

Status on NHa C400 Cyclotron for Hadrontherapy

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¹ NHa ; ² IBA



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Life.
Science.



Introducing ...



NHa is a company located in Caen, France

NHa 2 main shareholders are



&



(public private company with **Normandy Region** as main shareholder)



Design, produce and market
the ion therapy system



involve in the design

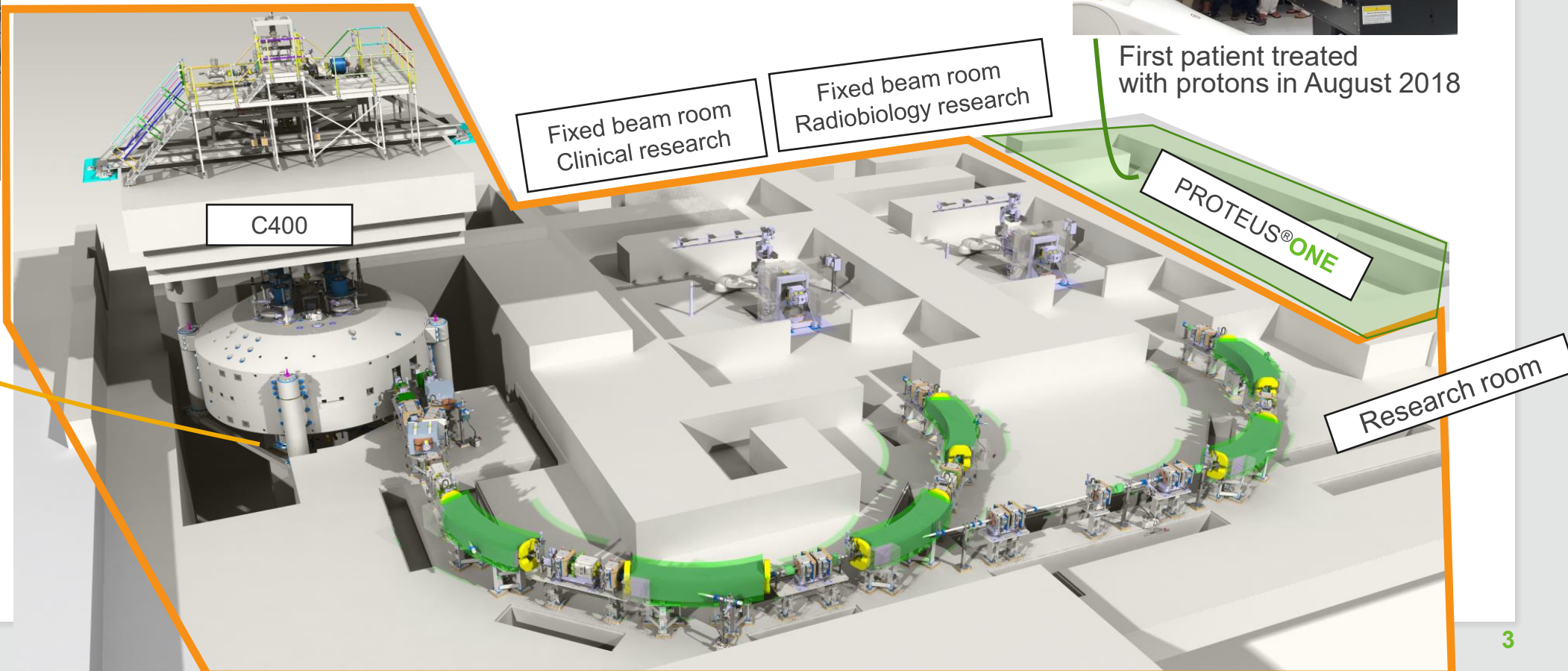
First site is CYCLHAD project



First patient treated with protons in August 2018

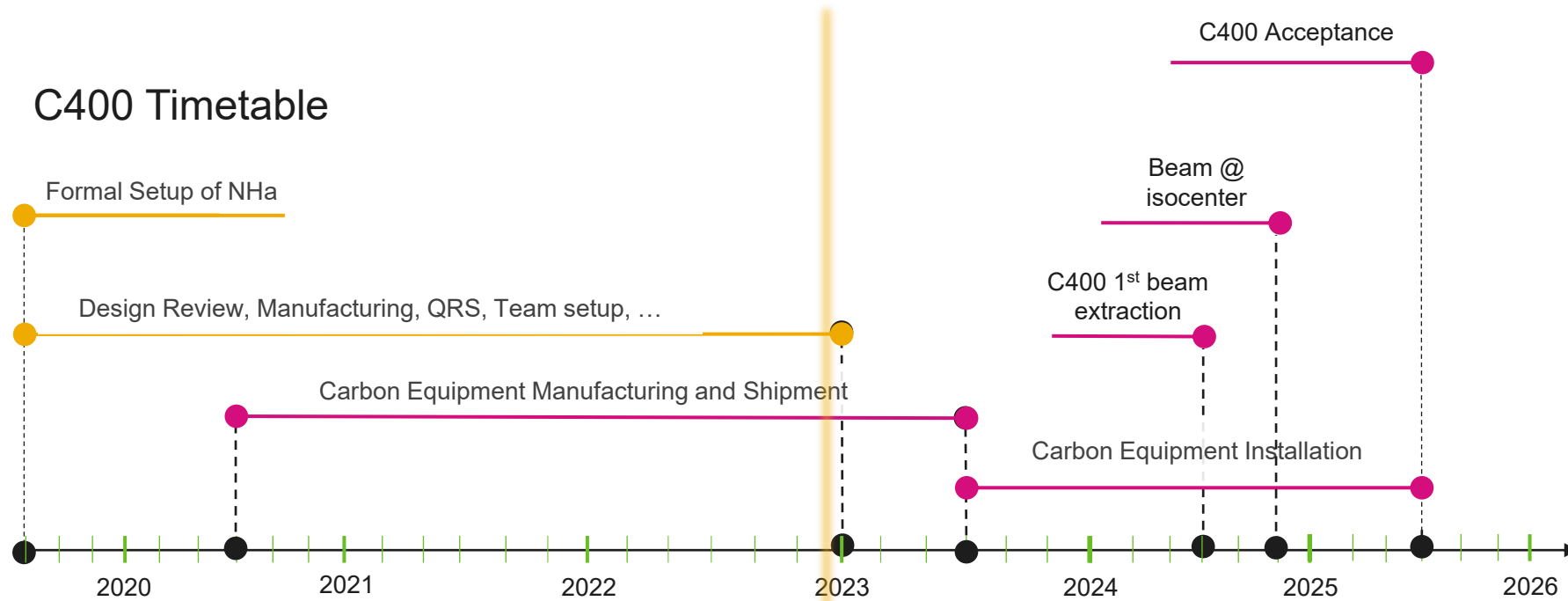


Bunker ready to host the C400



C400 timetable

C400 Timetable



Design overview

Present work is based on the design from the **IBA-JINR collaboration**, reviewed by experts of our community.

Table B1: Summary of the C400 cyclotron Main parameters

General properties	
accelerated particles	H ₂ ⁺ , ⁴ He ³⁺ , (⁶ Li ³⁺), (¹⁰ B ⁵⁺), ¹² C ⁶⁺
injection energy	25 keV/Z
final energy of ions, protons	400 MeV/amu 265 MeV/amu
extraction efficiency	70 % (by deflector)
number of turns	~1700
Magnetic system	
total weight	700 tons
outer diameter	6.6 m
height	3.4 m
pole radius	1.87 m
valley depth	60 cm
bending limit	K = 1600
hill field	4.5 T
valley field	2.45 T
RF system	
radial dimension	187 cm
vertical dimension	116 cm
frequency	75 MHz
operation	4th harmonic
number of dees	2
dee voltage center	80 kV
extraction	170 kV

We didn't change C400 parameters from 2009

... but we did an extra pass on all subsystems.

Design Report of Superconducting Cyclotron C400 for Hadron Treatment

JINR

V. Aleksandrov, G. Shirkov, E. Syresin,
G. Karamysheva, N. Kazarinov, S. Kostromin, N. Morozov, E. Samsonov, V. Shevtsov, A. Tusikov, V. Romanov

IBA

Y. Jongen,
W. Kleeven, S. Zaremba, D. Vandeplassche, F. Stichelbaut,
S. Deneuter, S. Déprez, W. Beeckman

SIGMAPHI & co

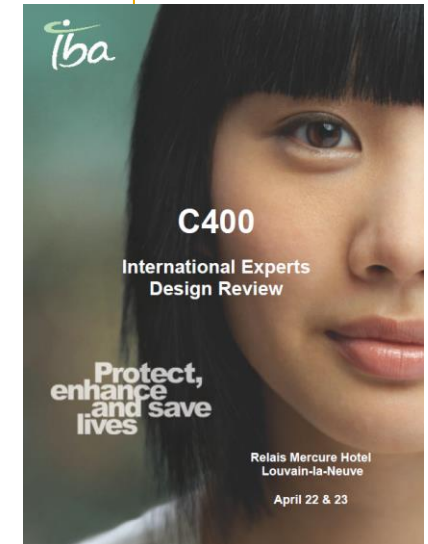
J-L. Lancelot,
W. Beeckman, F. Forest, M.N. Wilson, C. Monroe

International Experts Design Review
Louvain-la-Neuve
22 & 23 April 2009



C400 Design review April 2009

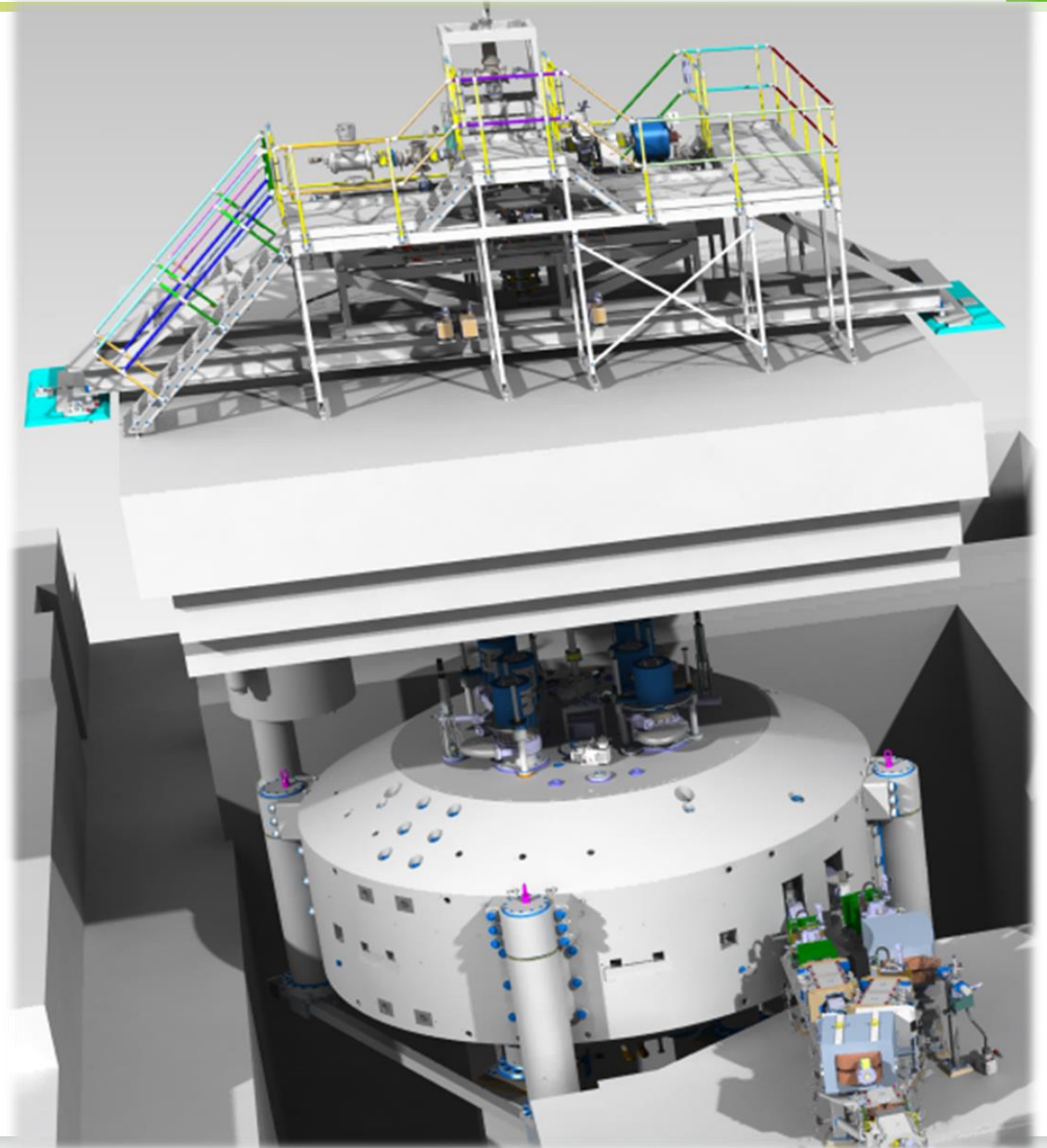
IBA Confidential



Design overview

Basics:

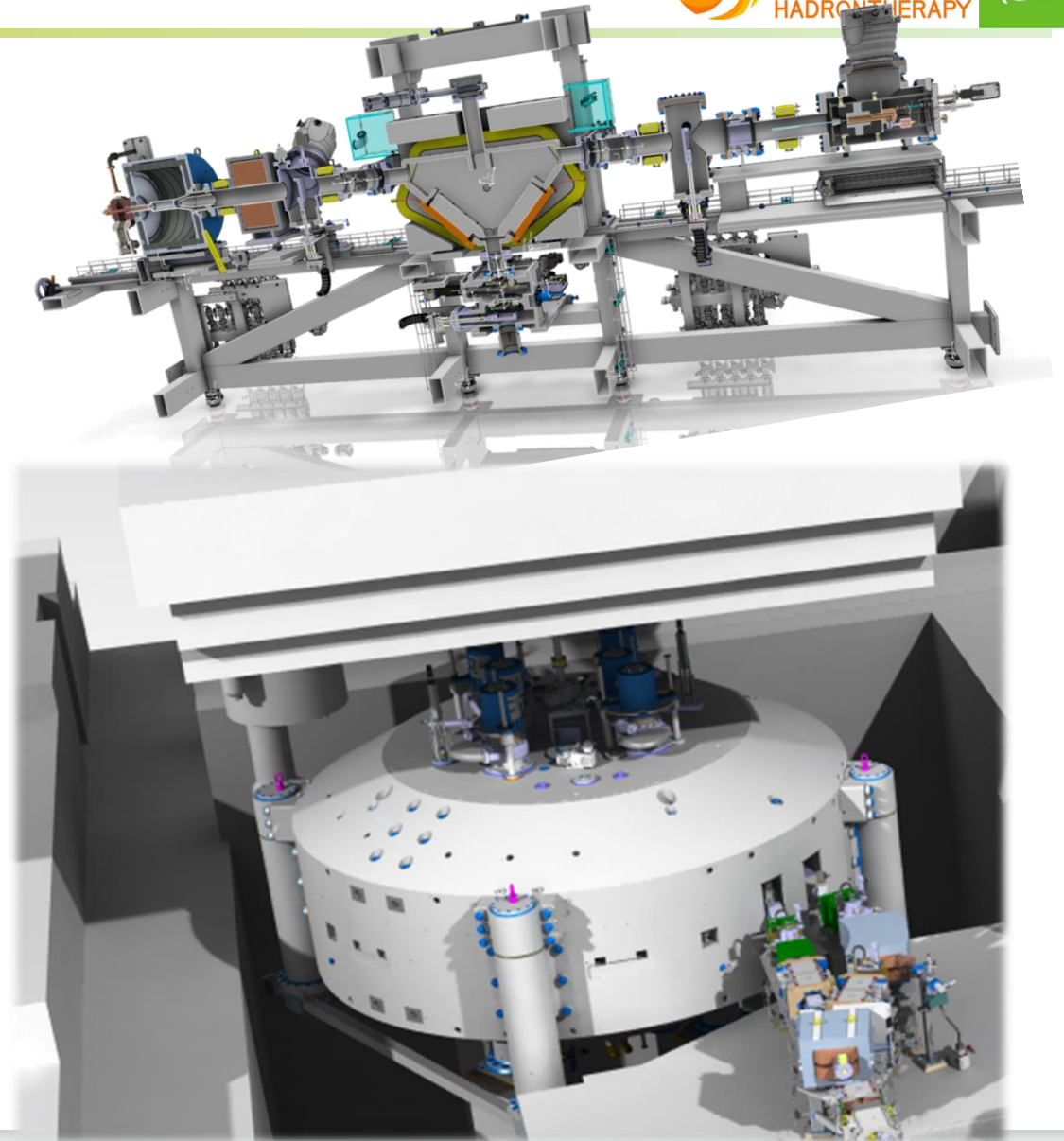
- 3 sources H_2^+ , $^4\text{He}^{2+}$ & $^{12}\text{C}^{6+}$
- Dual extraction:
 - H_2^+ @ ~265 MeV/u: protons extracted via stripping
 - $^4\text{He}^{2+}$ & $^{12}\text{C}^{6+}$ @ 400 MeV/u: via electrostatic deflector
- RF: 75MHz for $^{12}\text{C}^{6+}$, 75.6MHz for H_2^+ , Harmonic #4
- Large “compact” magnet
 - 740 Tons – 7m diameter yoke - pole radius 1.87m
 - pole is 4-fold symmetry / Elliptical gap / Spiralized poles
- Cryogenic coils
 - max field 4.5T,
 - 2 sub-coils/coil to adapt field to particle masses discrepancies.



Design overview

Basics:

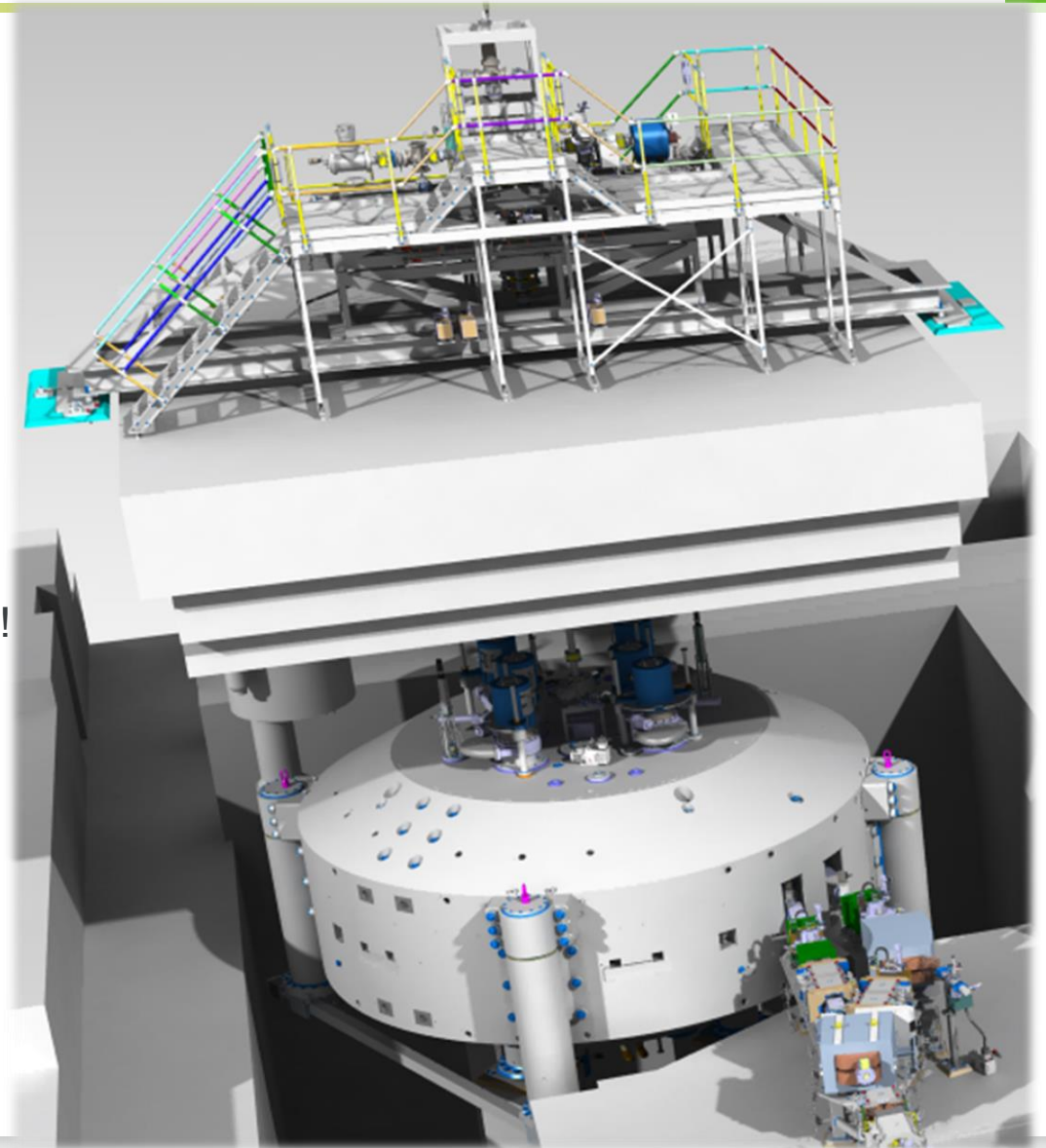
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Inherent challenges

