Cyclotrons for Research and Medical Application

Accelerator Seminar, DESY, August 22, 2014

Mike Seidel

Paul Scherrer Institut

Cyclotrons - Outline

- cyclotron concepts

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

- medical cyclotrons

  requirements for medical applications, cyclotron vs. synchrotron, present research: moving organs, contour scanning, cost/size optimization; examples

- cyclotrons for research

  high intensity, varying ions, injection/extraction challenge, existing large cyclotrons, new developments

- summary

  development routes, Pro's and Con's of cyclotrons

The Classical Cyclotron

two capacitive electrodes „Dees“, two gaps per turn

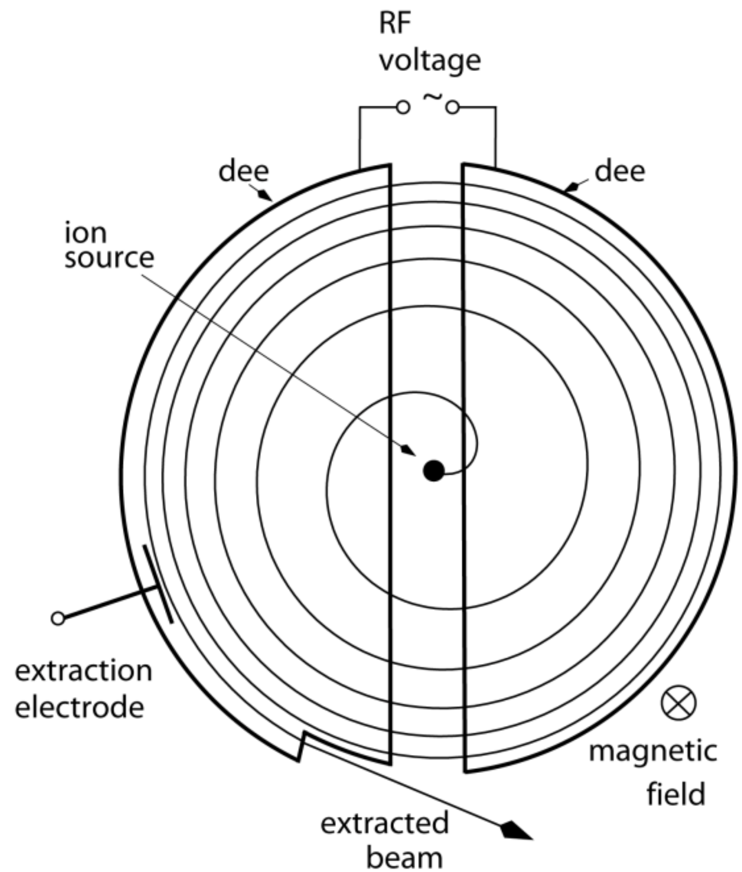
internal ion source

homogenous B field

constant revolution time

(for low energy, $\gamma\approx1$)

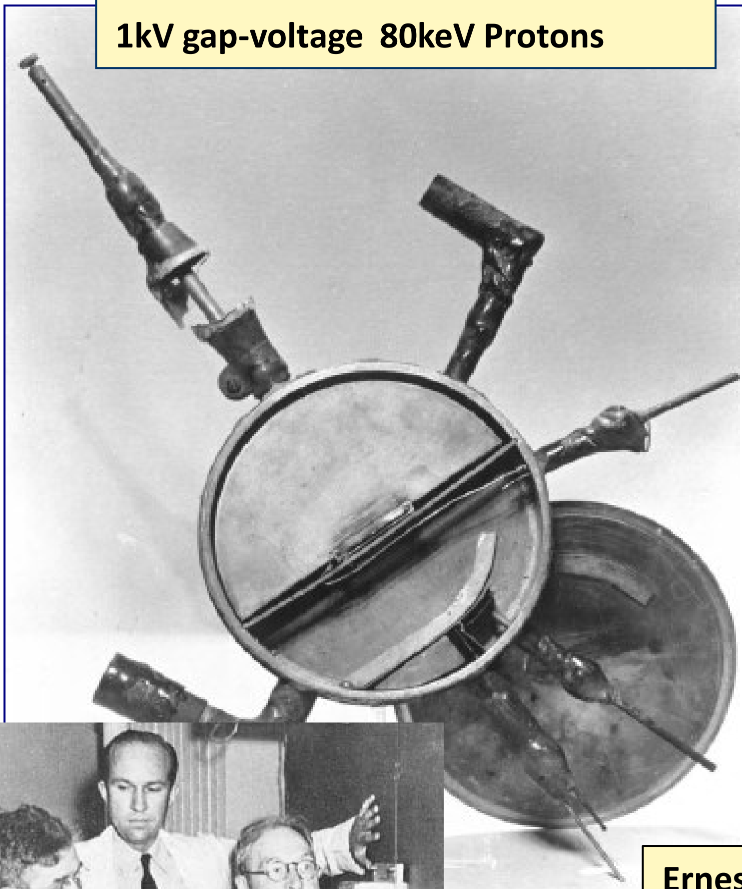
$$\omega_c = \frac{eB_z}{\gamma m}$$



powerful concept:

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

some History …



first cyclotron: 1931, Berkeley

1kV gap-voltage 80keV Protons

Lawrence & Livingston, 27inch Zyklotron

Ernest Lawrence, Nobel Prize 1939
"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"

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

classical cyclotron - isochronicity and scalings

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

magnetic rigidity:

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

orbit radius from isochronicity:

$$R = \frac{c}{\omega_c}\beta = R_\infty \beta$$

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*)

the field index describes the (normalized) radial slope of the bending field, is negative if isochronous!

$$n = -\frac{R}{B}\frac{dB}{dR} = -\frac{\beta}{\gamma}\frac{d\gamma}{d\beta} = 1 - \gamma^2 < 0$$

contradicting findings!

from equation of motion, betatron tunes in cyclotron:

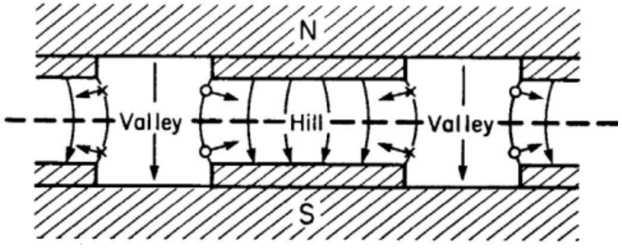
$$\nu_r = \sqrt{1-n} \approx \gamma; \quad \nu_z = \sqrt{n}$$

sector cyclotrons – solution to the focusing problem

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

Flutter factor:

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

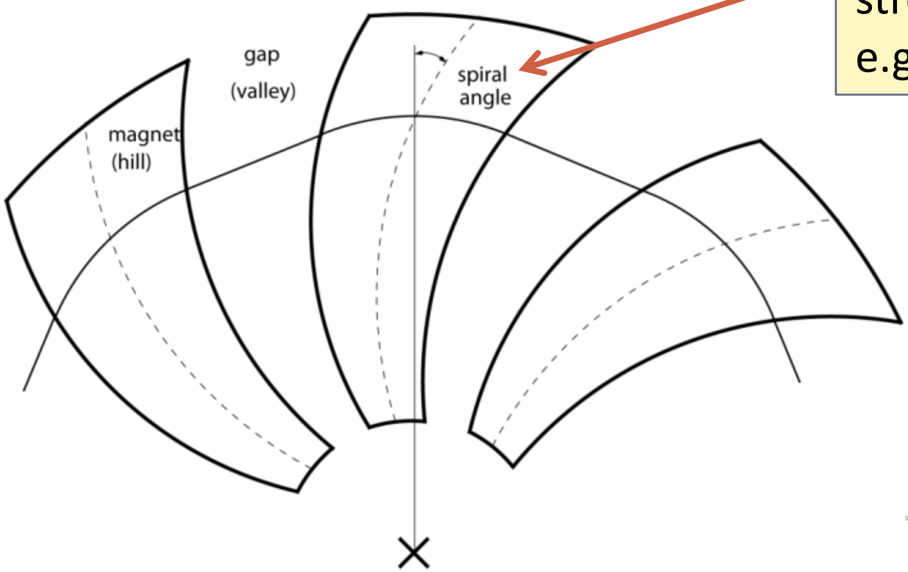


[illustration of focusing at edges]

with flutter and additional spiral angle of bending field:

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

strong term
e.g.: δ=27°: $2\tan^2\delta = 1.0$



in a cyclotron two conditions must be met

1.) resonant acceleration

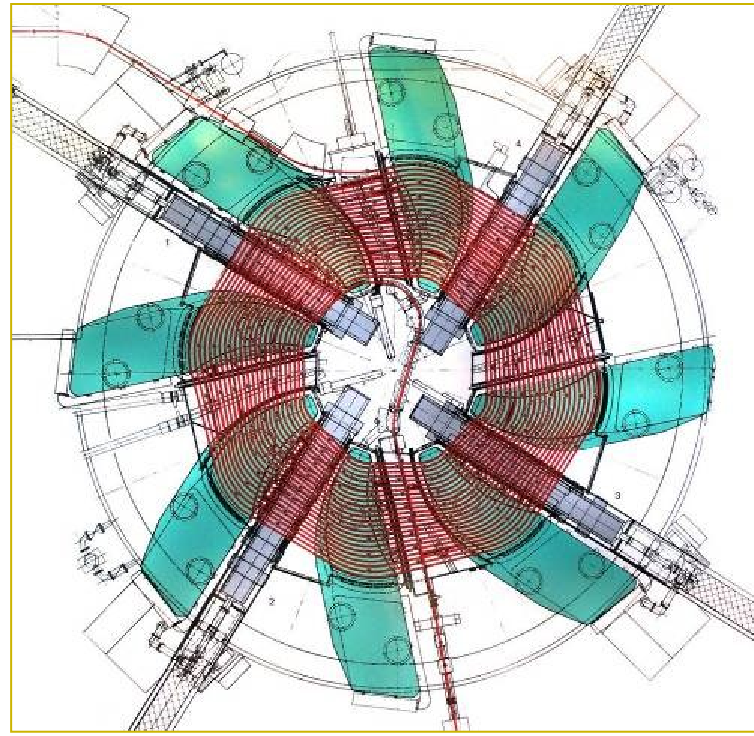
- limit energy / ignore problem
  [classical cyclotron]
- frequency is varied, slope neg
  [synchro- cyclotron]
- avg. field slope positive
  [isochronous cyclotron]

2.) vertical focusing

- negative field slope
  [classical/synchro cyclotron]
- focusing by flutter, spiral angle
  [AVF/sector cyclotron]

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: $99.98\% = (1 - 2\cdot10^{-4})$

energy reach - *K* value

- **cyclotron *K*-value**:

→ *K* is the **kinetic energy reach** for protons **from bending strength** in non-relativistic approximation:

$$K = \frac{e^2}{2m_0}(B\rho)^2$$

→ *K* can be used to rescale the energy reach of protons to other charge-to-mass ratios:

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

→ *K* in [MeV] is often used for naming cyclotrons

examples: K-130 cyclotron / Jyväskylä (Finland)

cyclone C230 / IBA (Belgium)

cyclotron radius increment

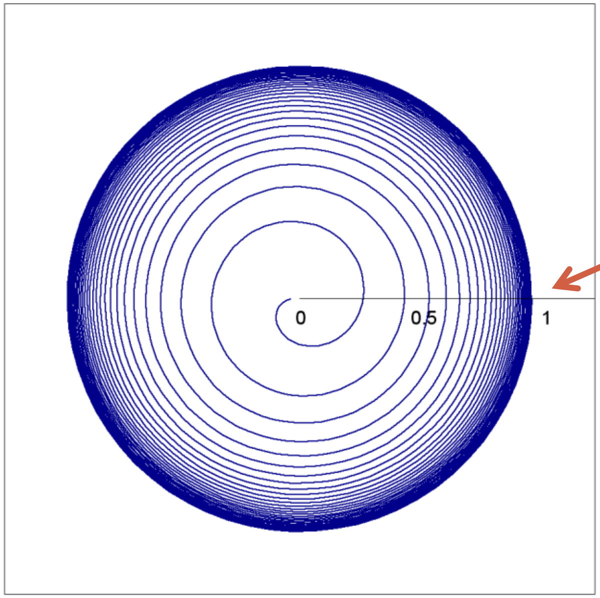
nonrelativistic: $$\Delta R = \frac{\Delta E_k}{E_k}\frac{R}{2} \propto \frac{1}{R}$$

relativistic: $$\Delta R = \frac{\Delta E_k}{E_k}\frac{R}{\gamma^2 - 1} \propto \frac{1}{R\gamma^3}$$

cyclotron language
(theoretical number)

$$R = R_\infty \cdot \beta$$

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



cyclotrons work at intermediate relativistic energies

A.Einstein
1879-1955

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

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

energy

$$E = \gamma E_0$$

kinetic energy:

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

velocity

$$v = \beta c$$

momentum

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

revolution time:

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

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

bending strength:

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

PSI cyclotron for protons

E_k [MeV]	γ	β	p [MeV/c]
590	1.63	0.79	1207

classification of cyclotron like accelerators

classical cyclotron
[B(θ) = const]

Thomas cyclotron
[Azimuthally Varying Field,
e.g. $B(\theta) \propto b+\cos(3\theta)$, one pol]

complexity

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

separated sector cyclotron
[separated magnets, resonators]

synchro-cyclotron
[varying RF frequency]

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

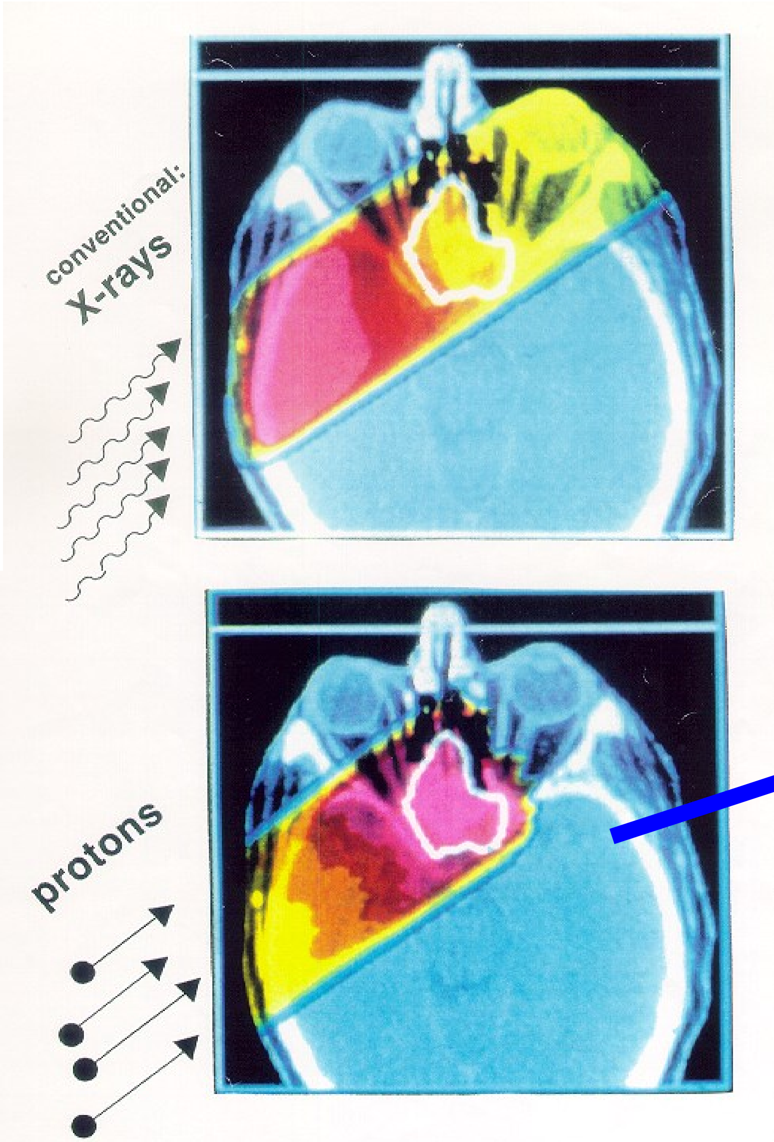
high intensity

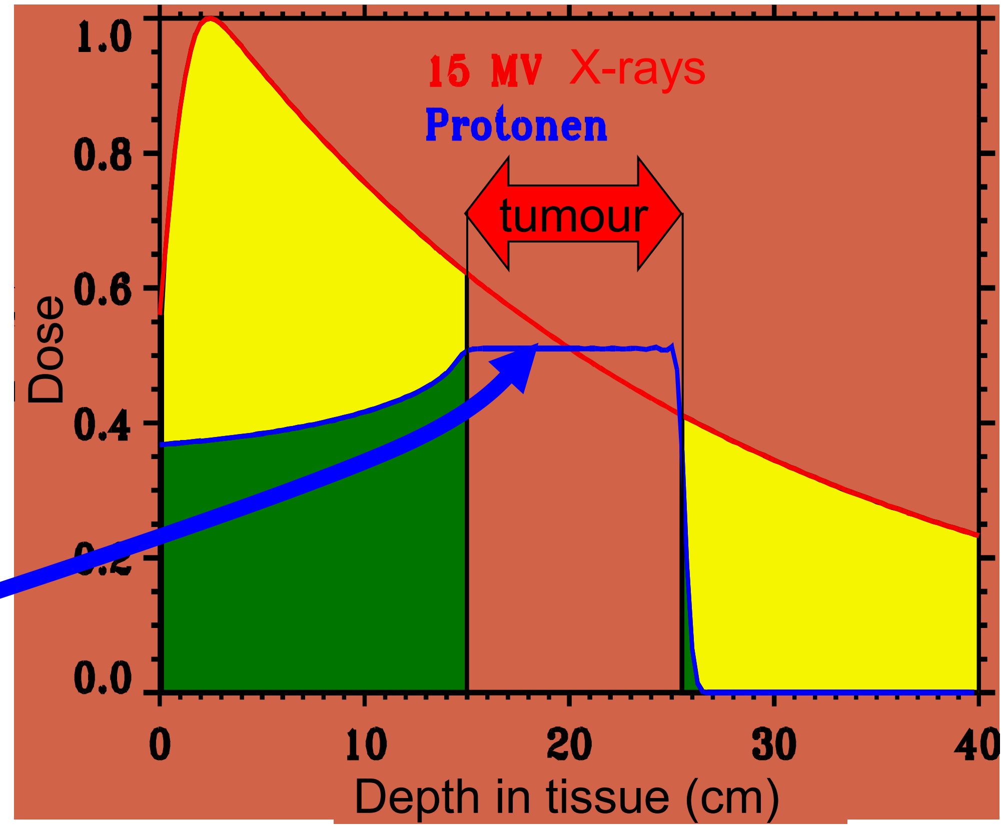
high energy

compact machine

- next: **medical cyclotrons**
  - **particle therapy; scanning technology**
  - **new developments**
  - **isotope production**

