Cyclotrons - II

CERN Accelerator School – Introductory Course
Constanta, September 25, 2018

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Cyclotrons II - Outline

- brief review of the previous lesson
- cyclotron subsystems

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

- applications and examples of existing cyclotrons

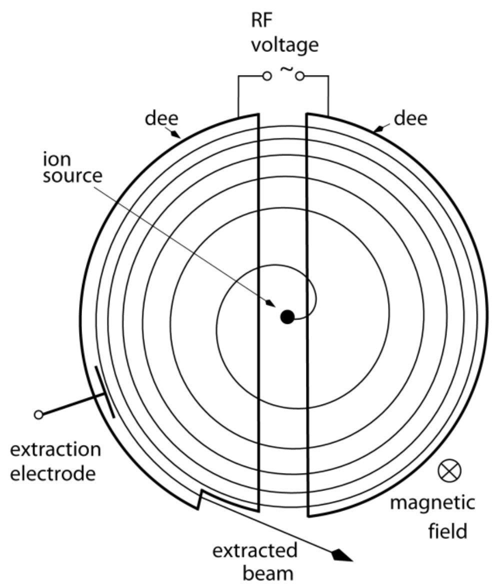
  TRIUMF, RIKEN SRC, PSI Ring, PSI medical cyclotron

- discussion

  classification of circular accelerators, cyclotron vs. FFAG, Pro’s and Con’s of cyclotrons for different applications

review of Cyclotrons-I

classical cyclotron

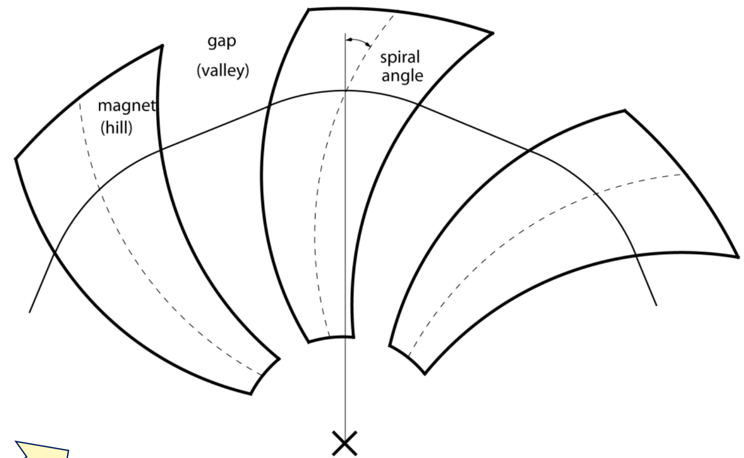


- ➔ simplicity, compactness
- ➔ continuous injection/extraction
- ➔ multiple usage of accelerating voltage

but:

- insufficient vertical focusing
- limited energy reach

sector cyclotron



flutter   spiral angle

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

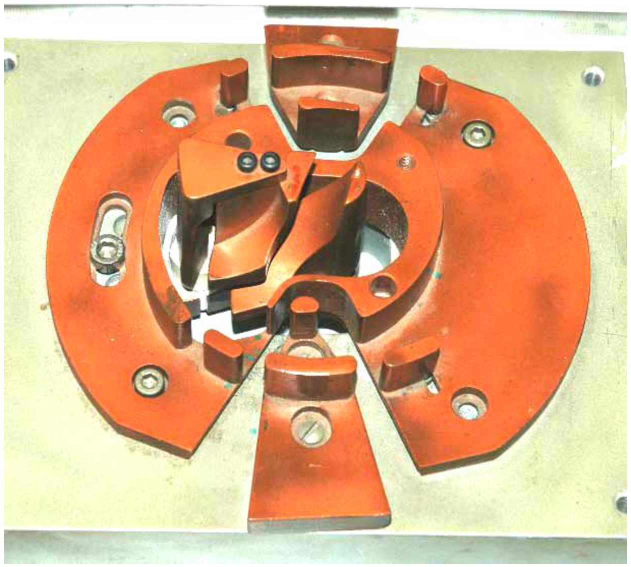
next: injection & extraction

- **spiral inflector, internal source, electrostatic deflectors, stripping**

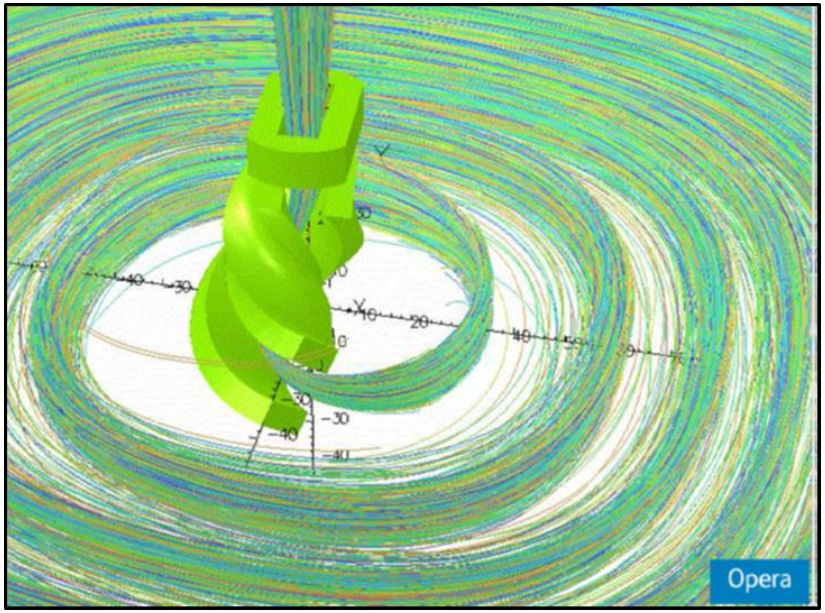
injection schemes – spiral inflector

- an electrostatic component, basically a capacitor
- E-field arranged perpendicular to orbit, particles move on equipotential surfaces

simulation of orbits injected through a spiral inflector

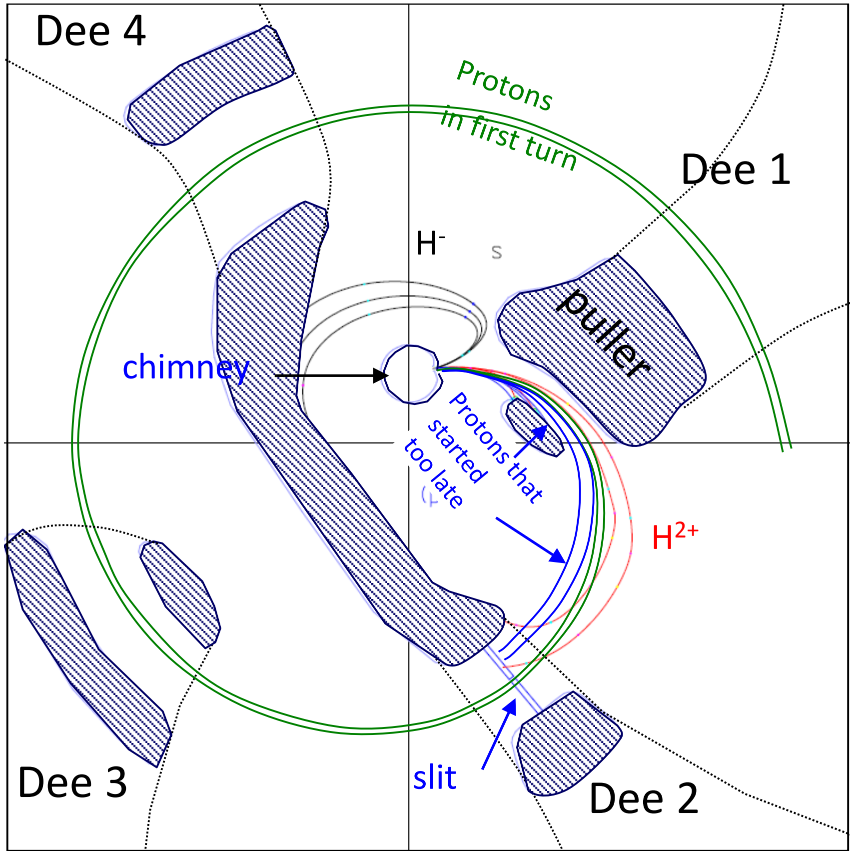


[inflector IBA Cyclone 30 cyclotron]



[courtesy: W.Kleeven (IBA)]

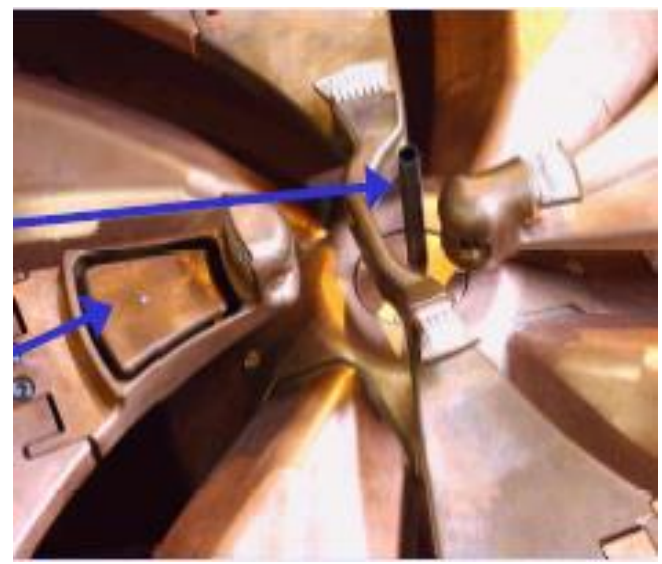
internal ion source
→ example COMET



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

chimney = ion source

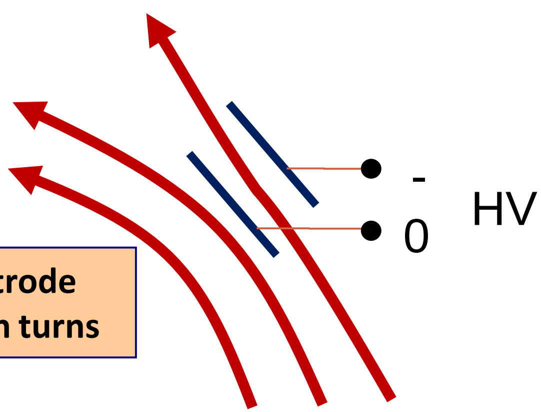
deflector electrode for intensity regulation



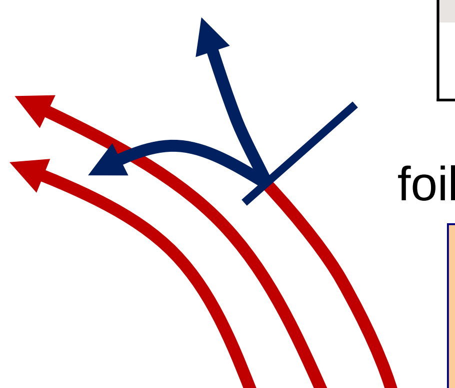
electrostatic septum and charge exchange extraction

