Cyclotrons – II & FFA

CERN Accelerator School – Introductory Course
High Tatras, September 19, 2019

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Cyclotrons II - Outline

- brief review of the previous lesson
- cyclotron subsystems

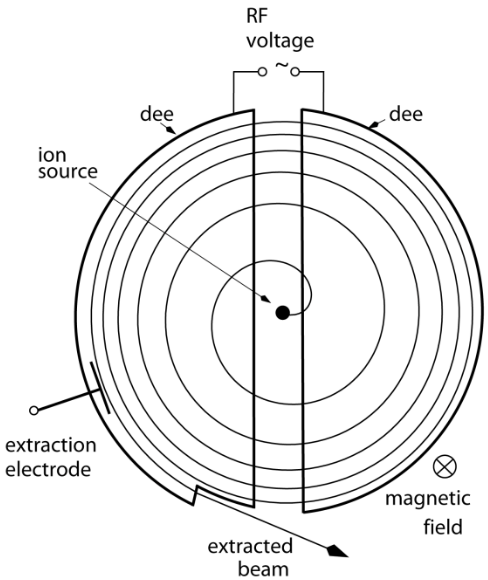
  Injection/extraction schemes, RF systems/resonators, magnets, vacuum issues, instrumentation
- FFA = Fixed Field Alternating Gradient Accelerators

  conceptual, scaling vs non-scaling, specific FFA technologies
- discussion

  classification of circular accelerators, Pro's and Con's of cyclotrons/FFA for different applications

review of Cyclotrons-I

classical cyclotron

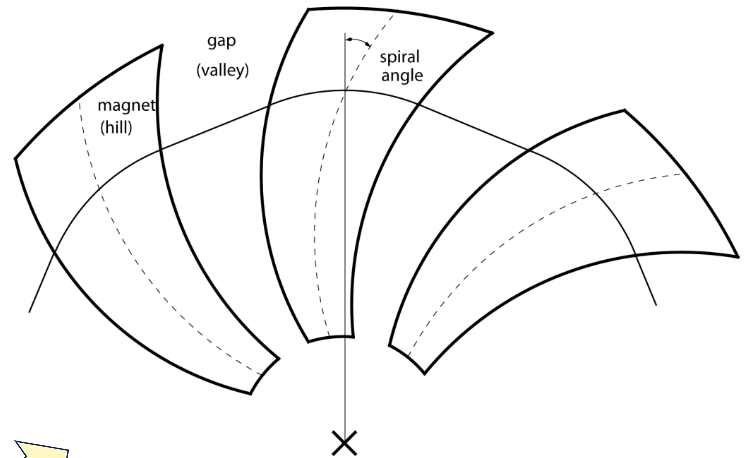


- simplicity, compactness
- continuous injection/extraction
- multiple usage of accelerating voltage

but:

- insufficient vertical focusing
- limited energy reach

sector cyclotron



flutter — spiral angle

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

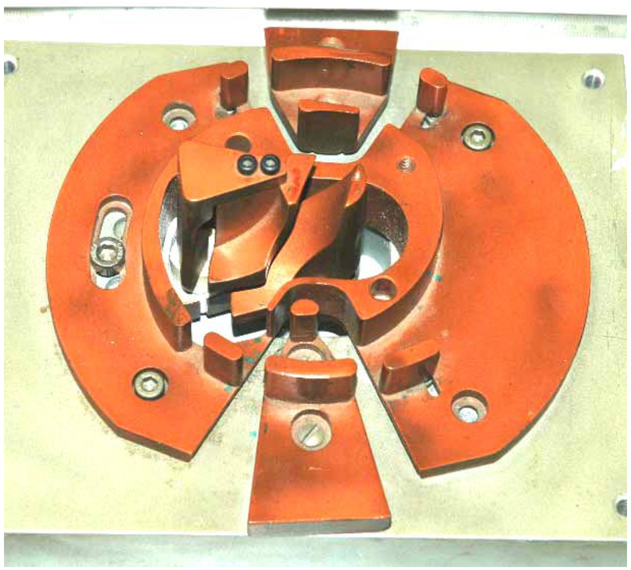
next: **cyclotron injection & extraction**

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

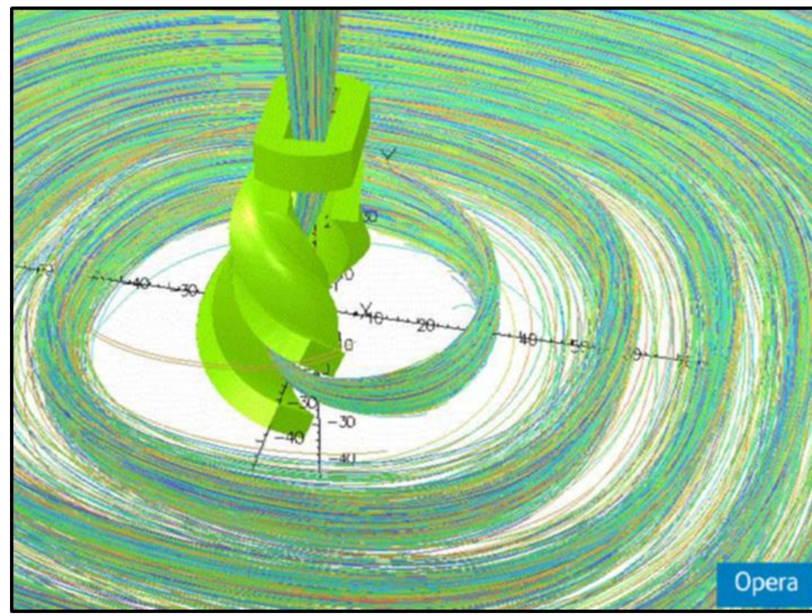
cyclotron injection schemes – spiral inflector

- 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

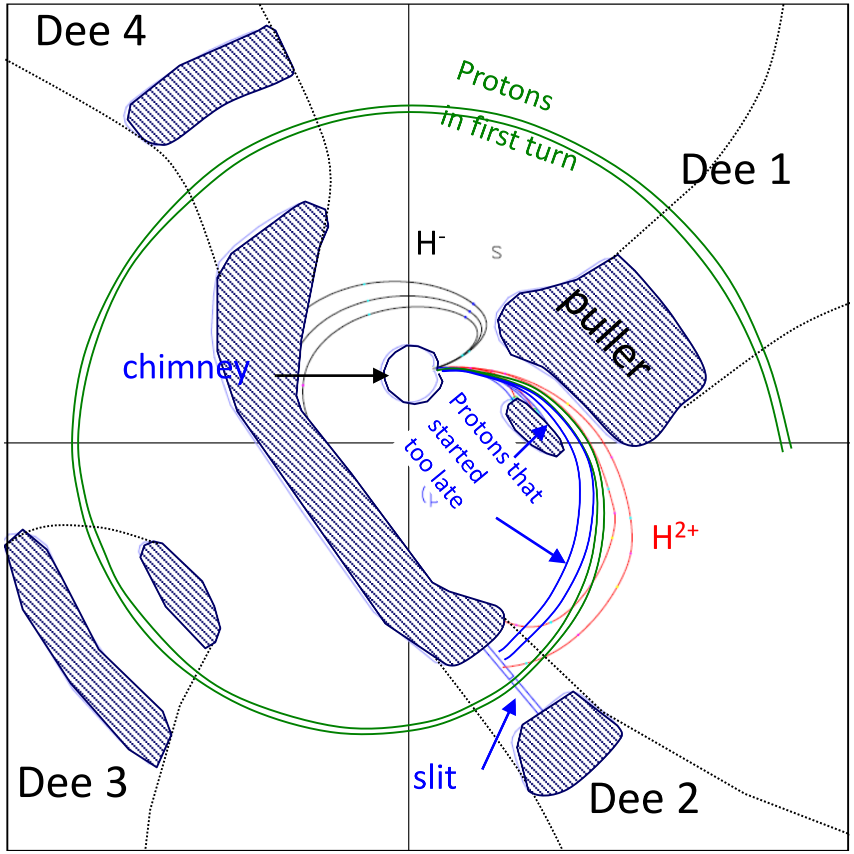


[inflector IBA Cyclone 30 cyclotron]



[courtesy: W.Kleeven (IBA)]

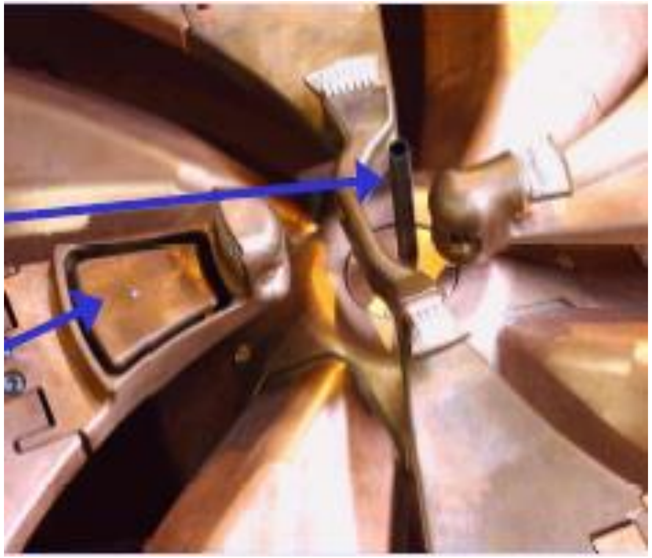
internal ion source
→ example COMET



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

chimney = ion source

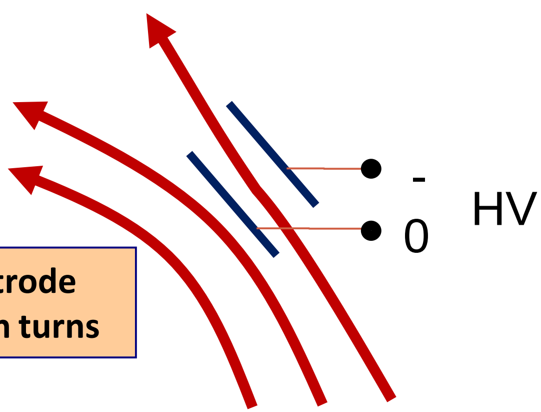
deflector electrode for intensity regulation



