INSTRUMENTATION IN SMALL LOW ENERGY MACHINES

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Abstract

Low energy particle accelerators are used either as injectors for higher energy machines or as dedicated machines for special purposes. These may be industrial, medical or prototype machines for testing new accelerating schemes. Low energy beams open measurement possibilities not available at higher energies due to the low magnetic rigidity of the particles, due to their small penetration depth and due to rather big beam spot sizes. On the other hand these beams also represent special challenges due to their high energy deposition in matter, space charge problems etc. which are not seen at higher energies. Measurement principles typical for small accelerators will be presented and explained with the help of example implementations.

INTRODUCTION: THE LHC

The Large Hadron Collider (LHC) is without any doubt CERN's biggest project and one of the most gigantic scientific endeavours ever undertaken in high energy physics. For this reason all eyes of the physics world are focused on it. But… what has the LHC to do with instrumentation in small and low energy machines?
The quality factor for a collider is its luminosity L:

$$L \propto \frac{k_b N^2}{\varepsilon_n}$$

where k_b is the number of bunches, N the number of particles per bunch and ε_n the normalised emittance.

In electron-positron colliders like LEP the synchrotron radiation emitted by electrons at high energy inhibits the move to even higher energies but it is also responsible for Landau damping of the beam emittance. The beam quality is to a good fraction determined by the highest energy machine. In hadron machines however, due to the much higher mass of hadrons, synchrotron radiation is very much suppressed and the beam brightness is essentially determined in the injector chain.

This shows the importance of being capable to measure the beam characteristics in the low energy machines well enough.

Acceleration of ions, foreseen for LHC, poses additional constraints. At low energies ions are only partially ionised and they further ionise through stripping when interacting with an intercepting sensor. In addition energy deposition in matter is at a maximum.

Small machines are however not only used as injectors. There are many industrial applications (e.g. material tests) and medical applications (cancer therapy) which need accelerated particles of rather low energy.

INTENSITY MEASUREMENTS AT LOW ENERGIES

FARADAY CUPS

At energies of up to a few MeV and low intensities Faraday cups are used for intensity measurements. Figure 1 shows a very simple cup design [1]. The sensor itself (2) consists of a stainless steel cone which is connected to a vacuum feed-through. Another feed-through is used for the supply of a polarisation voltage to a cylindrical repeller electrode (1) pushing secondary electrons, created when the beam touches the sensor surface, back into the cup.

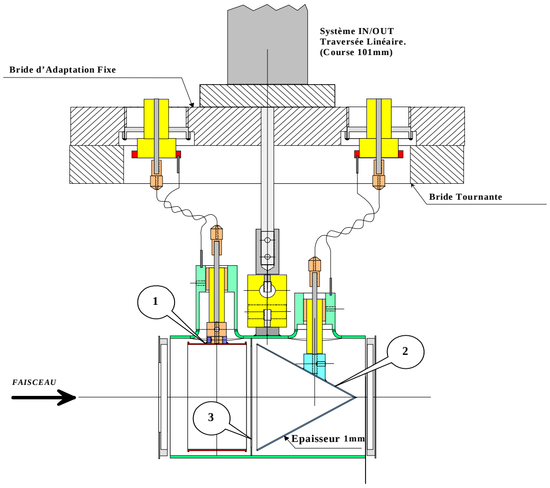

Figure 1: A simple Faraday Cup

Secondary electrons leaving the sensor would of course result in wrong intensity measurements. Since secondary electrons have very low energies of less than 20 eV a polarisation voltage of some 100V is sufficient. Figure 2 shows the current on the sensor with increasing polarisation voltage. At ~30V increasing the voltage further has no more effect on the measured current.

A typical application of Faraday Cups is the measurement of charge state distributions after the ion source. A whole range of different ion charge states is created of which only a single one can be accelerated through the following accelerator chain.

A spectrometer in conjunction with a slit is used to filter out this state. Before doing this however the full charge state spectrum is measured by ramping the spectrometer magnet and measuring the beam current passing though the slit into a Faraday Cup.

