MO4PB02

The IBA Superconducting Synchrocyclotron Project S2C2

Wiel Kleeven on behalf of IBA and AIMA Development (Nice, France)

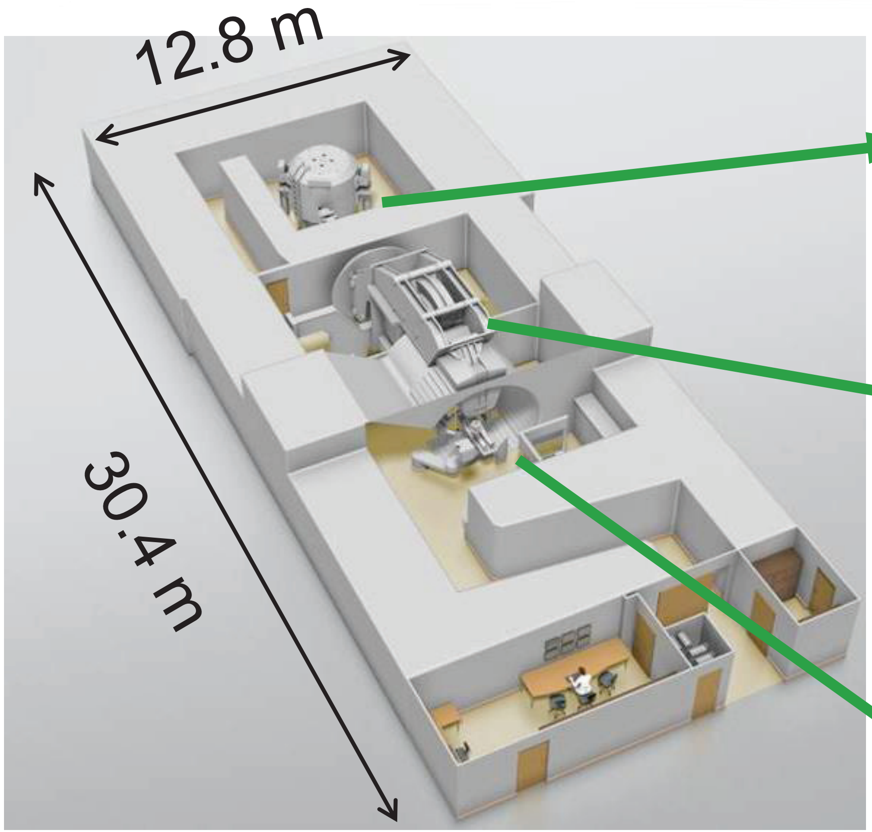
Outline

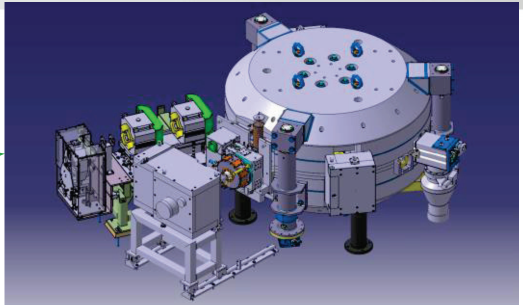
1. Intro (ProteusONE® and compact gantry)
2. Main features and parameters
3. Subsystems:
    - Magnetic Circuit
    - Superconducting coil
    - RF System
    - Ion Source+Central Region
    - Extraction System
    - Extracted beam line

4. Current status

The New IBA Single Room Proton Therapy Solution: ProteusONE®

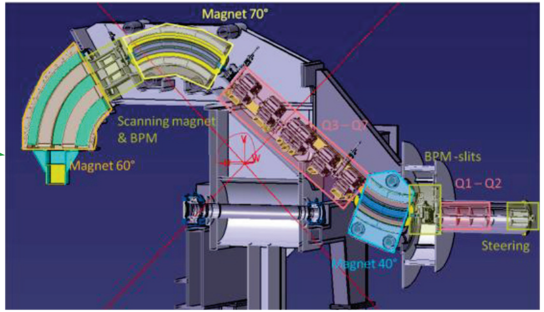
High quality PBS cancer treatment: compact and affordable





Synchrocyclotron with superconducting coil: S2C2

New Compact Gantry for pencil beam scanning

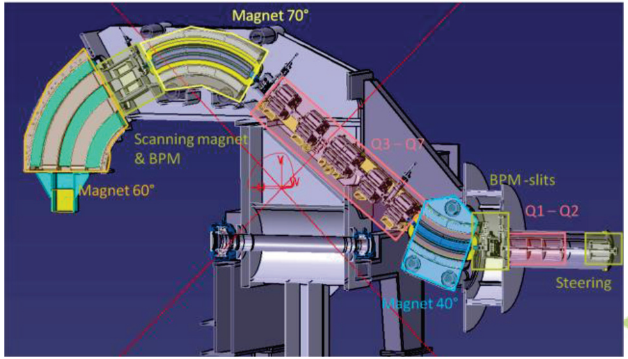


Patient treatment room

The new compact gantry for pencil beam scanning

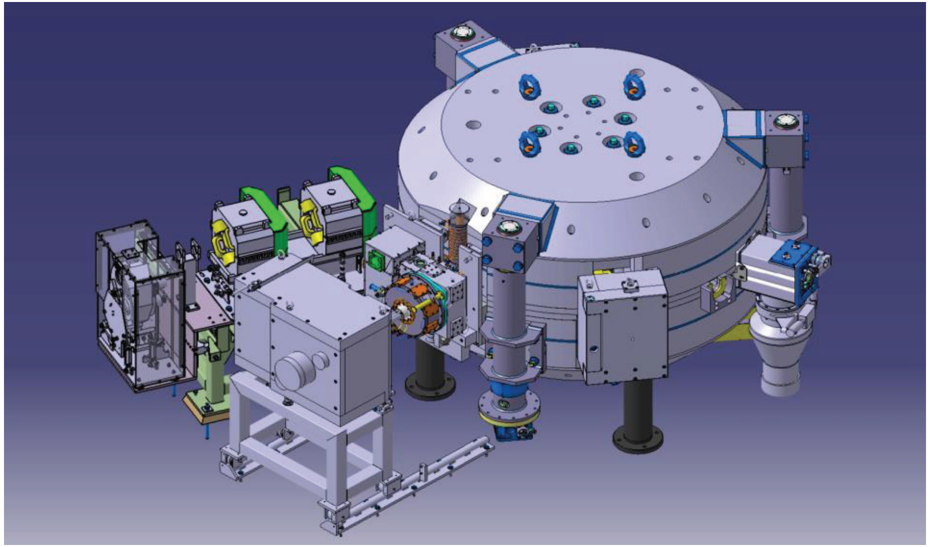
Design aimed at reducing footprint and cost

- Scanning magnets are placed upstream of the last bending magnet
- ESS integrated in the 45 deg inclined part
- Rotation angle 220˚
- Ready for shipment to first client before end of this year