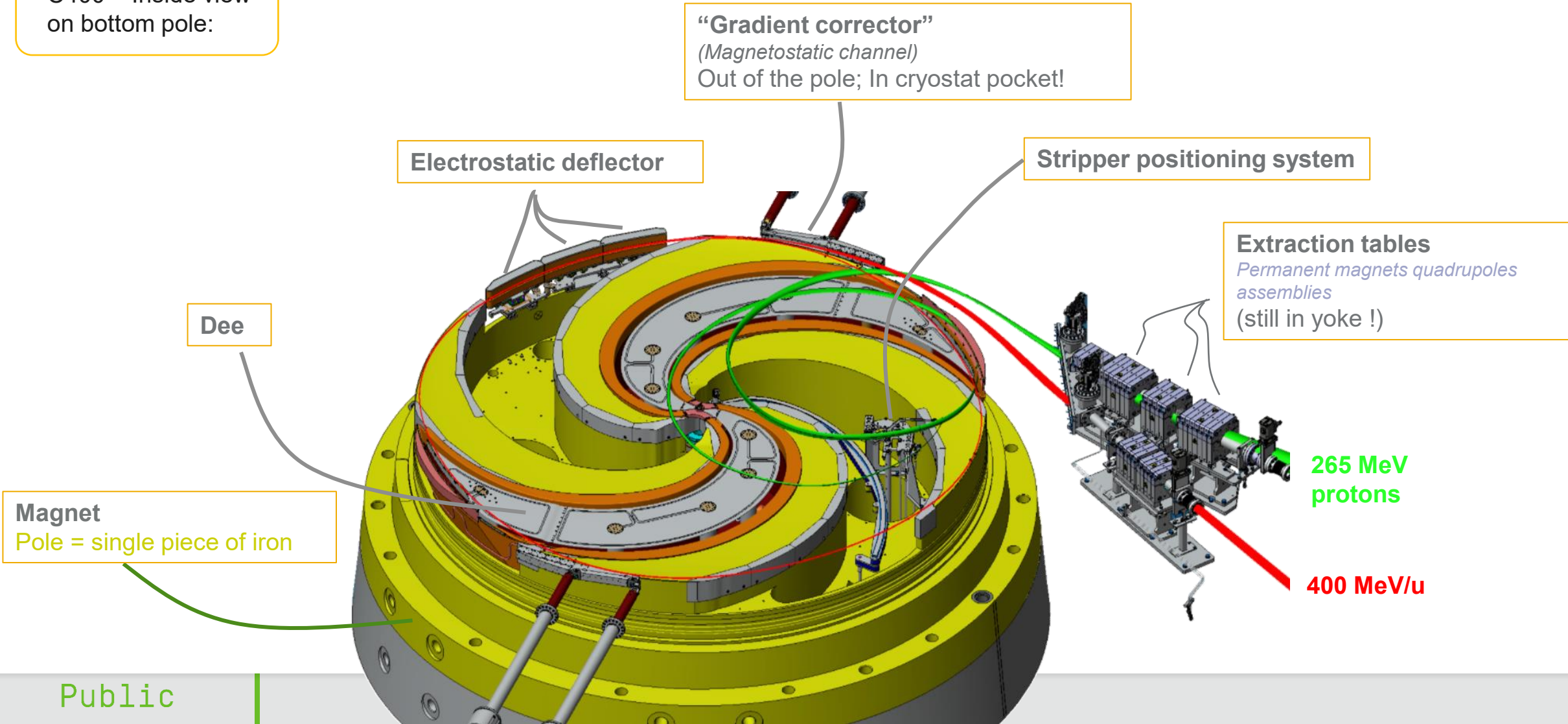
- Big cyclotron related:
 - Size & precision
 - Handling / transport / on site assembly / maintenance
 - Managing Beam Tuning capabilities
- Vacuum requirements @ $2 \cdot 10^{-7}$ mbar
- Fundamental resonance crossing $3Vr=4$

← See poster !



In this talk:

C400 – Inside view
on bottom pole:



Magnet updates

1

Diameter of the pumping holes increased (300 to 440 /520mm dia.),
with small impact on hills azimuthal width.

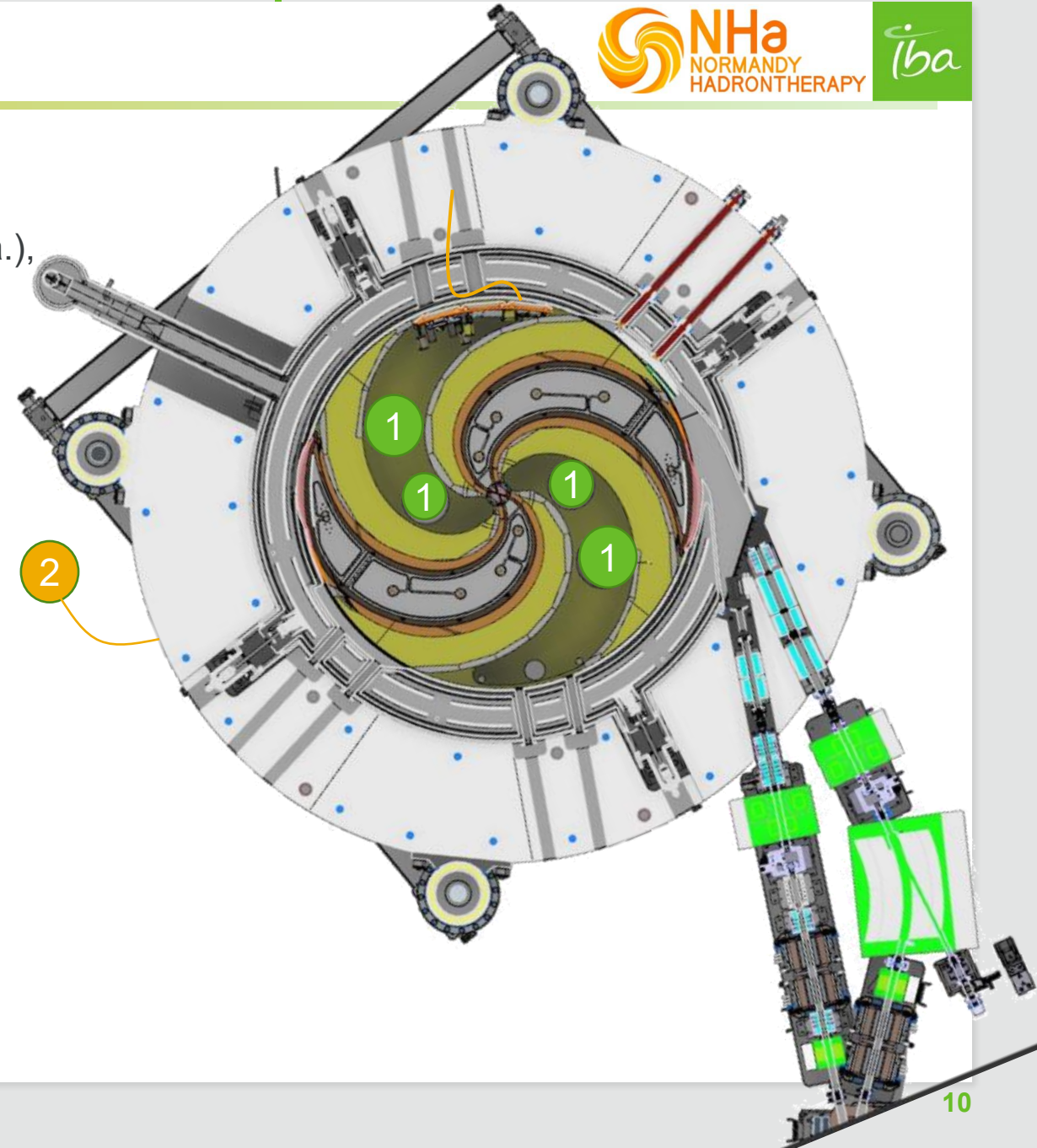
Vacuum requirements, reducing pumping time

2

Increase of Yoke radius because of all the modifications

Requirements on hoop stress for selected SC conductor

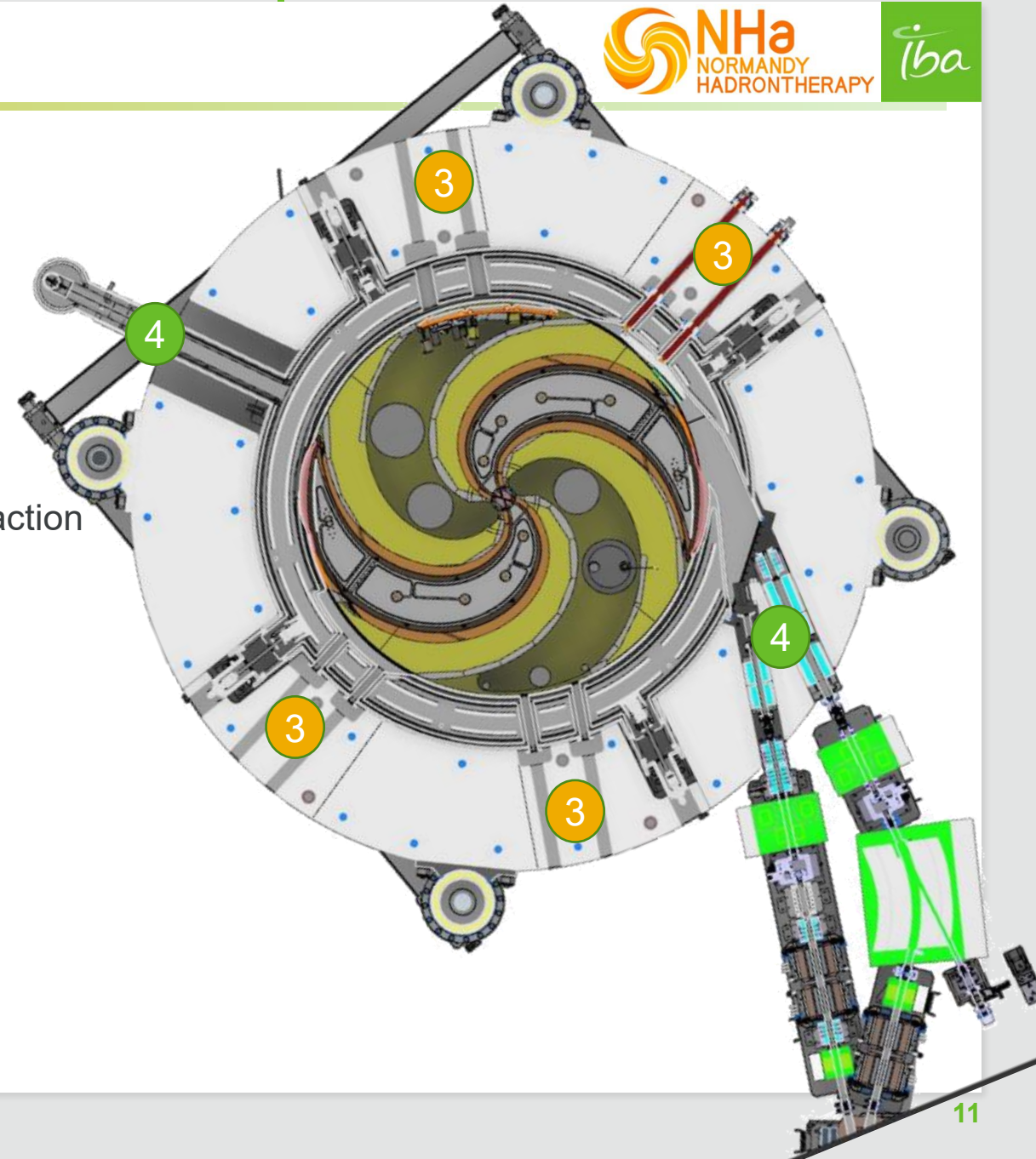
(more iron meaning less current & less stress)



Magnet updates

3 Yoke **penetrations** redefined + relocated + made in 180° symmetry

4 **Service turret for SC coils*** moved to an angle opposite to the extraction
Imposed by cryogenic design



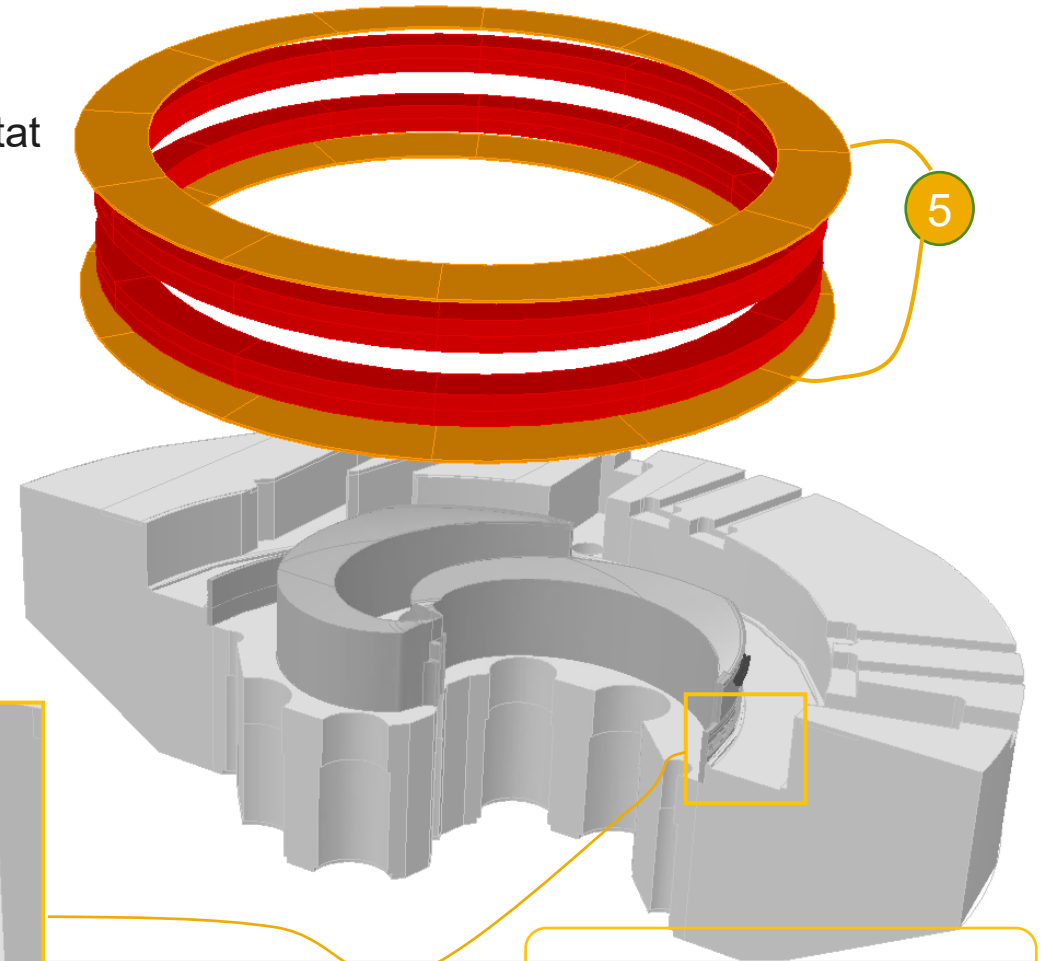
* 2009 Venting touret has been removed

Magnet updates



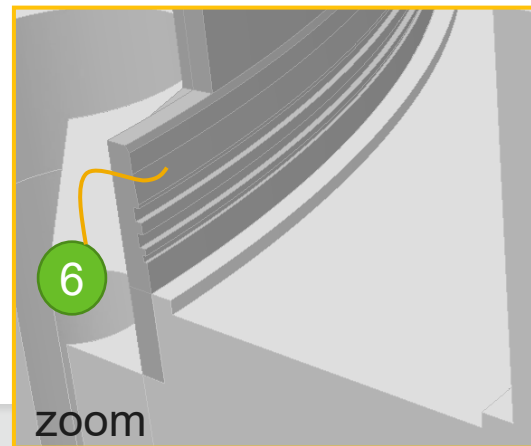
Median plan correction 5

Resistive compensation coils on top & bottom of the cryostat



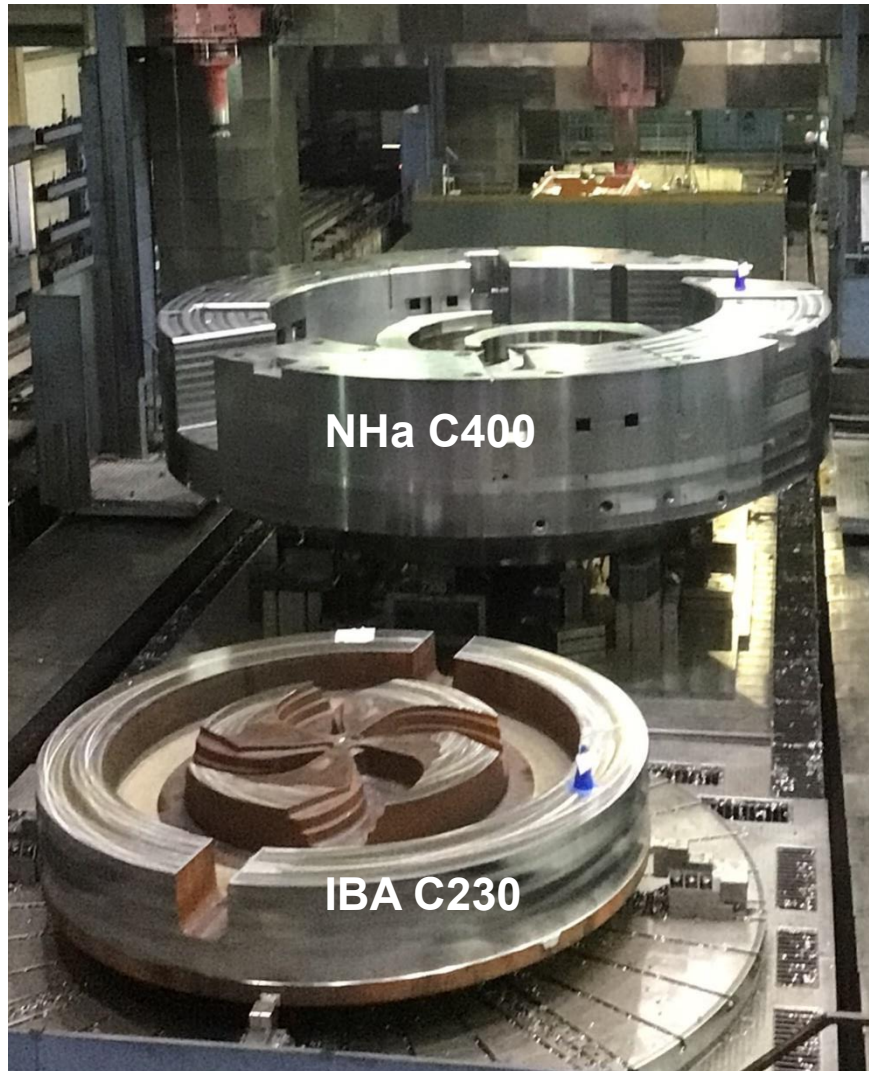
Radial vacuum seals between pole & cryostat

Iron ring in the bottom of the valley, 6



Cut through RF valleys

Magnet



Magnet

Manufacturing

NHa
NORMANDY
HADRON THERAPY

Iba



Magnet



Coils & cryostat



Manufacturing



Coils

Ramping time : 2 hours

Time to switch between particles : < 15 min

Stored energy: ~55.6 MJ

Cold mass at 4.3K: 14.6 tons

turns per coil : 1344

Supra material : NbTi

Critical current: 2800 A @ 4,5 T @ 4,2 K

Conductor peak field: 3.9T

Current density : ~31 A/mm²

Coils current:

- PS1 ~1034 A (on all 4 sub coils)
- PS2 (max 120A) (only on 2 sub coils)

