Accelerators for Ion-Beam Therapy

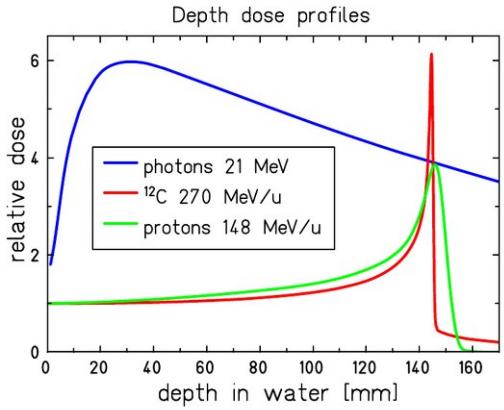
Claude Krantz
(GSI)

Christoph-Schmelzer Summer School

Scheinfeld, 27 July 2023

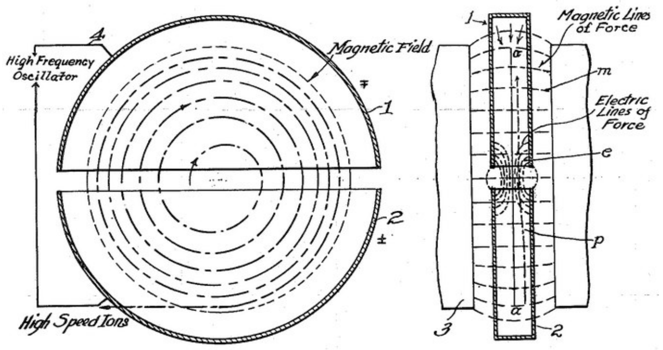
Outline

Beam requirements

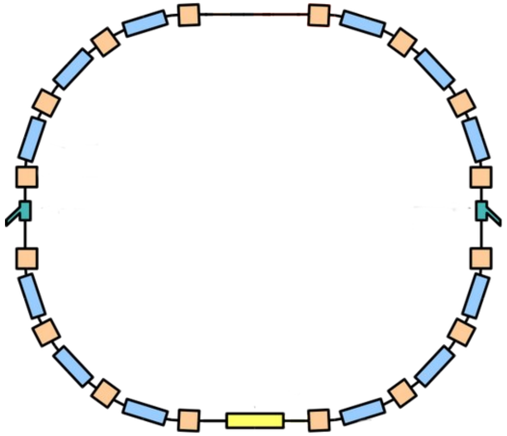


Accelerator systems

- Cyclotron vs. synchrotron
- Overview of some facilities
- Recent developments and alternative concepts



Latest synchrotron R&D



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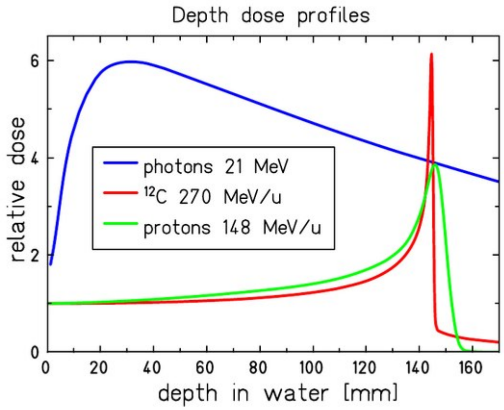

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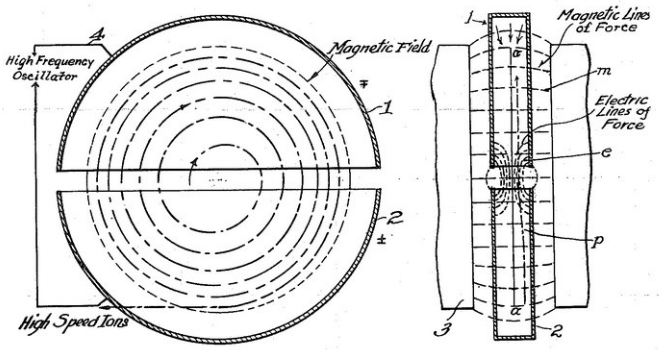

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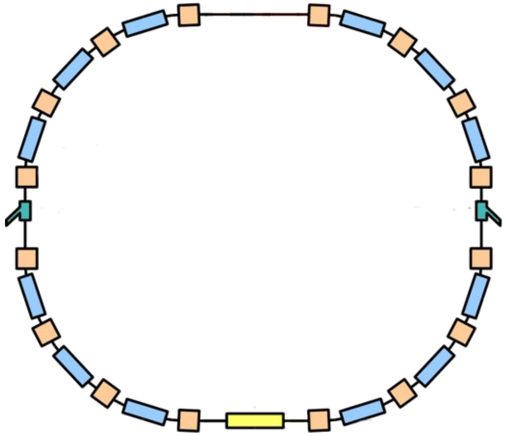
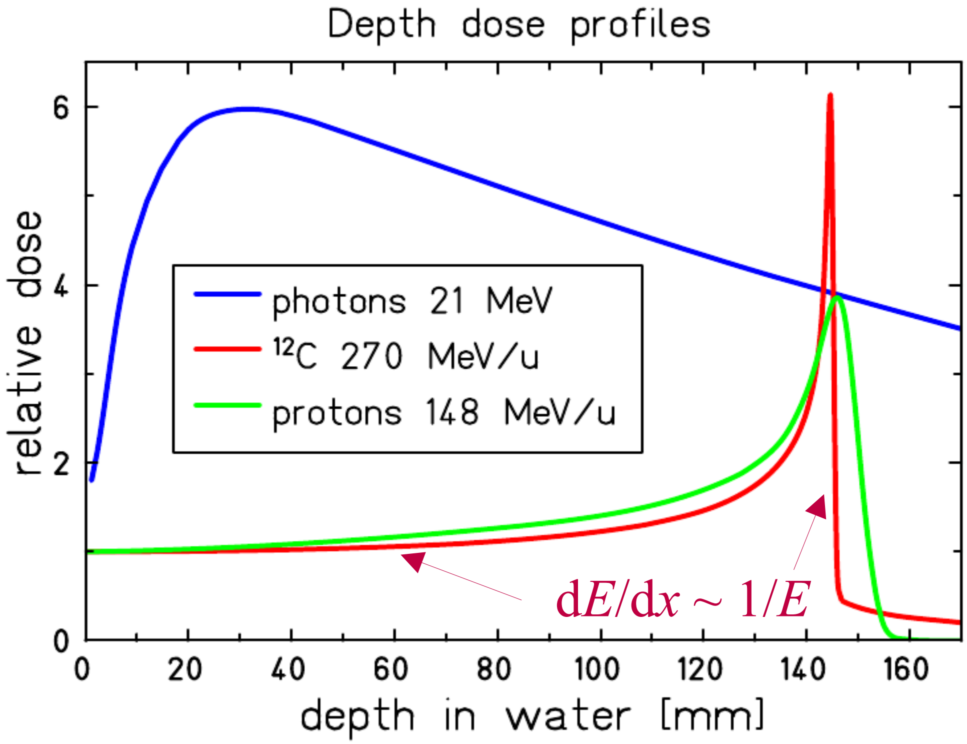


Beam requirements: p or $^{12}C^{6+}$

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{Z^2 e^4 n_e}{4\pi\varepsilon_0 m v^2} \cdot \frac{1}{2} \ln\left(\frac{2mv^2}{I}\right)$$



Krämer & Durante, Eur. Phys. J. D 60 (2010)

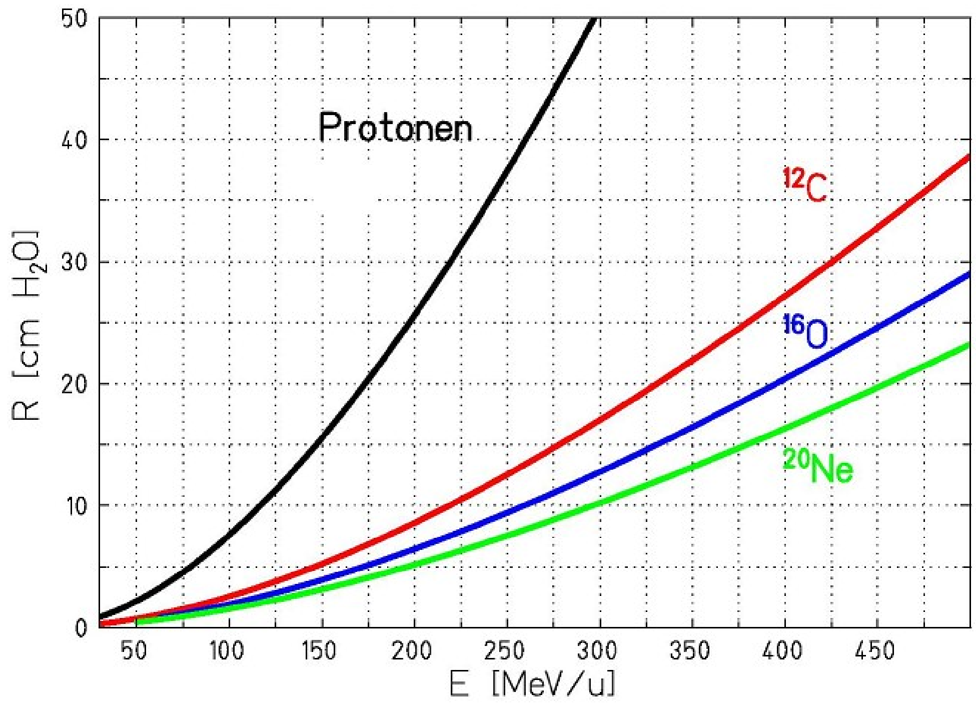
De-facto, p **and** $^{12}C^{6+}$ have their place in ion beam therapy …

… and they impose very different requirements on the accelerator system.

Beam requirements: Energy

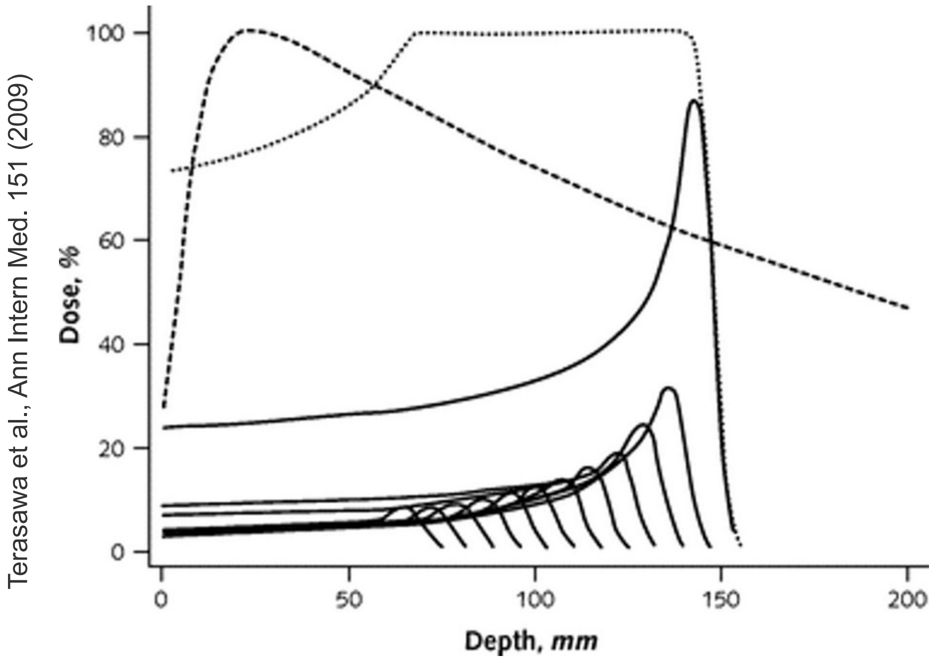
Energy: Defined by required penetration depth.

For 30 cm: **220 MeV** for p
430 MeV/u for $^{12}C^{6+}$



Requirements from dose distribution techniques

Logitudinal distribution (along beam axis):



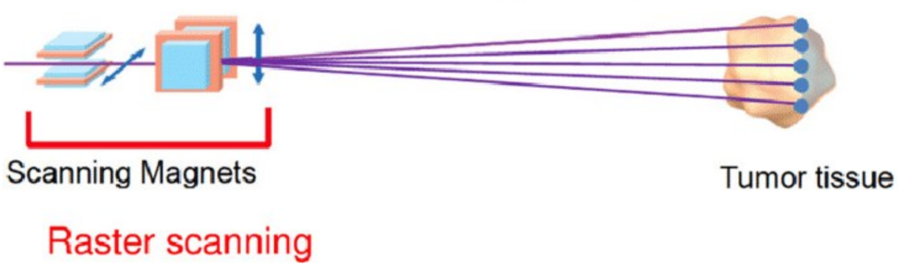
1) **stacking** of a sequence of beams of different energy, or
2) use of a single beam of "matching" broad **energy distribution**, or
3) a combination of the two.

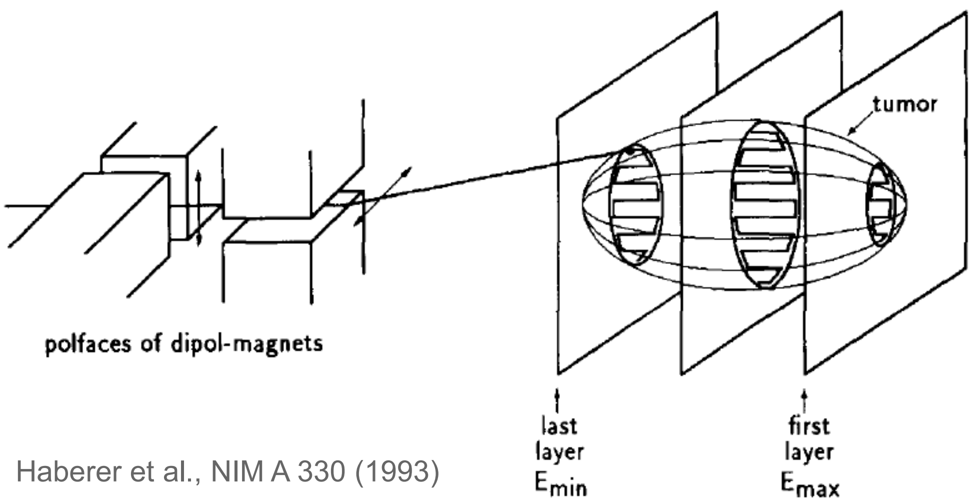
Accelerator system must provide a wide spectrum of ion energies for each ion species (p, $^{12}C^{6+}$, ...)

Requirements from dose distribution techniques

Lateral distribution (transverse to beam):

Durante and Paganetti,
Rep. Prog. Phys. 79 (2016)





Haberer et al., NIM A 330 (1993)

Pencil-beam scanning

"Paint" iso-energetic slice of the target volume.

Requires beam size, energy, and intensity to be **stable** over several **seconds**!

Required beam intensity

Rule of thumb:

$$D[Gy] \approx 0.1602 \times \phi \left[\frac{10^9}{cm^2}\right] \times \frac{S}{\rho}\left[\frac{MeV}{g/cm^2}\right]$$

with

D applied dose in Gy = J/kg

φ particle fluence in billions per cm²

S/ρ density-normalised stopping force $dE/ds \cdot \rho$ at Bragg peak in MeV cm² / g

Typical dose for therapy: ~ 1 Gy per fraction

Typical S/ρ (for protons): ~ 5 MeV cm²/g

→ Need ~ 10^9 protons per cm² of tumor cross-section (← Simplified 2D picture!)

→ An (average) proton rate of few 10^9 s^{-1} (0.1 … 1 nA) looks reasonable.

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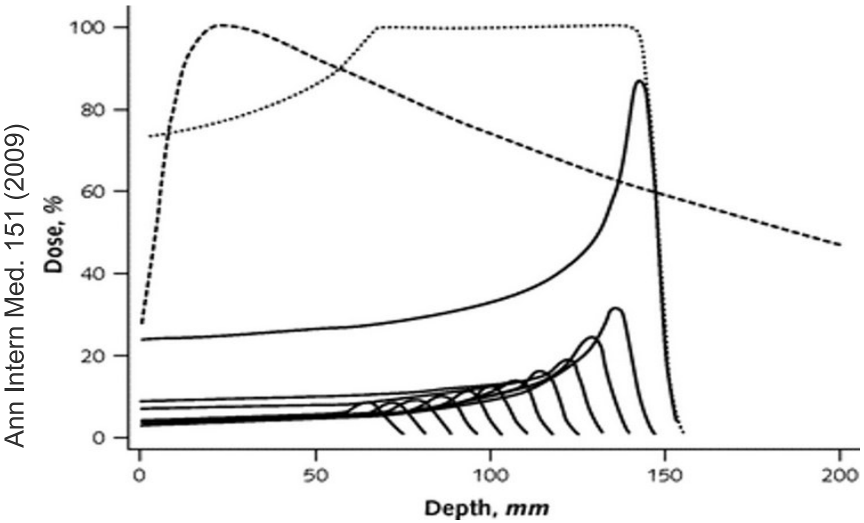
Remarks

(1) If the beam transport is lossy (e.g. due to energy degraders, collimators, …) the intensity at the accelerator may need to be much higher.

(2) Also much lower intensities should be available, e.g. for the fore-most pristine Bragg peak.

Terasawa et al., Ann Intern Med. 151 (2009)



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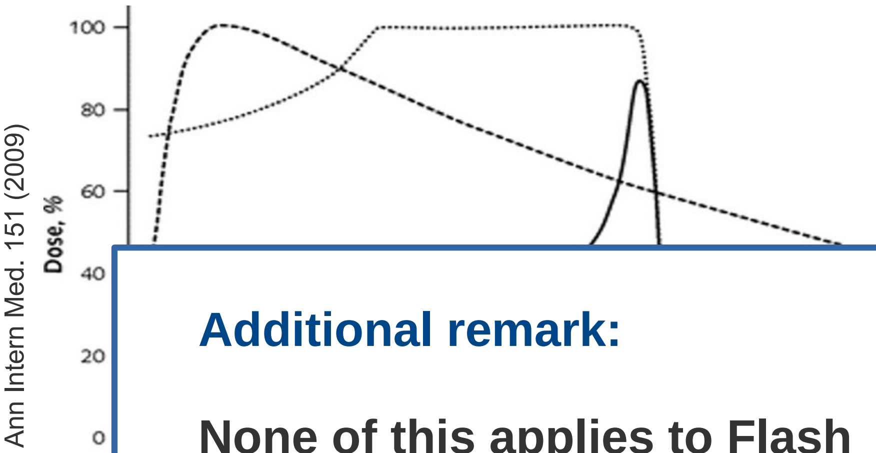


Terasawa et al., Ann Intern Med. 151 (2009)

Additional remark:

None of this applies to Flash therapy!

Key requirements for a therapy ion beam

Energy: Defined by required penetration depth.

For 30 cm: **220 MeV** for p
430 MeV/u for $^{12}C^{6+}$

Intensity: few **~ 10^9 protons/s**

few **~ 10^8 $^{12}C^{6+}$/s**

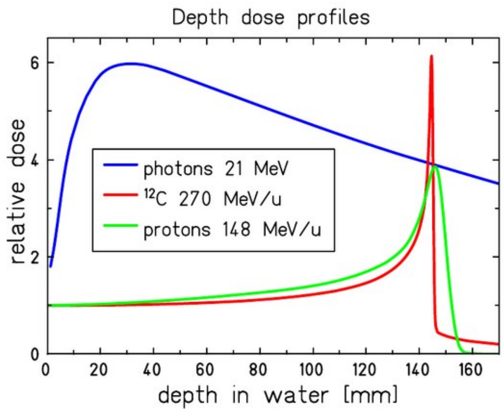
Time structure (raster scanning):

Quasi DC beam pulses of **1 … 10 s** duration

Stable emittance and energy.

Outline

Beam requirements



Accelerator systems

Cyclotron vs. synchrotron

Overview of some facilities

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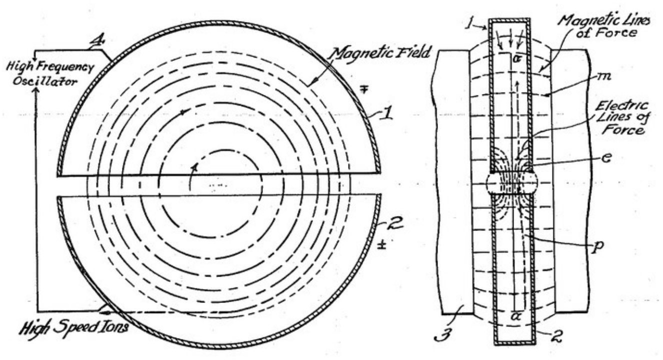

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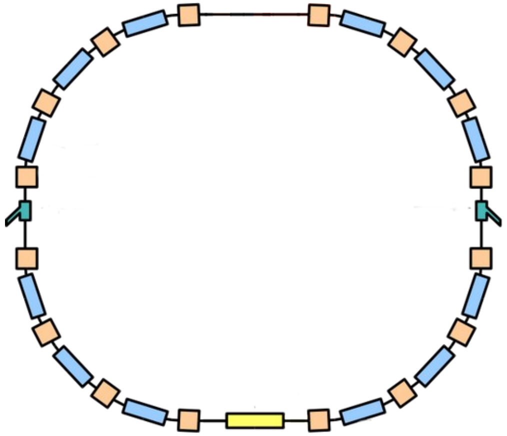
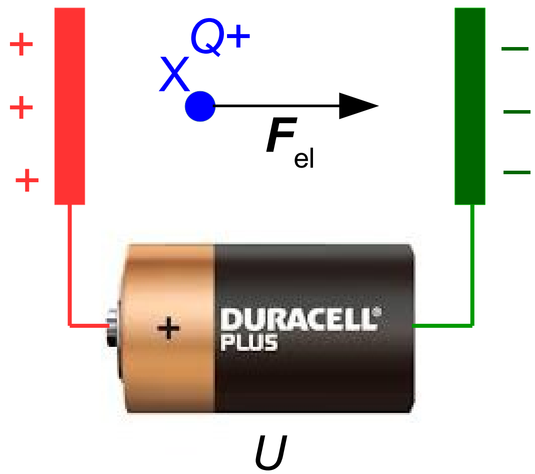


How to build an ion accelerator?

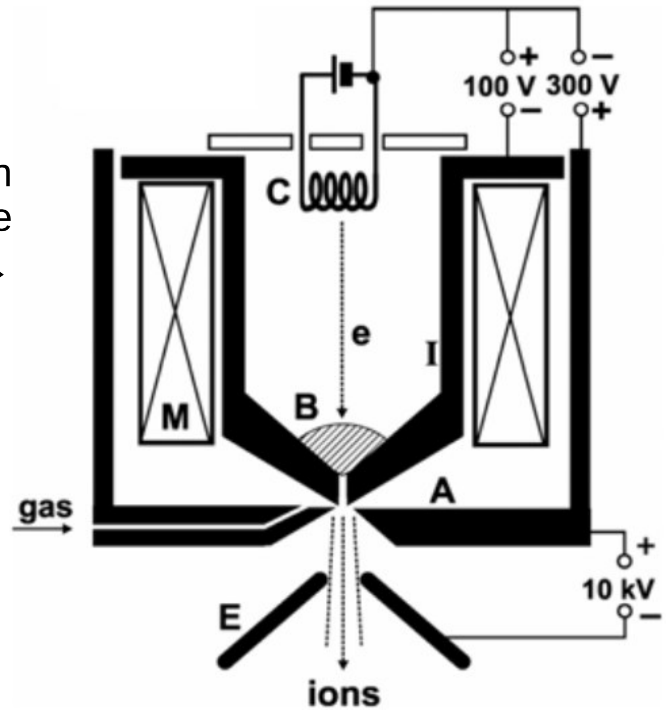
Use electric charge $q = Qe$ of particles:

Electric potential difference → Acceleration to kinetic energy $E = qU$



Electrostatic accelerator

duoplasmotron
ion source
→



Loeb Plasma Phys. Control. Fusion 47 (2005) B565

Used in ion sources

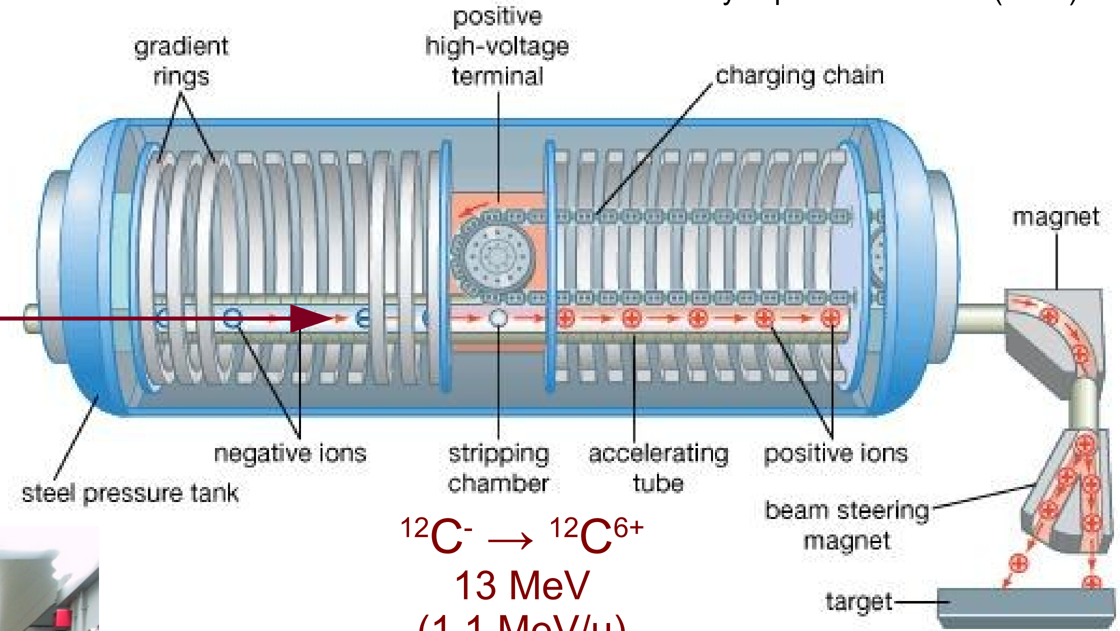
→ Provides the first few keV of kinetic energy.

How to build an ion accelerator?

Electrostatic acceleration *can* actually reach nuclear energies ...

13 MV

Encyclopedia Britannica (2008)



$^{12}C^{-}$
0 MeV

$^{12}C^{-} \rightarrow {}^{12}C^{6+}$
13 MeV
(1.1 MeV/u)

$^{12}C^{6+}$
91 MeV
(7.6 MeV/u)

↓ 13 MV tandem Van-de-Graaff accelerator

www.mpi-hd.mpg.de

… but even the largest machines are limited to ion energies ~ 10 MeV/u.

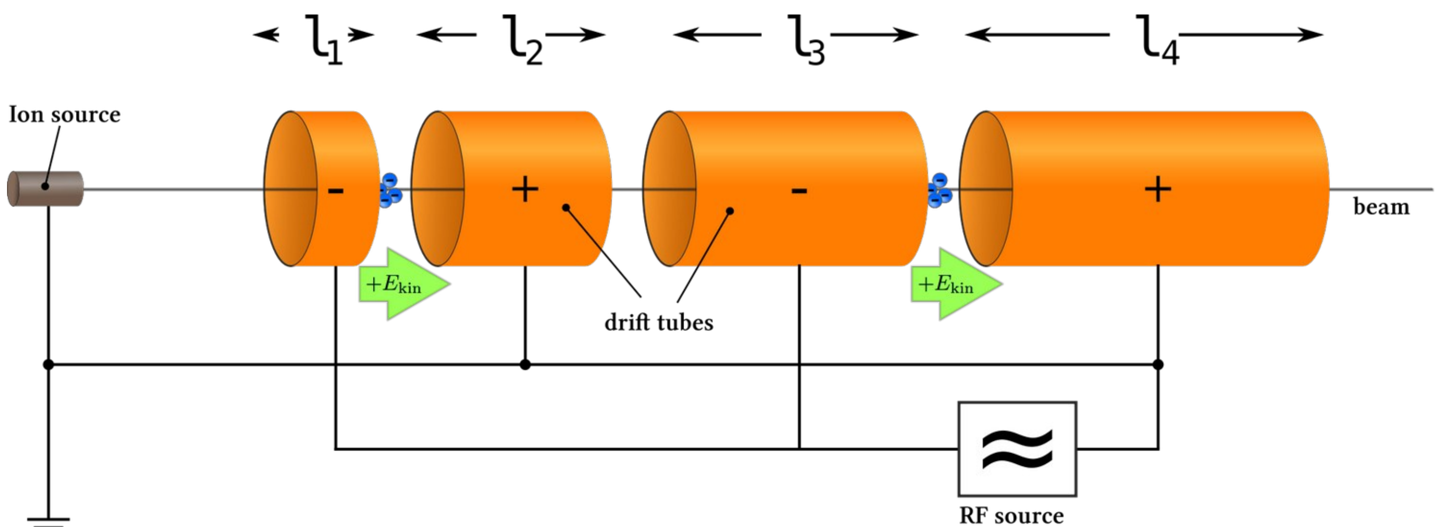
How to build an ion accelerator?

Radiofrequency Linacs

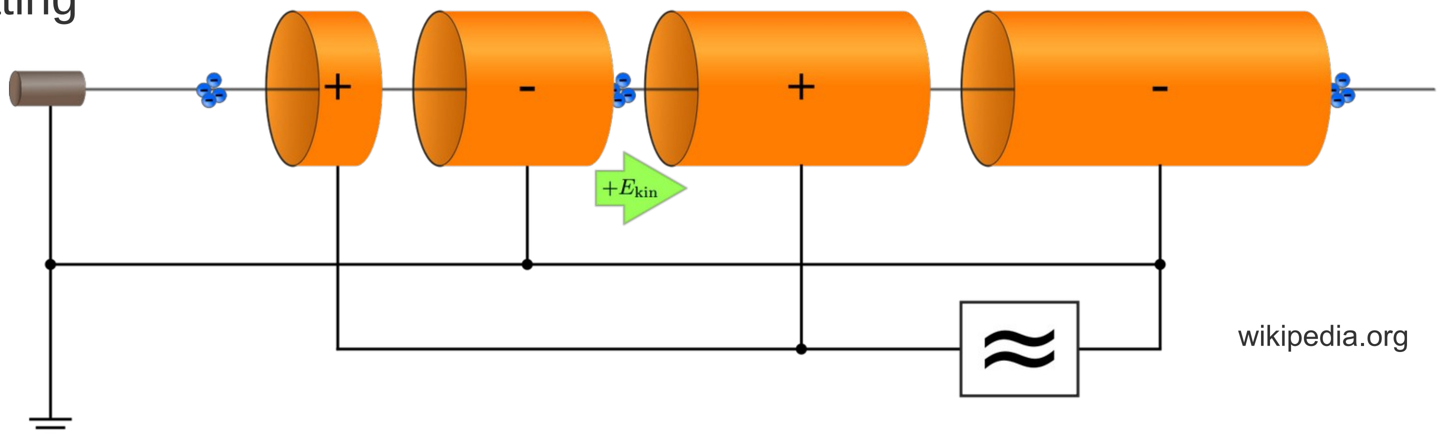
(1) Instead of one large electrostatic field, use oscillating E fields,

(2) synchronise particle motion with "accelerating" phase of E-field.

