METHODS FOR MEASURING THE TRANSVERSE BEAM PROFILE IN THE ESS HIGH INTENSITY BEAM

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Abstract

The European Spallation Source (ESS), currently under construction, consists of a partly superconducting linac which will deliver a 2 GeV, 5 MW proton beam to a rotating tungsten target. Beam transverse profile monitors are required in order to insure that the lattice parameters are set and the beam emittance is matched. Due to the high intensity of the beam and the constraint to perform non-disturbing measurements, non-invasive techniques have to be developed. The non-invasive profile monitors chosen for the ESS are based on the interaction of the beam with the residual gas. Two different devices are developed, one utilises the fluorescence process, the other one the ionisation process. The paper presents their latest preliminary developments.

INTRODUCTION

The ESS [1] is a multi-disciplinary research centre based on the world's most powerful neutron source. With an average flux of 1.6×10^{15} neutron cm^{-2} s^{-1} and a peak flux of 40×10^{15} neutron cm^{-2} s^{-1}, ESS will be around 30 times brighter than today's leading facilities. The spallation will occur by bombarding a tungsten target with protons accelerated by a linac up to 2 GeV with an average power of 5 MW. The ESS accelerator, illustrated in Fig. 1, consists of:

- an ECR source which will produce 75 keV protons,
- a warm linac part consisting of a Low Energy Beam Transport line (LEBT), a Radio Frequency Quadrupole (RFQ), a Medium Energy Beam Transport line (MEBT) and a Drift Tube Linac section (DTL), which will accelerate the protons up to 90 MeV,
- a cold linac part, made of a spokes section and elliptical cavities (called Medium β and High β) which will accelerate the protons up to 2 GeV,
- a High Energy Beam Transport line (HEBT) and an upgrade part which transports the beam to the target.

The linac will create a pulsed beam with an average pulse current of 62.5 mA, pulse duration of 2.82 ms and repetition rate of 14 Hz.

In beam diagnostics, it is important to measure the beam transverse profile in order to insure that the lattice parameters are set properly and the beam emittance is matched. Two different kinds of devices are currently been designed [2, 3] for the ESS linac, an invasive and a non-invasive one, which will both be located in the same module. The invasive device will be a wire scanner [4] and will be used during the commissioning at low beam current and short pulse. However the invasive system would get damaged by the beam at its full power, therefore the non-invasive profile monitors are being developed as well in order to provide the profile information without disturbing the beam during normal operation.

NON-INVASIVE TRANSVERSE PROFILE MONITORS

The ESS Non-invasive transverse Profile Monitors (NPMs) [5] are based on the interaction processes between the proton beam and the vacuum chamber residual gas, primarily composed of H_2 (65-80%) and the rest being a mixture of CO, CO_2, CH_4, Ar and H_2O. They exploit the secondary excited/ionised particles produced by these interactions to reproduce the transverse profile. For the ESS linac, two designs are being developed. The main parameters influencing the design are the residual gas pressure in the vacuum chamber, the excitation/ionisation cross sections between the primary proton beam and the hydrogen molecules and the space allocated for the devices.

In the warm linac and HEBT, Beam Induced Fluorescence monitors (BIFs) will be used. While the cold linac will host Ionization Profile Monitors (IPMs). The position and the number of the NPMs along the whole linac are showed in Fig. 1. Both technologies are already well developed by others facilities [6–9] however they have to be adapted to the ESS main constraints i.e. the beam intensity, the H_2 residual gas and the radiation level.

BEAM INDUCED FLUORESCENCE PROFILE MONITOR

In the warm linac, the main constraint is the 10 cm available space for the NPM. The BIF monitor [10], based on the fluorescence emission of the excited residual gas, is a good choice to that issue as both horizontal and vertical profile measurements can be performed at the same place. Furthermore, its optical design is quite simple and can be easily changed, since all the device components, except for the beam pipe viewport, are outside the beam pipe.

For this monitor, the major worries are the light yield level and the optical design. If the first question will be partially answered below, the second has still to be addressed as it is strongly depended on the ambient radiation levels which still have to be studied.

