BEAM DIAGNOSTICS FOR COMMISSIONING AND OPERATION OF A NOVEL COMPACT CYCLOTRON FOR RADIOISOTOPE PRODUCTION[*]

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Abstract

The AMIT cyclotron will be a 8.5 MeV, 10 μA CW H^- accelerator which aims to deliver a beam for radioisotope production. In order to properly validate all the beam commissioning steps, a set of diagnostics needs to be implemented. They must cover all the commissioning phases: ion source characterization, medium energy acceleration and nominal energy at full current. Due to compactness of the design, the number of beam diagnostics is limited and restricted to the most essential ones during operation. An overview of the diagnostics that are planned for the characterization of the cyclotron will be discussed in this contribution. In all the commissioning phases, beam current probes are essential to validate the cyclotron and each subsystem. As a main diagnostic, a movable probe has been designed and simulated for optimization of the cyclotron. The thermal simulations of the probe and the mechanical integration are presented.

INTRODUCTION

One of the most growing requests nowadays by the hospitals equipped with positron-emission tomography (PET) is the delivery of efficient radioisotopes. The most effective positron-emitting radioisotopes for biomedical human imaging, like ^{11}C or ^{18}F , have a short half-life (from 20 min to 2 h, respectively). In order to be able to spread the installation of PET diagnosis in more locations, it is required then, the use of smaller, lighter and cheaper accelerators that can be installed in small rooms, without the need of a big facility. Superconducting cyclotrons fit those requirements, as they reduce the size of the orbits, making the cyclotron more cost efficient and compact. The Spanish AMIT (Advanced Molecular Imaging Technologies) project [1] aims to developing the smallest possible superconducting cyclotron. The figures of the cyclotron -proton beam of 8.5 MeV and 10 μA- are requested for the medical experts for the production of the radioisotopes. With those figures, it is expected to deliver ^{11}C and ^{18}F in single doses for PET diagnostics. The cyclotron is presently finishing the design phase (Fig. 1) and entering into the manufacturing phase [2].

Figure 1: Mockup of the AMIT cyclotron.

DIAGNOSTICS LAYOUT

The compactness of the cycltron design makes the beam diagnostics very challenging. In addition, the diagnostics will be working inside a high magnetic field and a high radiation dose from the target producing the radioisotopes. The combination of those constraints limits the installation of some of the most common diagnostics so as to characterize the beam at the different stages of the cyclotron [3].

Beam Commissioning

Before the final operation of the cyclotron is mandatory to perform a beam commissioning in several stages of the machine. All the phases will start by producing the minimum possible current in order to protect the machine and limit the radiation exposure.

Phase 1: Ion source tests. This phase willl be performed in order to comission the ion source. A special high voltage test bench is being designed, as detailed later on. In this test bench, several beam diagnostics will characterize the hydrogen beam current delivered by the ion source and the possible particle contamination. The description of the beam diagnostics in this stage is given later on.

Phase 2: Low energy tests. The goals of this stage are the validation of the design of the central region, below 2 MeV, [2] - especially to validate the electrical defocusing-, and the minimization of the radiation before permitting higher beam energies. The mandatory diagnostics are the following: 1) a movable beam probe in radial direction to scan the beam current at the several cyclotron trajectories and 2) neutron and gamma detectors in the room

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that will be used as personal protection interlocks. In addition, as optional or more complex diagnostics, the following can be used: 1) a current monitor coupled to the ion source for fast check of ion source behaviour; 2) a current monitor downstream the stripping foil -depending on the travel range of the foil-,3) foil burns or similar to locate the position of beam losses and 4) slits for the characterization of the radial and axial behaviour of the beam.

Phase 3: Intermediate energy tests. Once the central region is well characterized and radiation levels under control, the following phase will consist of increasing the beam energy and bring the beam down to the stripping foil. For this stage the following instrumentation is needed: 1) a current monitor coupled to the ion source, 2) the beam current in the movable beam probe, and 3) the current in the stripping foil.

Phase 4: Stripping foil and target commissioning. Before target installation and nominal operation of the cyclotron the output beam has to be characterized at the target position in order to have the better knowledge of the beam quality delivered by the cyclotron. For that purpose, a Compact Diagnostics Line (CDL) will be installed in the space normally occupied by the target, with the following instrumentation installed as basis: 1) a current monitor (Faraday cup or similar), 2) a energy monitor especially developed at CIEMAT and 3) a transverse profile monitor. The profile monitor could be interceptive (foil burns, SEM grid or wire scanner) or non-interceptive, or a combination of both of them.

Summary: Table 1 lists the diagnostics that will be installed and used during all the commissioning phases of the cyclotron and Fig. 2 sums up the layout of the most important diagnostics during those stages.