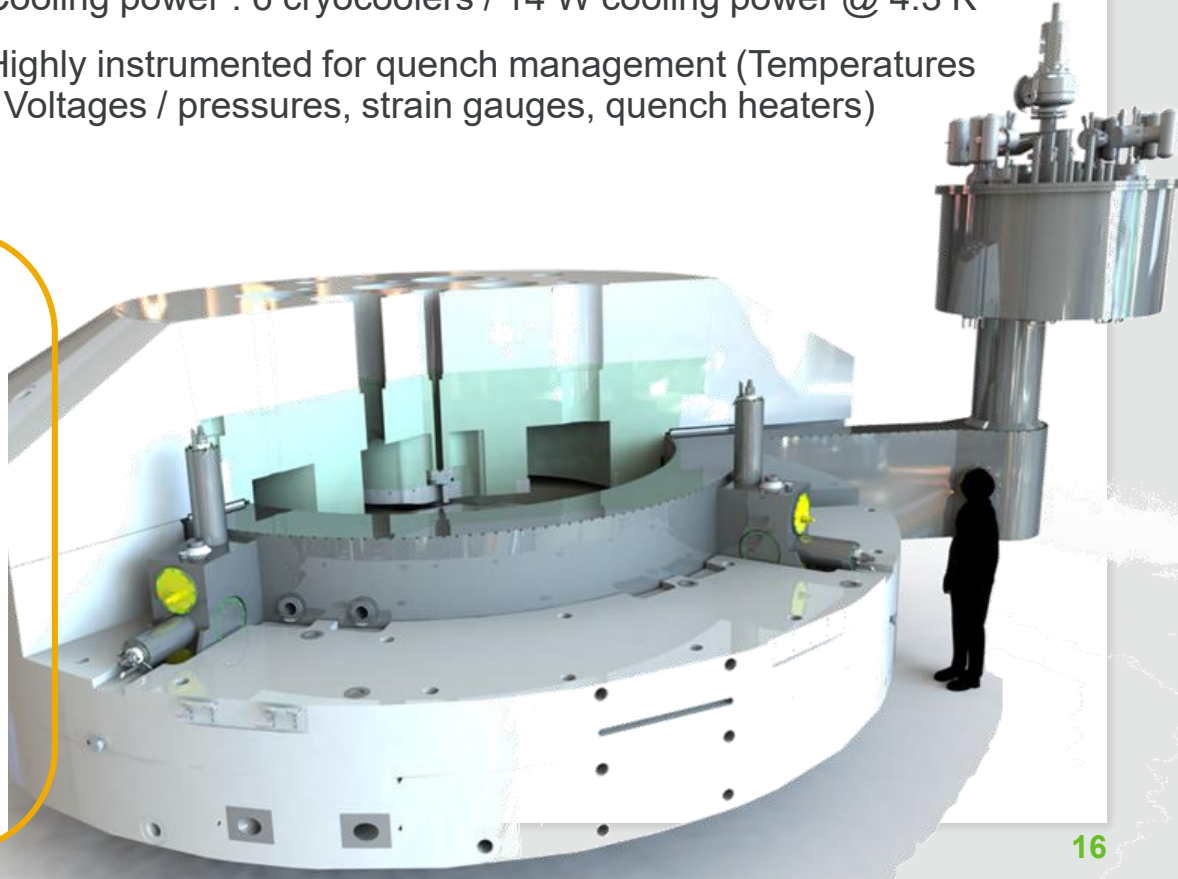
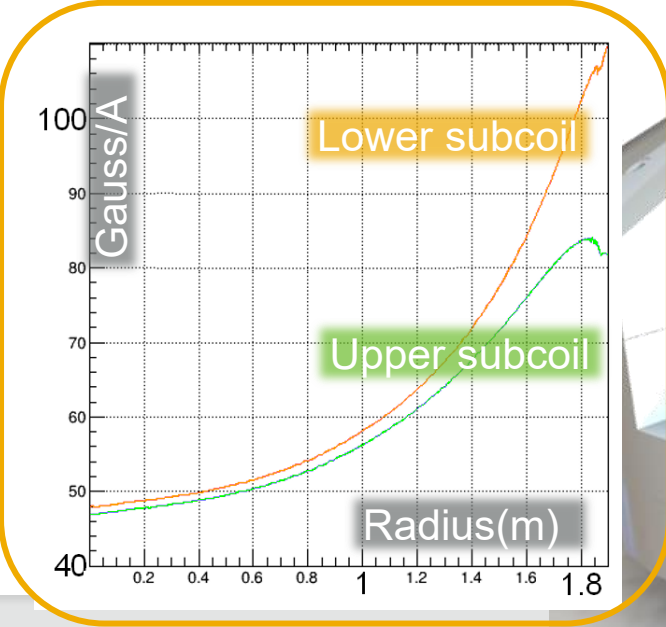
Cryostat

Outer diameter: 4.8m
Liquid helium bath T°: 4.3 K

Liquid helium thermosyphon circulation system

Cooling power : 6 cryocoolers / 14 W cooling power @ 4.3 K

Highly instrumented for quench management (Temperatures / Voltages / pressures, strain gauges, quench heaters)



Coils & cryostat

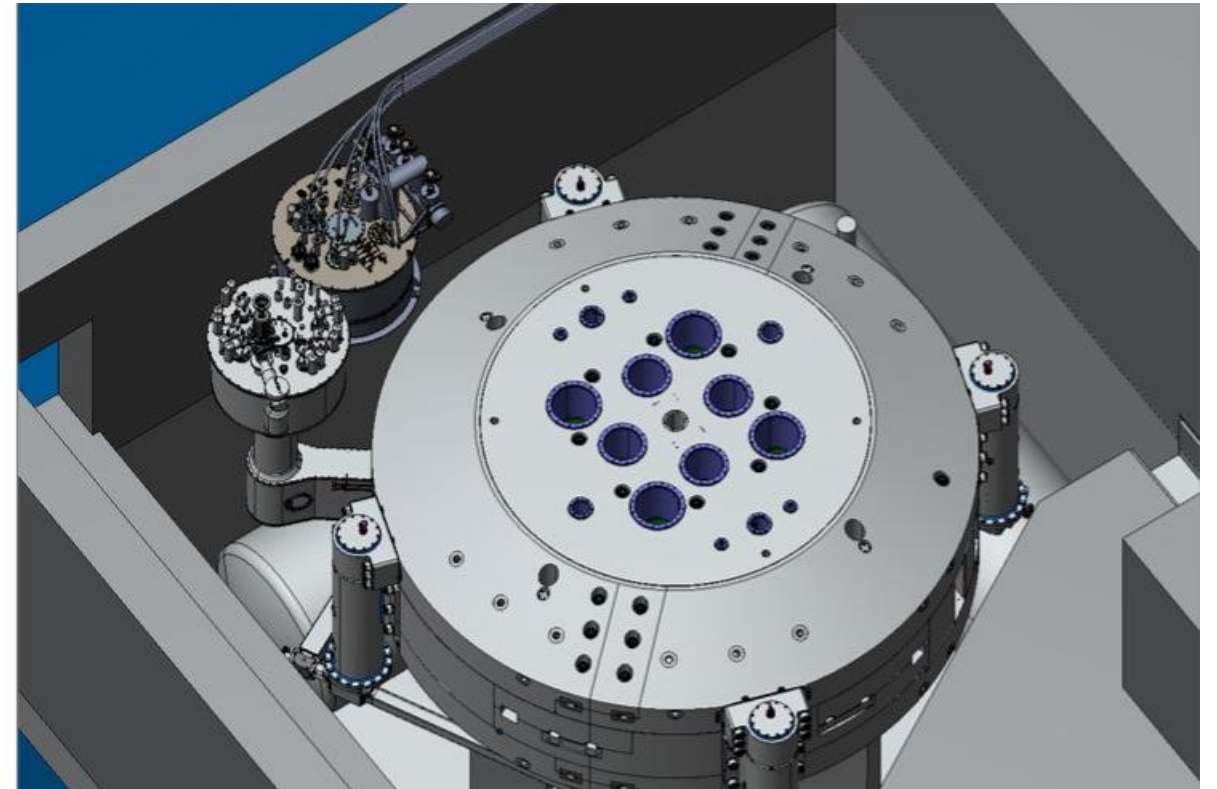
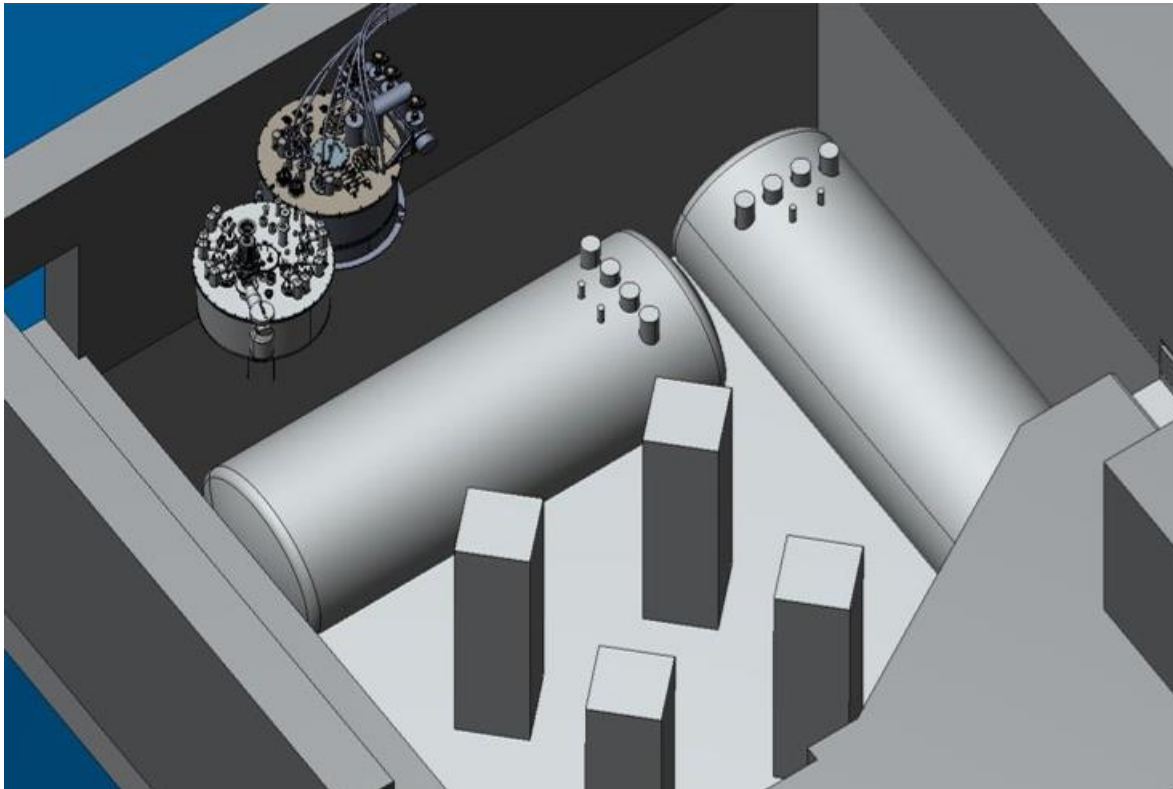
Under study



Liquefaction

Since 2009, price of Helium has been multiplied by > 6

Tanks installed below c400 to recover vaporized Helium during potential quenches.



Coils & cryostat

Manufacturing

NHa
NORMANDY
HADRON THERAPY

Iba

Helium vessel (Coils inside, welding completed)



Mapping wheel

Drawings released

Mapping

On critical path once cryostat in place

Mapping phase: 88 (!) pole edges to machine iteratively

Requirements for the wheel:

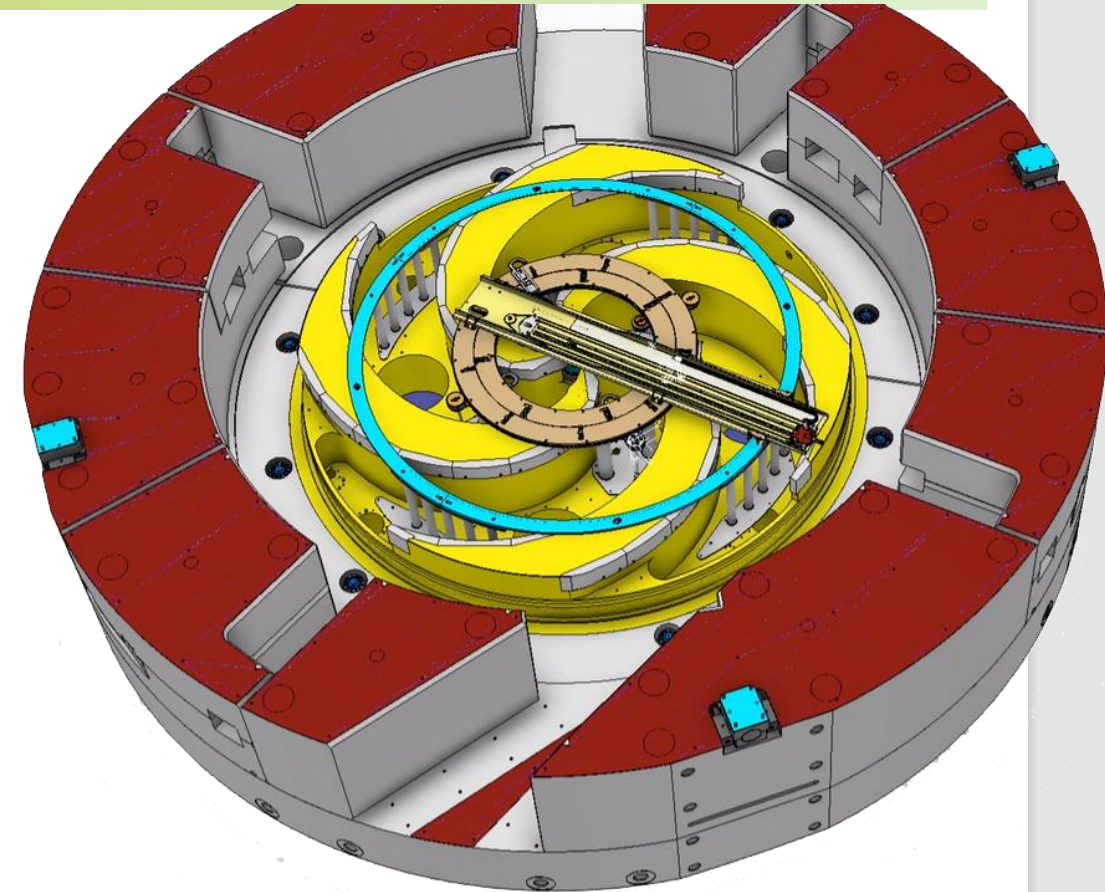
Down to (0.25° & 2mm steps) resolution needed

→ fast mapping option with search coil

2000 turns | harmonic #4

→ high accuracy (position / field)

- with mechanics (*clearance management, rigidity ...*)
- Possibility to map under vacuum
- Hall probe



Use of polymers & composites

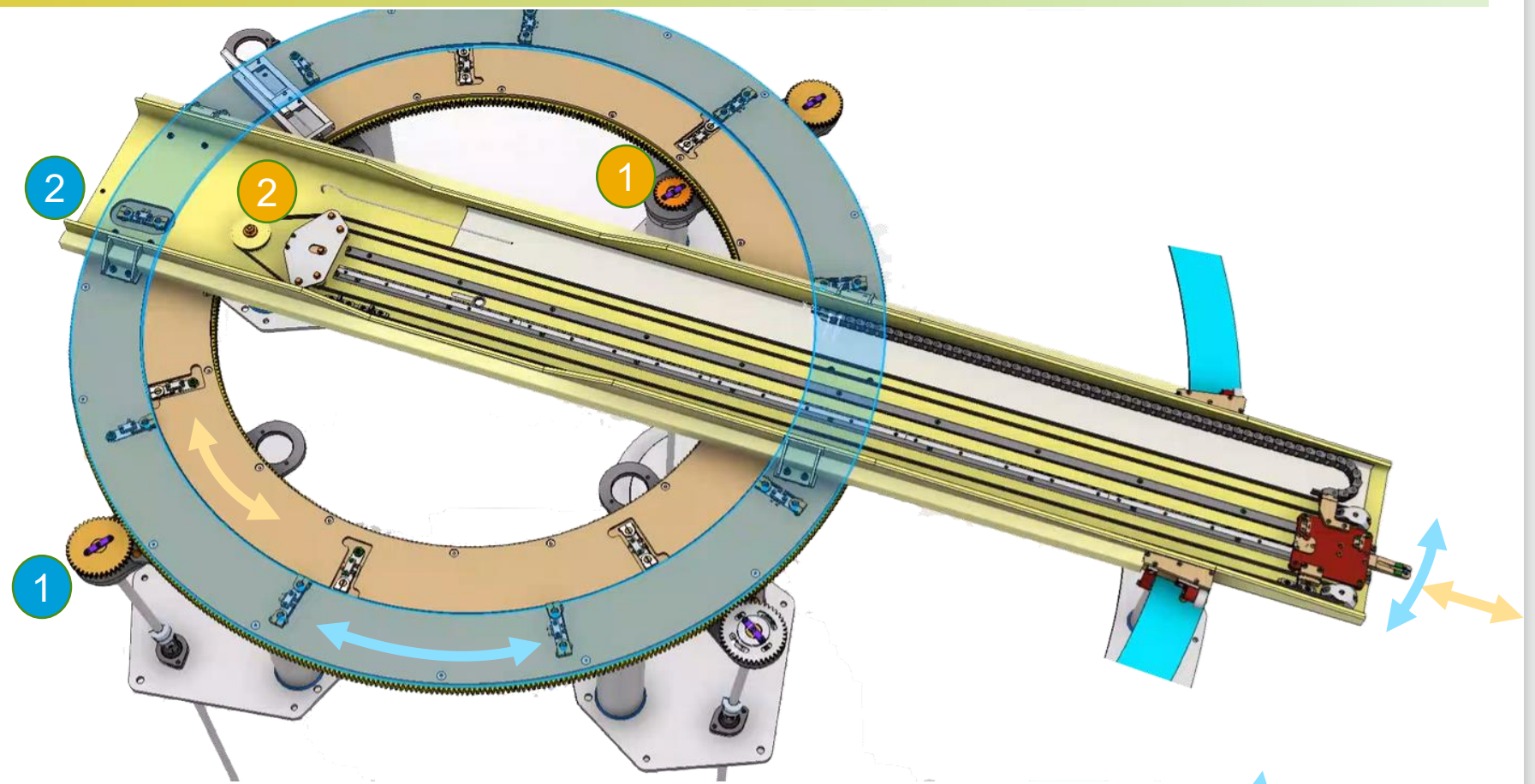
Non-magnetic / No induction / No thermal dilatation

Mapping wheel

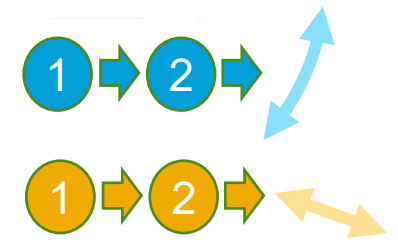
Drawings released



Motions



Independent rotation and translation of the shuttle, driven through pumping holes, via 2 independent discs.

