# Progress report on JRA WP6

M. Pullia on behalf of the WP6 collaboration

# ULICE WP6 Cooperation

**Istituto Nazionale di Fisica Nucleare (INFN)**

ETOILE (France)

IFIC (Spain)

| Work package number | 6 | Start date or starting event: | | M1 |
|---|---|---|---|---|
| Work package title | Carbon Ion Gantry | | | |
| Activity Type | RTD | | | |
| Participant id | 1 CNAO | 4 CERN | 5 MEDA | 6 Etoile | 18 INFN |
| Person-months per beneficiary | 117 | 9 | 6 | 4 | 18 |

CERN (Switzerland)

CNAO (Italy)

GSI (Germany)

Universitaetsklinikum Heidelberg (Germany)

Karolinska Institutet (Sweden)

TERA (Italy)

IBA (Belgium)

EBG MedAustron (Austria)

## CNAO Partnership

- **Necchi Monica (100%)**
- **Savazzi Simone (100%)**
- **Viviani Claudio (100%);** from the 1st September 2010 substituted by **LanteValeria**
- **Osorio Moreno Jhonnatan (100%) – PARTNER** Project WP21

Involvement of industrial partners has been pursued, other institutional and academic partners are participating, as well, **totally for free**

The ULICE project is co-funded by the European Commission under FP7
Grant Agreement Number 228436.

# Firms involved

## Schär

They built the two **protons gantry at PSI** (Villigen)
**PPS** and **PVS** for the treatment rooms at **CNAO** (Pavia)

❖ feasibility of the mechanical structure of a mobile isocentre gantry
❖ dimensions equal to 2/3 with respect to a fixed isocentre gantry
❖ total structure cost 20% less than a fixed isocentre gantry

## MT Mechatronics

It is an experienced international specialist in designing and constructing turn-key precision mechatronics structures including drive control hard- and software. They built **the only** existing carbon ion **gantry** in **Heidelberg:** turn-key supply including development, engineering, fabrication, erection, measurement and adjustment, commissioning and test.

❖Critical issues discussion
❖ Inputs useful for the treatment cabin design
❖ Comparison of costs for the 3 different mechanical structures

## Kone

They have competences in special lifts (e.g. escalators and autowalks); they set the standard for safety, reliability, visual design, space savings and environmental performance. They revolutionized the elevator industry through their sustainable, energy-efficient designs.

❖Design and study for the platform and service lift system
❖ Cost estimate for the complete system

## iba

IBA has pioneered proton therapy. With proven efficacy in more than 50,000 patients worldwide, more than 50% of the world's PT clinical centres designed and equipped by IBA.
Their Universal Nozzle provides 4 delivery modes with millimetre precision, including Pencil Beam Scanning

❖Critical issues discussion
❖ Inputs useful for the treatment cabin design
❖ Technical details of gantries

# ULICE Gantry Design WP6

| | | |
|---|---|---|
| **Start Date** | M1 | |
| **End Date** | M36 | |
| **Lead Beneficiary** | CNAO | |
| **Effort** | Planned @M36: 117 m/m | @M36(Sep. 12): >117 m/m |
| **Deliverables Submitted** | JRA6.1 – "Functional specifications" (M9)<br>JRA6.2 – "Conceptual design of the gantry explaining the choices made" (M30) | |
| **Milestones** | **M9 (July 2010)**: A report describing the optimized functional specifications<br>**M30 (April 2012):** Conceptual design of the gantry explaining the choices made<br>**M36 (October 2012)**: Final design of the gantry describing the device, the design strategy and the performances achieved. It will include the papers published, the mechanical structure aspects that are considered to be more critical and some technical details concerning magnets and power supplies | |
| **Active Delays** | N.A. | |

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# First deliverable: functional specifications

1. **Online survey written with the collaboration of CNAO physicians**
2. **Answers collection and analysis**
3. **Definition of the functional specifications → First deliverable**

**June 2010**

| **Gantry functional specifications** | |
|---|---|
| Field size | 15 x 15 $cm^2$ or 10/15 x 20 $cm^2$ |
| Number of fields per session | 4 |
| Penetration depth (range) | 3 – 30 cm (corresponding energy: p = 60 - 220MeV; C ion = 120 – 430 MeV/u) |
| Voxel dose accuracy | ±1% |
| Dose uniformity | ±2.5% |
| Voxels characterization | 3 x 3 x 3 $mm^3$ |
| Voxels out of range | 1% |
| Field position accuracy | ±0.5 mm |
| SAD | 4 m |
| Maximum treatment time | 30 min |
| Required space around isocentre | 60 cm |
| Achieved beam directions | ALL |

***"Deliverable Report JRA6.1 – Functional specifications", June 2010***

# The second milestone: conceptual design of the gantry

**July 2010 – April 2012**

**Analysis of different gantry typologies**

- Fixed isocentre
- Mobile isocentre
  - PSI 1 - like
  - Riesenrad - like

**Magnets simulations**

- Conventional
- Superconducting
- FFAG

**Optics simulations**

- Comparison among the various optics layouts
- Optimization of the chosen beam line

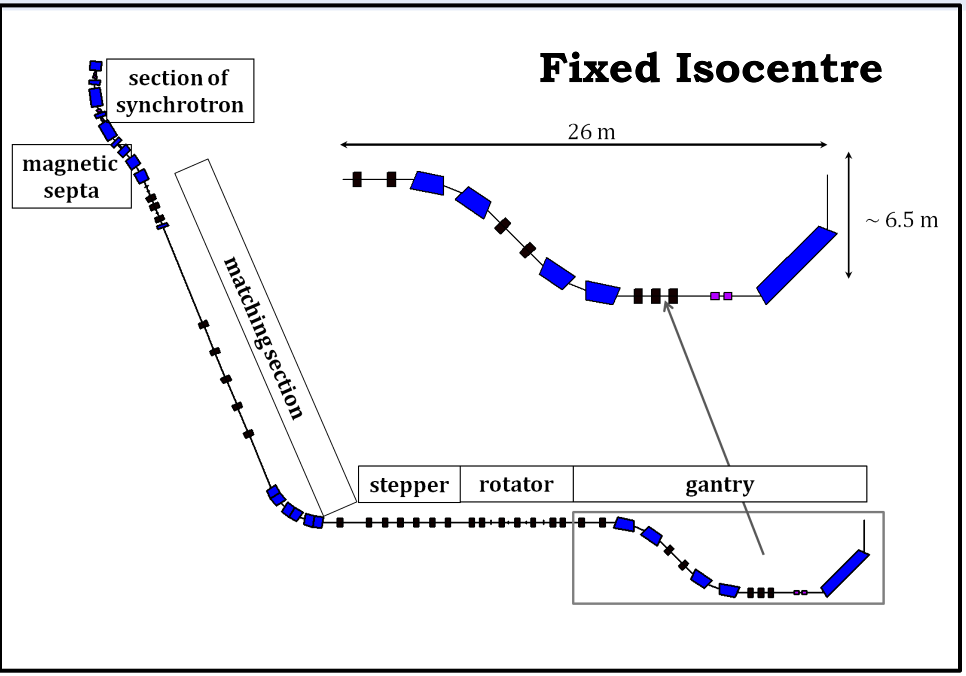
**Gantry building and mechanical structure**

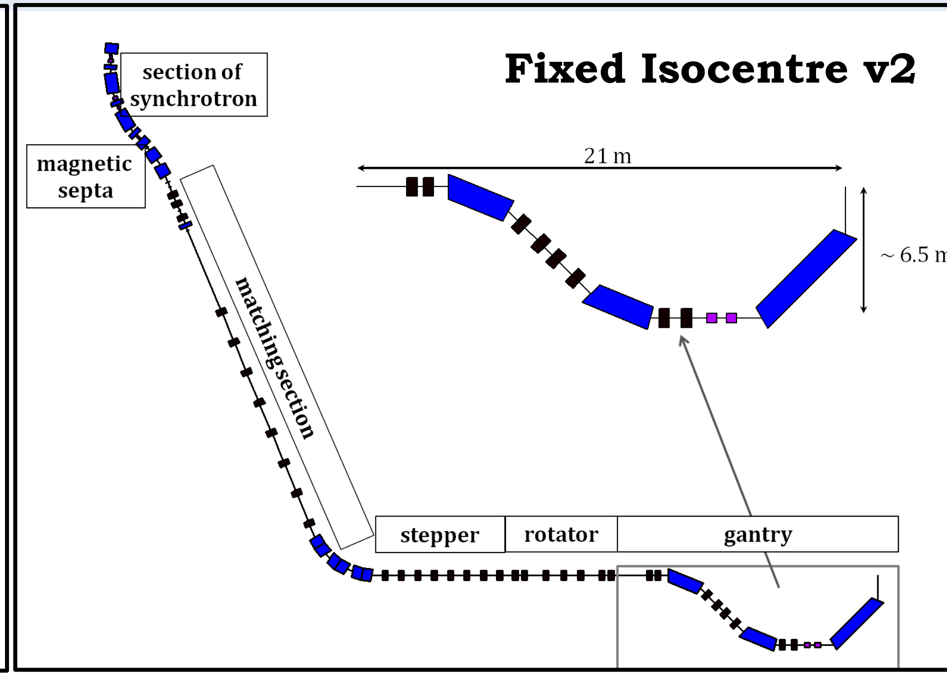
for the various layouts:

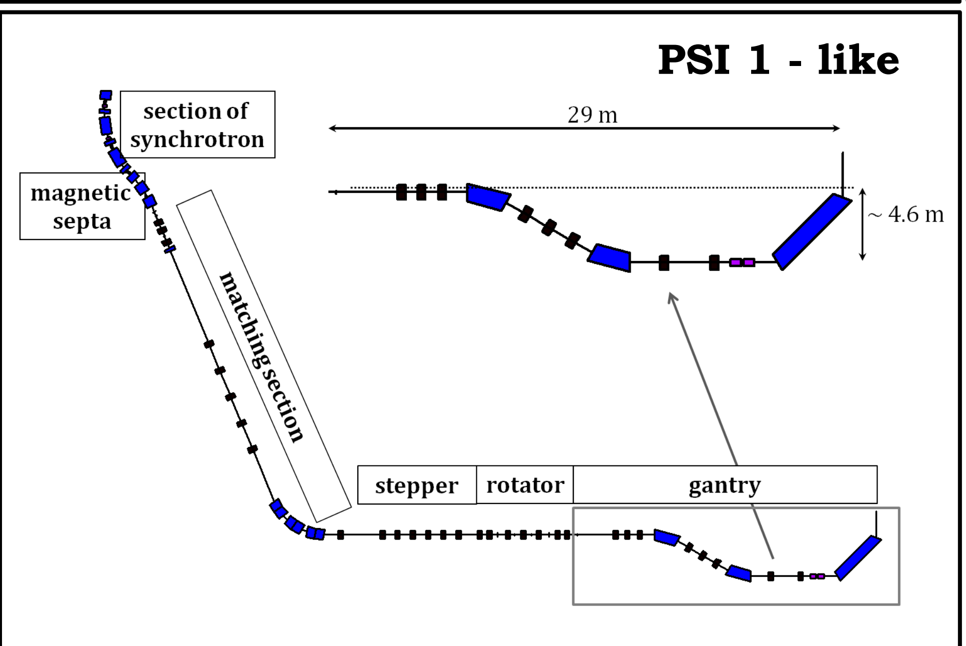
- Room dimensioning
- Preliminary shielding studies
- Sketchy mechanical structure designs
- Rough cost estimates

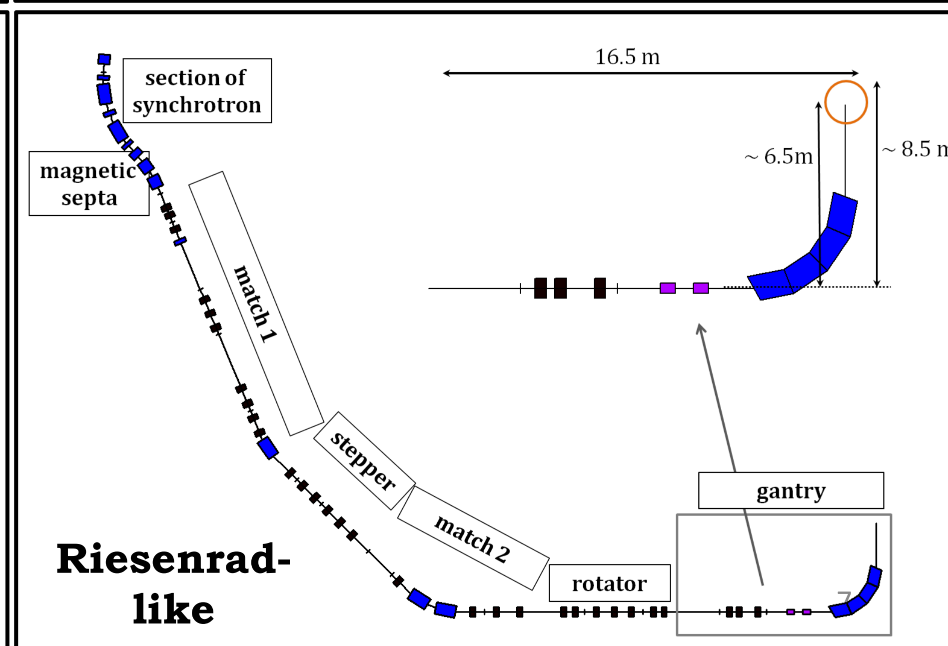
Optimization for the chosen gantry typology

