Low-energy/low-intensity beam diagnostics detectors: experience at INFN-LNS

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Abstract

In the framework of the interest in radioactive ion beam facilities, as well as in low energy ion traps, special diagnostic tools are needed in order to cope with low and very low intensity beams, sometimes also at very low energy. Particle detection techniques seem attractive under several aspects. In this paper we describe the main features of devices that we have tested throughout several years, as well as of those we are currently employing, at the EXCYT and FRIBS facilities at INFN-LNS.

INTRODUCTION

Recently an increasing interest has come out around many applications of particle beams sharing a common feature, namely the low intensity of the produced ion beams. Examples of such applications are the production of radioactive ion beams (RIB), facilities for low energy ion storage/trapping, low energy antiproton facilities, the cancer therapy by means of protons and ions.

Sometimes one might also wish to handle very low energy beams, thus complicating the already difficult task of a reliable beam diagnostics. Moreover, sometimes the need arises for single particle counting, hence the ideal device should be able to operate in two, partially overlapped, intensity regimes.

In the following a few possible ways are highlighted to borrow some hints from the nuclear detection techniques, in order to develop powerful beam diagnostic tools. Citation of work already done in this field will be helpful in this task, and for this reason we also list several interesting papers in the references section .

PHYSICAL BACKGROUND

One of the main requests for low intensity beam diagnostic tools comes from the RIB facilities. Unfortunately the produced beams may have a weak intensity, due to the small cross section for the production of several interesting nuclear species and to the obvious limitations in the primary beam intensity. A general recipe cannot be formulated since each particular species has a different cross section and lifetime: the final beam current can span several orders of magnitude, becoming critical when reaching below $\approx 10^8$ particles per second (pps), and still worsening when below 10^5 pps.

In such an intensity range the ordinary diagnostic techniques approach their intrinsic electromagnetic limitations, that are mainly due to electronic noise, that limits the attainable signal-to-noise ratio, and to the contamination of the useful signal by secondary emission of electrons from parts of the sensor exposed to the beam.

The required features, whenever possible, are: improved sensitivity, non-interceptivity, reliability, ease-to-use, robustness, this last especially regarding sudden variations of the beam intensity, operator mistakes, failures.

AVAILABLE TECHNIQUES

In order to increase the sensitivity of a beam sensor device there are two possible strategies: either reducing the noise or increasing the signal. The former should be attained by improving the electronic design and the shielding of usual devices, while the latter can be pursued by borrowing some hints from the experimental nuclear physics. In fact a nice method to increase the useful signal is to use a particle detector, that is usually sensitive to the energy released by the particle rather than to the carried charge.

Conversely, the main drawback of devices based on particle detectors is that their response is strongly dependent on the beam type and energy: we do not measure anymore the electric current carried by the beam. Moreover, the thickness of possible dead layers can introduce an energy threshold on the detectable beams, while the radiation hardness, as compared to the cost, is one of the most important parameters that have to drive the choice of a type of detector.

The available techniques are based on semiconductors, gas detectors, secondary emission (with physical amplification), scintillators; some further technique, like Cherenkov detectors and others, that can be used in particular cases, will not be described here.

SEMICONDUCTOR DETECTORS

The most widely used semiconductor detector is silicon. The signal in a silicon detector is due to the energy lost in it by an impinging particle, that can cross it or be stopped inside. The silicon is quite efficient in this process, since the average energy needed to produce an electron/hole pair in the depleted region is 3.62 eV. Unfortunately its radiation hardness is not high, while its cost, including the needed electronics, is a little bit expensive. Nevertheless the ease-of-use and reliability are enough to allow its use for specific applications.

Several groups have already developed and used silicon microstrip and/or pixel detectors for high energy physics experiments. They consist of a structure with typical pitch of $\approx 100\ \mu$m and thickness of ≈ 100-$300\ \mu$m; the overall size can be up to 10-15 cm. Such a device is best suited for single particle counting and tracking, even though it

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can also measure the energy deposition. Its use in current mode is obviously possible, but radiation hardness and cost impose severe limitations to it.