Table 1: Beam Instrumentation for the Different AMIT Commissioning Phases. x Stands for Mandatory Diagnostics for a Certain Phase, and o for Optional.

Measurement	**1**	**2**	**3**	**4**
Spectrometer	x			
After puller beam probe	o	o	x	x
Movable beam probe		x	x	x
Stripping foil current		o	x	x
CDL current monitor				x
Interceptive transverse profiler	o			x
Non-interceptive transverse profiler	o			o
Energy meter in CDL				x
Foil burns		x		
Gamma detectors		x	x	x
Neutron detectors		x	x	x
Transverse emittance meter	o			o

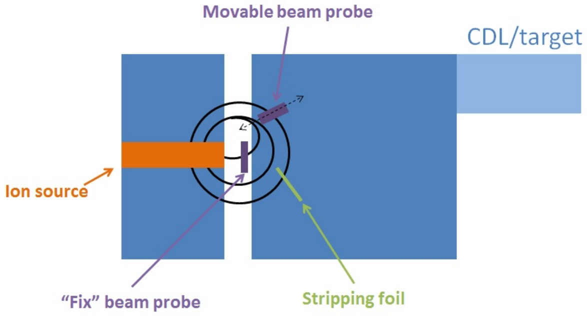

Figure 2: Layout of beam diagnostics during AMIT operation.

Operation

During operation, the aim is using as much as non-destructive or quasi non-destructive diagnostics as possible, in order to maximize the availability of the machine for radioisotope production. However, as for some diagnostics this is almost precluded due to technical reasons, for some operations, like to analyze the transmission in the machine, it will be necessary to stop and analyze the machine. To overcome this issue, a set of small and non-interceptive diags just upstream the target are being analyzed. However, the issue is challenging, since the compactness of the machine and the weak focusing at the extraction precludes the installation of a long diagnostics line -with or without magnetic transport- in this area.

STATUS OF BEAM DIAGNOSTICS DESIGN

The main work until now has been the definition of the diagnostics that are expected during the commissioning and operation of the cyclotron, the conceptual design of most of them, a preliminary design of the most critical ones like the movable beam probe, and a engineering design of the devices for the characterization of the ion source at the test bench.

Beam Probes

Beam probes will monitor the total beam current at several accelerator positions. There will be made of a simple sheet of material, electrically insulated from the driven stage. Unlike the typical faraday cups, there is no need of secondary electron supressor thanks to the presence of the high magnetic field, which gets the electrons back to the beam probe. The most critical one in terms of both mechanical integration and thermomechanical robustness is the beam probe which is inserted in radial direction to analyze the beam during commissioning and during nominal operation. The probe will have a movement range of more than 50 mm so as to approach as close as possible to the first beam turns, and to be totally removed during normal beam operation. The beam probe will cover then stopping beam energies from hundreds of keV to less than 10 MeV.

To maintain the compactness of the vacuum chamber, an in-vacuum actuator will drive the probe movement. Since the operation under a high magnetic field is complex, several tests, including the use during the ion source characterization, are foreseen. The main problem for the high energy beam probe is however the continuous beam power deposition. A maximum beam power of 85 W is expected as input design condition (10 μA at 8.5 MeV). Since the footprint at high energy is very small (around 1x4 mm), the power density is very stringent, more than 2000 W/cm^2. Thermomechanical simulations have been performed in order to evaluate the temperature reached by the beam probe in these conditions. The beam probe is made of graphite to maximize the maximum temperature accepted. The power deposition is assumed to be at the surface, which is a conservative approach, since the power is then not distributed over a volume. As boundary conditions, the model assumes thermal conductivity and radiation, with an emissivity of 0.7 at the surface exposed to vacuum. As seen in Fig. 3, in the stationary regime, the graphite reaches almost 2500^o at the beam impact region. The temperature drops smoothly on the beam probe surface down to around 1000^o. The temperature is well bellow the graphite melting point (c.a. 3700 ^{o}C), but yet very high for normal operation. Some attempts to decrease the temperature by increasing the beam probe volume have failed since the main contributions for the equilibrium temperature are the deposition power and the radiation. To avoid this, several options are available: 1) to monitor the beam probe temperature or 2) to limit either the beam current or energy used with the beam probe or3) to pulse the beam by using the RF. However, this last option should be carefullly studied as it could produce uncontrolled losses that damage or activate the machine.

