Compact accelerators for radioisotope production: The AMIT project

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on belhalf of the AMIT collaboration

ARIES WP3 kick-off

13th September 2017

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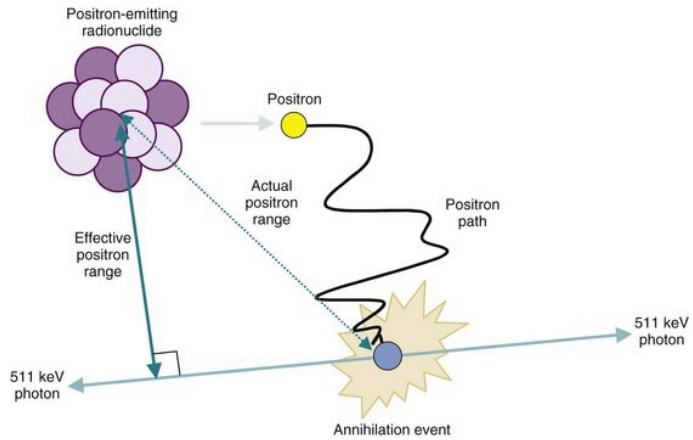
Introduction

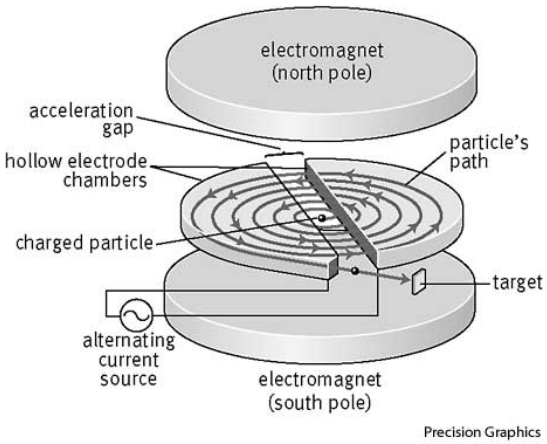
- Positron Emission Tomography (PET)

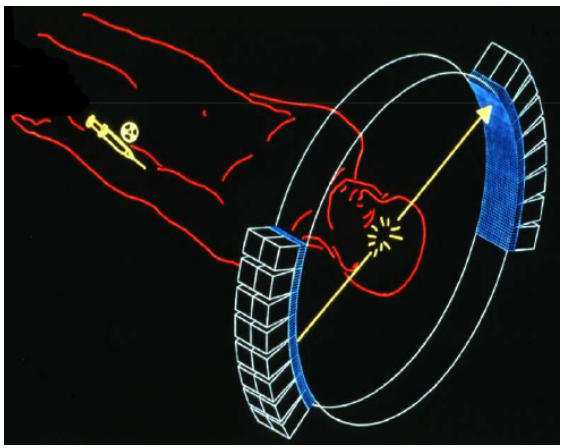
Medical technology employs radiotracers to diagnose tumours, obtaining a functional nuclear image.
PET technique is broadly used around the world as a diagnostic tool and for treatment planning and follow-up



Cyclotrons are the most widely used accelerators for the production of positron emitter isotopes

$$\text{Cyclotron} \Longrightarrow \text{Radiopharmaceutical synthesis} \Longrightarrow \text{Administration} \Longrightarrow$$
$$\Longrightarrow \text{PET scan} \Longrightarrow \text{Image}$$





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AMIT project

The AMIT project: Advanced Molecular Imaging Technologies

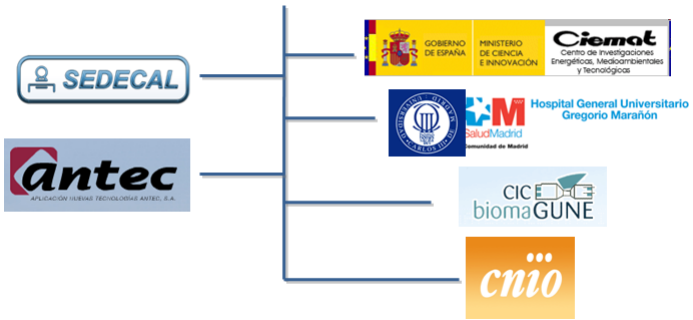
Work supported by the Spanish Ministry of Science and Innovation

Partners: 10 companies, 14 research labs and other collaborations

- Target: Development of the core technology for molecular imaging in Medicine and Biomedicine with special focus in the human brain and in particular in mental diseases

WP1. Development of a compact cyclotron for ^{11}C y ^{18}F single dose production

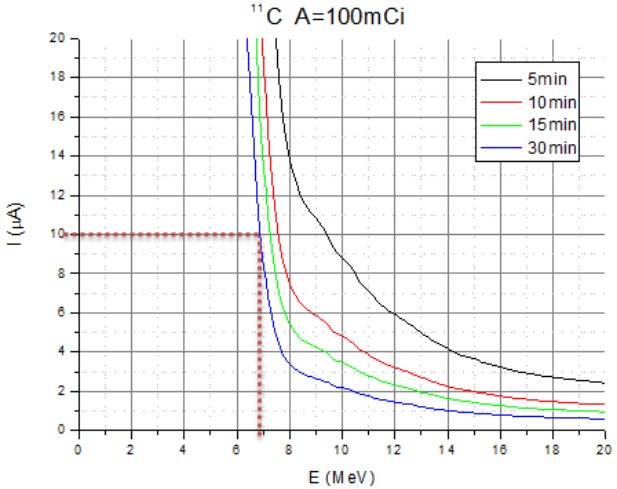
- CIEMAT is the scientific leader of this cyclotron project
  - Close collaboration with Spanish industry
  - External collaborations as CERN, MIT



AMIT cyclotron

Development of a compact cyclotron able to produce short half-life isotopes for sintering PET radiotracers, including:

- Capability of producing radiopharmaceuticals on demand
- Extending the production of radioisotopes to hospitals and institutes which are not prepared for hosting conventional facilities
- Disposing a back-up system for producing selected radiotracers at prices that can compete in specific cases with those of standard production centers



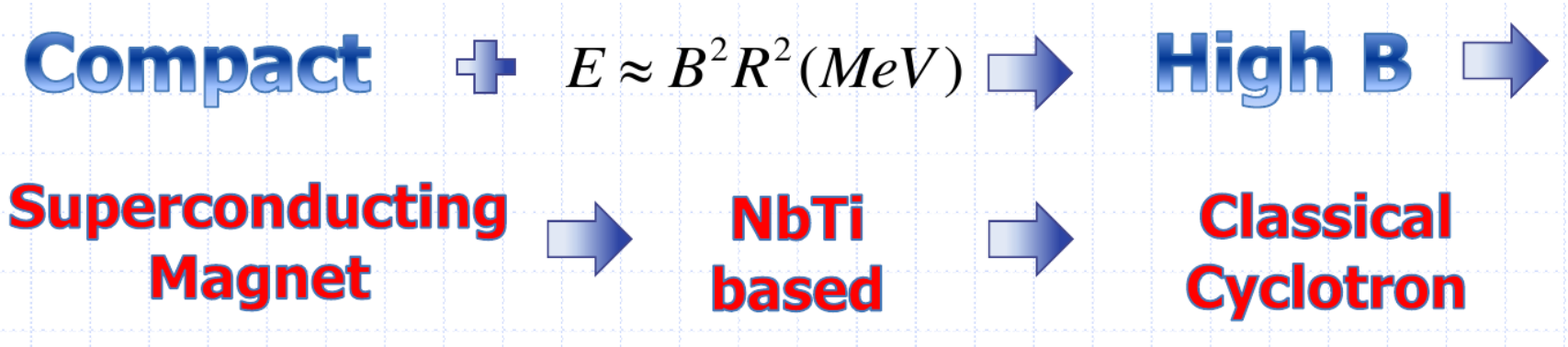
Isotope	Target	Reaction	$T_{1/2}$
^{18}F	Water enriched in ^{18}O	${}^{18}_{8}O + {}^{1}_{1}H \longrightarrow n + {}^{18}_{8}F$	109 min
^{11}C	Nitrogen gas	${}^{14}_{7}N + {}^{1}_{1}H \longrightarrow {}^{4}_{2}He + {}^{11}_{6}C$	20 min

Cyclotron requirements:

- ^{11}C and ^{18}F on-site production
- Single dose production
- Minimum size and weight
- Minimum radiation levels
- Affordable price

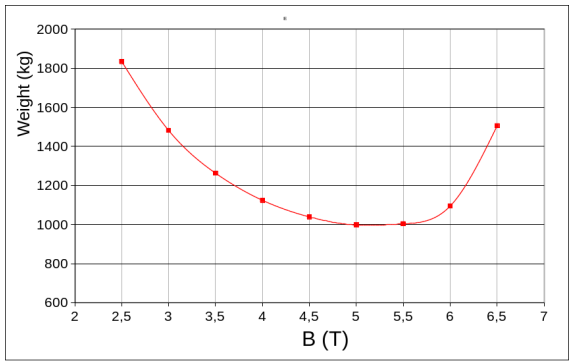
Beam requirements: $E > 8.5\text{MeV}$ $I > 10\mu\text{A}$