# Some layouts in the CNAO area



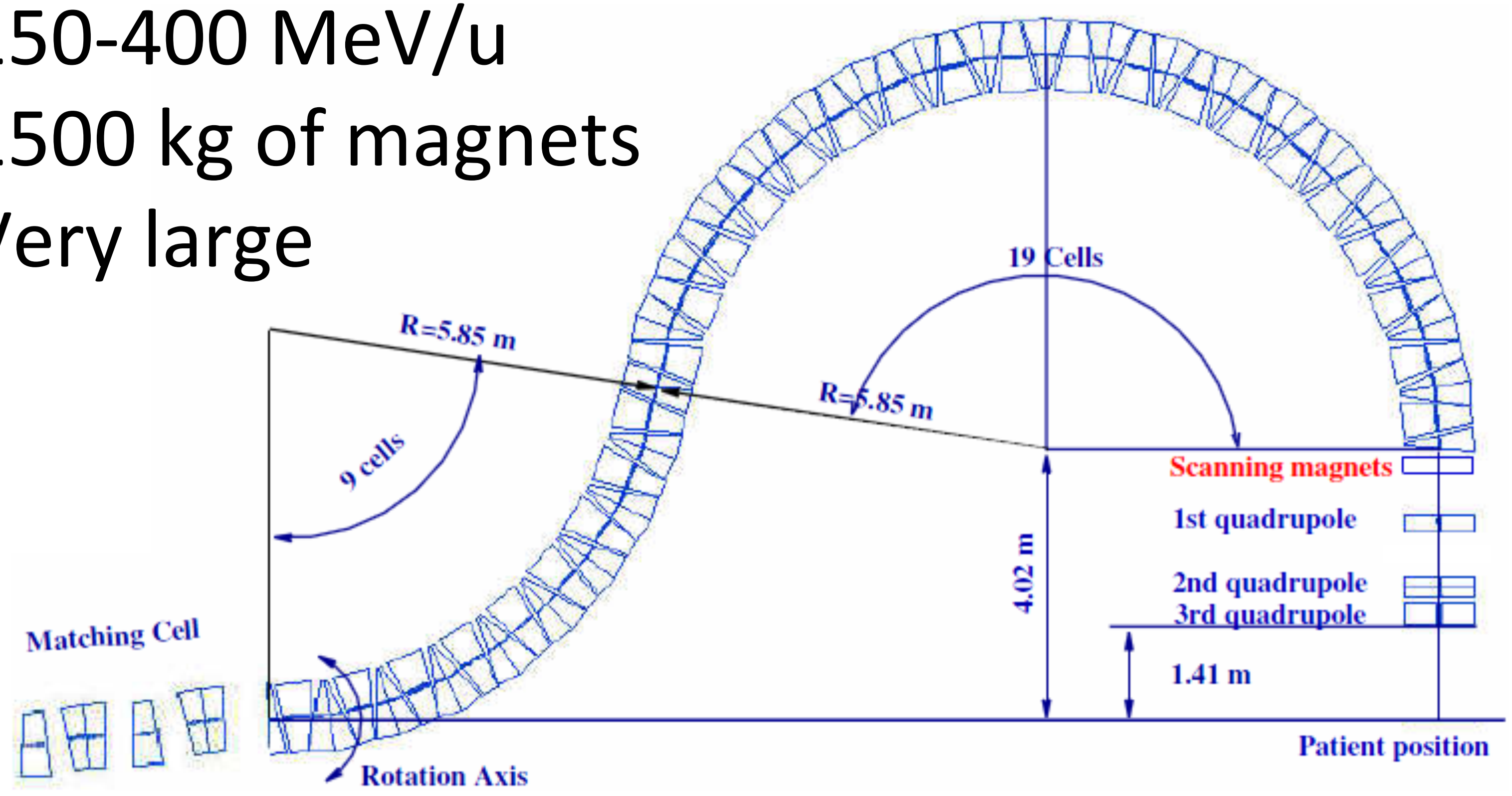



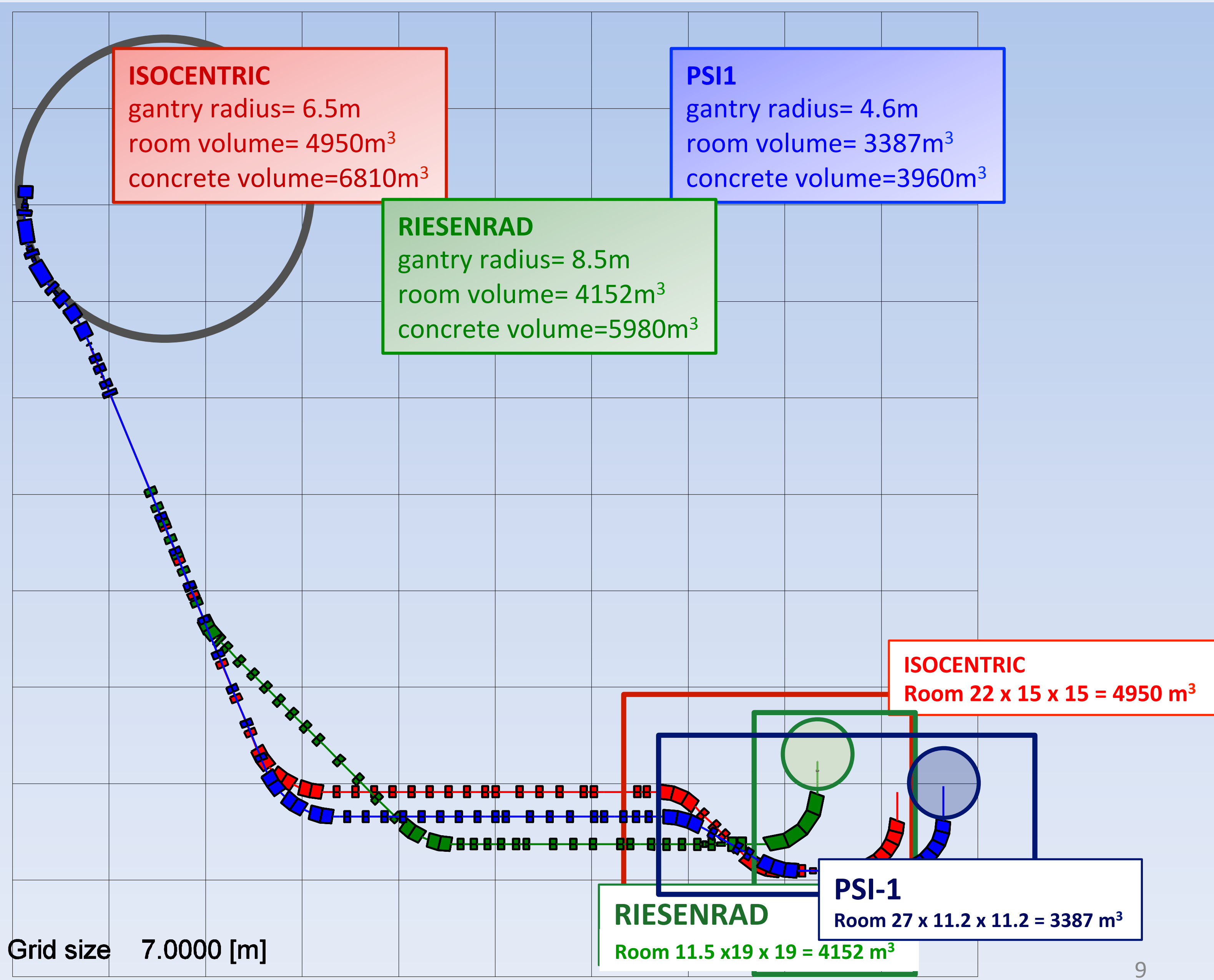



# FFAG Gantry

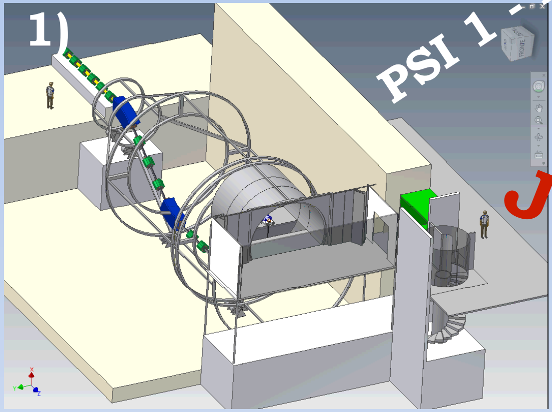
150-400 MeV/u
1500 kg of magnets
Very large