→ continuous acceleration.



non.-rel. case: $E_{kin} \sim n \rightarrow v \sim n^{1/2} \rightarrow l_n \sim n^{1/2}$

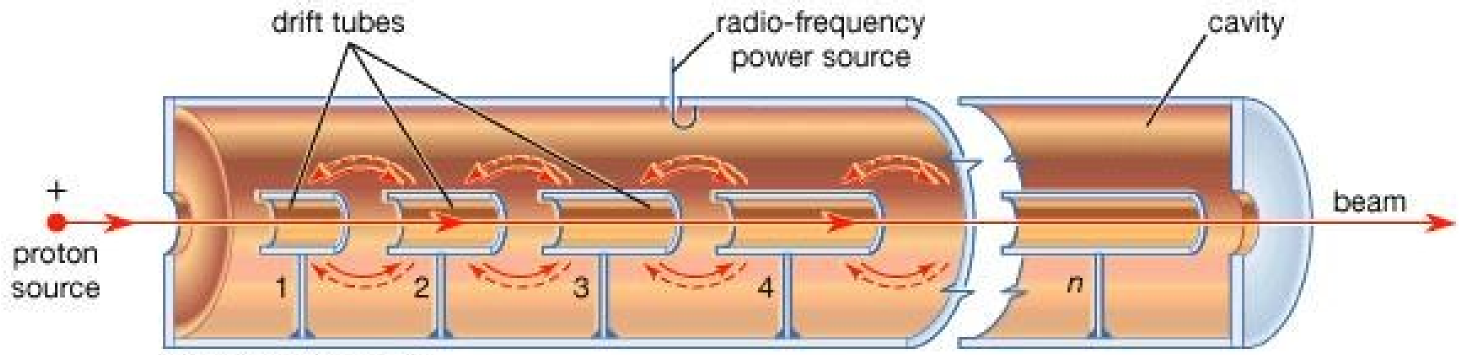


wikipedia.org

Original realisation: *Wideroe* drift tube linac (1928)

How to build an ion accelerator?

Encyclopedia Britannica (2007)



Radiofrequency Linacs

(1) Instead of one large electrostatic field, use oscillating E fields,

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→ continuous acceleration.

→ Alvarez structure of GSI's UNILAC

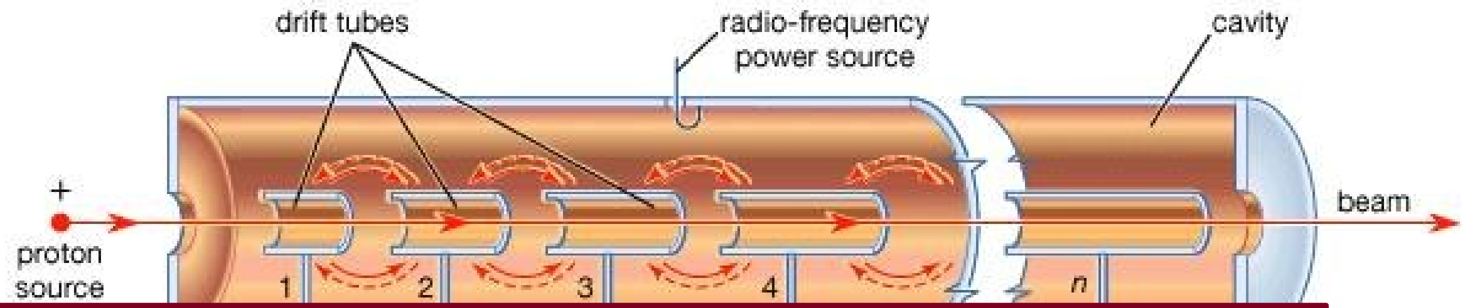
G. Otto, GSI

Later improved into **resonant** accelerator structures (*Alvarez*-type linacs). → *Higher rf power, higher frequencies*.

How to build an ion accelerator?

Encyclopedia Britannica (2007)

Radiofrequency Linacs



(1) Instead of one large

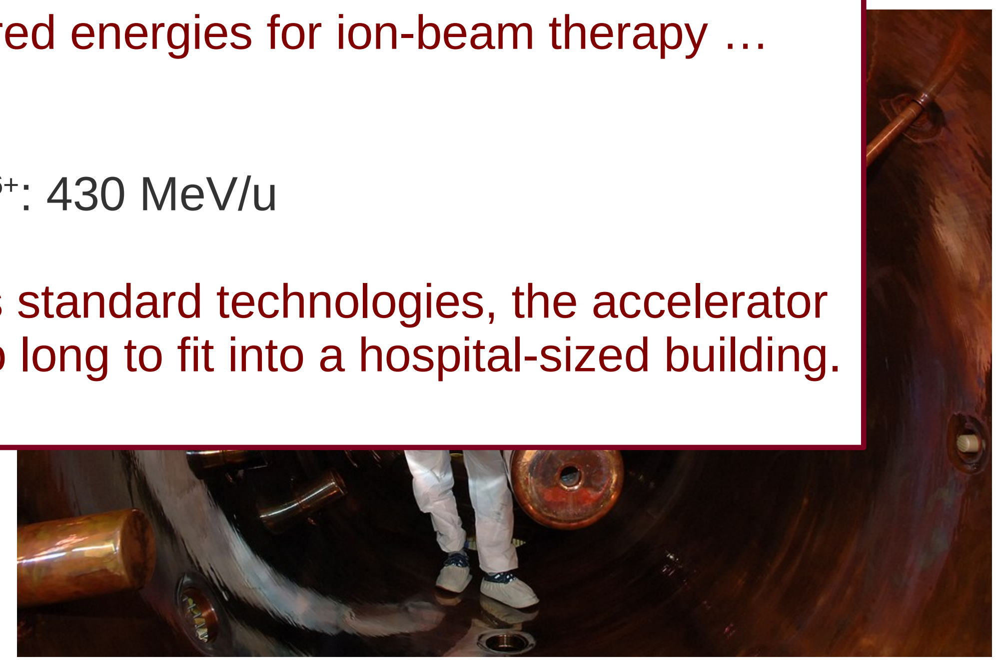
RF linacs *can* in principle deliver the required energies for ion-beam therapy …

p: 220 MeV; $^{12}C^{6+}$: 430 MeV/u

… but with today's standard technologies, the accelerator could be too long to fit into a hospital-sized building.

(2)

→ Alvarez structure of GSI's UNILAC



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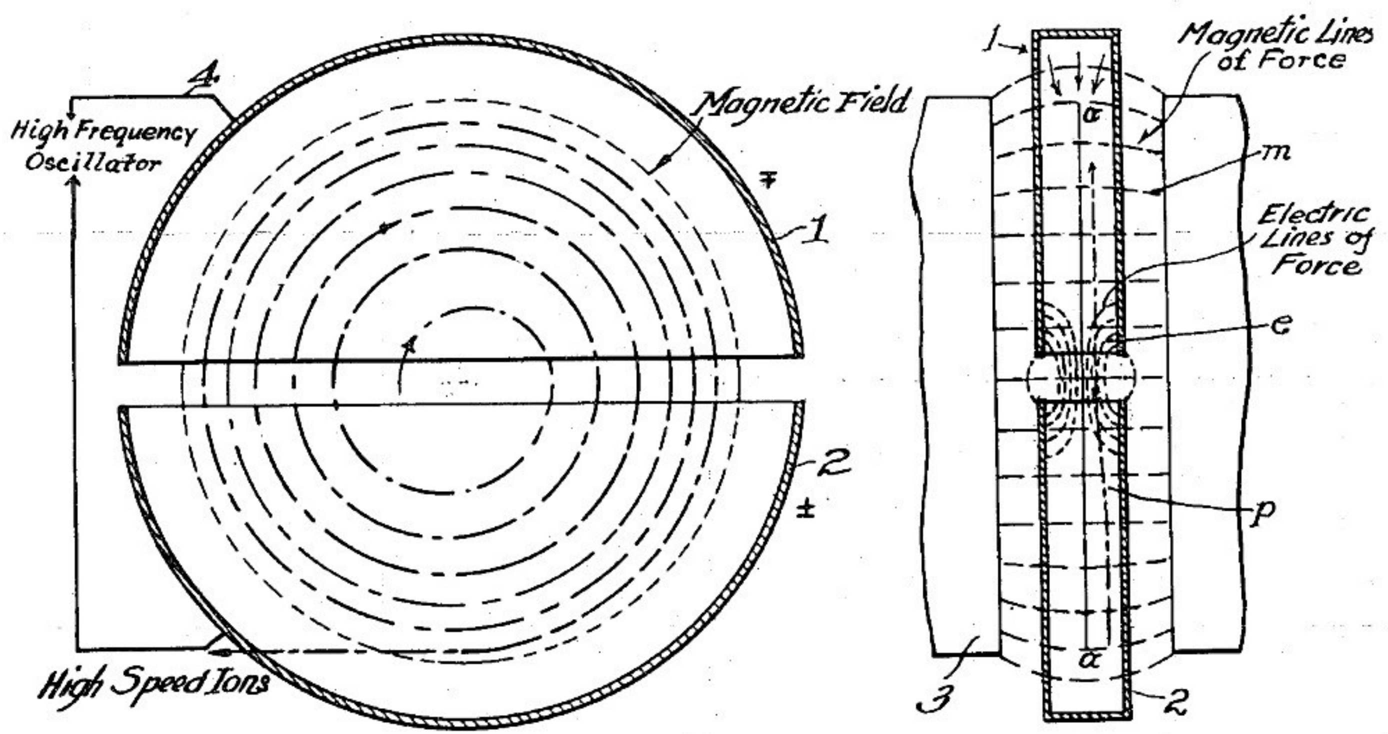
Cyclotrons

Idea: Re-use the same HF acceleration gap over-and-over again.



E. Lawrence's original concept of the cyclotron (1934 patent):

D-shaped RF electrodes ("*Dees*") placed in a disk-like vacuum chamber and embedded in a large (near-homogeneous) static magnetic field.

→ Radius of particle trajectory increases at each passage through the gap.

Classical cyclotron

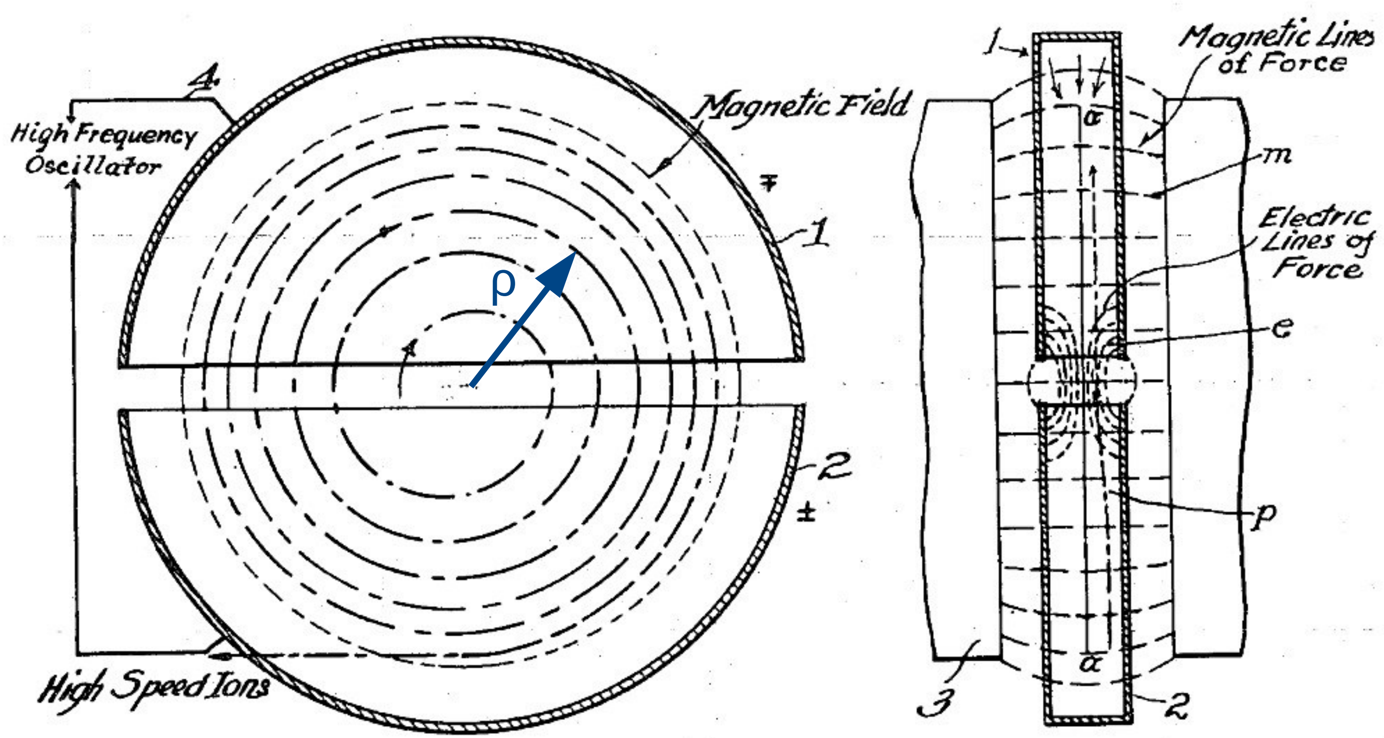
E. Laurence (1934):

Radial acceleration:

$$\frac{F_\perp}{m} = \omega^2 \rho = \frac{q \omega \rho B}{m}$$

→ constant (!)
cyclotron-frequency:

$$\omega_c = \frac{qB}{m}$$



Kinetic energy after n turns:

$$E = 2nqU_{RF}$$

From $E = m\,\omega_c^2 \rho^2 / 2$ → *"cyclotron radius"*

$$\rho(n) = \frac{\sqrt{2Em}}{qB} = \frac{\sqrt{4nqU_{RF}m}}{qB}$$

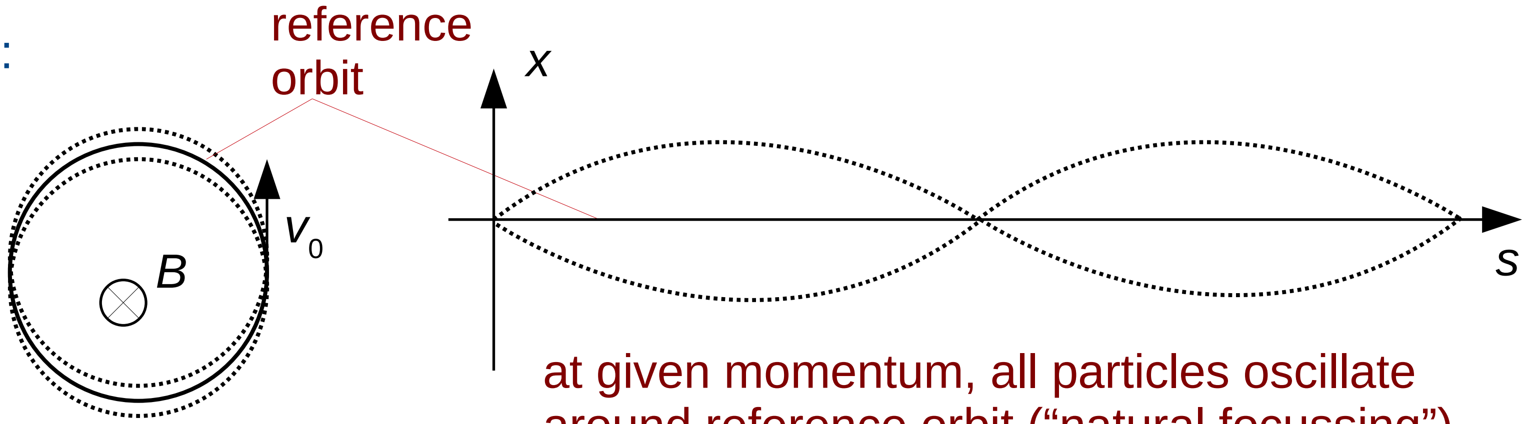
Classical case: machine size ~ $E^{1/2}$

Lawrence's first devices (Berkeley) had

1932: ρ = 35 cm → p (4.8 MeV)
1937: ρ = 47 cm → p (8.0 MeV)
1939: ρ = 76 cm → p (16 MeV)

Classical cyclotron: Stability of transverse motion

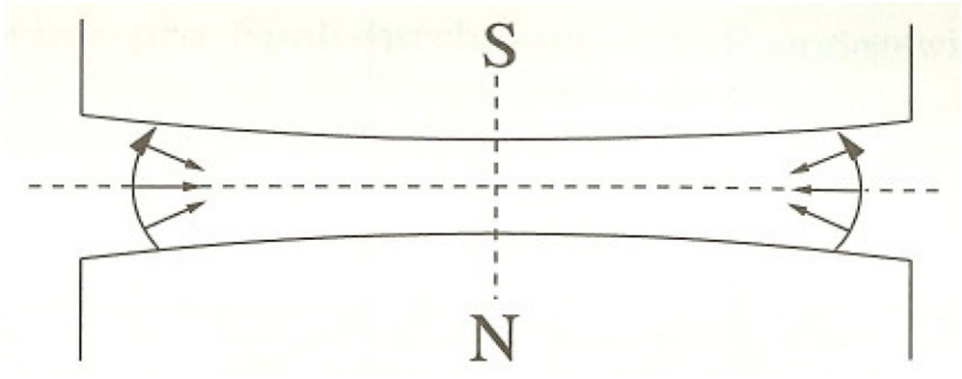
Horizontal direction:



at given momentum, all particles oscillate around reference orbit (“natural focussing”).

Vertical direction:

In the classical cyclotron, the magnetic field *B* decreases (slowly) with *r*.



“Automatic” focussing in the axial direction.

Relativistic cyclotron

For therapy, we need 220 MeV p ($\gamma = 1.25$) or 430 MeV/u $^{12}C^{6+}$ ($\gamma = 1.46$)

→ Relativistic corrections are not negligible!

$$\omega_c = \frac{qB}{m} \rightarrow \omega_{c,rel} = \frac{\omega_c}{\gamma} = \frac{qB}{\gamma m}$$ → Breaks synchronicity with RF. Solutions?

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(1) Synchrocyclotron

Keep **constant B**,
tune RF frequency.

wikipedia.org

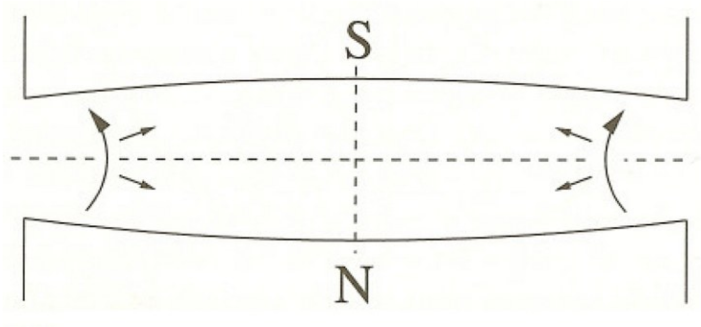
← CERN Synchro-cyclotron: 600 MeV p (1957)

Drawback: Only a short train of particles is in sync with RF ramp.

→ pulsed operation, lower average current.

(2) Isochronous cyclotron

Keep **RF** frequency **constant**,
increase *B* with *r*.



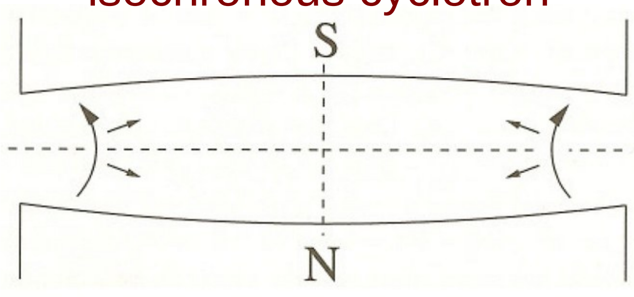
Most modern cyclotrons are isochronous.

→ cw operation

Relativistic cyclotrons

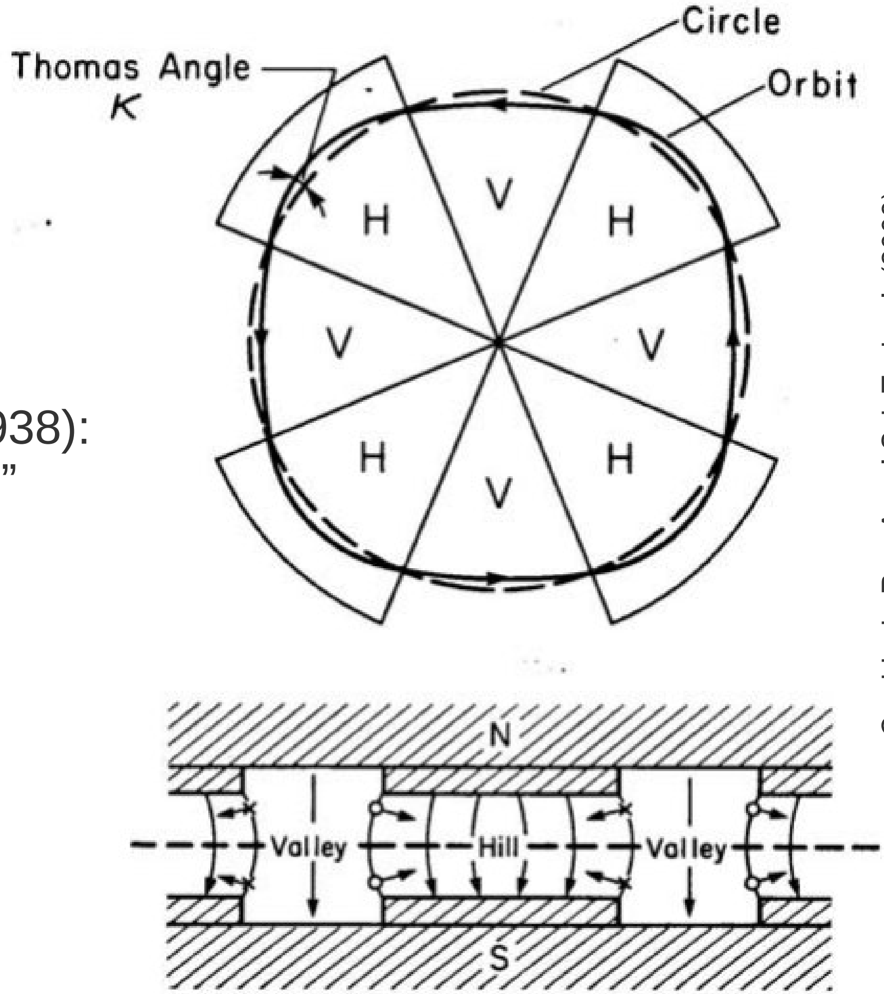
However, with positive gradient in *B*, there is no axial focussing “for free” anymore ...

isochronous cyclotron



Introduce “alternating gradients” (L. Thomas, 1938):
Shape magnet faces to have “hills” and “valleys”

Craddock, Rev. Accel. Sci. Technol. (2008)



Craddock, Rev. Accel Sci. Technol. (2008)

→ “Strong focussing” at sector edges.

Cyclotrons for ion-beam therapy

The cyclotron is *the most used* accelerator for medical purposes.

- Neutron therapy: *(Lawrence & Livingston around 1936 @ 8 MeV-cyclotron in Berkeley)*
  $p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$
  $d + {}^{9}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + n$

- Proton-beam therapy:
  Proposed by R. Wilson in 1946
  First applied 1954 in Berkely
  (J. Lawrence & C. Tobias,
  at the 184"-cyclotron, Berkeley)

- Radioisotope factories for nuclear medicine.

Cyclotrons for ion-beam therapy

Isochronous cyclotron C230 by IBA

Designed for proton therapy.

Installed at 16 facilities.

Mass: 220 t

E = 230 MeV

I_{max} = 300 nA

B = 2.2 T → $\rho \sim 1.1$ m ($D_{outer} \sim 4.5$ m)

A. Peters, CERN Academic Training Lecture (2013)

Cyclotrons for ion-beam therapy

www.psi.ch

COMET superconducting cyclotron

Developed by ACCEL / PSI
(later Varian Medical)
for proton therapy

Mass: 80 t

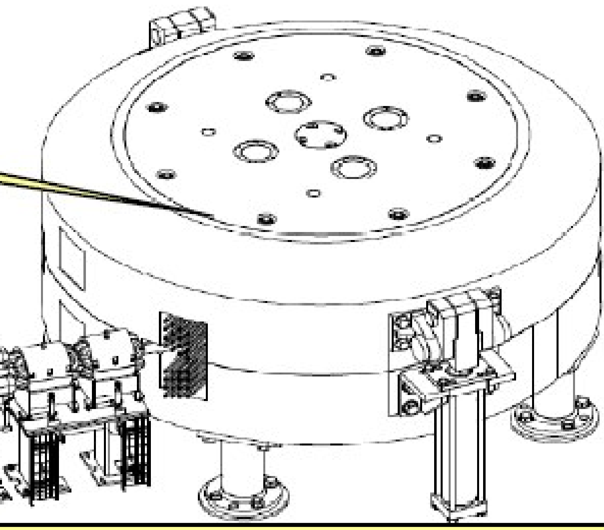
E = 250 MeV

I = 1 … 850 nA

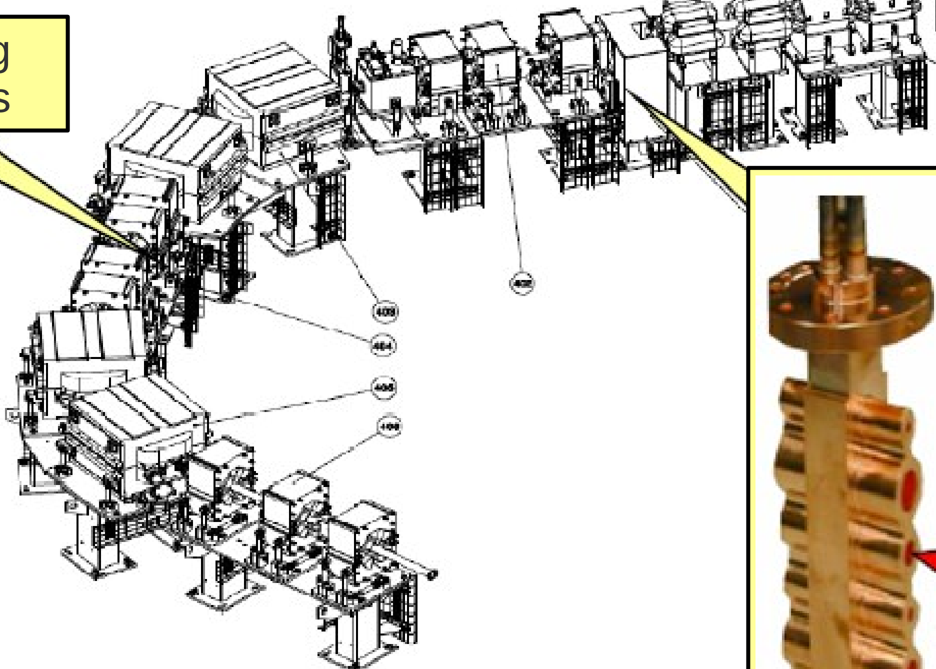
B_{max} = 3.8 T $\rightarrow$ $\rho \sim 0.8$ m
(D_{outer} = 3.1 m)

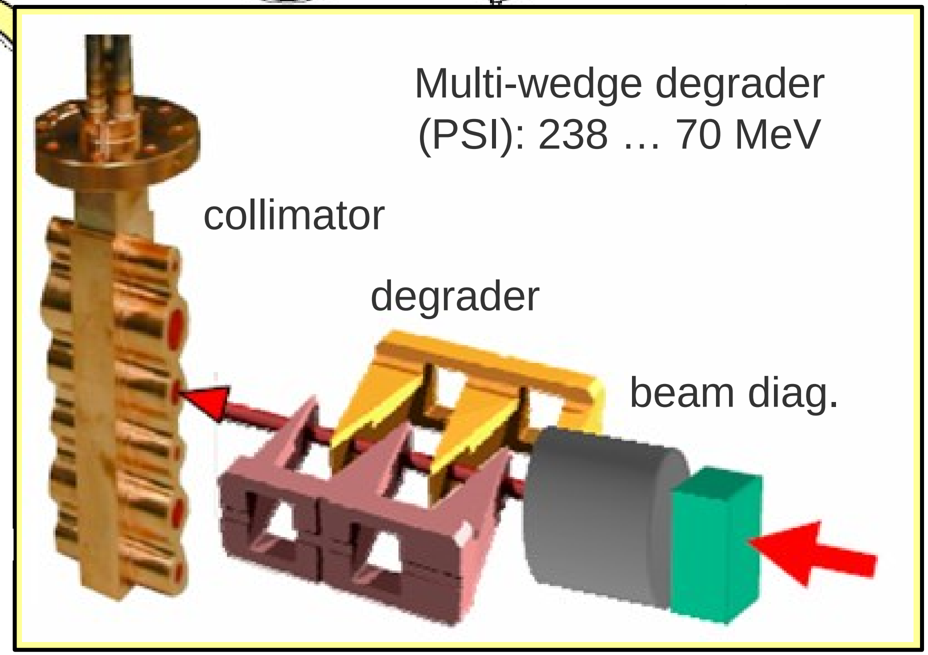
Cyclotrons for ion-beam therapy: Energy selection

A cyclotron is a fixed energy machine …



→ *Degrader* + momentum-selection.





A. Peters, CERN Academic Training Lecture (2013)

At low final *E* >99% of all p are lost!
→ Strong <u>activation</u> of beamline components.

Cyclotrons for ion-beam therapy: $^{12}C^{6+}$?

Cyclotron frequency: $\omega_c = \frac{q\,B}{\gamma\, m} \Leftrightarrow \frac{v}{\rho}\gamma\, m = q\,B \Leftrightarrow \boxed{\frac{p}{q} = B\,\rho}$

"magnetic rigidity":

Relates particle momentum and charge to magnetic field and bending radius.

Arguably the most important quantity in accelerator science!

Protons (220 MeV):	$B\rho$ = 2.3 Tm
$^{12}C^{6+}$ (430 MeV/u):	$B\rho$ = 6.6 Tm

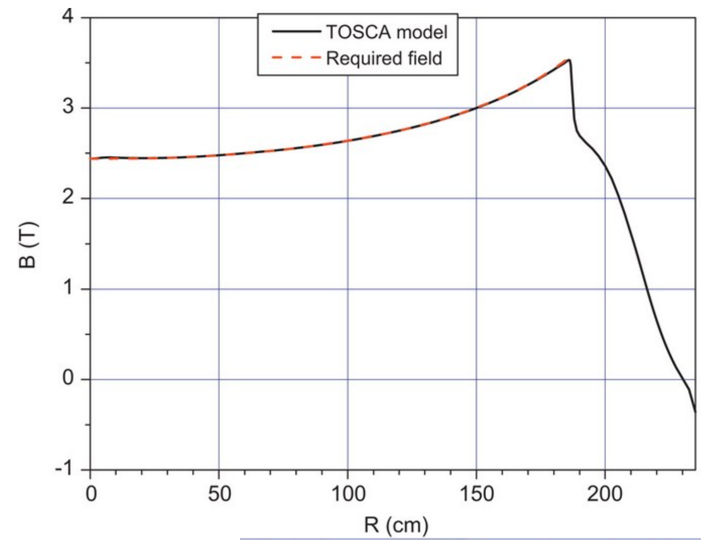
I.e. to go from protons to carbon ions, one needs to increase either the **magnetic field** or the **size** of the machine by a factor ~3.

Although they are very successful in proton therapy, there is no cyclotron for carbon-ion therapy yet.

Cyclotrons for ion-beam therapy: $^{12}C^{6+}$?