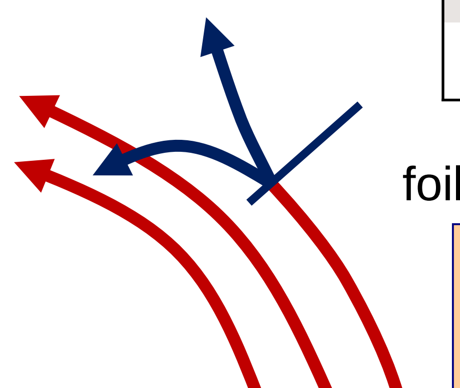
electrostatic septum and charge exchange extraction

- 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

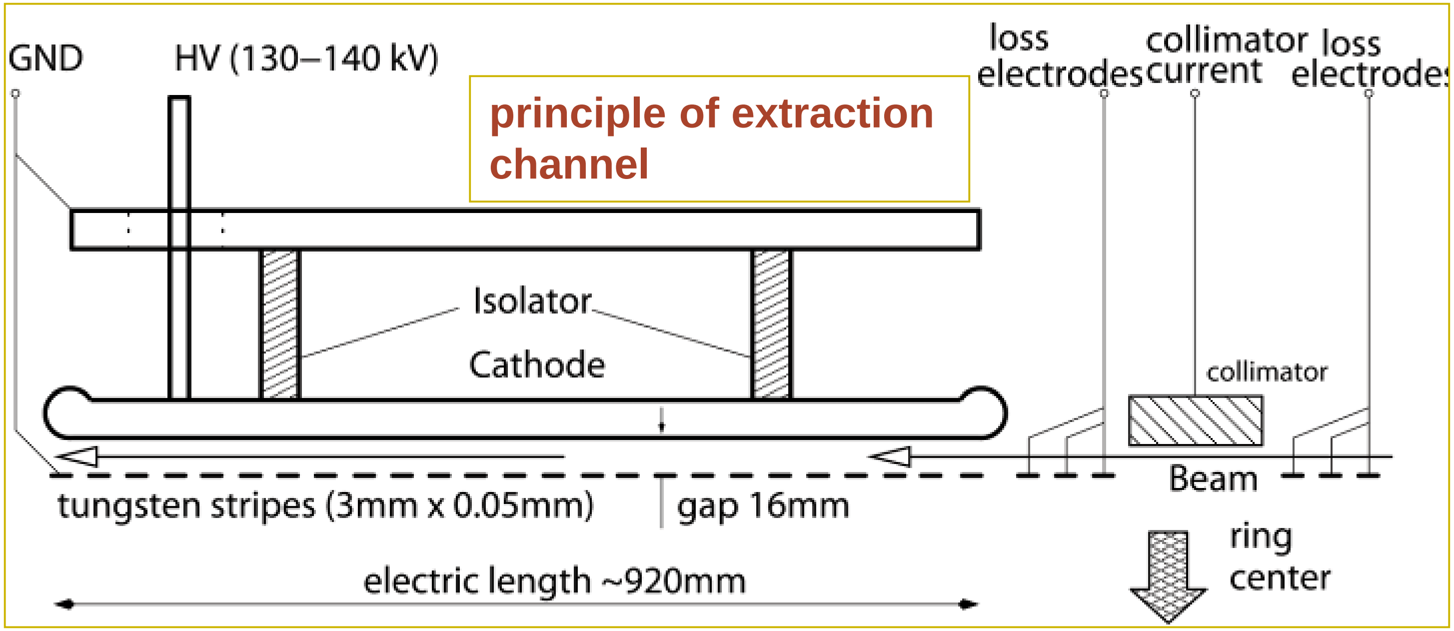


extraction electrode placed between turns



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

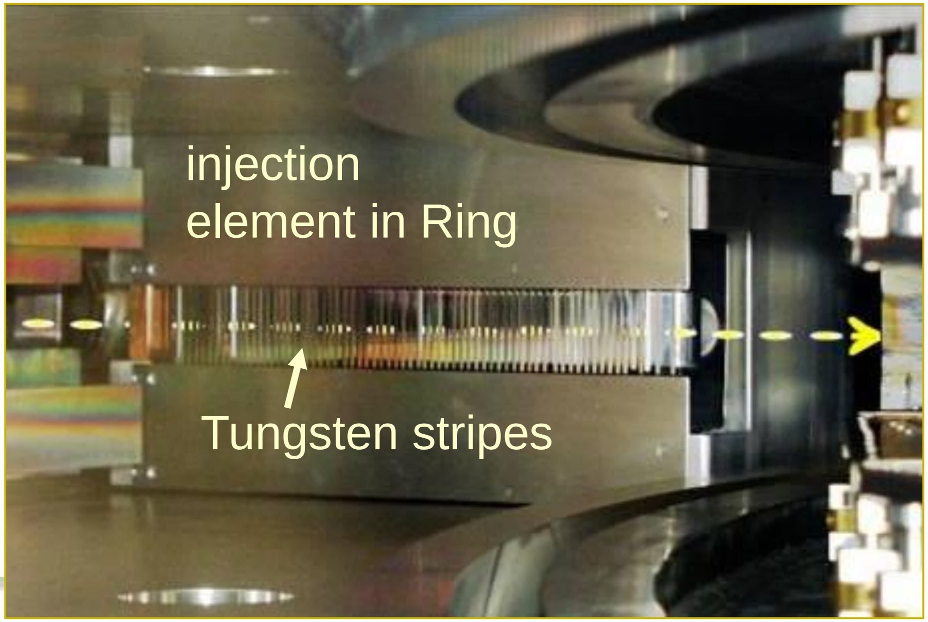
ρ = 115 m

U = 144 kV

major loss mechanism is scattering in 50μm electrode!

electrostatic rigidity:

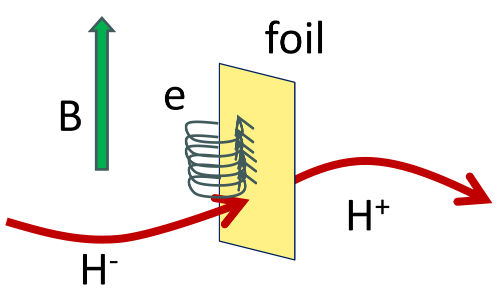
$$E\rho \quad = \quad \frac{\gamma+1}{\gamma}\frac{E_k}{q}$$



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*

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

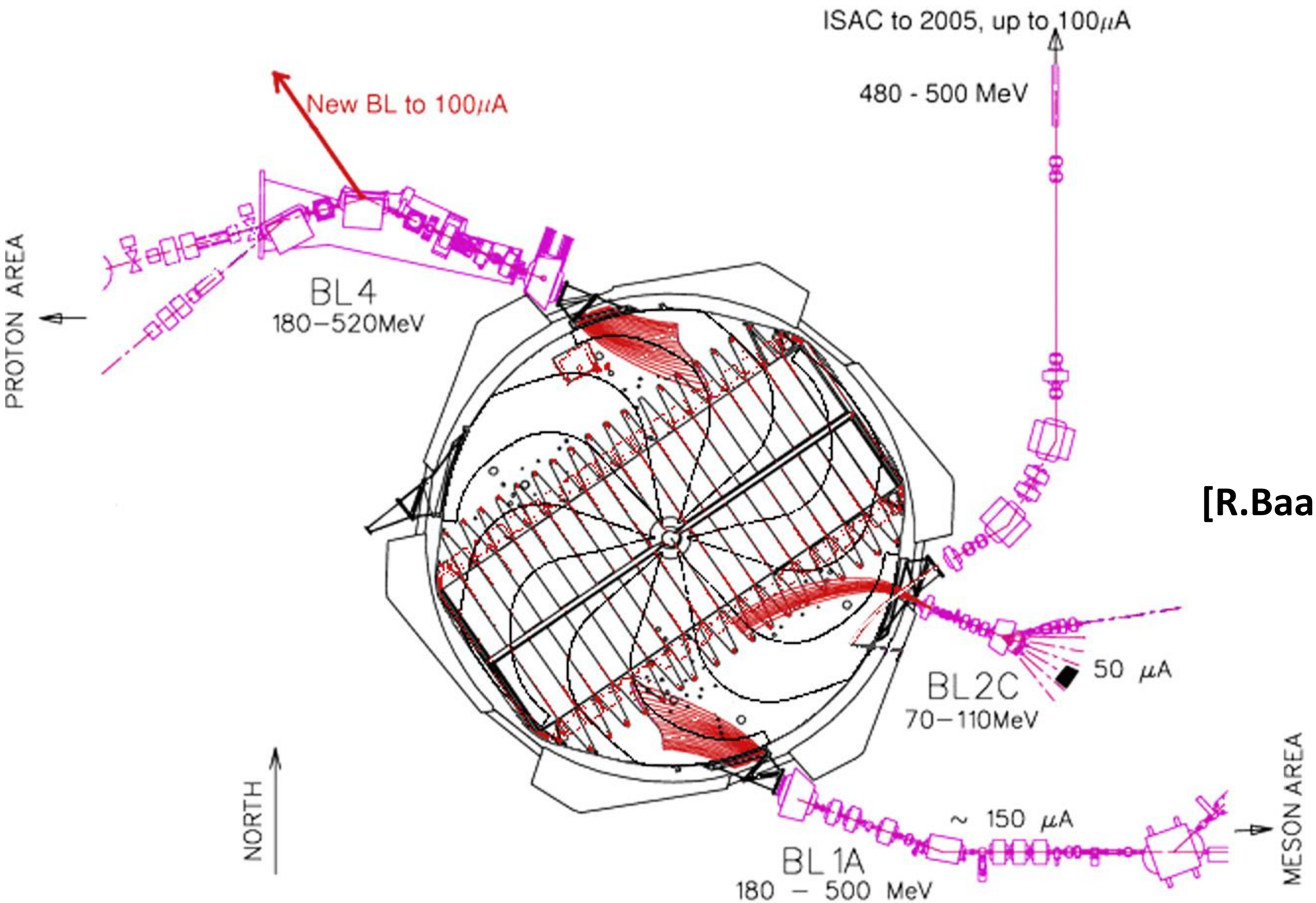
$$\rightarrow E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

Bending radius of electrons?