AMIT cyclotron



- Smallest cyclotron possible for a given E. For a NbTi magnet:
  - 50% less diameter and height
  - About 1/10 cyclotron weight
  - x2.5 less shielding weight
- Low power consumption
- Cryogenics needed

- Well known technology
- Affordable price for manufacturing and operation
- Higher improvements up to 4T



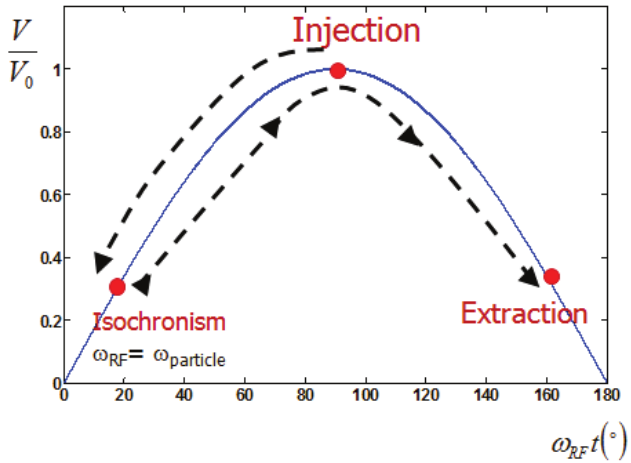
- Such saturation at 4T gives poor flutter for a conventional isochronous cyclotron, classical cyclotron is easier and cheaper
- Weak focusing is still suitable for this beam
- This solution is valid for such level of energy (8.5 MeV) provided the accelerating voltage is high enough (60 KeV)

Beam Dynamics

- Non particle-RF isochronism

$$\omega_{particle} = \frac{qB}{m} = \frac{qB(r,\theta)}{\gamma m}$$

- The energy gain will be lower than the maximum one (qV_{peak})
- The time that the particle can be accelerated is limited → Limitation on the maximum energy at extraction in a classical cyclotron



- ▷ High accelerating voltages → higher energy gain and higher extracted current by puller → 60 kV
- ▷ Limited field gradient of magnetic field → balance between beam focusing and phase shift
- ▷ Optimum phase excursion: maximum excursion for max. energy but limited to avoid losses by vacuum stripping and by electric defocusing forces → Beam tuning with RF frequency (B field) and stripping foil location
- ▷ Careful design of central region → given the internal ion source, high B and V and weak focusing magnetic forces

AMIT cyclotron: Specifications

Cyclotron properties

- Classical cyclotron
- Energy > 8.5 MeV
- Current $> 10\,\mu$A

RF System

- Configuration: One 180°
- Acceleration voltage > 60 KV

Source

- Type: Internal PIG
- Ions: H^-

Extraction

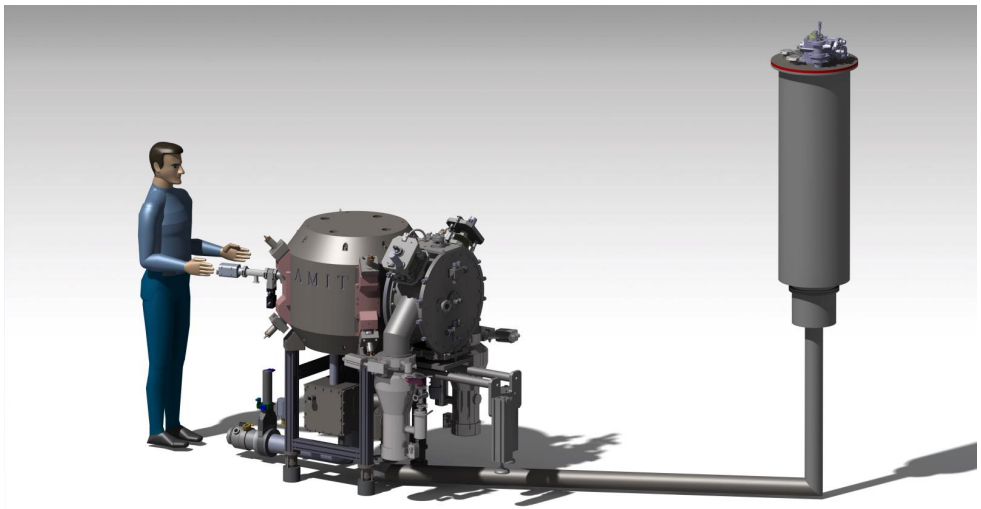
- Stripping foil
- Targets

Magnet

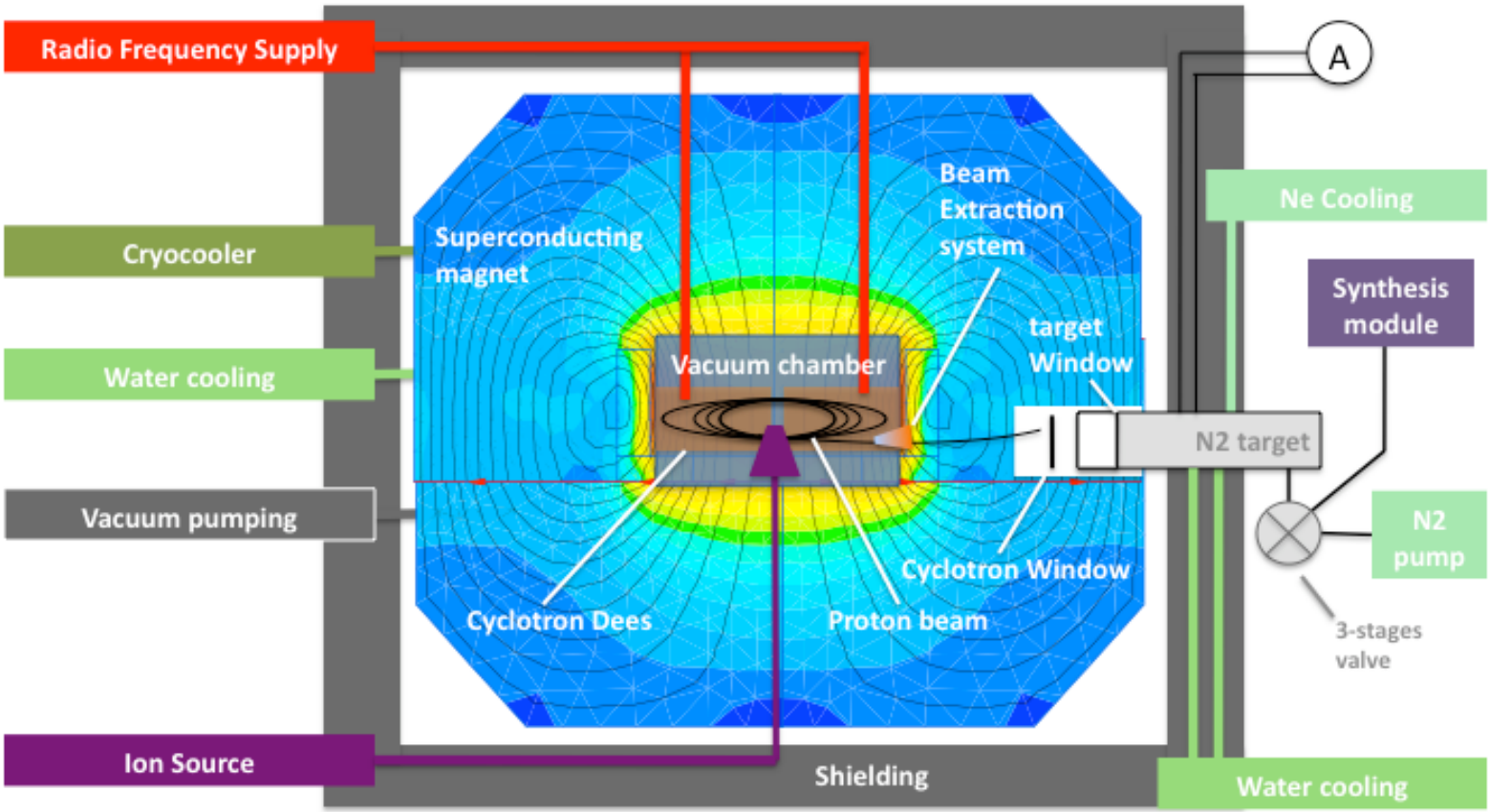
- Low T_c superconductor
- Superconductor material: NbTi
- Warm Iron
- Central field $= 4$ T
- Decreasing field $\rightarrow$ Focusing