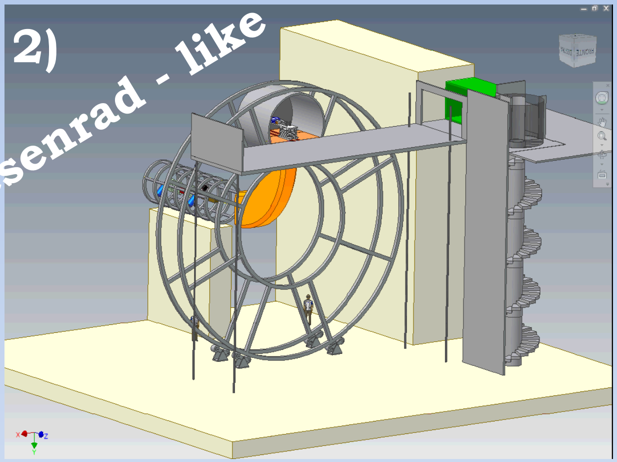


# Various layouts in the CNAO area



# Mobile isocentre gantries

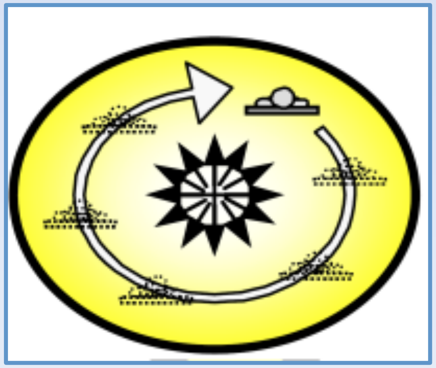


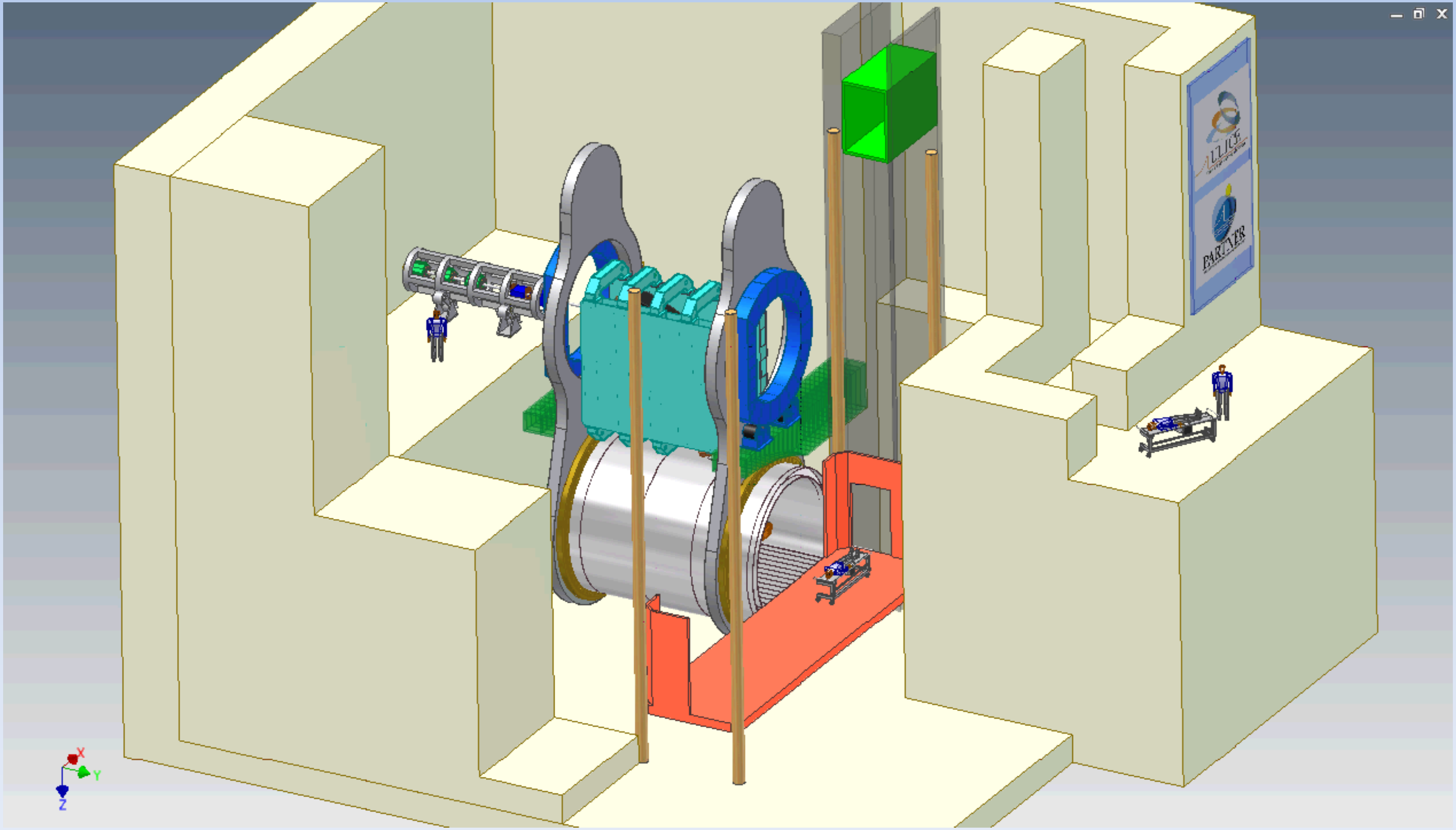




**July - December 2010**

Patient and magnets rotate around the central axis – smallest possible radius

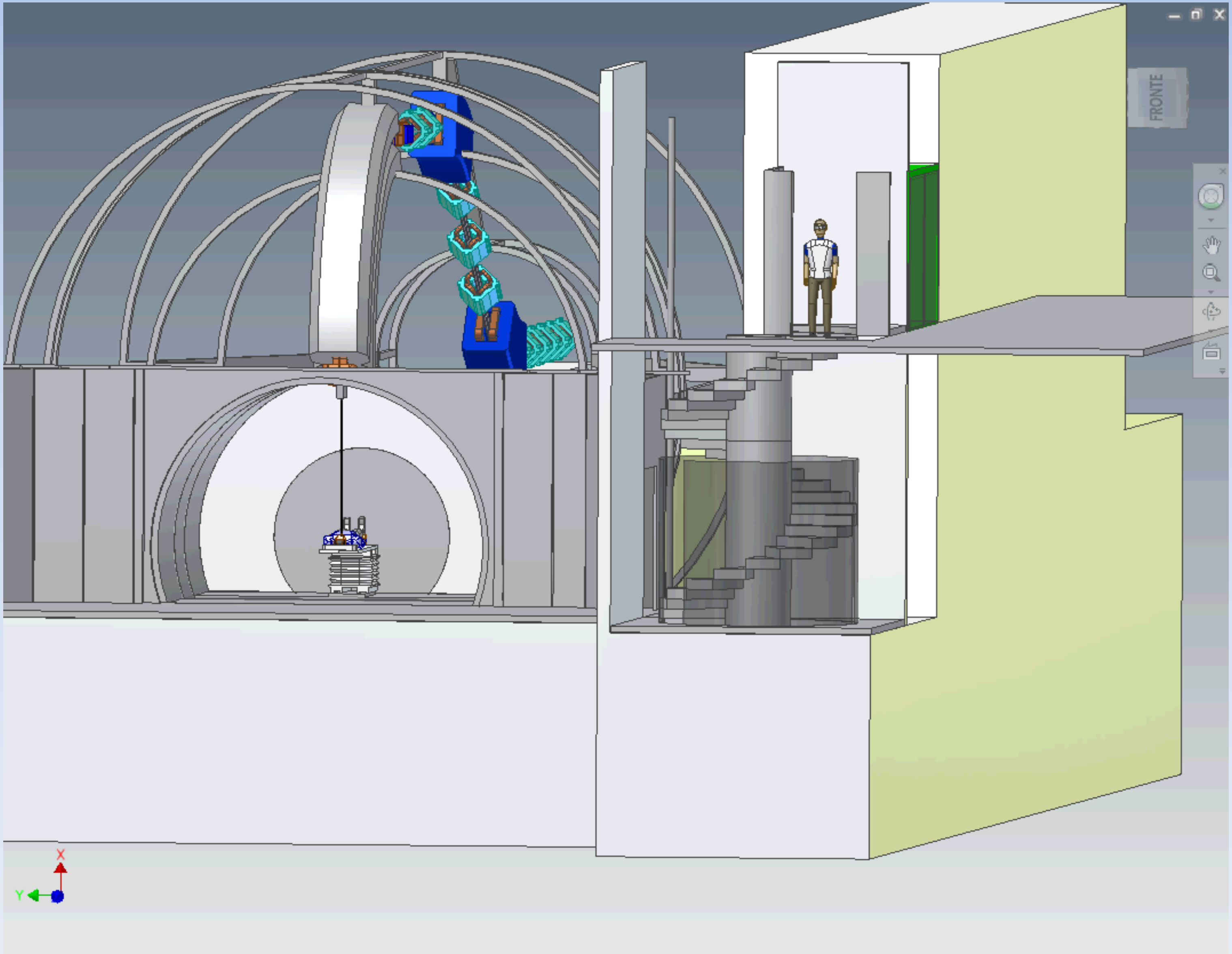
Isocenter moves according to the beam direction – only one 90° bending magnet, smallest possible momentum





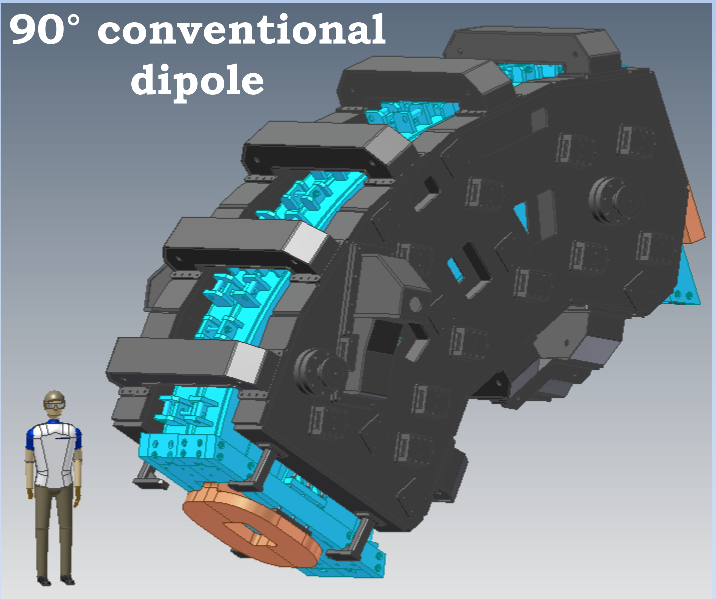
ALICE
PARTNER
X
Y
Z

# Access

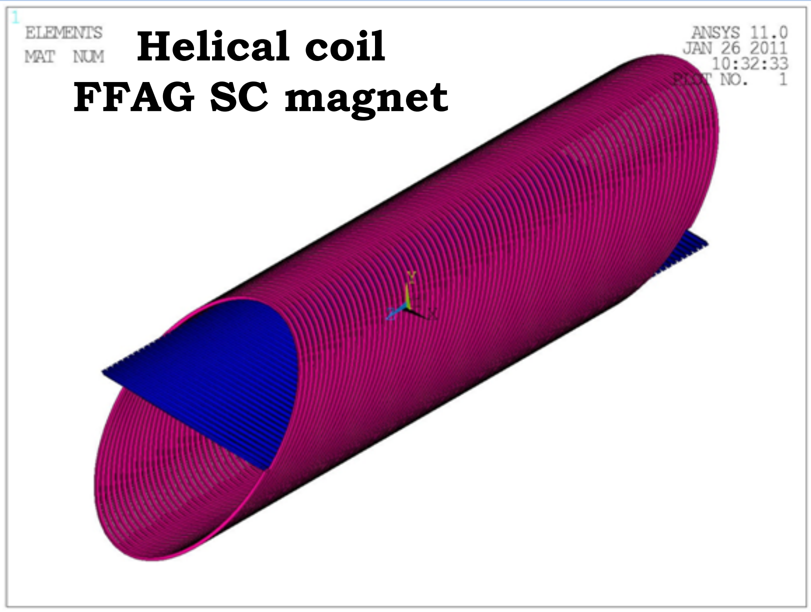


# Magnet analysis

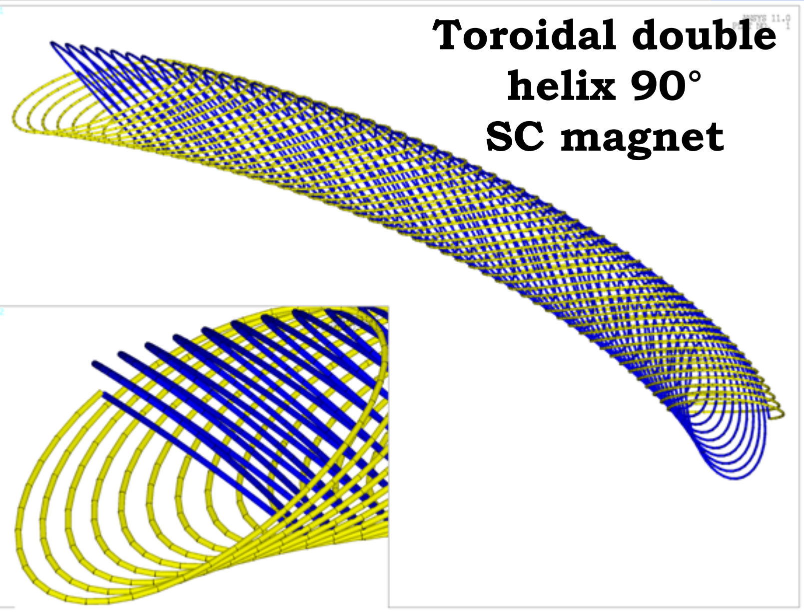
**since July 2010**



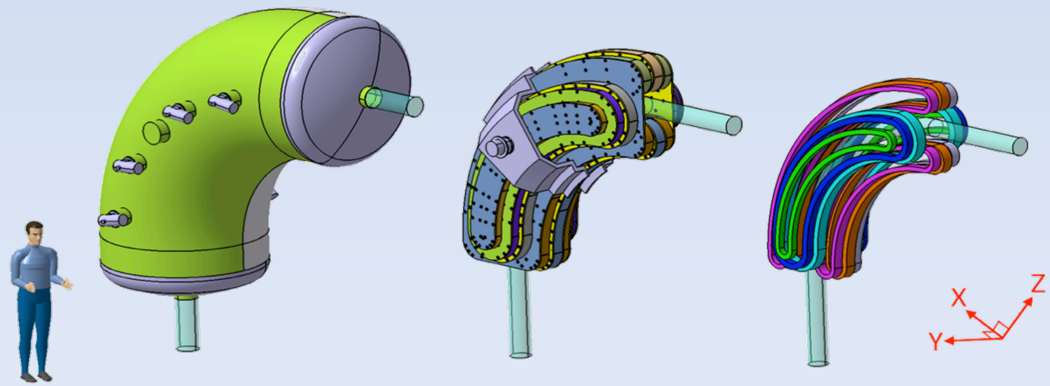
90° conventional dipole




Helical coil FFAG SC magnet



Toroidal double helix 90° SC magnet



# Conventional magnets
## 90° dipole

Comparison between the 90° bending magnet with reduced aperture (GRF 15 x 15 cm$^2$) and the reference 90° CNAO bending magnet (GFR 20 x 20 cm$^2$)

| | **GFR ( 15 x 15 cm$^2$)** | GFR ( 20 x 20 cm$^2$) |
|---|---|---|
| **Magnetic field [T]** | **1.814** | **1.87** |
| $\Delta B/B_0$ at GFR | [-0.58x10$^{-4}$, 1.375x10$^{-4}$] | [-0.8x10$^{-4}$, 1.03x10$^{-4}$] |
| Stored Energy [J] | 882227.24 | 1213924.48 |
| Inductance [H] | 0.26 | 0.47 |
| **Dissipated DC power [kW]** | **426.64** | **613.65** |
| DC voltage [V] | 164.1 | 269.16 |
| Inducted Voltage [V] | 150.6 | 236.8 |
| Feeding current[A] | 2600 | 2800 |
| Ampere-turns | 156000 | 182400 |
| **Magnet Weight [tons]** | **70** | **82** |

The (15 x 15 cm$^2$) reduced magnet gap allows to save approximately **10 tons** and to save **30%** of power consumption

# Price estimate: magnets

**March 2011**

| | Magnet typology | | | |
|---|---|---|---|---|
| **Feature** | **Conventional** **CNAO** | **SC** **Étoile** | **Iron dominated SC** **INFN Genova** | **FFAG helical coil** **INFN Genova** |
| **90° dipole weight (tons)** | 80 | 17(1) | 41 | not applicable |
| **90° dipole cost (M€)** | 1.5 | 1+1.3(2) | 2.5 - 3 | not applicable |
| **Overall bending dipoles (tons)** | 120 | | 41+2x16.5=74 | 3.5(3) + 5 cryostat |
| **Overall magnets line cost (M€)** | 1.9(4) | 3.0 (5) | 5 | 5 |

(1) Active shielding and cryostat included
(2) Magnet (1 M€), cryostat and cryocoolers (1 M€), PS, instrumentation and miscellaneous ((0.3 M€). Manpower included, except MP from labs.
(3) FFAG magnets are combined function magnets
(4) Four 22.5° dipoles, two scanning magnets
(5) 8 conv. quad, 2 conv. 45 d° dipole, 1 SC 90° dipole and 2 scanning magnets

# Price estimate: power supplies

March 2011

| | Power supply cost | | | |
|---|---|---|---|---|
| | **Conventional** CNAO | **SC** Étoile | **Iron dominated SC** INFN Genova | **FFAG helical coil** INFN Genova |
| **last bending magnet (k€)** | 400 | 125(1) | 500(2) | not applicable |
| **scanning magnets (k€)** | 2 x 90 | 2 x 80 | As for CNAO | As for CNAO |
| **for total magnet line (k€)** | 1100 + quads (3) | 700(4) | As for CNAO | 300 |

(1) 1 kA, 250 V, single quadrant, stability in the 1.E-4 range
(2) High cost in the order of 500 k€, 400 V - 1000 A ( for ramping at 0.2 T/s)
(3) PS cost for four 22.5° dipoles=4 x 130 k€, PS cost for single quadrupole=40 k€. Two quadrants PS considered.
(4) PS for quadrupoles included. Single quadrant PS considered.