S2C2 overview

General system layout and parameters

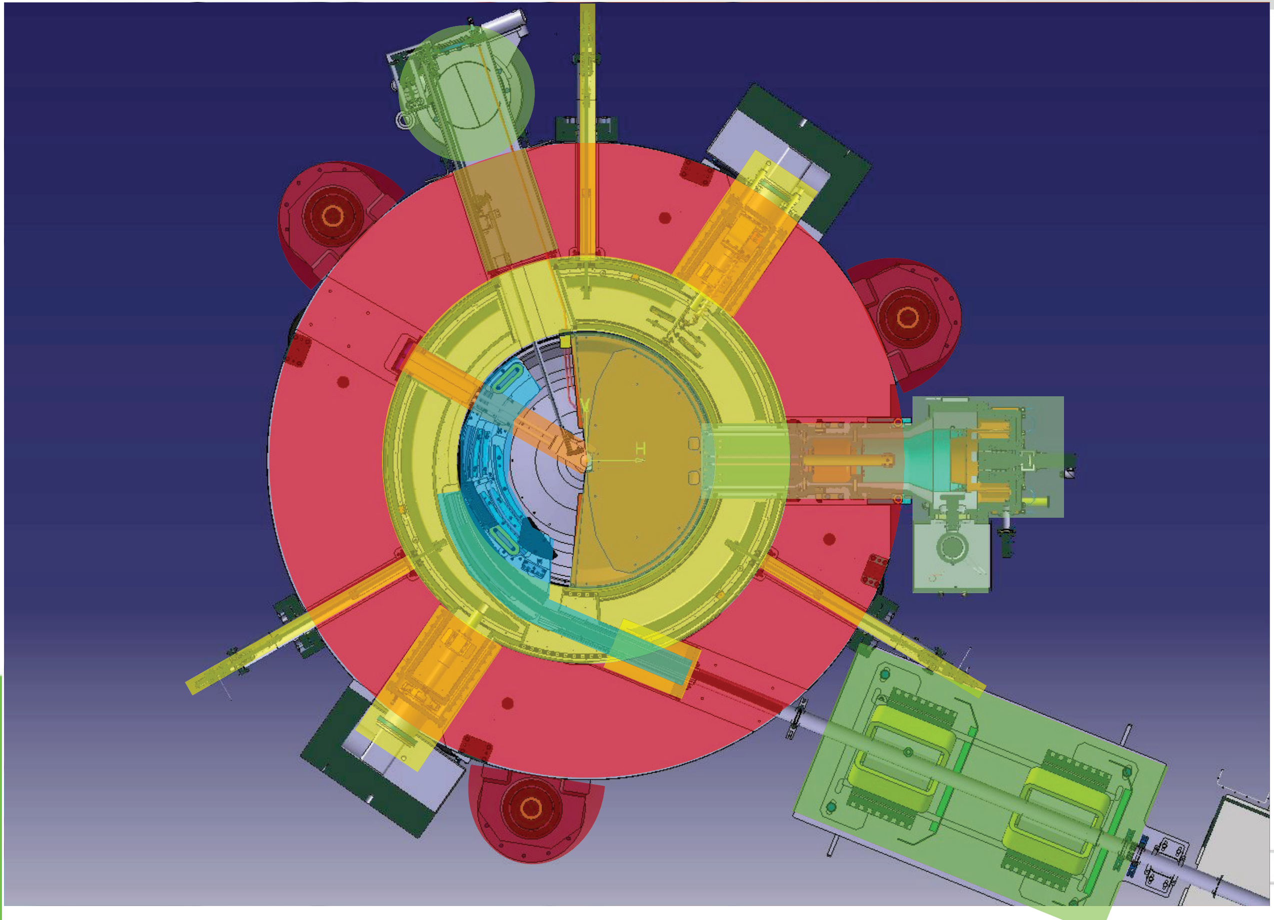


Maximum Energy	230/250 MeV
Size	
yoke/pole radius	1.25 m/0.50 m
weight	50 tons
Coil	NbTi - wire in channel
ramp up rate / time	2-3A/min / 4 hours
windings/coil	3145
stored energy	12 MJ
Magnetic field	
central/extraction	5.7 T/5.0 T
Cryo cooling	conductive
	4 cryocoolers 1.5 W
initial cooldown	12 days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

- A separate oral contribution on the field mapping of the S2C2 will be given by Vincent Nuttens (TU4PB01)
- Several contributions can be found on the ECPM2012-website

S2C2 overview

Main subsystems



Magnet yoke

Superconducting coil

RF system

Ion source+central region

Extraction system

Vacuum system

Yoke lifting system

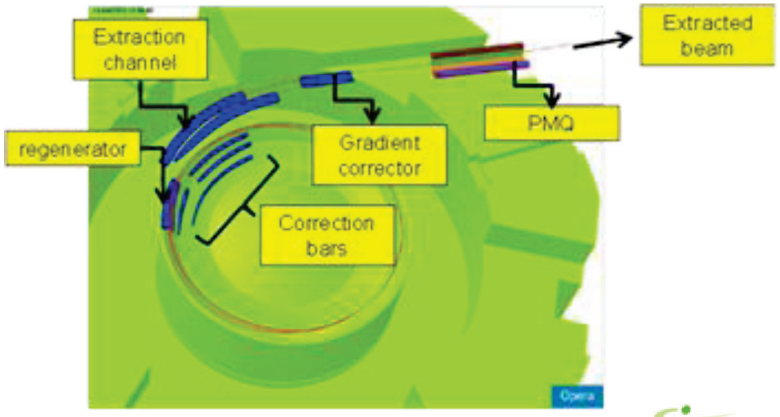
Extracted beam line

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 < => extraction system optimization
- Influence of yoke penetrations
- Median plane errors
- Magnetic forces

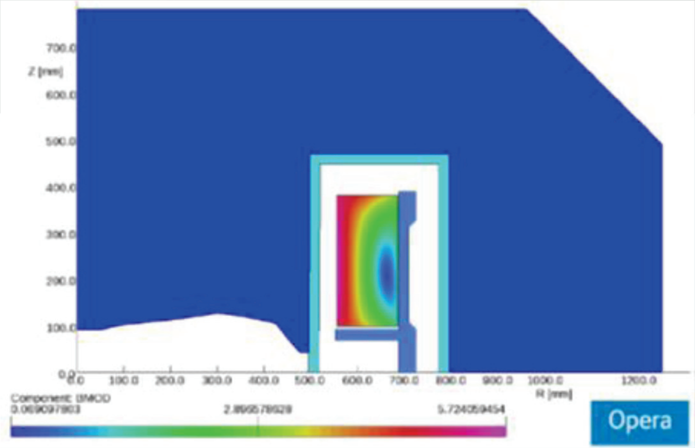
ITERATIVE PROCESS WITH STRONG INTERACTION TO BEAM SIMULATIONS

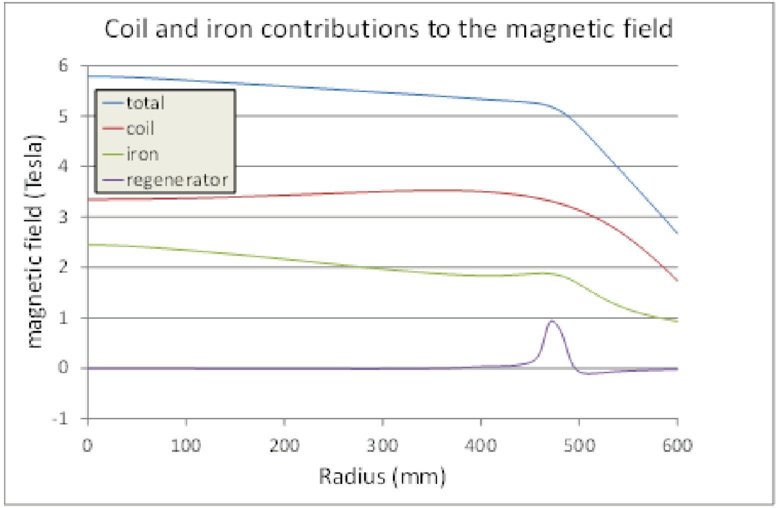


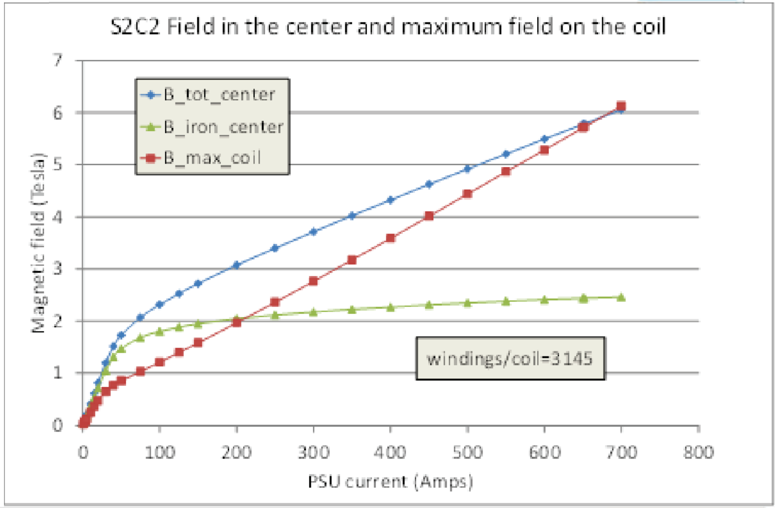
Magnetic circuit modeling

Some examples of OPERA2D results

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







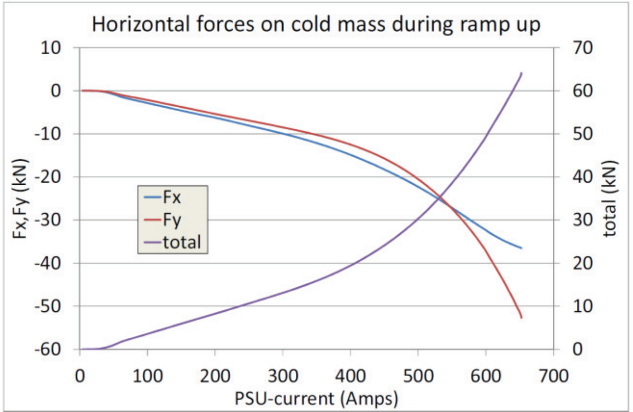
Magnetic circuit

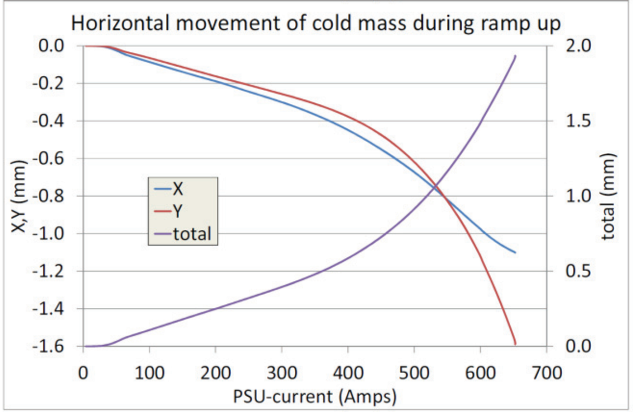
Forces acting on the coil => implications for tierod design

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

SIMULATED

FORCES AND TORQUES ACTING ON THE MAIN COIL SYSTEM DUE TO COIL DISPLACEMENTS AND ROTATIONS							
		FORCES			TORQUES		
		dFx ton/mm	dFy ton/mm	dFz ton/mm	dTx Nm/mm	dTy Nm/mm	dTz 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
coil rotation		dFx ton/deg	dFy ton/deg	dFz ton/deg	dTx Nm/deg	dTy Nm/deg	dTz Nm/deg
	around x-axis	-0.02	0.00	-0.12	91559	-4609	-80
	around y-axis	-0.05	-0.01	-0.30	-4484	91305	79



