CHAPTER VI - BEAM DIAGNOSTICS AND VACUUM SYSTEM

1. BEAM DIAGNOSTICS

1.1. Introduction

Different types of specific beam diagnostics must be installed and used to bring the accelerator and the beam transport lines into an operational condition. A first type of measurements is needed during the commissioning period:

- to help to reach the nominal performances of the accelerator
- to confirm the results of beam dynamics calculations
- to help in the understanding of the beam behaviour under both normal and abnormal conditions of operation.

A second type of measurement concerns the establishment of full beam power, and the normal daily operation. The beam instrumentation must thus provide sufficient and necessary beam information in order for the facility operators to run the machine. In case of beam breakdown, beam diagnostic instrumentation must minimize the time needed to identify a problem, to restore the beam and to revalidate the beam characteristics. A powerful command and control system is a prime necessity. Beam instrumentation is also necessary to control and monitor beam losses along the accelerating structure itself.

In future, beam instrumentation will also have to help to improve the accelerator performance.

1.1.a. General considerations on beam diagnostics

The accelerator proposed for SPIRAL2 leads to some difficulties for obtaining a complete characterization of the beam:

- Mainly because of space-charge forces and the energy dispersion of the beam, beam dynamics studies lead to beam line designs with little room for diagnostic devices.
- Even if some beam-destructive sensors could be used for specific measurements, the large quantity of beam energy deposited in any material forces us to use non-interceptive sensors. In addition to destroying the sensor, the interception of some fraction of the beam will lead to high activation of the structure of the accelerator and its surroundings.
- Lastly, we do not plan to install any beam diagnostics inside the tank of the superconducting cavities.

1.1.b. Operational conditions of for beam instrumentation

Diagnostics must be designed to carry out beam measurements under different accelerator conditions of operation:

- **CW operation**: 5 mA of deuteron beam intensity may be reached under this nominal operation mode. In addition, a special operational mode may be needed to accelerate a 150-μA deuteron beam.
- **Low-duty-factor, pulsed-mode operation**: we can easily surmise that the maximum beam power will be obtained in a step-by-step fashion. From present experience of pulsing the high voltage of an ECR source klystron, we can determine the expected beam sensors, the electronic instrumentation possibilities and the type of measurements that need to be made. An easily obtainable beam pulse duration ranging from 1 ms up to 10 ms with a repetition rate of 1 pulse per second has to be considered, in order to decrease drastically the average beam power for beam measurements using destructive sensors. In addition, this range of pulse duration is likely to be suitable for establishing the final behaviour of the beam.

1.1.c. Relevant beam parameters for beam instrumentation

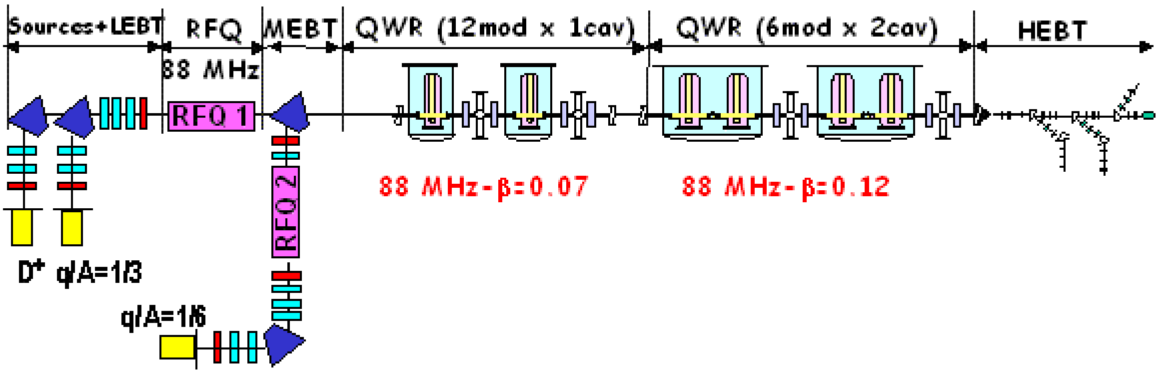


Figure 1: Simplified layout of the linac.

Deuterons	ECR deuteron source – DC, 5 mA, 40 keV
Ions A/q=3	DC, 1 mA, 20 keV/u
RFQ	Operating frequency: 88.05 MHz; energy: 750 keV; transmission efficiency: ~ 00%.
Linac	12 single-superconducting-cavity modules, plus 6 or more modules (the exact number depends on the maximum accelerating field produced) each containing 2 superconducting cavities, operating at 88.05 MHz. Maximum energy is 40 MeV for deuterons, and 14.5 MeV for heavy ions. Transmission efficiency: ~ 100%.

1.1.d. Type of measurements

First of all, we have obviously to measure the following three classical parameters:

- the intensity of the beam;
- the position of the transverse centroid of the beam;
- the transverse beam profiles.

Secondly, more sophisticated characteristics of the beam may have to be measured or may be drawn from these measurements: bunch shape, phase measurement of the bunch with respect to the accelerating RF voltage, transverse emittance and energy of the beam.

1.2. Intensity measurements

1.2.a. Non destructive measurements:

(a) DC measurements:

The measurement of the intensity DC component of the beam can be achieved along the accelerator structure by using a current transformer (DCCT), the working principle of which is based on the magnetic amplifier. A 100-µA accuracy can easily be reached by present commercial devices. This performance allows the measurement of the DC component of the 5-mA deuteron beam current.

Better resolution, in order to measure the intensity of the ions beams, will be obtained by selecting high quality sensors, decreasing the bandwidth of the associated electronics or increasing the integration duration. In this case, best obtainable resolution may be as low as 1 µA for a 1-second integration time. Thus the DC component of the intensity of the ions beams can be correctly monitored.

In the low-energy beam transport (LEBT) system, the use of DCCTs is the only way to monitor the DC beams delivered by ECR sources. DCCTs will therefore have to be located at the exit of the ECR sources.

(b) AC measurements:

After the RFQ, the beam is bunched and an AC beam current transformer (ACCT) has to be used to monitor the accelerated particle bunches under CW operation. Therefore the DC component of the measured beam intensity will be lost.

Once again, commercial devices are available. Their upper cutoff frequency may be as high as 1.5 GHz. However, careful attention has to be paid to the response droop of ACCT under low-duty-factor, pulsed-mode operation.

The ACCT may be also considered as a powerful tool for evaluating the fluctuations of the beam current under CW as well as low-duty-factor, pulsed-mode operation.

In addition, an ACCT is very useful in the LEBT system, to help to tune the ECR. sources in order to deliver a high quality beam to the RFQ

1.2.b. Destructive measurements:

A classical water-cooled Faraday cup can withstand a 10 kW beam and allows intensity measurements under both CW and pulsed-mode operation. The current measurement is obtainable over a large dynamic range and the resolution may be as low as 1 nA.

Figure 2: A 6-kW water-cooled Faraday cup in operation at GANIL.

Up to the exit of the linac, the use of water cooled Faraday cups (WCFCs) has to be considered according to the power of the beam under the different modes of operation and the range of deuterons in copper, which remains below 2 mm up to 40 MeV.

Entrance to the RFQ:

We plan to install a movable WCFC as close as possible to the RFQ. This installation will be possible (the available room ranges roughly from 20 cm to 25 cm) after an optimisation of the beam dynamics and the mechanical design of the WCFC.

- First, this WCFC will act as a beam stop during the tuning of the sources.
- Secondly, it will monitor the beam current at the entrance of the RFQ and will allow a crosscheck with the DCCT (on operation during normal running of the accelerators).