In particular cases a silicon detector can however represent a nice tool, as for instance the beam isotopic identification [1]. Such a device consists of a thin Au target and a silicon telescope that can be positioned around it. This method, that can be applied for not too energetic beams, allows the unambiguous isotopic identification of particles by building a typical ΔE-E scatter plot. An example of such a telescope, built at INFN-LNS, is shown in Fig. 1

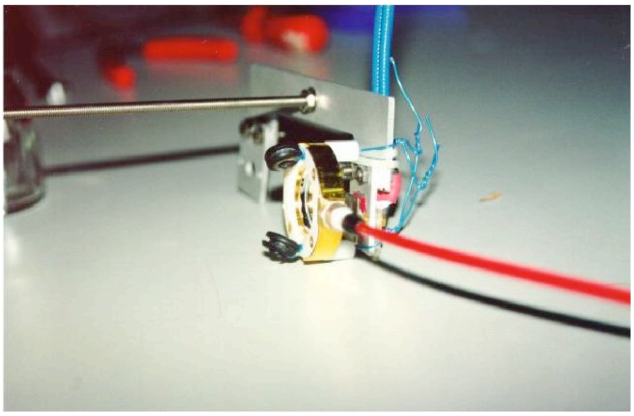

Fig. 1: example of a silicon telescope used at INFN-LNS for beam identification.

Quite recently we started to employ a 5x5cm^2 position sensitive silicon detector, readout at the four corners and from the back electrode. By using a well suited algorithm we are able to remove the position non-linearity and reconstruct the transverse profile of the beam. In Fig. 2 we show the reconstruction of the transverse beam profile after crossing a pepper-pot mask.

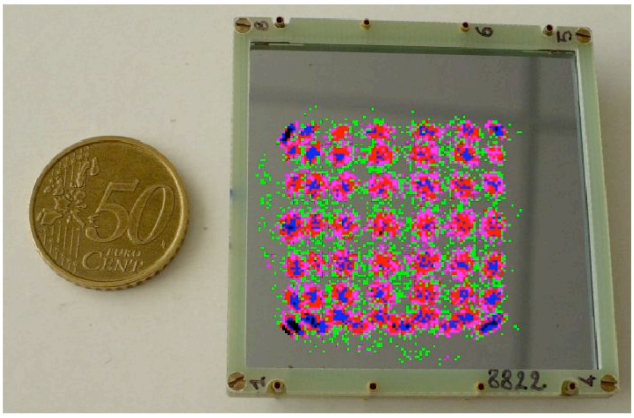

Fig. 2: a 5x5cm^2 position sensitive silicon detector. Superimposed to the picture one can see the linearized plot obtained after sending the beam on the sensor across a pepper-pot mask.

Another well known semiconductor detector is germanium, generally used as very high resolution gamma ray detector. Due to the very poor radiation hardness and to the high cost these detectors are completely unsuitable for particle detection. Nevertheless, in spite of their complex usage and low reliability as beam sensors, they can be successfully employed to identify very weak RIBs by means of their gamma decay “fingerprints” [2], [3].

DIAMOND DETECTORS

Unlike semiconductors diamond is rather a good insulator, even though its operating mode resembles the semiconductors. The detection principle is still the creation of pairs by energy loss, but in this case the noise is strongly reduced because of the high energy gap. The average energy to create a pair is ≈18 eV, the radiation hardness is very good since it is not a diode that is damaged because of the displacement of its dopants. Moreover, the thermal conductivity of diamond is better than copper, hence it can tolerate a high power deposition. So far the chemical vapour deposition (CVD) technique allows to produce good diamond films, that however are not monocrystalline: this implies that the charge collection length is limited by crystal defects that trap charges.

Nowadays detectors with 50-100 μm collection length are available, that can be usefully exploited both in pulse counting mode and in current mode. In addition the high electron mobility and dielectric constant, together with the short collection length, make the signal development very fast, thus allowing to build also segmented devices with <50 ps time resolution [4] and capable to sustain up to 10^8 pps count rate in pulse counting mode [5].

An example of the performance of CVD diamond films in current mode readout can be found in [6], where the authors report on tests made with a strip electrode structure of 100 μm pitch. The overall cost of this technique is still high, even though it is expected to decrease in the next future; concerning reliability and ease-of-use the technique looks promising.

Recently thin monocrystal diamond detectors have become available on the market, even though their cost is still quite high.

