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Peter Strehl

Beam Instrumentation and Diagnostics

With 301 Figures

Springer

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To Irene,
showing always sympathy for my professional work

Schreiben ist hart;
man kommt nur schwer dahinter,
wann man aufhören muss.

PETER USTINOV

Preface

This book summarizes the experience of many years of teamwork with my group, the beam diagnostics group of GSI. For a long time the group was also responsible for operating the machines and application programming. In my opinion, this connection was very efficient: first, because a beam diagnostic system has to place powerful tools at the operators' disposal; second, because data evaluation and presentation of results for machine operation demand application programs which can be handled not only by skilled experts.

On the other hand, accelerator developments and improvements as well as commissioning of new machines by specialists require more complex measurements than those for routine machine operation. A modern beam diagnostic system, including the software tools, has to cover these demands, too.

Therefore, this book should motivate physicists, constructors, electronic engineers, and computer experts to work together during the design and daily use of a beam diagnostic system. This book aims to give them ideas and tools for their work.

I would not have been able to write this book without a good education in physics and many discussions with competent leaders, mentors, and colleagues. After working about 40 years in teams on accelerators, there are so many people I have to thank that it is impossible to mention them all by name here.

In recognition, of all, I would like to thank very much my first teachers, Peter Brix and Friedrich Gudden for filling me with enthusiasm for nuclear physics, electron scattering, and accelerator physics at the DALINAC nearly 40 years ago. Starting in 1970 at GSI, it was Christoph Schmelzer, who was always a sympathetic listener, helping me with discussions and many suggestions. Under the leadership of Dieter Böhne, who managed most accelerator projects of GSI, the beam diagnostics group, responsible for all beam diagnostics up to the target, was established. I gratefully acknowledge this in memory of both.

I thank Norbert Angert and Klaus Blasche for helpful discussions and support during their leadership of the accelerator department. Furthermore, I would especially like to thank Jürgen Klabunde for many years of collaboration. Specification of beam diagnostic elements, elaboration of program algorithms, performing of accelerator experiments, and organization of machine operation was our common job.

This job could not have been done without the members of the beam diagnostics group. Especially, many thanks to Volker Schaa, for implementing many application programs and together with his team always available in case of software problems. Many thanks also to Fritz Bock, keeping the process computer system available day and night. In memory of Helgi Vilhjalmsson, I gratefully acknowledge his professional work and his very much respected engagement in the group.

It would be unforgivable not to acknowledge here Frank Peldzinski, together with Alfons Suderleith who were responsible for service, maintenance, and new installations of beam diagnostic elements. In this connection, the work of Günther Grimm and Horst Graf in the small beam diagnostics workshop contributed a big part to constructing the beam diagnostics system; thanks to both of them. I thank gratefully also Jörg Glatz and Ludwig Dahl for numerous physics discussions, resulting mostly in suggestions and improvements for operating the machines. In this connection, the good collaboration with Dieter Wilms and Uwe Scheeler, now both responsible for the operations group, is gratefully acknowledged.

In recognition of all members of the diagnostic group, I would like to mention Mohamed Fradj, Manfred Hartung, Tobias Hofmann, Wolfgang Kaufmann, Wilhelm Losert, Rolf Mayr, Peter Moritz, Hansjörg Reeg, and Norbert Schneider for professional discussions and their great engagement as operators, shift leaders, and designers. Many thanks to them and all other members of the beam diagnostics group.

Construction design and procuring of nearly all mechanical parts of the GSI beam diagnostic systems were managed by Hubert Kraus with the help of Jochen Störmer. I thank them both very much for their work and many years of close collaboration.

My special thanks go to Andreas Peters and Peter Forck, who now are the leaders of the beam diagnostics group. Designing together the beam diagnostic systems for SIS, ESR (partly), and the high energy beam lines, the collaboration could not have been better. In 2002, Peter Forck took over my courses on "Beam Instrumentation and Diagnostics" at the Joint University Accelerator School (JUAS). He improved and supplemented my lecture notes. Some of the contributions to this book are adapted from our common work.

After retirement, I miss very much the short meetings with Claus Riedel. We met nearly every day for half an hour or even more for discussion. I thank him very much for many suggestions concerning the solution of mathematical-physical problems.

For pictures marked GSI-Foto, I acknowledge the work of Achim Zschau and Gabriele Otto for taking them. The draft version of the book was written

with Scientific Workplace of MacKichan Software Inc. I can recommend it as a powerful tool.

