EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
**ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE**

**CERN – PS DIVISION**

PS/DR/Note 2000-011 (Tech.)

# INJECTION AND EXTRACTION LINES INSTRUMENTATION FOR PIMMS-

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**Abstract**

Efficient and safe operation of a medical accelerator complex depends on the measurement of many beam and accelerator parameters. The paper describes the instrumentation for determining the relevant beam properties in the PIMMS (Proton Ion Medical Machine Study) injection and extraction lines. The performance of the diagnostic system over the wide range of beam intensities and energies for both proton and carbon ion beams in the injection and extraction lines is discussed in two distinct parts of the paper. A particular care is devoted to the evaluation of non-destructive monitors for the measurement of the low-intensity beam during the irradiation of the patient in the extraction lines.

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# 1. INTRODUCTION

## 1.1 INTRODUCTION

Efficient and safe operation of a medical accelerator complex depends on the measurement of many beam parameters over a wide intensity range. The PIMMS (Proton Ion Medical Machine Study) beamline instrumentation system will include the monitoring of the beam along almost 50 meters of injection line and 150 m of extraction lines. This paper refers to study of the injection and extraction lines diagnostic system for the lines layout of the Italian version of PIMMS [1, 2]. The main difference with respect to the standard PIMMS layout is in the injection line where protons and ions are accelerated with the same linac at 7 MeV/u. In the extraction lines it is only a geometry matter due to local constraints. The paper does not include the study of the instrumentation for the first part of the injection line, from the source to the exit of the linac, designed at GSI, and comprehensive of the diagnostic system. The extraction line instrumentation does not include the gantries, the rotating magnetic structures that allows isocentric irradiation of the tumour, which are considered as independent finite units. However, the conclusions about the type, the number and the position of monitors are general and can be applied to any 'PIMMS-based' hadrontherapy complex.

The beam parameters needed for control and optimisation of the injection line are:

- the beam position and divergence at every straight section;
- the transverse beam profile (horizontal and vertical) at every straight section;
- the beam current at the linac exit, after the stripper and before injection in the synchrotron;
- the horizontal and vertical beam emittance before and after the stripper;
- the beam momentum spread before and after the RF cavity;
- the beam losses.

The beam parameters needed for control and optimisation of the extraction lines are:

- the beam position and divergence at every straight section;
- the transverse beam profile (horizontal and vertical) at every straight section;
- the beam current at extraction, at the entrance of each treatment room and at the end of each extraction line;
- the vertical beam emittance;
- the horizontal bar of charge[1][3];
- the beam losses.

The injection and extraction lines diagnostic system features are based on the beam parameters listed in Table 1 and Table 2 respectively. All monitors must be suitable for both proton and carbon ion beams. While with passive spreading the bean intensity is almost constant during the patient treatment, all the instrumentation should cope with the intensity variation required by the active scanning techniques [2, 3].

[1] The phase space distribution in the horizontal plane, due to third order resonance extraction, is near-rectangular (*bar of charge*).

Two steps are foreseen to obtain the required intensity variation of a factor 100 at the patient for both proton and ion beams. The first is to vary the number of injected particles of a factor 10 from spill to spill at the source. A further factor 10 is obtained at extraction by decreasing the velocity with which the betatron core moves the waiting stack into the resonance. In this way, a variation by a factor 10 in the number of particles for both proton and ion beams concerns the injection line and synchrotron instrumentation, while a factor 100 is "seen" by the extraction line monitors. The expected average current range in the injection line is 11 μA for carbon ions to 1.8 mA for protons with passive scanning (see Table 1). While in the extraction lines the expected intensity range is from 5 pA for carbon ions to 32 nA for protons for passive scanning (see Table 2).

| **Parameters in the injection line** | | |
|---|---|---|
| | **Proton beam** | **$^{12}C^{6+}$ beam** |
| Kinetic energy/nucleon [MeV/u] | 7 | 7 |
| γ | 1.007 | 1.008 |
| β | 0.121 | 0.122 |
| βγ | 0.122 | 0.123 |
| Pulse duration [μs] | 30 | 30 |
| Repetition rate [Hz] | 0.5 ÷ 0.8 | 0.5 |
| Injection revolution period [s] | $2.07 \cdot 10^{-6}$ | $2.06 \cdot 10^{-6}$ |
| Maximum number of injected particles: | | |
| active scanning | $1.9 \cdot 10^{10}$ | $8.3 \cdot 10^{8}$ |
| passive scanning | $7.2 \cdot 10^{10}$ | |
| Number of turns for multi-turn injection | 3.1(1) | 3.6 |
| Maximum average beam intensity [A](2) | $0.5 \cdot 10^{-3} \div 1.8 \cdot 10^{-3}$ | $0.11 \cdot 10^{-3}$ |
| Minimum average beam intensity [A] (2) | $50 \cdot 10^{-6} \div 180 \cdot 10^{-6}$ | $11 \cdot 10^{-6}$ |
| Intensity range (active scanning)(3) | 1 : 10 | 1 : 10 |
| R.m.s. horizontal emittance [π mm mrad](4) | 0.98 | 1.024 |
| Total horizontal beam size [m](5) | $5 \cdot 10^{-3} \div 30 \cdot 10^{-3}$ | $5 \cdot 10^{-3} \div 30 \cdot 10^{-3}$ |
| R.m.s. vertical emittance [π mm mrad](4) | 0.98 | 1.024 |
| Total vertical beam size [m](5) | $5 \cdot 10^{-3} \div 30 \cdot 10^{-3}$ | $5 \cdot 10^{-3} \div 30 \cdot 10^{-3}$ |
| Full relative momentum spread [‰] | ± 1.5 | ± 1.5 |
| Linac operating frequency [MHz] | 216 | |

(1) The number of turns for multi-turn injection of protons at 7 MeV has not been evaluated yet. The value considered is the one calculated for injection of protons at 20 MeV, as it will not differ much from the real one.

(2) The average beam intensity has been calculated dividing the number of particles injected in the synchrotron by the revolution period times the number of turns necessary for multi-turn injection.

(3) A factor 1:10 affects the instrumentation in the injection line and in the synchrotron (see Section 1.1).

(4) For space-charge and aperture calculations, the linac bunch is assumed to be a uniformly-filled 3-D ellipsoid which yields a 2-D elliptic distribution when projected on the transverse co-ordinates x, z. The total emittance in both planes is 5 times the r.m.s. emittance. The carbon ions emittance is quoted for the beam after the stripper.

(5) The minimum horizontal and vertical total size (100 % of the beam) are calculated with the program TRACE 3-D which provides the beam envelope taking into account self space-charge field effects. The values in the Table are indicative of the range of variation, as the optics is still under study.

***Table 1*** *Proton and carbon ion beam parameters ($^{12}C^{6+}$) in the injection line.*

| Parameters in the extraction lines | | |
|---|---|---|
| | **Proton beam** | **$^{12}C^{6+}$ beam** |
| Kinetic energy/nucleon [MeV/u] | 60 ÷ 250 | 120 ÷ 400 |
| γ | 1.06 ÷ 1.27 | 1.13 ÷ 1.43 |
| β | 0.34 ÷ 0.61 | 0.46 ÷ 0.72 |
| βγ | 0.36 ÷ 0.78 | 0.52 ÷ 1.02 |
| Spill length [s] | 0.25 ÷ 1 | 1 |
| Repetition rate [Hz] | 0.5 ÷ 0.8 | 0.5 |
| Maximum number of particles per spill: | | |
| active scanning | $1.3 \cdot 10^{10}$ | $5.2 \cdot 10^{8}$ |
| passive scanning | $5.0 \cdot 10^{10}$ | |
| Maximum beam intensity (average over the spill) [A] | $2 \cdot 10^{-9} \div 3 \cdot 10^{-8}$ | $5 \cdot 10^{-10}$ |
| Minimum beam intensity (average over the spill) [A] | $2 \cdot 10^{-11} \div 3 \cdot 10^{-10}$ | $5 \cdot 10^{-12}$ |
| Intensity range (active scanning)(1) | 1 : 100 | 1 : 100 |
| Total horizontal *emittance* [π mm mrad](2) | 5 (!) | 5 (!) |
| Total horizontal beam size [m](3) | $1 \cdot 10^{-3}$ | $3.6 \cdot 10^{-2}$ |
| R.m.s. vertical emittance [π mm mrad](2) | 0.67 ÷ 1.43 | 0.74 ÷ 1.43 |
| R.m.s. vertical beam size [m](4) | $8.2 \cdot 10^{-4} \div 6.2 \cdot 10^{-3}$ | $8.6 \cdot 10^{-4} \div 6.2 \cdot 10^{-3}$ |
| Minimum/maximum horizontal β-function [m] | 1 ÷ 30 | |
| Minimum/maximum vertical β-function [m] | 1 ÷ 27 | |
| Minimum/maximum dispersion [m] | 0 ÷ 5.5 | |
| Momentum spread [‰] | < 1 | < 1 |

(1) A factor 1:100 affects the extraction lines monitors (see Section 1.1).

(2) The phase space distribution in the horizontal and in the vertical plane, due to third order resonance extraction, is asymmetric. It is near-rectangular in the horizontal plane (*bar of charge*) and near-Gaussian in the vertical one. 5 π mm mrad is the total emittance of the ellipse, which include the *bar of charge* and is independent on the extraction energy.