Exit of the RFQ:

As the WCFC is able to withstand the nominal power beam during CW operation, it will be very convenient to install another one as close as possible to the exit of the RFQ

- During the commissioning period, tests and tuning, the WCFC will act as a beam stop and will monitor the current beam.
- The transmission efficiency of the RFQ can be measured.
- A crosscheck can be made with ACCT measurements (in operation during normal running of the accelerators).

Exit from the superconducting accelerating sections:

- Downstream of the first superconducting accelerating section, the WCFC cannot withstand the power of the beam under CW operation. Only low-duty-factor, pulsed-beam operation can be considered.
- Downstream the second superconducting accelerating section, the use of a WCFC will need thermo-mechanical simulations in order to estimate the possible duty factor under full-power operation.
- Lastly, some difficulties may occur due to the sputtering effect, since the WCFC will intercept the beam. Atoms and ions of copper may be ejected from the WCFC by sputtering and may travel along the beam pipe to the inside of the superconducting cavities. This effect can seriously disturb the running of the cavities. Further investigations on this subject have to be made to achieve a better understanding and find possible cures.

1.3. Position measurements

Position measurements of the centroid of the beam in the beam pipe are of prime importance for the accelerator operation. This information may be drawn from the beam profile measurements, but on-line measurements and non-interceptive techniques are required wherever possible in the accelerator.

1.3.a. LEBT

In the two LEBT sections, the beam is a DC beam. Therefore electromagnetic sensors, which sense the electromagnetic field accompanying the beam, cannot give any response. A quantitative measurement of the position of the beam will be deduced from the transverse profile measurements achieved by beam-profile grids. (Refer to the later paragraphs on transverse beam profile measurements.)

Other possibilities may be investigated. Owing to the energy loss by the incoming particle, the atoms of the residual gas are excited, which causes them to emit light as these atoms return to the ground state. A CCD camera can sense this light and the position of the beam can be deduced from this measurement [10, 11]. However, a difficulty may arise, as the camera has to be radiation resistant.

1.3.b. MEBT, linac, and HEBT systems

After the RFQ, a response to the electromagnetic field accompanying the beam is available from electromagnetic pickups. We may contemplate the use of capacitive or electromagnetic sensors such as strip-line pickups or directional couplers. These well-known sensors have four electrodes exposed to the electromagnetic field of the beam, each connected to a signal amplifier [16, 17].

Sensor considerations

Directional couplers are very popular for proton accelerators and provide higher amplitude signals, but ‘button’ electrodes have to be considered first, due to the reduced space available (~ 20 cm length) for any diagnostic box between the tanks of the superconducting cavities.

For example, in the MEBT system (E=750 keV, β=0.07) the passing bunch charge lasts for roughly 2 ns, according to its phase extent, and the bunch spacing is 11.38 ns. A first evaluation shows that, assuming a bunch shape of the $(\text{cosine})^2$ form and 50 pC for the bunch charge, we could choose a 35 mm diameter for the button in order to obtain 4 dBm on the 88-MHz fundamental frequency under the 5-mA standard operating mode, and –35 dBm under the special 0.15-mA operating mode. These amplitudes levels are compatible with available electronics.

Signal processing considerations:

The position measurement of the beam depends on the ratio of the signal amplitudes delivered by the electrodes. Several analogue or digital processing techniques allow the calculation of the position of the centroid of the beam from the signal delivered by opposite electrodes. At present, two methods have been selected:

- *Time multiplexing process*

In this, the four electrode signals are time multiplexed and processed by the same electronic circuit. The result of the calculation does not depend on the amplitude of the signals since normalization is achieved by keeping constant the sum of the signals using AGC amplifiers. This method offers the best possible accuracy obtainable.

- *Log ratio process*

Here, the position of the beam is deduced from calculation of the ratio of the logarithm of the two signals. This method is able to provide a very good dynamic range, but does not offer the same linearity and accuracy as the previous one.

The final choice will be made assuming that the position of the beam has to be performed during CW operation as well as low-duty-factor, pulsed-mode operation. A 0.1mm-resolution is foreseen and this criterion must also be taken in account.

Lastly, electrostatic monitors will be installed in the MEBT system, for proper alignment of the beam, as well as after each tank of superconducting cavities.

1.4. Beam profile measurements

The measurements of the transverse horizontal and vertical profiles are extremely important along the linac structure and especially in the superconducting section. A criterion which indicates that the beam is correctly tuned is its circular shape.

Three kinds of detector can be selected for SPIRAL 2:

- SPIRAL 2 accelerator beams are too intense under CW operation for traditional interceptive techniques such as harps, secondary-electron monitors, and wire scanners. The temperature attained by the wires would be too high and would lead to their destruction. Therefore, only under low-duty-factor, pulsed-mode operation can one expect slow wire-scanner or harp profile measurements to operate reliably: these beam profile diagnostic methods are all of the same family. We have to focus now on their capability to withstand higher average power beam than the beams presently produced at GANIL.

- Another minimally interceptive technique is worthwhile noting: residual-gas ionization profile measurements. The interaction between the beam and the background-residual gas creates electron-ion pairs (Figure 4). An electric field is placed across the beam region so that either electrons or ions are electrostatically accelerated toward a collection device consisting of multi-grid or micro-channel plate (MCP). The profile of the primary beam is deduced from the measurements of these collected charges. [Secondary-electron profilers and residual-gas ionisation monitors are already in operation at GANIL.]

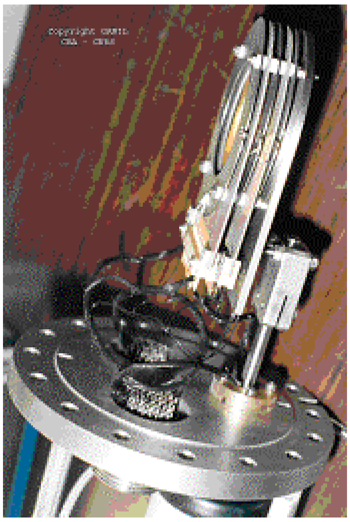
- Monitors based on the fluorescence of the residual gas interacting with the primary deuteron beam may also be considered here. The light, visible to the human eye, can be sensed by a CCD camera and is able to give useful information, at least on the size of the beam. For this purpose, glass windows have to be installed on the beam pipe of the LEBT. Obviously the efficiency of this kind of monitor decreases as the beam energy increases.

1.4.a. LEBT, MEBT, linac and HEBT systems

Destructive measurements

Secondary-emission monitors (SEMs)

The energy of the low-energy beam is so low that the range of deuteron in metallic material is less than 1 μm. Therefore the beam cannot pass through any window in the beam pipe to reach a sensor. Secondary-emission monitors (SEMs) may therefore be necessary for profiles measurements. In this kind of sensor, an electronic integrator measures the current resulting from the interception of the beam by a number of thin wires.



- 47 tungsten wires
- Diameter of the wire: 20 μm - minimum spacing: 0.5 mm
- Absolute precision (position): ± 0.1mm
- Electronic instrumentation: 2 ms < integration< 10 s
- **Intensity of the measured beam: 100 nA < I < 100 μA**
- **100 keV/u < beam energy range < 100 MeV/u**
- Present degassing ratio over 100 hours: 10^{-6} Pa .m^{3}.s^{-1}

Figure 3: SEM monitor in operation at GANIL.