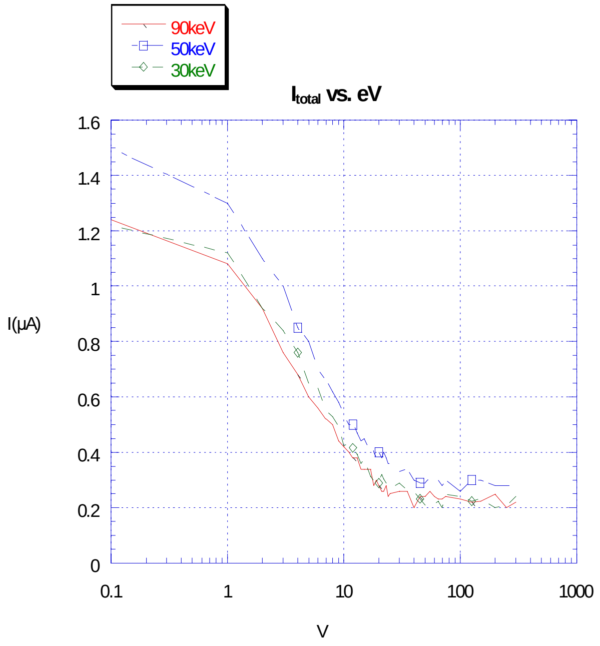

Figure 2: Suppression of secondary electrons

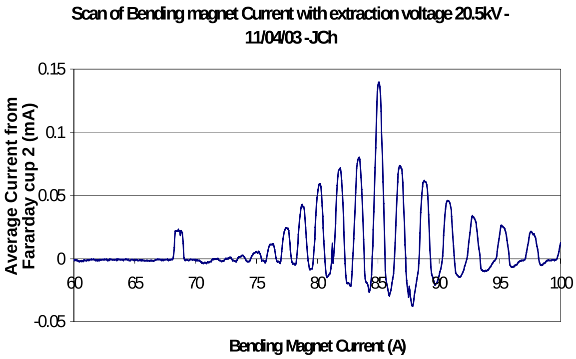

Figure 3: Ion Charge State Spectrum

BEAM CURRENT TRANSFORMERS

In order to produce high beam intensities as required by high energy storage rings, the particle sources produce long pulses in the order of several hundred μs length, which are pre-accelerated in linear accelerators (rfq + Alvarez Linac or IH structure) before being transferred through multi-turn injection into the first circular machine.

During acceleration the physical emittance of the beam is shrinking through adiabatic damping (between the exit of the CERN Linac (50 MeV) and the injection into LHC (450 GeV) the emittance shrinks by a factor 1500!), which means that at the level of the pre-accelerators large beams with particles having large angles must be expected. The mesh of quadrupole magnets used for focusing must therefore be rather narrow and the space for installing equipment is very limited.

For intensity measurements using fast beam current transformers (BCTs) this has two consequences:

- The pulse length is long enough to be sampled with fast industry standard ADCs
- Software based signal treatment on the digitized transformer signals can be used to correct baseline shifts and other aberrations induced by nearby pulsing magnets.

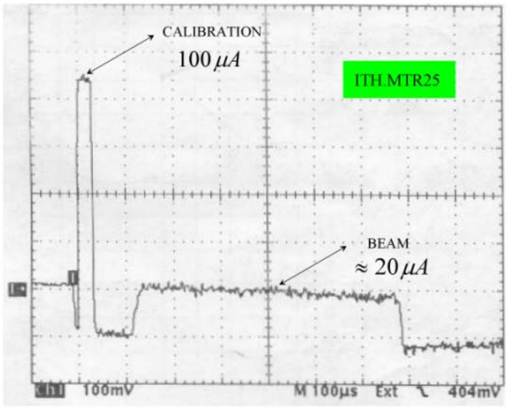

Figure 4: Signal of a low intensity ion pulse from a AC current transformer

Figure 4 shows a typical signal of a 20 μA lead ion pulse as measured by a BCT. A calibration pulse is injected into a separate calibration winding of the transformer shortly before the arrival of the beam. Please note that the total pulse length is 600 μs and that the baseline is inclined. Additional timing pulses are used to determine the start and end injection timing for the multi-turn injection such that the total number of charges injected into the first accelerator ring can be determined.

SCINTILLATING SCREENS

Long beam pulses of some 20μA current cannot easily be measured with beam position monitors and scintillating screens may be used as a fallback solution.

Looking at the Bethe-Bloch curve, describing the energy deposition of hadrons in matter, one can easily see that at very low energy and high charge states the energy deposition is at a maximum. This is the typical case for heavy ions at low energy. The estimated penetration depth of lead ions with 4 Mev/n is ~10 μm, which means that all the ion energy is deposited in an extremely small volume leading to massive heating of the material.

