nimms

HITRI plus
Heavy Ion Therapy Research Integration

Funded by the European Union NextGenerationEU

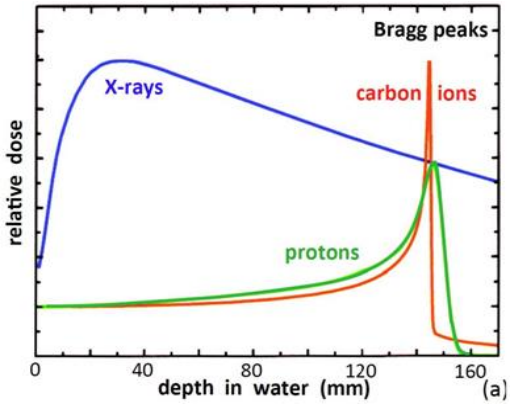
2027 National Development Plan

Design of a Suspension System for Cold-mass on Rotating Gantry for Medical Applications

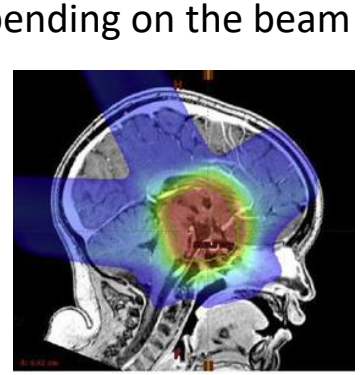
LUCA PIACENTINI

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

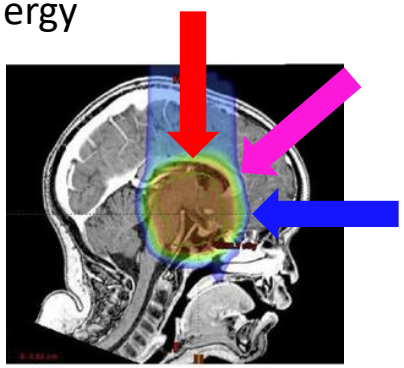
Why Hadron Therapy and Gantries



Bragg Peak: hadrons deposit energy @ specific depth, depending on the beam energy



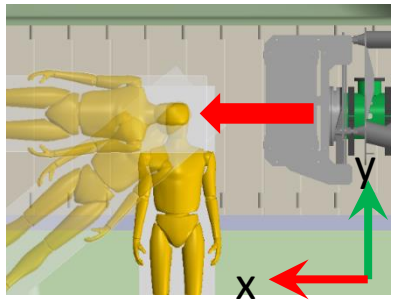
photons IMRT



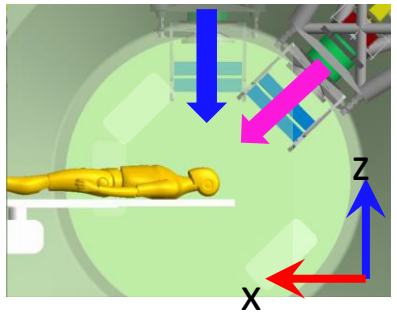
protons

https://doi.org/10.1016/j.ijrobp.2016.06.2446

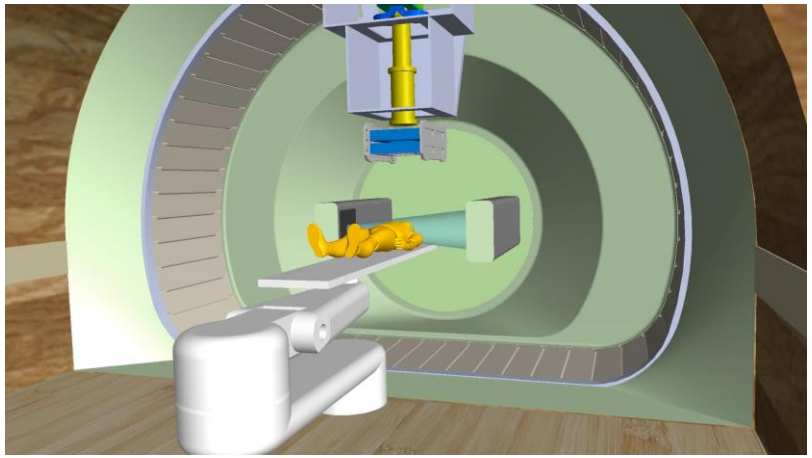
Fixed beam (XY)



Gantry (XZ)



Gantry



Medical community wants any degree of freedom possible to personalize the treatment plan -> higher efficacy, lower risks

