Lecture

Accelerators for Ion-Beam Therapy

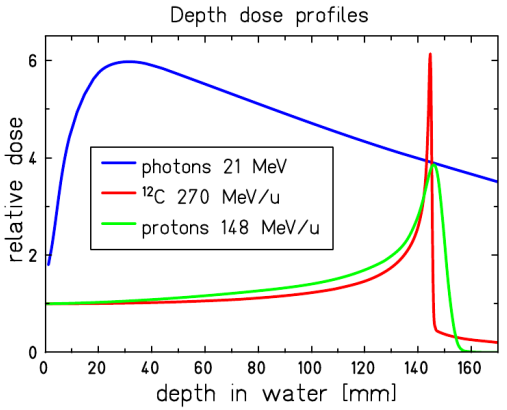
Claude Krantz

Marburger Ionenstrahl-Therapiezentrum

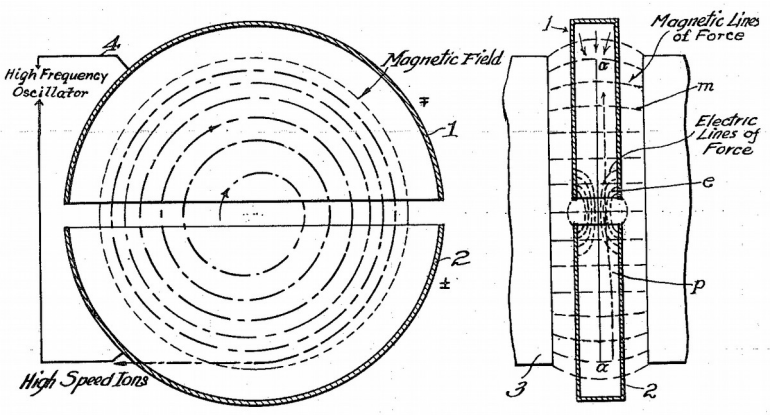
21 September 2017

Outline

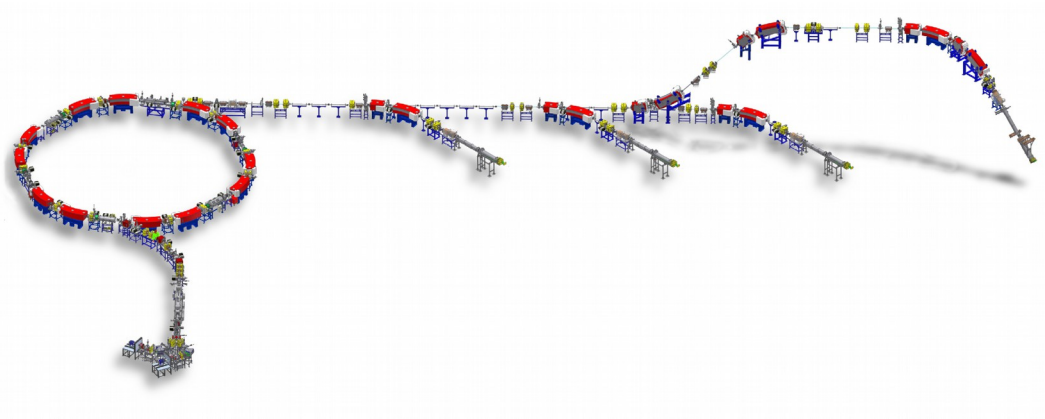
Ion-beam therapy



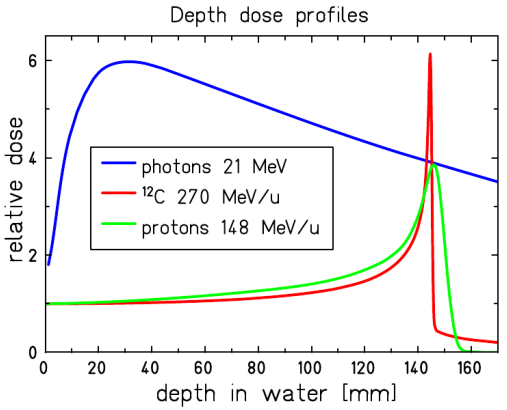
Accelerators for ion-beam therapy



MIT: A synchrotron-based $^{12}C^{6+}$ / p therapy centre



Outline



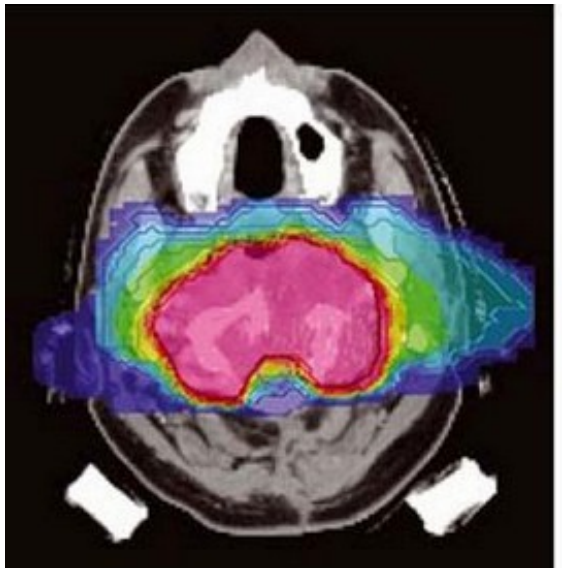
Ion-beam therapy

Accelerators for ion-beam therapy

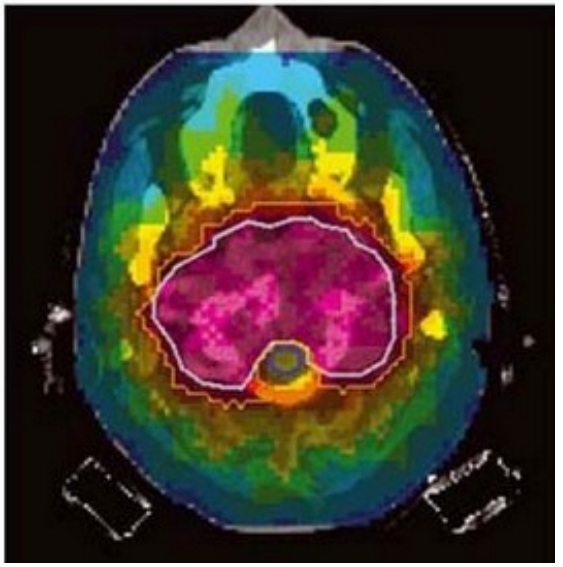
MIT: A synchrotron-based $^{12}C^{6+}$ / p therapy centre

Basic idea of tumour therapy using ionising radiation

Heavy-ion beam



High-energy X-rays



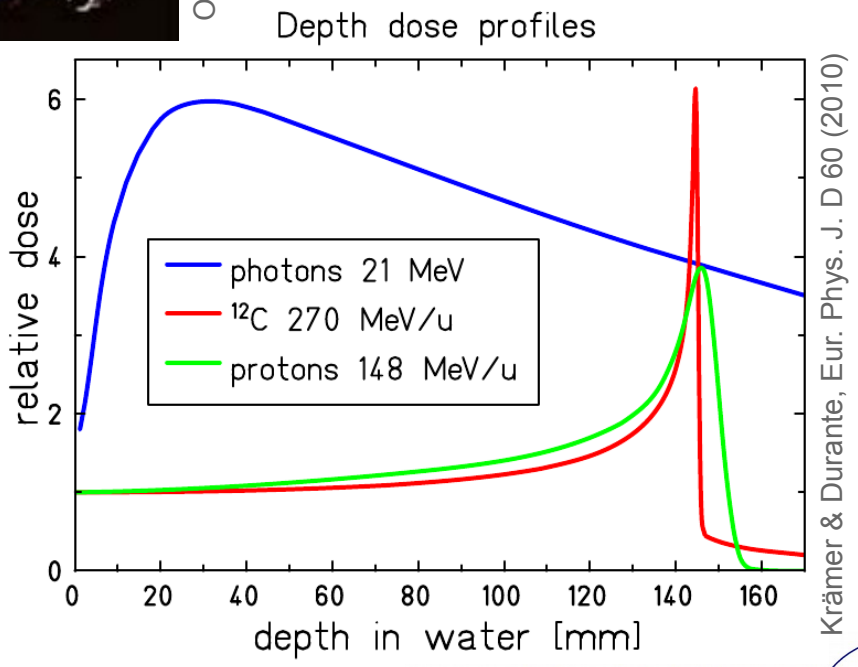
O. Jäkel, GSI

Kill-off cancer tissue by inflicting high doses of ionising radiation, sparing as much as possible the healthy structures.

Ion-beam therapy is one realisation of that idea.

varian.com

← Compact electron Linac for photon radiotherapy (Varian)



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

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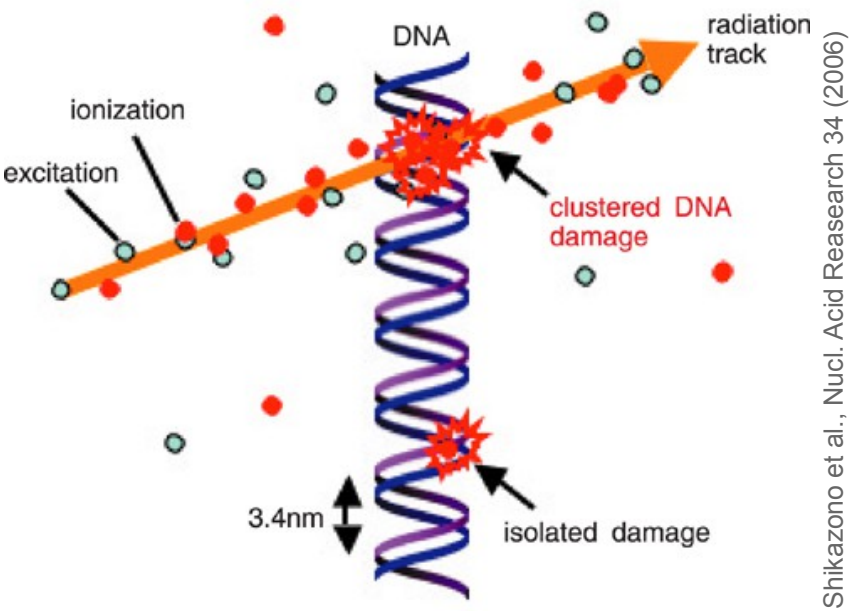
Basic idea of tumour therapy using ionising radiation

Radiation leads to ionisation damage of the DNA molecule in the cellular nucleus.



Shikazono et al., Nucl. Acid Reasearch 34 (2006)

→ 3 fundamentally different outcomes possible:

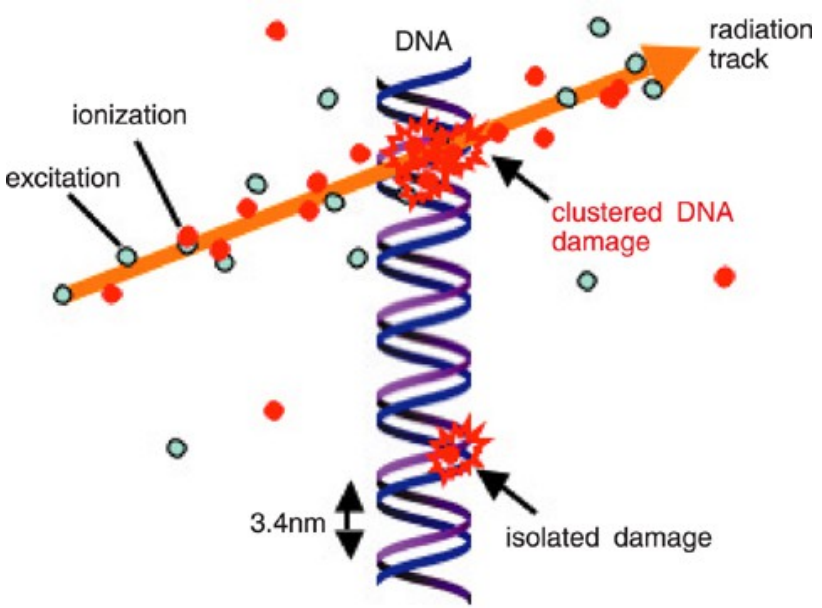
(1) Repair mechanisms reconstitute the DNA in its original state → Cell survives.

(2) DNA damage cannot be repaired (in time) → Cell dies (“apoptosis”).

(3) DNA repair leads to a non-original state → Cell survives, potentially leading to mutations.

Basic idea of tumour therapy using ionising radiation

Radiation leads to ionisation damage of the DNA molecule in the cellular nucleus.



Shikazono et al., Nucl. Acid Reasearch 34 (2006)

Evolution has tuned cellular biology such that

(1) is the most likely,

and

(3) the least likely

response to ***naturally*** **occurring** radiation damage.

→ 3 fundamentally different outcomes possible:

(1) Repair mechanisms reconstitute the DNA in its original state → Cell survives.

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Basic idea of tumour therapy using ionising radiation

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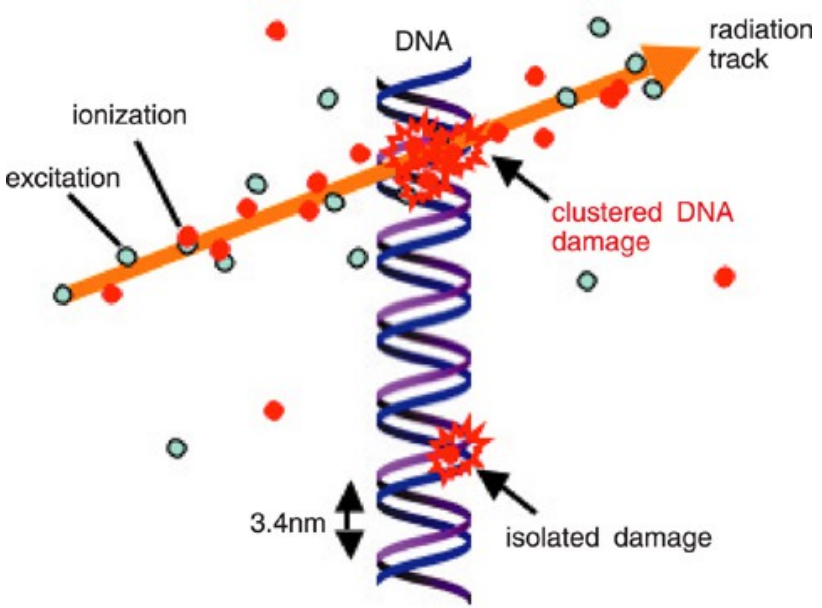

Shikazono et al., Nucl. Acid Reasearch 34 (2006)

Radiation therapy tries to induce apoptosis **preferentially in the tumour cells**, while allowing healthy tissues to survive.

→ 3 fundamentally different outcomes possible:

(1) Repair mechanisms reconstitute the DNA in its original state → Cell survives.

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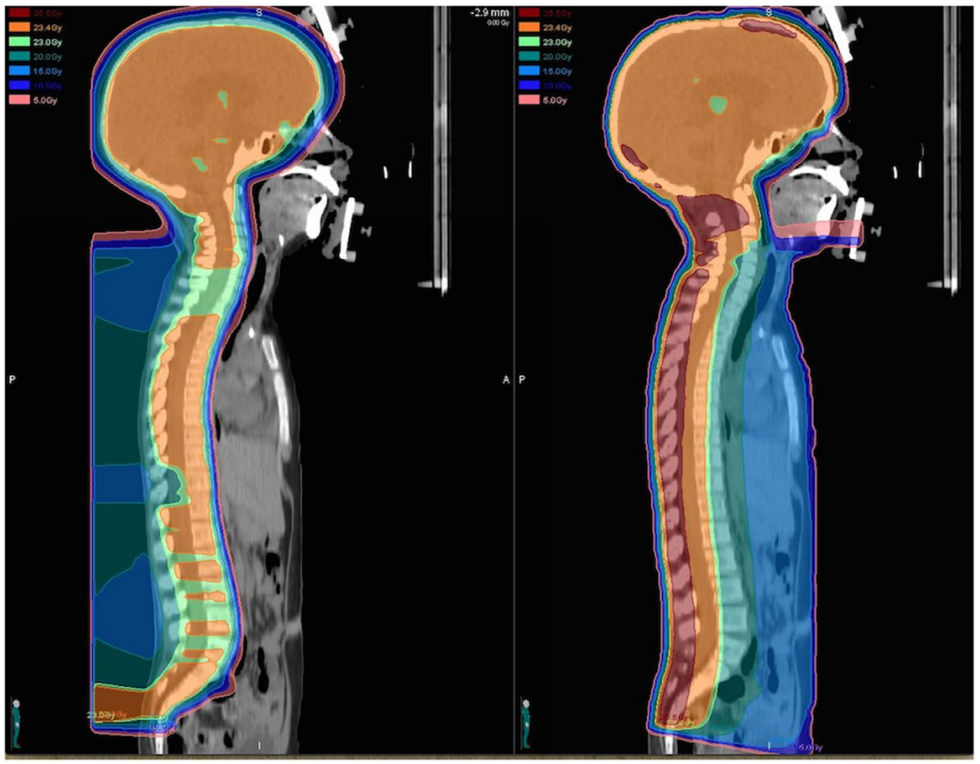
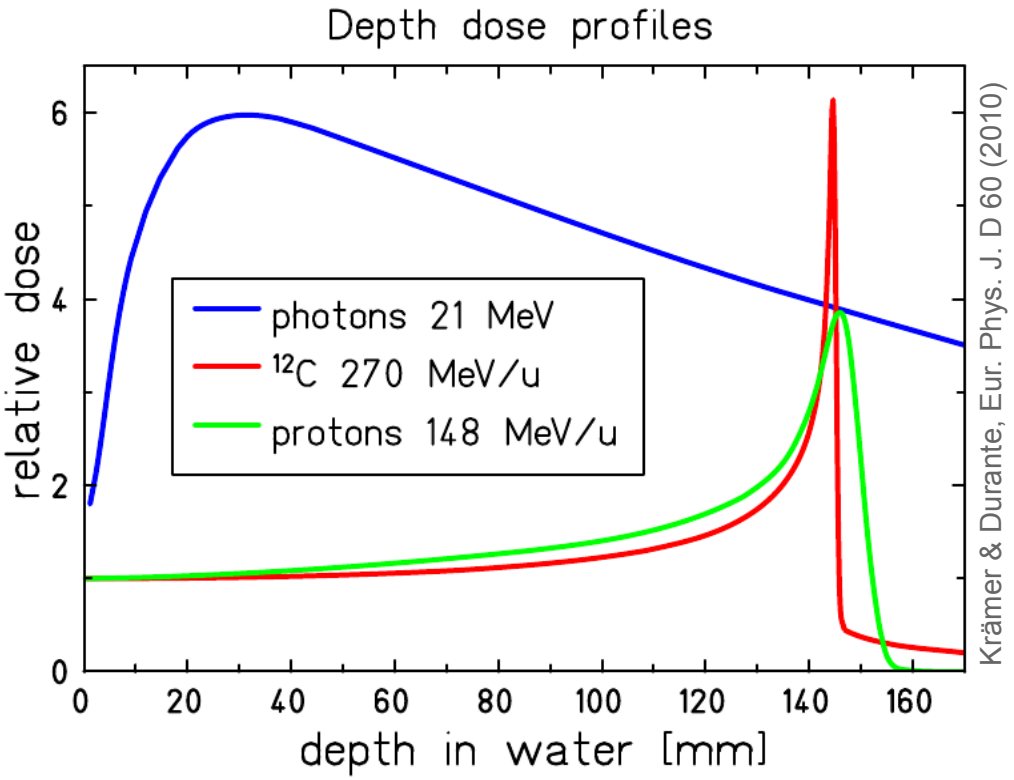
Physical differences in particle-matter interaction

Ion beam

Photons



Eaton et al., Front. Oncol. 5 (2015) 261



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

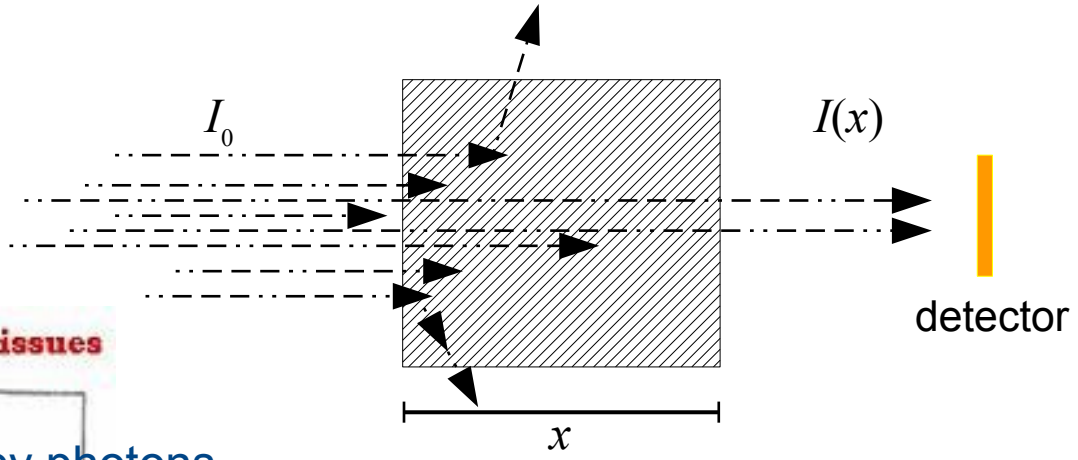
- Ion beams: **Well-defined range** in human tissue, with energy deposition peaking near the end-of-travel ("*Bragg peak*").
- X-rays: Energy deposition characterised by **exponential attenuation** of the photon beam.

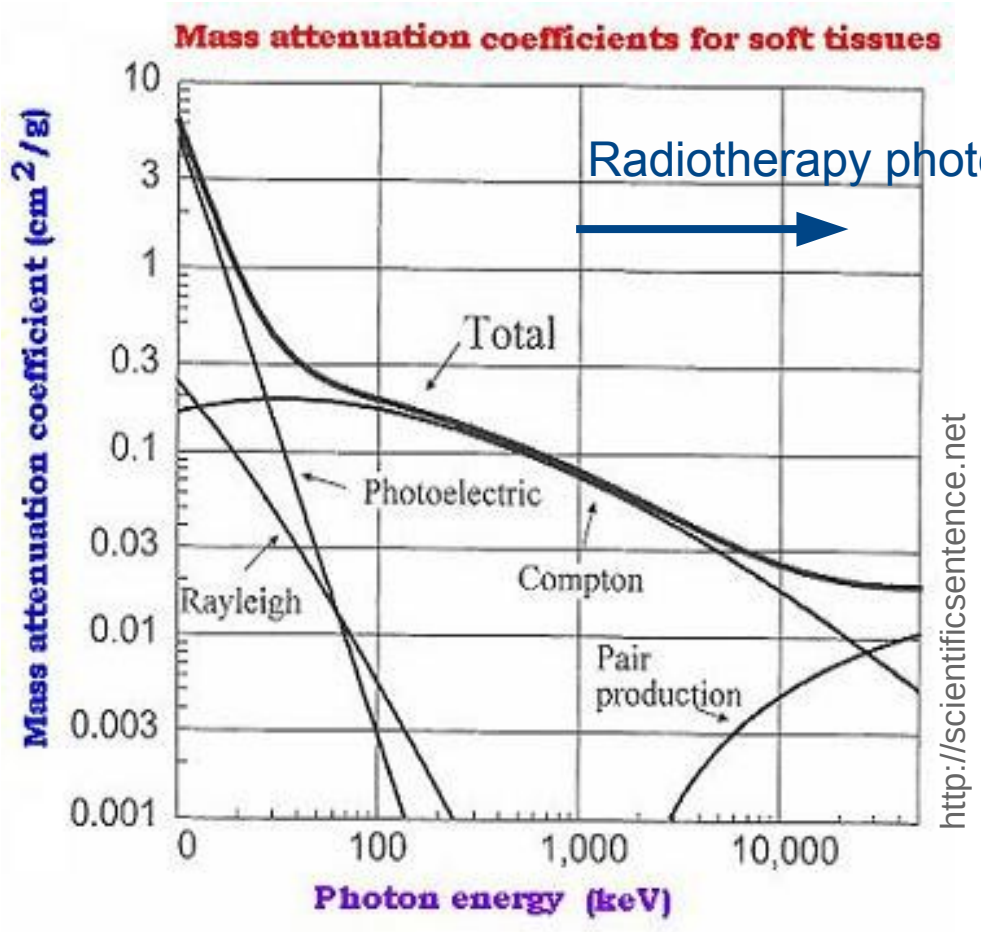
Particle-matter interaction: Photons

Attenuation law for photons in matter

$$I(x) = I_0 \exp(-\mu x)$$

with μ = "*attenuation coefficient*"





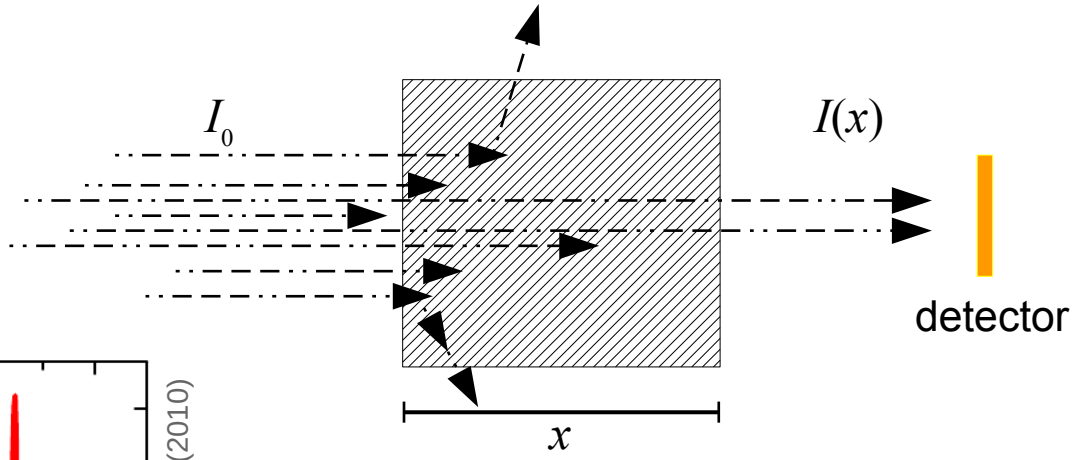
μ defined by (target-dependent!) cross sections for

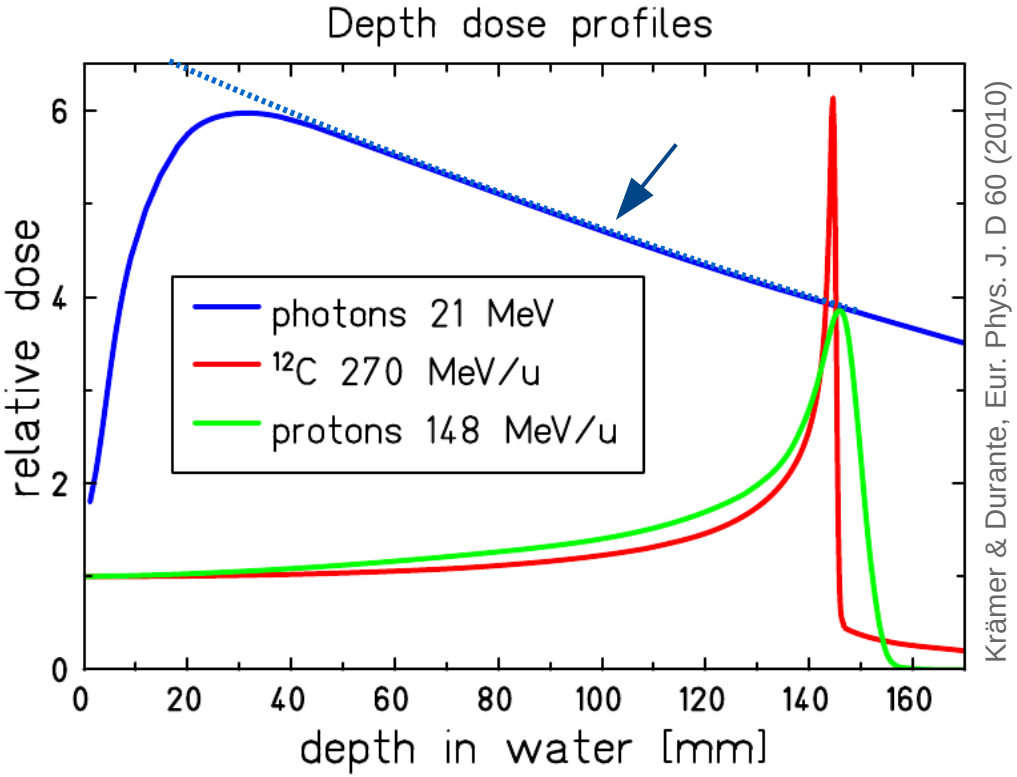
- photoelectric effect
- Compton scattering
- pair production

Particle-matter interaction: Photons

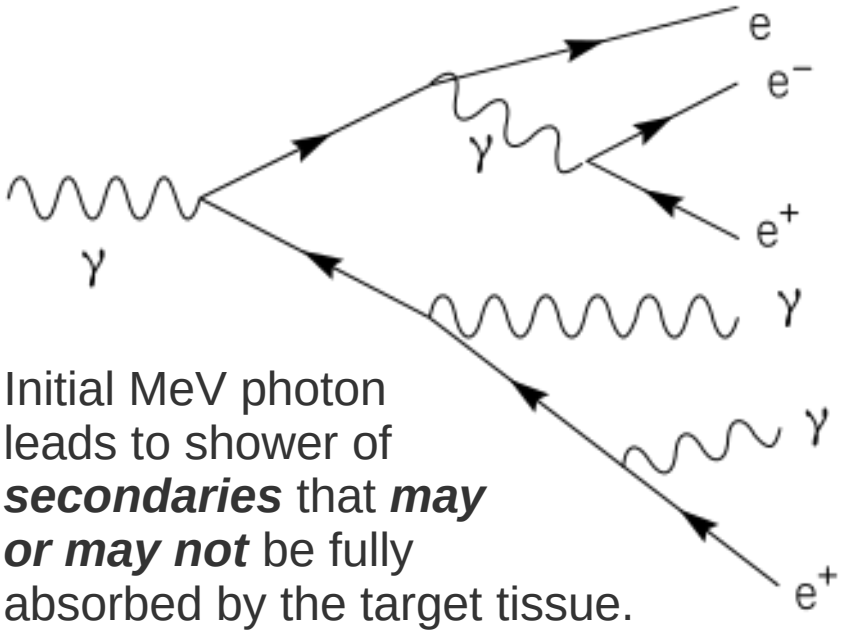
Attenuation law for photons in matter

$I(x) = I_0 \exp(-\mu x)$





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



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Initial MeV photon leads to shower of ***secondaries*** that ***may or may not*** be fully absorbed by the target tissue.

