DIAGNOSTICS FOR RADIOACTIVE BEAMS

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Abstract

The interest of generating and accelerating beams of unstable nuclei is continuously growing. Following pioneers, new facilities are put into operation or planned. In order to obtain and maintain the highest efficiency, dedicated diagnostics tools have to be developed. The specificities of such devices will be described. A review of existing and planned systems will be given as well as future developments.

1 INTRODUCTION

Investigation of nuclei far from stability has already and is expected to continue to open new ways for the exploration of nuclear matter. Producing and generating beams of unstable nuclei has become an important trend of nuclear physics facilities. Pioneers have been producing[1,2,3] and accelerating[4] such beams for years, followed by many, while ambitious projects are planned[5,6,7]. Overview of these facilities can be found elsewhere[8]. One can distinguish two ways of producing Radioactive Ion Beams : ISOL technique[1] and In-Flight Fragmentation and Separation[2,3]. In the first one the primary beam is fully stopped in a thick target and the reaction products are transported into an ion source to be ionised and later accelerated. In the second process heavy ions impinge into a thin target and the fragments are then selected. In the second case beams are already at high energy and the goal is to select the right specie and transport it to the experimental set up, while in the first one, not only it has to be selected but post accelerated and hence the post accelerator properly tuned. Dedicated tools have be developed in both cases to ensure the efficient transport and acceleration. Let us notice that while first generation facilities are running or about to be commissioned, second generation are already proposed (RIA, EURISOL…).

The problem of controlling RIB's has always been recognized as a challenging one : TRIUMF has organized a workshop in 1997[9] to address it. At the time, the experience was limited and the intention was to have a panorama in order to select the best solutions for ISAC. Since then, progress has been made, including at TRIUMF. Intention of this paper is to update the review (some have been done more recently[10,11]), to identify the main issues and trends.

2 REQUIREMENTS

The aim of the RIB diagnostics equipment is, as for any existing one, is not only to help to bring the beam to the target but also to optimize accelerator performance, with an emphasis on transmission efficiency for RIB's as beams are of low intensity and precious as production is costly. Reviews of what is needed for internal and external beams have been done in the past Cyclotron Conferences [12,13,14] and the reader should refer to them in order to have the detailed requirements and how they have been fulfilled. The needs are determination of space, time and energy distributions. In addition, RIB's have specific needs such as identification among the many products emerging from the source and other specificities that will be described below. One may wonder if dedicated diagnostics tools are indeed necessary : accelerator and beam lines are pre-tuned with a pilot beam and then a small known shift is made[15]. We feel that dedicated tools are necessary as precision may not be sufficient, even for a small shift and stability of the equipments requires minor adjustments anyway. In addition, malfunctioning of equipments requires also a rapid diagnostic and cure, as, again, running the primary beam and the target are costly. This is indeed what shows the present experience [16,17]. Monitoring at the end of the beam line at the experimentalist station is insufficient and intermediate check points mandatory. Another point is that an off line source is sometimes needed for this pretuning : emittance may not be the same as the one for the RIB's. Moreover, even if it is the same source, will it be necessarily the same beam properties for the RIB and the pilot beam?

3 SPECIFICITIES

As far as diagnostics are concerned, RIB's have the following specificities:

- First of all, they are radioactive, which can be an advantage, or a drawback, as we shall see
- Intensity is low
- The beam of interest may be polluted by beams of much higher intensity
- The required range may be large in terms of intensity and energy.

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Different techniques are possible and it is important to define clearly what are the detailed specifications in order to make the right choice. As will be seen the different laboratories have chosen different solutions according to their own specifications.

4 SOLUTIONS

There are two main possibilities among the existing techniques :

- Standard techniques[12,13,14], which have the advantages of being widely used and most of the time well integrated into the C&C system. Based on secondary electron emission, light emission, gas ionization or charge induction, they are also rugged and reliable. However extensive work is necessary to improve efficiency and signal-to-noise ratio : work on amplification and on noise reduction (cable, connectors, shielding, grounding…) Such efforts may not be sufficient to cover the required range.
- Particle detection techniques : very sensitive and precise, they have severe drawbacks such as complexity of use or fragility; considerable effort has to be devoted in order to transform these tools into a user friendly device for an operator. However in many cases they must be used, in particular for the identification, either at low energy with the properties of the radioactive decay, or at higher energy, with for example the E.ΔE technique or time of flight.