# Price estimate: operational costs

March 2011

| | Power consumption (1 year) | | | |
|---|---|---|---|---|
| | **Conventional** CNAO | **SC** Étoile | **Iron dominated SC** INFN Genova | **FFAG helical coil** INFN Genova |
| **last bending magnet (k€)** | 165 MWh(1) | 110 MWh | 30 kW continuous + 100 MWh/year(2) | not applicable |
| **scanning magnets (k€)** | | N/A | | |
| **for total magnet line (k€)** | | 450MWh per year for cryocoolers | | 9 cryocoolers - 90 kW continuosly |

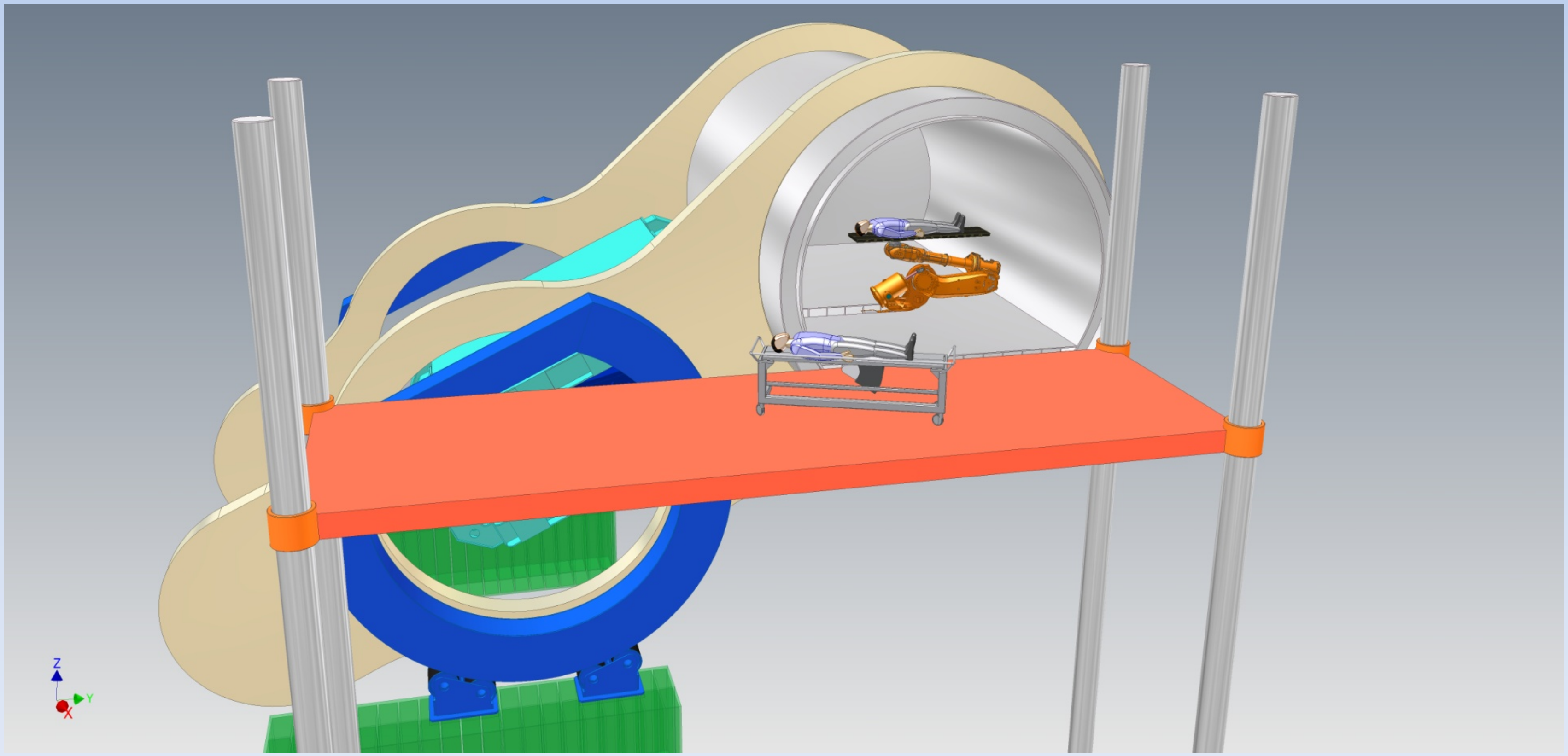
(1) $P_{ave}$=400KW, working days=330, working hours per day=10, using factor carbon ion gantry=0.25. Power dissipated ONLY ramping (half of the time).

(2) 3 cryocoolers + power supply active power

(3) During a treatment, magnets are used at 60% of their nominal rating (depth scanning)

# *March 2011: choice of typology*

The ULICE WP6 collaboration decided to realize the conceptual design of a **180°, normal conducting, mobile isocenter gantry, 20 x 20 cm$^2$ field**, revisiting the layout of the Riesenrad gantry investigated by the PIMMS



# Choice of the ULICE gantry layout

10th March 2011

## Reasons driving the choice

- Innovative layout
- Cheaper mechanical structure
- Design conceived for conventional magnets

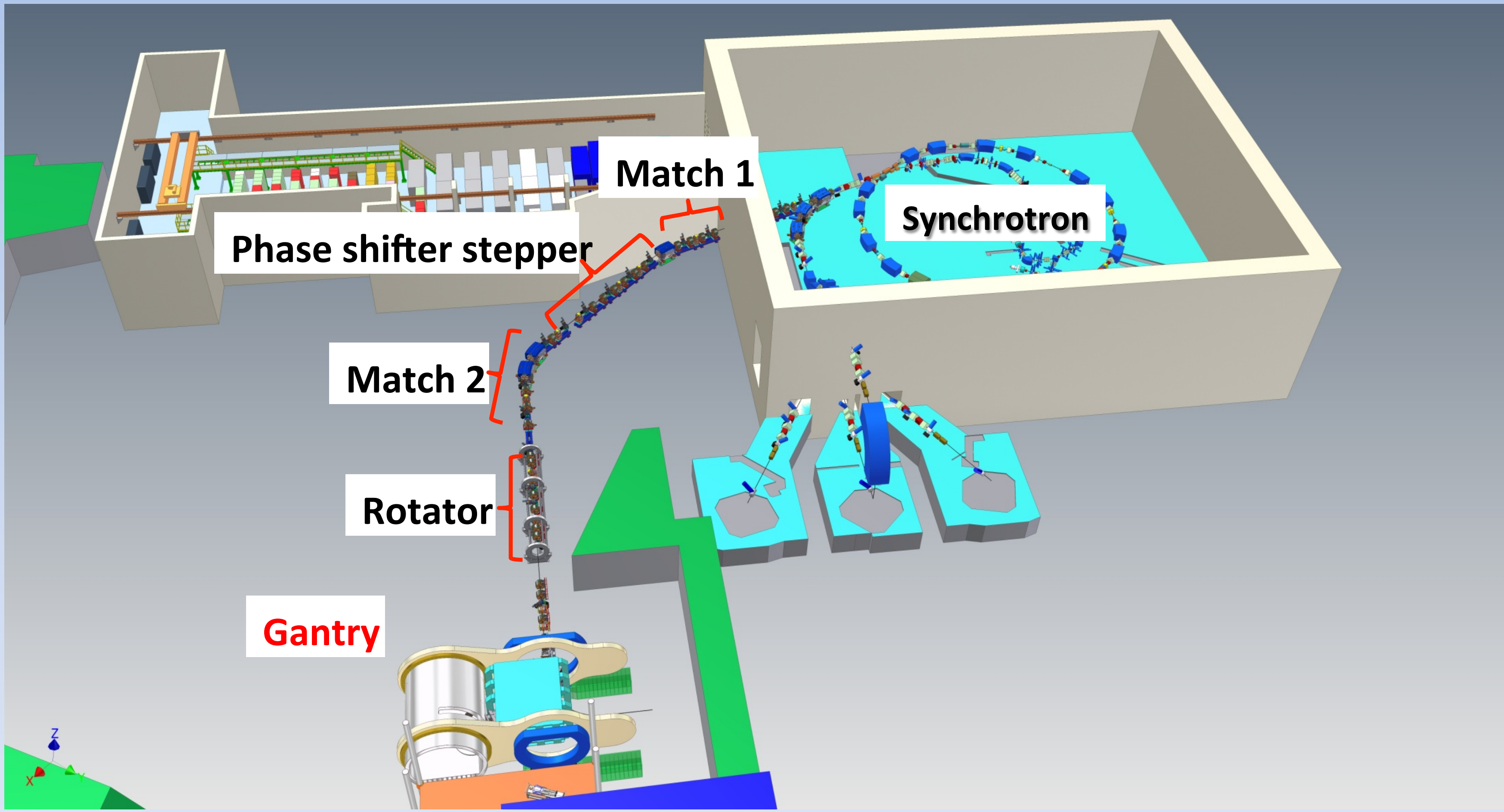
- Well known magnet technology
- Layout scalable to SC magnets
- Less magnets in the gantry line

| COSTS (M€) | Fixed isocenter | | | PSI-1 like | | | Riesenrad-like | | |
|---|---|---|---|---|---|---|---|---|---|
| Mechanical Structure | | 100% HIT | 120% Ries | 5,1 | 105% HIT | | 6,8 | 70% HIT | 11,5 |
| Civil works | 1,66 | | | 1,15 | | | 1,48 | | |

* Darimec Srl — MT- Mechatronics — Schär

*(considering mechanical structure ONLY!)

# Beam line




**Synchrotron**
- particle Beam source
- Initial beam conditions

→

**Match**
- Adjust the beam parameters to the following elemets

→

**Phase shifter stepper**
- Adjust the beam dimensions at the isocenter

→

**Telescope**
- Final Match
- Rotator
- Gantry

# Modular optics approach

- Phase shifter-stepper
- Telescopic match2+gantry section
- Rotator

$$\begin{pmatrix} x \\ x' \\ z \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ z_0 \\ z'_0 \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & -\sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & -\sin\theta & 0 & \cos\theta \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

# Optics studies: misalignments and corrections

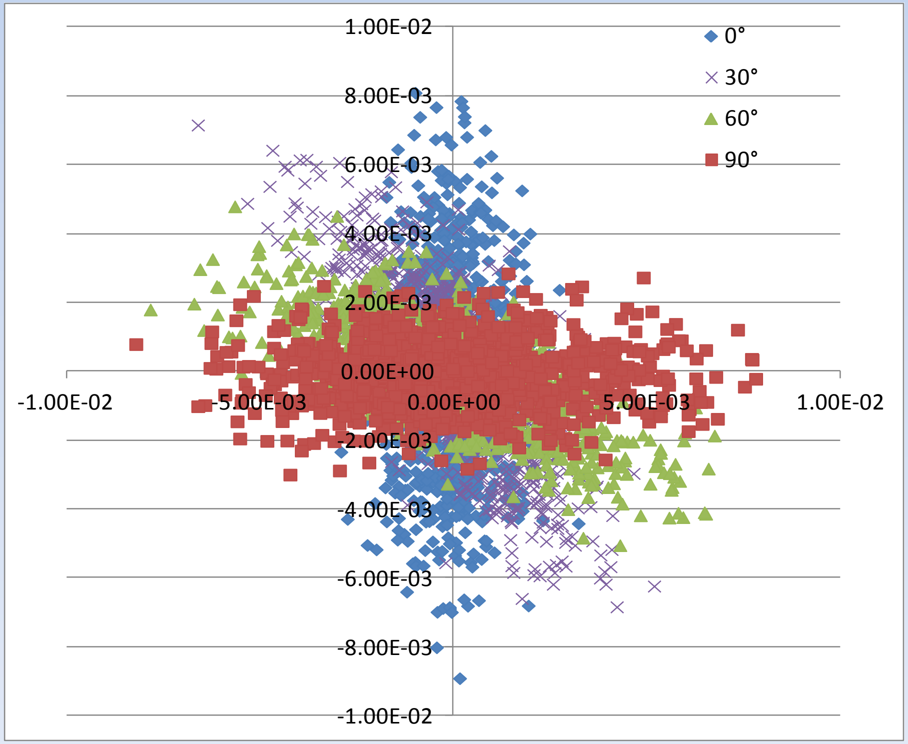
**Error sources**

- random misalignments
- structural deformations
- field excitation errors

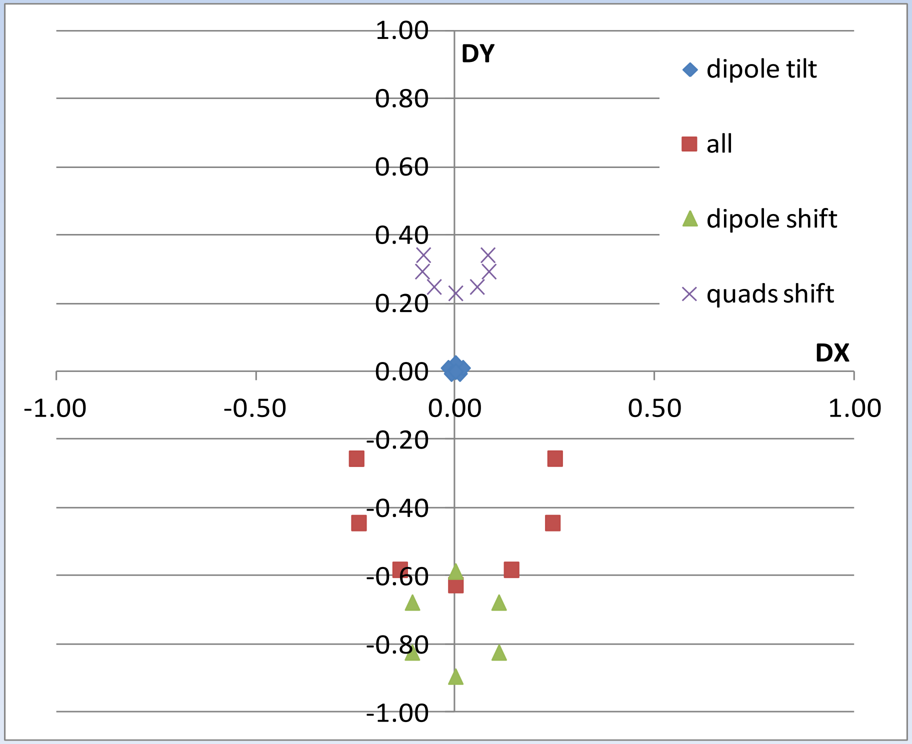
| Random error type | Sigma |
|---|---|
| Alignment tolerances: Δx, Δs, Δy [m] | $0.3 \times 10^{-3}$ |
| Tilt about all three co-ordinate axes, Δθ, Δφ, Δψ [rad] | $0.3 \times 10^{-3}$ |
| Relative excitation error $\Delta B/B$ and $\Delta g/g$ | $0.3 \times 10^{-3}$ |
| Relative excitation error $\Delta B/B$ for the 90° dipole | $0.1 \times 10^{-3}$ |