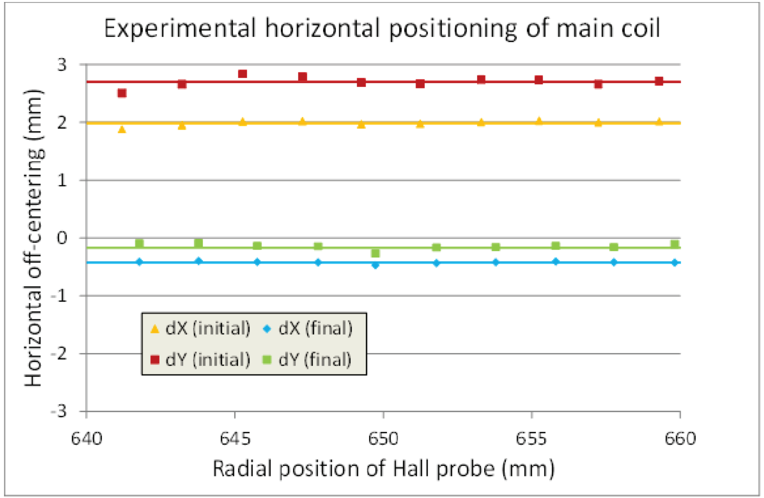


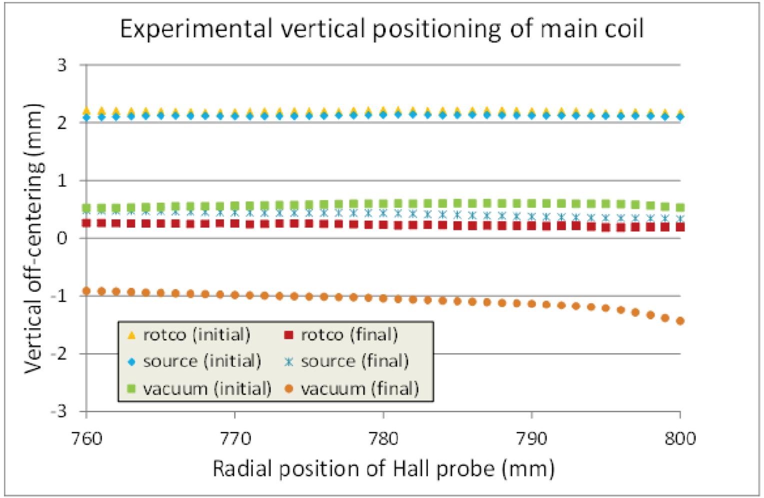
MEASURED

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 dBz/dr is maximum
- Vertical centering: measure $B_r(r)$ where $B_z=0$

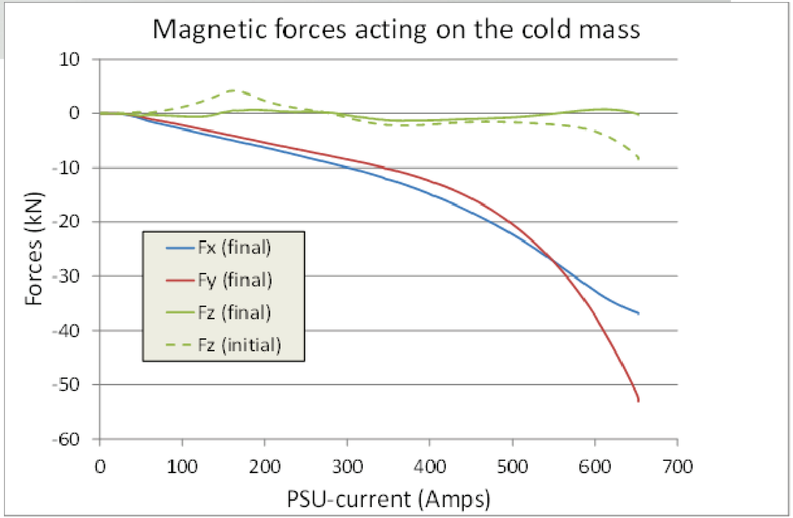




Magnetic circuit: centering of the cold mass (2)

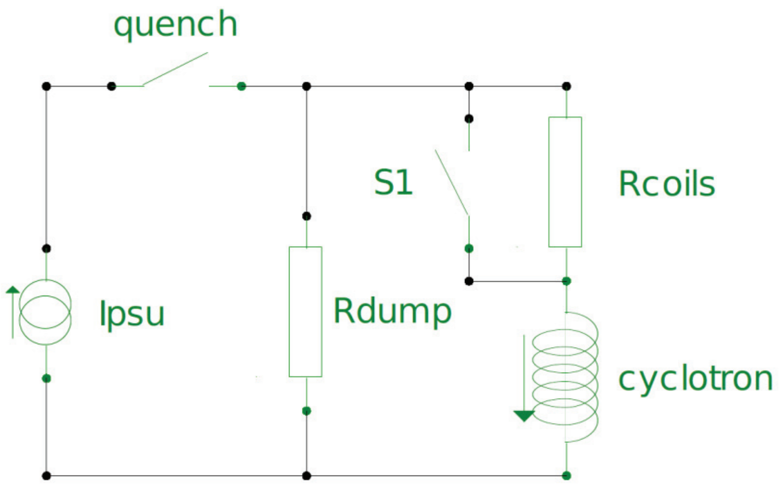
Minimize the vertical forces on the cold mass

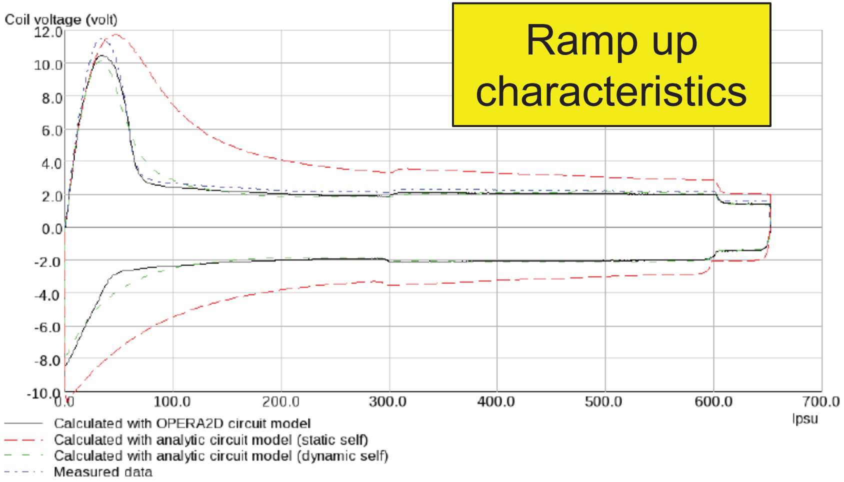
- Forces are measured with strain gauges placed in the tierod-assemblies
- Opera calculations:
  - Low vertical forces ⇔ small median plane errors
- Vertical forces are reduced by coil-centering and by external shimming
- Horizontal forces are large due to extraction system and yoke-asymmetries
- During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



Magnetic circuit:

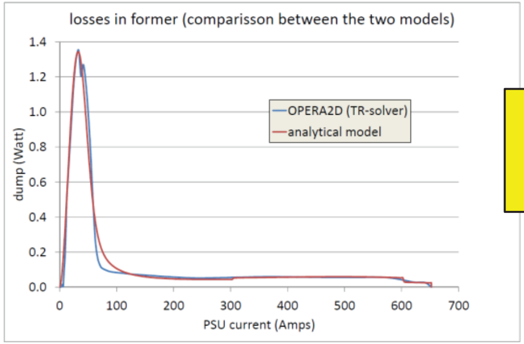
Dynamic behavior studied with Opera2D FE transient circuit model





Ramp up characteristics

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



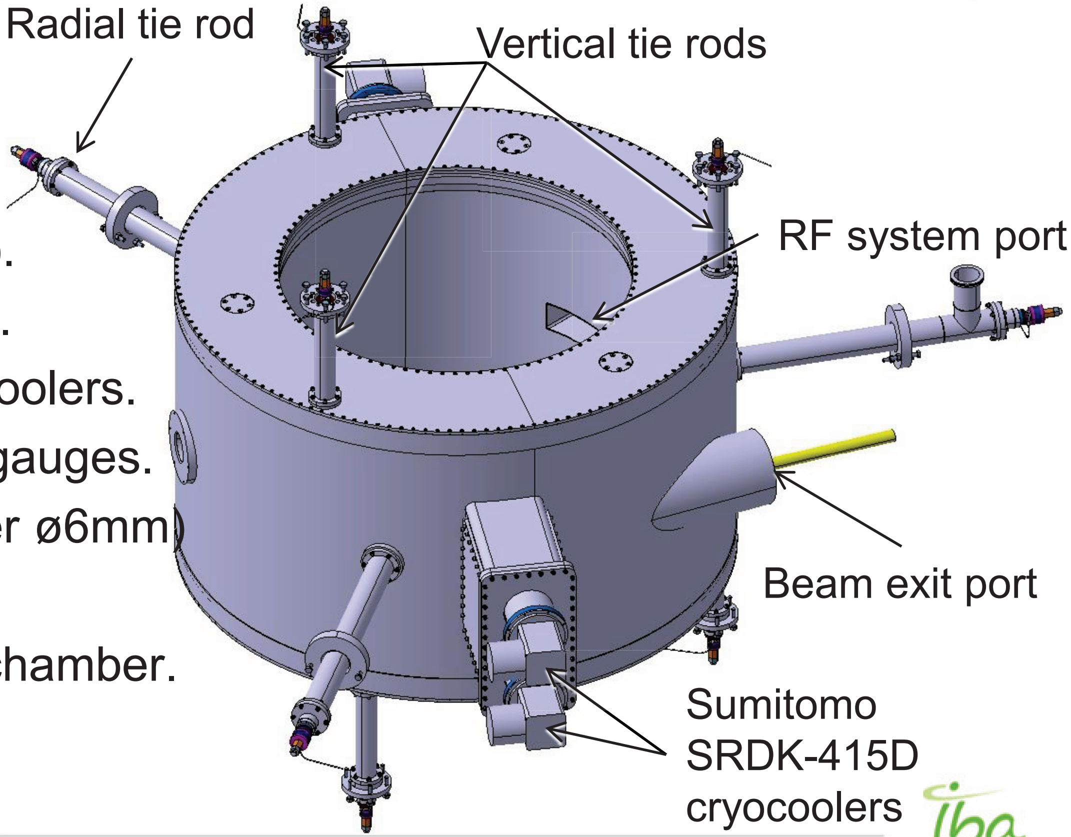
Eddy current losses

Superconducting coil

Designed and manufactured by ASG (Genua, Italy)

