A man in a white lab coat and glasses is looking at a large display of medical MRI scans. The scans are arranged in a grid, showing various cross-sections of a human body. The man is in the foreground, looking intently at the scans. The background is slightly blurred, focusing attention on the man and the scans.

MID 42331

PART IV:

The Superconducting Synchrocyclotron Project S2C2

Outline

1. Intro (ProteusONE® and compact gantry)

2. Main features and parameters

3. Subsystems:

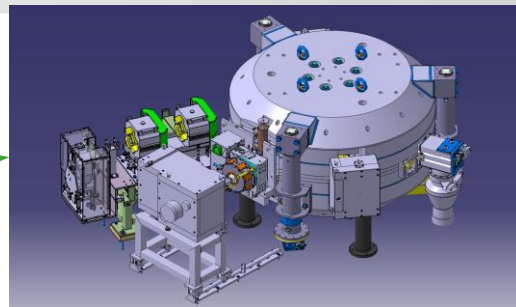
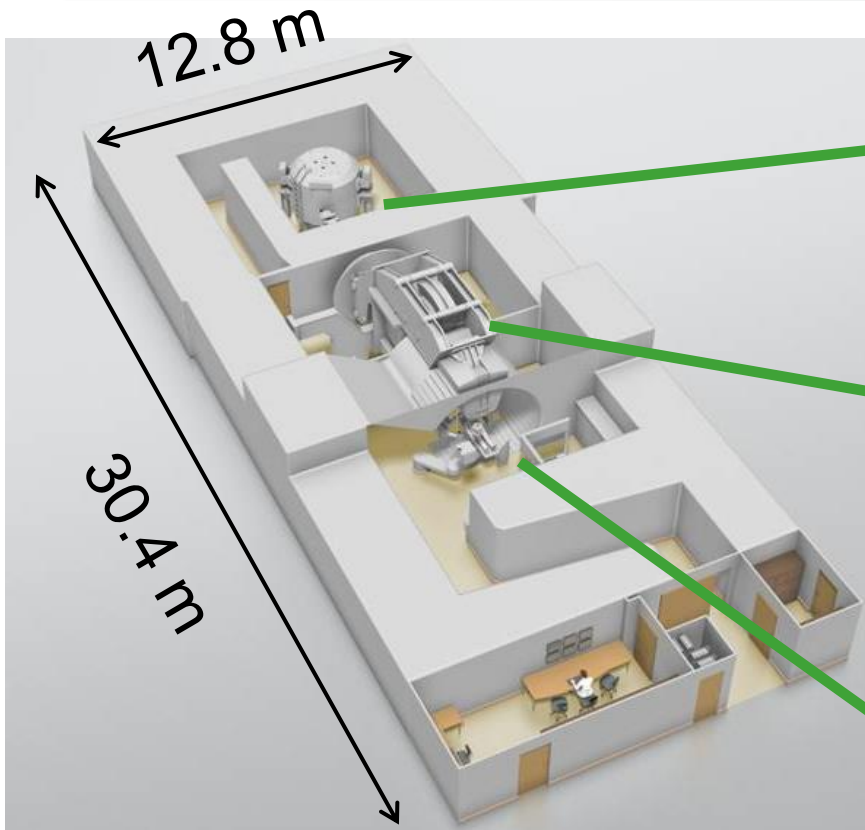
- Magnetic Circuit
- Superconducting coil
- RF System
- Ion Source+Central Region
- Extraction System
- Extracted beam line

4. Current status

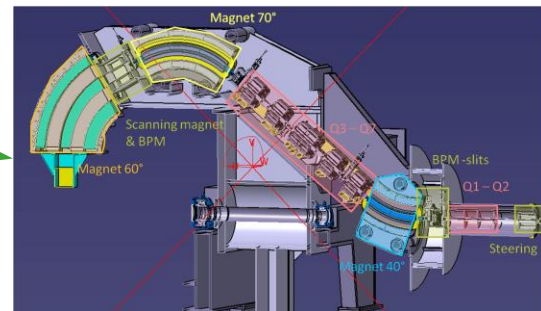


The New IBA Single Room Proton Therapy Solution: ProteusONE®

High quality PBS cancer treatment: compact and affordable



*Synchrocyclotron with
superconducting coil:
S2C2*



*New Compact Gantry for
pencil beam scanning*

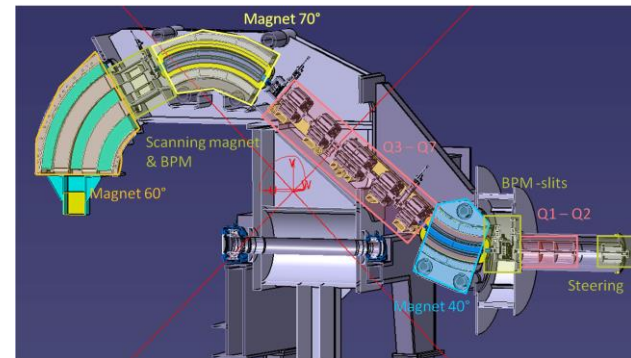


Patient treatment room

The new compact gantry for pencil beam scanning

Design aimed at reducing footprint and cost

- Scanning magnets are placed upstream of the last bending magnet
- ESS integrated in the 45 deg inclined part
- Rotation angle 220°
- Gantry has been fully manufactured and tested. Now installed at the customer site in Shreveport where the beam has already been transported to the gantry isocenter



How a Synchrocyclotron differs from a Cyclotron

Isochronous cyclotron:

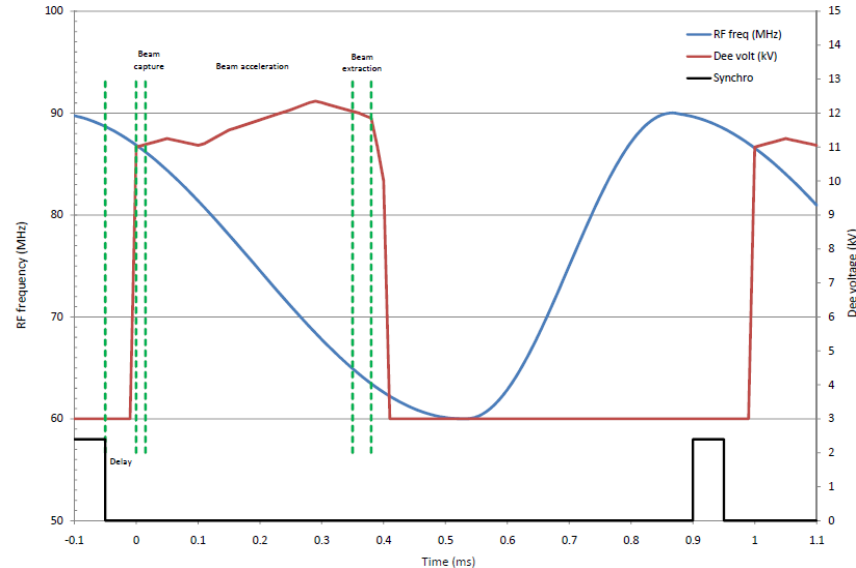
- Requires B to increase proportionally to m .
- Requires sector focusing for vertical stability.
- This leads to a smaller average magnetic field, thus a larger structure.
- All parameters being constant, operation is CW.

Synchro cyclotron:

- Requires B to decrease for weak focusing.
- Requires f to decrease during acceleration.
- Smaller structure due to high average magnetic field.
- Acceleration being frequency dependant, operation is pulsed.

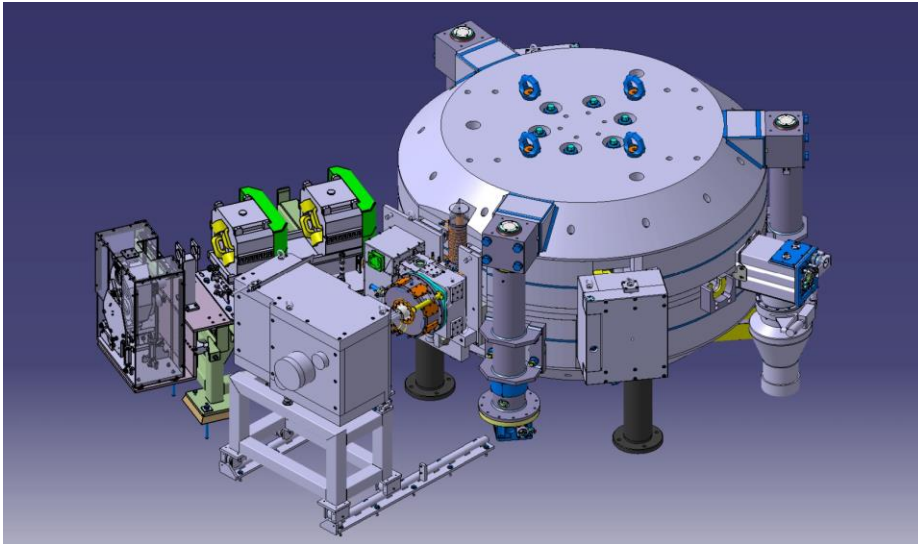
What is a Synchrocyclotron ?

A Synchrocyclotron is a circular accelerator in which the frequency of the accelerating electric field is modulated in order to compensate the decreasing period of revolution of the particles. This decrease is due to the relativistic mass increase and the decreasing field during acceleration.