Tests have shown [3] that Al_2O_3:Cr (chromium doped aluminum oxide, chromox) screens used for higher energy protons will quickly burn when used with low energy ions. In addition to the thermal load the evacuation of electric charges represents a problem.

The scintillation material of Table 1 has been exposed to 1 Hz ion beam pulses at 4 MeV/n for several hours and their scintillation properties have been examined.

Table 1: Scintillation material and its properties

Material	*ρ* *g/cm3*	*C_p at 20ºC* *J/gK*	***k** at 100ºC* *W/mK*	***Tmax*** *ºC*	*R at 400 ºC* *Ω.cm*
Al2O3	3.9	0.9	30	1600	10^{12}
ZrO2	6	0.4	2	1200	10^{3}
BN	2	1.6	35	2400	10^{14}

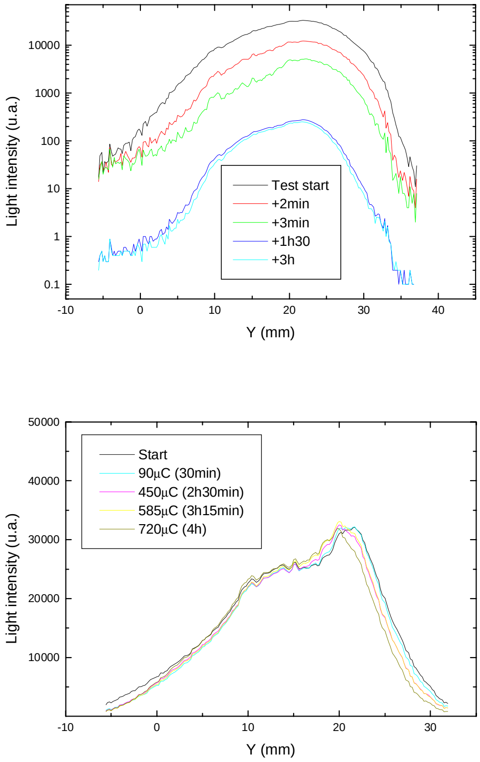

Figure 5: Emission efficiency after bombardment with low energy heavy ions
upper graph: AL_2O_3
lower graph: ZrO_2

While all screens show clear signs of deterioration (see Figure 6) the light emitting properties of ZrO_2 was least affected (Figure 5).

Figure 6: Screen damage

BEAM PROFILE MEASUREMENTS

When thinking about emittance or beam profile measurements in circular machines the wire scanner is the most commonly used device. A thin carbon of beryllium wire is quickly moved through the beam and secondary particles created by the interaction of the incident beam with the wire are detected with a scintillator and photomultiplier assembly outside the vacuum chamber. At beam energies of less than 150 MeV, the minimum energy needed to create pions, hardly any secondary particles are seen on the scintillator [4].

Figure 7 shows a measurement of the secondary particle shower intensity as a function of the primary particle energy where the pion threshold is clearly visible.

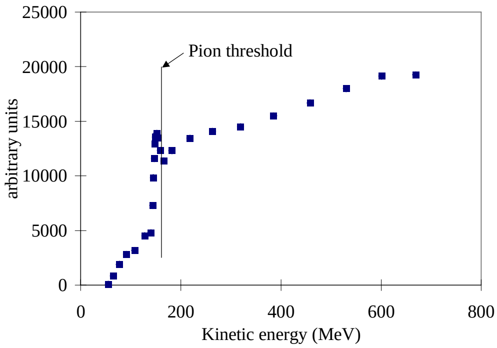

Figure 7: Shower intensities at low energy

If however the wire is mounted electrically isolated the secondary emission current from the wire can be measured. In this case the low energy of the primary beam particles is not an issue. As Figure 8 demonstrates very clean profiles can be measured with secondary emission, while the photo-multiplier signal becomes very noisy and asymmetric due to the bad statistics and due to geometrical effects of placement of the scintillator.

Profiles of partially stripped ions cannot be measured with such a wire scanner because the interaction of the ion with the wire will induce stripping (one or more electrons will be removed from the ions atomic shell) and the ion will be lost.

