Heavy Ion Therapy Research Integration

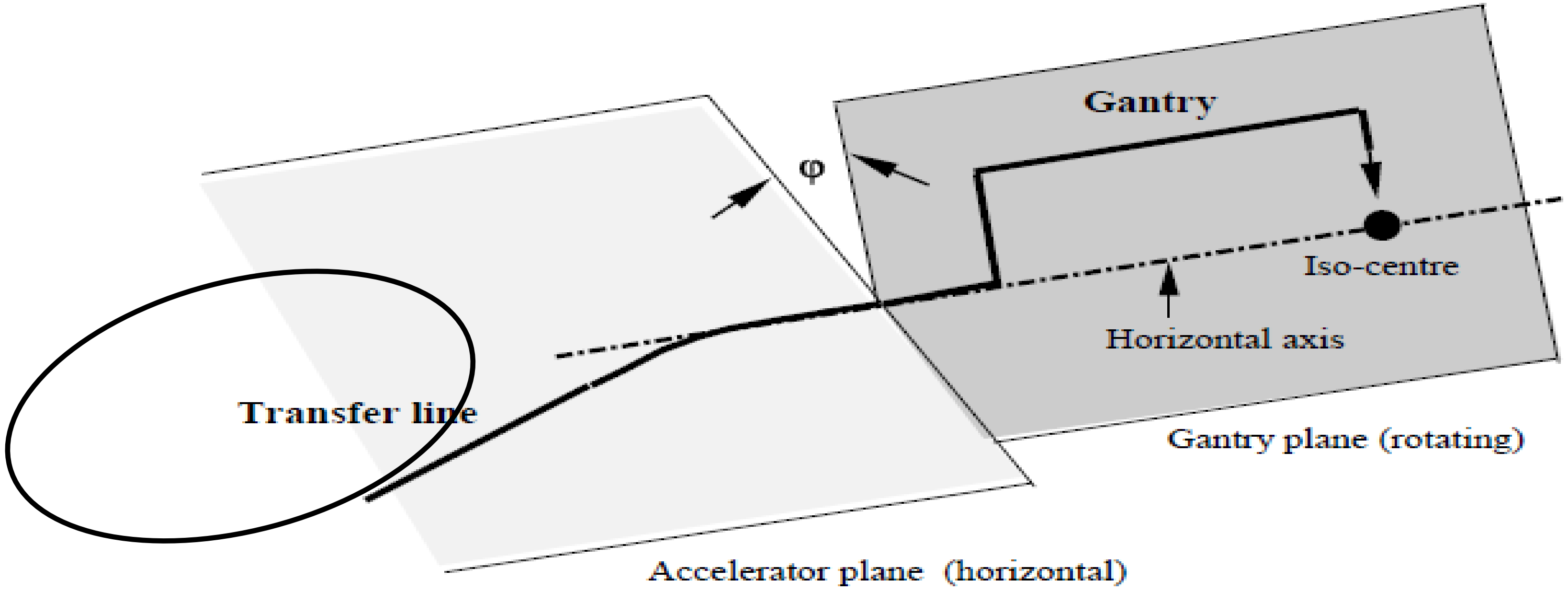
# Gantries

MARCO PULLIA

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

# What is a gantry?

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



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# Why a gantry?

- To treat patients in supine position (eventually prone) in the same position in which CT, PETand 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)



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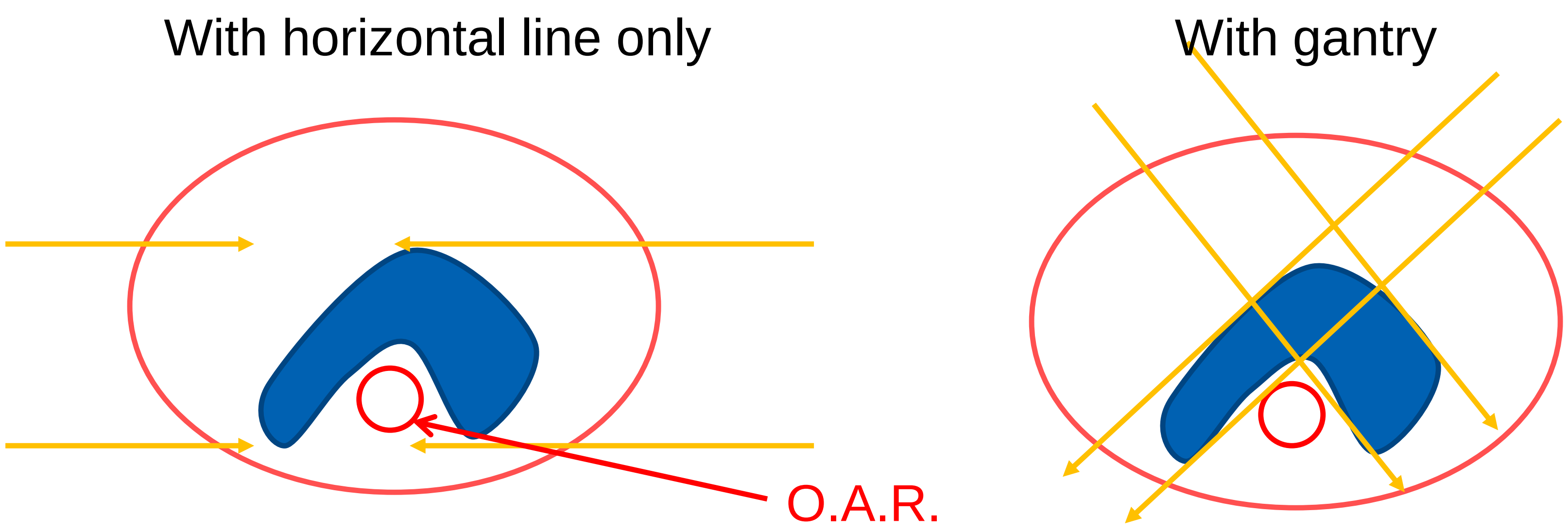
# Why a gantry

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

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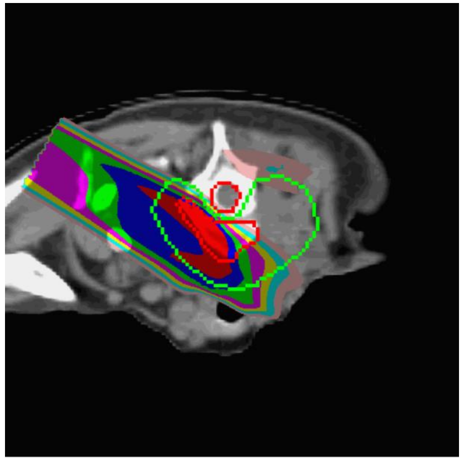
# Treatment planned with gantry



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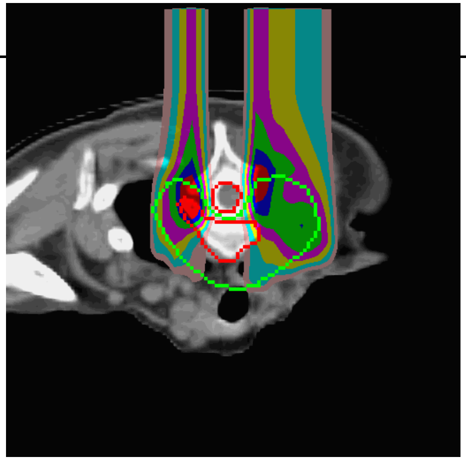

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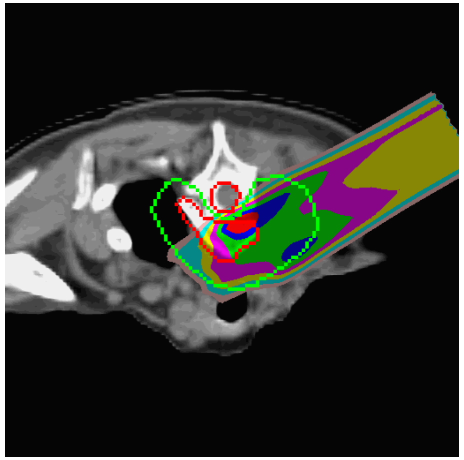

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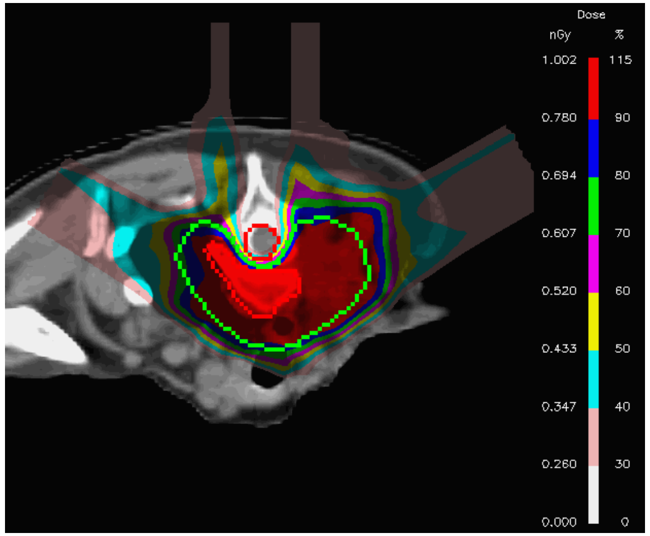


IMPT: each spot
has an individually
specified number of
particles. The sum of
the various fields is flat
(or as required by clinics).

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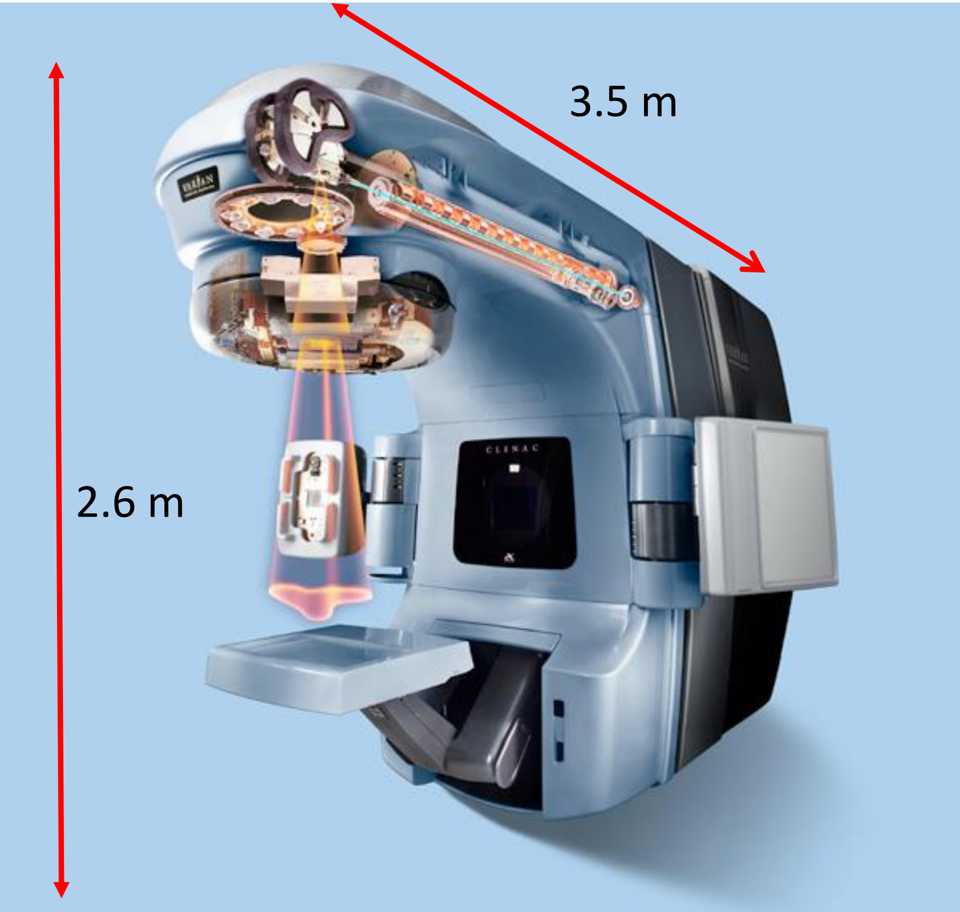
# Gantry in conventional radiotherapy

The whole linac is inside the gantry

The gantry head can pass between patient and floor for irradiation from below




(Varian Clinac IX)