→ Actual *depth-dose profile* is blurred with respect to 1/*e*-law.

Particle-matter interaction: Ions

Ions are not destroyed upon interaction with target electrons.

(we neglect strong interaction with target nuclei …)

Travel across target matter is characterised by **multiple scattering** with quasi-free electrons.

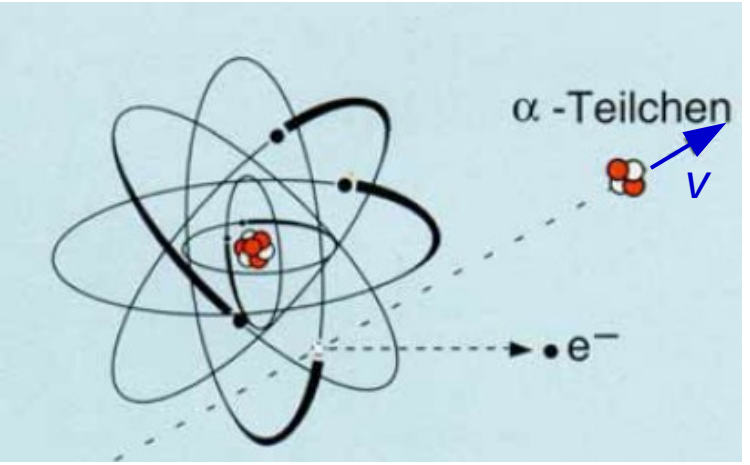
(→ "*binary collision model*")

Because of

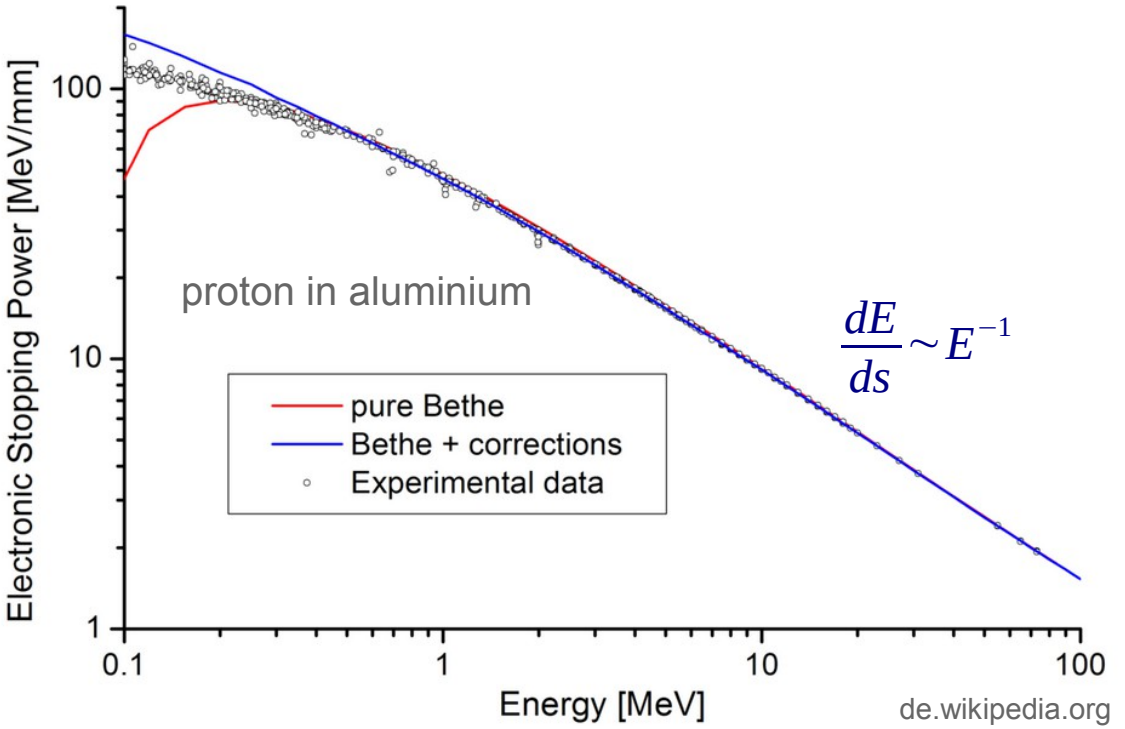
$$M_{ion} >> m_e$$

this results in an overall *stopping force*:

$$\vec{F} \sim -\frac{1}{v^2}\frac{\vec{v}}{v}$$

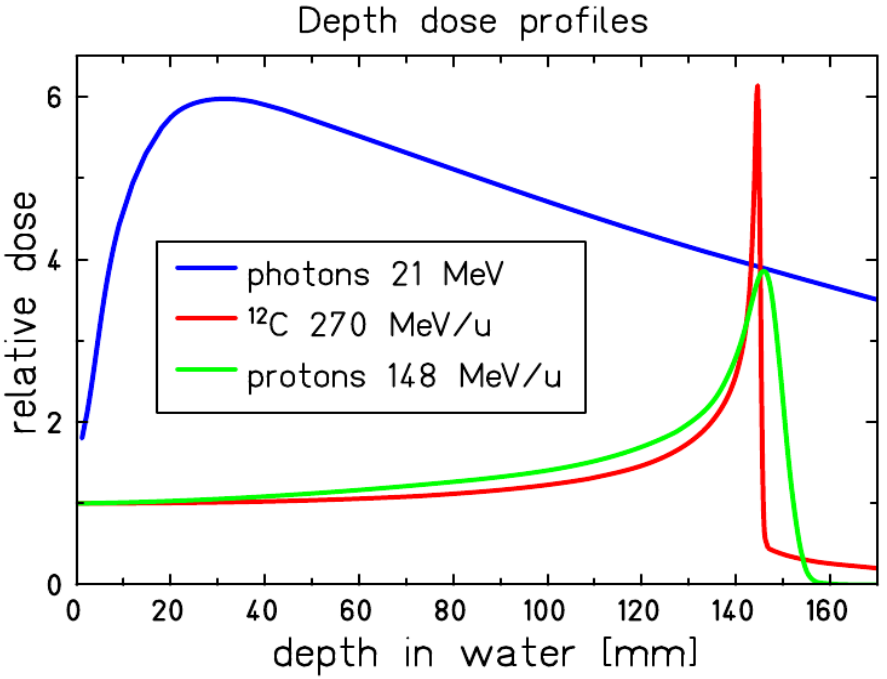


Kernenergie Basiswissen, DAtF, 2013



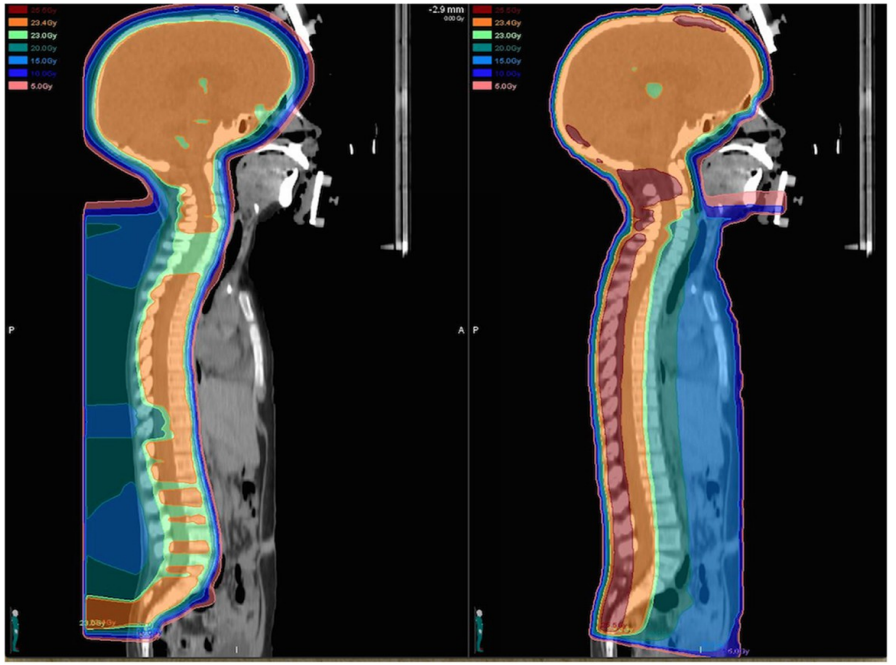
Particle-matter interaction: Ions

d*E*/d*s* rises as the particle velocity decreases:



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

Ion beam Photons



Eaton et al., Front. Oncol. 5 (2015) 261

Radiation therapy with ions uses this as an advantage:

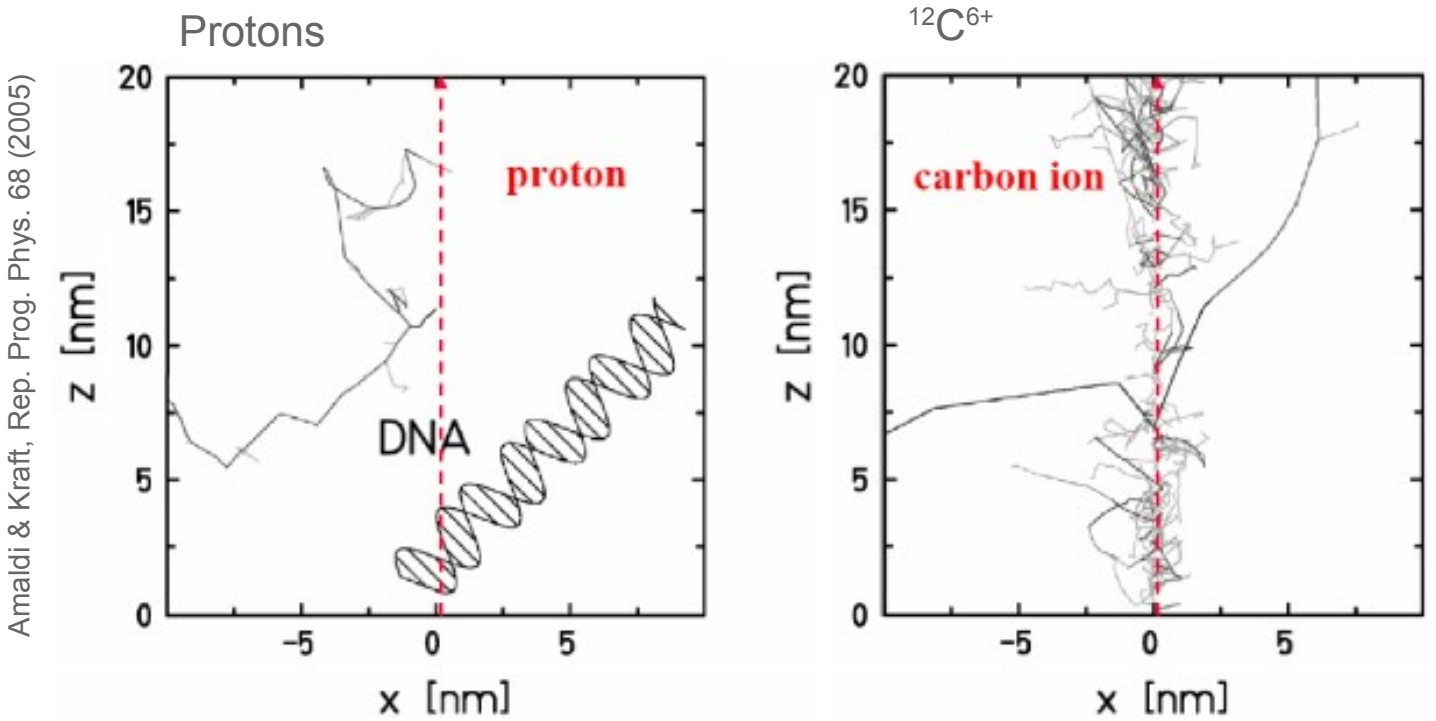
1) Particle stops at a range *defined* by its initial energy.
   → Avoids irradiation of (healty) tissue **behind the target volume**.

2) d*E*/d*s* is largest near the end-of-travel ("*Bragg peak*").
   → Lower dose distribution in the (healty) tissue of the **entrance channel**.

Linear Energy Transfer

Higher d*E*/d*s* → higher LET (effective energy deposition per length of track).

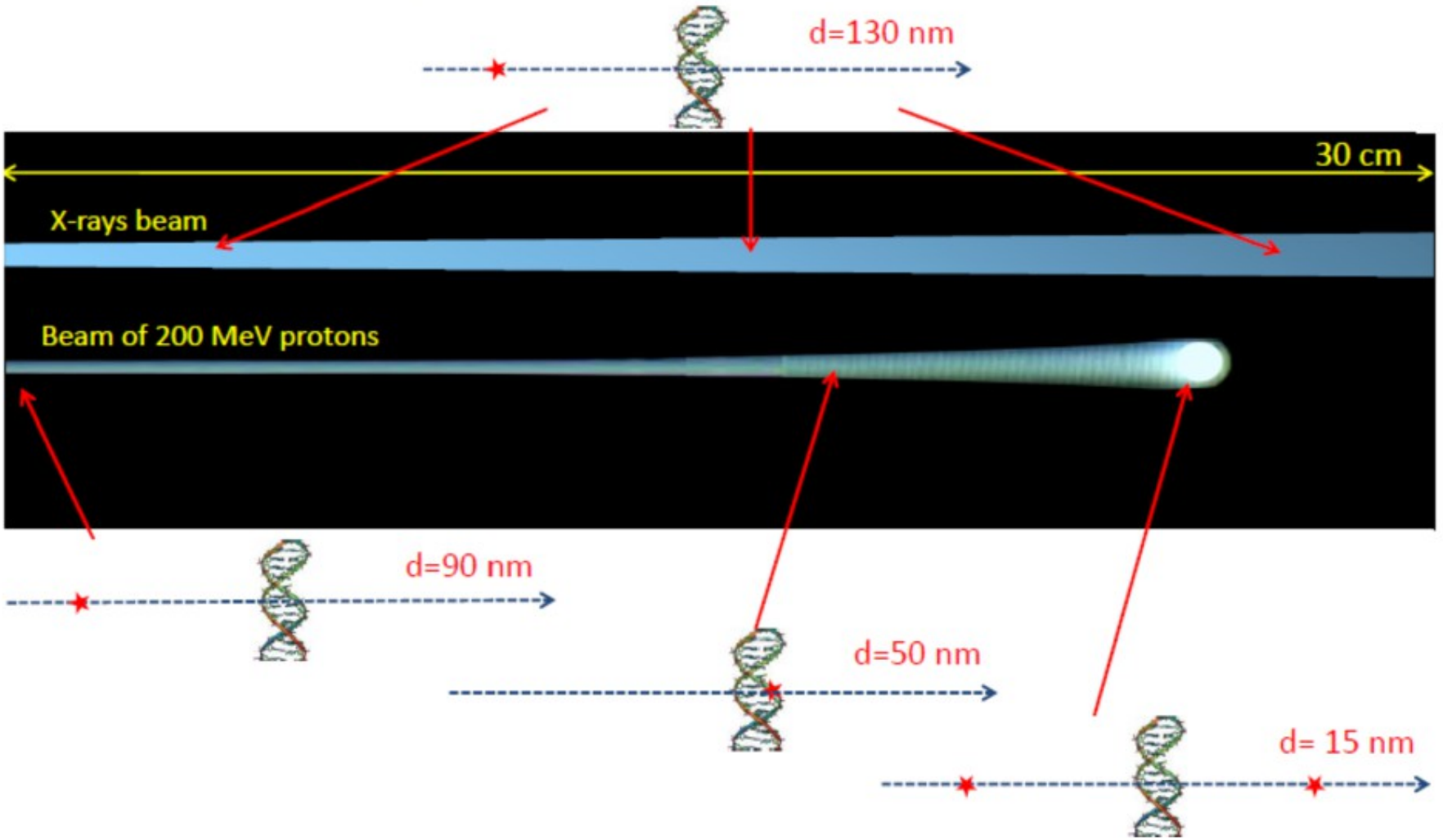
Mean distance between ionisation events depends on the nature of the projectile.
Higher LET means higher likelyhood to “hit” a DNA molecule along the track.



Projectiles leading to higher ionisation density are more likely to cause irreversible damage (“*double strand breaking*”) in DNA molecules.

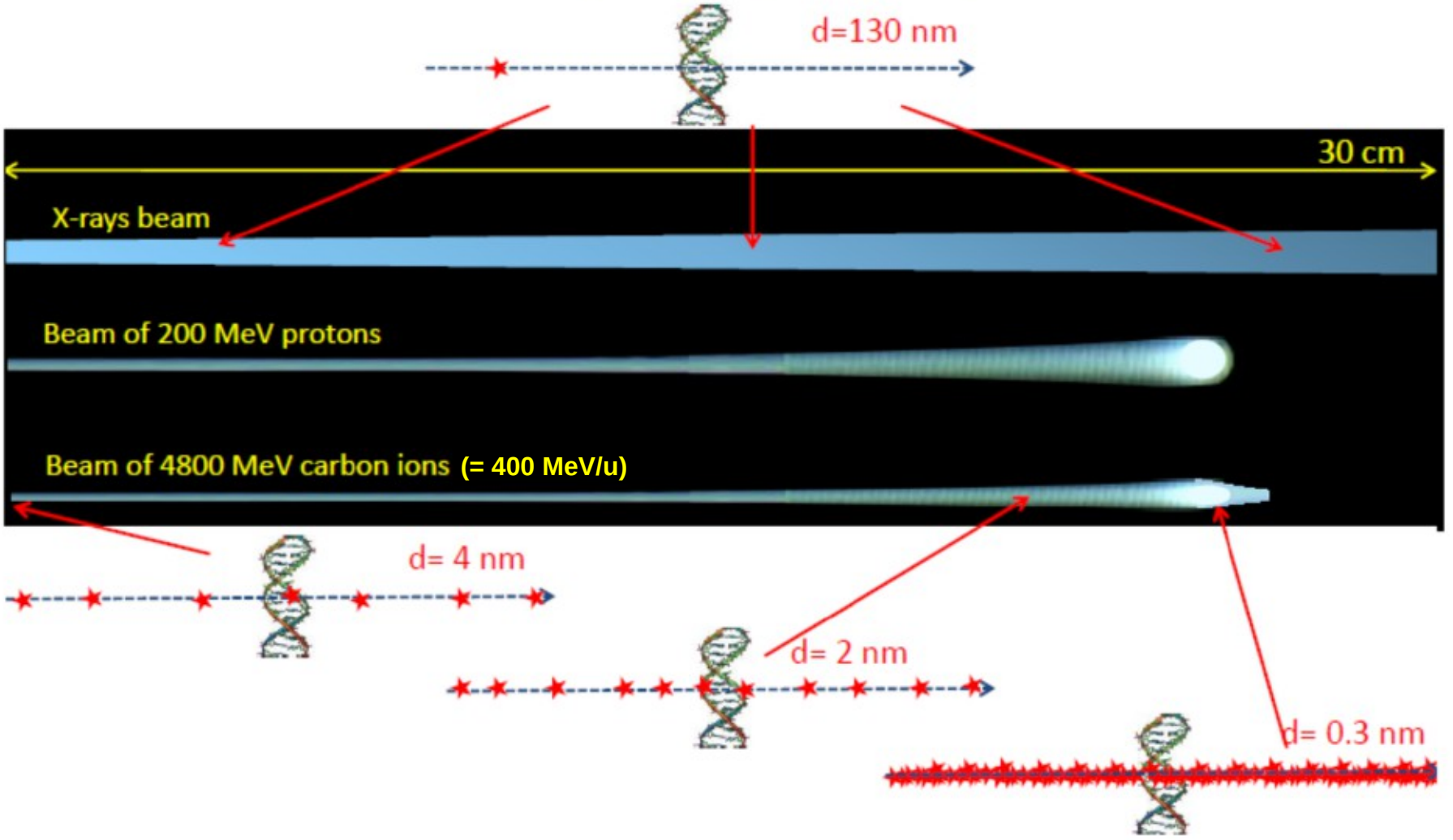
→ Higher “biological effectiveness”.

Linear Energy Transfer



G. Montarou, Radiobiology in Medecine, 17-12-2013

Linear Energy Transfer

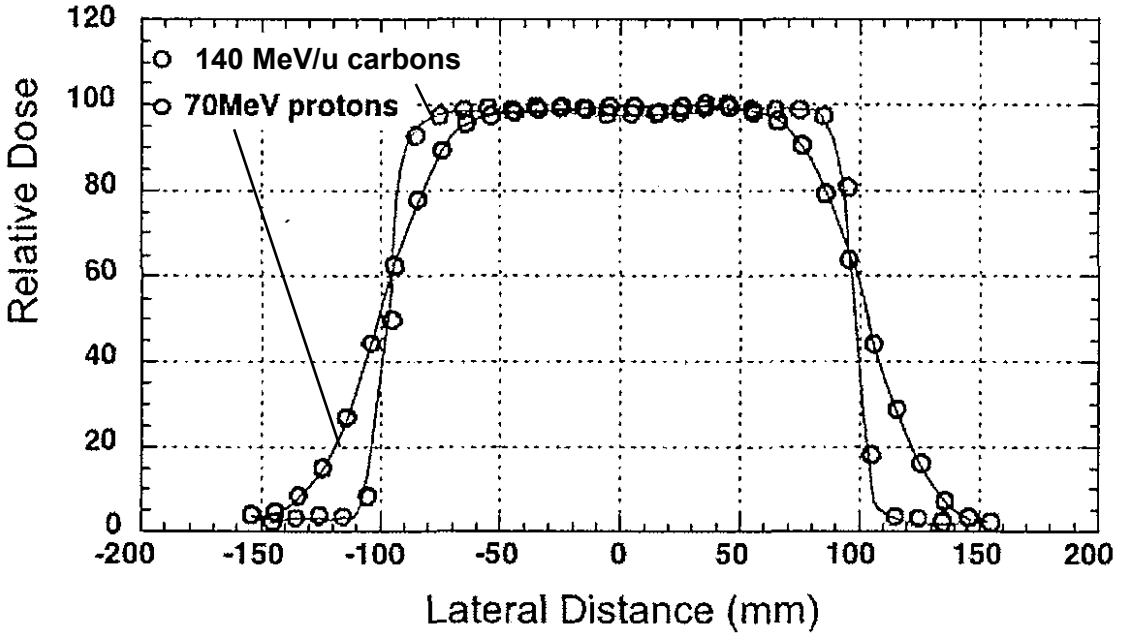


G. Montarou, Radiobiology in Medecine, 17-12-2013

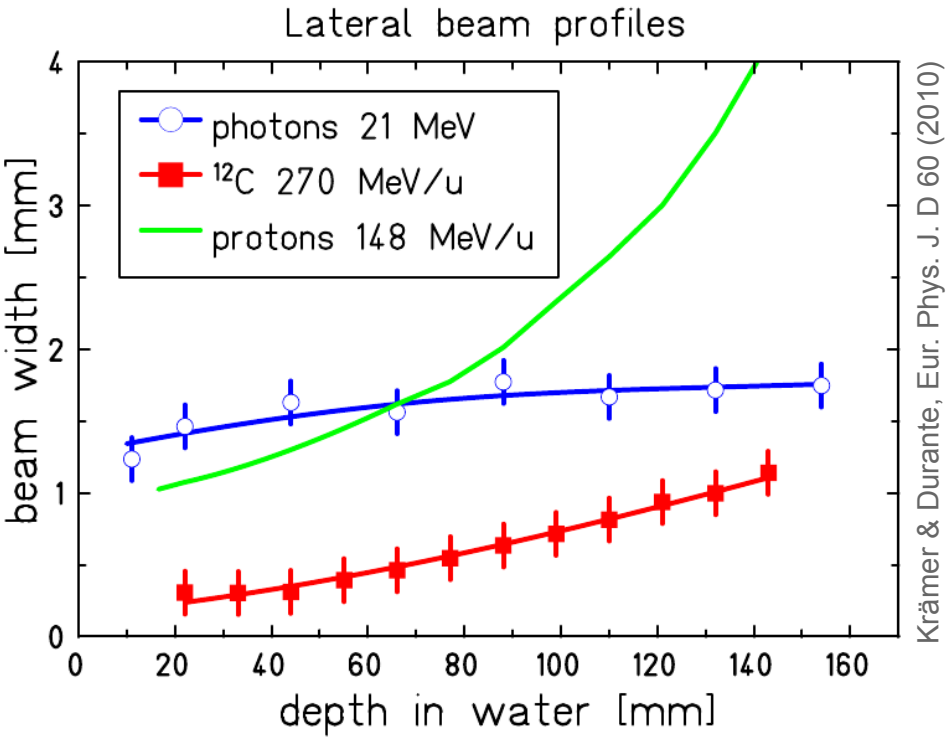
Physical differences in particle-matter interaction

Due to principle of interaction

- Diameter of photon beam is **largely independent** on irradiation depth.
- Ions **scatter laterally**, blurring the initially-defined beam edge. (“*penumbra*”)



H. Tsuji, PTCOG Meeting, 2002



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

Scattering effect is strongest for light ions (protons).

Outline

Ion-beam therapy

Accelerators for ion-beam therapy

MIT: A synchrotron-based $^{12}C^{6+}$ / p therapy centre

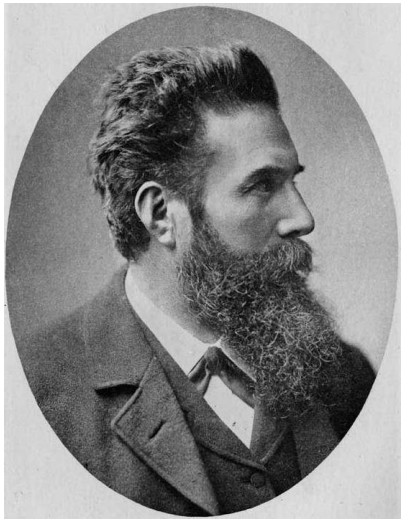
Radiation therapy using particle accelerators: History

1895 *Wilhelm Conrad Röntgen* (1845 – 1923) discovers X-rays at the University in Würzburg

1896 On 23rd January Röntgen announced his discovery and demonstrated the new kind of radiation by a photograph of the hand of his colleague *Albert von Kolliker*

1897 First treatments of tissue with X-rays by *Leopold Freund* at University in Vienna

1901 Physics Nobel prize for W. C. Röntgen



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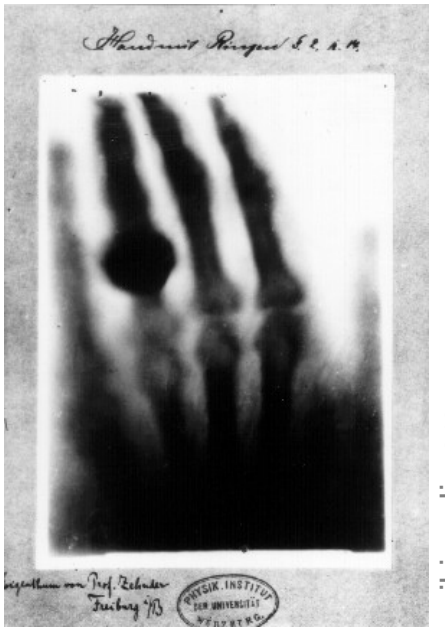

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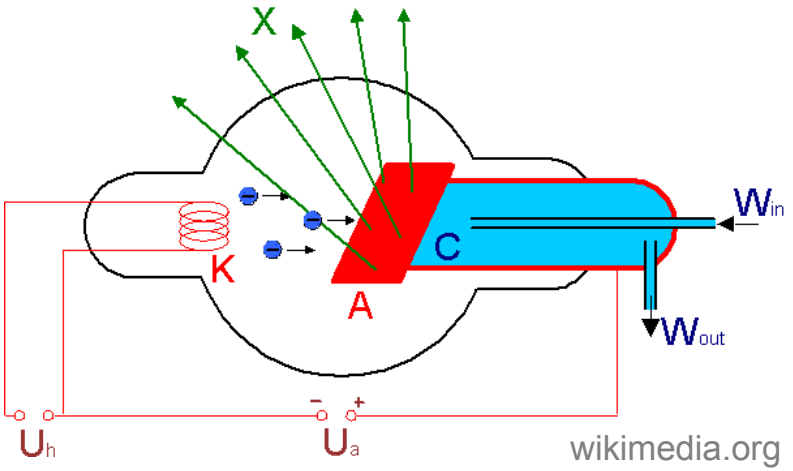


wikimedia.org

Working principle of an X-ray tube – a simple electrostatic accelerator

Radiation therapy using particle accelerators: History

1899 First X-ray treatment of carcinoma in Sweden by *Stenbeck* and *Sjögren*

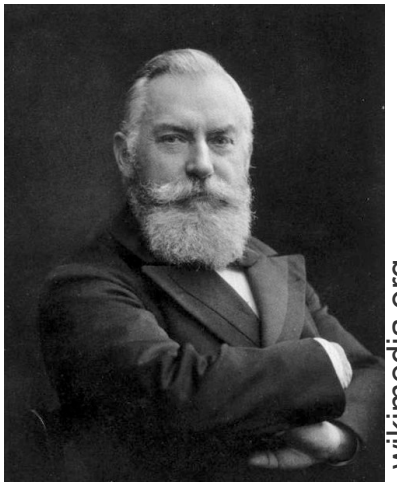
1906 Vinzenz Czerny founded the “Institute for Experimental Cancer research” in Heidelberg – the first of its kind

1913/4 Invention of partly and fullly rotatable radiation instrumentation

1920s Industrially manufactured X-ray apparatus'
Right: Reiniger-Gebbert & Schall AG (later: Siemens), Erlangen; 1922) with a high-voltage of 150 kV – without shielding!

