What is a gantry?

- A tall metal frame that supports heavy machines such as cranes, railway signals, or other equipment.
- A support for a barrel lying on its side.
Gantry at cinema

Hopefully not in our case...
Gantry food

WELCOME TO THE GANTRY,
COME AND SIT AT THE BAR, RELAX IN FRONT
OF THE FIREPLACE, DINE INDOORS AND IN
THE CONSERVATORY OR JUST SOAK UP
THE FRESH AIR IN OUR HIDDEN GARDEN.
Gantry in music

- I could not find a picture, but I think I remember of an english group called The Gantry...
... but for us

- A gantry is a section of beamline that can rotate around the isocenter in order to direct the beam onto the patient from any direction.
Why a gantry?

- To treat patients in supine position (eventually prone) in the same position in which CT, PET and MRI were acquired. Patient rotation only around gravity to preserve internal organs and soft tissue geometry.

- To provide the maximum flexibility in selecting the irradiation direction when optimising the dose delivery.

- To allow a “robust” treatment planning. Exploiting the sharp distal fall off can be risky in some cases and a gantry helps in avoiding fields directed towards an Organ At Risk (OAR).

- Avoid density heterogeneities

- Minimize SOBP extension (less energies required and better peak to plateau ratio)
Why a gantry

Allows better, more robust planning: e.g. minimize fields pointing towards OAR (Organ At Risk)

With horizontal line only

With gantry
Treatment planned with gantry

IMPT: each spot has an individually specified number of particles. The sum of the various fields is flat (or as required by clinics).
Gantry in conventional radiotherapy

- The whole linac is inside the gantry
- The gantry head can pass between patient and floor for irradiation from below

(Varian Clinac IX)

Dimensions:
- 2.6 m
- 3.5 m
Magnetic rigidity

\[ qvB = \frac{mv^2}{\rho} \quad \Rightarrow \quad B\rho = \frac{p}{q} \]

Electron, 20 MeV: \( B\rho = 0.068 \, \text{T m} \)

Protons, 60 MeV: \( B\rho = 1.14 \, \text{T m} \)

Protons, 250 MeV: \( B\rho = 2.43 \, \text{T m} \)

Carbon, 120 MeV/u: \( B\rho = 3.25 \, \text{T m} \)

Carbon, 400 MeV/u: \( B\rho = 6.35 \, \text{T m} \)

In practical units:

\[ 0.2998 \, B \, [\text{T}] \, \rho \, [\text{m}] = p \, [\text{GeV/c}] / q \, [\text{e}] \]

“Zero comma c”
Size and magnetic rigidity

Conventional RT
Proton Gantry
B_ρ < 2.4 Tm

Carbon Ion Gantry
B_ρ < 6.4 Tm
Deep pit under the patient
Proton gantry

Mitsubishi

Hitachi

IBA
Carbon ion gantry

Only one C gantry worldwide: \( L = 25 \text{ m} \times \phi = 13 \text{ m}, \ 600 \text{ t} \)

360° rotation
Parallel scanning
200 mm x 200 mm field
140 t magnets
120 t shielding-counterweight
600 t total rotating mass

Very large, very heavy, very expensive

(Udo Weinrich, GSI)
The CNAO 90° magnet during installation in the vertical line. The size is the same as for a gantry final magnet.
Carbon Ion Gantry

- The HIT Gantry: the only operational C Gantry

$L = 25 \text{ m} \times \phi = 13 \text{ m}, 600 \text{ t} \text{ rotating mass}$
Proton gantries, many geometries used

Corkscrew gantry at LLUMC

IBA
Proteus
One

MeVlon

ProTom

ProNova

IBA/SHI/
Hitachi
In-Plane

PSI 1 shortest radius

FFAG is the lightest

(Adapted from a slide of J. Flanz)
PSI gantry 2 (we will see it at MedAustron)

NB: a gantry is ~half a synchrotron in bending (and even more + large aperture magnet)
Thus gantries are useful, but especially carbon gantries are huge, expensive, difficult etc.

CAN WE DO BETTER?
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
Space around patient

- Patient size
- Walk around patient
- Imaging in situ
- Couch rotation

- Typical
  - ~ 45 – 65 cm
  - ~ 2 m opposite to nozzle

- Scattering, air and distance degrade beam quality

(Photon gantry used for illustration only, text refers to particles)
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
Field size

- Area that can be irradiated
- Trade off between performance and gantry cost/size
- Larger field requires thicker vacuum window.

- Typically
  - 20x20 in Europe to
  - 30x40 cm² in the US

(Photon gantry used for illustration only, text refers to particles)
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
Scanning or scattering

- Scattering is the most used spreading technique, but it is not suitable for carbon beams and anyway the trend is towards scanning also for protons.

- Let’s assume scanning in the following
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
- Source to Axis Distance (SAD)
SAD

- Treatment plans (at least many of them) consider parallel scanning
- Dose increase to the skin, which is a radiosensitive organ
SAD for separated scanners

One at infinity, SAD=3.40 \(d=0.3\) \(\text{Dose Inc}=10\%\)

One at infinity, SAD=1.83 \(d=0.3\) \(\text{Dose Inc}=20\%\)
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
- Source to Axis Distance (SAD)
- Scanning magnets position
Scanning magnets position

- Large aperture dipole: weight and power consumption
- Large gantry radius and large room size

One scanning magnet upstream and one downstream is often proposed
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
- Source to Axis Distance (SAD)
- Scanning magnets position
- 180° or 360°
360° vs 180°

- By rotating the couch by 180°, all the beam directions are possible also with only 180° of rotation of the gantry.