This detector is very well suited to measurement of transverse profiles in the LEBT line [1,2,3]. However, the technology of the components of the sensor, especially concerning the wiring, must be improved in order to be compatible with the vacuum environment of the LEBT line. Furthermore, simulations based on integration of the heat equation are needed to evaluate accurately the behaviour of these sensors under the SPIRAL2 deuterons beams and will lead to an optimisation of the tungsten wire diameter in order to withstand higher-intensity beams. We plan to install these detectors along the LEBT line from the source up to a position as close as possible to the entrance of the RFQ (in the diagnostic box of the WCFC).

In the MEBT system – and even more so in the HEBT system – this detector can only withstand very low duty-factor, pulsed-beam operation.

Wire scanners

In the same family of beam profilers, one may think of using wire scanners, the principle of which consists in moving a wire step by step through the beam. For each position of the wire, an amplifier measures the collected charges. The transverse profile is then deduced. Since only a few wires are needed for this kind of sensor to measure horizontal and vertical profiles, one can contemplate the use of very specific material such as carbon fibre or SiC. This fibre can reach very high temperatures – and can therefore sense high-power beams – without being destroyed. We had the opportunity to carry some experiments with SiC wires ($\phi = 30\ \mu$m) with the “SILHI” source designed for a high-intensity proton injector. We checked that this wire could withstand 95-keV pulsed proton beam operation (duration: 1 ms, repetition rate: 1 s, intensity: 100 mA). The beam shape was cylindrical and the current density in the range of 100 mA/cm^{2}. Thermionic emission occurred as the pulse duration was lengthened up to 2 ms (other conditions being kept constant) without destroying the wire.

Compared to the tungsten wires of secondary-electron monitors, these fibres may allow us to probe higher-power beam. However, we need to evaluate accurately the temperature which will be reached by these fibres when placed in the expected SPIRAL 2 beams.

b) Non-destructive measurements

Residual-gas ionisation monitors (RGIMs)

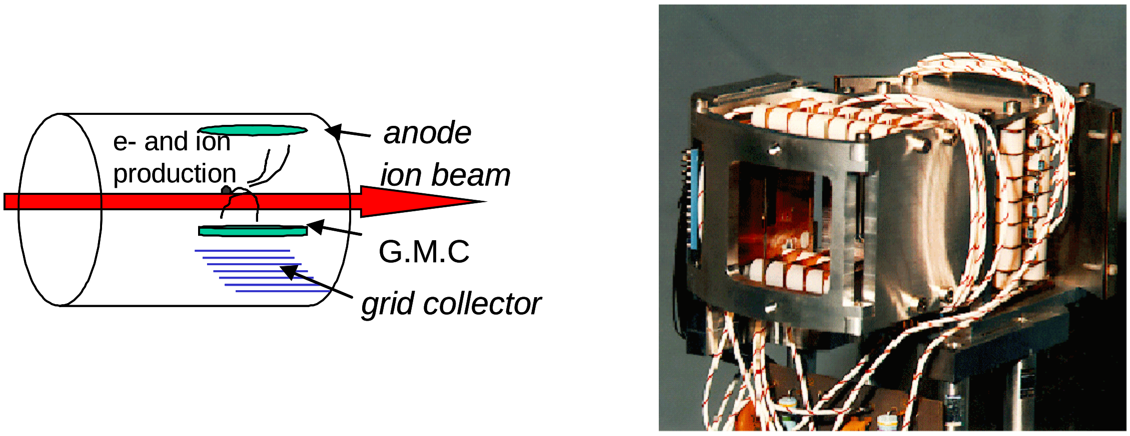


Figure 4: Residual-gas ionisation monitor used at GANIL.
Absolute precision (mechanical position): ± 0.3mm, resolution: ± 0.1mm, FWHM: + 20%.

The beam passes through the detector without intercepting any material. This feature makes it very attractive to measure the transverse profiles beams of high average power. However, the charges resulting from the ionisation of the residual gas are electrostatically accelerated and collected by mean of a transverse electric field (with respect to the beam), requiring voltage in the 2-kV range. The spatial resolution of the detector is mainly determined by this electric field, which may degrade the primary beam. For this reason, we do not plan to use this detector in the LEBT lines.

On the other hand, it is very well suited for sensing the MEBT and HEBT system beams. The performances already obtained at GANIL and the simulations made show that deuteron beams may be monitored in the range of several tenths of µA up to the maximum current, and ions beam from several µA up to the maximum, without the need of multi-micro-channel-plates. The possible intensity range measurement of this detector is given in [21].

However, modifications have to be made in order to make the sensor of this detector compatible with the ultra-high-vacuum environment of the linac, and experiments will have to be carried out to validate the profiles obtained by the new resultant sensor. [4, 5, 6, 7]

c) Beam high-order-moment measurements

The first-order moment gives the centroid of the beam and the second-order moment gives us information about the rms size of the beam. We recall that the main parameter needing to be checked for matching the superconducting accelerating structure is to have a circular transverse beam shape. This means that a measurement of the rms size of the beam is enough to match the beam.

Measurements of this kind of have already been achieved by means of electrodes placed around the beam pipe and acting as wall current monitors, which form a beam-position monitor (BPM). This BPM, characterized appropriately for this purpose, is able to deliver the first and second moment of the beam. Further improvements have even been made which lead to measurement of the transverse emittance of the beam. Several publications are available on this subject.

This method needs to be investigated further for tuning of the SPIRAL 2 linac. In this case, the same BPM would provide the position and the size of the beam. In addition, this sensor would avoid the difficulties relating to high-vacuum technology improvements and the sputtering effect of wire grid profilers.

1.5. Longitudinal measurements

1.5.a. Energy and phase measurement

Measurement of the relative phases of the RF structure of the beam bunch and the accelerator RF cavity fields is important for optimizing the accelerating cavities' phases and amplitudes. One possibility is to base this measurement on the four combined signals of a BPM Another is to design a specific capacitive pickup dedicated to this measurement.

A more specific measurement uses the superconducting resonator of the accelerator to detect the arrival time of the beam bunch. In this special 'detection' operating mode of the accelerating cavity, the resonator operates at a low field, comparable to the field induced by the beam bunch. The phase information is extracted by an electronic circuit specially developed to sense the resulting field in the cavity which is the sum of the reference RF signal and the beam-induced signal. A phase resolution of 1° at 48 MHz was obtained at ATLAS by this method (100-nA beam current) [12, 13].

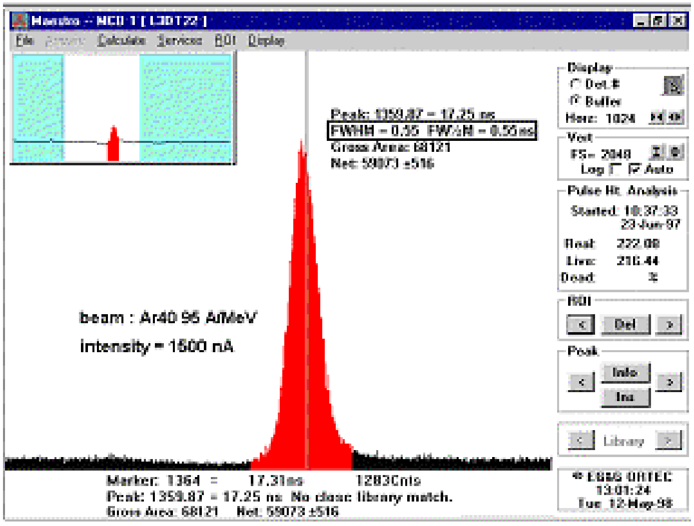
If two resonators are used in the detection mode, the difference in phase contains time-of-flight information and then absolute energy can be deduced.