1930 RF linear accelerator principle invented by *Rolf Wideroe*

1949 *Newberry* developed first linear accelerator for therapy in England



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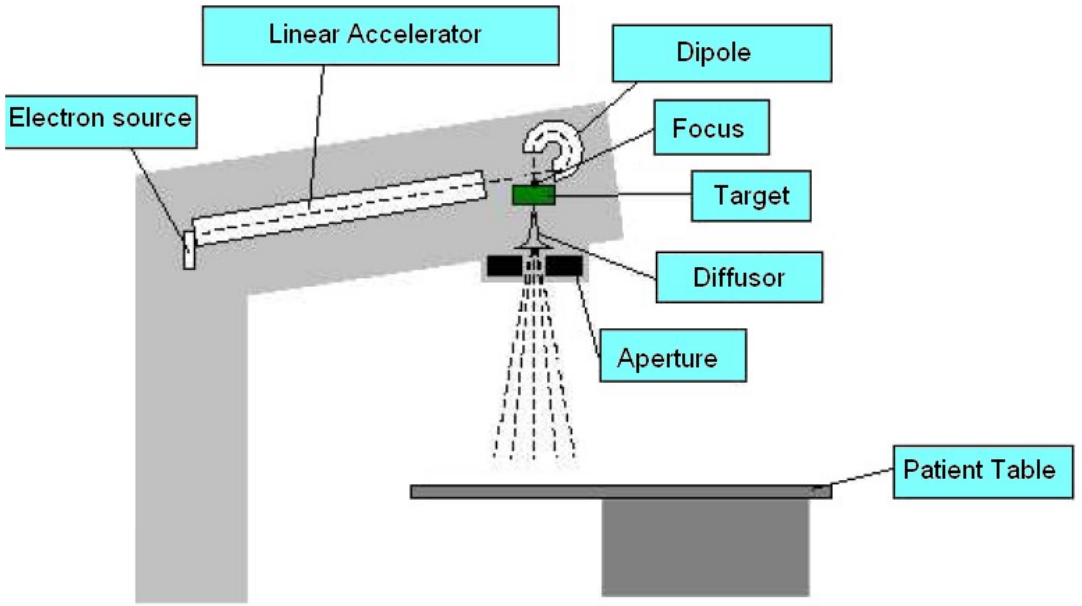
Radiation therapy using particle accelerators: History

1950s Development of compact linear accelerators by Siemens, Varian, Elekta, and other companies – reaching energies of 25 MeV (and above).

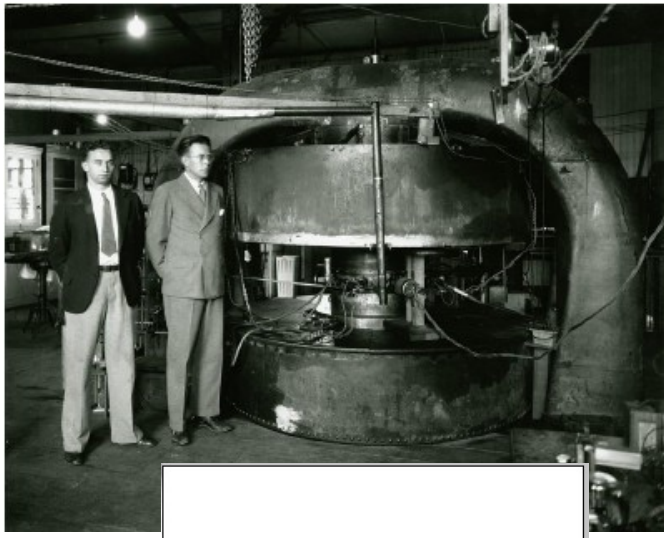


Layout of a modern electron "linac" for radiotherapy

↑ ONCOR from Siemens

Radiation therapy using particle accelerators: History

1929	Invention of the cyclotron by *Ernest Lawrence*
1930s	Experimental neutron therapy
1946	R. *R. Wilson* proposed proton & ion therapy
1950s	Proton therapy, LBL Berkeley (184” cyclotron)
1945	*Edwin Mattison McMillan* at University of California and *Vladimir Iosifovich Veksler* (Soviet Union) invent the synchrotron principle.
1975	Begin of carbon therapy at the Bevalac synchrotron (Berkeley) *(A total of >2000 patients were treated with He, C, Ne, Si, Ar until 1992)*

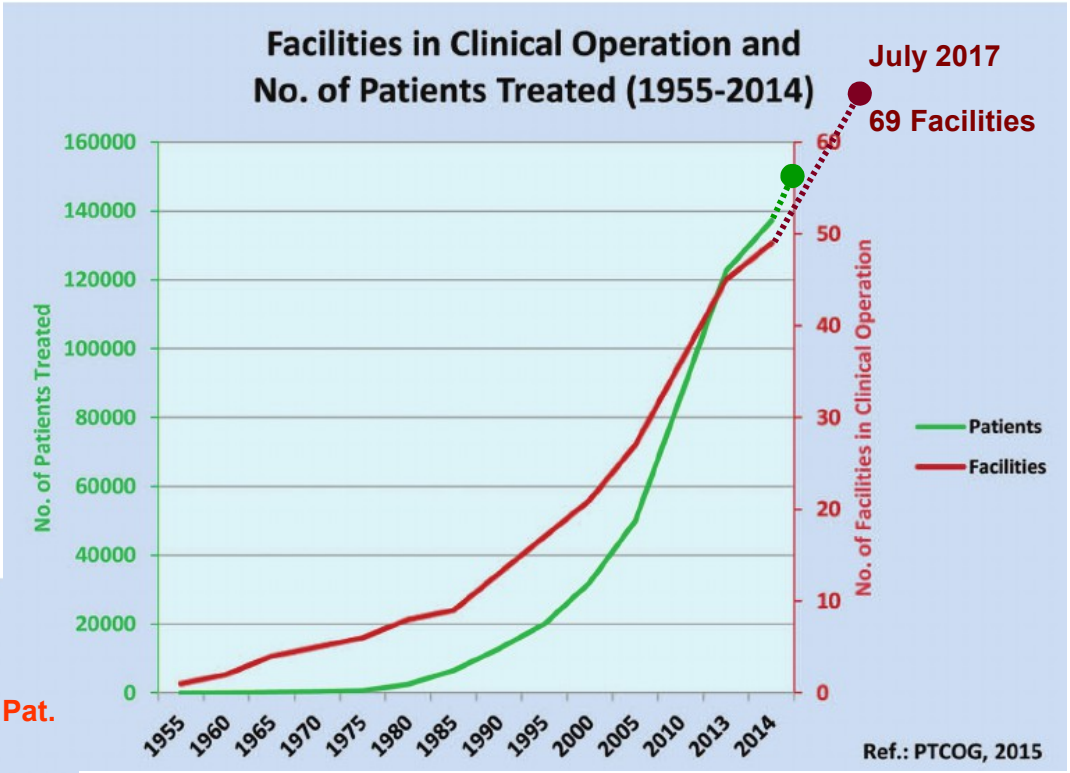


Robert Wilson (Harvard), *Radiological use of fast protons*, Radiology 47 (1946), 487

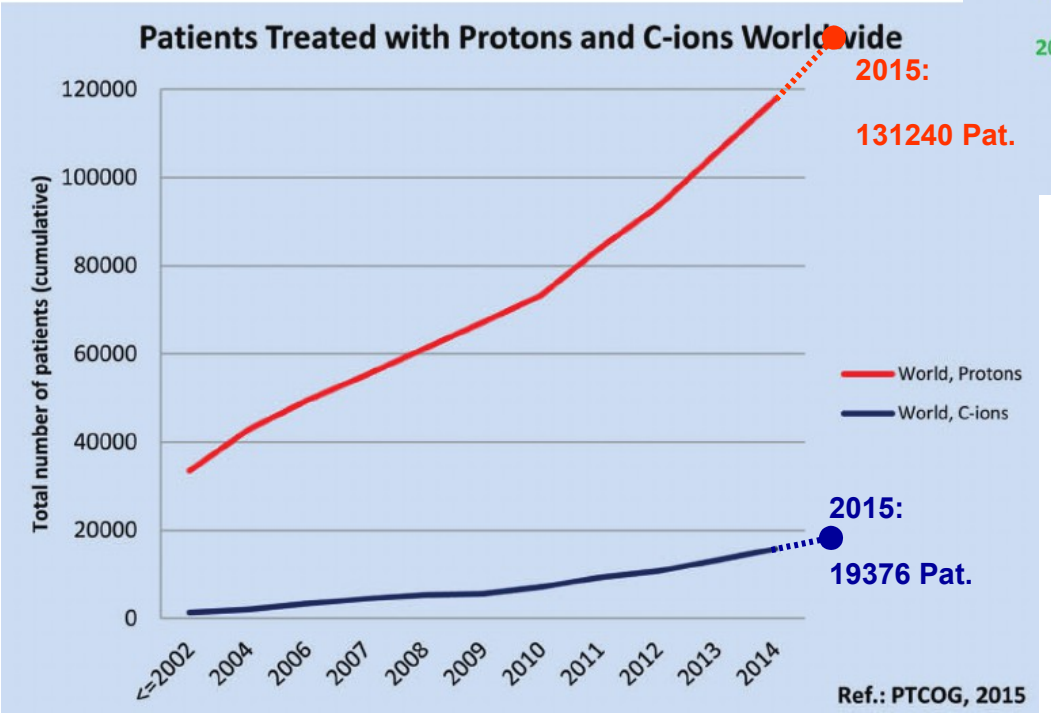
Radiation therapy using particle accelerators: History

since 1975

Radiotherapy with ion beams is a growing industry.



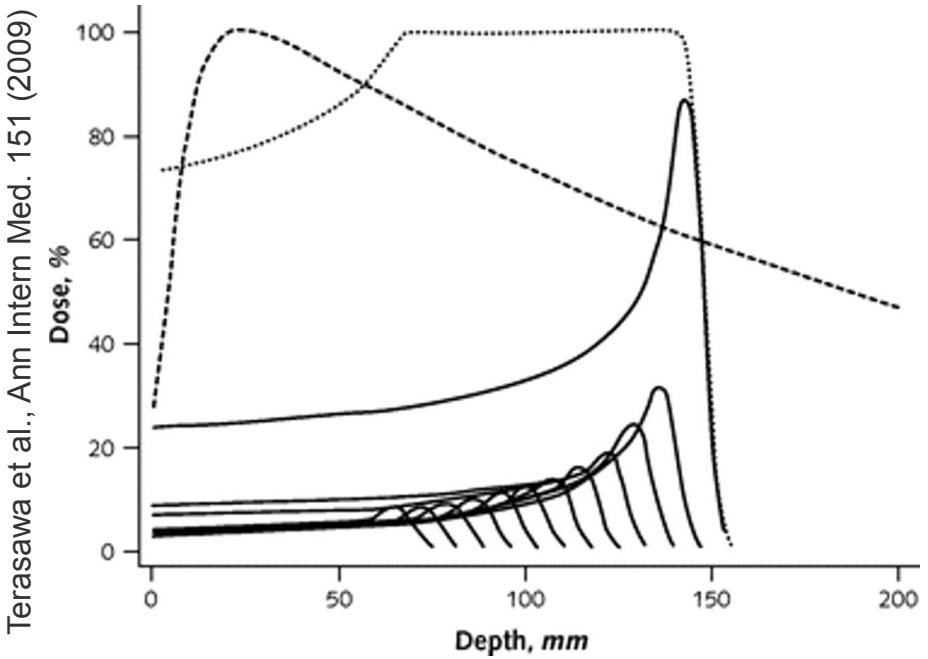
Jermann, Int. J. Particle Ther. 2 (2015) 50–54



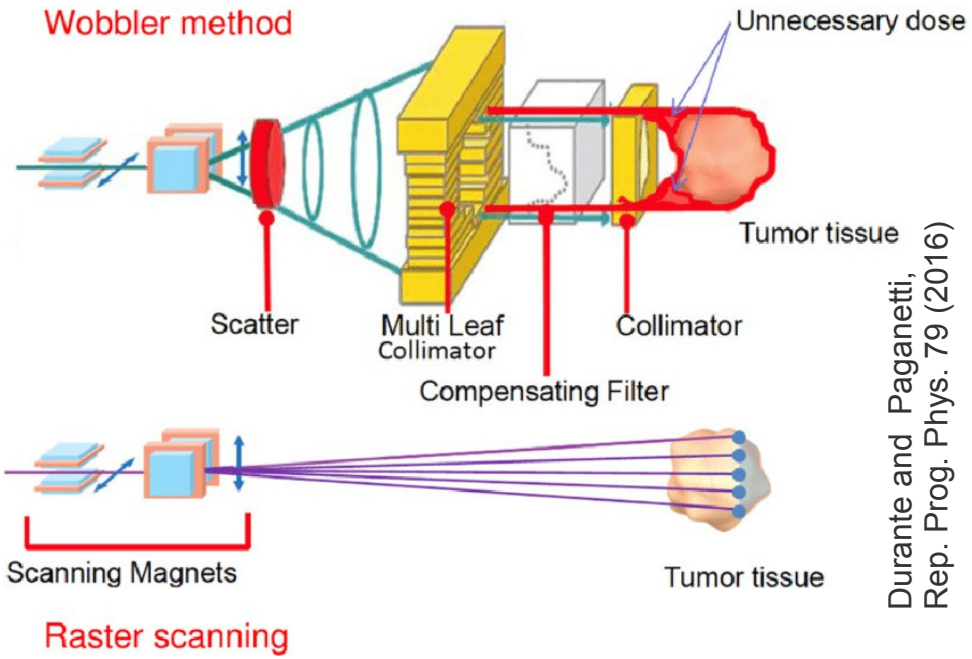
Jermann, Int. J. Particle Ther. 2 (2015) 50–54

Dose distribution techniques with ion beams

Logitudinal distribution (along beam axis):



Lateral distribution (transverse to beam):



Generate a "*Spread-Out Bragg-Peak*" by

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.

Achieve the wanted *transverse dose profile* by

1) tumour-conformal **collimation** of a wide beam (e.g. scatterer + collimator),

2) "painting" using a fine "pencil-beam" (**scanning**).

Dose distribution techniques with ion beams

Integral dose + beam intensity:

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

with

D	applied dose in Gy = J/kg
φ	particle fluence in billions per cm²
S/ρ	density-normalised stopping force dE/ds·ρ 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 tumour cross-section (← Simplified 2D picture!)

→ An (average) proton rate of a few 10^9 s^{-1} (1 nA) looks like a reasonable beam intensity.

Dose distribution techniques with ion beams

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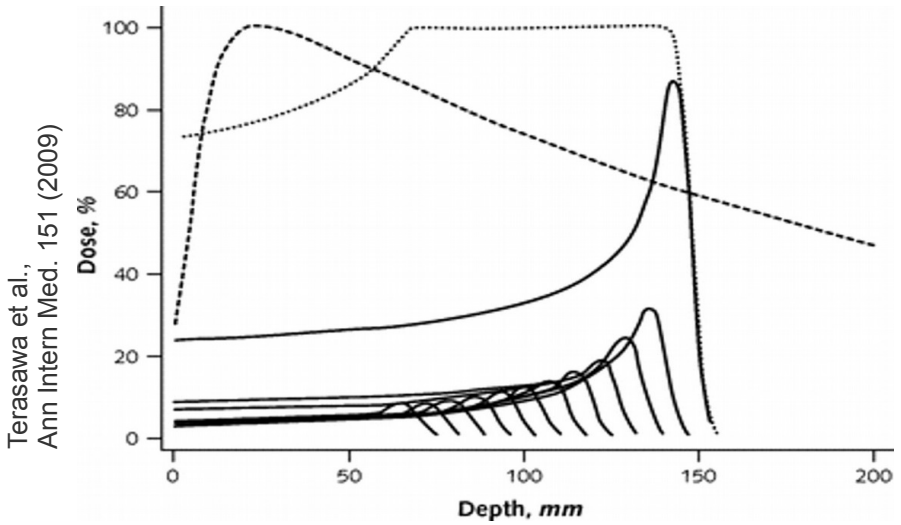
Remarks

(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.



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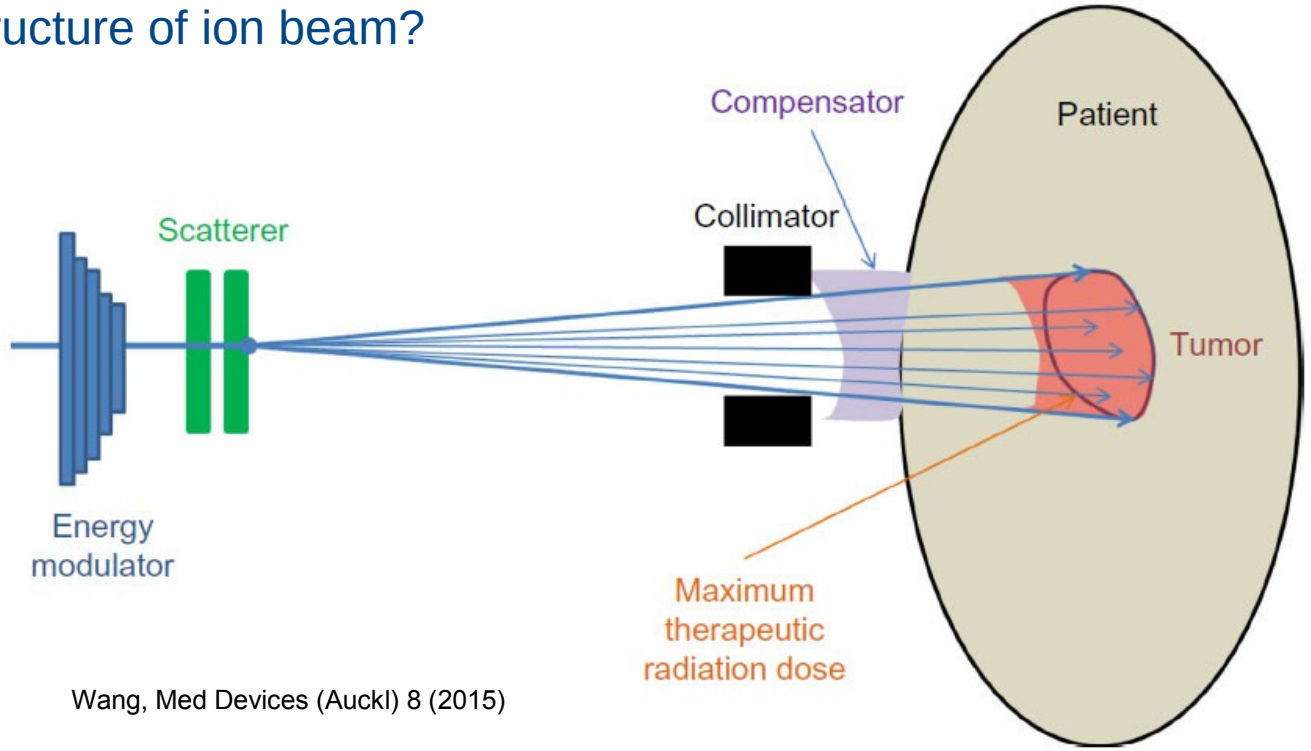
Dose distribution techniques with ion beams

Ideal time structure of ion beam?



Wang, Med Devices (Auckl) 8 (2015)

Traditional **"passive" scattering** and collimation technique requires only widening of the accelerator beam to a homogeneous, flat profile.

Tumour conformity of the dose distribution is ensured by the (patient-specific) collimating and filtering system.

→ **No specific requirement on the time structure of the beam.**

Dose distribution techniques with ion beams

Ideal time structure of ion beam?

Since the 90ies:

"Active scanning" pencil beams (*X*/*Y*)
+
"active" range stacking of beams of different energies (*Z*) and intensities from accelerator.

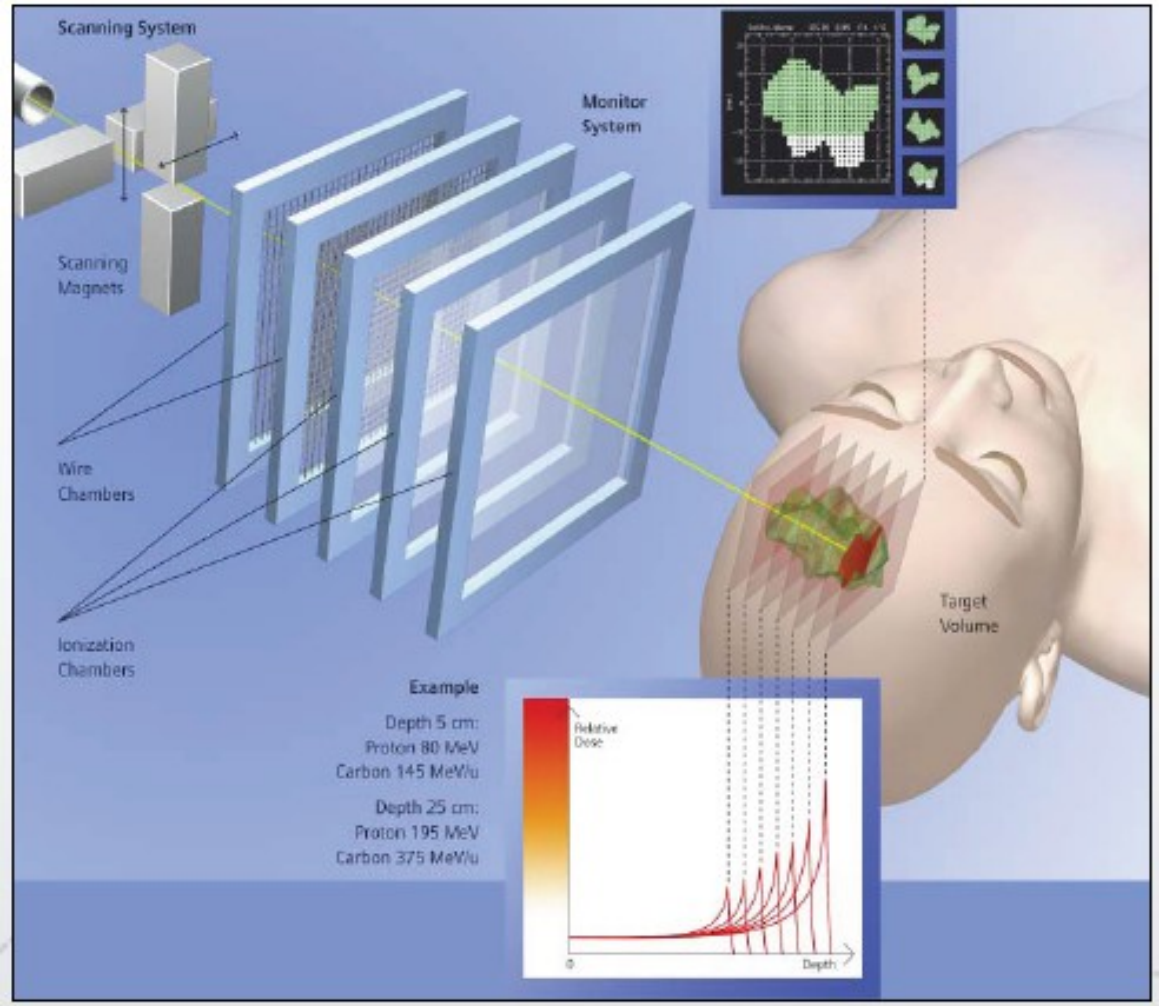
Advantages:

(1) Better tumour conformity.

(2) Less "wasted" beam in collimators and filters. (Secondary radiation!)

But:

Requires **quasi-DC beams**, whose position, spot-size, and intensity can be *monitored an controlled on-line*! **Typical pulses: 1...10 s**.

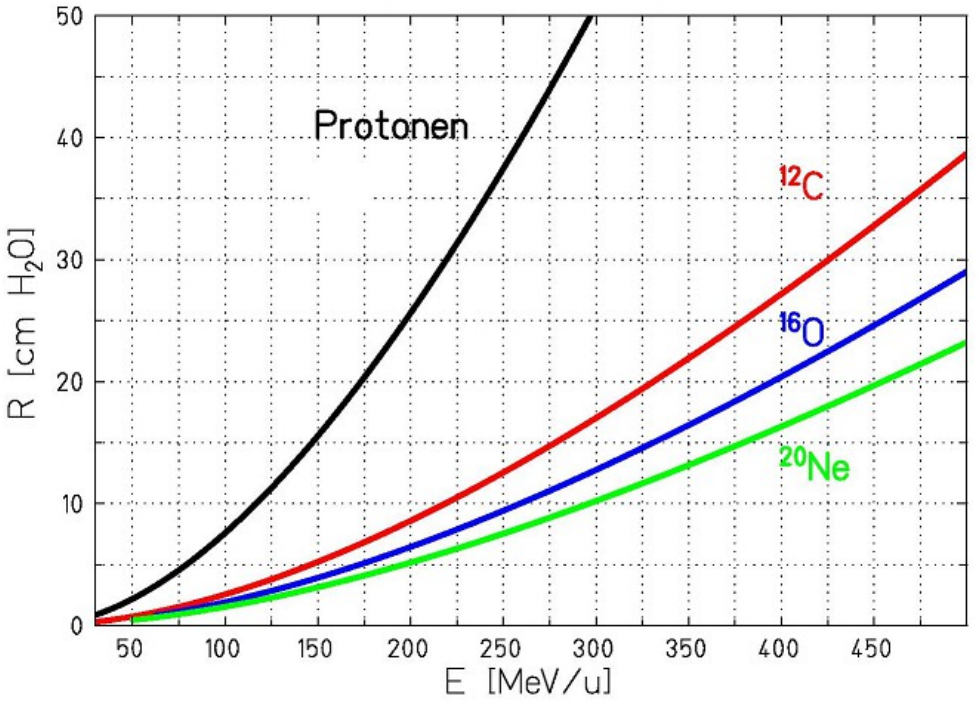


Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

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: up to **~ 10^{10} protons/s** (average)

up to **~ 10^9 $^{12}C^{6+}$/s** (higher LET and biological effectiveness)

Time structure (for raster scanning):

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

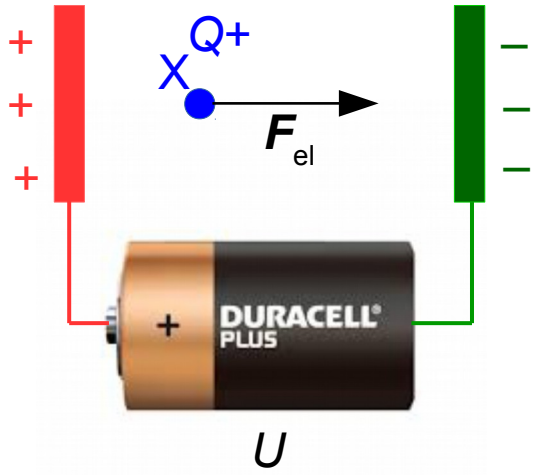
alternatively

Micro-bunches of high repetition rate and stable intensity (cw beam, “quasi-DC”).

How to build an ion accelerator?

