MULTIPLE CHANNEL MEASUREMENT OF ION BEAM PARAMETERS

S.V.Alexeyenko, V.V.Kushin, S.V.Plotnikov, D.N.Seleznev, ITEP, Moscow, Russian Federation
V.P.Zubovsky, MEPHI, Moscow, Russian Federation

Abstract

The approach for measurements of particle transversal distribution that taking into account Coulomb forces as well as beam losses at walls is considered. It is based on multiple channel separator (MCS) that includes parallel narrow pipes furnished with the system of beam current collectors at output those collect particles moved through individual pipes of MCS. With step-by-step change of angles in transversal directions the 4D phase volume distribution of beam is measured. Phase volume projections on XX' and YY' planes are defined by summing of currents passed through vertical and horizontal rows. The accuracy of the approach is rather well due to beam losses at walls are essential at short input stage only. At beam separation use the phase volume configuration is close to the real at any current densities.

The method is tested at measurements of experimental injector parameters. In particular, the 11-channel separator with collimator apertures of 6 mm in diameter and 90 mm length that is able to change longitudinal axis within $\pm 8^0$ was used for emittance measurements of proton and deuteron short pulse injectors based on spark ion source. The handle switcher of channels was used for step-by-step beam study that is proposed to be substituted with the multiple channel commutator device for simultaneous measurements of all multiple beam currents during the same pulse.

1 INTRODUCTION

Development of new generation of renewable energy sources based on effective ecologically clean nuclear techniques is one of the most priority problems of power generation. As one of main directions the realization of closed nuclear fuel cycle (CNFC) may be considered. This cycle may be used in various advanced nuclear reactors and first of all at fast reactor with lead heat-transfer agent which is under development in Russia [1]. On this way it is necessary to create means of non-destructive periodical check of heat producing elements (HPE) highly irradiated during their exploitation. In ITEP it was suggested to use for these purposes the source of nanosecond neutron pulses based on light ion (proton or deuteron) RF linac together with nuclear measurement equipment. The spectral compound of tested HPE may be defined by analyzing both gamma and neutron spectra those may be measured at irradiation of given HPE with fast neutron beam.

Creation of nanosecond pulse source of fast neutrons based on light ion RF linac is the most critical part of the facility. Spectra of HPE components at its irradiation by fast neutrons are recorded by nuclear detecting equipment [2]. In pulse regime of work the required value of accelerated beam current is estimated by 0.5-1.0 A. It supposes the use of multiple channel accelerator structure. The scheme of HPE inspection is shown in fig.1 [3].

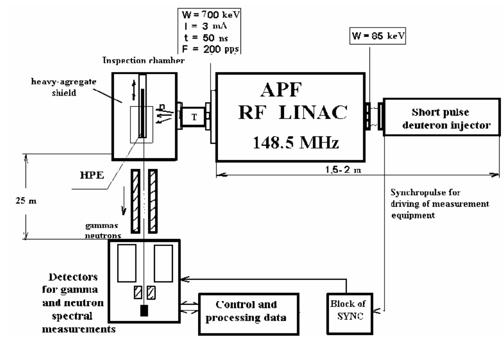

Fig.1. Functional scheme of measurement complex for HPE inspection

The realization of the approach is based on 19-channel accelerator structure with alternating phase focusing (APF) that accelerates of 50 ns pulses of deuterons to 0.7 MeV. In this work we consider the approach for measurement of transversal parameters of beams those are supposed to be used in multiple channel accelerator structures.

2 MEASUREMENT OF ION BEAMS TRANSVERSAL PARAMETERS

For analysis of beam current phase density it is necessary to measure beam current as well as projections of beam 4-D phase volume on a phase plane. Here the method is considered that is based on direct measurements of transversal velocity distribution of particles. The method takes into account Coulomb force, dissipation on walls, etc.

Let the set of narrow parallel pipes called hereinafter multiple channel separator (MCS) is placed on the beam path (see fig.2).

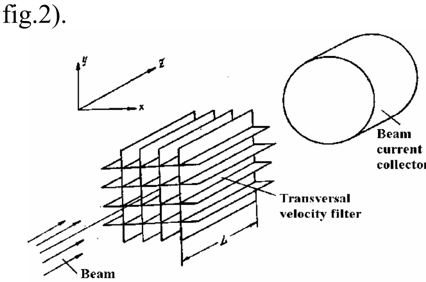

Fig.2. Schematic view of measurements.

The system of independent beam current collectors is established at the output of MCS. Every the collector catch a part of beam current that passed through a separate pipe (or several pipes) of MCS. Every the pipe cuts from a total beam only the particles with specific transversal co-ordinate (x_n,y_m) that is determined by a position of the pipe in MCS as well as with specific transversal velocity (x'_k,y'_l), that is determined by the slope of the MCS to the beam axis.