Fluorescence Light Yield

As previously said, the residual gas present in the beam pipe is expected to be composed of 65-80 % of H_2. In the warm linac and the upgrade part, the pressure is expected

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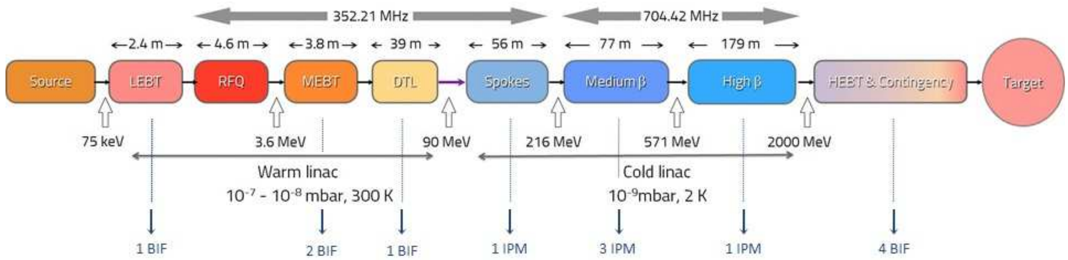

Figure 1: Schematic of the ESS linac and layout of the NPMs.

to be 10^{-7}–10^{-8} mbar and the temperature 300 K. One issue currently studied for the development of the BIF is the fluorescence yield and the H_2 wavelength spectrum. From the work of B. Pottin [11], the more intense spectral lines of the H_2 residual gas are expected to be the Balmer lines from the atomic hydrogen, see Fig. 2. His experiments were performed with 95 keV protons. For such energy, the dissociation cross section is much higher than the excitation one. Therefore the fluorescence process coming from the secondary hydrogen atom, produced by the dissociation of the hydrogen molecule, is much more probable than the one coming from the H_2. The cross section at 95 keV for the production of the H_α Balmer line (wavelength = 656.2 nm) is $\sigma = 3.4\ 10^{-18}$ cm^2.

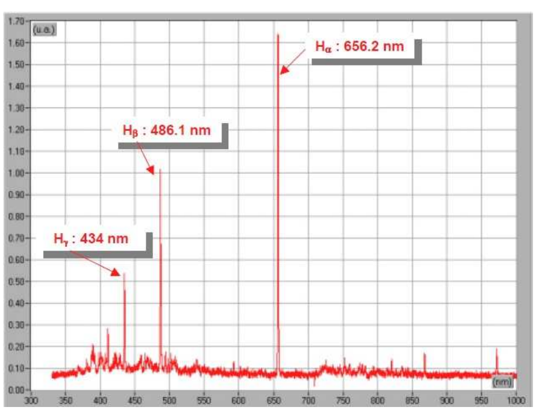

Figure 2: Spectrum analysis of a residual gas composed of 98 % of H_2 [11].

The number n of H_α photons produced per N_{inc} incident particles is given by $\sigma \cdot \rho \cdot N_{inc} \cdot L$, where ρ is the H_2 residual gas density and L the gas length through which the beam is passing.

With the result of B. Pottin, a first estimation of the H_α light yield can be performed at 95 keV. The gas density ρ is calculated from the ESS linac parameters by transforming the well-know ideal gas law

$$\rho = \frac{p}{\mathrm{R} \cdot T} \cdot \mathrm{N_A}$$

where p and T are respectively the pressure (10^{-7}–10^{-8} mbar) and the temperature (300 K) in the beam pipe, R is the ideal gas constant and $\mathrm{N_A}$ the Avogadro number. Table 1 presents the photon flux produced by a 95 keV beam pulse (1.1×10^{15} protons) passing through a gas of 1 cm length. In the worst case, (10^{-8} mbar and 65% of H_2), $6{\times}10^5$ photons would be produced with a wavelength of 656 nm.

Table 1: Estimation of H_α Photons Flux Produced by a Pulse of 95 keV Protons Passing Through the H_2 Gas

p **[mbar]**	ρ_{H_2} **[cm^{-3}]**	n **[photons/s]**
10^{-8}	$1.57\ 10^8$	$5.87\ 10^5$
10^{-7}	$1.57\ 10^8$	$5.87\ 10^6$
10^{-8}	$1.93\ 10^8$	$7.22\ 10^5$
10^{-7}	$1.93\ 10^8$	$7.22\ 10^6$

This calculation gives a first approximation of fluorescence yield for the low energies. As the warm linac accelerates protons from 75 keV to 90 MeV, further investigations have to be done to approximate and measure the fluorescence yield at higher energies.

