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To cite this version:

L. Boy, D. Bibet, M.H. Moscatello, B. Laune, a C. Mueller. Cyclotron isochronism tuning by phase measurements with a fast scintillator at very low beam intensity. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1997, 399, pp.195-201. 10.1016/S0168-9002(97)00925-X . in2p3-00000279

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The goal of this full scale experiment was to tune the cyclotron at very low intensity ($10^2 - 10^3$ pps). A special low intensity probe for phase measurements was built and tested in the GANIL SSC2 cyclotron. It is based on a fast plastic scintillator and mounted on a radial probe. Using this detector the phase extension and the central phase of the beam were measured and the cyclotron isochronism was accurately tuned.

Key words: Cyclotron, isochronism, plastic scintillator, phase measurements.

1 Introduction

The SPIRAL radioactive ion beam facility [1,2] under construction at GANIL will accelerate extremely low intensity radioactive ion beams (down to a few pps). These radioactive ions will be produced by the ISOL method [3] : after diffusion from the production target and ionisation in an ECR source, the ions will be transported, to be axially injected in a cyclotron, by means of a beam line which includes a relatively modest mass selection (1/200 for a 80 π mm.mrad emittance). The cyclotron will act as a powerful mass separator (1/2000 to 1/4000, according to the harmonic mode), but many pollutants will still be present during part of the acceleration. The low intensity of the beams and the mixing of several species imply special tuning methods [4] and associated diagnostics.

For a maximum energy gain in an isochronous cyclotron, the central phase of the beam must be such that the particle crosses the axis of symmetry of the dee when the RF voltage is zero. Thus the measurement of the beam phase versus the radius is an important and basic tuning procedure. Detection of

Preprint submitted to Elsevier Preprint *22 May 1997*

low intensity beams in a cyclotron was already made in nuclear physics experiments [5,6]. We built a similar but simpler low intensity detector based on a plastic scintillator, and mounted on a radial probe. This probe was successfully tested, and the results of this experiment are described below.

2 Experimental set-up

2.1 Description of the probe

For very low intensity, classical diagnostics cannot be used. One has to employ nuclear physics detectors, such as semiconductors, ionisation chambers, microchannel plates or scintillators. The plastic scintillator has been selected because it is rather robust, easy to use, cheap and has a good time resolution. As it is difficult to directly convert light into an electric signal in the cyclotron because of the high magnetic field, we used a light guide followed by an optical fibre in order to direct the light out of the cyclotron, where the photomultiplier can be easily shielded (see figure 1). The drawback of such a long optical device is a poor transmission, that can be critical if the energy of the particle is too low to generate enough light.

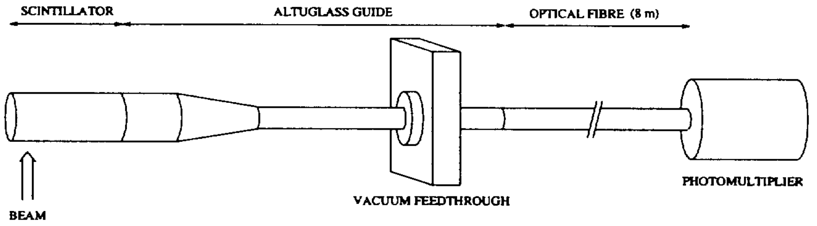

Fig. 1. *Layout of the probe*

2.1.1 Scintillator

We selected the PILOT-U plastic scintillator for its good time resolution (1.4 ns decay time). However, its energy resolution being rather poor it was necessary to measure the radial probe position, which in a cyclotron is related to the energy of the particle. It was also impossible to have access to the energy dispersion of the beam. The wavelength of the maximum emission (391 nm) is fully compatible with the photocathode spectral sensitivity and the fibre transmission efficiency is reasonable. In order to stop and collect all the ions (from ^{12}C to ^{238}U in the CSS2), we used a cylindrical 1.8 cm-diameter, 4.0 cm-long scintillator. To get a stable counting rate, we chose a plastic length larger than the turn separation.