GAS DETECTORS

Gas Chambers

Gas detectors are very well known since many years, and they have been developed in a wide variety of shapes and sizes. The signal in a gas detector is due to the energy lost by a particle in a chamber filled with a suitable gas. The average energy to produce an e/ion pair is generally of the order of 30 eV.

The radiation hardness is good since the gas is continuously flowed through the chamber, and the cost is usually cheap. Several operating modes are possible for gas detectors, depending on the pressure and on the electric field applied to the electrodes.

The main techniques mentioned here as suitable for beam diagnostics purposes are the ionization chamber and the wire chamber. Both of these detectors have been employed in a large number of nuclear physics experiments so far, and they are used as beam counters and/or trackers in several laboratories. They can be used in pulse counting and in continuous mode, starting to lose linearity around an incoming rate of ≈10^9 pps due to space-charge effects.

A remarkable improvement in gas detectors has come years ago with the introduction of the microstrip gas chamber (MSGC) [7]. Such a detector is based on the same principle of the wire chamber, with the difference that the wires (cathodes and anodes) are lithographically drawn and lay on the same plane. The main advantages are:

- high precision, with a pitch of ≈100-200 μm;
- simplification of the overall mechanical structure.

A prototype beam profile monitor employing an MSGC has been tested at LNS with remarkable results. It is based on a 5x5 cm^2 glass microstrip plate used as collecting electrode of a small ionization chamber. The collecting field is perpendicular to the beam direction, while the strips are parallel to it. It can be inserted/removed on the beam path and the signals, collected strip by strip, give rise to the beam profile (Fig. 3).

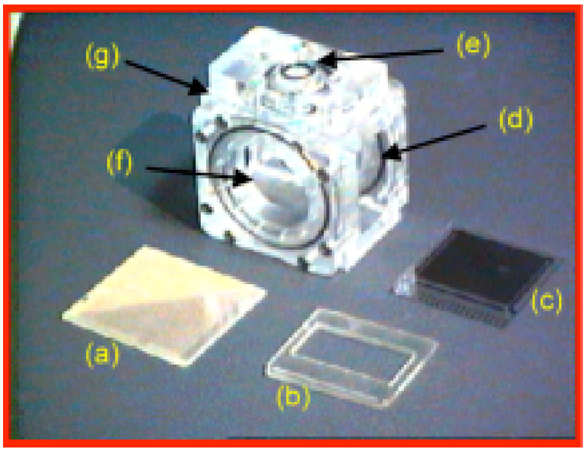

Fig. 3: a prototype gas detector, developed at INFN-LNS, based on MSGC. (a) electrical connection board ; (b) holding frame; (c) the MSGC plate; (d) the three parts (a+b+c) are sandwiched and installed here; (e) gas in/out; (f) mylar window; (g) chamber body.

A variation of this technique, still with transverse collecting field but with strips perpendicular to the impinging particle direction, becomes a multilayer ionization chamber. Such a device used in single particle counting can replace a silicon telescope in applications where low energy beams are involved: Z values up to 10 have been recently identified with an energy threshold around 200 keV/amu (< 1 μm silicon equivalent) [8].

Residual Gas Detectors

These detectors are based on the ionization produced by beam particles on the residual gas along the beam pipe. The very few ionizing collision events need some sort of physical amplification. What is generally used is a microchannel plate (MCP) onto which the electrons (or ions) produced are driven by a transverse electric field. Care has to be taken to prevent the MCP from being accidentally hit by the beam, that would destroy it.

MCP: Readout by Electrodes

This kind of device is rather sensitive and is mainly used in pulse counting mode. It can be employed for transverse beam profiling, with the collecting electrodes shaped in separate strips parallel to the beam [9], [10]. It is also used successfully for longitudinal beam profiling, due to its good timing resolution (≈100 ps) [10]. An application of such a device was proposed, where both ion and electron drift times are recorded, also allowing to identify the ion species drifting toward the electrodes [11].

An example of this application is shown in Fig. 4, where we report a Time Of Flight spectrum used at INFN-LNS to identify a ^{8}Li beam.

MCP: Readout by Scintillating Screen

An interesting device is made of an MCP coupled with a phosphor scintillating screen. By means of a suitable choice of the voltages applied to the MCP electrodes, the output electron cloud can be further accelerated toward the screen, thus producing a visible image that can be observed by means of a usual CCD camera. The device can easily reconstruct the beam trace across the active field of the sensor and the image is best acquired with a frame grabber that also allows a digital analysis [12].