# Magnet misalignment effect

Isocenter displacement for random magnet alignment errors in the gantry

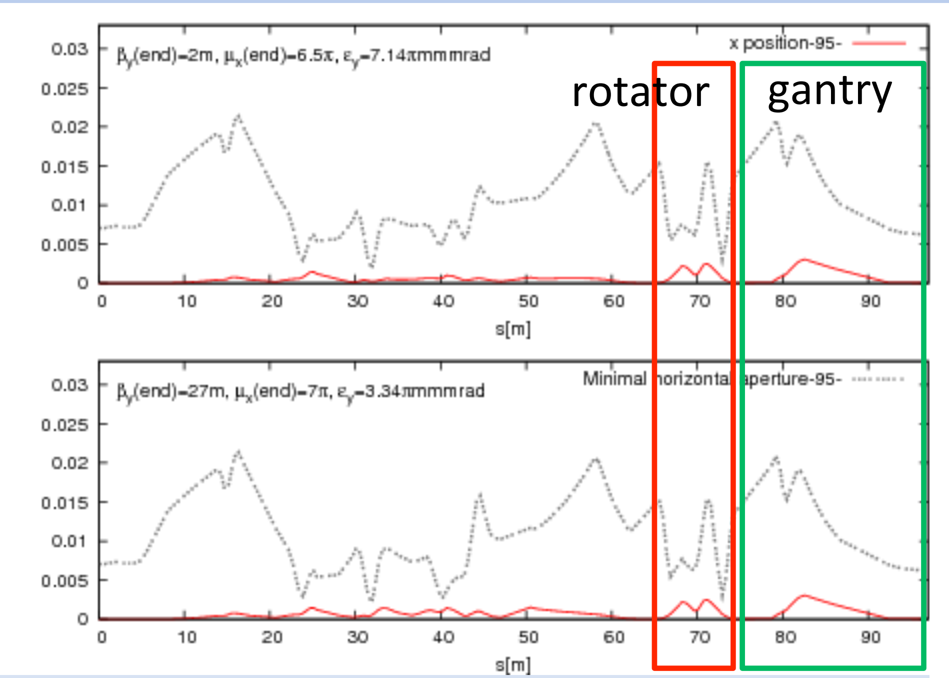


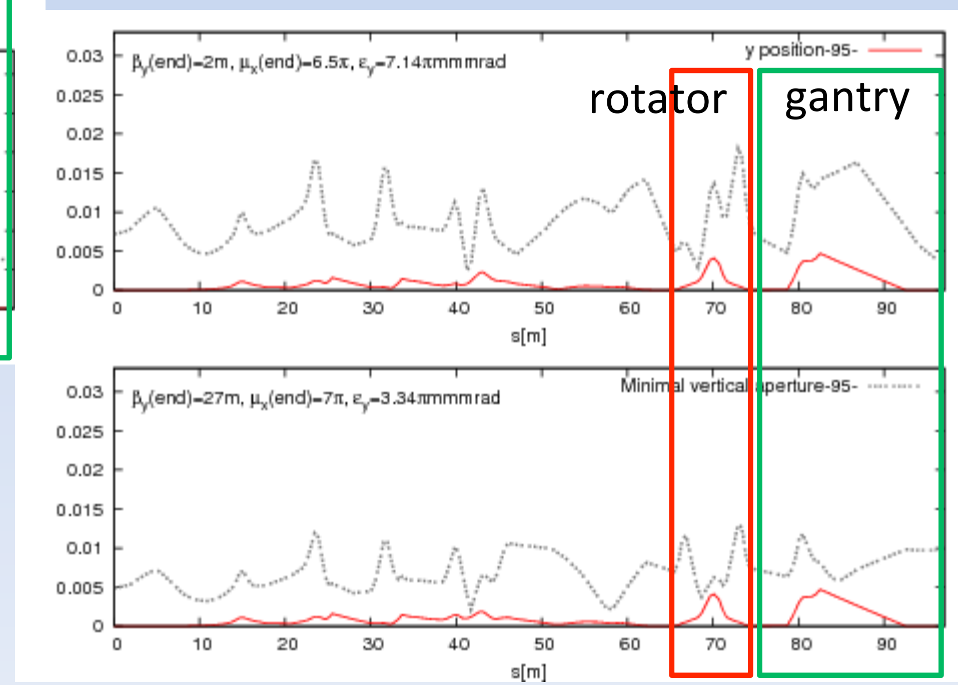

Isocenter displacement for structure deformation at various gantry angles



# Orbit margin and aperture after correction

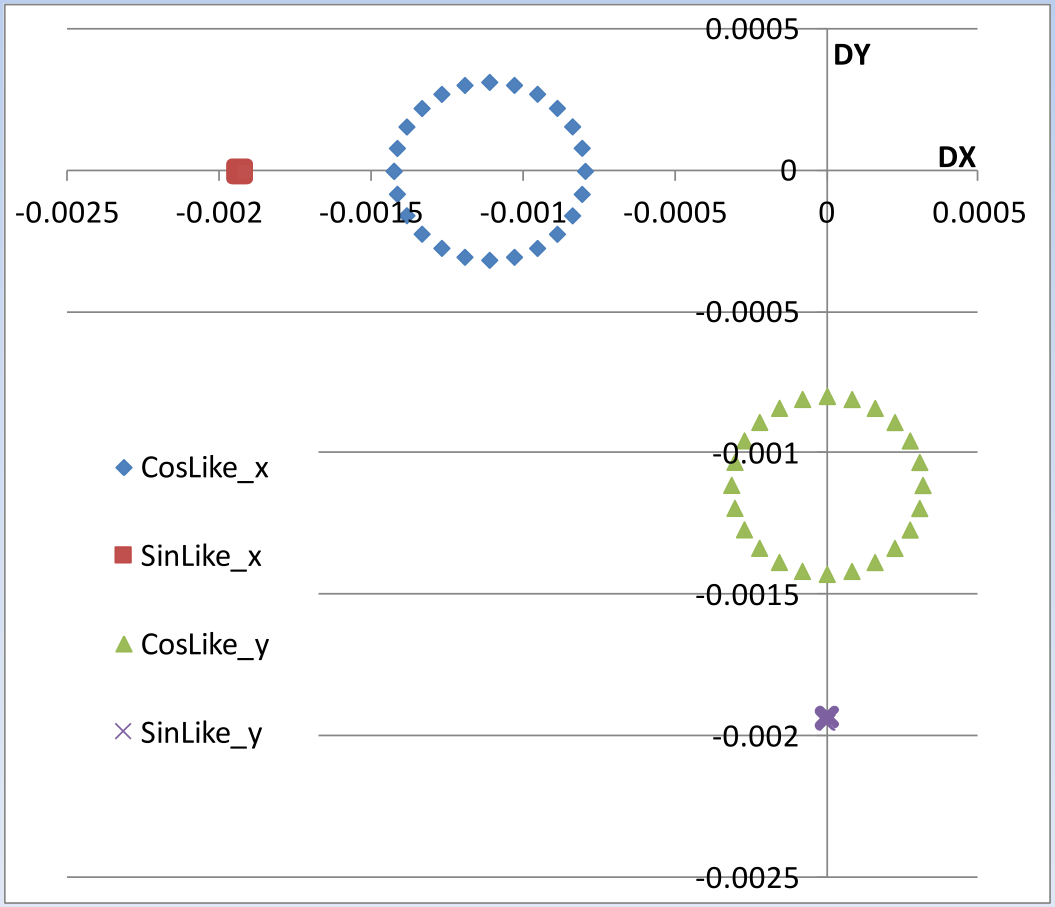
Orbit correction independent of gantry angle




Well inside magnet good field region

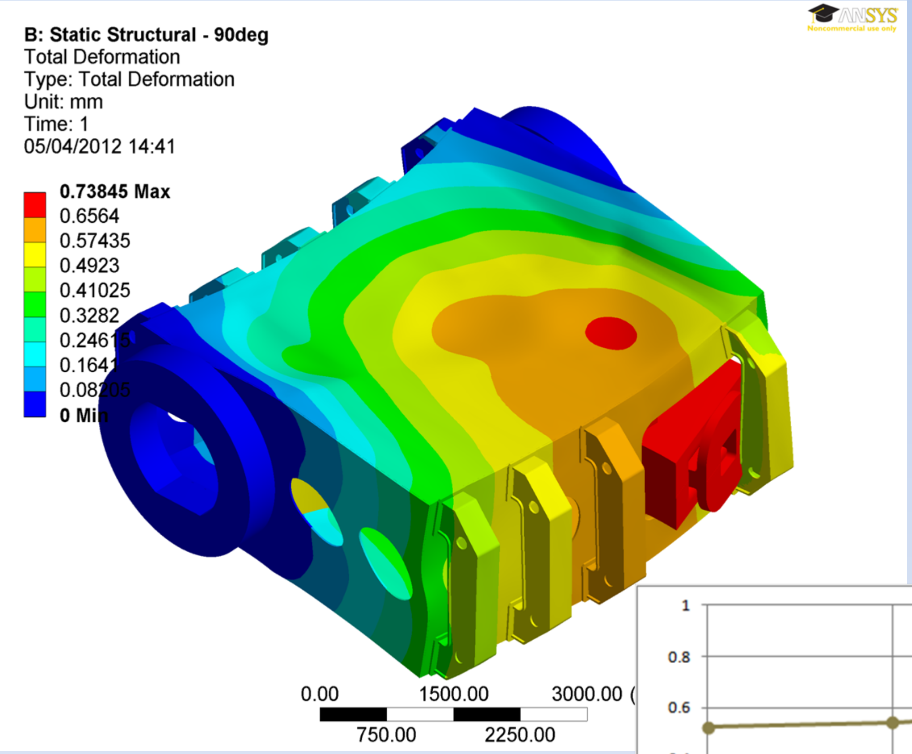
# Monitor misalignment effect

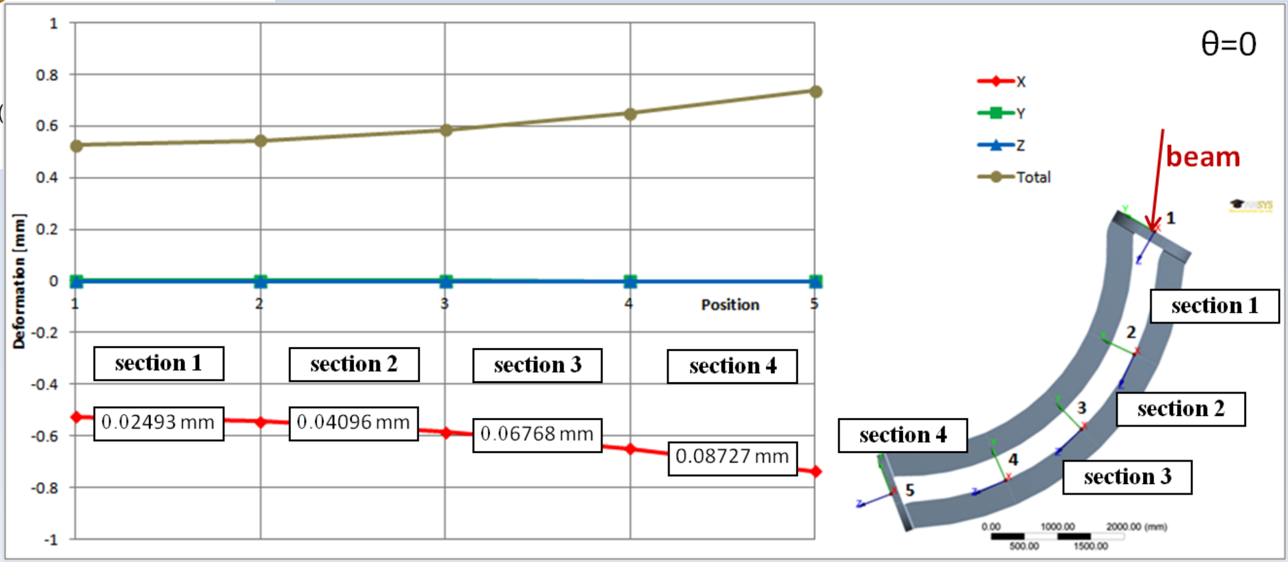



Strict alignment tolerance for
four dedicated monitors
(0.2 mm rms for 0.6 mm at isocenter)

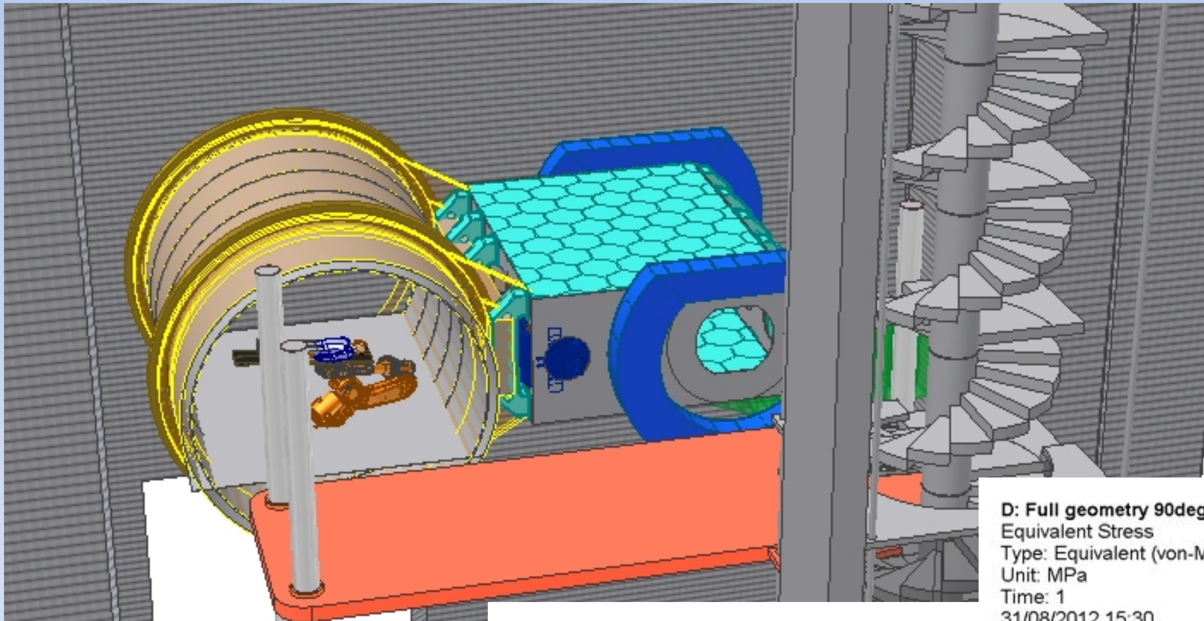
$$\Delta R_{ISO} = \sqrt{(C \cdot \Delta x)^2 + (C \cdot \Delta y)^2 + \left(S \cdot \sqrt{2}\Delta x / d\right)^2 + \left(S \cdot \sqrt{2}\Delta y / d\right)^2}$$