2.1.2 Lightguide and fibre: optical transmission

We used a 20 cm long Altuglass guide for the vacuum feedthrough and to make the adaptation of the 18 mm scintillator diameter to the 8 mm fibre diameter. To pass through the yoke of the magnet, we selected a 8 m-long LUMATEC 300 optical fibre. This liquid core fibre has a transmission efficiency of about 39 % and allows a larger acceptance angle, a higher transmission and a smaller bending radius than bundle fibres. The relative acceptance angle between the guide and the fibre gives a 34 % transmission then ensuring a 13 % transmission through the fibre.

We tried to optimise the shape of the Altuglass guide by measurements and simulations. Transmission measurements for different guide geometries gave no significant difference. We also measured the transmission of the guide with mylar and aluminium coating without improvement of the efficiency; so we chose to leave the guide uncovered.
We also made a simple two-dimensional numerical simulation to estimate the total optical transmission. Figure 2 is a fifty-photon raytracing simulation. Light is randomly created on the top left of the scintillator in a 2 mm circle corresponding to the range of the 60 MeV/u ^{86}Kr beam used in the experiment. We drew half of the device, and photons crossing the symmetry axis are reflected according to Descartes' law. The total simulated transmission from the scintillator to the photomultiplier window has been found to be around 1.8 %, and assuming an instantaneous light emission the simulated time dispersion is about 0.2 ns with an average number of reflections on the Altuglass guide/air interface of about 4. However as the light generation is out of the symmetrical axis a three-dimensional simulation would be more realistic and our simulated values are slightly overestimated.

