# VERY LOW INTENSITY BEAM DIAGNOSTICS

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Beam diagnostics measurements are a topic item in all accelerators based facilities. In particular, a big effort is in progress all over the word to develop new devices and techniques for low intensity beam measurements. Radioactive beams as well as medical facilities often need to work with beam intensities lower than $10^8$ pps in a wide range of energies. This means that standard techniques based on electrical devices (scanning wires, grids, etc.) or optical devices (scintillating screens, residual gas ionization, etc.), well suited for higher intensities, must be improved or subject to a drastic modification in order to develop a complete set of new devices able to grant high performances also at these low intensities. In this sense, also at the LNS we developed and the study is still in progress different devices able to satisfy all the requirement of the EXCYT project. In this paper the problem, the requested features and the most significant ideas will be presented.

## 1 Introduction

### 1.1 The motivation

The increasing interest for low intensity beam diagnostics started few years ago with the development of a new type of beams facility for the production of radioactive ion beams (RIB). The effort that was produced, still in progress, is mainly due to the fact that the conventional beam diagnostics is not able to furnish the same performances when the beam intensity goes down to $10^7 \div 10^6$ pps or even lower. At the same time rose also the necessity to characterize such particular beams for applications in medical as well as solid state physics. Of course, all these applications require different ions, intensities and energies for this reason it was necessary to develop a wide set of instrumentation able to satisfy all the requirements.

### 1.2 The problem

A facility for the production of radioactive ion beams is the best choice as reference for the problem evaluation. The typical variety of ions, energies and intensities involved in this application can represent the complete scenery inside which the new beam diagnostics has to be developed.

Several facilities were proposed and realized, each one with its own characteristics in terms of radioactive ion production, acceleration and transport [1]. For this reason it is possible to identify in the beam intensity the common problem, but the solution has to be found considering the specific energy and procedure that will be followed for the beam acceleration, identification and transport.

To fix the ideas, it is appropriate the effort to define an expected intensity and energy range. Starting from a general overview all around the projects it is possible to individuate the following ranges:

- beam intensity $10^5 \div 10^{11}$ pps
- beam energy $10^4 \div 10^7$ eV

The first problem is to individuate the right solution to develop a device able to work properly all over such wide ranges, the second one is the necessity to use the same device also when a high intensity stable beam is present in the same position.

### 1.3 The requirements

Once fixed the operative ranges of the low intensity beam diagnostics, it is necessary to fix also few general requirements related to the specific use of these devices. The typical parameters asked to characterize an ion beam are the current distribution, the position, the total current, the emittance and, sometime, also the time structure. A new request, typical for a RIB facility, is the unambiguous isotope identification.

To perform all these measurements in a very efficient way this set of devices has to guarantee:

- the highest sensitivity to the lower current
- the highest sensitivity to the lower energy
- the highest reliability
- the highest strength
- the highest simplicity to use and to maintain it.

Furthermore, all these requirements have to be added to the typical ones for standard beam diagnostics. It is evident that the ideal solution is not easy to achieve.

## 2 Solutions

There are two main guide-lines that are followed approaching the low intensity beam diagnostics problem. The first one, based on the performances improvement of standard techniques, consists of a deep investigation and analysis of the typical limitations of the standard devices. The second one is based on the evaluation of using particle detecting techniques very well proven foı sensitivity and precision in nuclear physics research. The main problem is the difficulty to develop such a device able to cover the full range of operations. For this reason a realistic solution is represented by two different sets of devices with an overlapping operative range.

### 2.1 Standard techniques

The number of devices nowadays available to do standard beam diagnostic is very big and they satisfy any kind of requirements. The simplest way to list all these devices is to group them from the point of view of the technique which are based on:

- secondary electrons emission (wire, grids, etc.);
- light emission (screen, fiber, etc.);
- gas ionization (residual, chamber, etc.);
- charge induction (pick-up, transformer, etc.);
- others.

Typical advantages are the simplicity in their structure and use. The reason of that is because they were developed mainly looking the fact that the procedures to accelerate and transport a beam from the source to the experimental point have to be performed by people (the console operators) that not necessarily are expert of particle detecting techniques.

The main limitation to the use of standard techniques also for low intensity beam diagnostic is the low signal-to-noise ratio. With the exception of the ionization chambers, extensively used also as nuclear physics detectors, all the others techniques have to be subjected to a deep revision in order to increase the general performances toward the lower limits. The items that drive this revision are: the research for new materials (as sensor) and the electronics improvement. For the material research the main items are:

- higher conversion efficiency;
- higher collection efficiency;
- lower noise;
- higher radiation hardness.