S2C2 overview

General system layout and parameters

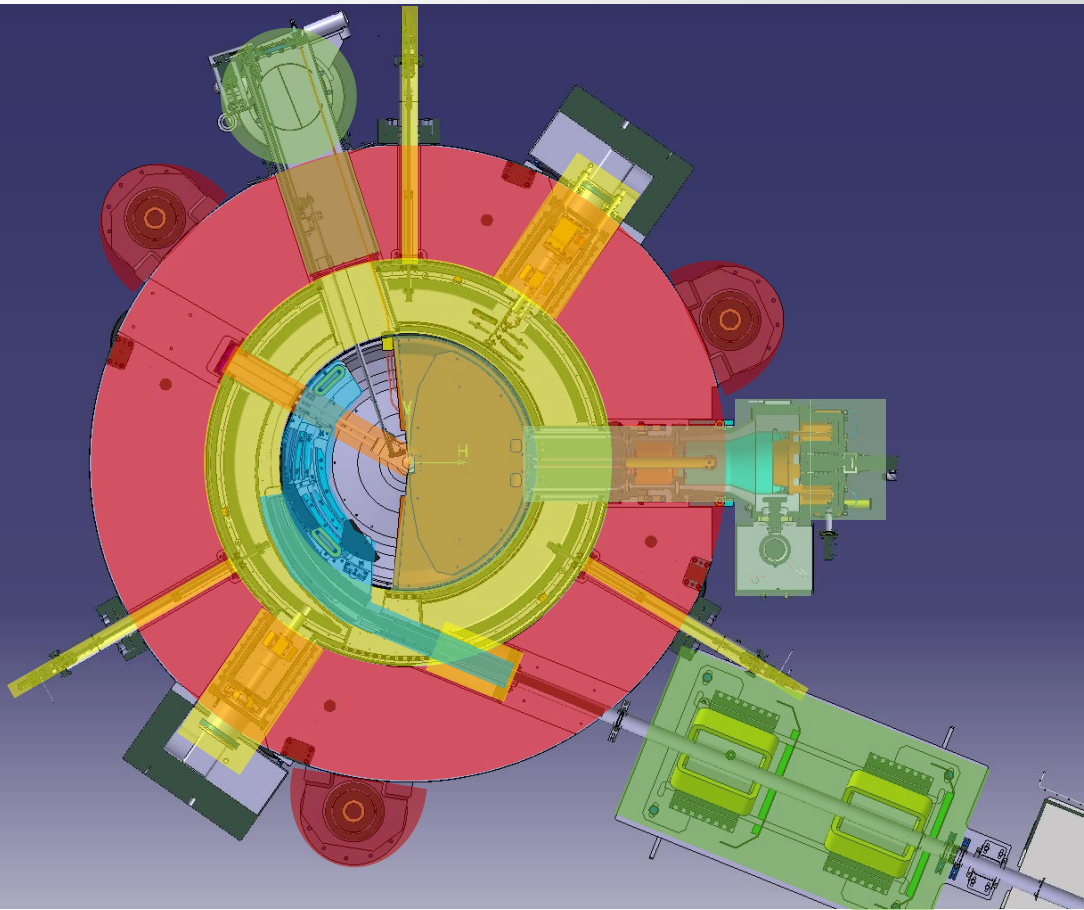


- An invited talk on this project was presented at the 2013 cyclotron conference in Vancouver
- Several contributions can be found on the ECPM2012-website

Maximum Energy	230/250 MeV
Size yoke/pole radius weight	1.25 m/0.50 m 50 tons
Coil ramp up rate / time windings/coil stored energy	NbTi - wire in channel 2-3 A/min / 4 hours 3145 12 MJ
Magnetic field central/extraction	5.7 T/5.0 T
Cryo cooling initial cooldown recovery after quench	conductive 4 cryocoolers 1.5 W 12 days less than 1 day
Beam pulse rate/length	1000 Hz/7 μ sec
RF system frequency voltage	self-oscillating 93-63 MHz 10 kV
Extraction	Passive regenerative
Ion source	PIG cold cathode
Central region	removable module

S2C2 overview

Main subsystems



Magnet yoke

Superconducting coil

RF system

Ion source+central region

Extraction system

Vacuum system

Yoke lifting system

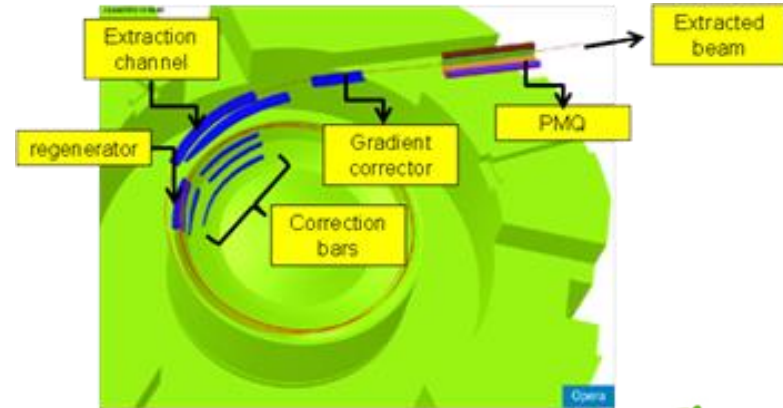
Extracted beam line

Magnetic circuit-modeling

OPERA3D full model with many details

- Long and tedious optimization process
- Yoke iron strongly saturated
- Influence of external iron systems on the internal magnetic field
- Stray-field => shielding of rotco and cryocoolers
- pole gap $< \Rightarrow$ extraction system optimization
- Influence of yoke penetrations
- Median plane errors
- Magnetic forces

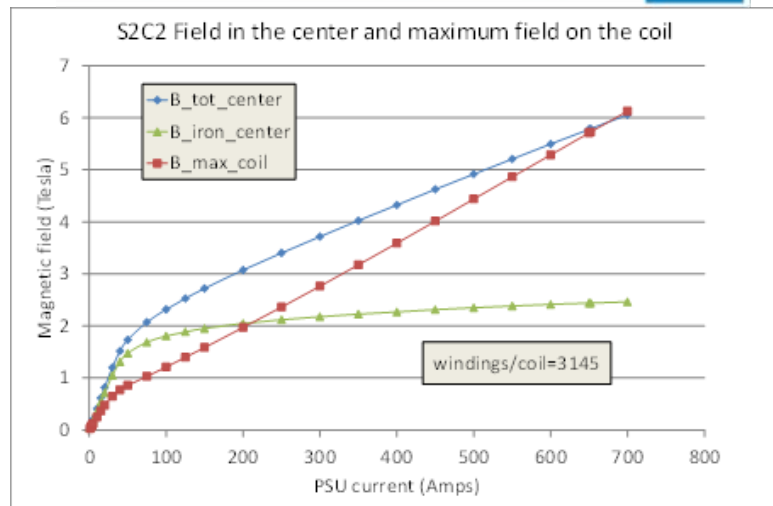
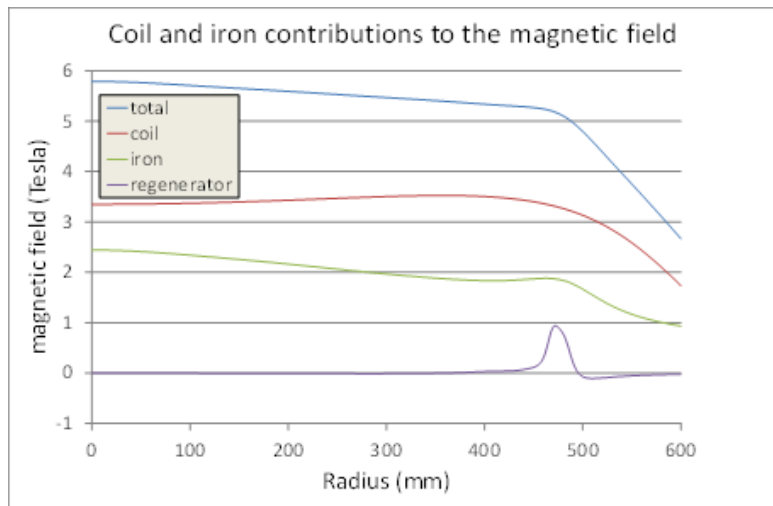
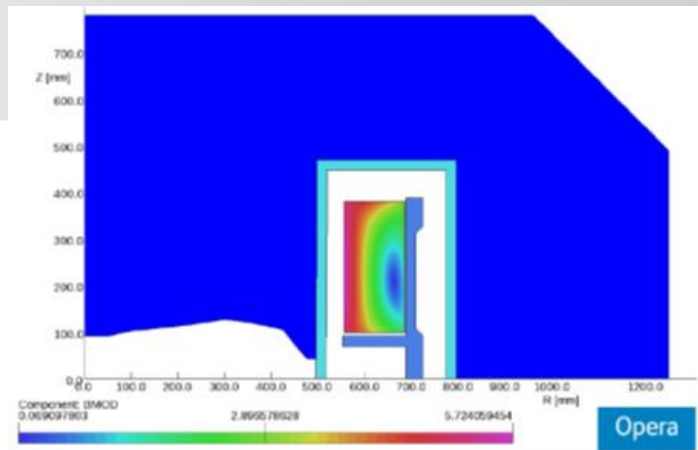
ITERATIVE PROCESS WITH STRONG
INTERACTION TO BEAM SIMULATIONS