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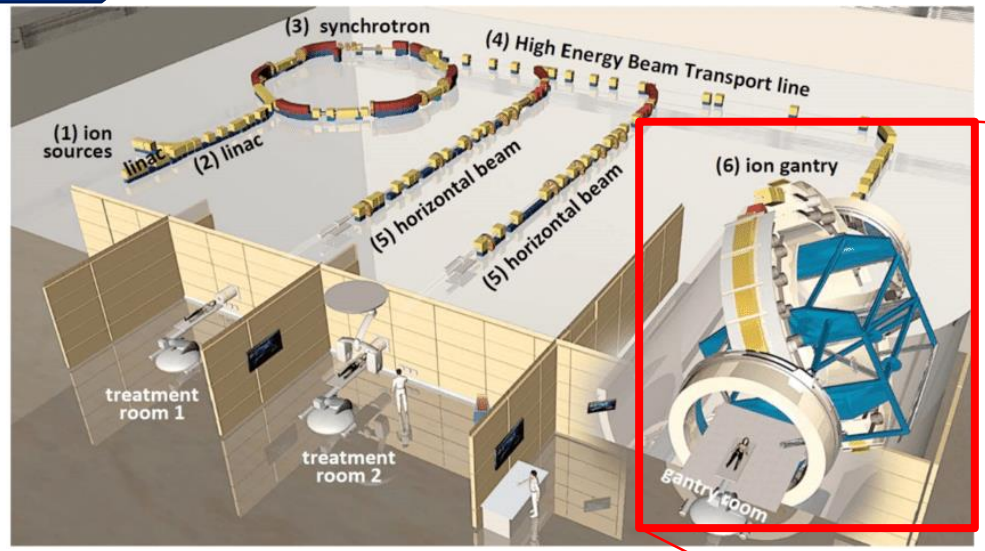
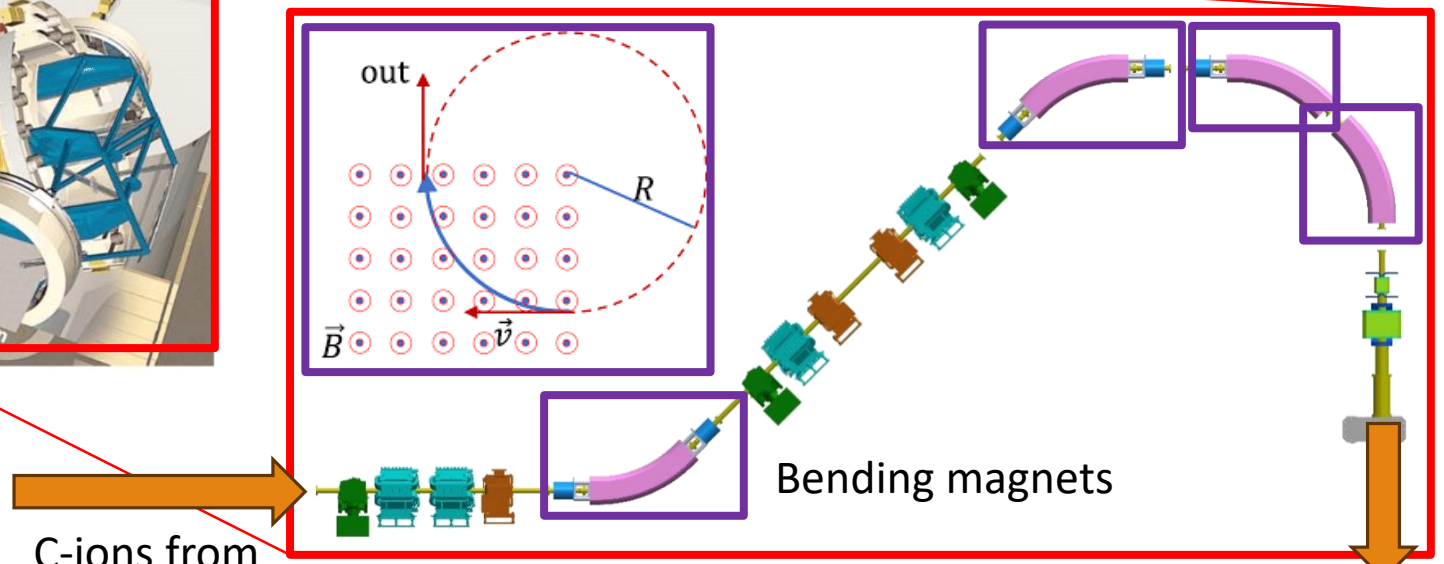
What is a Gantry



Source: HIT facility scheme

HIT gantry: 600 tons (normal conducting)
HITRIplus gantry: **200 tons (superconducting)**



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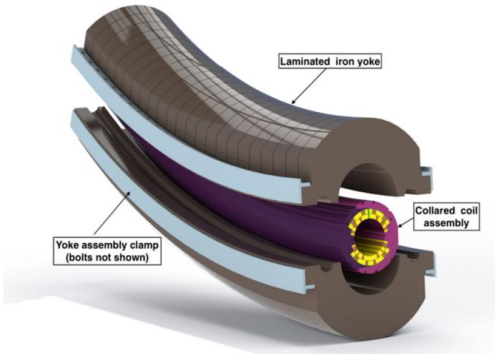
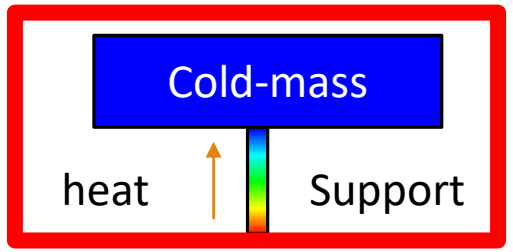
Challenges for the suspension system



[1] CT superconducting magnet
Courtesy of M. Karppinen

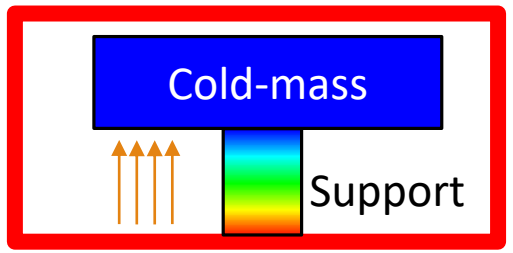
Features of Superconducting Dipole			
Material	Nb-Ti	**Bending angle**	45 °
Dipole Field	4 T	**Bending radius**	1.65 m
Aperture	80 mm	**Mass**	1500 kg
Length	1.3 m	**Operating T°**	4.5 K (-268 °C)