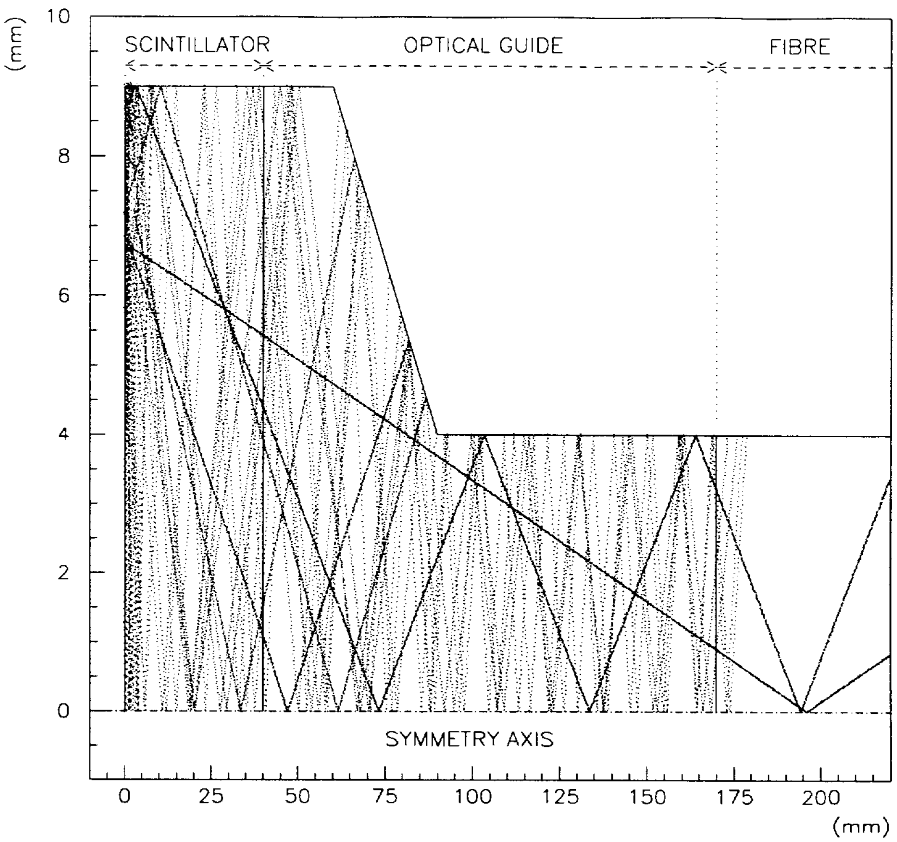

Fig. 2. *Photons raytracing simulation in the light guide. Light is created on the left top of the picture and is reflecting according to Descartes' law. In this particular case only two out of fifty photons could enter the fibre on the right.*

2.1.3 Photomultiplier

We attempted to locate the photomultiplier as close as possible to the scintillator in order to minimise the losses, that is in the cyclotron vacuum and magnetic field. We tested two photomultipliers specially designed for magnetic field: a microchannel plate based MCP-PMT [7] and a fine mesh HAMAMATSU R5505 PMT [8]. Unfortunately, the PM axis must be parallel to the magnetic field, or with a slight angle. Experiments performed in a magnetic field showed that the maximum tolerable angle is about 20 degrees, too small to allow the use in the limited cyclotron gap. For the experiment, the HAMAMATSU photomultiplier was located outside of the cyclotron at the end of the optical fibre.

2.2 Acquisition and data analysis

Acquisition was performed by two ADC's, for two-dimension histograms, and a PC computer. We used a HPC-2 card [9] associated with a new logical NIM module [10] developed by the SEP-IPN. Two 14-bit one dimension histograms and one 18-bit two-dimension histogram were simultaneously available. Time measurement with respect to the RF frequency provides the beam phase on one channel, while either the probe position or the energy are available on the second one.

2.3 Beam characteristics

The test was carried out on one of the four radial probes of the second GANIL separated sector cyclotron (SSC2). The experiment was performed with a $^{86}Kr^{34+}$ beam, the energy ranging from 8 to 60 MeV/u (from injection to extraction). The RF frequency was 11 MHz (1 RF degree corresponding to 0.25 ns) and the harmonic mode 2. The 500 nA / 10^{11} pps nominal intensity was reduced down to 10^{2-3} pps using three pepper pots (1/5, 1/25, 1/50) and limiting the radial emittance with slits from 8 down to 0.1 $\pi mm.mrad$. With this intensity there was much less than one particle per bunch, and so an extremely low pile-up probability for two ions. An additional reduction with an energy spread limitation was also possible and enabled us to reach a few pps.

3 Results

3.1 Resolution of the probe

Because of electronic limitation the maximum counting rate was 10^4 pps but scintillators can withstand higher rates. During this test a total number of about $2 * 10^9$ ions were detected without damaging the detector.
As mentioned earlier, the energy resolution of a plastic scintillator is rather poor and we measured a 12 % rms energy resolution. With such a low resolution the energy information is not usable in a phase law diagram and is only useful for light ions in an identification process. We then used the radial probe position to isochronise the cyclotron.

The time resolution is sufficient to measure the average phase and the phase extension of the beam. Figure 3 shows two phase measurements at injection and extraction radius.