For the electronics improvement the main items are:

- lower electronic noise (cables, connectors, contacts, components, etc.);
- lower electromagnetic noise (shielding, grounding, etc.);
- higher signal first amplification;
- improving the read-out electronics;
- higher radiation hardness;
- other.

The devoted effort has to be as much as possible. The goal is to lead the minimum sensitivity down to $10^7 \div 10^5$ pps. In this way it will be possible to match the typical highest limit of the nuclear detectors.

### 2.2 Nuclear techniques

Generally speaking, the meaning of this category is that the typical instrumentation and techniques used in nuclear physics research can be also used for beam diagnostics if it is redesigned looking the peculiarity of this application.

Typical solutions are:

- semiconductors based detectors;
- gas chambers based detectors;
- scintillators based detectors;
- others.

Typical advantages of these devices are the sensitivity and the absolute measurements that can be performed after a suited calibration. The main limitation is the setup complexity from the point of view of its structure and use. Beam diagnostic measurements require a fast read-out of the information, on-line if possible, and at the same time well understandable by the operators. In this sense the main effort has to be devoted to:

- reduce the setup complexity;
- reduce the measuring time;
- increase the general hardness;
- increase the automated procedures;
- others.

Only if all these recommendations will be satisfy the result can be considered useful.

### 2.3 The ideal solution

All the arguments up to now discussed allow the identification of the ideal solution is sense that all its characteristics are fixed and defined. Starting from the general issue to improve the whole experimental setup performances in order to satisfy any requirement for beam diagnostic measurements, it is possible to give a list of the recommendations for such a device. It must be able to:

- measure different beam characteristics;
- cover a wide intensity range;
- cover a wide energy range;
- allow self calibration;

- minimize the interferences with the beam;
- minimize maintenance operations and price;
- maximize reliability and versatility;
- allow different measurement modes:
  - charge/current collection;
  - continuous/pulsed acquisition;
  - integration time settable;
- others.

The achieved result will be as good as bigger will be the number of features satisfied. Two more general considerations have to be taken in account. Very important is the integration of the low intensity beam diagnostics in the main control system of the facility. This important feature means that the operator in the console must operate the beam management with no regard to the beam intensity. Furthermore, the choice of the right device has to be done considering that the setup structure has to be strong enough to resist to quick intensity changes. If necessary, a suited interlock system (beam stop) has to be provided in order to protect the device in case of mistakes or faults.

## 3 Semiconductors based detectors

The semiconductors probably are one of the most popular materials category used to develop nuclear detectors. Their versatility allows the realization of different configurations very useful also for beam diagnostics. In the end of this chapter it will be reported also some applications based on a particular material, the diamond. It is an insulator but it can be considered, from the applications point of view, the most important alternative to the use of semiconductors.

### 3.1 Silicon based detectors

To state the reason for the wide use of the silicon as particles detector the best and the easiest way is to list its main characteristics:

- the mean energy to produce a pair is 3.62 eV;
- well suited for different configurations;
- good timing performances;
- medium price.

Unfortunately its radiation hardness is very low. This aspect limits its use for beam diagnostics; in particular, it can be used only in single particle counting mode and, in any case, great care has to be devoted to protect it.

Silicon detectors can find useful applications for very low intensity beam diagnostics. Silicon micro-strips, for example, can be used as beam profile and position monitor. The sensitivity and the spatial resolution (higher than 100 μm over a $10\times10$ $cm^2$ area) are very high, but the electronics and the price are very expansive. Much more suited is the application for isotope identification [2]. A thin Au target is used and a silicon telescope is positioned at a suited angle in order to match a suited scattering counting rate. The ΔE-E information allows the isotope identification. The operative energy range depends by the silicon and dead layers thickness.

### 3.2 Germanium based detectors

This very sophisticated kind of detector is mainly used for high resolution gamma ray spectroscopy. Its main characteristics are.

- the mean energy for a pair production is 2.96 eV;
- operating at 77 °K;
- very low radiation hardness;
- very complex experimental setup;
- very high price.

It is obvious, from this brief description, that such a detector has several limits for beam diagnostics application but, for a specific use, can be very useful. For example, it is a powerful tool for very rare radio-isotopes identification [3]. The main advantage of this setup is that implanting the radio-isotope at very low energy it is possible its identification just after its production, allowing an efficient tune of the transport line avoiding any beam contamination.

### 3.3 Diamond based detectors

The operating principle of this isolating material is the same of the semiconductors one. Its main features are:

- the mean energy to produce a pair is ~ 13 eV;
- the collection length is 50 ÷ 100 μm;
- very good radiation and power hardness;
- very good timing performances;
- versatility for different configurations;
- high price.

