PRELIMINARY STUDY OF NON-INVASIVE BEAM PROFILE MEASUREMENTS FOR PROTON BEAMS*

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Abstract

Two non-invasive beam profile measurement methods were developed for China high intensity proton beams projects, including the CSNS and ADS. The first consists in an IPM (ionization beam profile monitor) system which detect the ionized products from a collision of the beam particle with residual gas atoms or molecules present in the vacuum pipe。 The second is an electron beam scanner which using a low energy electron beam instead of a metal wire to sweep through the beam. The deflection of electron beam by the collective field of the high intensity beam is measured. The charge density in the high intensity beam can be restored under certain conditions or estimated by various mathematical techniques. Here we present the design parameters of the IPM system, the signal intensity of ionization products, optimization of the electric field, machine designs of electrode, tracking of the ionization products and so on. The principle of the electron beam scanner and the test results which is based on a commercial electron gun from Kimball Physics are also introduced in details.

INTRODUCTION

The China-ADS project is a strategic plan to solve the nuclear waste problem and the resource problem for nuclear power plants in China. For the C-ADS accelerator that is a CW proton linac and uses superconducting acceleration structures except the RFQs, the design specifications for the proton beam is shown in Table 1. For the first phase, the project goal is to build a CW proton linac of 10 MeV and 10 mA by about 2015.

Traditional proton-beam transverse profile measurements such as flying wires or secondary emission devices involve intercepting the beam in some fashion. The flying wires don't survive the encounter with the beam. Alternatives to these invasive types include ionization based devices, which collect the ionization remnants of the residual gas. IPM system is used for various different accelerators, not only hadron accelerator[1-6], but also electron machine to measuring the size of the laser beam[7]. Another method is using a low energy electron beam instead of a metal wire to sweep through the beam[8-11].

Table 1: Specifications of the required proton beams for C-ADS.

Particle	Proton	Unit
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
RF frequency	325/650	Mhz
Duty factor	100	%
Beam loss	<1	W/m

EXPERIMENT

Electron Scanner System

When the trajectory of a charged particle brings it in close proximity to a charge distribution, e.g. a particle beam, the particle is deflected by the electromagnetic fields of the beam. The deflection of the particle is determine by the exact spatial distribution and motion of the charges, and as such, if one measures the deflection of a probe beam as it traverses a target beam, one should be able to derive information about the charge distribution of the target beam.

Figure 1(a) shows a transverse cross-sectional view of an arbitrary charge distribution in the X and Y directions and the trajectory of the electrons. Probe electrons of velocity v_x are directed horizontally from left to right ($-X$ to $+X$) at various heights Y, and acquire a velocity v_y orthogonal to v_x. For nonrelativistic beams of this nature we can assume the electron moves in such a way that $v_x >> v_y$ and thus the trajectories can be considered straight lines with a small angular deflection after passing near the proton beam. The e-beam accelerates when approaching the proton beam, and decelerates when moving away from the proton beam. However, the net velocity change in X is zero. The variation is very small, less than 1%, typically, and thus v_x can be considered constant along the e-beam trajectory.

If we define the charge intercepted by a thin wire or a slit at position y and of width dy as $dq(y)$, we have $\frac{d}{dy}\int E_y dx \propto dq(y)$ and, from the relationship between the deflection angle $\cdot$ and the y component of the electric field E_y, we have $dq(y) \propto \frac{d\Phi}{dy}$. Therefore a slit or wire-scan charge profile measurement can be related to an e-beam deflection scan measurement through its derivative.

Figure 1(b) shows the picture of the test device of the electron scanner. A Kimball Physics electron gun, model EMG-4212, step tuned, 0–20 kV, 10nA–10 μA electron current using a LaB$_6$ cathode can deliver spots down to

100 μm was used. The gun can be gated from 2 μs up to dc, with a maximum repetition rate of 5 kHz. The gun is also equipped with a focusing and steering component. The focus elements consist of three tubes in series. The first and third tubes are grounded, while the second (middle) element is at a variable, focusing potential. The steering (deflection) elements consist of two pairs of deflection plats located downstream of the focus element.
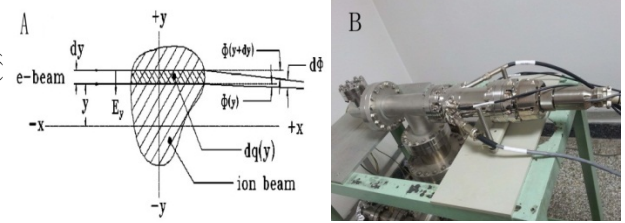

Figure 1(a) a transverse cross-sectional view of an arbitrary charge distribution in the X and Y directions. (b) The picture of test device of the electron scanner.