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

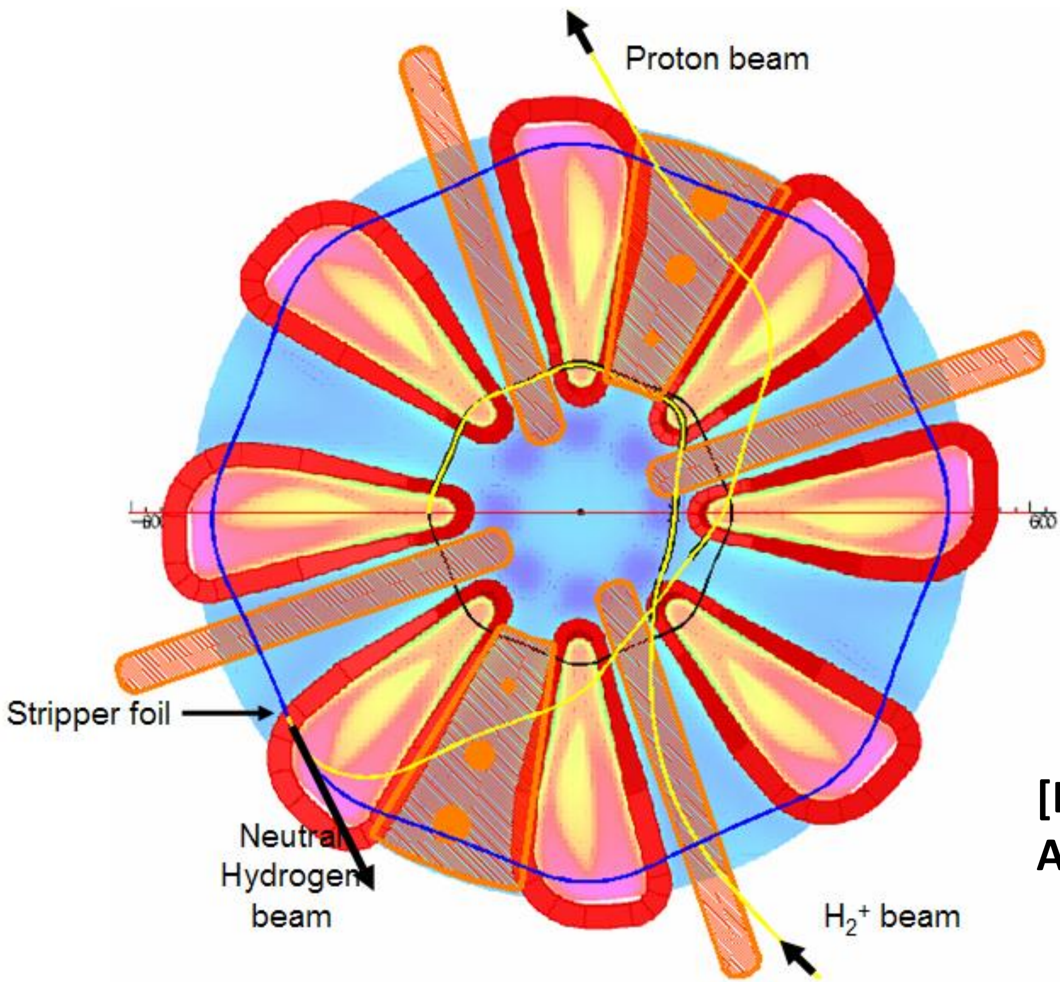
→ typically mm

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]

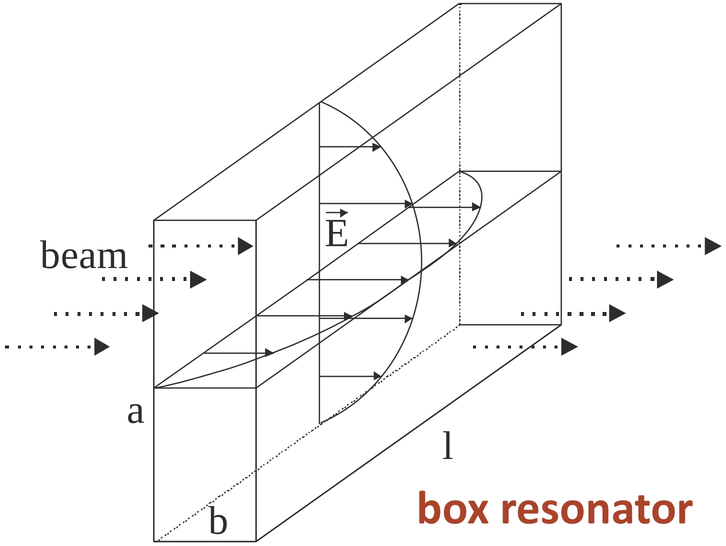
next: **RF, magnets, vacuum, diagnostics**

RF acceleration

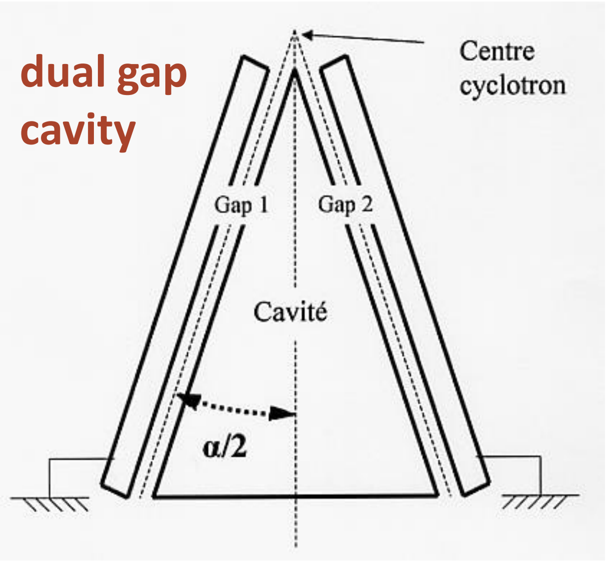
- acceleration is realized in the classical way using 2 or 4 “Dees”
- or by box resonators in separated sector cyclotrons
- frequencies typically around 50…100MHz, harmonic numbers h = 1…10
- voltages 100kV…1MV per device

RF frequency can be a multiple of the cyclotron frequency:

$$\omega_{\mathrm{RF}} = h \cdot \omega_c$$



box resonator

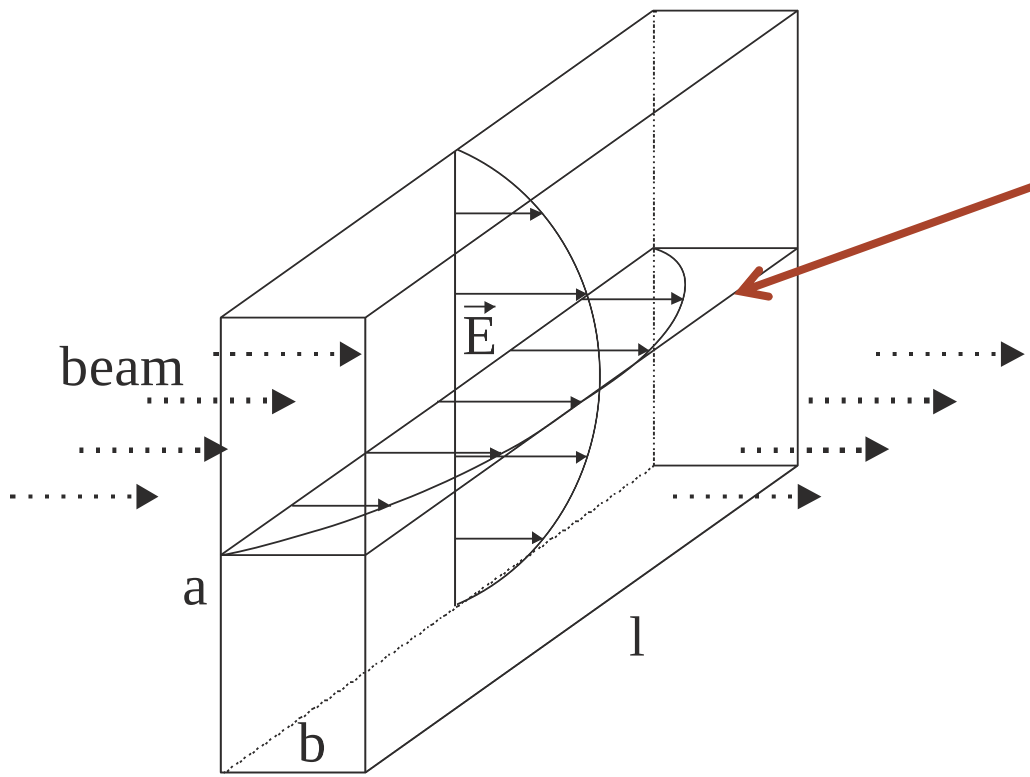


box resonator

cyclotron resonators are basically box resonators

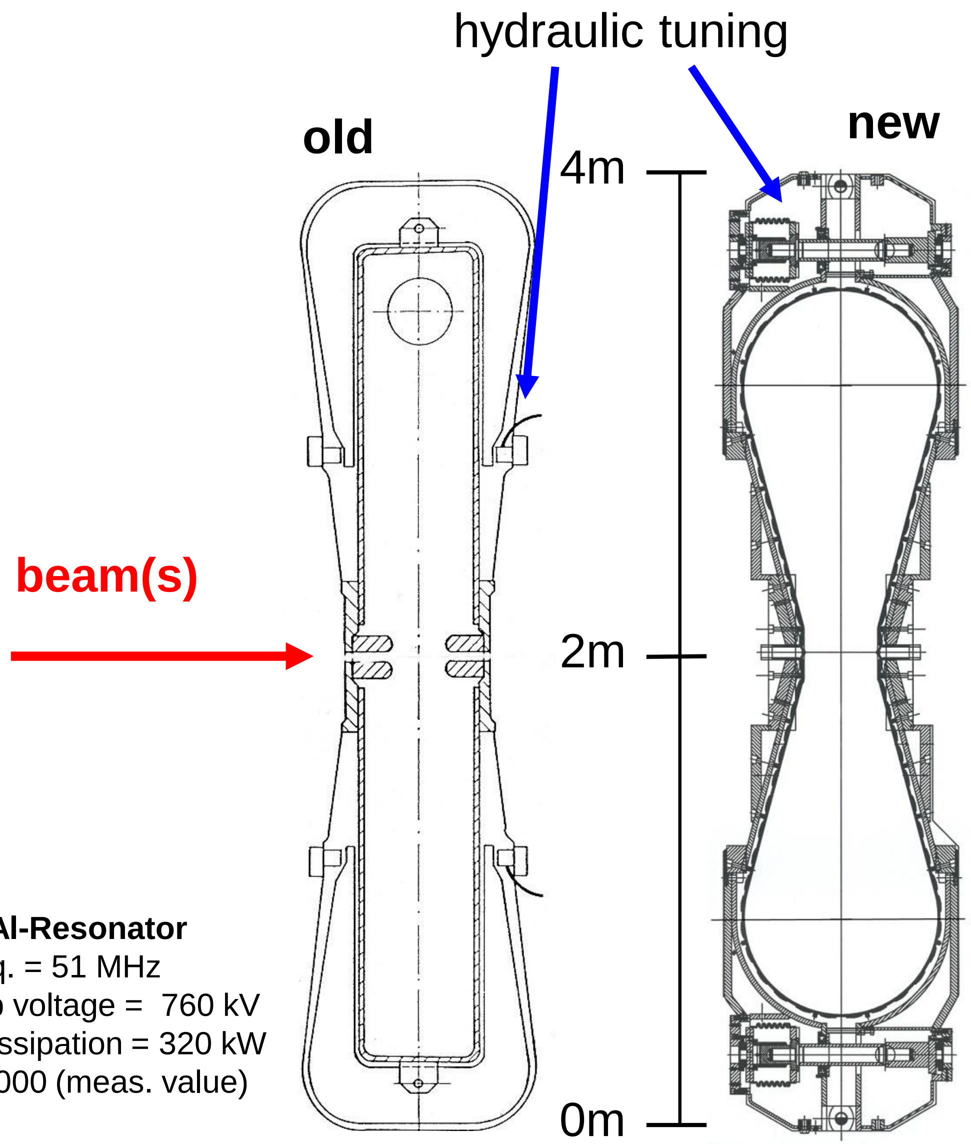
resonant frequency:

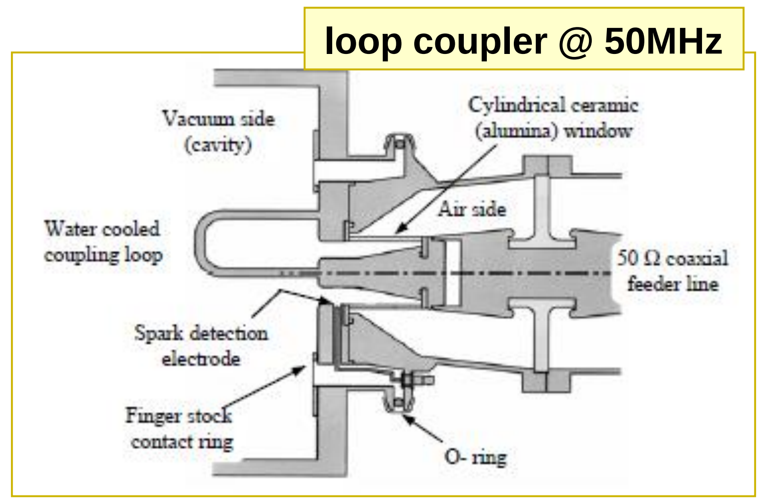
$$f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{l^2}}$$



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

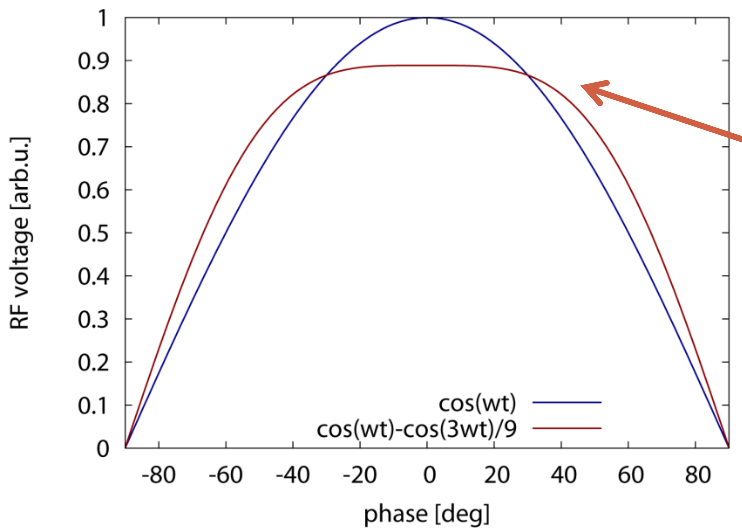
copper resonator in operation at PSI's Ring cyclotron

- **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%**

RF and Flattop Resonator

for high intensities it is necessary to flatten the RF field over the bunch length
$\rightarrow$ use 3rd harmonic cavity to generate a flat field (over time)

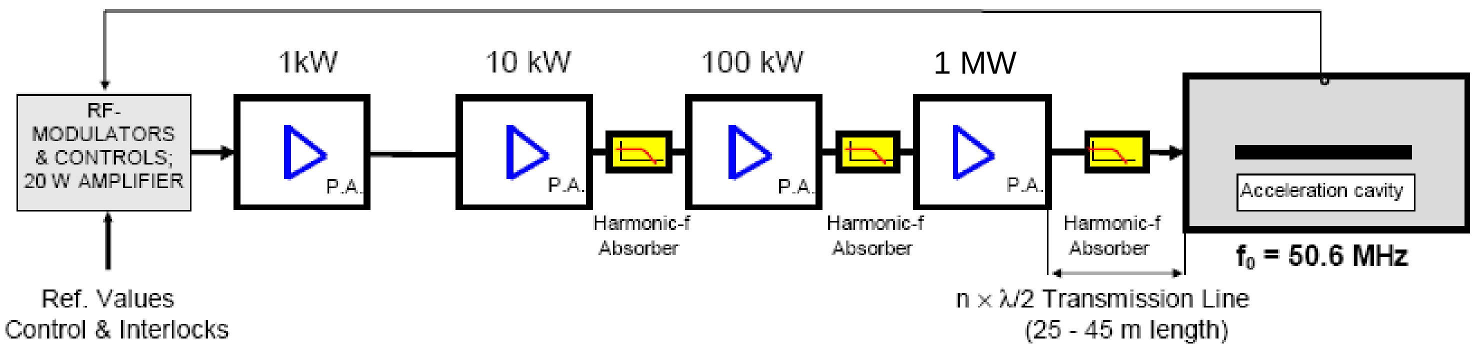
optimum condition: $U_{\mathrm{tot}} = \cos \omega t - \frac{1}{9} \cos 3\omega t$



broader flat region for bunch

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%]

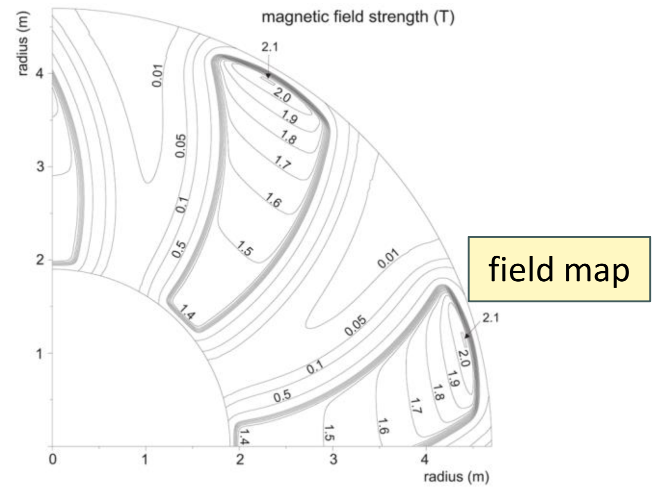
[L.Stingelin et al]

cyclotron technology: sector magnets

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

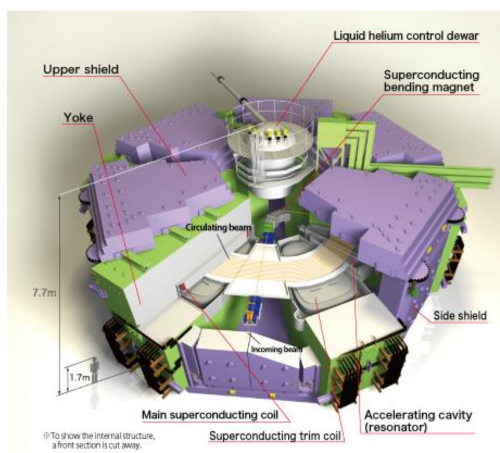
PSI sector magnet

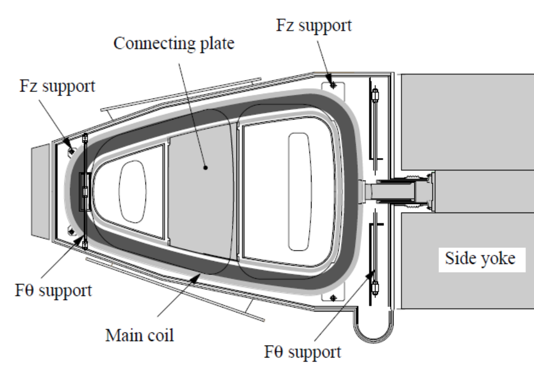
iron weight: 250 tons
coil weight: 28 tons
Field: 2.1T
orbit radius: 2.1…4.5 m
spiral angle: 35 deg