Nevertheless the higher energy to produce a pair, an important advantage with respect the semiconductors is the high energy gap that strongly reduces the noise. The strength of this material allows its use with high intensity as well as low intensity beams. The very short collection length, depending by the nature and density traps, determines very high performances in terms of spatial and time resolution. Can be used in pulses counting mode, for very low beam intensities, as well in current mode looking the continuos component of the signal produced by high intensity beams. An interesting application is the use of diamond film with 100 μm pitch micro-strips [4]; this setup allows the beam profile and position measurement.

The increasing interest on such a material is due to the advanced techniques nowadays available for the production of synthetic diamonds at realistic prices. The CVD (Chemical Vapor Deposition) technique allows the production of very thin diamond films of some centimeter size; the possibility to realize wide homogeneous layers with controlled impurity characteristics, justifies the big effort that is devoted to test new devices for beam diagnostics.

## 4 Gas based detectors

Many kinds of detectors are based on the ionization produced by a charged particle crossing a gas volume. The gas can be used to fill a chamber with thin entrance and exit windows, or can be the residual gas itself contained along the beam pipes used to transport the beam.

The most famous gas detector is the gas chamber; widely used as particle detector, it found many applications also for beam diagnostics. Its versatility in terms of dimensions and shapes allows to develop a variety of setups well suited for beam diagnostics applications. The signal is produced by the energy loss into the gas and its amplitude depends by the gas pressure and by the collecting electric field. The mean energy to produce a pair is about 30 eV, depending by the gas. The gas chambers have several very important features:

- very good radiation hardness;
- energy loss and charge multiplication effect;
- very good sensitivity;
- versatility for different configurations;
- medium price.

Different configurations can be developed, depending by the application, to improve the gas chamber performances. The most interesting configurations for beam diagnostics purposes are the wire chambers and the micro-strips chambers [5]. Both chambers were developed to improve their sensitivity; the signal produced by the primary ionization is further amplified by the electron avalanche due to the high intensity electric field close to the anode (the wire or the micro-strip). The main advantages of these setups are the sensitivity and the spatial resolution. Particular interest is devoted to the micro-strips chambers because the lithographic procedure to realize the strips on a suited substrate (typically glass) allows to obtain 100 ÷ 200 μm (the pitch) of spatial resolution. Also the chamber size can be reduced as well as the setup complexity.

Two very interesting devices were developed at the INFN-LNS to measure the beam profile [6] and for particles identification [7]. Both are based on the use of a 5×5 $cm^2$ glass plate with 200 μm pitch of Au strips positioned parallel with respect the beam direction and the collection field perpendicular with respect the beam direction. To measure the horizontal or the vertical beam profile the strips are parallel with respect the beam direction; for particles identification are positioned perpendicular with respect the beam direction. The whole setup structure, very simple and light, can be easily inserted or removed, through a suited actuator, to intercept the beam.

### 4.1 Residual gas detectors

The ionization produced by the beam interaction with the residual gas contained along the beam pipes can be used to measure several beam properties without any interference with the beam itself. Generally and especially with low intensity beams, the ionization events are very rare then it is necessary some signal amplification.

The typical setup foresees a charge collecting field perpendicular with respect the beam direction and an electron amplifier, generally a micro-channel-plate (MCP), to collect the charges. The common use of the MCP is due to the fact that for each charge hitting its surface it furnishes an electron multiplication of suited amplitude, depending by the stages number, that can be easily acquired.

The main advantage of this detector is that no interaction with the beam is required, for this reason can be used without interference with the beam operations and there are no problems for the radiation damage, on condition that it is prevented from the direct beam interaction. The MCP choice depends by the application; several model with different characteristics and performances are available.

#### 4.1.1 MCP with electric readout

The meaning of a MCP with electric readout is that the electric readout signal coming from the collecting electrode, the anode, is directly acquired and analyzed. This system, in different configurations, is very useful for both transversal and longitudinal beam profiles.

To measure the vertical or the horizontal beam profile, as well as the beam position, the ions collecting electrode is coupled with a silicon micro-strips plate that collects the electrons coming from the previous amplification stage; the spatial resolution is very good (0.3 ÷ 1 mm). A similar setup [8], but coupled with a 50 Ω anode is used to measure the longitudinal beam profile with a very good time resolution (100 ÷ 200 ps).

#### 4.1.2 MCP with light readout

The operating principle of the MCP with light readout is the same of the previous one; the only difference is that the electrons coming out from the last amplification stage are accelerated and sent on a scintillating screen. The light produced by the electrons hitting the scintillator can be acquired through a common CCD camera or directly through silicon strips.