A more complicated configuration can also reconstruct the 2D transverse profile of the beam, by exploiting two different field cages, as shown in [13].

SECONDARY EMISSION DETECTORS

These detectors exploit the emission of secondary electrons from several materials when hit by energetic particles [14], [15]. To this aim wires and/or thin foils are generally used, choosing a material with a sufficient mechanical strength and capable of withstanding or dissipating the foreseen power deposition. The generally used foils are made from carbon or aluminium, the wires from tungsten.

In case of low intensity beams the number of electrons produced is very low - usually from few units to two hundred per incident ion [15] - thus a physical amplification process is needed to get a useful signal.

This technique, exploiting an MCP to amplify the number of electrons, is well known since many years in heavy ion physics for time of flight measurements [16], and has also been used for longitudinal ion beam profiling [17], see an example in Fig. 4. Other devices have been proposed using a channeltron for integral beam current measurements [11] or an MCP plus scintillating screen combination to get an immediate 2D transverse profile image by means of a CCD camera and a frame grabber [12].

SCINTILLATORS

Scintillators are well known to the physicists since a long time. Their basic property is to emit as light part of the energy deposited by an impinging particle. A large family of polymeric plastic scintillators is today available on the market, and they are usually rather cheap and easy to be produced in any shape. Plastics can be practically chosen within a wide spectrum of characteristics like decay time, emission wavelength, attenuation length, etc.

Their main drawbacks are the poor radiation hardness and power dissipation; so special care should be taken when using a plastic scintillator in a high counting rate environment. The usage of a plastic on the beam is practically limited to a low intensity regime and for short time intervals: after irradiation with $\approx 10^{10}$-10^{12} particles/cm^2 all hydrogen atoms are completely ejected, and only carbon atoms are left (graphite) [18].

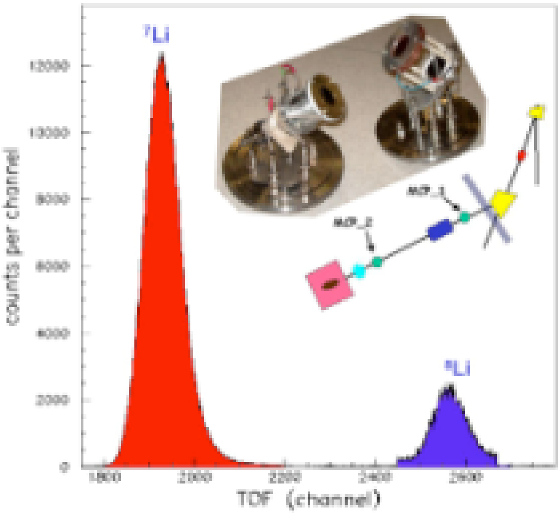

Fig. 4: example of Time Of Flight technique for online identification and tagging of the ^{8}Li radioactive beam by means of two MCPs detecting secondary electrons emitted by a thin carbon foil.

During the last years new families of inorganic scintillator crystals have come up to the attention of physicists, with rather good mechanical properties, radiation hardness, scintillation efficiency, and some of them have a surprisingly short decay time, even shorter than plastics.

Most of the currently used scintillators have an average energy to produce a scintillation photon of the order of ≈10-100 eV. The cost has large variations due to type, shape, quantity, doping, purity, but we can still say that it is cheap.

Among the inorganic scintillators we can also put some amorphous materials, like glasses, usually doped with rare earths elements like terbium, gadolinium, cerium, etc.

Concerning the light readout devices, many types of photosensors exist on the market, some of them suitable for current readout (photodiodes), some others for pulse counting (photomultipliers, avalanche photodiodes). Special devices also exist that are suitable for single photon counting (photomultipliers, hybrid photodiodes, silicon photomultipliers or SiPM).

So far the application of scintillators for beam diagnostics has been basically limited to plastics, mainly used for timing (e.g. [19]) or for integral current measurement (e.g. [20]) in pulse counting mode; the count rate limit is $I<10^6$ pps. The timing resolution of such a device can easily reach <100 ps [21] [22], and if used in shape of a scintillating optical fibre bundle it can also be used as tracker, allowing a transverse profile reconstruction [23].