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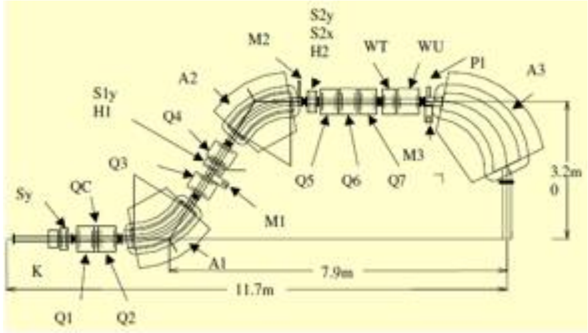
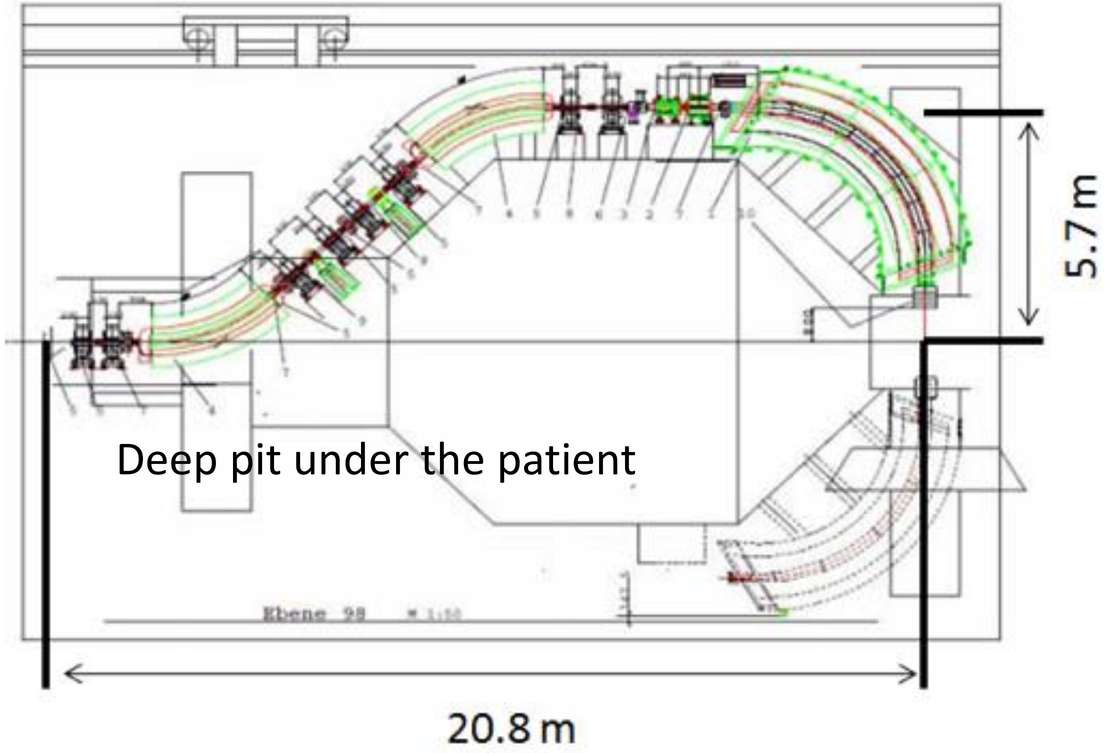
# Gantries for particle therapy are large

Conventional RT




Proton Gantry
Bρ < 2.4 Tm

Carbon Ion Gantry
Bρ < 6.6 Tm




Deep pit under the patient

The larger magnetic rigidity of carbon ions requires larger fields and larger bending radius

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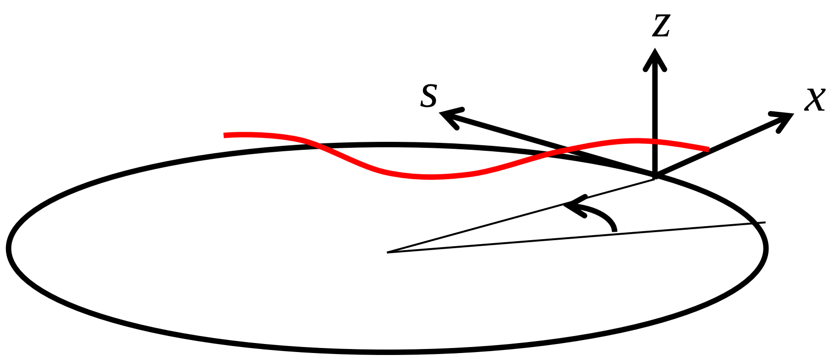
# Betatron oscillations recap

With all the possible simplifications and linearizations, the motion of a particle with nominal energy along a magnetic lattice is described by the Hill's equation

$$\frac{d^2y}{ds^2} + K(s)y = 0 \qquad y = x \text{ or } z$$




The Hill's equation looks like an harmonic oscillator, but K(s) varies along the lattice depending on the magnetic element at position s. Assume it is constant inside each magnet and varies abruptly when passing from one element to the following (hard edge approximation)

For each element we can write a transfer matrix transporting the initial coordinates to the particle position at the element exit.

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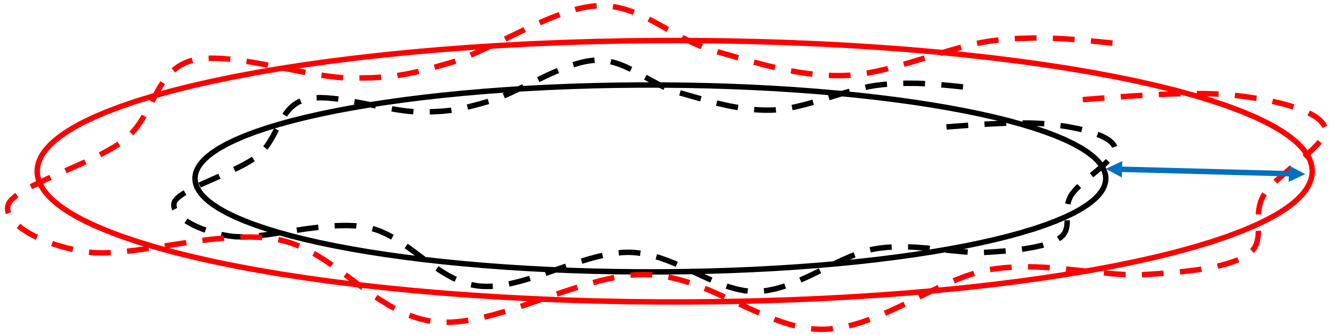
# Dispersion

Particles with a (small) momentum deviation are bent differently wrt the nominal particle. Anyway a closed orbit/reference trajectory for particles with the considered momentum can be found and particles not moving on this new path orbit perform betatron oscillations around it.

The dispersion function expresses the closed orbit variation in terms of $\Delta p/p$



$$\begin{pmatrix} \Delta x(s) \\ \Delta x'(s) \end{pmatrix} = \begin{pmatrix} D_x(s) \\ D'_x(s) \end{pmatrix} \frac{\Delta p}{p_0}$$

The dispersion function originates from the dipoles and when no dipole is traversed the quantity

$$\gamma D^2 + 2\alpha D D' + \beta D'^2$$

stays constant .



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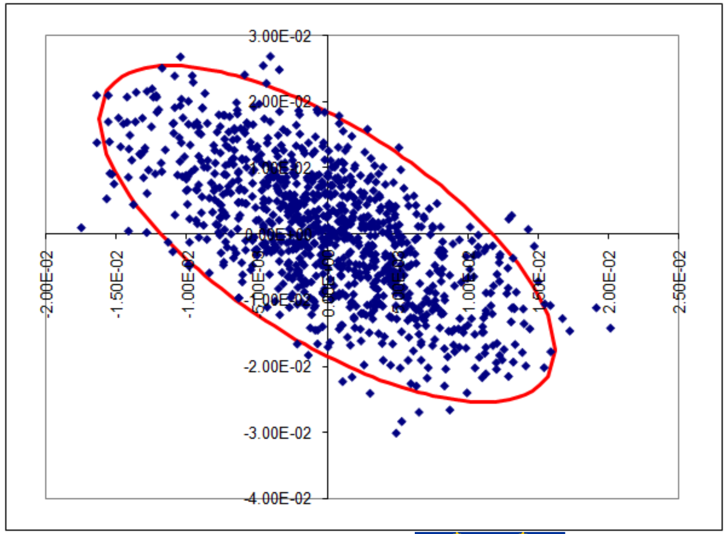
# Circular accelerators and beamlines

The beta function in a ring is derived considering periodic conditions K(s+L) = K(s). This defines clearly the meaning of the beta function, which describes the accelerator and the beam adapts to it.

In transfer lines the periodicity condition does not apply. One can choose the initial betas “freely”. Betas are useful if they describe the beam!

Area of ellipse = $\pi\varepsilon$

Now that it is defined by a beam
$\varepsilon$ is called **beam emittance**



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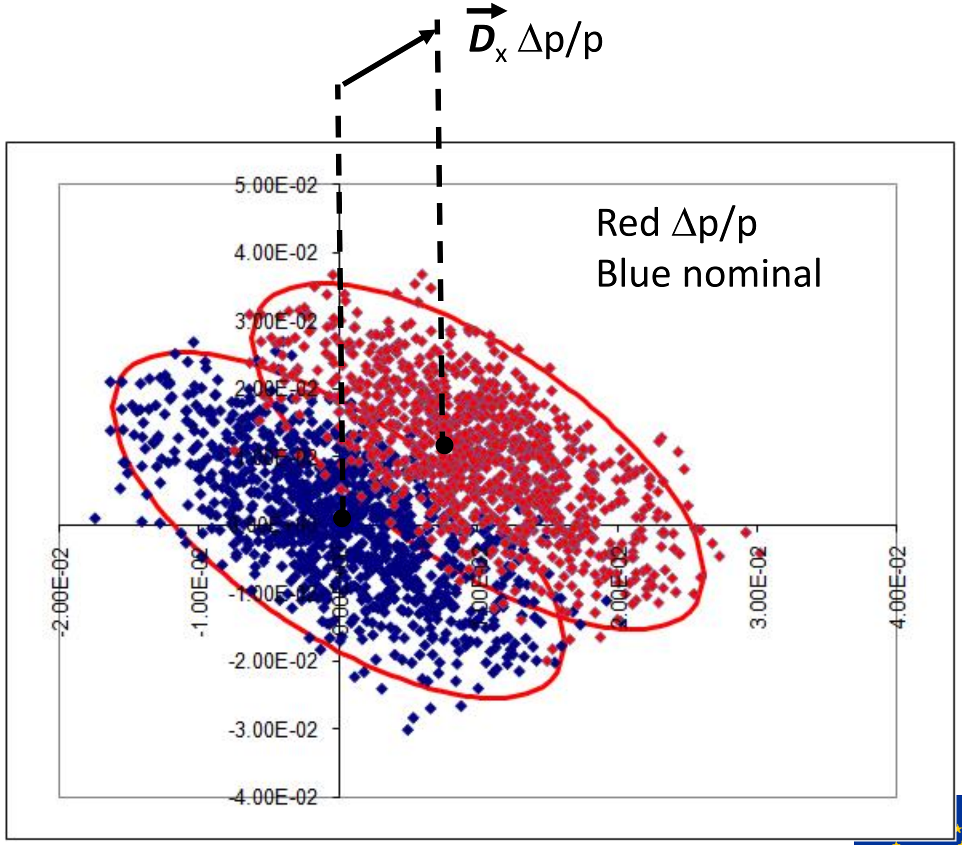
# Initial dispersion

As for betas, in a ring the periodic dispersion is clearly defined while in a transfer line the initial value of the dispersion function shall be based on the beam distribution

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# Matching to rotating gantries

**Symmetric beam** method with zero dispersion (exact)

- The beam at the entrance to the gantry must have zero dispersion and must be rotationally symmetric i.e. the same distribution (e.g. gaussian or KV) with equal Twiss functions and equal emittances in both planes at the entry to the gantry.
- The gantry must be designed to be a closed dispersion bump in the plane of bending (achromatic transport)

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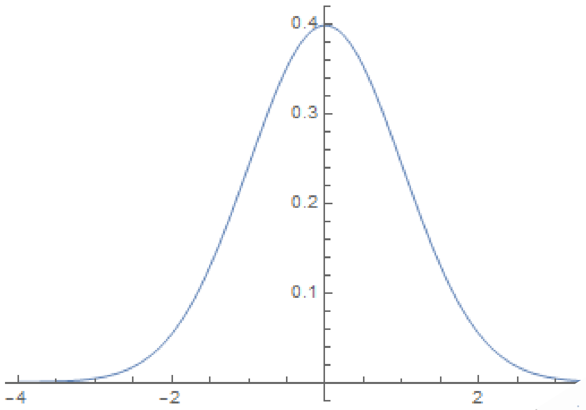
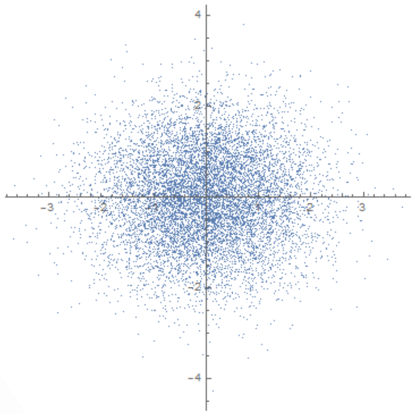
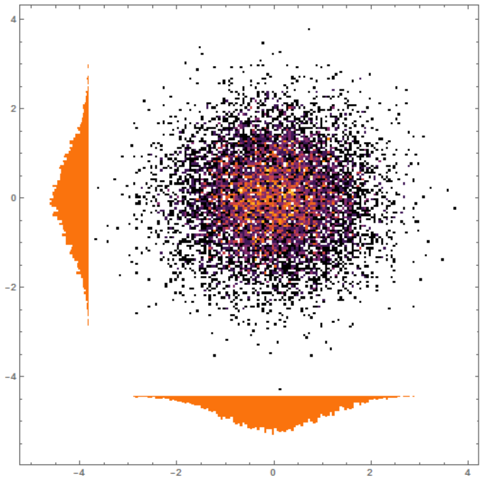
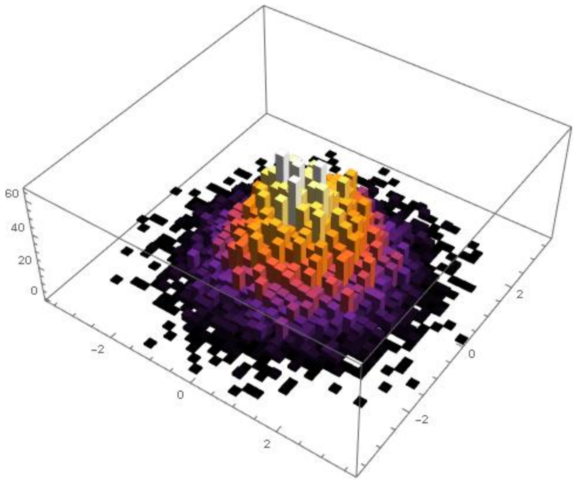
# Matching to gantries