Cryogenics

- Closed-loop LHe circuit
- Single commercial cryocooler



AMIT cyclotron subsystems



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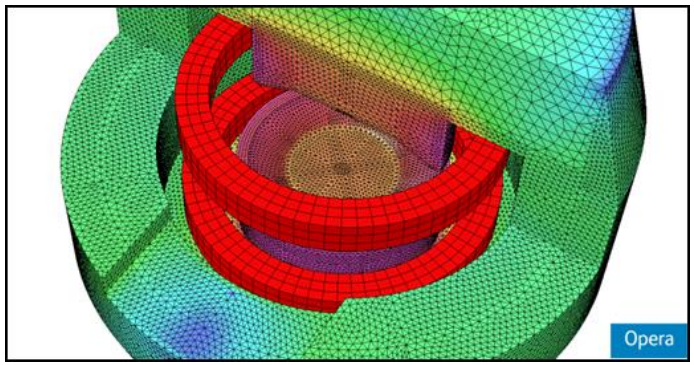
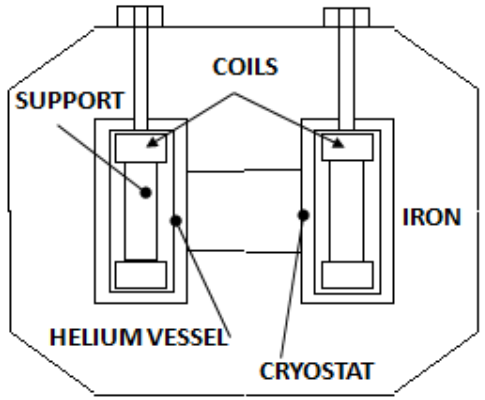
Magnet

Central Field	4 T
Radial Field Gradient	1.49 %
Cu/SC ratio	4.5 : 1
Operational temperature	4.2 K
Nominal Current	108.6 A
Working Point in the load line	$\sim$ 70 %
Self Inductance @ Nom.Curr.	38.35 H
Iron	Steel 1010
Peak Quench Temperature	95 K
Max. Voltage Temperature	1170 V

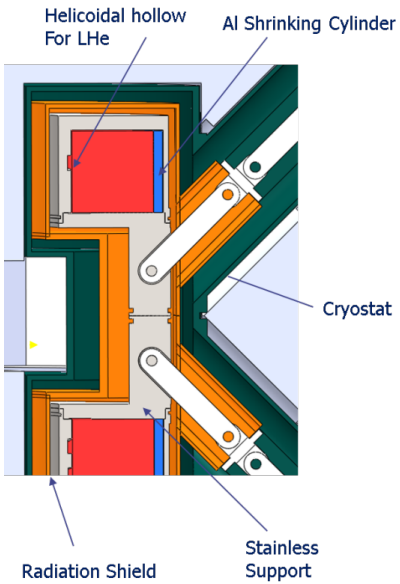


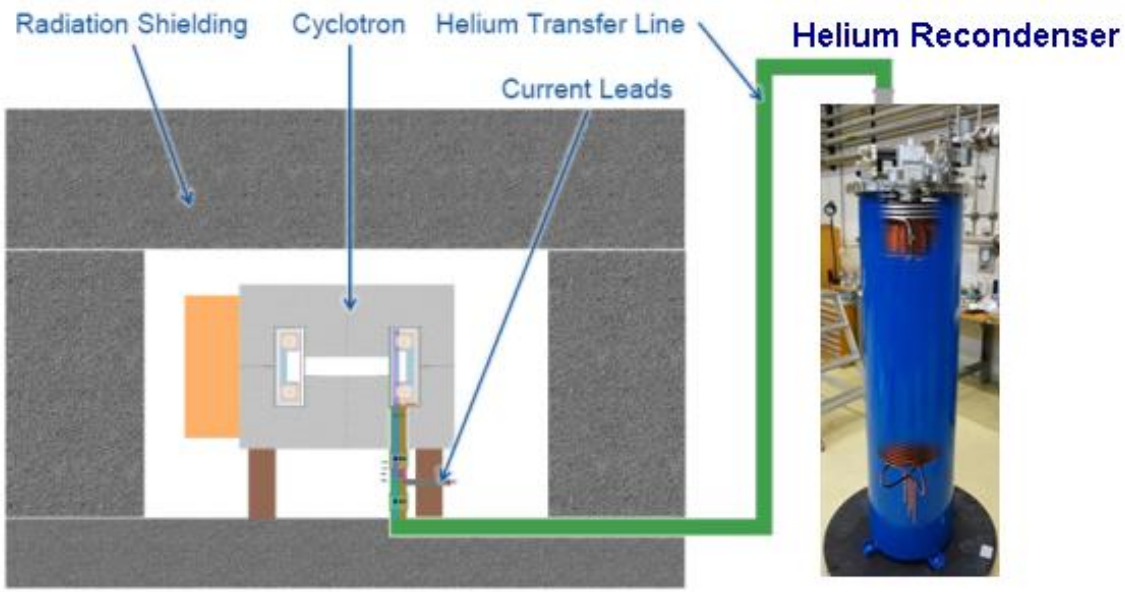


WARM IRON SOLUTION

- Two coils embedded in a stainless steel casing
- Aluminium shrinking cylinder to achieve radial compression in the coil
- Stainless steel structure to block axial movements of the coils
- A casing structure has been made to host the magnet. It includes a channel to circulate LHe to refrigerate the coils. The casing is fully tight to helium
- Radiation screen to reduce radiation losses from the cryostat

Magnet Cooling System





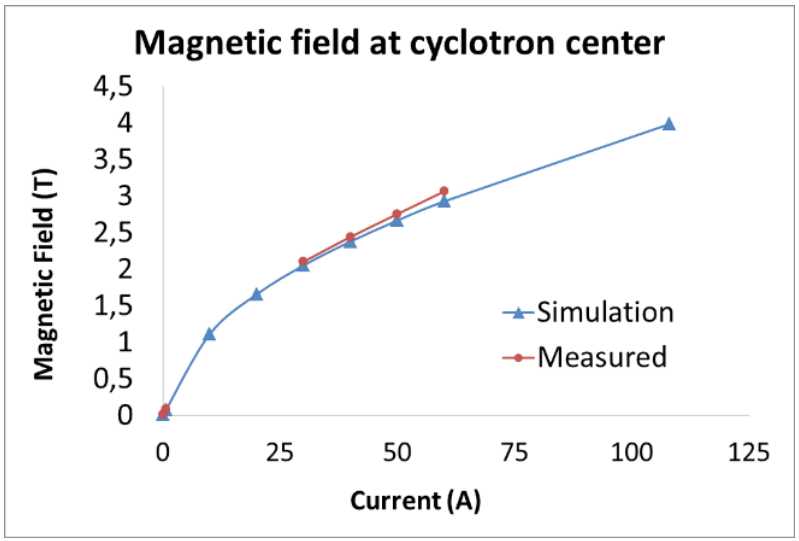
- Cryostat
  - Coils are placed inside a casing to house them allowing refrigeration
  - Casing is surrounded by a cryostat to maintain it at cryogenic temperature
- Thermal design
  - LHe flow inside casing intimate contact to coils
  - Gas He for shield cooling
  - HTS current leads
- LHe liquefaction and pumping:
  - System outside the radiation shielding (Cryogenic Supply System -CSS)
  - Just one cryocooler (1.5 W@4K)
  - Gas He used for thermal shield and current leads
  - Helium is transferred from the CSS through a low-loss Transfer Line that is connected to the Cyclotron Connection Box

- Magnetic Field tests

Magnetic field measurement bench at CIEMAT developed in collaboration with ALBA/CELLS

- Magnetic field at cyclotron center for different current values
- Magnetic field map at cyclotron mean plane

  Measured magnetic field along a cyclotron diameter shows less than 0.5% deviation for distances up to 150 mm to the center compared to the designed field at low (0.65 A) and medium currents (30 A)



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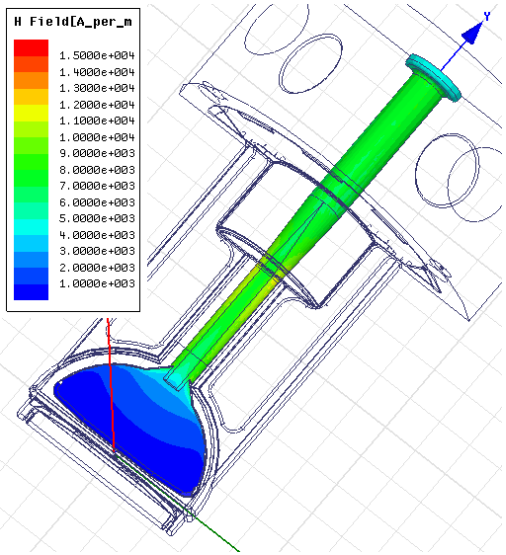
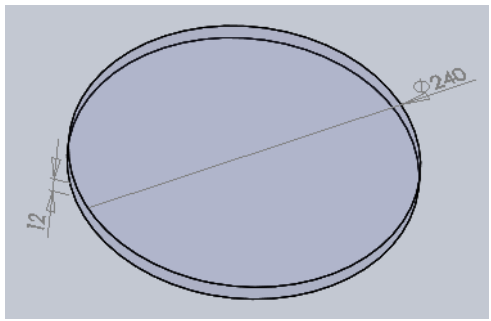
RF System