Rotation of the couch may require position verification (time and Xrays), but it saves space and requires less shielding on the wall “not irradiated”.

![Diagram showing 360° vs 180° couch rotation](image-url)
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
- Source to Axis Distance (SAD)
- Scanning magnets position
- 180° or 360°
- Field patching
Field patching

Scan in one go

Scan and move (~PSI gantry 1)

Move couch

Move couch

Move couch

Reduced magnet aperture, but slower procedure and difficulties somehow similar to simultaneous optimisation of multiple fields with IMPT
Field patching

- Fields have to be tapered (possible with active scanning)
- Alignment required

\[
\frac{\Delta x}{L} < \text{Rel dose precision}
\]

0.5mm/2cm = 2.5%
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
- Source to Axis Distance (SAD)
- Scanning magnets position
- 180° or 360°
- Field patching
- Fixed or mobile isocenter
Fixed or mobile isocenter

- Most of the existing gantries have a fixed isocenter on the rotation axis of the gantry. This implies large masses rotating at large radius.
An isocenter, through which all the directions pass, exists but its position depends on gantry orientation.
ULICE mobile isocenter gantry ("Riesenrad")

90° bending magnet
Scanning magnets
Quadrupoles
Corrector magnets
London Eye
ULICE mobile isocenter gantry ("Riesenrad")
Beam Based Alignment

Isocenter position moves and is not easy to measure/verify/define

Measure where the beam is and put the isocenter there…

One robot arm with two “tools”

CNAO treatment room #2: PPS and PVS
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
- Source to Axis Distance (SAD)
- Scanning magnets position
- 180° or 360°
- Field patching
- Fixed or mobile isocenter
- Superconducting magnets
Superconducting magnet studies

HIMAC

Vacuum chamber
Cold yoke
Beam duct (60mm)
Dipole coil
Quadrupole coil

Berkeley

INFN-CNAO

CEA-IBA

X
Y
Z
HIMAC superconducting gantry (under construction)

- Weight: order of 300 tons

Ion kind: $^{12}$C
Irradiation method: 3D Scanning
Beam energy: 430 MeV/n
Maximum range: 30 cm in water
Scan size: $200 \times 200 \text{ mm}^2$
Beam orbit radius: 5.45 m
Length: 13 m

(Courtesy of Y. Iwata)
Superconducting Gantry (HIMAC)

Combined function, Superconducting magnets

Progressively increasing perture
Ramping tests

- Tests with maximum slew-rate
- I=45~136 A (E=56~430 MeV/u)
- No quench observed
- Average temperature converged below Tc~6.8 K

![Graph showing coil current and temperature over time](image)
Aspects and possibilities to consider in a gantry

- Space around isocenter for patient dimensions and couch orientation
- Field size
- Active or passive beam delivery (scattering or scanning)
- Source to Axis Distance (SAD)
- Scanning magnets position
- 180° or 360°
- Field patching
- Fixed or mobile isocenter
- Superconducting magnets
- 3D tumor tracking
If one wants to follow a tumor moving in range one needs a fast energy changing machine (or an active energy degrader) and a gantry with fast magnets or...
FFAG Gantry

What if dispersion is so small that $\Delta p/p = \pm 35\%$ goes through?

CARBON GANTRY height 4.091m

$B_{\text{dip}} \sim 4.5$ T
$g$ up to 150 T/m

(Courtesy of Dejan Trbojevic)
FFAG mobile isocenter

Can be hosted in the ULICE gantry

(Courtesy of Dejan Trbojevic)
Permanent Halbach Magnet NS-FFAG Proton Gantry

14 cells-27 cells

ORBITS MAGNIFIED
-10<Δx<16 mm

r=2.71 m

162°

Proton kinetic energy range
30 – 250 MeV

(Courtesy of Dejan Trbojevic)
Alternatives

- Chair (with vertical CT)
Chair at Hyogo
Alternatives

- Chair with vertical CT
- Some patient rotation with 6d couch
- Cradle couch at HIMAC
Alternatives

- Chair with vertical CT
- Some patient rotation with 6d couch
- Multi room system
Multi-room system

- Proposed by A. Brahme

(M. Kats)
Alternatives

- Chair with vertical CT
- Some patient rotation with 6d couch
- Multi room system
- Planar system
Planar System

- Proposed by M. Kats

Circular exit face with center on beam entry position. Exit edge angle equals half bending angle.
Multi room planar system

- Proposed by M. Kats
Conclusions

- Carbon ion gantries are needed
- There are margins to improve the present schemes
- There are new ideas for new schemes
- There are large margins for compromise solutions and combinations of ideas

- Many aspects must be considered when designing a gantry
Conclusions

- Space between isocenter and last magnet for patient, beam delivery system (monitors and eventually scanning magnets), SAD
- Space downstream isocenter for patient and to go around patient
- Space for in situ position verification

- Gantry size depends on the space above plus bending radius plus magnet with supporting structure size.
- If mobile isocenter, the patient cabin will determine the gantry radius.
- Access to patient
Conclusions

- The gantry dimensions define the gantry room size and cost (digging, concrete, ventilation, climatization, shielding)

- No columns, thus single span roof. Generally roof thickness is defined more by radiation protection than by structural reasons, but anyway pre-built beams are likely to be necessary.

- Tumor tracking in energy

- And many others...
Thank you for your attention

“Physics is like sex: sure, it may give some practical results, but that's not why we do it.”

R. Feynmann