Magnetic circuit modeling

Some examples of OPERA2D results

- Pole-gap profile
- Iron and coil fields
- B_{\max} on the coil



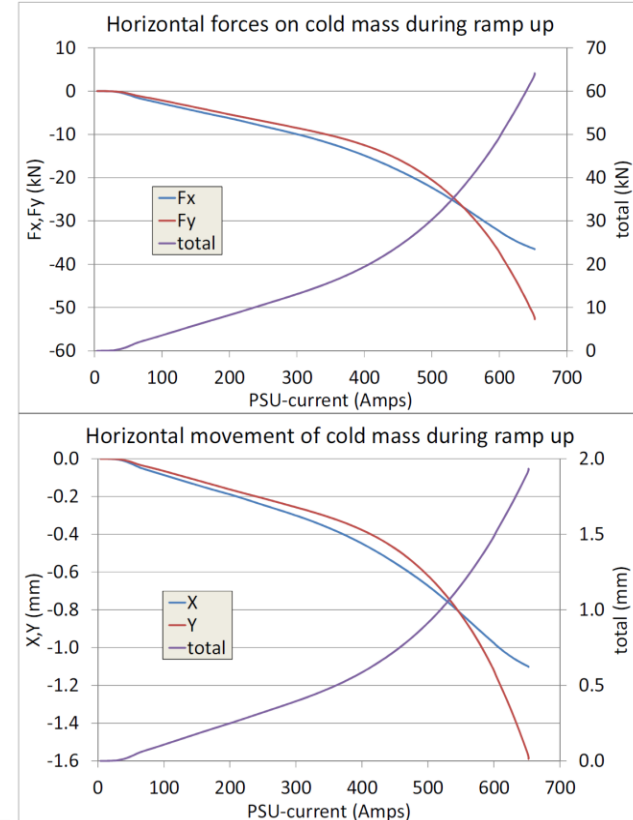
Magnetic circuit

Forces acting on the coil => implications for tierod design

- Unstable forces act on displaced cold mass
 - 2 tons/mm
- Large forces for well-centered coil due to
 1. External elements
 2. Extraction system
 3. Vertical asymmetries

SIMULATED

FORCES AND TORQUES ACTING ON THE MAIN COIL SYSTEM DUE TO COIL DISPLACEMENTS AND ROTATIONS							
		FORCES			TORQUES		
		dFx	dFy	dFz	dTx	dTy	dTz
		ton/mm	ton/mm	ton/mm	Nm/mm	Nm/mm	Nm/mm
coil shift	x-direction	1.99	-0.05	0.00	0	-9	8
	y-direction	-0.05	2.00	0.00	10	2	41
	z-direction	0.00	0.00	0.56	-80	-201	0
		dFx	dFy	dFz	dTx	dTy	dTz
		ton/deg	ton/deg	ton/deg	Nm/deg	Nm/deg	Nm/deg
coil rotation	around x-axis	-0.02	0.00	-0.12	91559	-4609	-80
	around y-axis	-0.05	-0.01	-0.30	-4484	91305	79

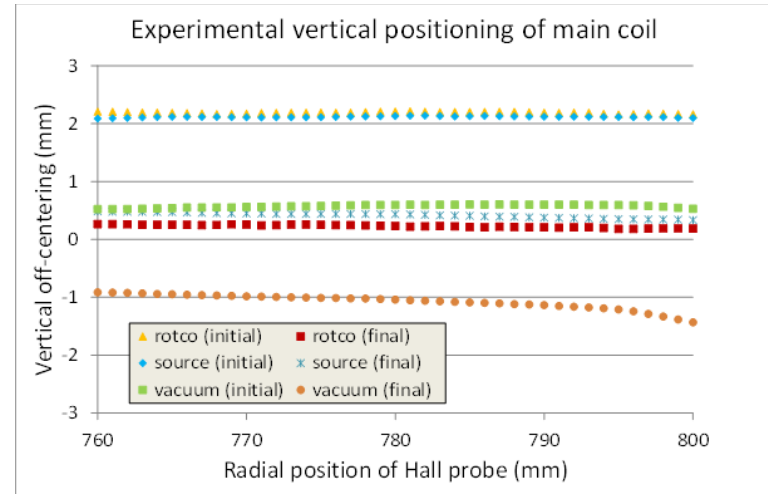
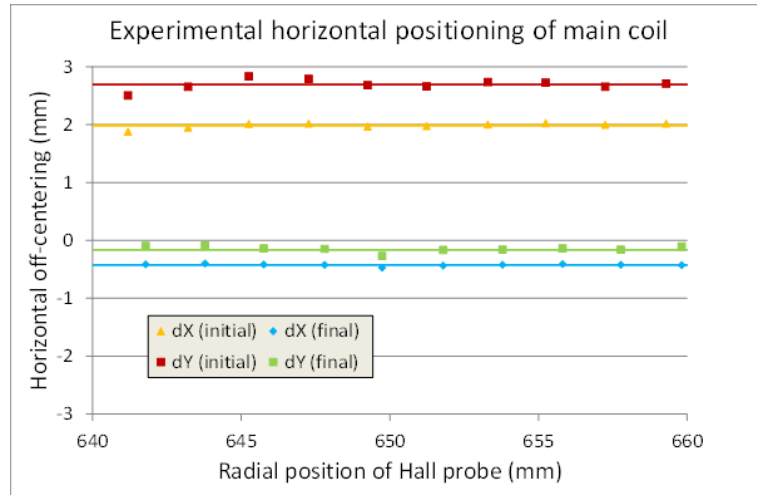


M
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Magnetic circuit: Centering of the cold mass (1)

An innovative method was developed

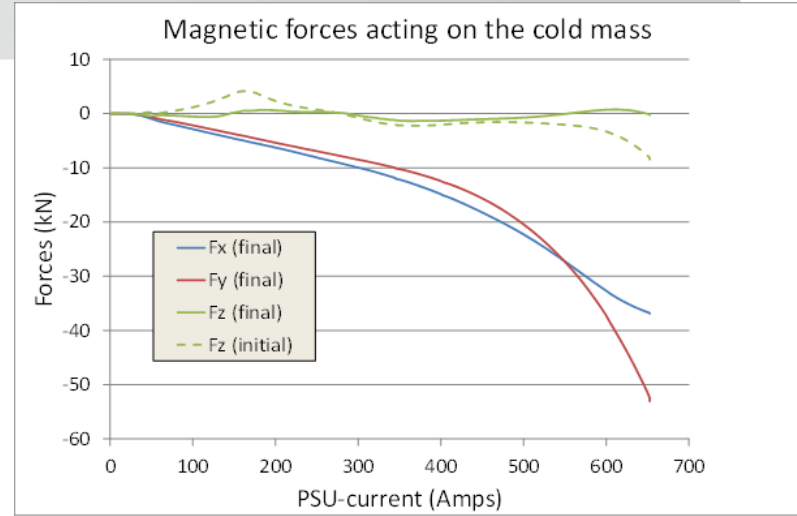
- Measure profiles in between the coils where the field is coil-dominated
- Three ports are available: RF-port, source port and vacuum port
- Horizontal centering: measure $B_z(r)$ where dB_z/dr is maximum
- Vertical centering: measure $B_r(r)$ where $B_z=0$



Magnetic circuit: centering of the cold mass (2)

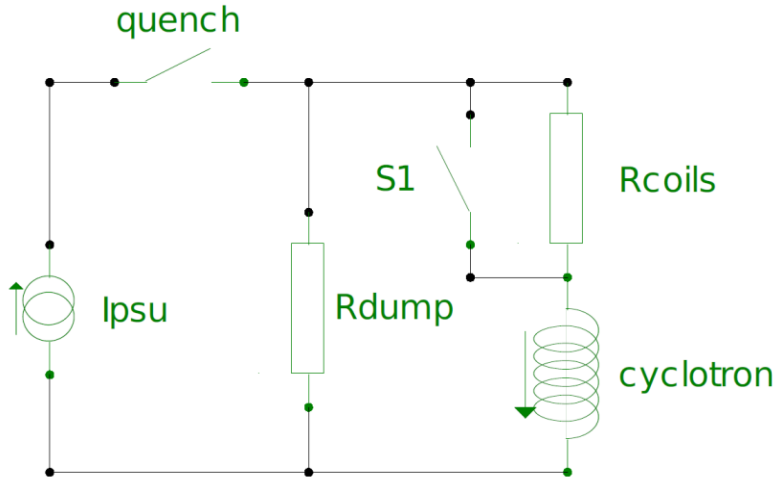
Minimize the vertical forces on the cold mass

- Forces are measured with strain gauges placed in the tierod-assemblies
- Opera calculations:
 - Low vertical forces \Leftrightarrow small median plane errors
- Vertical forces are reduced by coil-centering and by external shimming
- Horizontal forces are large due to extraction system and yoke-asymmetries
- During ramp-up coil moves 1.5 mm in to the centered position

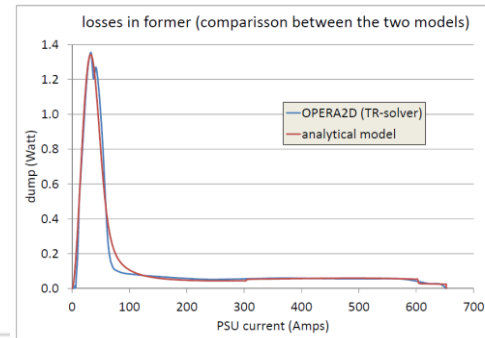
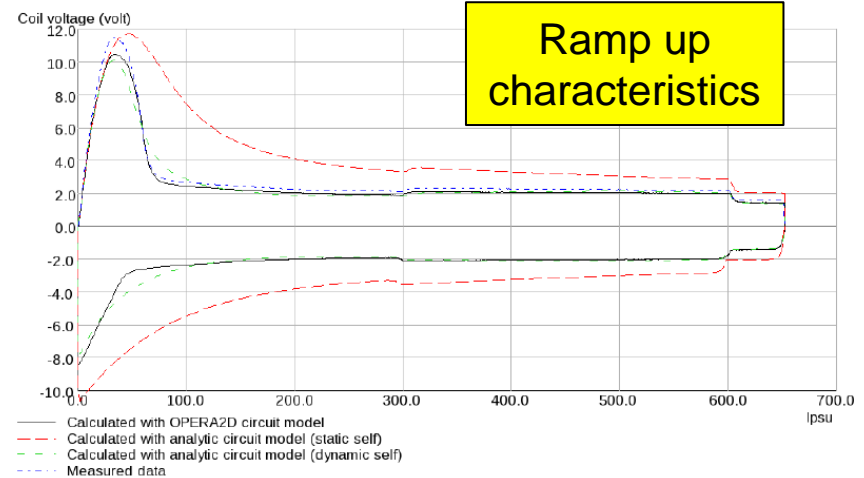