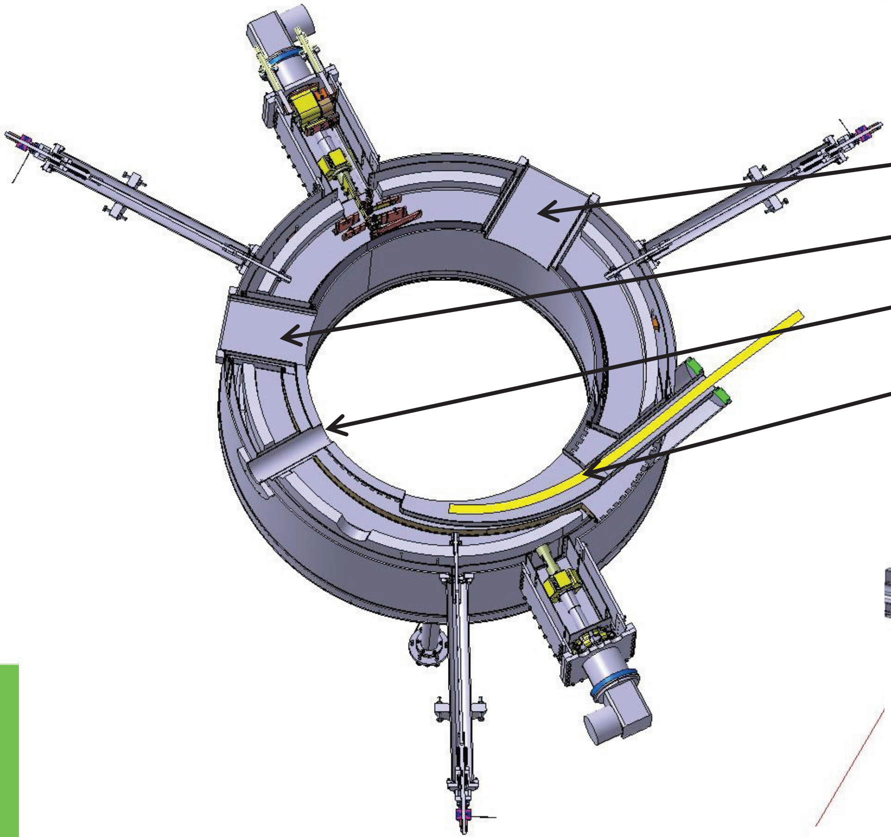
- NbTi wire in channel coil.
- Suspended cold mass: 3tons.
- Overall weight: 4tons.
- Nominal current: 650A (56 A/mm²).
- Nominal ampere-turns: $4.3 \times 10^{+6}$At.
- Conduction cooled by 4 SHI cryocoolers.
- 9 Inconel tension rods with strain gauges. (radial ø14mm; upper ø8mm; lower ø6mm)

- Cryostat is the cyclotron vacuum chamber.

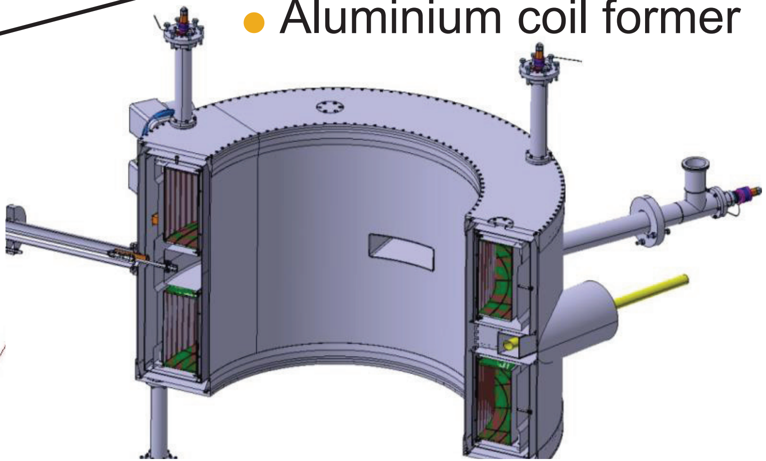


Superconducting coil

Cryostat penetrations

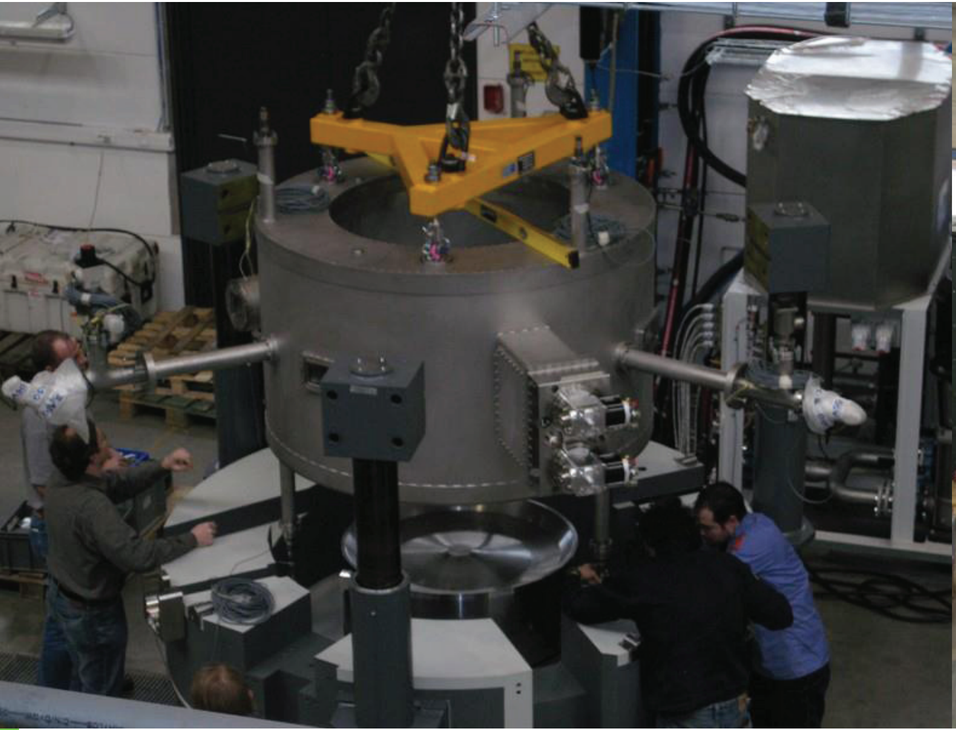


- Four cryostat penetrations
  1. RF port
  2. Vacuum pumping/radial probe
  3. Ion source
  4. Beam extraction
- Aluminium coil former



Superconducting coil

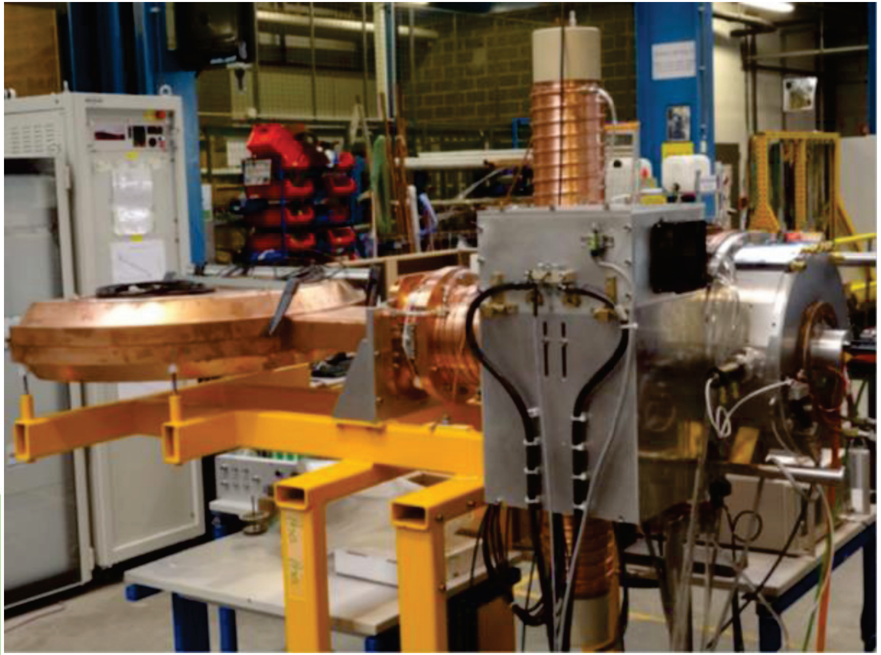
Installation of the cryostat in the yoke