1.5.b. Bunch shape measurement

Accurate measurements of the distribution of charge within a bunch and the longitudinal emittance are important tools for beam dynamics studies or for accelerator tuning. The main requirements are good time resolution and a wide range of measurements of primary beam characteristics

a) Residual-gas ionisation monitor

This method is used at GANIL to measure and check the time distribution of the accelerated beam on-line. The signal is obtained from residual-gas ionisation monitors in the same conditions as previously described for the profile monitors, but the localization strips are replaced by a 50-Ω anode. Each electron produced in the vacuum is directed towards the multi-channel plate and gives rise to a fast signal on this anode, which is the sensed by a constant fraction discriminator. A time-to-amplitude converter (TAC) gives a start signal; the stop signal comes from the cyclotron RF signal [6,7].



Peak: 1359.87 = 17.25 ns
FWHM = 0.55 FW⅕M = 0.55 ns
Gross Area: 68121
Net: 59073 ±516

beam : Ar40 95 A/MeV
intensity = 1500 nA

○ Det.#
● Buffer
Horz: 1024
FS= 2048
Log ☐ ☑ Auto
Started: 10:37:33
23-Jun-97
Real: 222.08
Live: 216.44
Dead: 3
13:01:24
Tue 12-May-98

Marker: 1364 = 17.31ns 1283Cnts
Peak: 1359.87 = 17.25 ns No close library match.
Gross Area: 68121 Net: 59073 ±516

Figure 5 : Bunch length measurement on-line for an argon-40 beam at GANIL.

The intensity of the beams of SPIRAL 2 may lead to a saturation of the MCP. A new kind of MCP has to be put into operation in order to withstand the high counting rates expected.

Finally, resolution may attain 50 ps, but information about phase with respect with the RF signal is not obtained with this device.

b) Bunch length monitor

A more complete diagnostic device is the bunch-shape monitor, based on the coherent transformation of the temporal structure of the beam into a spatial distribution. For this purpose, a wire is placed in the primary beam, and when hit, emits secondary electrons, which are accelerated and then focused by an RF deflector fed by a voltage in synchronism with the RF voltage of the superconducting cavities [13]. The distribution of secondary electrons is detected by a chevron-MCP coupled to a phosphor screen. Tests of this monitor done with $^{59}Ni^{15+}$ ions were made on the ATLAS booster. The beam energy range was 6.5–7.2 MeV and the intensity ranged from 10 pA to 100 pA. The time resolution for this particular measurement was 40 ps.

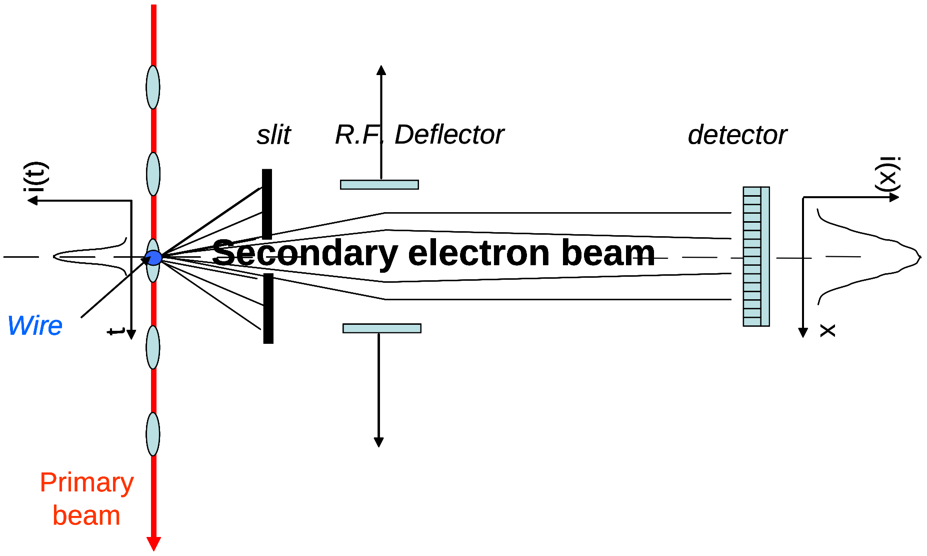


Figure 6: Schematic diagram of a bunch-length monitor.

1.6. Beam instrumentation in the secondary beam transfer lines

Due to the aggressive nuclear environment of the secondary beam transfer lines, the sensors used to measure the beam characteristics must be as robust as possible. Electronics associated with these sensors will have to be as far as possible from the beam pipe.

The following beam diagnostics have been selected:

1) Beam intensity measurements: The best candidate is the Faraday cup (described earlier).
2) Beam transverse profile measurements: owing to the very low energy of the beam in these beam transfer lines, the easiest way to achieve this measurement is to use secondary-emission detectors. Improvements to the electronics are planned in order to increase the sensitivity of this detector. [8]

These conventional devices used for heavy-ion accelerators require an intensity of at least 10^8 pps. Thus low-intensity beams such as radioactive ion beams may be beyond the limits of these devices. Developments are therefore under way at GANIL to design transverse beam profile monitors equipped with multi-channel plates in order to lower the sensitivity of these diagnostic devices. Tests have already been carried at GANIL with a $^{10}Ne^{6+}$ beam at 13 MeV/A and with an $^{16}O^{2+}$ beam at 3.9 MeV/A. This kind of monitor is currently used for the imaging of high-energy (6 MeV/A) radioactive beams produced by fragmentation at the ATLAS accelerator facility. [9]

Figure 7: General view of the prototype of the secondary-emission beam profile monitor (equipped with a multi-channel plate) under development and test at GANIL.

1.7. Beam-loss measurements

For the linac, the tolerable loss of beam power corresponds to 1 W or less per metre of the structure. This requires a reduction of the beam loss down to 10^{-6} in the linac, far beyond the present state the art of experiments as well as conventional approaches of computer simulation. The same considerations must be kept in mind for the beam transport from the accelerator to the target.

Although the biological protection along the whole linac has been designed to cope with a relative beam loss of 10^{-3}, i.e. 200 W at the final energy, the power deposited by the particles lost on the accelerator structures should be minimized in order to avoid activation of the accelerator equipment and to make hands-on maintenance easier. Apart from a few specific locations where extra shielding is foreseen (dedicated collimators), the relative beam losses per unit length should be less than 10^{-5}, especially along the high-energy portion of the linac. In addition, a larger beam power deposition on the superconducting cavity walls would lead to an excessive heat load for the cryogenic plant or even to quenching of the resonator.

Measurements of beam losses are required:

- to protect the environment against irradiation;
- to allow the machine to operate with minimum beam-induced activation of components and thus to prevent activation of the accelerating structure for hands-on maintenance;
- to sense an amount of beam loss below a pre-established level when slightly abnormal accelerator conditions such as mismatches occur: in this case, beam-loss diagnostics must allow tuning-up of the machine without stopping the accelerator operation;
- to act as input to the fast protection system that protects the components in case of failure.

The beam loss diagnostics are likely to be a major component of this machine protection system, which must obviously take into account the data delivered by these monitors. They will be used to cover selected areas of the machine or specific devices, such as superconducting cavities, so as to protect them from beam-loss related damages. For this purpose, a possibility could be to integrate the beam losses and to stop the beam in a time inversely proportional to the amount of beam loss. The machine protection system coupled to the beam loss monitors must then have a response time short enough to turn off the beam well before destruction of accelerator occurs. [20]

1.7.a. LEBT system

In the low-energy beam transfer system, the energy of the deuteron ion beam will be 40 keV. The interaction of the incident deuteron beam with the components of the LEBT line previously implanted with deuterons, leads to consideration of two possible d+d nuclear reactions:

- d(d,n)^{3}He – leads to neutrons production. Reaction cross section: 2.66 mbarns.
- d(d,p)^{3}H – produces tritium. Reaction cross section: 2.64 mbarns.