Magnetic circuit:

Dynamic behavior studied with Opera2D FE transient circuit model



- Eddy current losses
- AC losses in superconductor
- Ramp-up characteristics
- Quench behavior (qualitative)

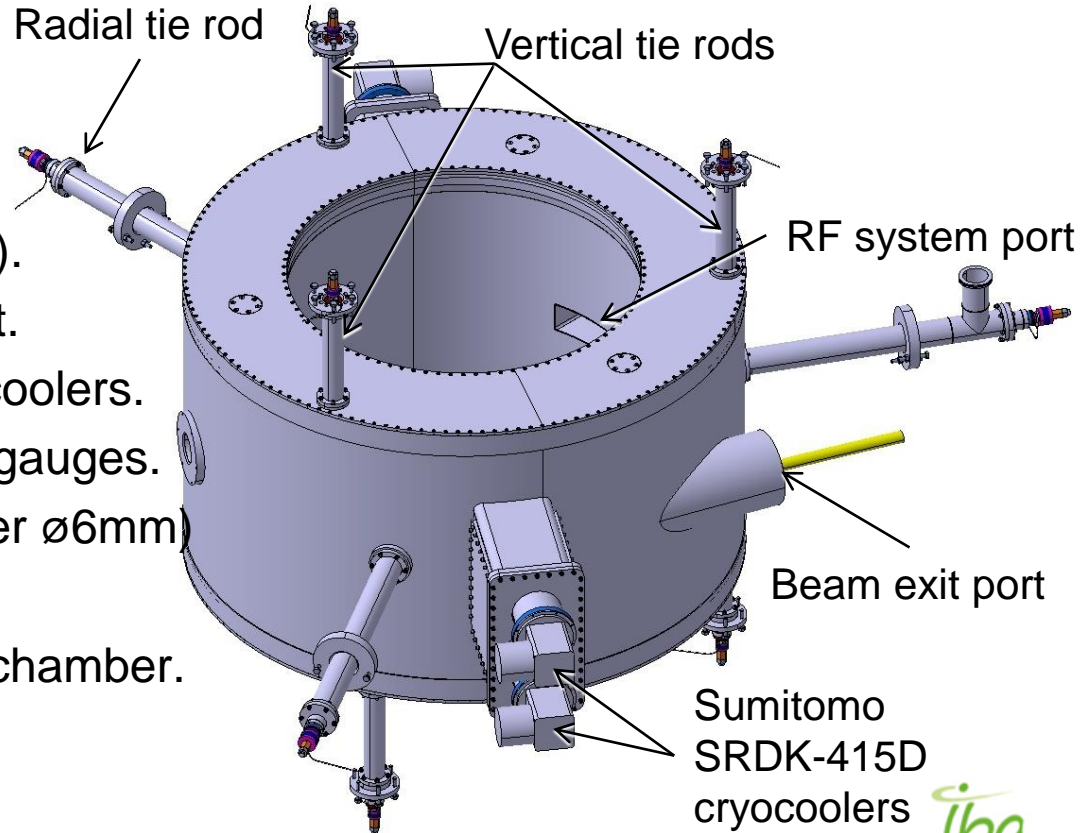


Eddy current losses

Superconducting coil

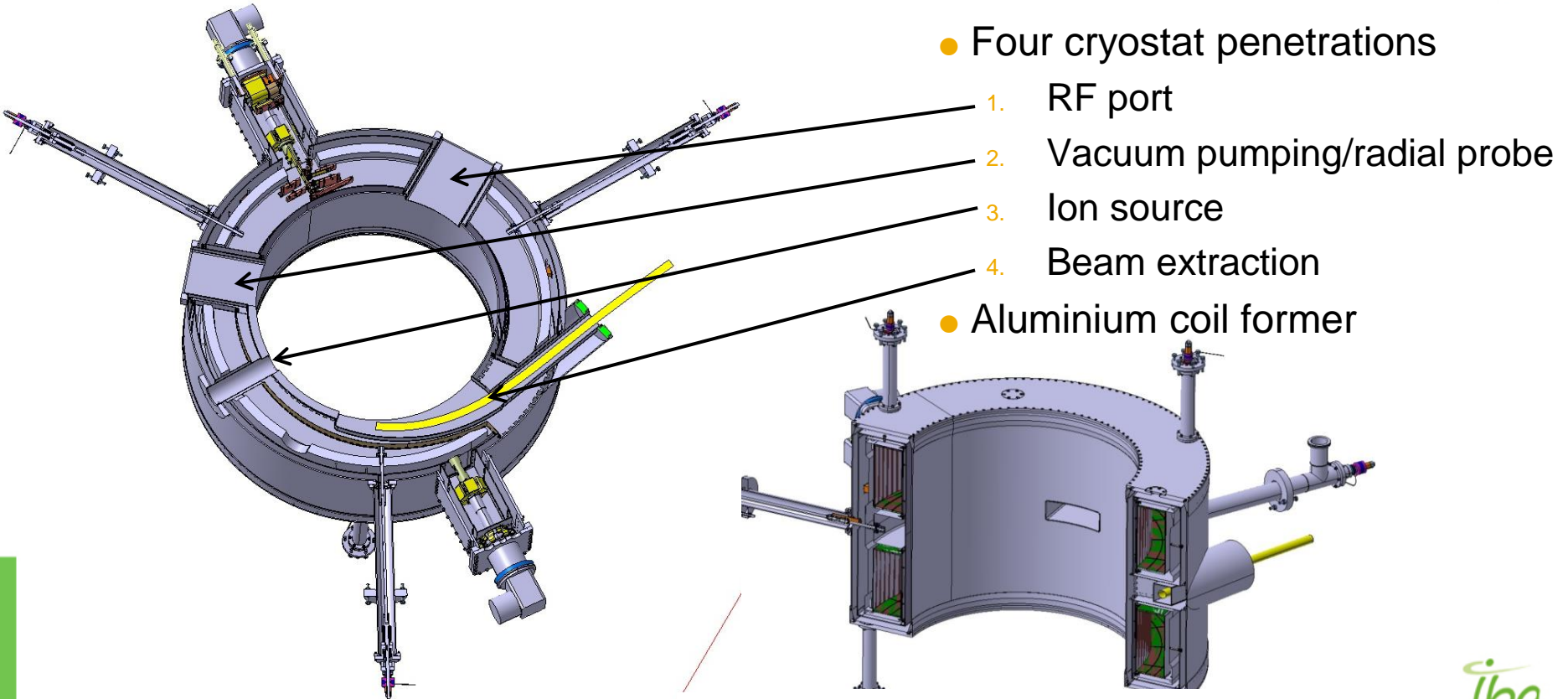
Designed and manufactured by ASG (Genoa, Italy)

- NbTi wire in channel coil.
- Suspended cold mass: 3tons.
- Overall weight: 4tons.
- Nominal current: 650A (56 A/mm²).
- Nominal ampere-turns: 4.3×10^6 At.
- Conduction cooled by 4 SHI cryocoolers.
- 9 Inconel tension rods with strain gauges.
(radial $\varnothing 14$ mm; upper $\varnothing 8$ mm; lower $\varnothing 6$ mm)
- Cryostat is the cyclotron vacuum chamber.