A very simple setup to measure the horizontal or vertical beam profile is based on the use of a CCD camera that collects the light coming out from a quartz window [9]. The TV signal is acquired by a frame-grabber PC board. A simple program allows to show on the display the acquired image together with the beam profile and position on-line information. Regarding the camera choice, is better to use a camera with gain and shutter (integration time) control to match the whole setup sensitivity. A most sophisticated setup, based on the use of a thin carbon foil allows to reconstruct both the beam profiles in the transverse plane at the same time and with higher sensitivity.

## 5 Secondary emission based detectors

SEM based devices probably are the most diffused ones for beam diagnostics. The ions hitting the outer layer of several materials produce an electron emission that is proportional to the released energy. Because only the electrons contained in the first microns can exit from the material, the emission is a typical surface effect and it is proportional to the surface exposed to the beam.

Moving wires, grids and thin foils are commonly used to measure several beam properties. The limitation of their use for low intensity beam diagnostics is mainly due to the bad signal/noise ratio. To improve their performances it is possible to devote particular care to the material selection and to the electronic noise reduction; in any case it is very difficult to increase their sensitivity more than $10^7$ pps. To do that, it is necessary to develop most sophisticated apparatus based on such an amplification (MCP, channeltron, etc.) of the detected signal [10].

## 6 Scintillators based detectors

As the previous category, also the scintillating materials are very well known and used for beam diagnostics applications. The main advantage with respect the SEM based devices is that the wide choice of materials and light detectors allows to develop several apparatus well suited also for low intensity beam diagnostics. Very briefly, the main items for the scintillating materials are:

- fluorescent light due to the particles energy loss;
- the mean energy to produce a photon is $10 \div 100$ eV;
- good radiation hardness for the inorganic ones;
- poor radiation hardness for the plastic ones;
- versatility for different configurations;
- medium price.

The first important question concerns the material choice. It is not so easy to have a global view on the scintillating materials because of their very big number, continuously in progress with the fast improvement of the technology to produce them. A significant contribute comes out also from other sectors of the scientific research where scintillating materials are employed for completely different applications. Just to give some criteria for their selection here is a list of the most significant items:

- the mean energy to produce a photon;
- the decaying time constant;
- the photon wave length;
- the refraction index of the material;
- the efficiency of photon collection;
- the radiation hardness.

Many other properties have to be taken in account: for examples, the mechanical features as well as the hygroscope one. The very simple tables 1 and 2 [11] report only few features of the most famous organic and inorganic scintillators. Furthermore, also some amorphous materials like glasses, usually doped with rare earths elements (Tb, Gd, Ce, etc.), represent an alternative choice for radiation hardness and light emission efficiency. Looking such a wide scenario it is possible to understand that each particular application requires the use of the right material.

Table 1: main organic scintillators properties.

| type[1] | photons/keV | index | $\tau$ (ns) | $\lambda$ (nm) |
|---|---|---|---|---|
| Anthracene (c) | 20 | 1.62 | 30 | 447 |
| Stilbene (c) | 10 | 1.63 | 4.5 | 410 |
| NE 102 (p) | 13 | 1.58 | 2.4 | 423 |
| NE 110 (p) | 12 | 1.58 | 3.3 | 434 |
| NE 213 (l) | 16 | 1.51 | 3.7 | 425 |
| NE 311 (l) | 13 | 1.41 | 3.8 | 425 |

Table 2: main inorganic scintillators properties.

| Type[2] | photons/keV | index[3] | $\tau$ (ns) | $\lambda$ (nm) |
|---|---|---|---|---|
| NaI(Tl) (h) | 38 | 1.85 | 230 | 415 |
| CsI(Tl) (no | 52 | 1.8 | 1000 | 540 |

[1] Type: c-crystal, p-plastic, l-liquid.

[2] Type: h-hygroscope, f-fast, s-slow, p-polycrystalline.

[3] Index of refraction.

| | | | | |
|---|---|---|---|---|
| LiI(Eu) (h) | 11 | 1.96 | 1400 | 470 |
| BaF (s) | 10 | 1.49 | 620 | 310 |
| BaF (f) | 2 | - | 0.6 | 220 |
| ZnS(Ag) (p) | 52 | 2.36 | 200 | 450 |
| BGO (no h) | 8.2 | 2.15 | 300 | 505 |

However, a scintillator based detector also consists of a suited photo-sensor and, sometime, a suited light-guide. Once fixed the scintillating material to be used, it is necessary to match its characteristics with the proper light-guide and photo-sensor. Also for the light detector there is a wide choice of devices. Rather than a long list of the available devices (photomultipliers tubes, photodiodes, avalanche photodiodes, hybrid photodiodes, etc.) it is better to do a brief overview of the most significant applications for low intensity beam diagnostics. Profile, total current and time measurements can be easily done using scintillating optical fibers and screens.

