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EMITTANCE MEASUREMENTS WITH THE CERN PS WIRE SCANNER

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Abstract

Fast wire scanners provide measurement of the profile and emittance of the CERN PS circulating beam. The first device was installed in 1985 and has been upgraded in 1994. The system is described briefly: mechanism, monitoring, electronics and controls. The effect of a measurement on the beam and on the wire are shown. The precision is discussed and the system evaluated and compared to ion profile monitors.

I. INTRODUCTION

Four wire scanners have been installed in the PS to monitor the circulating beam transverse profile and emittance. The principle is simple: A thin carbon wire crosses the beam rapidly. Secondary particles are created during the interaction. They produce a signal using a scintillator and photomultiplier placed downstream near the vacuum chamber. This signal as a function of the wire position gives the beam profile, and the emittance when the transverse β-function and the dispersion function is known. Two devices scan the horizontal plane and two others the vertical one.

These devices are used for most of the particles accelerated in the PS: electrons, positrons, protons, and antiprotons. The energy range is from less than 1 GeV to 25 GeV. The number of secondary particles is low for the lower energies, giving a noisy signal. The intensity ranges from 10^9 to more than 2×10^{13} charges (1.5 A).

The first operation took place in 1985 and was reported at the IEEE Particle Accelerator Conference in Vancouver, 1985[1,2]. A thorough upgrade was completed in 1994 when the beryllium wire was exchanged for a carbon wire and new position captors, monitors, electronics, interface and software were installed.

II. MECHANISM

Each monitor is installed in a tank using 2/3 of a PS 1 m short straight section (there are 100 straight sections in the PS). The movement is driven by a direct current motor with permanent magnet stator and printed circuit rotor (Fig.1). It is directly coupled with an angle resolver and a tachometer. Together with the crankshaft transmission to the moving assembly, this constitutes an exchangeable module. Transmission of the movement into the vacuum is done through 2 bellows with two moving rods in push-pull mode with a 7 mm stroke (Fig.2). Inside the vacuum, the fork holding the wire itself rotates around an axis driven by the rods through four rolling metal ribbons. Bearings in vacuum are made of "Vespel". The stainless steel fork prongs are designed for high rigidity and low inertia. The wire is held at both ends by insulating ceramic beads, which are fixed to leaf springs providing a 20 g tension to the wire. Insulation and connections with a vacuum feed-through allow checking the wire continuity by resistance measurement.

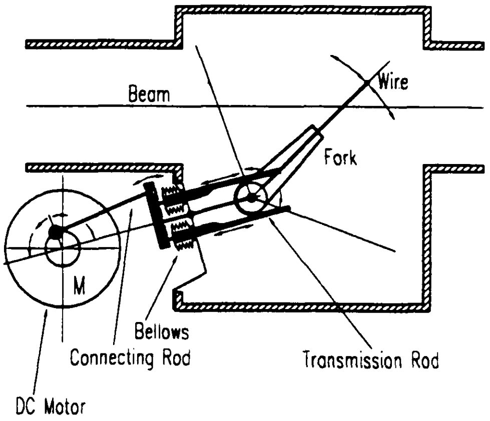


Fig.1 - Schematic view of the wire scanner mechanism

The wire is made of about 20 twisted 7 µm diameter carbon fibres, with a total equivalent diameter of 30 µm.

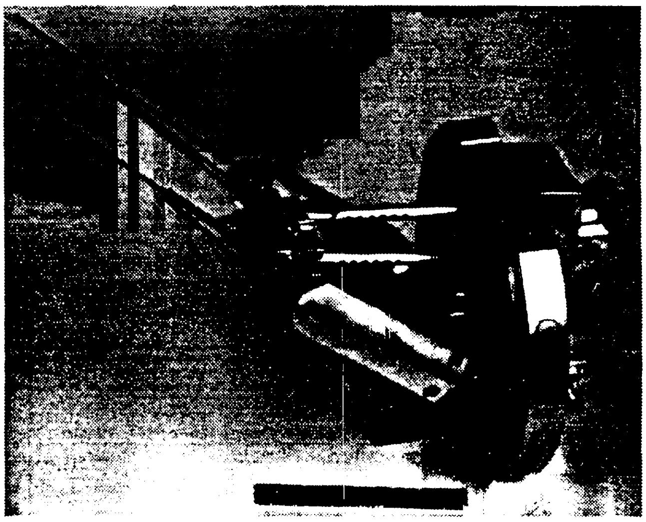


Fig.2 - The mechanical assembly inside vacuum

III. PROFILE AND POSITION DATA ACQUISITION

Two scintillators are installed near the vacuum chamber, one upstream and one downstream of each wire scanner, for profiles with both particle polarities.