Riken SRC sector magnet

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

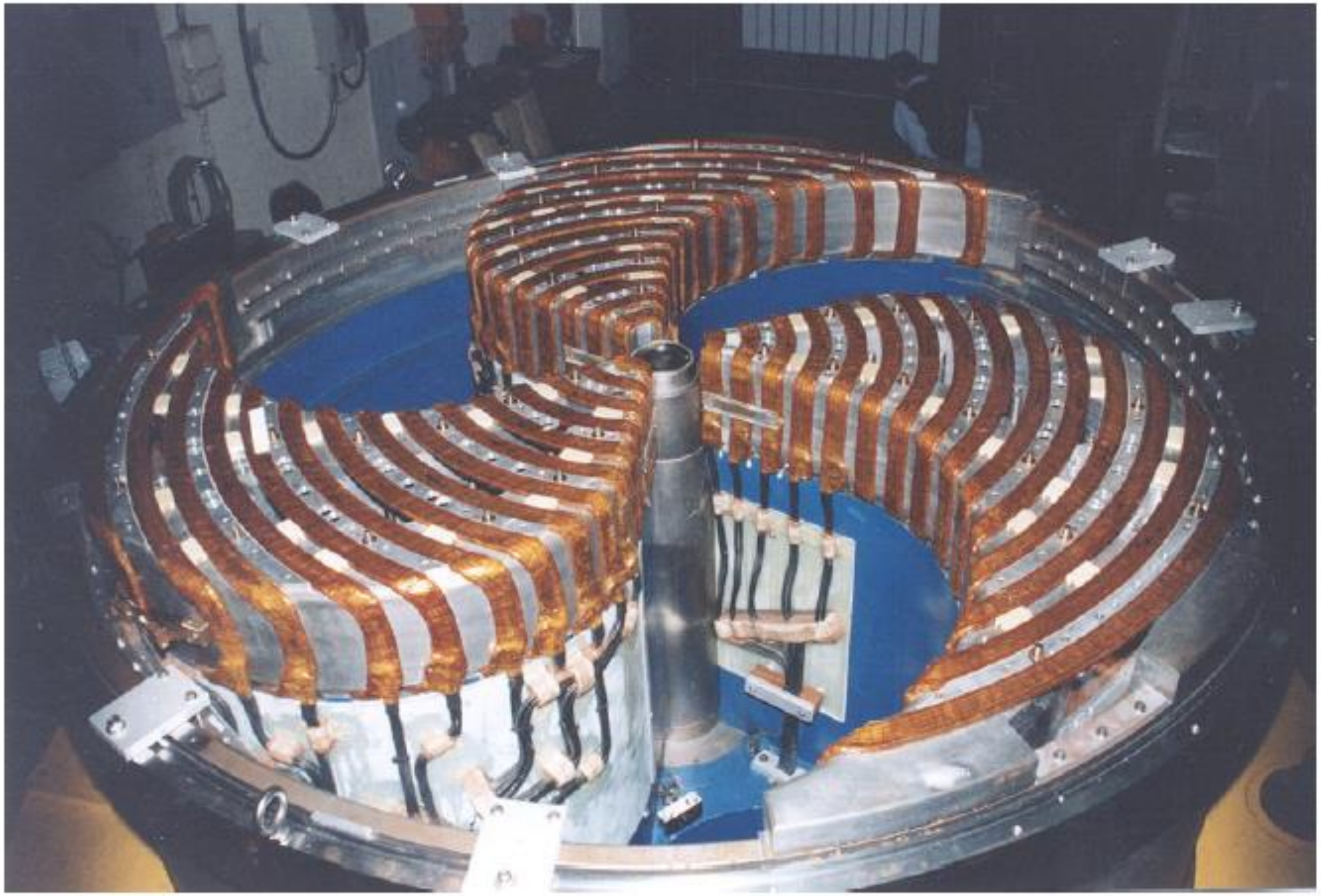




Magnets – Fine-tuning with trim coils

- 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:

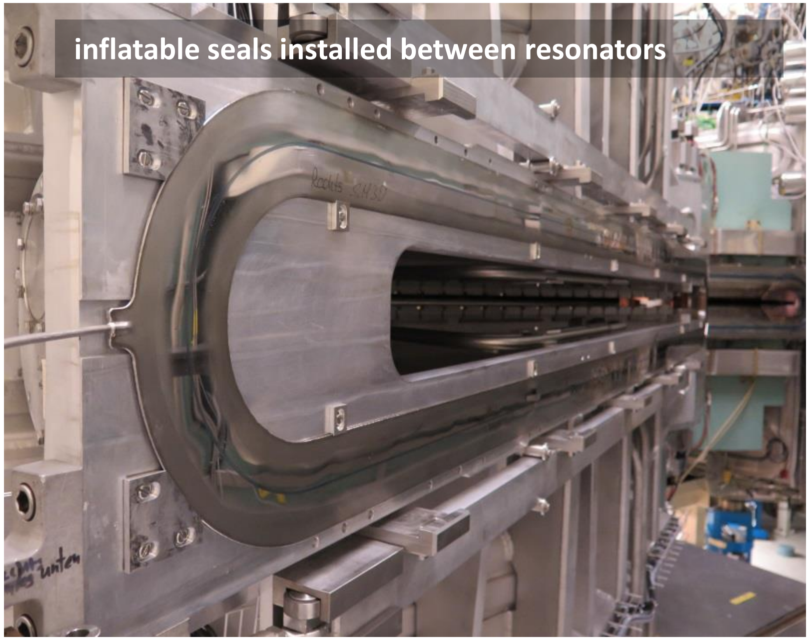
$$\frac{N_0 - N(l)}{N_0} = 1 - \exp(-l/\lambda_{\mathrm{eff}}) \approx l/\lambda_{\mathrm{eff}}$$

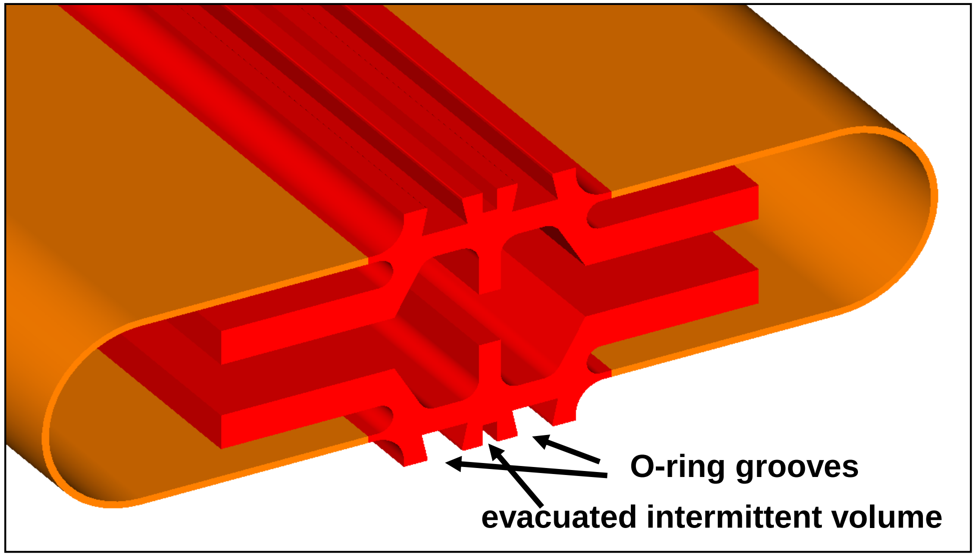
pressure for loss < 10^{-5}: P_i(air) < 10^{-3} mbar $\rightarrow$ **easy, vacuum no problem for p losses!**

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)

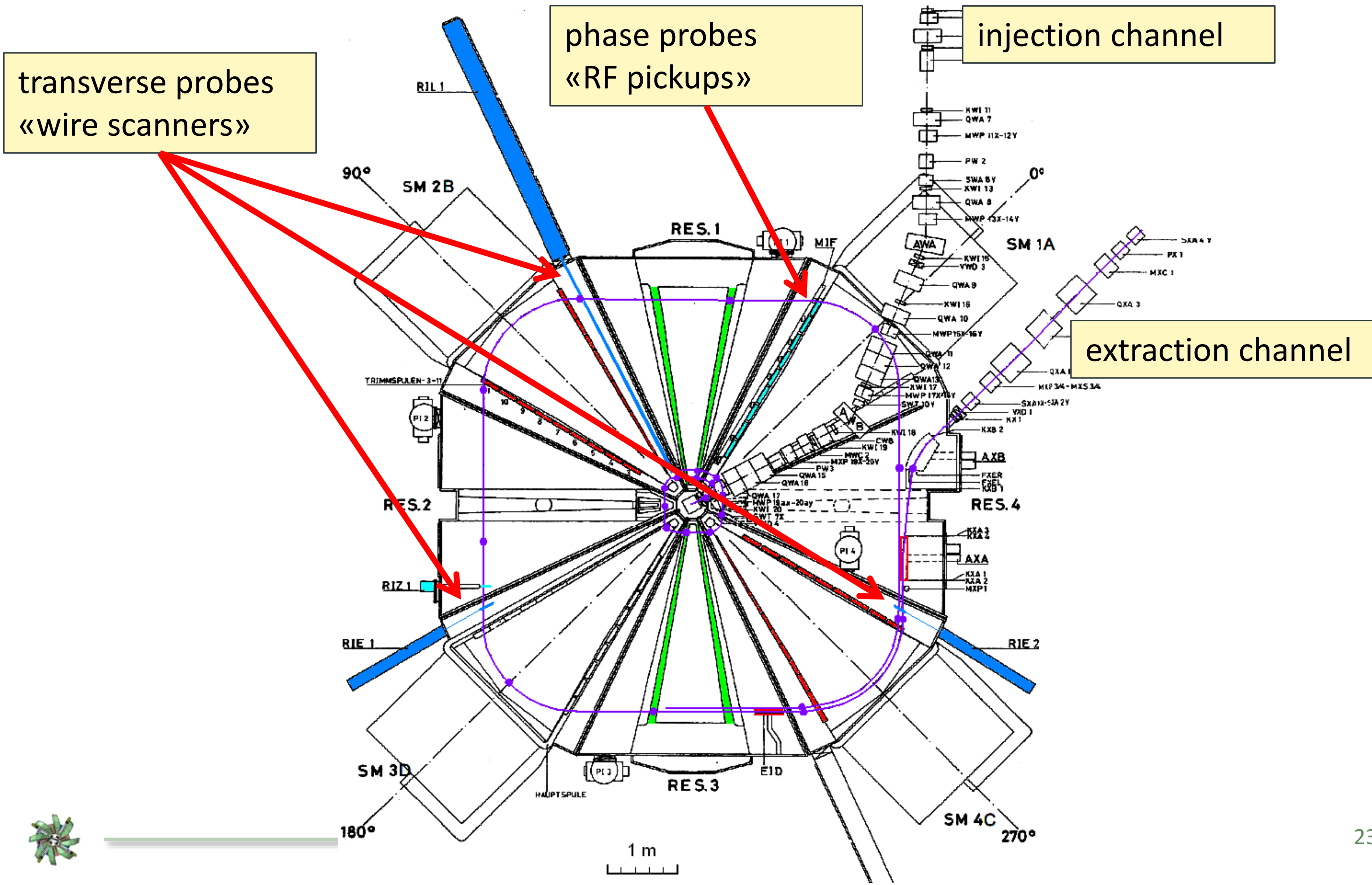
example: inflatable seals installed between resonators