(3) The minimum and maximum sizes in the horizontal plane correspond to the situation where *the bar of charge* is, respectively, vertical or horizontal in phase space and, in first approximation, do not depend on the extraction energy.

(4) The minimum vertical r.m.s. size is calculated for the minimum betatron amplitude function and at the maximum extraction energy; the maximum size is for the maximum betatron amplitude function and at the minimum extraction energy.

***Table 2*** *Proton and carbon ion beam ($^{12}C^{6+}$) parameters in the extraction lines.*

The approach of the study described in this report was to first examine the diagnostic systems of existing medical facilities in the world and then to make the choice for the PIMMS diagnostic system taking into account the present technologies and experiences. The medical centres with similar accelerator and beam properties considered are:

- LLUMC, USA. A synchrotron accelerates protons to kinetic energies in the range 70 ÷ 250 MeV with beam intensities in the range $10^{10} \div 5 \cdot 10^{11}$ pps;
- HIMAC, Japan. Two synchrotrons accelerate different ions from helium to argon (atomic number = 18) to kinetic energies in the range 100 ÷ 800 MeV/u with beam intensities in the range $10^{6} \div 10^{11}$ pps;

- GSI, Germany. The GSI is a centre for research in different physics domains; the medical facility uses just a fraction of the total accelerator time. A synchrotron accelerates different ion species up to uranium with maximum kinetic energies of 2 GeV/u and beam intensities in the range $10^4 \div 10^{11}$ pps (space charge limit). The extracted medical beam has the following features: fully stripped carbon ions with kinetic energies in the range 80 ÷ 430 MeV/u and beam intensities in the range $10^6 \div 10^8$ pps.

Due to the very different values and ranges of energy, intensity, size and duration of the beam in the injection and extraction lines, the two beamline diagnostic systems are treated in two separate parts of this paper. As the requirements on the extraction line instrumentation are more stringent than the injection line instrumentation ones, as explained below, the first section is dedicated to the extraction line diagnostics (Part I) so to maintain homogeneity in the choice of the type of detectors for the injection line (Part II) whenever possible.

The basic guideline behind the choice of the diagnostic system for a hospital-based accelerator complex is to be reliable and easy to manufacture and operate. While the beam parameters in the injection line are similar to those of many existing accelerators and make possible the use of standard instrumentation, the situation is more delicate for the extraction lines monitors. Due to the very low beam intensities, the instrumentation used in the extraction lines of the existing hadrontherapy facilities is interceptive. As any ‘standard’ monitor (thickness larger than a few μm) put on the path of the beam is strongly perturbative at the kinetic energies of Table 2, the instrumentation in the extraction lines of the hadrontherapy centres is used to set the lines and then removed while treating the patient. During irradiation, beam intensity, position and shape at the end of the extraction lines are determined only via the dosimetry system, the ensemble of monitors in air just before the patient, and the safety procedures rely exclusively on these measurements. It is clear, then, that the possibility of monitoring the beam during the treatment (on-line), independently from the dosimetry system, is strongly envisageable, as it makes possible an efficient operation of the accelerator complex and guarantees the maximum safety to the patient.

In this report, with the present knowledge, a conservative choice for the position and profile measurement with interceptive, destructive monitors in the extraction lines has been made as first choice. Therefore, to guarantee the maximum safety level during the treatment, the so-called ‘watchdog’ monitors, described in Section 2.2, are included in the extraction lines diagnostic system. These devices are located where the beam should not be and alert the control system every time the beam moves beyond a fixed region. In this way they make possible the control of the beam during the treatment of the patient, even if the absence of signals from a watchdog does not necessarily mean that everything is working as it should.

A particularly appealing alternative solution which provides on-line measurement of beam position, profile and current in the extraction lines is the use of monitors (Section 2.2) which are based on the collection of secondary emitted electrons [6, 7, 8, 9]. The thickness of these very thin aluminium foils (of the order of 0.2 ÷ 0.4 μm) is such that the perturbation caused to the beam can be accepted (Section 2.1). The main drawback is that these devices are still under study and this clashes against the choice to use conventional monitors tested and well known. At the same time, they represent the only possibility for on-line monitoring of the beam. They are therefore proposed as the best solution in the hypothesis that the results of the foreseen tests on a medical beam are positive and times are compatible with the planning and realisation of the medical machine.

The optics in the injection and extraction lines is still under study [1, 2]. Therefore, in the next sections the number and type of monitors in each straight section for the different measurements listed above will be determined, without specifying the exact position and the Twiss and beam parameters at the monitor. This work is left for a second iteration with the definitive line optics available. For some kind of measurements (as position and profile), the choice between different type of monitors that can cope with the wide range of beam intensities and energies is possible and is discussed in the relative sections. The simulations of orbit distortion due to misalignment and field errors of the magnets in both injection and extraction lines still need to be carried out. Therefore the number and position of horizontal and vertical correctors is not defined in this report.

### 1.2 RESOLUTION, ACCURACY AND SAMPLING TIME

The situation is more critical in the extraction lines where the beam measured is the same of therapy. Even if the requirements are not as strict as the ones on the dosimetry monitors, it is important to measure the beam with the best possible resolution and sampling time in order to determine the quality of the beam for the treatment and to have a countercheck with the dosimetry system. As the horizontal beam size goes from 1 to 36 mm and after the phase shifter[2] the orientation of the bar of charge can change from cycle to cycle, the beam profile should be measured with a resolution of a few tenths of mm. The accuracy on the position measurement determines the quality of the correction scheme and should be fixed with the help of the simulation on orbit errors due to magnet misalignment and field errors. Unluckily this has not been done yet, but it is foreseen that the required value will not differ much from 0.5 mm. The sampling time for the current and profile measurements is ideally 100 μs. This value, typical for these applications (PSI, GSI), is fixed from the error that can be accepted on the dose delivered to the tumour (± 2.5%) [3].

As mentioned above the requirements on the injection line instrumentation are less stringent. A resolution of 1 mm is required on the profile measurement and on the position accuracy [1]. A fast current transformer of 100 kHz bandwidth will allow the beam current and longitudinal profile measurement.

The beam loss monitors alert the accelerator operators on the onset of beam losses and help to localise their origin. The bandwidth of these detectors in both extraction and injection lines is of the order of 1 kHz.

[2] This insertion consists in a set of magnets that change the horizontal phase advance in order to rotate the bar of charge in phase space keeping constant the betatron amplitude function at the insertion exit.

# 2. PART I: EXTRACTION LINES

## 2.1 RELEVANT BEAM PARAMETERS

The choice on the type of monitor is strongly dependent on some beam parameters that can be derived from the data in Table 2. As explained in the introduction, the optics is still in definition and the behaviour of the optical functions is not included in this paper. Anyway, as the ranges of variation of the betatron and dispersion functions will not differ much from the ones listed in Table 2, these values are used to calculate the interval of variation of very useful beam parameters.

The total **beam size** varies from 3 to 25 mm in the vertical plane (Gaussian distribution cut at 2 $\sigma$, the total size correspond to $\pm$ 2 $\sigma$) and from 1 mm to 36 mm in the horizontal plane (vertical and horizontal bar of charge in phase space, respectively). Considering the maximum number of protons and carbon ions at the lower extraction energies, the maximum **linear charge density** (in number of particle per meter) range varies from 2 carbon ions/m to 2000 protons/m. For the minimum number of protons and carbon ions, the minimum linear charge density range goes from 1/41 carbon ions/m to 20 protons/m. The spill duration goes from 250 ms to 1 s (Table 2). These numbers implies that electromagnetic pick-ups responding to the linear charge density are not suitable to determine the position of the centre of charge of the extracted beam.

The information on the beam position can be obtained with the use of interceptive monitors, whose response to the passage of the extracted particles is based on ionisation or excitation processes. The most important parameter in this case is the **energy loss in matter**. The values for protons and ions at the lower and higher extraction energies are listed in Table 3, where the total energy loss refers to the energy lost by the entire spill. The energy loss has been calculated using the water mean ionisation energy in such a way to have a comparison between the total energy release in the tumour with the proton and ion beam. It is easy to scale the results to any other material used for the detection of the beam.

| **Energy loss in water** | | |
|---|---|---|
| | **Proton beam** | **$^{12}C^{6+}$ beam** |
| Energy loss on the lower flat-top (60 MeV protons, 120 MeV/u ions) per particle [MeV·cm$^2$/g] | 10 | 212 |
| Total energy loss on the lower flat-top [MeV·cm$^2$/g] | $1.3 \cdot 10^{11}$ | $1.1 \cdot 10^{11}$ |
| Energy loss on the higher flat-top (250 MeV protons, 400 MeV/u ions) per particle [MeV·cm$^2$/g] | 3.6 | 101 |
| Total energy loss on the higher flat-top [MeV·cm$^2$/g] | $5 \cdot 10^{10}$ | $5 \cdot 10^{10}$ |

***Table 3*** *Energy loss in water (mean excitation energy I= 60 eV) for proton and carbon ions ($^{12}C^{6+}$) (active scanning beams).*

It is evident from Table 3 that the reason for a lower intensity in the case of carbon beam rises from the fact that the same dose should be delivered to the tumour with both proton and ion beams. As the energy loss (Bethe-Block formula [10]) is proportional to the second power of the particle charge, the values of total energy loss for protons and ions are comparable. From the point of view of interceptive diagnostic, this means that the minimum intensity proton beam can be considered as the bottom reference for the intensity range in which each device should work.