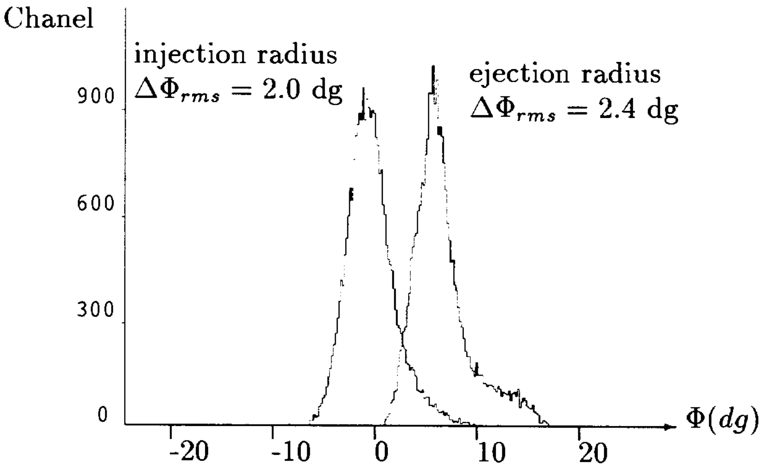

Fig. 3. *Phase measurements in CSS2 at injection and extraction radii*

3.2 Light production and collection efficiency

For heavy ions, the light production depends not only on the energies but also on the atomic number : calibration procedures are necessary. Those were undertaken by different authors : F. D. Becchetti [11], M. A. McMahan [12], and M. Buenerd [13]. It turns out that :

(i) for $E \geq 100\ MeV$, the light output is linear with E and decreasing with increasing Z
(ii) for $E \leq 100\ MeV$, it is roughly quadratic in E and still Z dependent
(iii) for light ions and low energy there is an additional A dependence.

The measurements given in arbitrary units were normalised using the response functions given by the manufacturer of the scintillator for electrons and protons, assuming that for electrons there is no quenching effect and that the electron conversion factor is 3 % [14].
Following this procedure we calculated a 1.4 % transmission for our apparatus, close to the estimated 1.8 % (2.1.2). On figure 4, we plotted the photon yield

as measured for Kr by the different authors, normalised as described earlier, and we added our measurements, assuming a 1.4 % transmission.

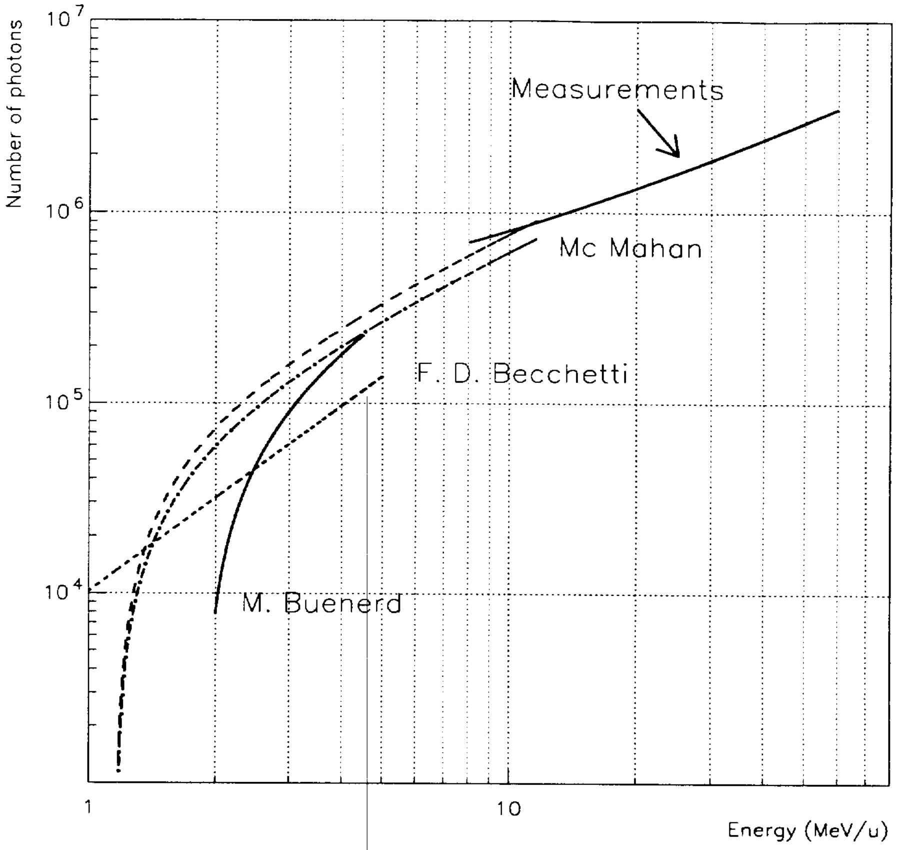

Fig. 4. *Number of photons produced by one Kr ion in a plastic scintillator after F. D. Becchetti, M. A. McMahan, and M. Buenerd. Also indicated are our measurements*