RF-system

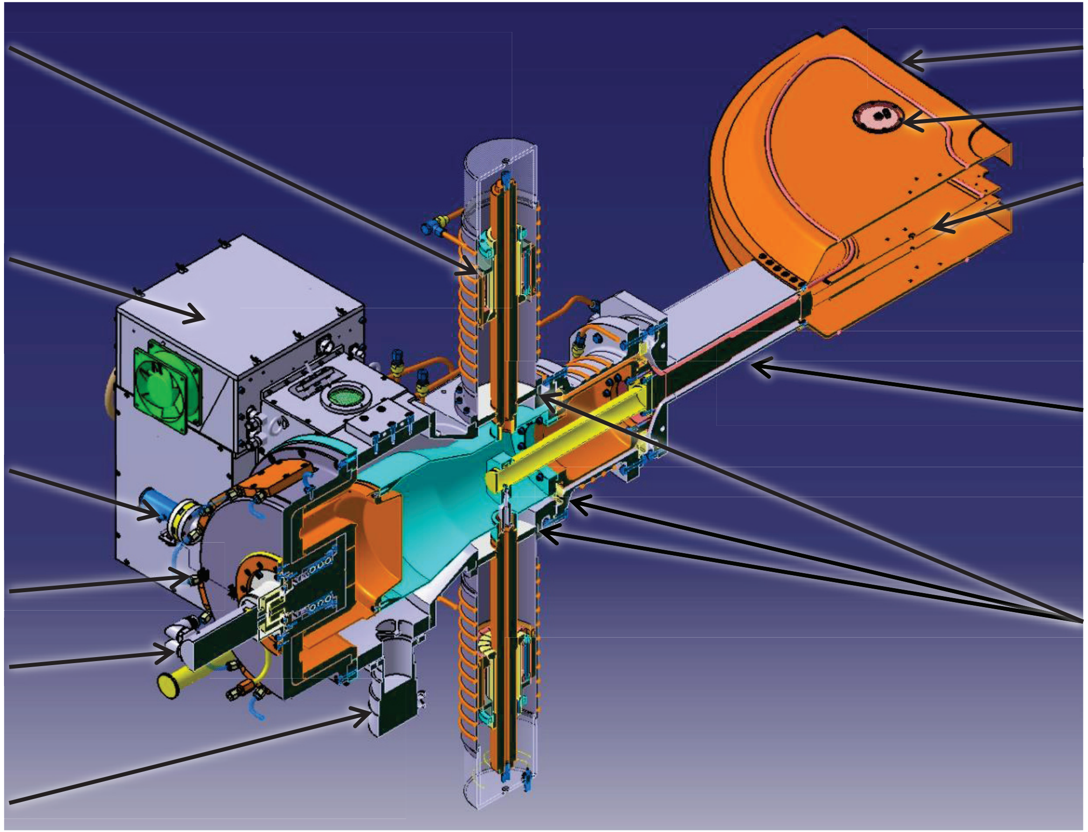
A triode-based self-oscillating RF system

RF system on the test bench



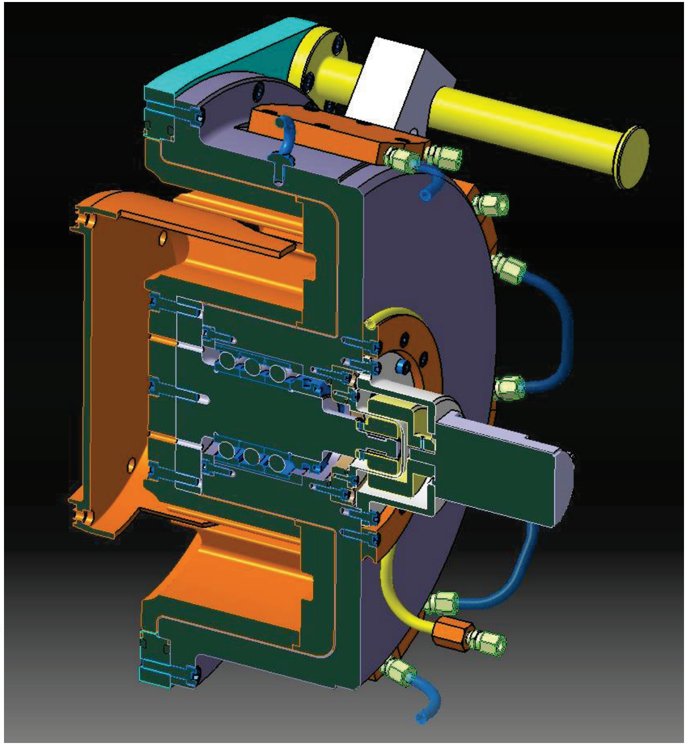
- $\lambda/2$-structure operating in 1th harmonic mode: terminated by the 180° dee on one side and the rotco on the other side
- Biased at 1 kVolt to supress mulipactor
- Two side stubs provide fine-tuning of df/dt during capture
- RF Frequency: 60~90MHz
- Modulation frequency: 1kHz
- Dee voltage: 3~12kV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

RF-system
layout



RF-system

Rotco=> Coaxially mounted with 8-fold symmetry

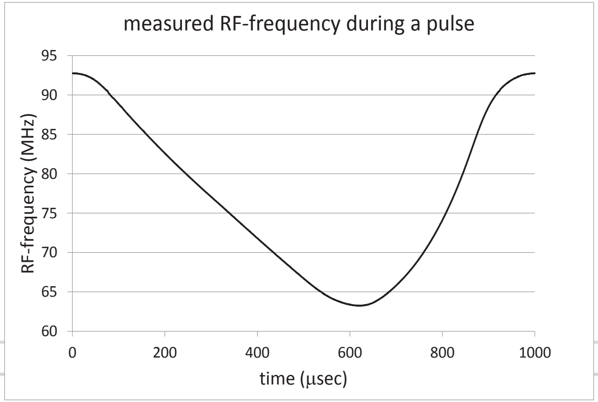


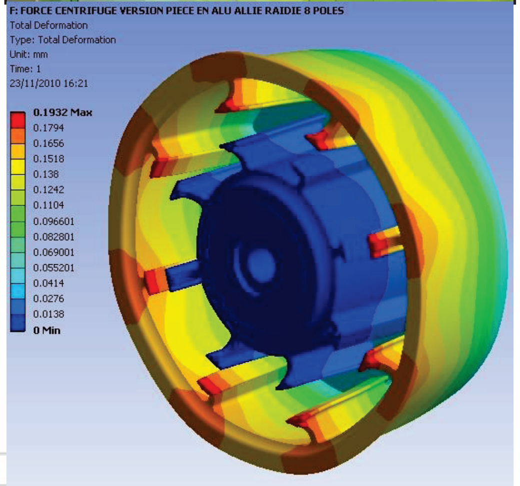
Innovative/patented design:

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)

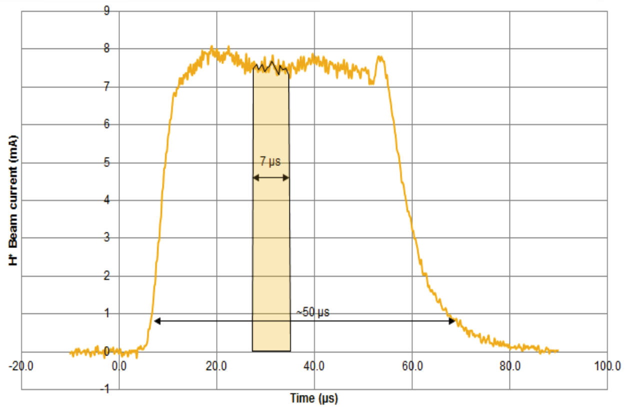


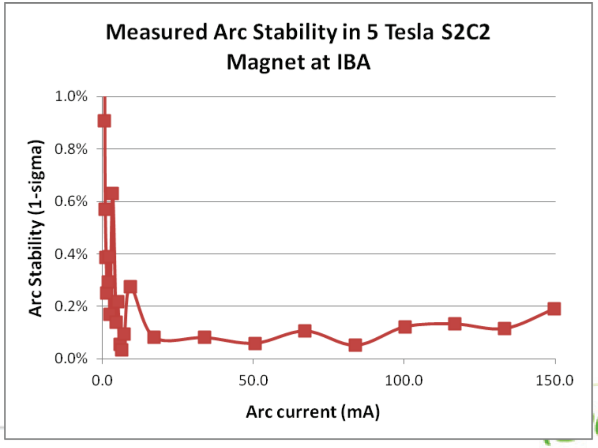


Ion source

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 μsec)
- 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 μsec
- 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