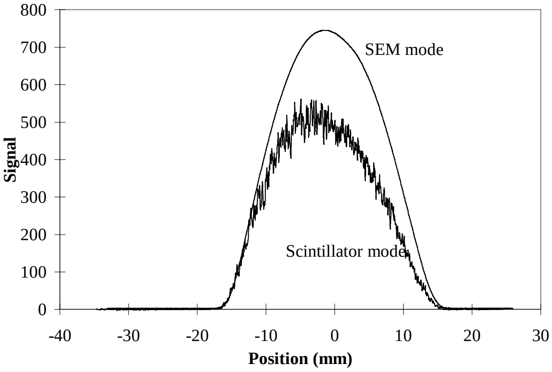

Figure 8: Wire profiles at low energy

One can however use the stripping effect to measure the betatron amplitude distribution. In this case the wire scranner (or a scraper) is used to scrape off the beam starting from the outside of the particle distribution and finishing as soon as the core of the beam has been reached. The losses are observed on a DC current transformer. Figure 9 shows a typical loss curve from which the betatron amplitude distribution can be determined by differentiation.

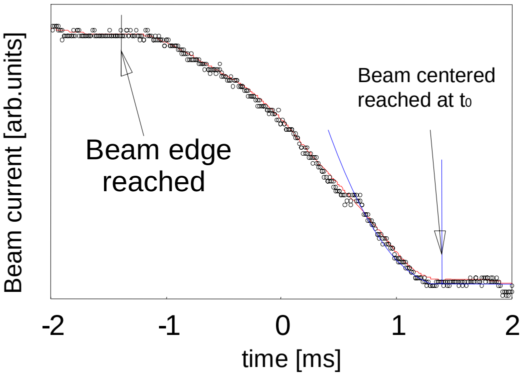

Figure 9: Beam losses due to stripping

TRANSVERSE EMITTANCE

During acceleration the transverse emittance of the beam shrinks due to adiabatic damping. The effect is large: a factor of 1500 for protons between 50MeV and 450 GeV. For this reason beam sizes expected at low energy machines are rather big (as can be seen in Figure) and it is at low energy that phase space cooling must be applied increasing beam brightness as may be required by a high energy collider.

Because of the big beam sizes phase space scans are often applied to measure the beam emittance e.g. at the exit of hadron sources Figure 10 and 11). A fine slit is moved through the beam and the particle angles at the slit position are converted into positions through a drift space and measured with profile measurement devices, often secondary emission or collector grids.

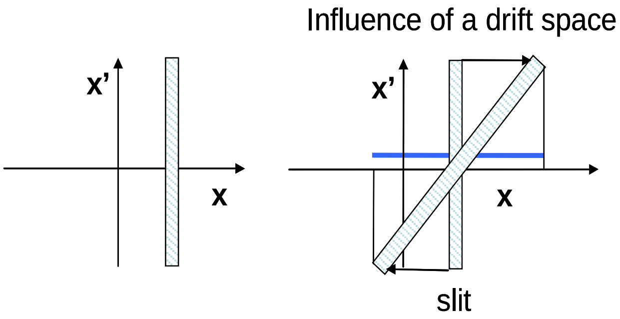

Figure 10: Principle of phase space scan

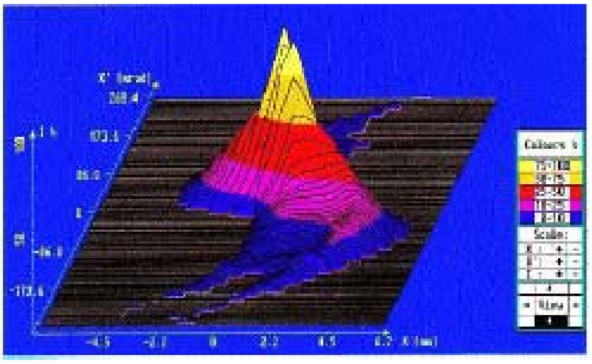

Figure 11: Results of a phase space scan

Advantages and disadvantages of this method are obvious: On one hand the position resolution can be made very fine by moving the slit only for very short distances. On the other hand the slit must be displaced before each measurement which means that scanning the full phase space can take several minutes when applied to a beam with low pulse rate (1Hz is a typical rate). Beam instabilities from one pulse to the next will result in measurement errors.