A R&D activity has been conducted at INFN LNS concerning the application of scintillators to low intensity beam diagnostics, moving along different lines. The main results so far obtained are outlined below.

Scintillating Fibres

Our interest has been attracted by scintillating fibres since they allow to rebuild a scanning wire beam profiler by replacing the wire with a fibre. The sensitivity is improved since the signal is due to energy loss, the electronic noise is strongly reduced. Such a device, named FIBBS (Fibre Based Beam Sensor) is capable of sensing even the single beam particle [24]. The usage of only one fibre per direction avoids calibrations, while the fibre diameter and the step size can be varied more or less at will (Fig. 5). An example of X and Y profiles is shown in Fig. 6.

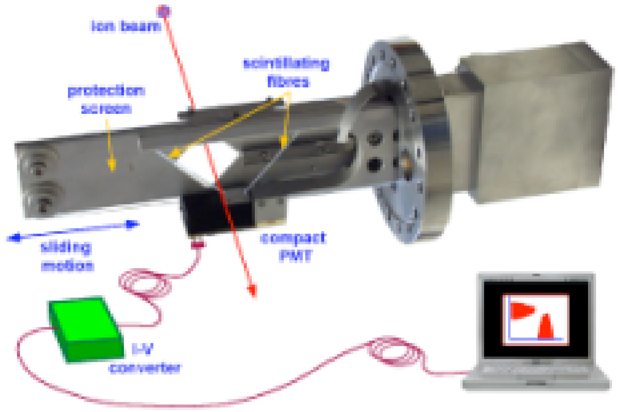

Fig. 5: the FIBBS XY beam profiler, exploiting two perpendicular scintillating fibres readout by means of a compact photomultiplier.

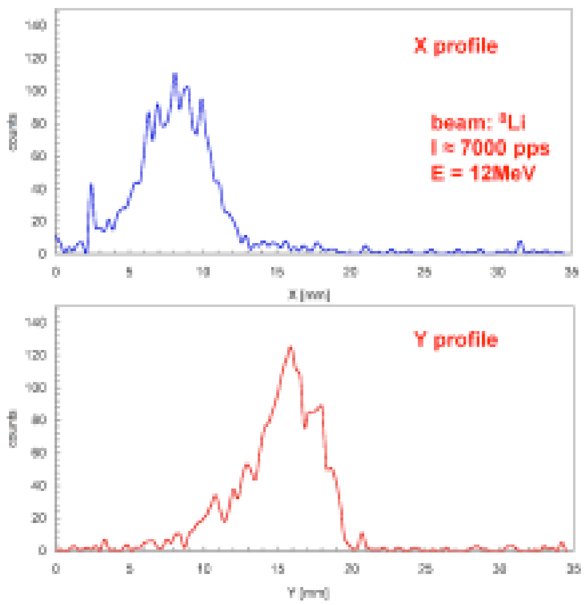

Fig. 6: example of X and Y beam profiles taken with plastic fibres, by counting particles at ultra-low beam intensity (≈7000pps ^{8}Li).

The employed photosensor is a compact photomultiplier. A special I-V converter has been developed for the photosensor readout: it allows both the pulse counting and the continuous readout modes to be simultaneously performed on two different outputs [25].

Two fibres are installed on the same moving structure, rotated by 90° with respect to each other but still connected to the same photosensor, thus allowing to reconstruct both the X and Y profiles in a single scan.

Two types of fibres have been tested so far: plastic and Tb-doped glass. The plastic fibres allow the pulse counting mode, since their decay time is short (3 ns); unfortunately they are not enough radiation hard, so they need to be used with care. Tb glass fibres are pretty harder but their decay time of 3 ms only allows the continuous readout mode. Nevertheless their light yield is good, and makes the device capable of sensing beam profiles even down to 10^5 pps integral current.

Bulk Inorganic Crystals

We have also built a scanning slit beam profiler, based on a moving slit and a small CsI(Tl) brick (1x1x0.5 cm^3). The operating principle of such a device is quite similar to the FIBBS, with a few differences. On the one hand it is completely interceptive while scanning the beam; on the other hand its overall light yield is about 50 times higher than a fibre.