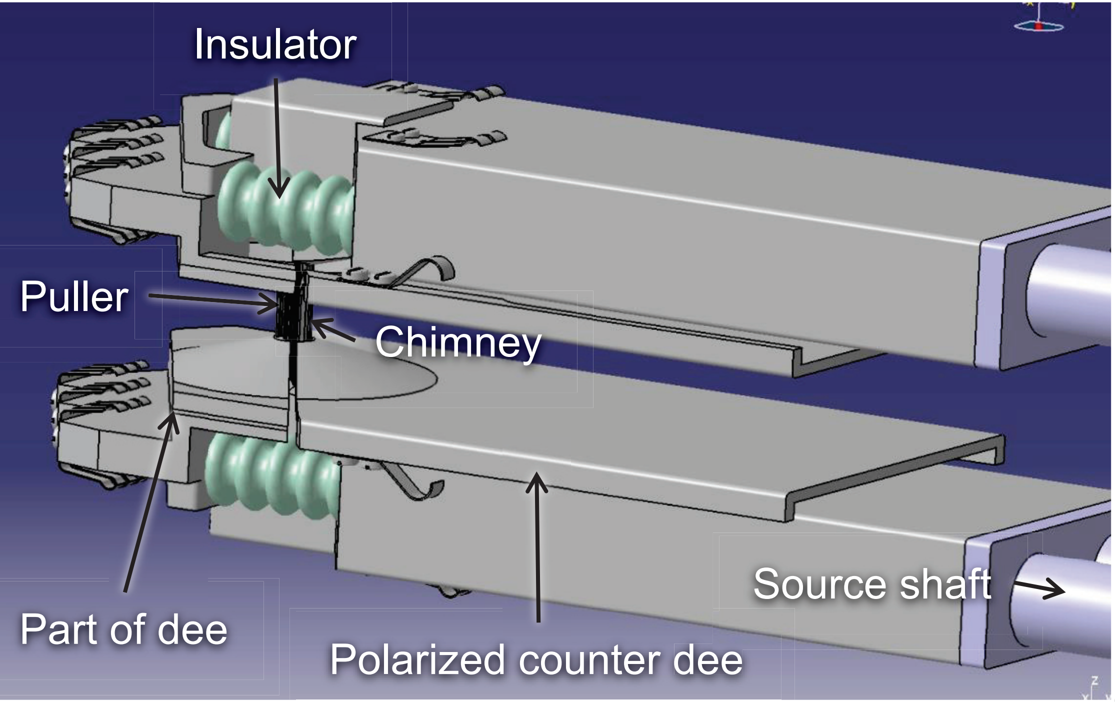




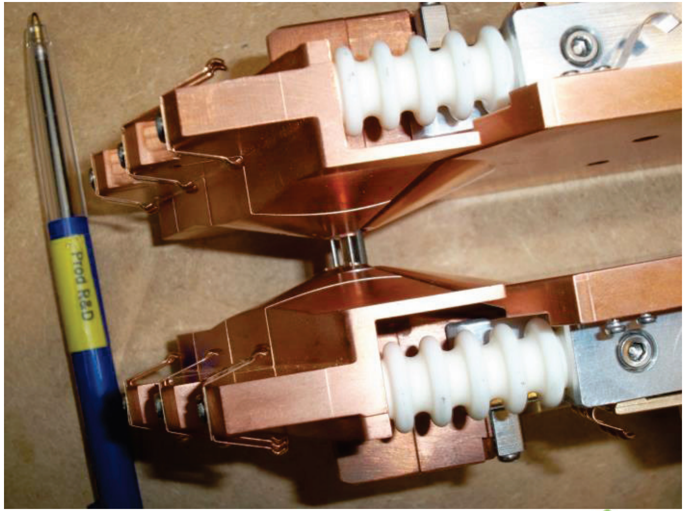
Ion source and central region

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.

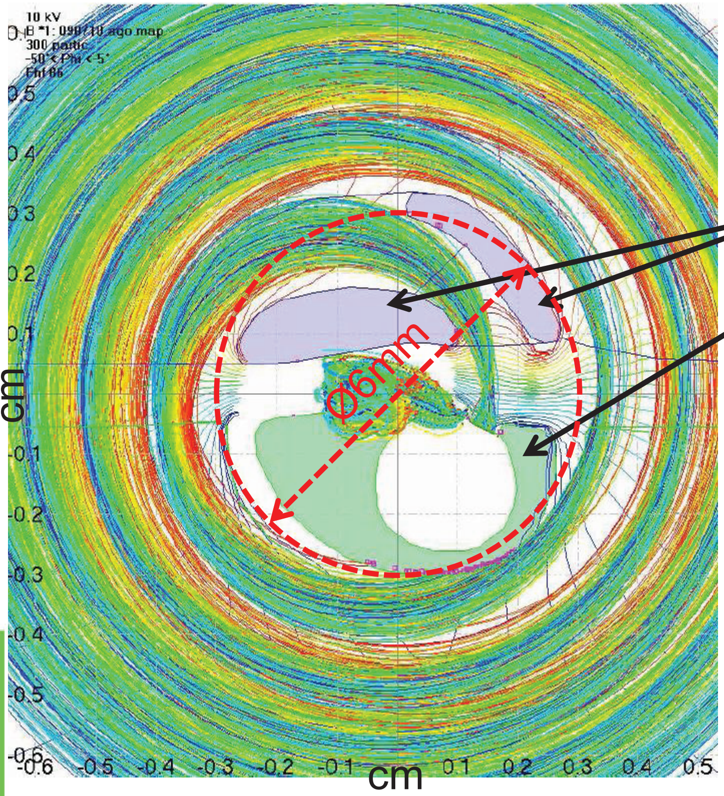


Both dee and counter dee are biased at 1 kV



Ion source and central region

Central region size



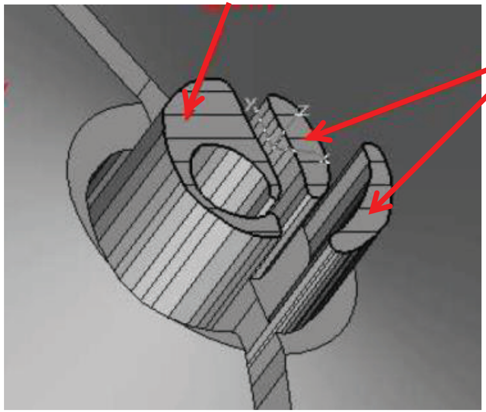
Puller

Chimney

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

Chimney

Puller



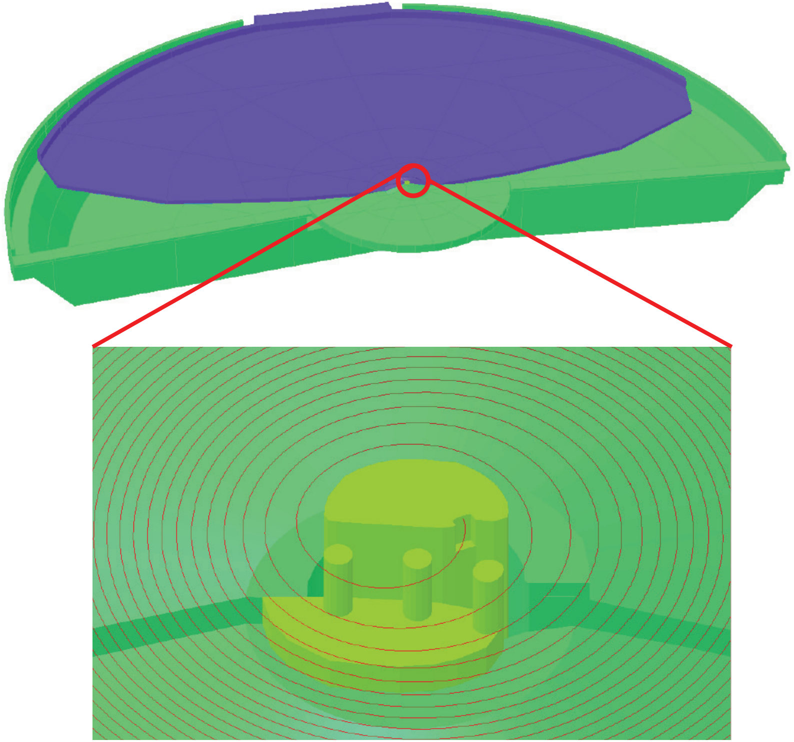
1. Source diameter < 5 mm
2. Vertical gap in the center 6 mm
3. First 100 turns within a radius of 3 cm

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

Central region

Simulations

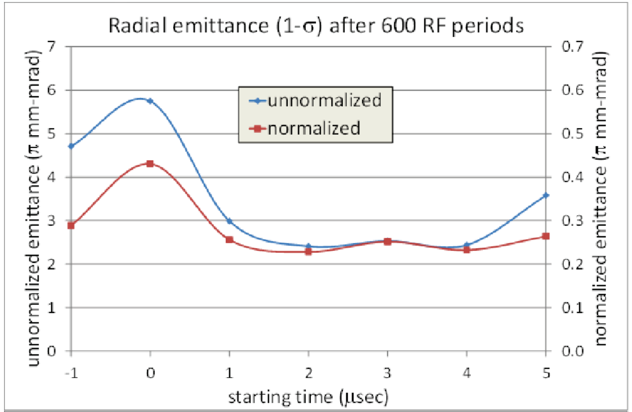
- Some calculation goals:
    1. Precise modeling of the electric fields
    2. Good beam centering and focusing
    3. Precise simulation of cyclotron acceptance
    4. Full dee modeling also for extraction calculations