Thus, the neutrons produced by the d(d,n)^{3}He reaction are a characteristic signal of the incident beam loss. As the energy of these neutrons is 2.5 MeV, one can use a ^{3}He-counter sensitive to thermal neutrons placed into a ~20 cm diameter polyethylene sphere acting as a moderator.

- Fast detection of prompt neutrons is possible if the components of the LEBT line are saturated by previously implanted deuterons.
- Several tens of seconds are needed to implant enough deuterons in order to turn the components of the LEBT line into possible neutron producer under interaction with the incident deuteron beam. The neutron production rate with a deuteron beam of 50 mA/40 keV has been already measured, and is $5.6.10^6$ n.s^{-1}.

An array of ^{3}He counters may be arranged along the LEBT beam lines in order to locate the beam losses roughly. The ^{3}He proportional counter can be obtained commercially. The cost of such detectors is around 4 k€/unit, including all associated electronics.

Because of the low energy of the heavy ions beam in the LEBT system (20 keV/u), well below the Coulomb barrier, it must be pointed out that no neutron or gamma ray can be produced by a nuclear reaction resulting from the interaction of heavy ions with the components of the LEBT beam lines.

1.7.b. RFQ and MEBT system

The RFQ increases the energy of the deuterons up to 1.5 MeV. The cross section of the d(d,n)^{3}He reaction (see Figure 8) is much higher and the neutron production rate is consequently much greater too. Nevertheless, the problem of the detection dynamic remains the same: deuterons have first to be implanted in the components of the RFQ and of the MEBT for the d+d reactions to occur.

In addition, some more classical beam-loss controls, already operated at GANIL, may also be employed in the MEBT system:

- Electrically isolated metallic rings, arranged inside the vacuum beam pipe may sense the halo of the beam and therefore to provide help in preventing beam losses.
- Non-interceptive differential methods using at least two beam intensity monitors, such as beam current transformers, are able to provide an estimate of the beam loss. The accuracy may reach a few percent.

Nevertheless, it would be worthwhile to carry some development of these two methods to improve their performance.

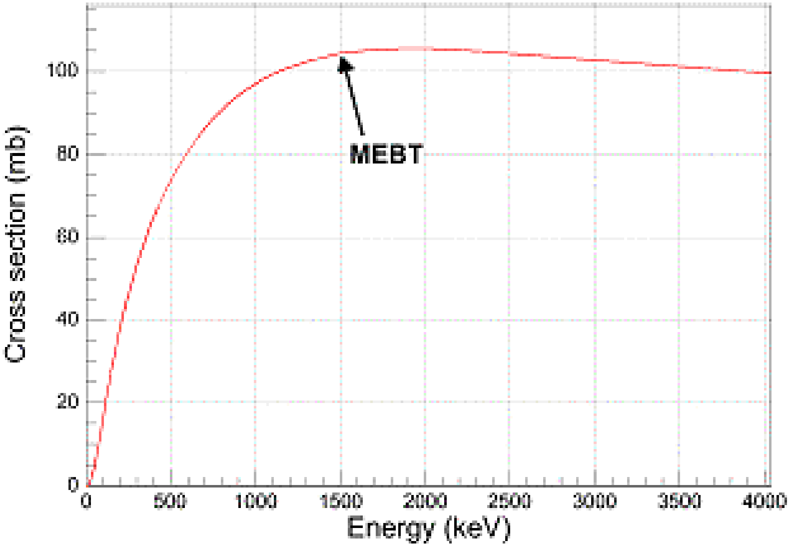


Figure 8: $d(d,n)^3He$ cross section.

1.7.c. Linac and HEBT system

Below the third or fourth linac cavity area, the energy of the deuteron beam remains too low to induce nuclear reactions with the components of the linac structure or the superconducting Nb cavities. In this section of the accelerator, beam loss has to be detected in the same way as in the LEBT system.

As the beam energy exceeds 7–8 MeV, nuclear reactions resulting from interaction of deuterons with the structure of the accelerator occur (i.e. d+Nb). Neutrons and gamma rays are then produced and offer different possibilities for beam loss measurements:

- Gamma rays resulting from beam loss may be easily measured. However the result will probably be seriously distorted by the contribution of hard X-rays produced by the superconducting cavities of the high-energy section of the linac.
- The He^3 counters are not sensitive to photons, but they require a rather large volume of moderator.
- Plastic scintillators are sensitive to photons and neutrons. They are cheap and can easily be coupled to optical fibres, allowing the installation of the photomultipliers and all associated electronics to be far away from the linac.
- The use of scintillators based on ZnS:Ag embedded in a plastic matrix is another solution being studied, due to the sensitivity of such scintillators to fast neutron and their low efficiency to photons and thermal neutrons which are the main source of background.

Figure 9 shows a very basic possible layout of this detector. Two cubic scintillators are set up and down at a distance d from the beam pipe (10 cm diameter). The beam loss is assumed to occur at distance D upstream of the scintillators plane. No secondary reactions of neutrons (or gamma rays) with surrounding materials have been considered. The ability of the system to localize the beam losses requires the ratio of counting rates to be as large as possible. Simulations have been done according to the available data for the production of neutrons by deuterons of 33 MeV on copper [19].

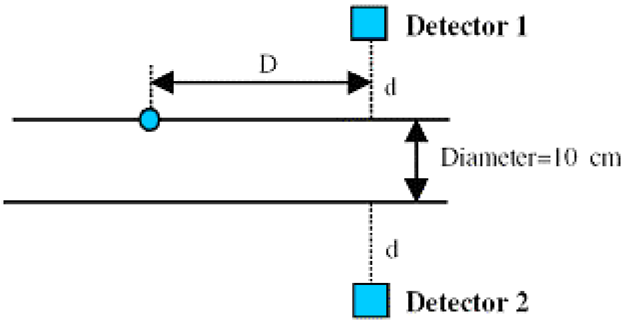


Figure 9: Setup geometry used for the simulation (see text).

First results (Figure 10) indicate, as expected, that the closer to the vacuum pipe the scintillators are, the better the accuracy of the localisation. Nevertheless, these results are very preliminary. Accurate data of double-differential neutron yields on Nb are needed in order to validate this method for the detection of the beam loss along the linac. Experiments are suggested for this purpose [20].

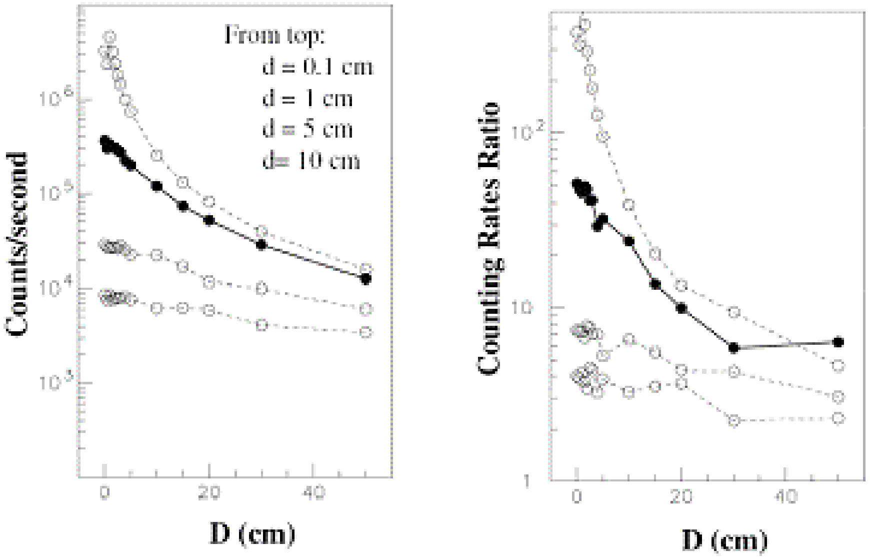


Figure 10: Simulation results. Left: neutron counting rates. Right: ratio of counting rates of the two detectors. Calculations for d=1 are shown by the solid lines and symbols.