The output signal is sent to the already mentioned I-V converter, in order to have both pulse and current measurements. This device has allowed us to reconstruct profiles even down to 10^4 pps integral beam current in continuous mode, and at the same time it is able to count pulses in order to have an absolute intensity calibration. A very strong point in favour of this device is that we have recently proved it is useful also for very low energy beam profiling. In fact it showed it can easily reconstruct a beam profile of 10^6 pps of $^{12}C^{+}$ ions at 50 keV [26].

Scintillating Plates

We have also developed a beam diagnostic set-up based on the direct optical inspection of the transverse profile [27]. To this aim we use some scintillating screen, directly hit by the beam, and a CCD camera that looks at it sending the images to a TV monitor and to a frame grabber system for digital analysis.

Several different plates have been tested so far, each one with interesting features and minor drawbacks. Among them it is worth mentioning CHROMOX6 (a doped alumina), NE102A, YAG, CsI(Tl).

An interesting screen type is the scintillating fiberoptic plate (SFOP): we tested thin plates made from a slice of a bundle of Tb doped glass fibres, whose light can thus be readout from the back. The light diffusion is constrained within the fibre diameter (≈10 μm), and the light yield allows to sense beam images even at 10^5 pps; the 3 ms decay time gives no evident afterglow. The SFOPs are radiation hard, but they break at high temperature; therefore they need some care when exposed to intense beams.

CsI(Tl) and SFOP proved to be the tools of choice when we want to perform precision diagnostics on very low energy/intensity beams. In particular we exploited them, for instance, when performing Deep Lithography with Ions [28]. On the one hand the SFOP allows a precision imaging of low intensity microbeams (we tested it down to a 20μm diameter collimated beam), on the other hand a CsI(Tl) plate was successfully used as scintillating imaging Faraday cup in the same application.

In Fig. 7 we show an example of transverse profile of a low intensity proton microbeam after collimating it to 150μm diameter, with a primary current of 30pA. The honeycomb structure of the SFOP is clearly visible, whereas the black dots are black fibres periodically interspersed in the plate to operate as Extra Mural Absorbers, inorder to suppress the stray light. The halo around the beam spot is due to gamma rays produced in the collimator.

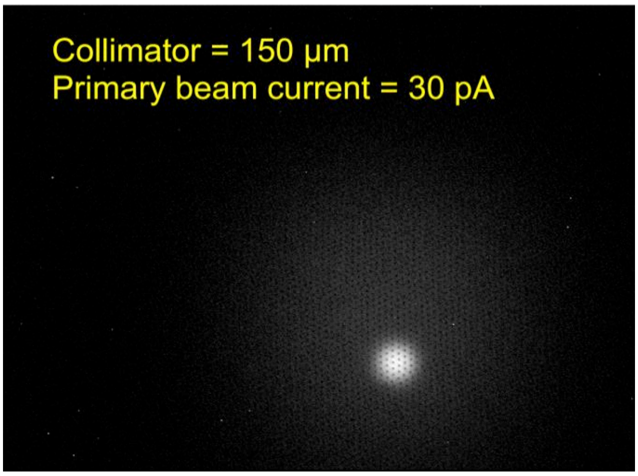

Fig. 7: transverse profile of a low intensity proton beam after collimating it to 150μm diameter. The primary current was 30pA.

THE LEBI SYSTEM FOR RIBs

The main achievement of our R&D was the design and construction of the multipurpose Low Energy Beam Imager/Identifier system, basically employed in the EXCYT unstable beams facility at INFN-LNS. It consists of a box, operated under high vacuum, capable of diagnostics on stable and radioactive beams down to ≈10^3pps and to 10keV [29]. A LEBI features a 50x50x1mm^3 CsI(Tl) scintillator plate, part of which is covered by a thin aluminized Mylar tape. In order to image a stable beam, we expose the plate directly to the beam itself, looking at it via a cheap and compact CCD camera installed outside of a quartz porthole. When imaging a radioactive beam, we use the Mylar tape to implant the beam (in order not to contaminate the scintillator). The scintillation light, in such a case, is produced by the decay products (typically beta rays) hitting the plate (Fig. 8). LEBI also features a 5x5x5cm^3 plastic scintillator, wrapped in aluminum foil and readout by means of a PMT, in order to count beta particles and identify the unstable beam by means of its half-life (Fig. 9).