Thinner support – Less heat – **Less cost**
– Less Treatment accuracy



cryostat

Thicker support – More treatment accuracy –
more heat – more costs



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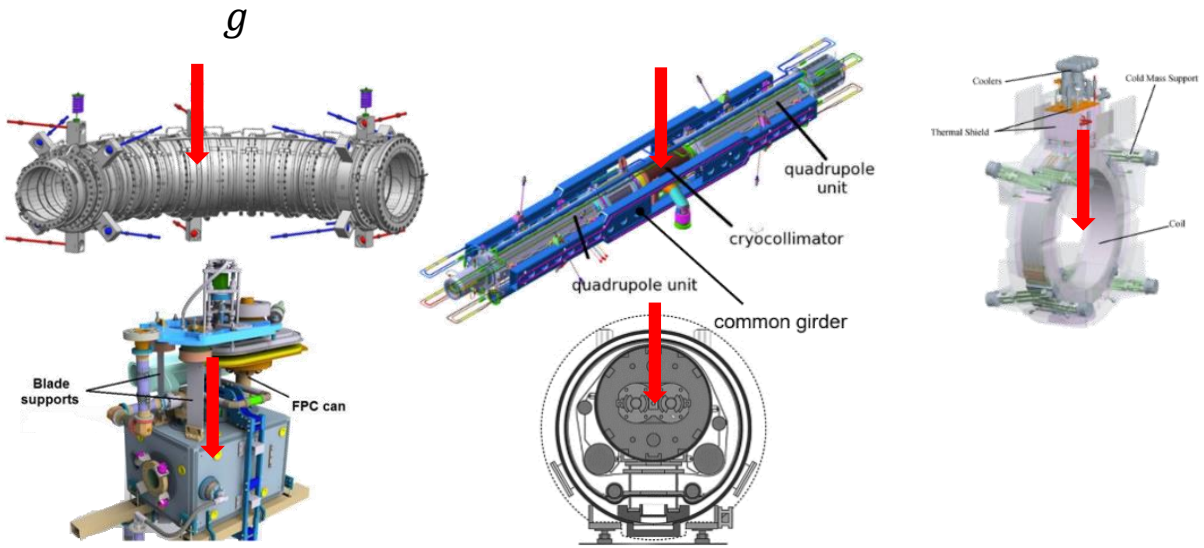
Literature review of suspension systems

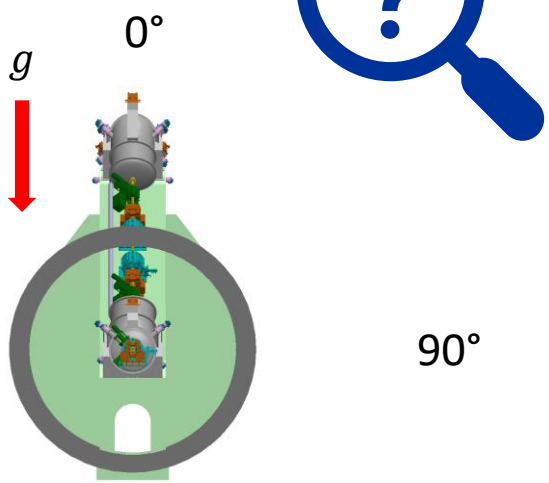
machines https://doi.org/10.3390/machines11100929 MDPI

Review

Literature Review of Suspension Systems for Superconducting Elements

Luca Piacentini [1,*], Luca Dassa [2], Diego Perini [2], Andris Ratkus [1], Toms Torims [1] and Stefano Uberti [3]





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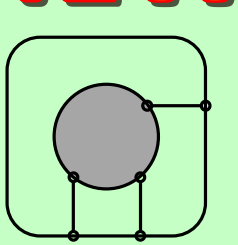
Proposal of multiple solutions

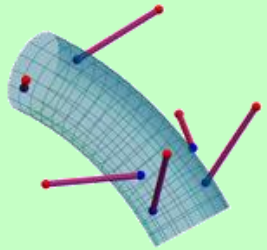
Structure design

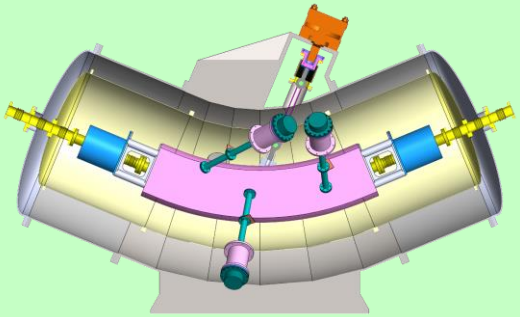
- **Exactly constrained**
- N equations = N variables

- **Over-constrained**
- N equations < N variables

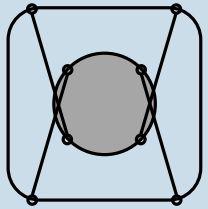
NEW!

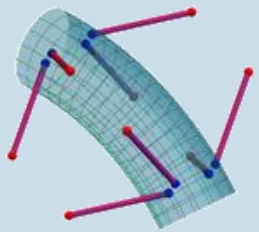


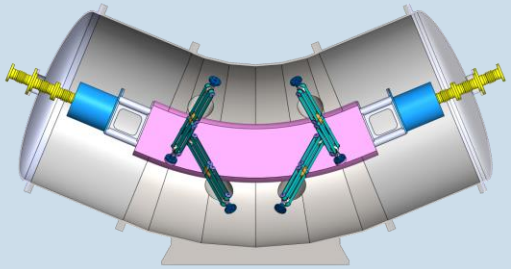




Concepts from Literature







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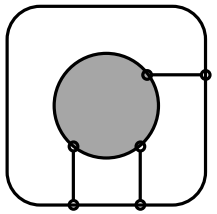
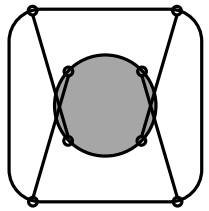
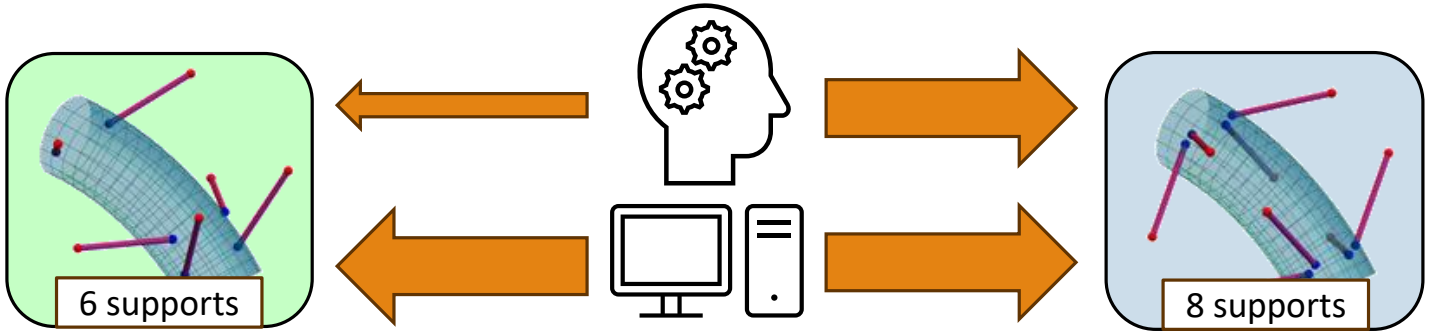
Fair comparison