I also thank the editorial board of Springer for helpful suggestions. Finally, I wish to express my special thanks to my editor, Dr. Christian Caron, and his team, especially, Gabriele Hakuba and Birgit Münch.

Darmstadt *Peter Strehl*
December 2005

Commonly Used Abbreviations

AC alternating current
ADC analog-to-digital converter
AlN aluminum nitrite
ATF accelerator test facility (KEK)
BCT beam current transformer
BPM beam position monitor
BNL Brookhaven National Laboratory
BTF beam transfer function
BeO beryllium oxide
CAD computer-aided design
CCC cryogenic current comparator
CCD charge-coupled device
COG center of gravity
CERN European Organisation for Nuclear Research
CT computer tomography
CVD chemical vapor deposition
CW continuous wave
DAC digital-to-analog converter
dc direct current
DESY Deutsches Elektronen Synchrotron
DSP digital signal processing
ECR electron cyclotron resonance
ESR experimental storage ring
FC Faraday cup
FD finite difference
FE finite element
FFT fast Fourier transformation
FWHM full width half-maximum
GSI Gesellschaft für Schwerionenforschung
HILAC heacy ion linear accelerator
IC ionization chamber
IF intermediate frequency

ICT integrating current transformer
ISR intersecting storage ring (CERN)
KEK High Energy Accelerator Research Organisation
LEP large electron-positron storage ring
LHC large hadron collider
LBL Lawrence Berkeley Laboratory
MART multiplicative algebraic reconstruction technique
MCP multichannel plate
MCA multichannel analyzer
MEVVA metal vapor vacuum
MUCIS multicusp ion source
MWPC multiwire proportional chambers
ODR optical diffraction radiation
OTR optical transmission radiation
OTDR optical time domain reflectometer
PC personal computer
PCI industrial personal computer
PIG Penning (ion source)
PLL phase-locked loop
PMT photomultiplier tube
pps particles per second
PS proton synchrotron (CERN)
PSI Paul Scherrer Institut (SIN)
RAM random access memory
RCT resonant current transformer
RHIC Relativistic Heavy Ion Collider
rf radio frequency
RFQ radio-frequency quadrupole
rms root-mean-square
SCM scintillation current monitor
SEM secondary electron emission monitor
SI International Unit System
SIS Schwer Ionen Synchrotron
SLAC Stanford Linear Accelerator Center
SPS super proton synchrotron
SQUID superconducting quantum interference device
TAC time-to-amplitude converter
TDC time to digital converter
TESLA TeV-Energy Superconducting Linear Accelerator
TDR time domain reflectometer
TOF time of flight
UNILAC Universal Linear Accelerator
UV ultraviolet
VCO voltage-controlled oscillator
VSWR voltage standing wave ratio
WEB WorldWide Web

Contents

1

Introduction

Some decades ago, particle accelerators were controlled and optimized mainly by looking at viewing screens – mostly based on ZnS – and simple beam current meters. Developments in the field of beam diagnostics have paralleled the development of computers, sophisticated electronic circuits, and PCI systems. A consequence is the design of more and more complex machines, using powerful simulation programs to describe particle dynamics in modern accelerator structures. Nowadays, computer-aided operation and on-line control of modern accelerators, operated in a great variety of modes, require the availability of many beam parameters. Due to the manifold machines, such as linacs, cyclotrons, synchrotrons, storage rings, and transport lines, the demands on a beam diagnostic system can differ. Taking additionally the broad spectrum of particles, such as electrons, protons, and heavy ions into account, it becomes very clear that the development of versatile measurement techniques became essential in recent years. The main beam parameters and their meaning for characterization of particle beams are

Beam Intensity

In the most general definition, beam intensity I is defined as

$$I = \frac{number\,(N)\;of\;particles}{time\;unit} \tag{1.1}$$

and covers a range from some particles per second (pps) up to 10^x pps with $x > 14$. For charged particles, beam intensity is related to the beam current i

$$Q = i \times t = N\zeta e \;\rightarrow \tag{1.2}$$

$$i = \frac{N\zeta e}{t}\,, \tag{1.3}$$

where $e = 1.602 \times 10^{-19}$ As and ζ is the charge state of the accelerated particle. For dc-machines, the time unit t is 1 s and i corresponds to the dc-current. For rf accelerators working in continuous mode, such as cyclotrons, the time unit is given by the bunch length Δt. Pulsed rf accelerators are characterized by two time units: T_{p} as the macropulse length and Δt as the bunch length. Defining the duty cycles