cancer treatment: X-rays vs. Protons



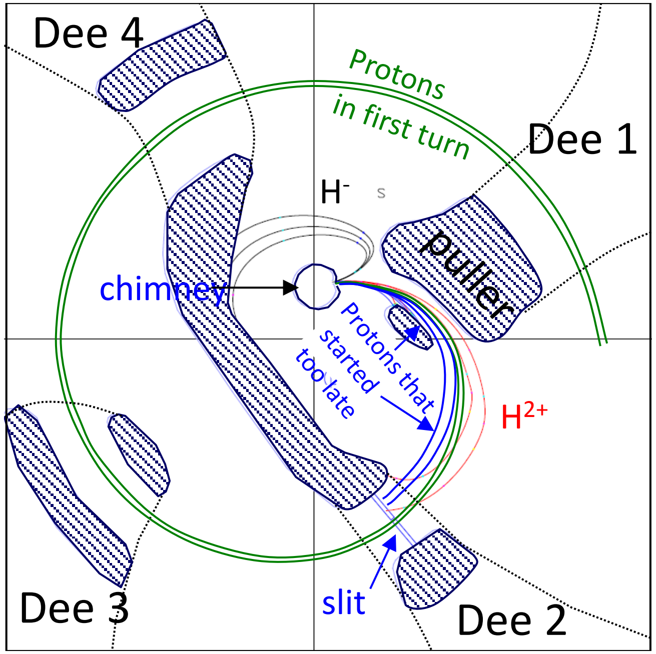


[M.Schippers]

Why Cyclotrons for Cancer Treatment?

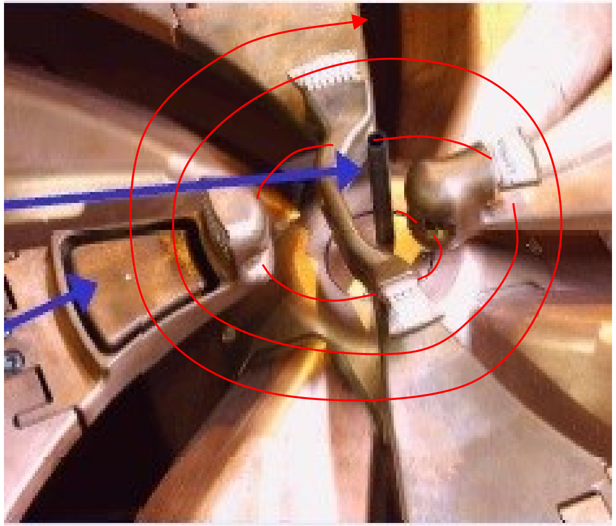
in favour of cyclotrons:

- 250MeV: suited energy for cyclotrons
- cost effective and compact; single s.c. magnet possible
- continuous beam; lots of intensity reserve, **e.g. repainting, moving organs**
- precise and fast intensity modulation at low energy possible



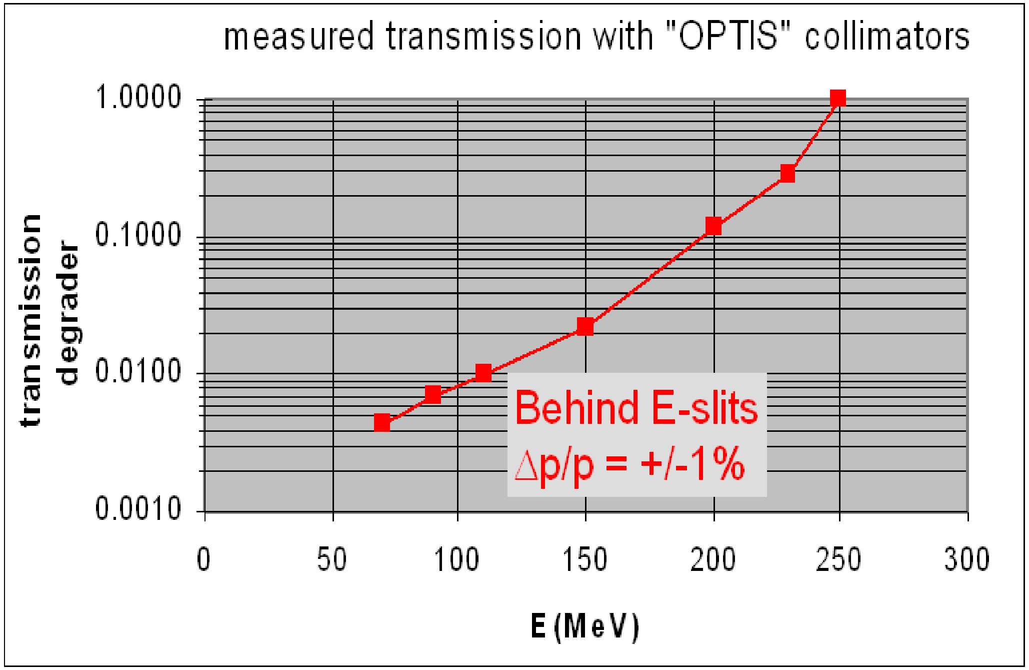
chimney = ion source

deflector electrode for intensity regulation

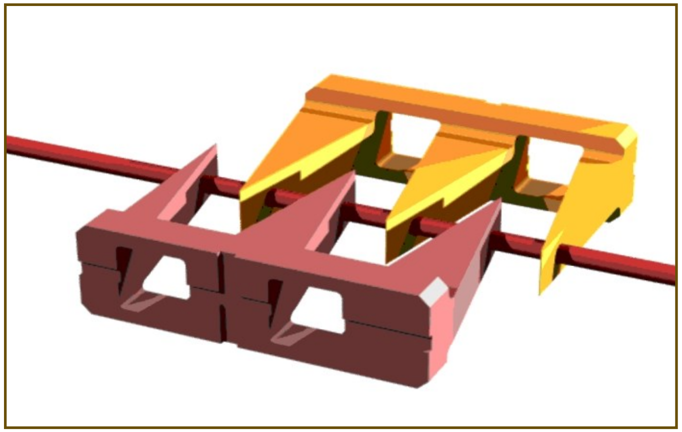


However, Cyclotron needs degrader :

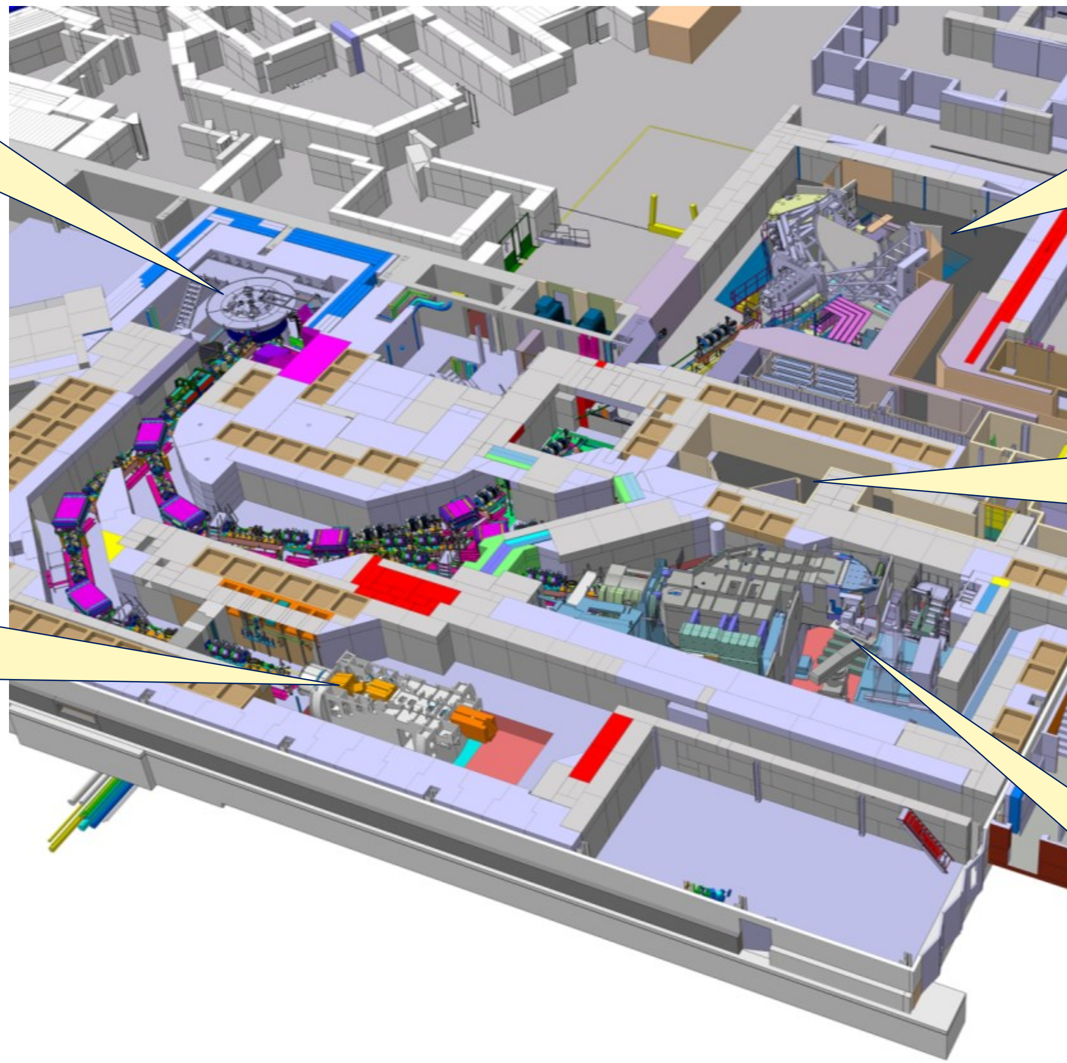
- cyclotron has fixed energy; need **degrader** for energies down to 70MeV
- collimation after degrader to keep emittance $\rightarrow$ lose intensity with degrader



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



PSI's Proscan Facility



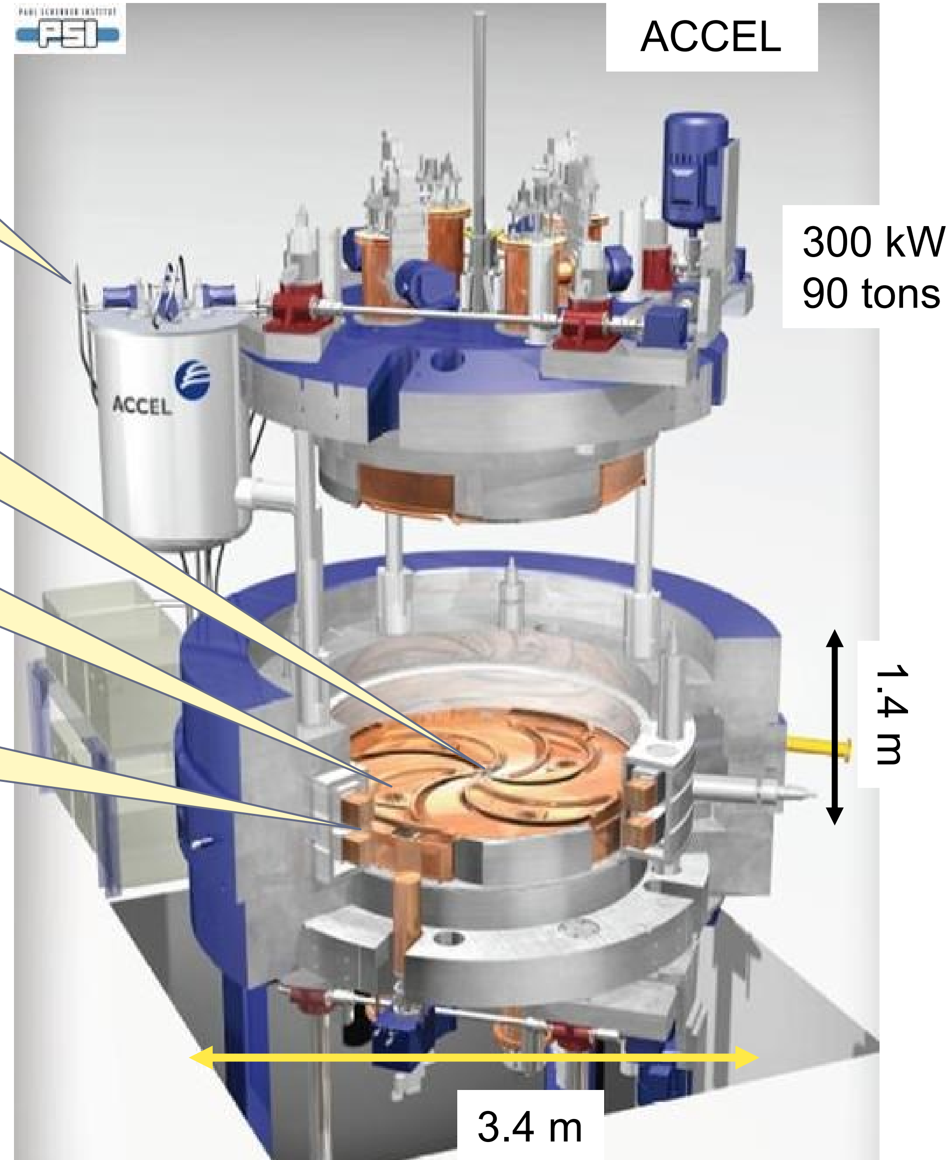
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