In general, a combination of these techniques is chosen, and additional tools such as intensity reduction systems are associated to match the intensity range, which are also useful to test the equipment when the RIB's are not yet available. And we recall that tuning the pilot beam requires a complete diagnostics set as well.

5 EXAMPLES

In the following section, we will review what the different facilities have selected according to their needs, describe their experiences and draw conclusions.

5.1 Standard techniques

Most laboratories have pushed the performances of their standard system. If the RIB's output is large, it might even be sufficient[16], however in most cases it is not. The pioneer Louvain-la-Neuve[1,18] uses a CYCLONE30 IBA-made cyclotron as primary beam driver (6 kW of proton beam) to produce through the ISOL technique RIB's not too far away from stability and post accelerate them initially in their existing K110 CYCLONE and more recently in CYCLONE44 dedicated to low energies. They take advantage of the separation power of the cyclotrons and they have chosen to push the standard techniques by developing an extremely sensitive amplifier measuring down to the fA range on a Faraday cup. SPIRAL developed a logarithmic amplifier to cover a range from pA to μA with a single device[19]. TRIUMF/ISAC also put a large effort on noise reduction[16].

5.2 Secondary emission

Secondary emission of electrons from a foil for instance is a very interesting way that enables a large range. Combined with an amplifier such as Micro Channel Plates (MCP), it provides an intensity, position and time monitor even for low energies. Direct use of MCP's is possible with radioactive ions, as the impinging ions have a larger signal than the decays, but it is not suitable because of damage to the MCP. Good examples of efficient use of such principle are the systems developed for REX-ISOLDE[20] and Oak Ridge[21]. For REX-ISOLDE[22], the requirements were severe :

- Intensity from pps up to nA
- Energy from 60 keV up to a few MeV/amu
- Beam profile measurements
- Measurement of time structure (ns pulses)

They succeeded in reaching this goal using secondary emission of electrons by a aluminium foil, these electrons are accelerated by a 5 kV voltage so that they impinge into a MCP or a MSC, followed by a phosphor screen and a CMOS camera (see fig. 1).

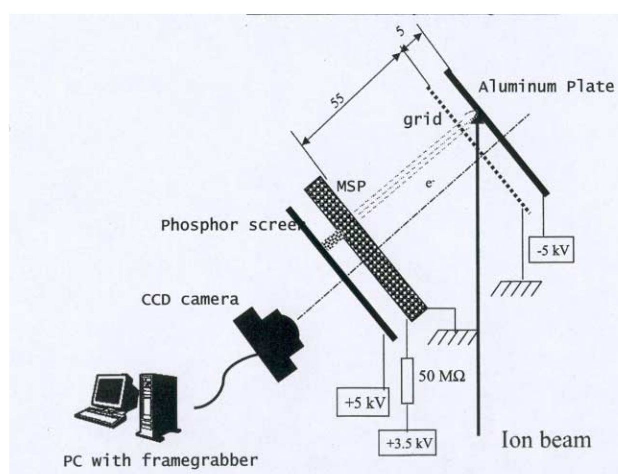

Fig. 1 : Principle of the REX-ISOLDE SE device

Spatial resolution is 1 mm FWHM and although the MCP they used was not optimized for timing, they reached a time resolution of about 1 ns. What is remarkable is that it is non-sensitive to β–radioactive beams, as SE from the incoming beam have a larger yield than from radioactive decay. Nevertheless this system has been successfully used for source imaging[23]; this property, as we shall see in section 5.6, can be used for our needs. Also, with appropriate shielding, it is compatible with the RF accelerating cavities.