IONIZATION PROFILE MONITOR

In the cold linac, the pressure is expected to be 10^{-9} mbar and the temperature 3 K. For this part of the accelerator, another type of NPM has to be used since the gas density is lower than in the warm part and so less secondary particles will be produced. Therefore, more space is allocated for the devices between the cryogenic modules than in the warm linac.

The IPM monitor is based on the secondary charged particles production during the interaction of the beam with the residual gas in order to obtain the profile of the beam. In the current model [5], shown on Fig. 3, these secondary ions are accelerated by an electric field from the centre of the device to a scintillator screen. Outside the beam pipe, an optical system collects the photons produced by the screen. Currently the electric field is produced via 2 symmetric plane electrodes on which a voltage of ± 30 kV is applied and lateral electrodes keep the electric field straight. The dimensions of the electric cage (10 cm × 10 cm × 10 cm) are restricted by the size of the tank hosting the transverse profile monitors and the space taken by the wire scanner. 327 mm in the spoke section and 359 mm in the Medium β and High β are allocated for the two IPM devices. In both cases the diameter of the tank is 246 mm.

Due to the expected energy deposition on the collecting plate which could easily damage electronic components,

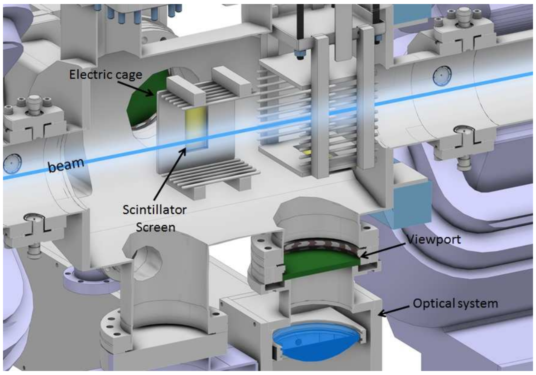

Figure 3: Longitudinal cutting plane of the current IPM monitor design.

scintillator screens [5] are preferred to collect the secondary ions. Like in the case of the BIF, the radiation background will influence the choice of the screen and the optical system design.

Space Charge Influence on the IPM Design

The electric field created by the IPM cage has two purposes. The first one is, as said before, to accelerate the secondary ions to the scintillator screen. The second one is to decrease the bunch space charge effect which disturbs the ion trajectory and distorts the profile. In order to determine the electric field required to compensate the space charge effect, rough approximations were previously made [3] and came to the conclusion that the electric strength should be around 600 kV/m.

To support that result, more detail calculations were performed. First, the dynamic electric field strength produced by a moving bunch in the IPM was simulated with the use of the Particle-in-Cell (PIC) solver of the CST STUDIO SUITE software [12]. After extraction of the electric field components calculated by CST, a custom made MATLAB routine was used in order to track H^+ secondary ions until they reach the screen in the total electric field, composed of the beam dynamic electric field and the static electric field of the IPM cage. The tracking was finished when the ions reached the screen. The static electric field of the IPM cage was chosen to be perfectly straight in these simulations[1].

The CST simulations were performed with the following parameters:

- 500 MeV, 1 GeV and 2 GeV bunches were simulated where one-side RMS bunch lengths of 6, 4.5 and 3 ps are respectively expected,
- the proton bunch was assumed to have a 3D gaussian distribution of charge with an RMS size equal in both vertical and horizontal planes to 2.2 mm,
- the total bunch length (distance between two bunch) is 2860 ps.

[1] When the best suitable field will be selected, simulation with the Electrostatic solver of CST will be performed in order to take in account the imperfections of the static field in the tracking of the secondary particles.

An example of the calculated electric field is shown on Fig.4 and the maximum electric field strength at the longitudinal centre of the bunch produced by a bunch for the three considered energies is shown on Fig. 5.