- 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

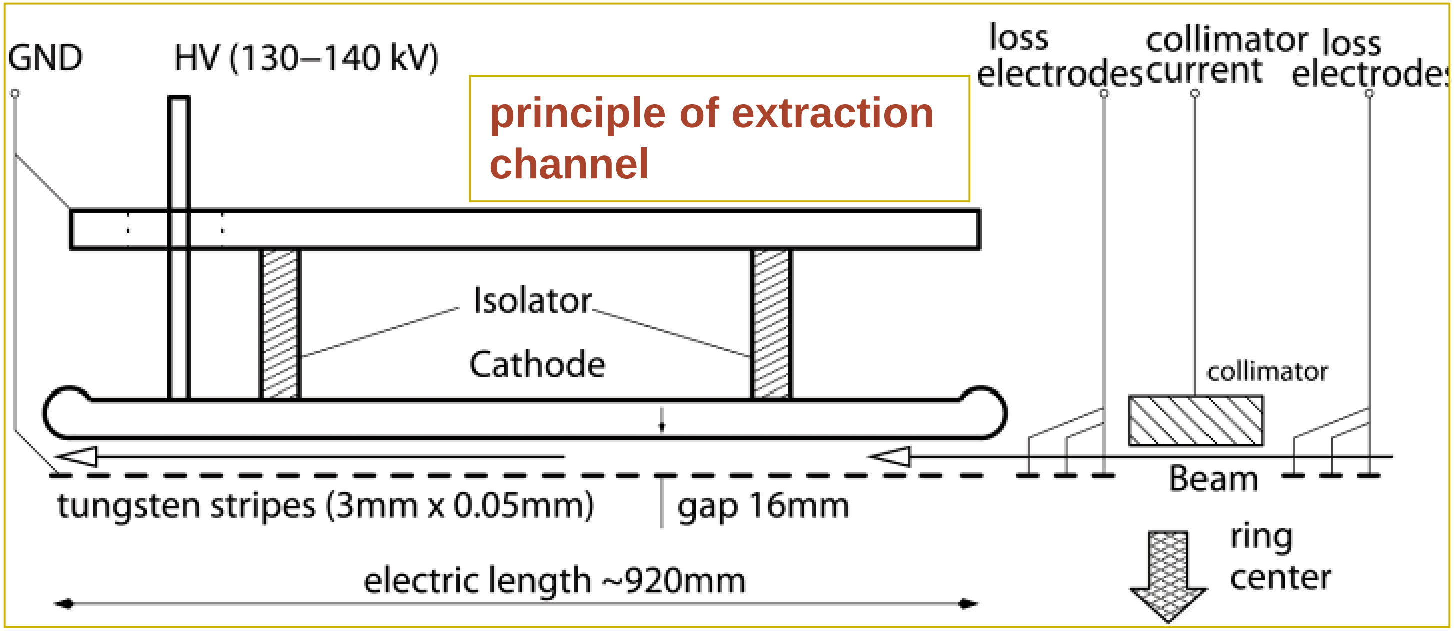


extraction electrode placed between turns



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

injection/extraction with electrostatic elements

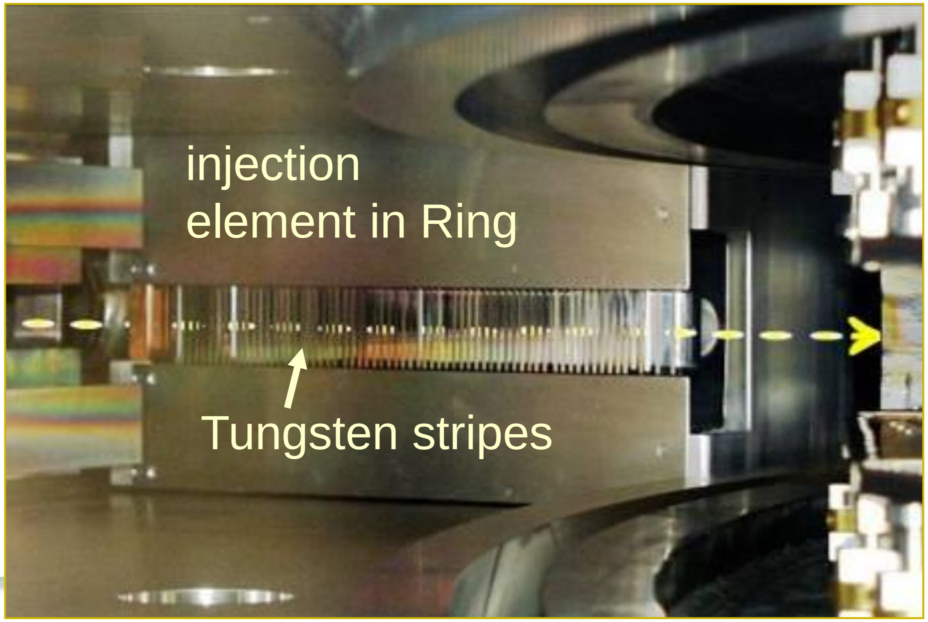


parameters extraction chan.:
E_k= 590MeV
E = 8.8 MV/m
θ = 8.2 mrad
ρ = 115 m
U = 144 kV

major loss mechanism is scattering in 50µm electrode!

electrostatic rigidity:

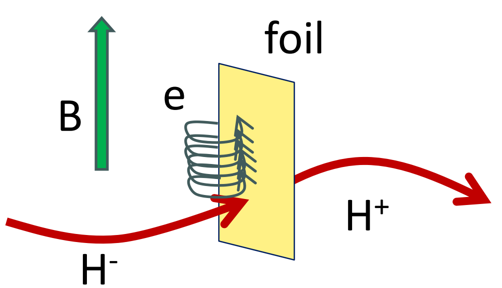
$$E\rho = \frac{\gamma+1}{\gamma}\frac{E_k}{q}$$



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*

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

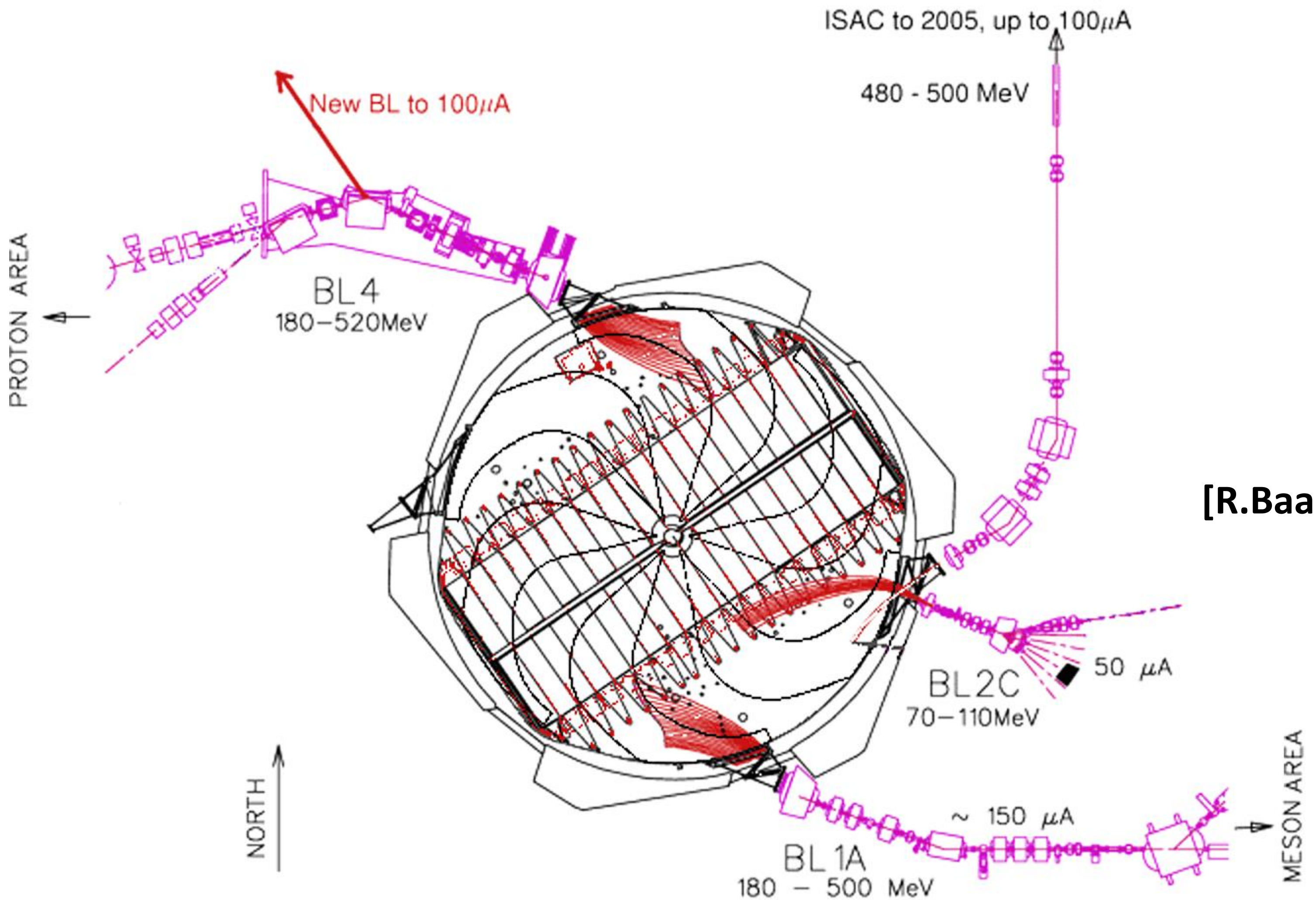
$$\rightarrow E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

Bending radius of electrons?