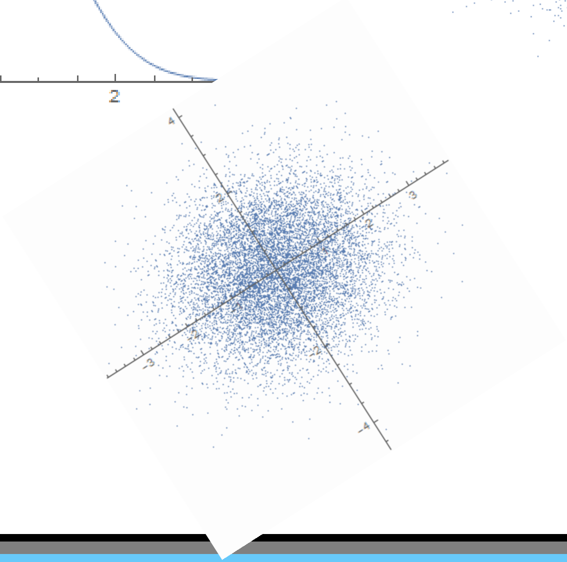
Factorised distribution $\rho_x(x) = \frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}}$ , $\rho_y(y) = \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}}$ , $\rho(x,y) = \rho_x \cdot \rho_y$









Round distribution!
When rotated it's invariant!

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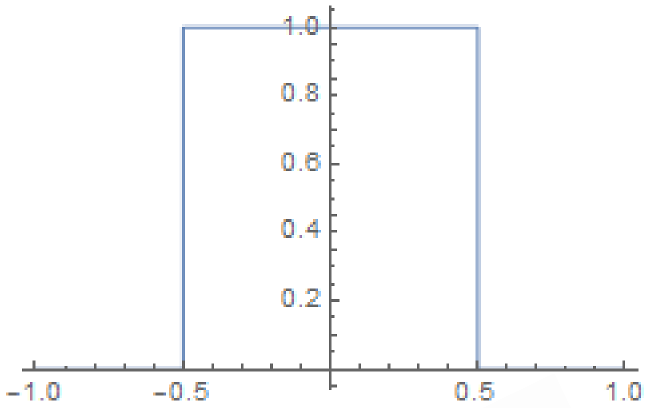
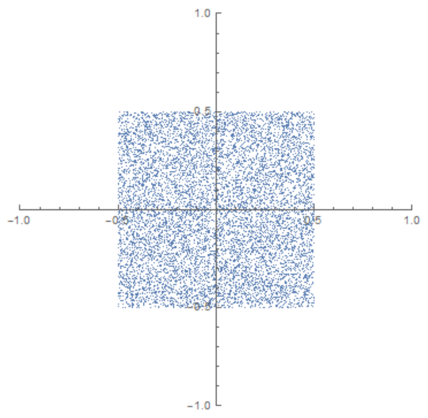
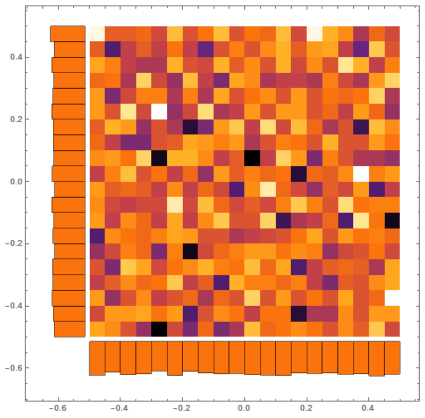
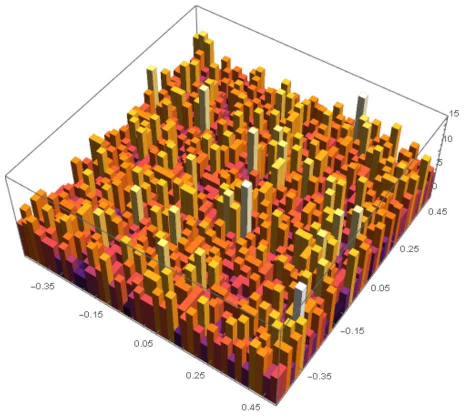
# Matching to gantries

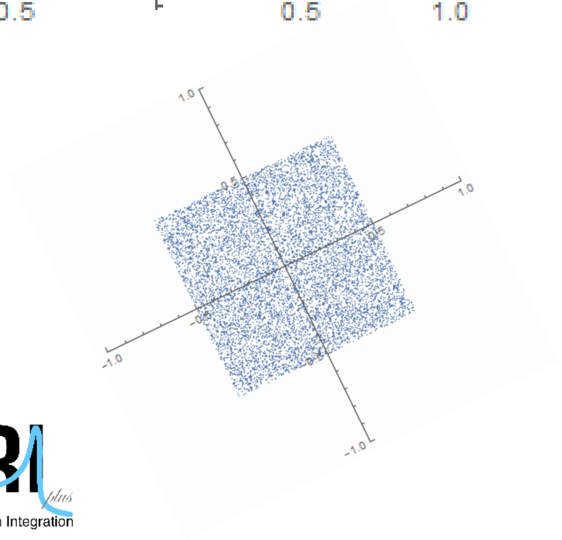
Factorised distribution $\rho_x(x) = 1/2A$, $\rho_y(y) = 1/2A$, $\rho(x,y) = \rho_x \cdot \rho_y$









Square distribution!
When rotated it's not invariant!

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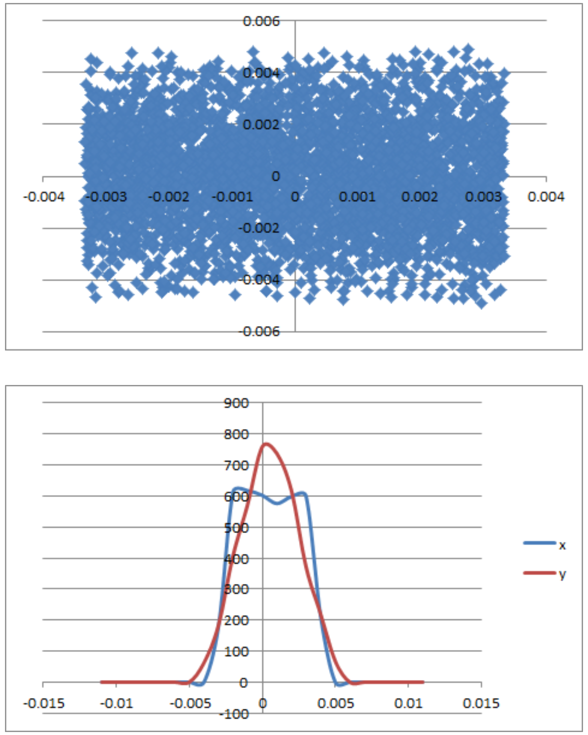
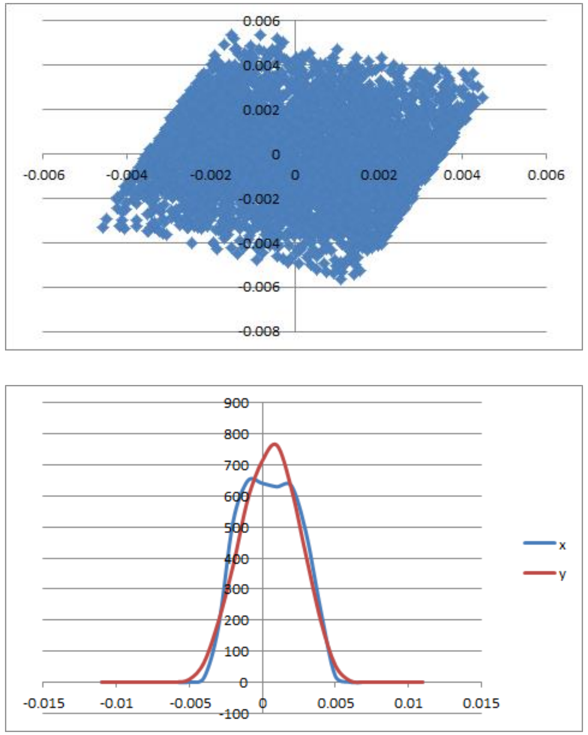
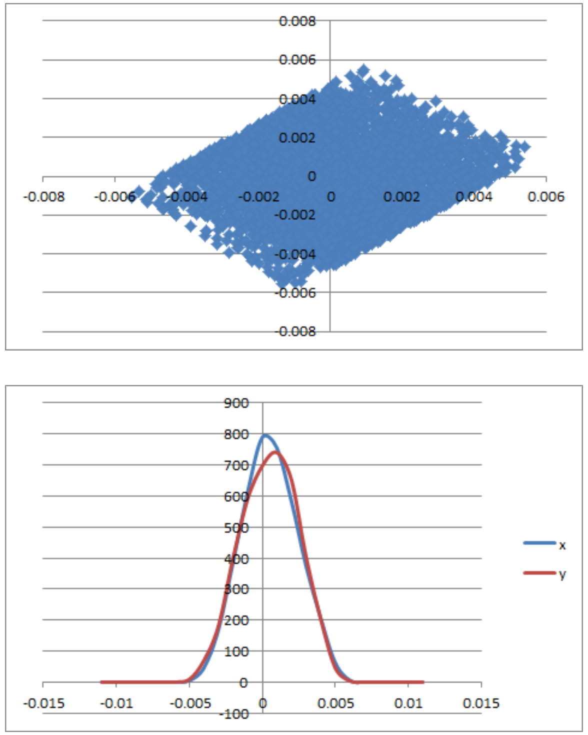
# Beam Rotation



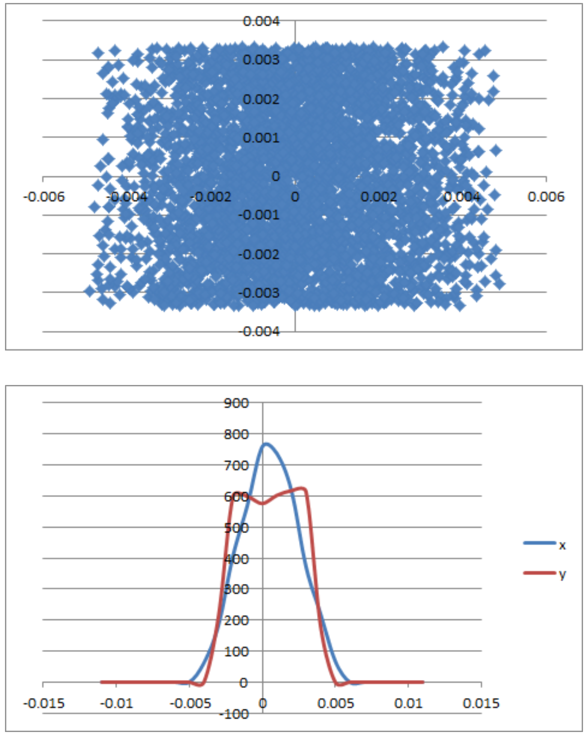

0°




20°




45°




90°

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# Sigma matching

Given a particle distribution we will call sigma matrix the covariance or better correlation matrix

Sigma Matrix

$$\sigma M = \begin{pmatrix} < x\,x > & < x\,x' > & < x\,y > & < x\,y' > \\ < x'\,x > & < x'\,x' > & < x'\,y > & < x'\,y' > \\ < y\,x > & < y\,x' > & < y\,y > & < y\,y' > \\ < y'\,x > & < y'\,x' > & < y'\,y > & < y'y' > \end{pmatrix}$$