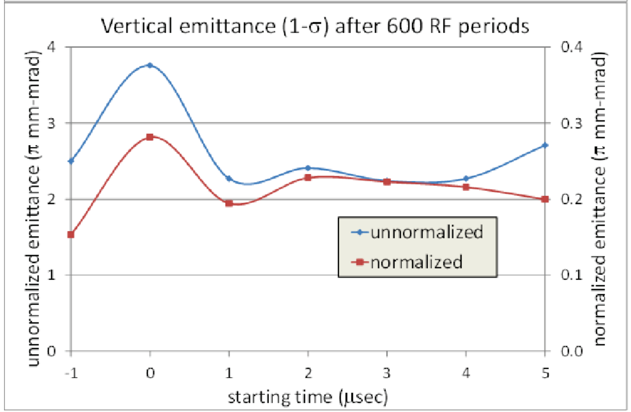


Simulation of central region acceptance phase space

Used in the extraction simulations

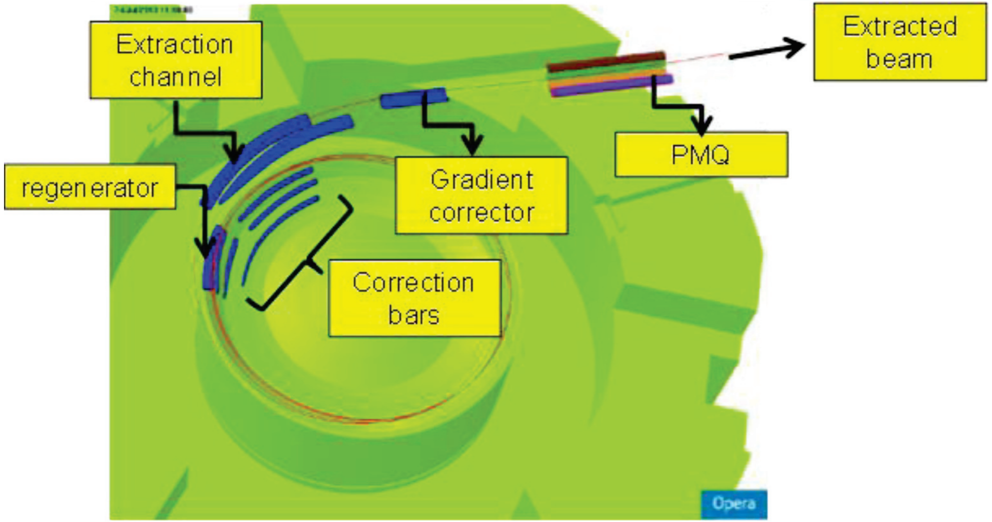
- Start tracking many particles (10000) from the ion source
- Initial conditions: 6-dimensional phase space which is larger than cyclotron acceptance
  1. Horizontal (x-Px)
  2. Vertical (z-Pz)
  3. Longitudinal (RF–phase and capture-moment)
- Analyse the accelerated phase space after the first longitudinal phase oscillation (2 MeV)
- Small normalized emittances are obtained (about 0.3 π mm-mrad (1-sigma))
- Extraction calculations use these values



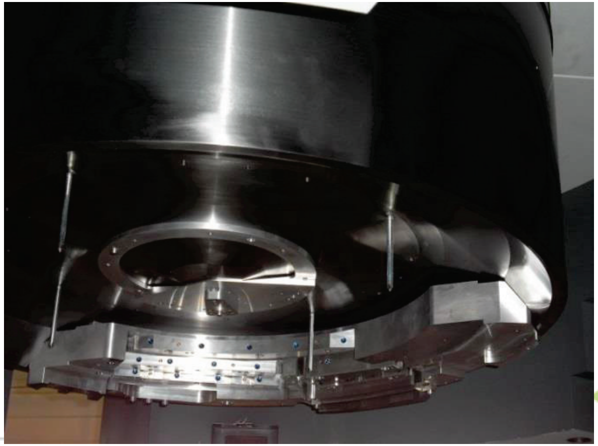


Layout of the extraction system

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.

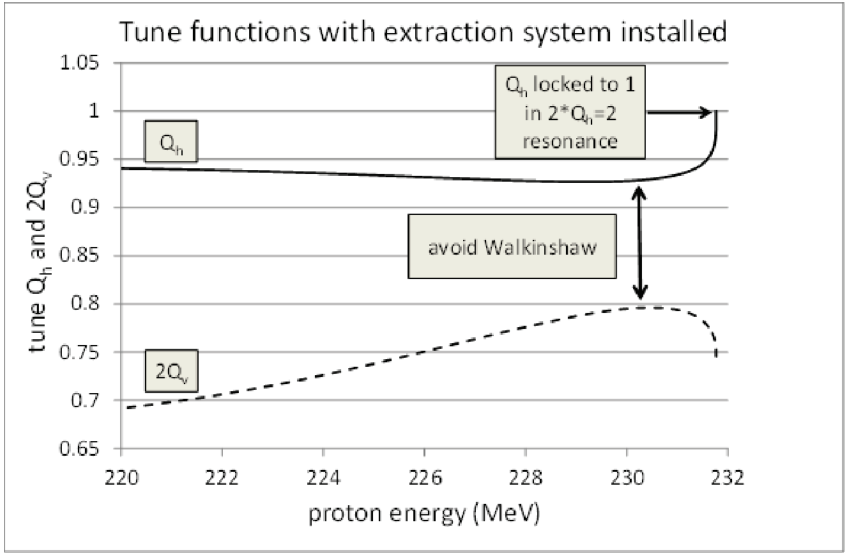


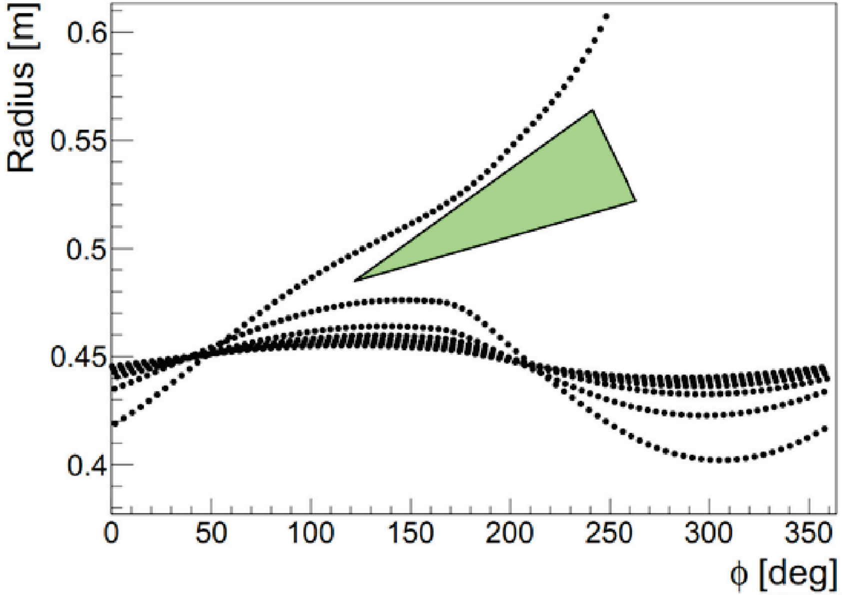
- Slow acceleration in a synchrocyclotron
- => Electrostatic deflector difficult to use.
- Use resonant extraction based on $2Q_h=2$ resonance.
- Strong local field bump produced by regenerator increases horizontal betatron frequency and locks it to unity.

Regenerative extraction based on $2Q_h$=2 resonance

Regenerator bump increases Q_h and locks it to 1

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





Extraction system

Layout (1)