Light-guides allow mounting of the photomultiplier (PM) away from the vacuum chamber so as to avoid direct radiation signals and radiation damage. They are simple straight empty pipes with reflecting walls. Carousels of optical filters moved by a stepping motor allow adjustment of the sensitivity over the large dynamic range.

Hamamatsu 2238 photomultipliers have been selected, with 12 mesh dynodes and tri-alkalide photocathodes, linear up to high output currents (600 mA). They work in proportional mode with a good linearity over a wide range. The cathode sensitivity is 60 µA/lm, and the current gain 5×10^5.

The linearity has been checked over a large dynamic range for various types of beams, with varying intensity and with the help of the optical filters. The worst results never differed from the linear fit by more than 2%, the beam intensity transformer imprecision being also included in this measurement.

The signals of the PMs in the ring are transmitted to the VME acquisition module through preamplifiers for impedance matching.

The position of the wire is measured by an 8 kHz resolver giving the sine and cosine of the motor angle, sampled synchronously with the PM signals. The geometry of the transmission gives the corresponding wire position in the vacuum chamber. The resolver is also used to control when the wire has passed the measurement range and should be decelerated.

IV. ELECTRONICS

The VME crate contains the following modules (Fig.3):

- the controller with 68030 processor,
- an 8 channel sampling ADC and its memory for the PM signals,
- an 8 channel transient digitizer for the position resolver signals,
- a 32 channel sampling ADC for real time acquisition of resolvers,
- an 8 channel DAC for the motor controls,
- a digital I/O register for various acquisitions and controls through the system,
- a "Program Line Sequencer" receiver to synchronise the measurement with the PS cycles, a high voltage power supply driver etc.

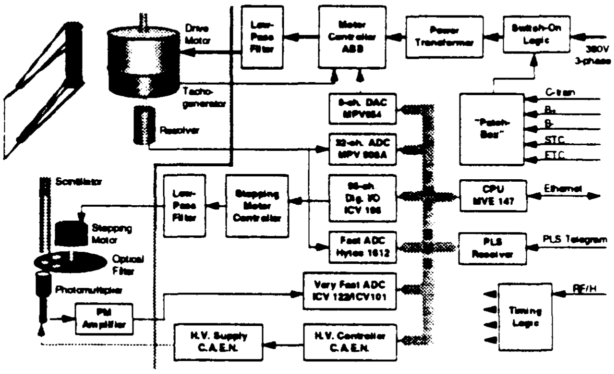


Fig.3 - Block diagram of the wire scanner electronics

The system needs additional specific electronics which essentially consist of:

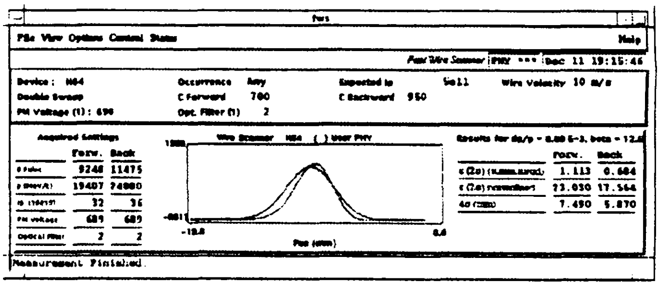
- a motor controller module and power supply to drive the fork motor,
- a stepping motor driver module for the optical filters,
- the PM high voltage power supply etc.

V. CONTROLS

The VME processor performs the specific tasks and the "equipment module" duties necessary to link the process with application programs:

1) specific software:

- input of the requirements: choice of device, plane, cycle, number of measurements, timing, wire velocity, sensitivity (which can be automatic on specification of foreseen intensity),
- measurement itself: setting of PM voltage and optical filter choice, magnetic field measurement, real time displacement of the wire, acquisition of results,
- data processing: calculation of positions from angles, elimination of the tails effects, search for distribution centre, calculation of root mean square, of σ of the distribution, of emittance, of energy from the field, and normalisation with the relativistic parameter βγ.
- output of results.