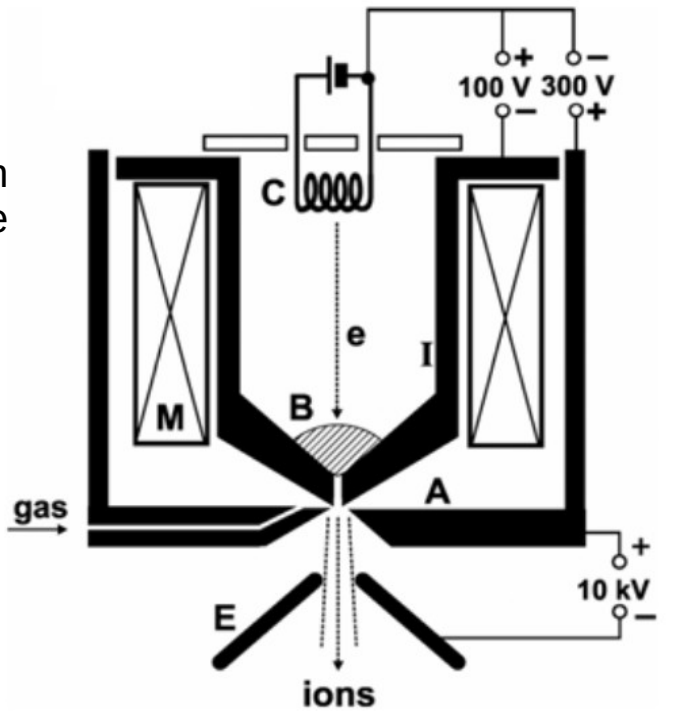
Use electric charge *q* of particles:

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



Electrostatic accelerator

duoplasmotron ion source →



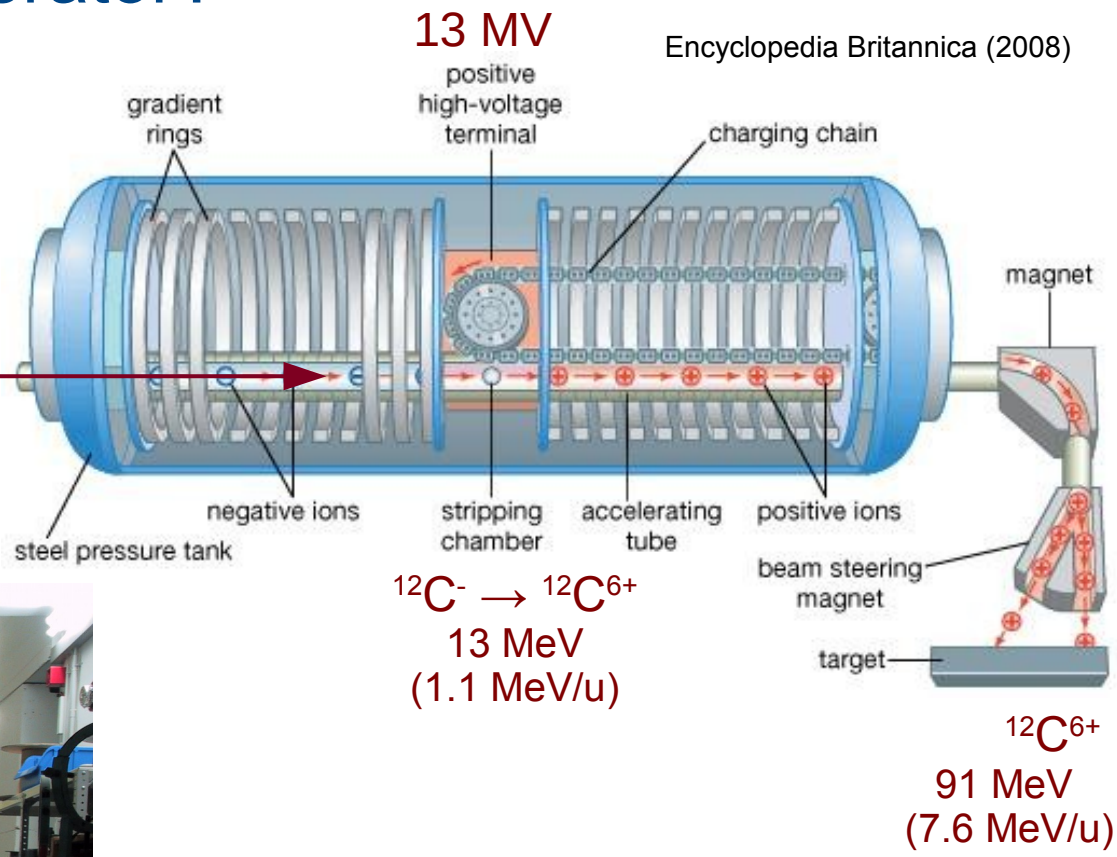
Loeb Plasma Phys. Control. Fusion 47 (2005) B565

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 ...



Encyclopedia Britannica (2008)

↓ 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.

Marburger Ionenstrahl-Therapiezentrum

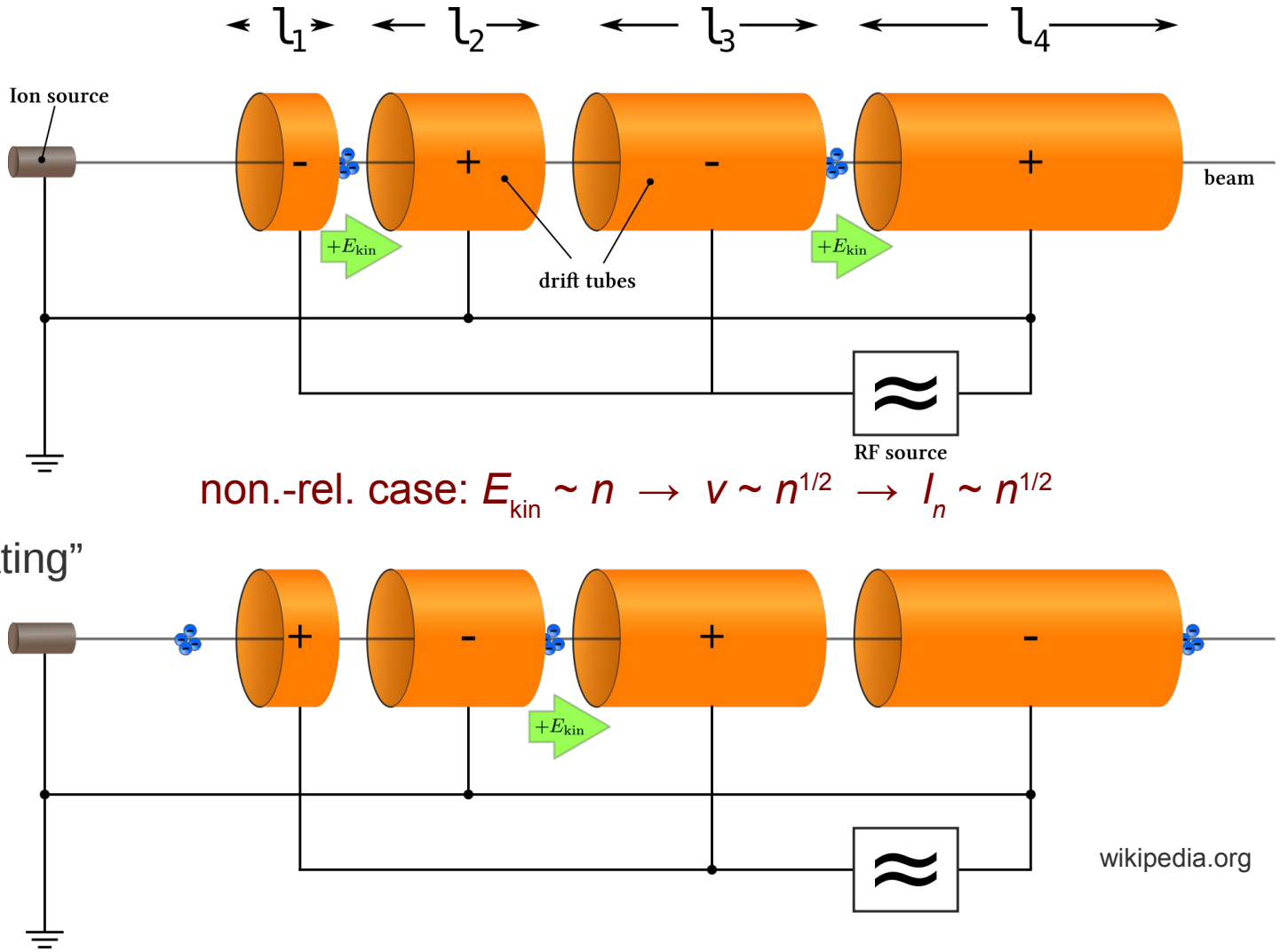
How to build an ion accelerator?

Radiofrequency Linacs

(1) Instead of one large electrostatic field, use an oscillating EM field,

(2) synchronise particle motion with “accelerating” phase of EM wave

→ Net acceleration.



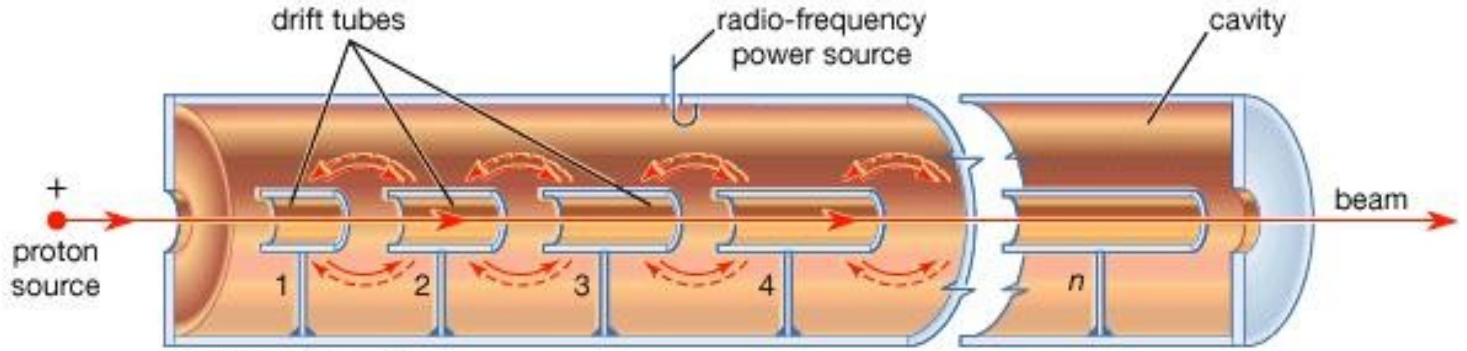
non.-rel. case: $E_{kin} \sim n \rightarrow v \sim n^{1/2} \rightarrow l_n \sim n^{1/2}$

Original realisation: *Wideroe* drift tube linac (1928)
Later improved into **resonant** accelerator structures (*Alvarez* linac, IH linac)

How to build an ion accelerator?

Encyclopedia Britannica (2007)

Radiofrequency Linacs



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→ Alvarez structure of GSI's UNILAC

G. Otto, GSI

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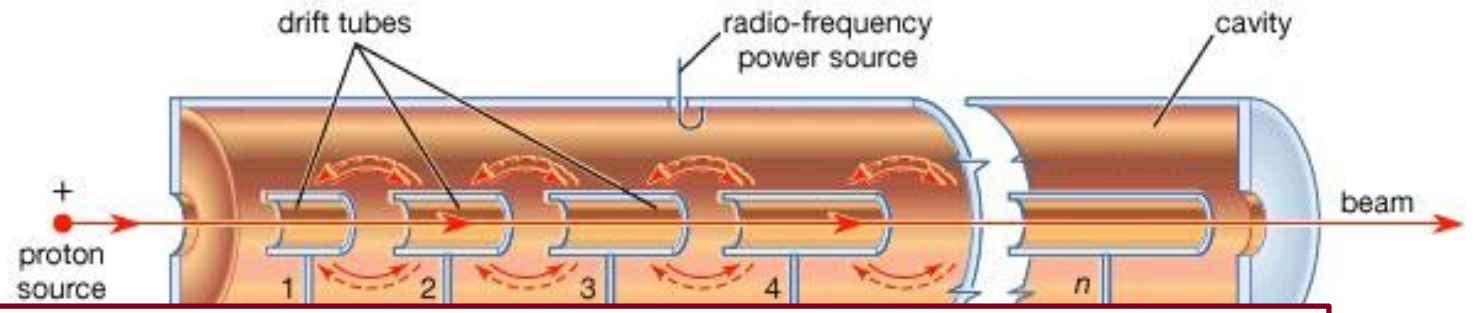


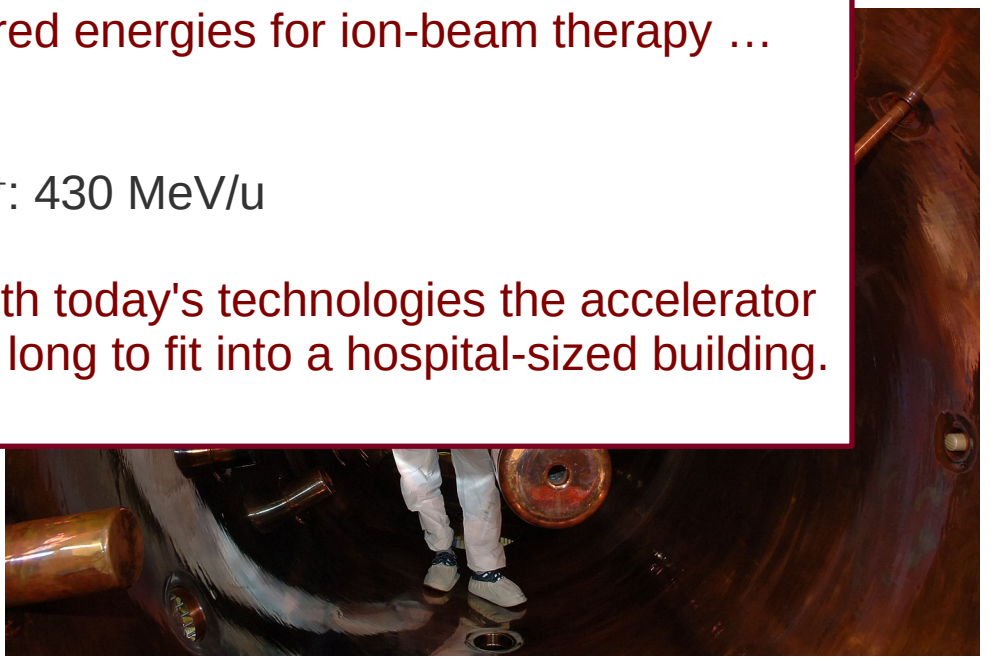
(1) Instead of one large

(2)

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 technologies the accelerator could be too long to fit into a hospital-sized building.



→ Alvarez structure of GSI's UNILAC

G. Otto, GSI

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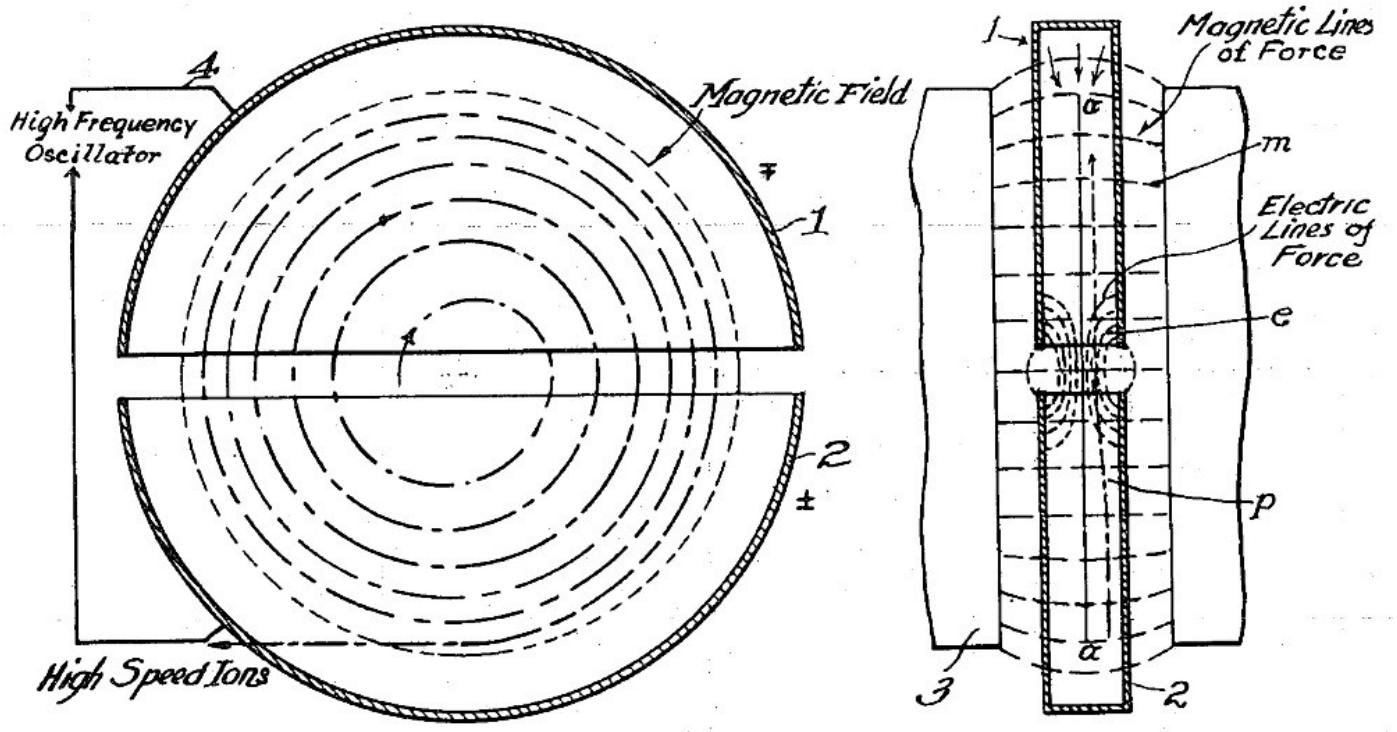
Cyclotrons

Idea: Re-use the same RF 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.

Cyclotrons

Classical cyclotron:

From Lorentz force

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

→ cyclotron frequency:

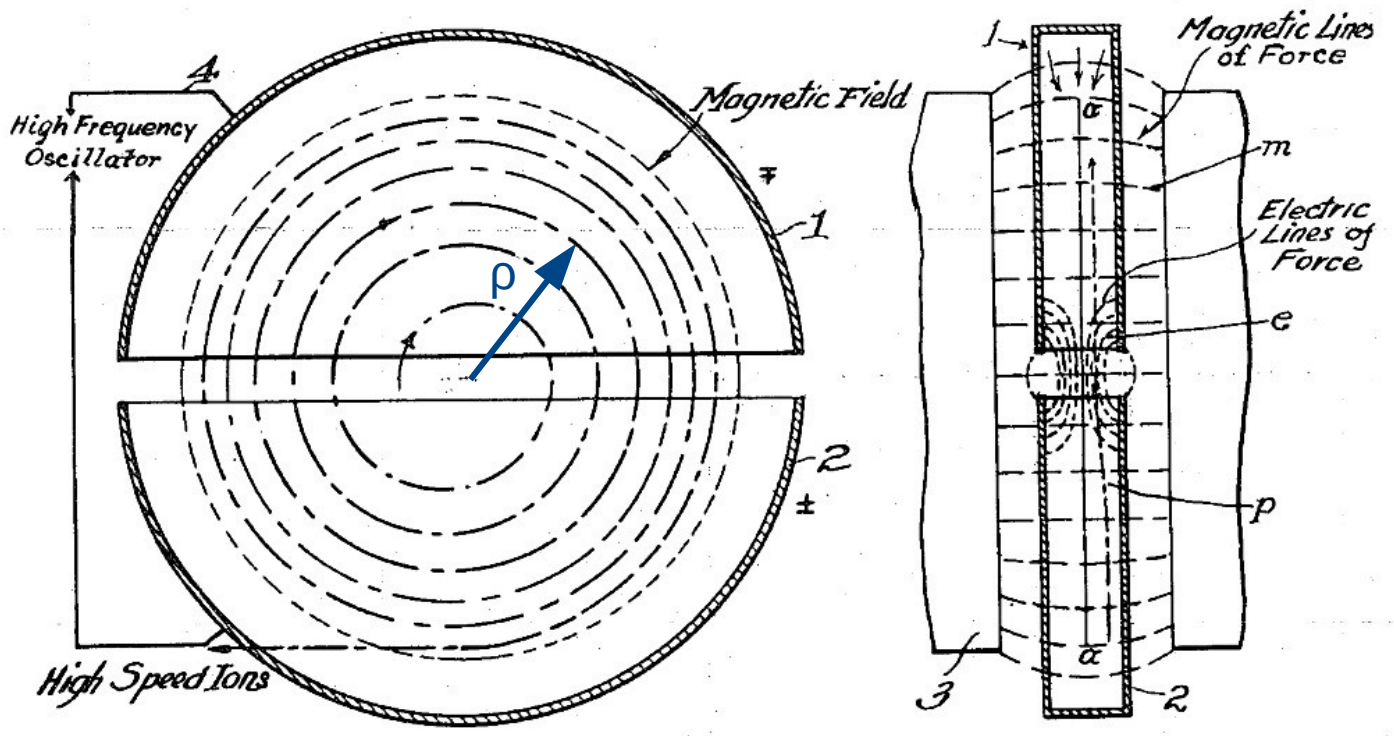
$$\omega_c = \frac{q\,B}{m}$$

Kin. energy after *n* turns

$$E = 2\,n\,q\,U_{RF}$$

With $E = m\,\omega_c^2 \rho^2 / 2$, we obtain the *cyclotron radius* after *n* revolutions

$$\rho(n) = \frac{\sqrt{2\,E\,m}}{q\,B} = \frac{\sqrt{4\,n\,q\,U_{RF}\,m}}{q\,B}$$



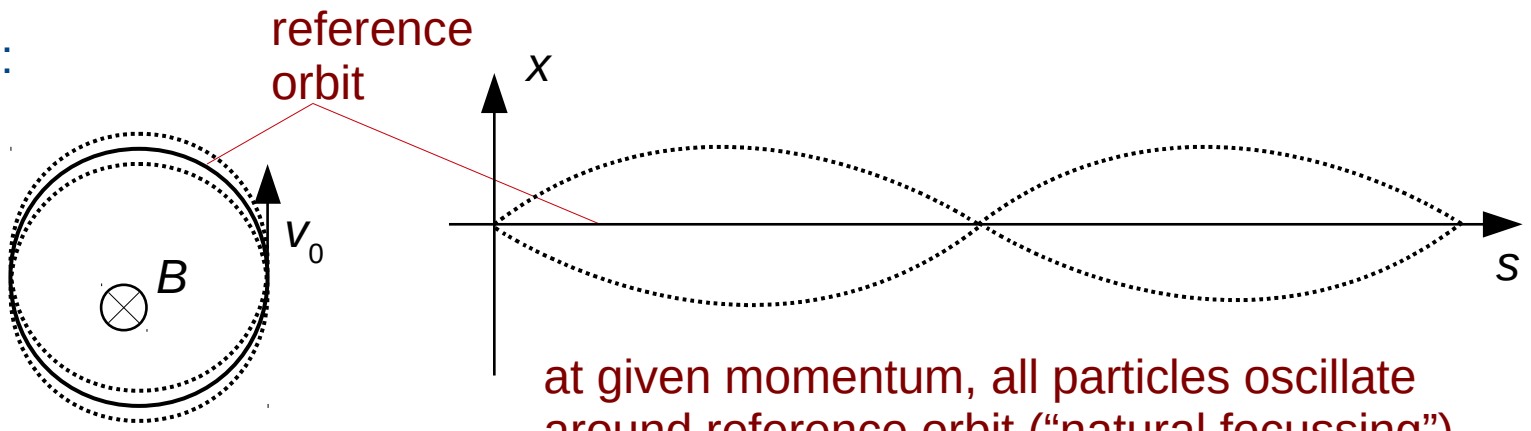
Machine diameter ~ $E^{1/2}$

Lawrence's first machines (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)

Cyclotrons: Transverse motion stability

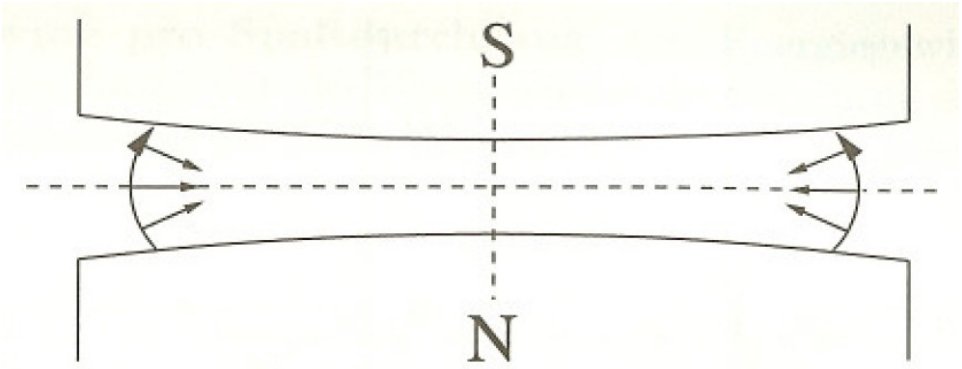
Horizontal direction:



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.

Cyclotrons: Relativistic energies

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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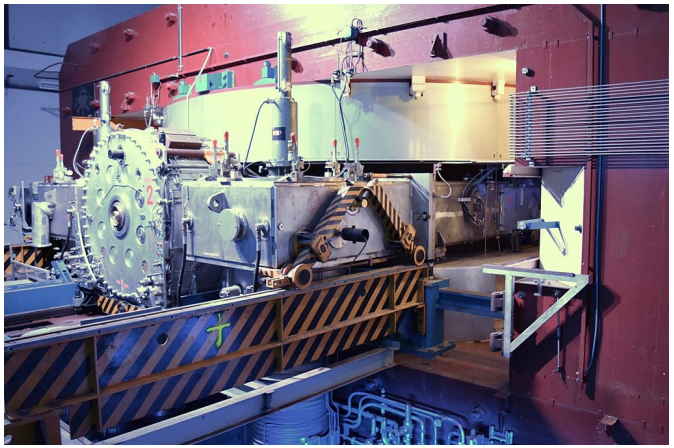
(1) Synchrocyclotron

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



wikipedia.org

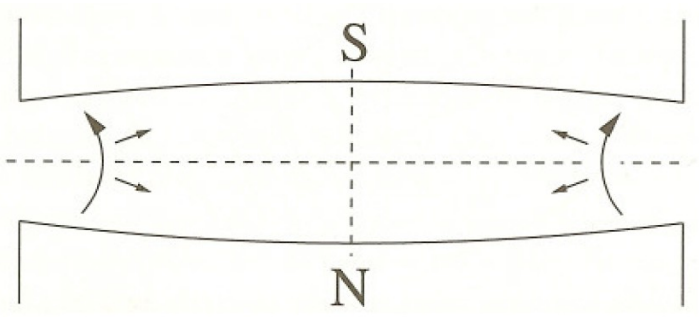
← CERN Synchro-cyclotron: 600 MeV p (1957)

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*.



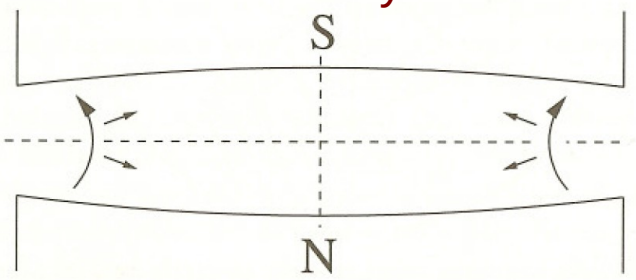
Most modern cyclotrons are isochronous.

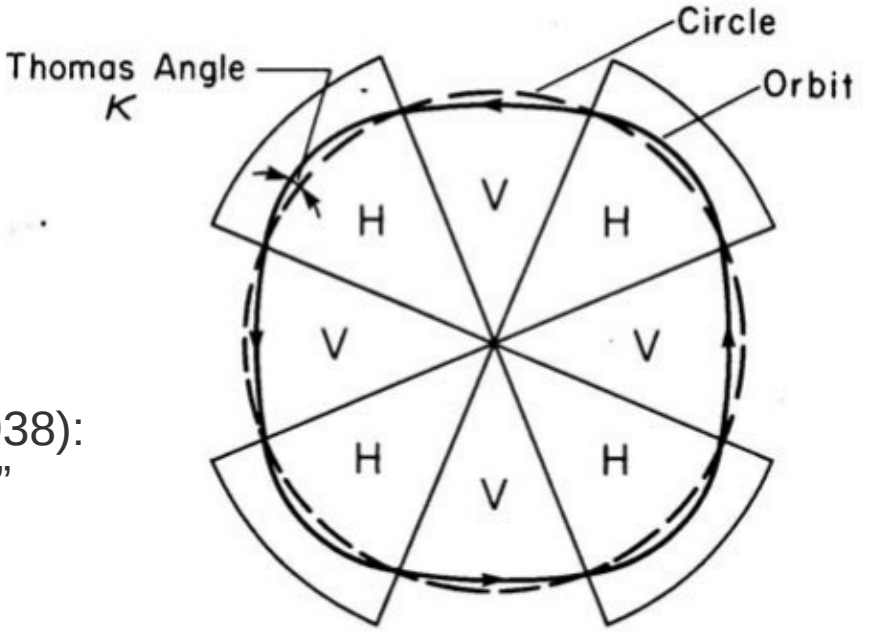
→ cw operation
→ Most proton beam therapy facilities

Cyclotrons: Relativistic energies

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

isochronous cyclotron

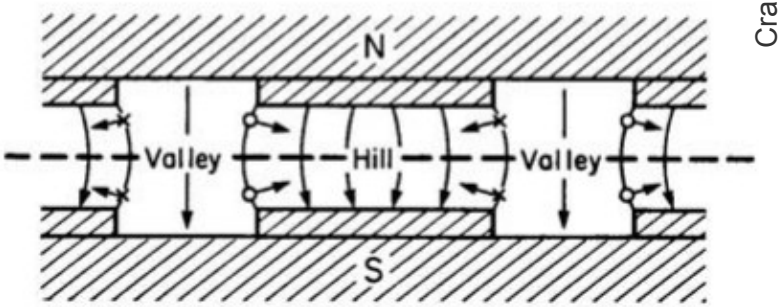




Craddock, Rev. Accel Sci. Technol. (2008)

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

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



→ “Strong focussing” at sector edges.