When the beam is transported through (a system described by) a transfer matrix TM, then the sigma matrix transforms according to

$$\sigma M_f = TM.\sigma M_i.TM^T$$

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Assume uncorrelated beam

$$\sigma M = \begin{pmatrix} <\mathrm{x\,x}> & <\mathrm{x\,x'}> & 0 & 0 \\ <\mathrm{x'\,x}> & <\mathrm{x'\,x'}> & 0 & 0 \\ 0 & 0 & <\mathrm{y\,y}> & <\mathrm{y\,y'}> \\ 0 & 0 & <\mathrm{y'\,y}> & <\mathrm{y'y'}> \end{pmatrix}$$

$$= \begin{pmatrix} \sigma 11 & \sigma 12 & 0 & 0 \\ \sigma 21 & \sigma 22 & 0 & 0 \\ 0 & 0 & \sigma 33 & \sigma 34 \\ 0 & 0 & \sigma 43 & \sigma 44 \end{pmatrix} = \begin{pmatrix} \sigma 11 & \sigma 12 & 0 & 0 \\ \sigma 12 & \sigma 22 & 0 & 0 \\ 0 & 0 & \sigma 33 & \sigma 34 \\ 0 & 0 & \sigma 34 & \sigma 44 \end{pmatrix}$$

$$\sigma M = \begin{pmatrix} \epsilon_{\mathrm{rms,x}}\beta_{\mathrm{x}} & -\epsilon_{\mathrm{rms,x}}\alpha_{\mathrm{x}} & 0 & 0 \\ -\epsilon_{\mathrm{rms,x}}\alpha_{\mathrm{x}} & \epsilon_{\mathrm{rms,x}}\gamma_{\mathrm{x}} & 0 & 0 \\ 0 & 0 & \epsilon_{\mathrm{rms,y}}\beta_{\mathrm{y}} & -\epsilon_{\mathrm{rms,y}}\alpha_{\mathrm{y}} \\ 0 & 0 & -\epsilon_{\mathrm{rms,y}}\alpha_{\mathrm{y}} & \epsilon_{\mathrm{rms,y}}\gamma_{\mathrm{y}} \end{pmatrix}$$

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# Transport through a rotated gantry

Rotation matrix

$$RM = \begin{pmatrix} \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] & 0 \\ 0 & \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] \\ -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] & 0 \\ 0 & -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] \end{pmatrix}$$

Gantry transfer matrix

$$GM = \begin{pmatrix} \mathrm{g11} & \mathrm{g12} & 0 & 0 \\ \mathrm{g21} & \mathrm{g22} & 0 & 0 \\ 0 & 0 & \mathrm{g33} & \mathrm{g34} \\ 0 & 0 & \mathrm{g43} & \mathrm{g44} \end{pmatrix}$$

$$\sigma M_f = GM.RM.\sigma M_i.RM^T.GM^T$$

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$$\sigma M_f = GM.RM.\sigma M_i.RM^T.GM^T$$

$$\begin{pmatrix} g11 & g12 & 0 & 0 \\ g21 & g22 & 0 & 0 \\ 0 & 0 & g33 & g34 \\ 0 & 0 & g43 & g44 \end{pmatrix} . \begin{pmatrix} \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] & 0 \\ 0 & \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] \\ -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] & 0 \\ 0 & -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] \end{pmatrix} . \begin{pmatrix} \sigma 11 & \sigma 12 & 0 & 0 \\ \sigma 21 & \sigma 22 & 0 & 0 \\ 0 & 0 & \sigma 33 & \sigma 34 \\ 0 & 0 & \sigma 43 & \sigma 44 \end{pmatrix} . \begin{pmatrix} \mathrm{Cos}[\theta] & 0 & -\mathrm{Sin}[\theta] & 0 \\ 0 & \mathrm{Cos}[\theta] & 0 & -\mathrm{Sin}[\theta] \\ \mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] & 0 \\ 0 & \mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] \end{pmatrix} . \begin{pmatrix} g11 & g21 & 0 & 0 \\ g12 & g22 & 0 & 0 \\ 0 & 0 & g33 & g43 \\ 0 & 0 & g34 & g44 \end{pmatrix}$$

Let’s evaluate some matrix element

$sM_f(1,1)=g11^2\ (\sigma 11\ \mathrm{Cos}[\theta]^2+\sigma 33\ \mathrm{Sin}[\theta]^2)+g11\ g12\ (\sigma 12\ \mathrm{Cos}[\theta]^2+\sigma 21\ \mathrm{Cos}[\theta]^2+\sigma 34\ \mathrm{Sin}[\theta]^2+\sigma 43\ \mathrm{Sin}[\theta]^2)+g12^2\ (\sigma 22\ \mathrm{Cos}[\theta]^2+\sigma 44\ \mathrm{Sin}[\theta]^2)$

$sM_f(3,3)=g33^2\ (\sigma 33\ \mathrm{Cos}[\theta]^2+\sigma 11\ \mathrm{Sin}[\theta]^2)+g33\ g34\ (\sigma 34\ \mathrm{Cos}[\theta]^2+\sigma 43\ \mathrm{Cos}[\theta]^2+\sigma 12\ \mathrm{Sin}[\theta]^2+\sigma 21\ \mathrm{Sin}[\theta]^2)+g34^2\ (\sigma 44\ \mathrm{Cos}[\theta]^2+\sigma 22\ \mathrm{Sin}[\theta]^2)$



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# Beam size independent of rotation angle

$sM_f(1,1)=g11^2\ (\sigma11\ Cos[\theta]^2+\sigma33\ Sin[\theta]^2)+g11\ g12\ (\sigma12\ Cos[\theta]^2+\sigma21\ Cos[\theta]^2+\sigma34\ Sin[\theta]^2+\sigma43\ Sin[\theta]^2)+g12^2\ (\sigma22\ Cos[\theta]^2+\sigma44\ Sin[\theta]^2)$

$sM_f(3,3)=g33^2\ (\sigma33\ Cos[\theta]^2+\sigma11\ Sin[\theta]^2)+g33\ g34\ (\sigma34\ Cos[\theta]^2+\sigma43\ Cos[\theta]^2+\sigma12\ Sin[\theta]^2+\sigma21\ Sin[\theta]^2)+g34^2\ (\sigma44\ Cos[\theta]^2+\sigma22\ Sin[\theta]^2)$

**Complete symmetry**: $\sigma11 = \sigma33$; $\sigma12 = \sigma34$; $\sigma22 = \sigma44$ that is same emittance and same Twiss parameters in the horizontal and vertical plane; in this case **the beam is in itself rotationally symmetric** and any gantry transfer matrix gives an angle independent result;

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# Beam size independent of rotation angle

$sM_f(1,1)=g11^2\ (\sigma11\ Cos[\theta]^2+\sigma33\ Sin[\theta]^2)+g11\ g12\ (\sigma12\ Cos[\theta]^2+\sigma21\ Cos[\theta]^2+\sigma34\ Sin[\theta]^2+\sigma43\ Sin[\theta]^2)+g12^2\ (\sigma22\ Cos[\theta]^2+\sigma44\ Sin[\theta]^2)$

$sM_f(3,3)=g33^2\ (\sigma33\ Cos[\theta]^2+\sigma11\ Sin[\theta]^2)+g33\ g34\ (\sigma34\ Cos[\theta]^2+\sigma43\ Cos[\theta]^2+\sigma12\ Sin[\theta]^2+\sigma21\ Sin[\theta]^2)+g34^2\ (\sigma44\ Cos[\theta]^2+\sigma22\ Sin[\theta]^2)$

**Round beam in (x, y)**: σ11 = σ33; then the beam size at the isocenter independent of the gantry angle is obtained imposing **g12 = 0 and g34 = 0**. The gantry matrix then looks like

$$GM = \begin{pmatrix} g11 & 0 & 0 & 0 \\ g21 & g22 & 0 & 0 \\ 0 & 0 & g33 & 0 \\ 0 & 0 & g43 & g44 \end{pmatrix} = \begin{pmatrix} g11 & 0 & 0 & 0 \\ g21 & 1/g11 & 0 & 0 \\ 0 & 0 & g33 & 0 \\ 0 & 0 & g43 & 1/g33 \end{pmatrix}$$

This is referred to as "**point-to-point**" optics, since particles with the same initial position in (x, y) end up in the same position independently of the initial divergence (x', y')

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# Beam size independent of rotation angle

$sM_f(1,1)=g11^2\ (\sigma11\ Cos[\theta]^2+\sigma33\ Sin[\theta]^2)+g11\ g12\ (\sigma12\ Cos[\theta]^2+\sigma21\ Cos[\theta]^2+\sigma34\ Sin[\theta]^2+\sigma43\ Sin[\theta]^2)+g12^2\ (\sigma22\ Cos[\theta]^2+\sigma44\ Sin[\theta]^2)$

$sM_f(3,3)=g33^2\ (\sigma33\ Cos[\theta]^2+\sigma11\ Sin[\theta]^2)+g33\ g34\ (\sigma34\ Cos[\theta]^2+\sigma43\ Cos[\theta]^2+\sigma12\ Sin[\theta]^2+\sigma21\ Sin[\theta]^2)+g34^2\ (\sigma44\ Cos[\theta]^2+\sigma22\ Sin[\theta]^2)$

**Round beam in (x', y')**: $\sigma22 = \sigma44$; then a beam size at the isocenter independent of the gantry angle is obtained imposing **g11 = 0 and g33 = 0**. The gantry matrix then looks like

$$GM = \begin{pmatrix} 0 & g12 & 0 & 0 \\ g21 & g22 & 0 & 0 \\ 0 & 0 & 0 & g34 \\ 0 & 0 & g43 & g44 \end{pmatrix} = \begin{pmatrix} 0 & g12 & 0 & 0 \\ -1/g12 & g22 & 0 & 0 \\ 0 & 0 & 0 & g34 \\ 0 & 0 & -1/g34 & g44 \end{pmatrix}$$

This is referred to as "**parallel-to-point**" optics, since particles with the same initial divergence (x', y') end up in the same position independently of the initial position (x, y)

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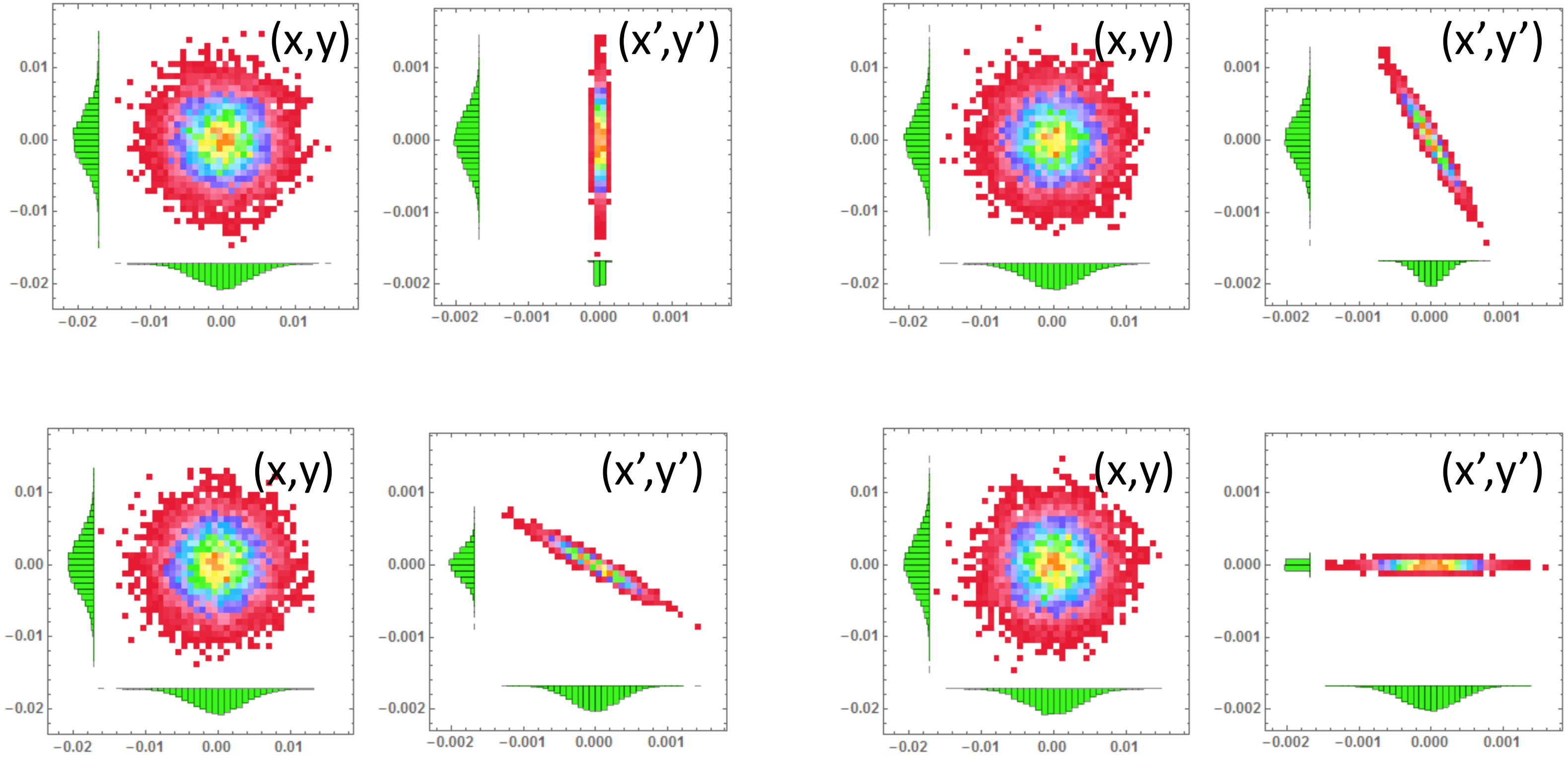
# Beam Rotation (point to point gantry)