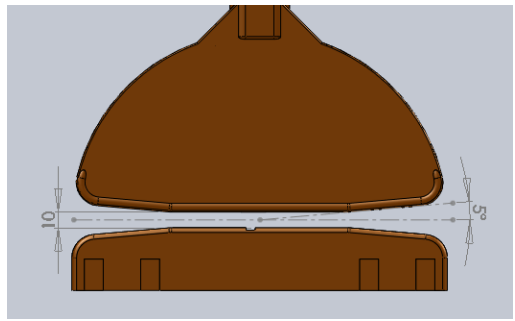
RF System provides the accelerating field for the beam and a little bit of focusing

Frequency	60 MHz
Gap Voltage	60 kV
Configuration	180° Dee
Q	5250
Power dissipated	5.36 KW
Tuners range	±140 KHz

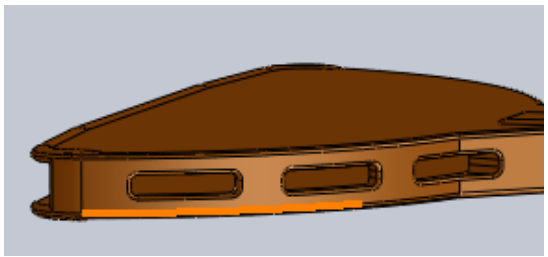


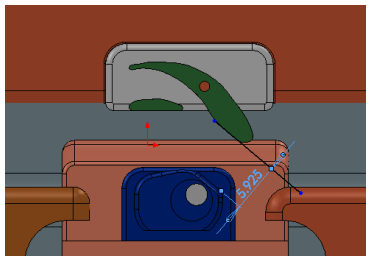
- Vacuum chamber independent from magnet (iron not pressurized)
- Free space for the beam (240 mm diameter, 12 mm height)
- Accelerating gap: 10 mm gap





- Open holes on dee wall to help vacuum extraction
- Ion source and puller geometry fixed by beam dynamics requirements

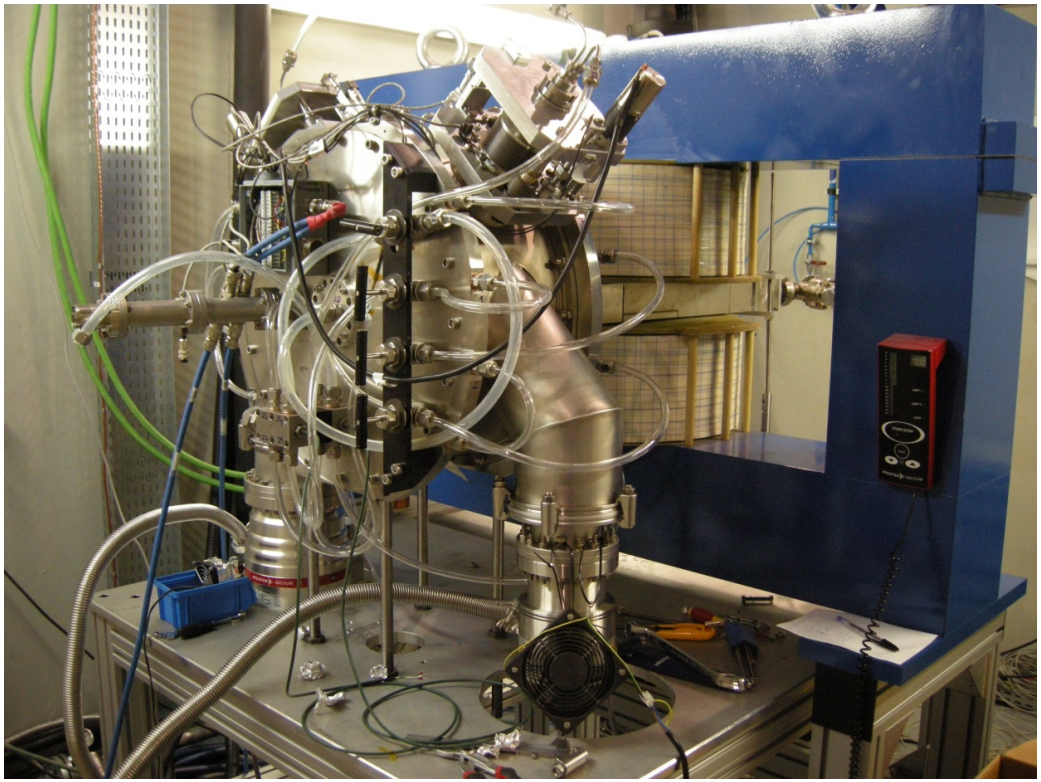




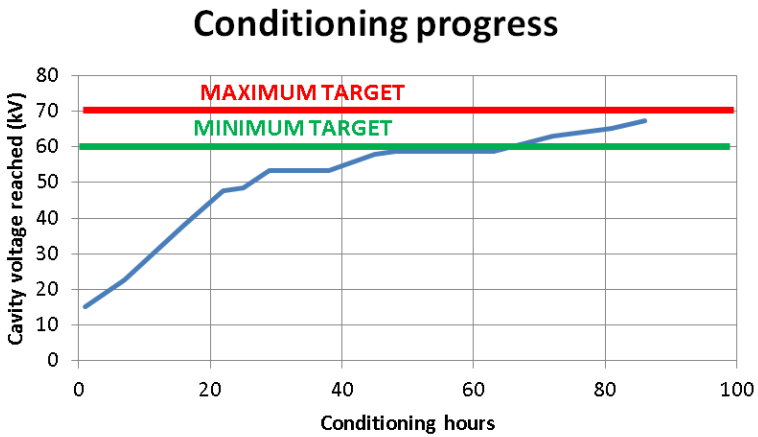
- Full simulation of the cavity: electromagnetic (RF), mechanical and fluids models

- High Power test and Conditioning

RF conditioning at ALBA facilities



- Conditioning without hydrogen:
  - Maximum Voltage: 67.1 kV
  - Maximum amplifier power: 8.43 kW
- Conditioning with hydrogen (10 sccm):
  - Maximum Voltage: 64 kV
  - Maximum amplifier power: 7.8 kW



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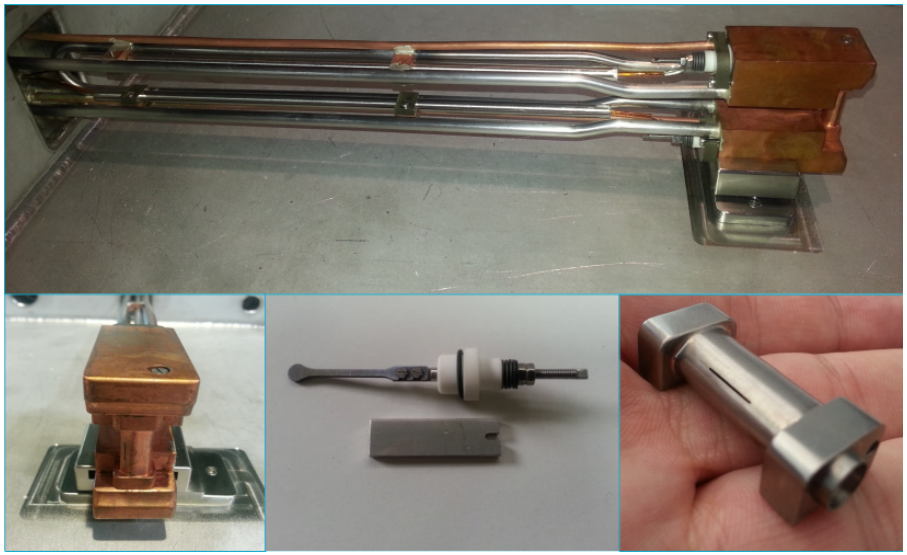
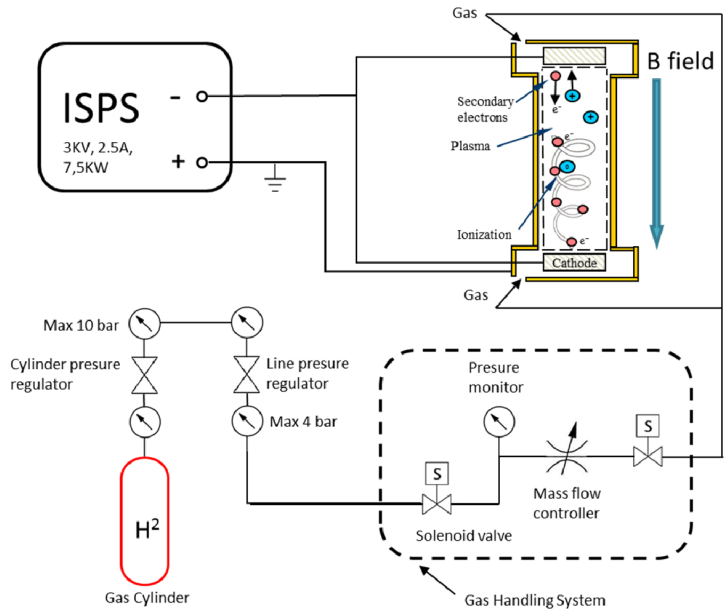
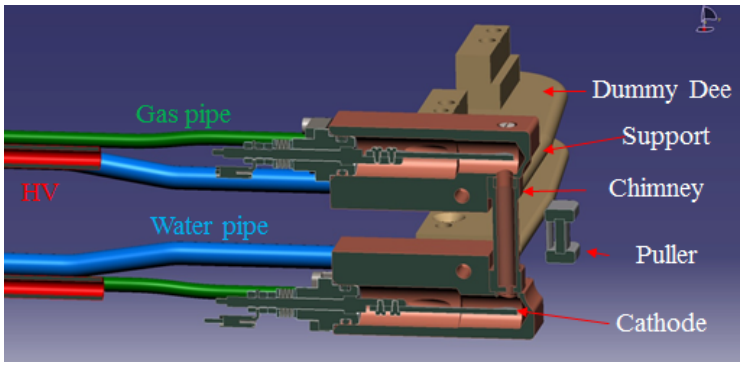
Ion Source