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_{max} = 2.2 T → ρ ~ 2 m

A. Peters, CERN Academic Training Lecture (2013)

Cyclotrons for ion-beam therapy

www.psi.ch

COMET superconducting cyclotron

Developed by ACCEL (now Varian Medical) for proton therapy

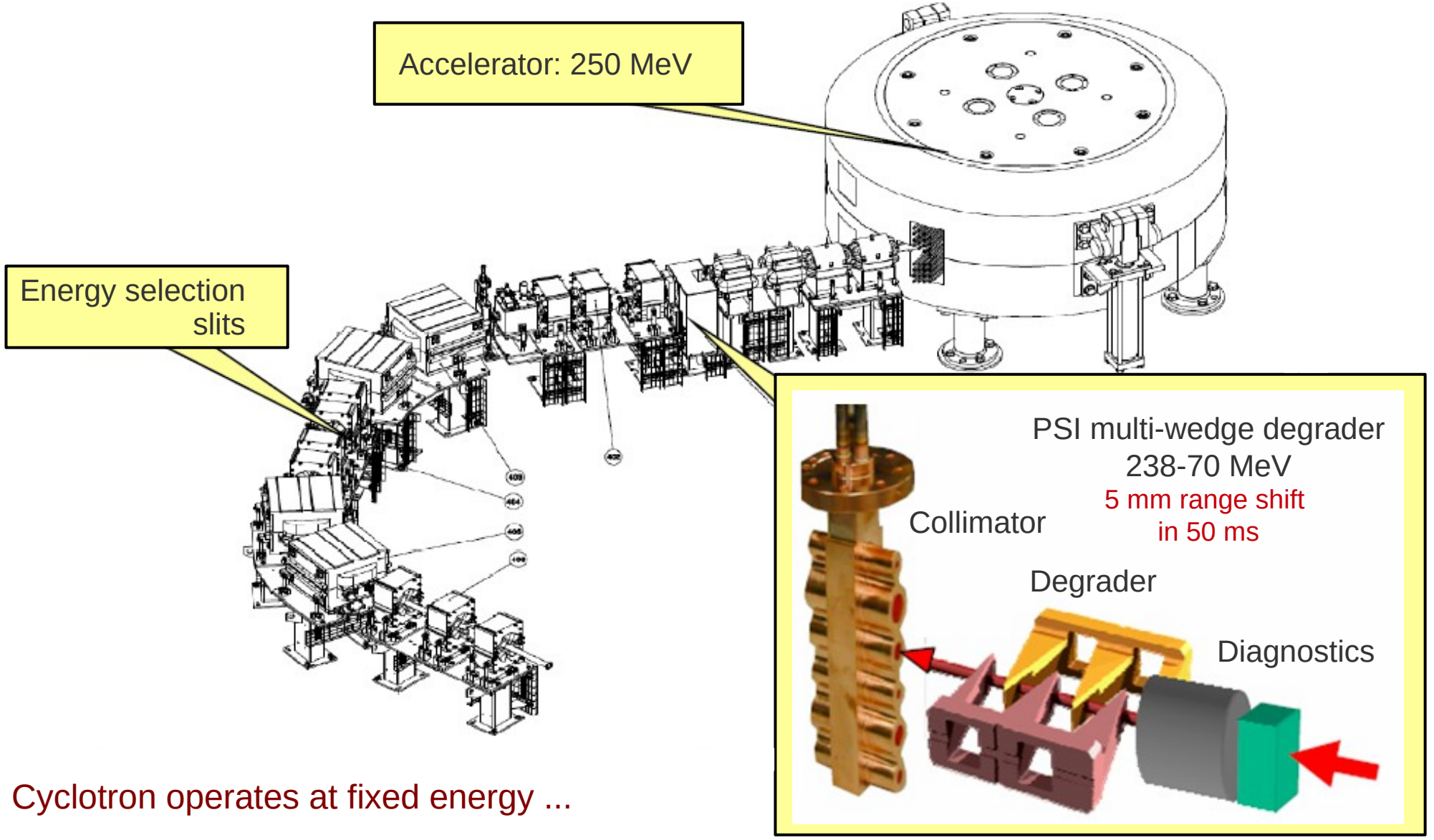
Mass: 80 t

E = 250 MeV

I = 1 … 850 nA

B_{max} = 3.0 T → ρ < 1 m

Cyclotrons for ion-beam therapy: Energy selection



Cyclotron operates at fixed energy ...

→ *E*-reducion by degraders + momentum selection in analysing magnets

A. Peters, CERN Academic Training Lecture (2013)

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

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

"magnetic rigidity":

Relates particle momentum and charge to the product of field and bending radius.

Protons (230 MeV):	$B\rho$ = 2.3 Tm
$^{12}C^{6+}$ (430 MeV/u):	$B\rho$ = 6.6 Tm

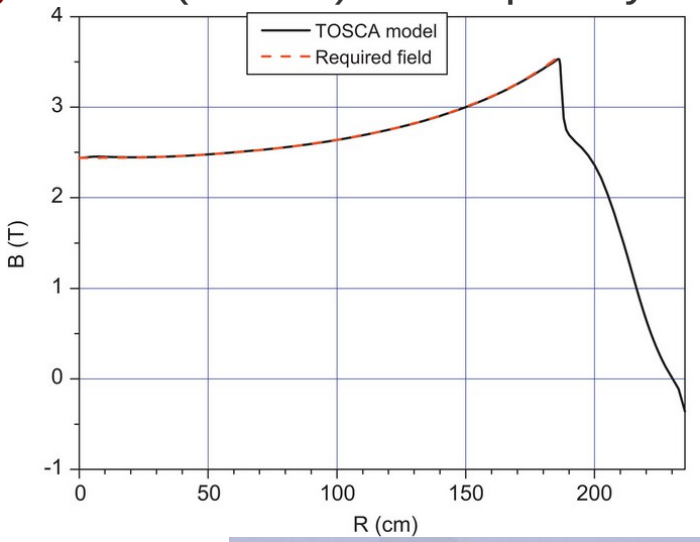
I.e. to go from protons to carbon ion beams, one needs to increase either the **magnetic field** or the **size** of the machine by almost a factor 3.

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

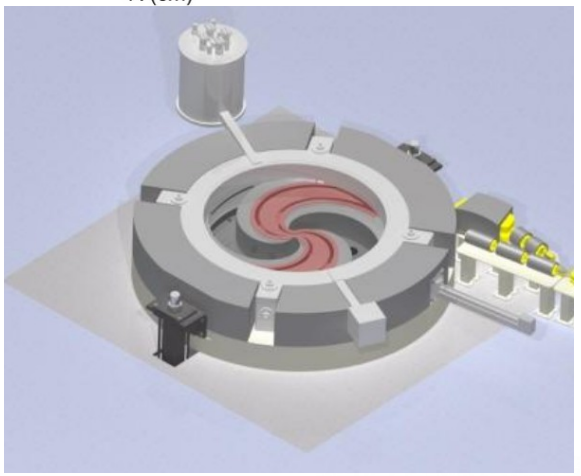
Cyclotrons for ion-beam therapy: $^{12}C^{6+}$?

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

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



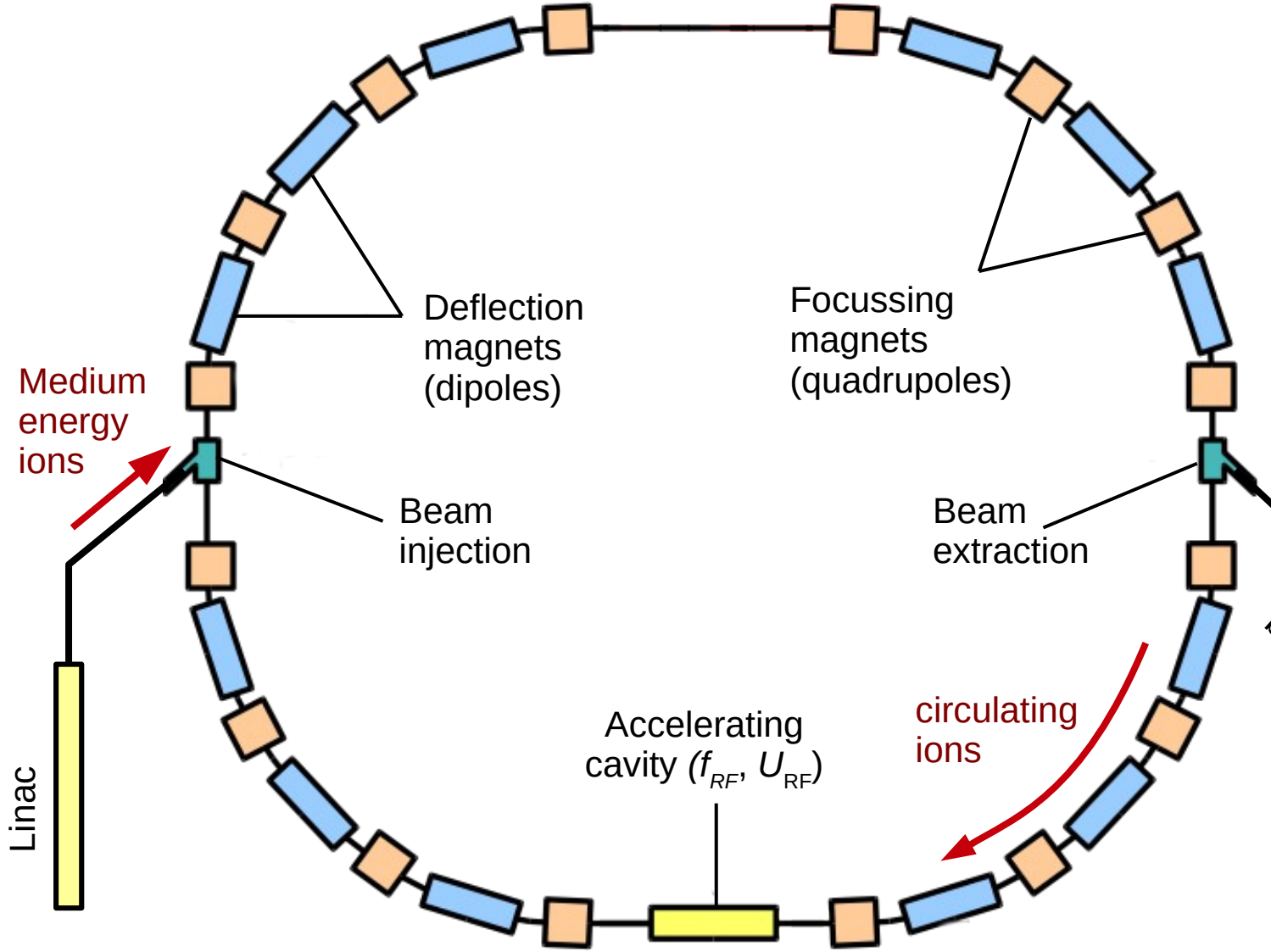
Yongen, NIM A (2010) 642



Yongen, Proc. of CYCLOTRONS 2010

In 2014, it was decided to build a proton facility first (start 2018) and the C400 project seems to have been postponed ...

Synchrotrons



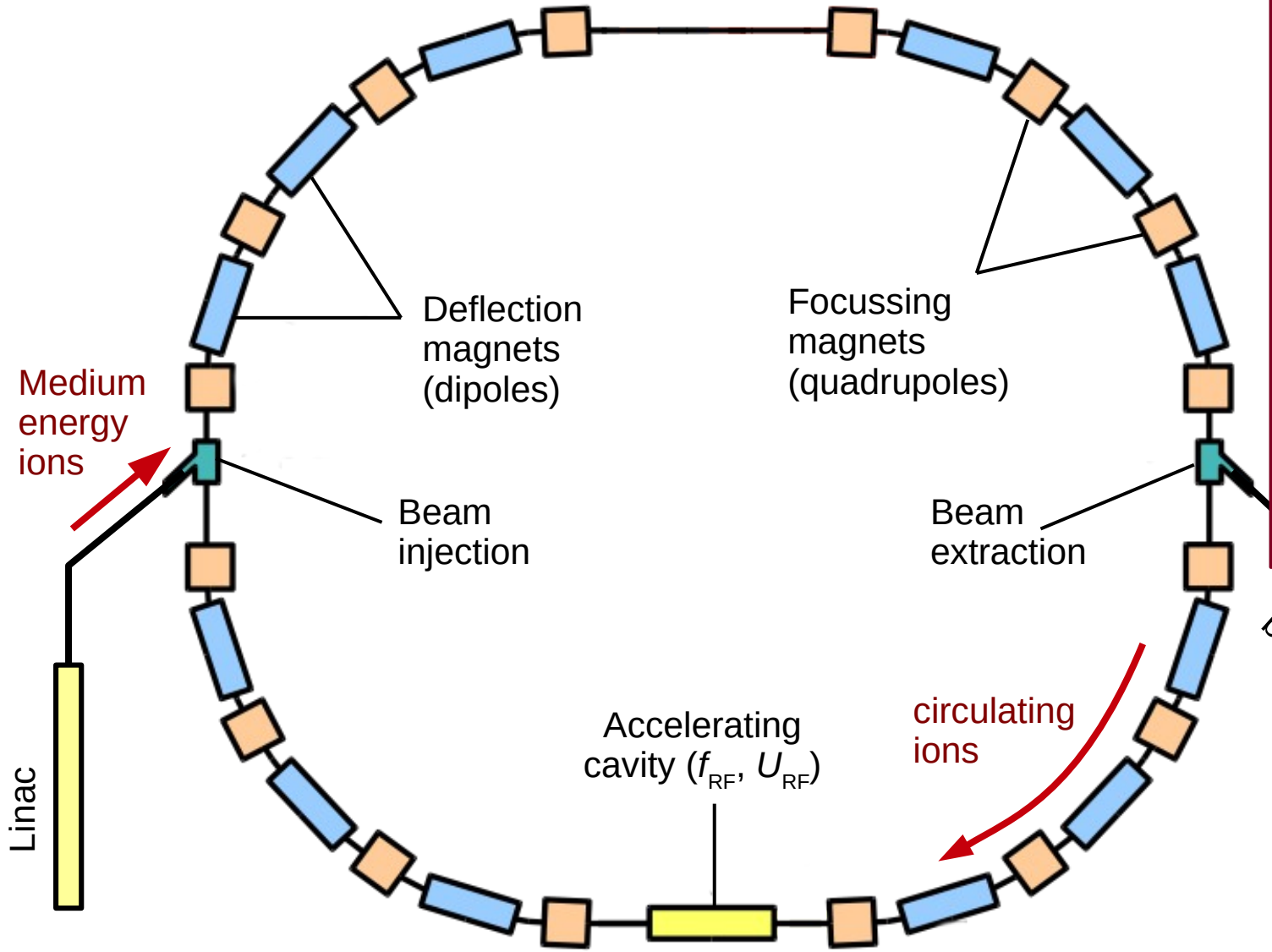
Basic idea:

(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**.

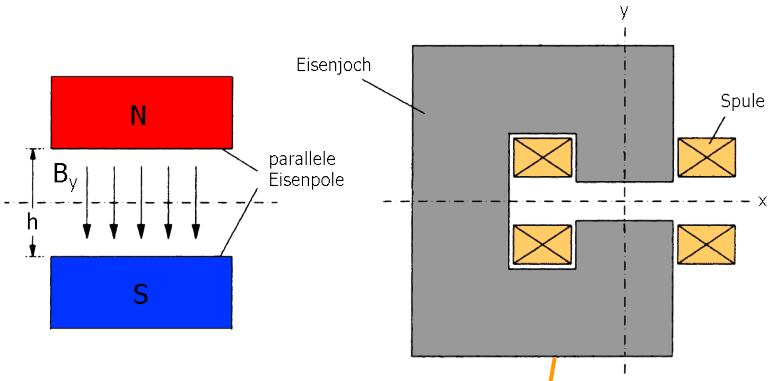
Typical size of p/C therapy synchrotron: 20 m diameter

Disadvantage: Orbit is very long even before acceleration.
→ Needs **pre-accelerator** providing ~ MeV ions.

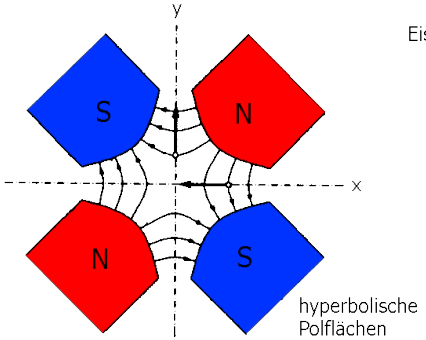
Synchrotrons

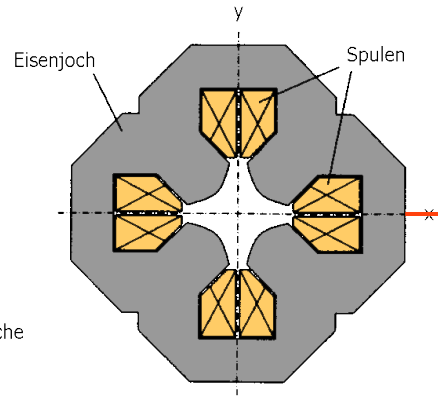
www.mpi-hd.mpg.de

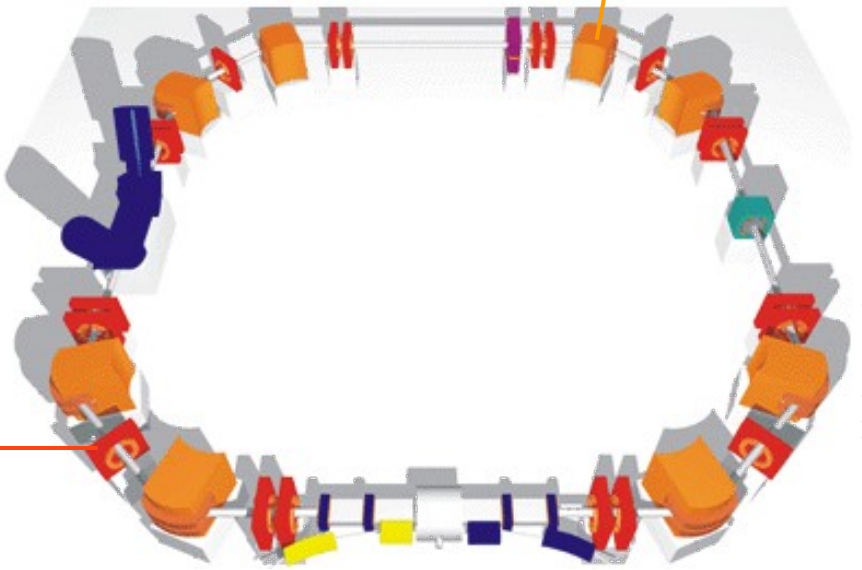
Dipole magnet → deflection



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



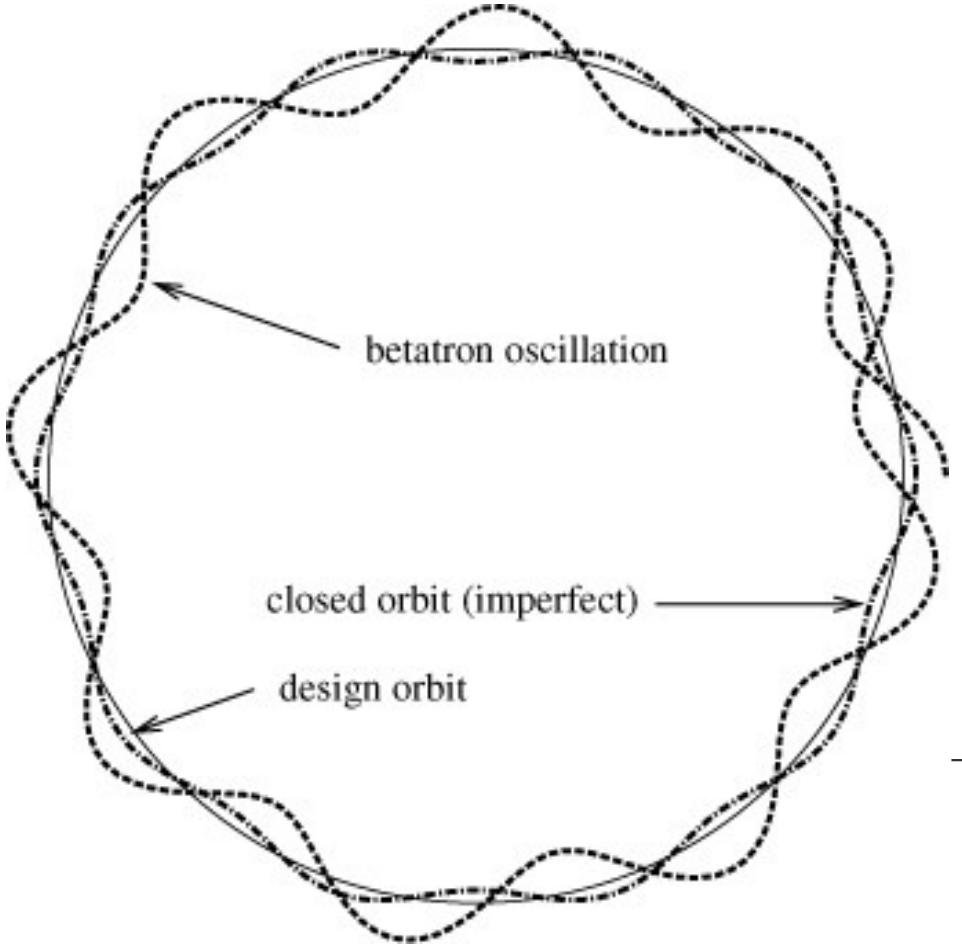




www.mpi-hd.mpg.de

Quadrupole magnet → (de-)focussing

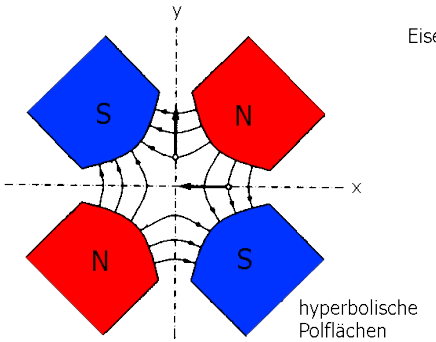
Synchrotrons: Transverse motion stability

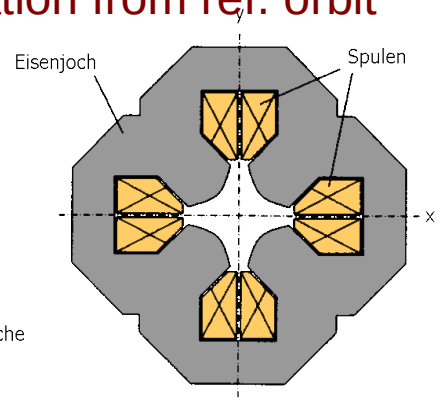


Mane et al., Rep. Prog. Phys. 68 (2005)

Quadrupole magnet:

Mag. force ~ deviation from ref. orbit





Focussing in X → Defocussing in Y
(and vice-versa)

But: sequence … -D-F-D-F- … has a **net focussing effect**.

→ Mathematical description by **harmonic oscillator formalism**:

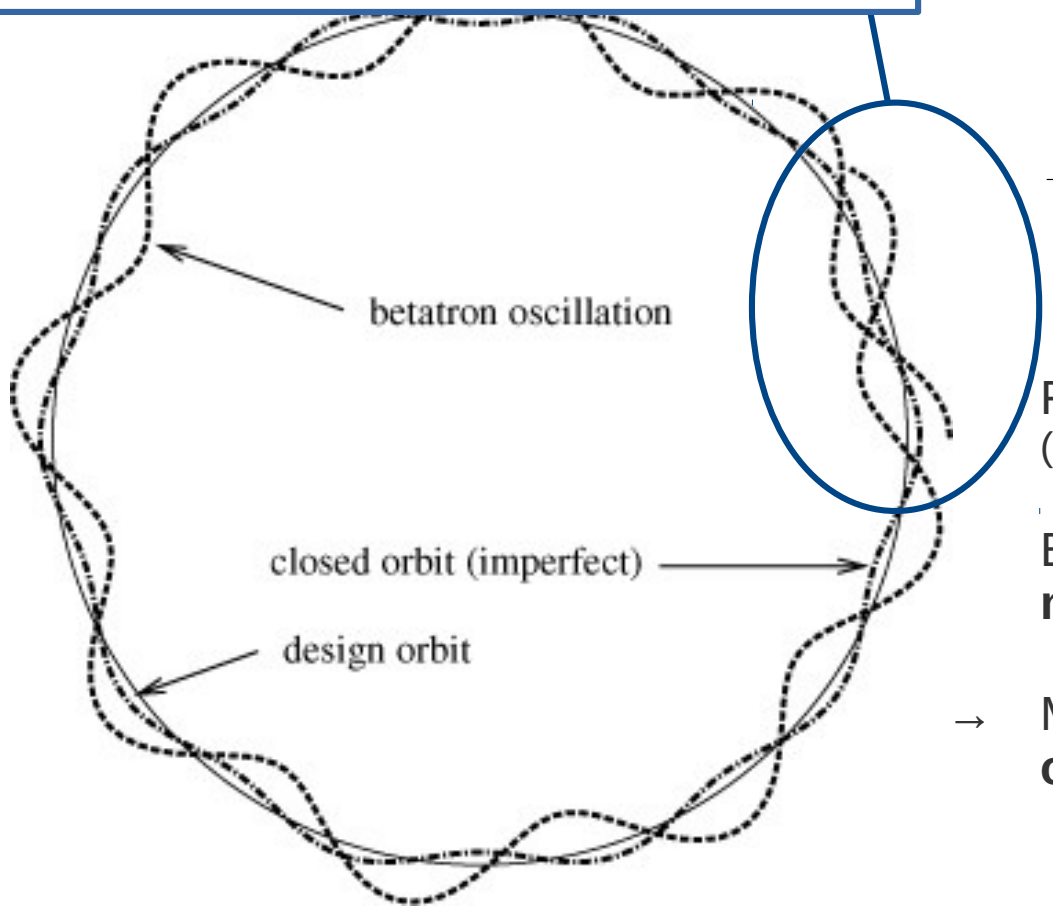
$$\frac{d^2}{ds^2}x + K(s)x = 0$$

with *K* periodic in *s*
(Hill's equation)

"Betatron oscillation"

Synchrotrons: Transverse motion stability

For stable beam storage, betatron frequency and revolution frequency should have ***NO*** small common multiple: $n f_{Beta} \neq m f_{Rev}$



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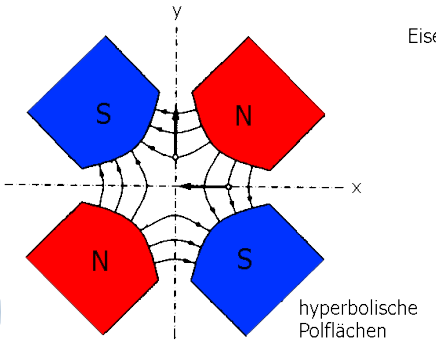

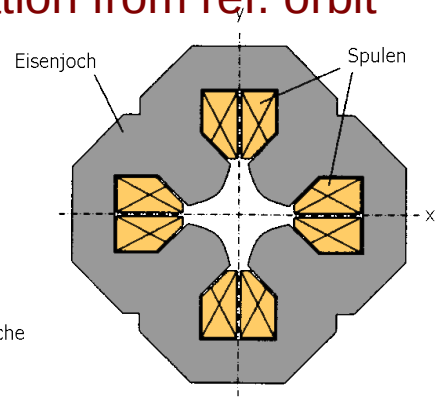

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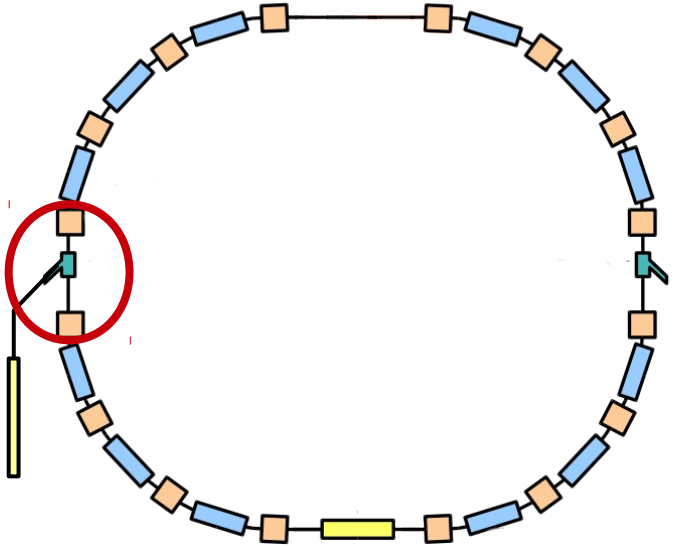
"Betatron oscillation"

Synchrotrons: Ion injection

The ring defines a stable, closed orbit …

… but how do we actually get particles onto that orbit in the first place?