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

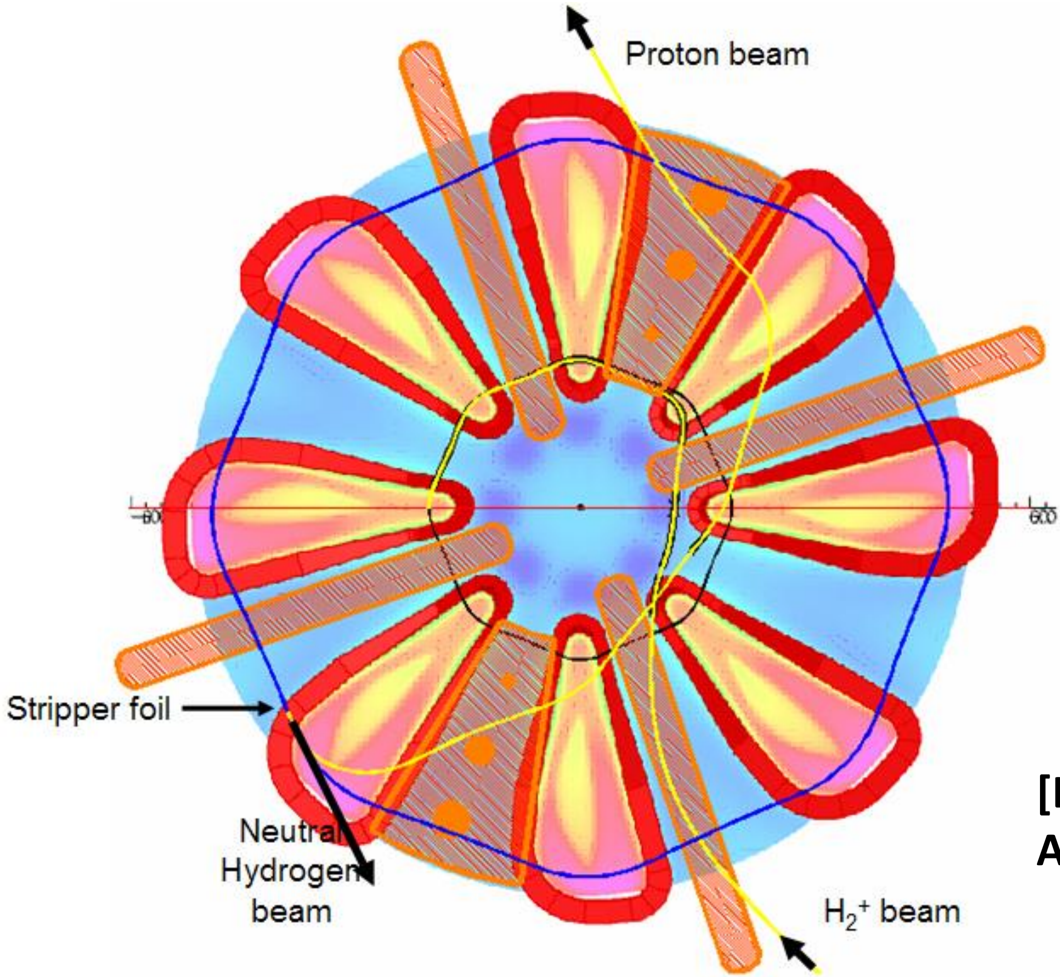
→ typically mm

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 kin. energy
- 5MW avg. beam power

[L.Calabretta, A.Calanna et al]

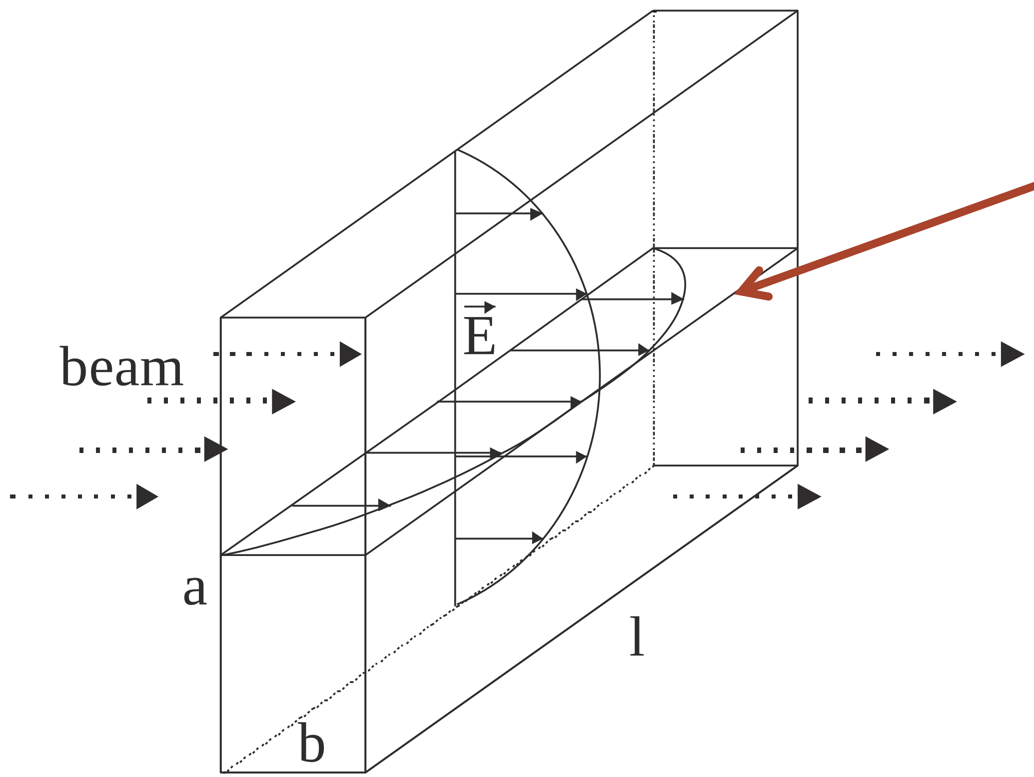
next: **RF, magnets, vacuum, diagnostics**

components: sector cyclotron resonators

cyclotron resonators are basically box resonators

resonant frequency:

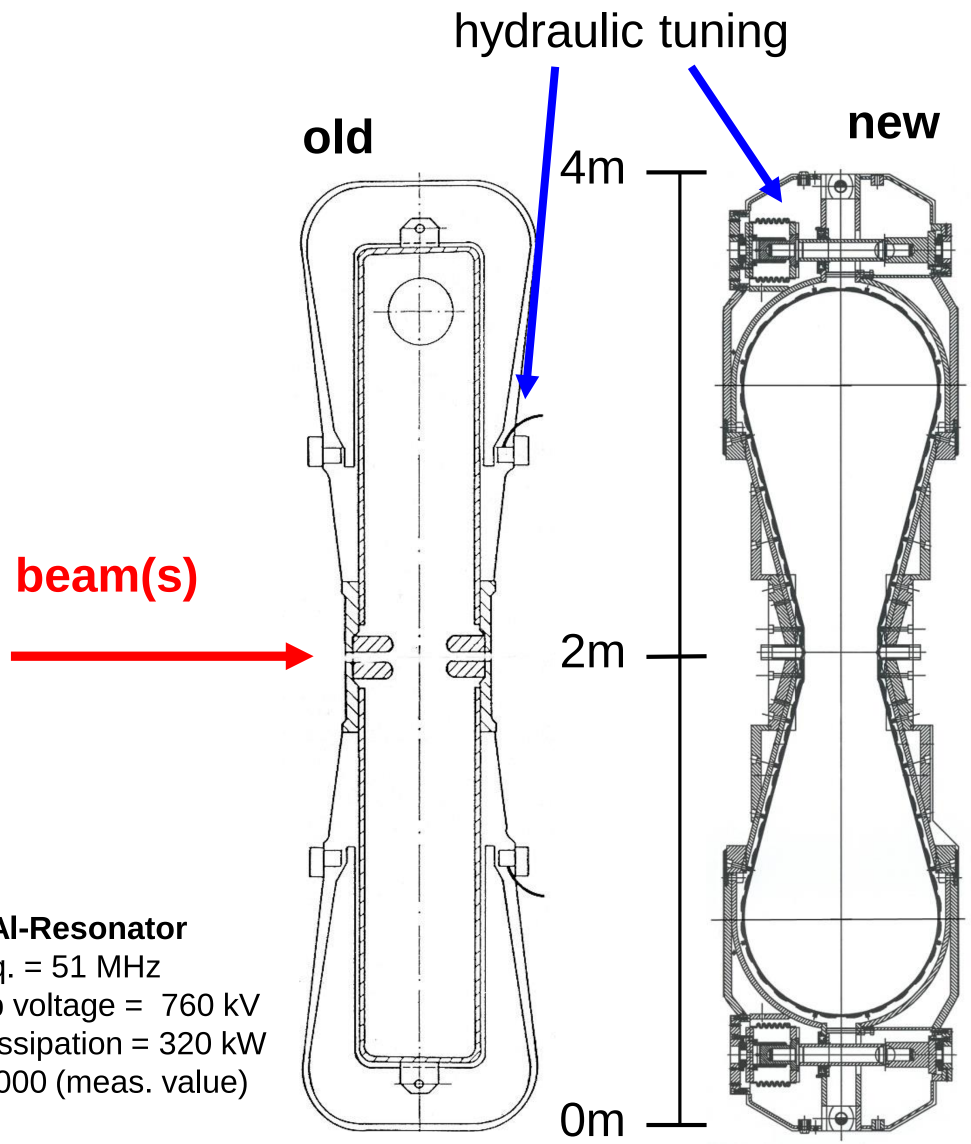
$$f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{l^2}}$$

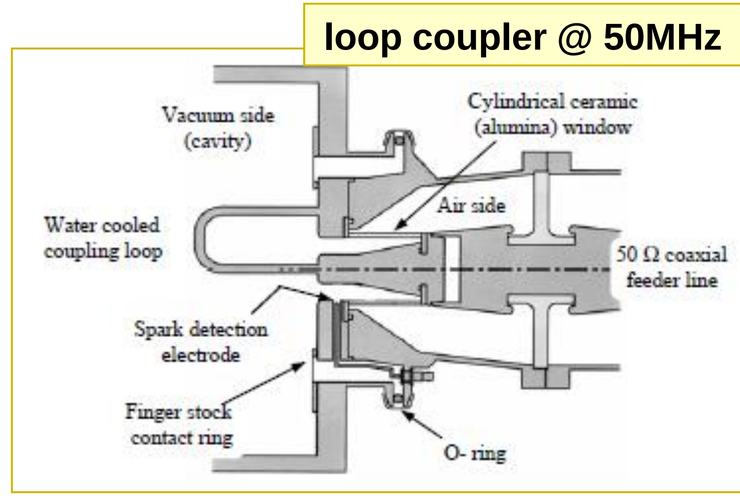


beam passes in center plane;

accelerating voltage varies as sin(r)