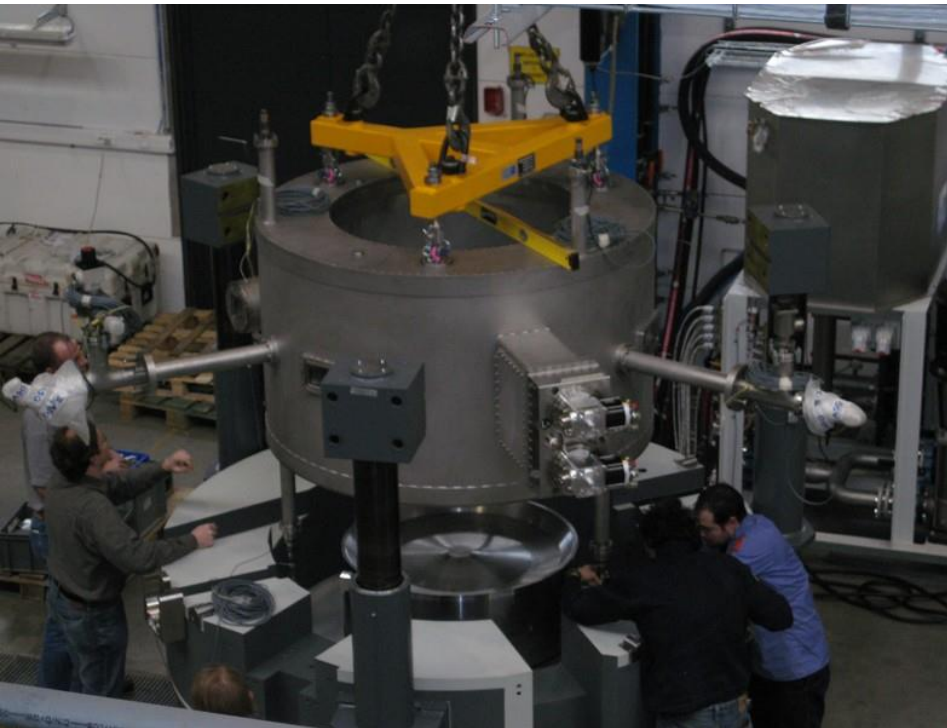
Superconducting coil

Cryostat penetrations



Superconducting coil

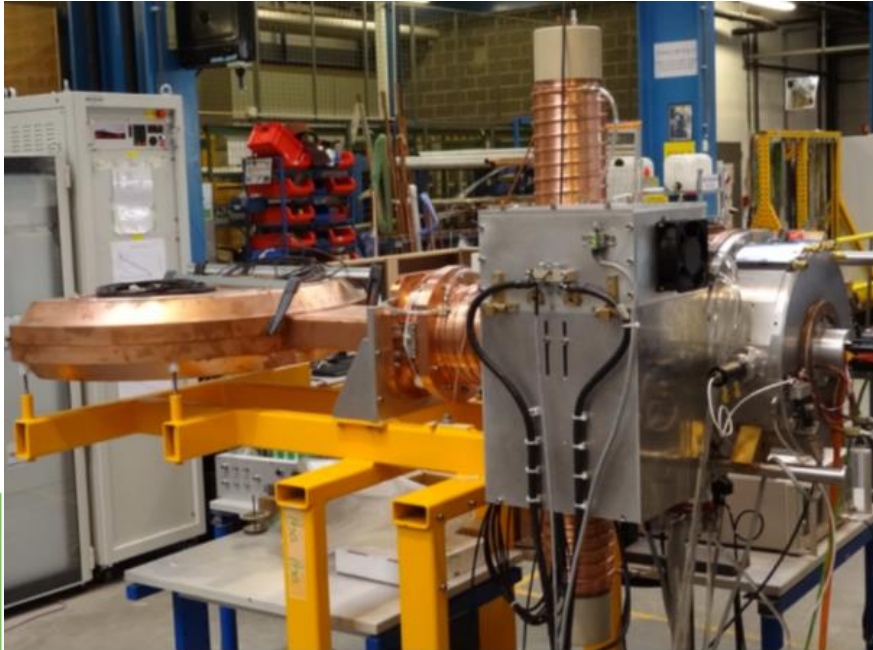
Installation of the cryostat in the yoke



RF-system

A triode-based self-oscillating RF system

RF system on the test bench



- $\lambda/2$ -structure operating in 1th harmonic mode: terminated by the 180° dee on one side and the rotco on the other side
- Biased at 1 kVolt to suppress multipactor
- Two side stubs provide fine-tuning of df/dt during capture
- RF Frequency: 60~90MHz
- Modulation frequency: 1kHz
- Dee voltage: 3~12kV
- Extensively modeled with CST
- Placed outside yoke in shielded volume
- Fully assembled in cyclotron and tested

RF-system

layout

Adjustable stub

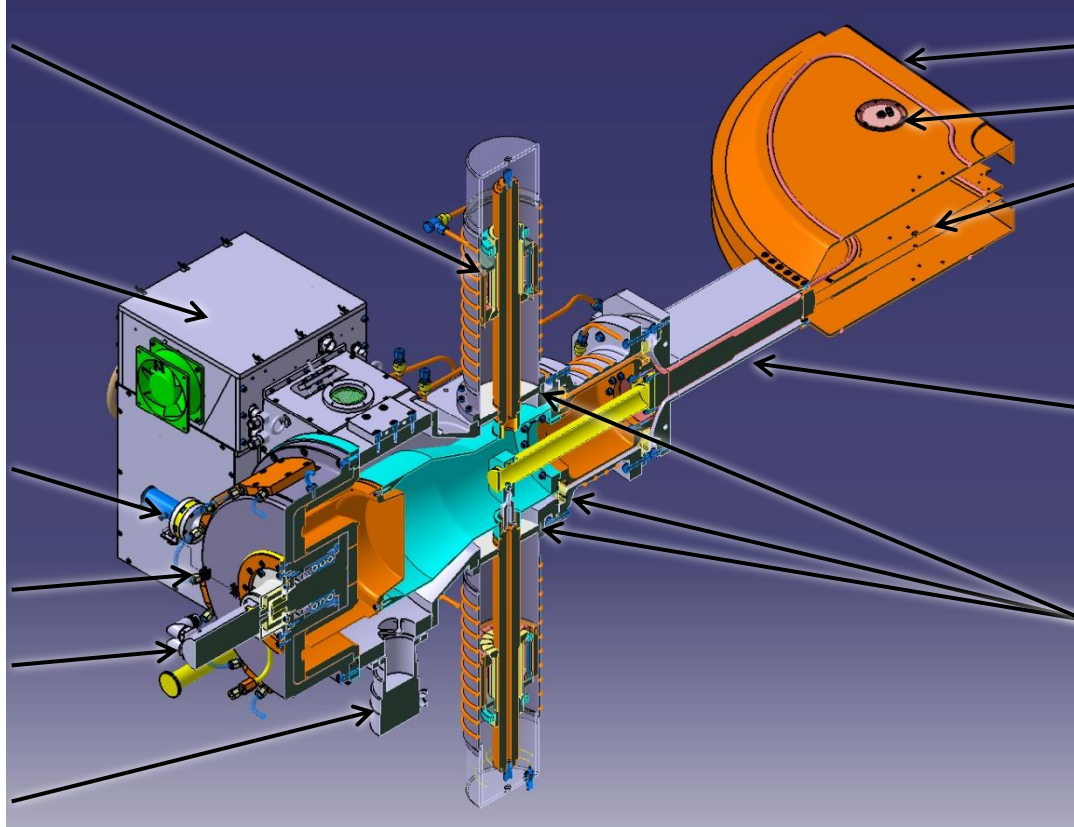
Oscillator

Pyrometer

Rotco

Servo motor

Turbo pump



Liner

RF pick-up

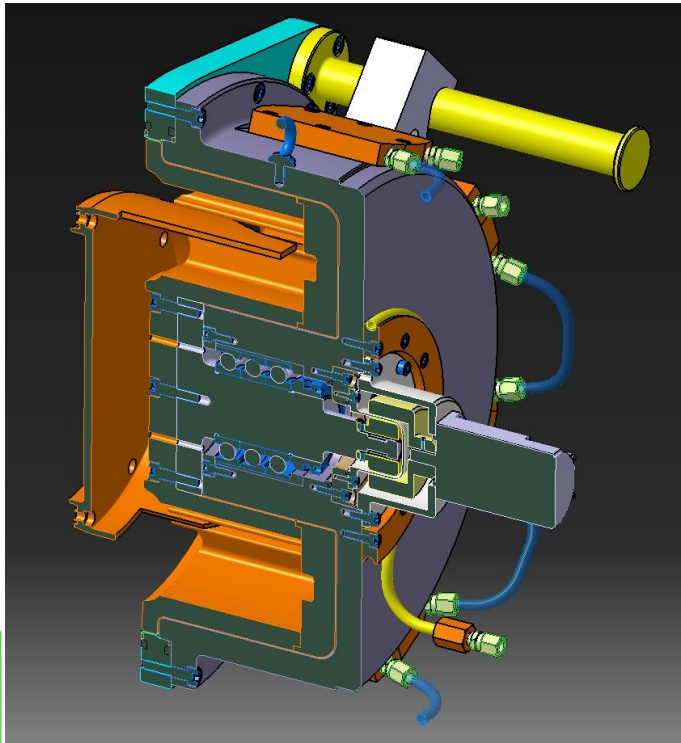
Dee

Line through
cryostat

Vacuum
feedthrough

RF-system

Rotco=> Coaxially mounted with 8-fold symmetry

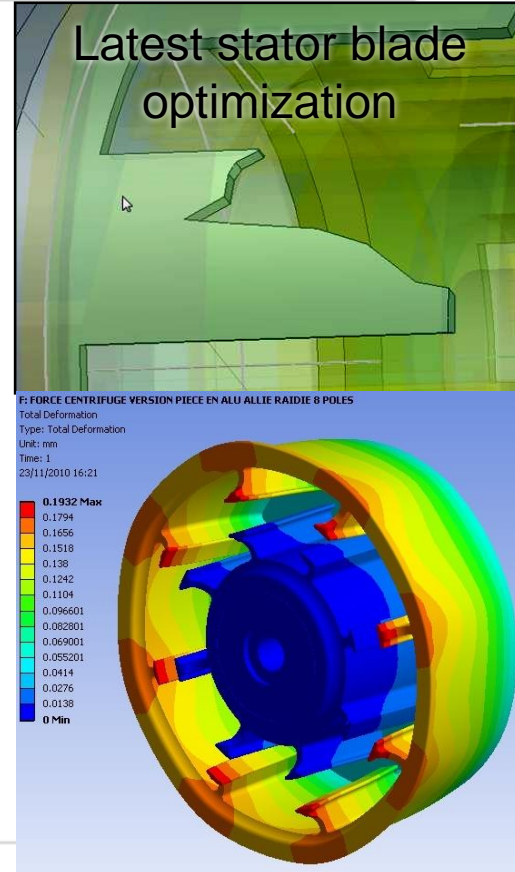
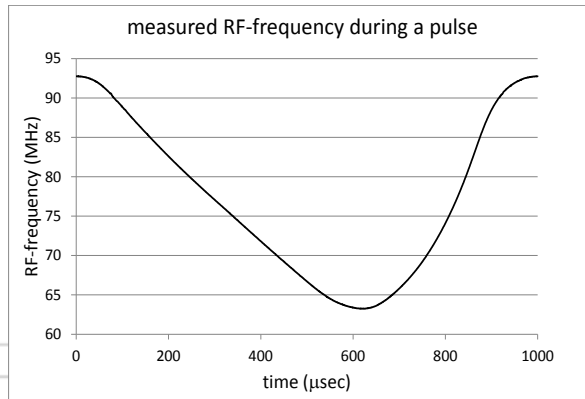


Innovative/patented design:

excellent mechanical stability
and good pulse reproducibility

Stator: 8 blades with a carefully
designed profile to have the
desired df/dt curve.