This problem can be solved by moving the beam with kicker magnets in front of a non-moving slit. Typical kicker rise times and the small magnetic rigidity of particles at low energies allow performing a phase space scan within a single beam pulse. In this case the angle distribution must be sampled in very short intervals (typical ~ 1μs).

Another way is the use of multiple slits. Again, this is only possible if the beam-spot is large enough. Here the number of slits determines the spatial resolution and a high resolution profile detector is needed since now the angle resolution of each slit must be measured in a single measurement. Generally scintillator screens are used. In order to measure horizontal and vertical emittances in a single measurement the pepperpot method is applied in which the multiple slits are replaced by small holes (Figure 12).

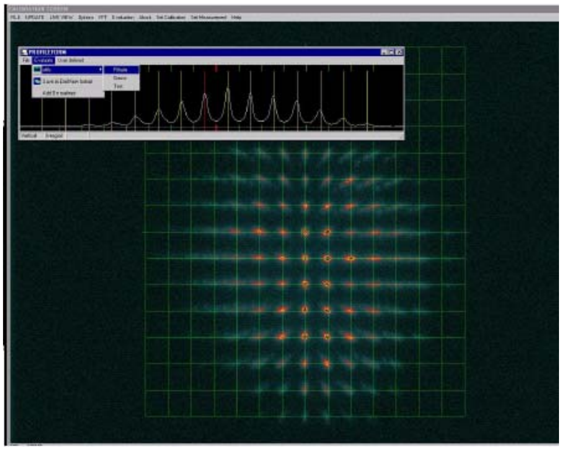

Figure 12: Pepperpot result

LONGITUDINAL PHASE SPACE SCAN

While transverse phase space scans are widely known longitudinal scans are much less common. The canonical parameters in this case are the particle energy and its time of arrival which is equivalent to its phase angle relative to the radio frequency.

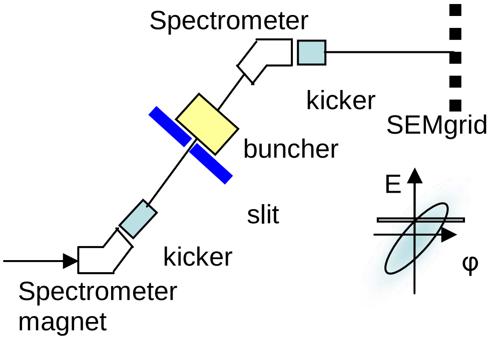

Figure 13: Longitudinal phase space scan

The conversion of particle energy to position can b obtained through a spectrometer magnet which selects a horizontal slice in phase space. As in the transverse case a kicker is used to scan along the E axis. The rotation in phase space of the slice selected is done by means of a buncher which converts the phase distribution into an energy distribution which in turn is converted to position by a second spectrometer (Figure 14).

CONCLUSIONS

Low energy beams from small accelerators present opportunities for instrumentalists which are not seen at higher energies. These are mainly related to big beam sizes, low magnetic rigidity of the particles and the possibility to entirely stop the beam in intercepting material.

On the other hand low energy beams also present problems mainly due to their low penetration depths in matter and due to their high energy deposition in very small material volumes leading to high thermal loads. In addition large emittances correspond to large displacements and angles with respect to the nominal orbit. This means that the beam must be re-focused very frequently leaving very little space for beam diagnostics instruments and bringing them very to close to pulsed elements causing electro-magnetic interference which must be cured by sophisticated shielding.

ACKNOWLEDGEMENTS

Many thanks go to E. Bravin, V. Prieto, T. Lefevre, P. Forck who allowed me to use their illustrations, tables or photographs.

REFERENCES

[1] G. Molinari, V. Prieto, Test d’une Coupe de Faraday avec la Source Duoplasmatron du PS, CERN internal Note PS/BD/2001-001

[2] P. Forck et al. Comissioning of IH-RFQ and IH-DTL for the GSIO high current Linac, 20th International Linac Conference Monterey, California, p. 166.

[3] C. Bal, E. Bravin, T. Lefèvre, R. Scrivens, M. Taborelli, Scintillating Screens Study for LEIR/LHC Heavy Ion Beams, this conference

[4] M. Arruat, C. Carli, A. Jansson, M. Lindroos, M. Martini, J. Olsfors, H. Schönauer, A comparative Study of fast Wire Scanners, Beamscope and SEM-Grids for Emittance Measurement in the PS Booster, DIPAC 1997