Fundamental rule: Phase space density of injected beam cannot be enhanced by the ring optics (Liouville's theorem).

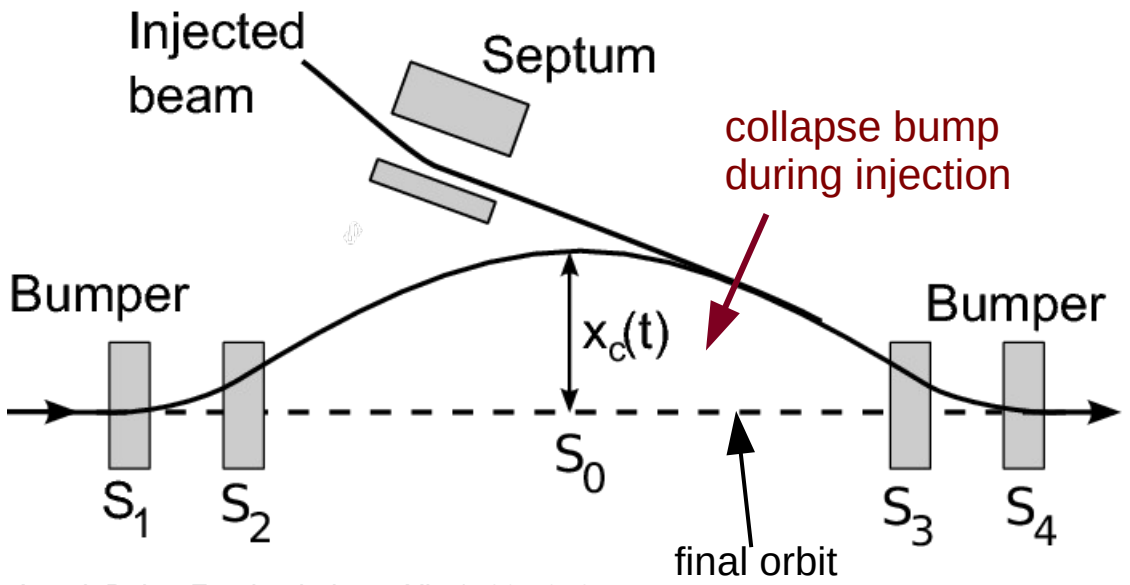
(1) Kicker injection: Fast-switching deflection magnet.

(2) Stripping injection: Strip H^- to p at ring entrance
→ Bending magnet deflects stored and injected beam in opposite directions.

(3) Multiturn injection: Accumulate beam by "winding up" injected pulse in transverse phase-space.

(4) RF stacking: Use RF acceleration to distribute particles in momentum space.

Synchrotrons: Ion injection

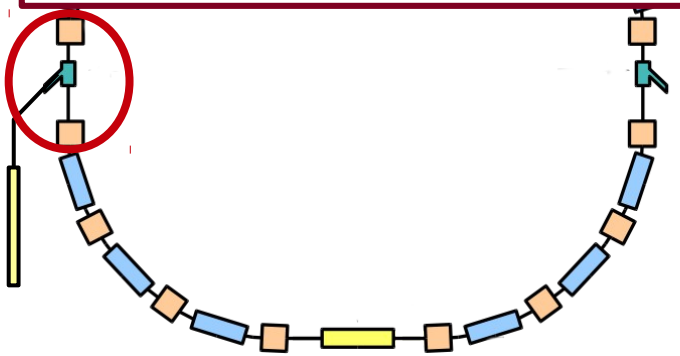


Appel, Boine-Frankenheim, arXiv:1403.5972

Mutliturn injection

Create local bump in closed orbit and *sweep it across* the injector beam axis.

→ Stored ion current *many times greater* than injector current.



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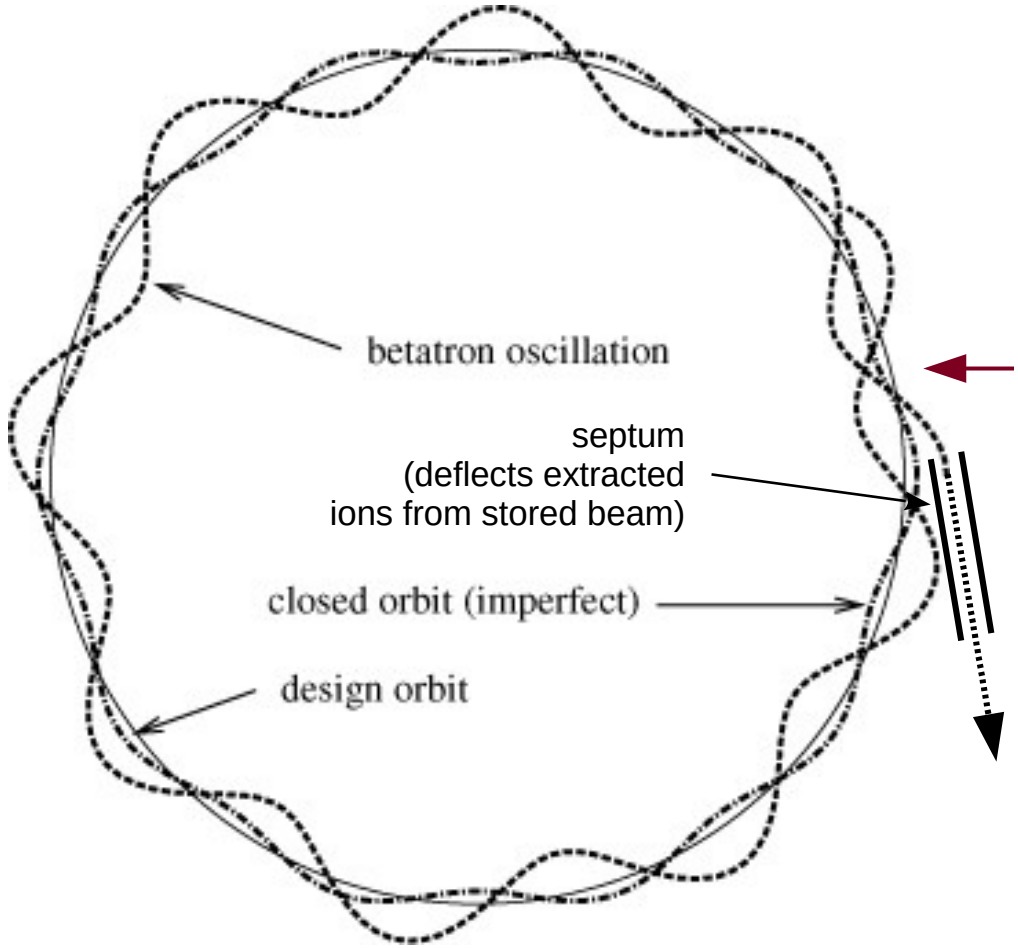
Synchrotrons: Ion extraction



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

After acceleration: How do we extract the fast particles into a directed beam?

(1) Kicker extraction:

Use a switching magnet that is fast compared to the revolution period.

→ That's too fast (~ µs)!!
Therapy needs a ~DC beam of a few seconds …

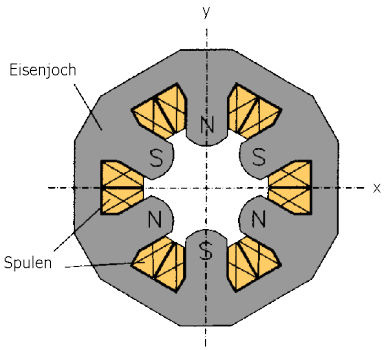
(2) Slow extraction:

Use **resonance** between revolution period and betatron motion.

→ Transverse oscillations grow and ions enter an *extraction septum*.

→ "Spill" of a few seconds.
Used at all therapy synchrotrons.

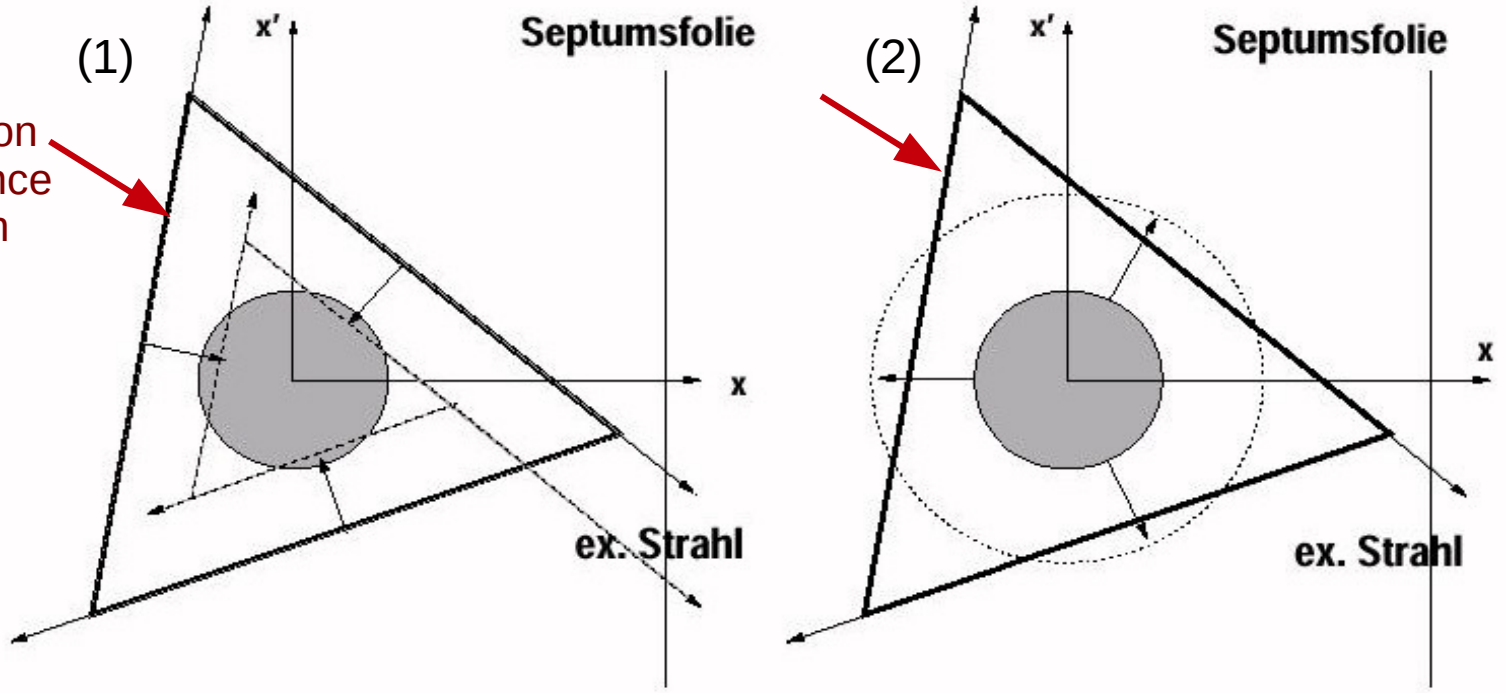
Synchrotrons: Ion extraction



Add sextupole components to the magnetic fields.

→ Betatron motion becomes **non-harmonic** at large amplitudes.
→ "Separatrix" in (x,x') phasespace, where oscillation is n/3-resonant with revolution.
→ For particles close to separatrix, amplitude grows beyond all limits.

"Separatrix": Betatron motion in n/3 resonance with revolution

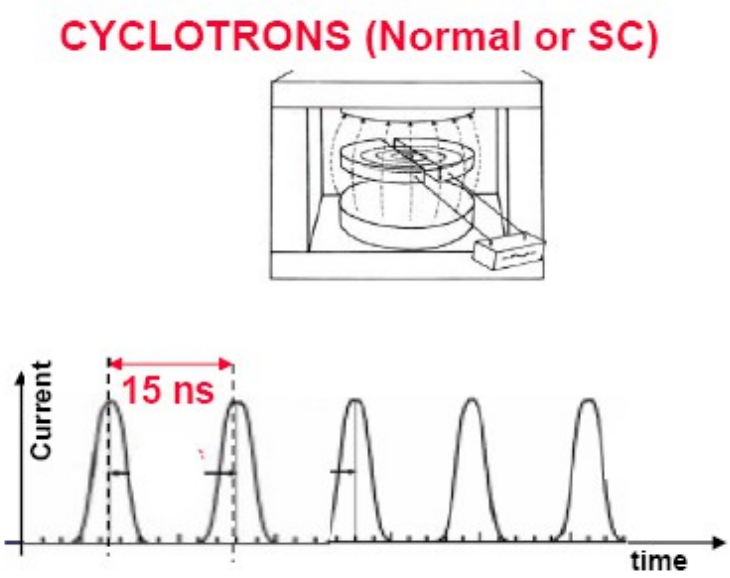


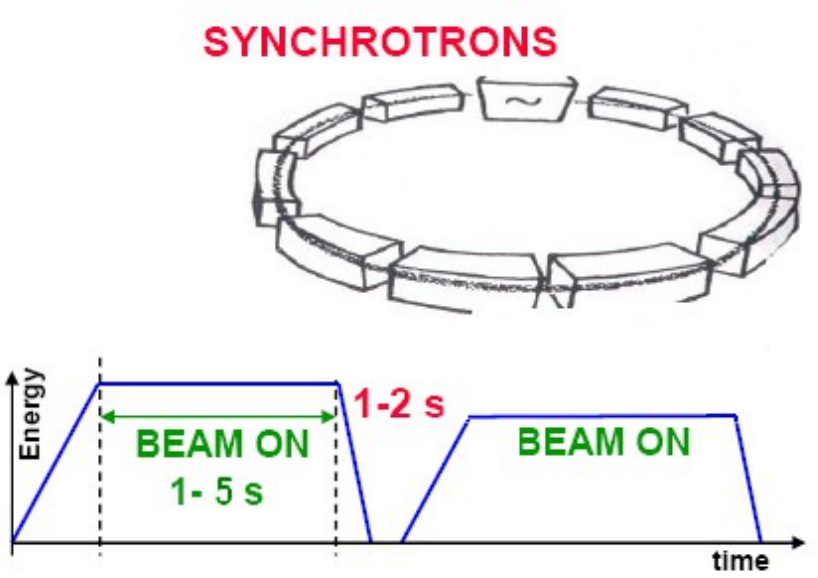
Drive particles into resonance by

Albrecht, PhD, 1996

(1) Slow shrinking of separatrix around particle phase-space.
(2) Transverse heating of beam (stochastic noise kicker).

Cyclotron beam vs. Synchrotron beam





cw beam: continuous train of short pulses.

Energy variation by degraders in high energy beam transport.
→ looses ions.

Fast current modulation at source.

No machine for carbon ions (yet)

"almost DC" beam, interrupted by phases of beam preparation.

Energy variation in accelerator
→ no beam loss.

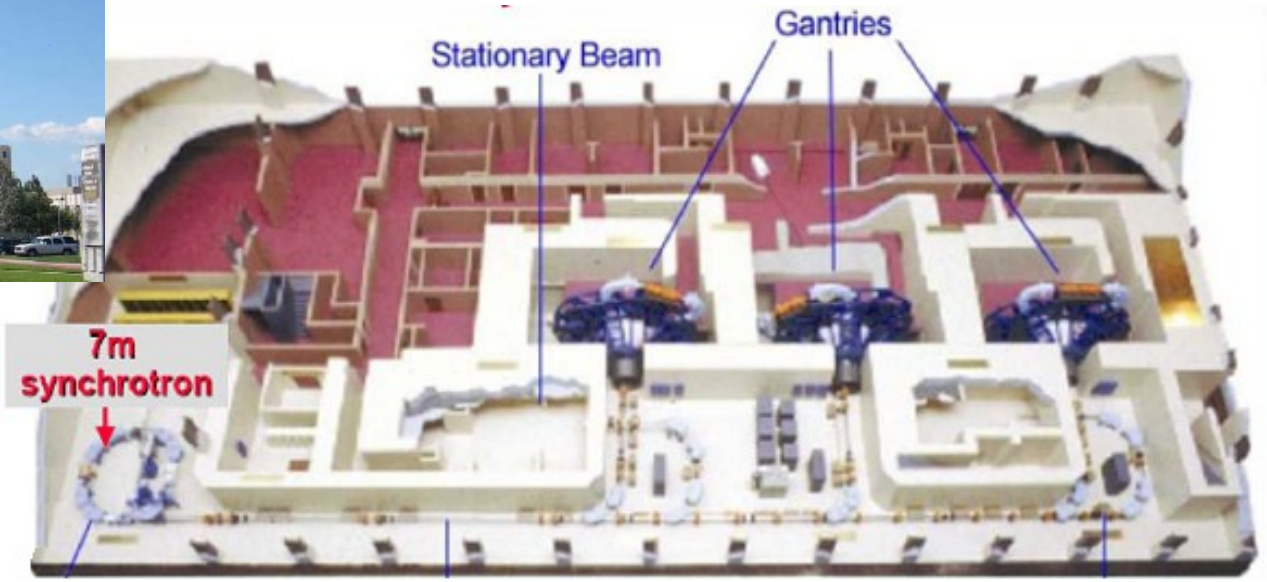
Injector defines amount of ions in cycle. Some rings support fast spill modulation.

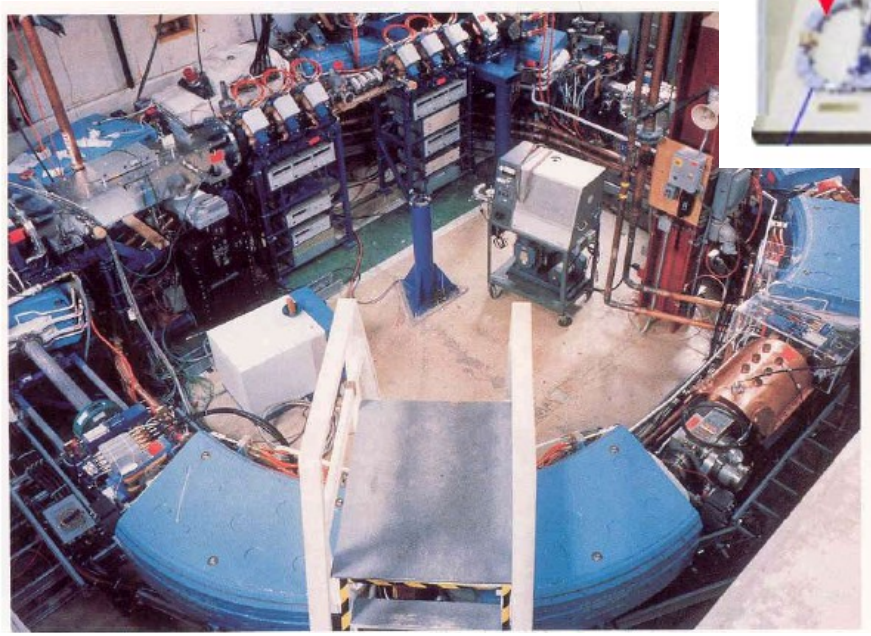
p and C available.

A. Peters, CERN Academic Training Lecture (2013)

Synchrotron ion-beam therapy facilities

Loma Linda, USA





1st hospital-based proton therapy centre

(since 1990)

Synchrotron designed by Fermilab

> 18000 patients treated (2015)

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 $^{12}C^{6+}$.

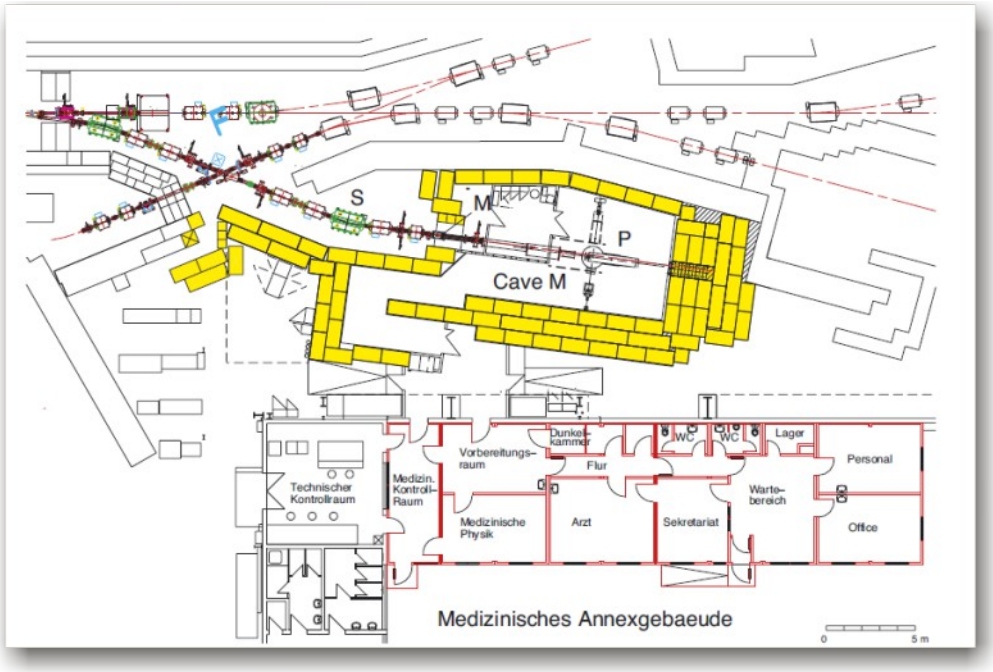
> 10000 patients treated with $^{12}C^{6+}$ (2015)

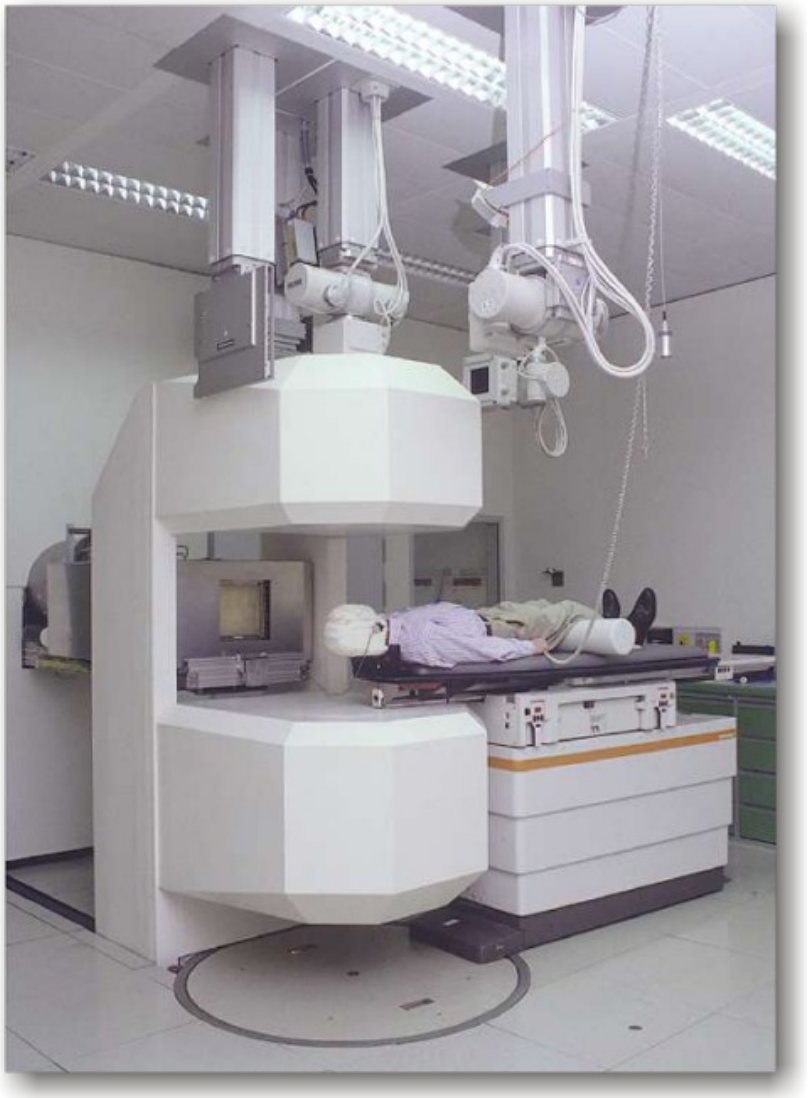
Nature (2017) 548

\+ 4 dedicated carbon-ion treatment centres all over Japan.

Synchrotron ion-beam therapy facilities

Darmstadt, Germany





A. Peters, CERN Academic Training Lecture (2013)

1997 – 2008

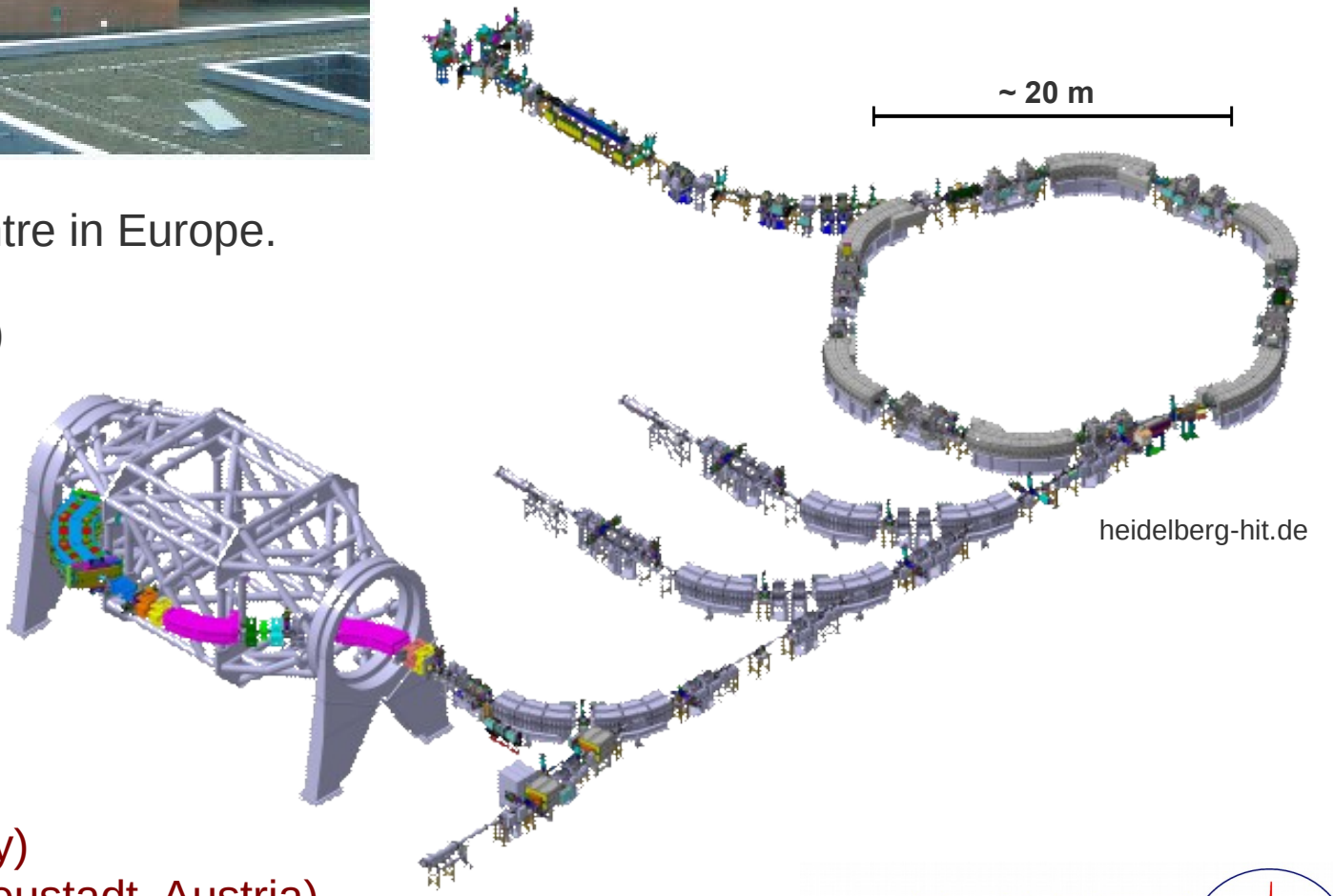
Experimental program on $^{12}C^{6+}$ ion beam therapy using the **GSI accelerator complex**. Total 448 patients.

Established the **pencil-beam scanning** method.

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.