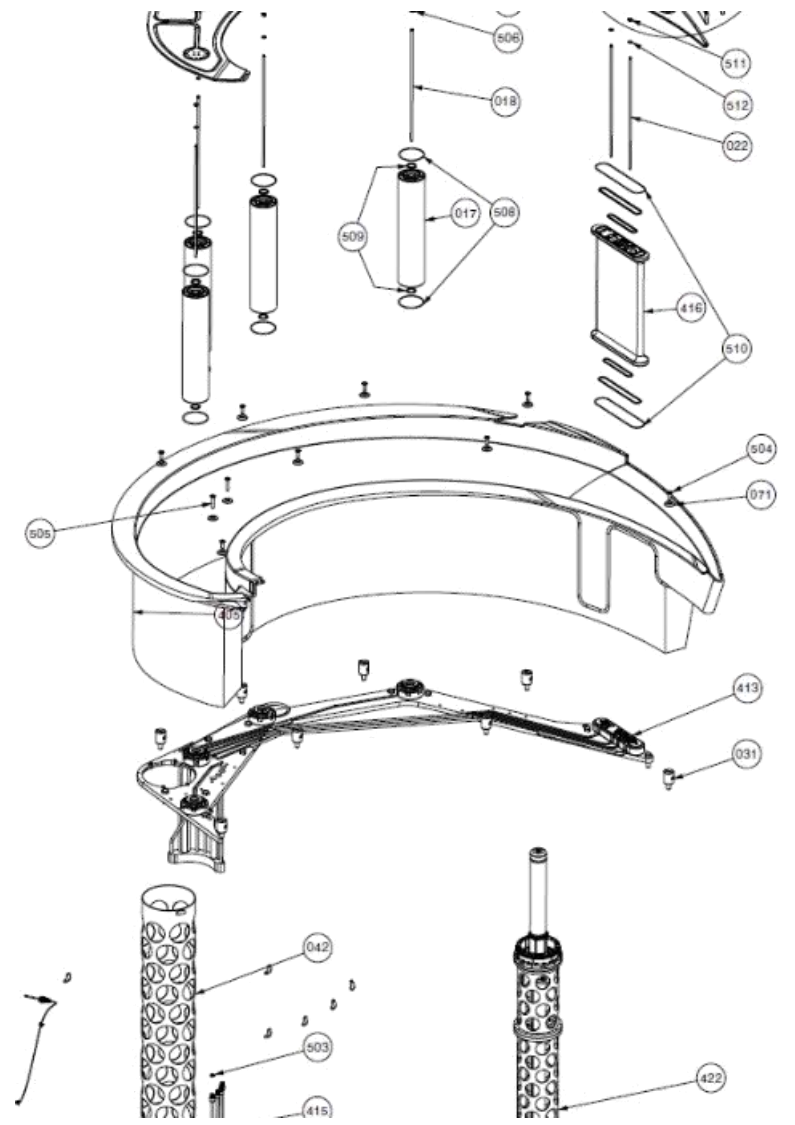
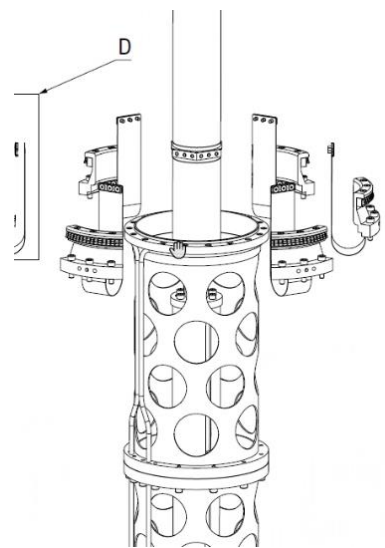
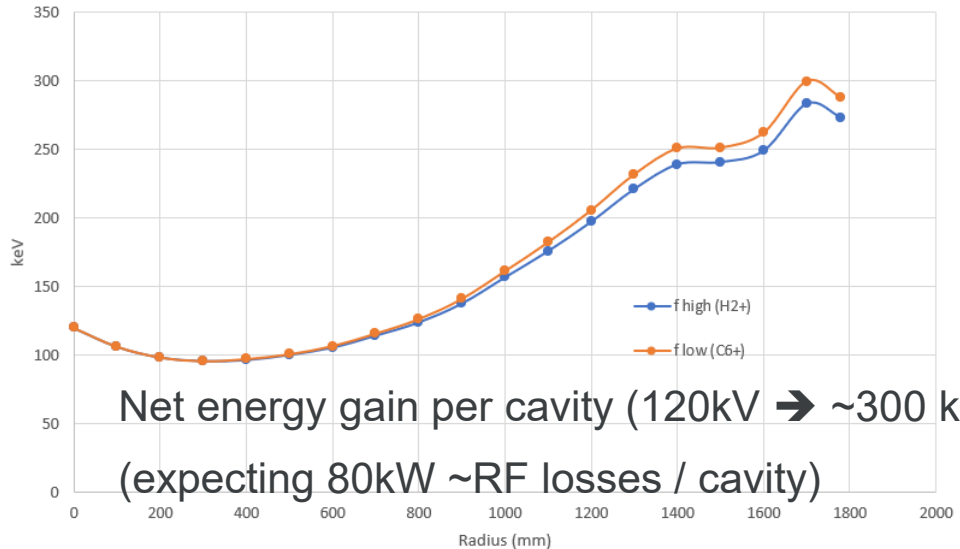


Power consumption has been optimized

mainly working on Dee stems geometry & acceleration gaps width adjustments.

Cyclotron equipped with 4 tuners

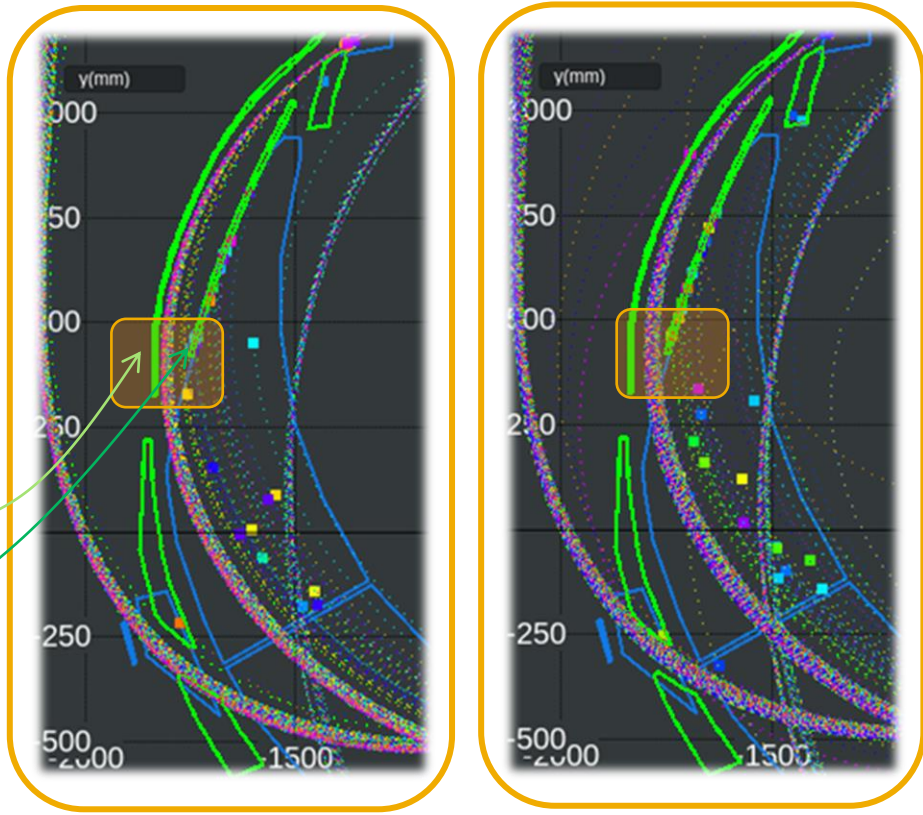
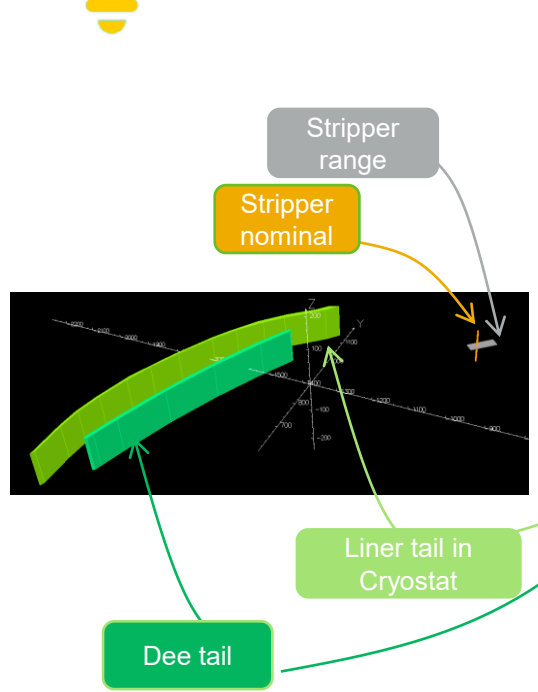
for 1 MHz max frequency tuning – 200mm span.



Each cavity powered by 128kW solid state amplifier (IBA design).

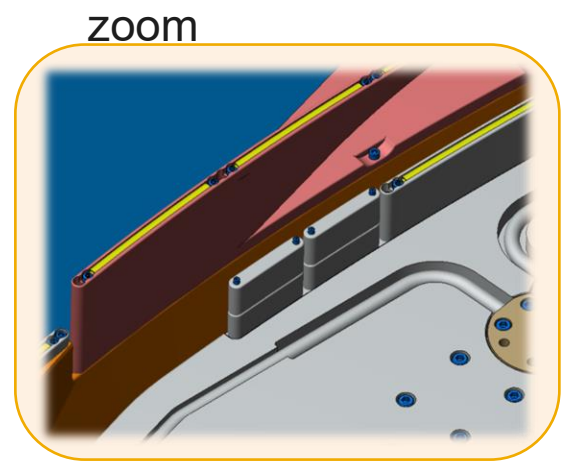


proton loop management



Proton beam between dee tail & RF Liner extension in cryostat

2 cases: 2 possible locations of stripper foil

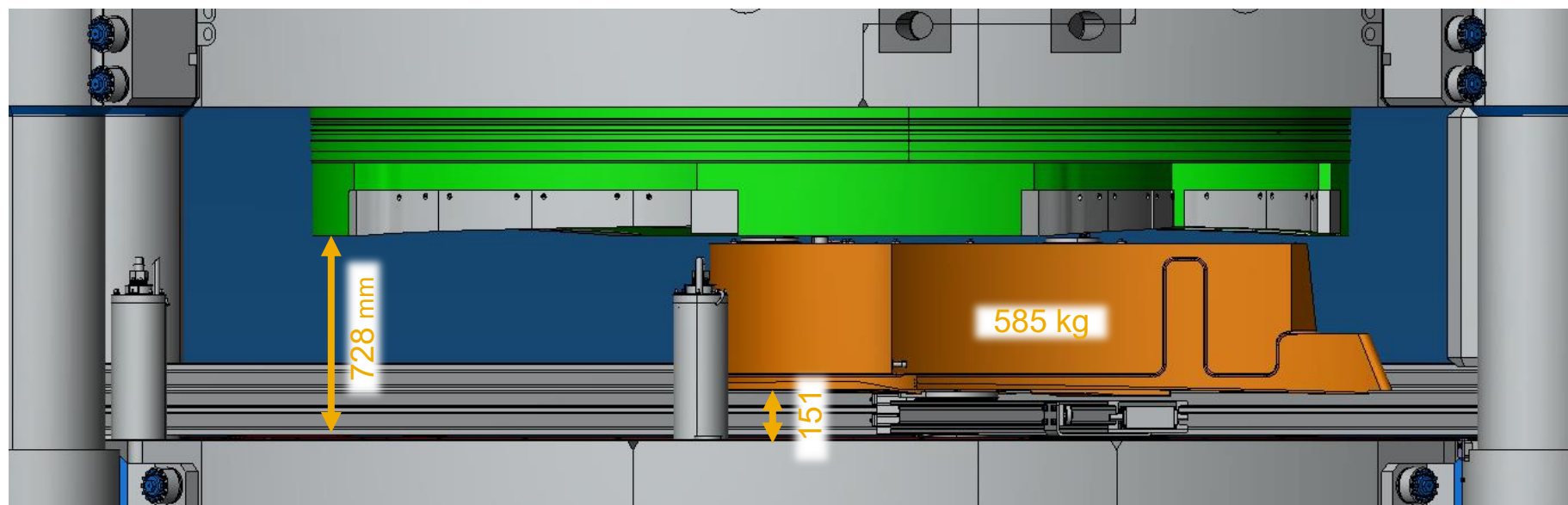


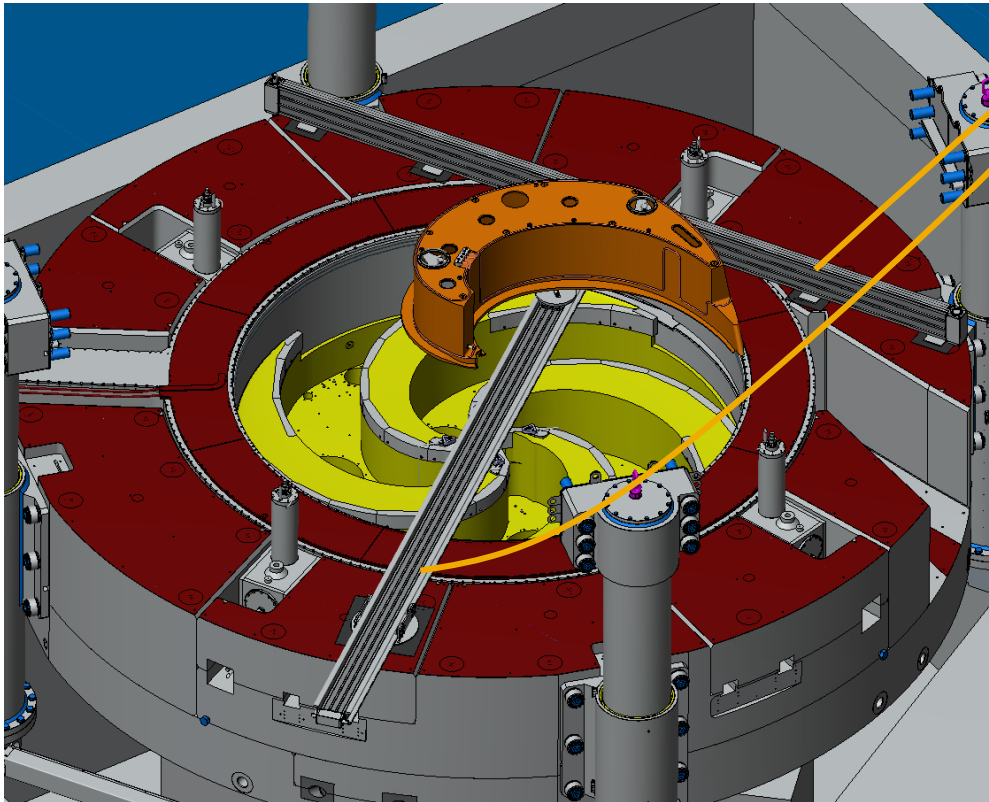
Additional tails once proton extraction tuned*.

* to enhance carbons energy gain per turn

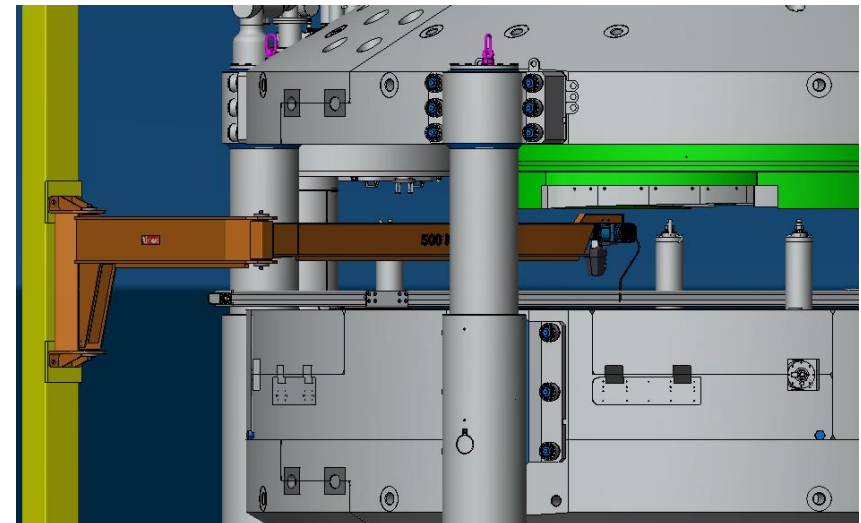


Cavity insertion



 Cavity insertion

Rails with trolleys to position the cavity in the horizontal plane before lifting it through the pumping holes.



A 500 kg jib crane will help the insertion of the rails itself

Process: Sheet metal work (boiler), TIG welding, re-machining



Electrostatic deflector (ESD) & Magnetostatic channel (Gradient corrector – GC)

Their locations affect: Transmission / Emittances size & orientation / position at cryostat exit flange.

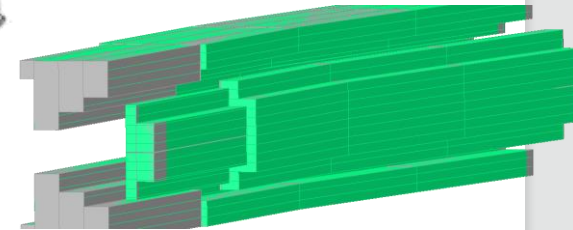
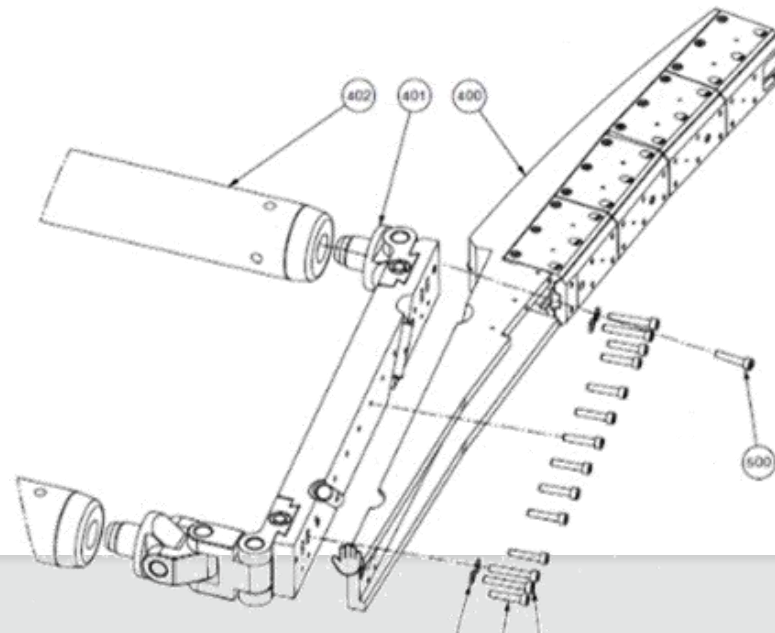
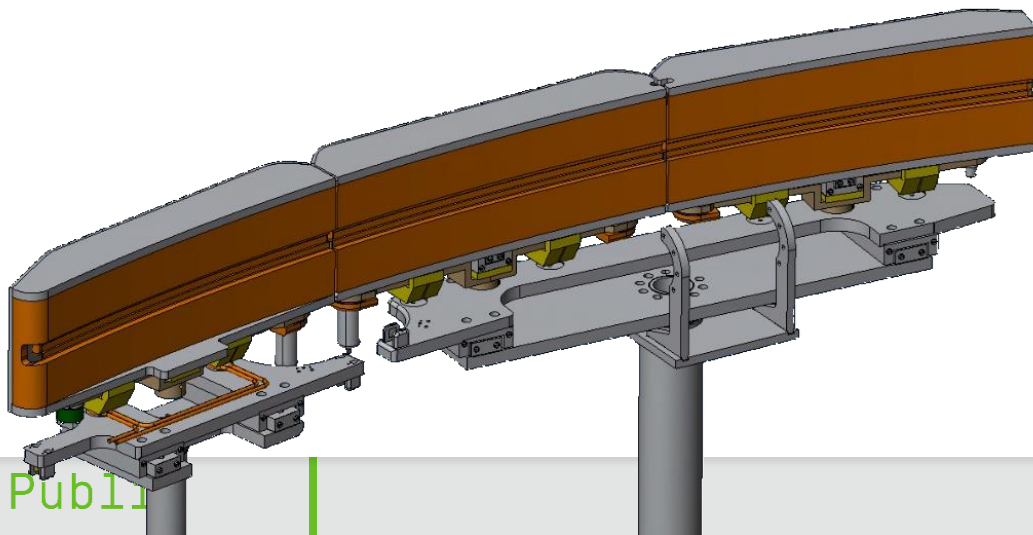
→ Actuators

ESD Design phase

- Entrance position, exit position, gap are adjustable
- Foreseen operating voltage: <50 kV

GC Manufacturing

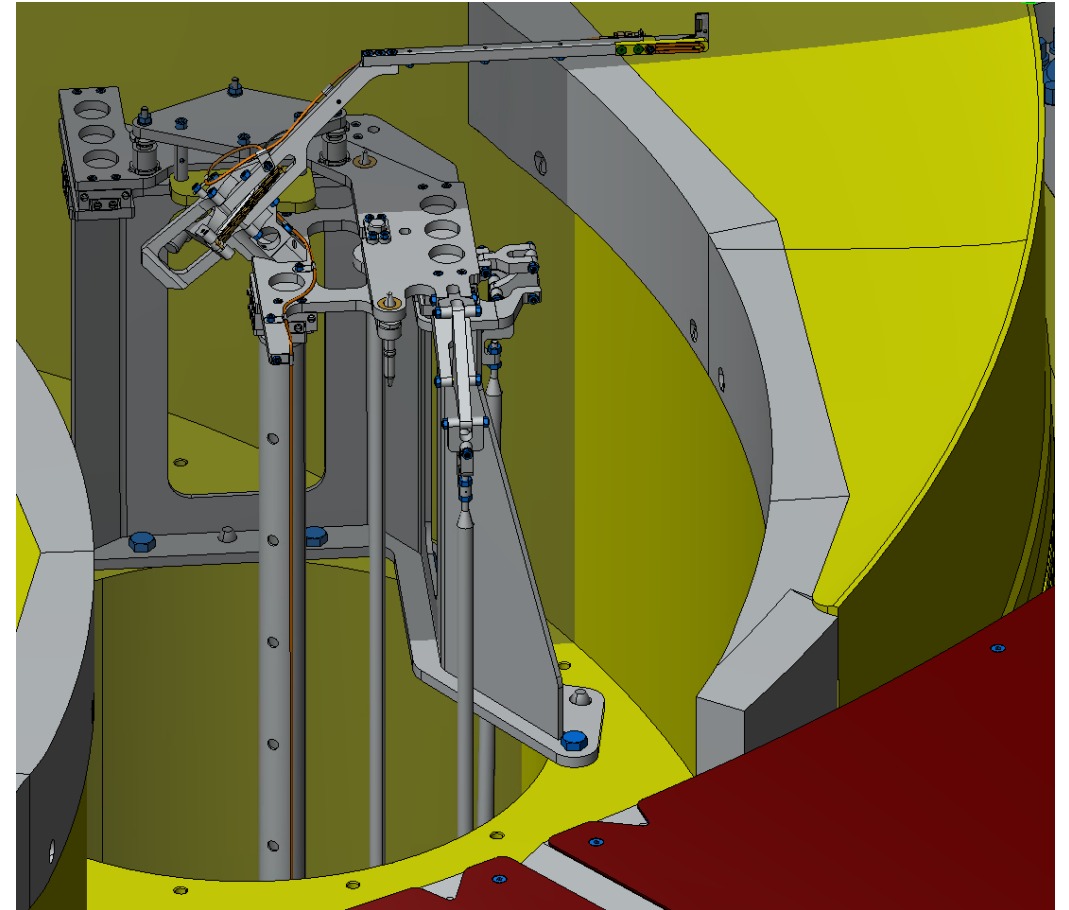
- Entrance position, exit position are adjustable