cross sections of PSI resonators



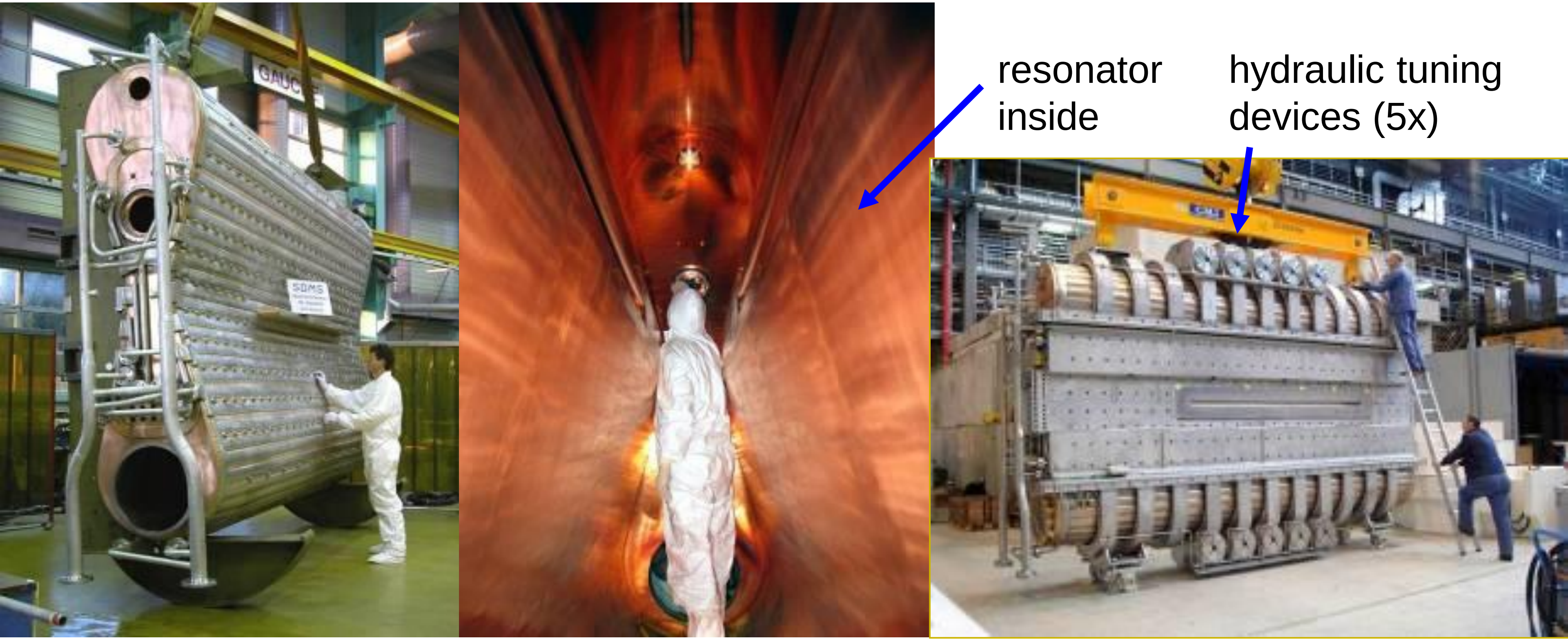


original Al-Resonator
Oper. freq. = 51 MHz
Max. gap voltage = 760 kV
Power dissipation = 320 kW
Q0 = 32'000 (meas. value)

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

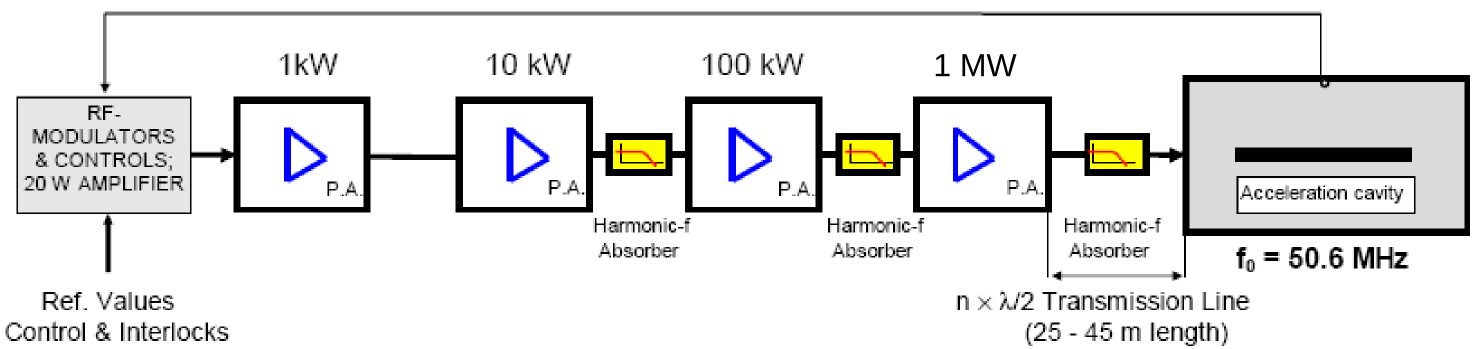
copper resonator in operation at PSI's Ring cyclotron

- **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%**



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%]

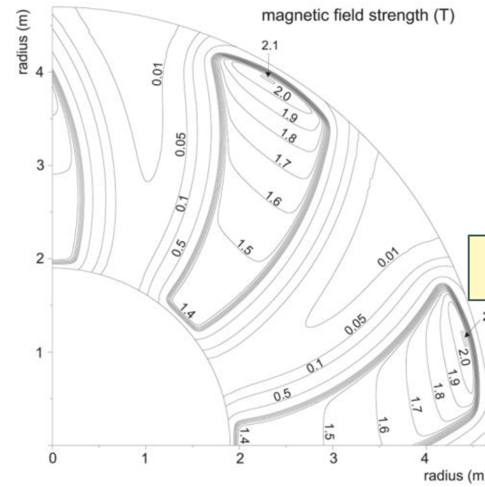
[L.Stingelin et al]

cyclotron technology: sector magnets

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

PSI sector magnet

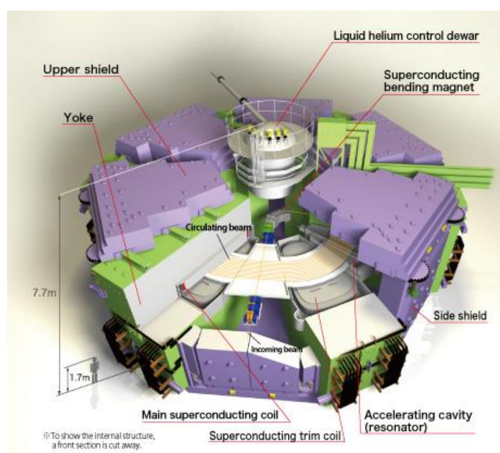
iron weight: 250 tons
coil weight: 28 tons
Field: 2.1T
orbit radius: 2.1…4.5 m
spiral angle: 35 deg

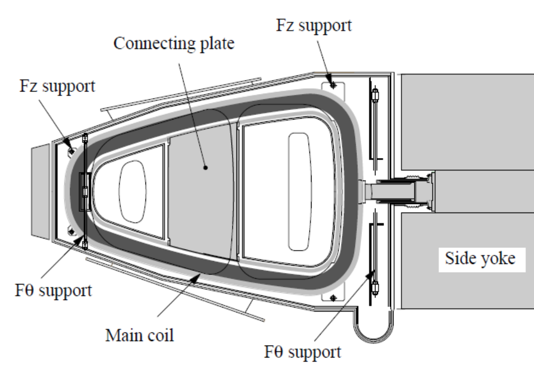


field map

Riken SRC sector magnet

weight: 800 tons
Field: 3.8T, 5000A
orbit radius: 3.6…5.4m

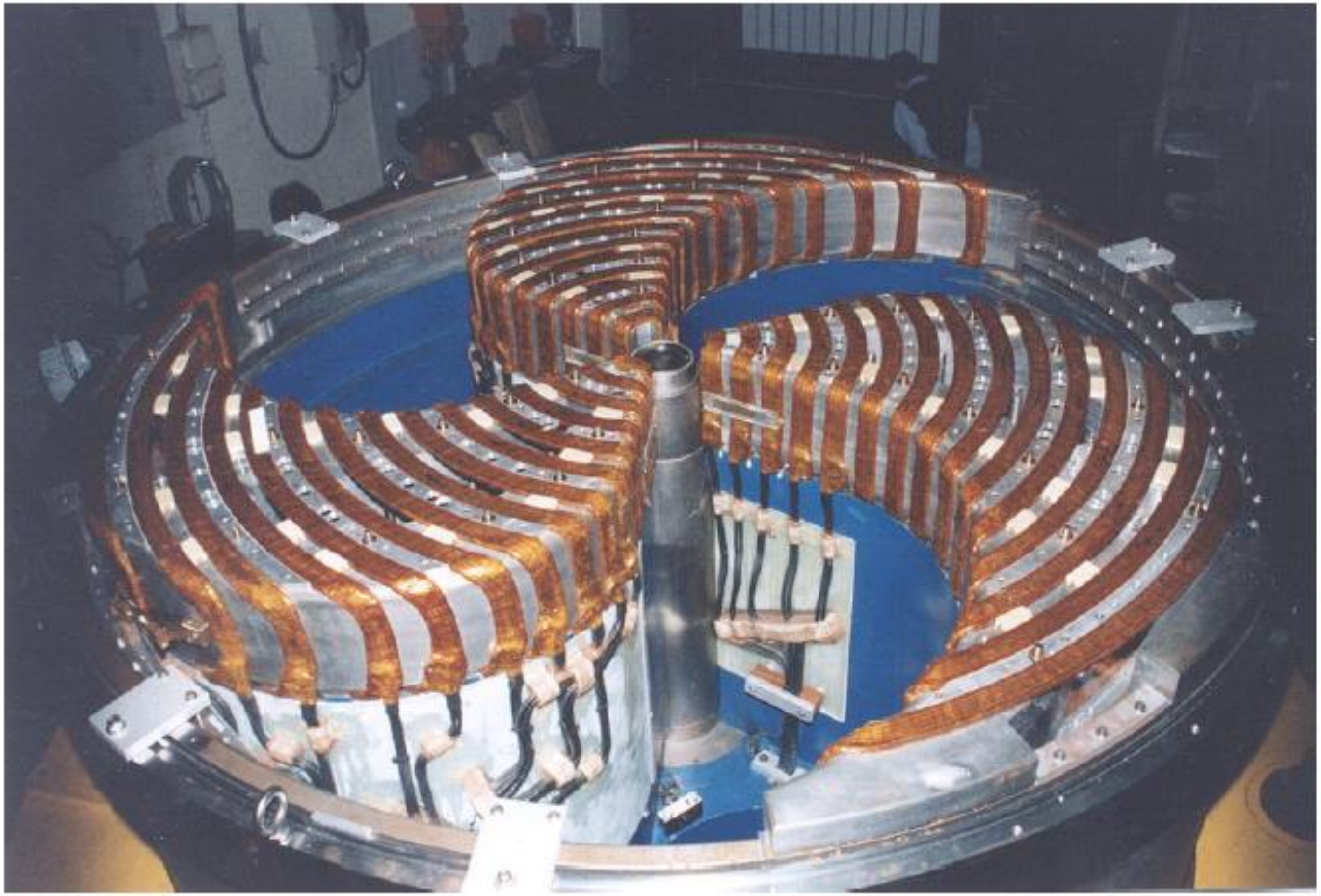




Magnets – Fine-tuning with trim coils

- isochronicity depends critically on exact field distribution
- circulation time is measured with phase probes and field shape is adjusted using radially distributed trim coil circuits

example: AGOR cyclotron in Groningen NL



vacuum in cyclotrons – proton losses from scattering

- 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, protons :
(atmospheric conditions)

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

mean free path:

$$\lambda_{\mathrm{eff}} = \left(\frac{1}{P_0} \sum \frac{P_i}{\lambda^i_{\mathrm{inel}}} \right)^{-1}$$

beam loss:

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

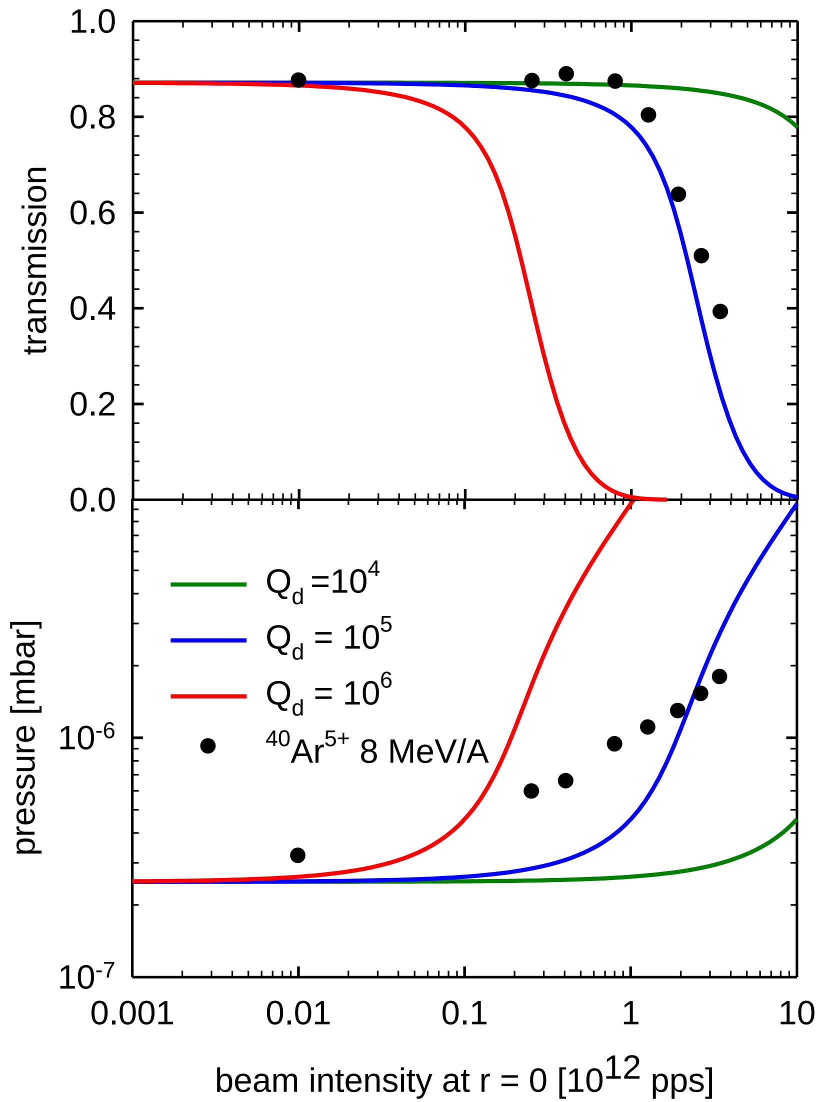
pressure for loss < 10^{-5}: P_i(air) < 10^{-3} mbar $\rightarrow$ **easy, vacuum no problem for p losses!**

heavy ion induced gas desorption

demonstration of transmission breakdown by gas desorption

[measurements in AGOR cyclotron, KVI-Groningen, S.Brandenburg et al]

- transmission of $^{40}Ar^{5+}$ 8 MeV per nucleon
- base vacuum 3 x 10^{-7} mbar
- injected intensity up to 6 x 10^{12} pps
- beampower: $\leq$ 320 W