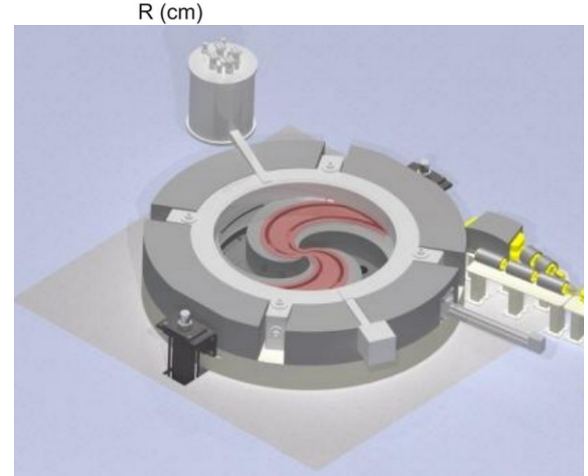
There was a project (“ARCHADE”) to install a carbon-treatment facility in Caen (France).

Should have been based on a superconducting cyclotron (“C400”) developed by IBA.



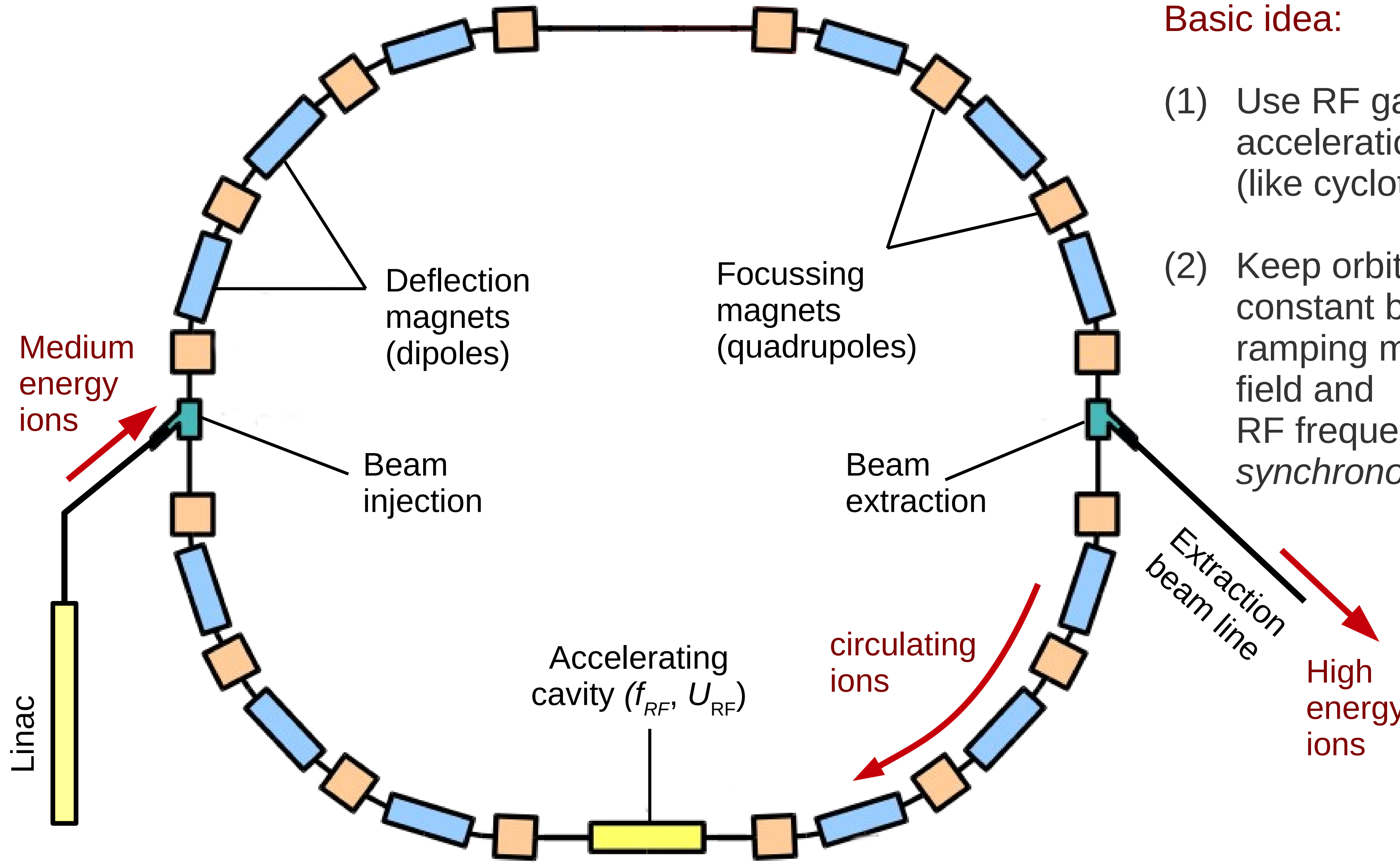
Yongen, NIM A (2010) 642

In 2014, it was decided to build a proton facility first and the C400 project has been postponed ...



Yongen, Proc. of CYCLOTRONS 2010

Synchrotrons



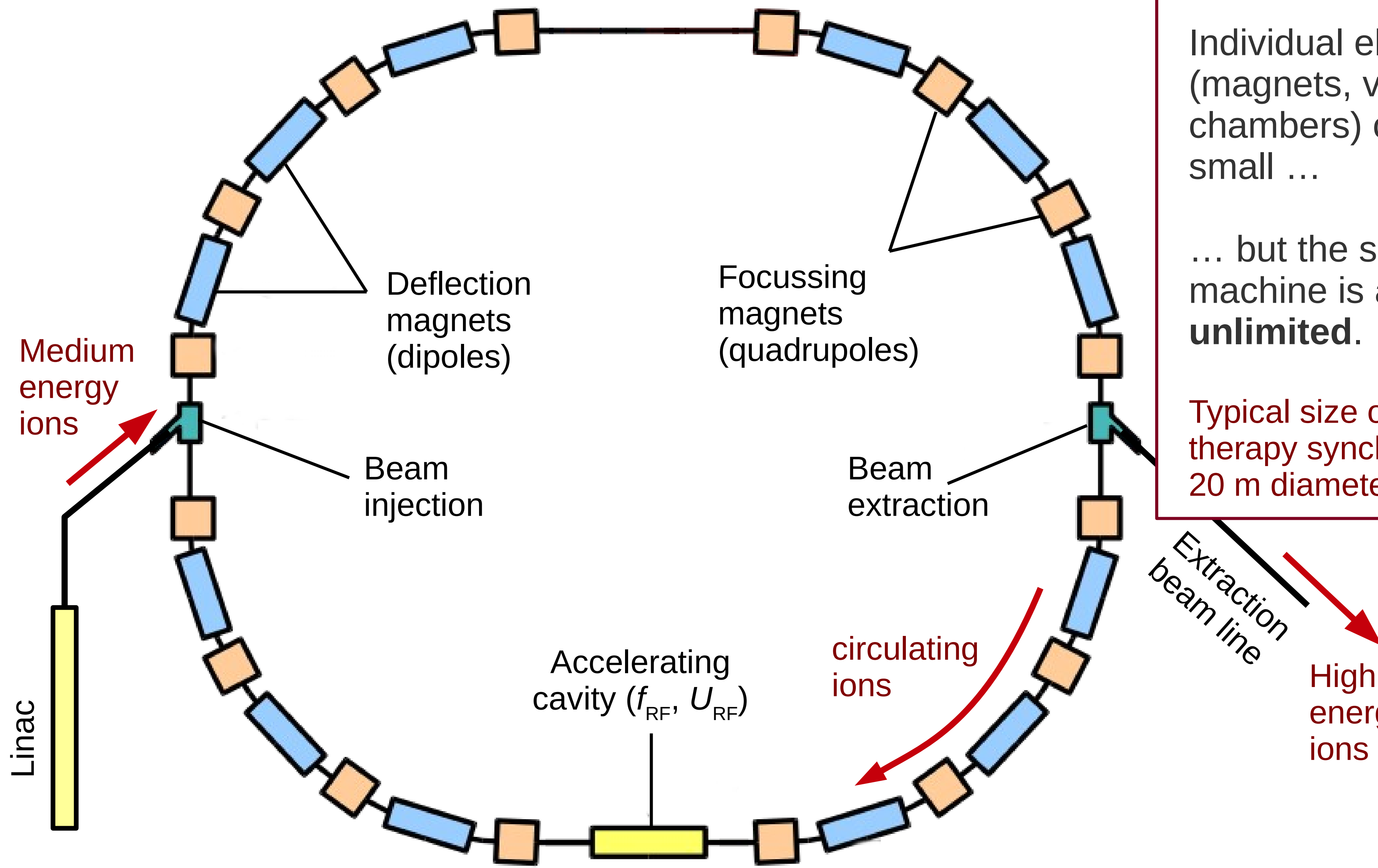
Basic idea:

(1) Use RF gap for acceleration (like cyclotron).

(2) Keep orbit radius constant by ramping magnetic field and RF frequency *synchronously*.

All carbon ion-beam therapy centres in operation use synchrotrons as main acceleration stages.

Synchrotrons



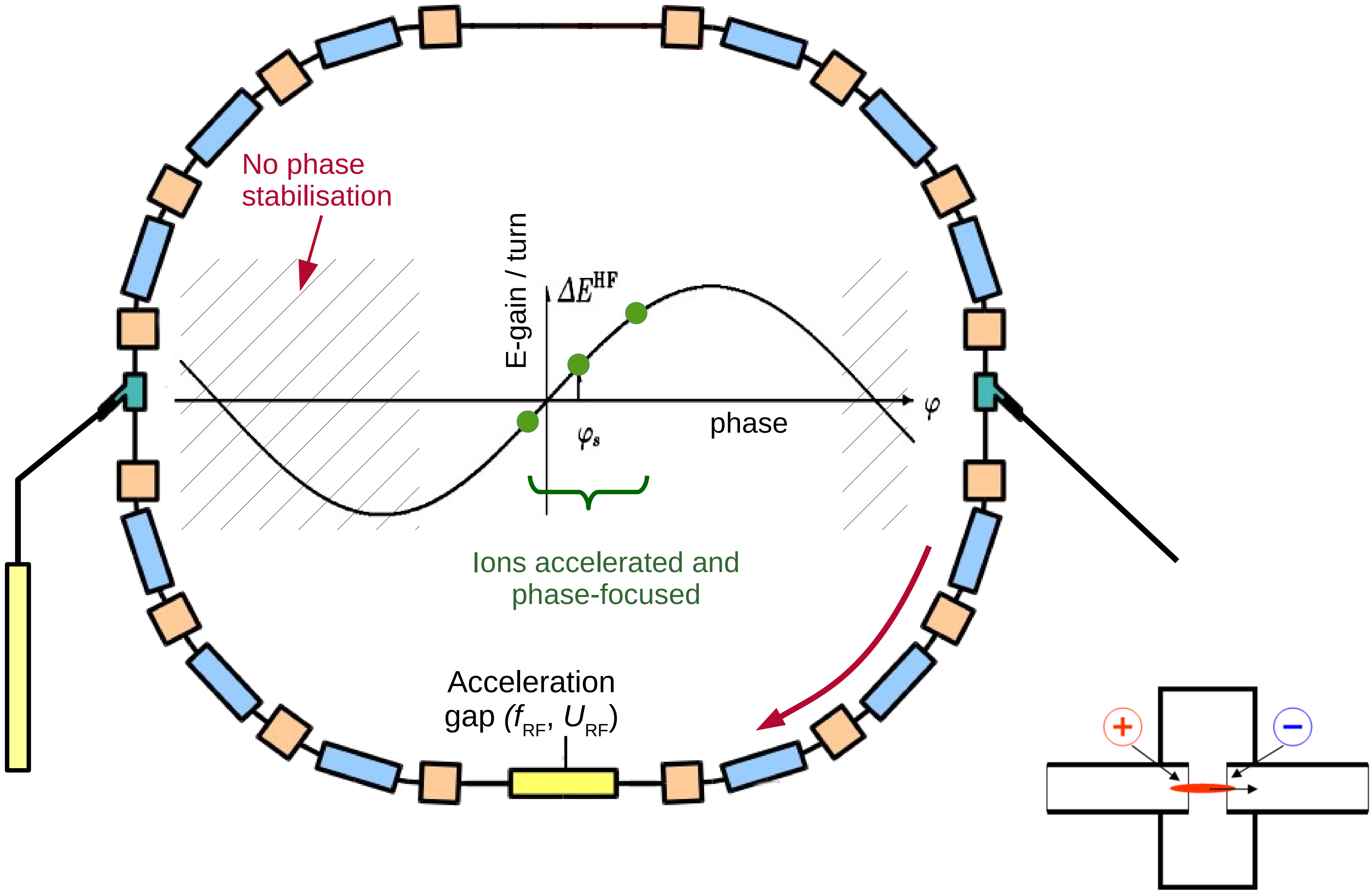
Advantage:

Individual elements (magnets, vacuum chambers) can be small …

… but the size of the machine is **almost unlimited**.

Typical size of p/C therapy synchrotron: 20 m diameter

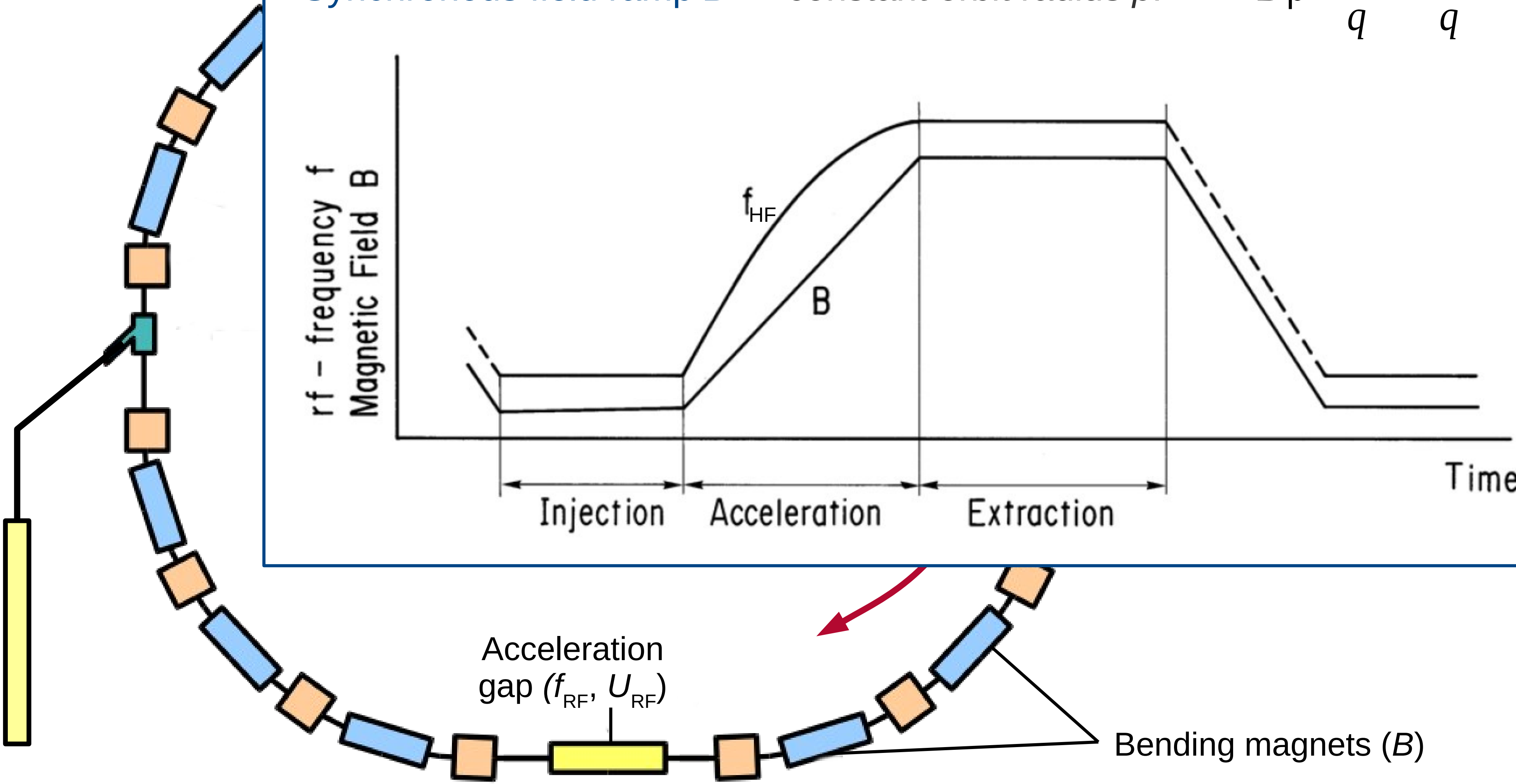
Synchrotrons



Synchrotrons

Particle velocity v ~ RF-frequency f_{RF}: $f_{HF} \sim v$

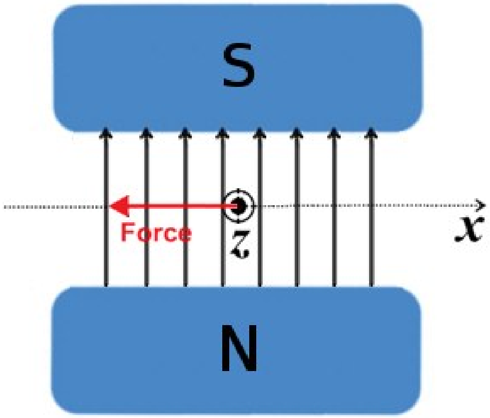
Synchronous field ramp B → constant orbit radius ρ: $B\rho = \frac{p}{q} = \frac{\gamma m v}{q}$



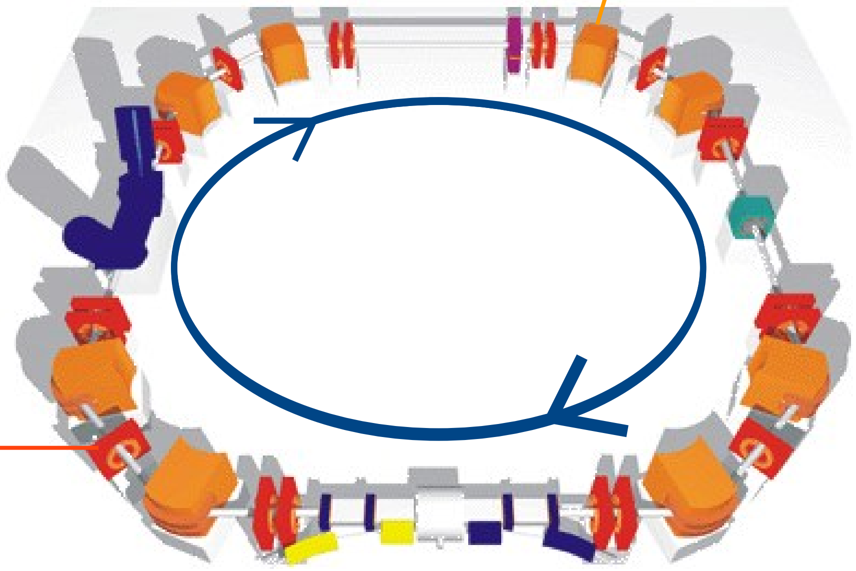
Synchrotrons

www.mpi-hd.mpg.de

Dipole → bending

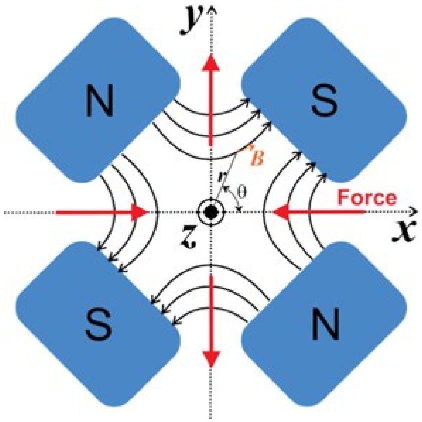


Today, most machines use a "separate function" layout, with individually specialised magnets.

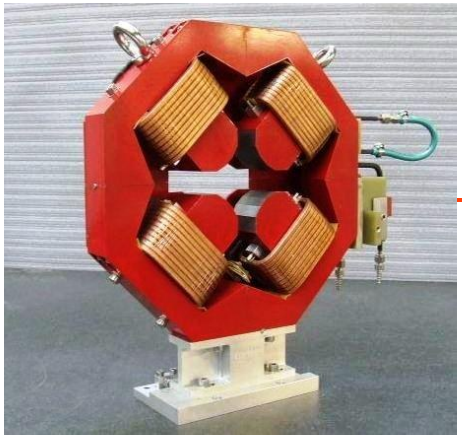


www.mpi-hd.mpg.de

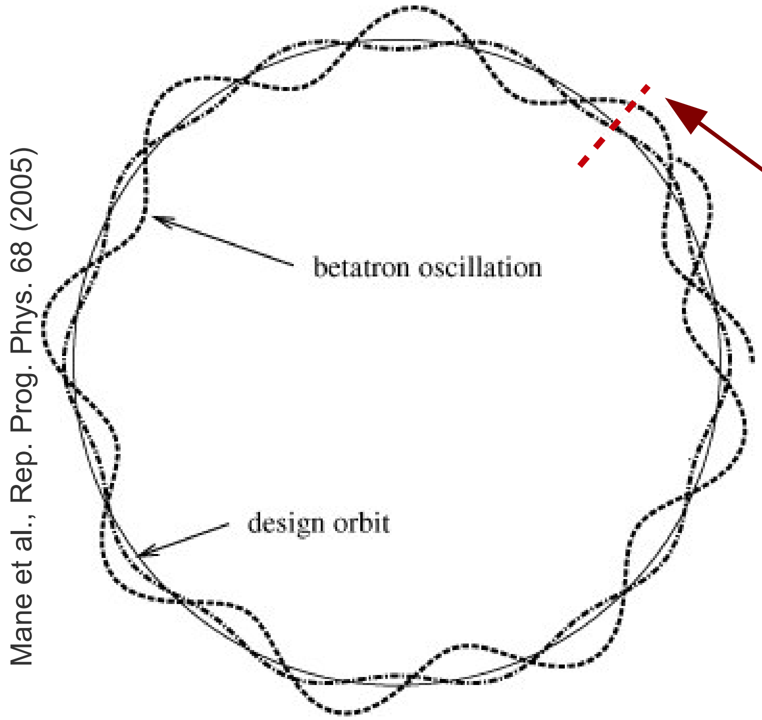
Quadrupole → (de-)focussing



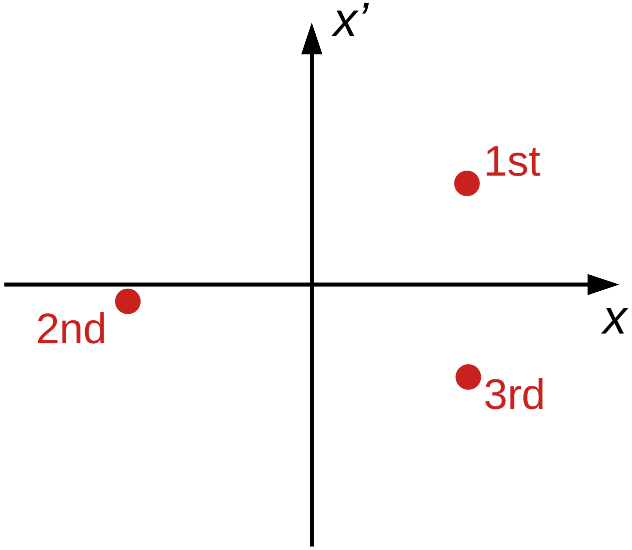
triumf.ca



Synchrotrons: Stability of transverse motion



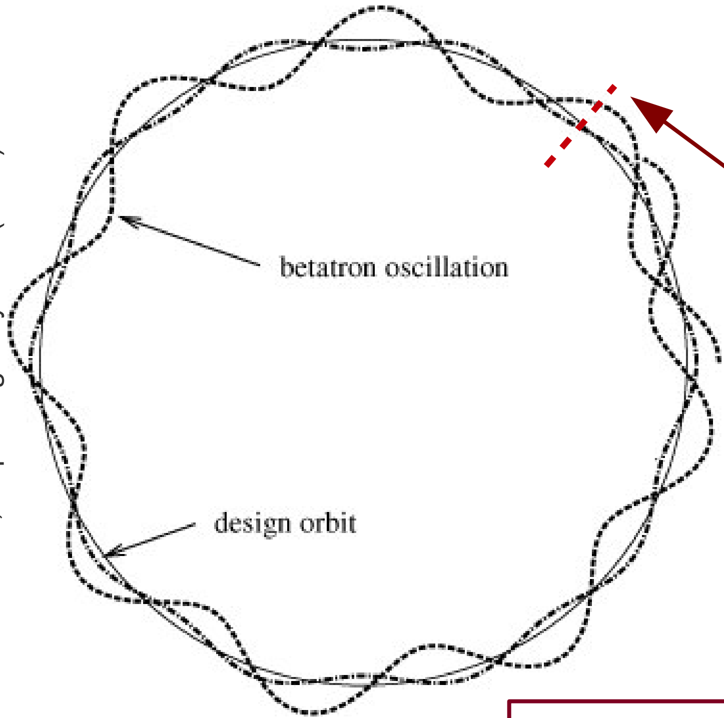
If, in a certain place of the ring, we observed
transverse position (x) and velocity (x')
of a specific ion over many revolutions ...



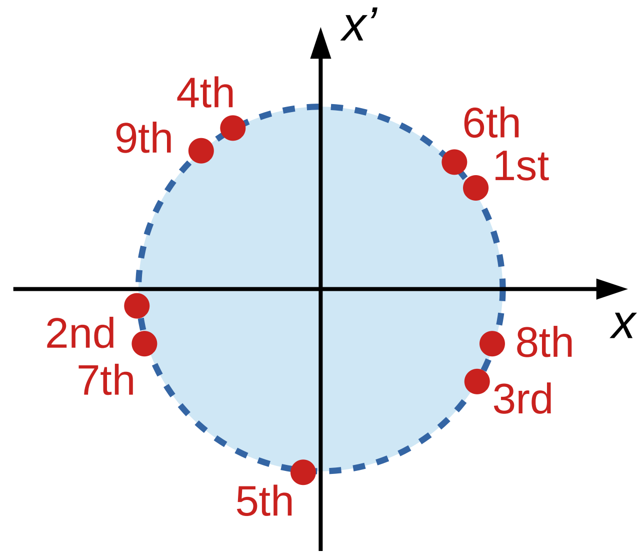
"Betatron oscillation"

Synchrotrons: Stability of transverse motion

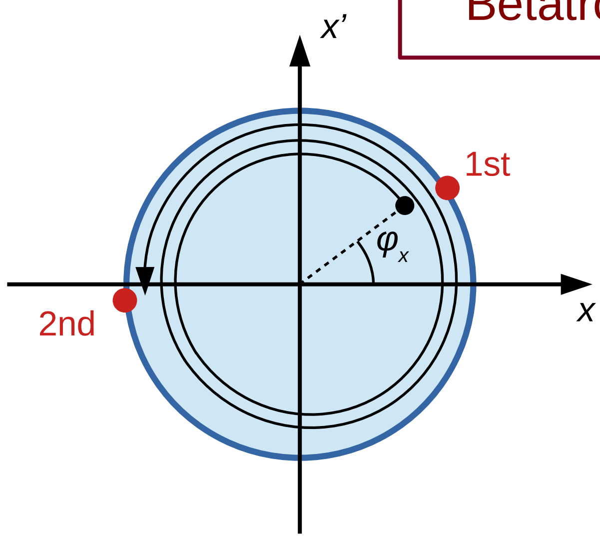
Mane et al., Rep. Prog. Phys. 68 (2005)



If, in a certain place of the ring, we observed transverse position (x) and velocity (x') of a specific ion over many revolutions ...



"Betatron oscillation"



… we'd find that all measured coordinates enclose an elliptic volume of (x, x') phase-space.

The single-turn phase advance defines the "tune":

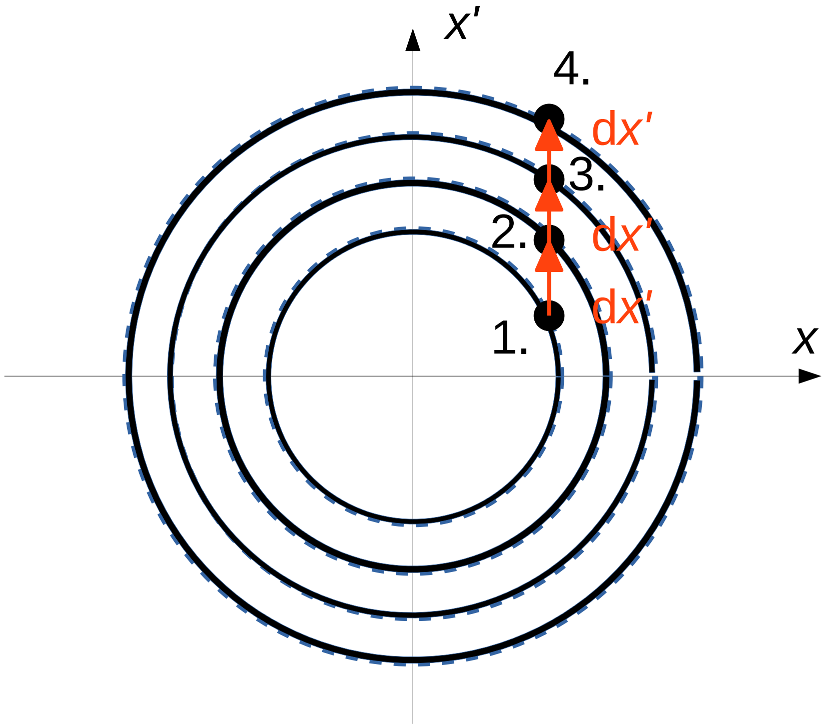
$$Q_x = \frac{1}{2\pi} \oint_{1\,turn} d\,\phi_x$$

Synchrotrons: Stability of transverse motion

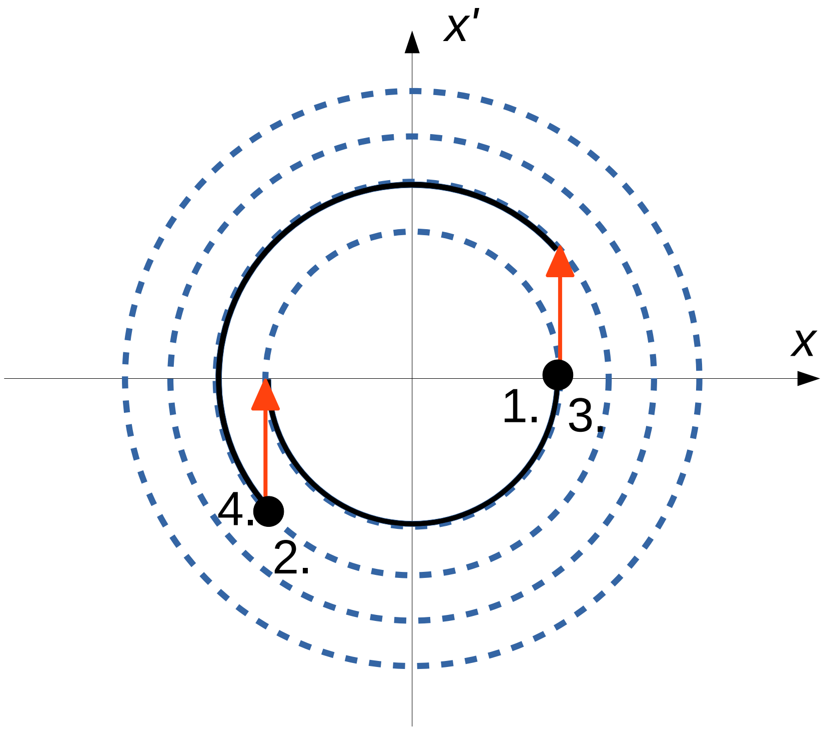
Not all tunes lead to stable transverse motion!