Stripper

Drawings released

- 25 by 100 mm position **adjustability**
- <0.1 mm position **repeatability**
- Stripper **must be removed** from the median plan to accelerate carbon
- Stripper is a **consumable** which needs to be replaced periodically.
We want to replace it without breaking the cyclo vacuum.
- Stripper **environment**
 - no room to have a radial arm holding the stripper from outside
 - Stripper is between the poles, no simple vertical holding arm



Design updates: Stripper

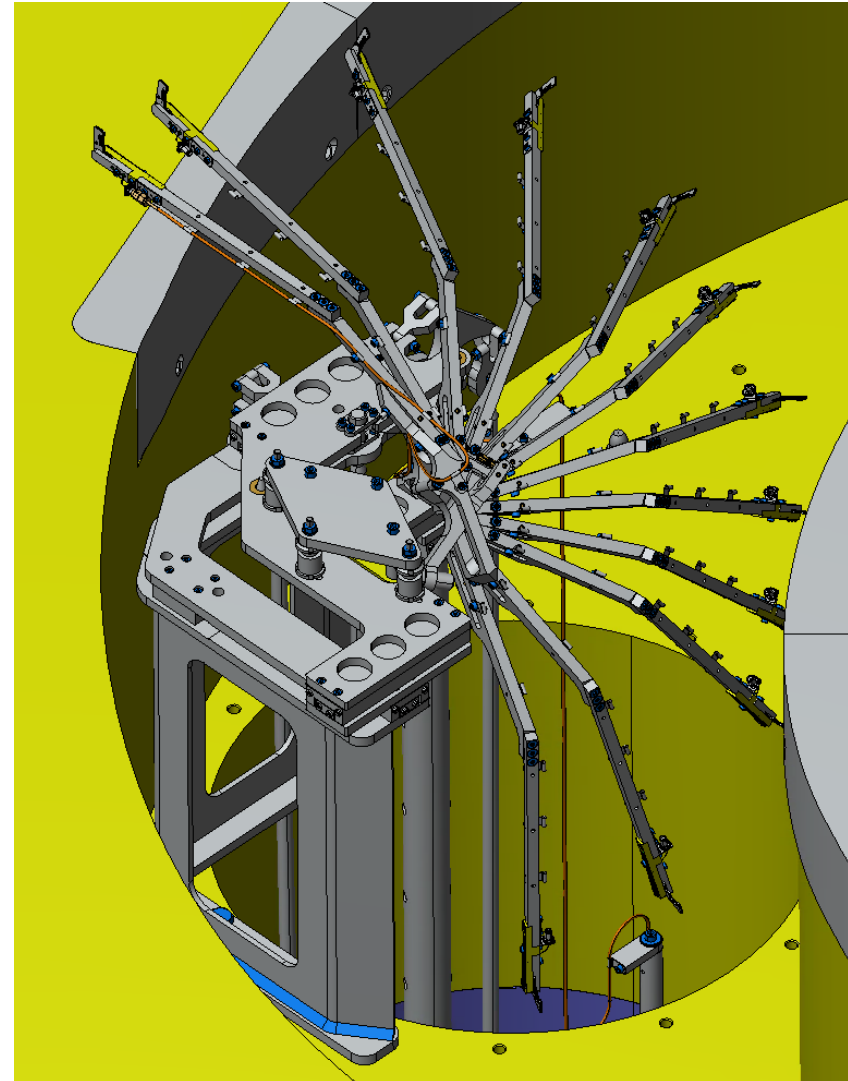
Drawings released



Stripper motion to air lock:

Combined motions of the holding arm

rotation (horizontal to vertical) + vertical translation



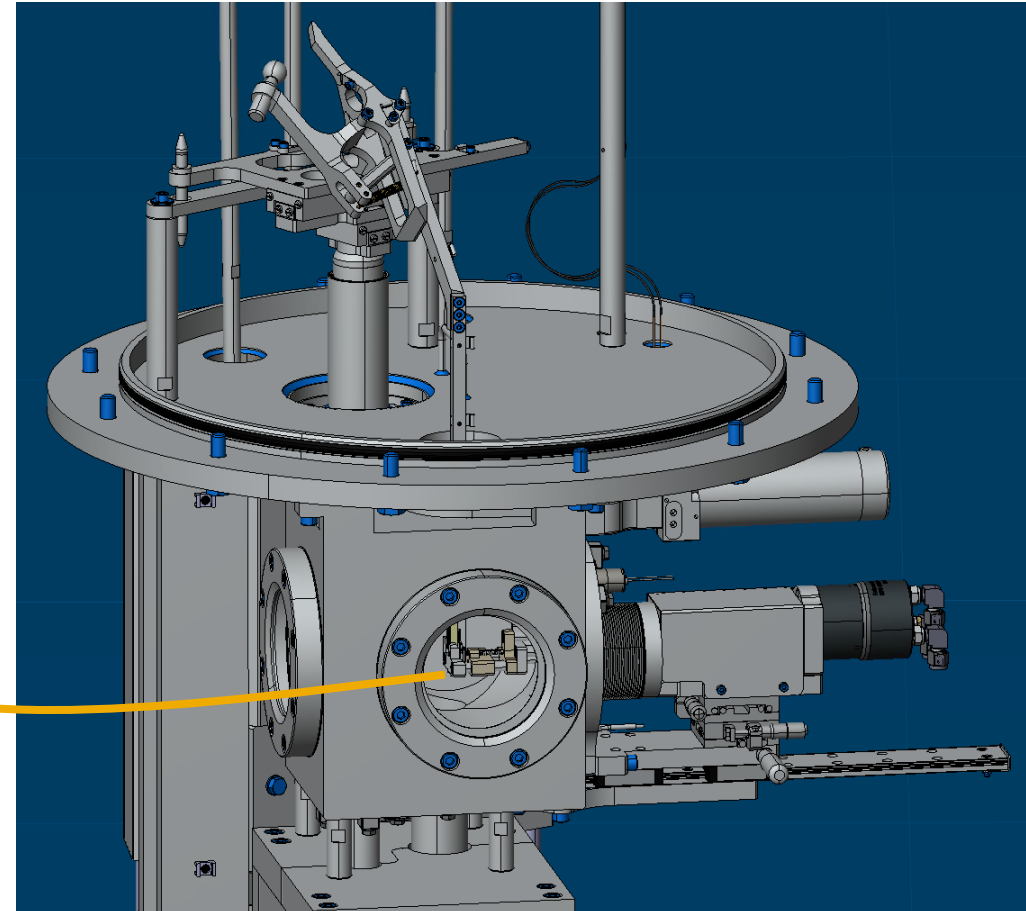
Design updates: Stripper

Drawings released

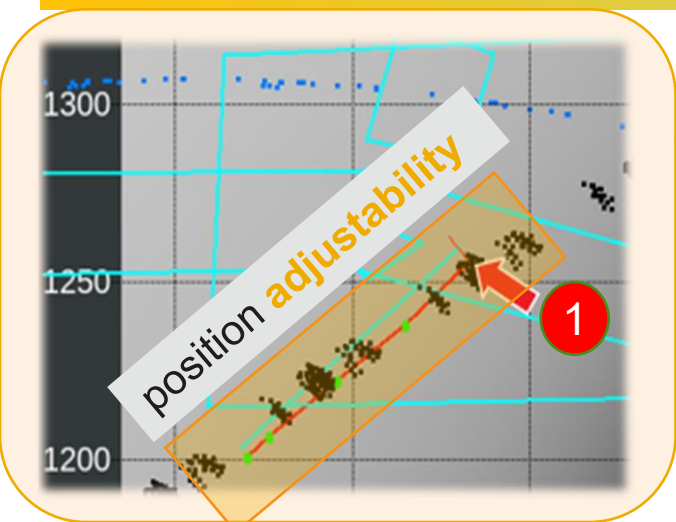


Sequence In the airlock:

- 1 – “Fork docking”: Fork locked on a pin
- 2 – Separation from its holding arm
- 3 – Arm goes back out of the airlock
- 4 – Closing the gate
- 5 – Venting

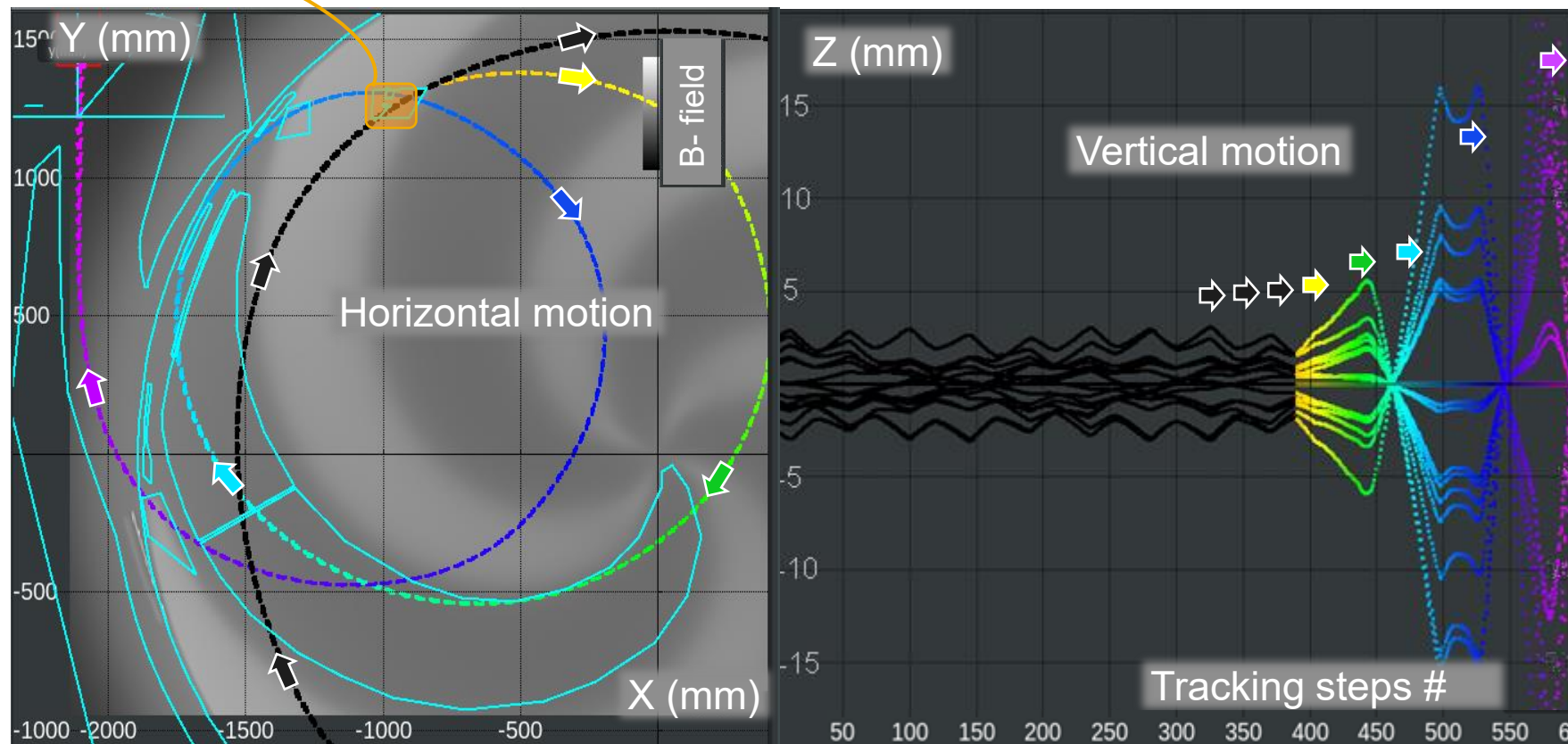


Protons extraction dynamics



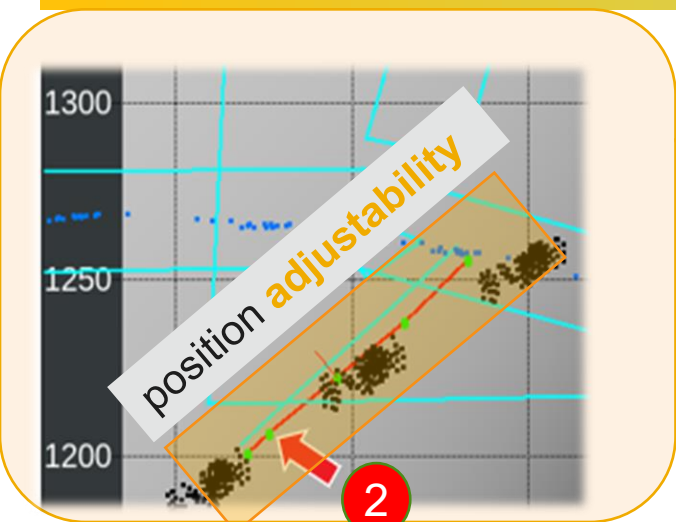
Zoom @ stripper location

Protons extraction: up to cryostat exit flange ; Stripper position 1



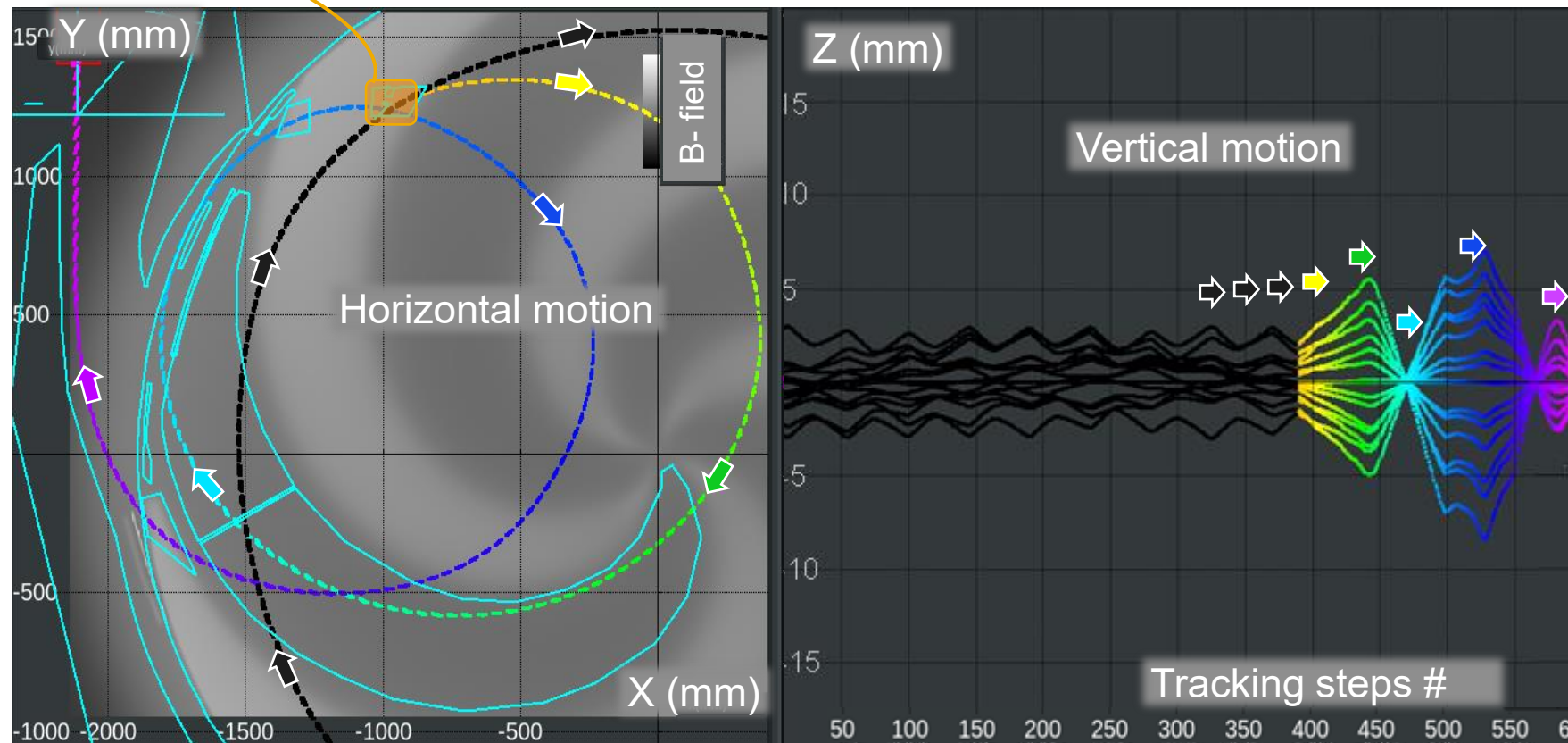
H_2^+ beam Proton beam

Protons extraction dynamics



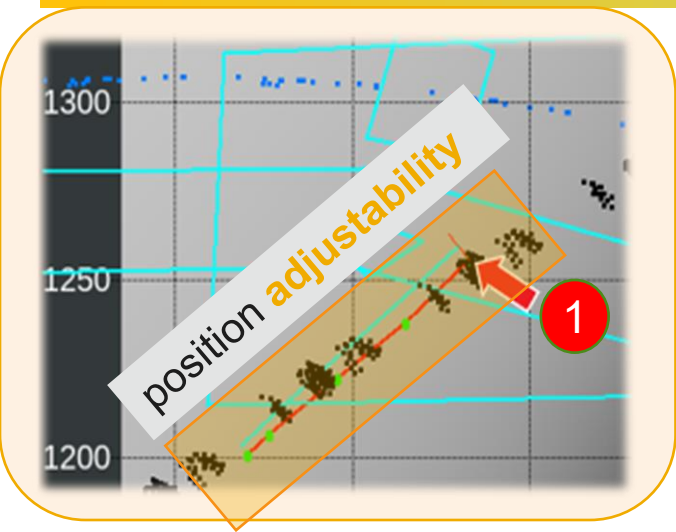
Zoom @ stripper location

Protons extraction: up to cryostat exit flange ; Stripper position 2



H_2^+ beam Proton beam

Protons extraction dynamics

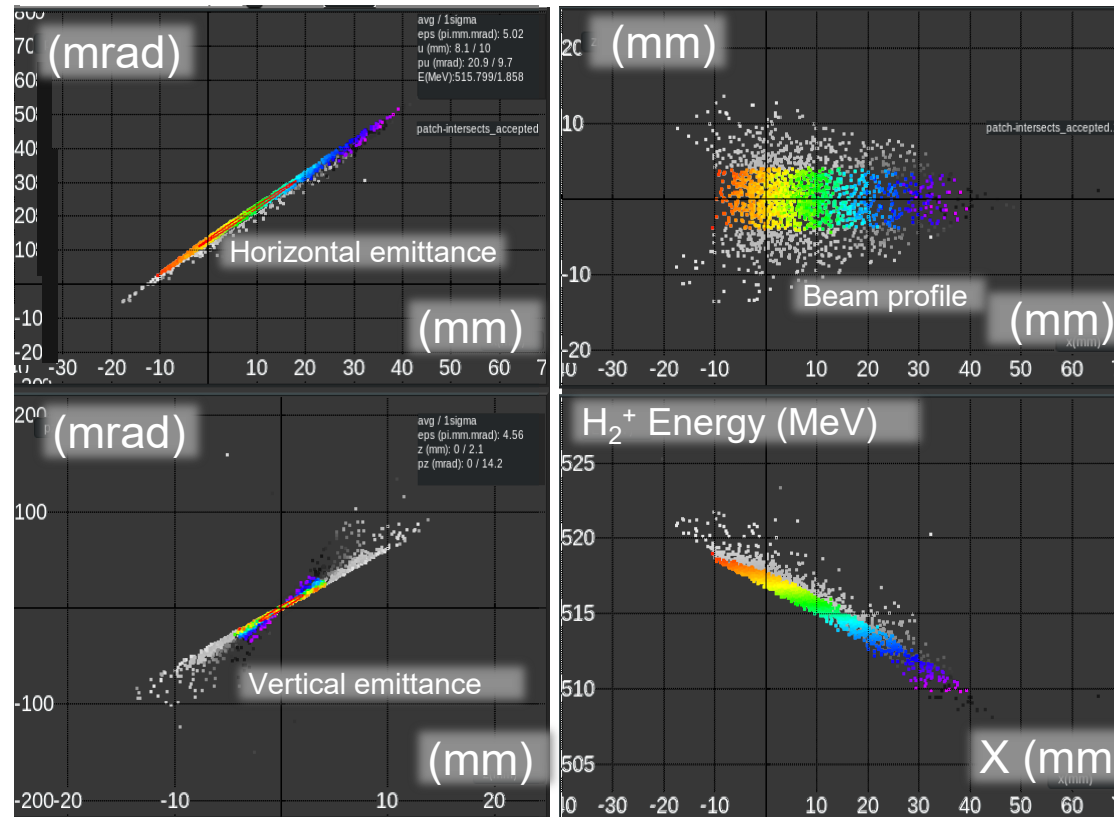


@ stripper location

Considering hits on internal geometry:

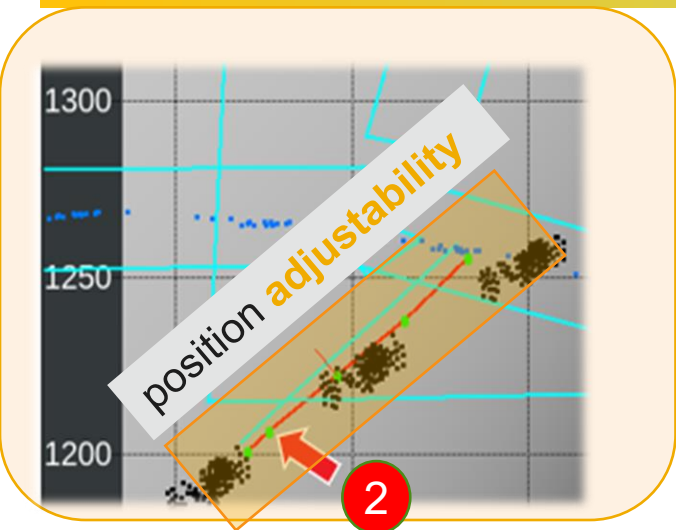
Acceptance

Beam @ cryostat exit flange ; Stripper position **1**



→ Following beam lines designed for large acceptance

Protons extraction dynamics

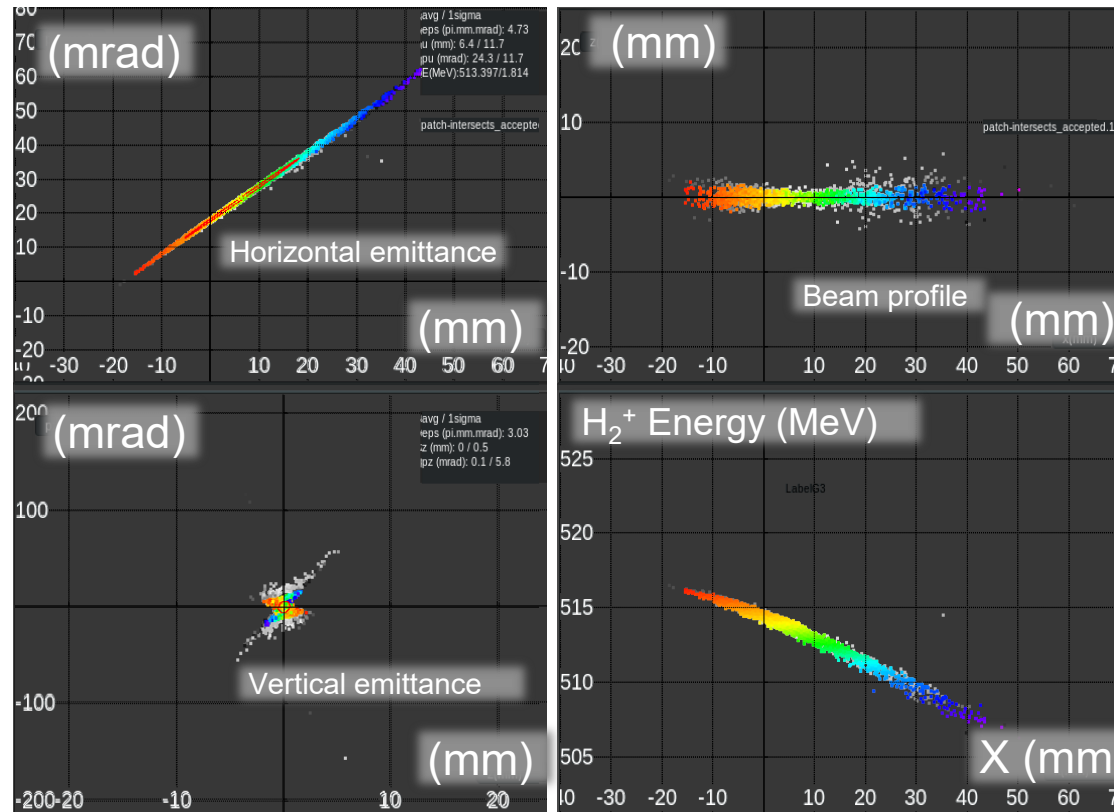


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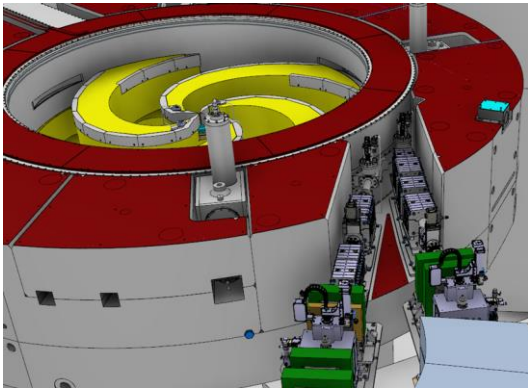
Considering hits on internal geometry:

Acceptance

Beam @ cryostat exit flange ; Stripper position 2



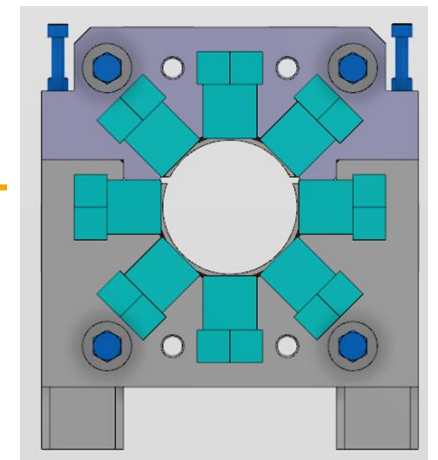
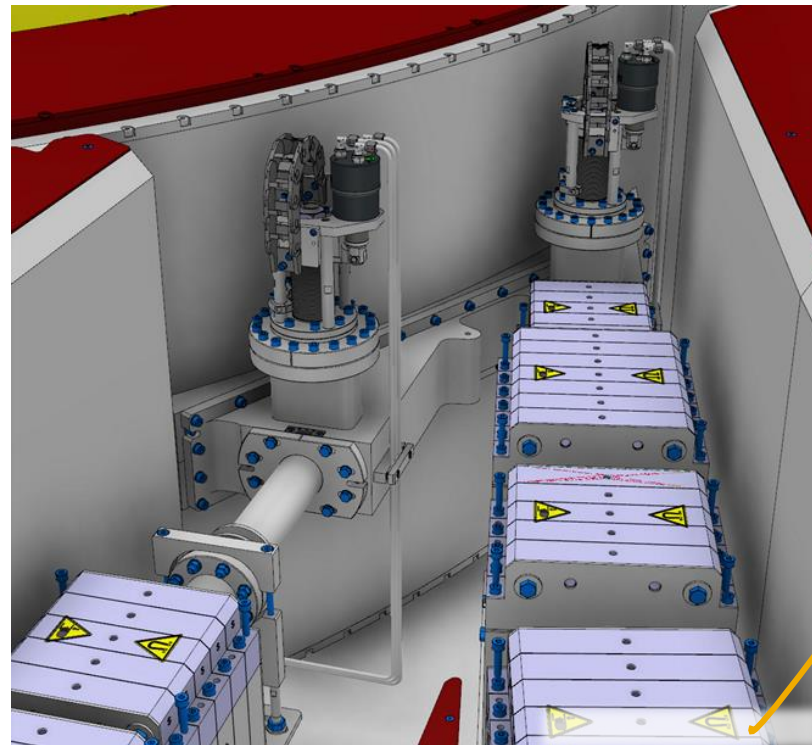
→ Following beam lines designed for large acceptance



On each extraction line, in yoke flux returns, we found:

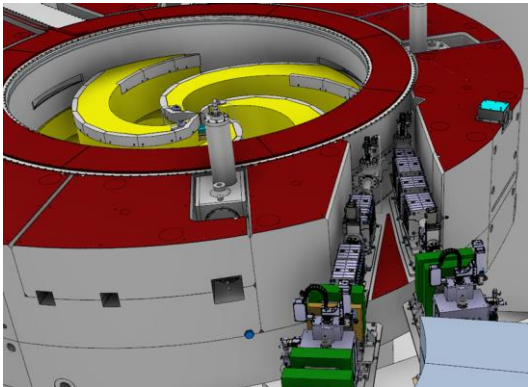
- 1 – BPMs* on cryostat exit flange
- 2 – followed by PMQ** sub assemblies

- *Beam Profile Monitor*
- ** *Permanent magnets quadrupole*



Extraction tables

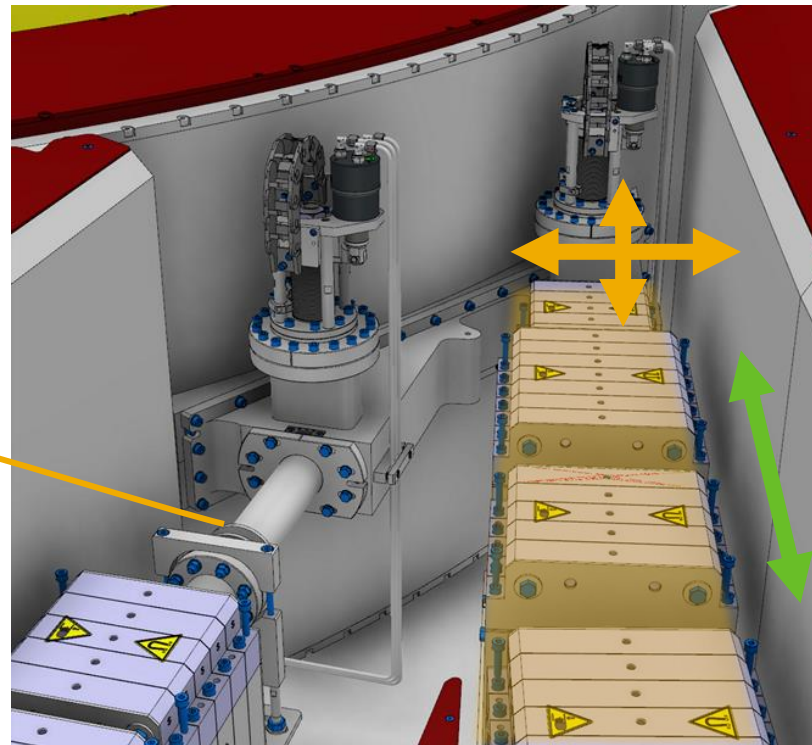
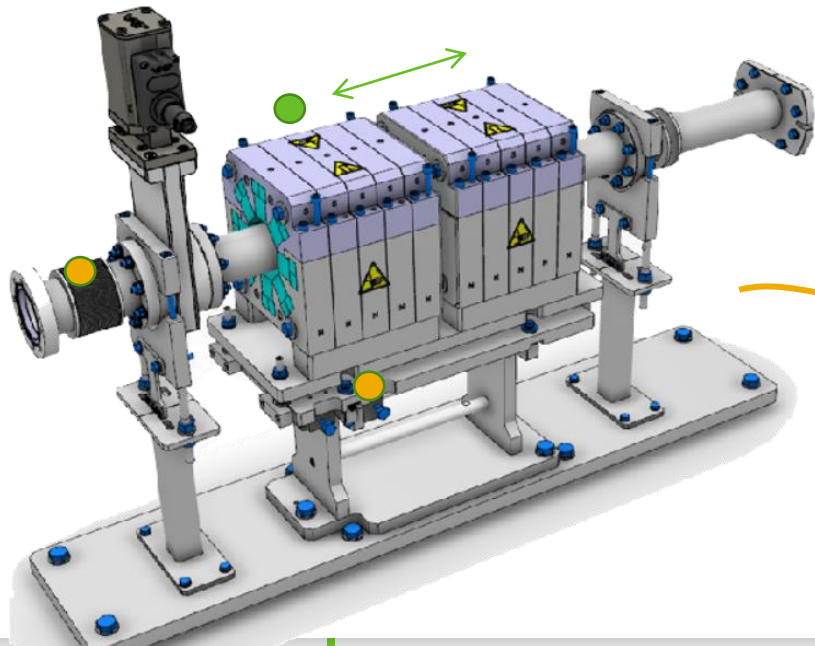
Final review



On each extraction line, in yoke flux returns, we found:

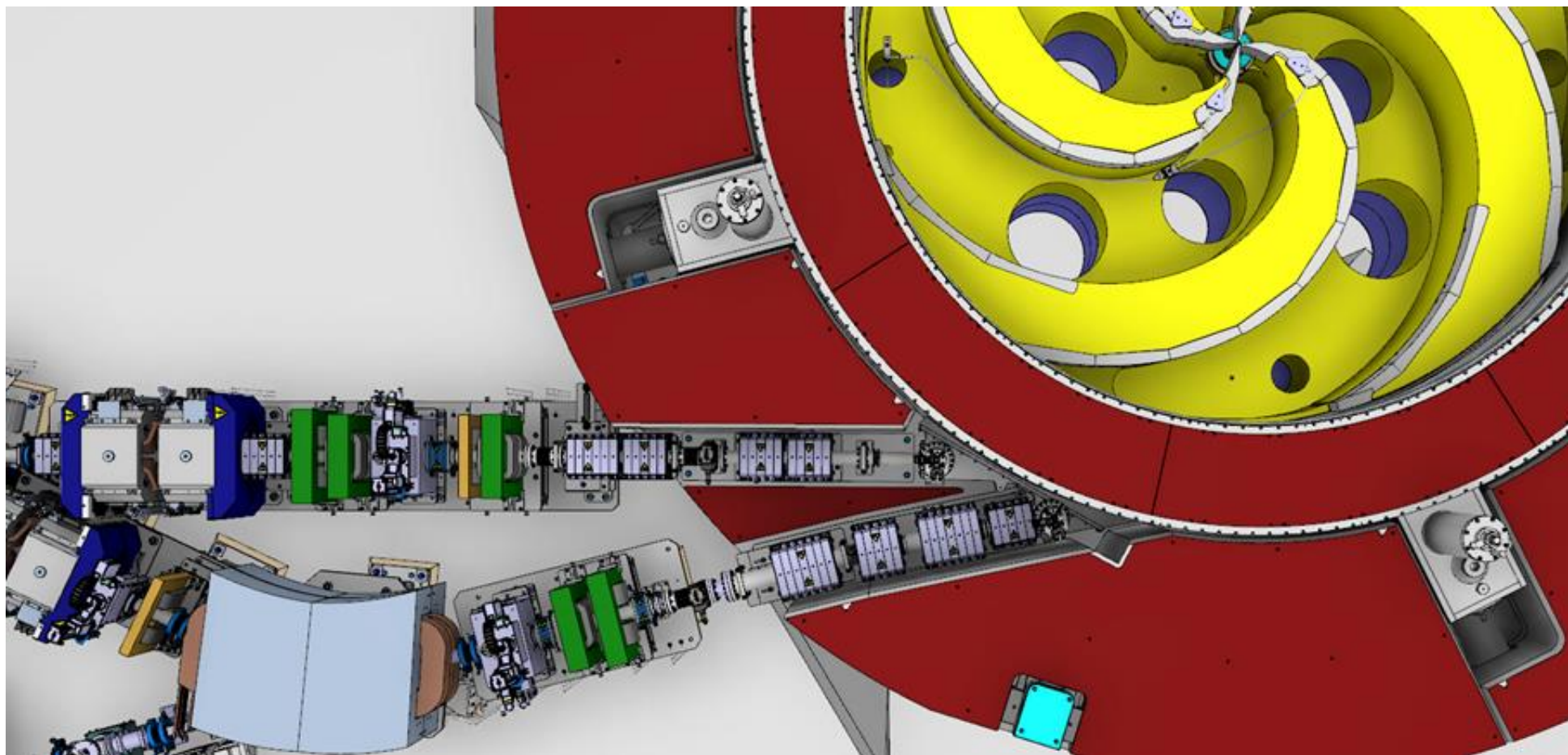
- 1 – BPMs* on cryostat exit flange
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- *Beam Profile Monitor*
- ** *Permanent magnets quadrupole*



Steering & focusing can be adjusted

Space constraint...



Minimize beam losses:

- Crossing the resonance FAST → **specific profiles on pole edges crossing.**
- Good centering of the beam → **“phase selection” & harmonic coils in central region.**

Limit the impact of the residual losses: Use of collimators.

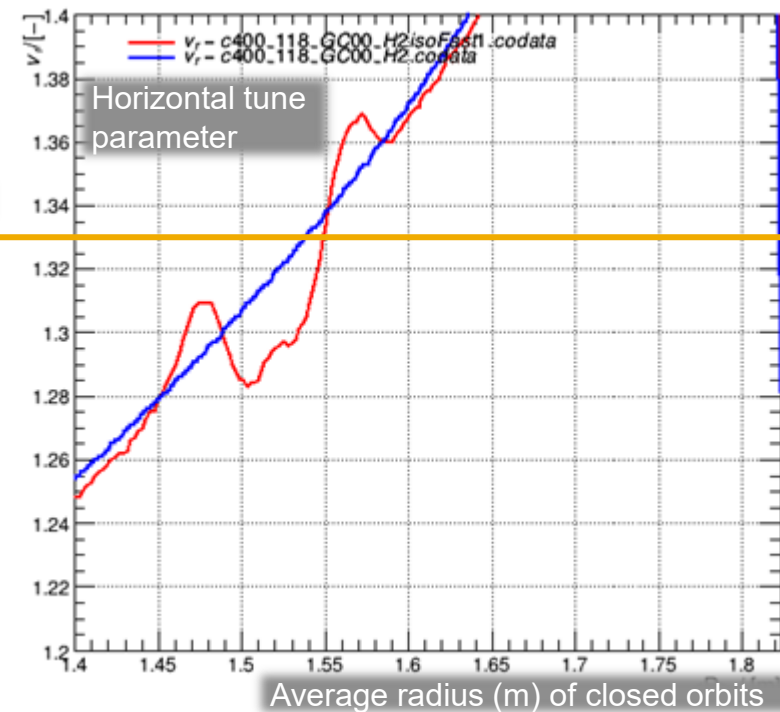
Fundamental resonance crossing

Minimize beam losses:

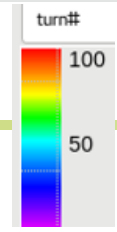
- Crossing the resonance FAST → **specific profiles on pole edges crossing.**

In practice: A groove and a rod on pole edges.

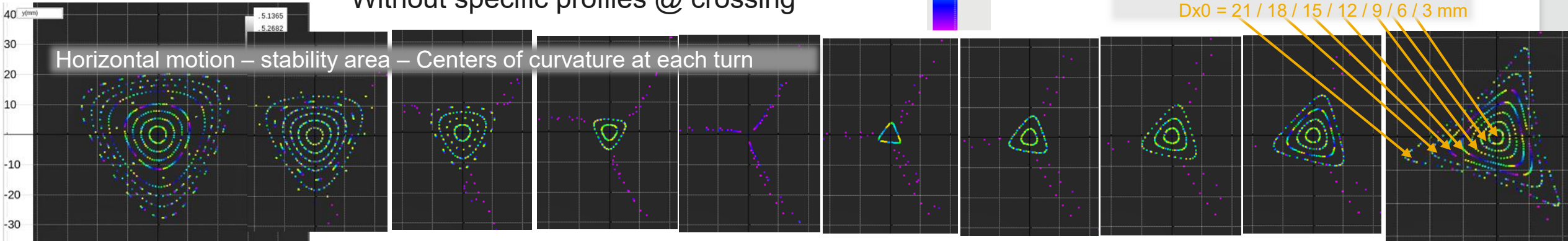
3 ν_r =4 crossing



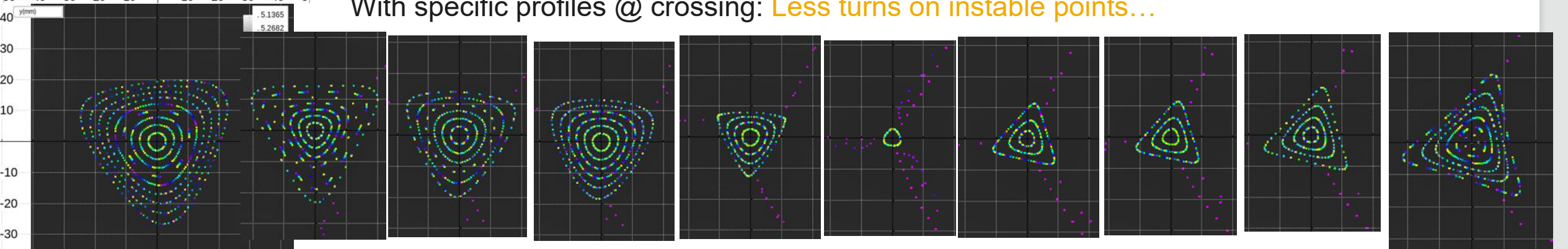
Fundamental resonance crossing



Without specific profiles @ crossing



With specific profiles @ crossing: Less turns on instable points...