MCP (Micro Sphere Plate)[24] have the following advantages over MCP (Micro Channel Plate) :

- It is more robust
- It has a larger acceptance angle
- It can work at a rather poor vacuum (0.1 mbar)

A second good example[21] is the one developed for HRIBF (Oak Ridge) by D. Shapira and collaborators : the same principle is used but the spatial resolution has been improved by the use of permanent magnets : down to 0.25 mm could be reached, removing one of the magnet allows even a magnifying effect. This solution could not be used for REX-ISOLDE, as the magnets would affect the low energy beam trajectory. Final performance in terms of counting rates and time resolution were also excellent. It is a development of the Channeltron© they first used for beam intensity measurements, from SE out of an aluminum foil [14]. M. Poggi (Legnaro) uses also a MCP for fA beam 2-D profile measurements.

5.3 *Light emission*

Scintillators can be used to monitor the spatial or time profile. P. Finochiarro (LNS-Catania) developed BPM made of plastic[25] and glass scintillating fibres [26], for much better radiation hardness. Fast plastic scintillators were developed at SPIRAL for timing and counting[27,28], in particular for phase measurements inside the CIME cyclotron : because of the magnetic field, the photomultiplier had to be located outside the cyclotron and hence the light collection efficiency is poor, leading to a relatively high energy threshold, which is harmful because the intention is to tune the isochronism of the cyclotron with it. Alternative solutions are pursued and a large effort is also put into the automation of the isochronisation process[29].

Imaging systems such as phosphor screen allow now to measure down to pps, thanks to up-to-date CCD's. It is successfully used at MSU for profile and emittance measurements[30].

5.4 *Gas detectors*

Another way of amplification of signals is to use gas ionisation chamber. A simple and elegant system as the readout electronics are identical as their SEM BPM's is the system developed by R. Anne and collaborators for LISE at GANIL[31], used for SPIRAL, again the drawback is the energy threshold due to the windows. Tests with thinner ones are underway and profile of beams down to 2 MeV/amu are visible. They are very rugged and the intensity range is very large (pps to nA). Another device is the gas detector employing a microstrip readout for high energy beams MSGC, LNS-Catania[32].

5.5 *Semiconductors*

Semiconductors have unique properties that make them necessary although they are expensive, fragile and difficult to use. Many laboratories make a large use of them, for example GANIL/SPIRAL[29] and ATLAS/Argonne[33] through scattering for the detector protection.

5.6 *Identification*

Identification is a unique requirement for RIB's. Many fragments emerge from the source and one must be selected. It may be done :

- At low energy, with a sophisticated separator of high resolution like in LNS-Catania/EXCYT[34] or TRIUMF/ISAC[35]
- With the accelerator itself if it is a cyclotron : GANIL/SPIRAL[36] or Louvain-la-Neuve[18]
- At high energy, for example for the In-flight facilities or to separate the isobars if the cyclotron is unable to provide it.

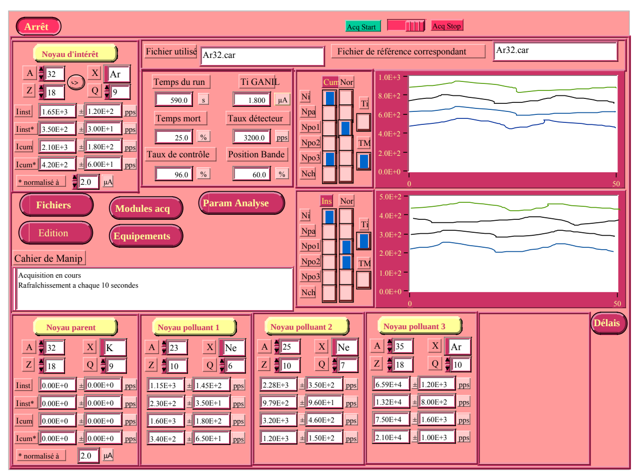

Fig. 2 : Example of Labview© page for the control of the flux of the radioactive beams (GANIL/SPIRAL/IBE)

It is necessary to check that the right specie is selected : at low energy, devices based on radioactive decays are developed while at high energy the E.ΔE method is used. It is also useful to measure the production rate and the efficiency of the post accelerator. For the first one, TRIUMF, GANIL or LNS-Catania/EXCYT are good examples, with design based on sytems that had been developed for low physics experiments : the GANIL/SPIRAL unit is interesting because a large effort has been made to ease its use with a user friendly interface[29,37], see fig. 2, while LNS-Catania/EXCYT LEBI (Low Energy Beam Imager/Identifier) one has a unique interesting feature [38] : it can perform as well the imaging and profiling of the radioactive ions by means of a CsI(Tl) scintillator plate [see fig. 3]. Of course selection of the right beam must be operated to take advantage of this property, even if separation of beams can be observed as the resolution is about 1 mm..