Proton source

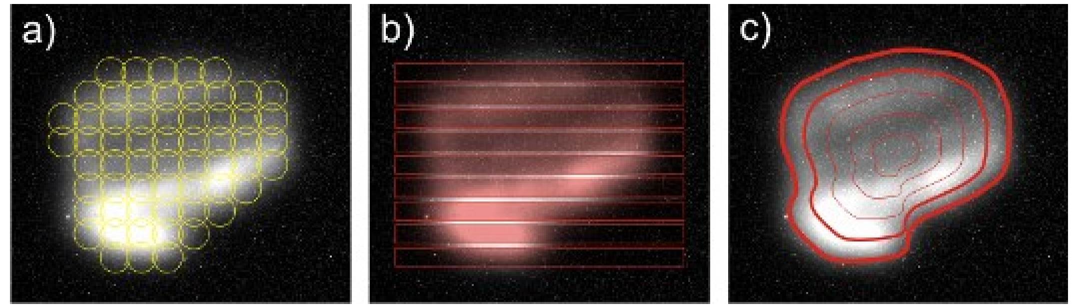
4 RF-cavities
≈100 kV on 4 Dees

superconducting coils
=> 2.4 - 3.8 T

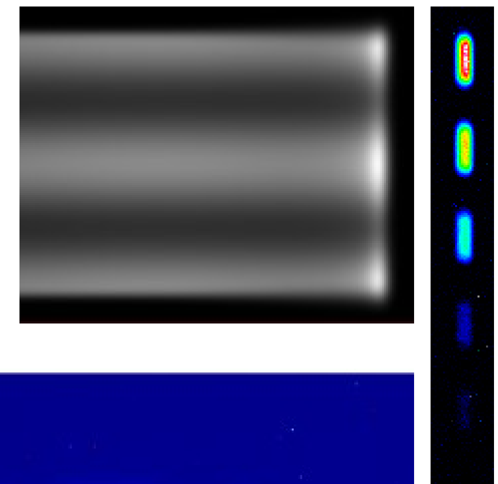


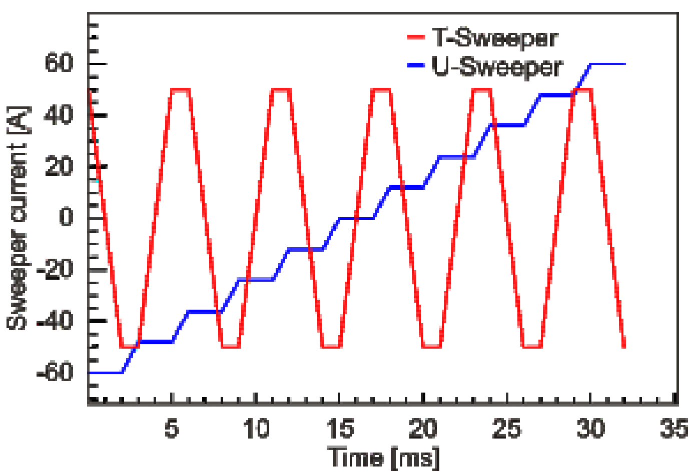
PSI developments: different scanning options [D.Meer]

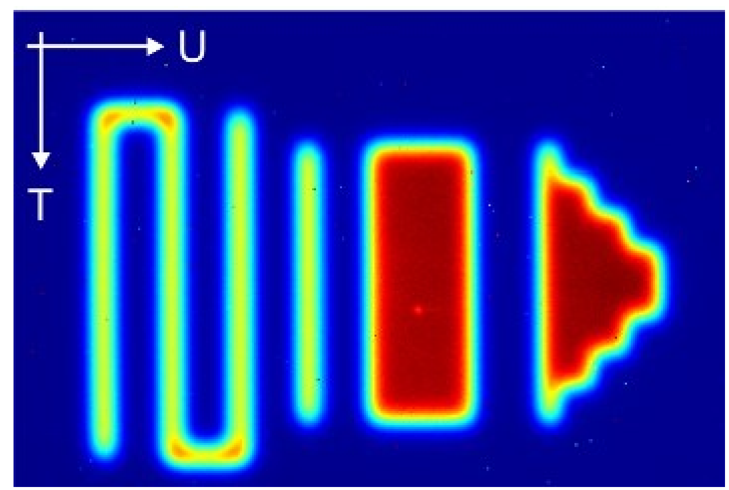
a) Spot scanning as the default mode
b) Lines scanning for max. repainting
c) Contours scanning for optimizing repainting and lateral fall-off (?)



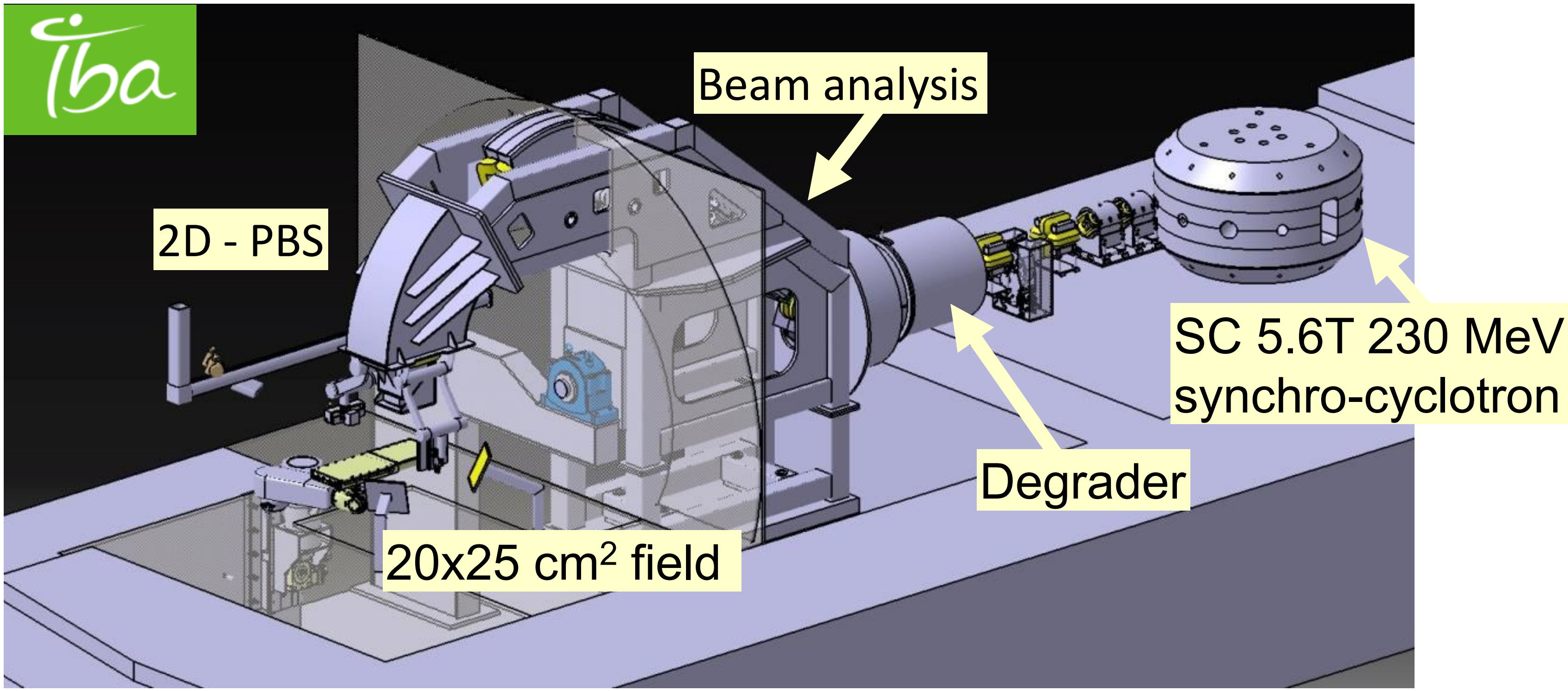
- **Vertical deflector plate for intensity modulation**
  - Fast intensity control on time scale of 100 ms
- **Requires flexible control system**
  - control of fast actuators (sweepers, deflector plate) with 100 kHz
  - tabulated dose delivery based on state-of-the-art electronics (FPGA)
  - example: Painting shaped energy iso-layer







new development by IBA:
compact treatment facility using the high field synchro-cyclotron

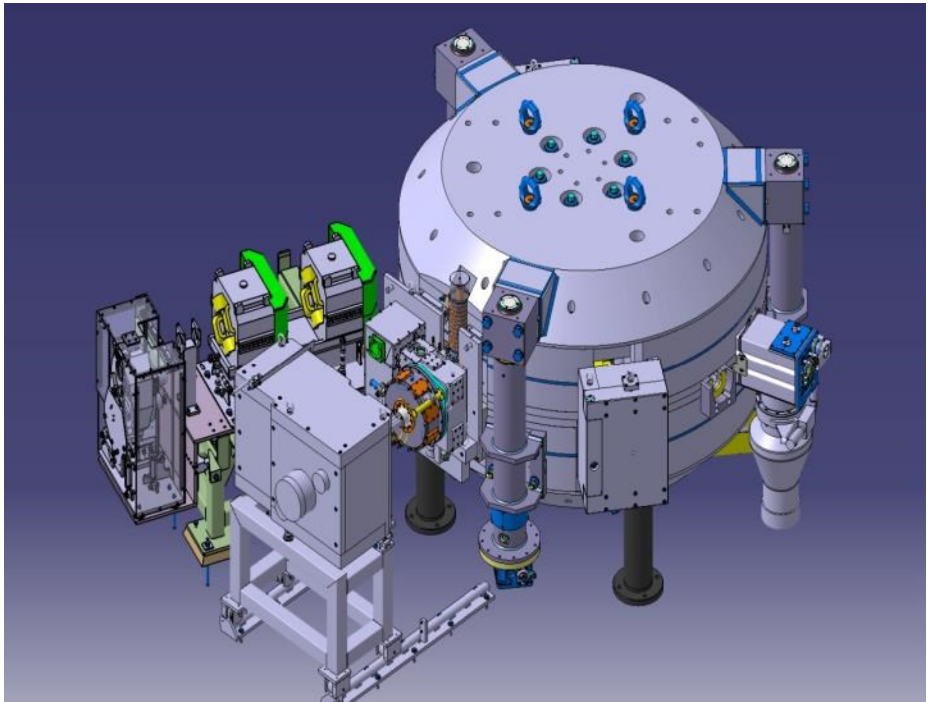


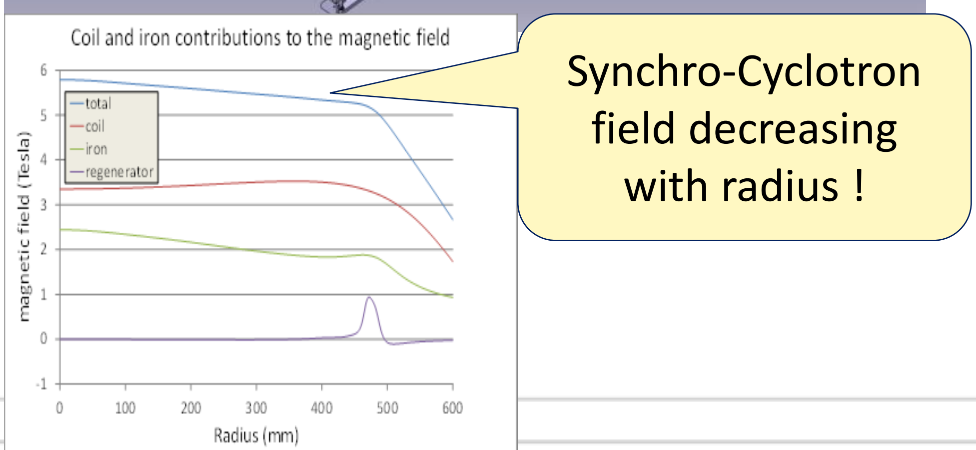
- required area: 24x13.5m^2 (is small)
- 2-dim pencil beam scanning

W.Kleeven, IBA

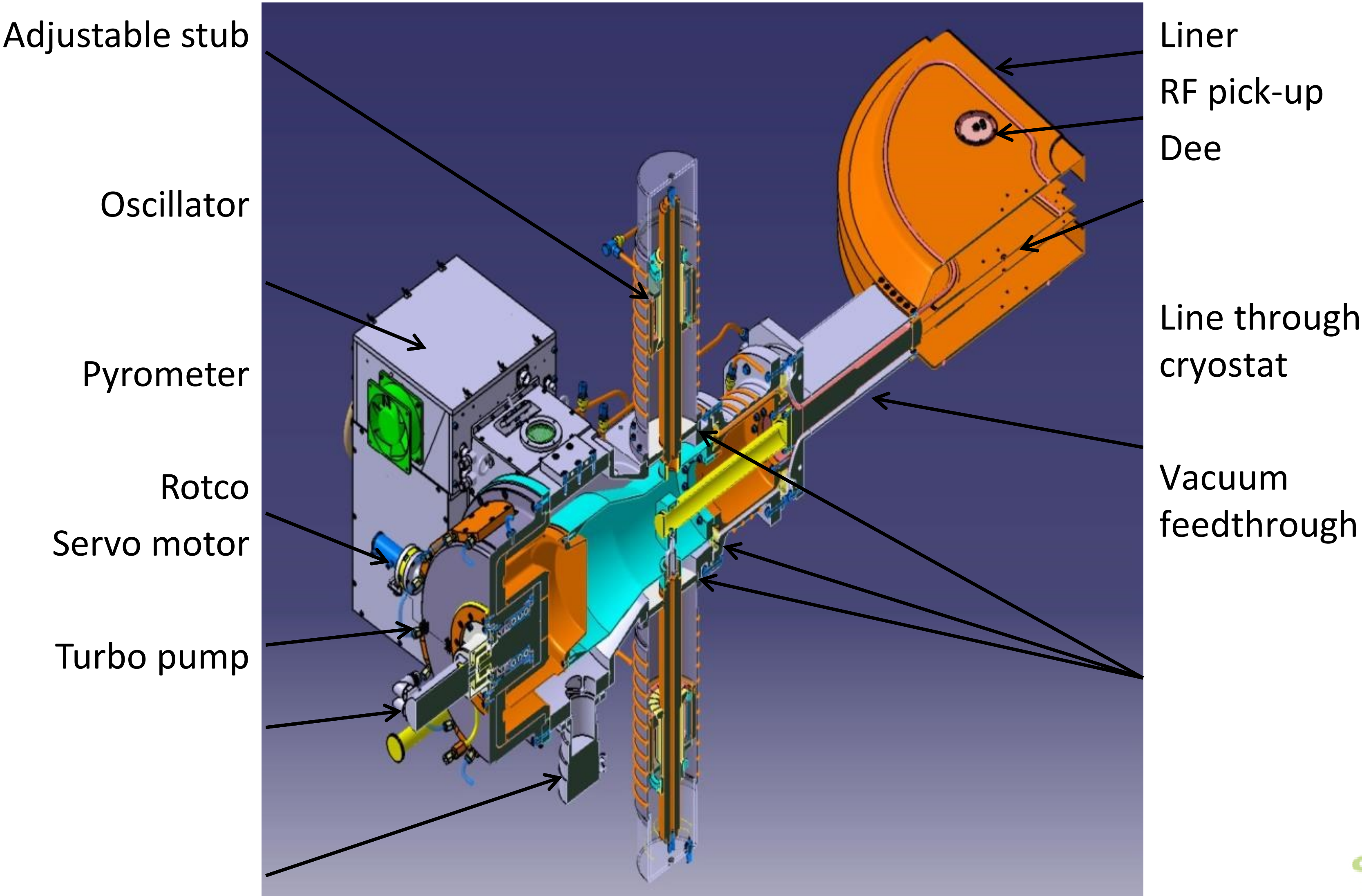
S2C2 overview

General system layout and parameters





Maximum Energy	230/250 MeV
Size	
yoke/pole radius	1.25 m/0.50 m
weight	50 tons
Coil	NbTi - wire in channel
ramp up rate / time	2-3A/min / 4 hours
windings/coil	3145
stored energy	12 MJ
Magnetic field	
central/extraction	5.7 T/5.0 T
Cryo cooling	conductive
	4 cryocoolers 1.5 W
initial cooldown	12 days
recovery after quench	less than 1 day
Beam pulse	
rate/length	1000 Hz/7 μsec
RF system	self-oscillating
frequency	93-63 MHz
voltage	10 kV
Extraction	Passive regenerative
Ion source	PIG cold cathode
Central region	removable module

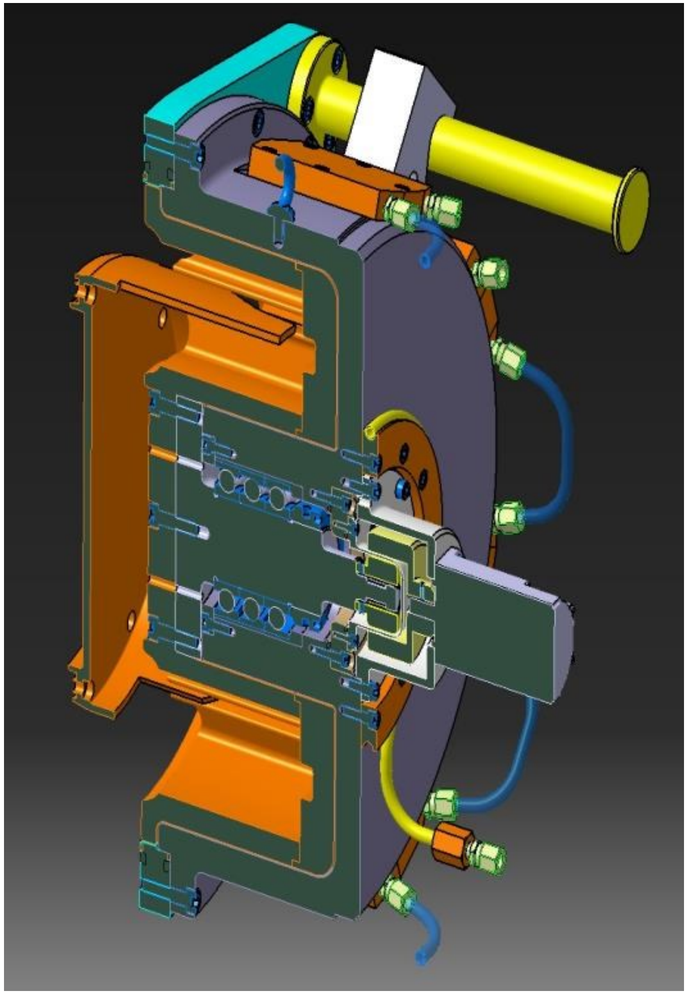


Adjustable stub
Oscillator
Pyrometer
Rotco
Servo motor
Turbo pump
Liner
RF pick-up
Dee
Line through cryostat
Vacuum feedthrough