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# Rotator

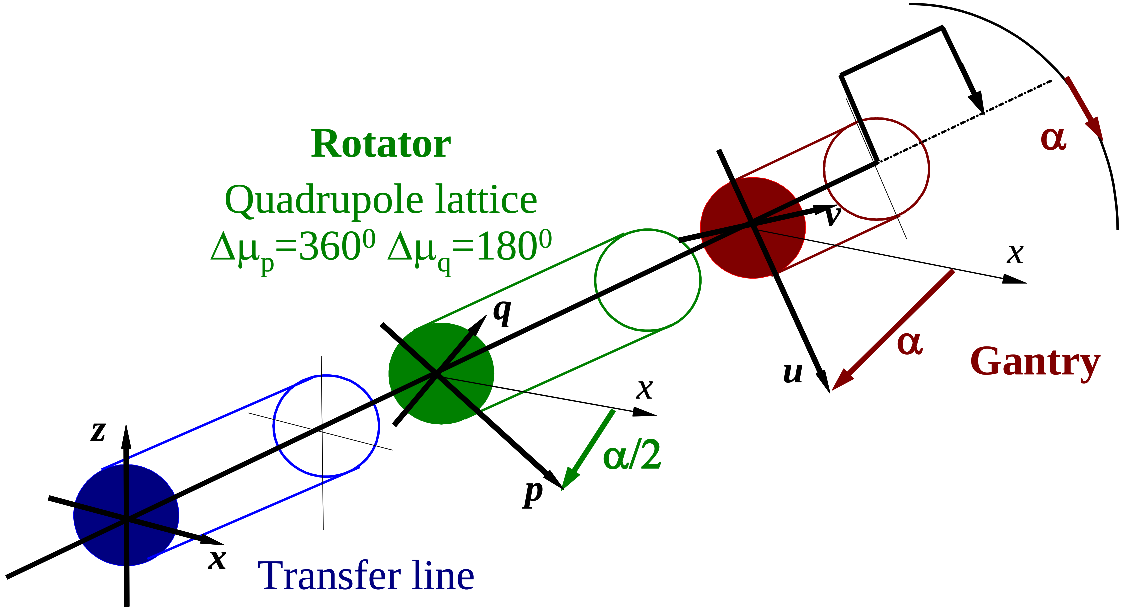
The rotator is a lattice with transfer function

It is rotated by half the gantry angle

$$RTM = \begin{pmatrix} r11 & r12 & 0 & 0 \\ r21 & r22 & 0 & 0 \\ 0 & 0 & -r11 & -r12 \\ 0 & 0 & -r21 & -r22 \end{pmatrix}$$

Historically/often

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

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# Rotator

When the rotator is rotated by half of the gantry angle, **it maps the incoming beam to the gantry rotated axes**, as shown by the matrix multiplication of: rotation (fixed line to rotator) times rotator times rotation (rotator to gantry). If the rotator is rotated by $\theta$ and the gantry by $2\theta$, then

$$\begin{pmatrix} \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] & 0 \\ 0 & \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] \\ -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] & 0 \\ 0 & -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] \end{pmatrix} . RTM . \begin{pmatrix} \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] & 0 \\ 0 & \mathrm{Cos}[\theta] & 0 & \mathrm{Sin}[\theta] \\ -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] & 0 \\ 0 & -\mathrm{Sin}[\theta] & 0 & \mathrm{Cos}[\theta] \end{pmatrix} = RTM$$

Which is independent of $\theta$, showing that an incoming particle enters into the gantry always in the same way (with the same initial coordinates in the gantry reference system) independently of the rotation angle.
The rotator **rotates also the dispersion** function and allows therefore to close the dispersion in the fixed part of the beamline.

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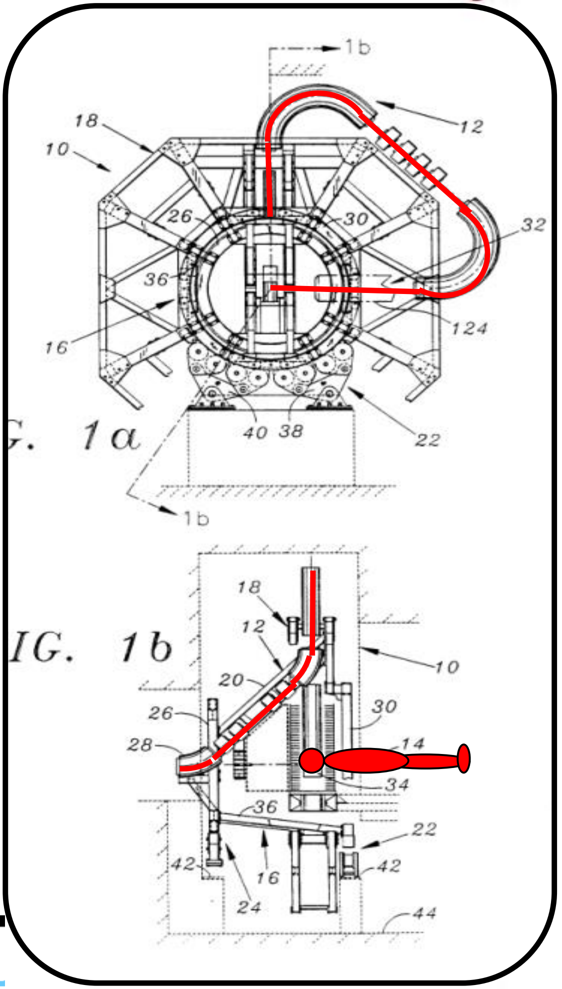
# Gantry overview

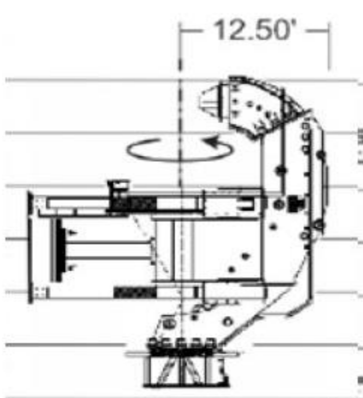
Heavy Ion Therapy Research Integration

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

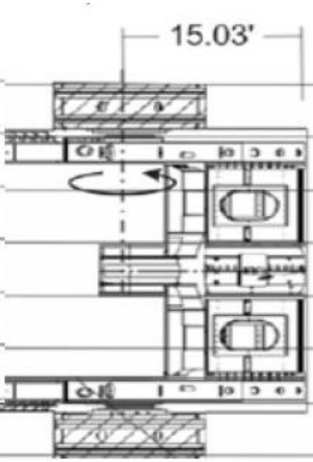
# Many geometries used



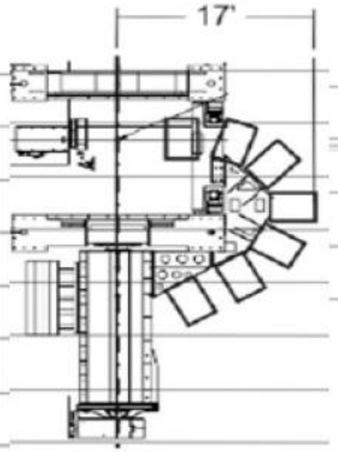

Corkscrew gantry at LLUMC



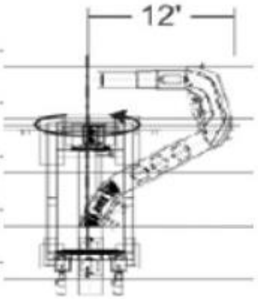

IBA Proteus One



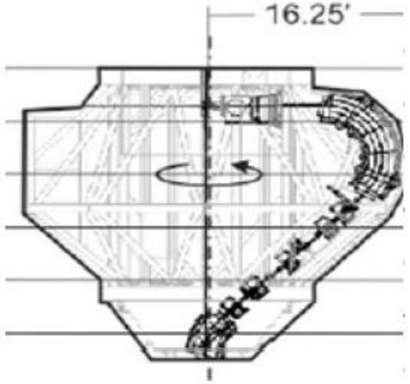

MeVIon



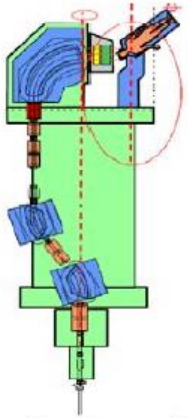

ProTom



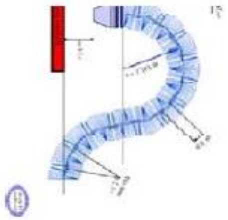

ProNova




IBA/SHI/ Hitachi In-Plane



PSI 1 shortest radius



FFAG is the lightest

(Adapted from a slide of J. Flanz)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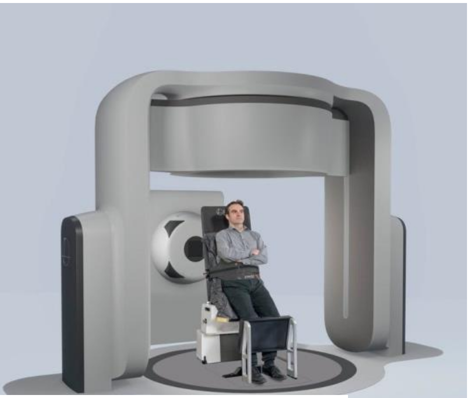
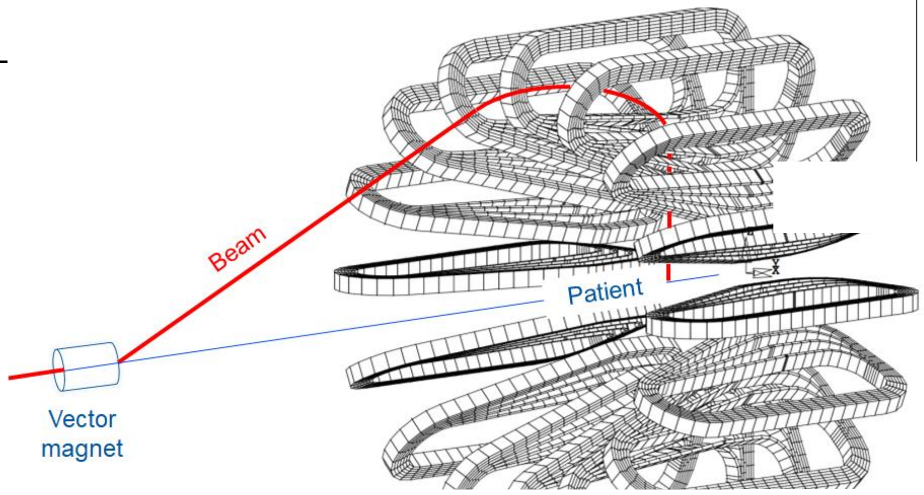
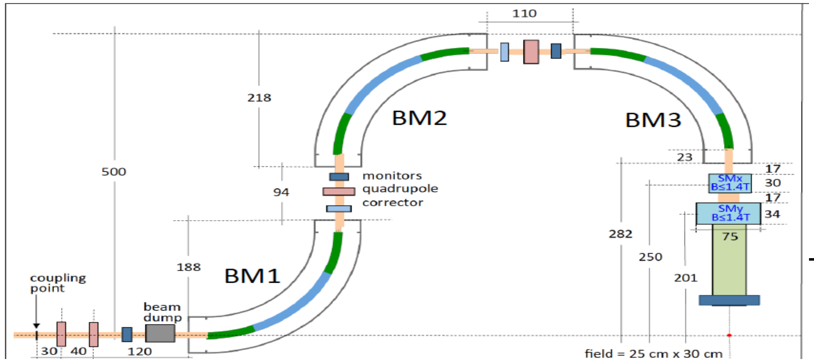
# Alternative designs and large momentum acceptance



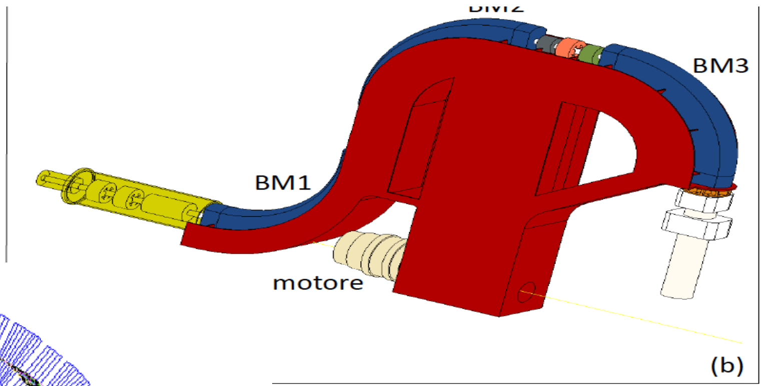
Leo cancer care

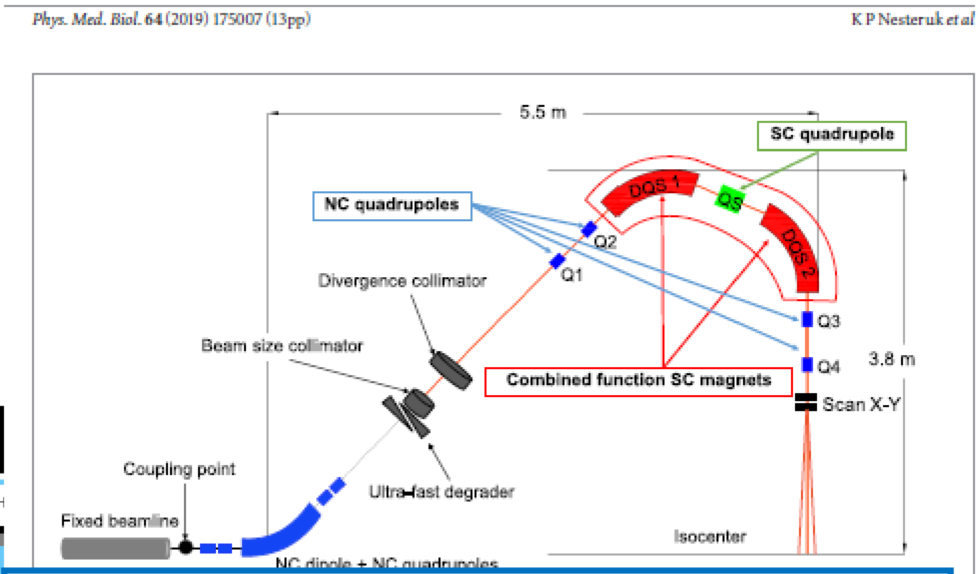



Toroidal magnet SC design (L. Bottura)