cyclotron instrumentation

example: PSI 72MeV injector cyclotron



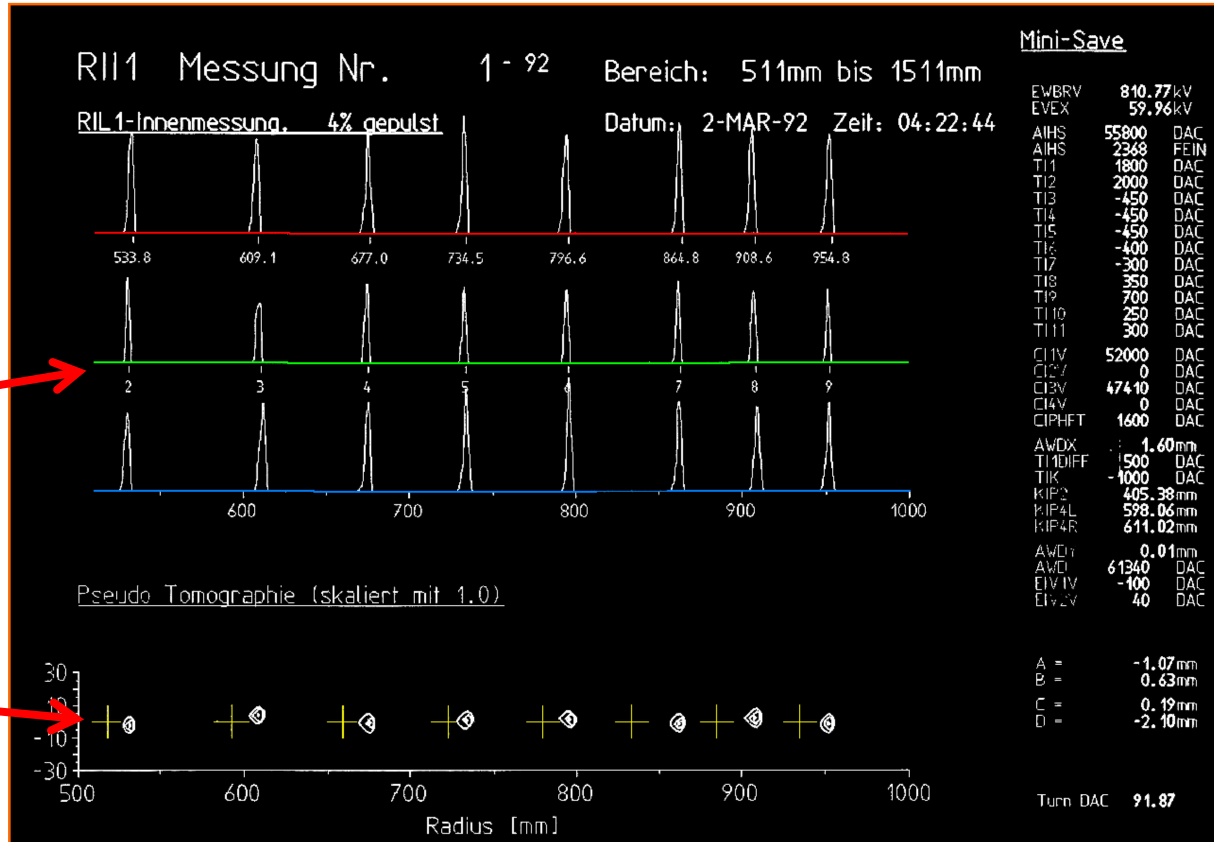
instrumentation: radial probe for turn counting / orbit analysis

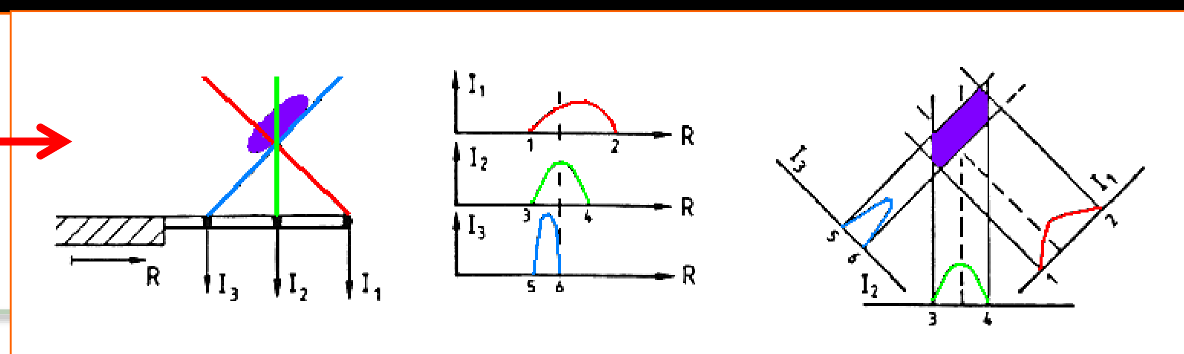
wire scanner with three tilted wires delivers radial beam profile and some vertical information

radial: positions of individual turns

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

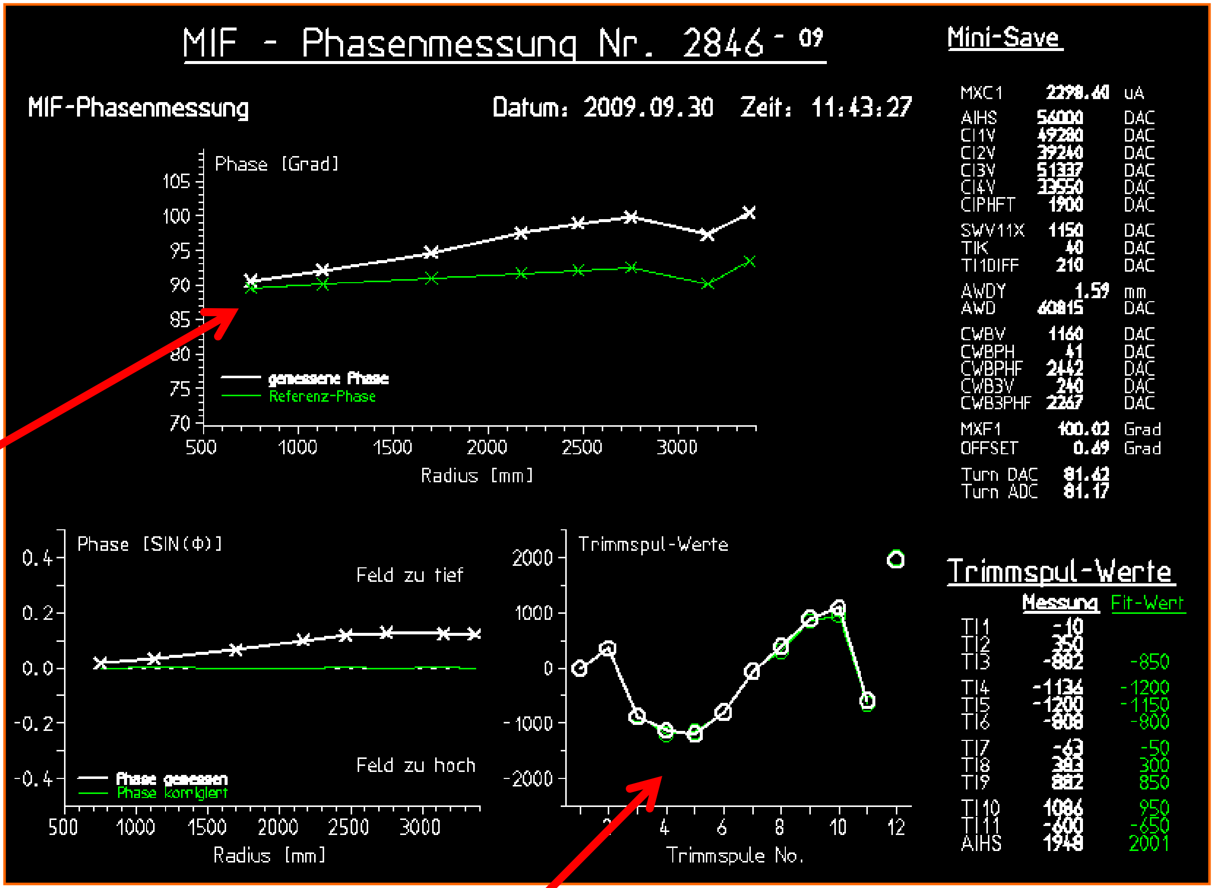
«pseudo tomography» with tilted wires





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»

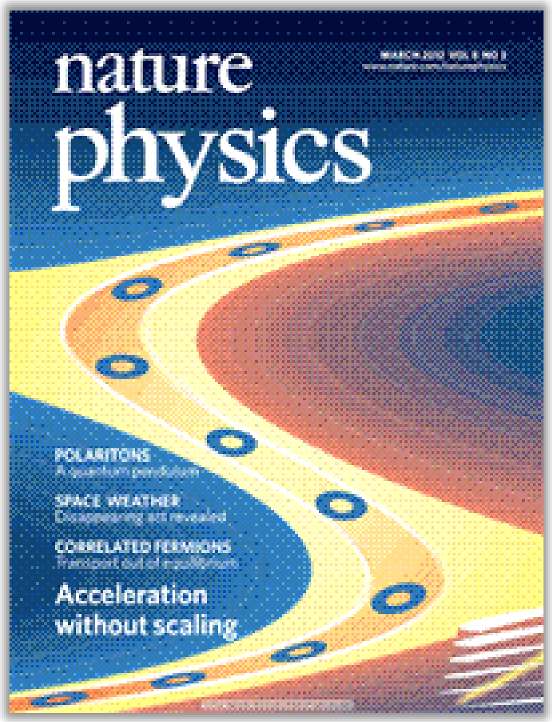
trim coil settings (12 circuits across radius)
green: predicted from phase measurement

next: **Fixed Field Alternating Gradient Accelerator FFA**

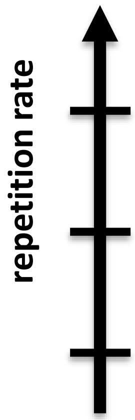
conceptual, scaling vs non-scaling, specific FFA technologies

materials & support by Suzie Sheehy ASTeC/STFC

S. Machida et. al.
Nature Physics 8, 243–247 (2012)



Fixed Field Alternating Gradient Accelerator (FFA)



isochr. cyclotron: **no cycling**, intense CW beam

FFA: **fast cycling** of RF frequency ~ kHz

synchrotron: **slow cycling** of magnets, $\leq$ 50Hz

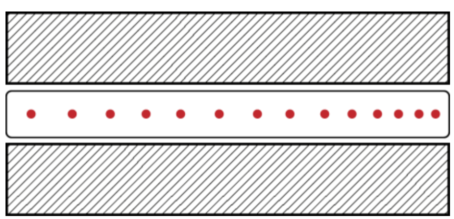
FFA:

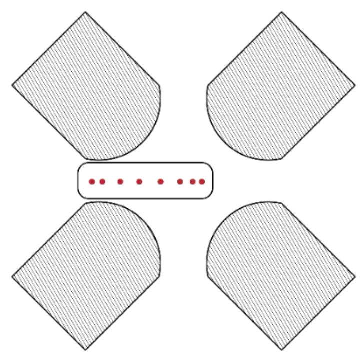
- … a concept in-between cyclotron and synchrotron; FFA = FFAG
- **strong focusing** (a. gradient) compared to cyclotrons (flutter & edge focusing)
- **constant magnet strength** over time, but frequency needs ramp
- types of FFA: **different scaling of field index *k*** with particular implications …
- **applications**: particle therapy, muon acceleration, high intensity

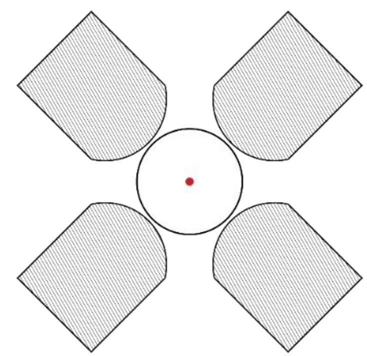
Cyclotron, FFA, Synchrotron – Qualitative Comparison

	AVF Cyclotron	FFA	Synchrotron
orbit variation?	large	small	none
main focusing mechanism?	edge focusing	alternate gradient	alternate gradient
magnets ramped?	no	no	yes
frequency ramped?	no	yes, no in some designs	no

section sketch







FFA developments over time

1956: Symon, Kerst et al (US), Ohkawa (JP), Kolomensky (SU)

1950-60: MURA Group (Mid-western Universities Research Association), electron models

from 2003: Y.Mori et al, Univ. Kyoto proton accelerators

recently: EMMA electron model non-scaling FFA in Daresbury

Fixed-Field Alternating-Gradient Particle Accelerators*

K. R. Symon,† D. W. Kerst,‡ L. W. Jones,§ L. J. Laslett,|| and K. M. Terwilliger§
Midwestern Universities Research Association
(Received June 6, 1956)

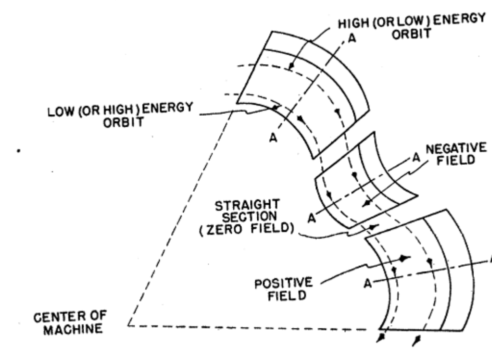
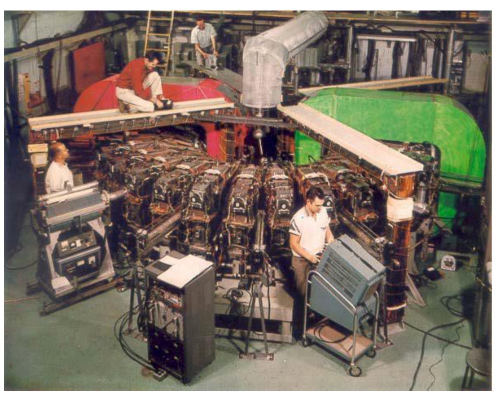
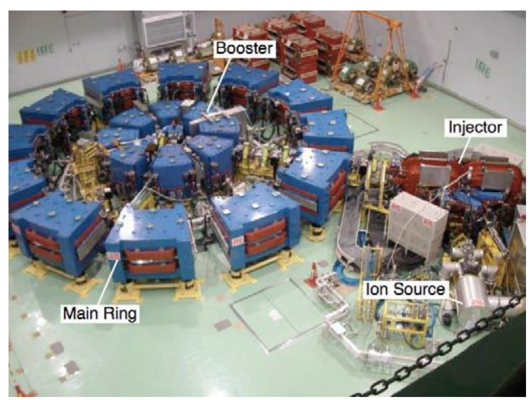


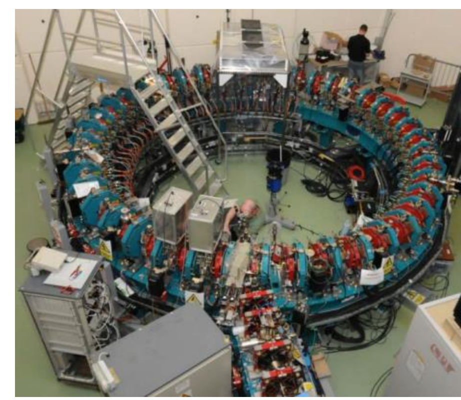
Fig. 2. Plan view of radial-sector magnets.



MURA 50 MeV electron model



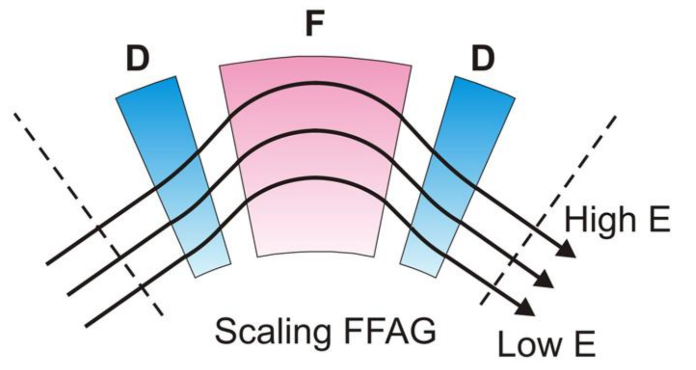
20 MeV booster & 150MeV main ring, Kyoto University



EMMA: 10-20 MeV electron linear non-scaling FFA

scaling FFA

idea: keep field index *k* constant
$\rightarrow$ no resonance crossing
$\rightarrow$ zero chromaticity, large acceptance
$\rightarrow$ self similar orbits
$\rightarrow$ but not isochronous, need f-sweep !



$$k = \frac{r}{B_z}\frac{dB_z}{dr} = \text{const}$$ field index

$$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k F(\theta)$$ sector type

$$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k F\left(\theta - \xi \ln\left(\frac{r}{r_0}\right)\right)$$ spiral type

non-scaling FFA

***k* ≠ const. , but fast resonance crossing**
→ simpler magnets, flexible optics
→ solutions with fixed RF frequency
→ linear scaling with *k*=1 is important
sub-class, but many proposals

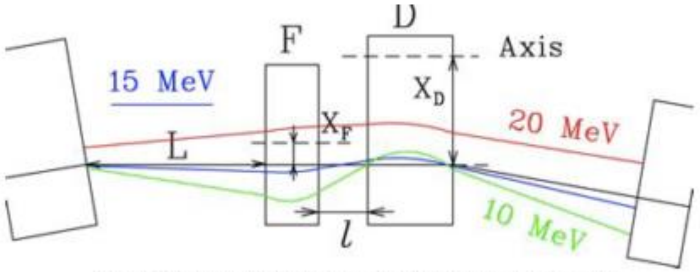
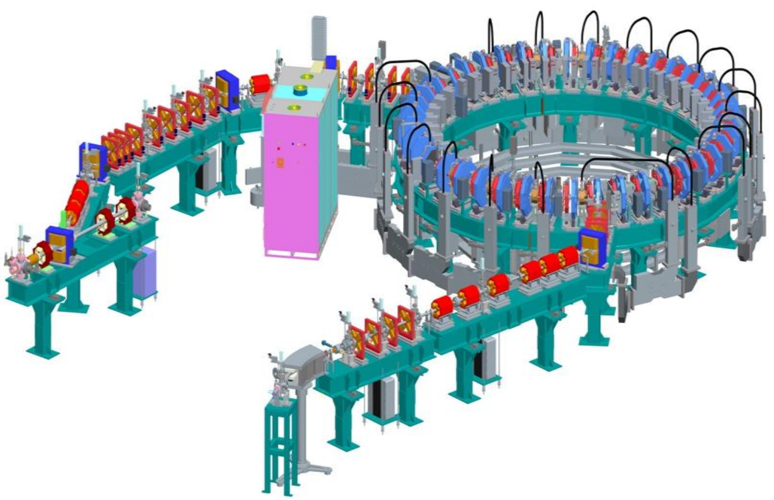


Figure 2: Orbits in a quadrupole doublet cell.

example: EMMA electron model

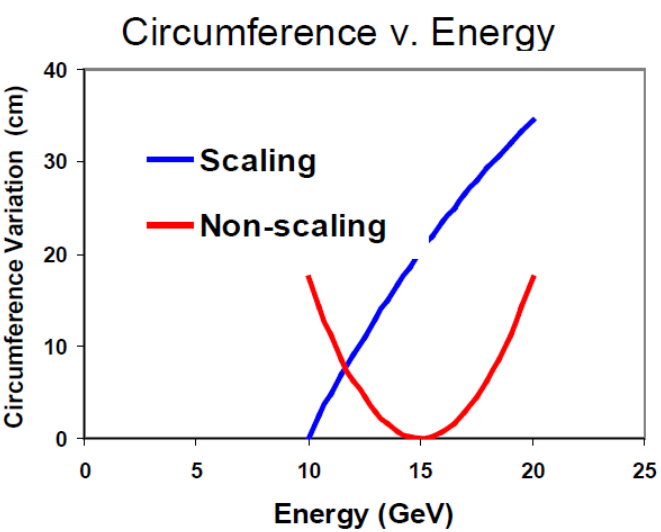


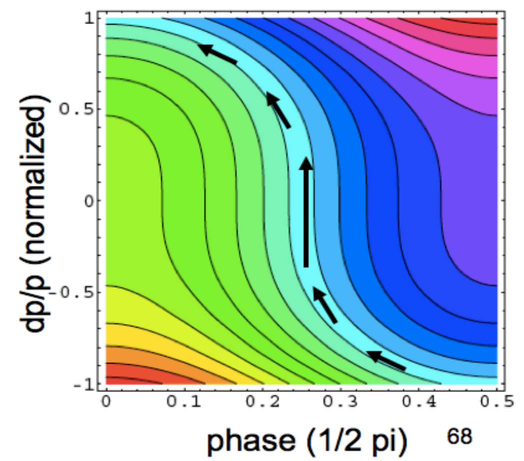
Energy	10-20 MeV
Circumference	16.57 m
Cells	42
F quad length	5.88 cm
D quad length	7.57 cm
RF frequency	1.3 GHz
Cavities	19 x 120 kV