For many types of beamline monitors, it is necessary to define the **beam charge density**. In first approximation, it is assumed a square distribution in both horizontal and vertical planes and that the beam reaches its maximum (or minimum) size in both planes at the same position of the extraction lines. With this simplifying hypothesis the charge density range goes from $1.5 \cdot 10^5$ to $6.7 \cdot 10^{10}$ protons/($mm^2 \cdot s$), having considered just the proton beam as explained above. With the more realistic assumption that in the horizontal plane the beam follows a uniform square distribution and in the vertical plane a Gaussian distribution, it should be taken into account a further reduction factor of 10. This value is obtained with the hypothesis of measuring the beam edge at 2 $\sigma$. If the monitors are placed in a position where the horizontal and vertical size are average (e.g. 20 x 10 mm) and with the further factor 10 between the vertical peak intensity and the edge at 2 $\sigma$ intensity for a Gaussian beam, the beam charge density goes from a minimum of $10^5$ to a maximum of $10^9$ protons/($mm^2 \cdot s$). Therefore the monitors must cover a density range of a factor 10000. These numbers will be revised as soon as the optics in the extraction lines and the exact monitors' position are fixed.

The main drawback of interceptive monitors is that through multiple scattering they cause a non-negligible beam **emittance blow-up**. For example, a 40 $\mu$m aluminium foil (this thickness is the lower validity limit of Highland formula [11] for multiple scattering [12]), causes an r.m.s. scattering angle of $1.8 \cdot 10^{-3}$ rad for 60 MeV proton beam and $4.5 \cdot 10^{-4}$ rad for 120 MeV/u carbon ion beam. This means, for a small betatron function amplitude ($\beta \sim 7$ m, $\beta max = 30$ m from Table 2), a relative emittance blow-up of 300 % for protons and 56 % for carbon ions, while for the minimum $\beta$ (monitor at a focus, $\beta \sim 1$ m), the blow-up is 80 % for protons and 7 % for ions. It is clear that these monitors are destructive and should be removed from the beam trajectory during the treatment of the patient. As the extraction lines beam intensity is too low for the use of SEM grids, the only non-destructive interceptive devices considered in this paper for on-line measurements in the extraction lines are the SEM thin foils mentioned in the Introduction that could be used to monitor the extracted beam position, profile and current as explained in Section 2.2. Their typical thickness of $0.2 \div 0.3$ $\mu$m does not allow the use of the Highland formula. A Monte Carlo programme for plural scattering [13] has been developed. The emittance blow-up caused by a thin aluminium foil of 0.2 $\mu$m thickness is less than 10 % for 60 MeV protons. This number depends on the beam energy (bigger for lower energies) and on the monitor position in the beamline. If the SEM foil is placed at a minimum of the $\beta$-function, the increase is of the order of 2, 4 % for 60 MeV protons. If the SEM foil is placed at a maximum of the $\beta$-function, the increase is of the order of 7, 10 %. It is evident that it is possible to study an optical scheme that includes one (or a few) of these monitors in some specific 'less sensitive' position, without causing unacceptable disturbance to the beam. A previous study [14] of the extraction line was including 10 thin SEM foils in 60 meters of extraction lines (from the extraction section to the farthest treatment room). It was showed in Reference [14] that the perturbation due to the material in the beam caused a change in the Twiss parameters and an emittance increase (from 3.0 to 5.5 π mm mrad) that was acceptable compared to the emittance value for which the lines were designed (8 π mm mrad). A similar study should be repeated for the new lines layout as soon as the optics will be fixed.

## 2.2 BEAM POSITION AND TRANSVERSE PROFILE MEASUREMENT

Due to the very low beam intensity, the conservative choice for position measurement in the extraction lines are interceptive monitors, as explained in the Introduction. This inconvenient is exploited to perform the position and transverse profile measurement with the same monitors.

To verify the correct alignment of the beam in every straight section, at least two position monitors per straight section are required. The first monitor is close to the entrance, the second monitor is close to the exit of the section. In case of very long drifts, a third monitor is placed in between. It is useful to measure the beam size and shape at the entrance of every straight section; this measurement is performed with the same monitors. Some of the profile monitors are used together to provide the vertical beam emittance and the horizontal bar of charge, as explained in Section 2.4. The extraction lines layout with the beam position and transverse profile monitoring system is shown in Figure 1 [2].

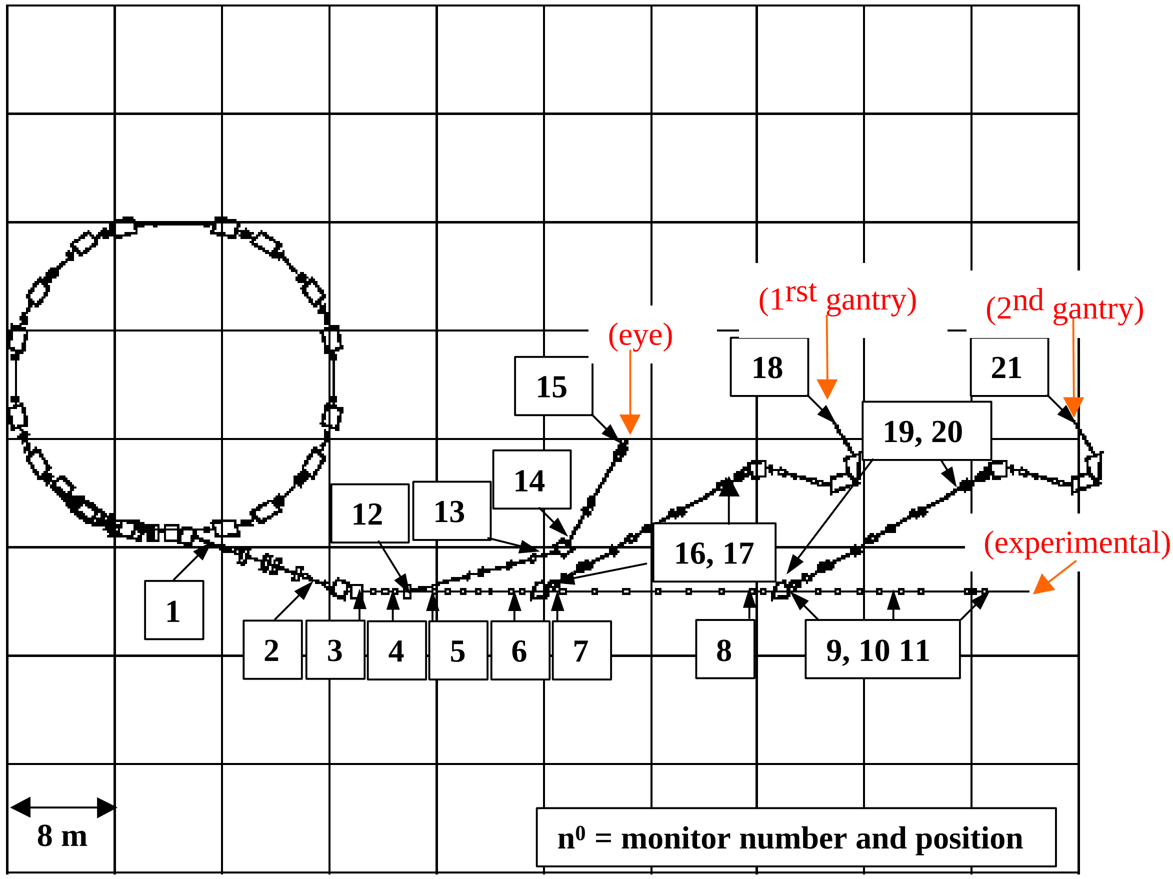


***Figure 1*** *Extraction lines layout with the beam position and transverse profile monitoring system (in brackets the use of the different treatment rooms).*

Looking at Figure 1, from left to right, the first beam line transports the beam to the eye treatment room; the second and the third transport the beam to the two isocentric gantries; the fourth line carries the beam to the experimental room.

Three possible kind of monitors have been taken into consideration:

- Scintillation Screens observed with CCD camera;
- Multi-Wire Proportional Chambers (MWPC);
- SEM Grids (SEM).