- H^- Ion Source for beam generation
- Internal ion source for compact machine
- Cold cathode PIG
- Cathode material: Tantalum
- Macor as high voltage insulator
- Chimney (anode) material: Copper-Tungsten alloy
- Chimney geometry required for the beam dynamics



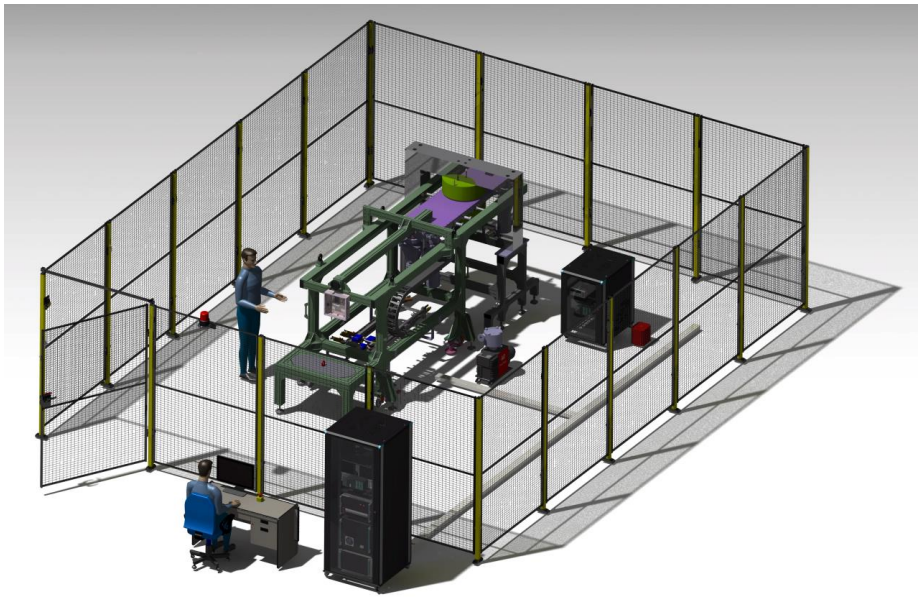


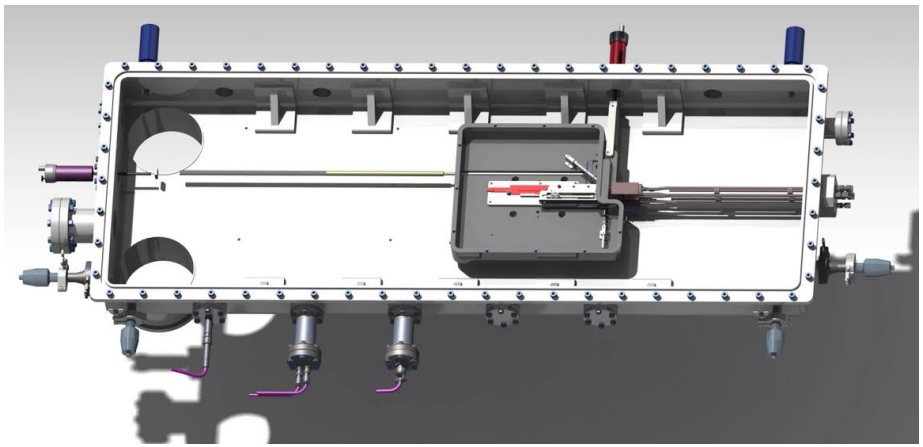


- Ion Source Test Bench (IST)

Components:

- Dipole magnet (Resistive magnet)
- Vacuum chamber
- Gas handling system
- Faraday cage with DC movable puller
- Water cooling system
- High voltage and mechanical cage protection





- Validation and optimization of ion source
- Characterization H^- beam
- Ion current extracted: $> 500\,\mu A$

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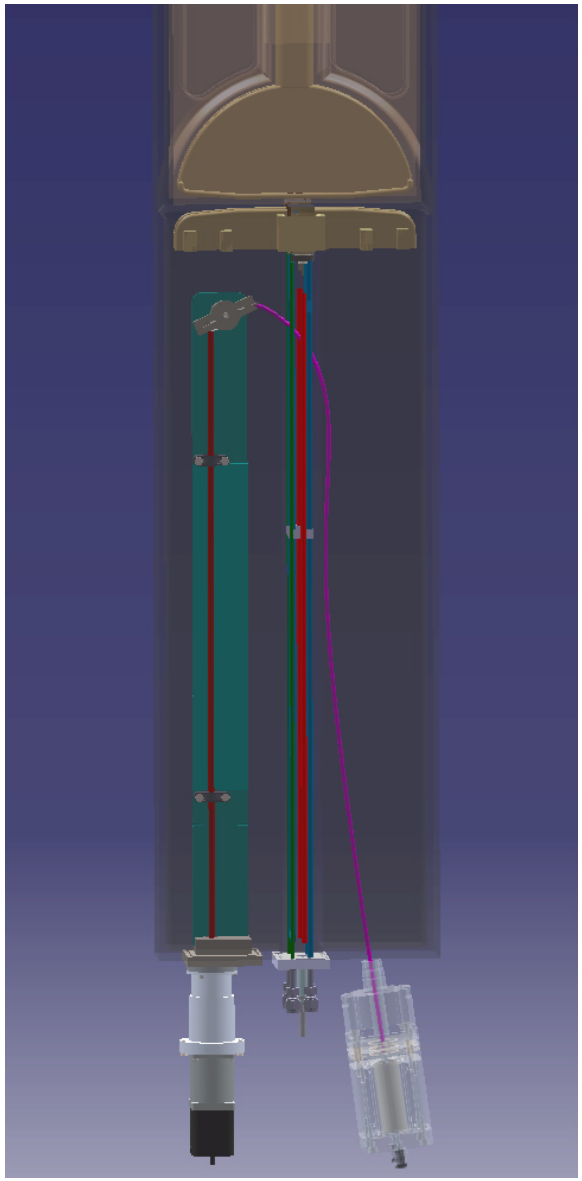
Stripping foil

- Proton extraction by stripping mechanism
- Thin carbon sheets
- Extraction at different energies $\longrightarrow$ Mechanical system with two degrees of freedom (one longitudinal and one rotary)
- The stripping foil movement system has to be completely integrated inside the vacuum chamber and has to be compatible with the high vacuum level and the high magnetic field
- The stripping foil system will be accessible for modifications or for the replacement of the carbon sheets from the upper window of the vacuum chamber
- The current deposited on the carbon foil has to be measured $\longrightarrow$ The foil is located on a insulator material