E.g. for an **integer tune**, particle coordinates repeat identically at every turn.

Bending errors d*x*' due to dipole imperfections accumulate,
amplitudes grow beyond *acceptance*.



Integer tune:
bending errors accumulate

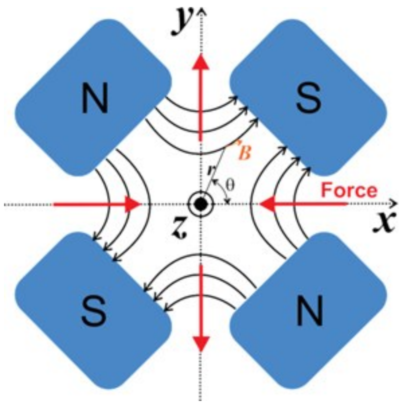


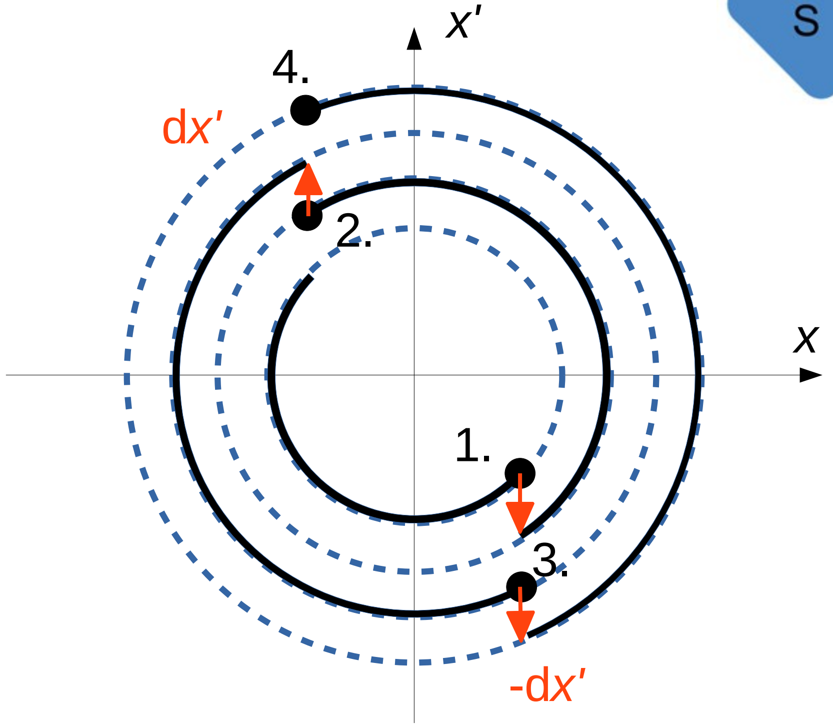
Half-integer tune: bending
errors cancel every 2nd turn.

Synchrotrons: Stability of transverse motion

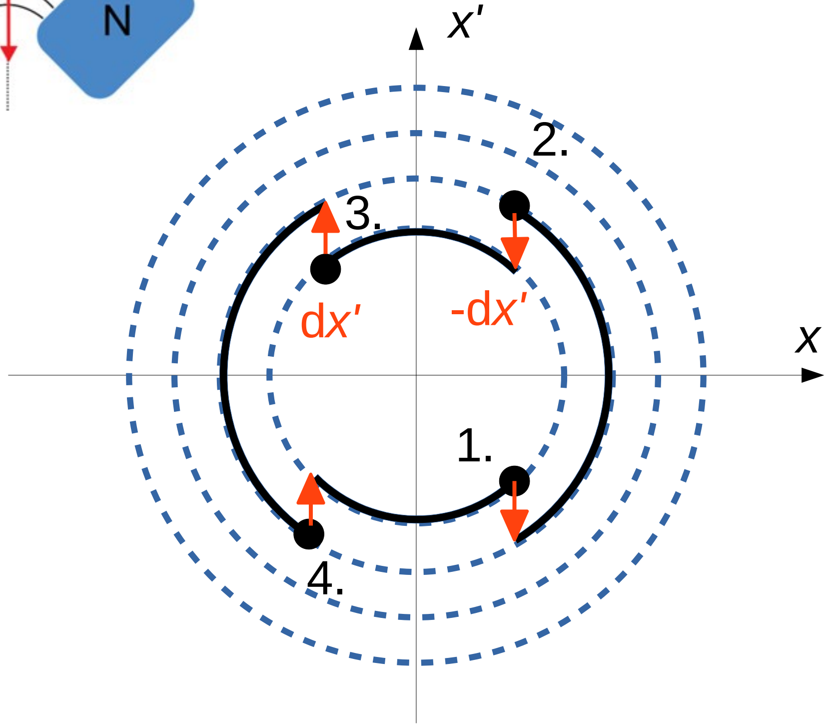
A **half-integer** tune is vulnerable to quadrupole imperfections.

Quadrupole: Deflection **d*x*'** ~ ***x***.



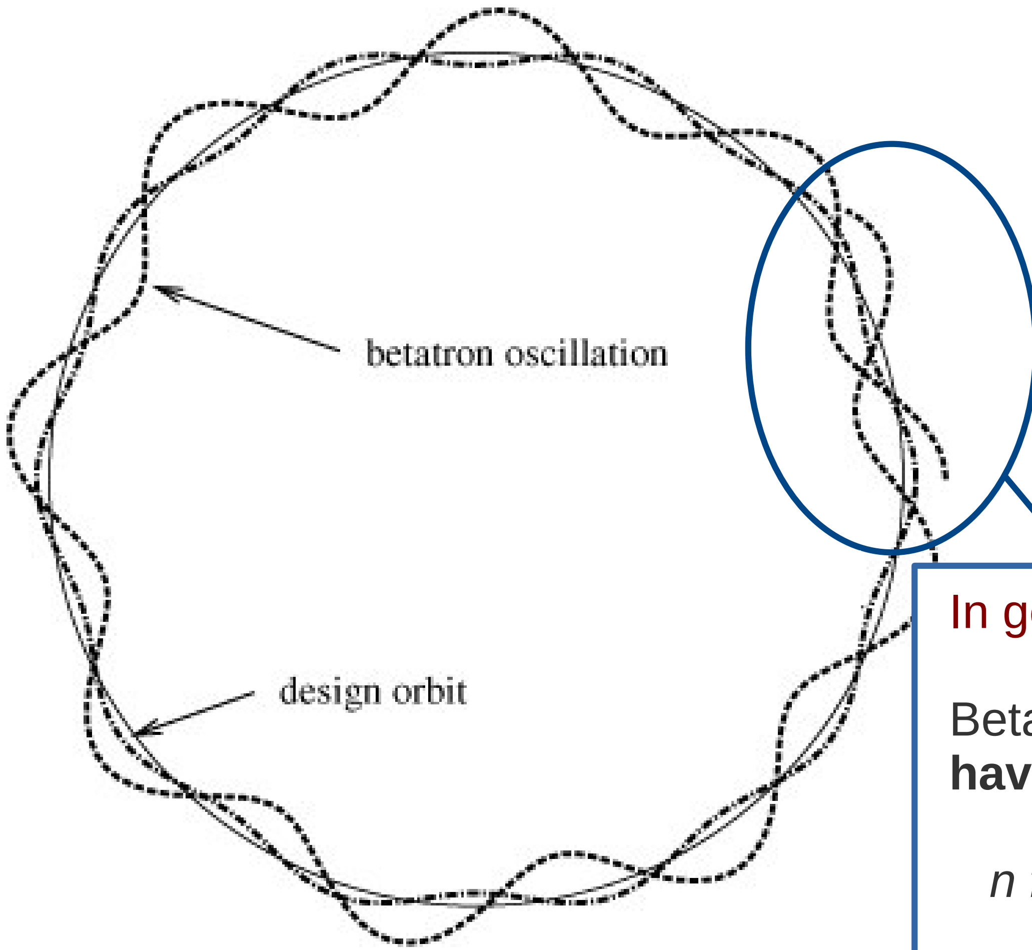


Half-integer tune: quad errors accumulate beyond limits.



Forth-integer tune: quad errors cancel out.

Synchrotrons: Stability of transverse motion



Mane et al., Rep. Prog. Phys. 68 (2005)

In general:

Betatron and revolution frequencies must **not have** a small common multiple ("resonance"):

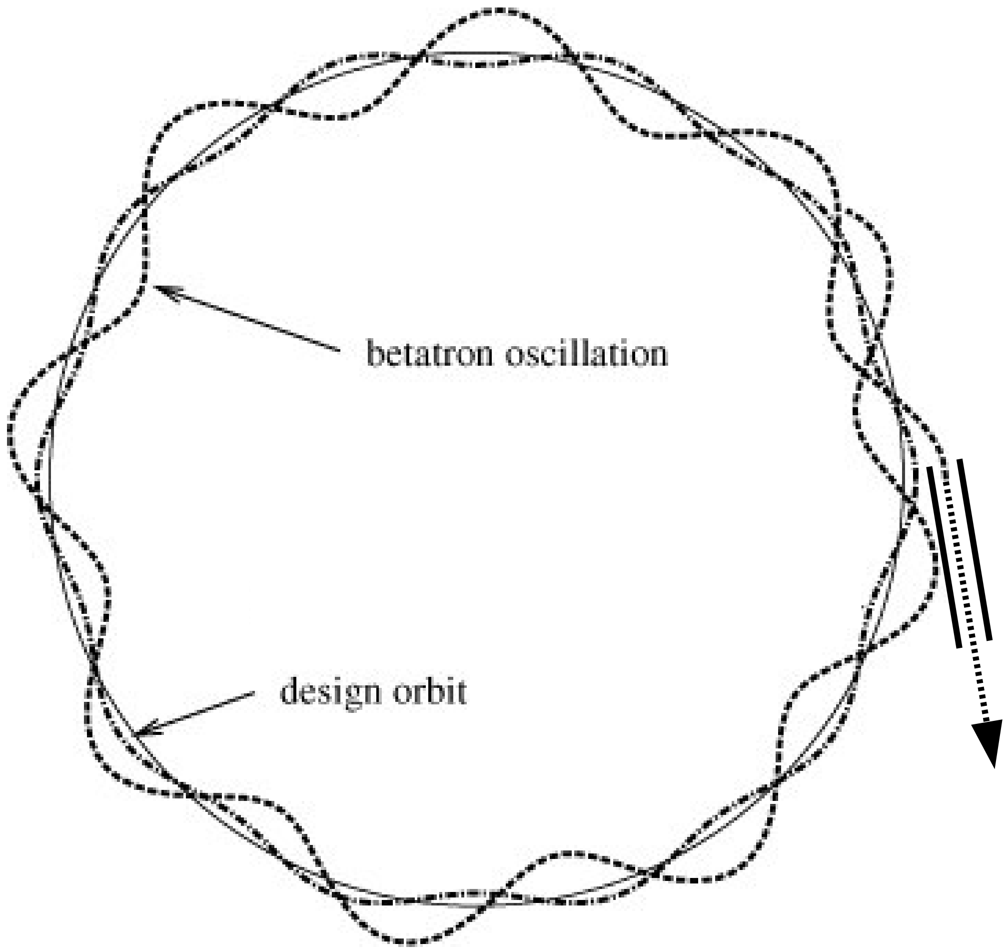
$$n\, f_{\mathrm{Beta}} \neq m\, f_{\mathrm{Rev}}$$

Otherwise energy is transferred efficiently from forward motion to betatron oscillation, leading to particle loss.

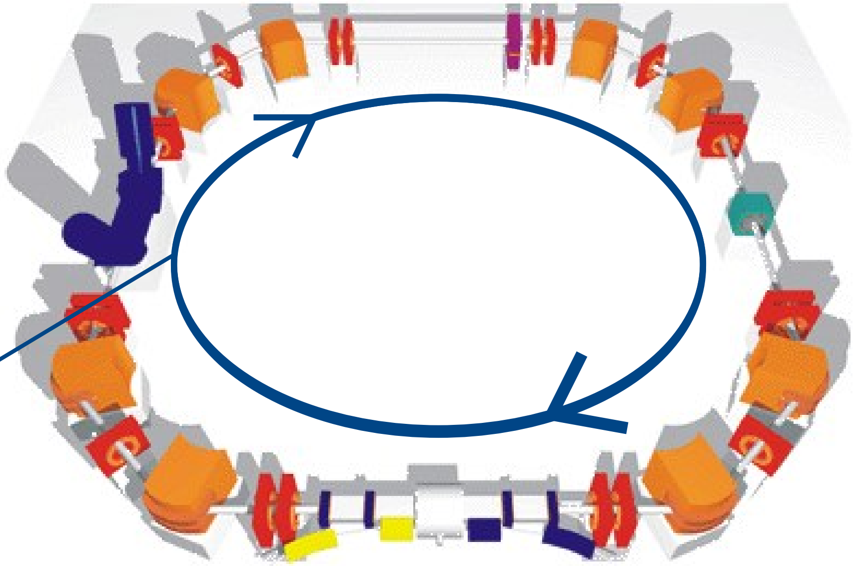
Synchrotrons: Beam extraction

“Slow extraction”

Exploit instability of horizontal betatron motion at resonance conditions: $\boldsymbol{n\ f_{\mathrm{Beta}} \approx m\ f_{\mathrm{Rev}}}$



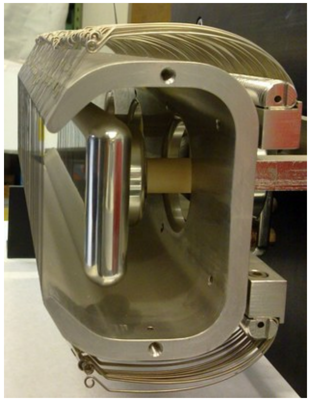
Mane et al., Rep. Prog. Phys. 68 (2005)



www.mpi-hd.mpg.de

Extraction septum:

Very thin electrostatic deflector



Synchrotrons: Beam extraction

Exploit instability of horizontal betatron motion at resonance conditions: $\boldsymbol{n\, f_{\mathrm{Beta}} \approx m\, f_{\mathrm{Rev}}}$

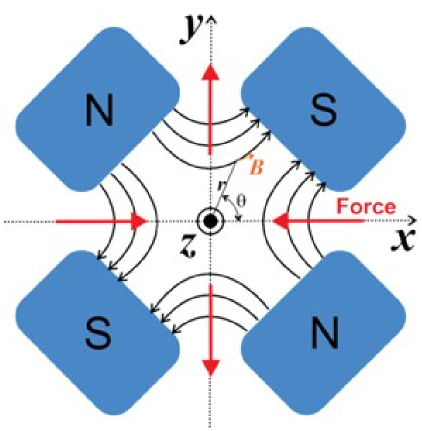
The “art” of slow extraction: *Make sure particles enter resonance “one-by-one”.*

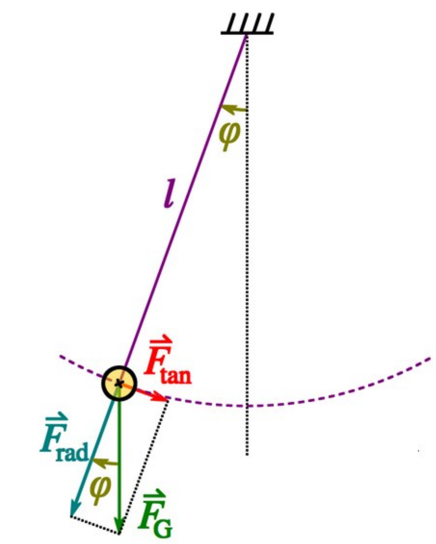
→ if successful: Quasi-DC emitted beam of several s duration (“spill”)

General approach:

Take advantage of the fact that f_{Beta} is not the same for every particle!

E.g. Betatron frequency depends on betatron amplitude if one considers higher field orders!





Analogy

Gravitational pendulum:

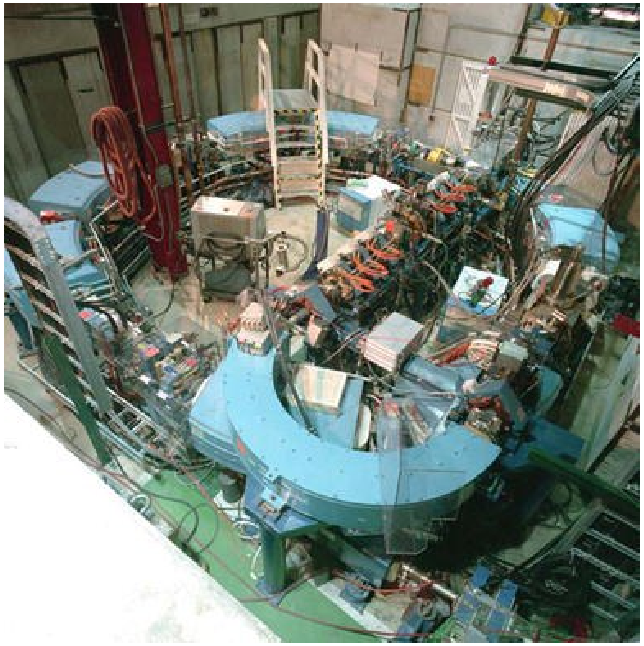
Motion is harmonic only for small displacements.

Synchrotrons: Beam extraction

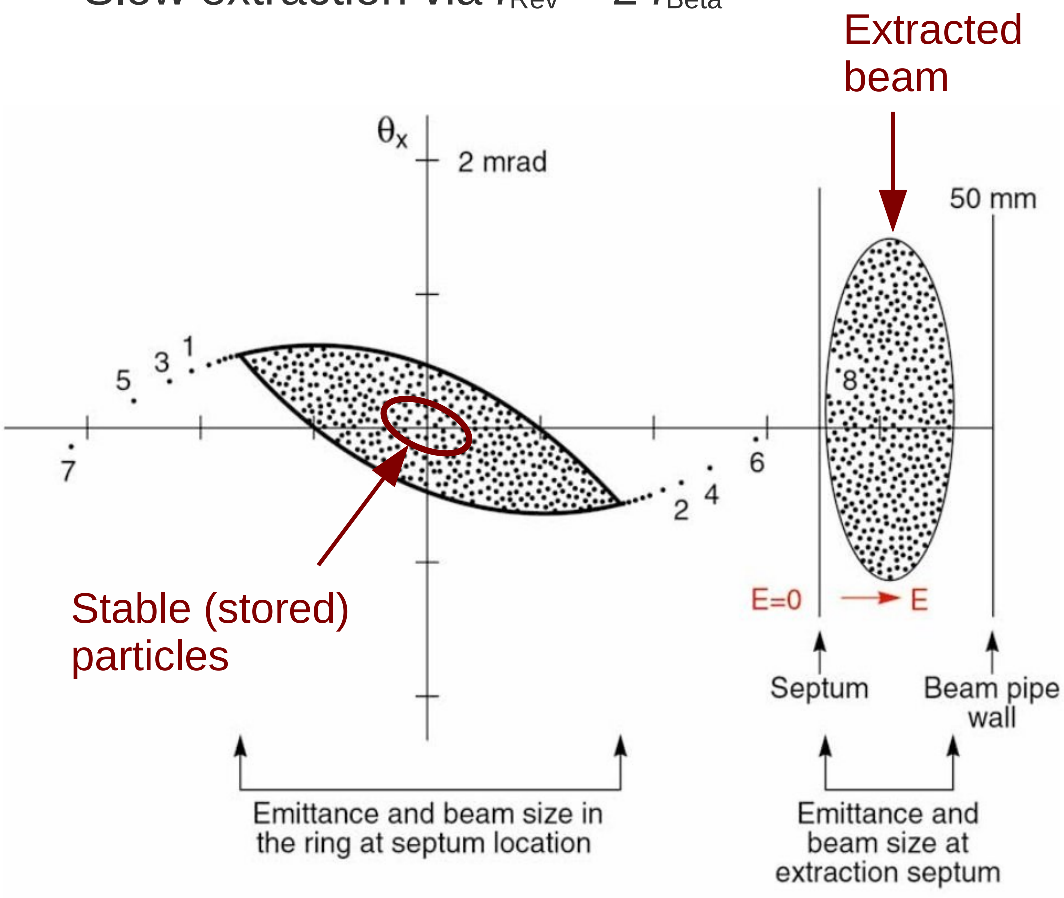
Example 1: Loma Linda University Medical Center (USA)

250-MeV *p*-synchrotron for ion-beam therapy.

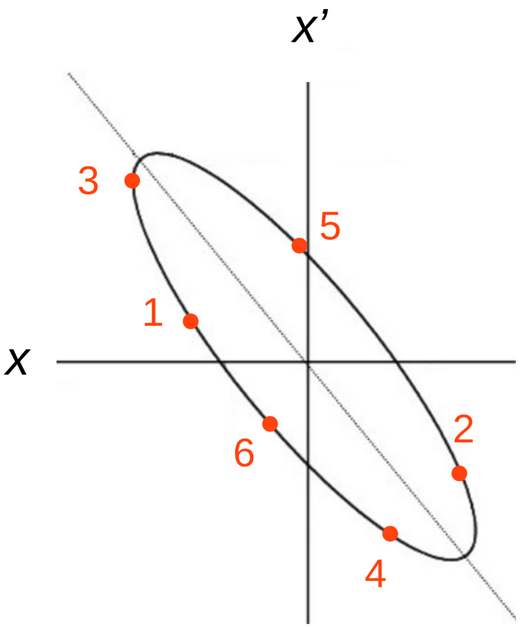
Slow extraction via $f_{\mathrm{Rev}} \approx 2\, f_{\mathrm{Beta}}$



Endo, M. Radiol Phys Technol (2018) 11: 1



G. Coutrakon, PTCOG 47



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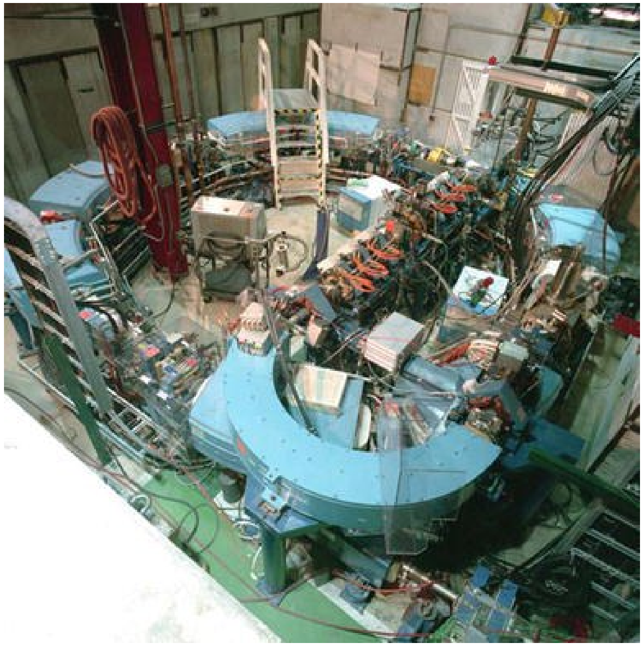
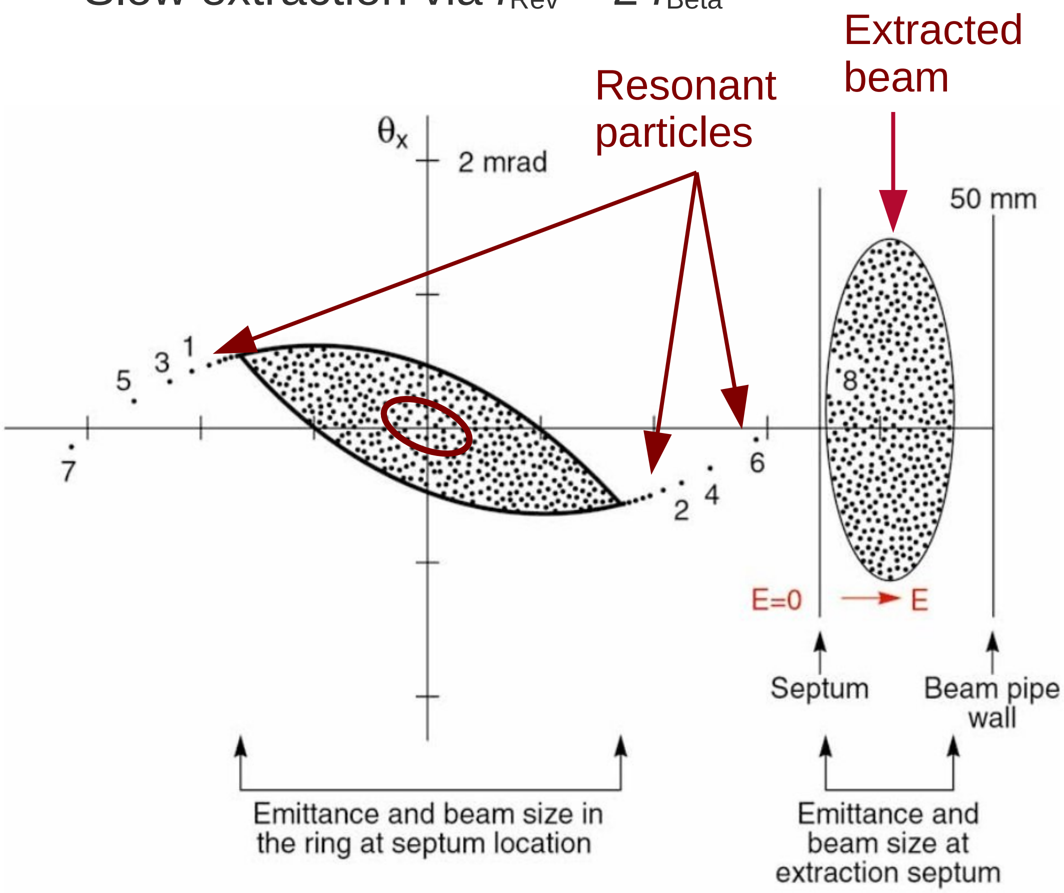
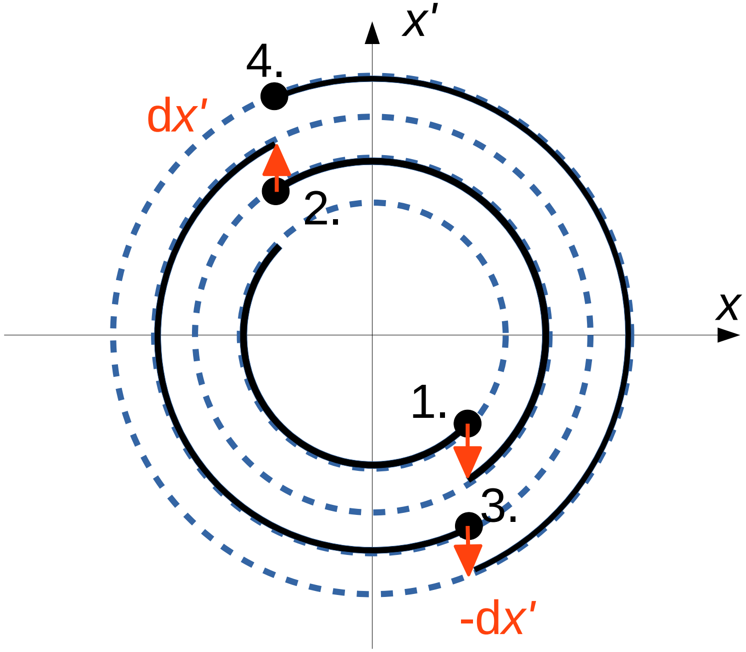


Endo, M. Radiol Phys Technol (2018) 11: 1



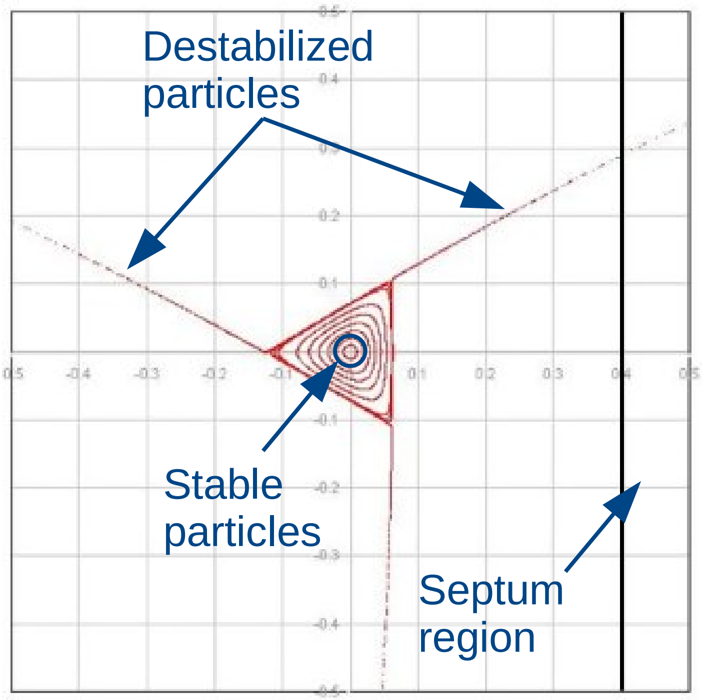
G. Coutrakon, PTCOG 47

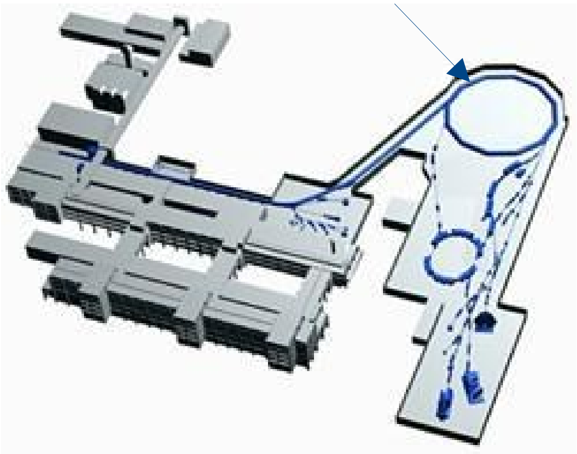


Synchrotrons: Beam extraction

Example 2: GSI experimental $^{12}C^{6+}$ program

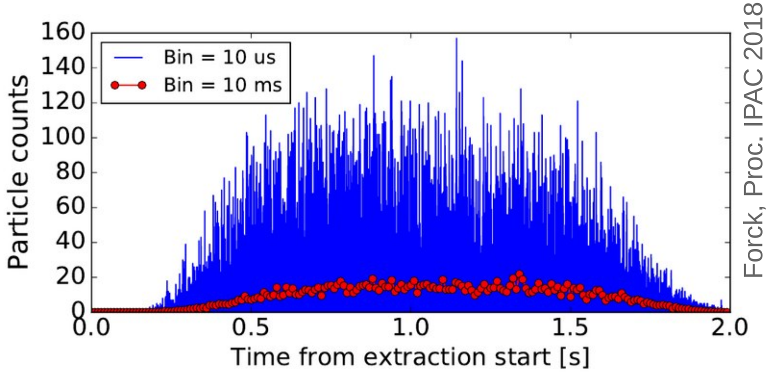
Slow extraction from SIS18 synchrotron via 3rd order (sextupole) resonance.