Because of the high levels of background radiation expected, the radiation hardness of the scintillators and of the optical fibres, needed to carry the light from the scintillator to the photomultiplier, must be estimated. Experiments are proposed to determine the threshold in neutron detection, before and after neutron and gamma irradiation, of the scintillators and the optical fibres.

The counting rates show a strong dependence on the distance from the point where the loss occurred. The intensity of the beam loss can be obtained only if the position is also known.

1.8. Conclusion

Accelerator diagnostics

- Intensity measurements of D^+ and ions beams are possible with well-established techniques: non-interceptive beam monitors will be based on AC and DC current transformers. Interceptive measurements will be achieved by Faraday cups. Specific electronics already in operation at GANIL, dedicated to differential measurements between two sensors, must be adapted and improved in order to control the intensity of the beam along the accelerating structure of SPIRAL2 as accurately as possible.

- Transverse position measurements of bunched beams downstream of the RFQ will be performed on-line by an electrostatic pick-up. A first estimation of the signal amplitude delivered by the pick-up has been made and is compatible with available electronics. However the final choice of this electronics will depend on the beam intensity range of measurement and a ± 0.1mm required resolution. Obviously, it is necessary to extend the dynamic range of the measurements as widely as possible to facilitate the initial start-up and the tuning of the accelerator under all the foreseen operating modes. It would be very useful to carry out studies in order to measure the rms size of the beam of SPIRAL 2 by means of an electrostatic pick-up. Transverse position measurements of DC beams in the LEBT lines will be drawn from the measurements delivered by the transverse profile monitors.
- Phase measurements will be achieved on line by an electrostatic pick-up or drawn from the sum of the four channels of a BPM. The length of the bunch will be measured (resolution ~50 ps) in a non-destructive manner by a residual-gas ionisation monitor. However, this detector does not provide the information of phase with respect to the accelerating voltage. The only way to obtain phase information and the bunch length (resolution ~ 30 ps) simultaneously is to design and build a specific bunch-length monitor. This monitor would work under low-duty-factor, pulse-mode operation. This would be a new development at GANIL.
- We propose to measure transverse beam profiles under full CW power by residual-gas ionisation monitors. The operation of these detectors is now well established at GANIL. However, in the case of SPIRAL 2, these monitors must be sized to fit into the short diagnostics boxes located between the superconducting modules. The wiring of the sensor has to be reconsidered in accordance with the ultra-vacuum environment of the linac. One of the most important points is to replace the epoxy substrate of the printed-circuit board by alumina.
- A system specially dedicated to beam-loss measurement for SPIRAL 2, based on plastic scintillators and He^3 counters, has been proposed and is now under development. The cost of this system remains to be evaluated. At the exit of the RFQ up to the first superconducting cavities, the losses cannot be measured through neutron and gamma detection. Therefore, classical solutions based on electric measurements already in operation at GANIL must be adapted and improved for SPIRAL2.

Secondary beam lines diagnostics

- Beam instrumentation for the secondary beam-lines will be as robust as possible. Intensity measurements will be achieved by Faraday cups, transverse profile measurements by secondary electron monitors. The material of the associated sensors intercepting secondary beams will have to be carefully selected in order to withstand the aggressive nuclear environment expected in the production building. The mechanical system of these detectors already on operation at GANIL has also to be reconsidered. Special studies are planned for this purpose. The electronics system must be located outside from the production building. Developments are in progress at GANIL to improve the sensitivity and dynamic range of measurement of this associated electronics. If necessary, a secondary-emission beam profiler equipped with a multi-channel-plate electron intensifier is proposed to make the profile measurements of low-intensity radioactive ion beams ($<10^8$ elementary charges per second)
- The different operational modes of the accelerator and the final characteristics of the beam have now to be finalized to permit an evaluation of the specific performance of the beam diagnostics that we plan to use.

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2. THE VACUUM SYSTEM

2.1. Specifications

The required SPIRAL 2 vacuum levels are fixed firstly by heavy-ion beams losses by the charge-exchange process with the residual gas, and in the secondly by the authorized energy losses in the vacuum vessels (i.e. the safety constraints) [1].

The average pressur0s values needed for the vacuum system design are:

Primary beam lines	
LEBT	2.10^{-6} Pa
RFQ	$< 5.10^{-6}$ Pa
MEBT	1.10^{-6} Pa
Linac	$< 5.10^{-6}$ Pa
HEBT	5.10^{-6} Pa
Secondary beam lines	**-**
Converter	$< 10^{-3}$ Pa
ECS	$< 5.10^{-5}$ Pa
1+ beam lines	1.10^{-5} Pa
n+ beam lines	1.10^{-6} Pa

These vacuum values and the particular environmental constraints impose the following general requirements:

- UHV technology
- Dry pumping (without hydrocarbons)
- Good efficiency on the light gases pumping (sources, LEBT, RFQ, linac)
- Limited maintenance vacuum systems
- Homogeneity of the vacuum system equipment.(maintenance constraints).

2.2. Primary Beam Transfer Lines

2.2.a. RFQ

The mechanical aspects of the RFQ and the prototype results are presented in the RFQ final report [2]. In accordance with the specifications, two solutions are possible for the vacuum system: magnetic-bearing turbopumps (Figure 11), or a mixed solution with turbopumps and cryopumps cooled by cryogenerators. In any case, dry pumps are used for roughing out. The choice of solution will depend on the nature and the quantity of gas which comes from the source via the LEBT line to the RFQ.