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Beam Diagnostics

Current

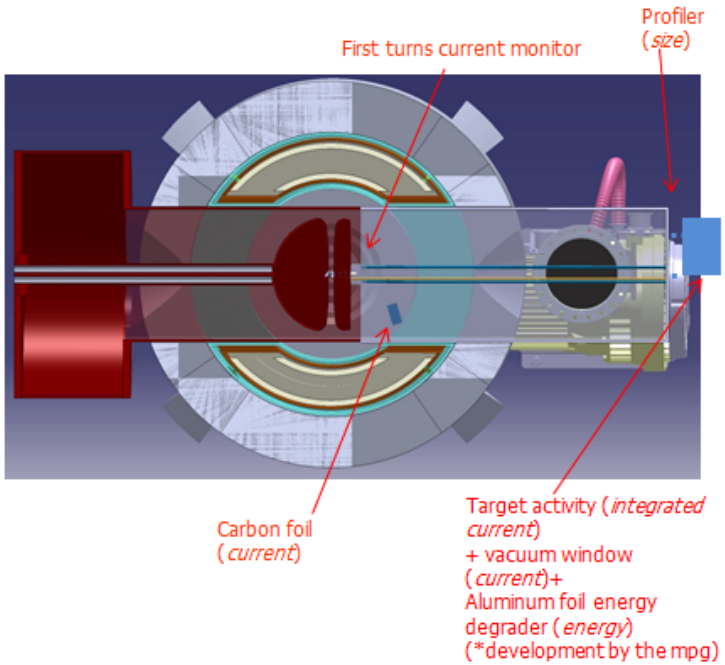
* Movable beam probe to detect where the beam is lost at first turns
* Simple current measurements of the charges deposited in the carbon foil
* Current measurement in the target assembly
* Measurement of target activity after irradiation

Beam profile

* Study the feasibility of using non-interceptive techniques or screens for optimization and safety of the carbon and aluminium foils

Energy

* A measurement of the energy by aluminium foils energy degrader has been developed



- Additional diagnostics could be foreseen for a commissioning stage of the cyclotron without target and/or a temporary beam diagnostics line

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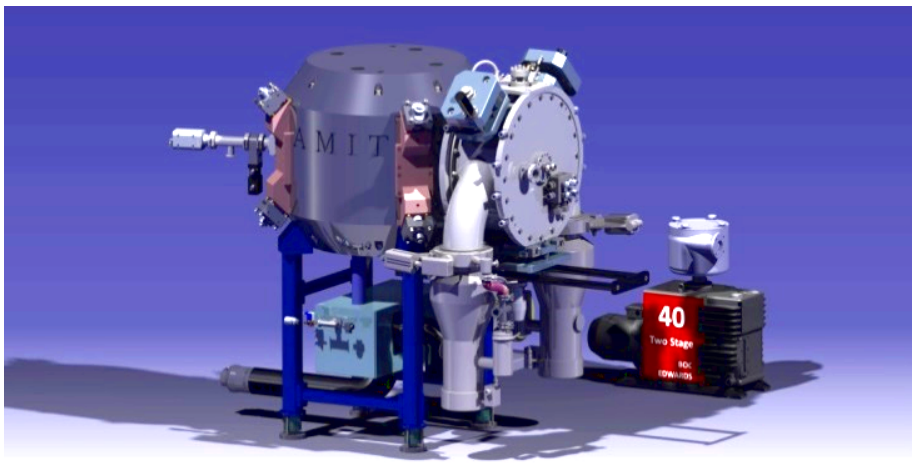
Vacuum

Vacuum conditions:

- ◊ Pressure during operation: $\sim 10^{-5} - 10^{-4}$ mbar
- ◊ High fringe field ($30 - 100$ mT)
- ◊ High radiation environment (avoid electronics inside the shielding area)
- ◊ Target window foil breakdowns, especially during commissioning phase of the target. Lower probability during normal operation
- ◊ System is designed as UHV ($10^{-7} - 10^{-8}$ mbar) even though in operation the pressure is higher, but due to the ion source gas injection

Vacuum system:

- ▷ Diffusion pumps have been selected in order to prevent any damage of Turbopumps due to target foil breakdown
- ▷ 2 diffusion pumps in the resonator area



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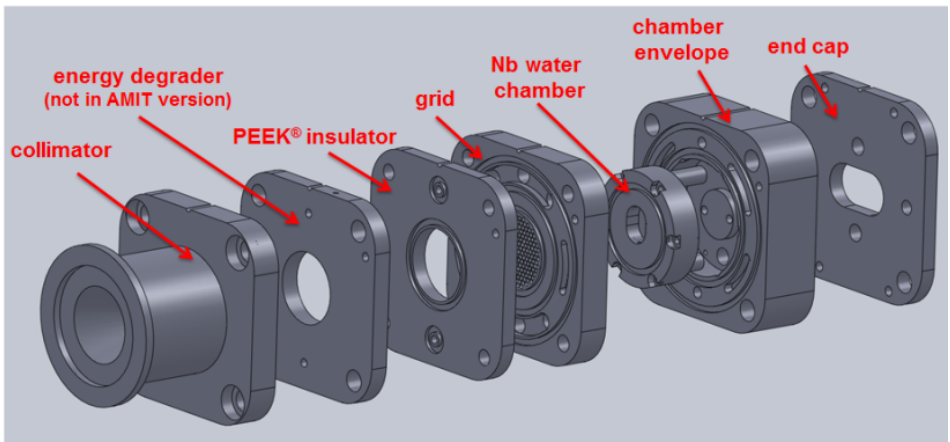
Targets

$^{18}F \longrightarrow$ 40 mCi Water enriched in $^{18}O \longrightarrow {}^{18}O(p,n)^{18}F$

$^{11}C \longrightarrow$ 100 mCi Nitrogen gas $\longrightarrow {}^{14}N(p,\alpha)^{11}C$

^{18}F Target

- Water cavity of Nb (Al reacts with oxygen)
- Cavity 1 cm long, 1 cm diameter + expansion room
- Case: 7×7 cm
- Aluminium alloy (AL6082) for low radiation and activation



^{11}C Target

- Gas cavity 7 cm long, 2.5 cm diameter
- Case: 7×7 cm
- Aluminium alloy (AL6082) for low radiation and activation
- Extraction ^{11}C through CO_2 or CH_4

* Targets have been validated with different tests
* Results of produced activity compatible with the objectives of the project

Acknowledgment

Many thanks for your attention and to the AMIT team and collaborators!!!

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- E. Molina
- J. Munilla
- D. Obradors
- C. Oliver
- J.M. Pérez
- I. Podadera
- F. Toral
- R. Varela
- C. Vázquez

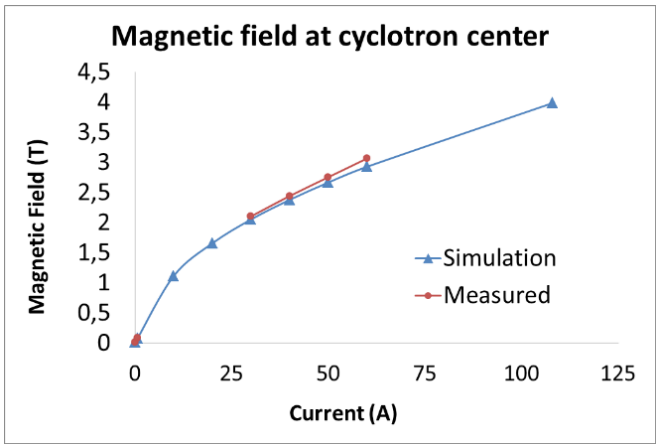
Extra slides

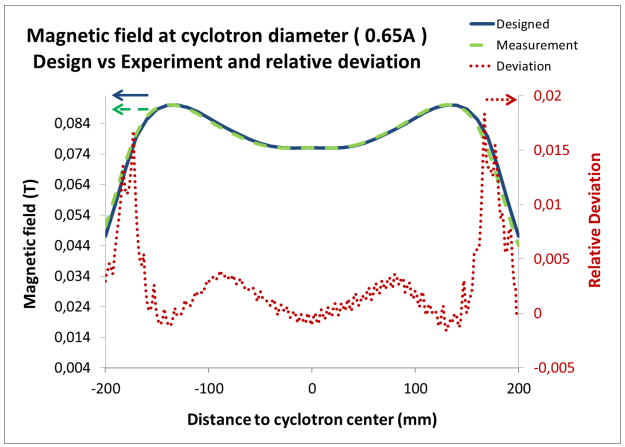
- Magnetic Field tests

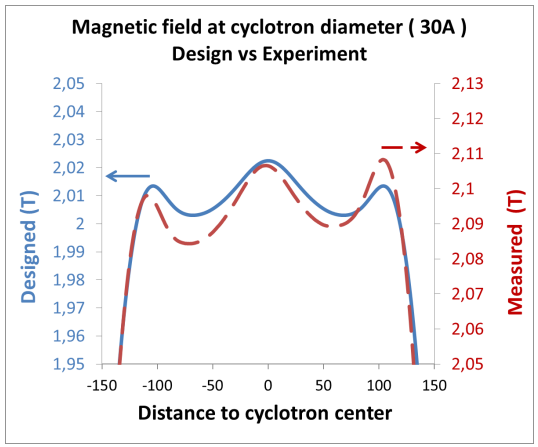
Magnetic field measurement bench at CIEMAT developed in collaboration with ALBA/CELLS

- Magnetic field at cyclotron center for different current values
- Magnetic field at cyclotron mean plane