Dec 11 19:15:46

Device : H04
Double Sweep
PM Voltage (1) : 690
Occurrence Any
C Forward 700
Opt. Filter (1) 2
C Backward 950
Wire Velocity 10 m/s

Acquired Settings

	Forw.	Back
[illegible]	9248	11475
[illegible]	19407	24880
[illegible]	32	36
PM voltage	689	689
Optical Filter	2	2

	Forw.	Back
ε (2σ) [illegible]	1.113	0.684
ε (2σ) [illegible]	23.030	17.564
4σ (mm)	7.490	5.870

Measurement Finished.

Fig.4 - Application program display of results

2) remote access to and from main computer system.

An application program in the work-stations provides the interface to the device. It displays profiles and emittance values (Fig.4).

VI. PROJECTED PROFILE AND EMITTANCE

The measurement takes many revolutions, so that it only makes sense if the beam is matched to the machine acceptance. We shall therefore assume that the beam shape is a matched ellipse, and we can then carry out the following classical analysis.

The measured profile gives the projected transverse density. Calculation of the beam size including a certain fraction of the beam requires the lengthy solution of Abel-type integrals.

A usual approximation assumes that the distribution is Gaussian, with:

$$\rho_x = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}$$

In normalised phase space, the angular distribution is, likewise:

$$\rho_{x'} = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x'^2}{2\sigma^2}}$$

and the matched contours of equal density are circles c. Integrating the density inside this circle gives the fraction of particles within c:

$$\iint_c \rho_x \rho_{x'} dx dx' = N$$

with:

$$\iint_\infty \rho_x \rho_{x'} dx dx' = 1$$

Changing variables to polar co-ordinates in normalised transverse space plane allows the calculation of N as a function of the beam radius:

$$N = \iint_c \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x'^2}{2\sigma^2}} dx\, dx' = \iint_c \frac{r}{2\pi\sigma^2} e^{-\frac{r^2}{2\sigma^2}} dr\, d\theta$$

$$N = \int_0^r \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} dr = 1 - e^{-\frac{r^2}{2\sigma^2}}$$

The emittance included within the radius r is $\varepsilon = r^2$ (in π µmrad when r is in mm) so that the number of particles within the emittance ε is:

$$N = 1 - e^{-\frac{\varepsilon}{2\sigma^2}}$$

The 2σ emittance includes 86.5 % of the beam and 95 % of the particles lie within 2.45 σ.

VII. CORRECTION OF DISPERSION

The measured emittance is in fact a convolution of the mono-energetic emittance and the dispersion due to the momentum spread. If the latter is also taken as Gaussian with $4\sigma_p$ value Δp/p, then the mono-energetic emittance is:

$$\varepsilon = \frac{4\sigma^2 - \left(D\frac{\Delta p}{p}\right)^2}{\beta_t}$$

D and β_t being the dispersion coefficient and transverse β–function at the measurement location.

VIII. SENSITIVITY

The output is given by the approximate formula

$$S \cong kpI_p(1+50\, T_f)V^4$$

where S is the maximum of the acquired profile, I_r is the beam intensity, p the momentum, T_f the transmission of the optical filter, V the PM voltage. When compared with the dynamic range of the ADC converter, it gives the limits of use: 10^9 ppp with 1500 V and the 100% filter, 2×10^{13} ppp being measured with 500 V and the 5% filter. This covers the intensity range in the PS well.

IX EFFECT ON THE BEAM

Scattering

The emittance blow-up due to the beam scattering during the wire traversal is given by:

$$\Delta\varepsilon_x = \frac{\pi}{2} \frac{\beta_x d^2}{v\tau X_0} \left(\frac{15}{\beta p}\right)^2$$

where β_x is the Twiss parameter in the considered plane, d the wire diameter, v the wire velocity, τ the revolution period, X_0 the scattering length in carbon, β the relativistic parameter and p the particle momentum, units being metres, seconds and MeV/c.

Table 1 gives the blow-up calculated with this formula for three important energies during the PS acceleration:

- the standard proton injection energy, 1 GeV,
- the p-bar injection momentum, 3.5 GeV/c,
- the highest operational momentum, 26 GeV/c.