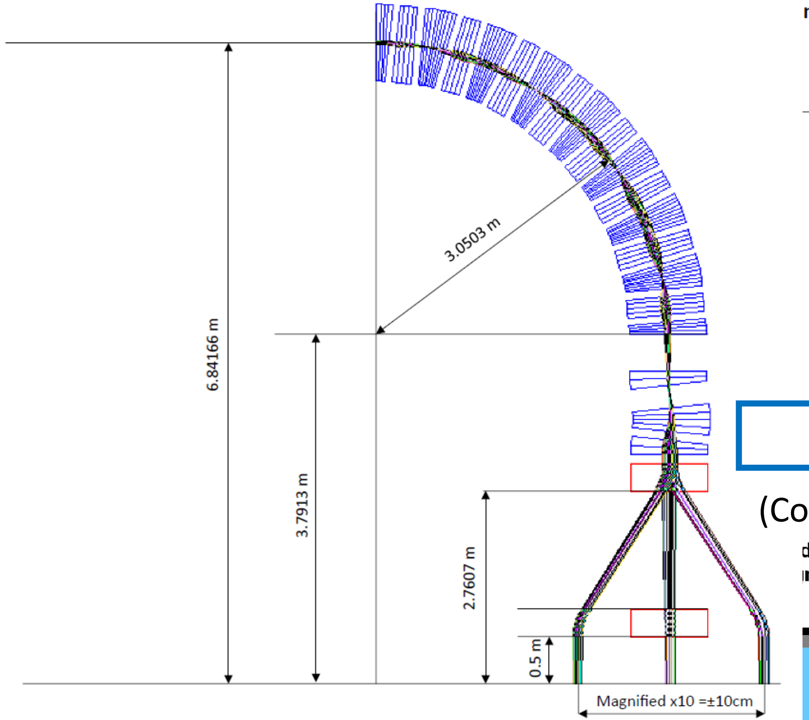



**TERA-CERN-LBNL (SC canted cosine theta)**




**PSI (large acceptance SC magnet)**




**FFAG**

(Courtesy of Dejan Trbojevic)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# Proton gantries

Mitsubishi

Hitachi

IBA

Heavy Ion Therapy Research Integration

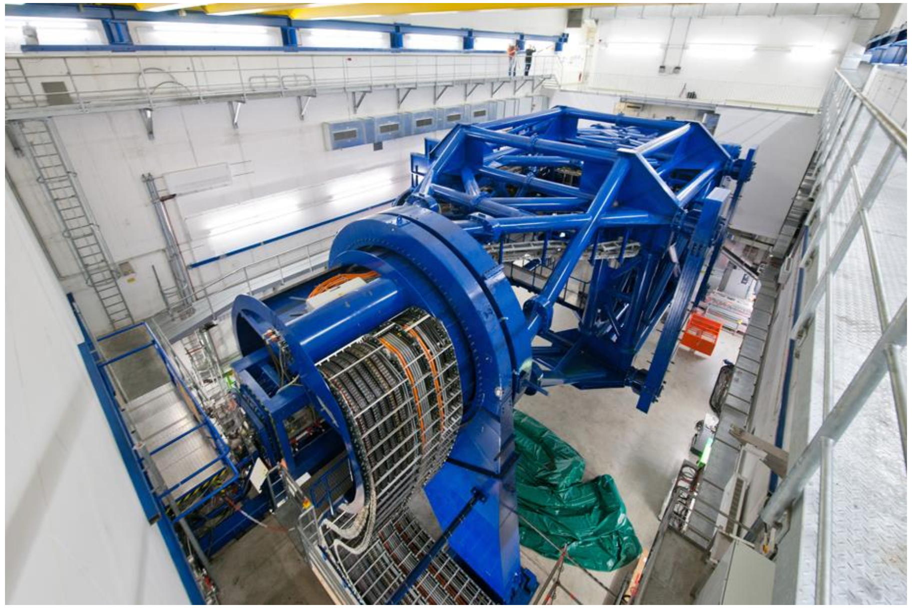
Horizon 2020
No 101008548

# Carbon Ion Gantries

The first one:

The HIT Gantry

L = 25 m x $\phi$ = 13 m,
600 t rotating mass



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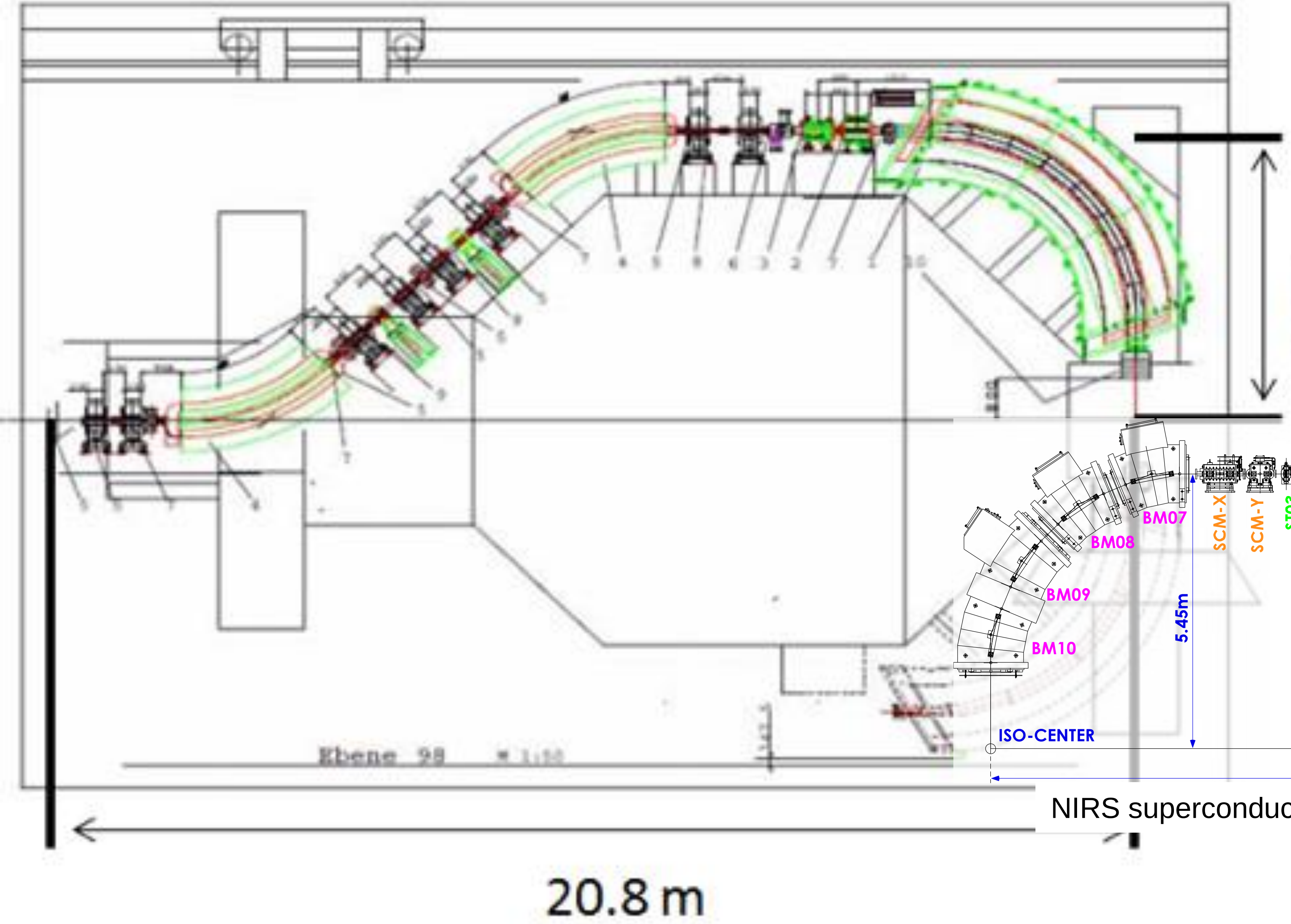
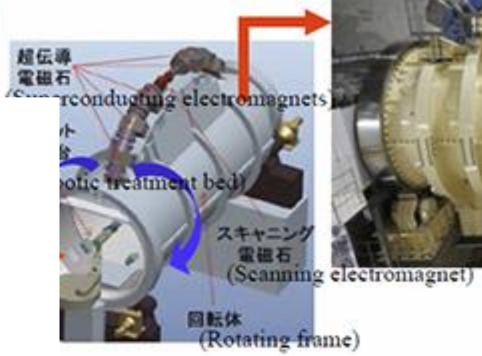
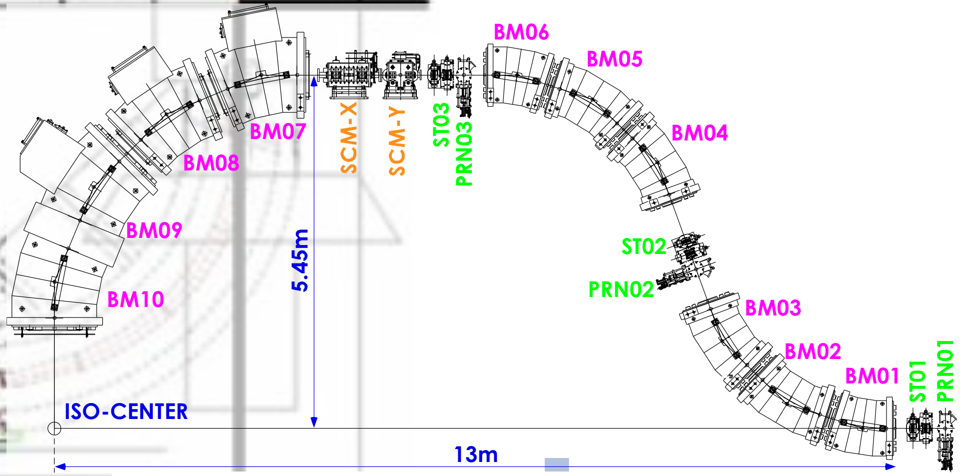
# HIMAC