To produce a suitable deflection is crucial for the electron scanner, the deflection (different with or without proton) is equal to the deflection angle ˙ times L which is the distance between the electron detector and CM of the proton beam in X direction. We track the trajectory of the electron using the CST. In simulation, a static electric field produced by an electrified body is used for instead of the field of the proton beam. In order to simulate a gauss charge distribution, an elliptic cylinder is divided into several coaxial layers with different charge density. Figure 2 shows the deflection with different beam parameter and experiments set. While the electrons are similarly deflected if the scan is aligned vertically, one can no longer uniquely associate the electron path with the deflection. One must instead analyse the density distribution of the projected electrons to derive the profile[10]. A 45 degree scan can solve this problem. The results show that the lower electron beam, the higher proton current, the smaller proton size, the longer distance of detector the bigger deflection.
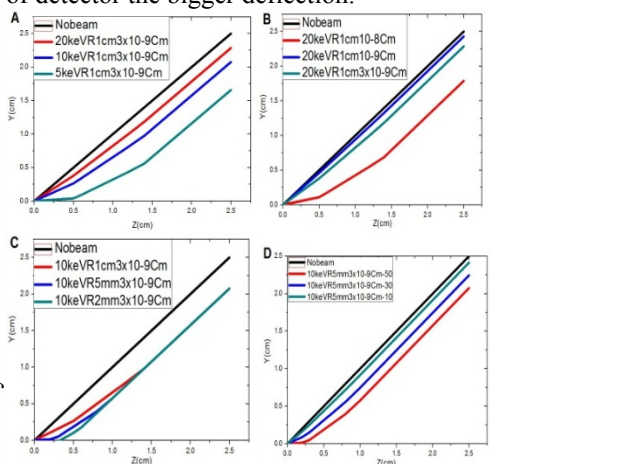

Figure 2: calculated deflection as a function of (a) the probe electron energy (b) linear density of proton which decide by the current and energy of the proton beam(c) proton beam size (d) distance between the detector and the centre of the proton beam.

Figure 3(a) and 3(b) show the test results of the electron gun. The absolute current of electron is measured by a Faraday cup and emission current is given by the power supply of the e-gun. Figure 3(c) and 3(d) are the picture of faraday cup and the mechanical design of screen which is used for profile measurements. Figure 4 shows the different spot on the screen.
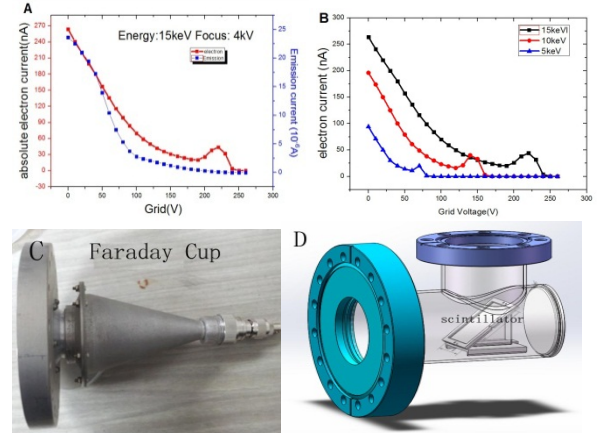