RF-system

W.Kleeven, IBA

Rotco=> Coaxially mounted with 8-fold symmetry

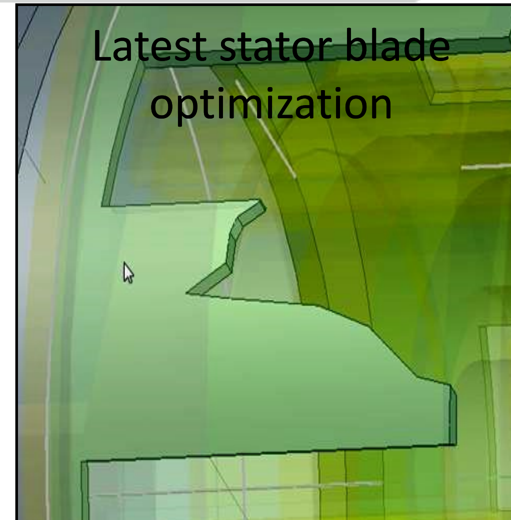


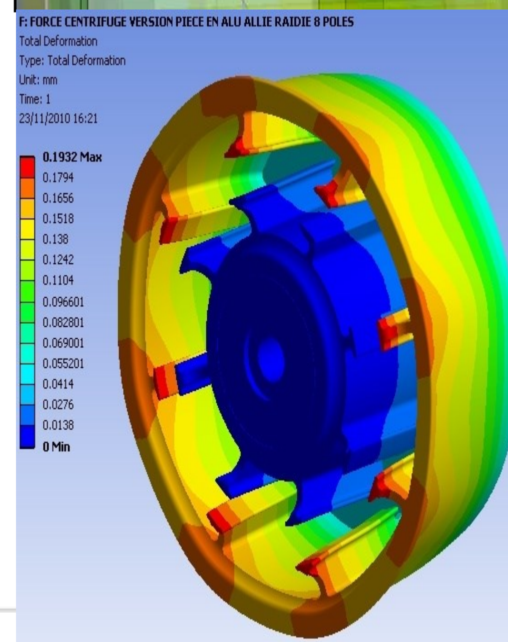
Innovative/patented design:

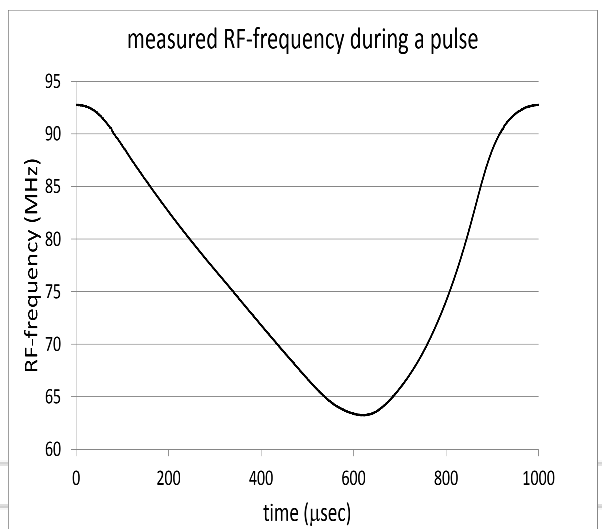
excellent mechanical stability and good pulse reproducibility

Stator: 8 blades with a carefully designed profile to have the desired df/dt curve.

Rotor: wheel with 2x8 electrodes turning at 7500rpm (1 kHz pulse)







Carbon Ions vs. Protons

Pro Carbon:

- higher dE/dx produces more *correlated damage in DNA* of cancer cells; hence more effective; potentially less fractions
- smaller rms scattering angles within body tissue allows better focusing of beam in target volume

Contra Carbon:

- significantly higher bending strength required → accelerator, beam transport and Gantry are more expensive
- tail of dose can reach to higher depth since C-nucleus could be split, which is not the case for p

Heidelberg Gantry for Carbon, 670 tons

250 MeV Protons:

$$(B\rho)_p = 2.43\mathrm{Tm}$$

p vs. C for same depth

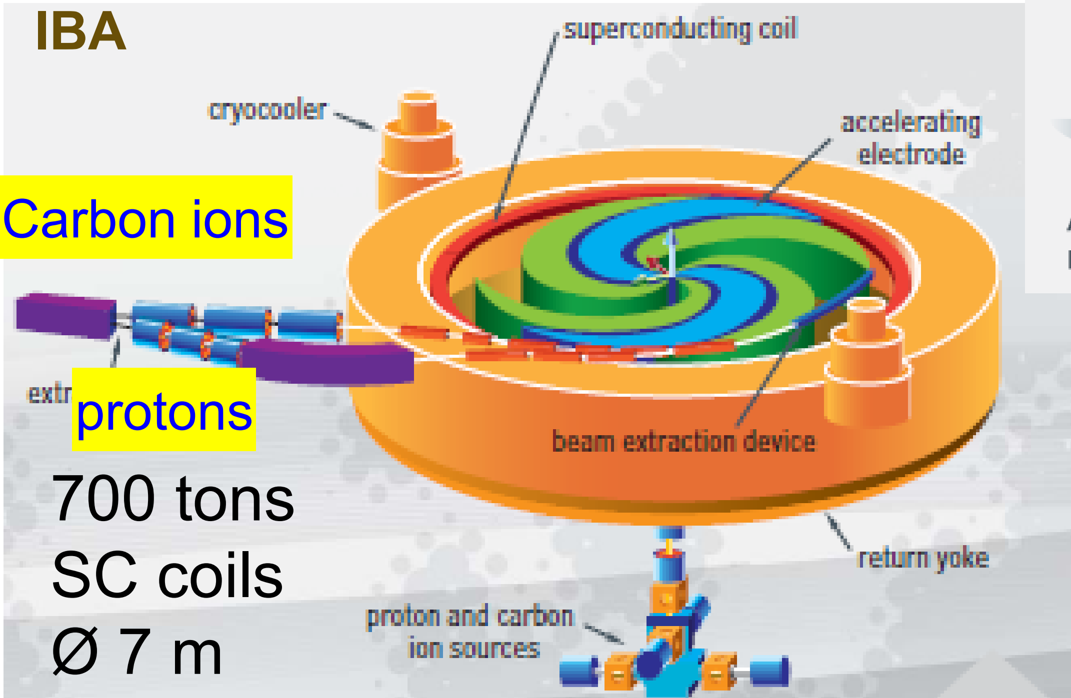
450 MeV/nucleon Carbon:

$$(B\rho)_C = 6.83\mathrm{Tm}$$

Cyclotron for carbon ions

Archade project, Caen (Fr)

IBA

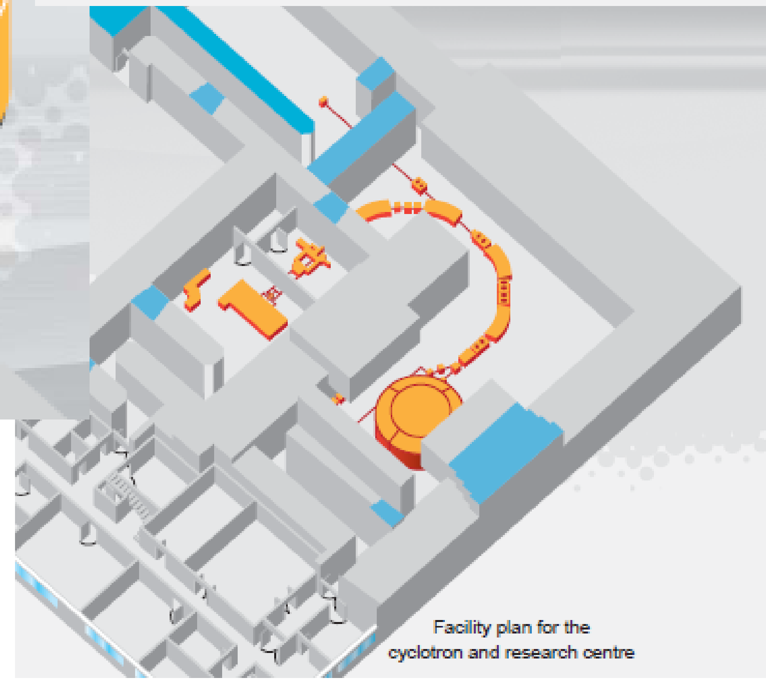


Carbon ions

protons

700 tons
SC coils
Ø 7 m

Archade
ADVANCED RESOURCE CENTRE FOR HADRONTHERAPY IN EUROPE



Facility plan for the cyclotron and research centre

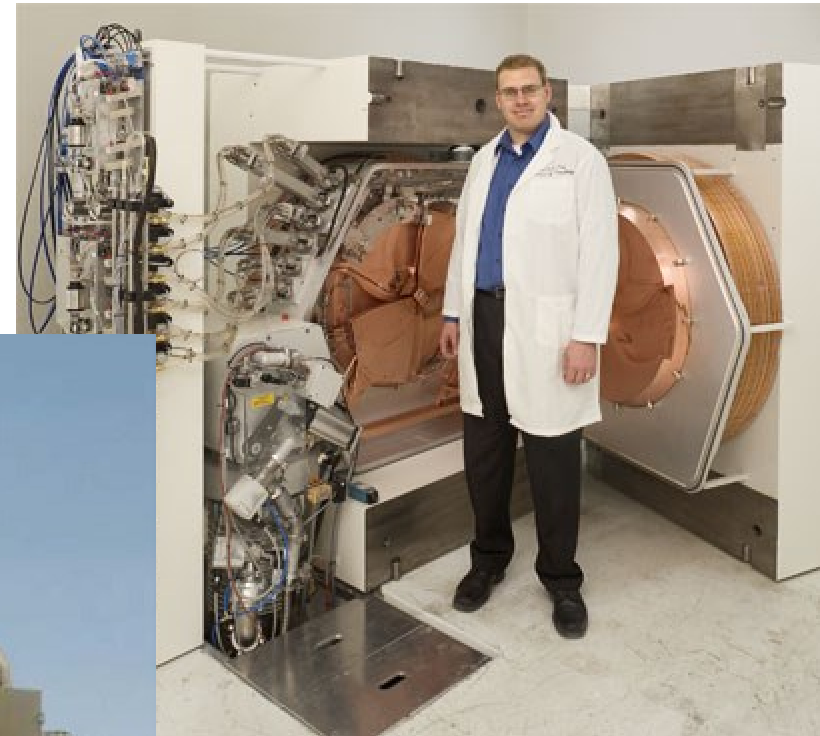
Int. Conf. Cyclotron and appl, Tokyo 2004

IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY

Y. Jongen, M. Abs, W. Beeckman, A. Blondin, W. Kleeven, D. Vandeplassche, S. Zaremba, IBA, Belgium
V. Aleksandrov, A. Glazov, S. Gurskiy, G. Karamysheva, N. Kazarinov, S. Kostromin, N. Morozov, E. Samsonov, V. Shevtsov, G. Shirkov, E. Syresin, A. Tuzikov, JINR, Russia.

compact cyclotrons for Isotope production

CYCLONE 30 (IBA) : H^- 15 à 30 MeV



vertical setup (!)

next:

High Intensity Cyclotrons

- PSI facility; technological aspects; beam loss
- application for ADS systems
- ions and RIB's

figure: person inside resonator

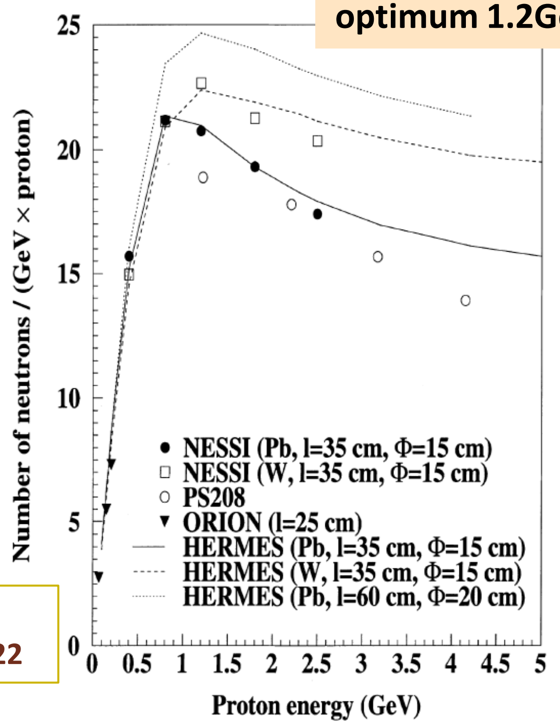
High Intensity Beams – Applications

- neutron production for neutron sources and ADS; e.g. 800MeV
- muon production in targets via Pi-production
  (PSI, ISIS, TRIUMF, BNL?)
- neutrino production: Daedalus study

$\rightarrow$ losses: $\approx$ 100Watt acceptable

$\rightarrow$ ADS: $10^{-2}...10^{-1}$ trips per day(!)