NIRS superconducting rotating gantry

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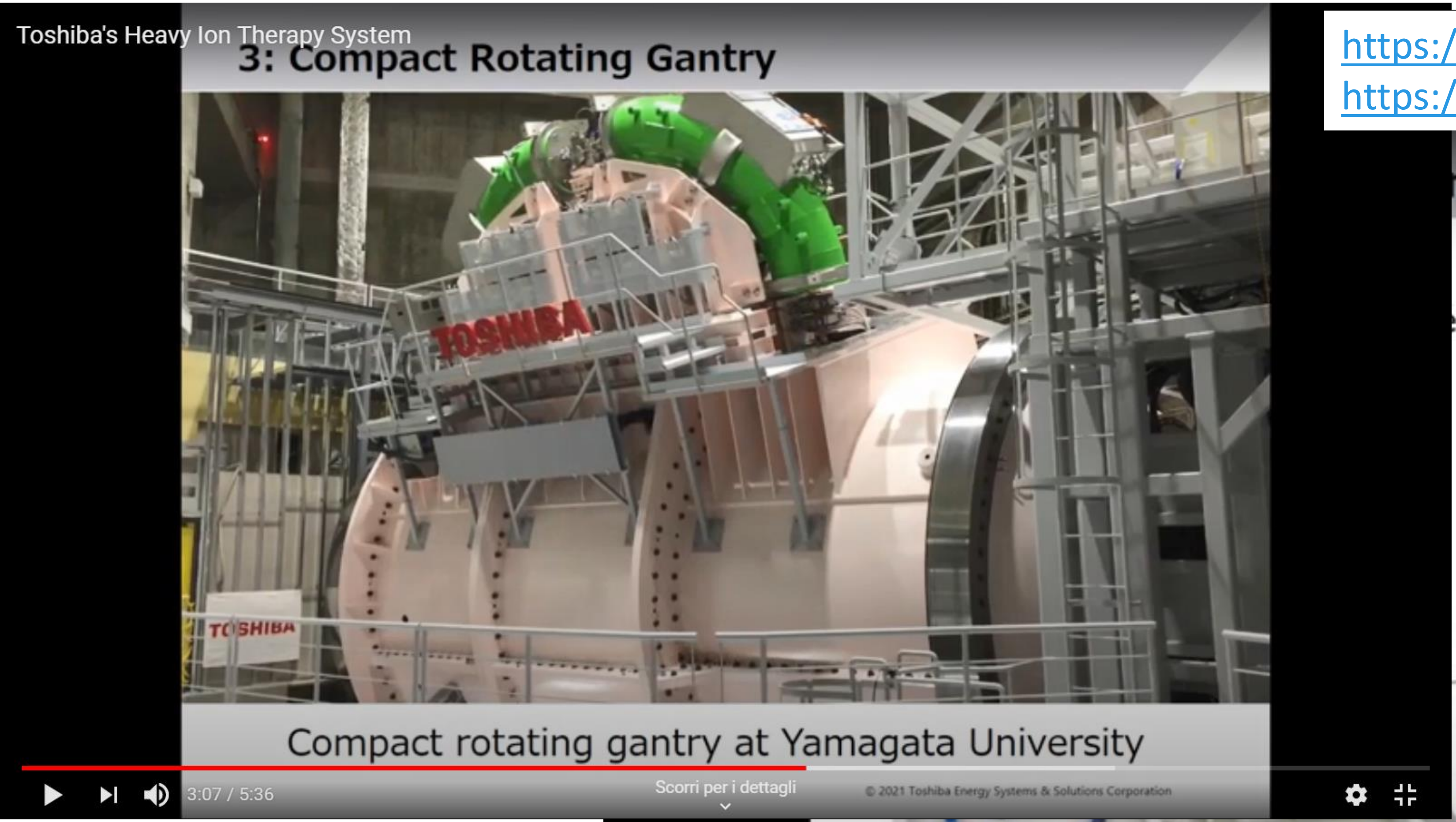
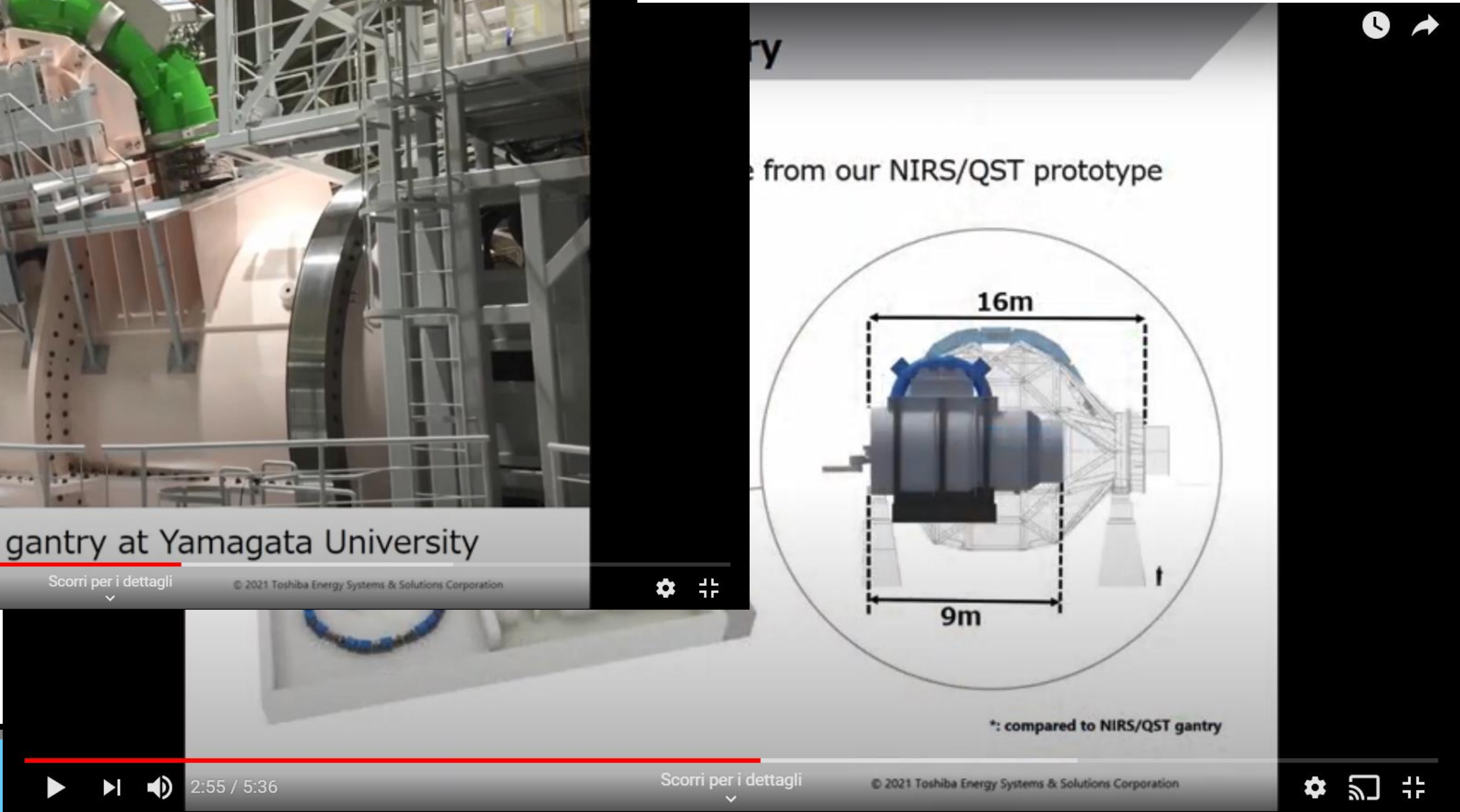
# Yamagata




https://www.youtube.com/watch?v=8mAkVcW2LtA
https://www.youtube.com/watch?v=iVTBzCBCY90



# Space around the isocenter

Patient size

Walk around patient

Imaging in situ

Couch rotation

Additional, future instrumentation

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)

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# Field size

Area that can be irradiated

Trade off between performace and gantry cost/size

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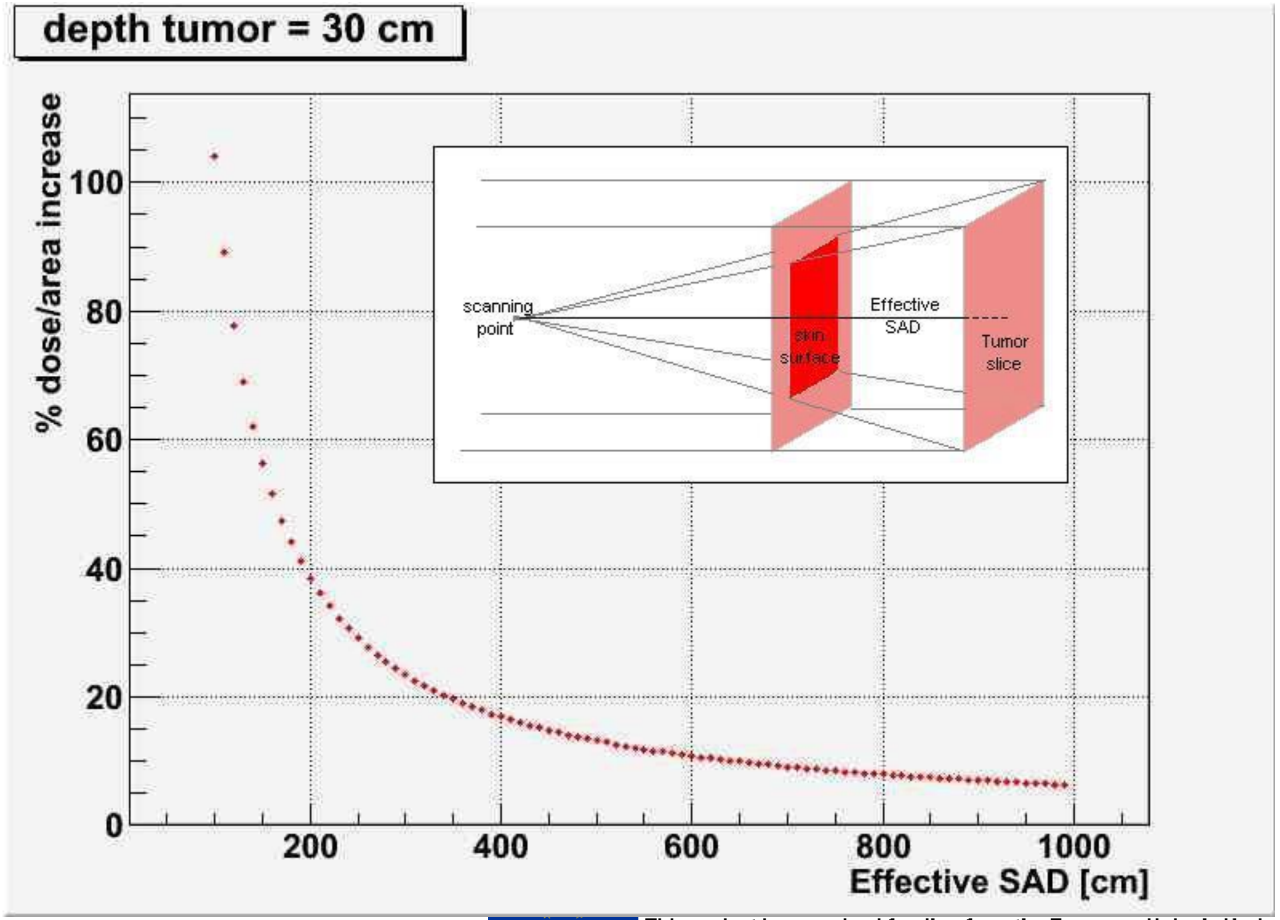
# SAD

SAD - Source to Axis Distance

Dose increase to the skin

(which is a radiosensitive organ)

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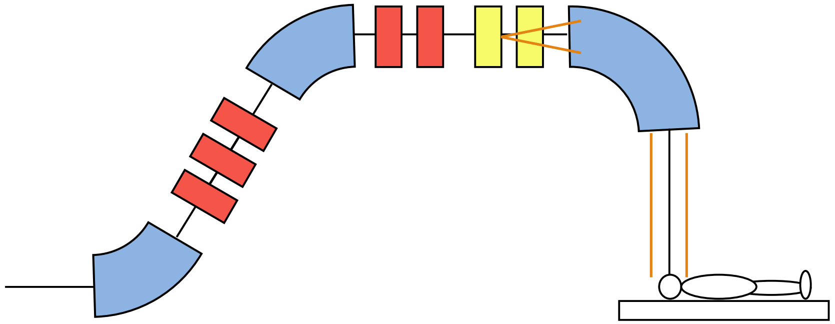
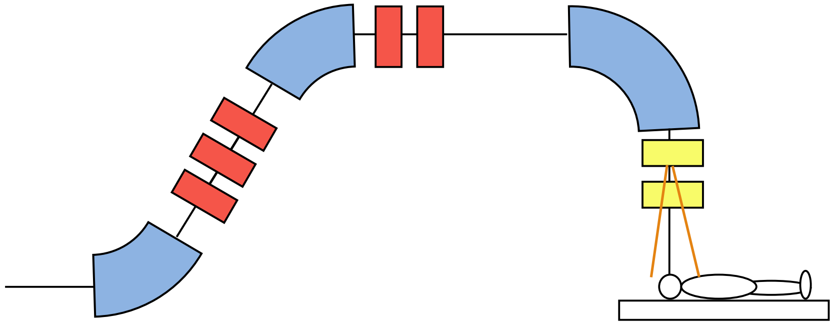
# Scanning magnets position



- **Large aperture dipole: weight and power consumption**
- **Parallel scanning**



- **Large gantry radius and large room size**

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# 180 vs 360

By rotating the couch by 180º, all the beam directions are possible also with only 180º 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”.

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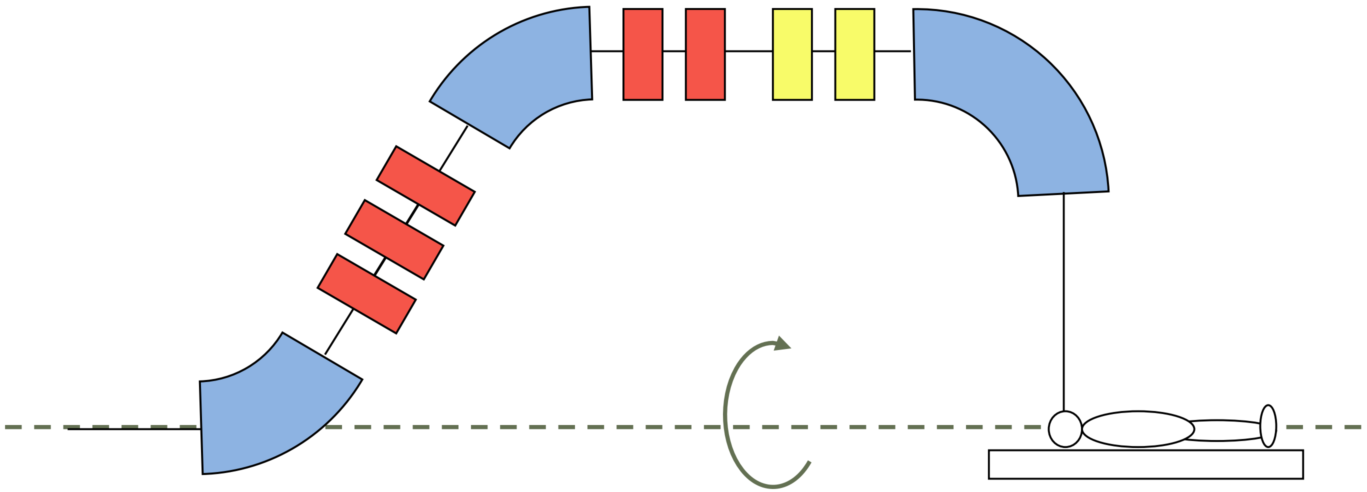
# Fixed or mobile isocenter

Most of the existing gantries have a fixed isocenter on the rotation axis of the gantry.  This implies large masses rotating at large radius.