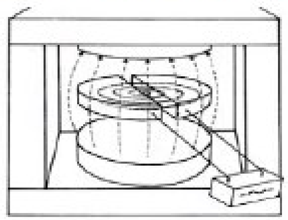
SIS18, GSI (Darmstadt)

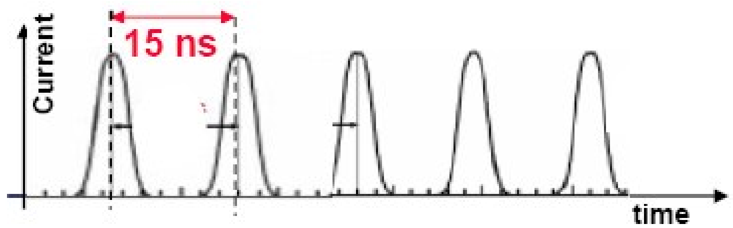
Extracted SIS18 "spill"



Cyclotron beam vs. Synchrotron beam

Cyclotron





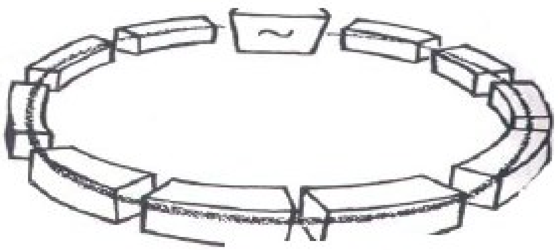
Pros

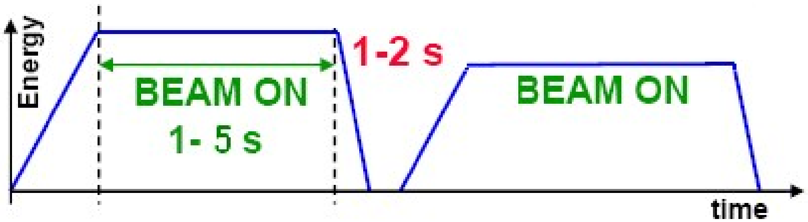
- cw-operation: continuous train of short particle bunches.
- High intensity (high dose rates).
- Ion intensity easily variable *(modulation of ion source current).*

Cons

- Fixed energy: needs degraders *(particle loss, radiation safety issues)*.
- Heavy ions ($^{12}C^{6+}$) would require very large magnet and chamber.

Synchrotron





Pros

- Scalable to arbitrary *Bρ*, can deliver heavy ions.
- Variable energy, (almost) no particle losses.

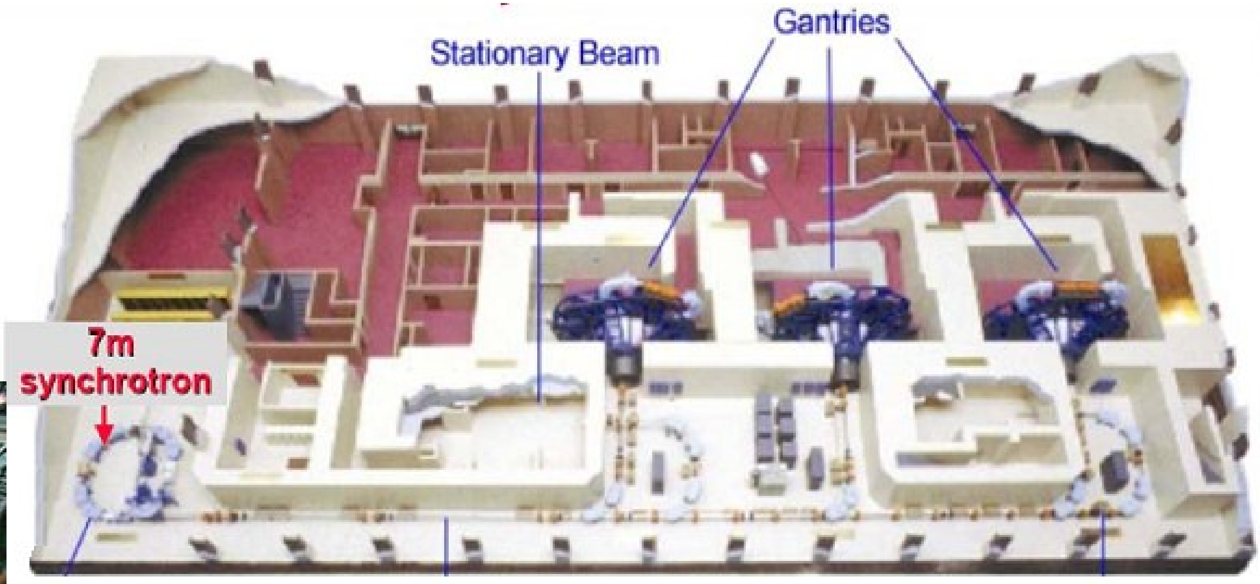
Cons

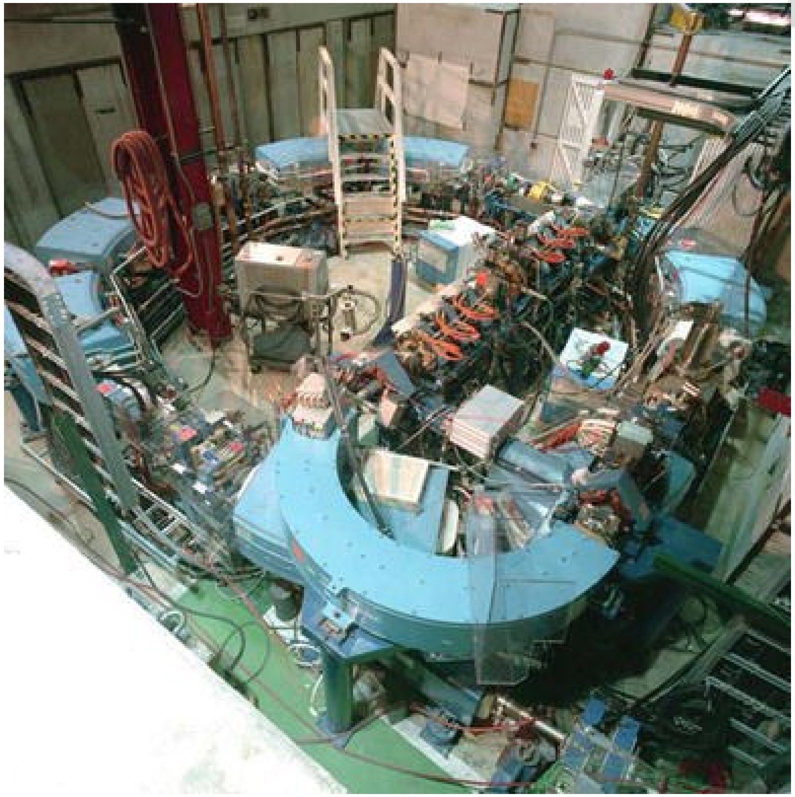
- Control of beam intensity is difficult.
- Pulsed operation, breaks between cycles
- Very high dose rates hard to achieve.

→ *see advanced topics chapter!*

Synchrotron ion-beam therapy facilities

Loma Linda, USA





Endo, M. Radiol Phys Technol (2018) 11: 1

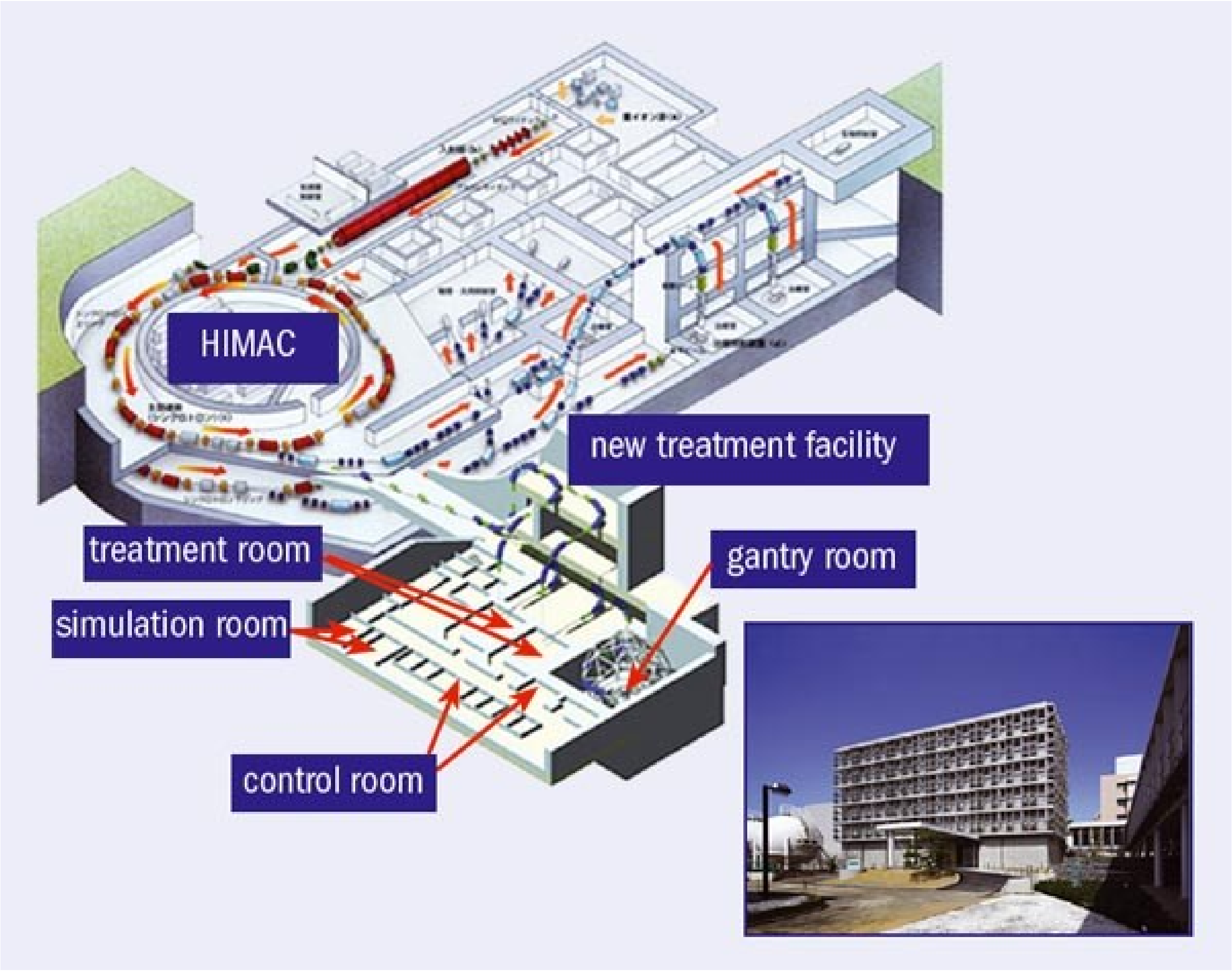
1st hospital-based proton therapy centre

(since 1990)

Proton synchrotron designed by Fermilab

> 20000 patients treated

Synchrotron ion-beam therapy facilities



cern.ch

Chiba, Japan:

HIMAC (Heavy-Ion Medical Accelerator in Chiba, NIRS, 1994)

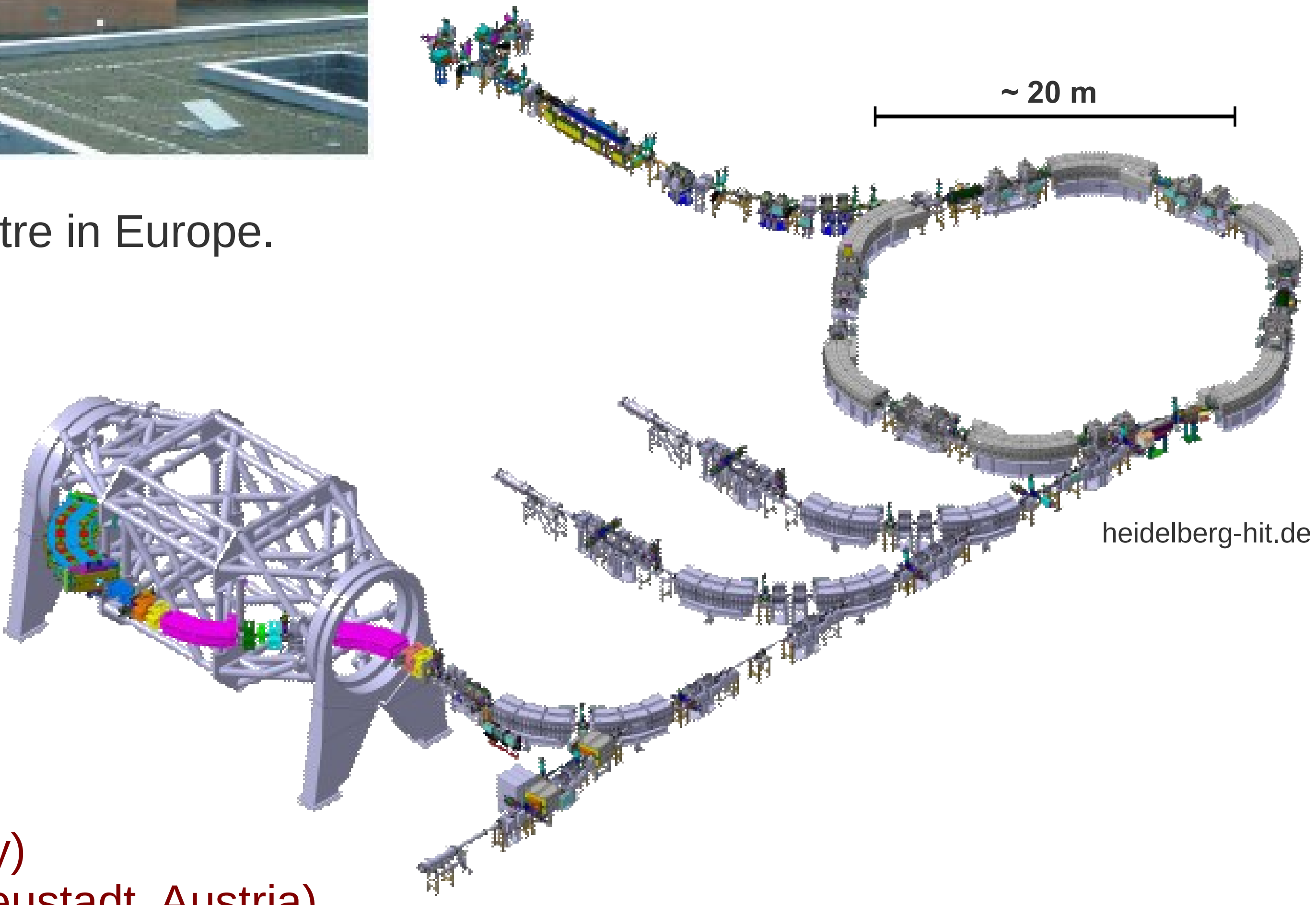
Two 800 MeV/u synchrotrons, for ions up to $^{40}Ar^{18+}$, mostly $^{12}C^{6+}$.

> 10000 patients treated with $^{12}C^{6+}$ (2015)

Synchrotron ion-beam therapy facilities

Heidelberg, Germany

Heidelberg Ion-Beam Therapy Centre (HIT), from 2009, based on GSI experiments.



First hospital-based p/C centre in Europe.

> 7000 patients (2022)

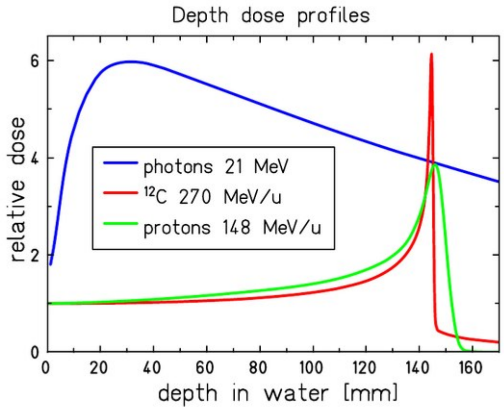
First isocentric $^{12}C^{6+}$ gantry.

Today, 3 more facilities in Europe, closely following the HIT design:

CNAO (Pavia, Italy)
MIT (Marburg, Germany)
MedAustron (Wiener Neustadt, Austria)

Outline

Beam requirements

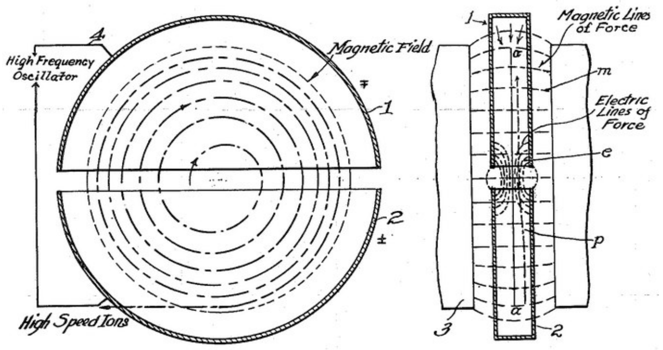


[**Accelerator systems**]()

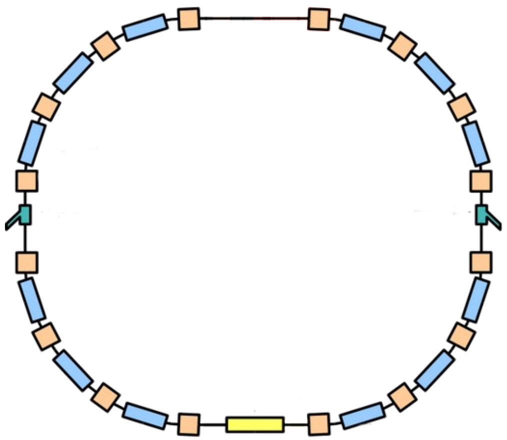
Cyclotron vs. Synchrotron

Overview of some facilities

[Recent developments and alternative concepts]()



Latest synchrotron R&D



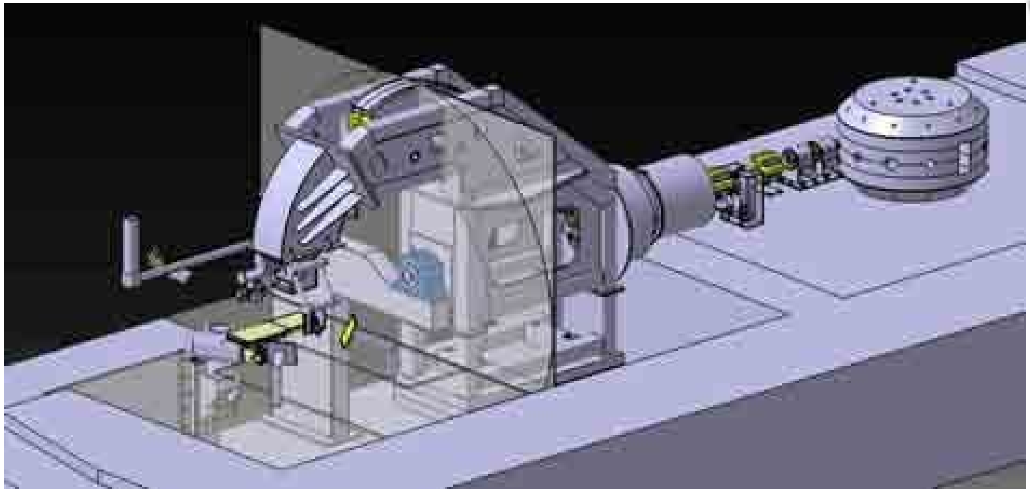
Single-room solutions

Many efforts to down-size proton accelerators.

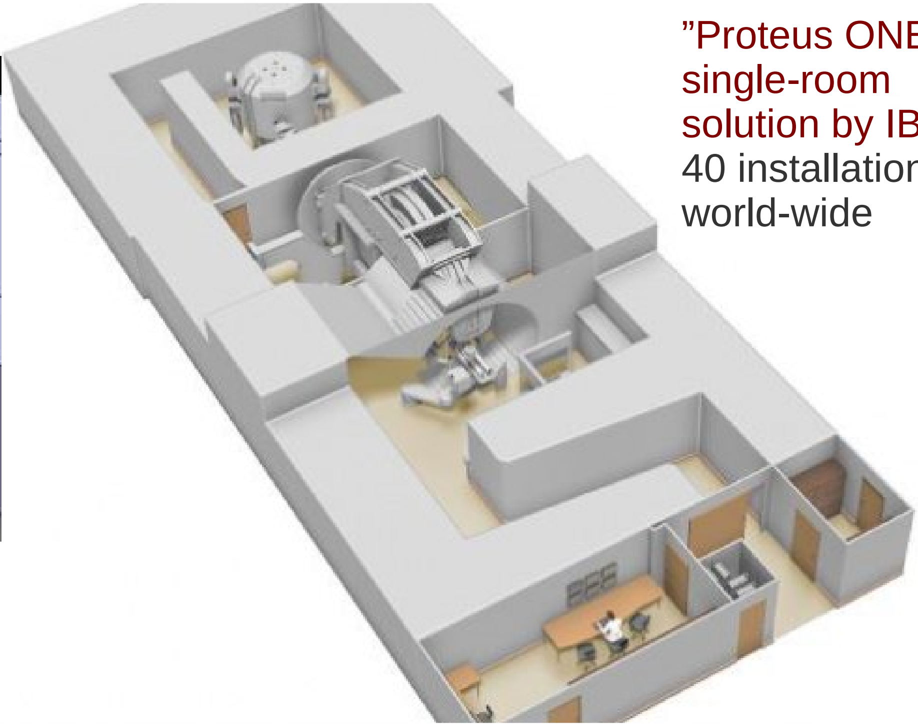
Many newly-installed systems are single-room solutions.

S2C2 superconducting synchrocyclotron (IBA)
2.5 m diameter.

iba-worldwide.com



Alonso and Antaya, Rev. Accel. Science Technol. 5 (2012) 227



”Proteus ONE” single-room solution by IBA:
40 installations world-wide

Single-room solutions

Alonso and Antaya, Rev. Accel. Science Technol. 5 (2012) 227

mevion.com

S250 system by Mevion

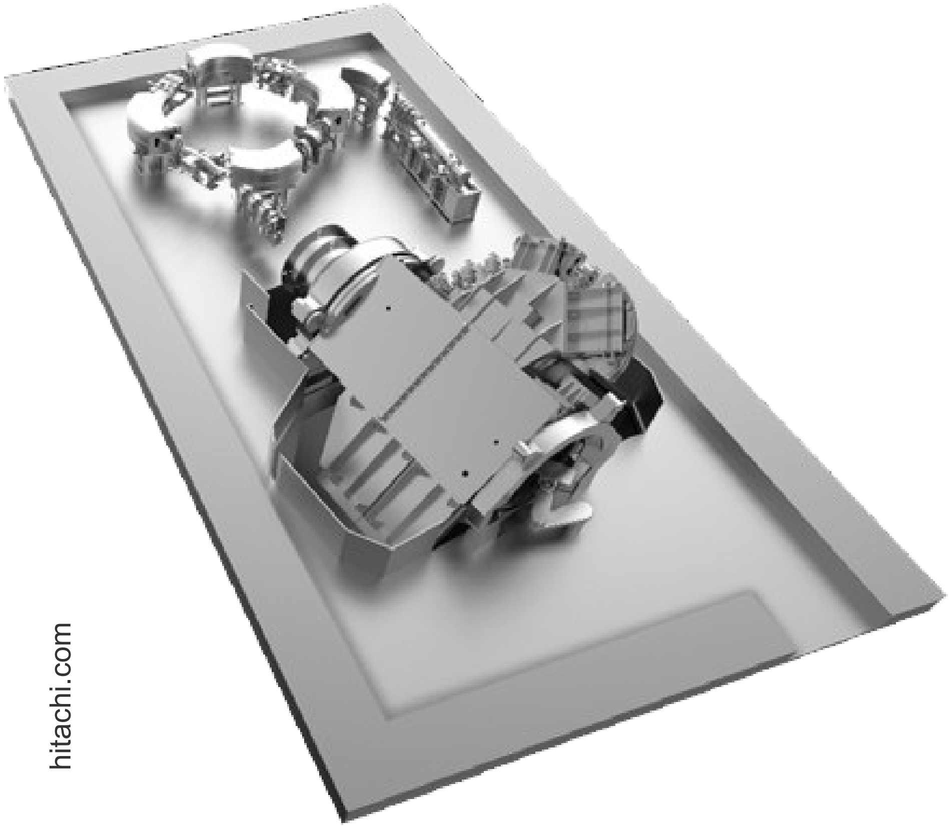
←
Gantry-mounted superconducting synchrocyclotron.
Installed at 15 sites.

2022: Development of a fixed-beamline variant ("S250-Fit") that fits into existing linac-cave.

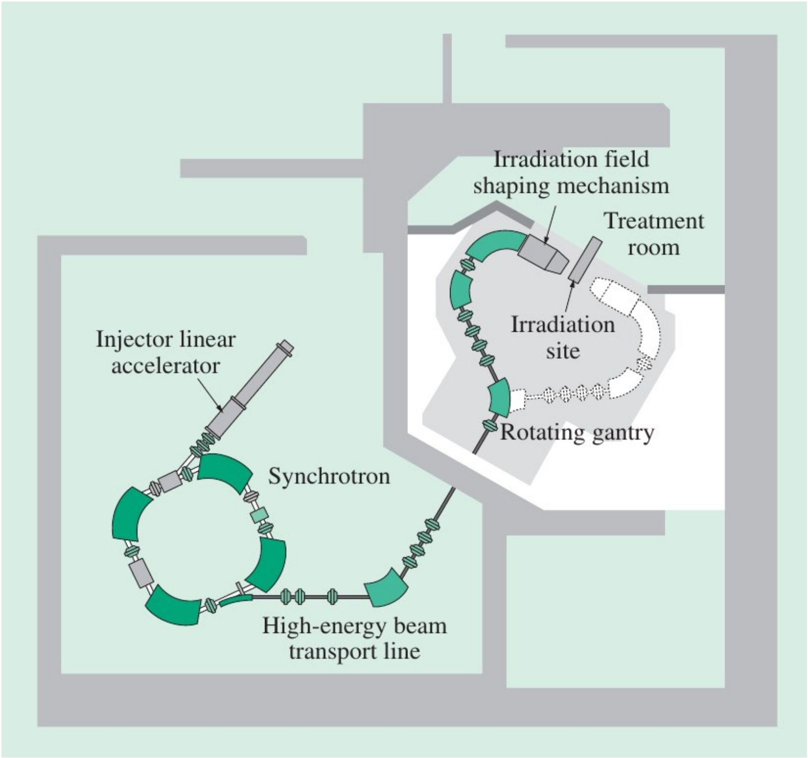
Single-room solutions

Hitachi ProBeat V System

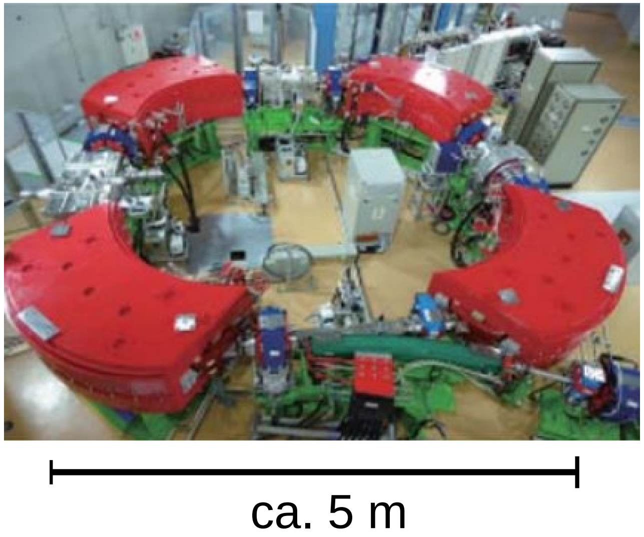
Compact p-synchrotron (250 MeV)
with single-room solution



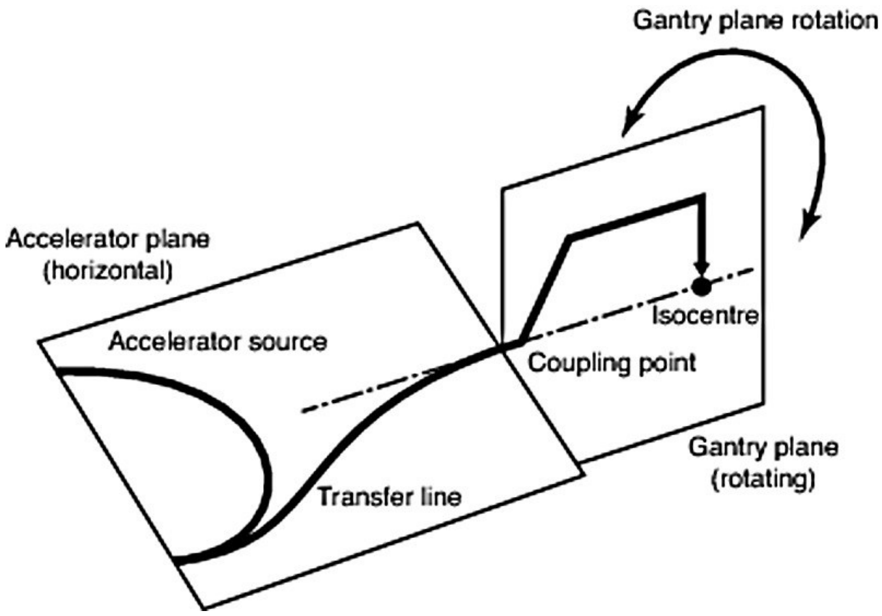
hitachi.com



Umezava et al., Hitachi Rev. 64 (2015) 508

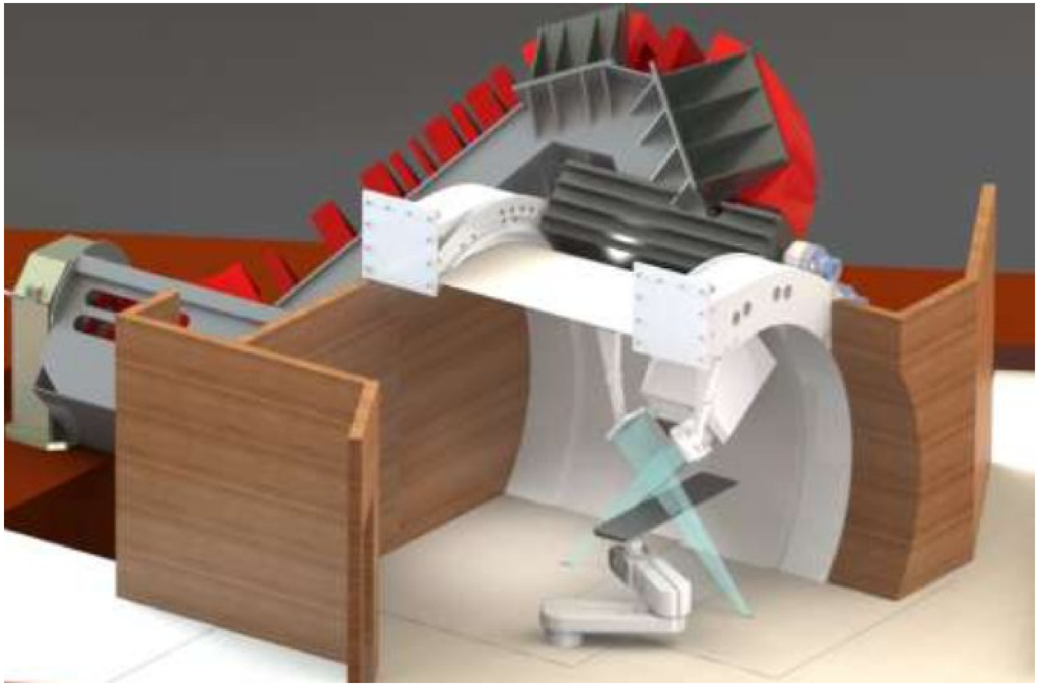


Gantries



Hitachi ProBeat proton gantry

hitachi, ltd.



varian.com

← Key element to provide all the DoF in application one is used to from photons ...