Moreover, in case one wishes to perform RIB identification by means of gamma decay fingerprints, LEBI features two cylindrical hollow cups, made from thin Ergal, to allow for the insertion of two Germanium detector heads to be placed very close to the beam implantation position.

In spite of the two initially foreseen systems, so far we have built and installed thirteen LEBIs.

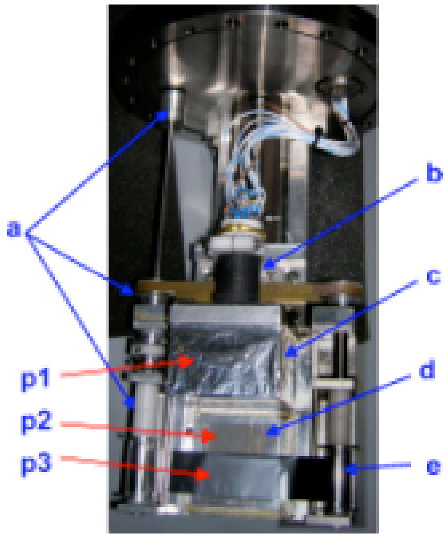

Fig. 8: the LEBI system for low energy and low intensity stable and radioactive beam imaging and identification. Shown are: (a) the tape transport system; (b) photomultiplier; (c) the plastic scintillator; (d) the CsI(Tl) plate; (e) the Mylar tape. The system can be positioned in beam into three measuring positions: (p1) beam rate measurement; (p2) imaging of stable (pilot) beams; (p3) imaging of radioactive beams.

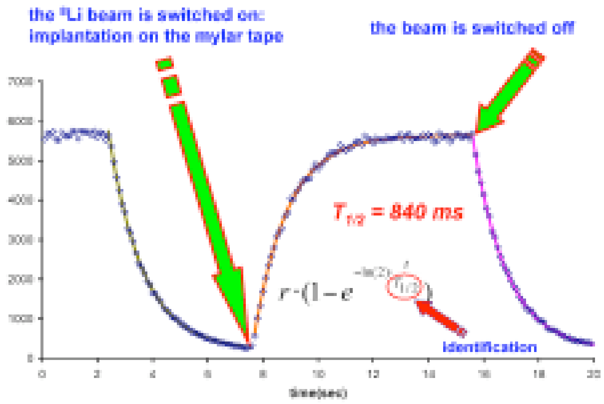

Fig. 9: identification of the ^{8}Li beam by means of its beta-decay curve.

TOWARD THE SENSITIVITY LIMITS

Recently we have started to investigate the lowest detection limits of the scintillation/imaging techniques, and found out that the CsI(Tl) screens actually have powerful performance. In particular we proved that such a screen can sense down to the fA regime, with beam energies below 100keV (Fig. 10 and Fig. 11) [30].

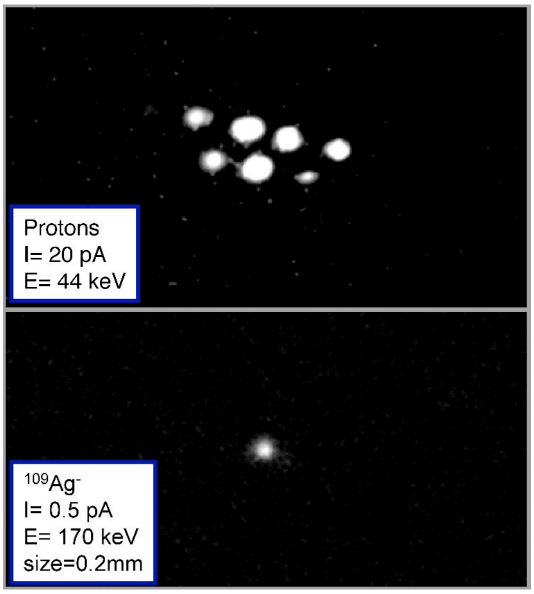

Fig. 10: sample images of very low energy and intensity proton and Silver beams detected by means of a CsI(Tl) screen and a CCD video camera. The spots are due to a pepper-pot grid placed in front of the beam, the hole size is 200μm.