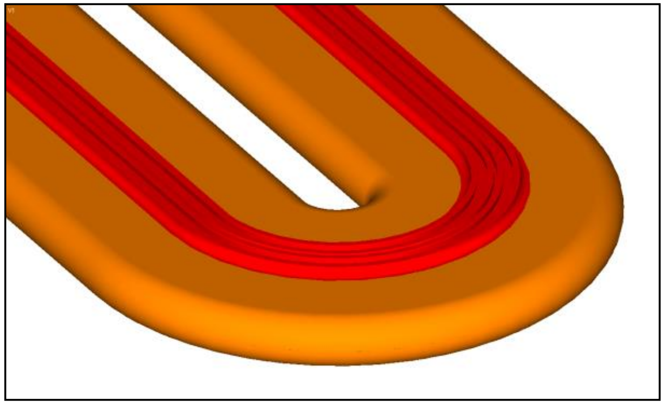


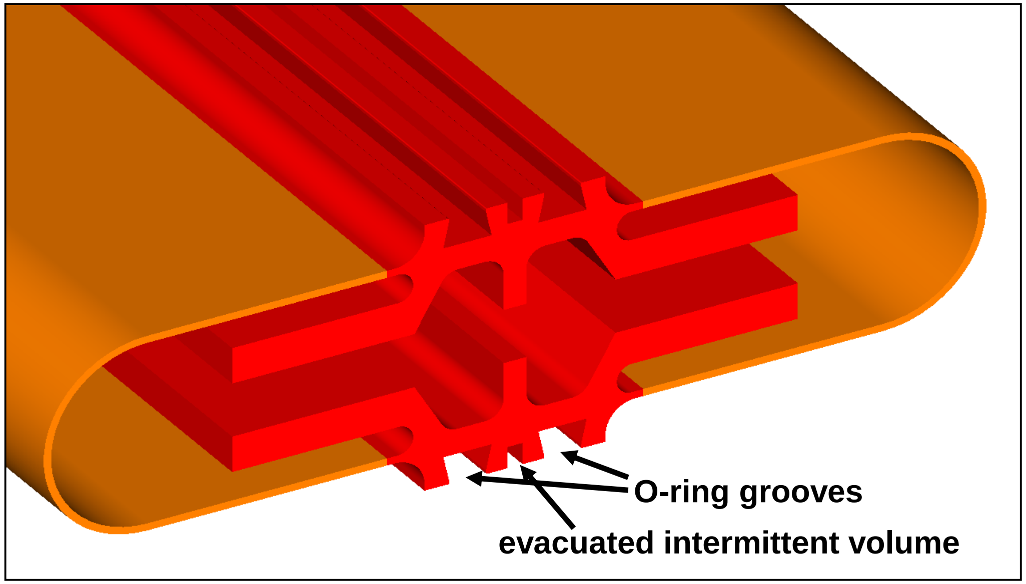
comments on cyclotron vacuum system

- 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

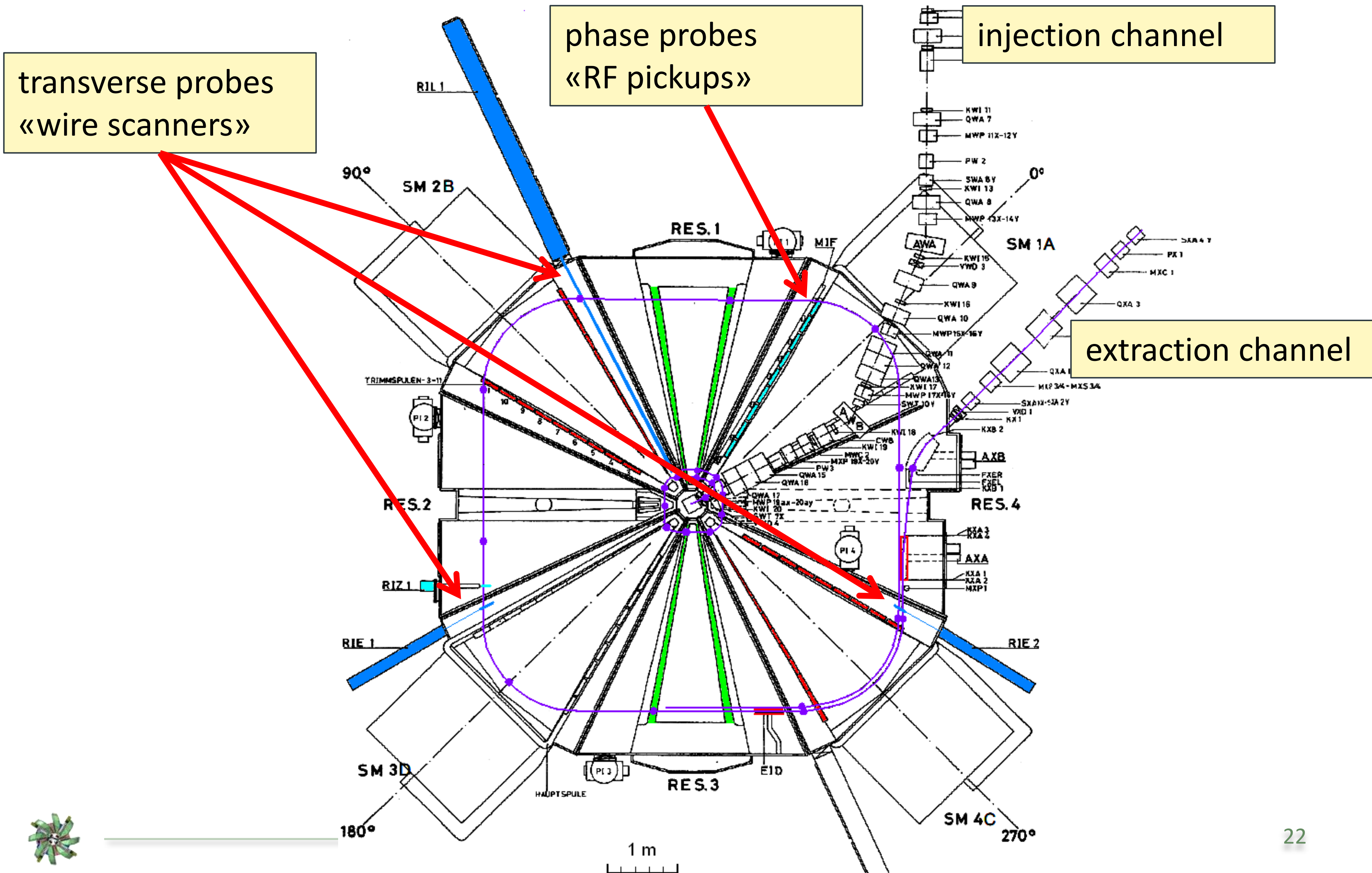
length: 3.5m





cyclotron instrumentation

example: PSI 72MeV injector cyclotron



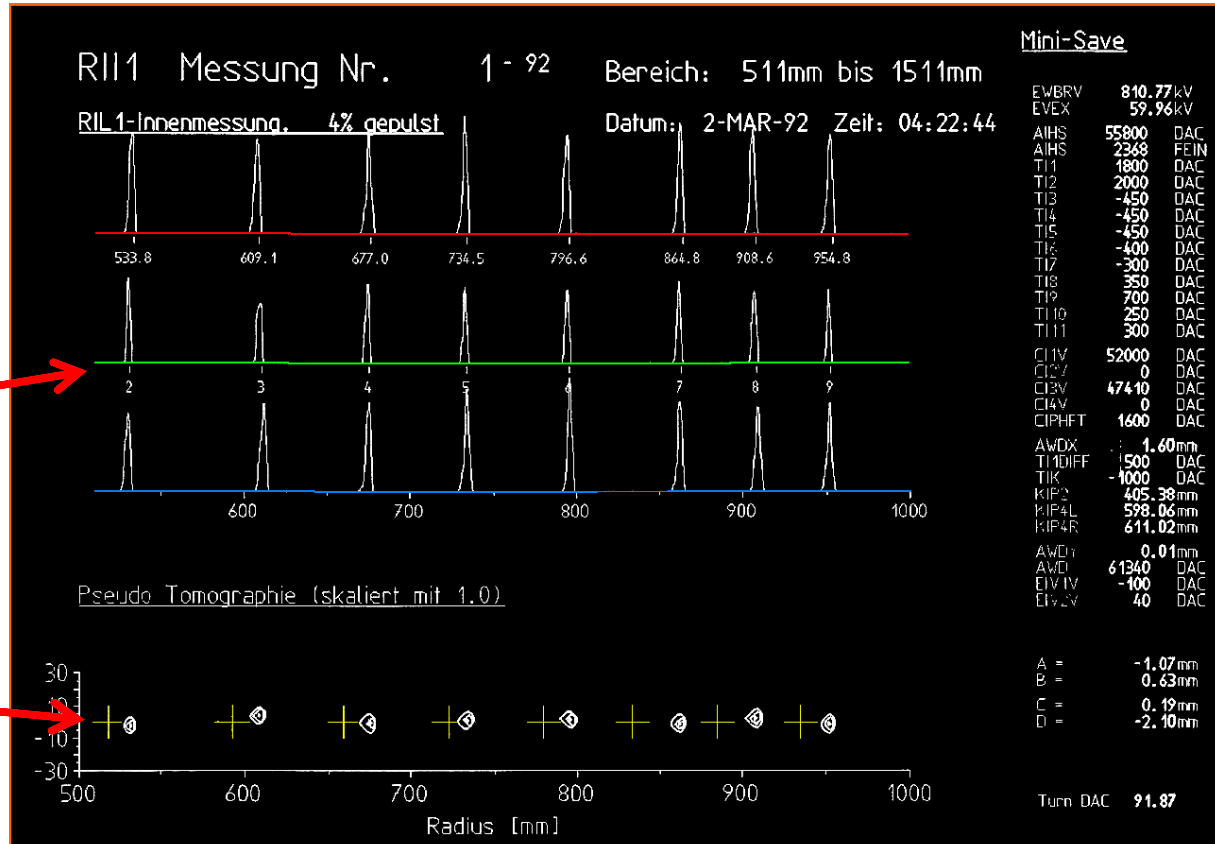
instrumentation: radial probe for turn counting / orbit analysis

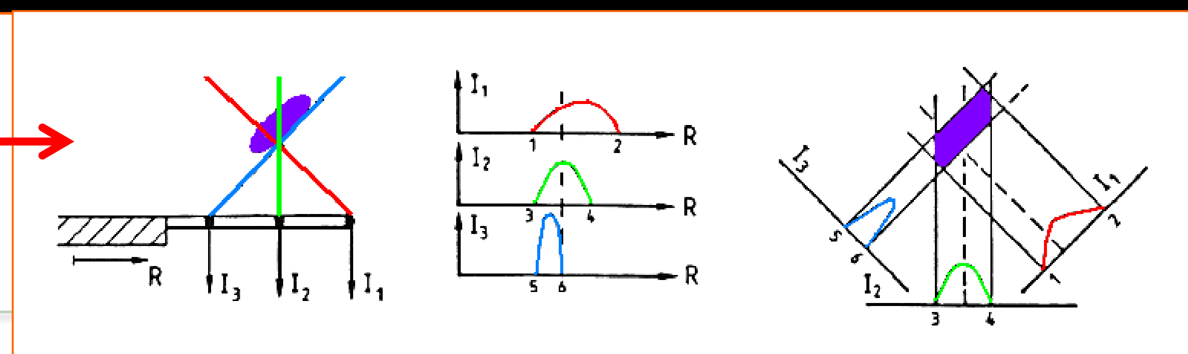
wire scanner with three tilted wires delivers radial beam profile and some vertical information

radial: positions of individual turns

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

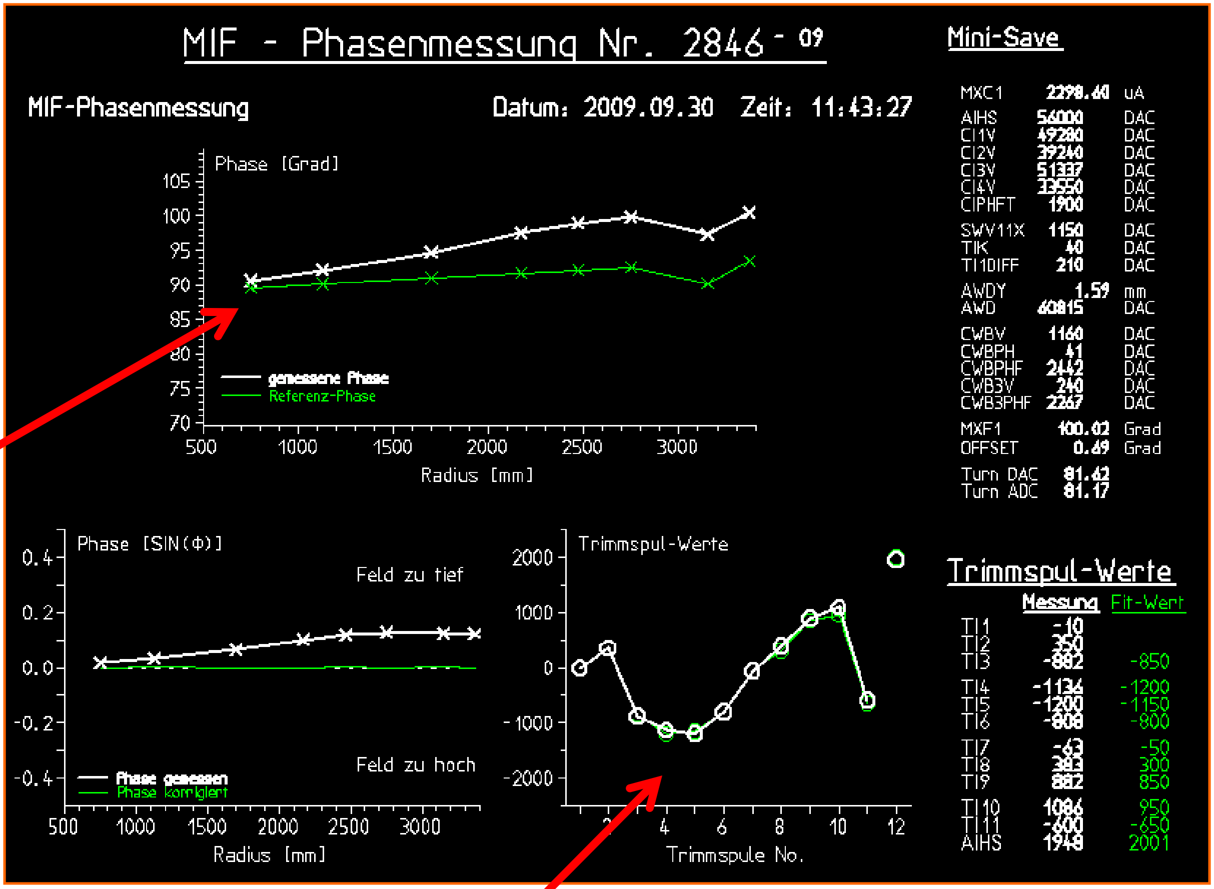
«pseudo tomography» with tilted wires





instrumentation: phase probes

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

next: **cyclotron examples**

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

compact cyclotrons for Isotope production

CYCLONE 30 (IBA) : H^- 15 à 30 MeV

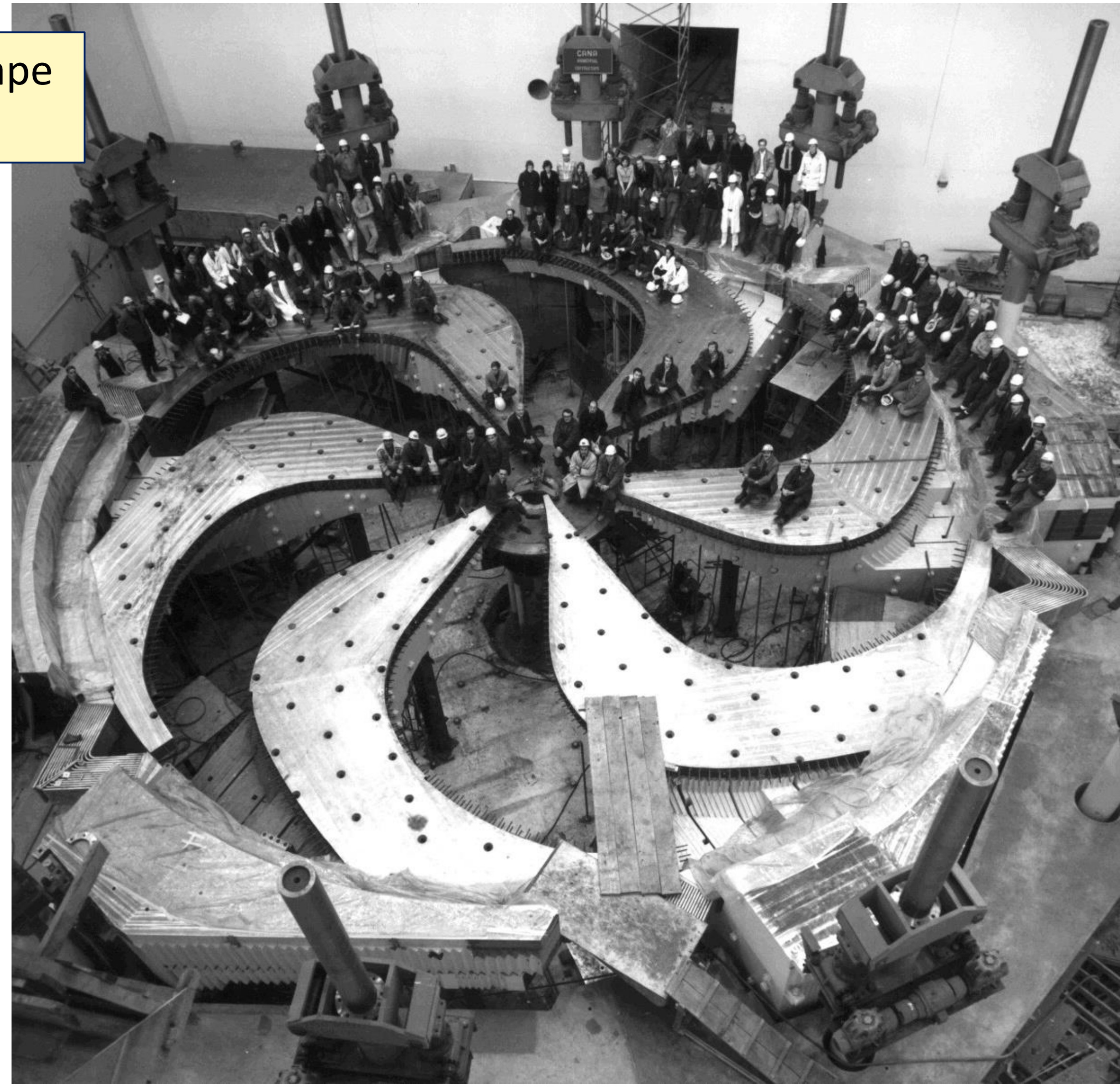
Vertical setup

some 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)