$$D_{\mathrm{m}} = \frac{T_{\mathrm{p}}}{T_0} \quad T_0,\ \text{repetition period} \tag{1.4}$$

$$D_{\mathrm{rf}} = \frac{\Delta t}{T_{\mathrm{rf}}} \quad T_{\mathrm{rf}}, \text{rf period} \tag{1.5}$$

currents in the bunch i_{b} or macropulse i_{p} can be related to the average current i_{a}, measured with a dc-meter

$$i_{\mathrm{p}} = i_{\mathrm{b}} D_{\mathrm{rf}} \tag{1.6}$$

$$i_{\mathrm{a}} = i_{\mathrm{p}} D_{\mathrm{m}}\ . \tag{1.7}$$

The great variety of intensity measuring systems is discussed in Chap. 2.

Beam Profile

In a three-dimensional rectangular coordinate system, "beam profile" means the intensity distribution over one of the coordinates. In accelerator physics, it is usual to distinguish between longitudinal and transverse directions. The longitudinal coordinate runs along the beam axis and determination of the intensity distribution along this axis requires measuring techniques other than those for the two transverse axes. This is explained and discussed in Chaps. 4 and 5.

Beam Position

The beam position is defined only in the two transverse coordinates and can be derived immediately from beam profile measurements. In general, the term "beam position" refers to the center of gravity within the transverse intensity distributions. This holds especially for measuring devices which measure only the beam position. Beam position monitors are of great importance for operation and optimization of circular machines. In these machines, much more information such as tune, chromaticity, and closed orbit is extracted from the beam position monitors (BPM). In most cases, the measuring electrode systems are based on capacitive coupling to the beam. More explicit information is given in Chaps. 5 and 6.

Emittance

The terminus "emittance" was introduced to accelerator physics from the Hamilton formalism. The ease with which a particle beam can be transported, the accuracy of beam energy determination, the bunch shape and microstructure in time, and the precision with which scattering angles and a time focus can be determined in physics experiments, depend on the distributions in the phase spaces. As for the beam profile, it is usual to discriminate between two transverse emittances and a longitudinal one, as derived in Chap. 6.

Beam Energy

Of course, the required beam energy is determined mainly by planned experiments or in industrial use by special applications such as ion implantation, inertial fusion, and sputtering systems. On the other hand, determination of beam energy, energy spread, and the related quantities momentum and momentum spread is of great importance in evaluating beam quality and optimizing machine parameters. We deal with the matter in Chaps. 5 and 7.

Charge States and Mass Numbers

In heavy ion machines, the ratio between the charge number ζ and the mass number A of the ions ζ/A is important, because the rf power needed for acceleration is proportional to $(A/\zeta)^2$. Therefore, the accelerator constructor is faced with the problem of maximizing the ratio ζ/A. Highly ionized ions are preferred in such machines. However, all types of ion sources deliver a spectrum of ions composed of different charge states of different isotopes. Therefore, charge state and mass separation become essential for beam diagnostics. This holds also for the charge state separation behind strippers which are used in most heavy ion machines to reduce the required rf power. This is discussed in Chap. 4.

Q Value

The Q value, respectively, tune, is a quantity defined only in circular machines. It relates the number of betatron oscillations around a circular machine to the settings of the focusing and beam guiding elements. In older machines, the Q value was determined from an appropriate number of position measurements around the machine. As discussed in Chap. 7, measurement of Schottky noise and analysis of the so-called beam transfer function (BTF) in response to beam excitation are now the most applied methods.

Chromaticity

The chromaticity ξ may be considered a proportionality factor in the relation between tune spread and momentum spread. The methods of determination are similar to those used to determine the tune.

Modern beam diagnostic systems should cover mainly the needs of operators and shift leaders during routine machine operation. On the other hand, accelerator developments, improvements, and commissioning of new machines require more complex measurements by skilled experts.

Considering the high demands on beam diagnostic systems, it becomes very clear that many fields of science and technique are involved, mainly

- vacuum and high vacuum technique;
- material research, mainly for the suitability of materials in vacuum systems and their thermal characteristics;
- computer-aided design (CAD) of complex electromechanical devices,
- signal calculations, including
  - electrodynamics, considering also relativistic effects,
  - particle dynamics, including space charge effects;
- analog and digital techniques, applying modern signal analysis; and
- computer techniques, mainly process control and implementation of physical application programs, including tools for operators and accelerator scientists.