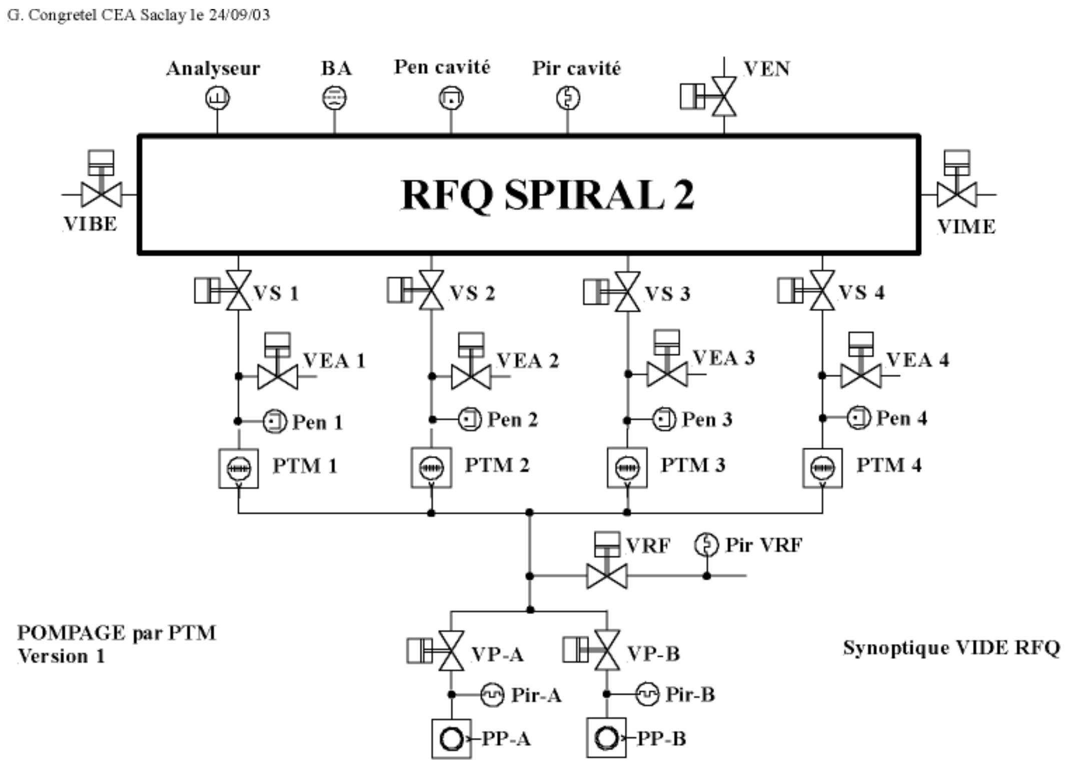

Figure 11: RFQ pumping (turbomolecular version).

2.2.b. The linac

The cavities are pumped after being assembled in a ‘clean room’ by a mobile pumping system (a classical dry turbomolecular system). At room temperature, ion pumps are used to maintain vacuum in the cavities (~ 0.03 $m^3.s^{-1}$).

At low temperatures, to reduce the gas load from diagnostic boxes to the cold cavities, the pressure in the diagnostic boxes between cryomodules is fixed at $P < 5\times10^{-6}$ Pa before cooling down the cavities [3].

In order to obtain these values, a reduction of the gas-desorption rate is required from the monitors, particularly for the profile monitors (the desorption rate measured on these diagnostic devices reaches 1×10^{-6} $Pa.m^3.s^{-1}$). A new profile monitor is being designed with low desorption materials. At least a factor of 10 reduction of the highest desorption rate is anticipated.

The equipment installed under vacuum between cryomodules must allow a 150°C bake-out at least, if this becomes necessary. The ‘hot’ pumping system is installed on the diagnostics boxes on a DN100 flange (Figure 12). A proposed solution is to equip each vacuum vessel with a magnetic-bearing turbopump station (0.2 / 0.3 $m^3.s^{-1}$). This system must guarantee permanent pumping without any vibration (because of their proximity to the cavities) with high efficiency for the light gases (H_2 and He).

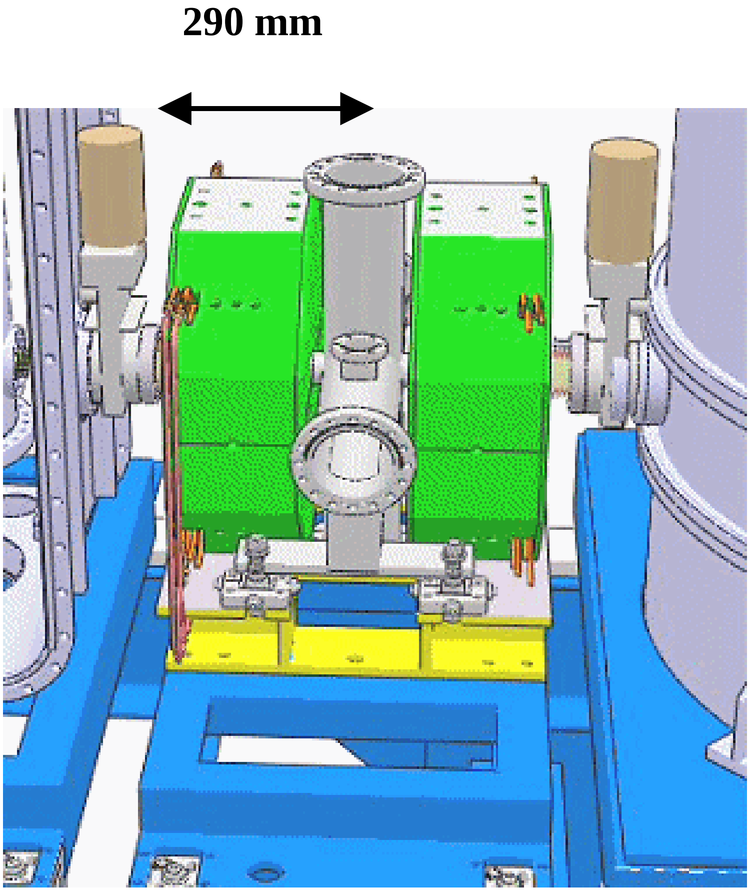

Figure 12: Diagnostic/pumping warm box between cryomodules.

2.3. Secondary Beam Transfer Lines

2.3.a. Plug vacuum system

The ‘plugs’ are shielded boxes which contain all the components needed for the production of radioactive ions. The plug vacuum system must ensure:

- a static barrier, with confinement under vacuum during transport of the plug for maintenance,
- a dynamic barrier during production (the vacuum system tank and the vacuum system beam are independent),
- a vacuum level according to specifications.

The tank is pumped at low pressure and isolated from the vacuum beam by remote-controlled bellows [4] (Figure 13).

To protect equipment during operation, the pump units are located on the service cap at the top of the plug. This particular configuration involves a severe reduction of the pumping speed in the lower part of the plug. In order to obtain the minimum vacuum level in the TIS (10^{-5} Pa range), the total gas flow in this part should not exceed 2.10^{-5} Pa.m^{3}.s^{-1}.

Thus, the tightness between the converter part and the TIS must be optimised, and a gas load evaluation emanating from outgassing TIS components in this particular environment must be made.

In view of assuring a high efficiency for the light gases as well as for maintenance reasons, we suggest magnetic-bearing turbopumps for the plug vacuum systems.