Harmonic coils

Correction bars

Regenerator

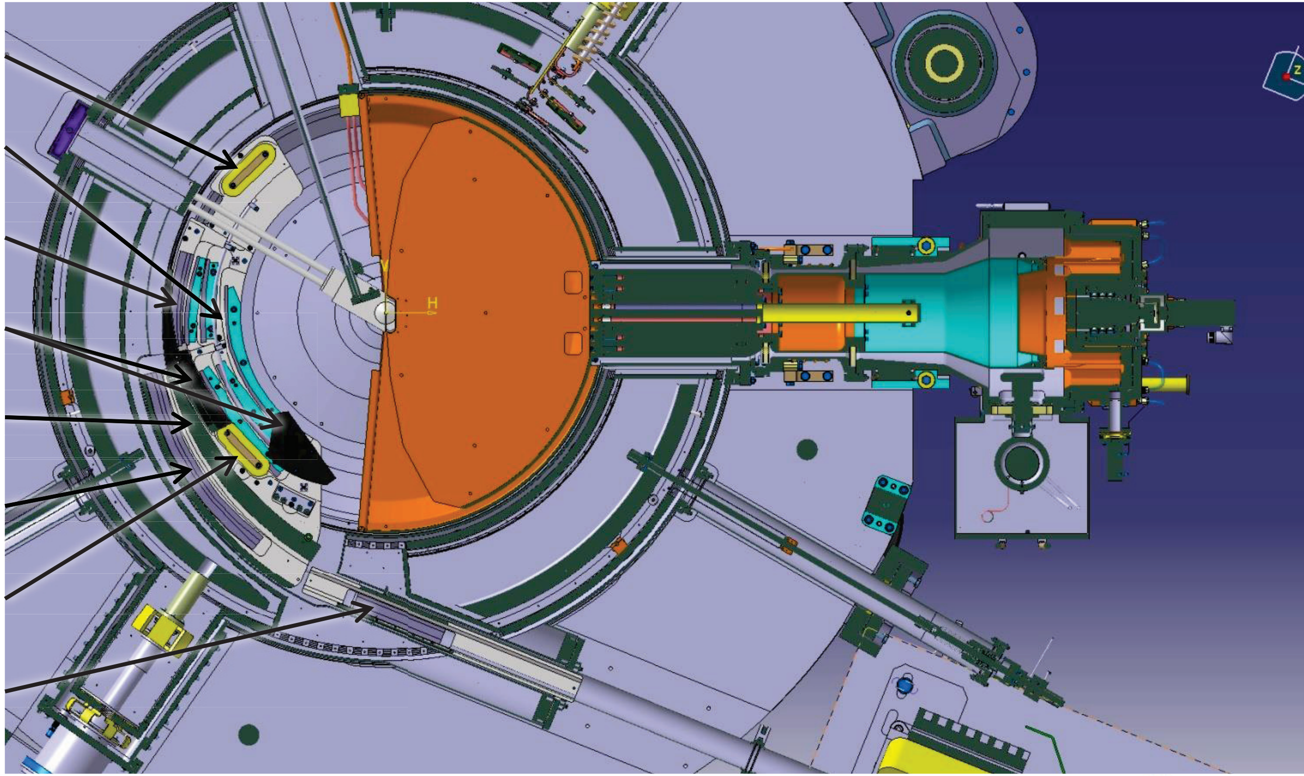
Graphite beam stops

Magnetic septum

Anti-septum

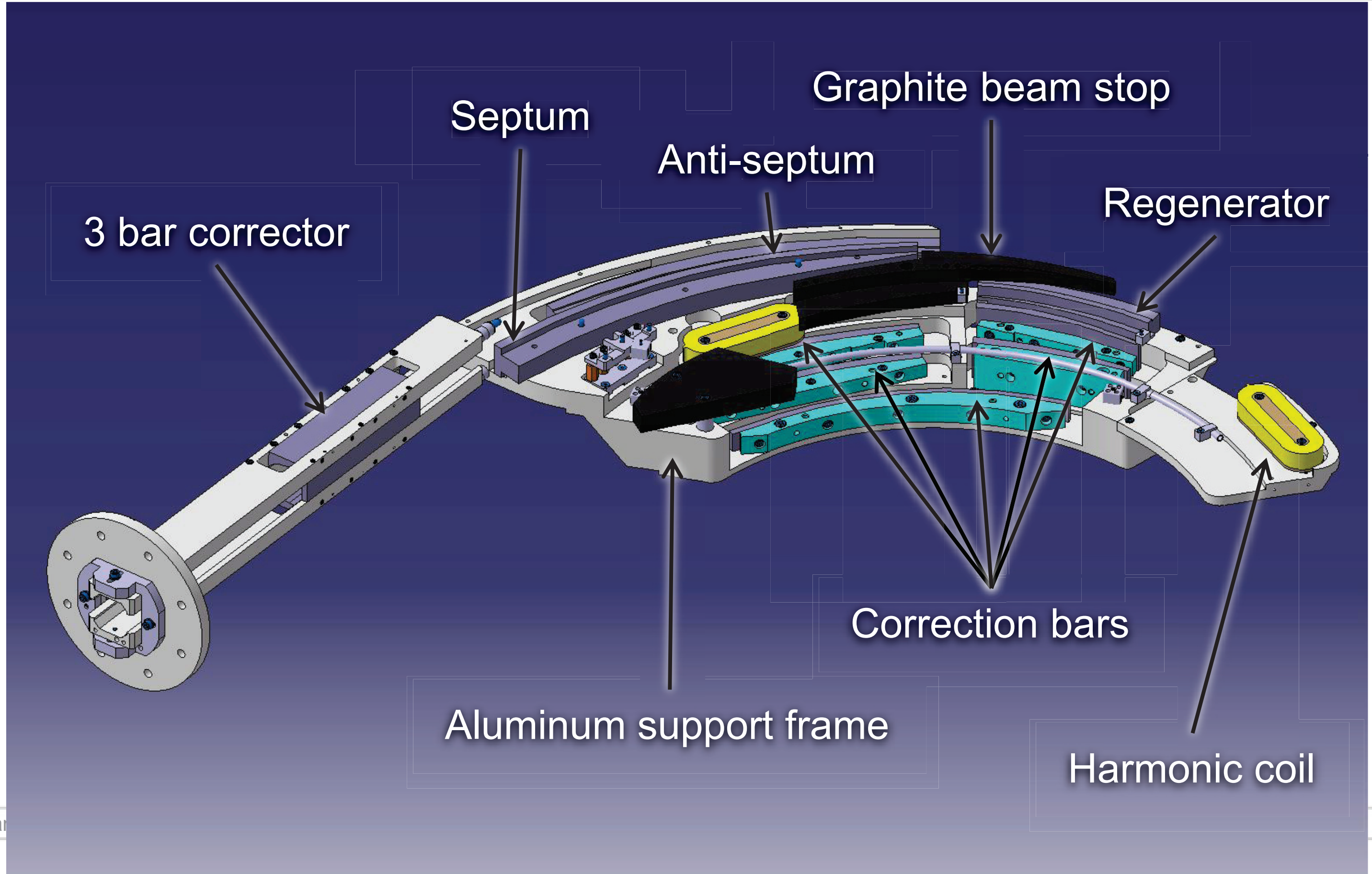
Harmonic coils

3 bar gradient corrector



Extraction system

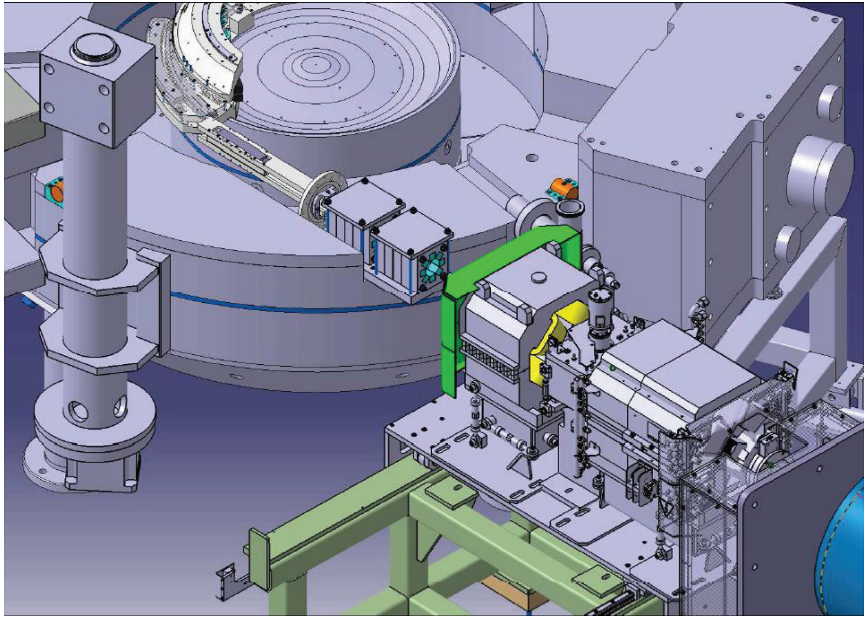
Layout (2)



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



Current Status

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

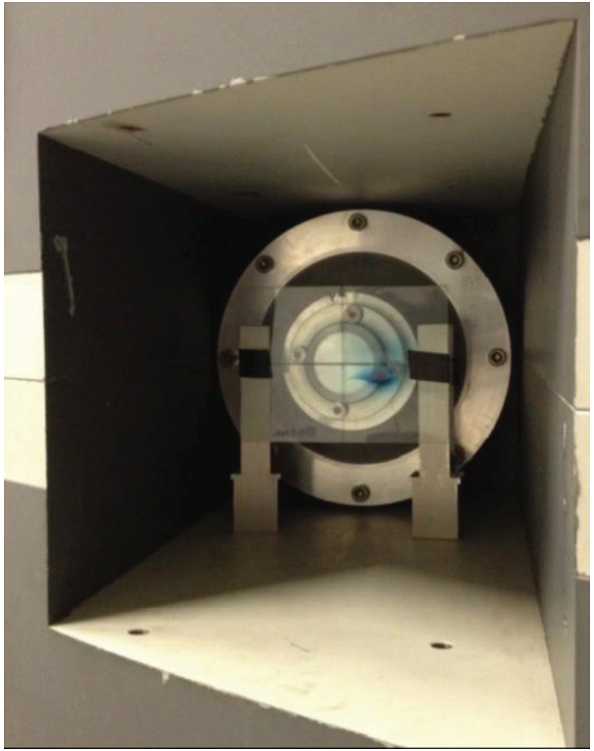
- Magnet:
  - Successfully cooled down and ramped up
  - Coil well centered in cryostat
  - Magnet fully mapped, no shimming needed
  - Extraction system fully mapped, no shimming needed
- Vacuum system operational
- Ion source operational; central region installed
- Rotco tested and operational
- RF-system 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

- Beam extraction has been observed by colour change of a radiation sensitive foil at the beam exit window
- This was a few days after the start of the beam-tests
- No design modifications or other adjustments where needed in any of the subsystems
- After beam injection from the PIG source and 40000 turns of acceleration the beam was immediately ejected by the passive extraction system
- Expected shipment of cyclotron to Nice before end of this year



Acknowledgements

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

Thank you!