Considered the positive experience at CERN [15], the monitors chosen for the PIMMS position and profile measurement in the extraction lines are the scintillation screens. The CsI(Tl) is the most convenient material for the screens in the extraction lines, as its measured sensitivity for minimum ionising protons is of the order of $10^5$ protons/mm$^2$. This value corresponds to the minimum estimated beam density in the PIMMS extraction lines at the monitor positions (see Section 2.1). This number can be improved by use of image intesifiers: sensitivities up to 10 protons/mm$^2$ in 40 ms have been reported for profile measurements in the LEAR transfer lines [16]. CsI(Tl) screens can cope with a factor ($10^3$ x 10) in beam density (first factor due to different beams, second factor in the same Gaussian beam from the central peak to the 2 $\sigma$ edges, as explained in Section 2.1) and with the help of an image intensifier that can gain up to a factor $10^4$ [17], the CCD camera can work always in the same light intensity range. Screens have the advantage of being simpler in construction than MWPC and SEM and their spatial resolution can go down to 0.05 mm. Moreover they are fast (decay time < 1 μs) and can therefore be used for time structure analysis in the 1 μs range together with a photomultiplier. In the CERN SPS complex the video signals are acquired and digitised over 8 bits in a VME card; the horizontal and vertical profiles are calculated every 40 ms and stored in the card [19]. It is in this way possible to have the evolution of the horizontal and vertical beam position and profile every 40 ms with a spatial resolution better than 0.1 mm. Ageing effects were not observed in normally operating condition in SPS with relativistic proton beam densities per pulse up to $10^{13}$ protons/mm$^2$ · μs) [13]. Application at SLAC (Stanford Linear Accelerator Center) showed that scintillation screens have withstood proton fluxes of more than $10^{18}$ protons/mm$^2$ with number of particles/pulse and kinetic energies of the order of the CERN ones [18].

The main drawback of scintillation screens is that, due to their thickness (~ 1 mm), they cause a beam blow-up and, depending on the beam energy, only a limited number of screens can be used simultaneously. For example, a 1 mm CsI screen, causes an r.m.s. scattering angle of 27 mrad for 60 MeV protons and 7 mrad for 120 MeV/u carbon ions at an average $\beta$-function value ($\beta$ = 7 m). The energy loss in 1 mm screen is ~ 4 MeV for 60 MeV protons and ~ 90 MeV for 120 MeV/u carbon ions.

The second device examined is the Multi-Wire Proportional Chamber (MWPC) [19], as it is the most popular solution in the extraction lines of medical complexes (Loma Linda, Himac). This is mainly due to the fact that these monitors have been widely used in particle physics since more than 30 years and work properly in the intensity range of interest. At HIMAC, for example, MWPC were tested with a 70 to 800 MeV proton beam and worked well in the intensity range $1.4 \cdot 10^6 \div 1.4 \cdot 10^{11}$ pps [20]. The reasons why screens where preferred to MWPC in the PIMMS extraction lines, is that the seconds are more complicated to manufacture and to operate (high voltage, filling with gas), they are also destructive and they do not provide the same spatial resolution of screens (MWPC position resolution limit of the order of 0.5 mm).

The third possibility, the SEM grids used at GSI (in combination with scintillators and multi-wire proportional chambers for the lower intensities) were discarded, as these devices do not work with the lower intensities reported in Table 2. The minimum required current to measure a profile was estimated [17, 21]. A minimum charge of $(I_{wire} \cdot T_{integration}) = (0.1\ \text{nA} \cdot 5\ \text{ms})$ is required per wire with typical low-noise grid electronics. Considering an optimist secondary emission efficiency of 10 % and a factor 10 between the beam peak and edge intensity, the required integration time would be prohibitively long with the lower intensities of the PIMMS extracted beams.

As scintillation screens are not usable during patient treatment, a possible solution to control the beam position on-line is to place monitor where the beam should not be. Such monitors behave as watchdogs alerting the system every time the beam moves beyond a fixed region. Watchdogs have been tested in the GSI medical line [17] as a nearly non-destructive method to determine the beam centre of mass, width and intensity. They consist of four stepping motor driven scintillator paddles (two horizontal and two vertical) that detect 0.1-1% of the particles from the beam halo. For a schematic diagram and work principle of the monitor see Figure 2.

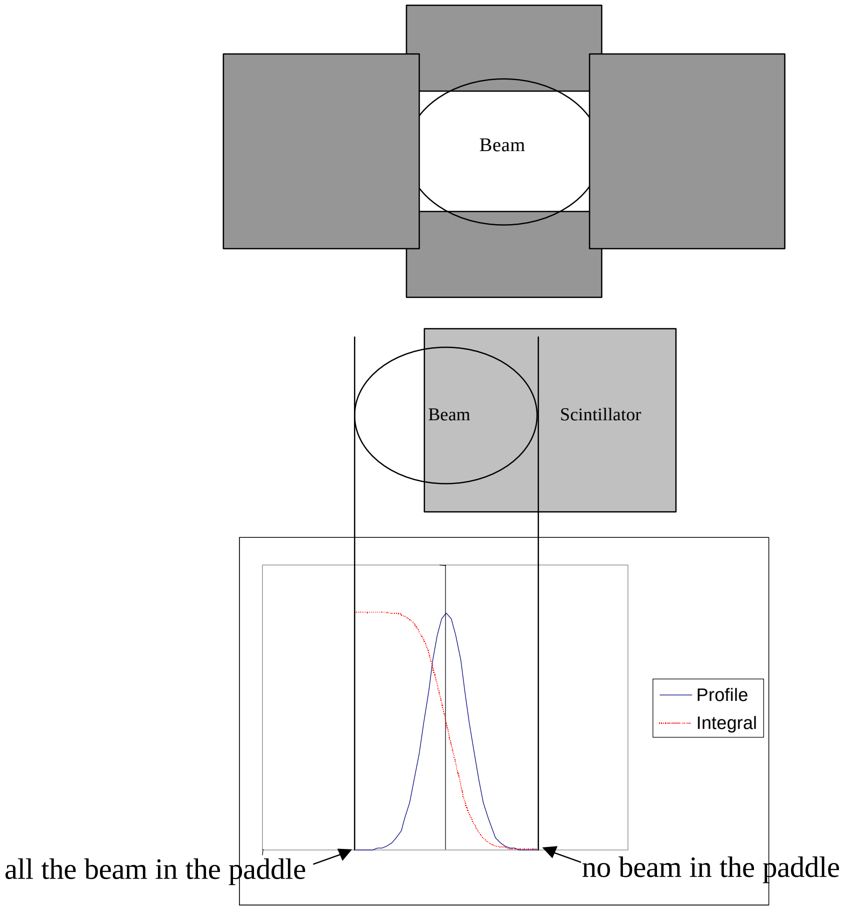


***Figure 2*** *Schematic diagram and work principle of the watch-dog monitor.*

Preliminary tests with a watchdog were performed also at CERN in spring 1998 [23]. Results were not satisfactory mainly because of the slowness of the measurement system, which was completely manual. Further tests are planned with the automation of the movement of the monitor into or out of the beam and the relative data acquisition system. The efficient and safe operation of the extraction lines would benefit of at least ten watchdogs (~ 1 monitor/straight section) in the positions that are the most critical for the beam transport. The exact position will be determined as soon as the definitive optics is available.

As mentioned in the introduction, a particularly appealing solution for the online measurement of the beam parameters is the use of very thin secondary emission foils. This non-destructive detector measures the spatial and intensity distribution of the beam by determining the position and intensity of secondary electrons produced by particle beam interactions with the thin foil. The secondary electrons are collected with a high voltage onto an imaging detector (profile measurements) or an anode followed by an integrator (intensity measurements). The secondary emission yield depends on the type of foil and on the type, velocity and angle of incidence of the incoming particles. A conservative coefficient of 5 % for a 1 GeV proton beam on aluminium foils has been considered in this study [24]. Several types of detectors can be used to measure the secondary electrons. Scintillators or semiconductors are insensitive to electrons having energies below 5-10 keV, therefore secondary electrons from the foil must be accelerated to this energy. This creates problems of very high background counting rates and big distortion to the incoming beam. A better situation prevails when the secondary electrons from the foil are accelerated directly onto an electron multiplier structure. Only an accelerating voltage of ~ 1 kV is required to achieve the maximum efficiency.

Figure 3 shows the arrangement with an electron multiplier structure plus a phosphor and a CCD camera to observe the beam profile. It is assumed that all the emitted secondary electrons are collected on the micro-channel plate (MCP) (or on the anode for intensity measurement) by the focalisation voltage between the foil and the MCP; the value of this voltage is of the order of 1 kV in such a way to have a good lateral resolution and the maximum efficiency of the MCP. The gain of the MCP is changed varying the polarisation voltage according to the extracted beam intensity so that the CCD camera can always work in the same light intensity range. With the use of a conductive phosphor, as P47, the intensity measurement can also be performed connecting the phosphor to an integrator. The advantage of the layout of Figure 3 is that the kick given to the beam by the focalisation potential for the profile measurement is compensated by the kick given by the focalisation potential for the intensity measurement. The uncompensated beam displacement together with the r.m.s. scattering angle due to the interaction beam-foil should be taken into account in the beam optics calculations.

A scintillation screen plus a TV camera in front of the beam dump is proposed to help the accelerator operators t get an immediate feeling of the beam position, size and intensity independently from the control system.