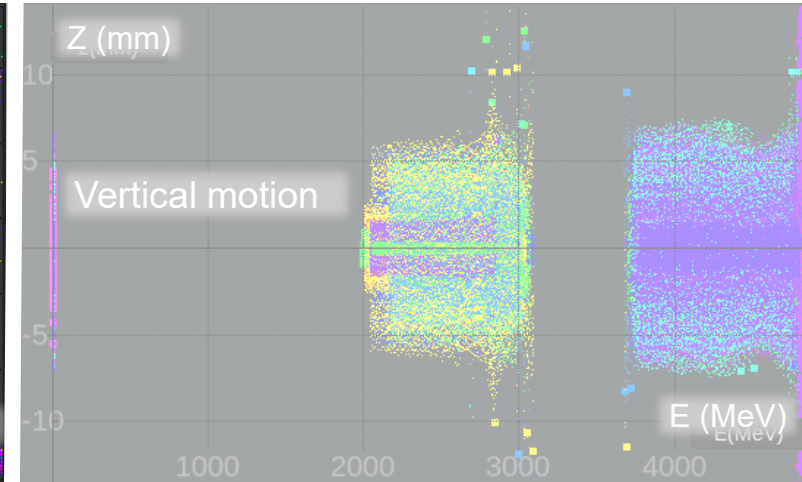
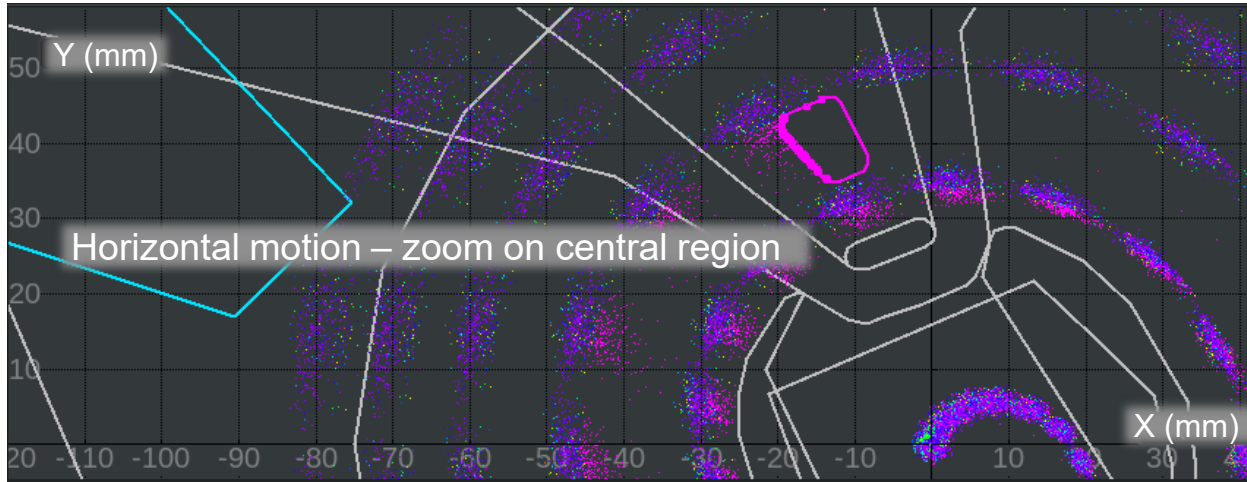


MeV - C6+



Fundamental resonance crossing

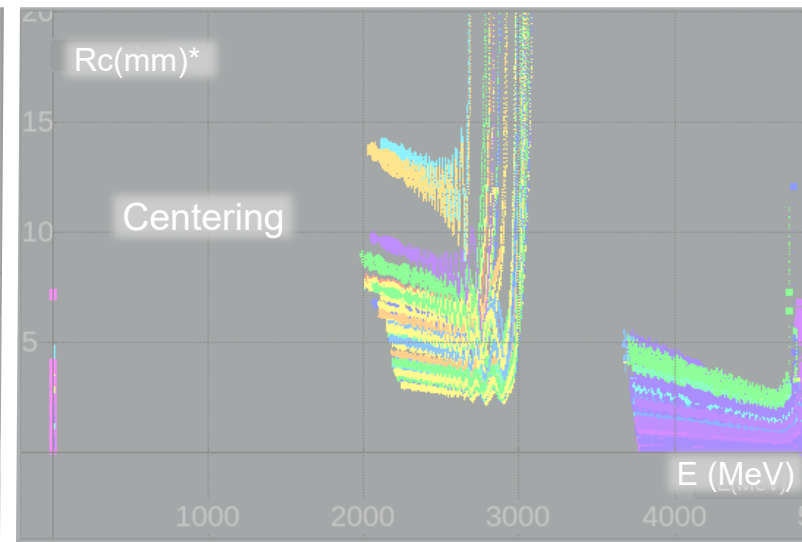
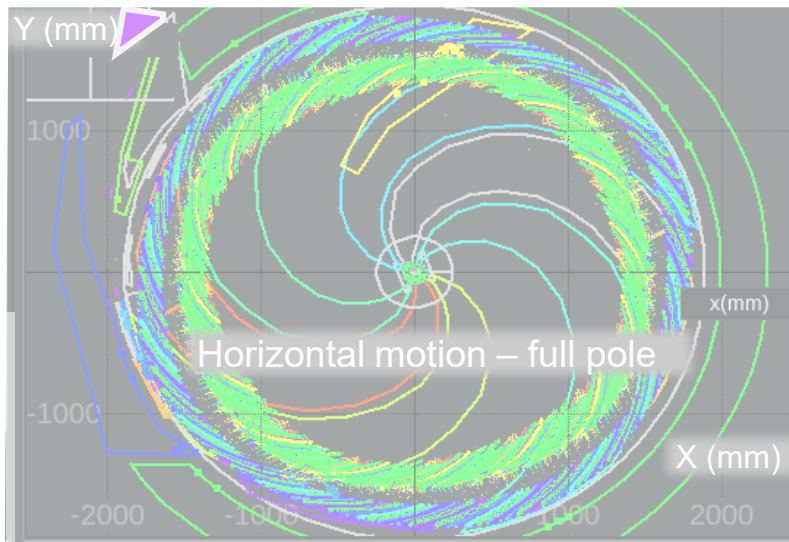
Complete dynamics model: Beam from axial injection to cryostat exit flange



Color is given by element hit 1st:
Dee#1 ; Dee#2 ; Cryostat ;
Alum. Collimator ; ...etc.

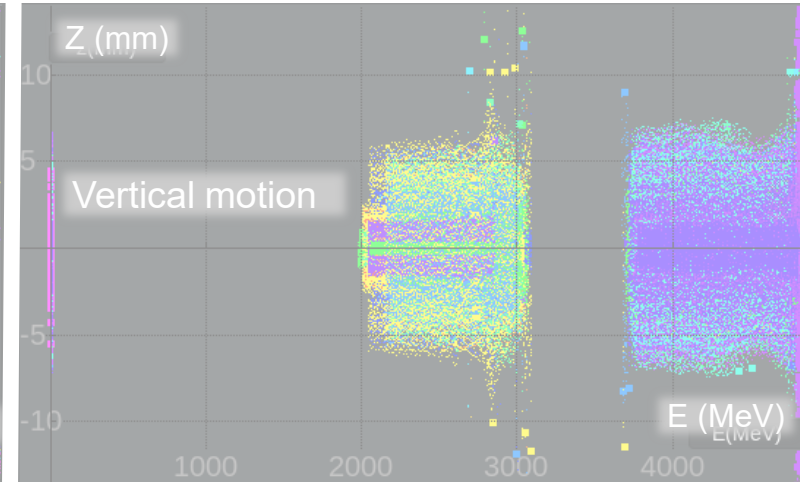
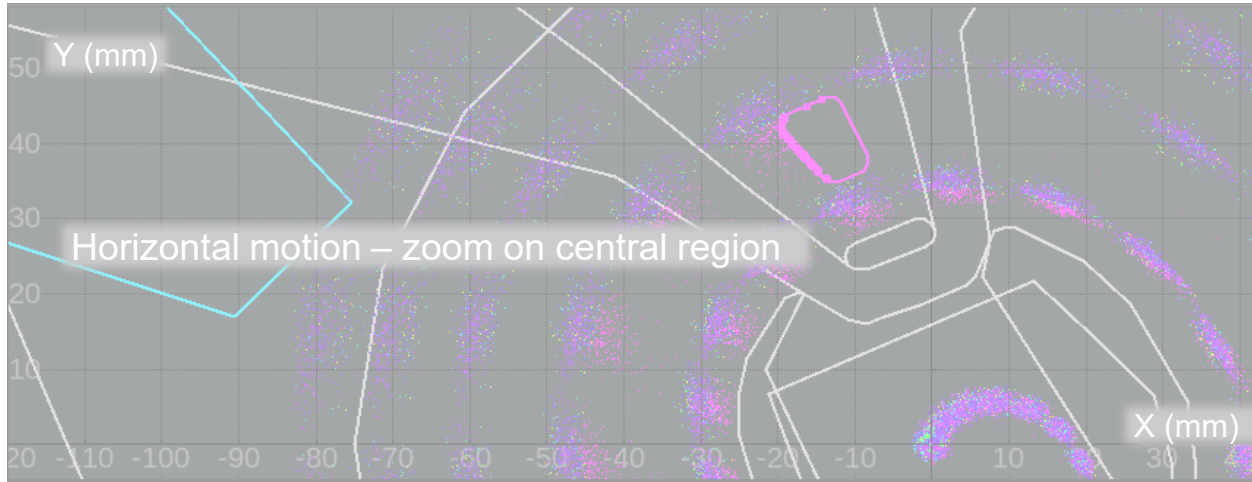
In center: Phase selector pillar

▶ Cryostat exit Flange



Fundamental resonance crossing

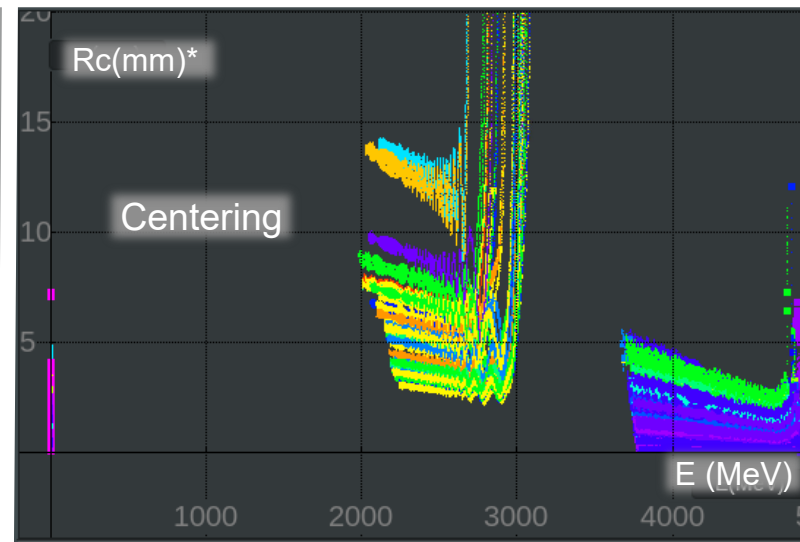
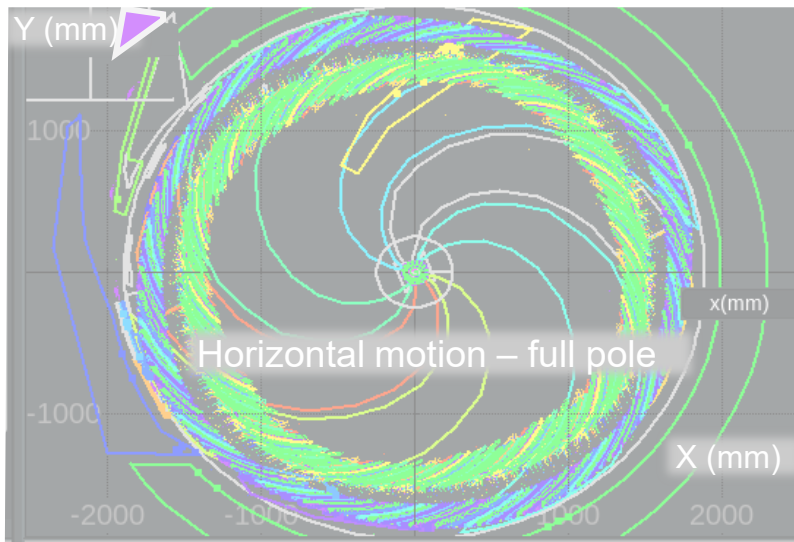
Complete dynamics model: Beam from axial injection to cryostat exit flange



Color is given by element hit 1st:
Dee#1 ; Dee#2 ; Cryostat ;
Alum. Collimator ; ...etc.

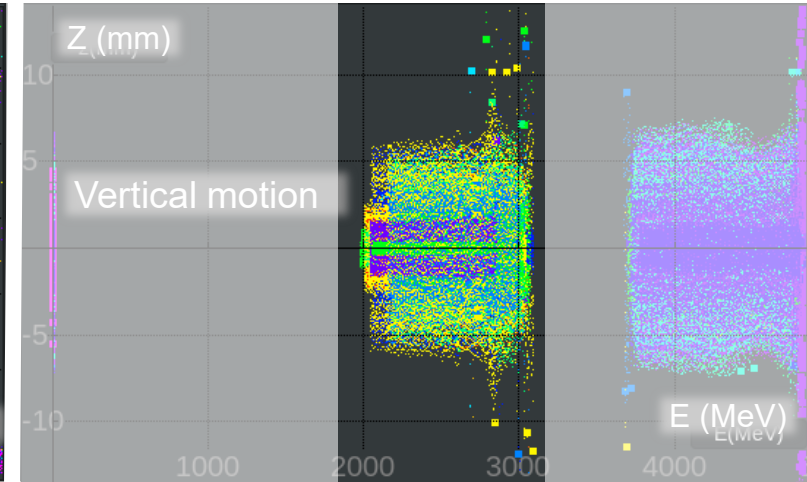
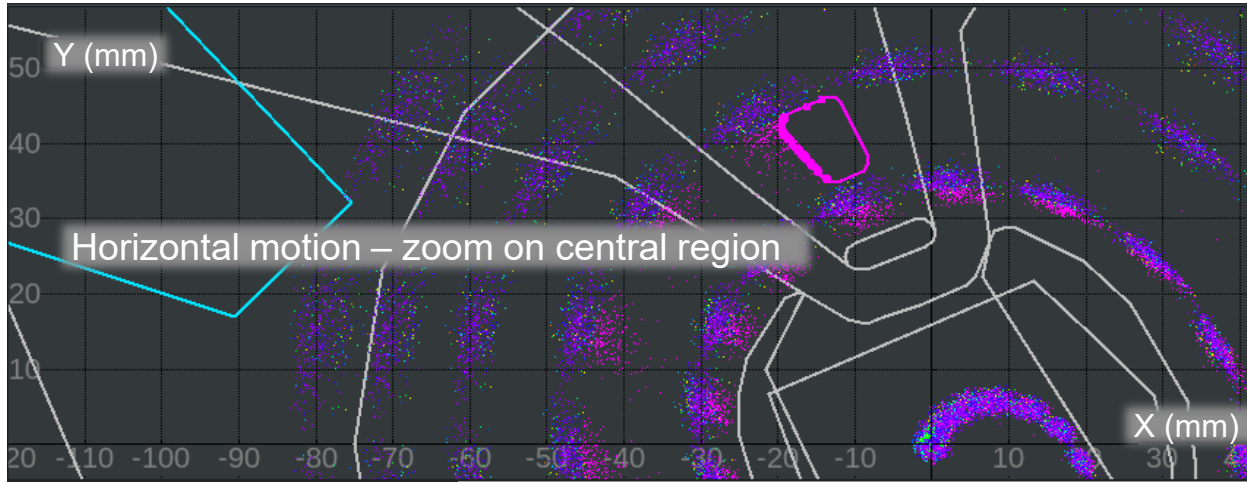
In center: Phase selector pillar

▶ Cryostat exit Flange

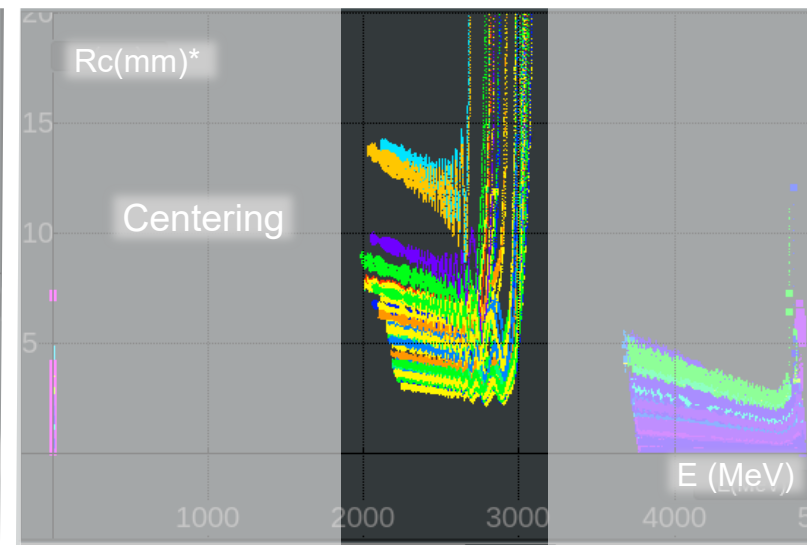
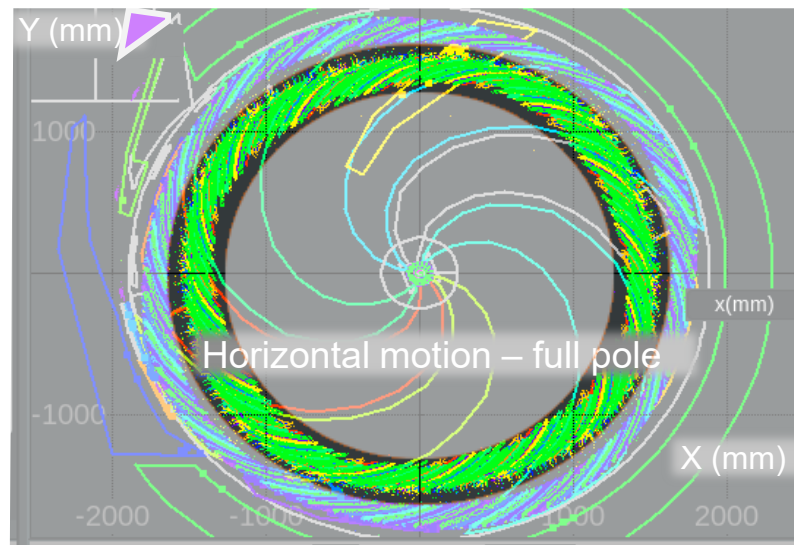