> 3000 patients (as of 2015)

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

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

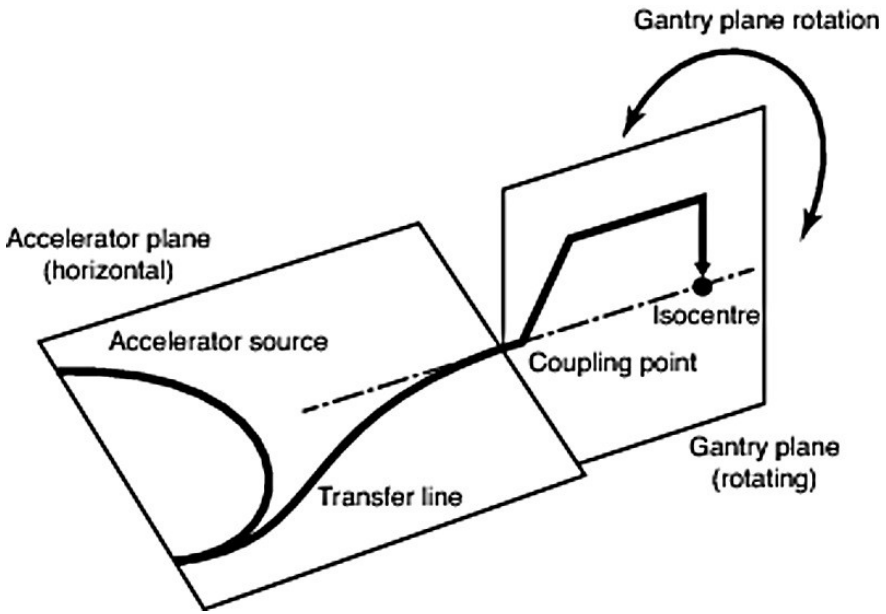
CNAO (Pavia, Italy)
MIT (Marburg, Germany)
MedAustron (Wiener Neustadt, Austria)

Gantries

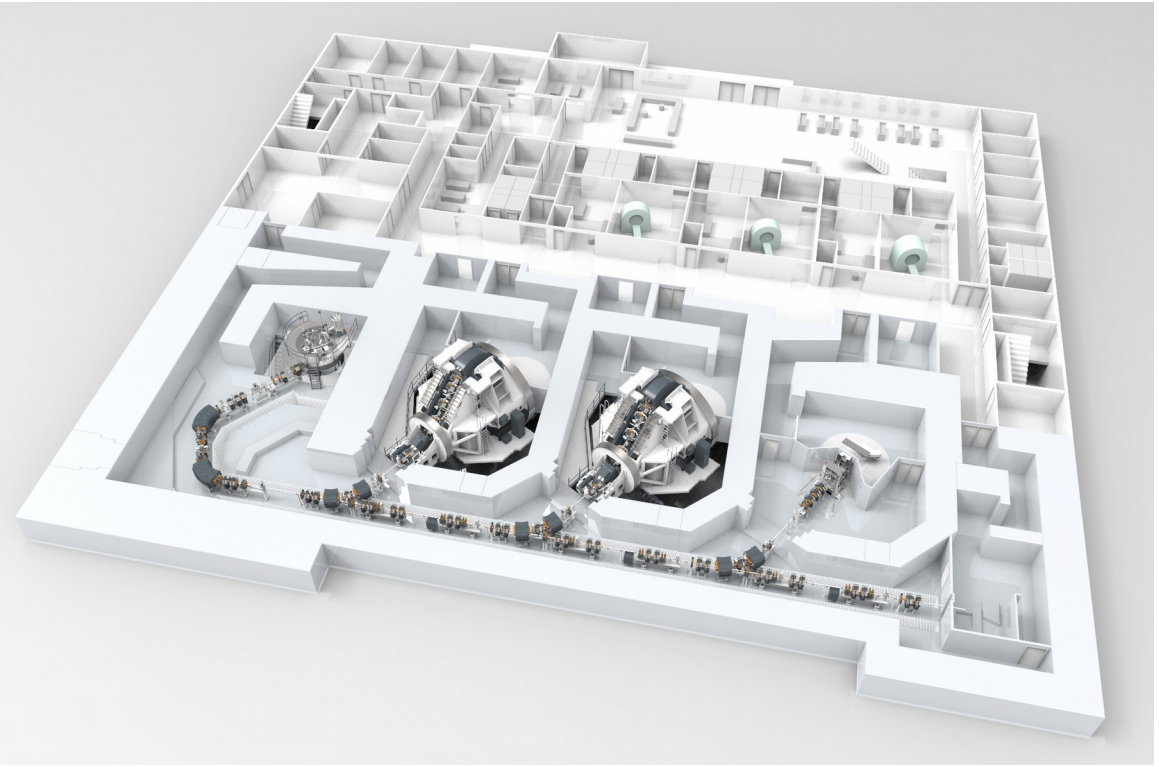
Idea: Allow patient to be irradiated from any side (similar to photon radiotherapy).

varian.com

← for photons: can rotate entire accelerator ...



Commercial p-only solution (Varian) ↓



varian.com

Gantries

www.helmholtz.de

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

www.uniklinikum-heidelberg.de

Up to $B\rho$ = 6.6 Tm

Diameter 13 m, length 25 m

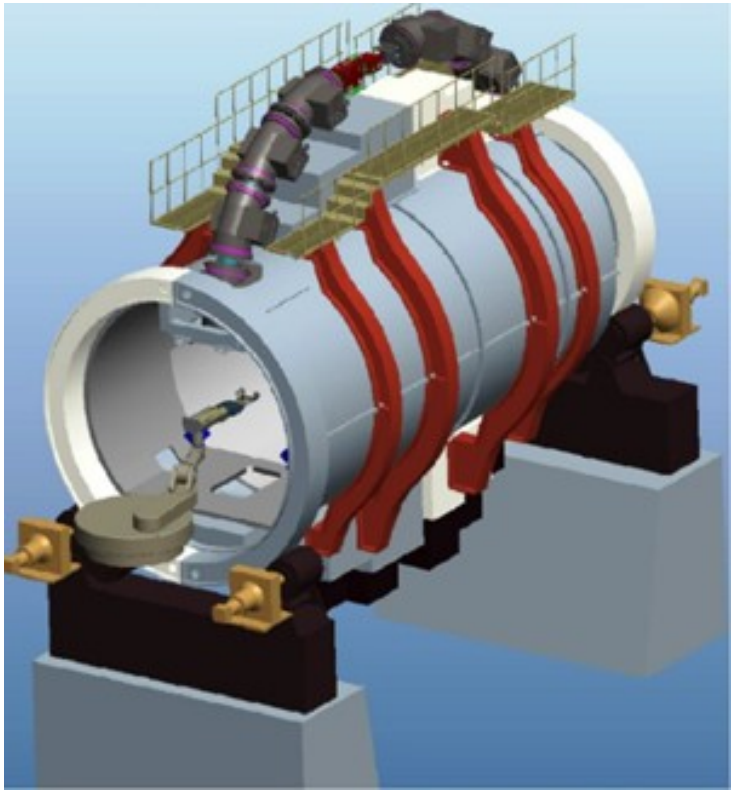
Raster-scanning pencil beam

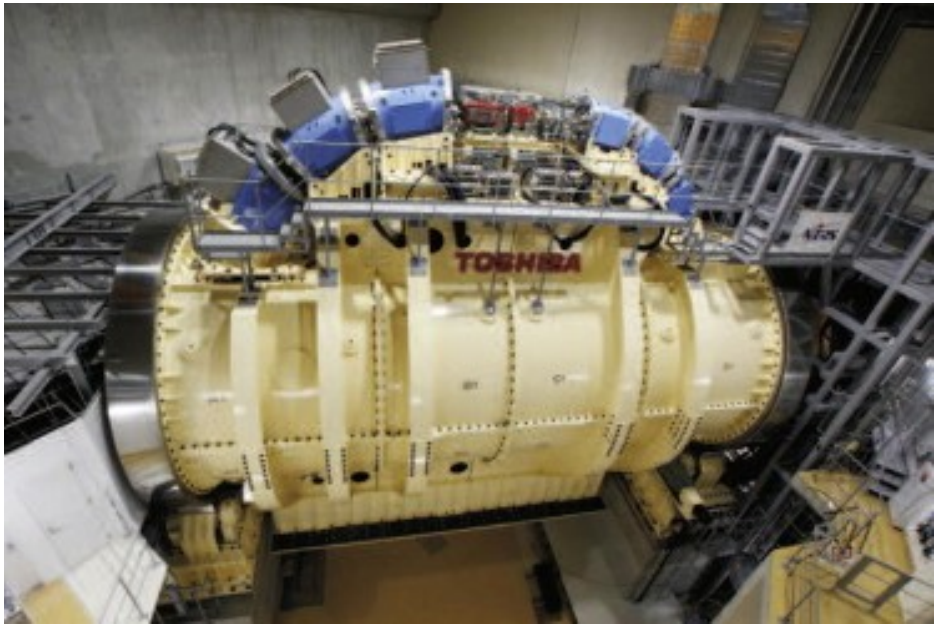
Overall weight 600 tons

Gantries

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

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)

Recent developments

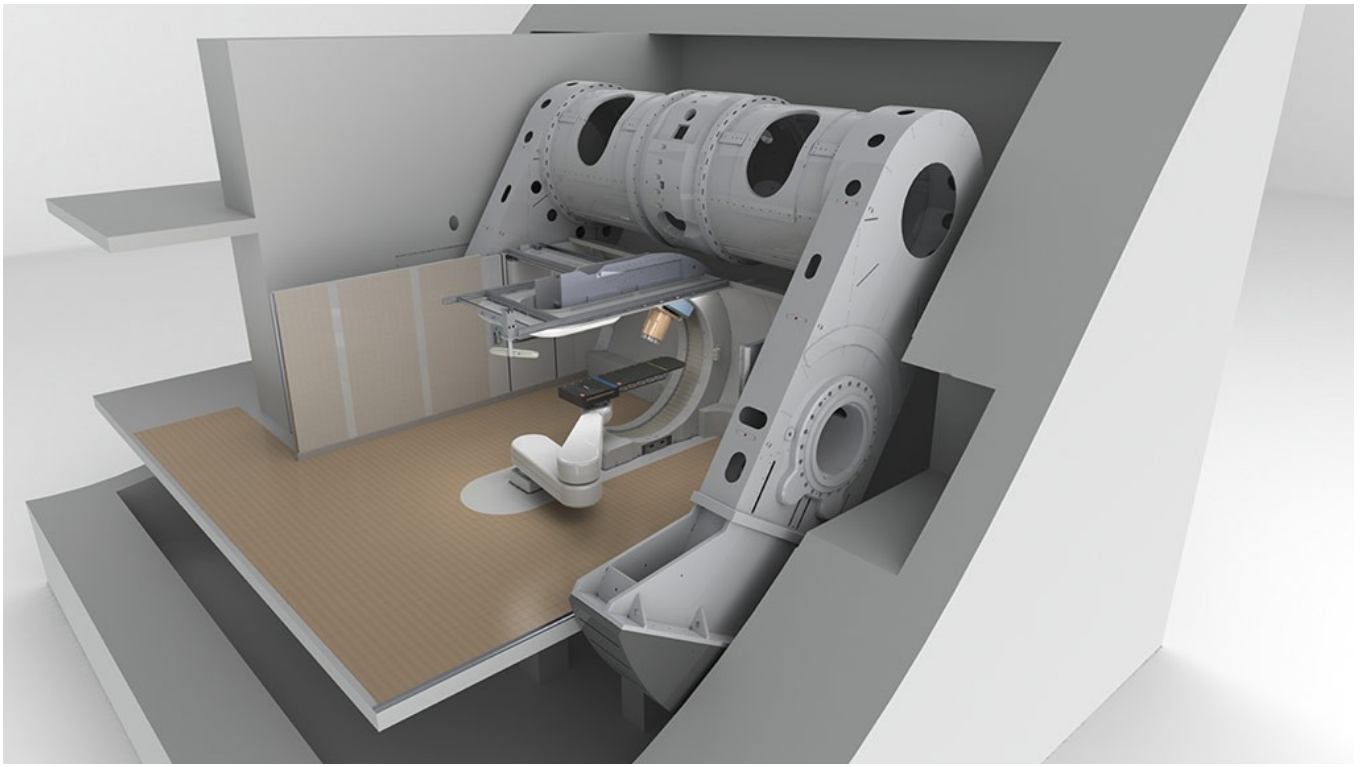
Proton-beam therapy:

Many efforts to *shrink* accelerators and beam delivery systems.

→ Easier and cheaper to fit into hospitals.
→ Single-room solutions become possible.

iba-worldwide.com

S2C2 superconducting ↑ synchrocyclotron by IBA
2.5 m diameter



mevion.com

Synchrocyclotron: no valleys and hills → higher **average *B***.

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

S250 system by Mevion
←
Gantry-mounted superconducting synchrocyclotron.
Operating at 6 sites.

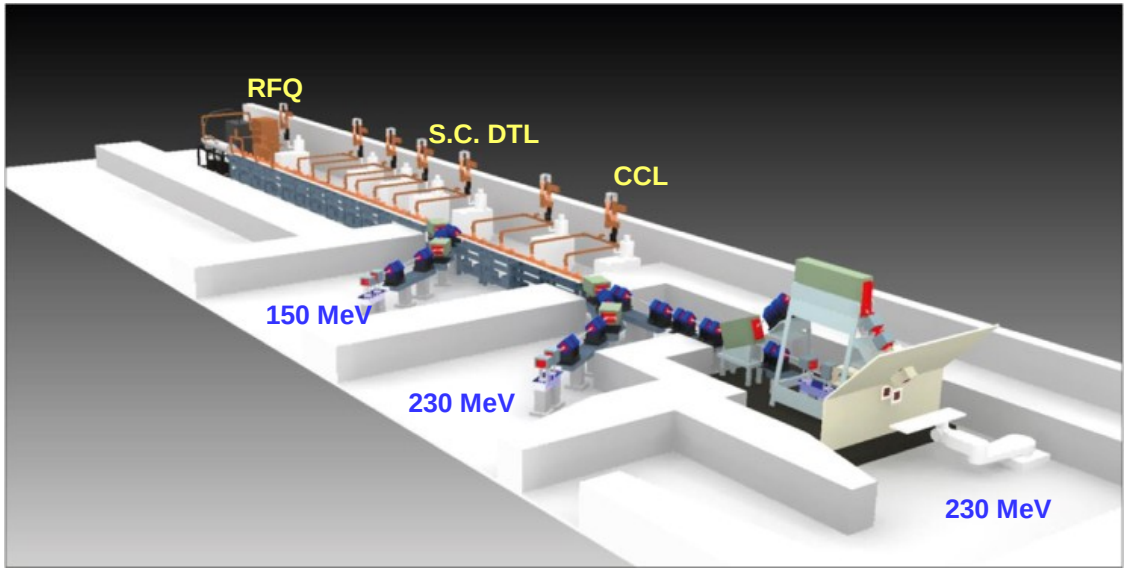
Recent developments

Amaldi, Proc. of LINAC 2014

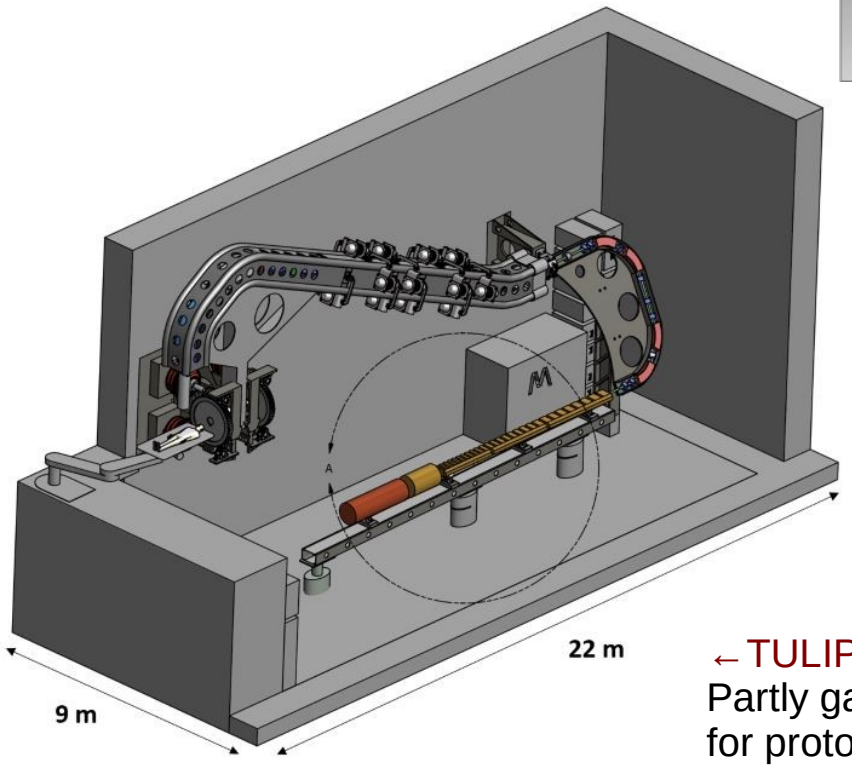
RF linear accelelarators

Partly superconducting to obtain shorter machines.

Can vary energy in accelerator by (de-)activating booster cells.



↑ LIGHT
Proposed Linac-only proton accelerator for ion beam therapy.



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

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

… also for carbon ions?

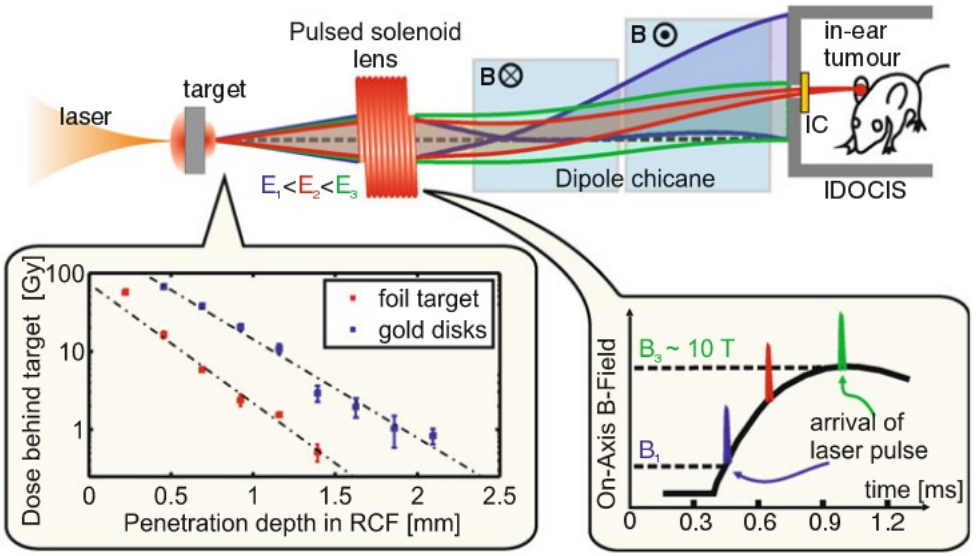
Recent developments

Laser acceleration

Beam pulses of high intensity and broad energy distribution

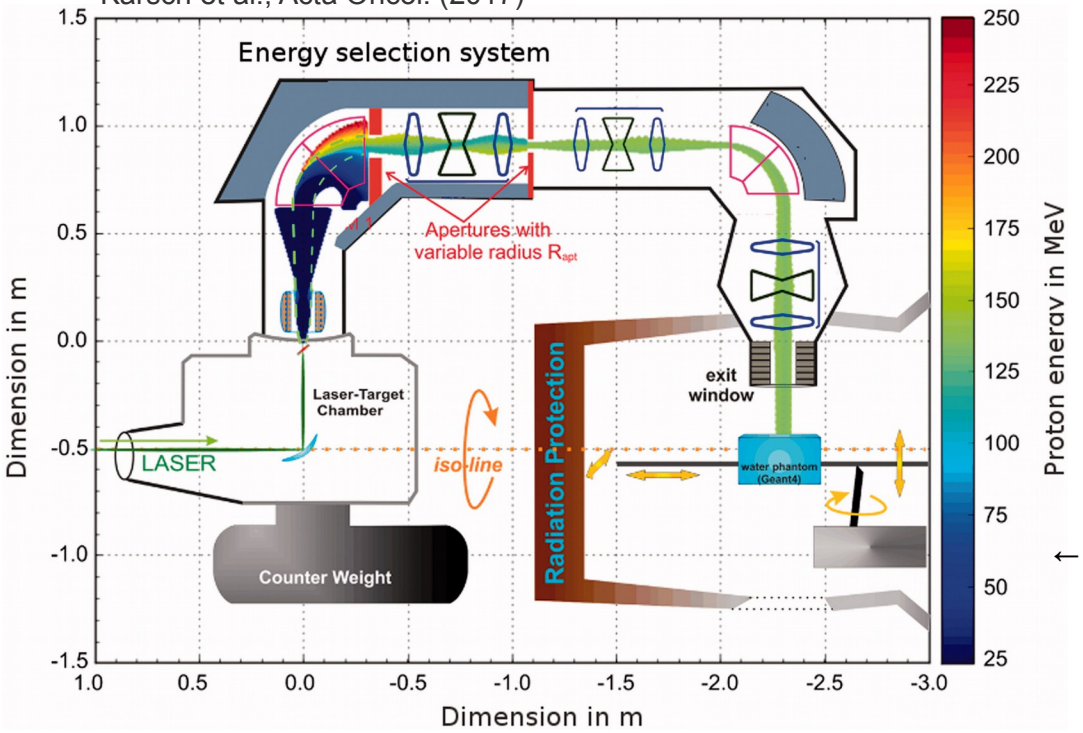
→ Energy selecting beam line
→ No accelerator: compact
→ High power (~ 100 TW) Laser required

Zeil, Appl. Phys. B 110 (2013) 437



Set-up for irradiation of mice using ↑ 25 MeV laser-accelerated protons from Dresden DRACO system.

Karsch et al., Acta Oncol. (2017)



←

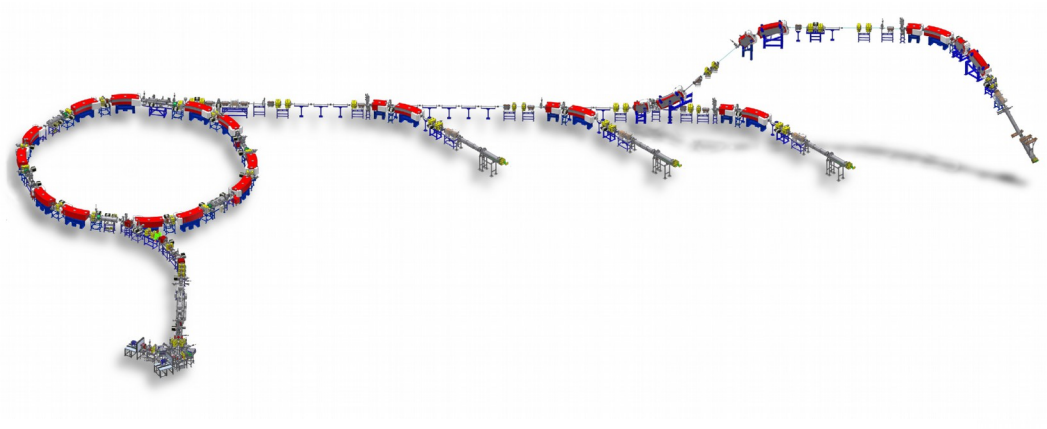
Proposed 230 MeV proton gantry for patient treatment using laser acceleration.

Outline

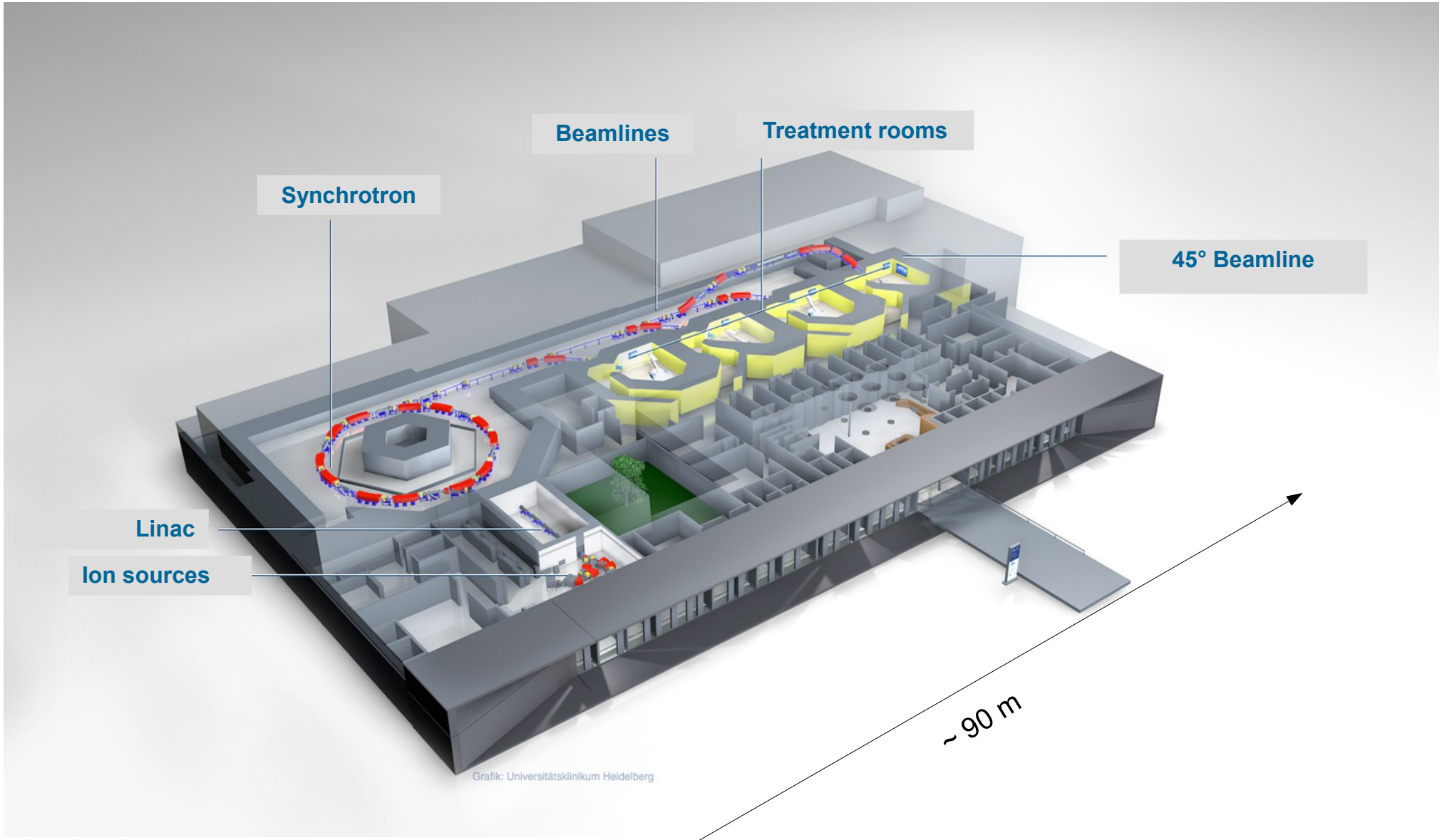
Ion-beam therapy

Accelerators for ion-beam therapy

MIT: A synchrotron-based $^{12}C^{6+}$ / p therapy centre

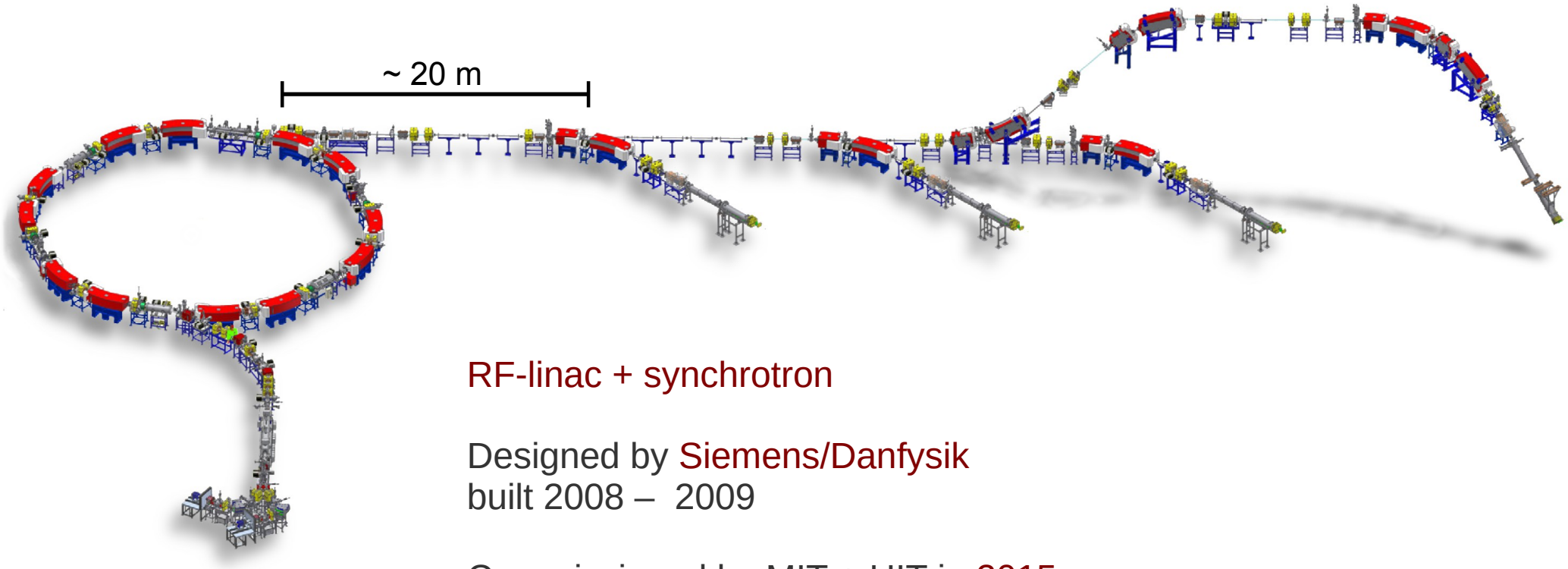


MIT: The Marburg Ion-Beam Therapy Centre



mit-marburg.de

MIT: The Accelerator



Rohdjeß et al., Proc. of PAC 2009
Lazarev et al., Proc. of IPAC 2011
Scheeler et al. Proc. of IPAC 2014

RF-linac + synchrotron

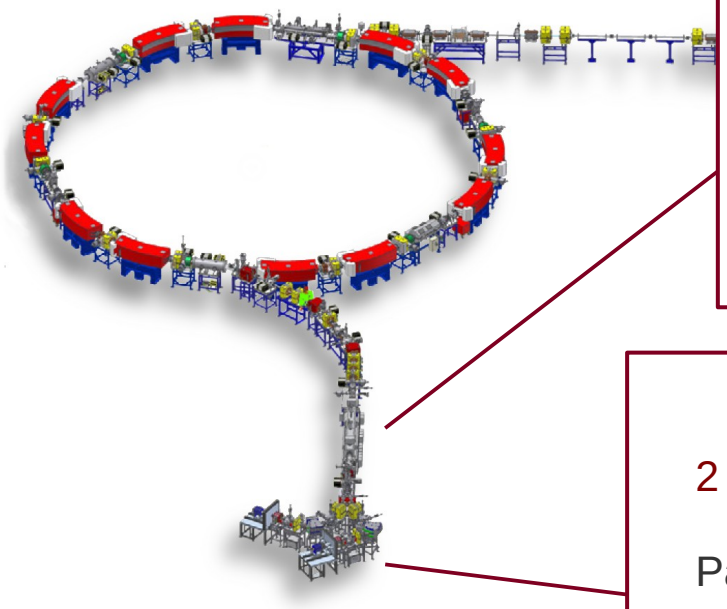
Designed by Siemens/Danfysik
built 2008 – 2009

Commissioned by MIT + HIT in 2015

Similar to HIT accelerator and
PIMMS-types (CNAO, MedAustron).