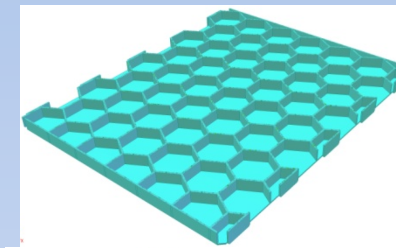
# Dipole and stiffening structure

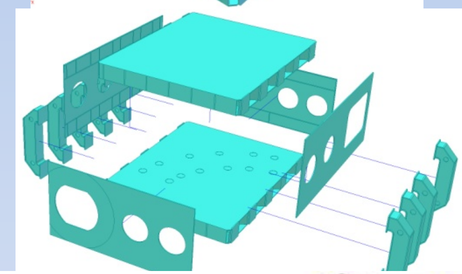


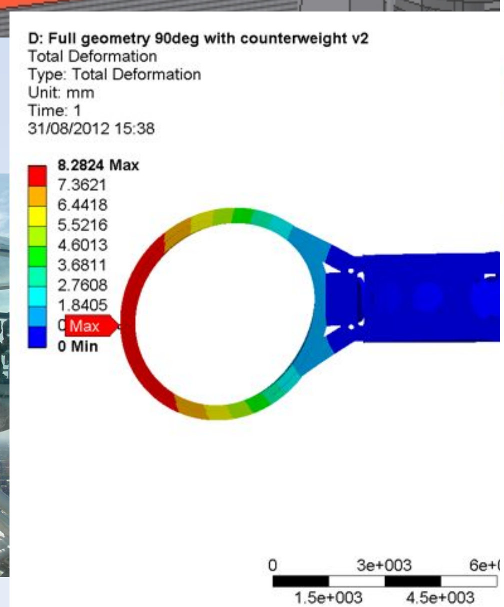



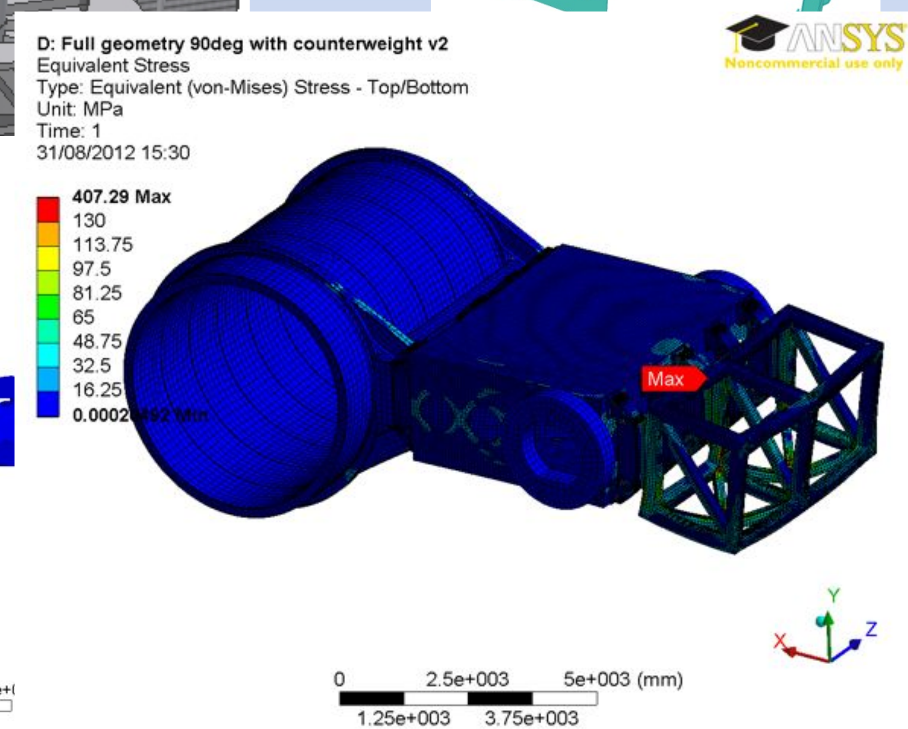
# The ULICE gantry: mechanical structure without brackets

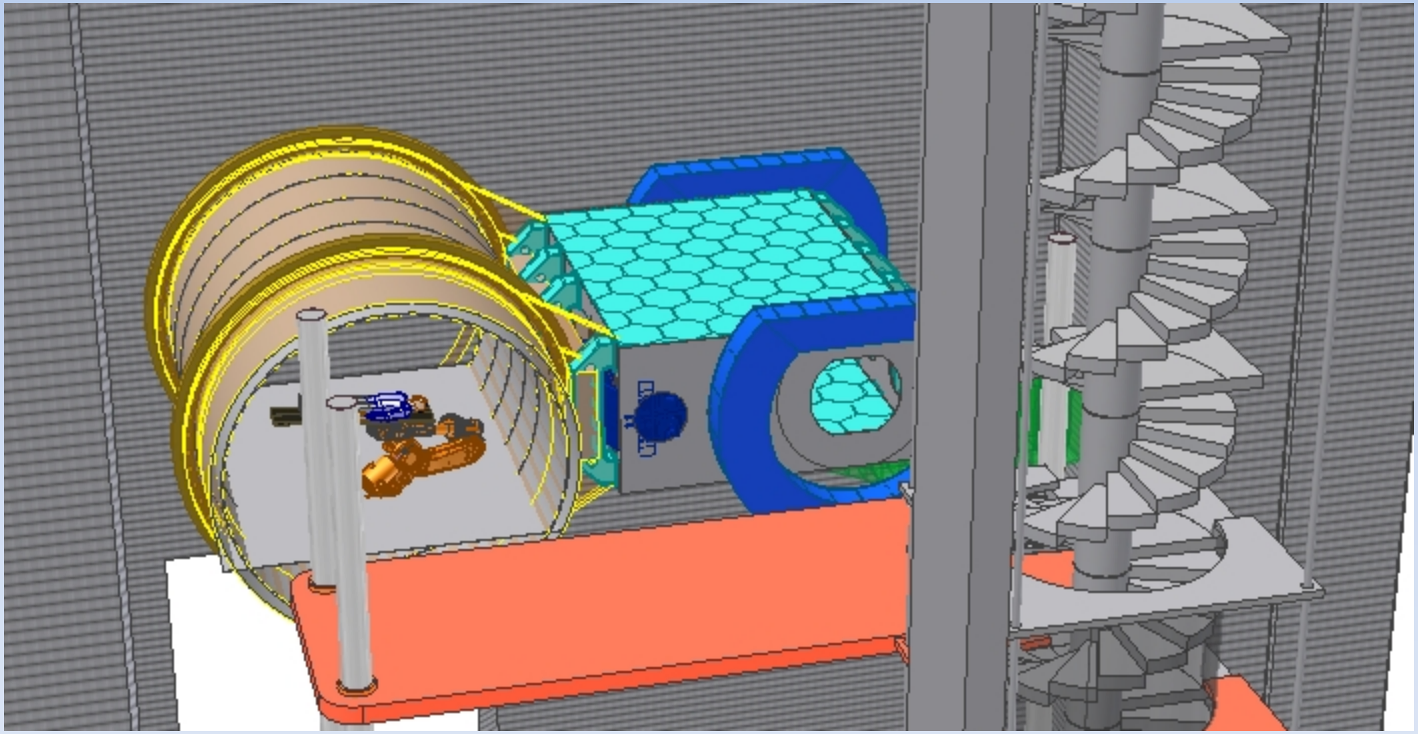




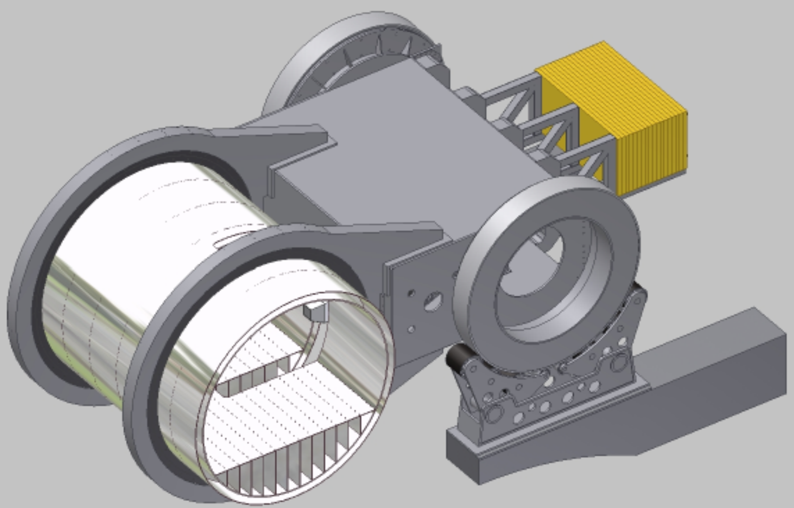


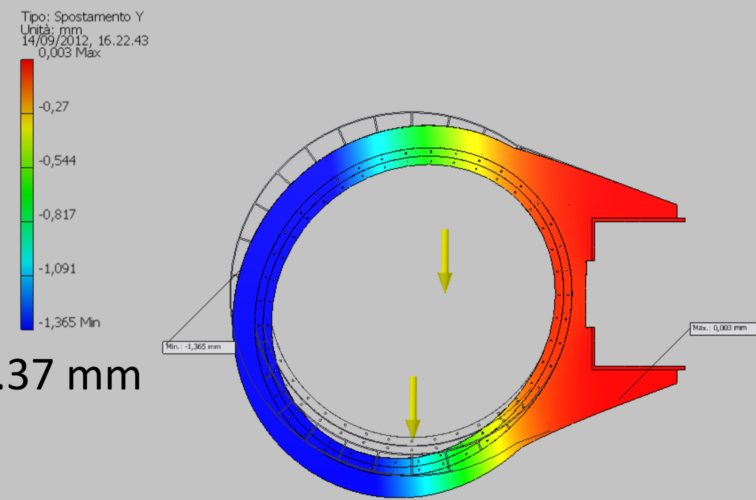





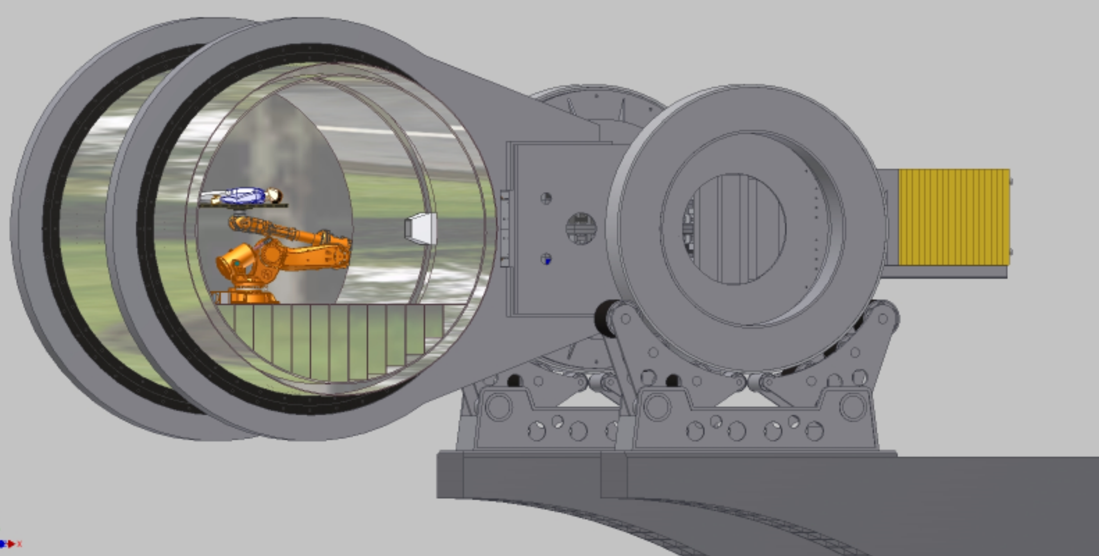
# The ULICE gantry: mechanical structure with half brackets