Energy or momentum	Blow-up in meas. plane	Blow-up in other plane	Normalised blow-up in measurement plane	Normalised blow-up in other plane
1 GeV	0.11 π	0.20 π	0.19 π	0.36 π
3.5 GeV/c	0.025 π	0.046 π	0.094 π	0.173 π
26 GeV/c	0.0005 π	0.0008 π	0.013 π	0.023 π

Table 1 - Emittance blow-up in µmrad
for 2σ emittances and a velocity of 20 m/s

Interaction

The collision length in the carbon wire is 34 cm, so that the proportion of particles interacting with the wire is as low as 5×10^{-5} for a wire velocity of 20 m/s. The average particle energy loss in the traversal is also very small, of the order of 5 keV, which represents a Δp/p of 7×10^{-6} % at PS injection. The intensity and energy loss of the beam can be therefore considered as negligible.

Heating of the wire

Particles lose energy during the wire traversal. This energy is partially deposited in the wire. The temperature increase is proportional to the ionisation loss in carbon and can be expressed as:

$$\Delta T = \frac{k}{C_v} \frac{dE}{dx} \frac{\beta I_p}{v\tau} \sqrt{\frac{3}{\pi\beta_z\varepsilon_z^*}}$$

where k is the fraction of ionisation loss converted into heat, C_v the heat capacity of the wire material, dE/dx the ionisation loss of the particles in the wire, I_p the number of particles, β_z and ε_z the β-function and emittance in the other transverse plane.

Experience and previous measurements[3] have shown that k is of the order of 1/3.

For example, the formula gives the following results, for an horizontal measurement at 25 GeV with an intensity Ip = 2×10^{13} ppp and a normalised vertical emittance of 30 π μmrad:

for $v = 20$ m/s $\quad \Delta T \cong 530°C$
for $v = 10$ m/s $\quad \Delta T \cong 1060°C$

X. PERFORMANCE

Limits of precision

The precision with which the wire position is measured dynamically during the beam traversal is probably the determining factor in emittance measurement accuracy. The difficulty comes mainly from the mechanical rigidity of the device. At the maximum velocity of the wire, it seems that non-reproducible flexion of the fork limits the expected precision.

The scintillator-PM non-linearity is also a cause of inaccuracy, though this is considerably less serious.

After the beam profile is obtained, the knowledge of the local β-function and dispersion is necessary to calculate the emittance. These parameters are obtained from machine optics and in practice from the MAD simulation program. There is, unfortunately, no precise way to verify the quality of the PS modelling.

Moreover, it should be pointed out that the result of the measurement is an average over the measurement time (usually less than 1 ms).

Taking all these considerations into account, we estimate the precision to be of the order of ± 5% in emittance for small beams.

Limits of use

The principle of the measurement involves some limitations in the use of the wire scanner.

Since the beam traversal takes many machine revolutions, precision can only be achieved if the beam is stable and matched throughout the measurement. It should, however, be relatively easy to notice if it is not, since, in this case, the profile will probably show some fine structure or asymmetry.

The PMs are sensitive to any beam losses in the neighbourhood of the monitor. One must therefore be careful to avoid using the wire scanner when losses are likely to occur. This problem could be avoided by the use of charge measurement instead of PMs, counting secondary electrons emitted by the wire. This is only possible for high intensities, however, and was not implemented in our system.

The wire scanner cannot be used to measure profiles of partially stripped ion beams. This was tried with Pb^{53+} ions but failed because the wire traversal strips the electrons, at least partly, and the beam is lost during measurement without giving significant results.

Comparison with ion scanners

It is interesting to compare the wire scanner with the other most common circulating beam profile measurement device, the residual gas ion monitor.

In principle, the wire scanner is probably better as far as precision is concerned because the position of the wire is easier to measure than the origin of residual gas ions or electrons. Another advantage of the wire scanner is its immunity to space charge problems since monitoring is done with relatively high energy secondary particles.

Ion scanners, on the other hand, present the advantage of a faster and repetitive measurement. Interaction with the beam is usually lower too, unless the vacuum has to be degraded to increase the sensitivity, or an ion jet is used to enhance the sensitivity.

XI. CONCLUSION

The PS wire scanner provides a straightforward, precise, one shot, almost non-destructive way of measuring profiles and emittances in both planes, over a wide range of particles, energy and intensity. Since emittance is, nowadays, one of the most critical beam parameters, it is used extensively and has become an essential beam quality monitoring instrument of the CERN PS.

XII. ACKNOWLEDGEMENTS

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