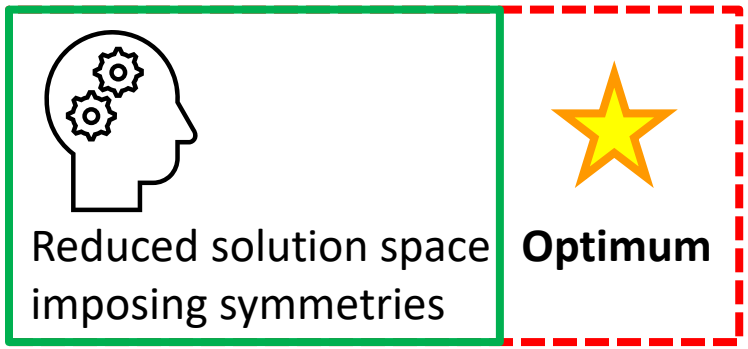
 OR  ?

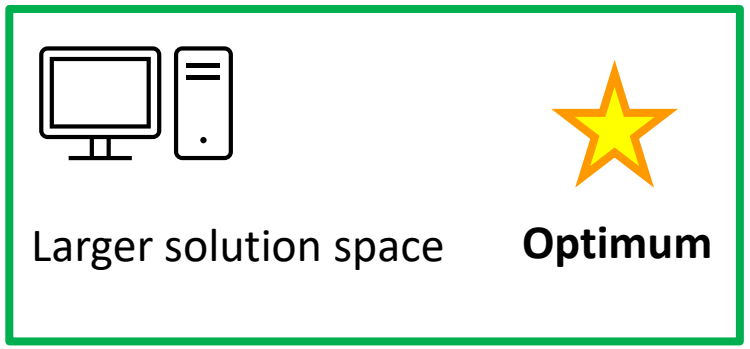
How to place the supports so that the rigidity of the system is maximized during the rotation?



- **20** parameters

- **6** parameters (symmetry)
- Existing examples





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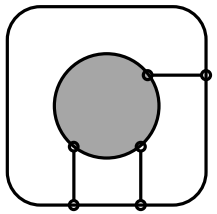
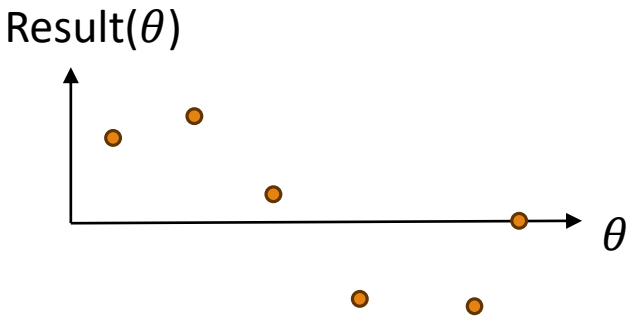
Fast comparison



- Material A
- Dimension B

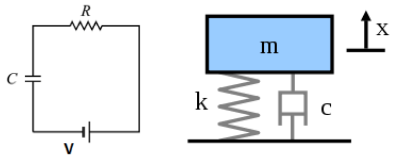
θ_1 → FEA → Result(θ_1)

θ_n → FEA → Result(θ_n)

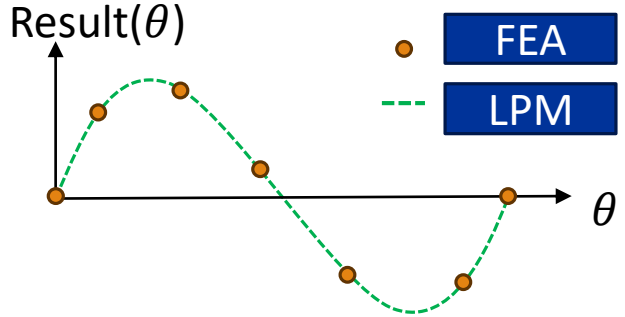


What if I change material, dimensions?

Lumped Parameter Model:



θ → LPM → Result(θ)



- Faster
- Global view
- Possibility to change most input parameters (material, length, …)

optimization

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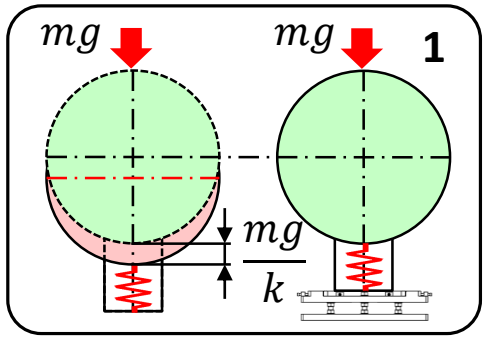
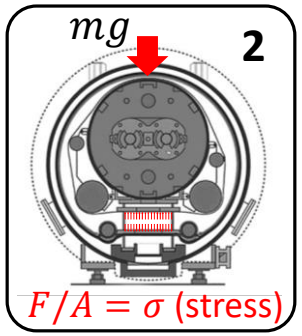
Lumped Parameter Models Desirables

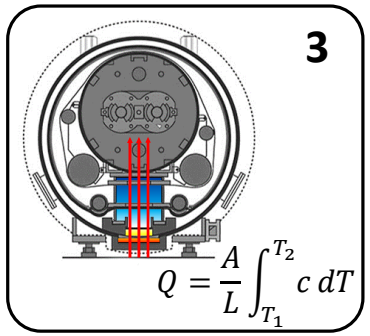
Position accuracy
(Treatment Efficacy)



Mechanical resistance
(safety)

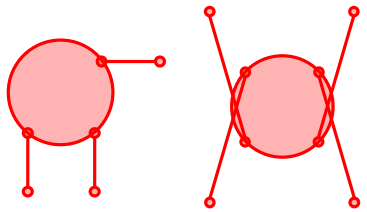


Heat loads
(operating costs)

