NON-DESTRUCTIVE HEAVY METAL JET PROFILOMETER FOR HIGH POWER BEAMS*

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Abstract

"Scanning wire" is the most common method of beam profile measurement, where thin wire is transported across the beam and secondary electrons or radiation are detected. It cannot be used for beams with high power density because the wire cannot sustain a heat load. A possible solution is to substitute wire by a low-density jet of a metal vapor. Profilometers of this type were successfully used in the ion storage rings [1], but background electrons from residual gas ionization can pose a limit in a less clean vacuum environment. Alternative configuration of the device based on the separation of the jet material ions from the background is suggested and analyzed. Technical feasibility for the SNS MEBT parameters is demonstrated.

1 INTRODUCTION

The most common method of beam profile measurement is "scanning wire", where thin wire is transported across the beam and secondary electrons or scattered beam particles are detected. It cannot be used for high power beams because wire cannot sustain heat load from the beam losses in the wire. Possible solution is to substitute the wire by low-density jet of metal vapor as shown. Feasibility of this kind of diagnostics for the SNS accelerator depends on the following factors, which are considered in this paper:

- current of the ionized particles from the jet (output signal)
- current of the ionized particles from the residual gas (background signal)
- working temperature of jet chamber
- consumption of the jet material

Profile monitor with magnesium jet was successfully used for heavy ion beams in the heavy ion accumulator ring [1]. Use of magnesium for the jet is not mandatory. It is chosen often because of high vapor pressure below melting point, which simplifies design of the jet chamber. Other materials with high vapor pressure at reasonably low temperature can be used and have some advantages. Materials used for comparative calculations in this note and their relevant properties are shown in Table 1.

2 IONIZATION CROSS SECTION

Energy loss due to collision ionization depends on gas properties and velocity of ionizing particle. It can be found in reference tables [2] or calculated using Bethe-Bloch energy loss formulae for protons :

$$\frac{dE}{dx} = 31\frac{MeV\cdot cm^2}{g}\frac{Z}{A}\frac{1}{\beta^2}\left(\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{\varepsilon_i}\right)-\beta^2\right),$$

where βc is the beam velocity, Z is atomic number and A is atomic mass of the ionized atom, m_e is electron mass, ε_i is ionization potential of the atom. Then cross section σ_i can be derived from energy loss per unit length:

$$\sigma_i = \frac{dE}{dx}\cdot\frac{Am_a}{w_i} \quad ,$$

where m_a is atomic mass unit, w_i is average energy required to produce an ion pair. Calculated cross sections for 2.5MeV proton beam and materials from Table 1 are shown in Table 2.

Table1. Parameters of some elements suitable for jet profilometer.

	N	Mg	Cd	In	Sb	Hg	Pb	Bi
Z	7	12	48	49	51	80	82	83
A	14	24	112	115	122	201	207	208
ε_I [eV]	14	7.6	9.0	5.8	8.6	10.4	7.4	7.3
T_{melt} [°C]	-	650	321	156	631	-39	820	217

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Table 2. Cross section of ionization by 2.5MeV protons*.

	N	Mg	Cd	In	Sb	Hg	Pb	Bi
σ_I [cm^2]10^{-15}	.13	.25	.98	1.1	1.1	1.6	1.7	1.8

*Ionization cross section for H^- is the same as for protons.

Table3. Calculated parameters of jet profilometer.

	Mg	Cd	In	Sb	Hg	Pb	Bi
I_{d0} [nA]	292	292	292	292	292	292	292
R	100	100	100	100	100	100	100
P_j [torr]	.17	.04	.05	.05	.15	.03	.025
T_j [°C]	472	271	930	564	41	725	512
F [mg h^{-1}]	510	286	255	331	207	246	213
τ [h]*	3.4	30	29	20	66	46	46

*Last row represents operational time with 1 cm^3 of material loaded to the jet chamber.

3 IONIZATION RATE AND JET PARAMETERS.

Number of ion-electron pairs per second per unit length created by the measured beam in residual gas is

$$N_{ir} = \frac{I_b}{e}\sigma_{ir} n_r ,$$

where I_b is the beam current, n_r is density of the residual gas, e is an electron charge. Number of ion-electron pairs per second per unit length created by the beam in the jet, positioned at beam maximum, is

$$N_{ij} \approx \frac{I_b(x)}{e}\sigma_{ij} n_j \frac{h_j}{h_b},$$

where n_j is density of the jet, h_j is jet width, h_b is beam width. If the collector of length L collects ionized particles, then total current in the detector is

$$i_d = I_b \sigma_{ij} n_j \frac{h_j}{h_b}(1 + \frac{\sigma_{ir} n_r}{\sigma_{ij} n_j}\frac{h_b}{h_j})L = i_{d0}\cdot(1+\frac{1}{R}),$$

where $i_{d0} = I_b \sigma_{ij} n_j \frac{h_j}{h_b} L$ is useful signal from ionized jet atoms, $R = \frac{\sigma_{ir} n_r}{\sigma_{ij} n_j}\frac{h_b}{h_j}$ is the signal to background ratio. Any noise is not taken into account here and background is assumed to be from the residual gas ionization only. Density of the residual gas is $n_r = \frac{P_r}{k_B T}$, where P_r is pressure of the residual gas, T is its temperature and k_B is Boltzman constant. Then minimal detectable current or acceptable signal to background ratio whatever is larger defines jet density at the point of interception with the beam:

$$n_j \geq \max\left\{ i_{d\min}\cdot\frac{h_b}{h_j}\frac{1}{I_b\sigma_{ij}L}, R\cdot\frac{\sigma_{ir} n_r h_b}{\sigma_{ij} h_j}\right\}.$$