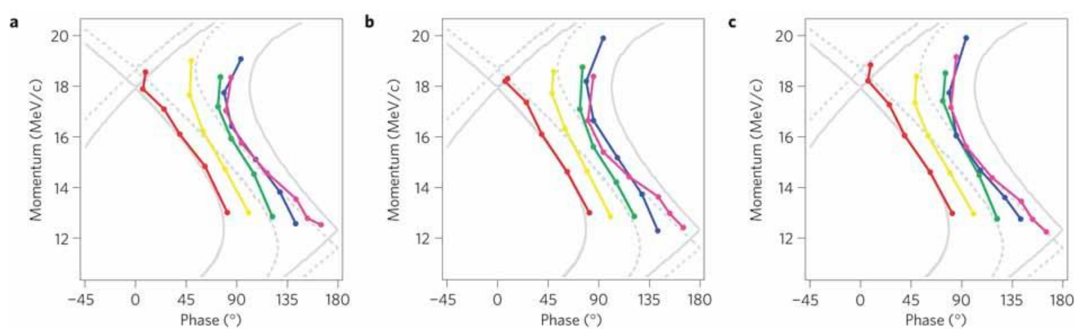
LNS FFA: serpentine acceleration

- acceleration can be done within a few turns (no long-term stability required)
  → **Fixed frequency!**
- along a serpentine path in long. phase space (ensure acceleration at all times)
- path length varies little, but limited overall energy gain compared to synchrotron, e.g. factor 4 maximum

$$C(p) = C(p_m) + \frac{12\pi^2}{e^2 S^2 N L_{\mathrm{fd}}} (p - p_m)^2$$





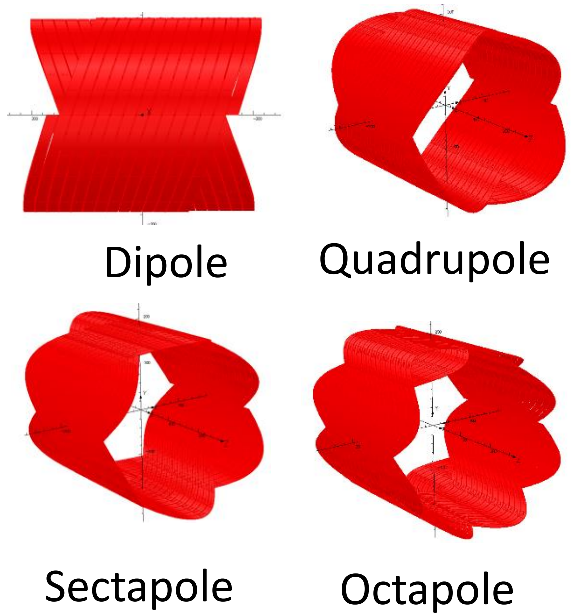


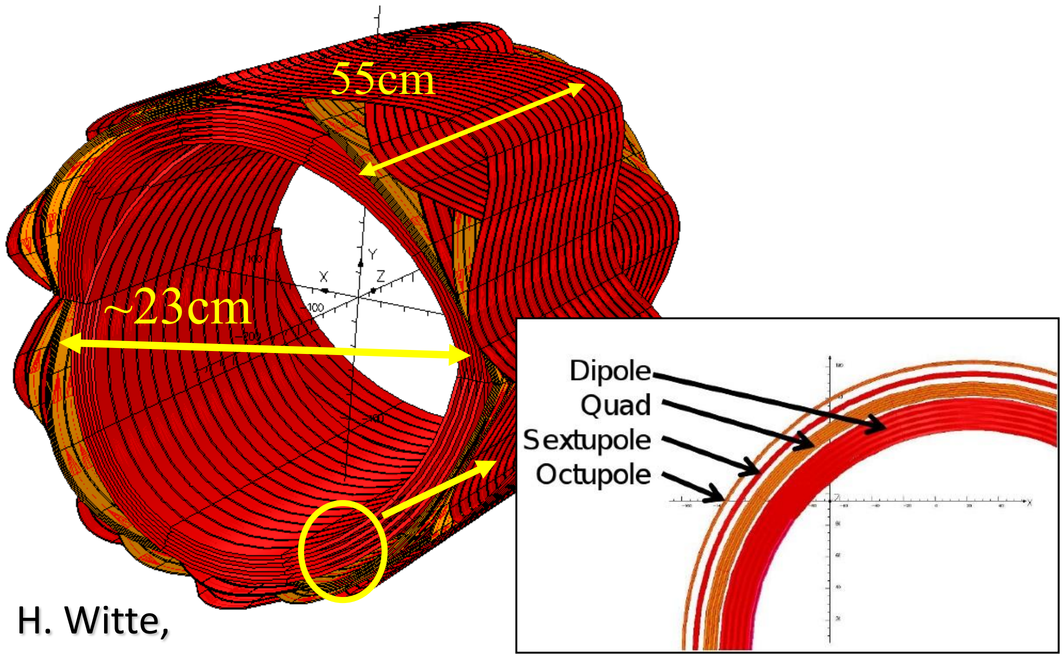
→ concept demonstrated in EMMA

scaling FFA magnet design

- helical coils, known as Canted Cosine Theta (CCT), can provide pure multipole fields
- in superposition truncated Taylor expansion of r^k scaling $\rightarrow$ compact FFA magnet

$$B_0 \left(\frac{r}{r_0}\right)^k = B_0 \left(1 + \frac{k}{r_0}x + \frac{k(k-1)}{2r_0^2}x^2 + \ldots\right)$$





By H. Witte,

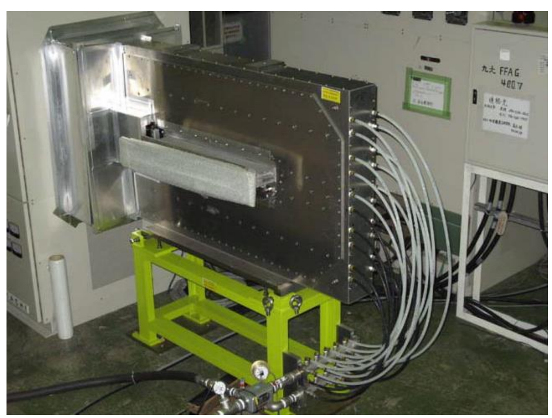
courtesy T.Yokoi, FFAG´09

Variable Frequency RF for scaling FFA

example RF system:

Kyoto University FFA, 150MeV
- high-permeability soft magnetic alloy (MA) core
- low Q = 0.47 @ 2.7 MHz
- high power broadband amplifier

Number of Cavities	2
Gap Voltage	4.0 kV/cavity
RF frequency	1.5 – 4.2 MHz
RF output power	200 kW
Core material	FINEMET (FT-3M)
repetition rate	100 Hz
kinetic energy (p)	10 – 125 MeV
radius variation	4.47 - 5.20 m



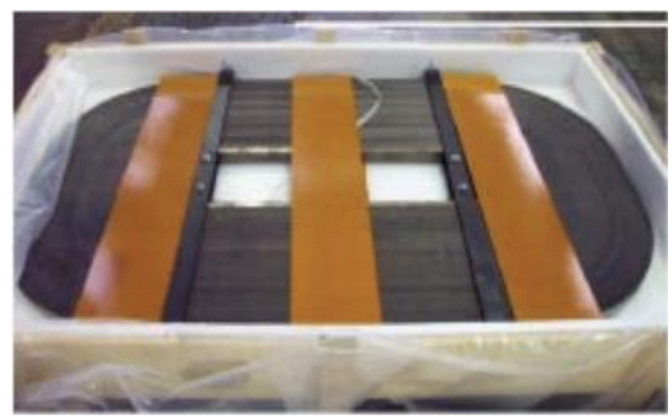


Image credit: A.Takagi, Y.Mori

finally: **discussion**

- **comparison of circular accelerators**
- **suitability of cyclotrons and FFA for applications**
- **some literature**

classification of circular accelerators

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

pro and contra cyclotron / FFA

limitations of cyclotrons	typical utilization of cyclotrons
• energy ≤1GeV (relat. effects) • weak focusing: space charge, 10mA? • tuning difficult; field shape; many turns; limited diagnostics • wide vacuum vessel (radius variation)	• medical applications; plenty intensity • isotope production: several 10MeV • acceleration of heavy ions (e.g. RIKEN) • very high intensity proton beams (PSI:1.4MW, TRIUMF: 100kW)

Fixed Focus Alternating Gradient Accelerator (FFA)

- strong focusing, compact magnets & chamber
- large acceptance, e.g. 10.000 mm mrad

but:

- CW operation difficult (serpentine, HNJ …)
- low loss extraction difficult (high rep., fast kicker ?)
- no demonstrator for high intensity after many years of discussion …

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; 2019 edition this month in Cape Town; 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 & FFA

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**
50 Years of Cyclotron Development	L. Calabretta, M. Seidel IEEE Transactions on Nuclear Science, Vol. 63, No. 2, 965 – 991(2016) http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7410111
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
ICFA BDN Nr 43	series of high level FFA articles (2007) https://www-bd.fnal.gov/icfabd/Newsletter43.pdf
FFA Optics	M. Craddock, FFA Optics (2011) https://www.cockcroft.ac.uk/events/ffag11/FFAG_talks/11/5.Craddock.pdf
comparison of cyclotron and FFA	M. Craddock, Was the Thomas cyclotron of 1938 a proto-FFAG? https://www.cockcroft.ac.uk/events/FFAG08/presentations/Craddock/Thomas-FFAG.pdf


Thank you for your attention !