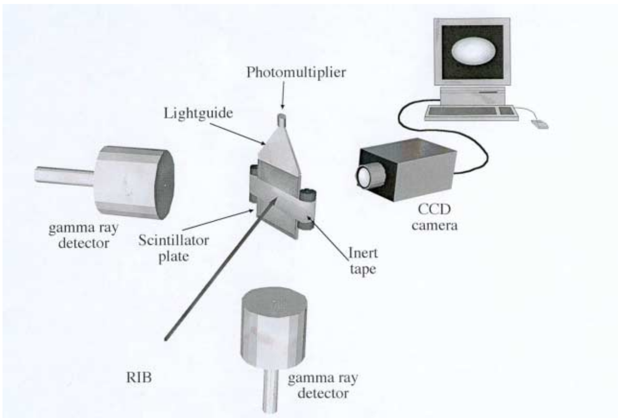

Fig 3 : Low Energy Beam Imager/Identifier (LNS/Catania)

At high energy, for example LNS-Catania/EXCYT HEBI (High Energy Beam Identifier) is composed of a silicon telescope positioned around the target[38]. This laboratory is also developing a monolithic telescope with a very thin ΔE, down to 1 μm[39], lowering the energy threshold. Another possibility is the use of a gaseous Bragg peak detector, able to work down to 0.5 MeV/u, see U. Giesen[9].

Another interesting way, if separating the isobars is impossible, is to tag them, as demonstrated by D. Shapira and collaborators at Oak Ridge[40].

6 FUTURE DETECTORS

One certainly can expect progress in many (unexpected) directions, but I would like to pick up one promising detector : the diamond, for its unique properties. Natural diamonds are out of reach but now CVD (Chemical Vapor Deposition) are available at reasonable price[41]. Advantages are the following :

- Radiation hardness
- Short carrier lifetime, then very good timing properties
- Short collection length

However, as CVD leads to non uniform polycrystalline material :

- Efficiency is not 100%
- Energy resolution is poor (50%)

It has been used, mostly at synchrotron radiation[42,43] facilities, also at CERN[44], but only at GSI[45] for high energy heavy ions. If it can withstand high level of neutrons without damage (up to 10^{16} n/cm^2), the integrated dose for low and medium energy heavy ions is not known. Tests will be perform in the near future at SPIRAL with heavy ions and at IPNO for C-clusters, as its properties make this material highly attractive.

7 FINAL REMARKS

In conclusion, no unique solution exists but solutions do exist so that the required specifications can be fulfilled, however the solutions are very much specification dependant. Some degree of trade off might be nevertheless necessary. It does not mean that it does not require a large amount of work, in particular ease of use and for protection, as mixing of beams and fragility of some detectors makes the installation of a fast beam suppressor necessary. The collaboration between accelerator and nuclear specialist must be improved to reach these goals. One should also take advantage of the continuous progress made with the nuclear physics detectors.

Unfortunately, due to the low intensity, all devices developed so far are intercepting : there is room for more ideas, as such device will be useful to obtain stability through a feedback : a system, based on a plastic scintillator, taking a small fraction of the beam has been developed at Argonne to monitor the time-of-arrival of the RIB and control the bunching system of ATLAS.[46].

The long term experience of running these devices is somehow lacking. The first generation of radioactive beam factory has come or will come soon to operation, new projects are preparing the road to the second generation facilities[47], which may require further developments of diagnostics systems as production will be so expensive that no mistake will be allowed for the tuning of the post accelerators, which may present challenges for their efficient tuning with RIB's. Since the dedicated 1997 Vancouver Workshop, no new workshop has been organized and I feel that sufficient experience has been gained so that organizing a second one would be highly profitable.

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