A beam diagnostics group has to meet requirements that demand teamwork among technicians, engineers, physicists, and software workers. Experience has shown that members of the diagnostic group should take part in operation and improvements of the machines.

Of course, there is great variety of specialist literature available around the world, covering this matter in scientific journals, numerous articles, and excellent books, e.g., [1–12]. Two well-established international workshops dedicated to beam diagnostics give further detailed information:

- The Beam Instrumentation Workshop (BIW), organized every two (even) years since 1994 by American accelerator centers [13–19]
- The Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC), organized every two (odd) years since 1993 by European accelerator centers [20–25].

It would be an unforgivable omission in the age of the Web not to mention the excellent services in the publication of conference proceedings etc. via the Net, (e.g., [26, 27]).

This book aims to give all experts involved in beam diagnostic system design, routine operation, and improvement of machines application programming and construction design ideas and tools for their work. A recently published book by Minty and Zimmermann [28] is an excellent treatise, showing very clearly the importance of beam diagnostic data for machine operation and optimization. It deals with linacs and circular machines but is focused mainly on highly relativistic electrons and protons. Besides numerous examples of the use of beam diagnostic data for beam dynamics and optic studies, the book also covers machine theory such as cooling, bunch compression, injection, extraction, synchrotron radiation, and polarized beams.

This new book complements it insofar as the design of beam diagnostics devices and measurement procedures are also described in more detail. Furthermore, instead of considering mainly relativistic light particles, non-relativistic heavy ions are the subject of this book. As far as beam diagnostics and measurements in synchrotrons are concerned, it aims to complement the book of Minty and Zimmermann by contributions, characteristic of machines accelerating heavy ions from low β values to β near one. Giving examples concerning

- construction design of diagnostic devices,
- signal calculation and signal processing,
- implementation of application programs for operators, shift leaders and skilled experts,

the author would be happy to inspire young engineers and physicists to work in the fascinating field of beam diagnostics.

Most beam diagnostic devices, including signal processing and application software were developed for the accelerator facilities of Gesellschaft für Schwerionenforschung (GSI) and in consequence most of the contents refers to long term work at GSI. The main parameters of the machines under discussion are given in Tables 1.1–1.6, starting with the Universal Linear Accelerator (UNILAC) [29].

Table 1.1. Technical parameters of the UNILAC

Ion source and LEBT	
Ions sources	MEVVA[1], PIG[2], MUCIS[3]
Max A/ζ	65
Injection energy	2.2 keV/u
Relative velocity ($\beta = v/c$)	0.217%
Magnetic rigidity	0.44 Tm
Extraction voltage	10–50 kV
Postacceleration	$\leq 135\,\mathrm{kV}$
Transversal emittance (normalized)	$\leq 0.4\,\pi\cdot$mm$\cdot$mrad
Transversal emittance (not normalized)	$\leq 190\cdot$mm$\cdot$mrad
Energy spread $\Delta W/W$	$\leq \pm 1 \times 10^{-4}$
Mass resolution $m/\Delta m$	≤ 210

Table 1.2. Technical parameters of the UNILAC, continued

Prestripper rf accelerator		
Resonator	RFQ	Superlens
Frequency [MHz]	36.136	36.136
Tank length [m]	9.35	0.8
Inner tank diameter [m]	0.762	0.86
Energy range [keV/u]	2.2–120	120
β [%]	0.217–1.605	1.605
100% horiz. rms emittance, norm. [mm·mrad]	0.050	0.069
100% vert. rms emittance, norm. [mm·mrad]	0.050	0.069
100% longitudinal. rms emittance [keV/u·ns]	0.139	0.250
Particle transmission in relation to RFQ input [%]	89	88

Table 1.3. Technical parameters of the UNILAC, continued

Prestripper rf accelerator, cont.		
Resonator	IH1	IH2
Frequency [MHz]	36.136	36.136
Tank length [m]	9.1	10.3
Inner tank diameter [m]	1.829	2.034
Energy range [keV/u]	120–743	743–1395
β [%]	1.605–3.995	3.995–5.473
100% horiz. rms emittance, norm. [mm·mrad]	0.085	0.111
100% vert. rms emittance, norm. [mm·mrad]	0.085	0.111
100% longitudinal. rms emittance [keV/u·ns]	0.390	0.446
Particle transm. in relation to RFQ input [%]	88	88

