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Summary on Transverse Emittance Measurement and Instruments

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1. INTRODUCTION

Preservation of emittance and, as a prerequisite, emittance measurement, take on a particular importance in the long chain of accelerators and storage rings of big hadron colliders. Not only has one to provide instruments capable of measuring transverse emittance with the necessary precision, one also has to make sure that the data stemming from instruments of quite different nature are treated such that the results can be validly compared, throughout the chain.

Although all instruments have the final goal of determining the emittance, what they primarily measure are such varied properties as projected density distribution, 2-dimensional density distribution, amplitude distribution, etc., and the methods vary greatly as well.

It was therefore most valuable to be able to compare, in the course of the Workshop, the experience made with the many different instruments used in so many different laboratories. It was also valuable to understand why experience with the same kind of instrument quite often differed from lab to lab: what the one scorned, the other praised.

The differences of appreciation have essentially three causes:

a) What is good for one type of beam, may not be so for another (depending on the kind of particle, energy, intensity, time structure).
b) Most instruments work well only when certain precautions are taken (linearity, clearing field, magnetic focusing).
c) Last but not least, treatment of the raw data and interpretation of the results play a decisive rôle.

In a 2-dimensional table of labs and instruments, an appreciation matrix was shown in the verbal conclusions at the end of the Workshop. Although useful and instructive for that purpose, it will not be shown here, because its correctness in the details could only to easily be disputed. Instead, we report in the following paragraph the advantages and disadvantages, quoted during the Workshop, for each of the discussed instruments. In a summary like this, we cannot give a description of the instruments commented upon, and must thus assume the reader's familiarity with them.

2. THE INSTRUMENTS

SCAN WITH SLITS

The modern variants, using either a single slit and a SEM-grid, or two slits and a single collector, are sophisticated descendants of the ancient "pepper-pot". With it, they share the destructiveness and limitation to low energies, at the output of ion-sources, or RFQs, or linacs of moderate energy. There they are the standard instruments to measure emittance, reliably and in phase space (not only a 1-dimensional projection).

SCINTILLATOR SCREENS

They are the ever-greens of diagnostics, used since nearly a century. The modern versions consist of doped alumina, and stand high intensity beams and large amounts of integrated charge. They are the simplest and most convincing device when one has to thread a beam through a transfer line, into an accelerator, and around and out of it.

In their simplest form, just a graticuled screen, observed with a TV-camera, they certainly deliver a wealth of information to the eye of an experienced observer, but only in a semi-quantitative way. Much can be done about that with modern means of rapid image treatment, but questions concerning linearity of screens at high beam densities remain.

OPTICAL TRANSITION RADIATION

OTR screens are a welcome and cheap substitute for scintillator screens. Although usable only for highly relativistic particles, they are absolutely linear in response and can be made so thin as to hardly disturb a beam in a transfer line, and even permit observation over many turns on a circulating beam. High time-resolution is easily achieved. As the scintillator screens, they profit from modern means of rapid image treatment.

SEM-GRIDS

Also known as harps, they may consist of ribbons or wires. They are the most widely used means to measure density profiles of beams in transfer lines, and sets of three, properly spaced, allow determination of the emittance ellipse. What makes them popular is their simple and robust construction, the fact that there is little doubt about the measured distribution, and the high sensitivity, in particular at low energies and for ions. At higher energies they can be considered semi-transparent. Amongst the drawbacks are the limited spatial resolution (0.25 mm appears to be smallest wire-spacing achieved) and the rather high cost for mechanism and electronics.

WIRE-SCANNERS

They are nearly non-destructive, in particular the fast ones, over a wide range of energies. Their spatial resolution can reach the micrometer range and, with fast electronics, bunches can be observed individually. Their great sensitivity allows the study of halos.

At very low energies, multiple Coulomb scattering affects the beam and falsifies the measurement. Heating of the wire limits use at high intensities, but the problem of thermal emission can be avoided by looking at the secondary particles instead of measuring the secondary emission current. High mechanical precision is required. The measurement is not continuous.

Of all the instruments used on circulating beams, the wire-scanners were certainly considered the most trustworthy one.

RESIDUAL GAS PROFILE MONITORS

Quite non-destructive and delivering continuous information, they might be the ideal profile monitors for circulating beams. However, spatial resolution, whether one uses the electrons or the ions, is limited, as space charge perturbs the profiles of all but the weakest beams. That can be greatly improved upon by applying high extraction voltages and a focusing magnetic field in the same direction, but this is usually avoided, because it perturbs the closed orbit and may need to be compensated.

Most users consider these monitors to be semi-quantitative, even after calibration against some other instrument.

BEAMSCOPE

There seem to be only two instruments of that kind in use in the world. Driving the circulating beam into a stationary obstacle allows the most valuable direct measurement of amplitude distribution. Its advantage is that no fast-moving devices are needed. On the other hand, the deflection of the beam can introduce some uncertainties, e.g. through interaction with the accelerating RF. It is a destructive method, although one may limit the measurement to scraping off only a small fraction of the beam.

SYNCHROTRON RADIATION

What is a curse for acceleration is a boon for diagnostics. Limited to highly relativistic particles, it offers a completely non-destructive and continuous measurement of the 2-dimensional density distribution. Spatial resolution is usually limited to some 0.2 mm by diffraction and depth-of-field effects.

SCHOTTKY SCANS

They are a paradigm of diagnostics free of charge (if one doesn't count the time it takes to make a scan). The measurement is completely non-destructive, can be made continuously, and delivers a wealth of information. Mostly useful for coasting beams, with the necessary precautions also bunched beams are accessible. The sensitivity is unparalleled.

Quantitative measurements, however, need calibration, the scans take time and the absolute precision is limited.

QUADRUPOLE PICK-UP

What it measures is not the dimensions of a beam, but rather the ellipticity of its cross-section and its variation in time. This makes it a potentially useful tool, completely non-destructive, to verify whether upon injection the beam was well betatron-matched to the ring lattice.

Deriving an information that can be quantitatively interpretated is quite an art. A prerequisite is careful centering of the beam in the pick-up, otherwise the dipole oscillations will completely swamp the weak quadrupolar component.

3. **GENERAL CONCLUSIONS**

It appeared very clearly that a prequisite for any emittance measurement is the precise definition of emittance that one uses. That there is a variety of different definitions is quite justified: they need to be tailored to the particular situation at hand. But, whenever data are presented, they should be accompanied by the definition. That still leaves the question of how to convert results from one definition to another.

Furthermore, the rms-value of a profile, or whatever else one quotes, can often depend critically on the exact method with which the raw data were treated. Here again, the method used ought to be indicated.

On-line calibration of each instrument and cross-calibration with others is important. One should not rest before reasonable agreement of results (without fudge-factors !) is obtained.

The overall conclusion is that no emittance measurement is yet proven to be precise to better than 10 %. Certainly, a number of instruments are basically capable of measuring the beam size quite precisely, but the details of data treatment play an important rôle for the final result. Furthermore, when calculating emittance from beam size, one relies on the knowledge of the beam optical parameters at the place of the instrument and these are often fraught with considerable uncertainties.

And a final comment: there is evidently not enough exchange of information and experience between the labs. Were it better, many wheels would be invented only once, and much bad experience would not be repeated. But that is what workshops like this one are for. We are looking forward to the next one.