n vs p-energy: optimum 1.2GeV



A. Letourneau et al. / Nucl. Instr. and Meth. in Phys. Res. B 170 (2000) 299±322

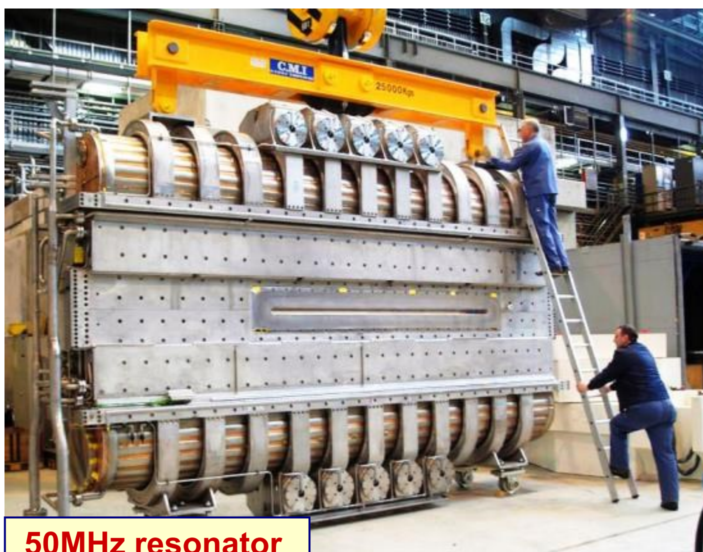
Example: PSI Facility

Beam: 1.3MW, Grid: 10MW

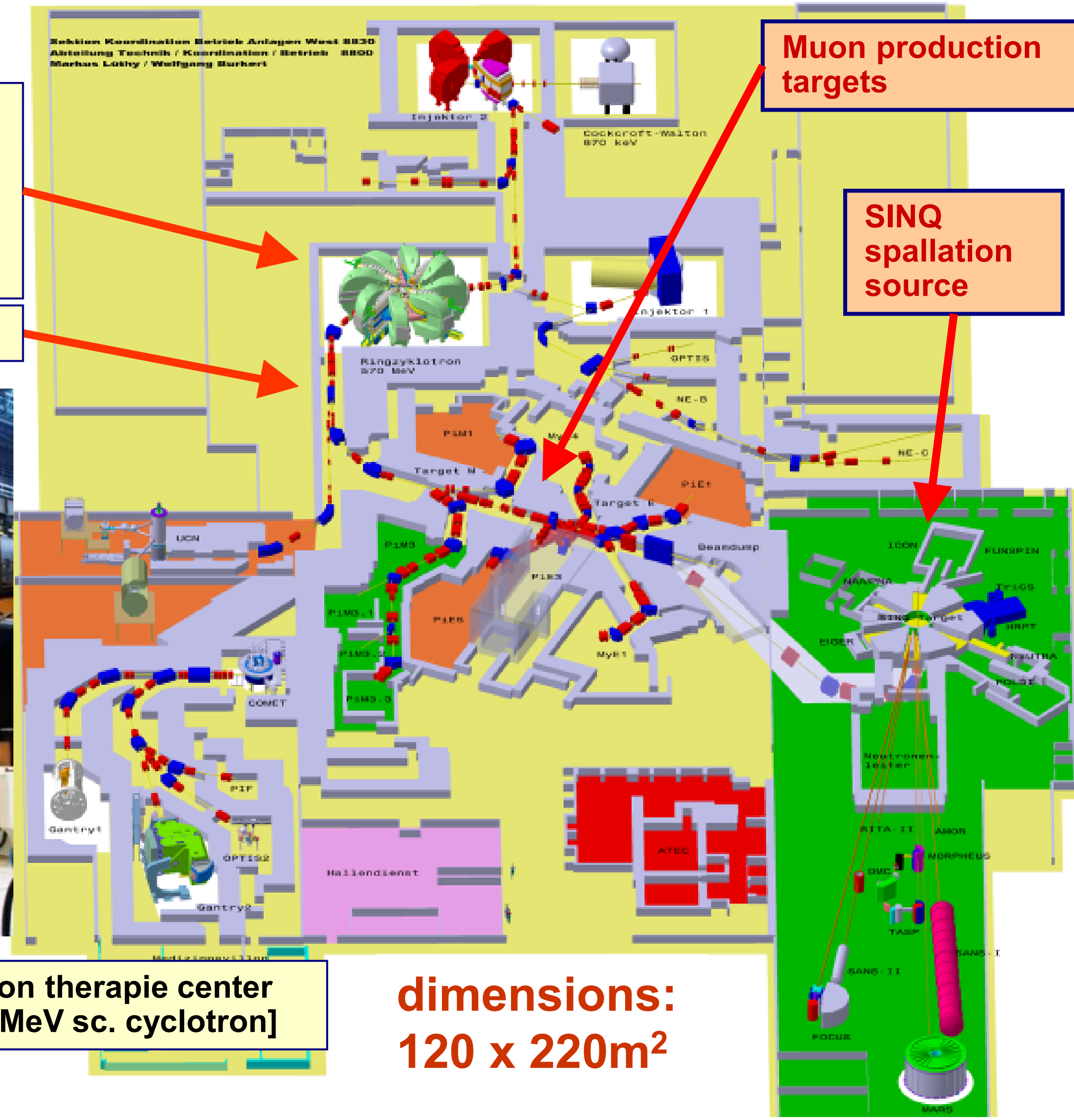
Ring Cyclotron 590 MeV
loss ≈ 10^{-4}

Power transfer through
4 amplifier chains
4 resonators 50MHz

2.2 mA /1.3 MW



50MHz resonator



Muon production targets

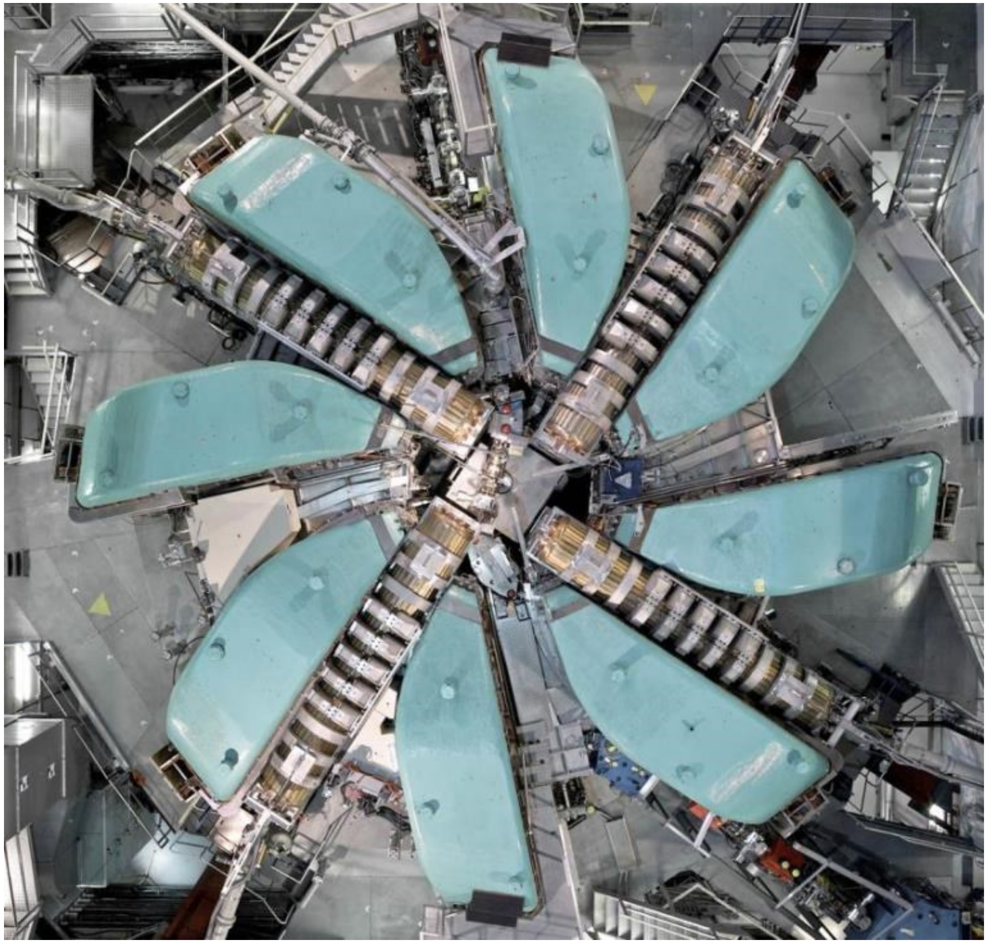
SINQ spallation source

proton therapie center
[250MeV sc. cyclotron]

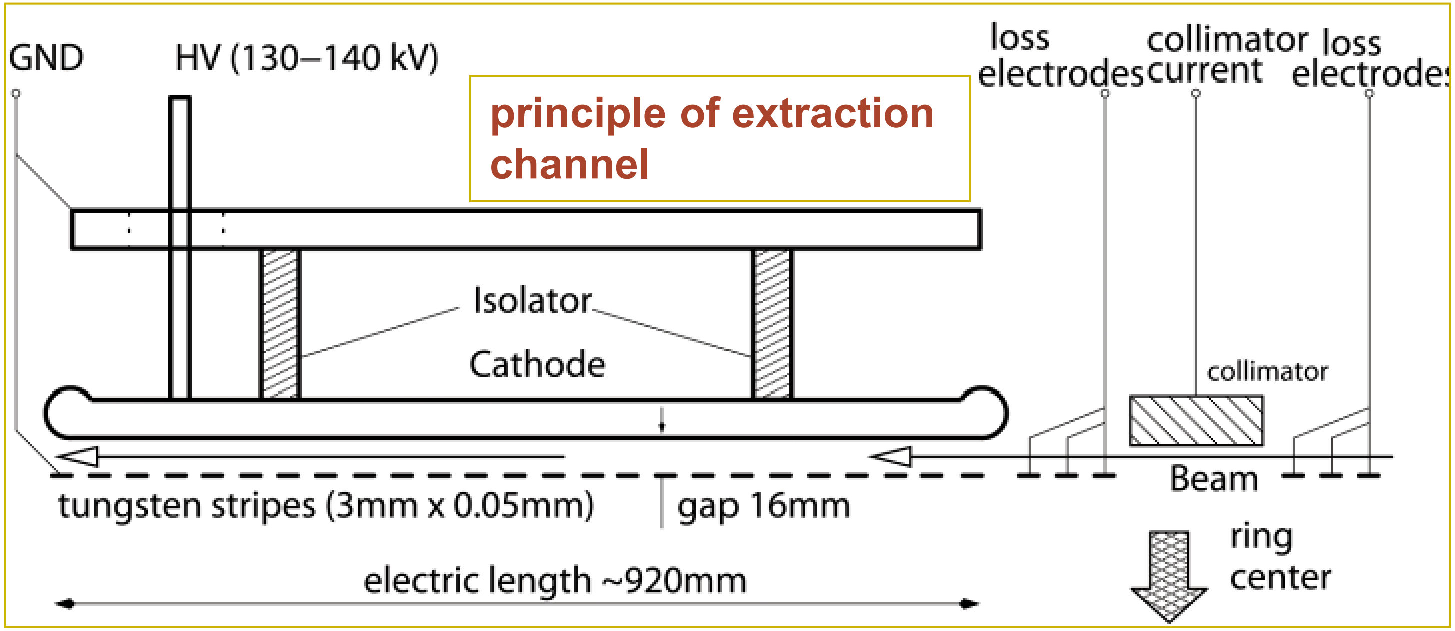
dimensions:
120 x 220m^2

PSI Ring Cyclotron

8 Sector Magnets:	1.6 .. 2.1 T
Magnet weight:	~280 tons
4 Accelerator Cavities:	860 kV (1.2 MV)
1 Flat-Top Resonator	150 MHz
Accelerator frequency:	50.63 MHz
harmonic number:	6
kinetic beam energy:	72 $\rightarrow$ 590 MeV
beam current max.:	2.4 mA
extraction orbit radius:	4.5 m
outer diameter:	15 m
RF efficiency Grid/Beam	0.90×0.64×0.55 = 32%
rel. losses @ 2.2mA:	-~1..2$\cdot 10^{-4}$
transmitted power:	0.32 MW/Res.



injection/extraction with electrostatic elements



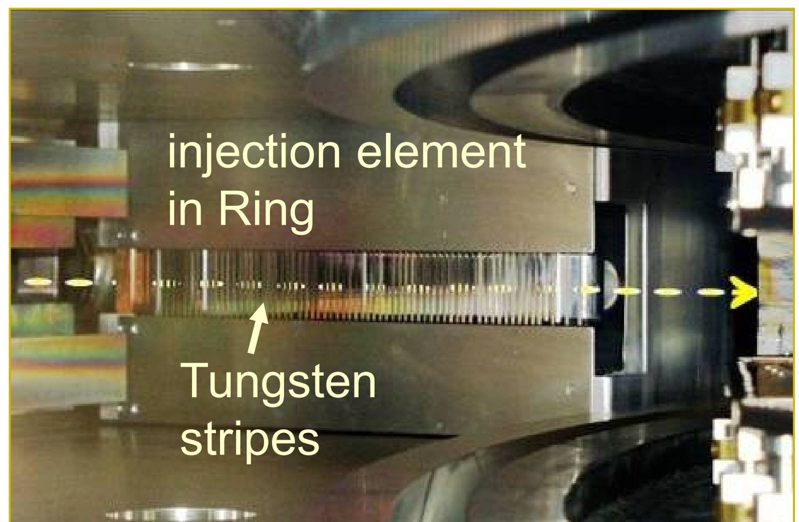
parameters extraction chan.:
E_k= 590MeV
E = 8.8 MV/m
θ = 8.2 mrad
ρ = 115 m
U = 144 kV

major loss mechanism is scattering in 50μm electrode!

electrostatic rigidity:

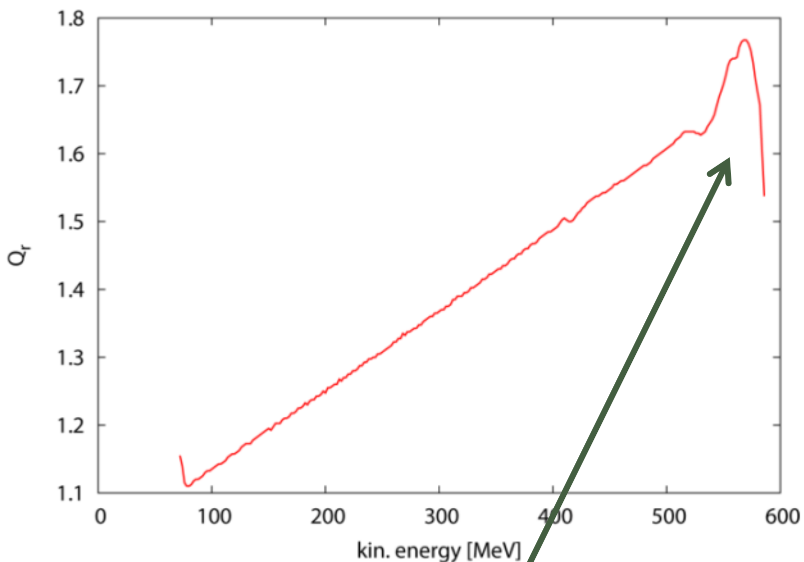
$$E\rho = \frac{\gamma+1}{\gamma}\frac{E_k}{q}$$

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



extraction with off-center orbits

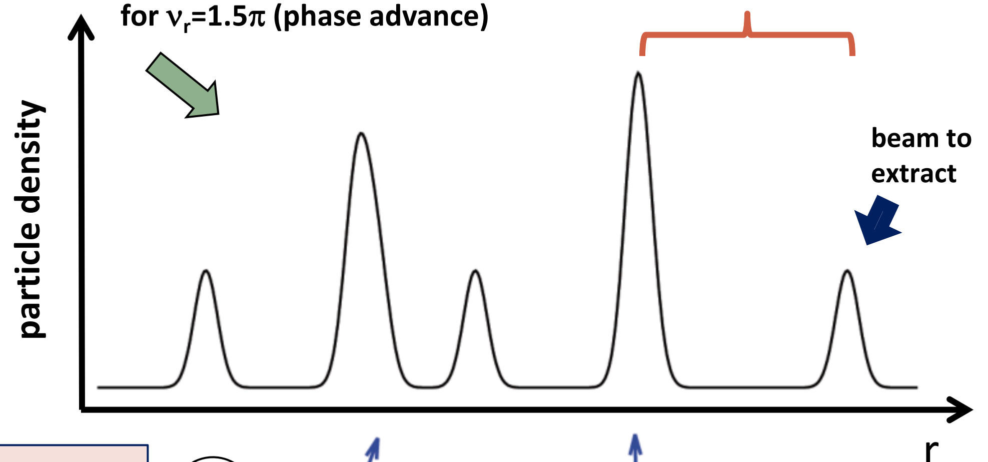
betatron oscillations around the "closed orbit" can be used to increase the radial stepwidth by a factor 3 !



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)

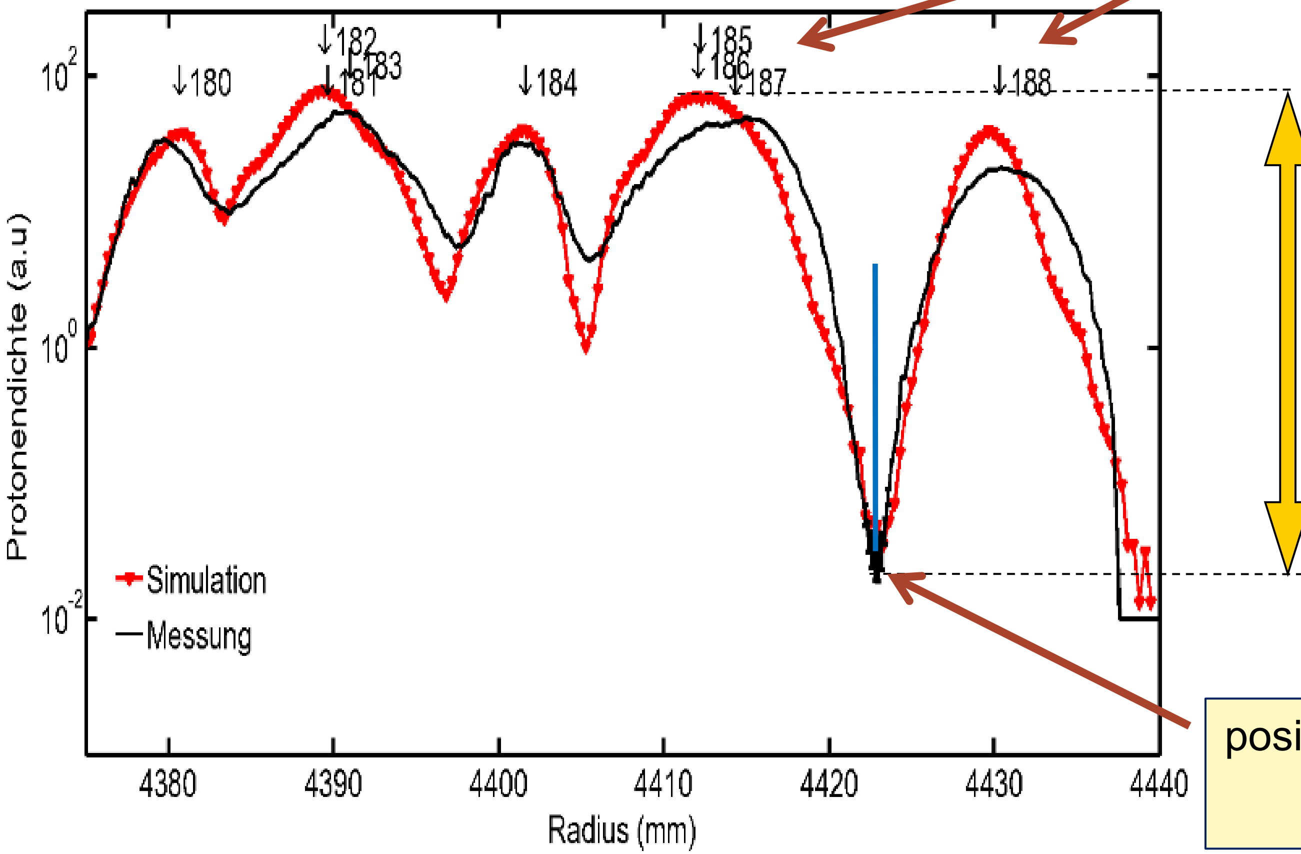
with orbit oscillations: extraction gap; up to 3 x stepwidth possible for ν_r=1.5π (phase advance)



phase vector of orbit oscillations (r,r')

extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement



turn numbers

from simulation

dynamic range:
factor 2.000 in particle density

position of extraction septum

d=50µm

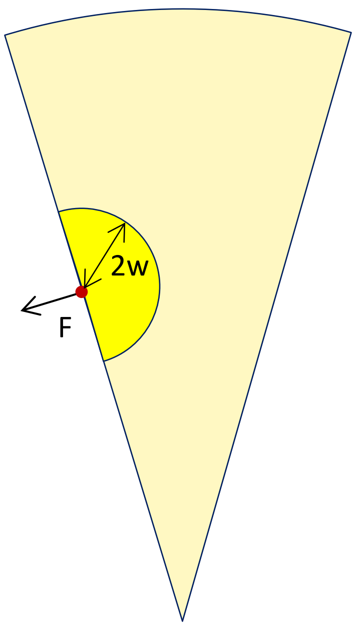
[Y.Bi et al]

longitudinal space charge

sector model (W.Joho, 1981):