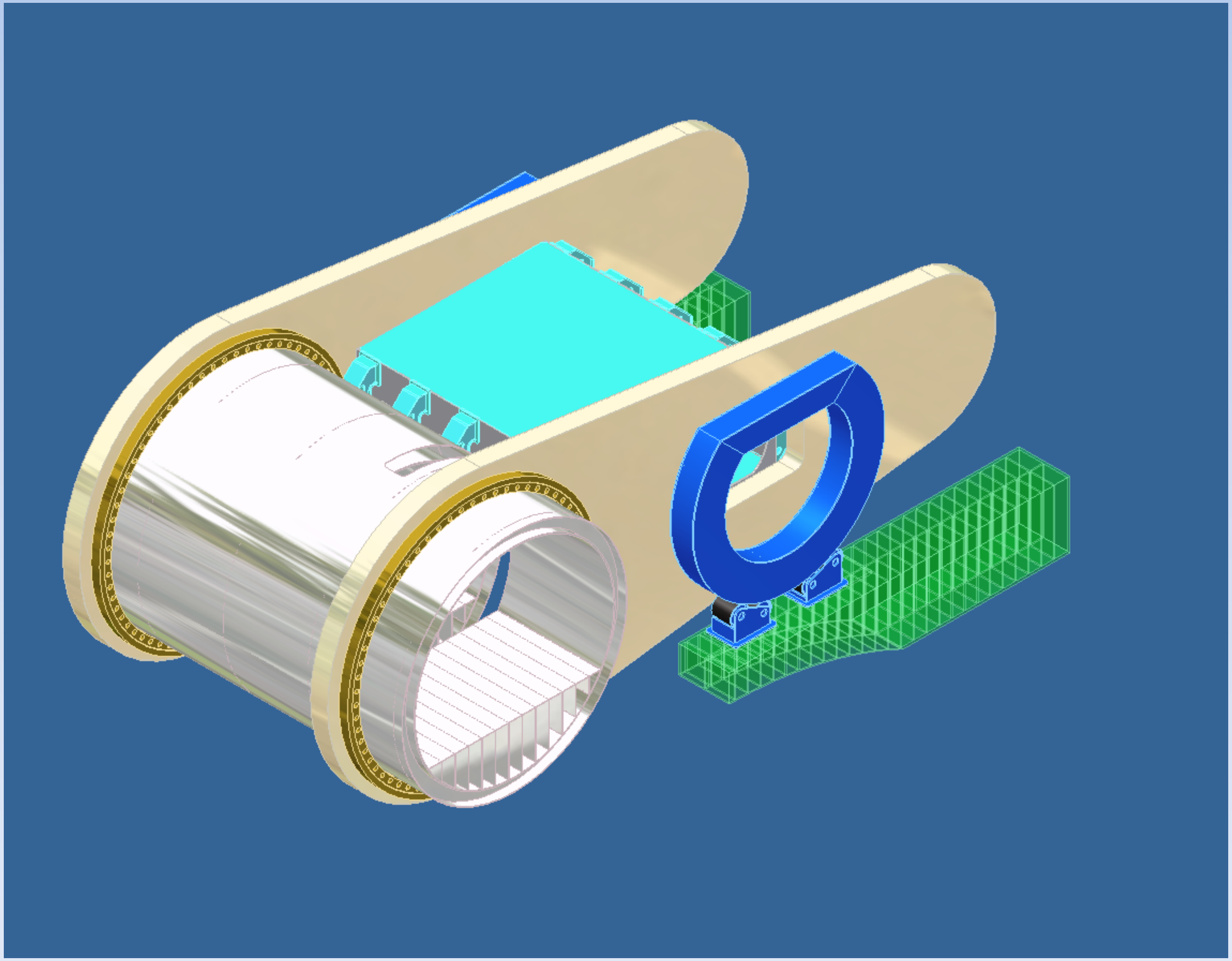



-1.37 mm

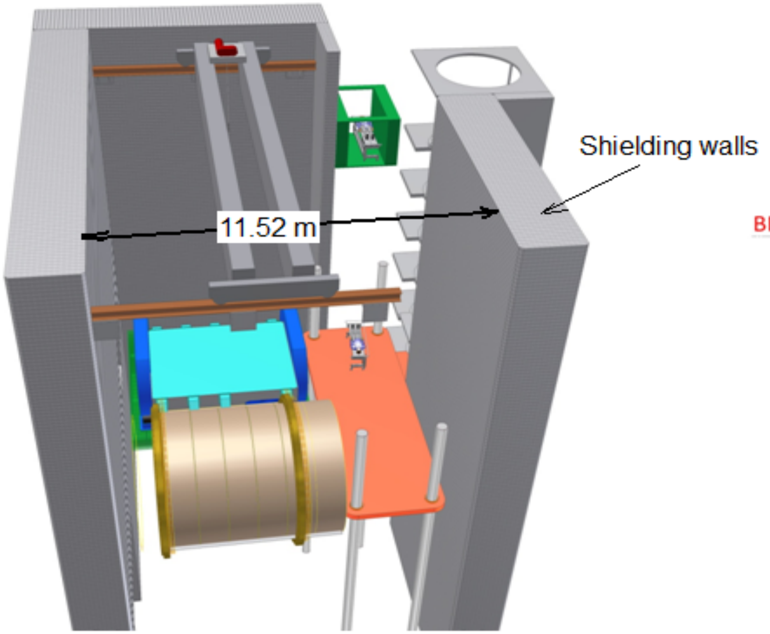
Gantry mass: 350 t

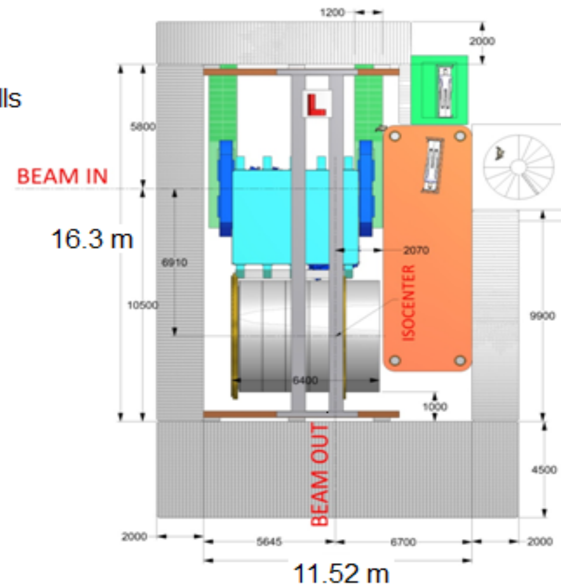


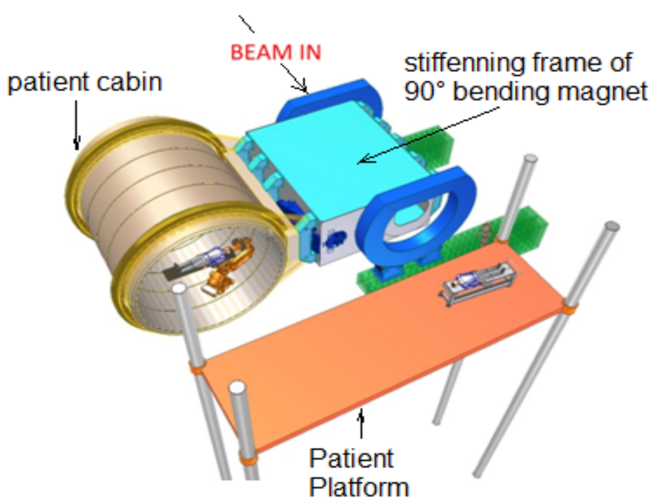
# The ULICE gantry: mechanical structure with brackets

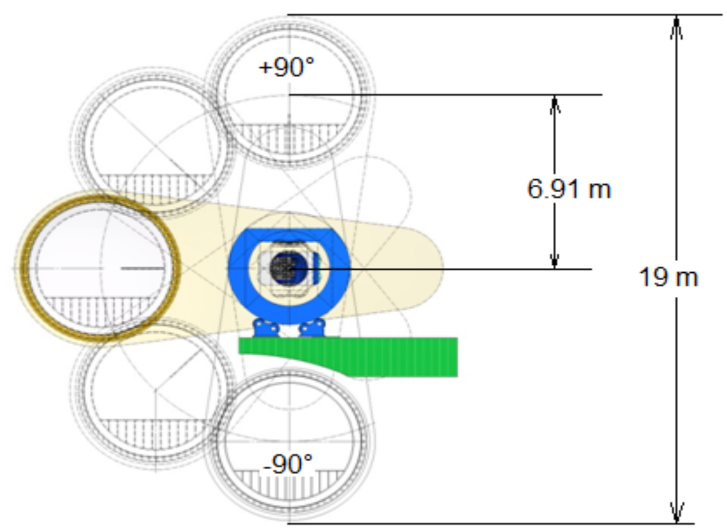


# Gantry room

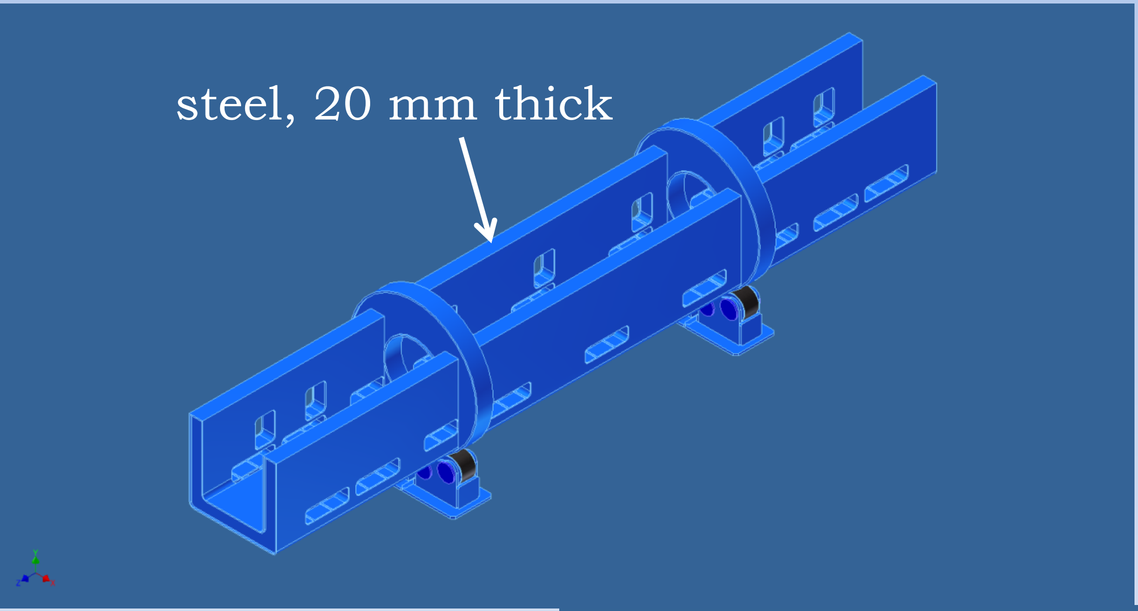

11.52 m
Shielding walls


1200
2000
5800
BEAM IN
16.3 m
6910
10500
2070
ISOCENTER
9900
6400
1000
4500
BEAM OUT
2000
5645
6700
2000
11.52 m

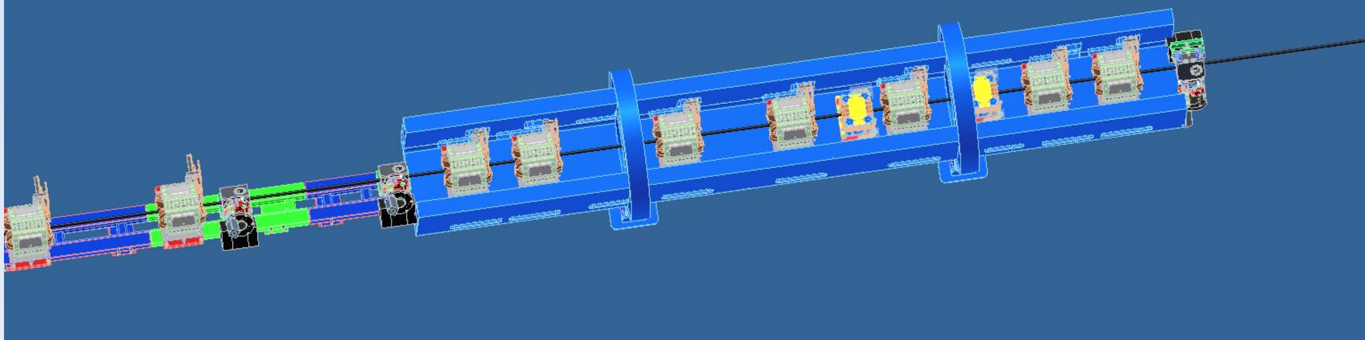

BEAM IN
patient cabin
stiffenning frame of
90° bending magnet
Patient
Platform


+90°
6.91 m
19 m
-90°

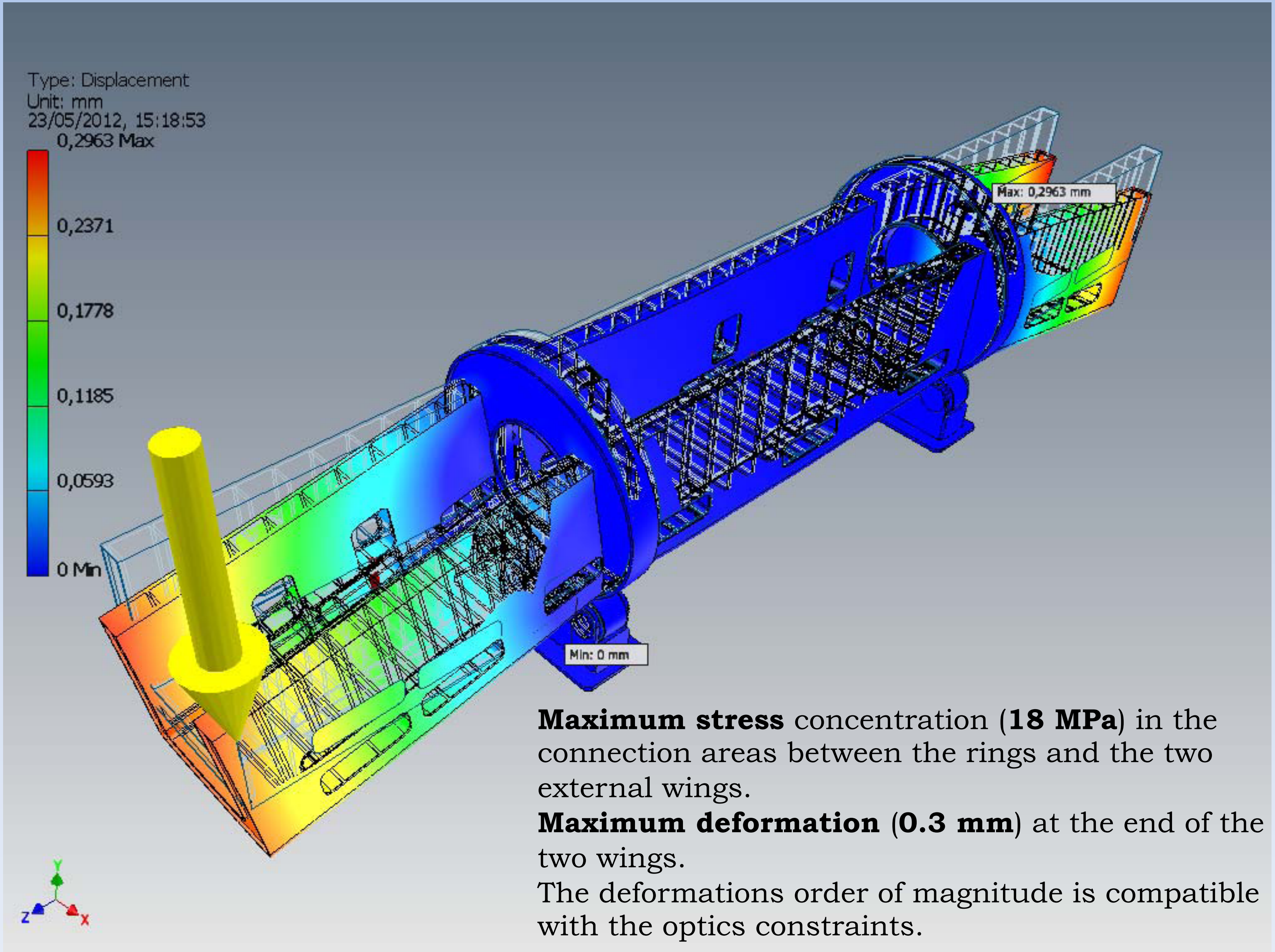
# The rotator frame




- Mass = 12.4 tons
- Length x width x height) = **9.8 x 1.3 x 1.9 m³**
- Rings inner diameter = 850 mm



