TOWARDS THE ZERO BEAM DIAGNOSTICS

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1 INTRODUCTION

Low intensity beam diagnostics is a challenge that has involved the accelerator community in the last years. The interest in this activity is due to the fact that a number of applications are based on the use of low intensity beams. The produced effort is mainly oriented to improve the performances of the conventional beam diagnostics in order to work properly also when the beam intensity goes down to $10^8 \div 10^6$ pps. A very important incentive for this activity came few years ago with the development of a new type of beam facility for the production of radioactive ion beams (RIB) [1]. The new challenge was very hard because the required sensitivity for the beam diagnostics was in the range $10^{10} \div 10^5$ pps, or even lower. The necessity to measure the beam characteristics all over such a wide range and the variety of ions and energies involved forced the development of a complete set of beam instrumentation able to satisfy all the requirements.

2 THE PROBLEM EVALUATION

A facility for the production of radioactive ion beams is the best reference to evaluate all the problems related to the low intensity beam diagnostics; the typical variety of ions, energies and intensities involved, offers the meaningful scenery inside which the new apparatus have to be developed [2]. The first items to be considered are the expected intensity and energy range. From an overview all around the projects it is possible to individuate two ranges:

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

Once fixed the operative ranges, it is necessary to fix also few general requirements related to the specific use of these devices. In addition to the typical parameters to characterize an ion beam in the longitudinal and in the transverse plane, a new request, typical for a RIB facility, is the unambiguous isotope identification. To perform all these measurements these devices have 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.

3 THE GUIDELINES

Two main guidelines are followed approaching the low intensity beam diagnostics problem. The first one, based on the performances improvement of conventional techniques, consists of a deep investigation about the typical sensitivity limitations of the beam diagnostics. The second one is based on the evaluation of using particle detection techniques very reliable for sensitivity and precision in nuclear as well as high energy physics research. It is evident that a realistic solution is represented by two different sets of devices with an overlapped operative range to perform relative calibrations for absolute measurements.

3.1 Conventional techniques

Conventional beam diagnostics is a very wide set of instrumentation: secondary electrons emission (wire, grids, etc.), light emission (screen, fiber, etc.), gas ionization (residual, chamber, etc.) and charge induction (pick-up, transformer, etc.) are the most diffused techniques. The typical advantages are the simplicity in their structure, use and maintenance. This is a very important consideration that has to be always taken in account also developing low intensity beam diagnostics. The reason of this simplicity is that they were developed mainly looking the operative procedures performed by the people (the console operators), which are not necessarily expert of particles detection techniques, that have to accelerate and transport the beam from the source to the experimental point. The low signal-to-noise ratio of a lot of these devices is the main limitation to their use for low intensity beam diagnostic. With the exception of the ionization chambers, extensively used also as particles detector, all the others techniques have to be subjected to a deep revision in order to increase the general performances toward the lower limits. This revision has to be performed following two directions: the research for new materials (as sensor) and the electronics improvement. The new materials have to guarantee:

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

The electronics improvement has to guarantee:

- lower electronic noise (connectors, contacts, cables, components, etc.);

- lower electromagnetic noise (grounding, shielding, etc.);
- higher signal first amplification;
- improving the read-out electronics;
- higher radiation hardness;

The goal is to reach the minimum sensitivity of $10^7 \div 10^5$ pps. In this way it will be possible to overlap the typical highest limit of the nuclear detectors and to perform absolute calibrations with respect reference devices.

3.2 Particles detection techniques

The typical instrumentation and techniques used in nuclear as well as high energy physics research can be used for low intensity beam diagnostics if they are modified looking the peculiarity of this application. Semiconductors, gas chambers and scintillators based detectors offer, together with other ones, a wide choice in terms of performances and versatility.

The advantages are the sensitivity, the precision 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;

3.3 The ideal solution

All the arguments up to now mentioned allow the identification of the ideal solution. A list of the recommendations for such a device is the following:

- 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;

Very important is the integration of this instrumentation in the main control system of the facility. This 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 has to be provided in order to protect the device in case of mistakes or faults.

4 SEMICONDUCTORS

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.

4.1 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 based 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 10×10 cm^2 area) are very good, but the electronics and the price are very expansive. Much more suited is the application for isotope identification [3]. 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.

4.2 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 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 radioisotope identification [4]. 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.

4.3 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 continuous component of the signal produced by high intensity beams. An interesting application is the use of diamond film with 100 μm pitch micro-strips [5]; 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.

5 GAS BASED DETECTORS

Many 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; it founds many applications also for beam diagnostics. Its versatility in terms of dimensions and shapes allows to develope 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. Very important features are:

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

The most interesting configurations for beam diagnostics purposes are the wire chambers and the micro-strips chambers [6]. Their main 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 LNS to measure the beam profile [7] and for particles identification [8]. Both are based on the use of a 5×5 cm^2 glass plate with 200 μm pitch of Au strip. To measure the beam profile the strips are parallel with respect the beam direction, while for particles identification are perpendicular. The whole structure, very simple and light, can be inserted or removed, through a suited actuator.

5.1 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 and an electron amplifier, generally a micro-channel-plate (MCP), to collect the charges. This setup has 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. Here is reported a brief description of two different techniques.

The MCP with electric readout is a detector where the signal coming from the collecting electrode is directly acquired and analyzed. This system, in different configurations, is very useful for both transversal and longitudinal beam profiles. To measure the transverse beam profile, as well as the position, the collecting electrode is coupled with a silicon micro-strips plate; the spatial resolution is very good (0.3 ÷ 1 mm). A similar setup [9], but coupled with a 50 Ω anode is used to measure the longitudinal beam profile with a very good time resolution (100 ÷ 200 ps).

The MCP with light readout is similar to the previous one; the only difference is that the electrons coming out from the amplification stage are sent onto a scintillating screen. The light produced by the electrons hitting the scintillator can be acquired through a common CCD camera [10] or directly through silicon strips. The signal is acquired by a frame-grabber PC board. A simple program allows displaying the on-line acquired images together with the beam profile and position information; is better to use a camera with gain and shutter control to match the setup sensitivity.

6 SEM BASED DETECTORS

Secondary electrons emission 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-to-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 [11].

7 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 beams. Very briefly, the main items for the scintillating materials are:

- fluorescent light due to the particles energy loss;
- mean energy to produce a photon is 10 ÷ 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. A simple way for a choice is to select them in terms of:

- 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. In literature [12] are reported the most important features of the common organic and inorganic scintillators; 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. 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.

7.1 Beam profile and position monitor

The simplest setup 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. The main limitation is the bad light collection efficiency that limits the use with low intensity beams. To improve its performances it is possible to use 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 more sensitive setup was developed for very low intensity ($10^4 \div 10^6$ pps) and energy (higher than 10^4 eV) [13]. It is based on the use of the CsI(Tl). 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 use of faster scintillators (CsI, BaF_2, etc.) increases the upper limit of the count rate allowing absolute calibrations with normal intensities.

The scintillating fibers offer an interesting alternative. 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]. It is based on the same idea of the moving wires 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 measurements over the widest intensity range. 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 at the lower energies.

7.2 Time structure and total current monitor

For this 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 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. 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 measurements can be performed using very fast scintillators after a suited calibration [17]. 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.

8 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 produces an increasing quantity of experimental apparatus very different in terms of performances and operating ranges. In any case, this is an encouraging situation meaning that the interest 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.

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