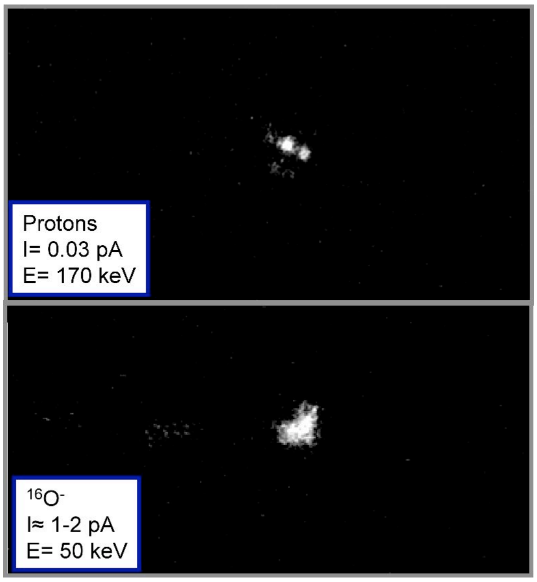

Fig. 11: sample images of very low energy and intensity proton and Oxygen beams detected by means of a CsI(Tl) screen and a CCD video camera. The spots are due to a pepper-pot grid placed in front of the beam, the hole size is 200μm.

We have also been able, by means of this technique, to detect and identify the impurities and/or previous species accelerated by our ion source months before, both in elemental and molecular form [30].

We have also become involved in the test of a possible diagnostic technique for low energy antiproton beams, based on scintillators. For this reason we have set up a test configuration employing a plate holder with three different scintillators (Tb-glass SFOP, CsI(Tl), YAG), looked at by means of a high performance 14-bit CCD camera. The CCD can be cooled down, in order to reduce its noise.

The preliminary results, obtained with low energy and very low intensity proton beams, are quite promising for CsI(Tl) and also for the SFOP. As to the YAG, in spite of its much better radiation hardness, the light yield was disappointingly low [31].

In Fig. 12 we show a few preliminary sample images, taken with this setup, with a CsI(Tl) screen (upper plots) and a SFOP (lower plots).

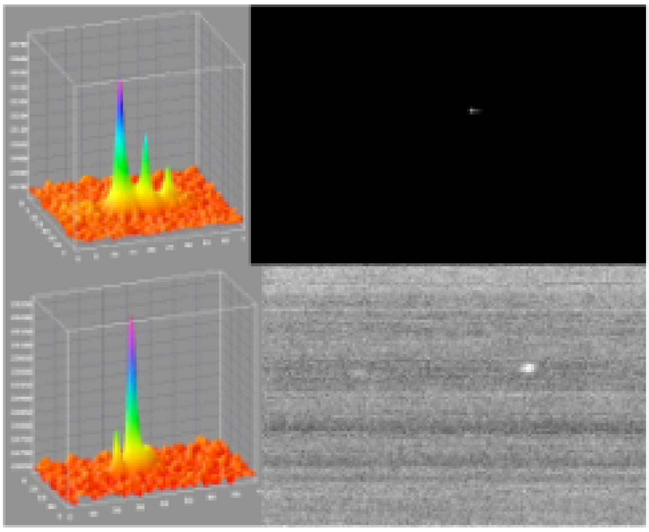

Fig. 12: attenuated (by means of a pepper-pot grid) proton beam images taken at E = 200keV, I ≈ 2.5fA [5pA/2000], $t_{exposure}$ = 20s. Upper plots: CsI(Tl) screen. Lower plots: Tb-glass SFOP. The still camera features a 14-bit cooled CCD.

SUMMARY AND CONCLUSIONS

Several techniques have been explored in order to help in ion beam diagnostics at low intensity, and the know-how already available with particle detectors has been quite useful in this respect. The envisaged devices, mainly based on semiconductors, gas detectors, secondary emission and scintillators, seem capable of satisfying most of the requirements so far needed. However the most promising techniques seem to be inorganic scintillators and doped glasses, even though many ad-hoc devices based on other types of detectors are (and will be) helpful. It is worth to be mentioned that beam imaging by means of Tb-doped glass or CsI(Tl) plates appears as a very promising technique for beam diagnostics a very low energy and intensity.

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