Fundamental resonance crossing

Losses at resonance crossing: off centered particles



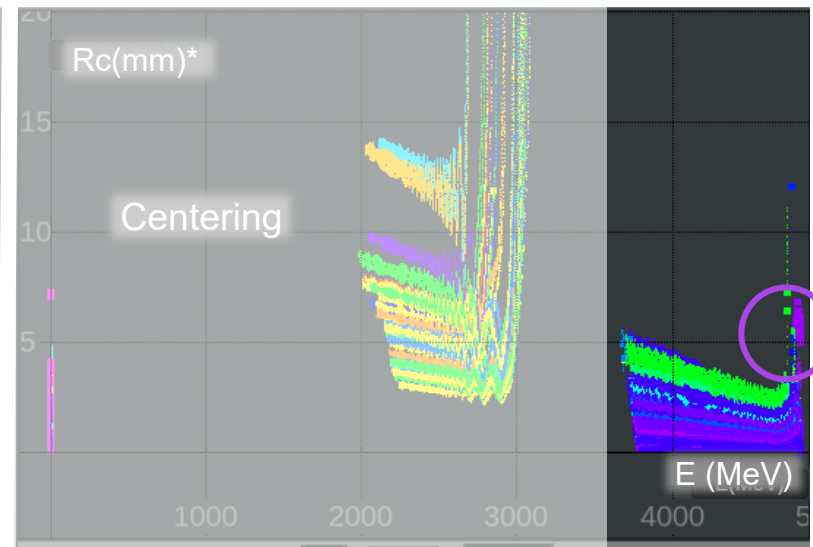
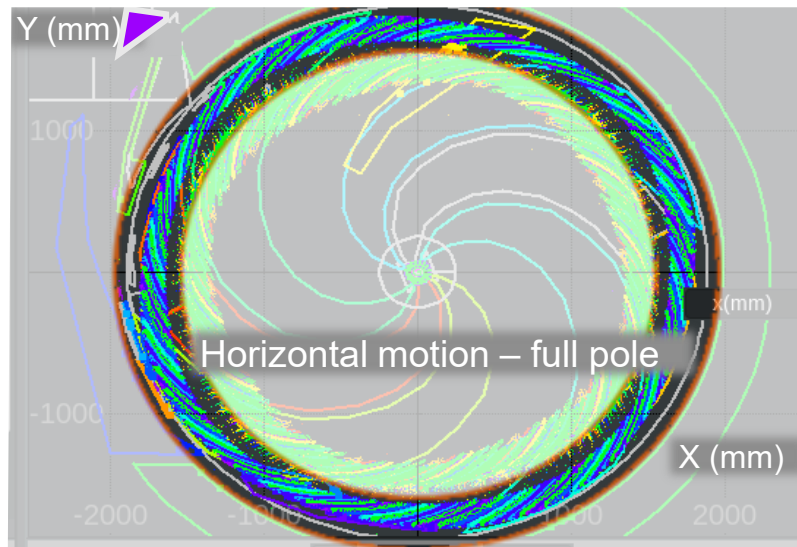
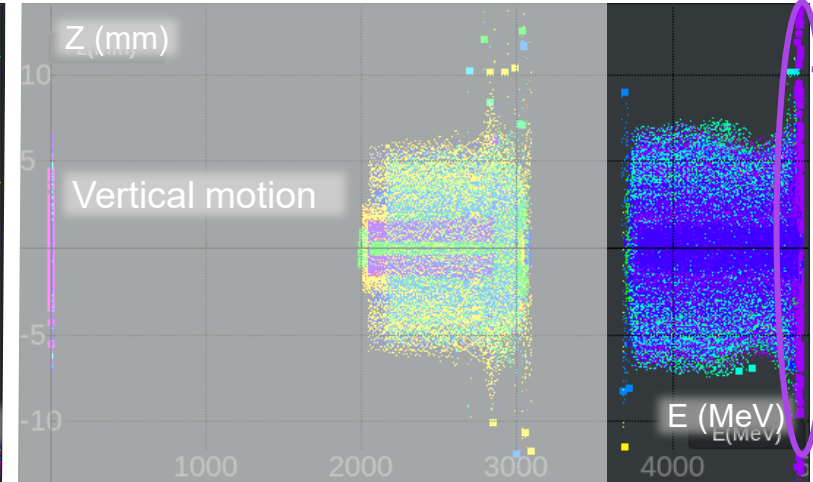
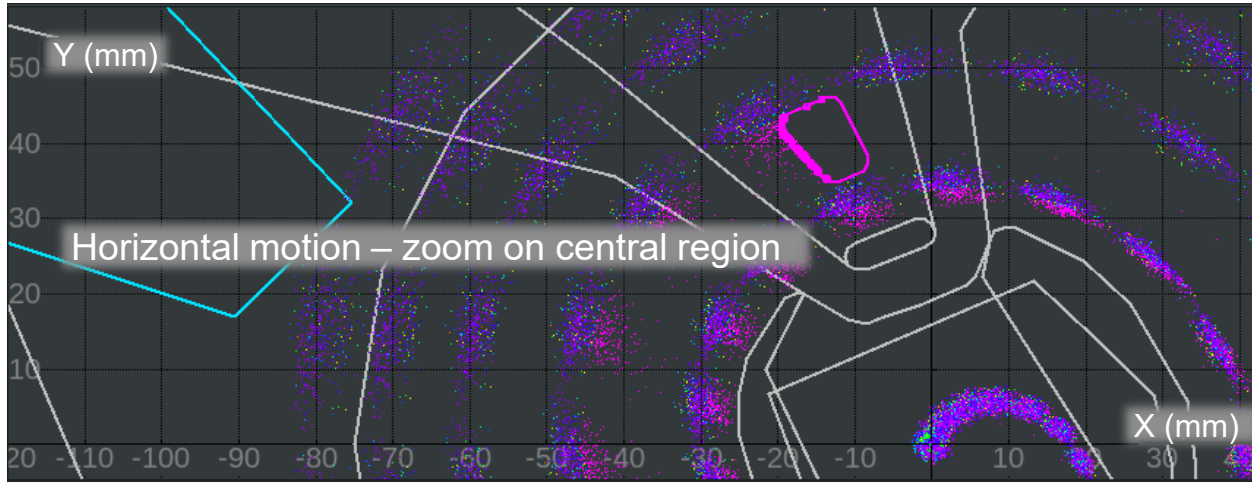
1 particle lost in resonance for 5 reaching cyclo exit...



Fundamental resonance crossing

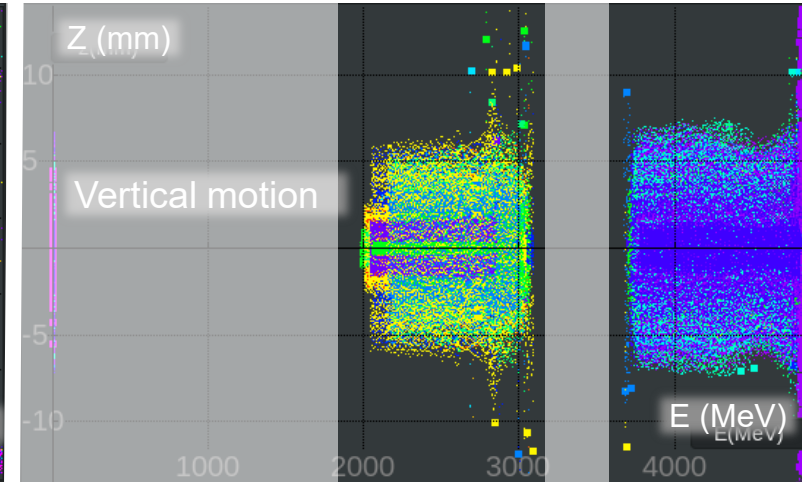
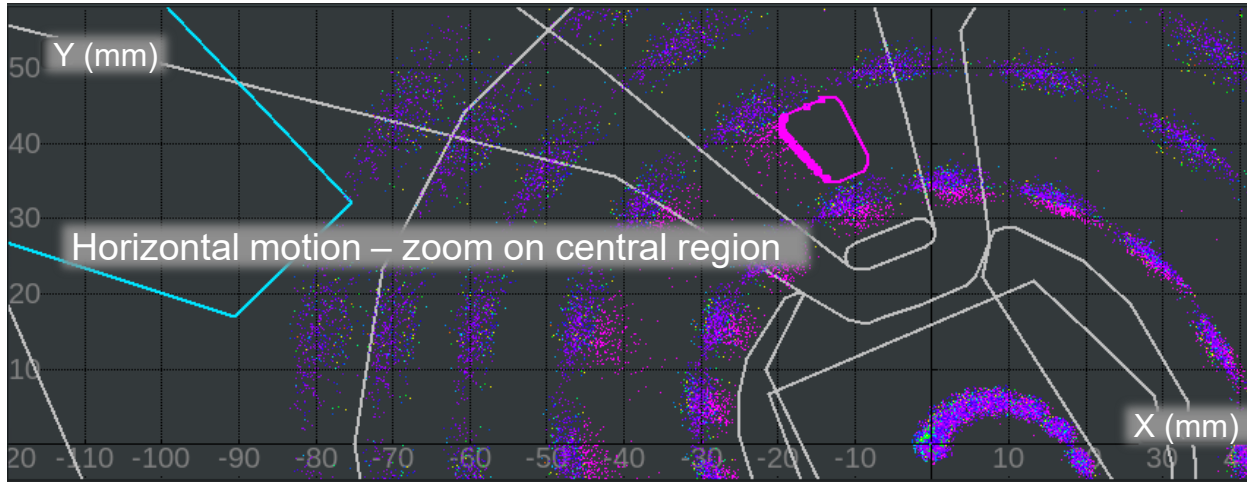
Some particle reaching max energy:

Beam reaching exit flange



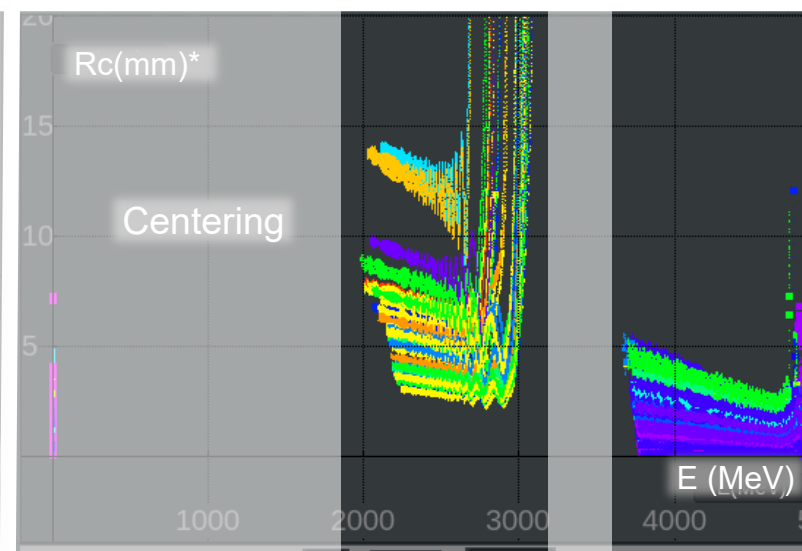
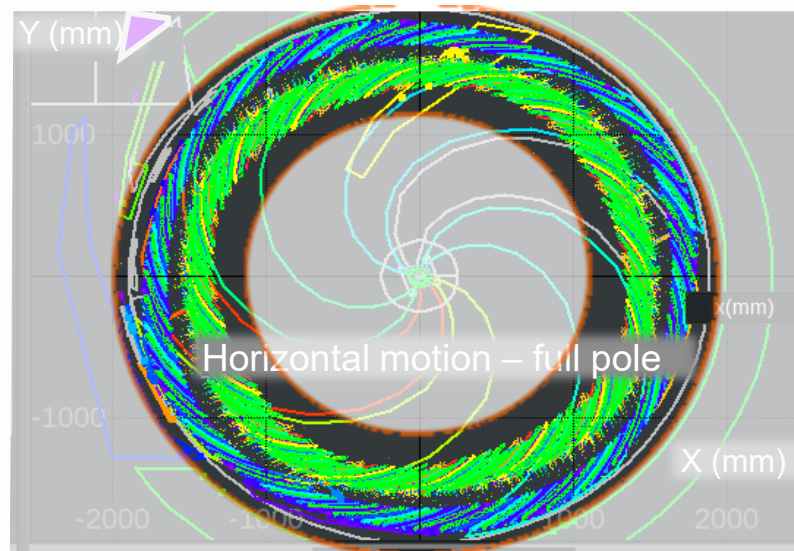
Cryostat exit Flange

Some lost at resonance crossing: off centered particles

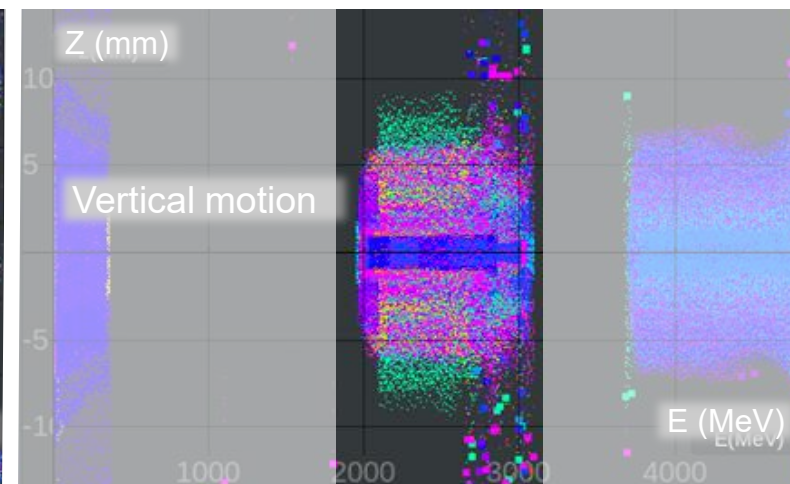
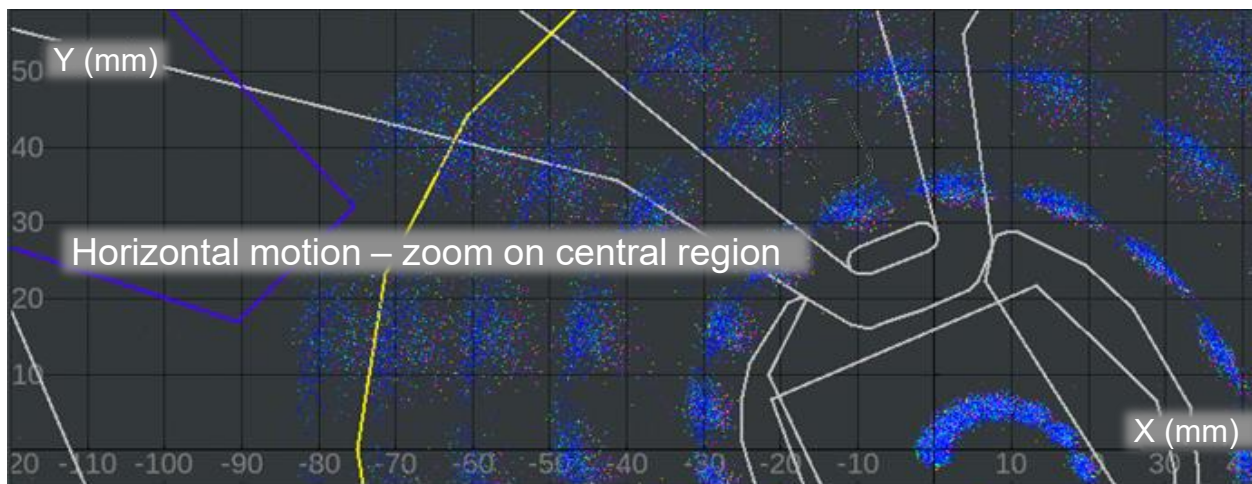


50% of the accelerated beam reach cyclotron exit.

Among losses, 60% touch the deflector.

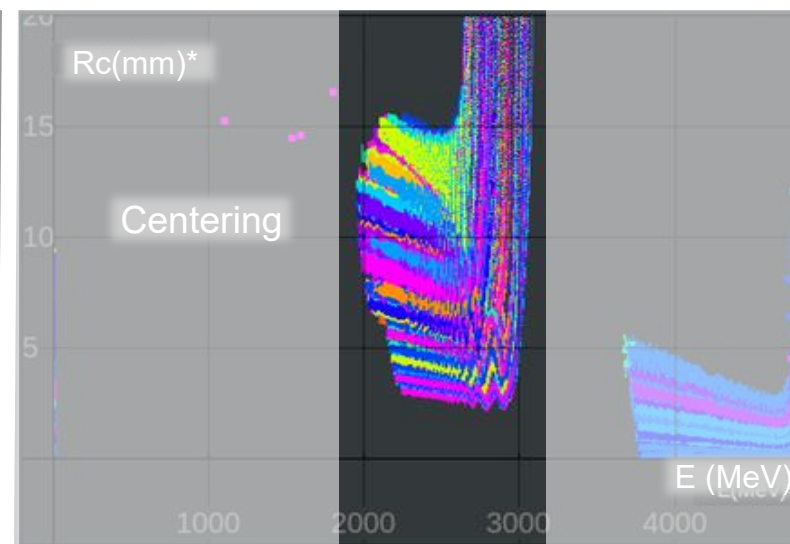
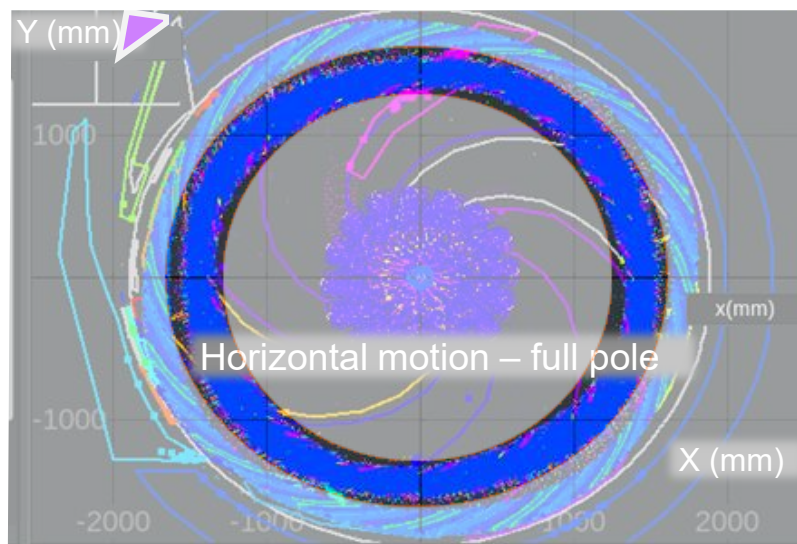


Fundamental resonance crossing



without the phase selector pillar

1 lost in resonance for 1 reaching cyclo exit...

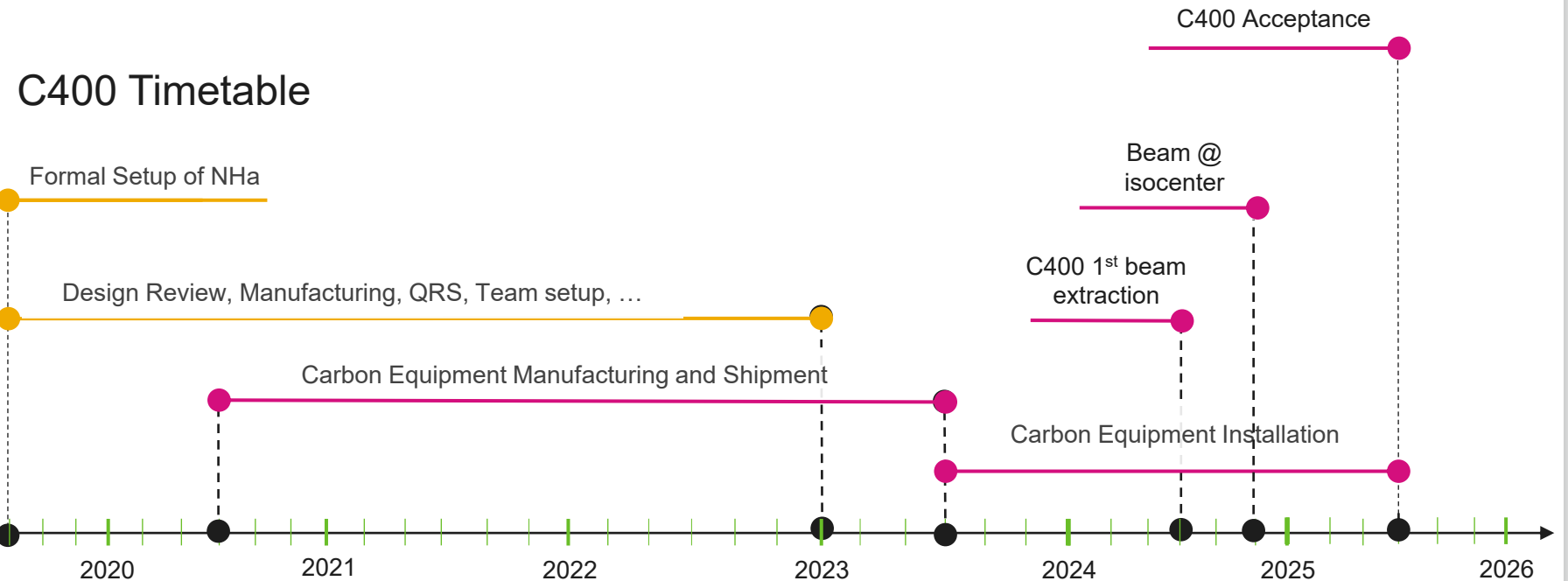


Conclusions

Starting from 2009 design, we did a final pass on all subsystems.

C400 is now under construction.

Any aspect of such a large cyclotron needs detail studies.



Thank you for your attention