6.1 Beam profile and position monitor

The simplest setup to perform beam profile and position measurement is based on the use of a scintillating screen that intercepts the beam; the emitted light is collected through a quartz window by a CCD camera and analyzed by a frame-grabber PC board [12]. The main limitation is the bad light collection efficiency that limits its use for low intensity beams. To improve its performances it is possible the use of more efficient scintillating screens (Cr doped alumina, rare earths plastic sheets, etc.) or collecting with the same camera the light emitted at different solid angles.

A most sensitive setup to measure the beam profile was developed for very low intensities ($10^4 \div 10^6$ pps) and energies (higher than $10^4$ eV) [13]. It is based on the use of the CsI(Tl), a very performing material in terms of light yield. A small brick of this material is positioned behind a moving slit and it is coupled with a compact photo-tube by means of a PMMA prism. The photo-tube is completely shielded by the slit itself with respect to the beam. The electronics allows both continuos and impulsive mode acquisition. The use of faster scintillators (CsI, $BaF_2$, etc.) increases the upper limit of the count rate allowing absolute measurements also with normal intensities.

The scintillating fibers offer an interesting choice for very low intensities beam diagnostics applications. The advantage with respects the previous systems is that the efficiency in the light transmission is strongly improved. Plastics as well as glass fibers can be successful used depending by the application.

A very simple setup was developed to measure the beam profile and position [14]. Its structure is based on the same idea of the moving wires profile monitor. Sensitivity and spatial resolution depend by the fiber choice. Using glass fibers the radiation hardness is higher but the mechanical strength is lower. The light collection is performed through a compact photo-tube able to work also inside the beam pipe. A special I/V converter [15] was developed to get the continuous signal component as well as the impulsive one coming from the tube. This configuration allows to do beam measurements over the widest intensity range. Another important feature is that during the measurement it only partially intercepts the beam. The only limitations are the damage produced by the power released by the beam and the outer dead layer of the fiber (only the core is scintillating); this last problem limits its functionality with respect to the lower energies. The investigation on the use of material with different time and strength performances can be very useful to realize the most suited device.

Another interesting device is the scintillating optical fibers plate. The most important features of this Tb doped glass fibers bundle are: high spatial resolution (10 μm), sensitivity (~$10^5$ pps), no light memory effect and radiation hardness.

6.2 Beam time structure and total current monitor

For this kind of applications the best choice is the use of very fast organic scintillators. The high counting rate obtainable allows, if coupled with a suited photo-sensor, to get high time resolution and absolute current measurements over a wide intensities range.

To measure the phase and the phase width of pulsed beams a useful setup is based on the use of a fast plastic scintillator [16]. The PILOT-U sensor is coupled with a photo-tube through a long optical fiber; the whole setup is mounted on a radial probe to measure the beam time characteristics inside the cyclotron [17]. The operating range is $10^4 \div 10^6$ pps. The same setup can be also coupled with a silicon detector to perform ΔE-E measurements but at lower rates ($10^3$ pps).

Total current absolute measurements can be performed using very fast scintillators after a suited calibration [18]. The short decay time of the polymeric plastic scintillators allows very high acquisition rates; they can be easily shaped in different geometry and are very cheap. The main drawback is their poor radiation hardness if used at low energies and high intensities.

## 7 Summary and prospects

It is not so easy to report a complete overview of the activities that are coming out developing low intensity beam diagnostics. The wide choice of materials, detectors and techniques involved in this field produces an increasing quantity of experimental apparatus very different in terms of performances and operating ranges. In any case, this is an encouraging situation because this means that the interest in this activity is very high as well as the number of the possible applications.

At the end of this very general overview it is possible to draw some conclusions regarding the state of art and the prospects of this activity. To satisfy all the requirements for the low intensity beam diagnostics the investigation on the use of particles detecting techniques has produced the most promising results. Gas chambers as well as scintillators based detectors represent the preferred solutions for their versatility, reliability and cost. For the next future, also the diamond based detectors will represent a good alternative.

As guide lines for this activity, few general statements come out from the experience gained during the last years.

- Necessity to reduce the setup complexity.
- Necessity to improve the integration with the control system.
- Necessity to increase the dynamic range of the sensitivity to avoid duplication of the apparatus.
- Necessity to improve the collaboration with the particle detecting, materials and electronics experts in order to develop new ideas, materials and electronics with better performances.

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