf.web.cern.ch/AccelConf/c81/papers/ei-03.pdf
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
OPAL simulations; documentation	J.Yang, A. Adelmann, et al. Phys. Rev. STAB Vol. 13 Issue 6 (2010) http://amas.web.psi.ch
cyclotrons 2013 conference Vancouver	http://accelconf.web.cern.ch/AccelConf/CYCLOTRONS2013/ conference summary: http://accelconf.web.cern.ch/AccelConf/CYCLOTRONS2013/talks/fr2pb03_talk.pdf

thank your for your attention !