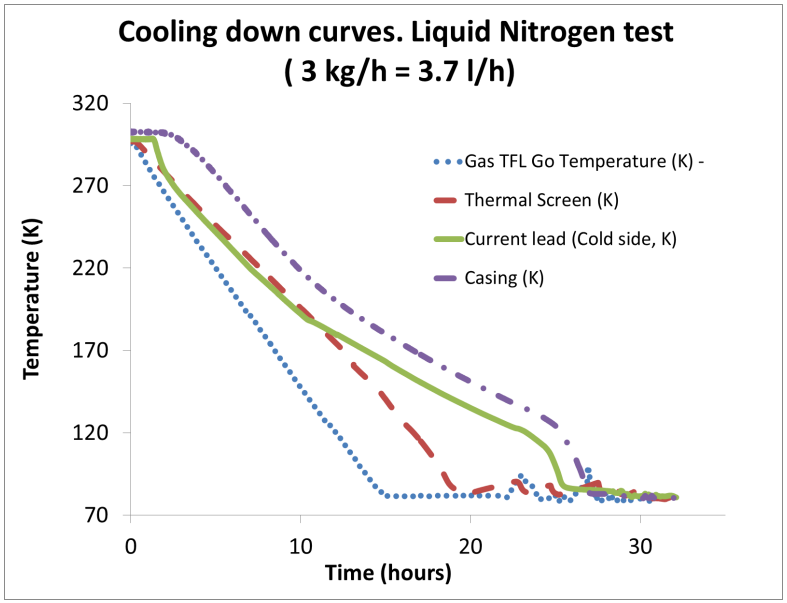
  Measured magnetic field along a cyclotron diameter shows less than 0.5% deviation for distances up to 150 mm to the center compared to the designed field at low (0.65 A) and medium currents (30 A)





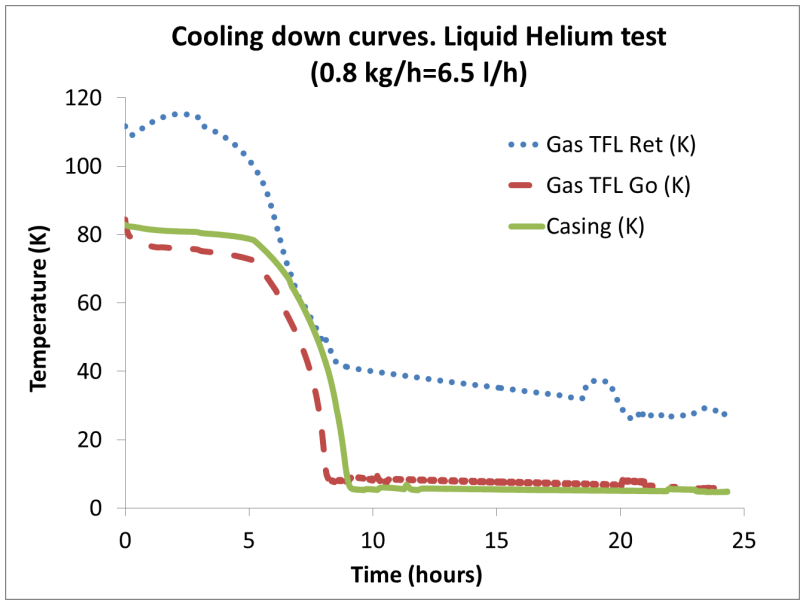


Thermal tests



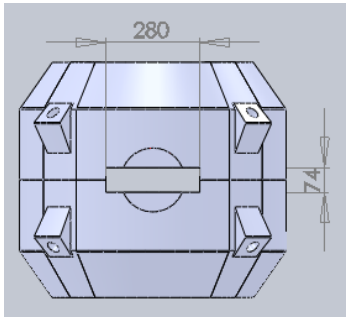
- Cooling down curves during Liquid Nitrogen test:
  - Good agreement between expected time and flow needed. 3 kg/h results in 27 hours needed. About 29 h expected.
  - After 15 h, first circuit is full of two phase Nitrogen
  - Thermal screen reaches liquid temperature before casing
  - High thermal inertia of coils compared to the cooling capability of the forced flow inside the casing is the limitation for improving cool down rate

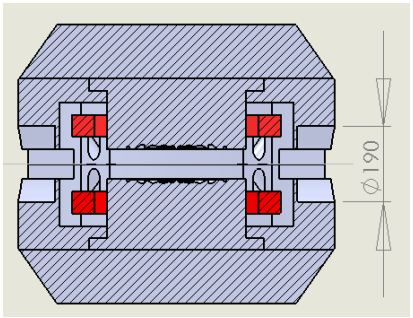
- Cooling down curves during Liquid Helium test:
  - Expected time needed for a 0.8 kg/h flow was around 11h
  - Steady thermal state conditions are achieved just after more than 20 hours
  - The total losses of the cyclotron at both circuits (Enthalpy absorbed by the Helium) can be evaluated as 31 W. The nominal design value is 34 W

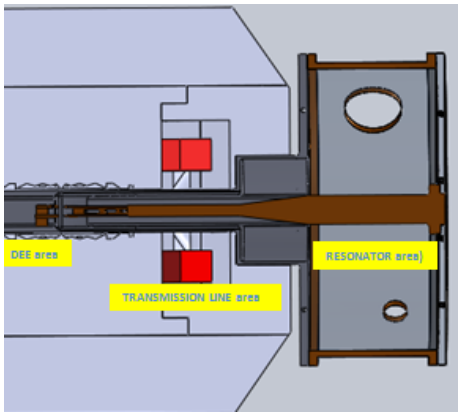


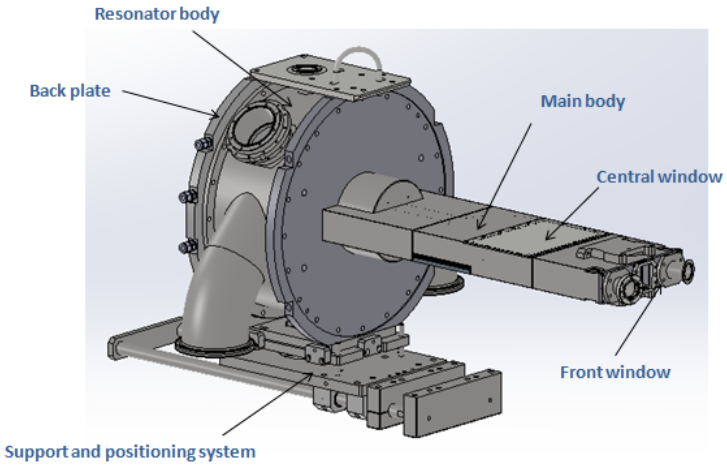
RF subsystems

- Vacuum chamber
  - It has to be adapted to available space inside the magnet
  - Material: stainless steel
  - Inside coating: copper
  - A variable thickness chamber has been designed to keep reasonable mechanical stress and deformation, and try to give as much space as possible to the RF in the most critical parts
- Liners
  - Two liners have been designed on the higher voltage areas of the chamber
  - Liners are made in OFC (oxygen free copper) and are designed to adapt to the chamber internal surface shape
- Dee
  - Very high voltage on relatively small gaps: very careful design and fabrication of the geometry to avoid high electric fields concentration
  - Available space for the beam circulation and gaps required for the beam dynamics to be respected
  - Material: OFC (oxygen free copper)