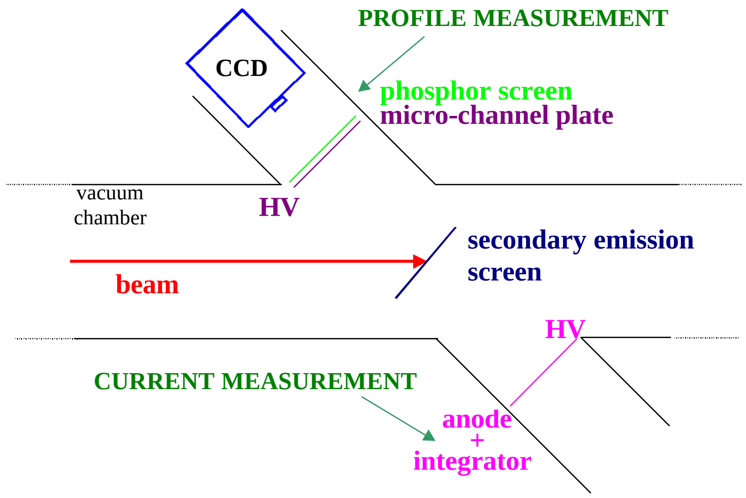


***Figure 3*** *Schematic diagram of the detector using electron emission from a thin foil for profile and intensity measurements (HV = high voltage to collect the secondary emitted electrons), size not to scale.*

## 2.3 BEAM CURRENT MEASUREMENT

To evaluate the quality of the beam extracted from the synchrotron, it is crucial to measure the beam intensity on-line (during the treatment of the patient) with a wide bandwidth system (10 kHz, see Section 1.2) in such a way to examine the beam time structure. As intensity measurements of the LEAR extracted beam with currents close to the lower values of the medical beam were performed successfully with a thin secondary emission foil similar to the ones described in Section 2.1 [9], it is proposed to provide the beginning of the extraction line (monitor $n^0$ 1 of Figure 4) and the end of each transfer line (monitors $n^0$ 3, 5, 7 and 9) with one of this detector. In this case the secondary emitted electrons were accelerated on a scintillator optically coupled to a photomultiplier tube. Monitor $n^0$ 1 will allow on-line check of the extracted beam quality and eventual action on the extraction process. Monitors $n^0$ 3, 5, 7 and 9 will allow the on-line evaluation of the extraction lines transport quality and efficiency together with a countercheck with the dosimetry system measurements. This action is important for maximum safety during patient treatment and time sparing in beam transport and quality checks.

It is also foreseen to provide the entrance of each room with a current measurement via a Faraday cup (monitors $n^0$ 2, 4, 6 and 8 of Figure 4). The interesting aspect of this solution is the monitor double function as diagnostics and safety devices. Faraday cups are always kept on the beam path and moved away only when the beam is ready for the treatment. The time to move the monitor into or out of the beam is of the order of a few seconds. In this way they act as beam stopper in case of misfunctioning of the control system. Moreover, as they provide an absolute current measurement, they can be used for calibration of the other monitors. The lower charge that can be measured with Faraday cups used together with low noise electrometers is 1 pC (S/N =1) [25]. This value is limited by the offset current of classical amplifiers (of the order of 1 pA). Faraday cups designed for dosimetry measurements were successfully tested with 200 MeV proton beam [26]. The prototype used consisted of a block of 13 cm aluminium. Further study on electron yield and suppression with carbon ion beam should be carried out.

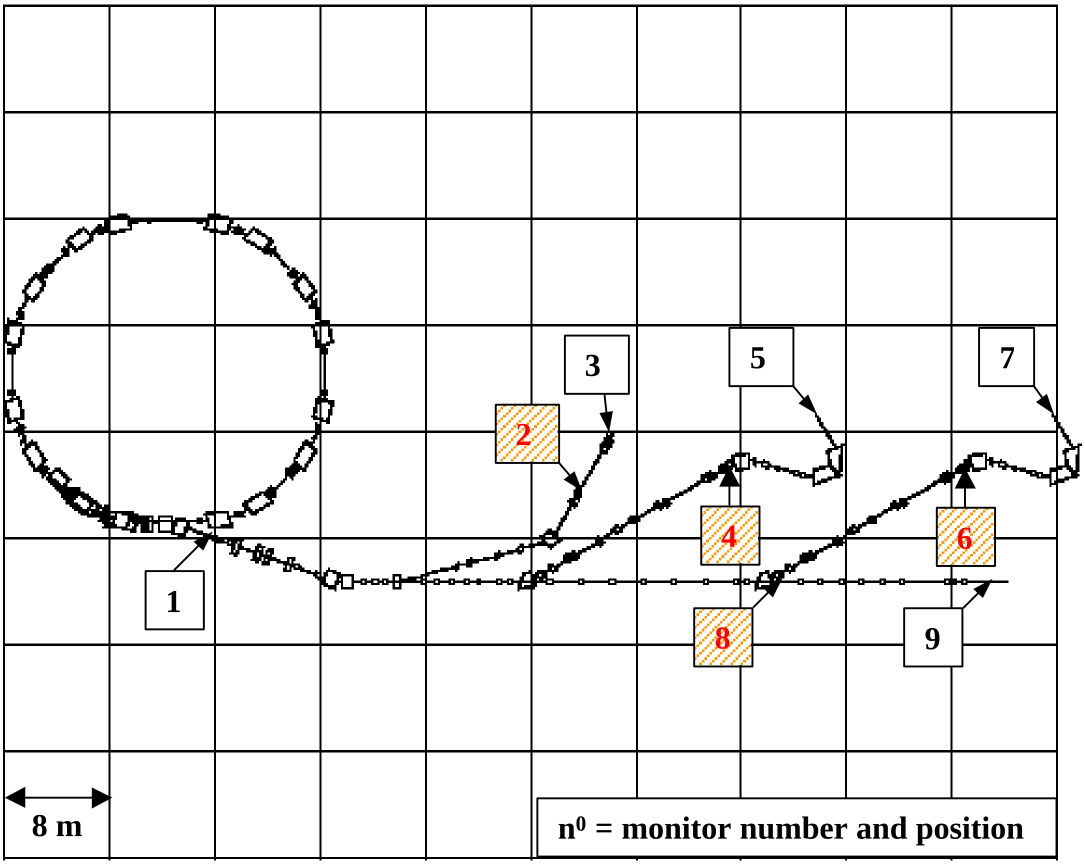


***Figure 4*** *Extraction lines layout with the beam current monitoring system; the dashed square are Faraday cups.*

## 2.4 BEAM VERTICAL EMITTANCE AND HORIZONTAL BAR OF CHARGE MEASUREMENT

For an unambiguous determination of size and orientation of the vertical plane emittance ellipse, the beam size need to be known at least at three locations, with known transfer matrices between them. A particularly simple case occurs around a waist with a betatron phase advance between the profile monitors of $60^0$ [27]. Referring to Figure 1, profile monitors $n^0$ 3, 4 and 5 can be used for the vertical emittance measurement, as they are located in the fix optics part of the transfer lines. An alternative measurement of the vertical emittance can be carried out with the gradient variation method: the beam width is measured with a profile monitor varying the strength of a quadrupole upstream the detector. Knowing the transfer matrix between quadrupole and monitor, a least square fit leads to the determination of the Twiss parameters and therefore of the ellipse area and orientation.

As mentioned in the Introduction, the phase space distribution in the horizontal plane is near-rectangular (bar of charge) due to third order resonance extraction. The bar of charge orientation and area are determined with a profile monitor ($n^0$ 6 in Figure 1) located just after the phase shifter. This insertion consists in a set of magnets that change the horizontal phase advance in order to rotate the bar of charge in phase space keeping constant the betatron amplitude function at the insertion exit.

## 2.5 BEAM LOSSES MEASUREMENT

Beam loss monitors play an important role in the protection and operation of synchrotrons, as they allow the detection of the onset of beam losses and their localisation in the ring or along the lines. This is important in order to identify and correct the cause of the loss and to keep the irradiation of the accelerator components as low as possible. They are not used to run the accelerator, but they work as an alarm system every time there is a serious problem. The primary signature of lost protons in the PIMMS energy range are neutrons and the neutron yield rises roughly quadratically with proton energy. Thus loss monitors must be neutron sensitive and must have a very large dynamic range.

Two possible solutions have been considered: scintillators coupled to phototubes and ionisation chambers. The first possibility is very sensitive (100 μA per rad for 0.5 litres scintillator oil) and has the ability to observe beam losses with rise times in the 10 ns range but, due to unstable gain, individual monitors require to be calibrated often. The second possibility is a factor 100 to 1000 less sensitive for the same useful volume (0.1 to 1 μA per rad), but the gain of individual monitors is very stable albeit rather slow (~ 1 μs rise time).

It is foreseen to distribute ten monitors along the extraction lines in correspondence of each bending and to group them more densely close to the injection and extraction kicker and septa, the more critical zones for beam losses. It is also foreseen to provide some mobile device with long cables that can be positioned according to specific needs. Since the monitor type does not impose any constraint on the accelerator complex design, the choice between the two possible solutions is left open. This will be resolved, once the detailed simulations of beam losses and secondary particles production have been made.

# 3. PART II: INJECTION LINE

## 3.1 RELEVANT BEAM PARAMETERS

The choice on the type of monitor is strongly dependent on some beam parameters that can be derived from the data in Table 1. As explained in the introduction, the optics is still in definition. However, to visualise the beam behaviour in the injection line, the most updated horizontal and vertical beam envelopes, that will not differ much from the final ones, are shown in Figure 5 and Figure 6. They correspond to √5 the rms value and include 100% of the beam. From the four envelopes, calculated with the program TRACE 3-D, that takes into account self space-charge field effects, it is possible to derive the beam size behaviour along the injection line.