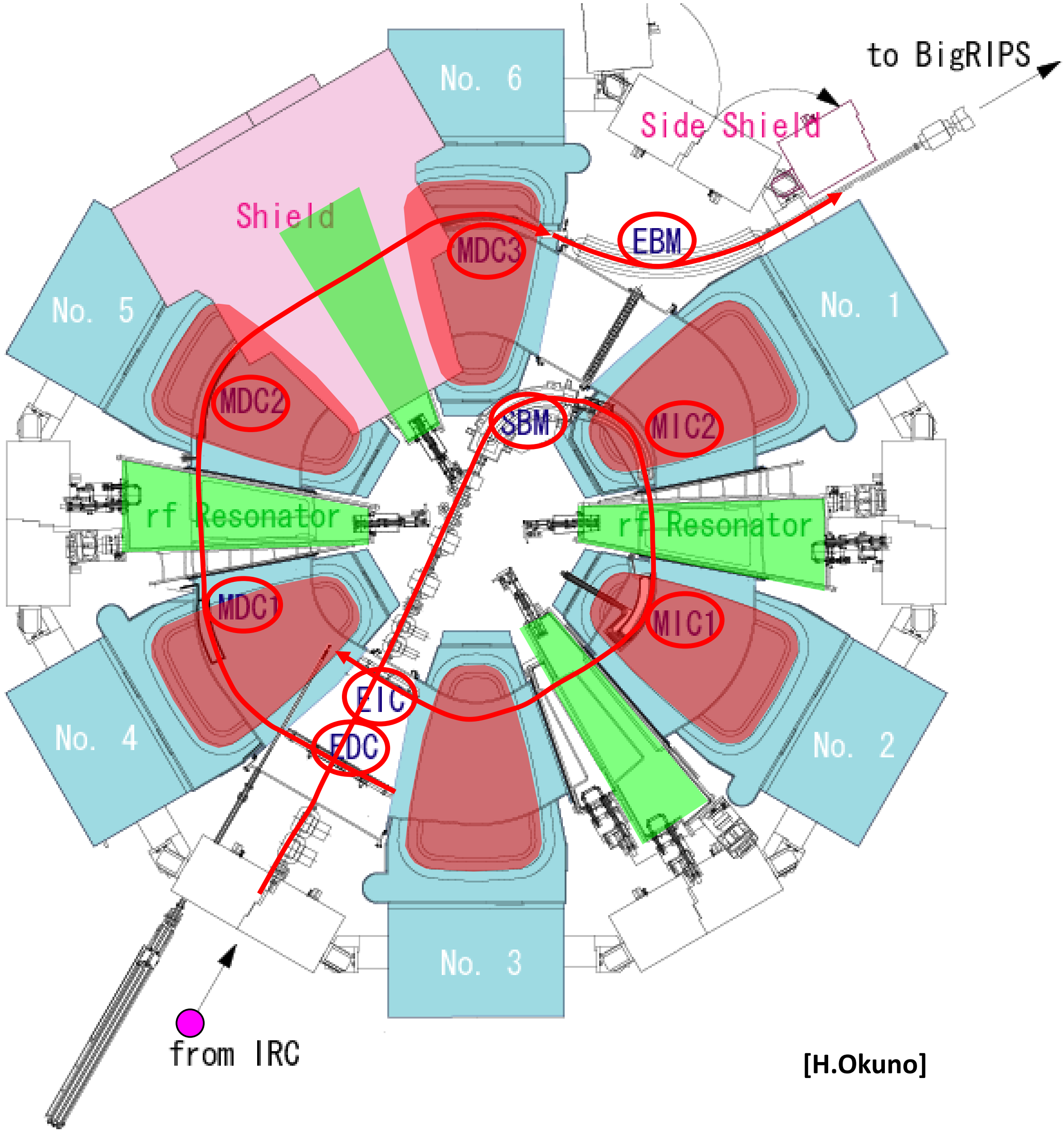
- p, 520MeV, up to 110kW beam power
- diameter: 18m (largest n.c. cyclotron worldwide)
- extraction by stripping H^- $\rightarrow$ variable energy; multiple extraction points possible

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.

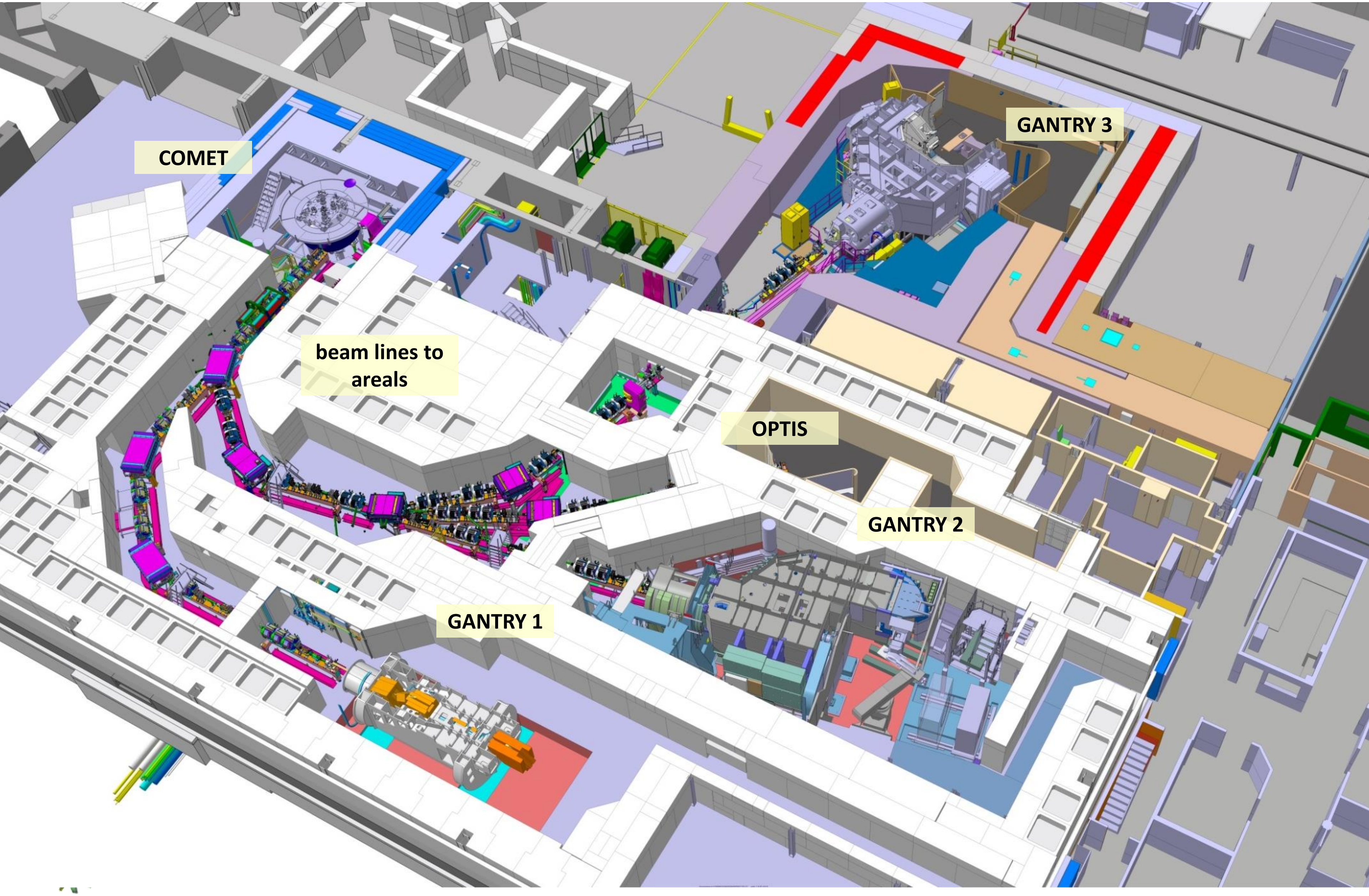
utilization:
broad spectrum of
ions up to Uranium



[H.Okuno]

RIKEN SRC in the vault

PSI Proton Therapy Facility



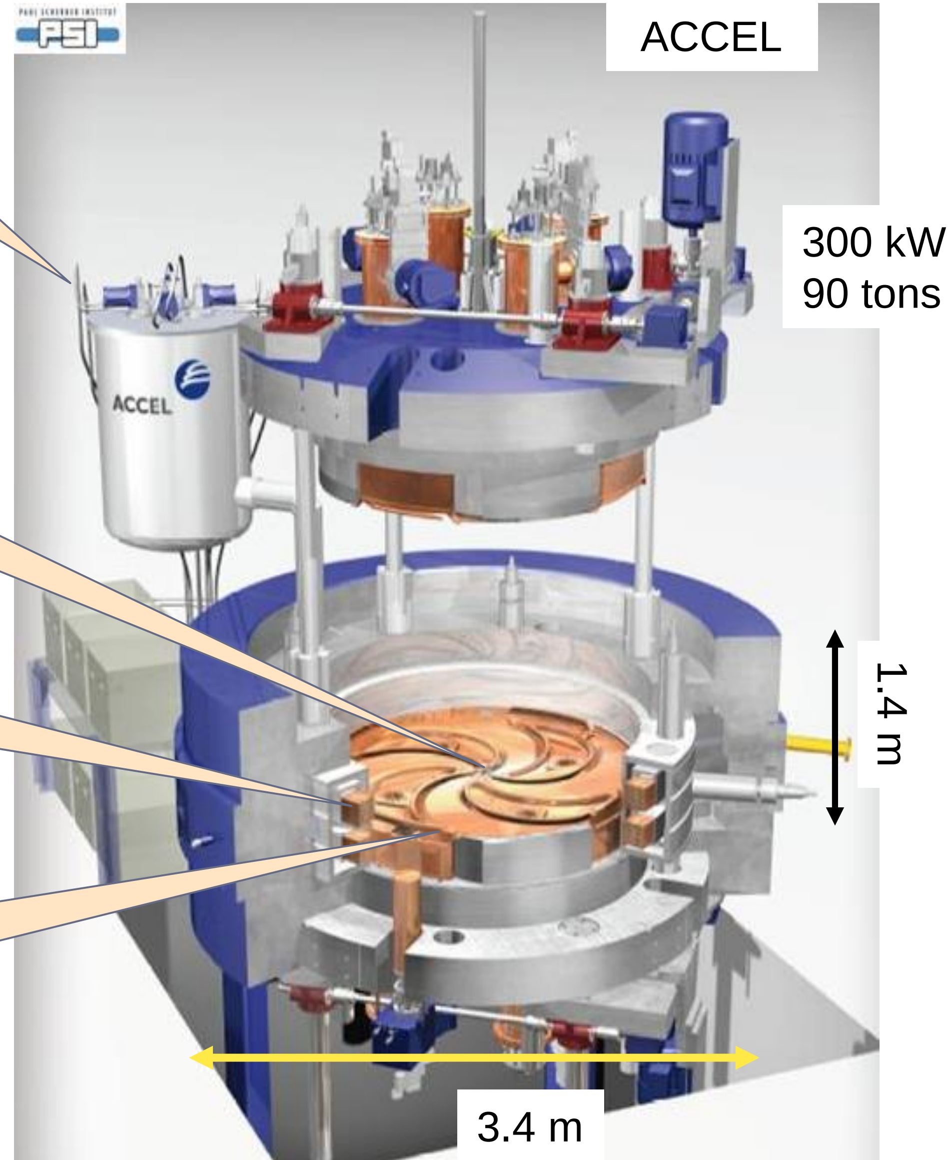
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