Table 1.4. Technical parameters of the UNILAC, continued

Stripper section at 1.4 MeV/u			
	IH2 exit	Stripper gas	Alvarez entrance
Bunch frequency [MHz]	36.136	36.136	36.136
β [%]	5.473	5.473	5.473
100% horiz. rms-emitt., norm. [mm·mrad]	0.111	0.122	0.225
100% vert. rms-emitt., norm. [mm·mrad]	0.111	0.123	0.296
95% longitudinal. rms-emitt. [keV/u·ns]	0.264	0.303	1.39
Particle transm. in rel. to RFQ input [%]	88	88	88

Table 1.5. Technical parameters of the UNILAC, continued

Poststripper accelerator		
	Alvarez 1	Alvarez 2
Frequency [MHz]	108.41	108.41
Energy [MeV/u]	3.6	5.9
β [%]	8.761	11.216
100% horiz. rms emitt., norm. [mm·mrad]	0.244	0.269
100% vert. rms emitt., norm. [mm·mrad]	0.306	0.287
95% longitudinal. rms emitt. [keV/u·ns]	1.42	1.52
Particle transm. in rel. to RFQ input [%]	87.7	87.7
Beam intensity [emA]	15	15
Beam power (pulsed) [kW]	459	752
Power (average) [kW] (duty factor 2%)	9	15

Table 1.6. Technical parameters of the UNILAC, continued

Poststripper accelerator, cont.		
	Alvarez 3	Alvarez 4
Frequency [MHz]	108.41	108.41
Energy [MeV/u]	8.6	11.4
β [%]	13.514	15.591
100% horiz. rms emitt., norm. [mm·mrad]	0.320	0.349
100% vert. rms emitt., norm. [mm·mrad]	0.301	0.298
95% longitudinal. rms emitt. [keV/u·ns]	1.47	1.44
Particle transm. in rel. to RFQ input [%]	87.7	87.6
Beam intensity [emA]	15	15
Beam power (pulsed) [kW]	1097	1454
Power (average) [kW] (duty factor 2%)	22	29

Remark. The three types of ion sources are the ones mostly used. Their use may be characterized as follows:

1. MEVVA: Mainly for injection into the Schwer Ionen Synchrotron (SIS), high currents, low repetition rate, short pulses.
2. PIG: Mainly heavy metal ions, long pulses, moderate currents.
3. MUCIS: Gas ions up to Xe, high currents, low repetition rate.

Remark. For further acceleration, deceleration as well as fine-tuning of the output energy, there are 10 single gap resonators installed behind the Alvarez 4. The maximum effective acceleration voltage is 1.2 MV for each of them. Therefore, the maximum beam energy for a $^{238}U^{28+}$ ion is 12.8 MeV/u.