Prototype of SPHIC machine in Shanghai (start: 2014).

MIT: The Accelerator

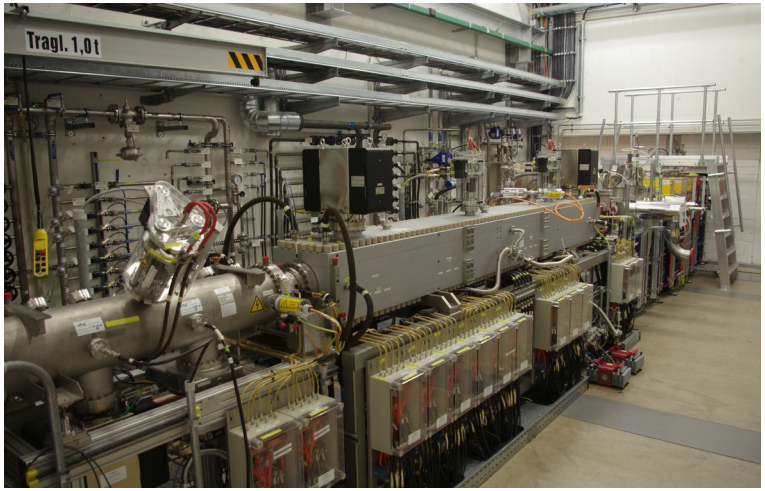


Rohdjeß et al., Proc. of PAC 2009
Lazarev et al., Proc. of IPAC 2011
Scheeler et al. Proc. of IPAC 2014

Linear accelerator

RFQ (400 keV/u)
+
IH structure (7 MeV/u)

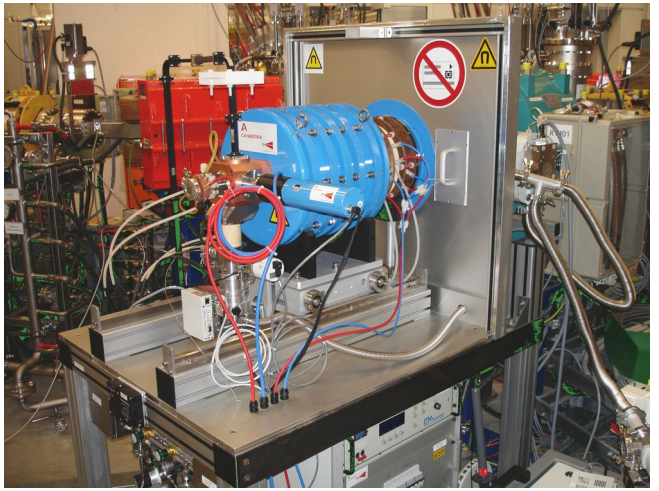
then stripping to
p and C^{6+}



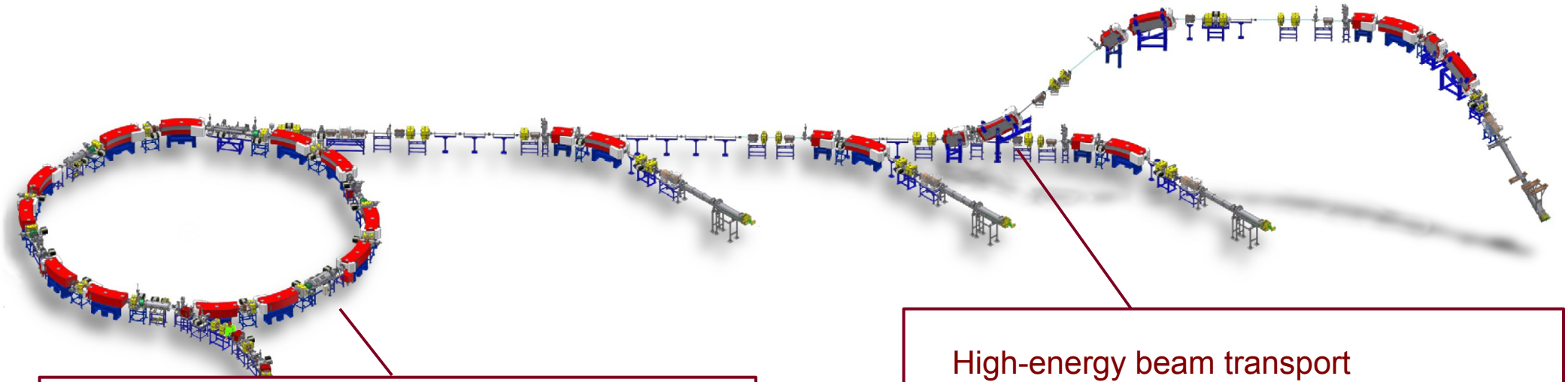
2 ECR ion sources

Pantechnik Supernanogan

H_3^+ : 800 µA
C^{4+} : 180 µA



MIT: The Accelerator



Synchrotron (65 m circ.)

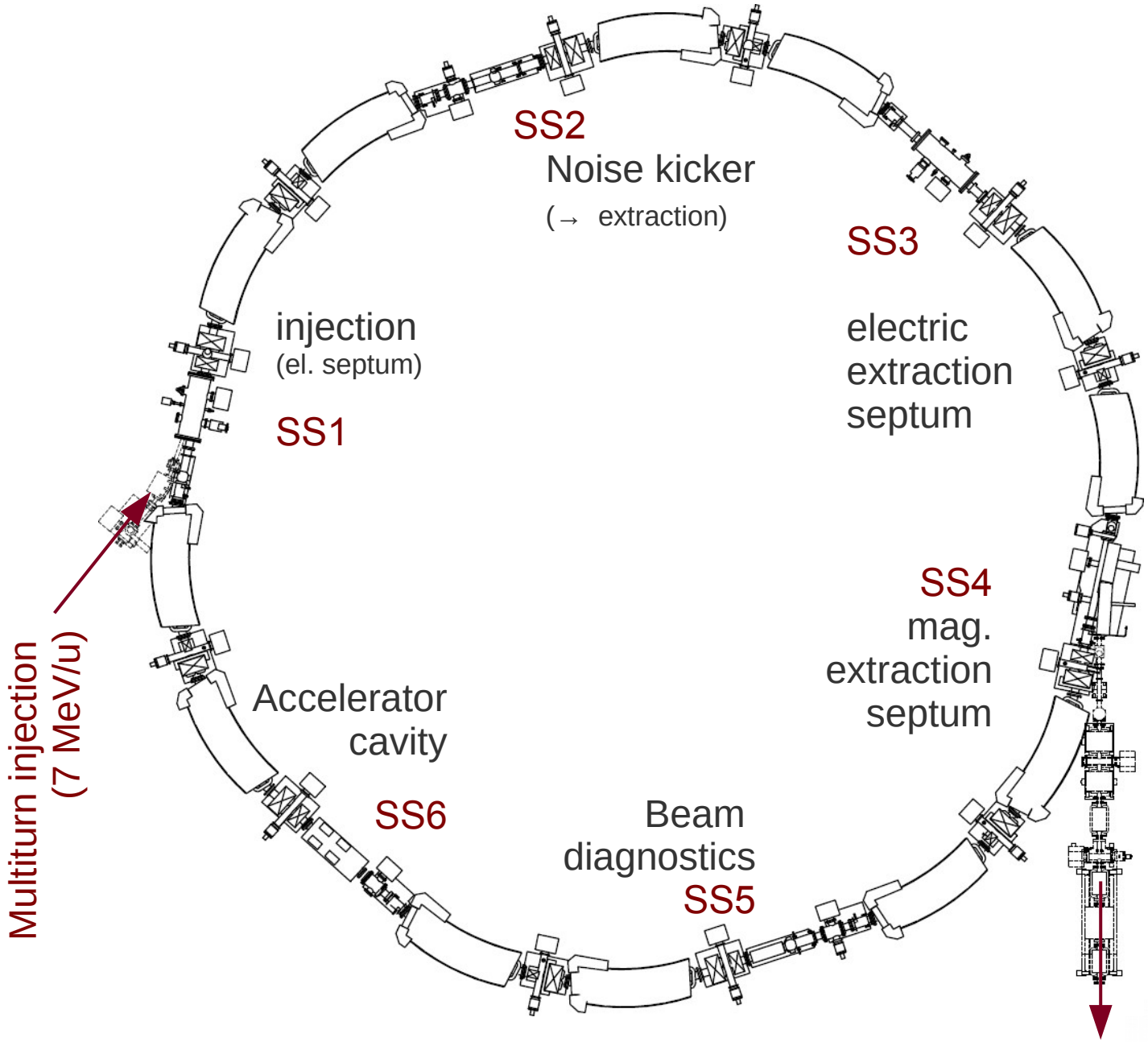
0.5 Tm – 6.6 Tm
Ramping time ~1 s

Extraction 1 – 8 s
(noise excitation)

Møller et al., Proc. of PAC 2007

High-energy beam transport

MIT: Synchrotron



Circumference: 65 m

$B\rho_{max}$ = 6.6 Tm

f_{Rev} = 0.56 … 3.37 MHz

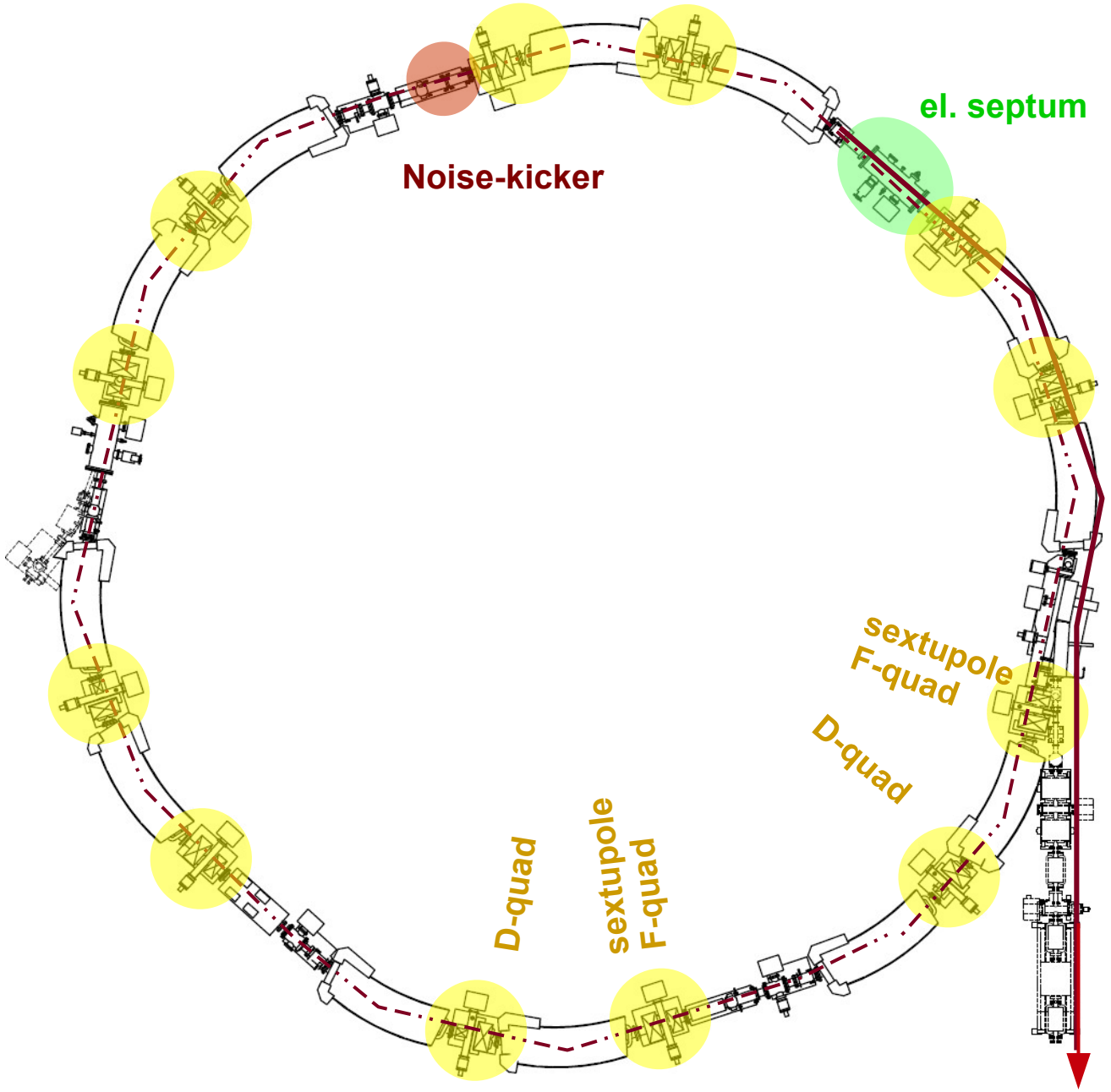
High energy beams

p: 48 … 221 MeV

$^{12}C^{6+}$: 88 … 430 MeV/u

Marburger Ionenstrahl-Therapiezentrum

MIT: Synchrotron extraction



Slow extraction via 2/3 resonance.

Active transverse beam heating by noise kicker ("KO-excitation").

→ Can **control** the **extraction rate** on ms-timescales!

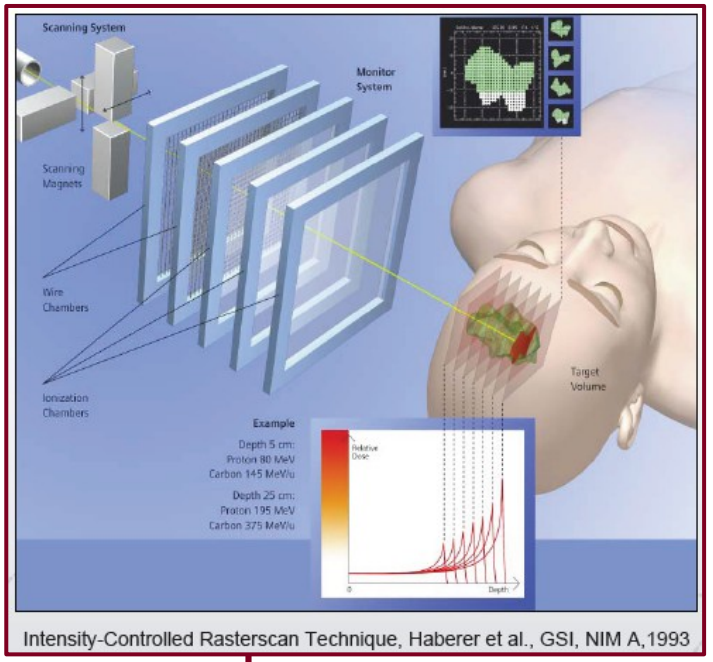
High energy beams

p: 48 … 221 MeV

$^{12}C^{6+}$: 88 … 430 MeV/u

Marburger Ionenstrahl-Therapiezentrum

MIT: Synchrotron extraction

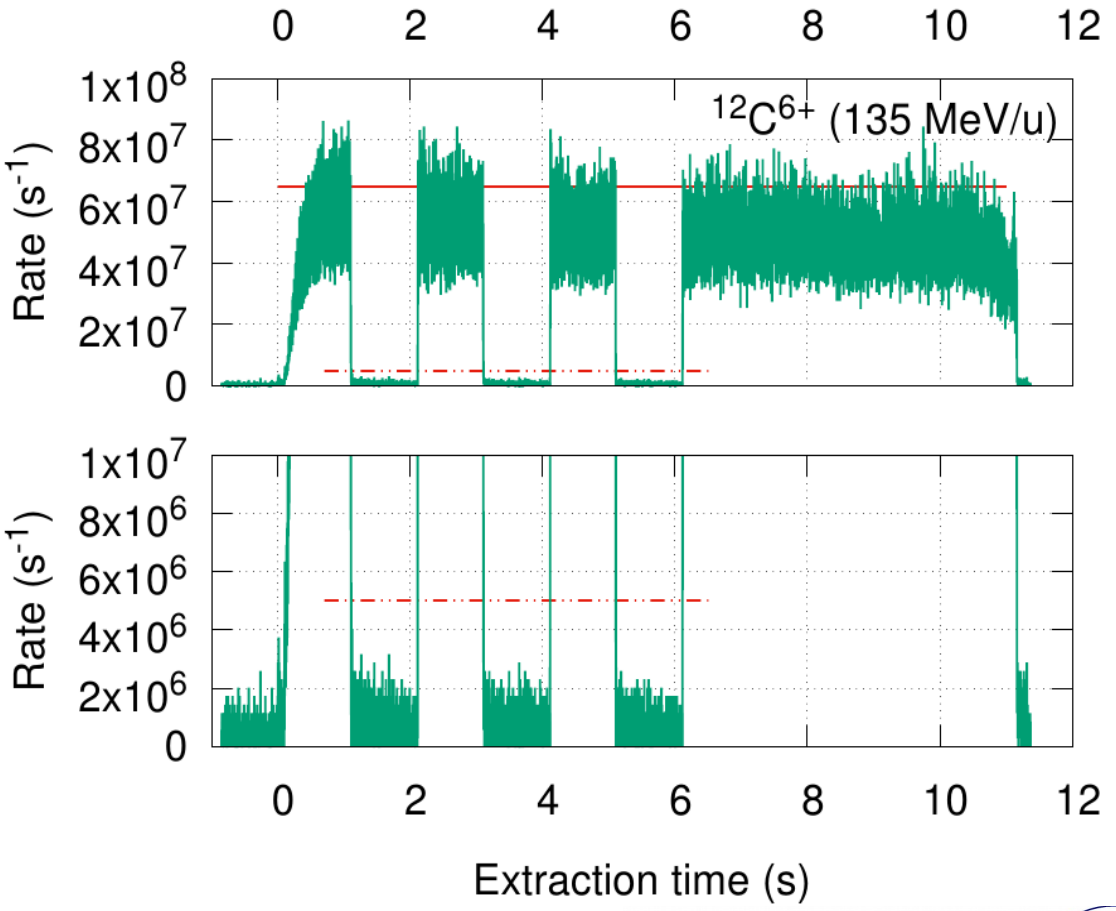


Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

KO-Exciter

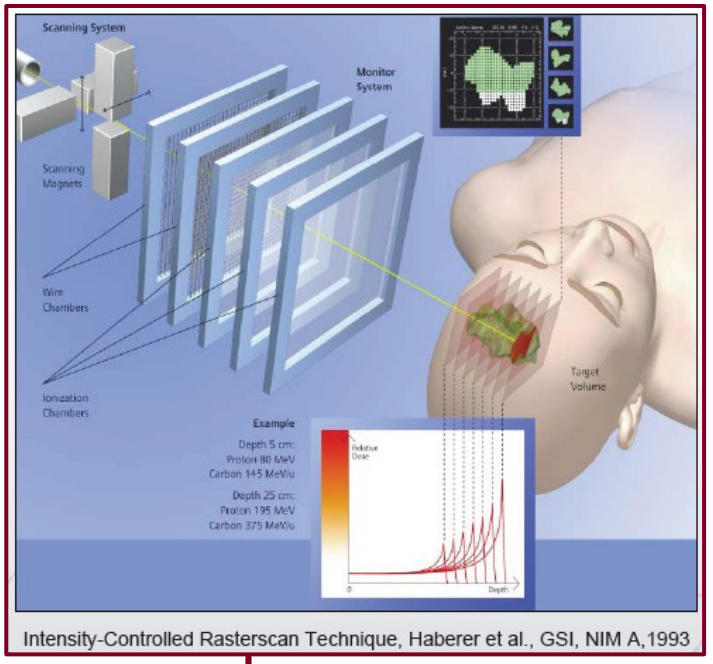
Therapy Control System has direct control over ion extraction rate.

→ Two orders of magnitude dynamic range!



Scheeler, Proc. IPAC 2016

MIT: Synchrotron extraction



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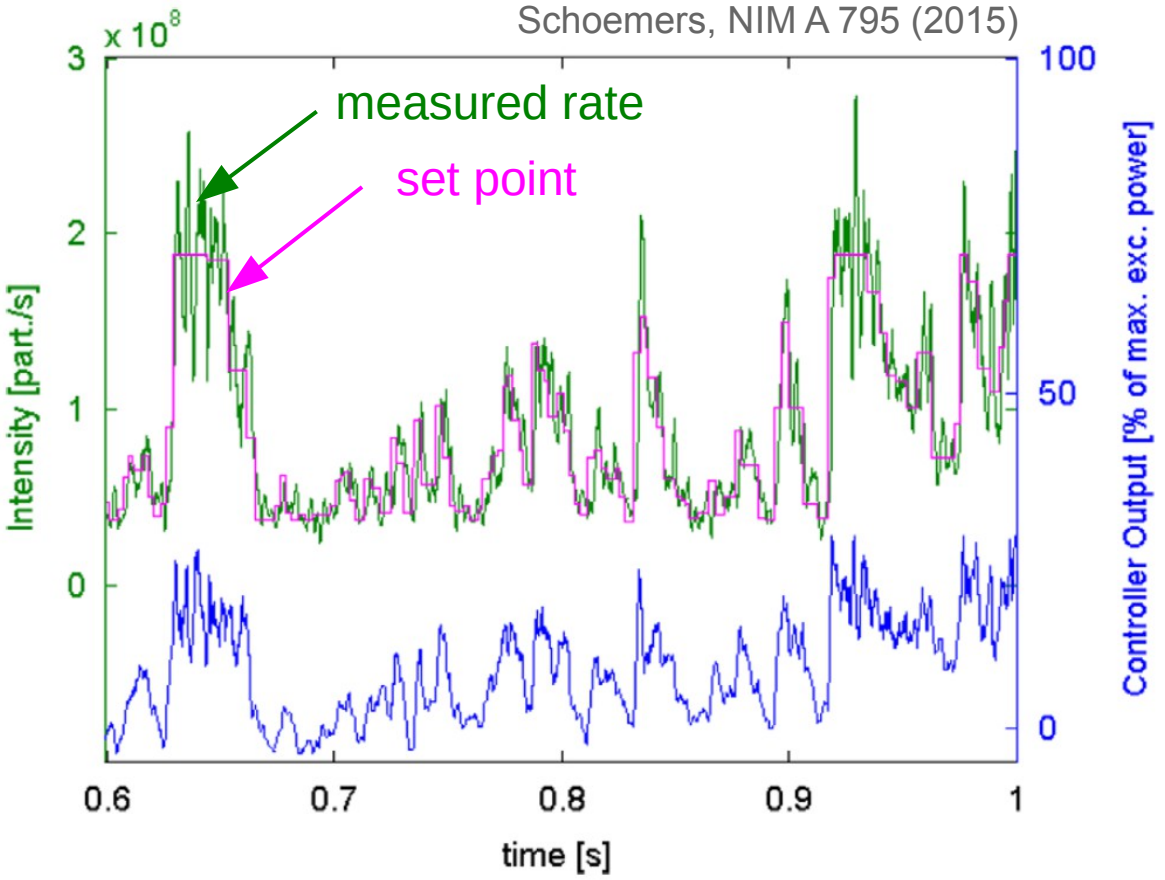
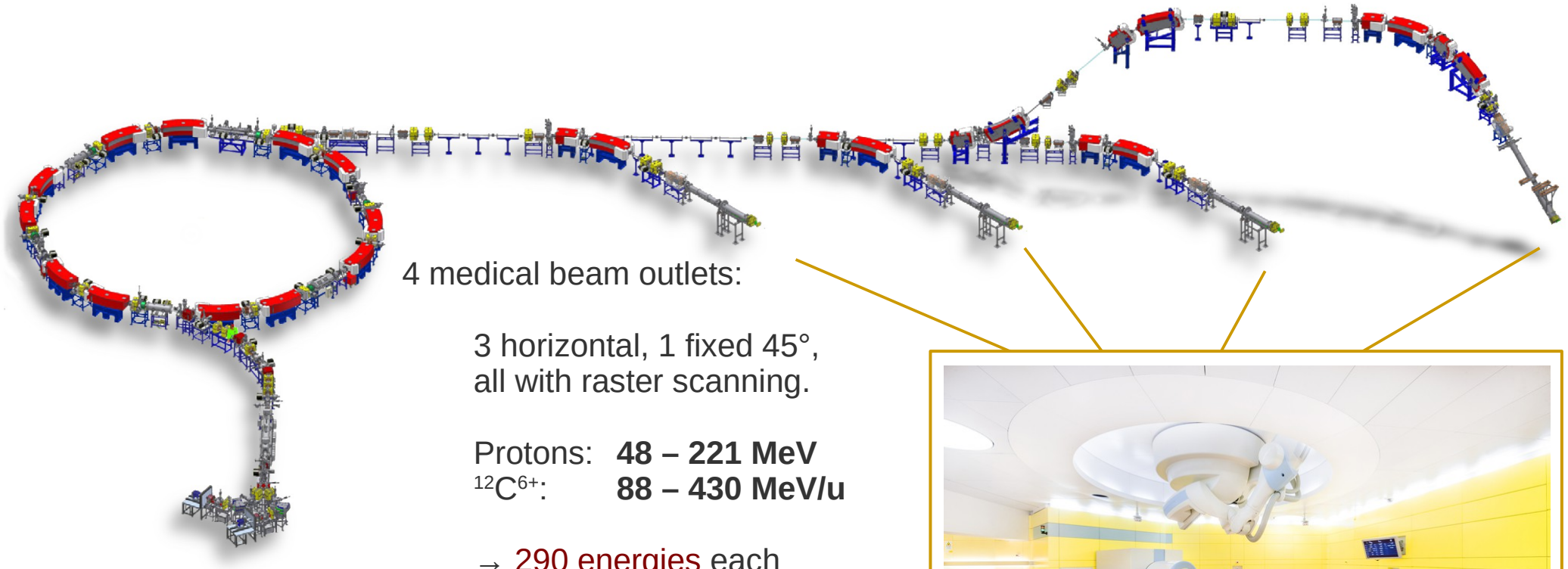


MIT: Therapy caves



Rohdjeß et al., Proc. of PAC 2009
Lazarev et al., Proc. of IPAC 2011
Scheeler et al. Proc. of IPAC 2014

4 medical beam outlets:

3 horizontal, 1 fixed 45°,
all with raster scanning.

Protons: **48 – 221 MeV**
$^{12}C^{6+}$: **88 – 430 MeV/u**

→ 290 energies each

Protons: **$4 \cdot 10^8$ – $2 \cdot 10^{10}$**
$^{12}C^{6+}$: **10^7 – $5 \cdot 10^8$** per spill

→ 13 base intensities with
"Dynamic Intensity Control"

5 beam widths

mit-marburg.de

Thank you for
your attention.