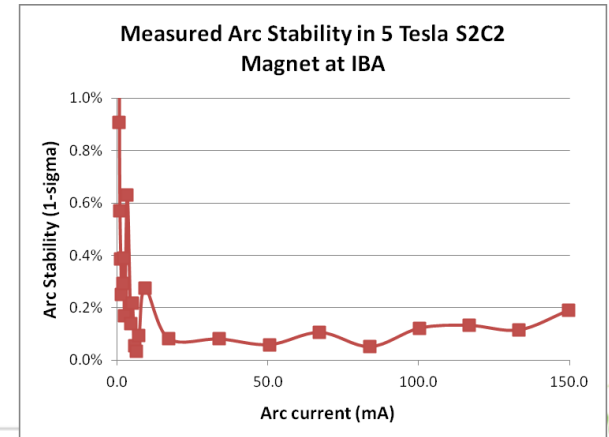
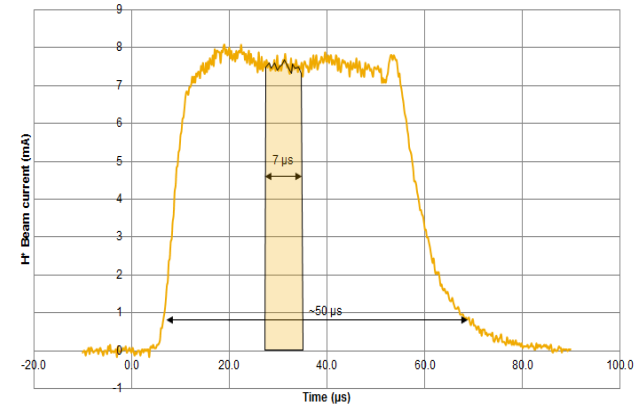
Rotor: wheel with 2x8 electrodes
turning at 7500rpm (1 kHz pulse)



Ion source

Use of cold cathode PIG internal ion source

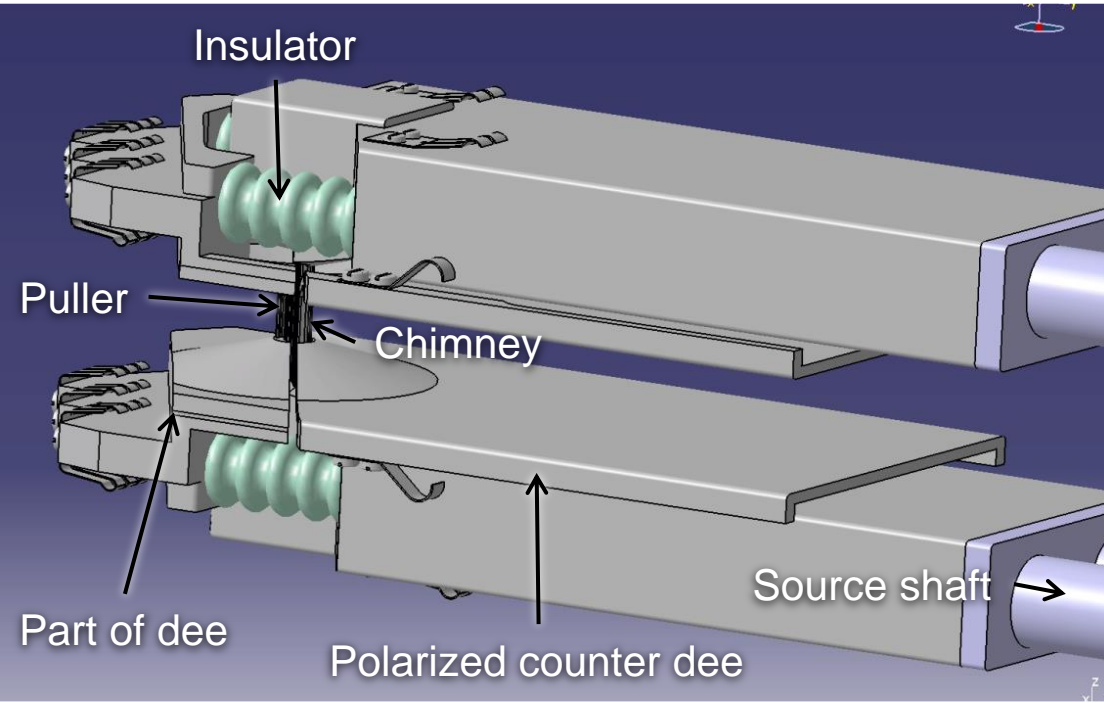
- For fast and precise PBS treatment we want:
 1. High dynamic range in output current (factor 100)
 2. Good pulse-to-pulse stability ($<1\%$)
 3. Fast rise times ($< 10 \mu\text{sec}$)
- Best candidate is cold cathode PIG source:
 1. Slow thermal effects/decreased thermal drifts
 2. Long lifetime (less evaporation of cathodes)
 3. Pulse frequency 1 kHz (synchronized with rotco)
 4. Pulse duration about $50 \mu\text{sec}$
- Test-stand measurements:
 1. Up to 6 mA H^+ current extracted
 2. Good reproducibility of plasma impedance
 3. Very good arc-current stability at 5 Tesla



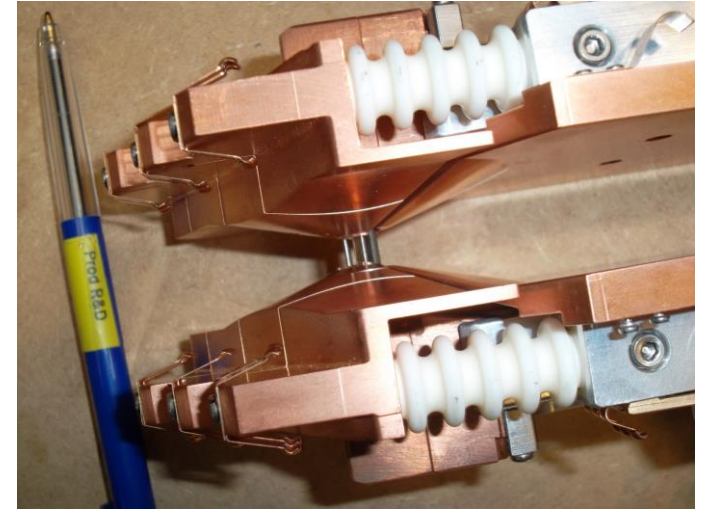
Ion source and central region

Assembly

The Ion Source and the central region, can be extracted as one assembly for easy maintenance and precise repositioning, without turning down the magnetic field.



Both dee and counter dee are biased at 1 kV



Ion source and central region

Central region size

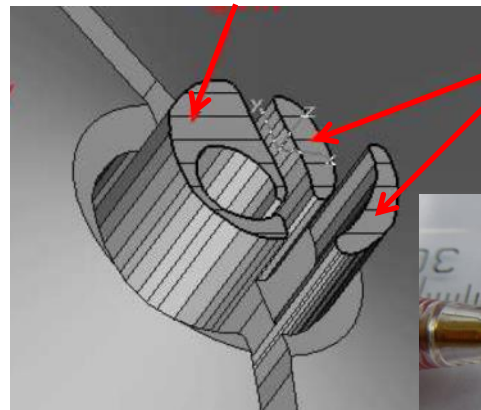
Due to the high magnetic field (5,74T) and the low dee voltage (11kV), the source has to be extremely compact:

Chimney

Puller

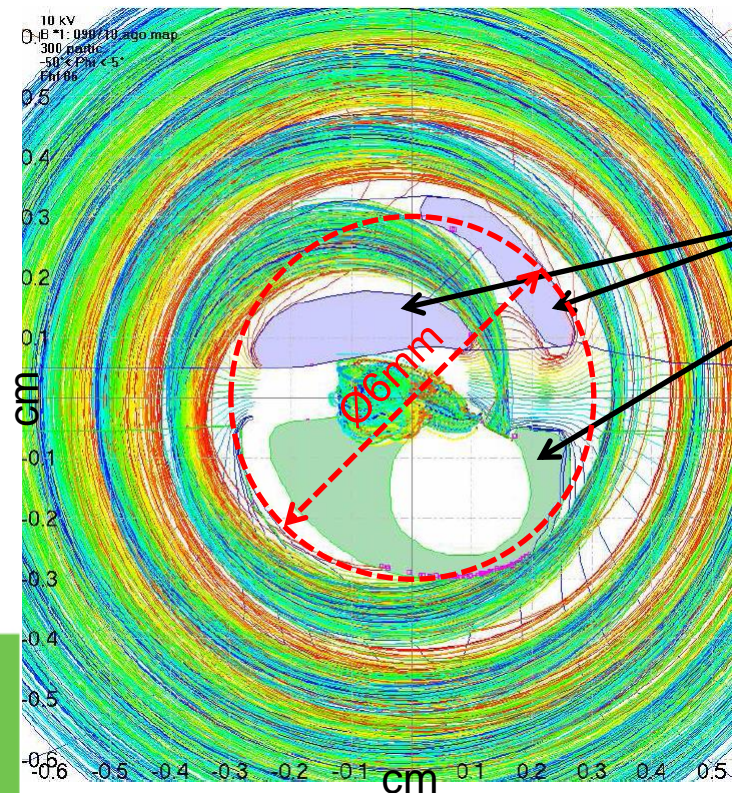
Puller

Chimney



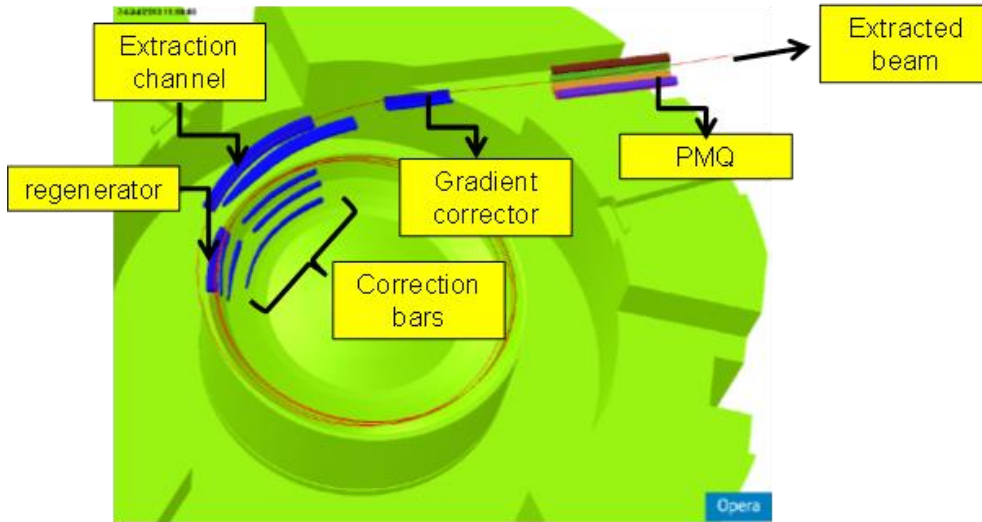
1. Source diameter < 5 mm
2. Vertical gap in the center 6 mm
3. First 100 turns within a radius of 3 cm

Tapered vertical gaps in the center, to reduce transit time factors



Layout of the extraction system

Fully passive system => only soft iron



- Unstable orbit is pushed outward by first harmonic into the extraction channel.
- Horizontal focusing by gradient corrector and permanent magnet quadrupole (PMQ) in strongly decreasing field.
- Correction bars are needed to reduce strong first harmonic error during acceleration.

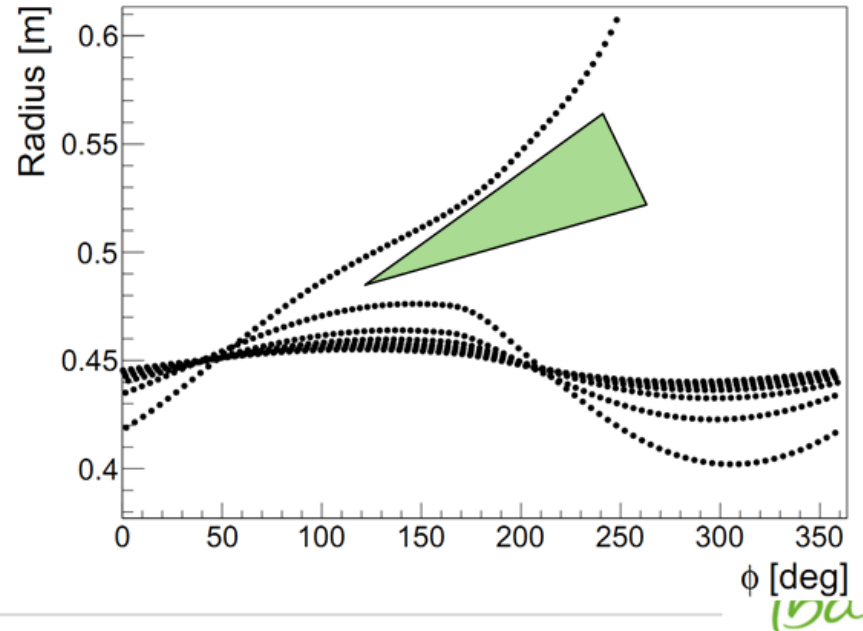
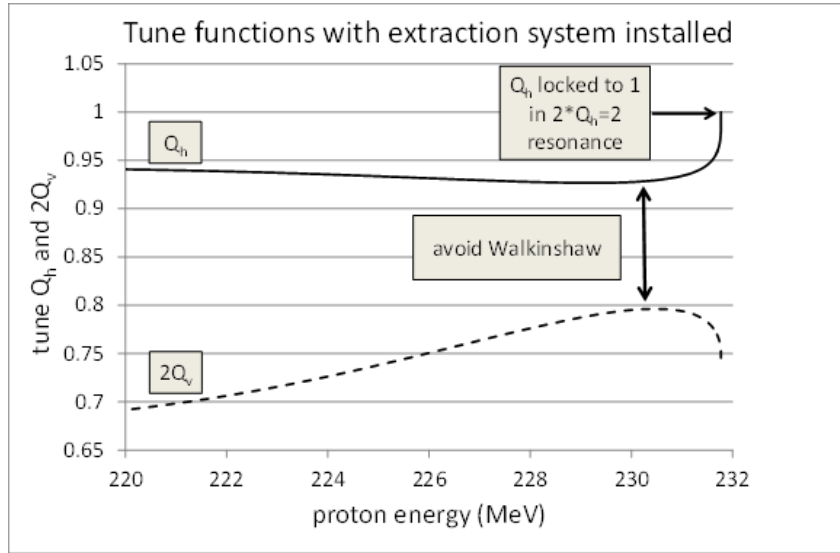
- Slow acceleration in a synchrocyclotron
- => Electrostatic deflector difficult to use.
- Use resonant extraction based on $2Q_h=2$ resonance.
- Strong local field bump produced by regenerator increases horizontal betatron frequency and locks it to unity.



Regenerative extraction based on $2Q_h=2$ resonance

Regenerator bump increases Q_h and locks it to 1

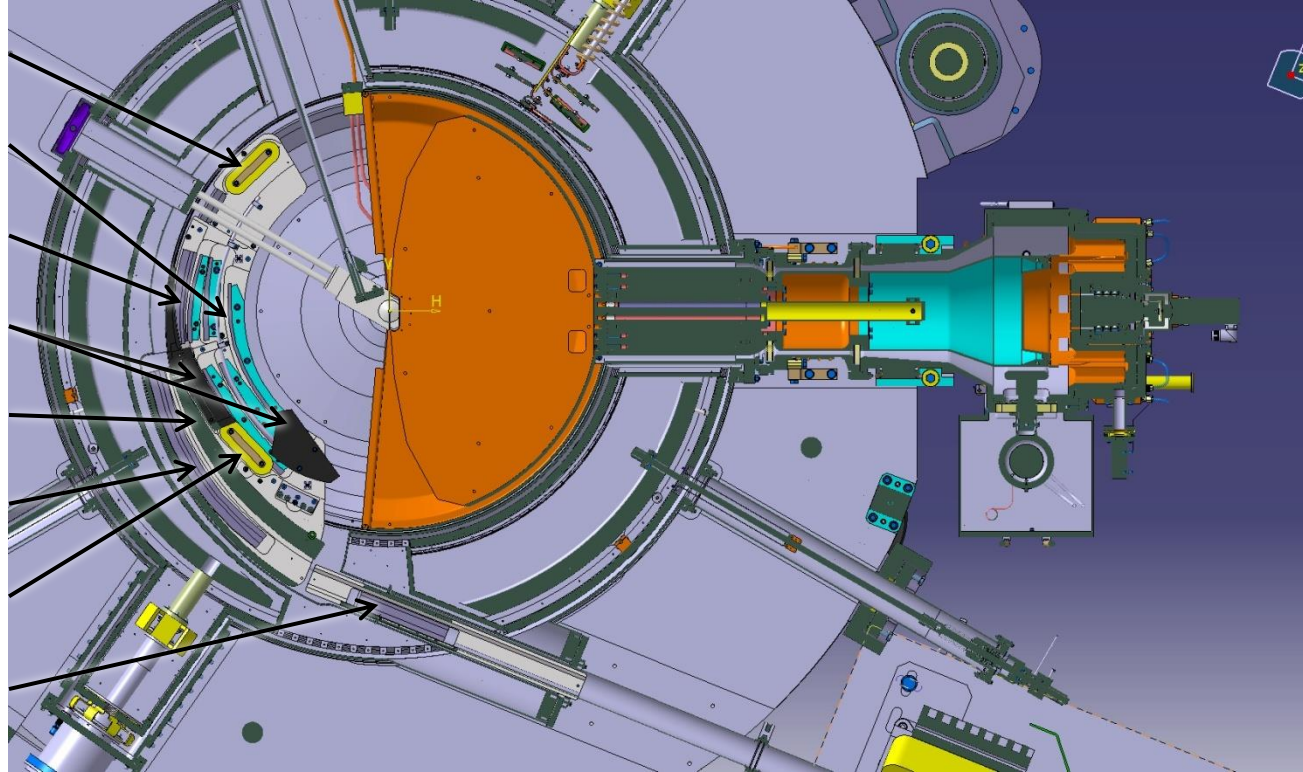
- Strong enough field bump $\Rightarrow Q_h=1$
- Avoid Walkinshaw resonance (Q_h-2Q_v)
- A steady shift of the beam towards the extraction channel builds up