# Stress analysis and deformations

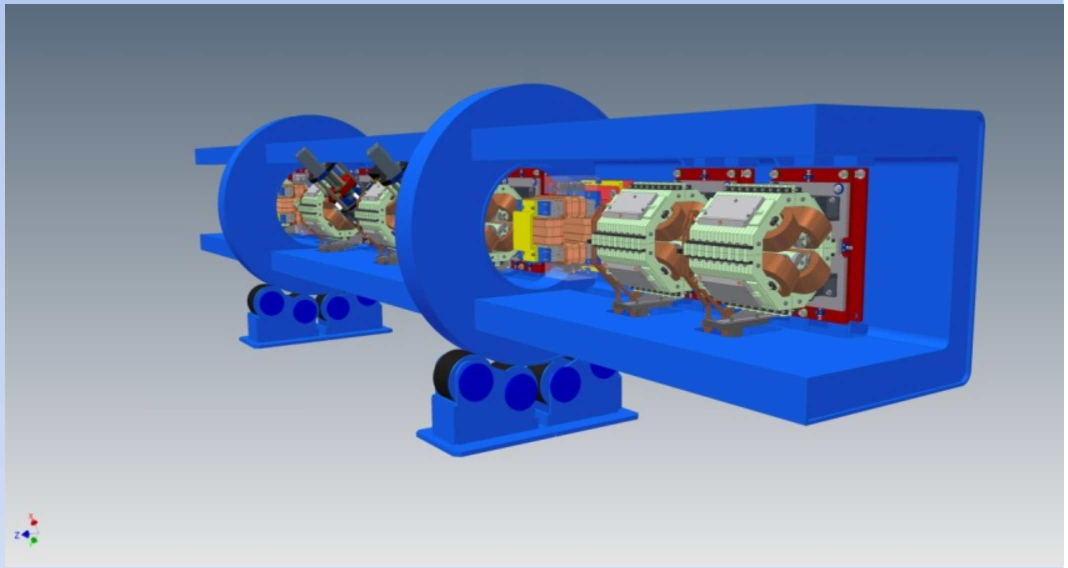


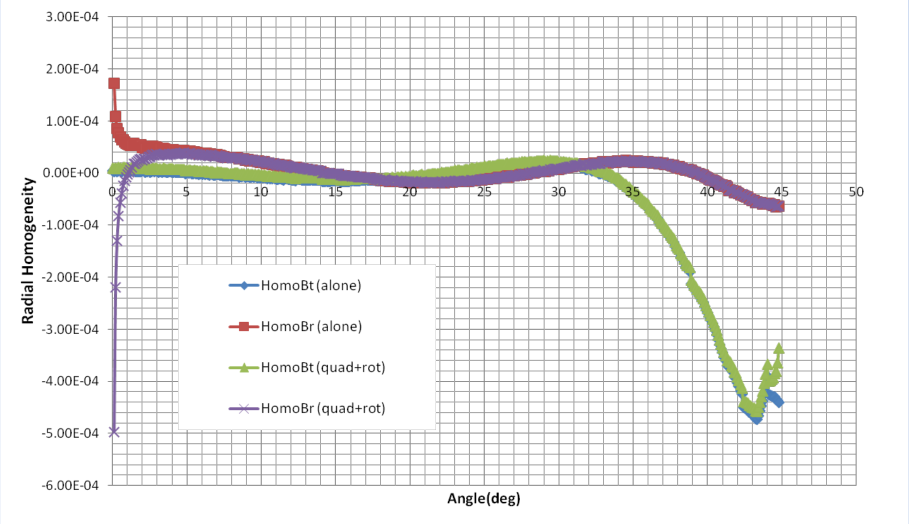

**Maximum stress** concentration (**18 MPa**) in the connection areas between the rings and the two external wings.

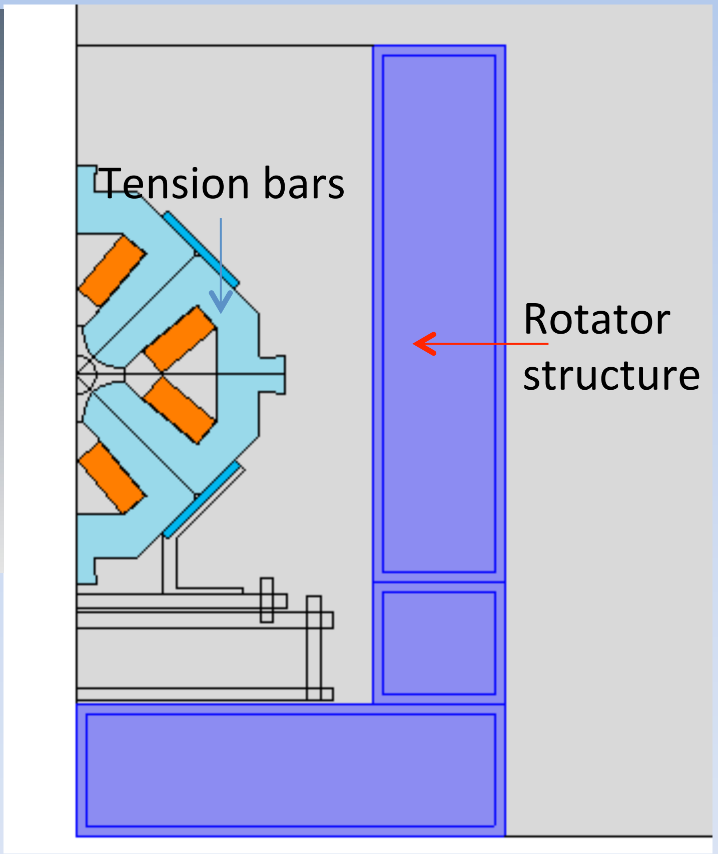
**Maximum deformation** (**0.3 mm**) at the end of the two wings.

The deformations order of magnitude is compatible with the optics constraints.

# Effect of the rotator on the magnet field

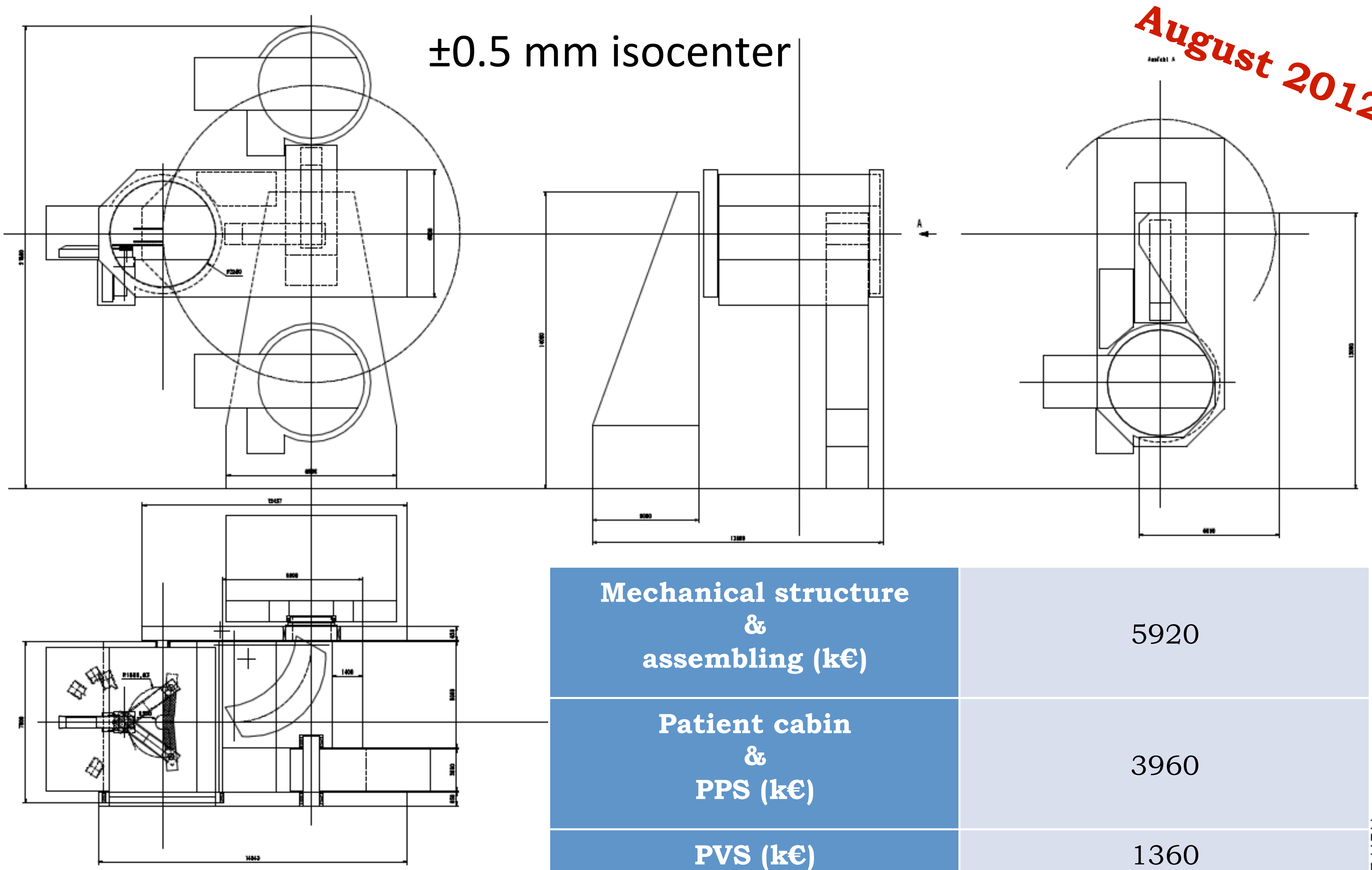





2D geometry implemented in the FEM code

# Bracket gantry: offer from Schaer




| | |
|---|---|
| **Mechanical structure & assembling (k€)** | 5920 |
| **Patient cabin & PPS (k€)** | 3960 |
| **PVS (k€)** | 1360 |

# Platform and lift: Kone study & offer

Platform provides access to the treatment cabin. Access to the platform is guaranteed by an auxiliary lift connecting the entrance floor to the platform, wherever the platform is.
The platform follows the cabin keeping the cabin floor and the platform at the same height, during the gantry rotation. A sliding door system provides access to the patient enclosure following the horizontal cabin position while keeping the rest of the platform closed.

## Functional specifications

| | Load | Speed | Travel | Doors | Hoist | Power | Landing |
|---|---|---|---|---|---|---|---|
| | (kg) | (m/s) | (m) | W x H (mm) | | (kW) | |
| **Platform** | 3000 | 0.15 | 14 | 1400 x 2100 | hydraulic | 42 | Variable |
| **Lift** | 2000 | 1.6 | 14 | 1400x2100 | electric | 18.5 | Variable |

**The lift is powered from an uninterruptable power source, with battery backup**

**Budgetary quotation**

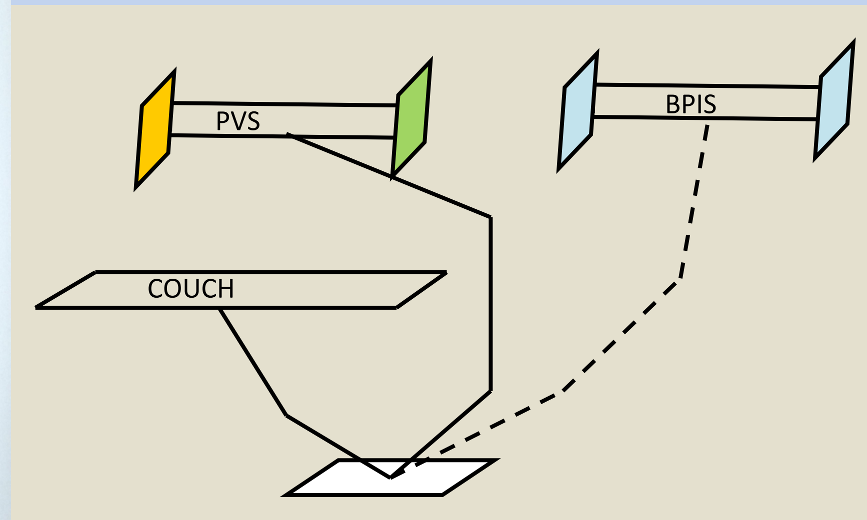
26 Person/2000 kg Electric Passenger Lift with "mobile landing" technology
40 Person/3000 kg Hydraulic Platform with "real-time chase" technology

**May 2012**

€ 1,740,000.00

# The ULICE gantry: Beam Based Alignment

Measure where the beam is and put the isocenter there…




One robot arm with two "tools"

CNAO treatment room #2: PPS and PVS

# Parasitic dose to patient

- Measurement have been performed shooting four spills against water tanks simulating the preliminary beam position measurement
- The dose measured 0.5 m on the side of the target was less than 10 uSv for both protons and carbon ions.

# The ULICE gantry: cost estimates

| | |
|---|---|
| **Magnets (k€)** | 1705 |
| **Magnets PS (k€)** | 975 |
| **Mechanical structure & assembling (k€)** | 5920 |
| **Patient cabin & PPS (k€)** | 3960 |
| **PVS (k€)** | 1360 |
| **Patient handling (k€)** | 225 |
| **Gantry building (k€)** | 1500 |
| **TOTAL (k€)** | **15645** |

+ conventional plants, cooling and ventilation, access control…
common to any solution

# Conclusions

The ULICE gantry design provides:

- lighter and more compact design wrt fixed isocentre type
- appreciable savings in the total cost wrt standard design
- orbit corrections independent of the gantry angle
- beam based patient alignment

- Final report in preparation