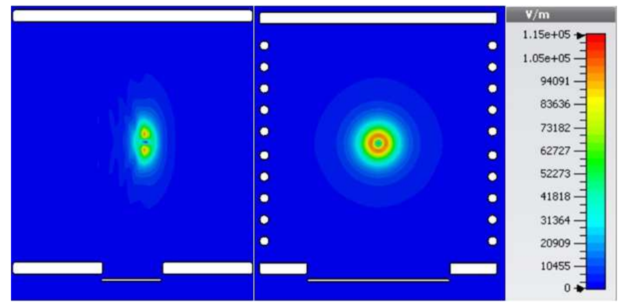

Figure 4: Calculated bunch dynamic electric field strength in the IPM cage for the 500 MeV proton beam. From the left to the right: longitudinal and transverse cutting plane.

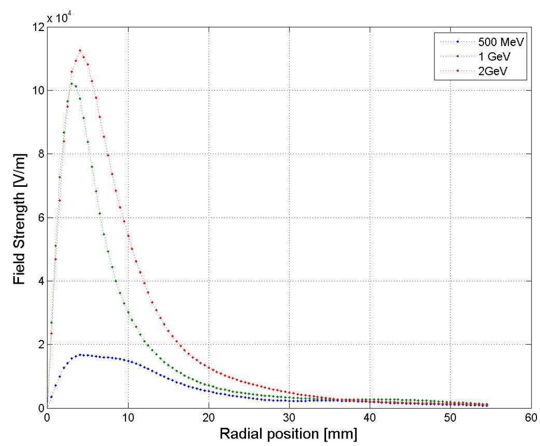

Figure 5: Maximum electric field strength at the longitudinal centre of the bunch produced by a bunch for three different energies.

For the MATLAB tracking, the parameters were:

- the secondary particles were created on a 2D plan, transverse to the beam trajectory, with a 2D Gaussian distribution of 5 RMS radius. This 2D tracking is a first approximation and a fully 3D tracking is planned in the future.
- the H^+ ions were tracked in 4 different static electric fields: -600, -300, -150 and -50 kV/m.
- the tracking finished when the particles arrive at the screen, i.e. at 57 mm of the centre of the beam.

Table 2 presents the maximum transverse deviation with respect to the expected position without space charge effect of the secondary particle. Even for -50 kV/m the deviation is not significant. Therefore it is planned to perform simulations where the field is gradually decreased to te point where the static electric field stops to compensate the space charge effect.

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Table 2: Maximum Deviation of an H^+ Ion Present in the Beam Pipe at 57 mm of the Centre of the Beam

Beam Energy [GeV]	Cage electric field strength [kV/m]	Deviation [%]
0.5	-600	0.09
0.5	-300	0.13
0.5	-150	0.18
0.5	-50	0.31
1	-600	0.02
1	-300	0.03
1	-150	0.05
1	-50	0.08
2	-600	0.08
2	-300	0.08
2	-150	0.17
2	-50	0.20

These results show that the electric field which has to be applied on the IPM electrodes could be significantly reduced. However the results are preliminary and are planned to be rechecked. But the result may be explained with the fact that ions are affected by the bunch space charge only in a small fraction of the drift length(approximately 5 RMS). The fact that the expected ESS bunches are short additionally supports these results since short bunches lead to short time for ions to be influenced by the space charge compared to the whole drift time.

CONCLUSION AND FUTURE WORK

Two designs are currently under development for the ESS NPMs. The first one is a BIF monitor which will be used in the warm linac and the HEBT section. The fluorescence yield at 95 keV for the Balmer line is expected to be at around 6×10^5 photons/(s cm). Additional investigations have to be performed in order to estimate the fluorescence yield at higher energies. The optical design, which depends mainly on the ambient radiation level, will be studied in the following months as well. The second NPM type is an IPM monitor which will be used in the cold part of the linac. The preliminary study of the space charge effect shows that the perturbation of the transverse profile by the dynamic electric field of the beam is not an issue for an cage electric field strength higher than -50 keV/m. In-depth studies have to be performed to confirm these results. In parallel, scintillator screen hardness is planned to be tested and the optical device will be developed.

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