3.3 Cyclotron isochronism tuning

The phase versus radius measurements were made in flight with about 10^3 pps. With such an intensity it took about two minutes to acquire the data necessary to control the isochronism over a two-meter scan from the 1.2 m injection to the 3.2 m extraction radius. It has been checked that the central phases were identical to those obtained at high intensity with the thirteen capacitive probes [15].

3.3.1 Trimcoil optimisation

These fixed capacitive probes do not cover the last turns as it is the case for the low intensity radial probe. Thus, with this detector, we can monitor the phase and act on the trimcoils in order to correct the isochronism at the largest radii. Figure 5 shows a phase versus radius measurement for two trimcoil current optimisations: the cyclotron isochronism was first tuned with the capacitive pick-up probes, the intensity was reduced, the phase measured with our apparatus (on the top of figure 5). This data was used to calculate a trimcoils field correction, which was implemented; data were again taken and they are shown on the bottom of figure 5.

3.3.2 Main magnetic field variations

Several variations of the main magnetic field were made, figure 6 is a radius versus phase plot with a main coil current variation of 1.5 A which corresponds to a magnetic field variation of $3.6 * 10^{-4}$. With such a variation the beam reaches a maximum radius of 2.4 m before being decelerated. Figure 7 is the corresponding 100-particle numerical simulation. A precession effect (turn stacking) can be observed on both pictures.

4 Conclusion

We have shown that this kind of diagnostic is simple, reliable and easy to use. As the SPIRAL energy ranges from 1.7 to 25.2 MeV/u, developments will be made to improve the optical transmission for the lower energies. A scintillator of smaller diameter and a shorter (half length) fibre will improve the light collection and transmission by more than 70%. Our estimation of light production is consistent with previous measurements and allows us to calculate the yield for the SPIRAL beams. Extrapolation of this test gives a lowest detectable energy of about 2 MeV/u. As an example this energy is reached at 70 cm with an Ar beam in the CIME cyclotron tuned for a final energy of 10 MeV/u. Below this threshold, the electronics will not be triggered.

This experiment clearly showed the interest in having such an equipment for the SPIRAL future tuning and sets the limit of our probe. An effort will be made to include it in an automatic tuning procedure as it is routinely the case for the capacitive phase probes. It should also be pointed out that, by carefully reducing the intensity, this kind of tool can be used for abundant beams and will allow a new insight into the beam properties.