$\rightarrow$ 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*



three factors are proportional to the number of turns:

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

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

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

in addition:

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

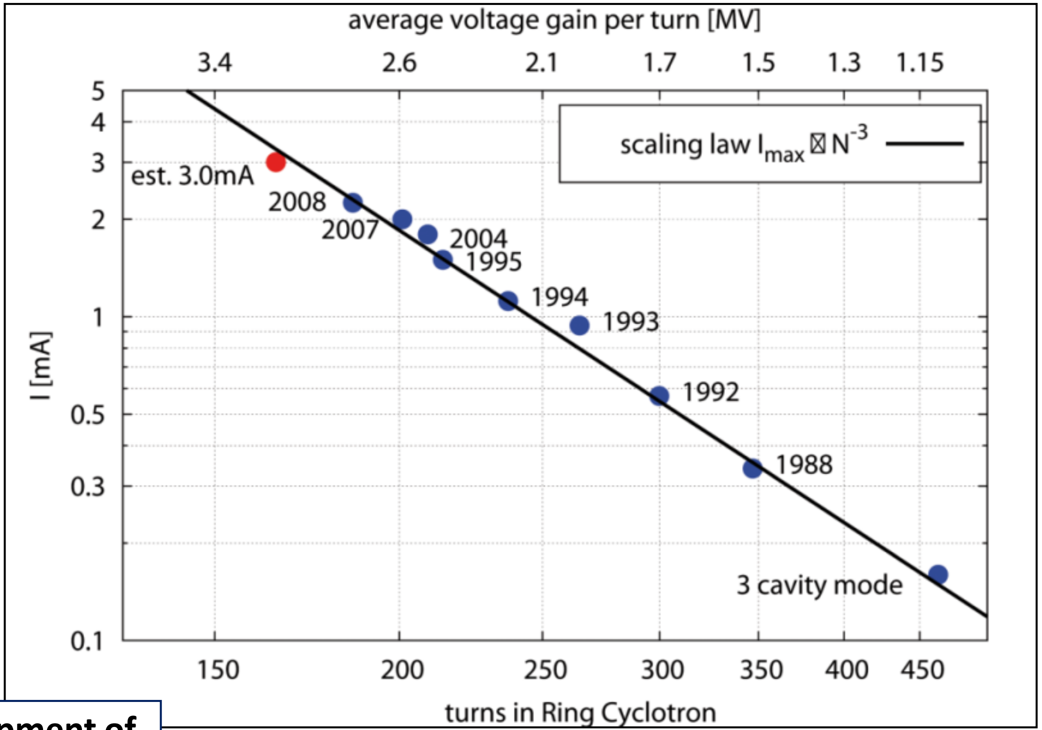
► thus the attainable current at constant losses scales as $n_{\max}^{-3}$

longitudinal space charge; evidence for third power law

- at PSI the maximum attainable current indeed scales with the third power of the turn number$\rightarrow$ voltage per turn matters!

$\rightarrow$ with constant losses

$$I_{\max} \propto n_t^{-3}$$

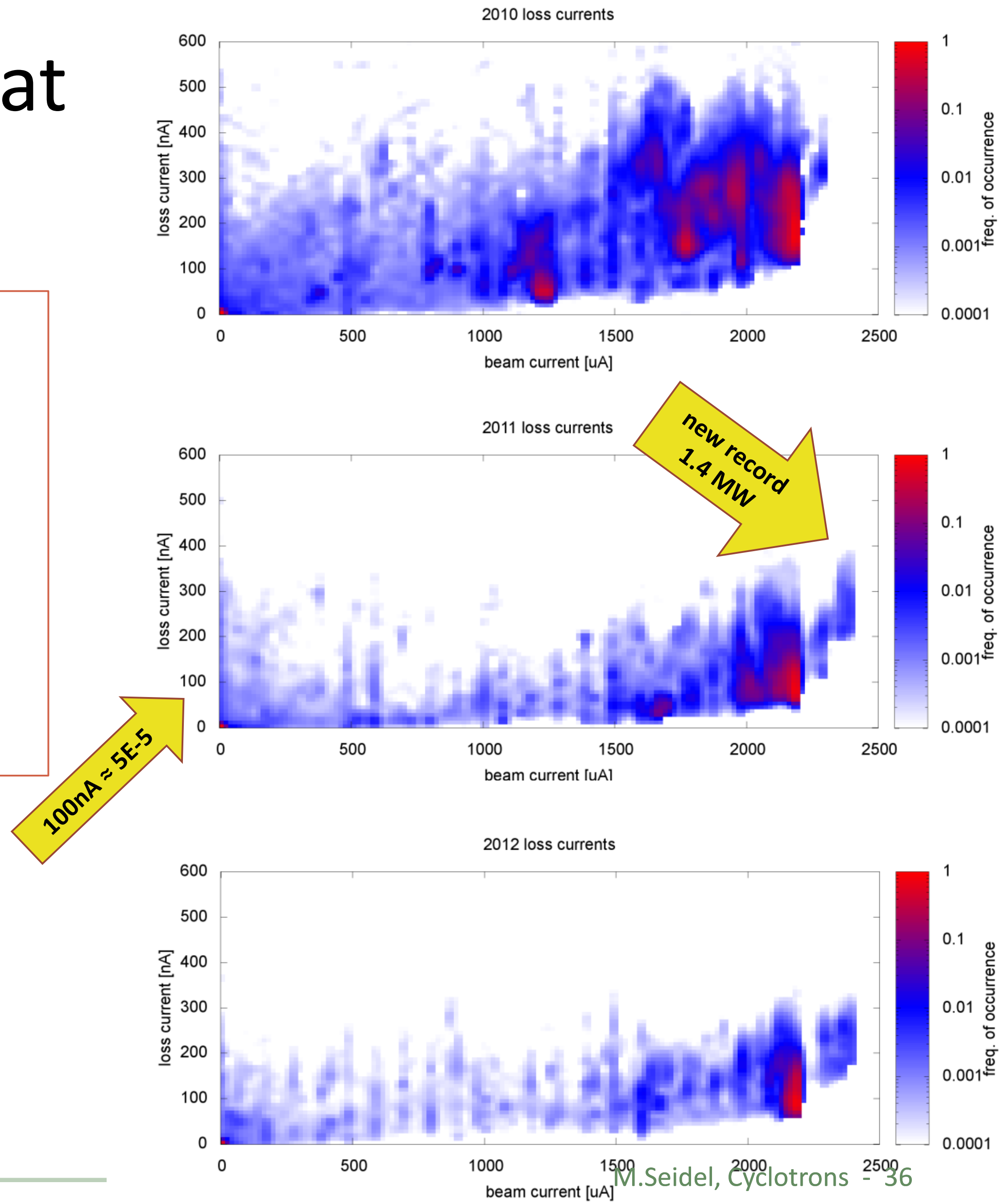


historical development of current and turn numbers in PSI Ring Cyclotron

loss development at PSI-HIPA

plots:

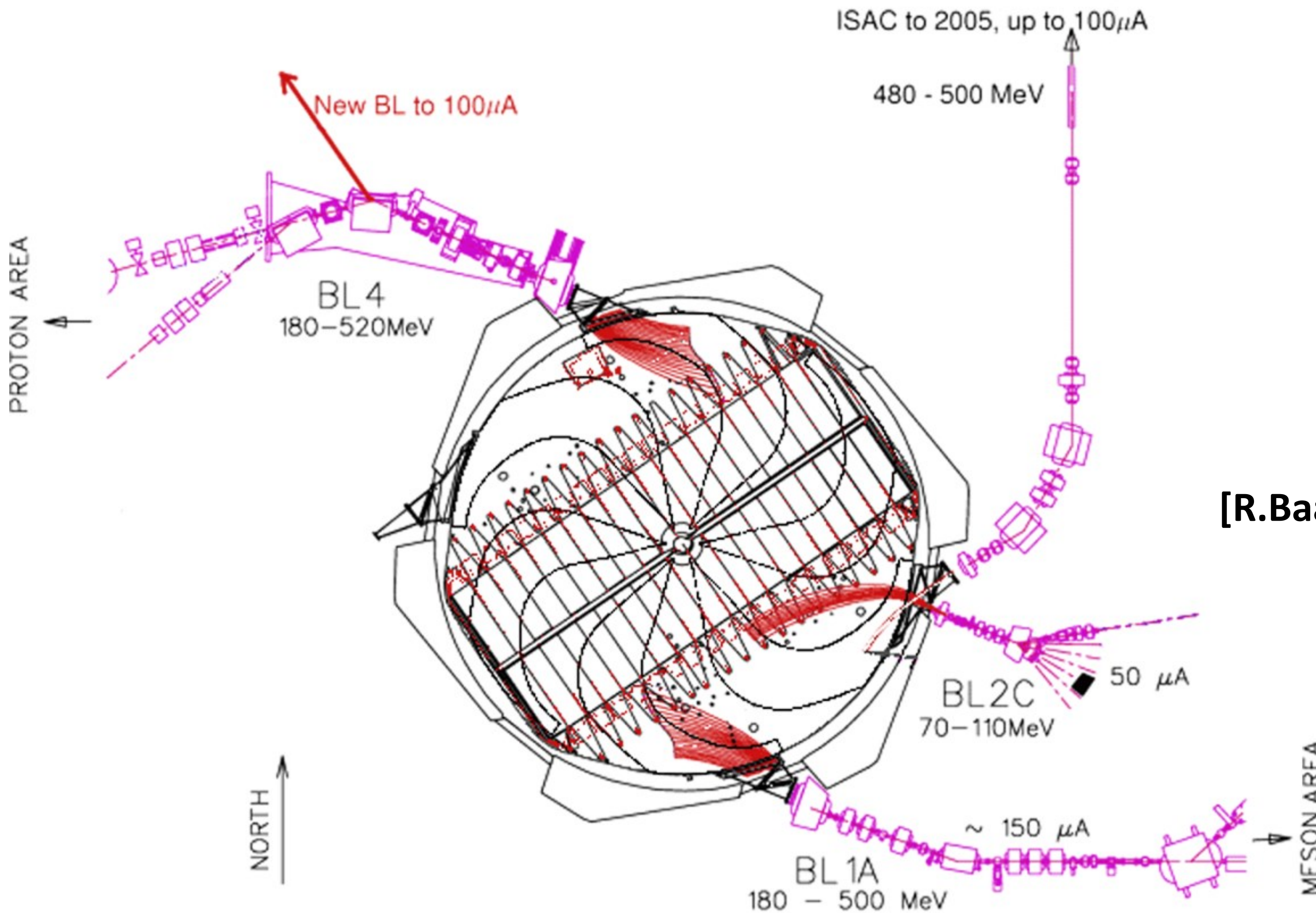
- **loss current [nA] vs. beam current [μA]**
- color code = frequency of operation at particular working point
- limit at 2200μA for standard operation;
  beyond that: test operation



parameters 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

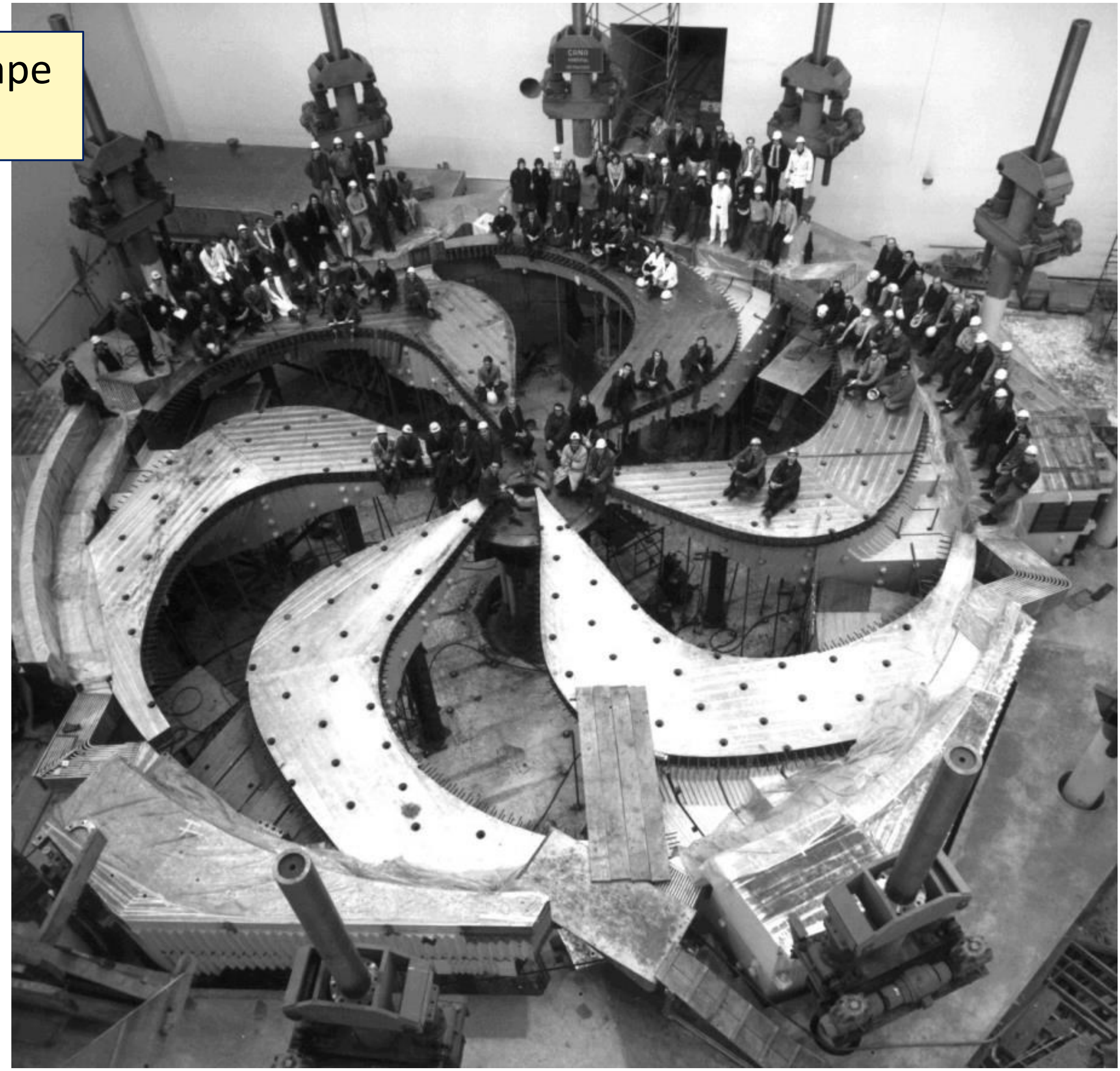
TRIUMF: multiple H^- stripping extraction



[R.Baartman]