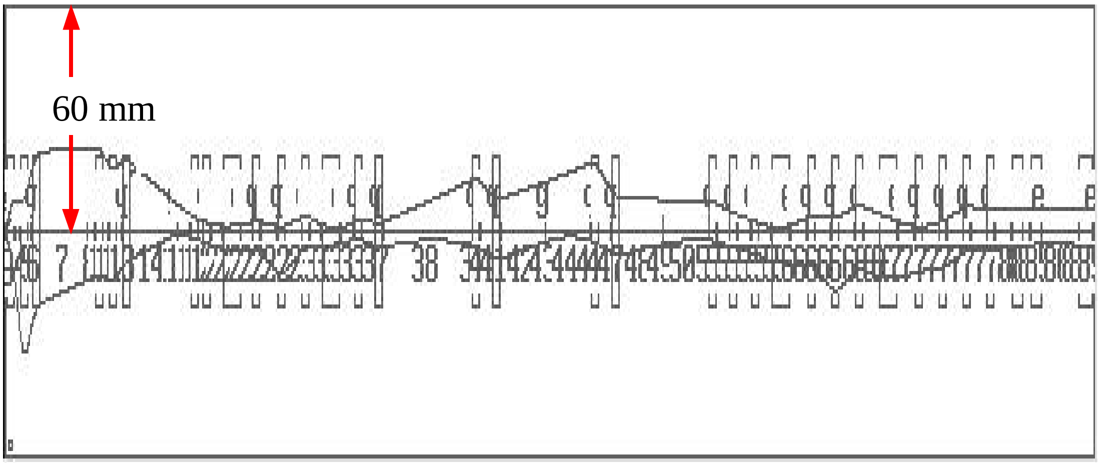


***Figure 5*** *Horizontal (upper part of the picture) and vertical (lower part of the picture) beam semi-envelopes versus distance in the injection line for proton beam.*

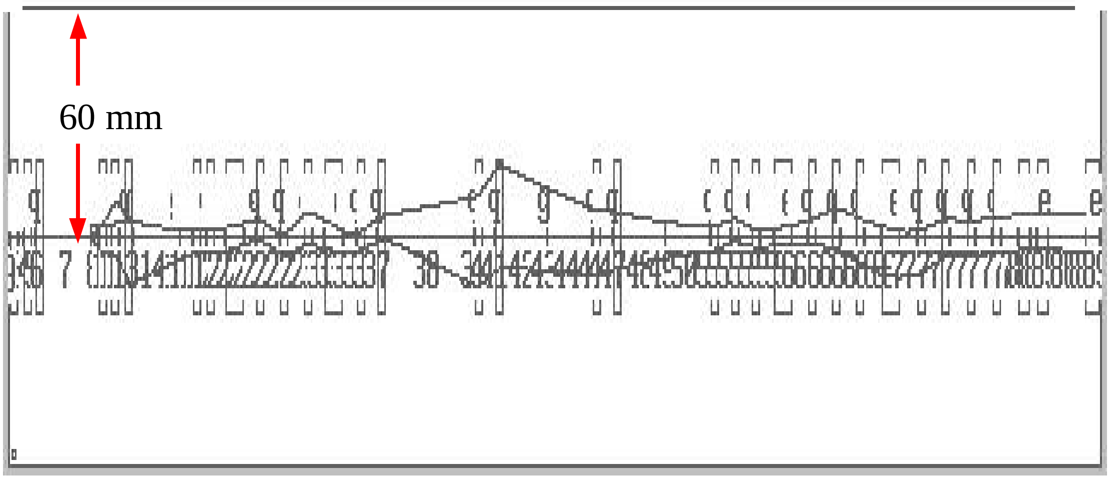


***Figure 6*** *Horizontal (upper part of the picture) and vertical (lower part of the picture) beam semi-envelopes versus distance in the injection line for carbon beam.*

The total **beam size** is assumed to vary from a few mm to a maximum of 30 mm in both planes (see also Table 1), excluding a few specific points with bigger excursion. Considering the maximum number of protons and carbon ions at the injection energies, the **linear charge density** (in number of particle per meter) range varies from $3 \cdot 10^6$ carbon ions/m to $3 \cdot 10^8$ protons/m. The duration of the pulse is 30 μs (Table 1). These numbers, on the contrary of extraction line ones (see Section 2.1), imply that electromagnetic monitors responding to the linear charge density are suitable to measure some beam parameters (see Section 3.2 and 3.3).

The information on the beam profile can be obtained with the use of interceptive monitors, whose response to the passage of the particles is based on ionisation or excitation processes. The most important parameter in this case is the **energy loss in matter**. The values in water (see Section 2.1) for protons and ions at the injection energy are listed in Table 4.

| **Energy loss in water** | | |
|---|---|---|
| | **Proton beam** | **$^{12}C^{6+}$ beam** |
| Energy loss per particle at 7 MeV [MeV cm$^2$/g] | 58 | 2000 |
| Total energy loss at 7 MeV [MeV cm$^2$/g] | $1.1 \cdot 10^{12}$ | $1.7 \cdot 10^{12}$ |

***Table 4*** *Energy loss in water (effective binding potential I= 60 eV) for proton and carbon ions ($^{12}C^{6+}$) (active scanning beams).*

As explained in Section 2.1, from the point of view of interceptive diagnostic, the minimum intensity proton beam can be considered as the bottom reference for the intensity range in which instrumentation should work.

For many types of interceptive monitors, it is necessary to define the **beam charge density**. In first approximation, it is assumed a square distribution in both horizontal and vertical planes and that the beam reaches its maximum (or minimum) size in both planes at the same position in the injection line. With this simplifying hypothesis the charge density range goes from $4 \cdot 10^{11}$ to $4 \cdot 10^{14}$ protons/(mm$^2$ · s), having considered just the proton beam as explained above. With the more realistic assumption the beam follows a Gaussian distribution in both planes (it was assumed parabolic only for aperture calculations), it should be taken into account a further reduction factor of 100 between the peak and the edge at 2 σ. If the monitors are placed in a position where the horizontal and vertical size are average (e.g. 15 x 10 mm, see Figure 5 and Figure 6) and with the further factor 100 between the peak intensity and the edge at 2 σ intensity for a Gaussian beam, the beam charge density goes from a minimum of $6 \cdot 10^{10}$ to a maximum of $1.6 \cdot 10^{14}$ protons/(mm$^2$ · s). Therefore the monitors must cover a density range of a factor 3000. These numbers will be revised as soon as the optics in the injection line and the exact monitors' position are fixed.

The main drawback of interceptive monitors is that through multiple scattering they cause a non-negligible beam **emittance blow-up**. For example, a 40 μm aluminium foil (this thickness is the lower validity limit of Highland formula [11] for multiple scattering [12], causes a r.m.s. scattering angle of 15 mrad for 7 MeV proton beam and 7 mrad for 7 MeV/u carbon ion beam. The foil is clearly destructive. At the higher intensity of the injection line, a possible solution for position/profile measurements are the SEM grids, that are just slightly perturbative as they intercept a small percentage of the beam. For example, 98% of the beam passes unaffected trough a grid with wires of 20 μm of diameter and 1 mm spacing.

A parameter that is more relevant at the low injection energy, is the **particle range** in a medium. It is, for example, 0.64 mm for protons and 0.21 mm for ions in water and ~ 240 μm for protons and ~ 80 μm for ions in aluminium.

### 3.2 BEAM POSITION AND TRANSVERSE PROFILE MEASUREMENT

The injection line layout with the beam position and transverse profile monitoring system is shown in Figure 7 [1]. The criteria followed to fix the total number of monitors are the ones summarised in Section 2.2. Also in the injection line some of the profile monitors are used together to measure the beam horizontal and vertical emittances (Section 3.4) and in combination with a movable slit and a bending dipole they determine the beam momentum spread (Section 3.5).

As explained in the Introduction, the requirements on the extraction lines instrumentation are more stringent than the injection line ones. Therefore it has been decided to examine first the monitors for the extracted beam and subsequently the ones for the beam in the injection line so to maintain homogeneity wherever possible. This is the case for the position/profile measurement. As discussed in Section 2.2, after examining SEM foils, multi-wire proportional chambers and scintillation screens, the latter have been chosen as the most convenient solution for the PIMMS extraction lines. They are then proposed also for the injection line position/profile monitoring.

As the beam density is higher than in the extraction lines, the Li-Glass is foreseen as a less sensitive scintillation material. It can cope with the range of beam densities in the PIMMS injection line, as its measured sensitivity for minimum ionising protons is of the order of $10^8$ protons/($mm^2 \cdot s$). These screens can cope with a factor (30 x 100) in beam density (first factor due to different beams, second factor in the same Gaussian beam from the central peak to the 2 $\sigma$ edges, as explained in Section 2.1) and with the help of a light attenuator, the CCD camera can work always in the same light intensity range. As described in Section 2.2, the video signals are acquired and digitised over 8 bits in a VME card in such a way to have the evolution of the horizontal and vertical beam position and profile every 40 ms with a resolution better than 0.1 mm. Moreover Li-Glass is fast (decay time ~ 100 ns) and can therefore be used for time structure analysis in the 1 μs range together with a photomultiplier.