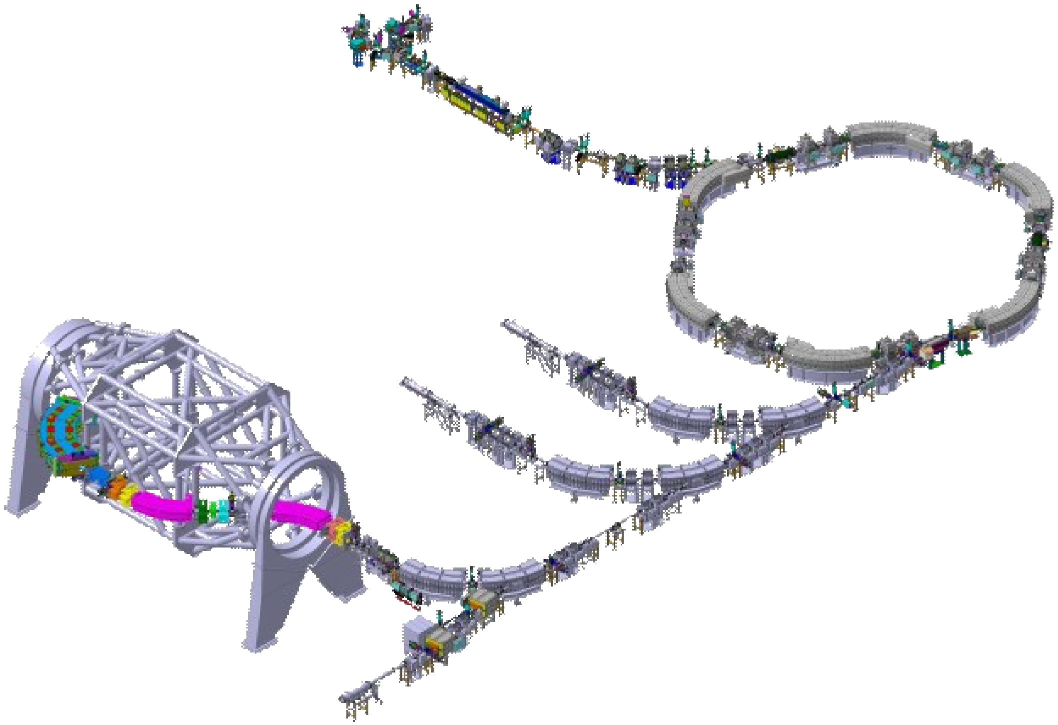
Gantries

Heidelberg $^{12}C^{6+}$ Gantry (HIT)

$B\rho$ = 6.6 Tm

Overall weight 600 tons

In operation since 2012.



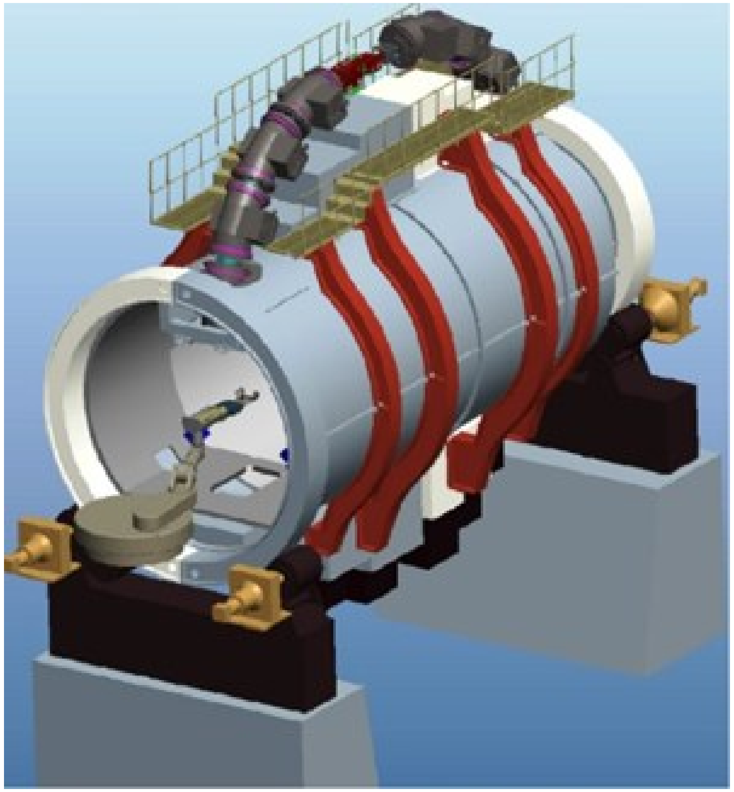
www.uniklinikum-heidelberg.de

Gantries

Superconducting $^{12}C^{6+}$ gantry at HIMAC (2016)

Now produced commercially by Toshiba.

nirs.qst.go.jp



Raster-scanning pencil beam.

Lighter and smaller than normal-conducting gantry for heavy ions (~ 300 t).

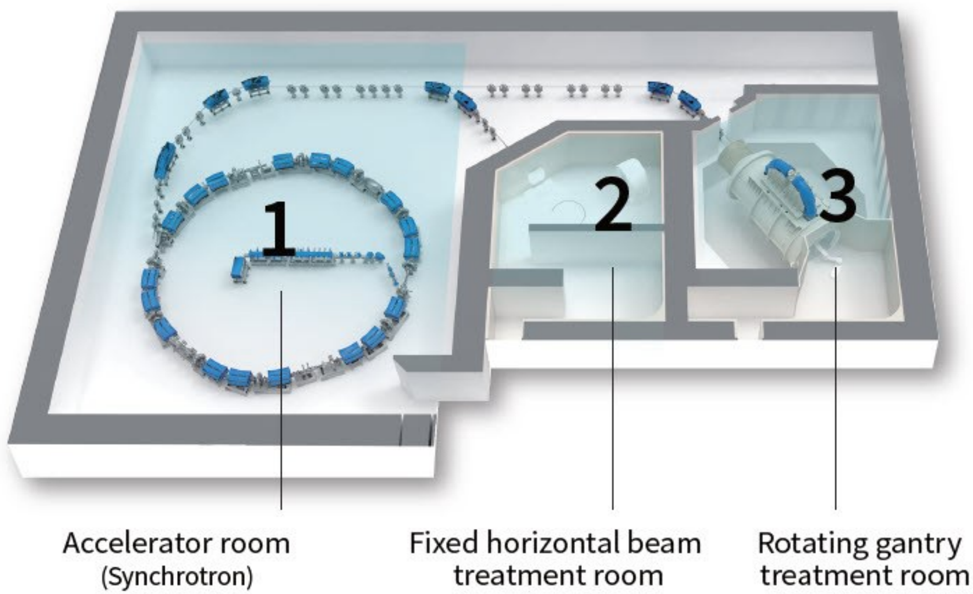
Iwata et al., NIM A 834 (2016)

Industrial $^{12}C^{6+}$ machines …

global.toshiba

Toshiba Heavy Ion ($^{12}C^{6+}$) Therapy System

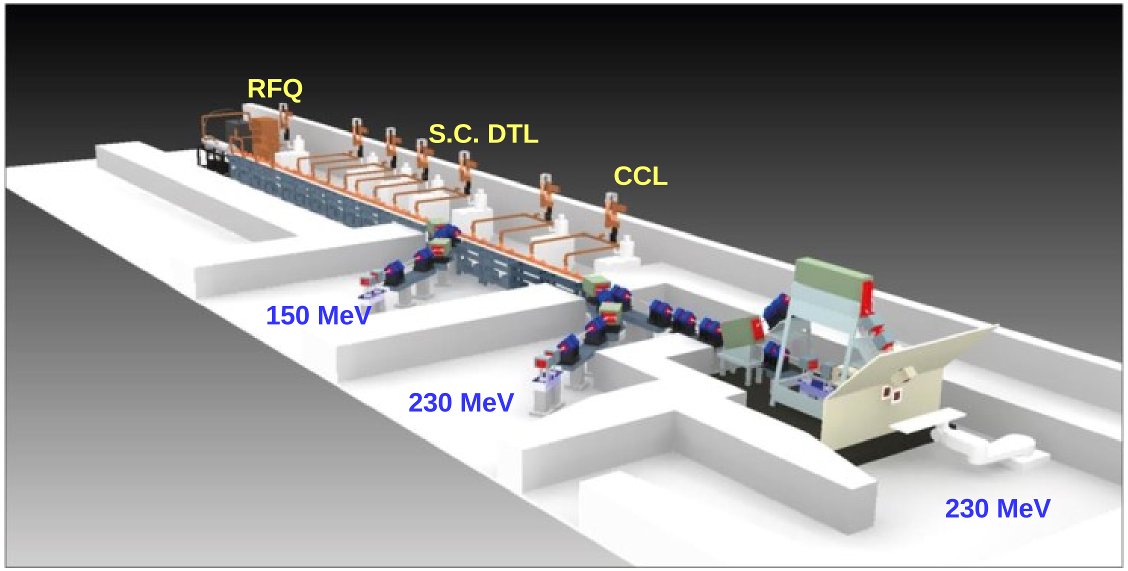
Installed at multiple sites
in Japan and South Korea.



www.toshiba.com/heavy-ion/

Alternative accelerator concepts

Amaldi, Proc. of LINAC 2014



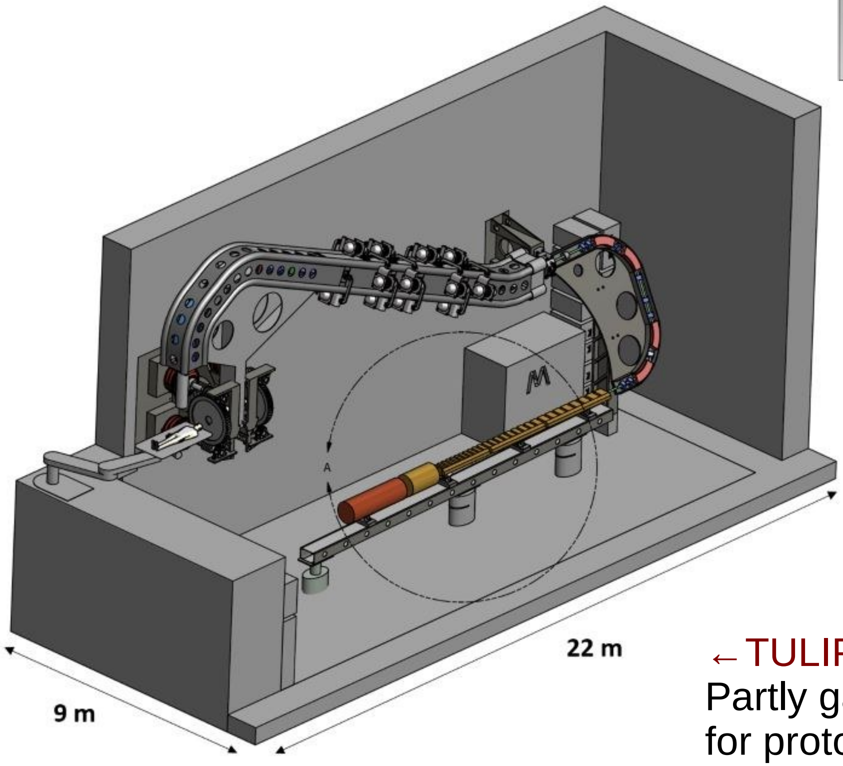
Linacs for proton therapy

Partly superconducting to obtain shorter machines.

Can vary energy in accelerator by (de-)activating individual cavities.

↑ AVO LIGHT
Linac-only proton accelerator. (London, UK)

First medical trials scheduled for 2023.



←TULIP project
Partly gantry-mounted linac for proton beam therapy.

S. Benedetti et al., Phys. Rev. Accel. Beams (2017)

Alternative accelerator concepts

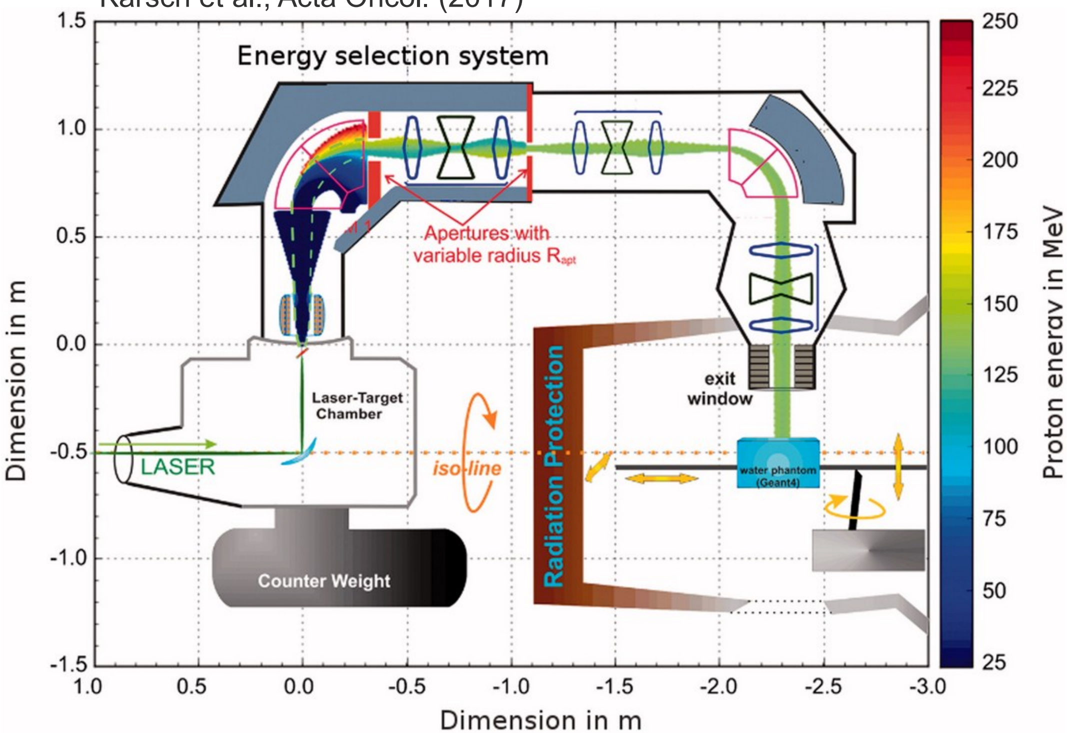
Laser acceleration

Beam pulses of high intensity and broad energy distribution

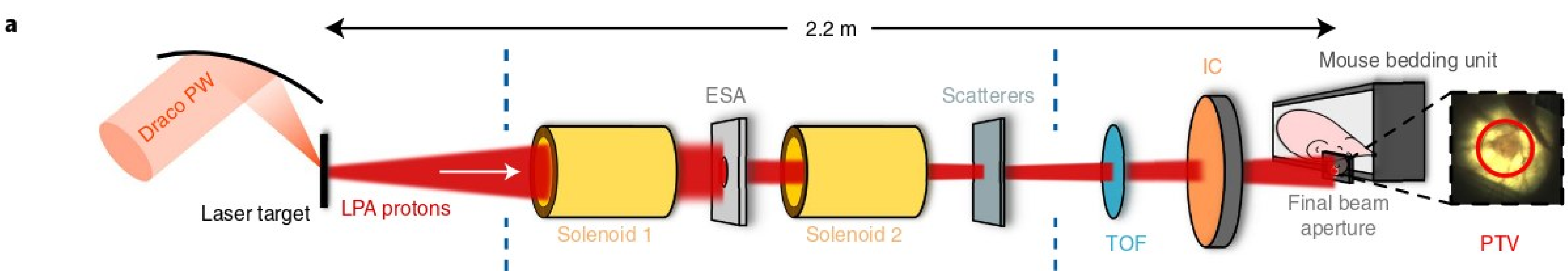
→ Energy selecting beam line
→ No accelerator: compact
→ High power (~ 100 TW) Laser required

Proposed 230 MeV proton gantry for patient treatment using laser acceleration.

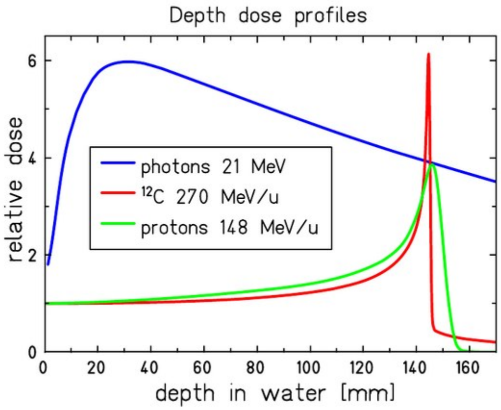
Karsch et al., Acta Oncol. (2017)



Set-up for irradiation of mice using 25 MeV laser-accelerated protons from Dresden DRACO system. Kroll et al., Nature Physics 18 (2022) 316



Outline



Beam requirements

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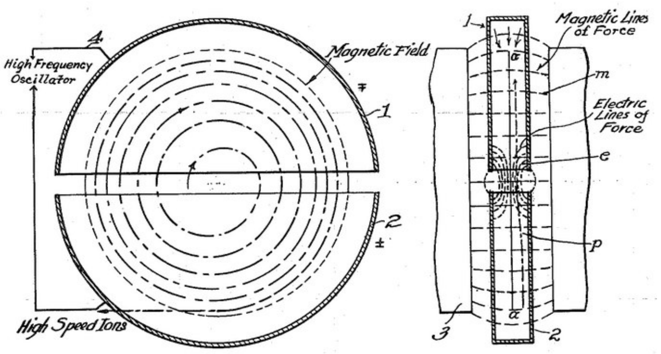
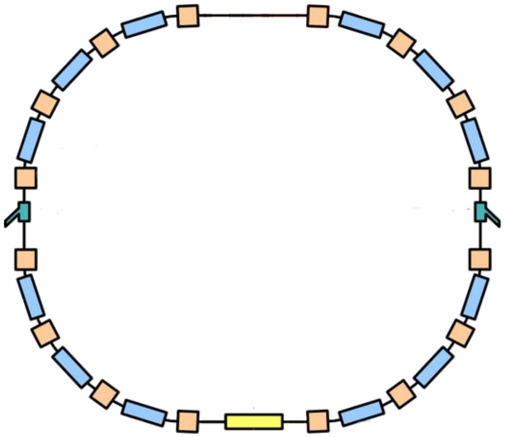
Overview of some facilities

Recent developments and alternative concepts

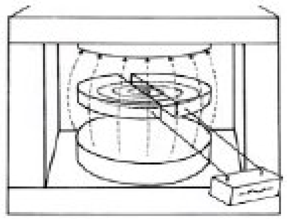


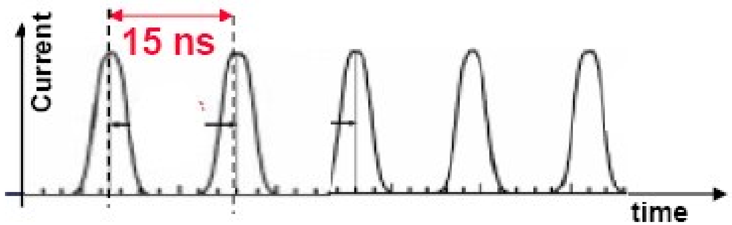
Latest synchrotron R&D



Synchrotron R&D

Cyclotron





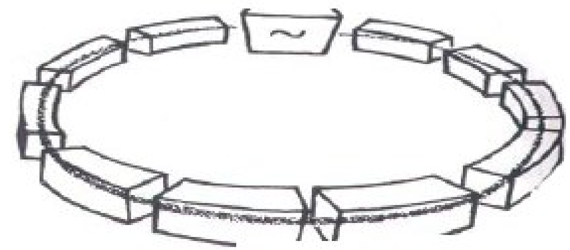
Pros

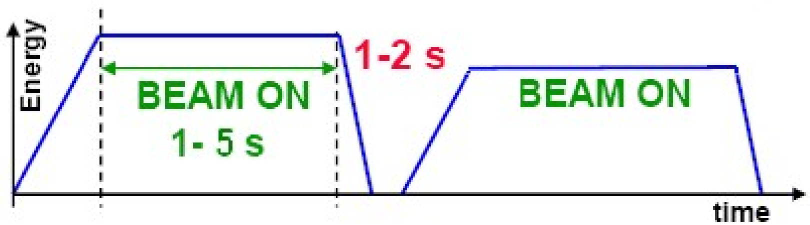
- cw-operation: continuous train of short particle bunches.
- High intensity (high dose rates).
- Ion intensity easily (and quickly) variable *(modulation of ion source current).*

Cons

- Fixed energy: needs degraders *(particle loss, radiation safety issues)*.
- Heavy ions ($^{12}C^{6+}$) would require very large magnet and chamber.

Synchrotron





Pros

- Scalable to arbitrary *Bρ*, can deliver heavy ions.
- Variable energy, (almost) no particle losses.

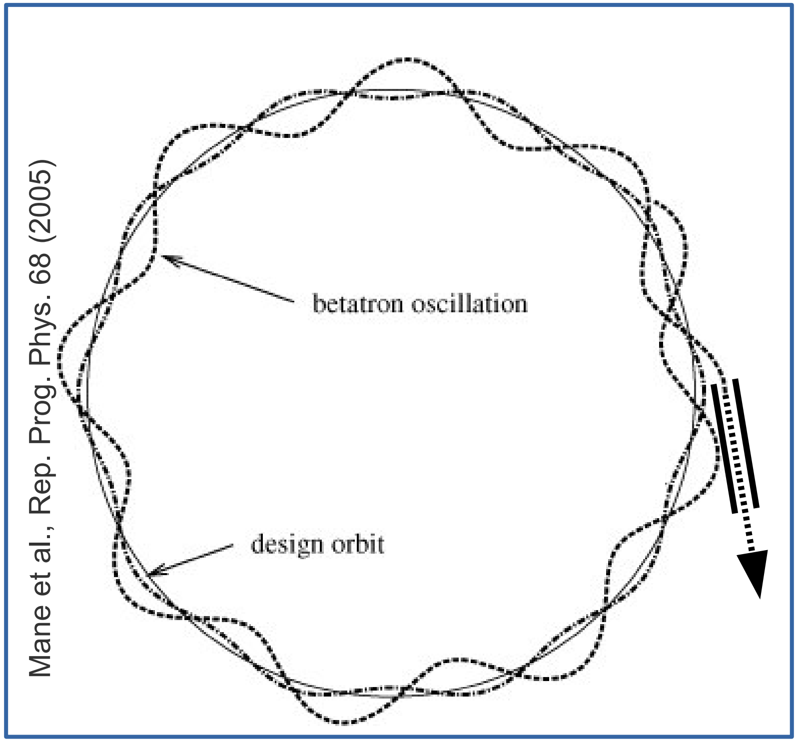
Trying to fix these

Cons

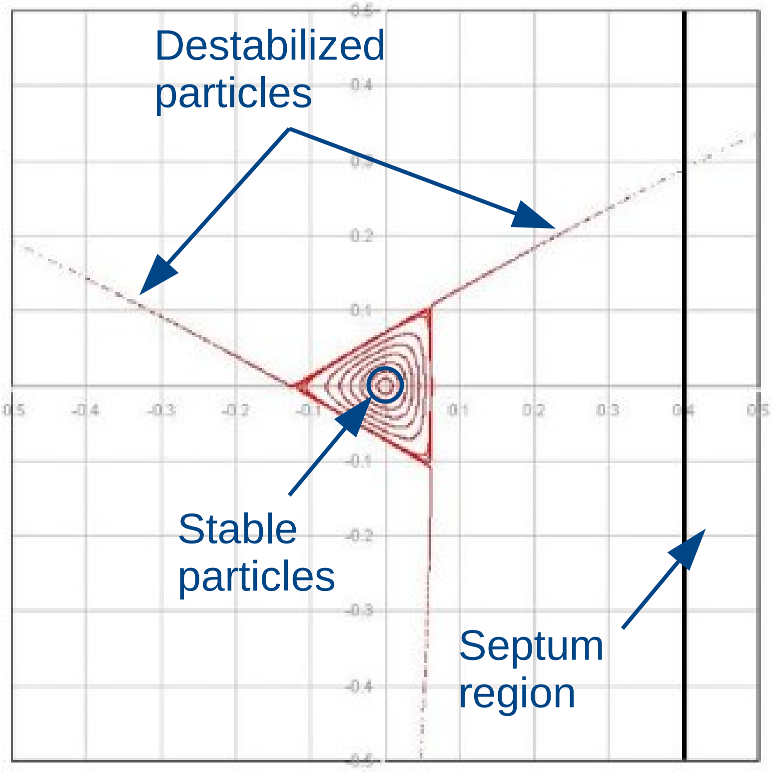
- Control of beam intensity is difficult.
- Pulsed operation, breaks between cycles
- Very high dose rates hard to achieve.

→ *see advanced topics chapter!*

Synchrotron R&D: Intensity control



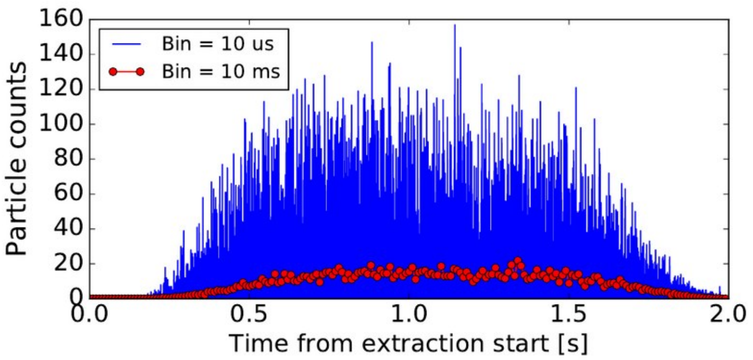
Mane et al., Rep. Prog. Phys. 68 (2005)



Remember: Slow extraction

Emitted beam is formed by slowly "feeding" particles to a betatron resonance.

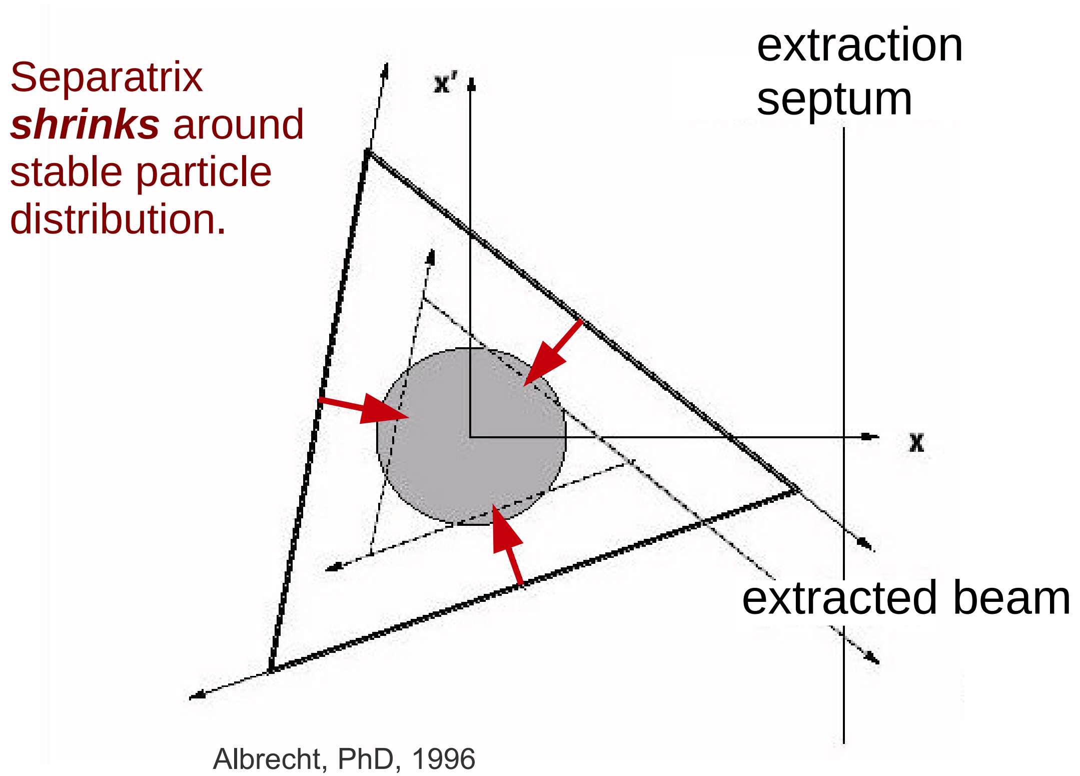
Extracted SIS18 "spill"



Forck, Proc. IPAC 2018

Synchrotron R&D: Intensity control

There are two methods of slowly “feeding” the resonance:



Albrecht, PhD, 1996

(1) Change betatron tune of the low-amplitude particles.

Examples:

Slow quadrupole ramp

→ changes linear focussing.

Slow acceleration
(using cavities, induction cores, stochastic noise)

→ changes particle momenta.

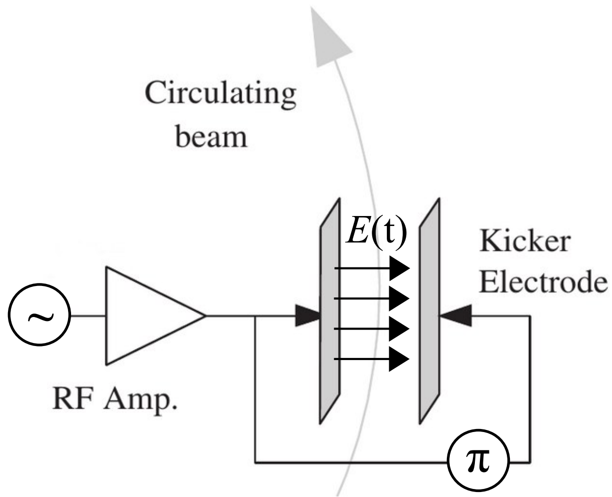
→ changes particle tunes via chromaticity.

Synchrotron R&D: Intensity control

There are two methods for slowly “feeding” the resonance:

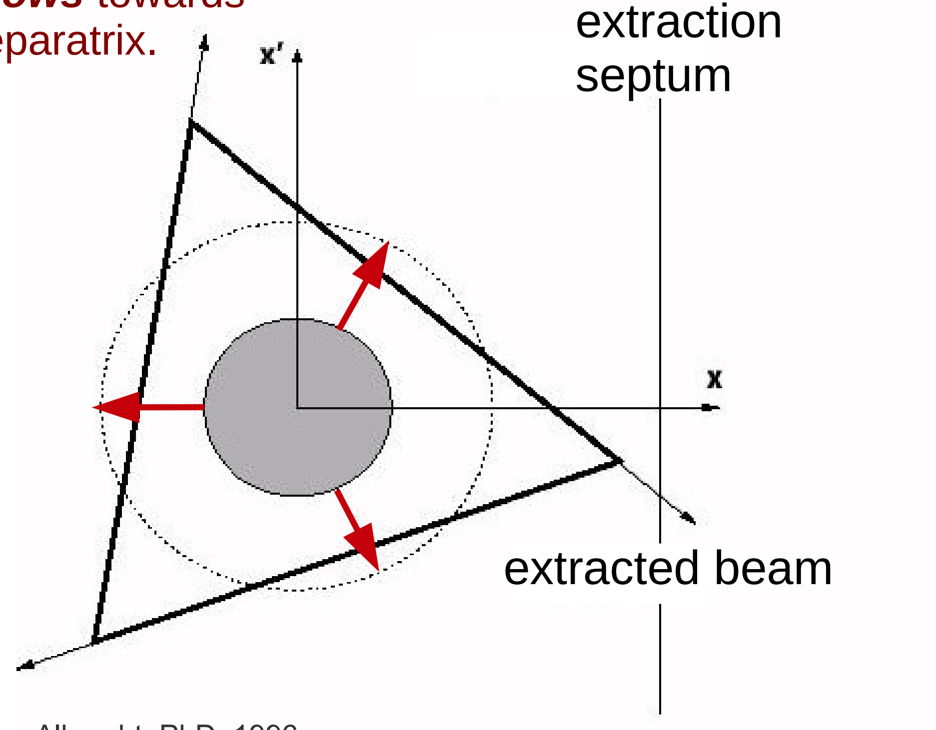
(2) Excite horizontal betatron motion of stable particles

Horizontal RF-kicker electrode
~ in sync with horizontal particle tune.