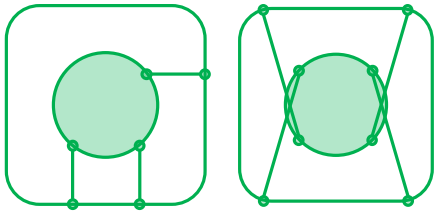


The LPM must be able to:

1. Estimate the **position of the cold mass** to ensure **treatment efficacy**
2. Estimate **loads on the supports** to ensure the mechanical reliability of the system **(safety)**
3. Model all components required to **compare** the two solutions



The **Vacuum Vessel** must be included as it is subject to **different loads – different deformations**



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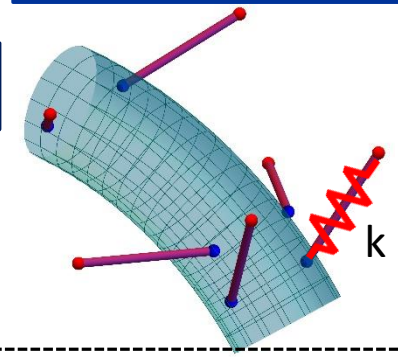
LPM 6S: linearization of the Vacuum vessel

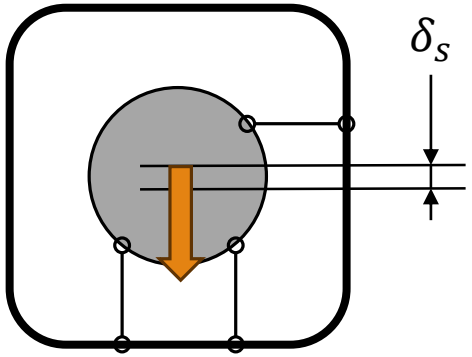
- Introduction
- Method
- **Models**
- Results

Deformation of supports

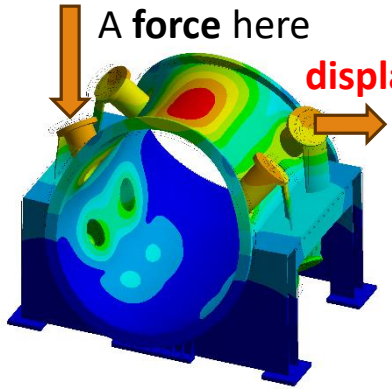


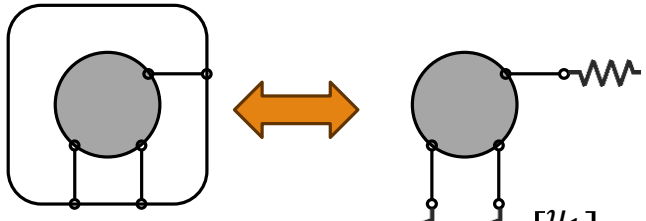
Literature

$$\mathbf{F}_q = \mathbf{J}^T\mathbf{F}_s$$
$$\mathbf{dS} \simeq \mathbf{J}\mathbf{D}_q\mathbf{J}^T\mathbf{F}_s = \frac{1}{k}\mathbf{J}\mathbf{J}^T\mathbf{F}_s$$

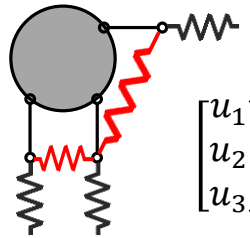


Deformation of vacuum vessel

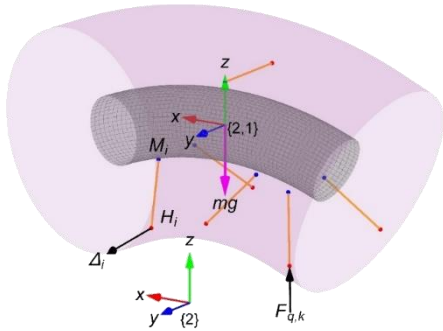




$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & 0 \\ 0 & 0 & d_{33} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}$$



$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}$$



$$\Delta_{ij} = D_{v,ijk} F_q^k$$ **NEW!**

Valid for “n” number of supports

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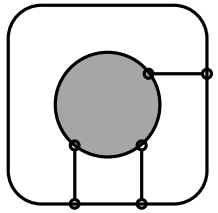
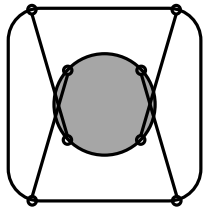
LPM 8S: Principle virtual work solution