The main drawback of scintillation screens is that, due to their thickness (~ 1 mm), they are completely destructive. The particle range in Li-Glass screens is ~ 0.1 mm for 7 MeV proton beam and ~ 50 μm for 7 MeV/u carbon ion beam. A possible alternative solution to monitor beam position and profile, as the beam intensity is higher than in the extraction lines, is the use of SEM grids. These monitors intercept just a small percentage of the beam and are, therefore, only slightly perturbative (see Section 3.1). The advantage of this solution is that grids allow multiple measurements on the same beam. However, as grids are not sensitive enough to detect the extraction lines beam (see Section 2.2) and are anyway more complicated to manufacture and operate and more expensive than screens, it is preferred to keep the same choice for position and profile measurements as in the extraction lines.

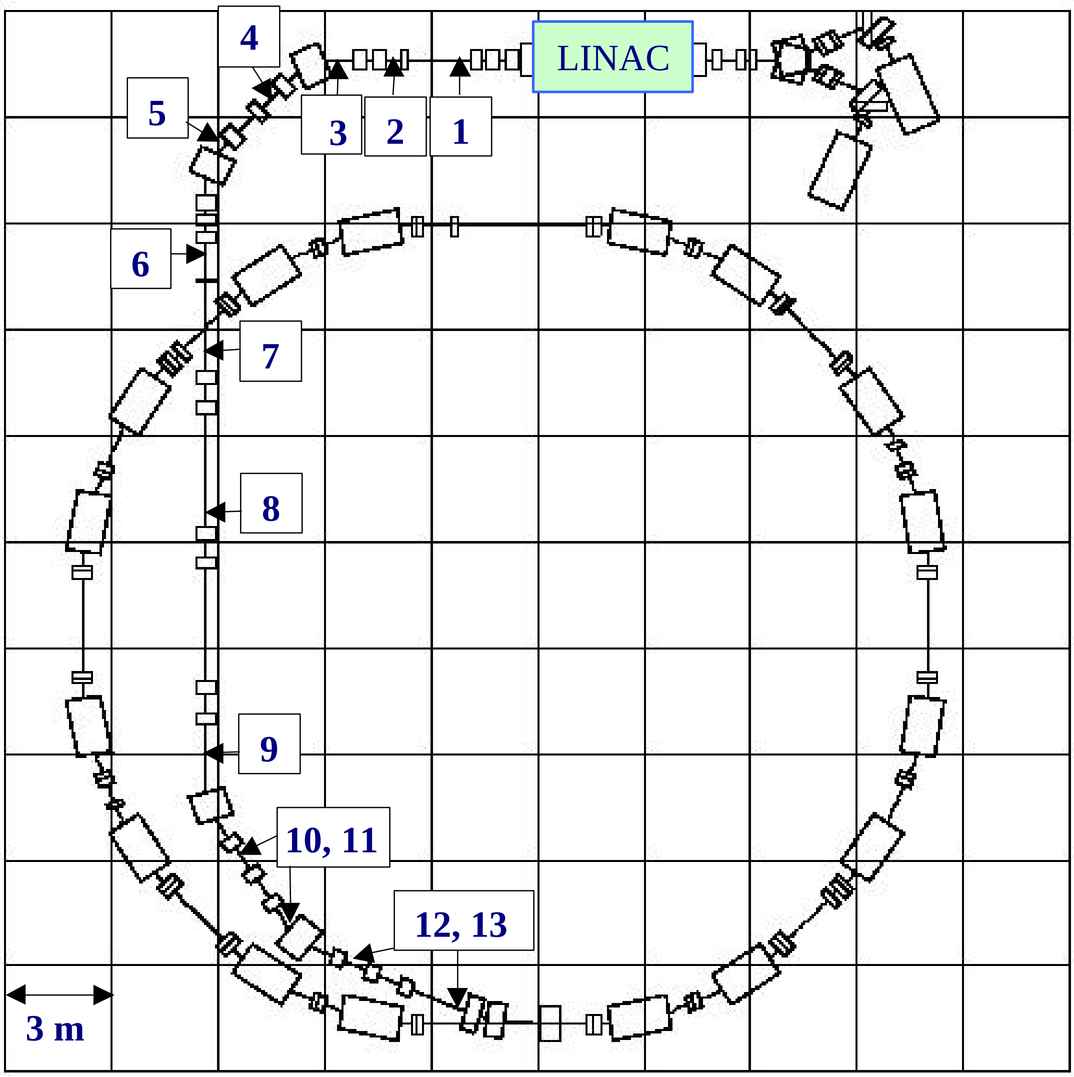


***Figure 7*** *Injection line layout with the beam position and transverse profile monitoring system.*

As scintillation screens are not usable during patient treatment, a possible additional solution fully un-perturbative to detect the beam position is the use of electrostatic pick-ups as the ones proposed for position measurement in the synchrotron. The low signal level makes it preferable to locate the electronics as close as possible to the pick-up. Considering the low beam losses expected, the intensity and the kinetic energy, the low-noise head amplifier with high-input resistance will be mounted directly on the vacuum chamber. Assuming a head amplifier rms noise of 1 nV/√Hz and a 70 pF single electrode to ground capacitance, measurements are made with a resolution of 0.5 mm for a full scale of 50 mm (the radius of the vacuum chamber is not fixed yet, but should be about 40 mm) over the entire intensity range. In analogy with one of the possible solutions for the synchrotron beam position measurement system [28], it is proposed to use fast digitizers to acquire the pick-up signals. The efficient and safe operation of the injection line would benefit of at least seven on-line measurements (~ 1 monitor/straight section) in the positions that are the most critical for the beam transport. The exact position will be determined as soon as the definitive optics is available.

A scintillation screen plus a TV camera in the long straight section is proposed to help the accelerator operators to get an immediate feeling of the beam position, size and intensity independently from the control system.

### 3.3 BEAM CURRENT MEASUREMENT

The beam current monitoring system is required to monitor the current at the linac exit, the carbon ion stripper efficiency and the efficiency of the beam transport. Monitors n$^0$ 1 and n$^0$ 2 of Figure 8 are used for the first two purposes, while monitors n$^0$ 1, n$^0$ 3 and n$^0$ 4 serve the third aim.

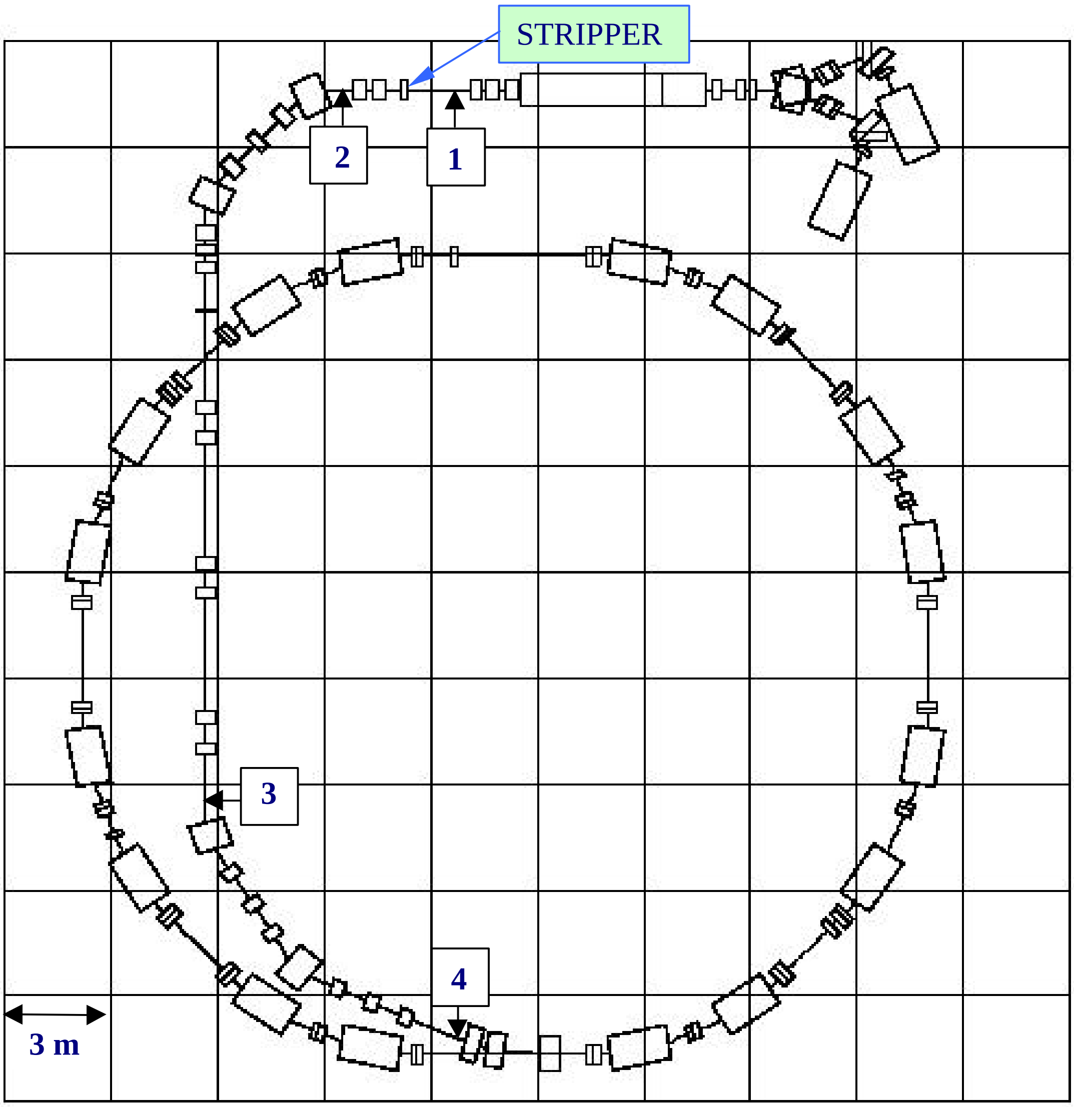


***Figure 8*** *Injection line layout with the beam current monitoring system.*

Fast current transformers (FCT) are foreseen to monitor the beam current and longitudinal profile. The FCT for the injection lines of the CERN PS Booster, was designed for beams with parameters similar to medical beam ones ($Pb^{53+}$ ion beam of 4.2 MeV/u kinetic energy and 20 µA intensity for a 400 µs long pulse and proton beam of 50 MeV kinetic energy and 180 mA intensity for a 10 µs long pulse). The transformer works in two ranges: one for protons with 200 mA full scale and resolution < 1 mA and the other for ions with 20 µA full scale and resolution < 2 µA.