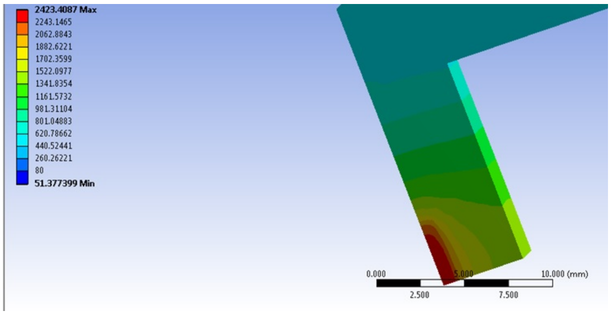

Figure 3: Example of temperature distribution (in ^{o}C) in the probe during nominal beam impact.

Ion Source Characterization

As a first stage of the cyclotron beam commissioning, an ion source will be assembled and characterized in a special test bench developed by CIEMAT in collaboration with CERN. The tests will consist of using a high magnetic field dipole (around 0.8 T) to validate the ion source design. The magnet is placed at a CERN building where a high voltage cage will be set for the tests. During this phase, the energy of the extracted ions will be limited due to the negative particles which disturb the high voltage operation loading the puller [4]. To overcome this issue, the method used in [4] will be used. This technique proposes the use of a electrical shielding box to insert all the diagnostics inside a metallic box where there are no interferences from gas ionized particles or a high electric field. The design plans the installation of a movable probe to scan the beam current at several positions, depending on the high voltage extraction and the magnetic field strength (see Fig. 4. The tests will start with small high voltage extractions (around 3 keV) but it is planned to increase the voltage. A maximum of 30 keV are accepted at the test stand. During the tests, both the ion source and the vacuum chamber are grounded, while the puller, the metallic box and the beam diagnostics are kept at high voltage. A special rack with the acquisition electronics of the beam probes are floating at high voltage. The acquisition electronics of the beam probes is a typical picoammeter (Keithley 6485) which is connected directly to the beam probe by a low loss BNC cable and in-vacuum connections. The picoammeter is to be grounded to the same high voltage than the metallic box. A fix beam probe at the exit of the puller is foreseen in order to measure all the charges going through the aperture of the puller. More sophisticated measurements to characterize the transverse beam phase space are prepared by using a movable slit and a movable beam probe, similar to the method used in [5].

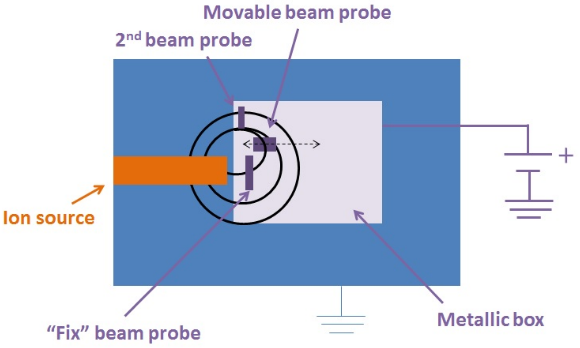

Figure 4: Layout of beam diagnostics during ion source characterization with DC high voltage.

Energy Measurement

Since the energy region of the output cyclotron beam is very close to the radioisotope production limit of the target -for ^{11}C- [6], it is essential the characterization of the energy of the beam hitting the target. This measurement has several requirements:

- It should be possible on-line or at least by exchanging the target for a fast check.
- The device has to have a high energy resolution due to sensitivity mentioned of the radioisotope yield to energy variations.

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- It should be valid for operation inside electromagnetic and high magnetic fields.
- A wide range of beam currents should be accepted.
- A wide range of input beam energies can be measured.

In order to fulfill all the constraints, a new device is under development at CIEMAT. The device can be installed permanently during beam commissioning for constant monitoring of the mean energy 5. During normal operation the device can be placed in replacement of the target in case there are some doubts arising about the energy of the particles out of the cyclotron (see Fig. 5).

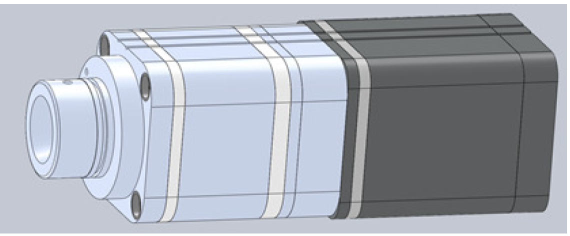

Figure 5: Picture of the energy monitor.

CONCLUSIONS

A complete set of diagnostics is proposed for the proper commissioning and operation of a brand new compact cyclotron for PET production. The proposal has a minimum number of diagnostics not to counteract the compact nature of the machine. However, it combines well-established monitors, like beam probes, with more complex instruments, like beam energy monitors for characterization online. A first set of those monitors is designed, and some of them will be tested for the first time during the measurements of the AMIT ion source at CERN.

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