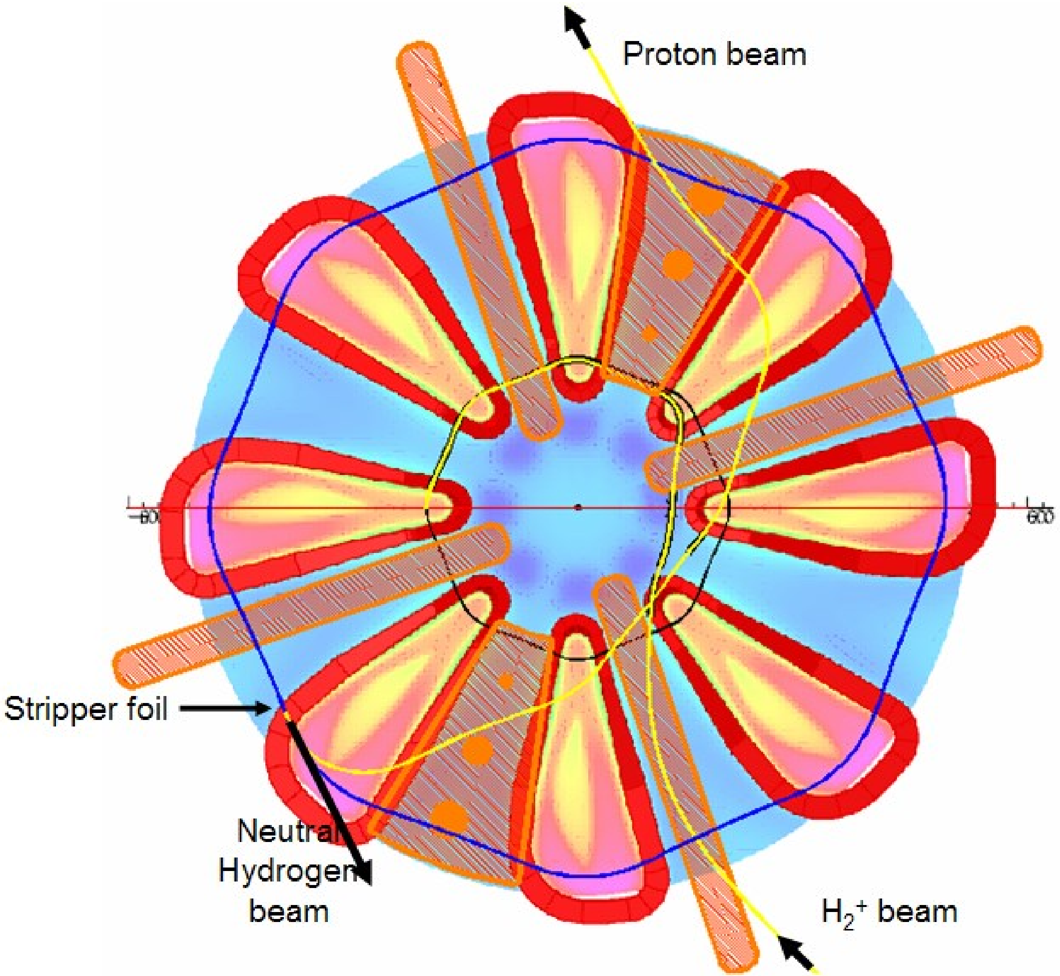
cyclotron examples: TRIUMF

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

ideas I: H_2^+ Daedalus cyclotron
[L.Calabretta et al, INFN Catania]



purpose: pulsed high power beam for neutrino production

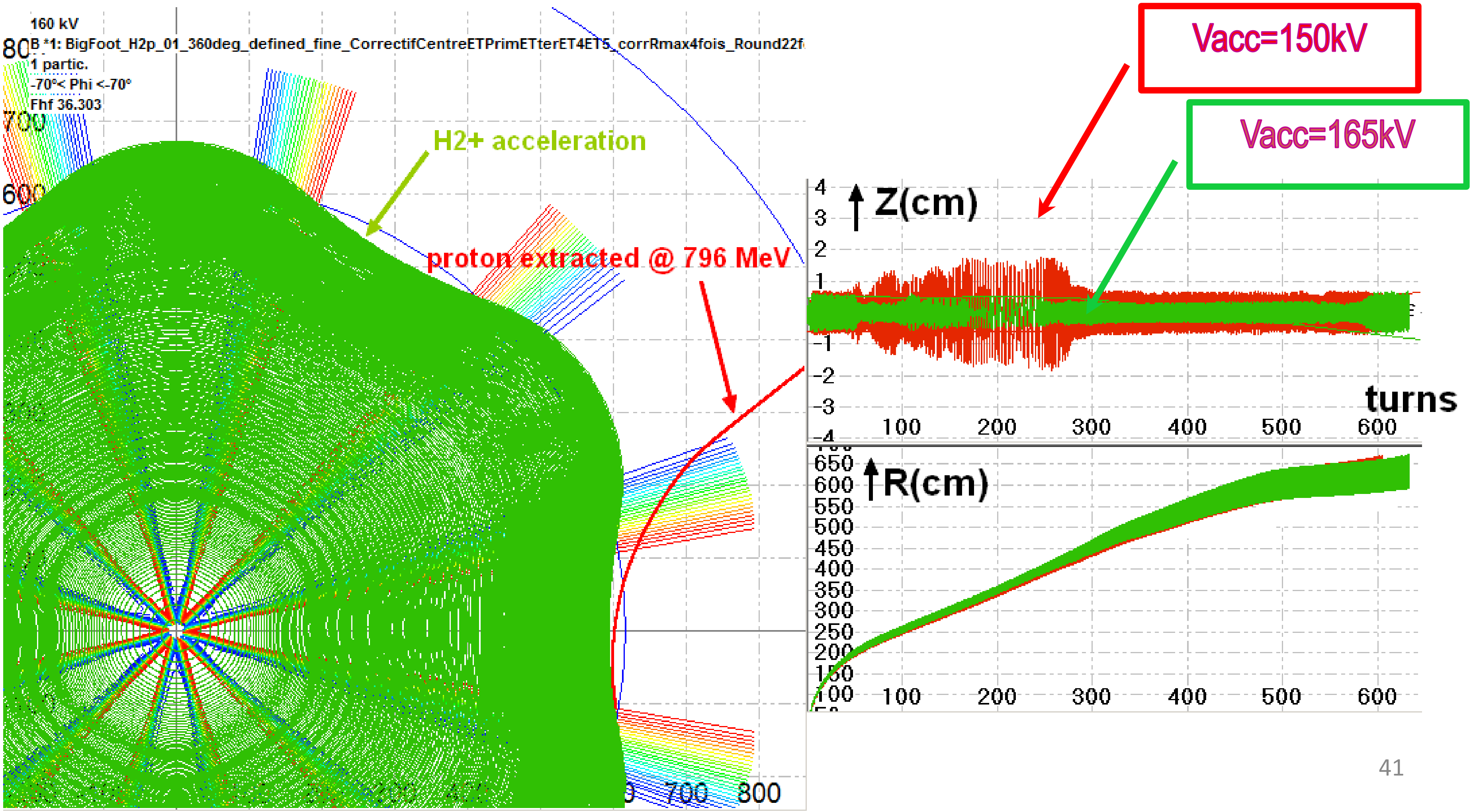
- 800MeV kin. energy
- 5MW avg. beam power

note:
complex extraction path

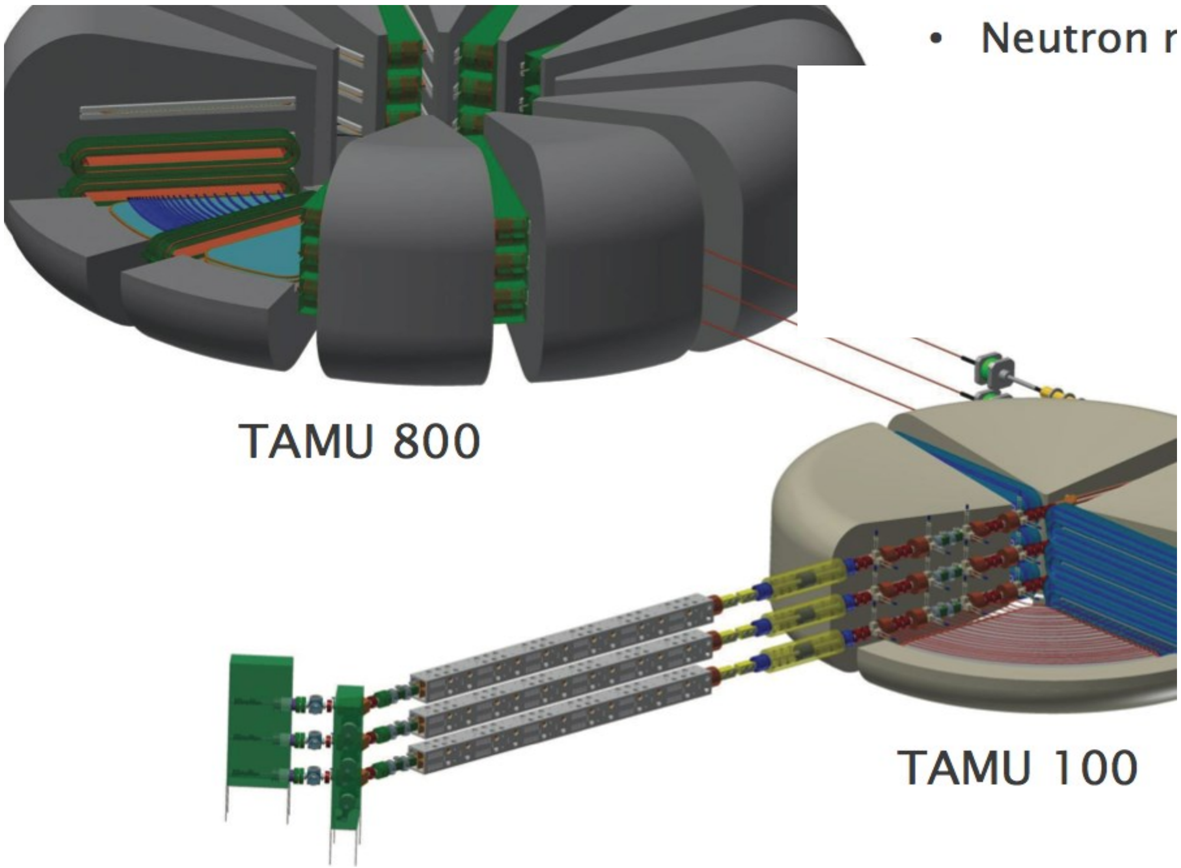
binding	energies
H^-	H_2^+
0.75eV	15eV

ideas II: H_2^+ AIMA Cyclotron w reverse bend and multiple 60keV injection [P.Mandrillon]

The reverse valley B-field concept avoids the internal loop (cf. DAEdALUS extraction) for the stripped proton beam from H2+.

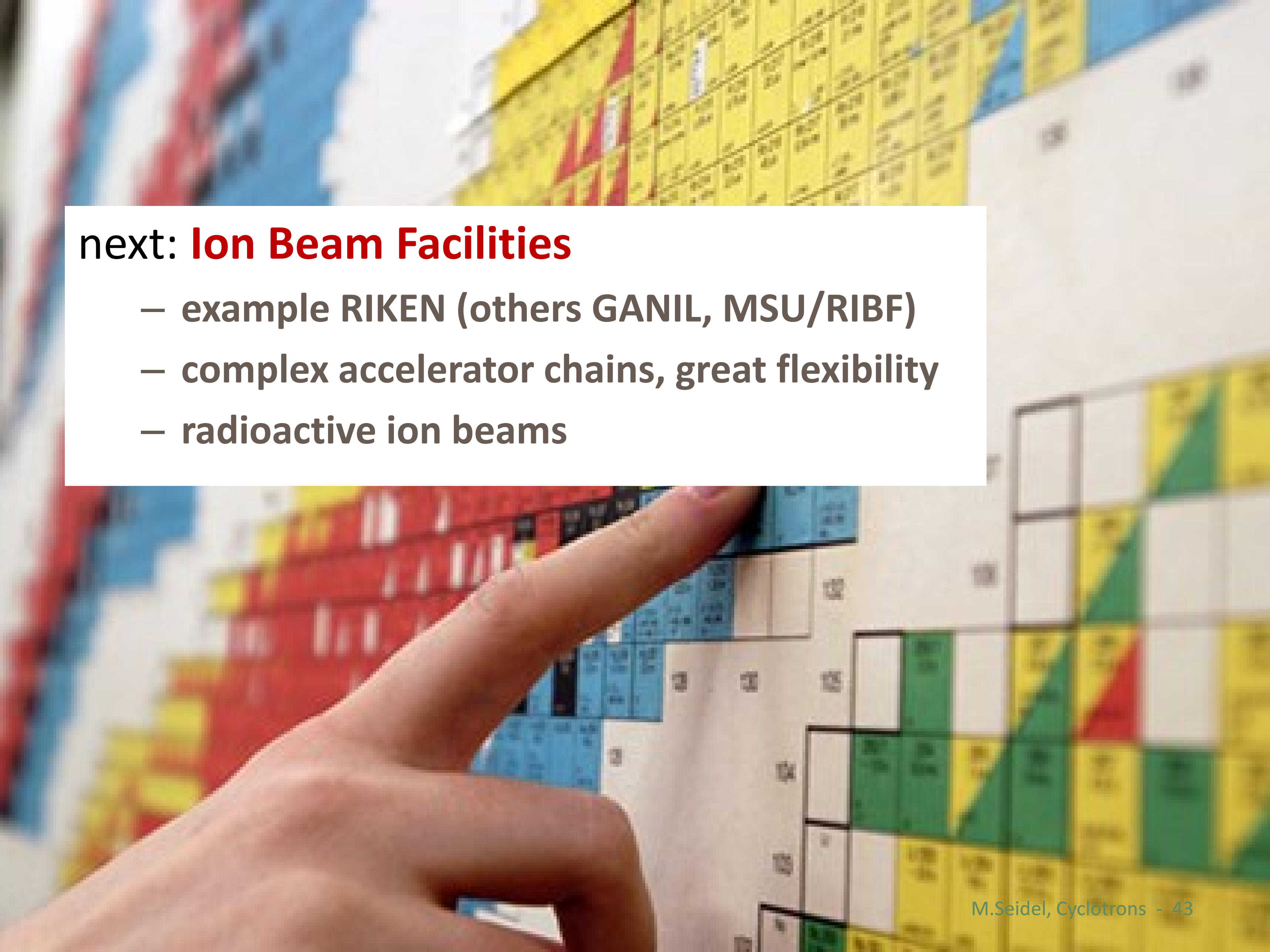


ideas III: 800 MeV SUPERCONDUCTING STRONG-FOCUSING CYCLOTRON [P.McIntyre, TEXAS A&M]



- Two Stages Cyclotron: 100 MeV SF injector + 800 MeV SF booster.
- Stack of 3 Cyclotrons in //
- Booster: 12 Flux coupled stack of dipole magnet sectors
- 10 Superconducting 100 MHz RF cavities providing a 20 MeV Energy Gain/turn
- multiple power couplers per cavity
- Large turn separation allowing to insert SF beam transport channels made of Panofsky Qpoles (G=6T/m)

[P.McIntyre, Texas A&M]



next: Ion Beam Facilities

- example RIKEN (others GANIL, MSU/RIBF)
- complex accelerator chains, great flexibility
- radioactive ion beams

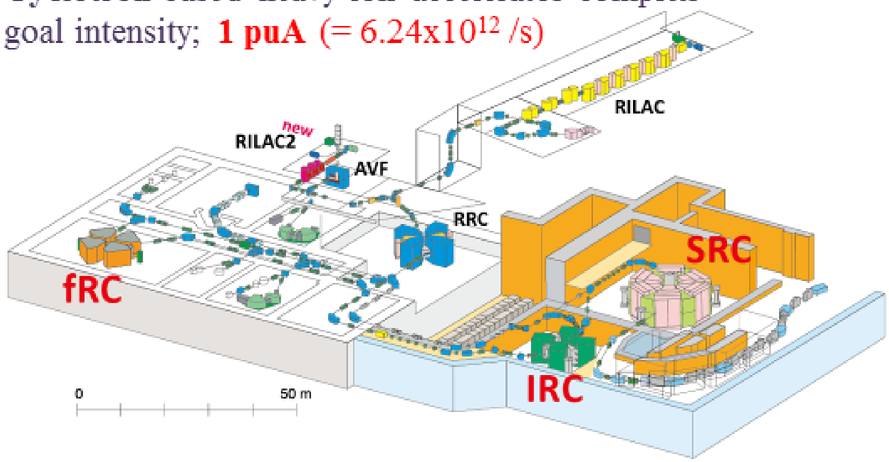
Ion Beam Facility: Example RIKEN

1. U acceleration

Intensity upgrade of U beams at RIBF

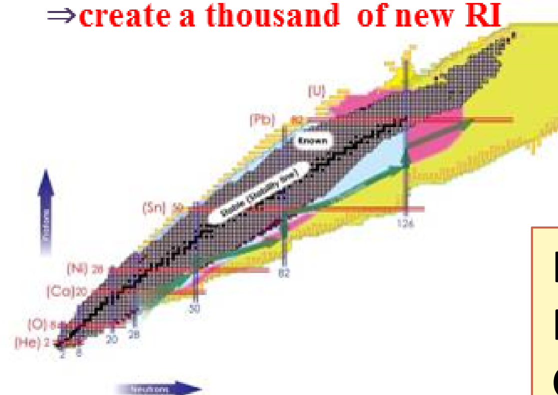
Riken RI Beam Factory (RIBF)