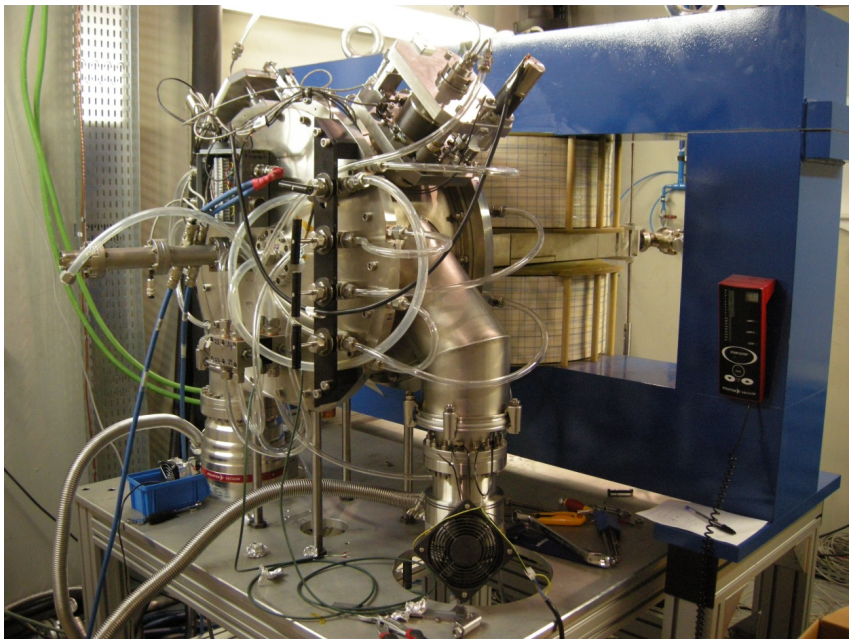




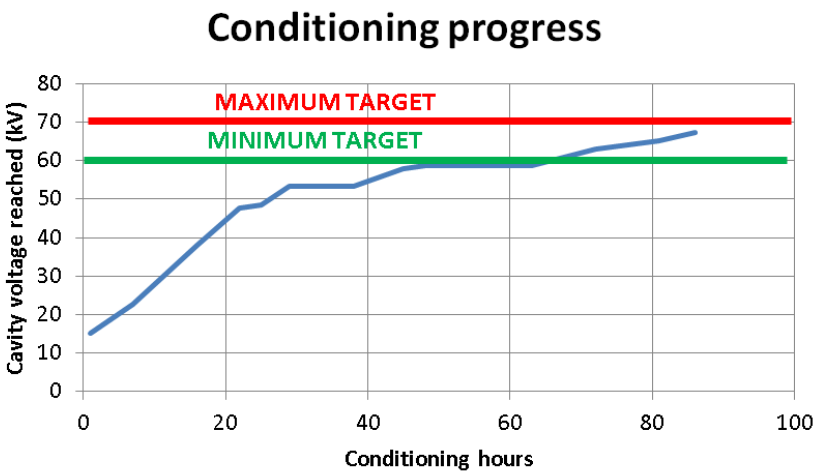


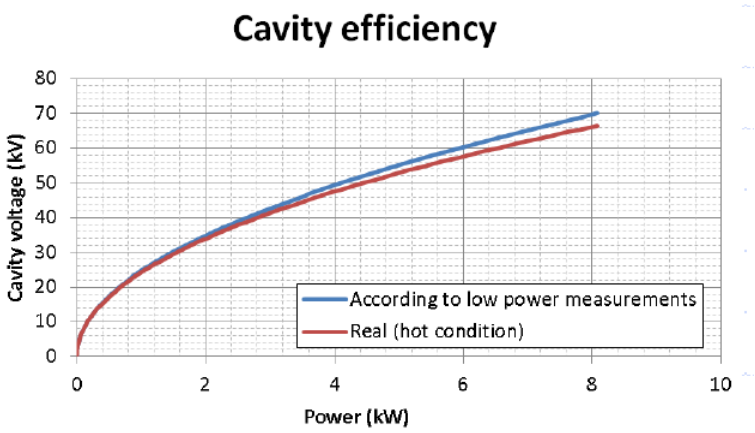
High Power test and Conditioning

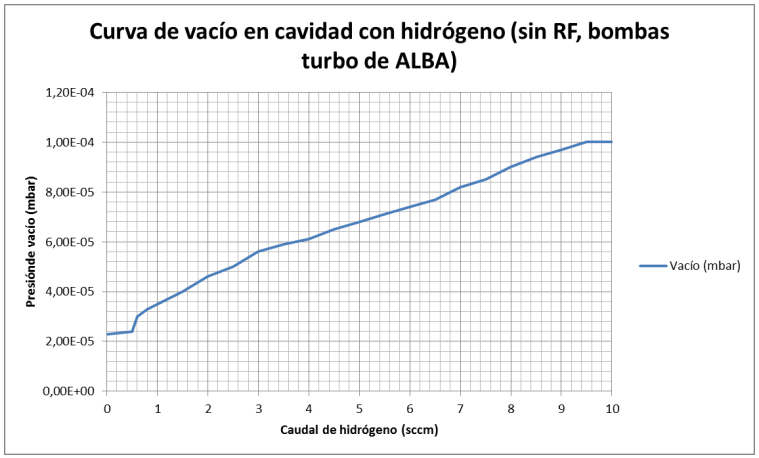
RF conditioning at ALBA facilities



- Conditioning without hydrogen:
  - Maximum Voltage: 67.1 kV
  - Maximum amplifier power: 8.43 kW
- Conditioning with hydrogen (10 sccm):
  - Maximum Voltage: 64 kV
  - Maximum amplifier power: 7.8 kW

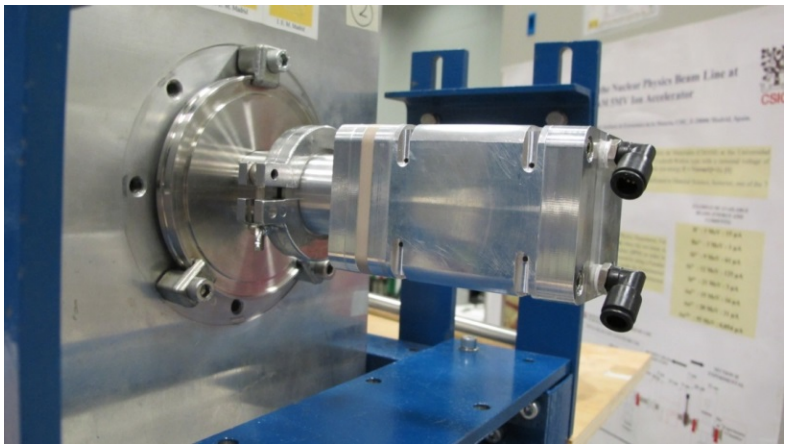


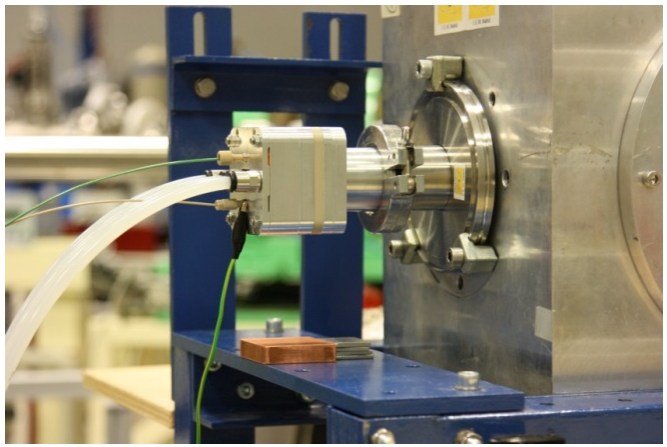




Designed and built final versions of ^{11}C y ^{18}F targets

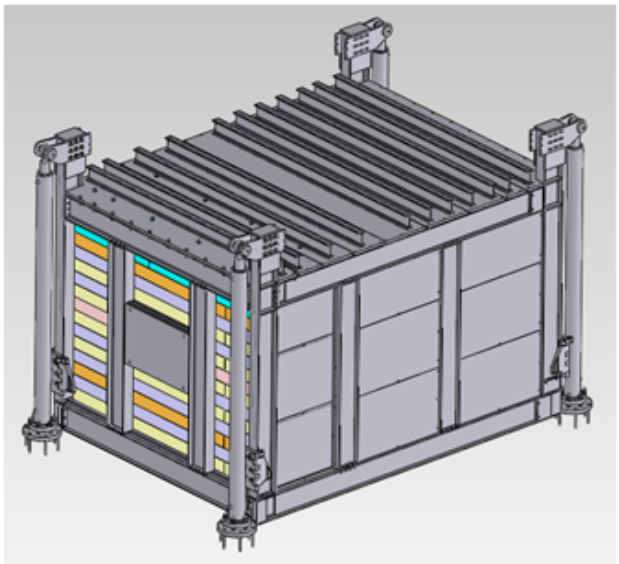
- Tests at CIEMAT: Targets were submitted to engineering tests (tightness, resistance of the entrance window) at high pressure and temperature
- Tests at Massachusetts General Hospital (Boston, USA) in a GE PETrace cyclotron and to estimate the end-of-bombarment activity (EOB) and specific activity figures
- Test at BiomaGUNE cyclotron (Spain) to estimate the same figures with an IBA Cyclone 18/9 cyclotron
- Results of produced activity compatible with the objectives of the project
- Designed and built the auxiliary systems for filling and transfer to the radiopharmacy systems activation





Shielding

- Shielding has been designed to get a personal equivalent dose below $0.5\,\mu$Sv/h
- Self-shielded cyclotron concept in two stages:
  - Autoshielding (reduces dose to $\sim 5 - 10\,\mu$Sv/h)
  - Thin concrete wall (Reduces dose to $\sim 0.5\,\mu$Sv/h)
- Shielding calculations: Most precise tool: simulation codes based on Monte Carlo (GEANT4, MCNP)
- Materials have been selected to minimise thickness and weight, while having an affordable price
- Access to the cyclotron by lifting the autoshielding

Autoshielding structure

* 1^{st} layer to stop primary gamma rays ($p \longrightarrow \gamma$): Lead (surrounding target as a cap)
* 2^{nd} layer to thermalize and stop neutrons: Borated polyethylene (1% Boron)
* 3^{rd} layer to stop gammas produced in neutron interactions (n in Boron produces alphas, but other inelastic or capture reactions produce gammas): Fe