“Transverse RF-Knock-Out” (RF-KO) technique.

Horizontal envelope ***grows*** towards separatrix.

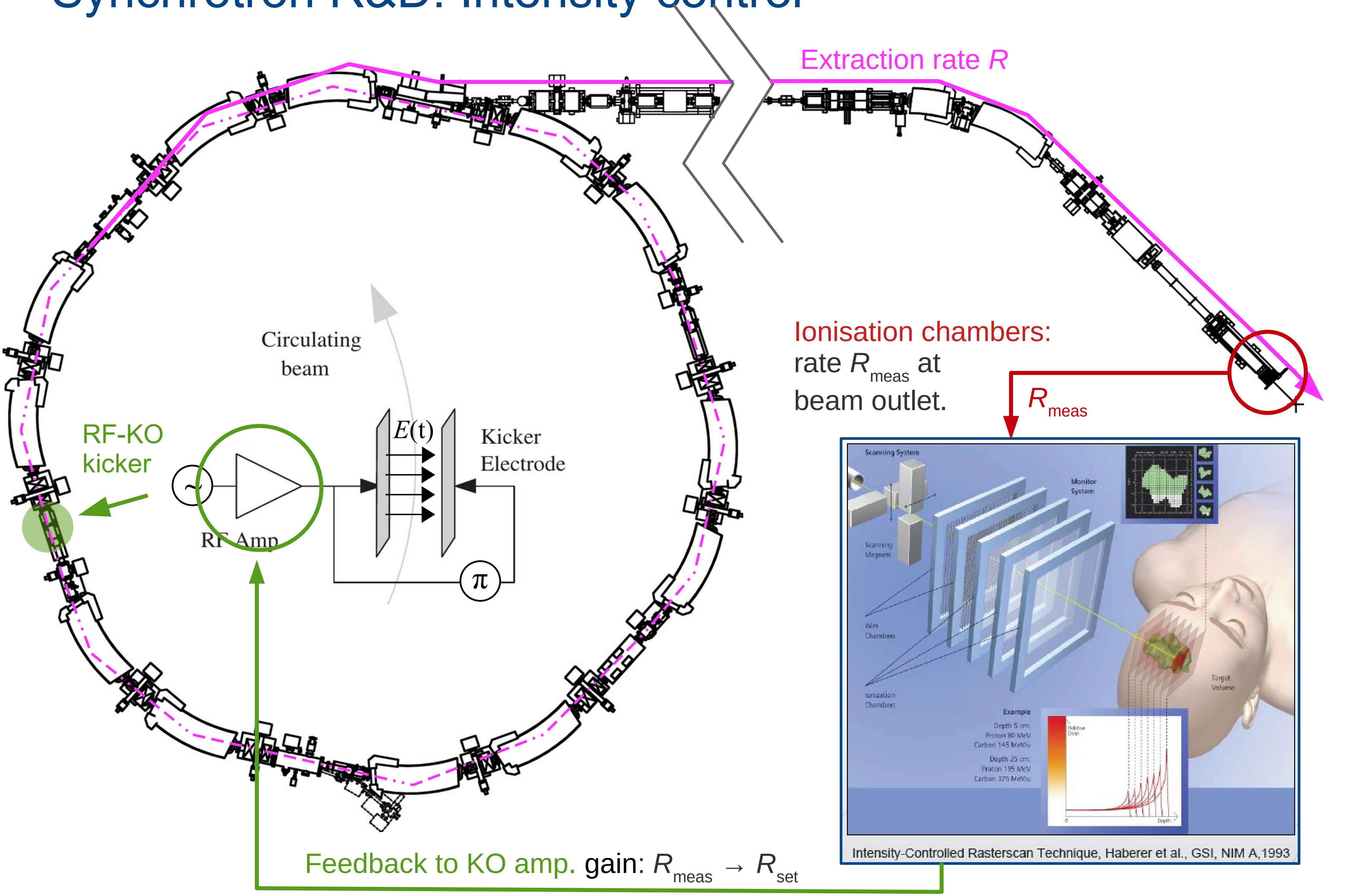


Albrecht, PhD, 1996

→ First implemented at HIMAC. A. Noda, NIM A 492 (2002) pp. 253

→ <u>Faster</u> and more direct control of destabilization rate.

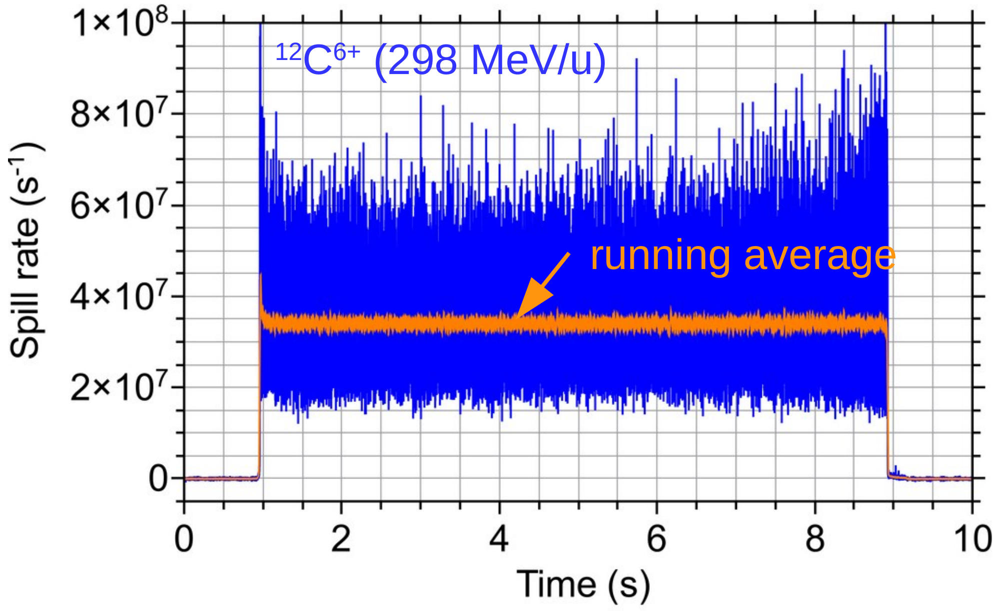
Synchrotron R&D: Intensity control



Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

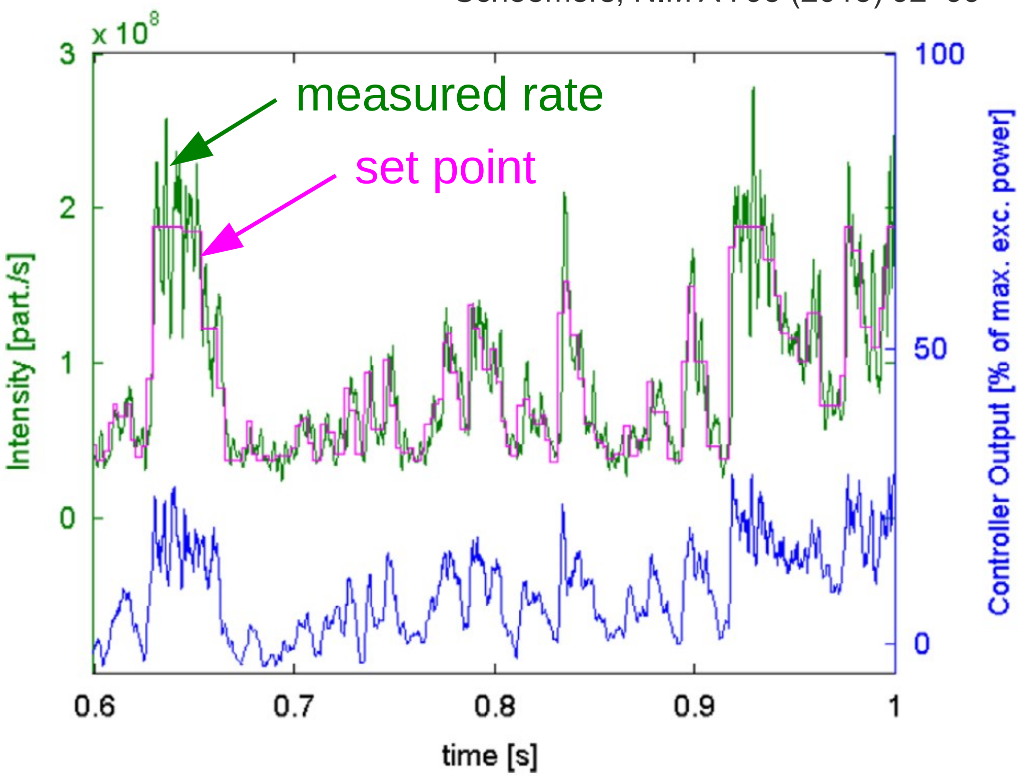
Synchrotron R&D: Intensity control

RF-KO allows for fast (~ms) control of the average spill rate.



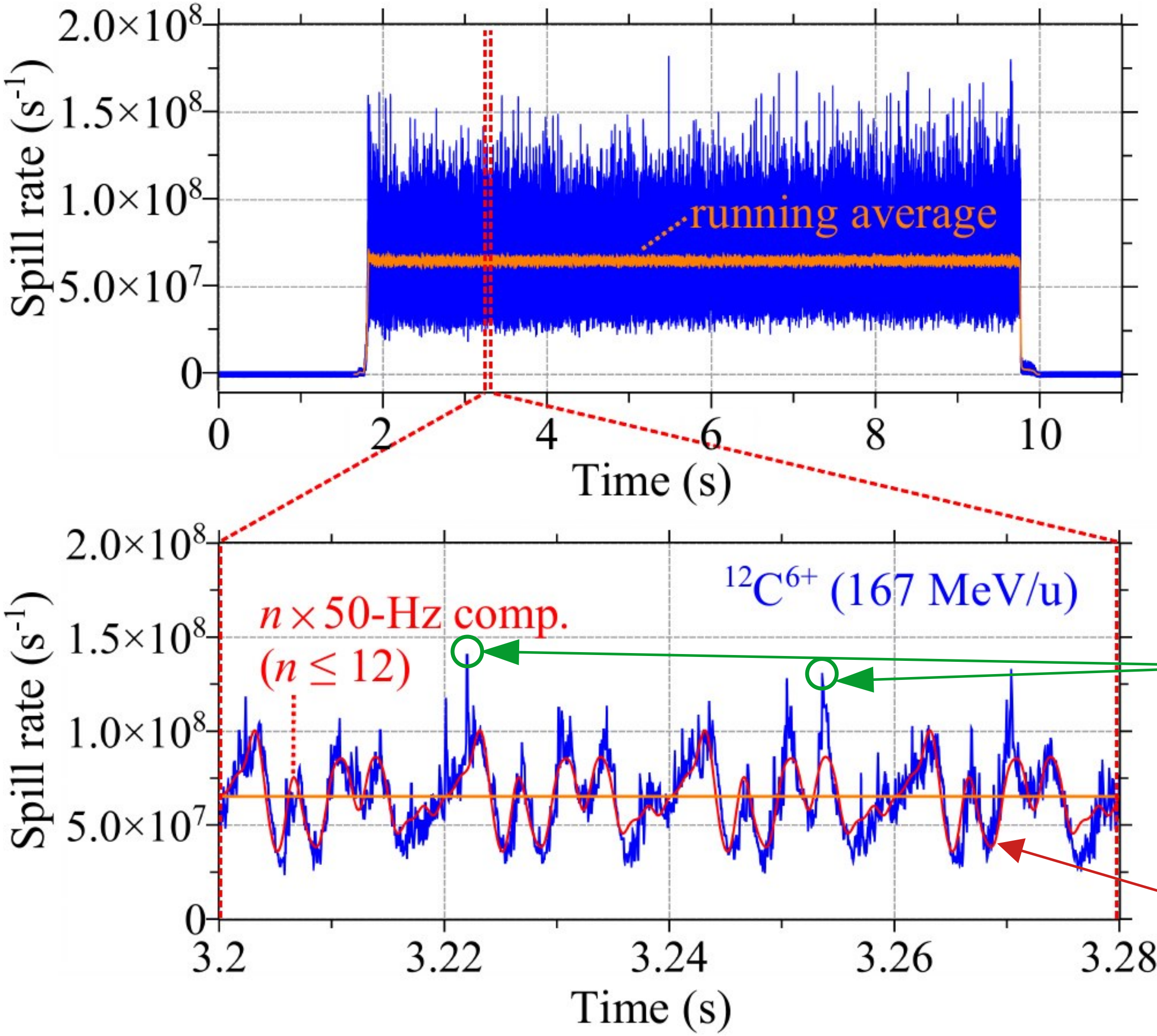
Spill stabilisation …

Schoemers, NIM A 795 (2015) 92–99



And controlled spill modulation …

Synchrotron R&D: Intensity control



on shorter times, an unwanted **"micro structure"** remains. (kHz ... MHz frequencies).

Spikes in extraction rate
→ can saturate ICs
→ automatic beam dumps

Much of the < 1 kHz structure composed of power-grid harmonics.

Krantz et al., Proc. of IPAC 2018

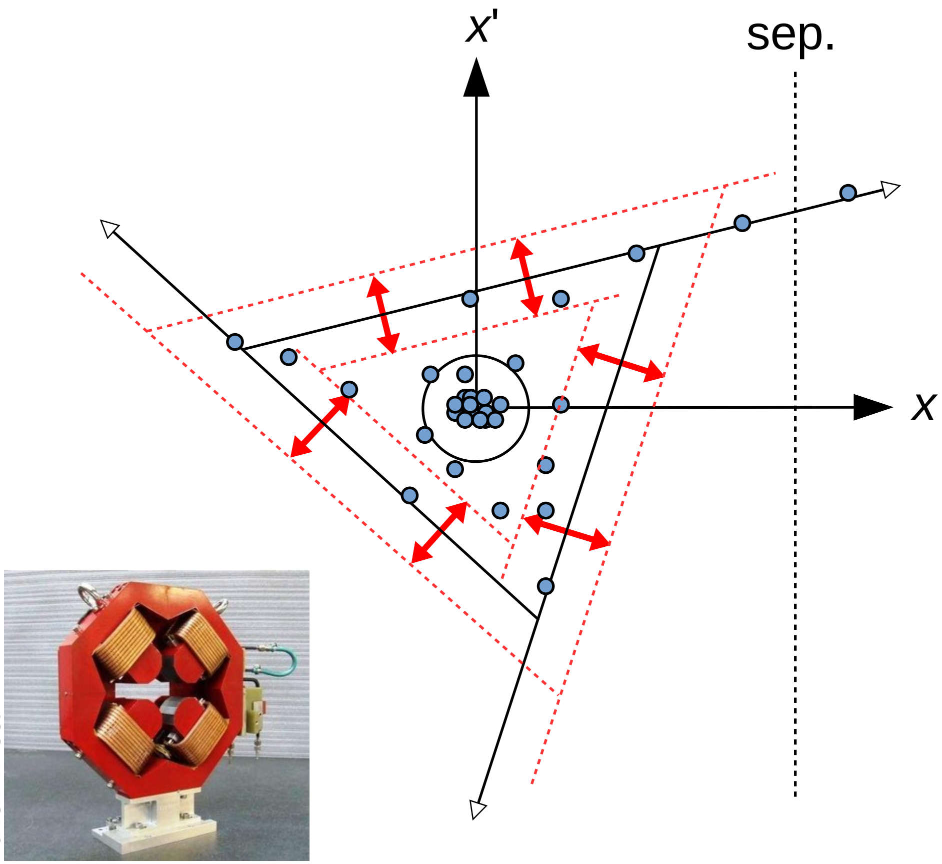
Synchrotron R&D: Intensity control

Major source of < 1 kHz spill ripple:

Instability of power converters

→ Tune ripple

→ “Pulsing” of separatrix



triumf.ca

Example: Sensitivity of SPS spill to power supply ripples

[Prieto et al., Proc. of IPAC 2018]

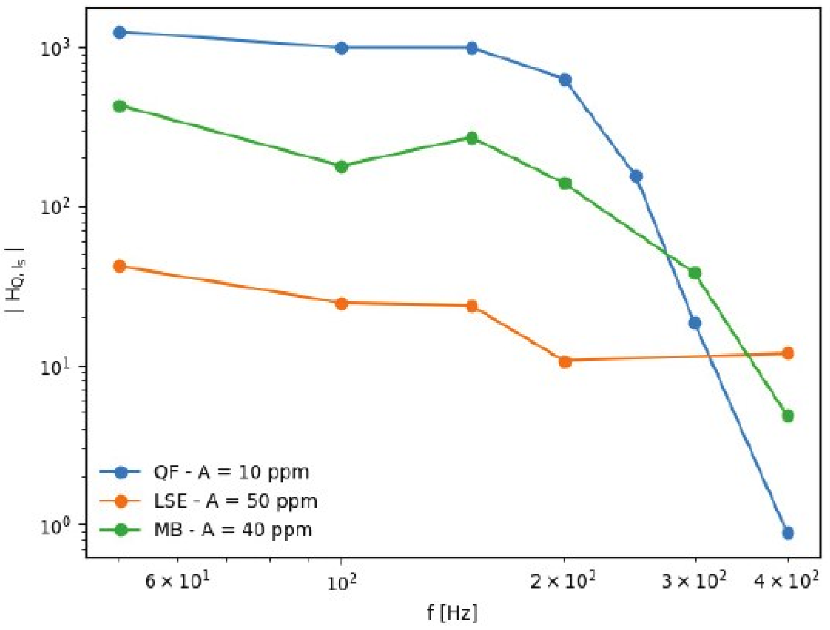
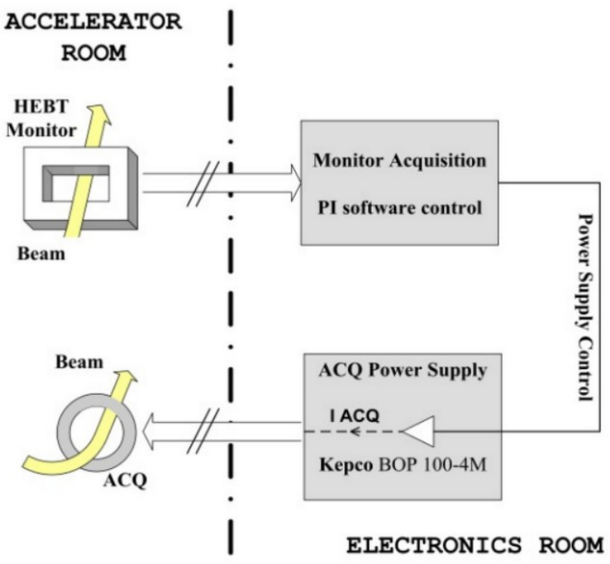


Figure 3: Transfer function for focusing quadrupoles (blue), extraction sextupoles (orange) and main bends (green).

Synchrotron R&D: Intensity control

Solution 1: Active tune stabilisation

Air Core Quadrupole (ACQ) magnet at CNAO, Pavia.



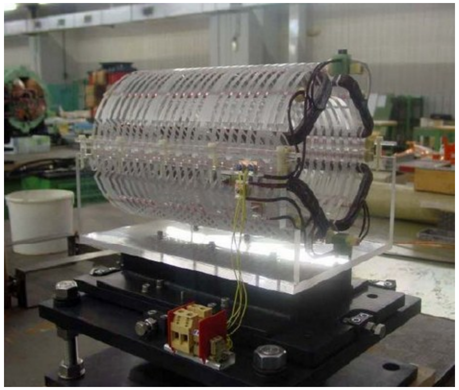
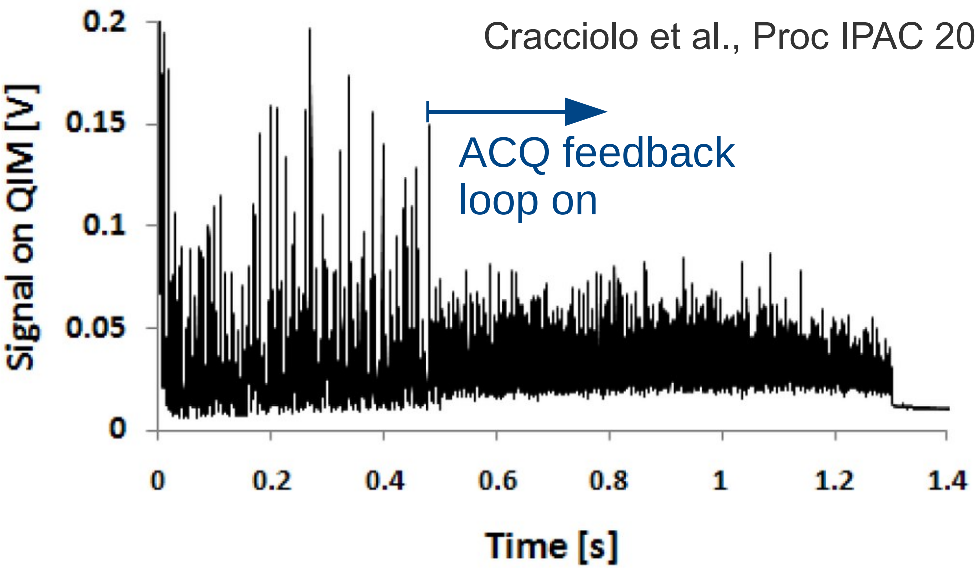


image: courtesy of M. Pullia

fondazionecnao.it

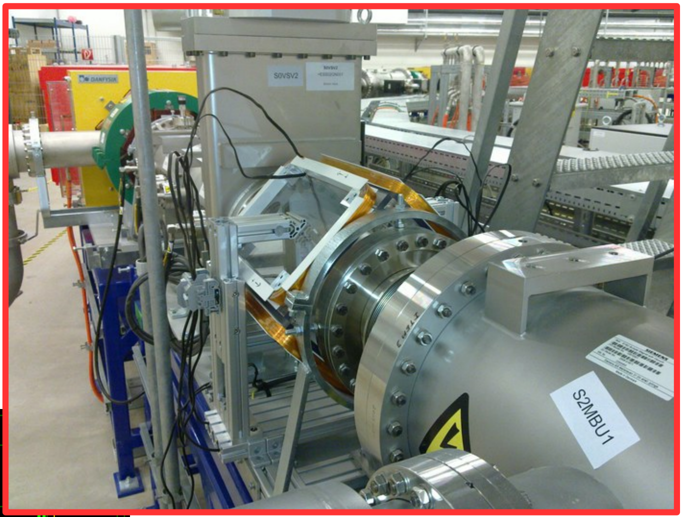


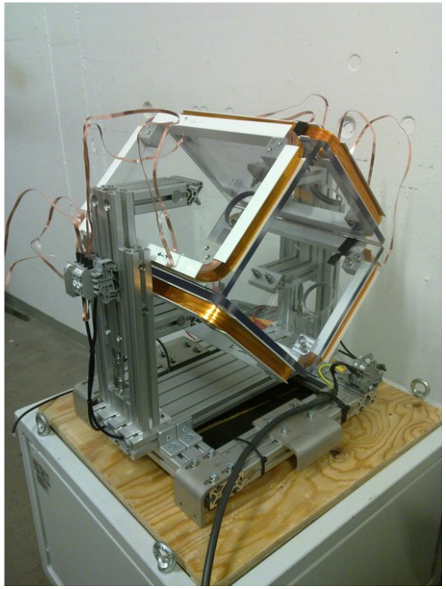
Cracciolo et al., Proc IPAC 2011

Synchrotron R&D: Intensity control

Solution 1: Active tune stabilisation

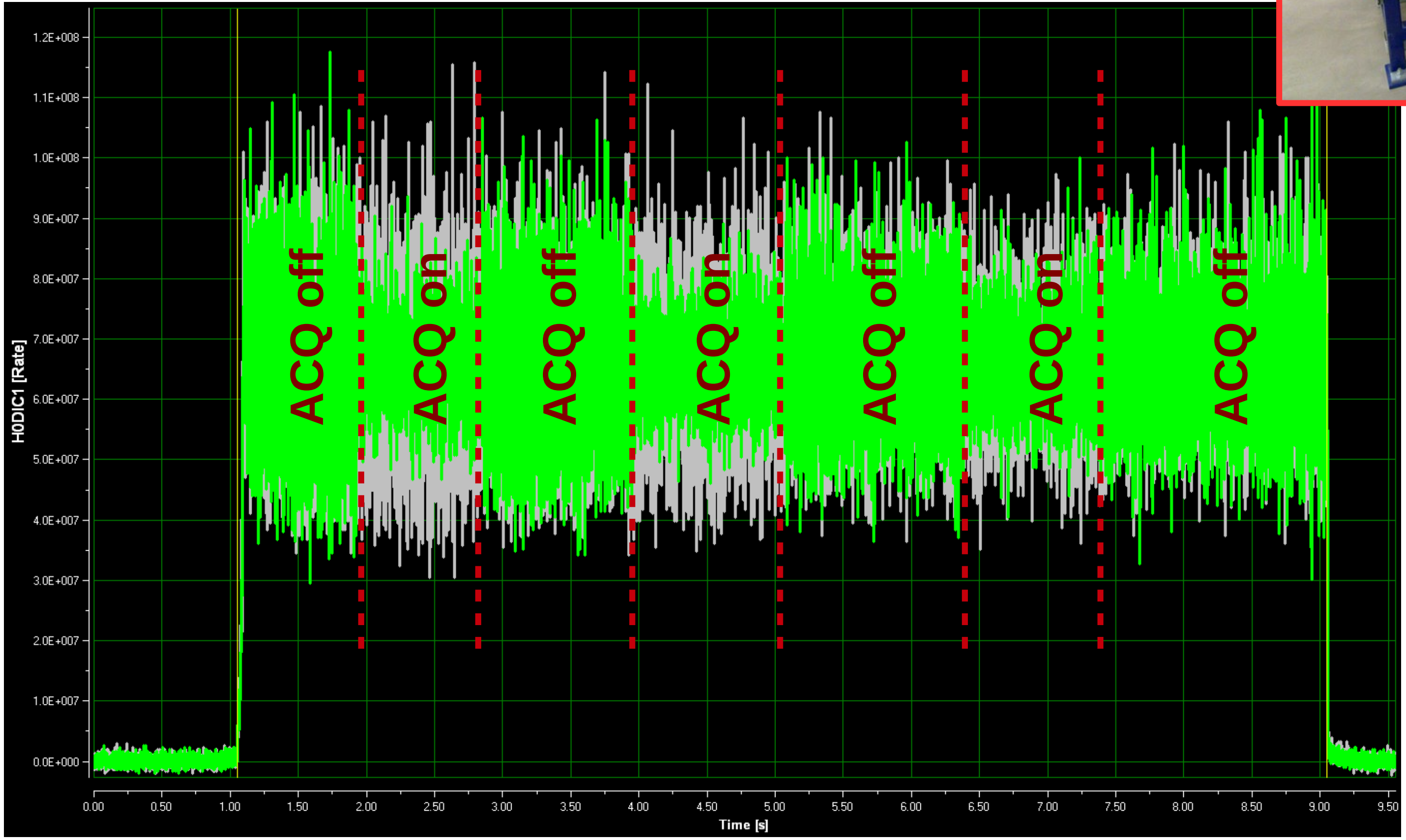
Experimental Air Core Quad system at MIT, Marburg.





Krantz, Slow Extraction Workshop, 2019

MIT: $^{12}C^{6+}$ @ 167 MeV/u

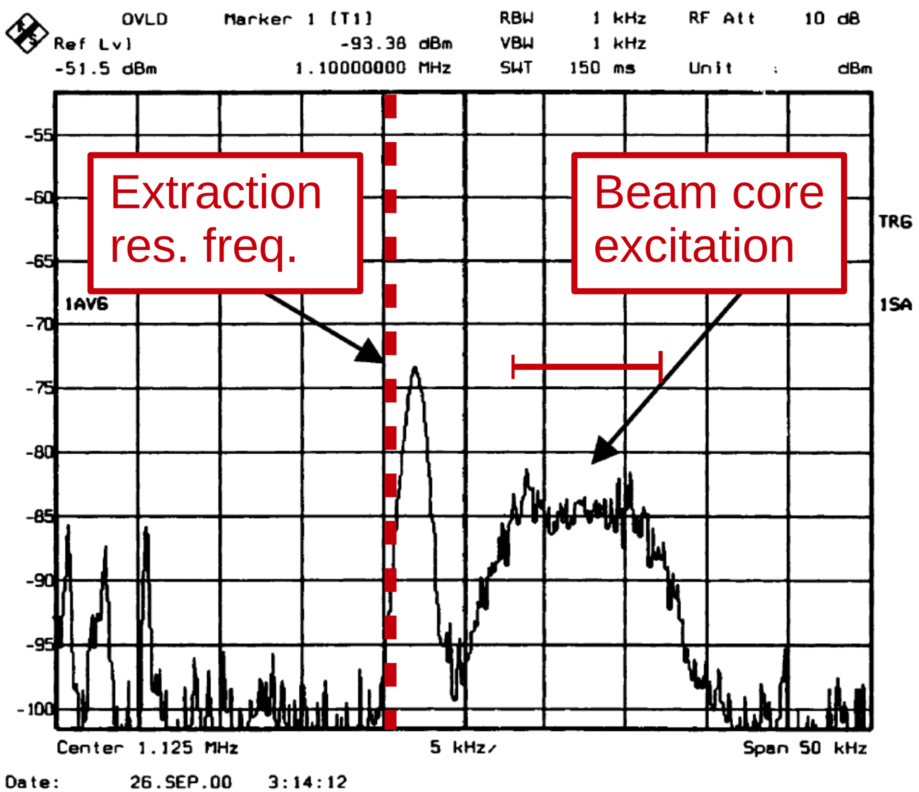


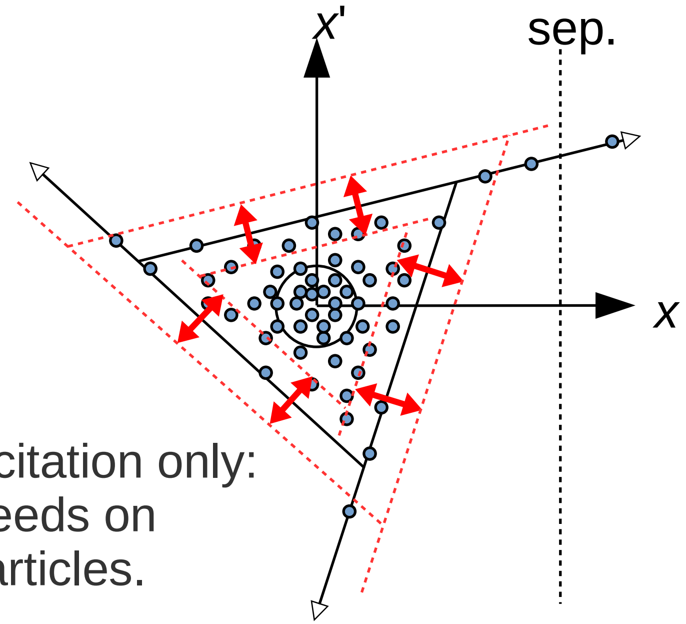
Synchrotron R&D: Intensity control

Solution 2: Control of phase-space population

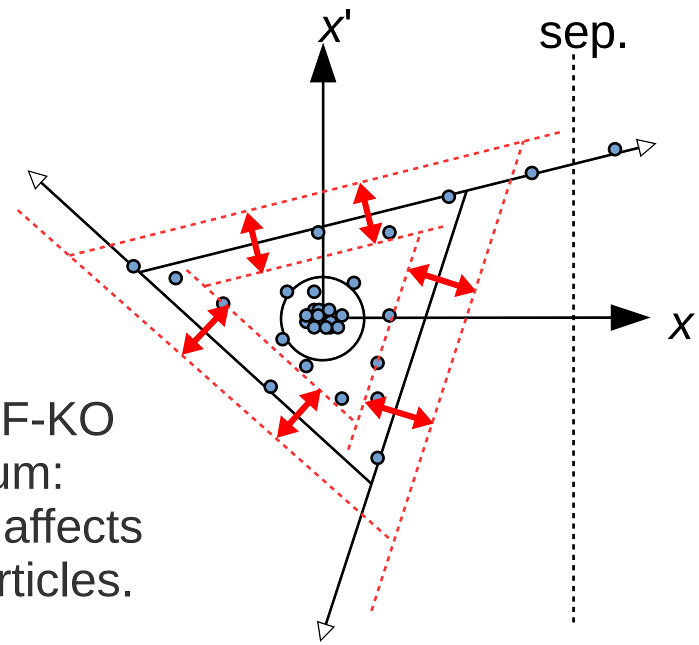
Use an elaborate RF-KO excitation spectrum to keep the “ripple region” of phase space free of particles.