If the axis of MCS is located at an angle of φ_k to the horizontal plane XOZ as well as at an angle of ψ_l to the vertical plane YOZ, through any of the MCS channel in the given position x_n y_m will pass ions with the same transversal velocities as follows:

$$x'_k = \beta_z \cdot c \cdot \varphi_k \,, \qquad y'_l = \beta_z \cdot c \cdot \varphi_l \,.$$

Here $\beta_z \cdot c$ is a longitudinal velocity of ions.

If the value of cross section of a separate channel is $\Delta x \cdot \Delta y$ and the length of MCS is L the particles those passed through the channel with co-ordinates (x_n,y_m) will occupy in the 4D phase space of XX'YY' a voxel of ($\Delta x \cdot \Delta y \cdot \Delta x' \cdot \Delta y'$) in the vicinity of the point with co-ordinates (x_n,x'_k,y_m,y'_l). The ratio of measured current to the given voxel of the phase volume is the phase density of the beam current in the vicinity of the indicated point. The distribution of phase density of the beam in the cross-section of $x' = x'_k$, $y' = y'_l$ is determined by results of measurement of beam currents passed through each of the MCS channels (see fig.3).

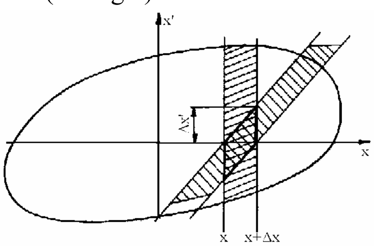

Fig.3. Element of phase volume projection on axis XX'

The beam distribution within all the 4-D phase volume is determined as a result of step by step changes of angles in both transversal directions. The projections of this phase volume to the plane YY' are determined by summation of beam currents those passed on MCS horizontal rows and the projection to the plane XX' - by summation of beam currents on vertical columns of channels. The spectrum of transversal velocities, that is the projection of the phase volume to the plane X'Y' is determined by measurements of total current that passed through all the MCS channels. It is the procedure of 4D phase volume of beam as well as its projections measurements. The photo of the device that is based on this approach is shown in fig.4.

Both a proximity of pipe walls and Coulomb force have an effect on the accuracy of measurements. These factors may be taken into account as follows. Let ions those are passing through the MCS pipes produce a bulk charge that is distributed uniformly within a pipe cross section.

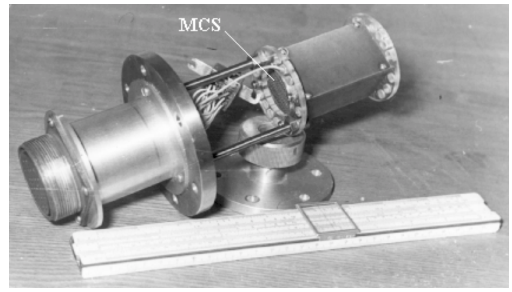

Fig.4. Photo of measurement set.

The solution of Poisson equation for rectangular area with boundary conditions at conductive walls is known. The analysis of the solution has shown that within all the considered area the field of Coulomb force exceeds the field that is caused by walls effect. That is why for the worst case the electric field strength is adopted equal to the double value of Coulomb forces field:

$$E_x = \frac{\rho(z) \cdot x}{\varepsilon_0}, \qquad E_y = \frac{\rho(z) \cdot y}{\varepsilon_0}. \qquad (1)$$

In non-relativistic approaching the equations of particles motion may be written in the following form:

$$\frac{d^2 x}{dz^2} = \frac{2 \cdot J(z) \cdot x}{\beta^3 \cdot I_0}, \qquad \frac{d^2 y}{dz^2} = \frac{2 \cdot J(z) \cdot y}{\beta^3 \cdot I_0}. \qquad (2)$$

Here I_0 is the value of a characteristic current that is equal to $3{,}14 \cdot 10^7$ A for protons.

There is a beam spreading due to thermal spread of particle velocities. So the value of the beam current in a channel I(z) is reduced with particles settling at pipe walls. The solution of the eq. (2) is only possible by direct computer calculations. However for estimation of the accuracy of measurements it is possible to simplify the situation taking into account only the beam divergence due to particles thermal velocities. The losses of particles are supposed to be more moderate in this case so the influence of the beam field contribution exceeds the real value. The radius of beam envelopes due to thermal velocities may be calculated according to the ratio:

$$\left(\frac{r}{\Delta r}\right)^2 = 1 + \left(\frac{E}{R} \cdot \frac{z}{\Delta r}\right)^2 \cdot \left(1 - \frac{x_n^2 + y_m^2}{R^2}\right) = 1 + F^2(z).$$