Extraction system

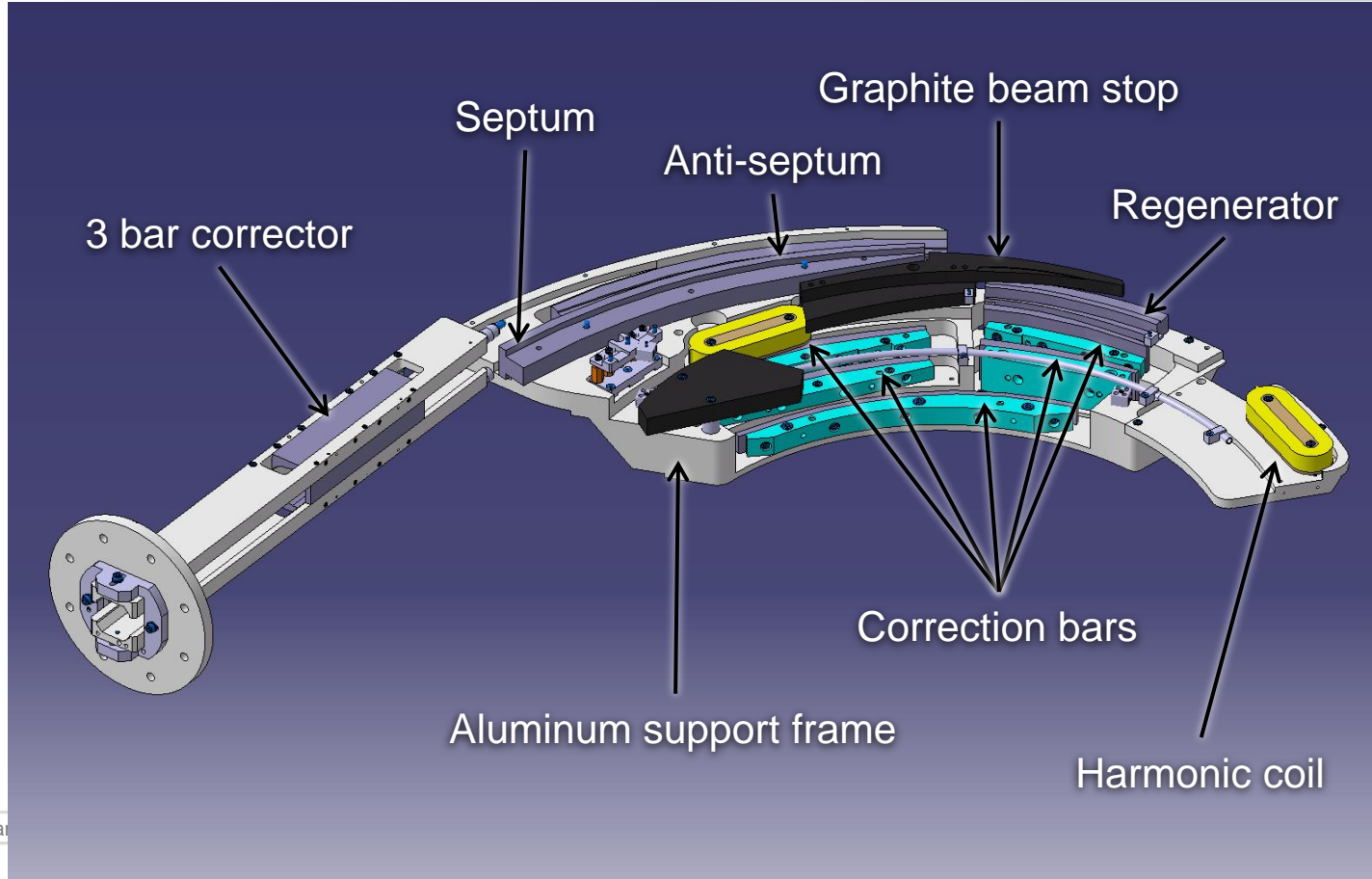
Layout (1)

- Harmonic coils
- Correction bars
- Regenerator
- Graphite beam stops
- Magnetic septum
- Anti-septum
- Harmonic coils
- 3 bar gradient corrector



Extraction system

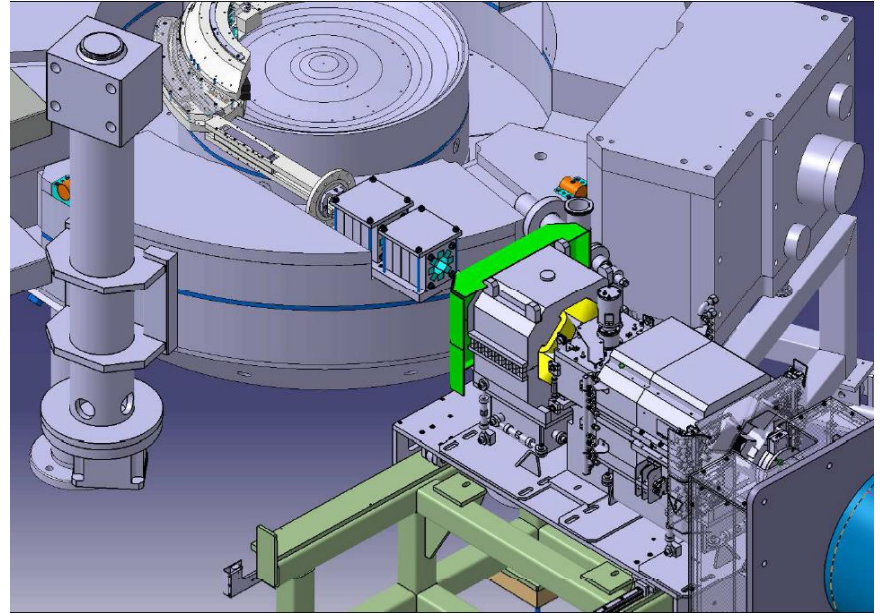
Layout (2)



External beam line

layout

- A variable energy degrader is placed at 2 meters from the yoke exit
- A permanent magnet quad matches the beam phase space with respect to the beam line optics
- A quadrupole doublet provides a 1 mm double waist (1-sigma) on the degrader.
- A variable horizontal collimator between the two quads cuts the horizontal divergence providing constant optics independent of gantry angle
- Full assembly can be shifted aside for access to the quads in the shielding wall



Status after assembly and installation in the

Cyclotron fully assembled and installed in shielded beam test vault (August 2013)

- Magnet:
 - Successfully cooled down and ramped up
 - Coil well centered in cryostat
 - Magnet fully mapped, no shimming needed
 - Extraction system fully mapped, no shimming needed
- Vacuum system operational
- Ion source operational; central region installed
- Rotco tested and operational
- RF-system installed in cyclotron and tested at full voltage
- Cyclotron installed in the shielded bunker
- First beam tests started middle of August

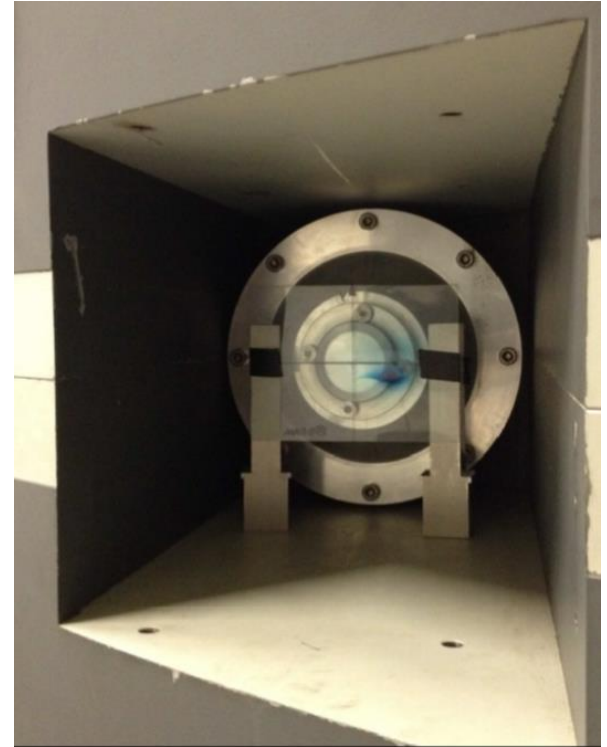


*The assembled S2C2 in the IBA
beam test vault, August 2013*

Extracted beam

First extracted beam observed end of August 2013

- A few days after the beginning of commissioning, beam extraction was observed by colour change of a radiation sensitive foil at the beam exit window
- After beam injection from the PIG source and 40000 turns of acceleration the beam was immediately ejected by the passive extraction system without any major design or other modifications
- Measured beam emittances and beam stability are in full agreement with expectations.
- Beam has been transported in the external beam line to the position of the degrader
- Shipment of cyclotron to Nice March 2014



Acknowledgements

A large team of IBA, AIMA and ASG experts have taken part in the design and testing of the S2C2...