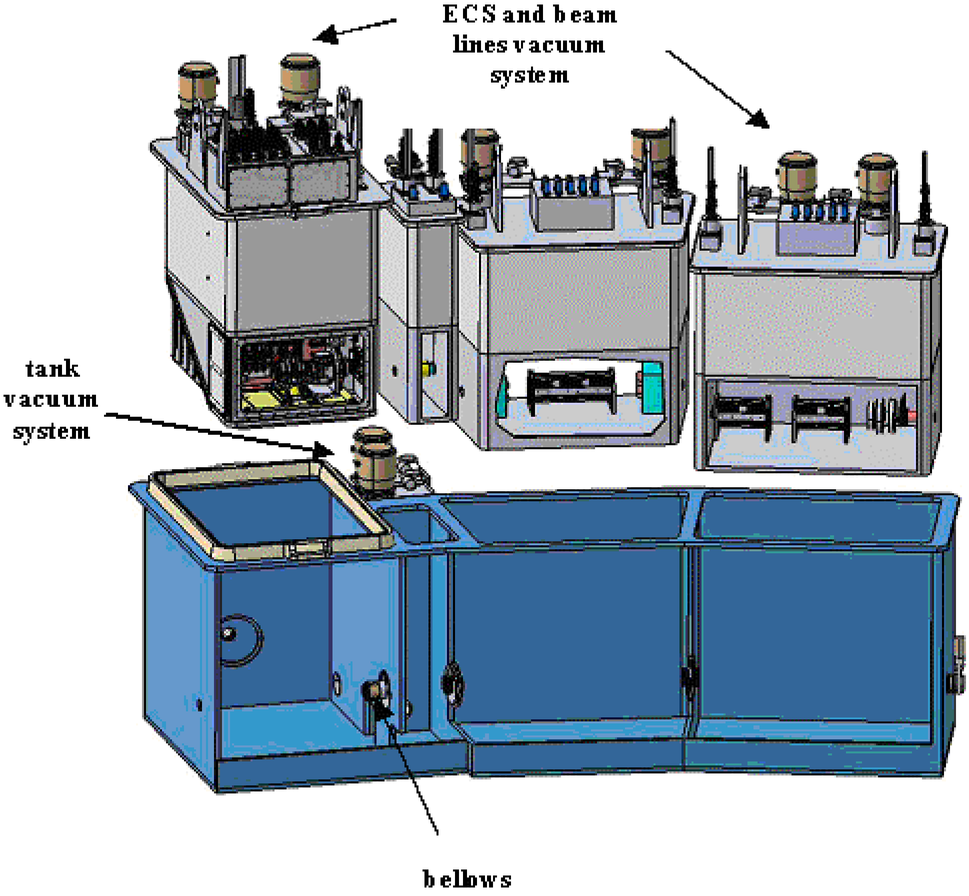

Figure 13: Plug vacuum system (BRAMA version).

2.3.b. Transfer line vacuum systems

The particular vacuum system specifications for this part of the installation are fixed by the multicharged ion beam transmission at low energies, on the one hand, and on the other by the constraints of the strong radioactive environment. Thus, the beam line vacuum system must ensure both static and dynamic barriers to contain radioactive gases.

The transmission calculationse fix a vacuum level of $P = 1\times10^{-5}$ Pa for the 1+ line and $P = 1\times.10^{-6}$ Pa for the N+ line, respectively. These average values impose UHV technology and fix the localised outgassing specifications (diagnostics) for this section: $Qg < 6\times10^{-8}$ $Pa.m^3.s^{-1}$.

The beam line vacuum system proposed is composed of optimally localised pumps, with three possible vacuum system options [5]:

i) Cryopumps and turbomolecular pumps
ii) Magnetic-bearing turbopumps
iii) Ion pumps and turbomolecular pumps.

In addition to this, the technical choices for the secondary-beam pumping system located in the production hall will take into account the following aim: the use of equipment and materials adapted to the radioactive environment, which are either low-maintenance or maintenance-free.

To confine the radioactive gases produced in the target, the secondary-beam pumping system must be connected to a dedicated storage tank. The gas quantities produced by the vacuum system have been estimated [6]. The total volume expected from the roughing phases is 22 m^3 (NTP) for the largest option (BRAMA version: from ECS to CIME). The total volume generated by the high-vacuum pumping during 3 months will be around 300 litres (NTP). Thus, the pumping units must be adapted to the radioactive gas storage system (tightness specifications for backing pumps and the fore-lines).

These constraints for the SPIRAL 2 facility are also being studied for relevance to the existing facilities (from CIME to the experimental areas).

2.3.c. Cryogenic trapping system (cryotraps)

To limit the propagation of the radioactive gases coming from the separator into the beam lines, we propose to install a trapping system on the beam line. A first study of the system has been made to evaluate the radioactive gases which are to be found in the separator. A technical solution is proposed with an on-line cryogenic system with two temperature levels, allowing us to reach a theoretical flow-rate for N_2 of close to 10^2 $m^3.s^{-1}$ (Figure 14). The principle and the efficiency of the system will have to be validated by building a prototype (planned for 2005)

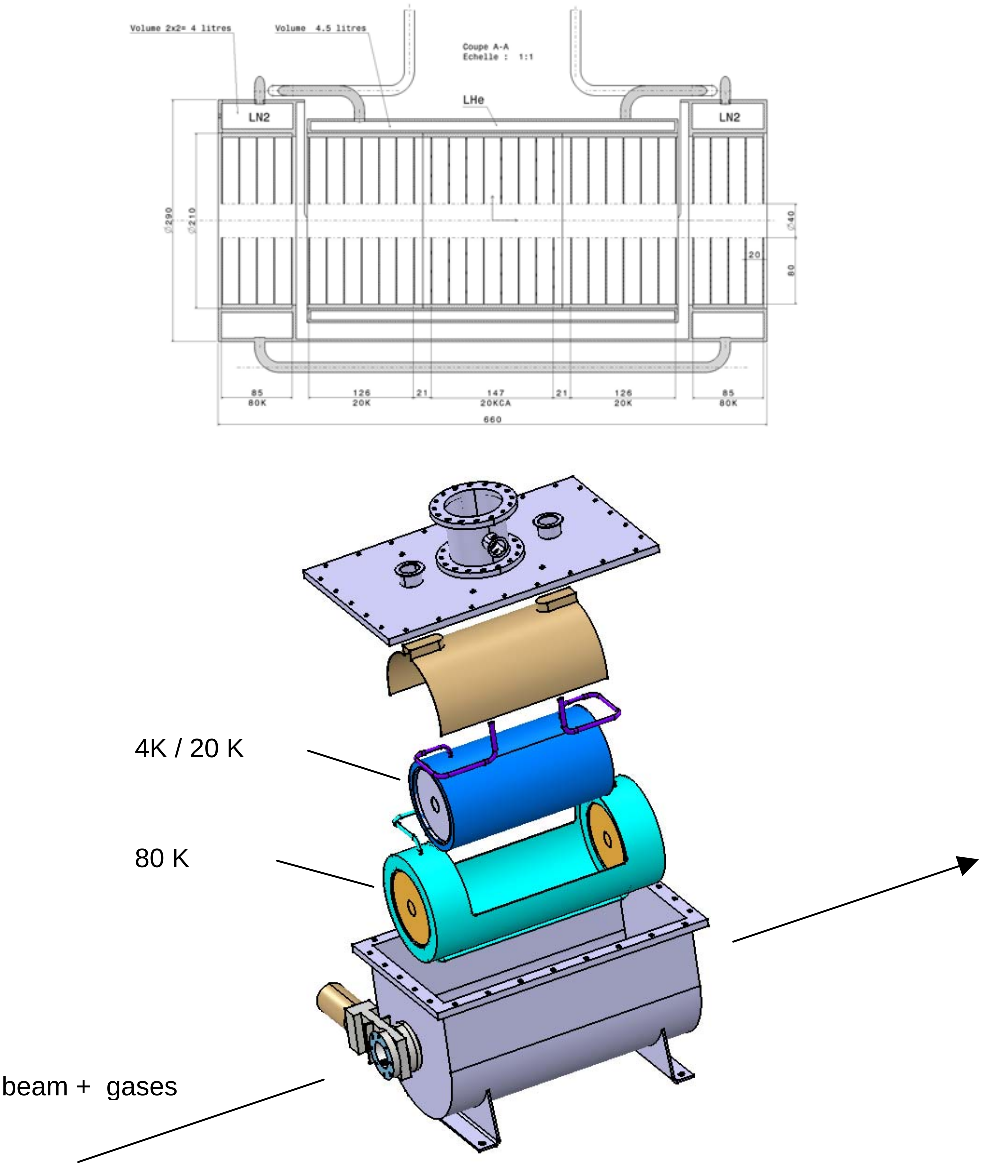

Figure 14: Proposed on-line cryotrap system.

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