A. Noda, NIM A 492 (2002) pp. 253





Core excitation only:
Ripple feeds on
many particles.

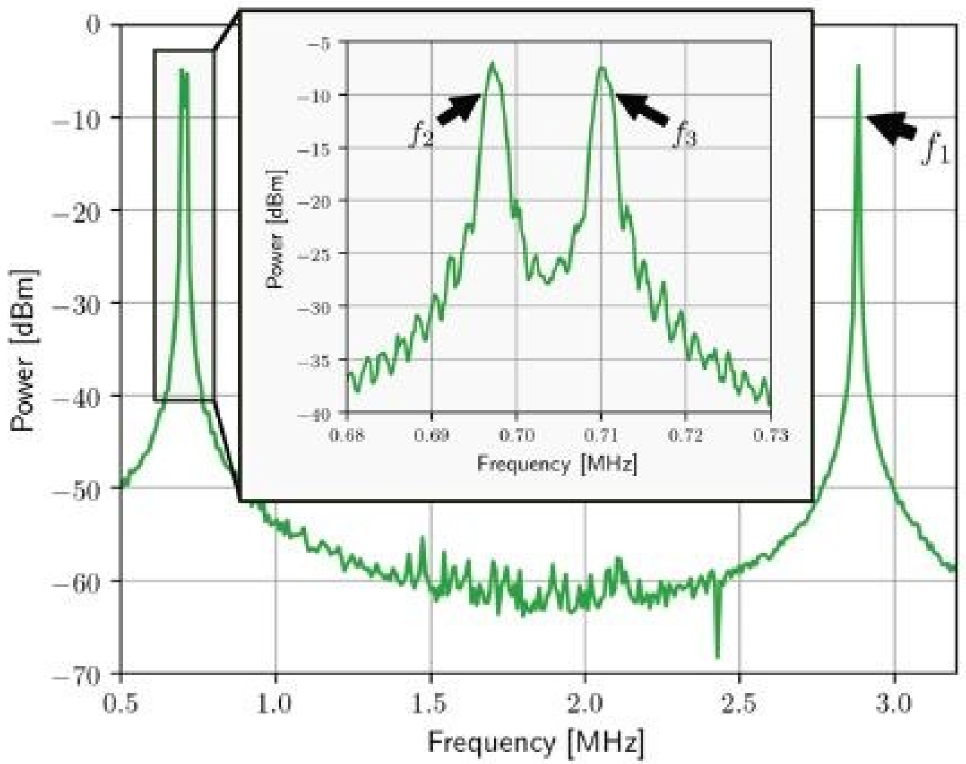


Dual RF-KO spectrum:
Ripple affects
few particles.

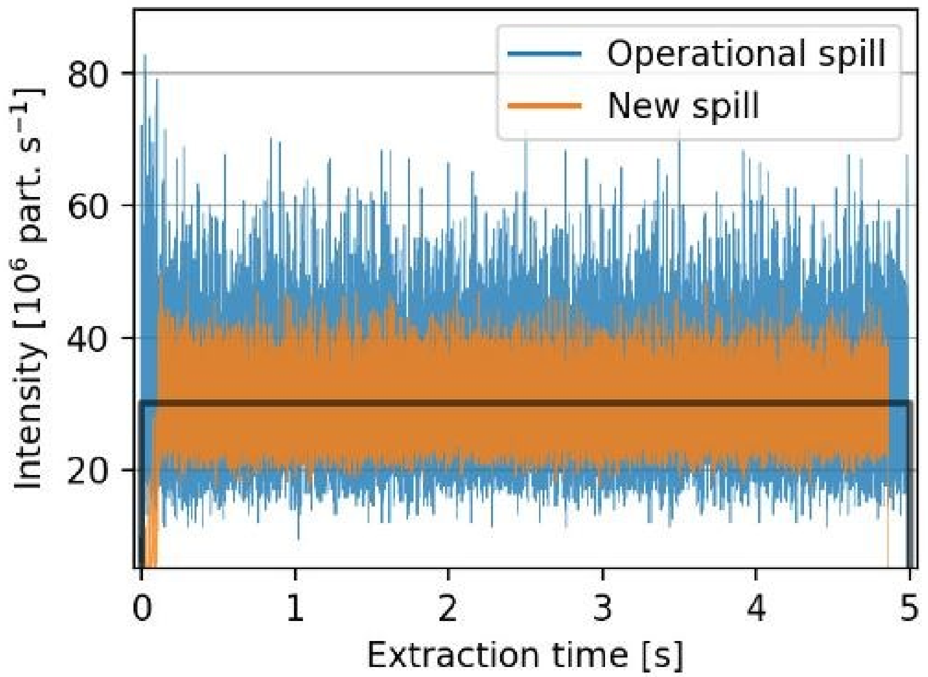
Synchrotron R&D: Intensity control

Solution 2: Control of phase-space population

Recently realised at HIT, Heidelberg.

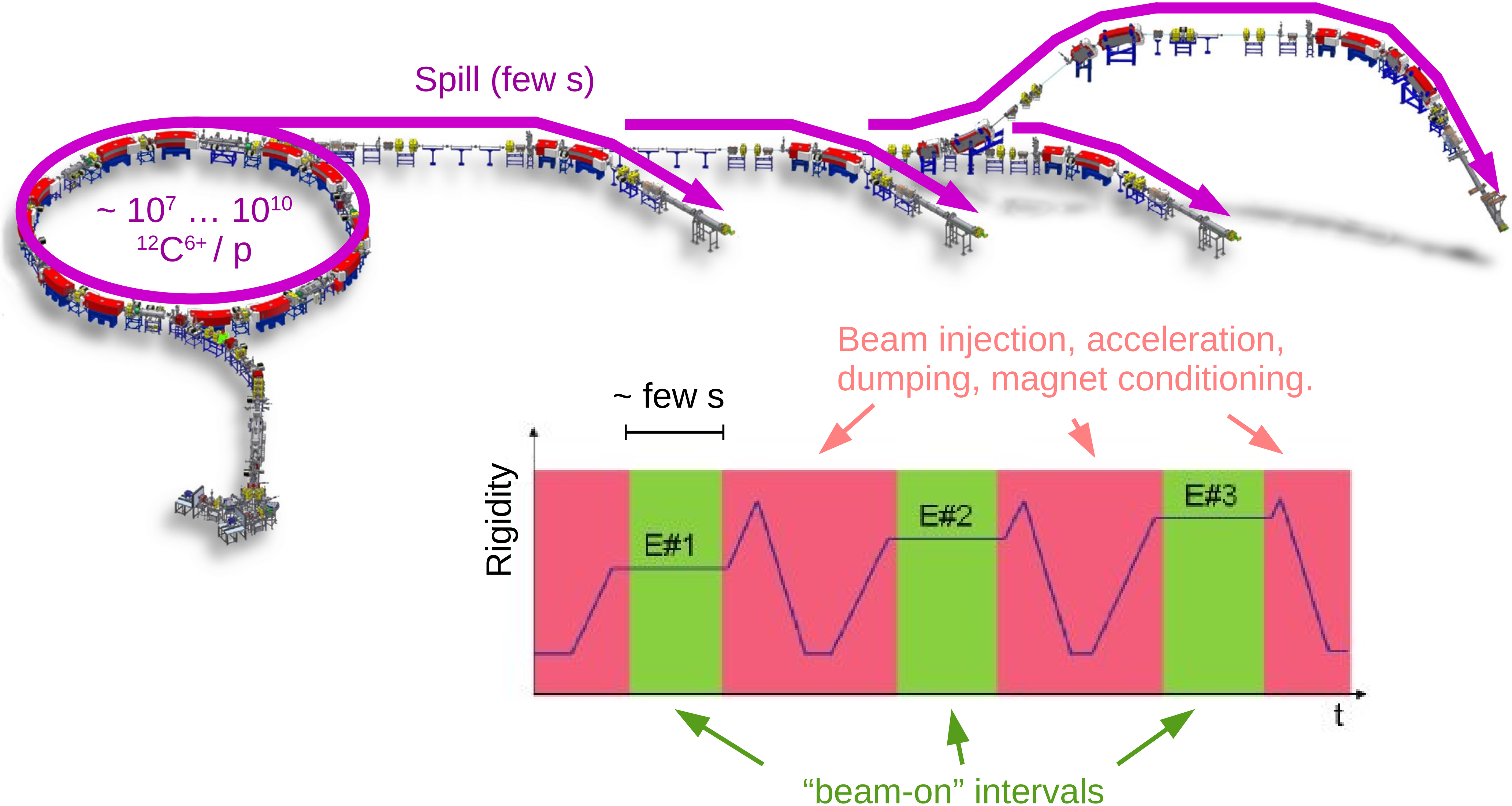


$^{12}C^{6+}$, 317 MeV/u

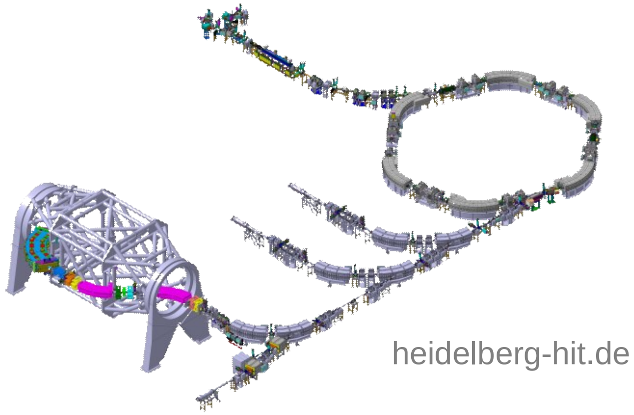


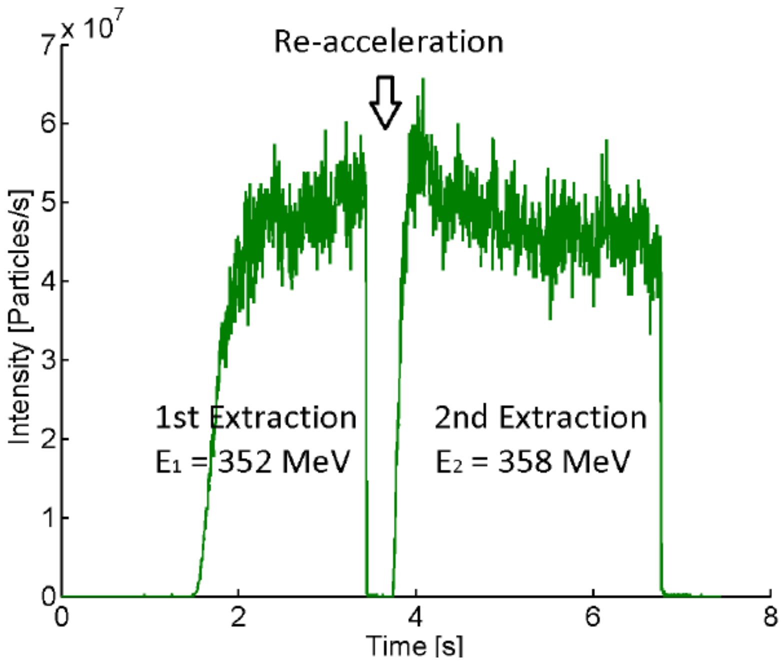
Cortés García, Feldmeier et al., NIM A 1022 (2022)
Feldmeier et al., Proc. of IPAC 2022

Synchrotron R&D: Multi-flattop extraction

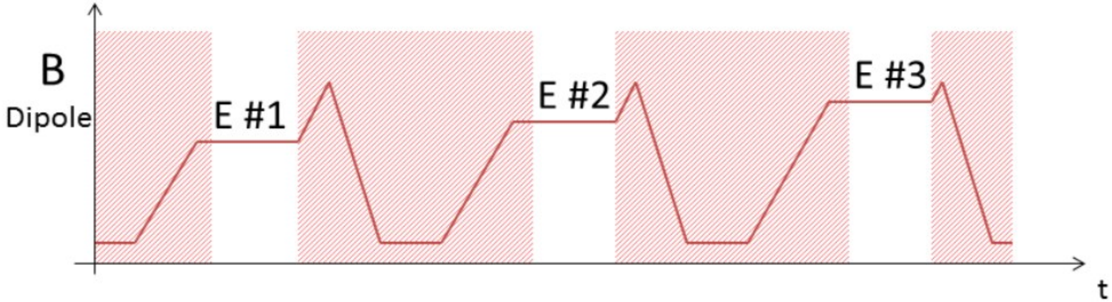


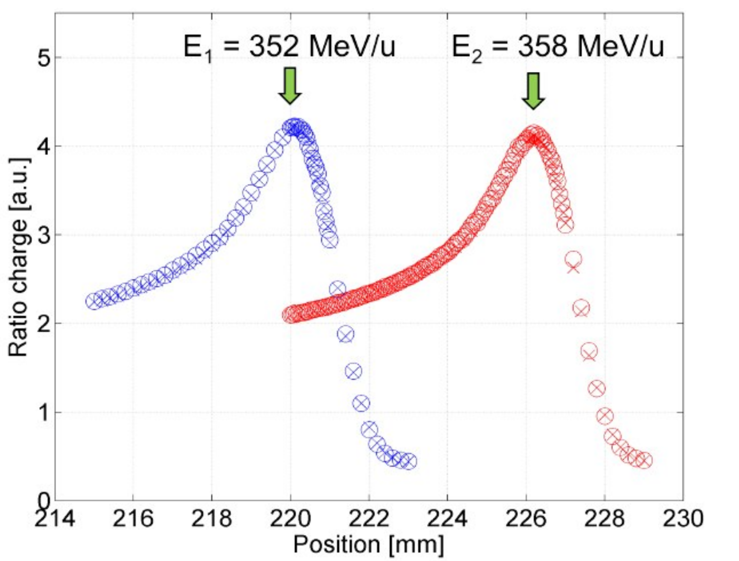
Synchrotron R&D: Multi-flattop extraction



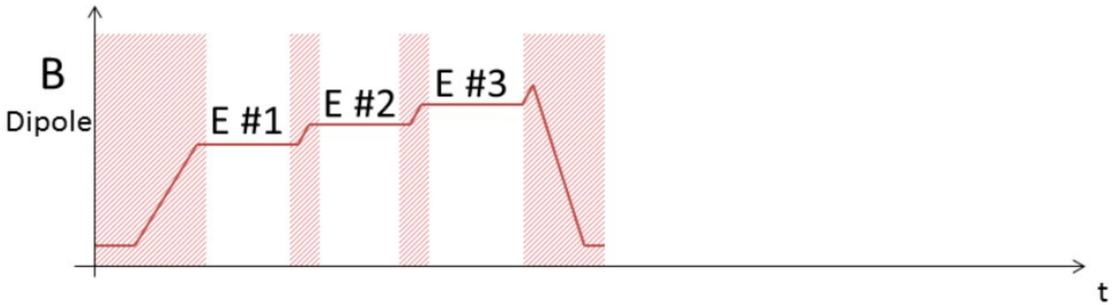


Multiple extraction flats: Irradiate several energy slices in one cycle. Being implemented at HIT.





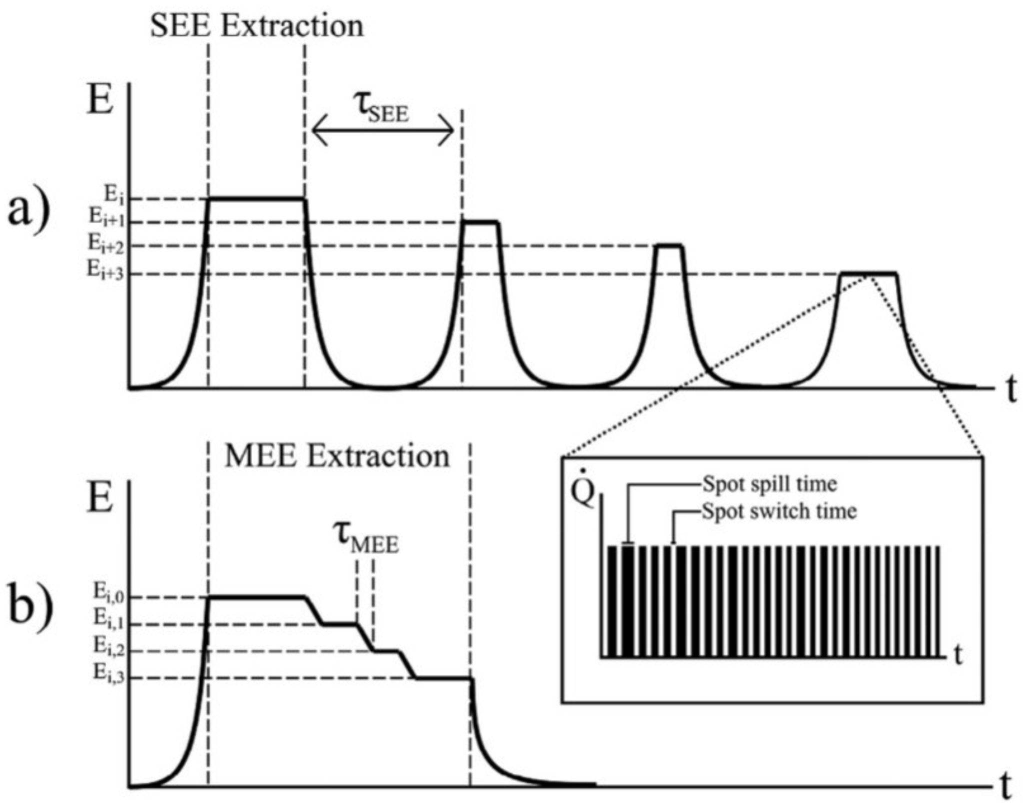
Schömers et al., Proc. IPAC 2017, 4648



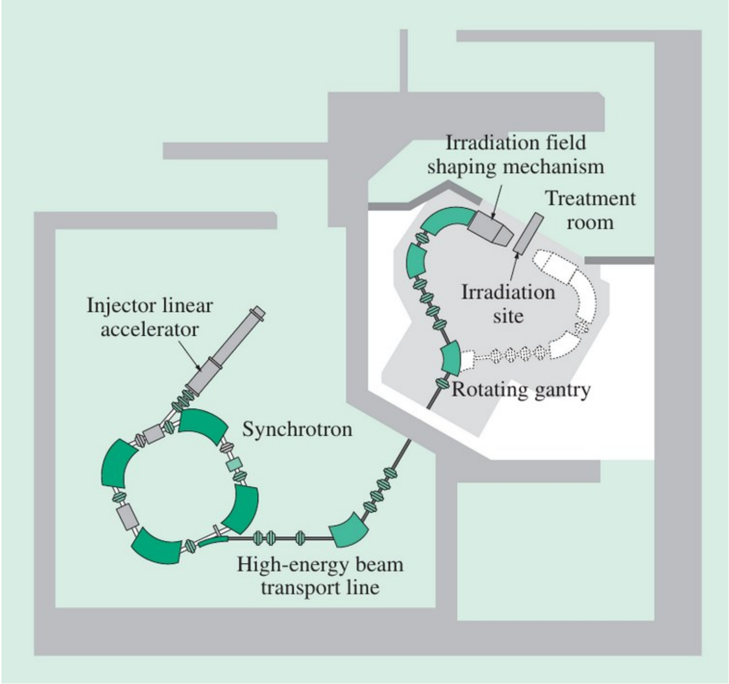
Synchrotron R&D: Multi-flattop extraction

Experimental (?) support by

Hitachi ProBeat system



Younkin, Adv. Rad. Oncol. 3 (2018) 412



Umezava et al., Hitachi Rev. 64 (2015) 508

ca. 5 m

Synchrotrons and Flash irradiation

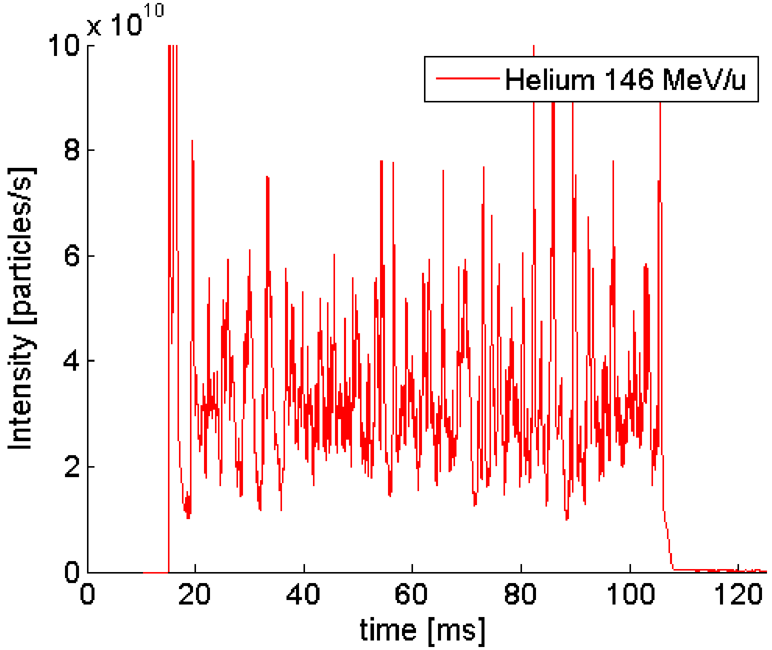
HIT, Heidelberg

Experimental RF-KO extraction
at FLASH dose rates > 40 Gy/s.

e.g.

M. Durante, W. Tinganelli, U. Weber, Physica Medica 94 (2022)

Weber, Scifoni, and Durante, Medical Physics. 49 (2022) 1974



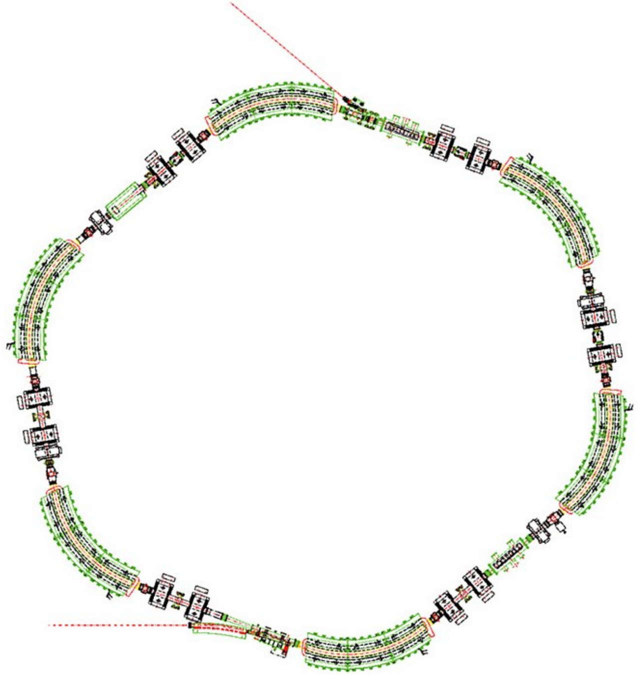


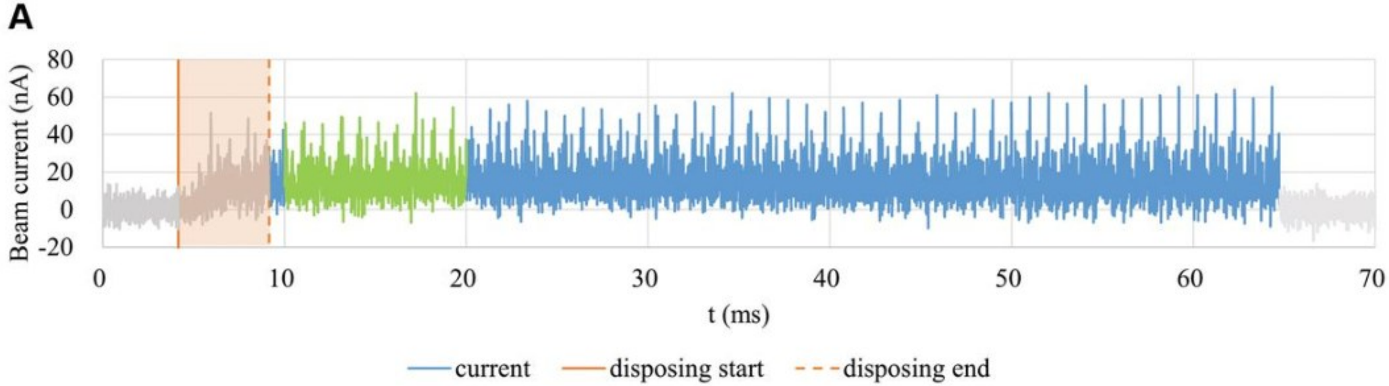
Table 2: Intensities reached for FLASH conditions at HIT. Each number is the result of an optimisation for a particular experiment session. They do not show the technical limitation.

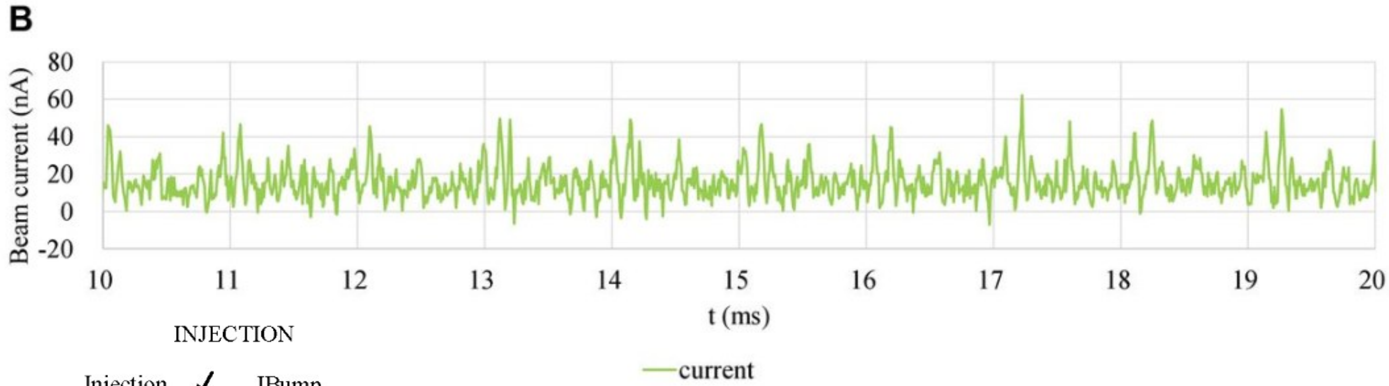
Ion	particles per spill	spill duration (ms)	intensity (ions/s)
Protons	$1 \cdot 10^{10}$	200	$5 \cdot 10^{10}$
^{4}Helium^{2+}	$3.5 \cdot 10^{9}$	90	$3.9 \cdot 10^{10}$
^{12}Carbon^{6+}	$4.2 \cdot 10^{8}$	200	$2.1 \cdot 10^{9}$
^{16}Oxygen^{8+}	$2 \cdot 10^{8}$	180	$1.1 \cdot 10^{9}$

Synchrotrons and Flash irradiation

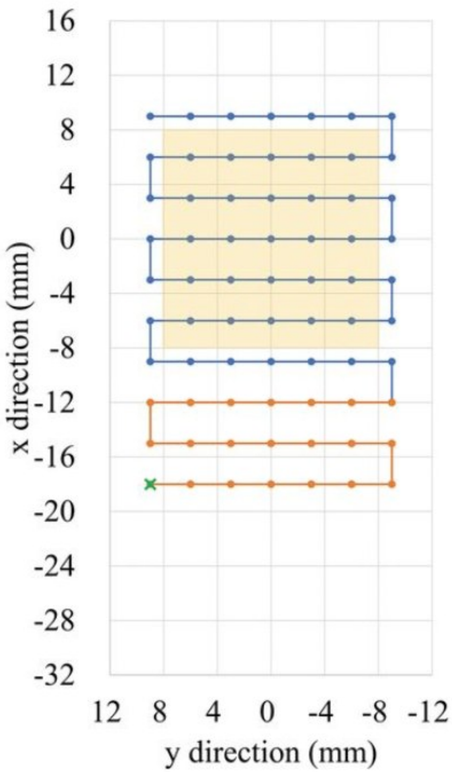
208 MeV/u $^{12}C^{6+}$ at 92 Gy/s from Hitachi HyBEAT synchrotron. →

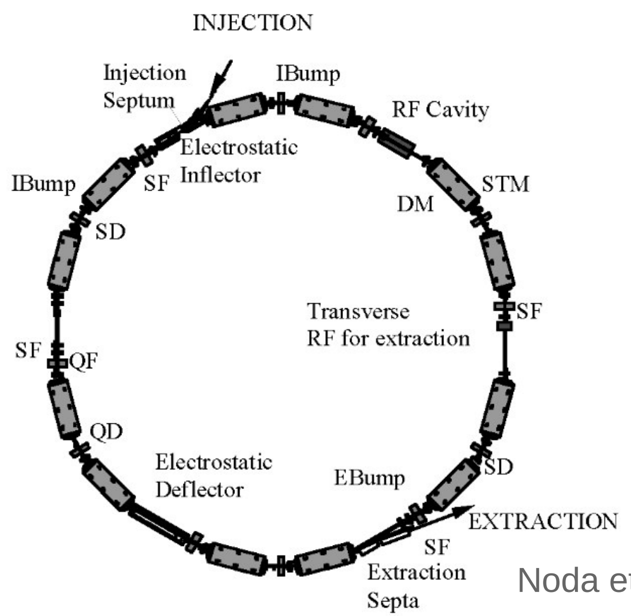
Scanned area:
1.6 x 1.6 cm²





Yagi et al., Anticanc. Res. 43 (2023)





Noda et al. Proc. of PAC 2009

Take-home messages

Different accelerators serve different purposes.

Proton therapy accelerators and their R&D are almost fully industrialized by now.

Carbon therapy is still more closely tied to research facilities (Europe) …

… but commercial $^{12}C^{6+}$ solutions are getting more common (Japan).

Therapy accelerators *will* change as new technologies become available.