Deformation of supports

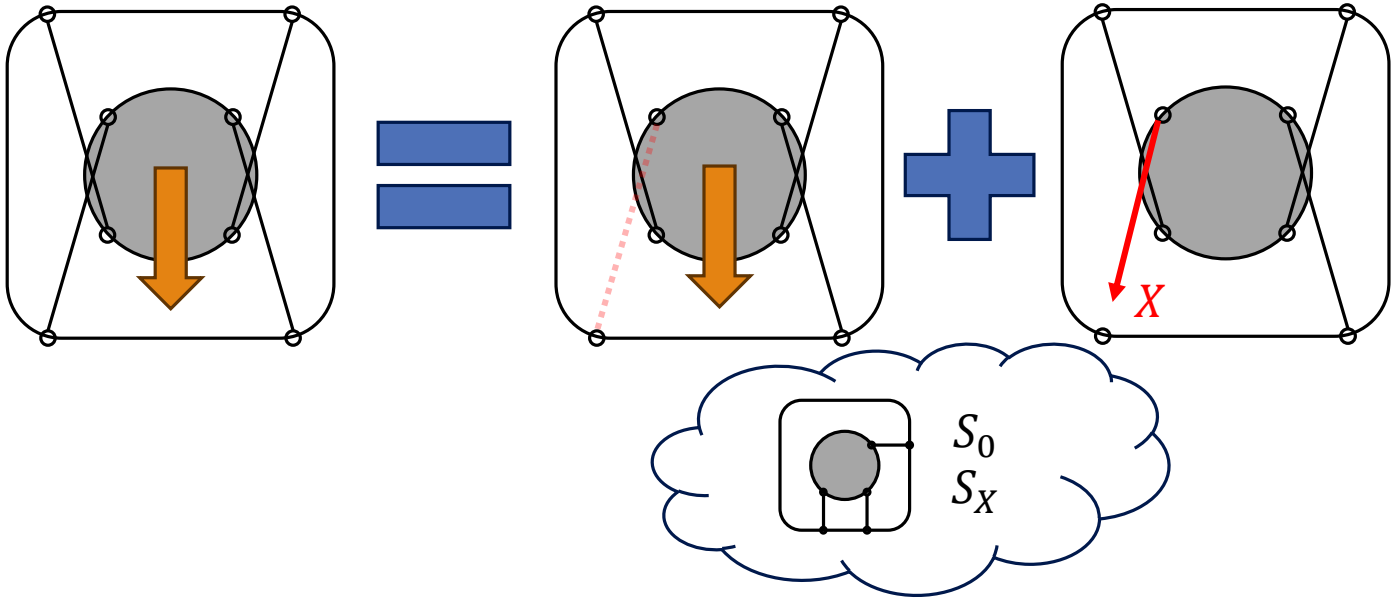


- 3 equilibrium equations
- 3 variables



- 3 equilibrium equations
- **4 variables**

Principle of Virtual work: $W_{ext} = W_{int}$ $S = S_0 + XS_X$



$$\sum_{i=1}^{n} \int_0^{L_i} N_{j,i} \left(\frac{N_{0,i} + \sum_{p=1}^{n-6} X_p N_{X_p,i}}{E_i A_i} + \frac{\delta_i}{L_i} - \frac{\delta_{P,i}}{L_i} \right) ds = \mathcal{W}_{\text{ext},j}$$

NEW!

Valid for “n” tie-rods (supports) of different shapes and dimensions

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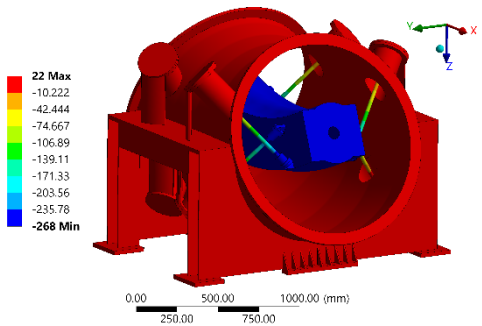
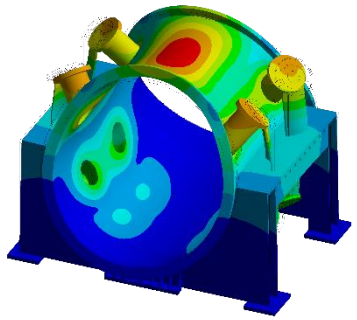
Validation of the models

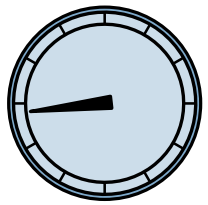
FEAs

Thermo-mechanical analysis:

- Preload
- Cool-down
- Rotation
- Vacuum pressure

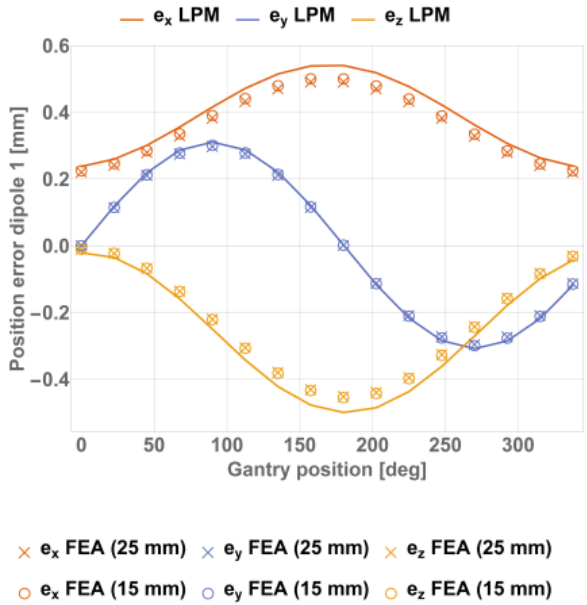


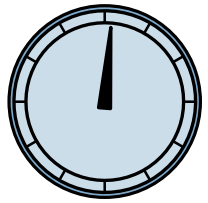




FEA evaluation > 40 min

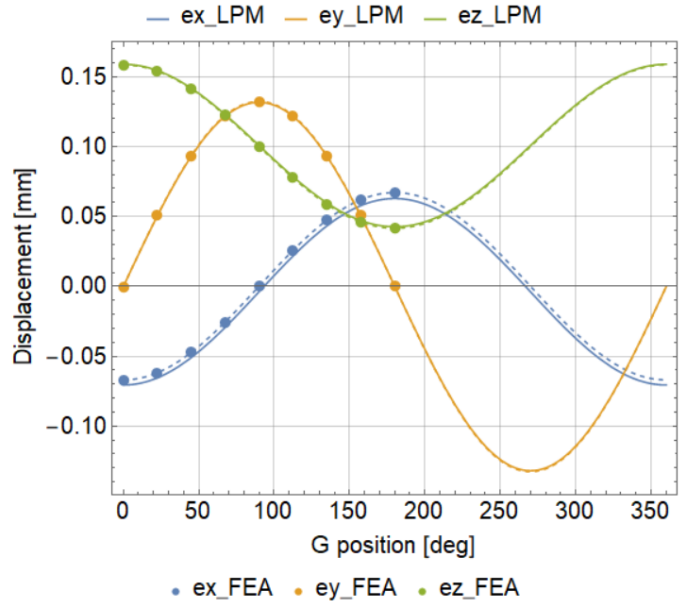
Validation of **6S** LPM





LPM evaluation < 10 sec

Validation of **8S** LPM



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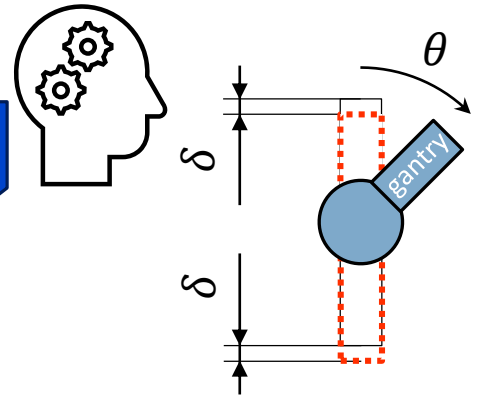
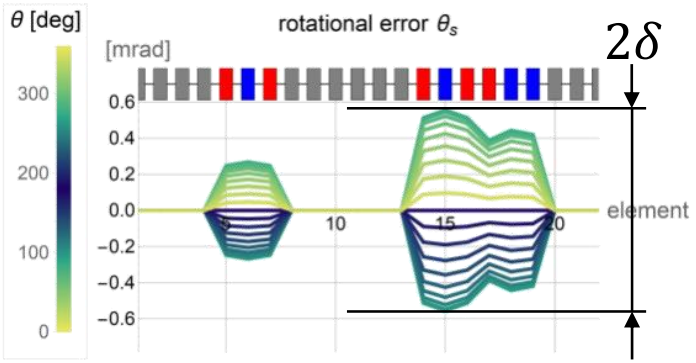
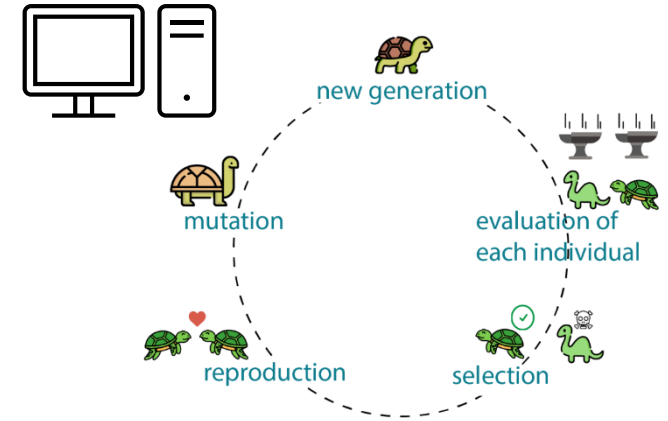
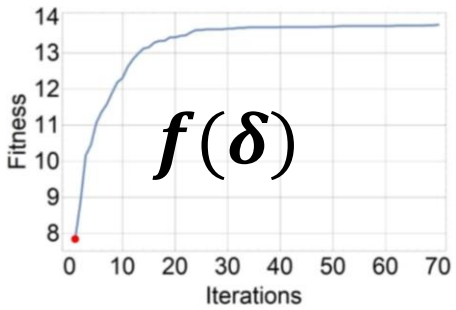
Optimization

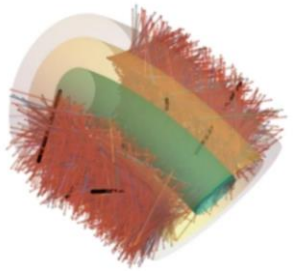
How to place the supports so that the rigidity of the system is maximized during the rotation?



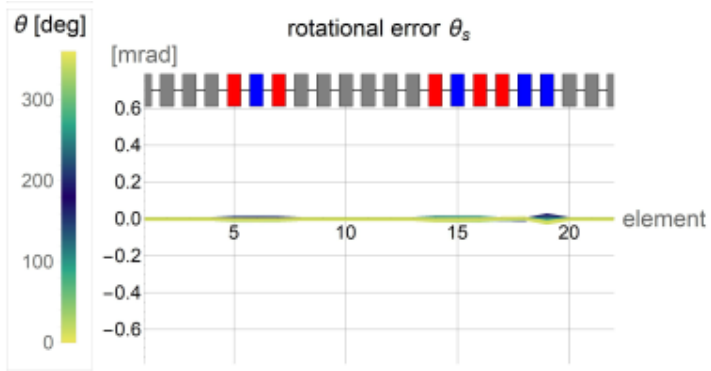








45 to 80 % reduction of 2δ depending on the DOF considered



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Design

Materials:

Titanium
Stainless steel
Invar
G10
CFRP

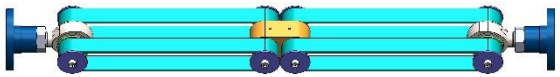
Dimensions:

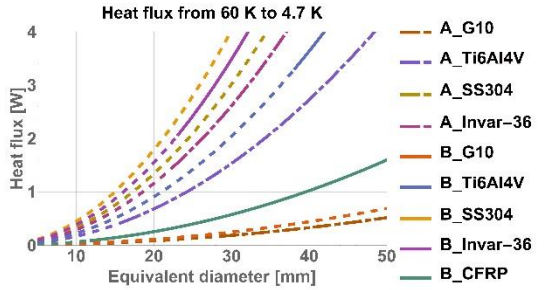
5 – 50 mm

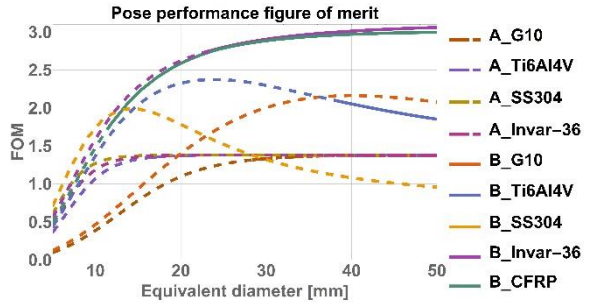
LPM

6S support design

8S support design







Comparison of 6S and 8S

		A	B	% improv.
Material		Ti6Al4V	CFRP	
Geometry		tube	double band	
Equivalent diameter	mm	18.0	13.2	
e_x	mm	0.36	0.37	-4%
e_y	mm	0.32	0.24	23%
e_s	mm	0.45	0.36	20%
θ_x	mrad	0.16	0.04	73%
θ_y	mrad	0.36	0.12	65%
θ_s	mrad	0.56	0.22	60%
FOM dipole 1		1.3	1.8	38%
FOM dipole 2		2.3	1.3	-43%
FOM dipole 3		2	1.4	-30%
FOM dipole 4		1.7	1.3	-24%
FOM average		1.79	1.44	-20%
Max load	kN	19.9	22.3	
Safety factor		12.2	12.2	
Heat flux @ 4.5 K	W	0.55	0.11	80%
Compressor input power	kW	2.6	0.5	80%