Figure 3: test results of the electron gun (a) electron beam current as a function of grid voltage (b) current of different energy (c) picture of faraday cup (d) the mechanical design of screen which is used for profile measurements.
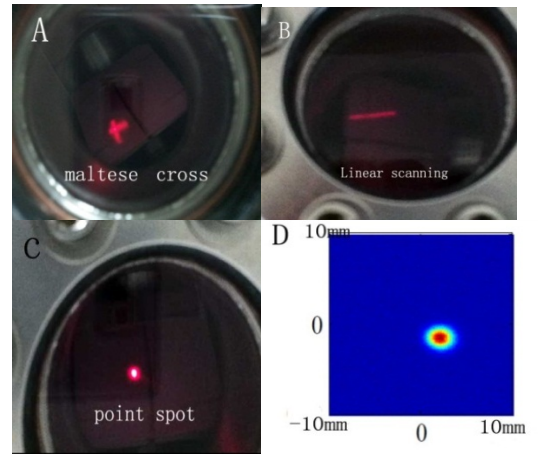

Figure 4: different spot on the screen (a)maltese cross(b)line(c)point(d)a spot below 1mm.

IPM（Ionization Profile Monitor）System

When the beam passes through the residual gas, collisions with the residual gas molecules can occur. During such collisions, the residual gas molecules can get ionized or excited. By applying an electric field, one can extract the ionization products, i.e. ions or electrons. They are accelerated towards position detectors, where the ionization current density is measured. Based on the ionization current density, the actual beam profile can be determined.

The ionization product yield is decided by the beam parameters such as the energy and current, the vacuum

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condition and the longitudinal dimension of the detector. The ionization current can be calculated by $I_{ion} = n * d * \sigma * I_{beam}$ with n being the particle density in the beam pipe, d being the active depth in which ionization occurs, σ being the ionization cross section and I_{beam} being the beam current. Ionization cross section can be derived from bethe-bloch formula. Figure 5(a) shows the stopping power of proton in H_2. We can see that the cross section will become smaller with the higher proton energy in the energy range of MeV to 1 GeV. For a typical parameter where the IPM will installed (I_{beam}=10 mA, E=3.2~10 MeV, pressure=10^{-6}Pa), the current of ionization will be several µA.

The beam profile is not measured directly, but over the ionization current. The distribution of the ionization current will be influenced by the electric field generated by the field box itself and the electric field generated by the accelerator beam during the drift towards the detector. In order to estimate the effect of different parameters, a CST simulation is using to track the trajectory of the ion of H_2. After optimization of electrode design, the last diagram of mechanical assembly and design parameter of IPM is shown in the figure 5(c) and table 2. The deliever simulation (figure 5d) results also show an acceptable transverse excursion.
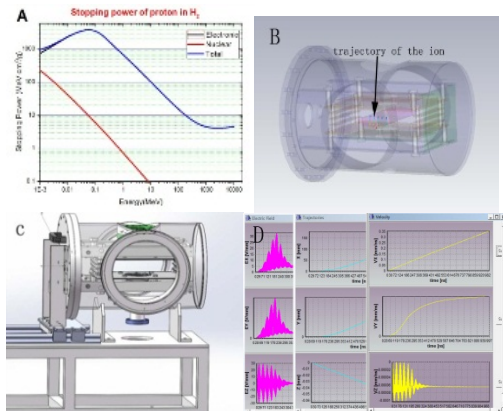

Figure 5: (a) the stopping power of proton in H2 (b) CST simulation the trajectory of the ion (c) diagram of mechanical assembly (d) Deliever simulation of trajectory of the ions.

Table 2: IPM Design Parameter of ADS Proton Injector I

Parameter	Value
electric field intensity(V/m)	1e5
Distance of two big plate (cm)	8
Size of MCP (mm)	Φ 75
Size of EGA (mm)	Φ 70
Detector	Screen + CCD
Work mode	Ions
magnetic field	0

To investigate the basic properties of IPMs, a prototype was build. Figure 6 shows the picture of IPM components, including the OFC electrodes, high voltage feed through, MCP, vacuum chamber.

Figure 6: Picture of IPM components (a) inside view of the OFC electrodes (b) external view of the chamber (c) a MCP +Screen (d) inside view of the empty chamber.

CONCLUSION

In order to measure the profile of proton beam of C-ADS which will operated in a CW mode, two non-invasive beam profile measurement methods were developed. Preliminary mechanical design and processing of IPM system have done. A low energy electron beam scanner has also been considered. A commercial electron gun has been test, a current about 1µA with a spot below 1mm have been achieved. The spot can scan in the screen with a different frequency or different range. Both are at an early stage of feasibility study and will be test on the proton beam in next stage.

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