Cyclotron-based heavy-ion accelerator complex
goal intensity; **1 puA** (= 6.24x10^{12} /s)

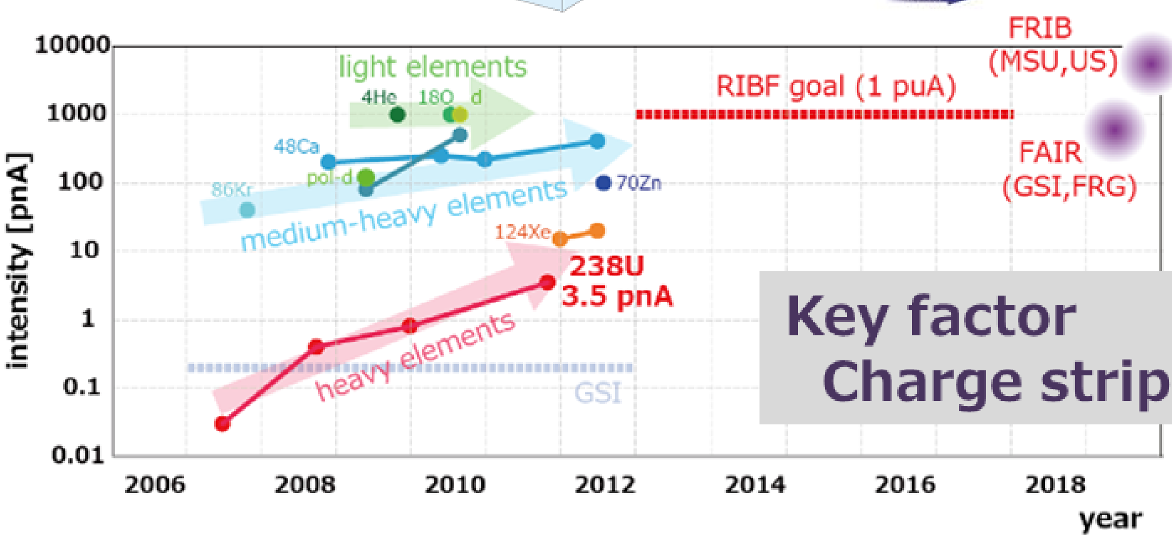


Upgrading of ^{238}U intensity

RI beams via in-flight fission
Expansion of nuclear chart
⇒**create a thousand of new RI**



H.Imao
Riken/Nishina C.
Cyclotrons 2013



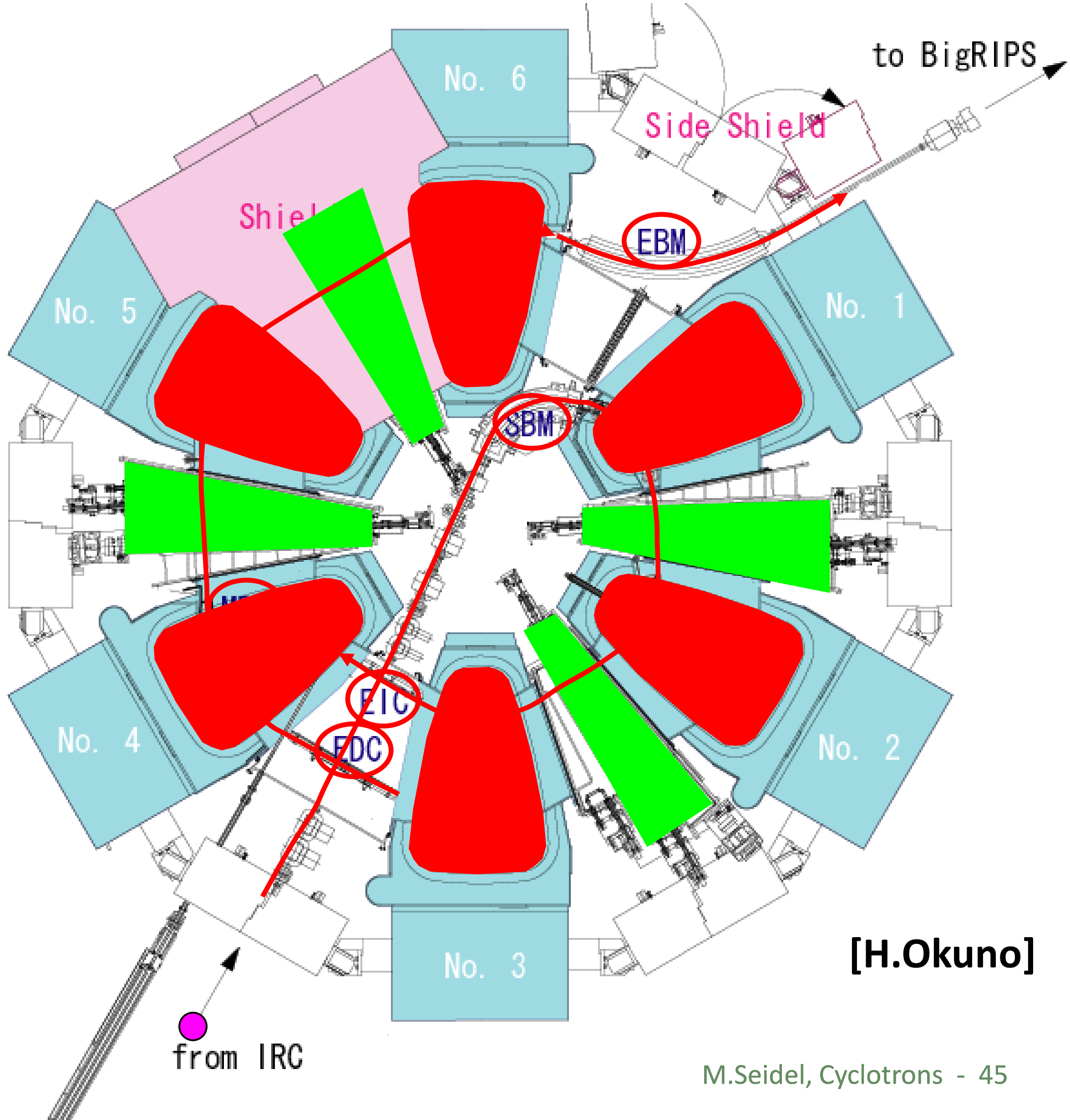
Key factor
Charge stripper

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

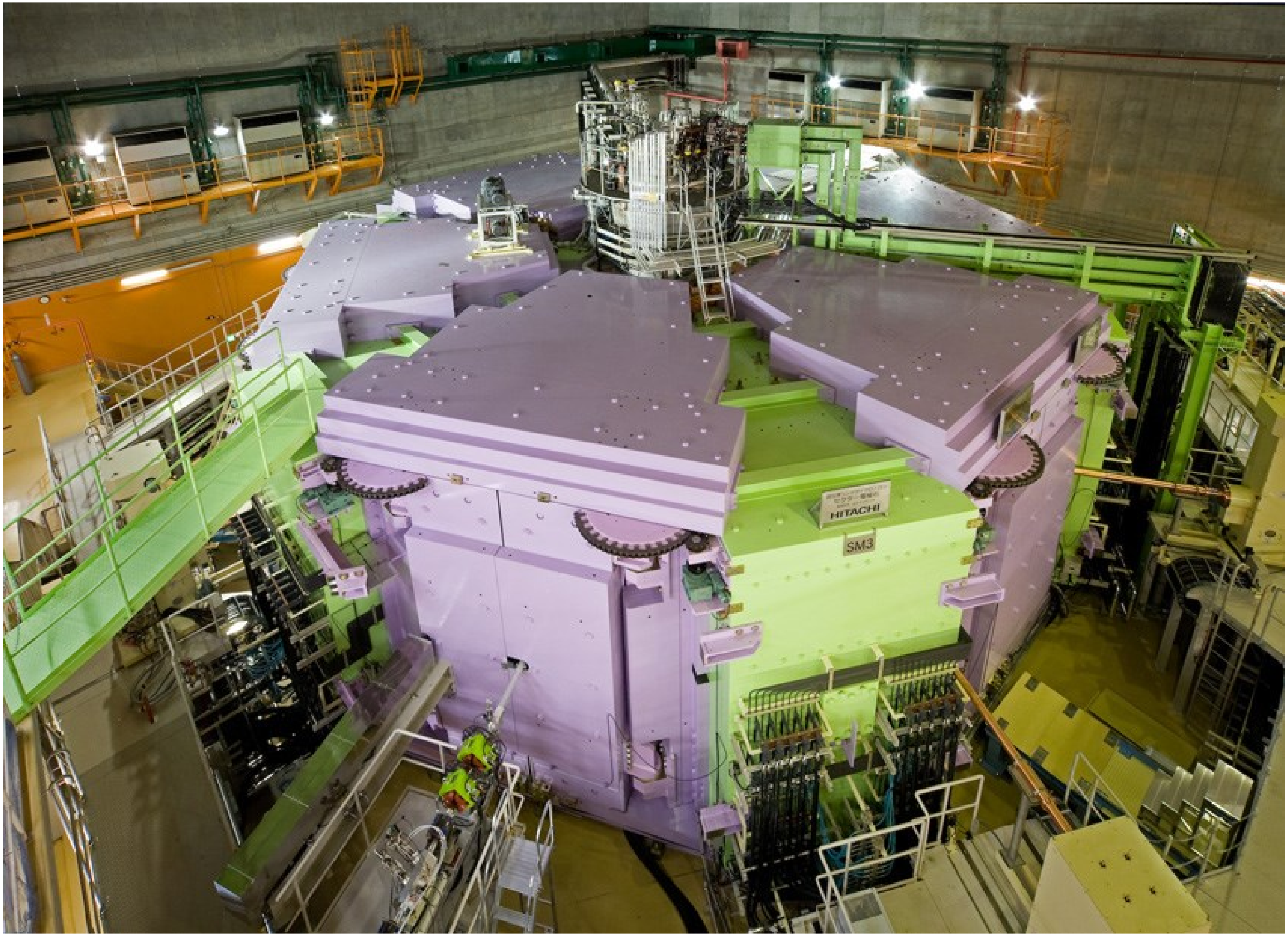
superconducting
Sector Magnets :6
RF Resonator :4
Injection elements.
Extraction elements.

utilization:
broad spectrum of
ions up to Uranium

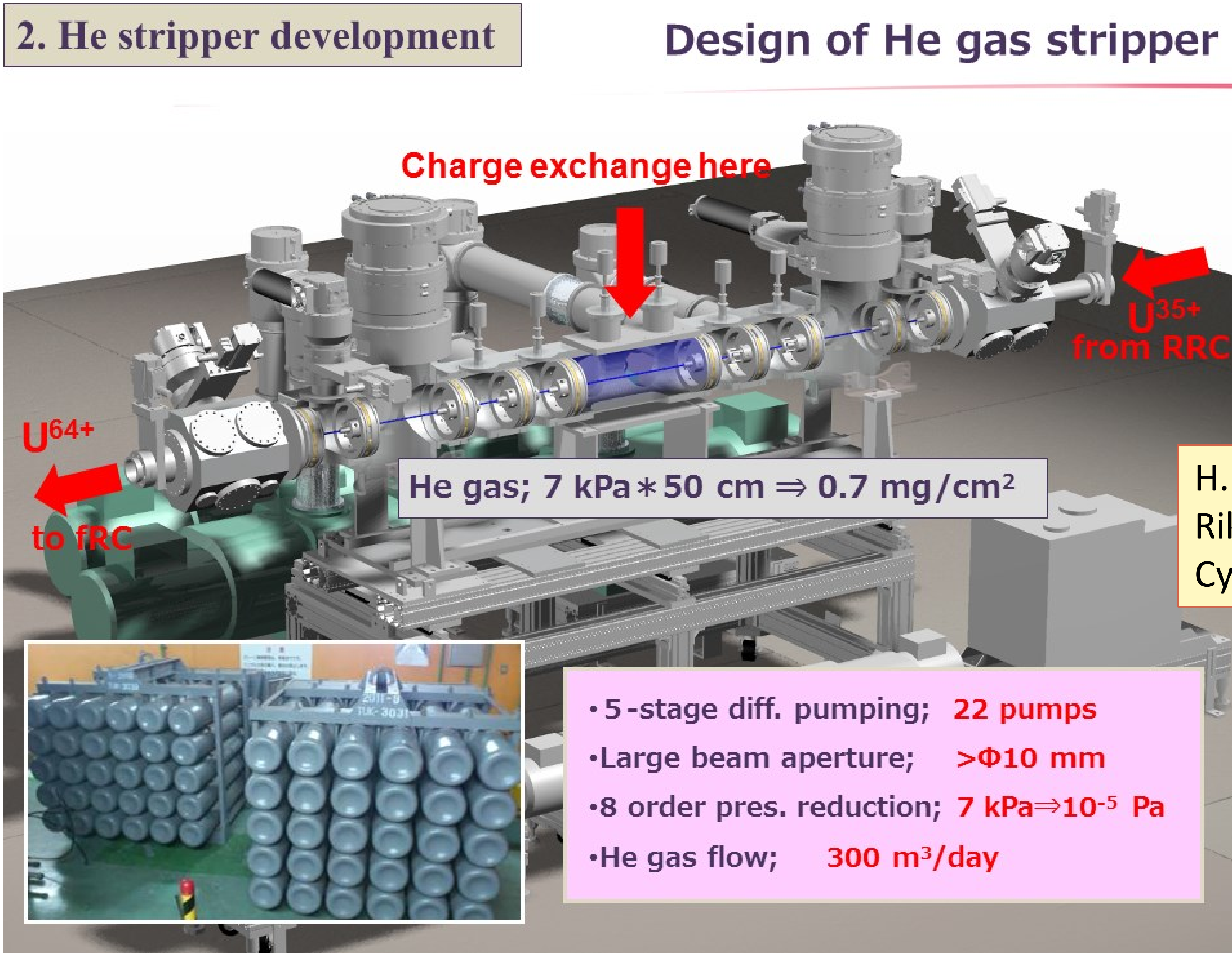


[H.Okuno]

RIKEN SRC in the vault



Key Element: He Gas Stripper

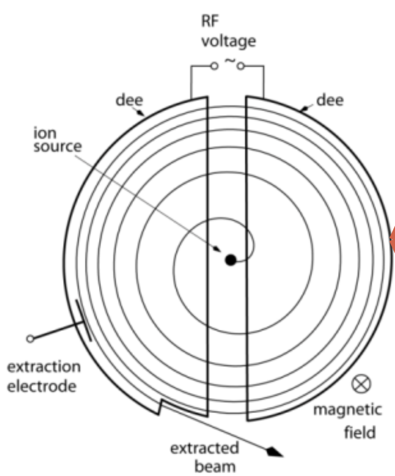


H.Imao
Riken/Nishina C.
Cyclotrons 2013

finally: wrapping up

- usage of cyclotrons and development routes
- cyclotron conferences

today: development directions for cyclotrons



very high intensity
[n-production; ADS; neutrinos…]

- clean extraction, low loss
- energy efficiency
- reliability

ion acceleration
[nuclear physics; RIB‘s]

- great flexibility; varying Z/A
- efficient extraction; stripping
- high fields, s.c. magnets

medical application
[particle therapy p,C; isotope production]

- cost/size optimization
- s.c. magnets
- simple/reliable operation

commercial / research

JACOW conferences

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

cyclotrons 2013 in Vancouver: http://accelconf.web.cern.ch/AccelConf/CYCLOTRONS2013/
conference summary: http://accelconf.web.cern.ch/AccelConf/CYCLOTRONS2013/talks/fr2pb03_talk.pdf
cyclotrons 2016: organized by PSI in Zürich

Cyclotrons - Conclusions

- cyclotrons represent a mature field of accelerators with advanced developments ongoing

$\rightarrow$ **ranging from large, high intensity, low loss, some super flexible**

$\rightarrow$ **to small, low intensity, cost effective, robust, and super specialized**

- about 600 operating cyclotrons for isotope production; growth 50/year
- more than 20 particle therapy centers and many in planning
- few research facilities with high intensity p or ion beams:

  PSI, RIKEN, TRIUMF, GANIL, NSCL

- BUT: cyclotrons not suited for high energy (protons: < 1GeV); require large dipoles; rel. weak focusing, thus space charge limited compared to linacs

$\rightarrow$ **accordingly research directions are going towards high intensity developments and cost effective, compact devices for medical purpose**

thank your for your attention !