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Conclusions

- A literature review highlighted the **lack of a solution** for the suspension system of **superconducting magnets on rotating machines**,
- Two conceptually **different architectures have been proposed**, one new to the field of superconducting elements,
- A machine-oriented optimization has been chosen to have a fair comparison between the two proposed structures,
- **Lumped Parameters Models (LPM)** for both architectures have been **formulated, enabling the machine-oriented optimization** at a much lower computational/time cost,
- **LPMs have been validated** by mean of a standard simulation software proving a **good accuracy** of the models,
- The **optimization** allowed for a **considerable improvement of the accuracy** of the systems,
- The two solutions have been compared: **Solution 6S** being **easier to align** and more **reliable in the alignment** while solution **8S being more accurate during operation** and **less expensive** to maintain in terms of **cryogenic cooling**.

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Thank you for the attention!

HITRI
Heavy Ion Therapy Research Integration

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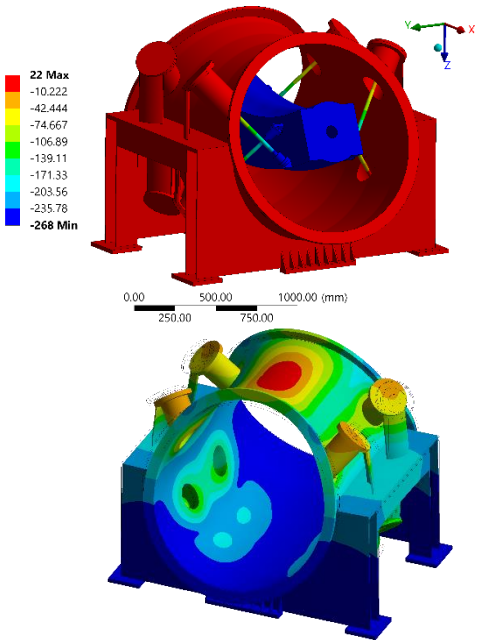
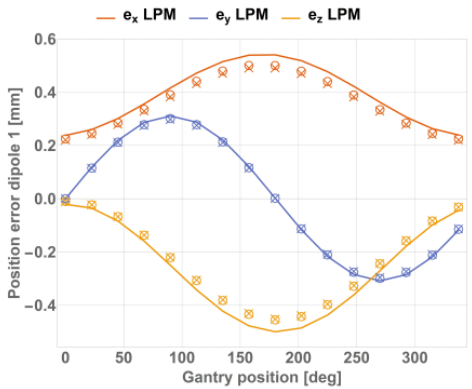
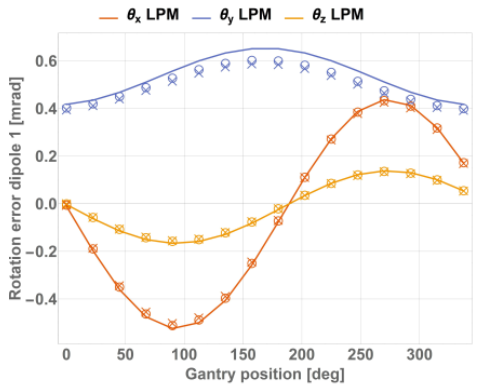
Validation of the models

- Introduction
- Method
- Models
- **Results**



Validation of **6S** LPM

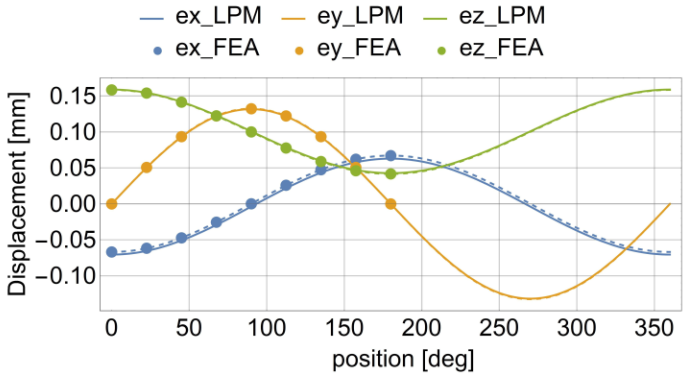


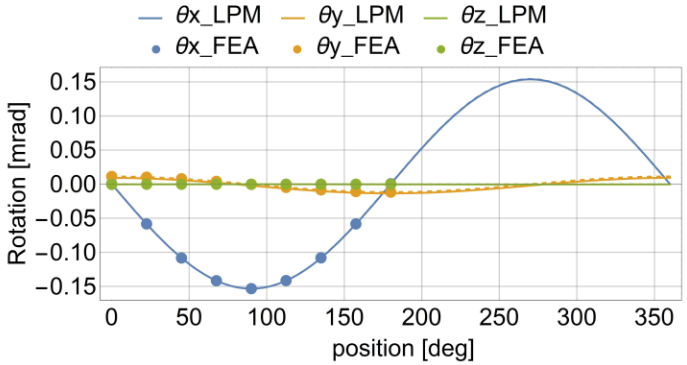


e_x FEA (25 mm) e_y FEA (25 mm) e_z FEA (25 mm)
e_x FEA (15 mm) e_y FEA (15 mm) e_z FEA (15 mm)

θ_x FEA (25 mm) θ_y FEA (25 mm) θ_z FEA (25 mm)
θ_x FEA (15 mm) θ_y FEA (15 mm) θ_z FEA (15 mm)

Validation of **8S** LPM





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