The latter range can be increased easily [29]. The specifications of a typical FCT developed for the GSI (Darmstadt) [21] also fulfil the requirements at injection as the quoted resolution for 10 μA range and 100 kHz bandwidth (pulse length ~30 μs) is 100 nA.

### 3.4 BEAM HORIZONTAL AND VERTICAL EMITTANCE MEASUREMENT

The horizontal and vertical beam emittance in the injection line is measured with the technique of phase space scanning. A movable slit, that selects a narrow slice in x (the transverse coordinate), is positioned where the beam is wide in the plane in which the emittance is to be measured. The slice is left to diverge over a drift space. Its extension in x' is thus transformed into an extension in x, measured with a profile detector. The same procedure is repeated moving the slit across the beam; for every extension of x, the extension of x' at the slit is obtained and the emittance can be reconstructed.

A possible alternative method for single pulse emittance measurement based on "multi-slit" technique is described in Reference [23]. The movable single slit solution is adopted here so to use the slits in close position as beam stoppers. These latter are needed to separate the linac ($n^0$ 1 of Figure 9) and the synchrotron ($n^0$ 6 of Figure 9) from the injection line and to stop the beam after the stripper and protect the RF cavity ($n^0$ 2 and $n^0$ 4 of Figure 9 respectively). The slits before the dipoles are also used to determine the beam momentum spread (see Section 3.5).

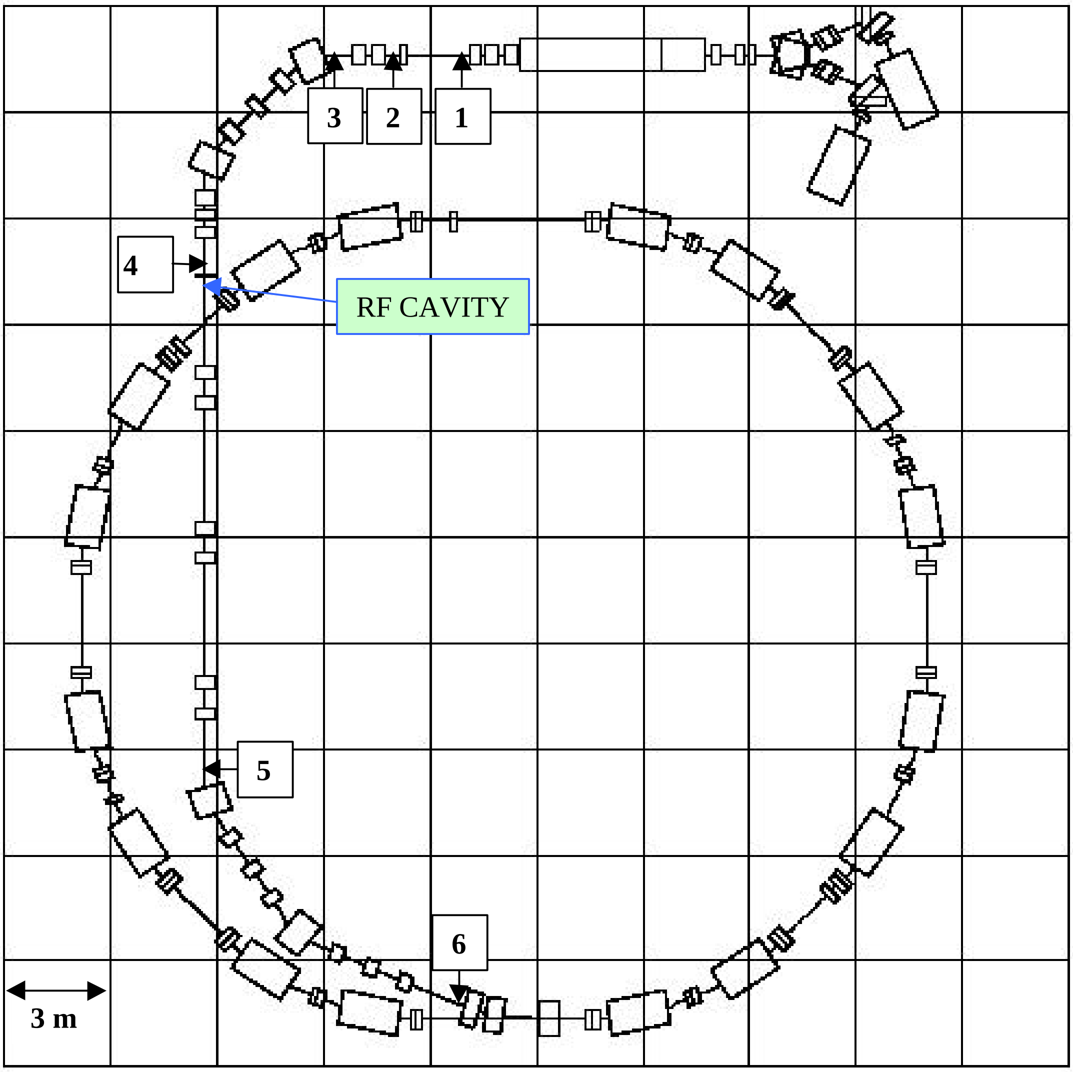


*Figure 9* *Injection line layout with the slit-beam stopper system.*

### 3.5 BEAM MOMENTUM SPREAD MEASUREMENT

Slit n$^0$ 3 and n$^0$ 5 of Figure 9 together with profile monitors n$^0$ 4 and n$^0$ 10 of Figure 7 are used to determine the beam momentum spread at the linac exit and after the RF cavity respectively.

### 3.6 BEAM LOSSES MEASUREMENT

The injection line will be provided of 5 beam loss monitor in correspondence of each bending plus one monitor close to the injection septa, the more critical zone for beam losses. It is also foreseen some moveable device with long cables (see Section 2.5) that can be positioned according to specific needs. The type of monitor to detect the onset of beam losses will be chosen once the detailed simulations of beam losses and secondary particles production at injection energy will be carried out. As for the extraction lines, these monitors are used to alert the accelerator operators every time there are serious problems that lead to the loss of the beam.

# 4. CONCLUSIONS

The beam monitoring system for the PIMMS extraction lines includes:

- 21 scintillation screens (CsI) + CCD camera;
- 1 scintillation screen + TV camera;
- 10 watchdogs;
- 5 thin SEM foils for ‘on-line’ intensity measurement;
- 4 Faraday cups;
- 10 beam loss monitors.

The beam monitoring system for the PIMMS injection line includes:

- 13 scintillation screens (Li-Glass) + CCD camera;
- 1 scintillation screen + TV camera;
- 7 electrostatic pick-ups;
- 4 fast current transformers;
- 6 movable slits;
- 5 beam loss monitors.

Up to a certain extent, it was possible to maintain homogeneity in the choice of instrumentation for injection line, extraction lines and synchrotron. For example, scintillation screens are proposed for position and profile measurement in both injection and extraction lines diagnostic systems. Also electrostatic pick-ups in the injection lines are proposed in analogy with the beam position measuring system of the synchrotron.

The choices summarised in the two lists above were dictated by the criterion to use standard and tested instrumentation. Nevertheless, the use of new monitors for on-line measurement of beam position and profile in the extraction lines are kept as the best alternative solution as they guarantee the maximum safety to the patient and makes operation of the accelerator complex more efficient. Tests with a medical beam in terms of position, profile and intensity measurement and perturbation of the detector to the beam are foreseen. If the results are positive, these detectors will replace in the extraction lines the 10 watchdogs and most of the scintillation screens.

Beam loss monitors are not used to directly operate the accelerator, but have the function of alarm in case of serious problems that lead to the loss of the beam. This role is particularly critical in a hospital-based environment, where the radiation level should be kept as low as possible and not much time can dedicated to machine developments.

## ACKNOWLEDGEMENTS

This work was performed at CERN, within the framework of the Proton-Ion Medical Machine Study. I would like to thank the PS beam diagnostics group for their continuous support and help during my stay at CERN. I am particularly indebted to Jacques Bosser, Michel Chanel, Remo Maccaferri, Gianni Molinari of the LEAR team and to Heribert Koziol (PS Division) and Gianfranco Ferioli (SL Division, BI group) for many useful discussions and suggestions.

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