Proton source

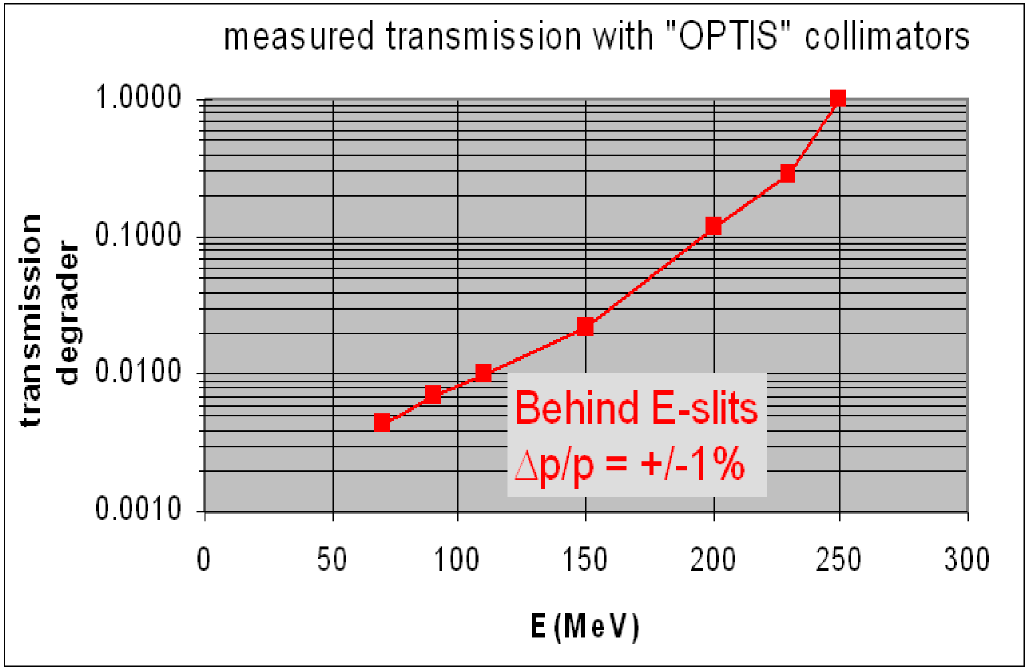
superconducting coils
=> 2.4 - 3.8 T

4 RF-cavities
≈100 kV on 4 Dees

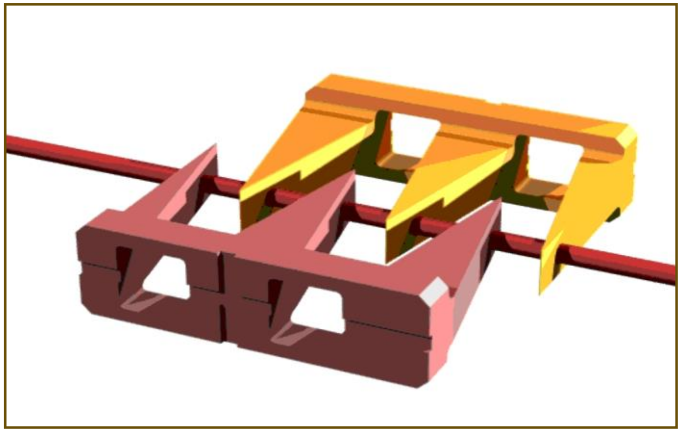


Cyclotron needs degrader :

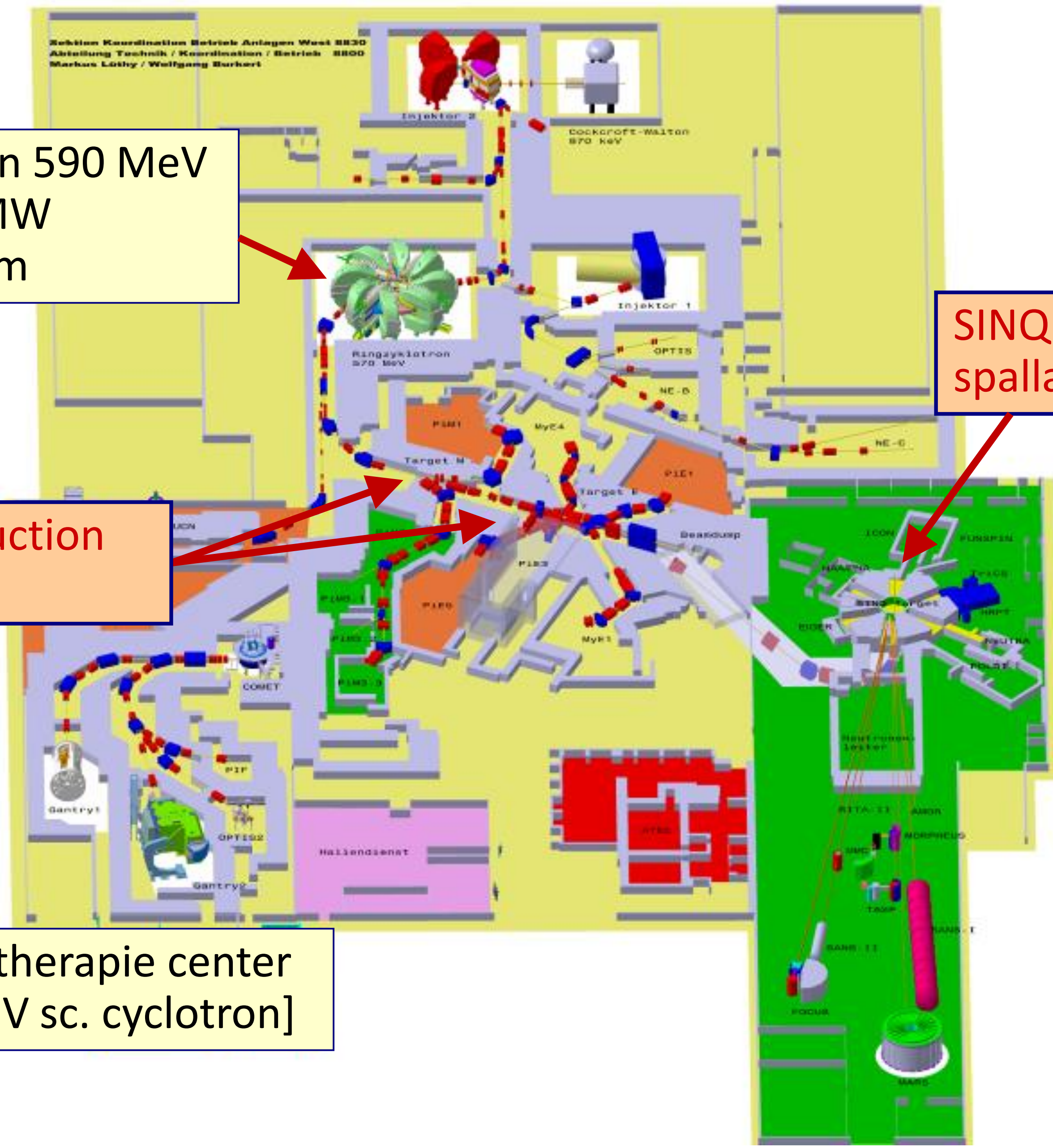
- cyclotron has fixed energy; need **degrader** for energies down to 70MeV
- collimation after degrader to keep emittance → lose intensity with degrader



degrader: (carbon wedges in vacuum) and laminated beam line magnets for fast energy changes < 80 ms / step



examples: PSI High Intensity Proton Accelerator



Ring Cyclotron 590 MeV
2.4mA / 1.4MW
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**
- **cyclotron vs. FFAG**
- **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
classical cyclotron	↗	→	→ ↘	→	▬	simple, but limited E_k
isochronous (AVF) cyclotron	↗	→	↗	→	▬	suited for high power!
synchro-cyclotron	↗	→	→ ↘	↘	⊓⊓⊓	higher E_k, but low P
FFAG	↗ →	→	↗	↗	⊓⊓⊓	strong focusing!
a.g. synchrotron	→	↗		↗ →	⊓⊓⊓	high E_k, strong focus

Cyclotron vs. FFAG

- many discussions on relation FFAG/Cyclotron;

  e.g. **a synchro-cyclotron is actually an FFAG**
- in fact both concepts **can be distinguished via the dominating focusing mechanisms** (M.Craddock):

	Thomas cyclotron	sector FFAG
alternating B’	yes	yes
lens pattern	FFFFFF	FDFDFD
edge focusing	dominant	negligible
AG focusing	negligible	dominant

https://www.cockcroft.ac.uk/events/FFAG08/presentations/Craddock/Thomas-FFAG.pdf

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)

cyclotron conferences – a valuable source of knowledge

- old cyclotron conferences have been digitized for JACOW (effort of M.Craddock!)
- intl. cyclotron conference every 3 years; last month 2016 edition in Zürich; in-between European Cyclotron Progress Meeting (ECPM)

Jacow conferences

Select Conferences

ALL	
ABDW	HB'18 FLS'18 ERL'17 eeFACT'16 HB'16 ERL'15 HF'14 HB'14 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	'17 '15 '13 '11 '09 '07
Cyclotrons ☑	'16 '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	'16 '14 '12 '10 '08
EPAC	'08 '06 '04 '02 '00 '98 '96 '94 '92 '90 '88
FEL	'17 '15 '14 '13 '12 '11 '10 '09 '08 '07 '06 '05 '04
HIAT	'15 '12 '09
IBIC	'17 '16 '15 '14 '13 '12
ICALEPCS	'17 '15 '13 '11 '09 '07 '05 '03 '01 '99
ICAP	'15 '12 '09 '06
IPAC	'18 '17 '16 '15 '14 '13 '12 '11 '10
LINAC	'16 '14 '12 '10 '08 '06 '04 '02 '00 '98 '96 '94 '92 '90 '88 '86 '84 '81 '79 '76 '72 '70 '68 '66 '64 '63 '62 '61
MEDSI	'16
NA-PAC	'16 '13 PAC'11 '11
PAC	'09 '07 '05 '03 '01 '99 '97 '95 '93 '91 '89 '87 '85 '83 '81 '79 '77 '75 '73 '71 '69 '67 '65
PCaPAC	'16 '14 '12 '10 '08
RuPAC	'16 '14 '12 '10 '08 '06 '04
SAP	'17 '14
SRF	'17 '15 '13 '11 '09 '07 '05 '03 '01 '99 '97 '95 '93 '91 '89 '87 '84 '80

cyclotrons

first PAC

some literature w.r.t. cyclotrons

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Thank you for your attention !