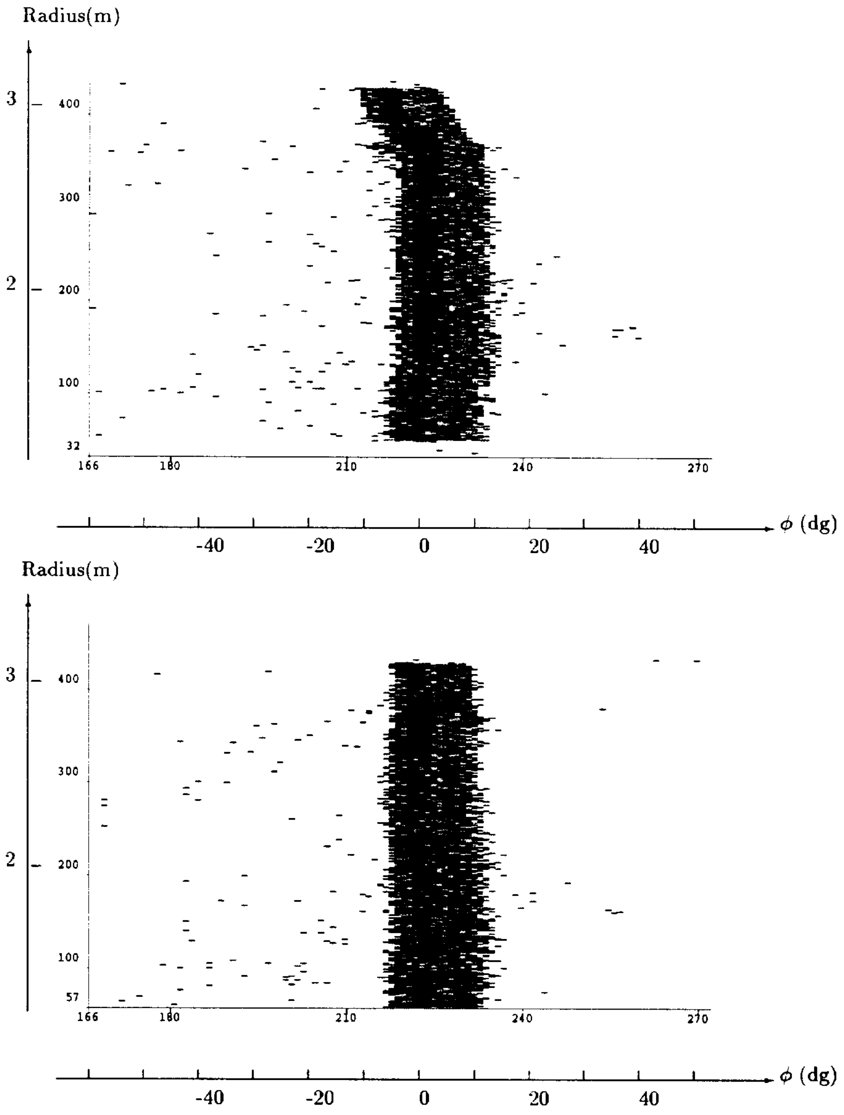

Fig. 5. *Radius versus phase in flight measurements in CSS2 before and after low intensity trimcoil optimisation*

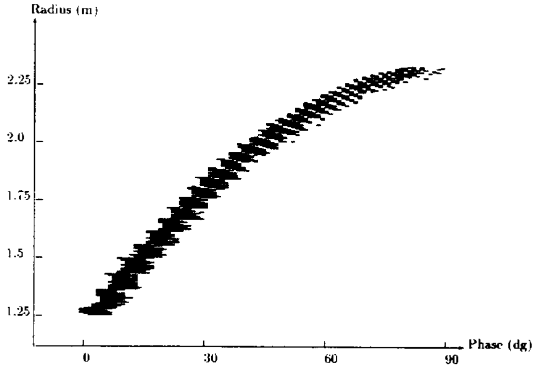

Fig. 6. *Radius versus phase histogram in CSS2 for a main magnetic field variation of* $3.6 * 10^{-4}$

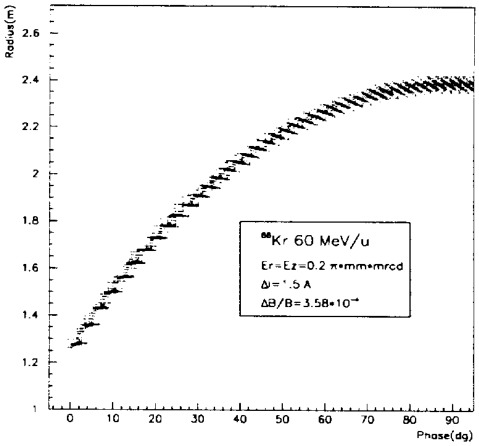

Fig. 7. *Numerical simulation of a main magnetic field variation of* $3.6 * 10^{-4}$ *in CSS2*

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