The value of beam current *J(z)* in eq.(2) is defined as follows:

$$J(z) = \frac{J_0}{1 + F^2(z)}.$$

The transversal motion equations may be rewritten in the form:

$$\frac{d^2 x}{dz^2} = \frac{2 J_0 x}{\beta^3 I_0 (1 + F^2(z))}, \qquad \frac{d^2 y}{dz^2} = \frac{2 J_0 y}{\beta^3 I_0 (1 + F^2(z))}.$$

The Coulomb field influence on particle motion is rather moderate due to small cross sections of MCS channels. So the solution may be written in the form:

$$x_{out} = x_{in}\cdot(1+a(B)) + x_{in}'\cdot L(1+b(B)),$$
$$y_{out} = y_{in}\cdot(1+a(B)) + y_{in}'\cdot L(1+b(B)),$$

Here $B = 2J/(\pi^2\cdot\beta^2\cdot\varepsilon^2)$ is the beam brightness, $x_{in}, x_{in}', y_{in}, y_{jn}'$ and x_{out}, y_{out} are the transversal coordinates and velocities of particles at input and output of the separator accordingly. The values of factors a(B) and b(B) are rather complicated so they are not shown here. The Coulomb repulsion contribution may be neglected down to B ~ 10^6 A/(cm^2·rad^2) at $\beta \sim 0{,}05$. For example, at ε = 10 cm·mrad the permissible value of a measured beam current is 1A, and at ε = 5 cm·mrad the permissible value of beam current is 200 mA.

The accuracy of measurements of the considered method seems to be rather good even at high values of current density due to the fact that beam losses at the MCS walls are essential only at the short input segment. The application of beam separation affects on measurement of phase density. In particular, at measurements of beam emittance according to beam spreading along drift segments the Coulomb repulsion of particles increases the value of emittance of a measured part of beam.

Therefore the value of measured emittance appears to be overrated in contrast with the true value. In case of particles separation the phase portrait configuration is in agreement with the true value at any current densities. Thus the value of phase density appears overestimated due to part of particles settling at walls of the MCS pipes. The remaining factors, such as dissipation of particles on walls of channels, influencing of a bulk charge due to multiplier electrons, do not render essential influencing on accuracy of measurements.

3 SCHEME OF MEASUREMENTS

In fig.5 the scheme of device for emittance measurements is shown.

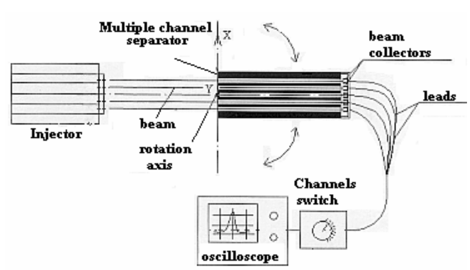

Fig.5. Scheme of beam emittance measurements.

The MCS is mounted within the frame that gives angles to the beam axis. The MCS construction was made in two variants. The first variant is designed for measure-ments of pretty nice beams with small angular divergence. In this case the transversal sizes of the MCS cell are 1x1 mm at the set longitudinal length of 80 mm. In the second variant the 90 mm length MCS is made as a cylindrical set with 11 through holes of 6 mm in diameter within it with walls of 1.5 mm between channels. Taking into account preliminary parameters of the inspected injector based on spark ion source the method was tested with the MCS construction of the second variant (fig.6).

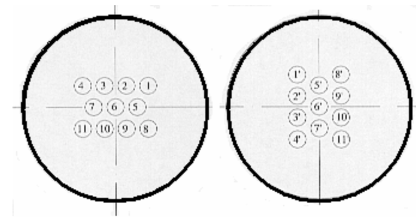

Fig.6. Configuration of beam collectors (Faraday cups) at various positions of MCS channels

At the measurements firstly the MCS was set up in parallel to beam axis. The values of beam current that passed through every the channels were measured in turn. Then the measurements were repeated at various MCS slope angles to the beam axis in both transversal directions. According to the measurement data, in fig.6 the view of the central beam core at the phase plane of XX' is shown with the drawn equal-current lines.

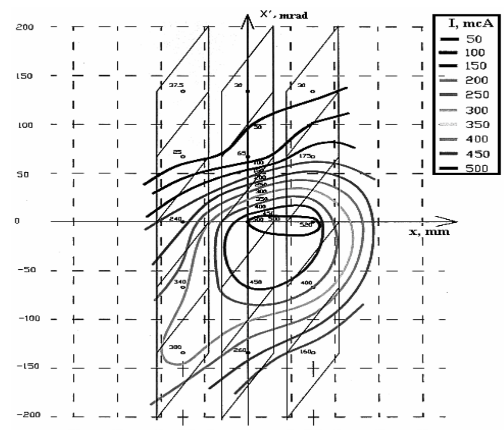

Fig.7. Lines of equal current at phase plane XX'

The fig.7 shows the beam axis is displased to the axis of the measurement system.

4 REFERENCES

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