Assuming that jet density is low enough to be in the molecular flow regime (in contrary to hydrodynamic one), density in the container with jet material can be estimated as

$$n_{j0} = n_j \frac{2\pi d^2}{S_0},$$

where d is distance from jet nozzle to the interception with the beam, S_0 is nozzle cross section. When density in the container is known, temperature T_j and pressure P_j can be found from equation of state for saturated vapor of jet material [3]. Average velocity of the jet atoms is $v_j = \sqrt{\frac{8k_B T_j}{\pi m_a A}}$, then mass flow rate is $F_j = n_{j0} v_j S_0$. Results of calculations for materials from Table 1 are shown in Table 3. The following parameters were assumed in calculation: residual gas pressure $P_r = 10^{-7} torr$, minimum current $i_{d\min} = 1nA$, signal to background ratio $R = 100$, beam width $h_b = 3mm$, jet width $h_j = .1mm$, jet chamber outlet cross section $S_0 = .2mm\cdot 10mm$, distance from container to the beam $d = 20mm$, length of the detector along the beam $L = 10mm$.

As one can see from this Table the flow rate of the jet material have to be unacceptably large in order to provide the required signal to background ratio of 100. The reason is large pressure of residual gas leading to large background current. Typical pressure in ion storage ring is about three orders of magnitude less, which allows successful operation of Mg jet devices.

We can conclude that profilometer based on metal vapor jet can not work in the SNS MEBT environment if used in standard configuration. But it can work in modified configuration suggested below.

4 MODIFIED JET PROFILOMETER

It was shown that high pressure of residual gas prevents jet profile monitor from normal operation, because the beam ionizes atoms of the residual gas as well as atoms of the probe jet. If the detector can distinguish ionized atoms of the residual gas from ions of the jet we can suppress background and reduce necessary jet density. It can be achieved if

1. Detector collects ions instead of electrons.
2. Atoms of the jet have mass considerably different from mass of atoms of the residual gas.
3. Velocity or mass selection is provided in the detector.

Jet parameters calculated for the same parameters as in the previous section but in assumption of 99% suppression of background from the residual gas are shown in Table4. Demands to the jet generator can be relaxed considerably. As seen from the Table 4, Mg is not the best choice of jet material for this scheme. The best material can be bismuth. It has large atomic number and large atomic mass. Large Z leads to large ionization cross-section, while large A makes separation from residual gas easier. Note that Bi is very environment friendly material in contrast to many other heavy metals. Operational time with 1 cm^3 of Bi in the container of about 5000 hours and working temperature of about 420°C are very reasonable from the practical point of view. Background suppression of 100 assumed in the calculations above can be easily achieved by using uniform magnetic field as a simple spectrometer. If more advanced device is used, then much higher separation can be achieved, comparable to separation of 10^4 - 10^6 readily achievable in commercial RGAs. It opens wider possibilities for use of the jet profile monitor:

1. For fixed jet density achievable dynamic range of measured beam density can be made very large, allowing measurement of the beam halo. (Dynamic range is limited by dynamic range of the detector that can be of the order of 10^4 - 10^6, as in common RGA..)
2. For fixed dynamic range of moderate magnitude of 10^2-10^3, jet density can be made very small (limited by the detector sensitivity). It allows to reduce the risk of contamination of clean environment by stray jet material or to use high temperature materials matched to environment (for example niobium jet near superconducting niobium cavity.

5 CONCLUSION

Calculations show that jet profile monitor in standard configuration (Mg jet profilometer) cannot work in the SNS MEBT environment because large background current due to relatively high pressure of the residual gas leads to necessity of unacceptably dense jet. However, if heavy metal is used for jet and ions are collected instead of electrons, then velocity filter or mass separation can be used for background suppression and jet monitor becomes technically feasible for the SNS MEBT. Bismuth can be the optimum choice for jet material. It has high atomic number and therefore large ionization cross-section moreover its large atomic mass simplifies separation from residual gas atoms. Potentially large dynamic range of jet profilometer with mass separation makes it suitable for beam halo measurements. Risk of contamination of the accelerator by the jet material also can be reduced substantially.

6 REFERENCES

[1] A.V. Bublei et al., "Magnesium jet profile monitor", HEACC'98
[2] http://physics.nist.gov/cgi-bin/Star/ap_table.pl
[3] "Handbook of physical quantities", 1991.

Table 4. Calculated parameters of the modified jet profilometer.

	Mg	Cd	In	Sb	Hg	Pb	Bi
I_{d0} [nA]	2.92	2.92	2.92	2.92	2.92	2.92	2.92
R	100	100	100	100	100	100	100
P_i [torr]	.17	.04	.05	.05	.15	.03	.025
T_i [°C]	382	204	776	466	1.3	594	418
F [mg h^{-1}]	4.79	2.68	2.38	3.11	1.93	2.29	2.00
τ [h]*	363	3229	3072	2151	7013	4942	4899

*Last row represents operational time with 1 cm^3 of material loaded to the jet chamber.