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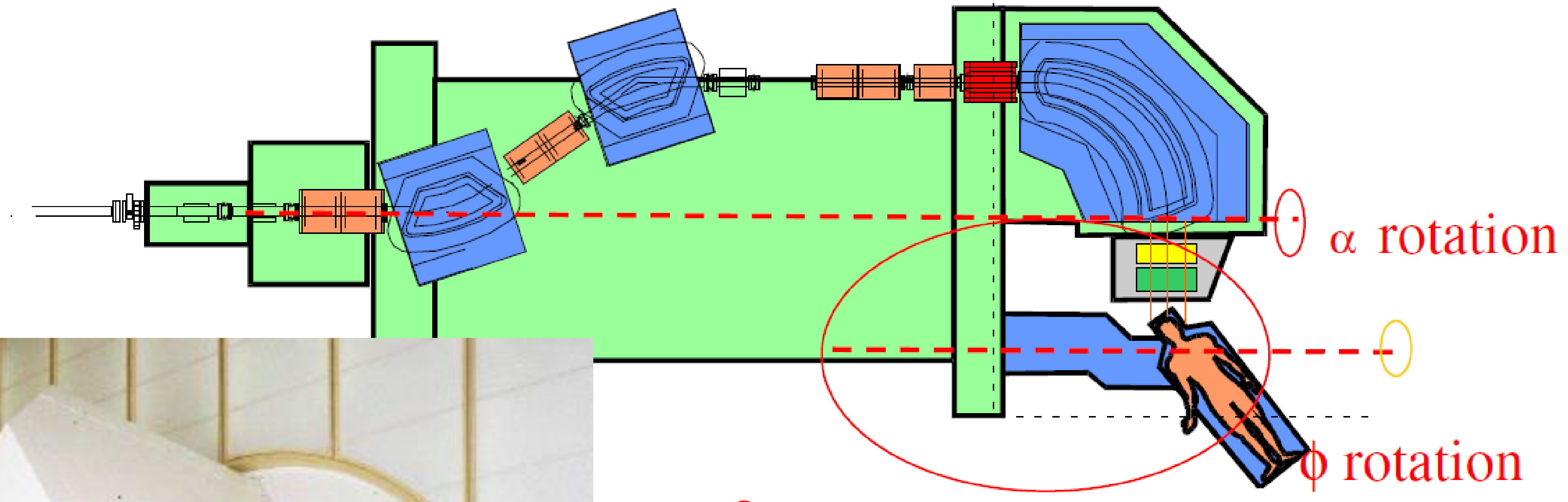
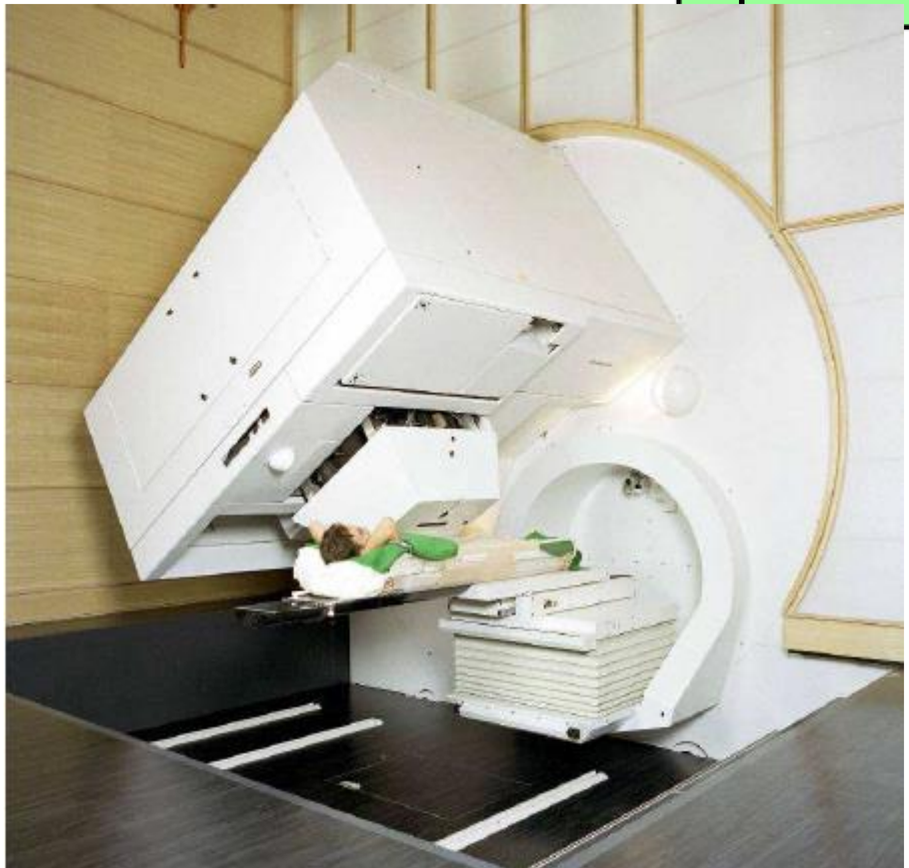
# PSI gantry 1




First scanning gantry worldwide



(Courtesy of *E. Pedroni*)

An isocenter, through which all the directions pass, exists but its position depends on gantry orientation.

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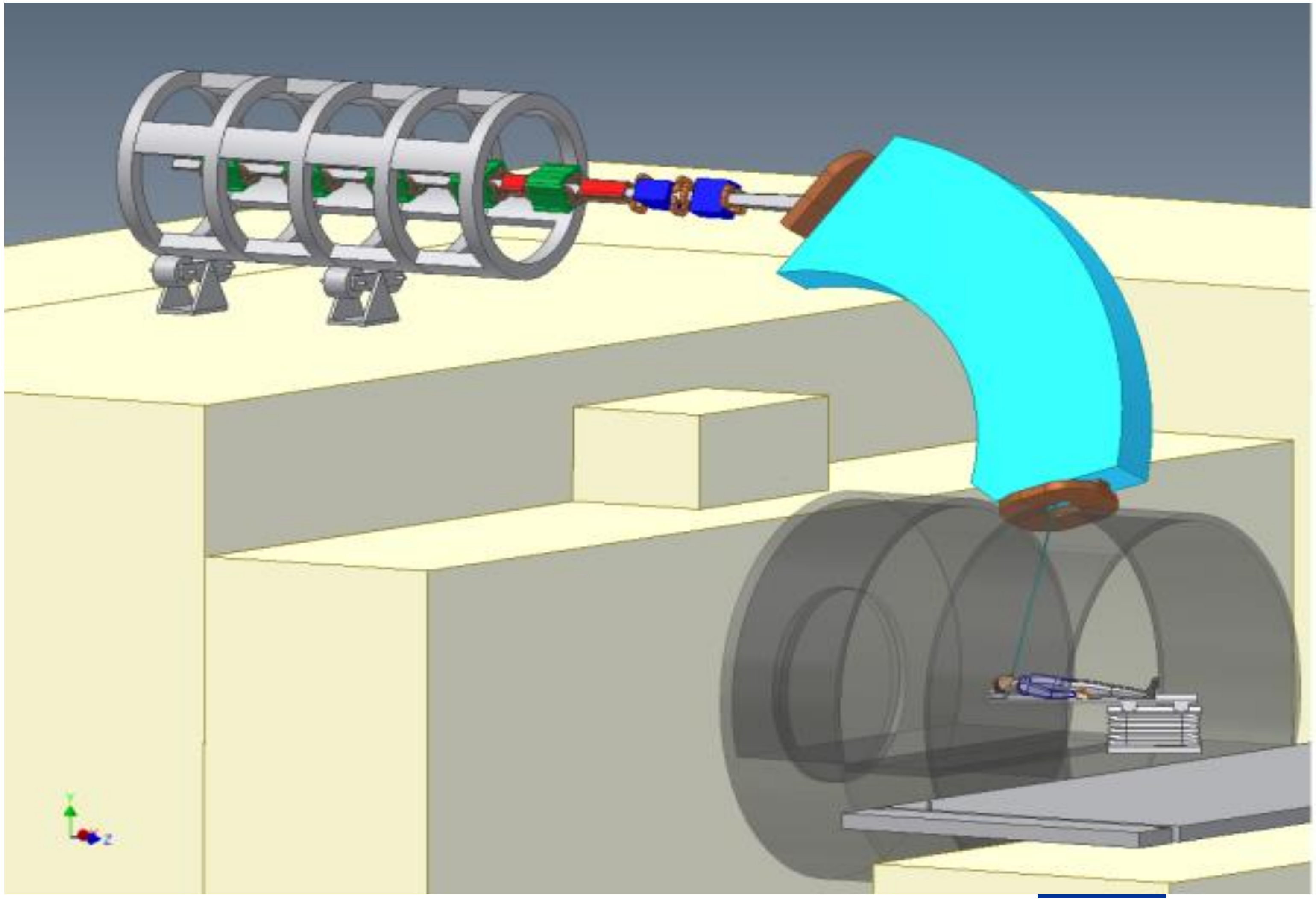
# “Riesenrad” gantry

ULICE Gantry

Dispersion is closed in the fixed line



90° bending magnet

Scanning magnets

Quadrupoles

Corrector magnets

Heavy Ion Therapy Research Integration

the European Union’s Horizon 2020
der grant agreement No 101008548

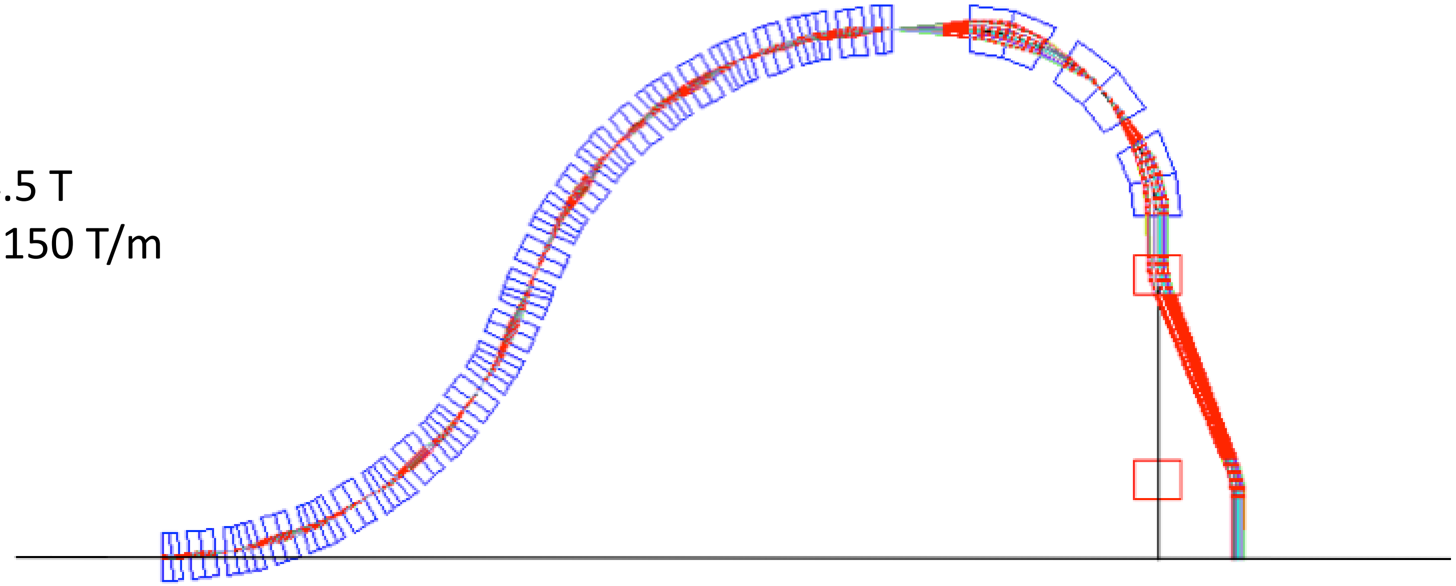
# FFAG

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

p 142 MeV
C 245 MeV

CARBON GANTRY height 4.091m

Bdip ~ 4.5 T
g up to 150 T/m



(Courtesy of Dejan Trbojevic)

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# Plenty of other aspects to consider

Magnet misalignment and corrections

Mechanical structure deformations

Integration, floor, access to patient

Patient positioning

Position verification

“Range” verification, In room imaging

Dose delivery

Scanning speed

Maintenance

Safety and many other aspects to consider in gantry design…

…

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# 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

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