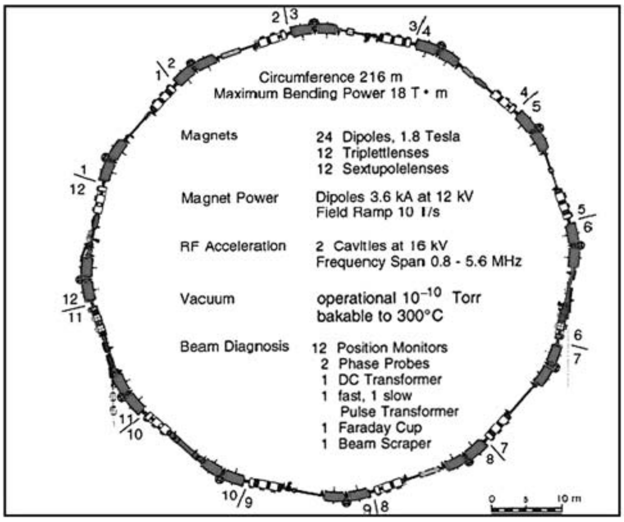

Fig. 1.1. Layout of the SIS

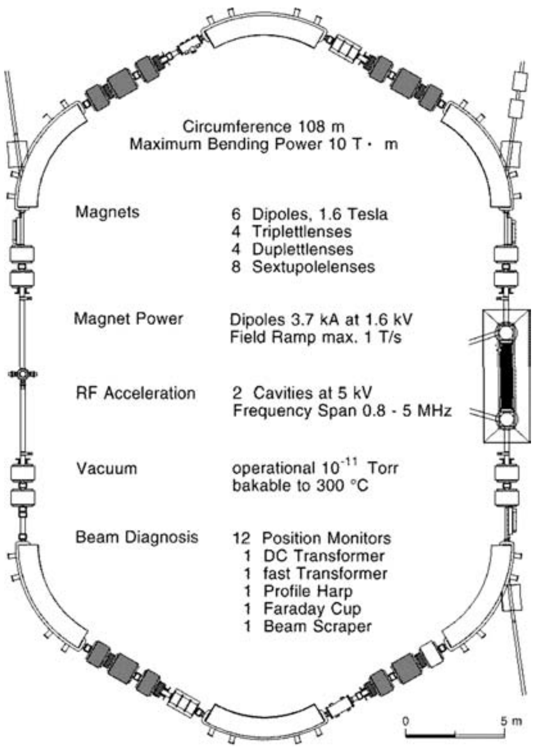

Fig. 1.2. Layout of the ESR

Table 1.7. The most important beam properties of the SIS

SIS Beam properties	
Particle energy	50–1000 MeV/u for U 50–2000 MeV/u for Ne
Energy definition	ca. 10^{-3}
Cycle length	1 to 10 s
Extraction	fast: ca. 1 μ*s* slow: 10–8000 ms
Beam emittance depending on ring filling and extraction time	3–30 π·mm·mrad

Table 1.8. The most important beam properties of the SIS

ESR – main features	
Particle energy	3–560 MeV/u for U 50–830 MeV/u for Ne
Energy definition	ca. 10^{-4} with e-cooling
Cycle length	Field ramp: 1.5 s
Storage time	Minutes to hours
Extraction	Fast: ca. 0.5 μs Slow: to some 10 s
Beam emittance	0.1 π·mm·mrad, with e-cooling
Particle number per cycle	Typically 10^8 with cooling

Figure 1.1 shows a layout of the SIS, including some information about the equipment, and Table 1.7 summarizes the most important beam properties.

The corresponding layout of the experimental storage ring (ESR) is shown in Fig. 1.2, and the main features of the storage ring are given in Table 1.8.

2

Beam Intensity Measurements

Measurement, continuously monitoring and optimizing of beam intensity is one of the most important activities during operation of complex accelerators [30]. In general, a certain intensity measuring system covers only a limited range of intensities, which is caused by

- the great variety of accelerator types,
- the manifold accelerated ion species covering a wide range of energies and charge states, and
- the great variety in the time structure of the particle streams.

As a consequence, detectors and measuring systems show great diversity. The measuring principles applied depend on the expected intensities and cover a wide spectrum ranging from absolute determination by particle counting and simple current measurements to more complicated relative methods, requiring calibration by an absolute measurement. Detector systems may be classified according to properties, such as

(1) on-line measurement
(2) non-destructive
(3) radiation resistant
(4) absolute measurement
(5) vacuum compatible
(6) kind of output signal

Table 2.1 gives a selection of commonly used principles. The classifications 1–6 are marked by + = yes, − = no and o = only under favorable conditions; N = number of particles; ζ = charge state of the particles; ΔW = energy loss; W_{ion} = average energy needed to generate one ion pair, and p = pressure.

From Table 2.1, it becomes evident that absolute determination of beam intensity is possible either at quite low particle streams by counting single particles or at high intensities by using beam transformers. In the range of about $10^7 < N < 10^{12}$ particles, respectively, charges per second (for $\zeta = 1$, it corresponds to $1.6\,\text{pA} < i < 160$ nA), only more or less indirect methods

Table 2.1. Principles of intensity measurements and their classification. TC = track counting, FC = Faraday cup, IC = ionization chamber, SPC = scintillation pulse counter, SCM = scintillation current monitor, SEM = secondary electron monitor, RGM = residual gas ionization monitor, NRM = nuclear reaction monitor, BCT = beam transformer (from P. Heeg, A. Peters, Strehl, P., AIP Conference Proceedings 333, Vancouver, B.C., Canada 1994, pp. 287–293. With permission)

Principle	On-line	Nondes-tructive	Radiation resistant	Absolute calibration	Vacuum compatible	Output signal
TC	−	−	−	+	−	N
FC	+	−	+	+	+	$N\zeta e$
IC	+	−	+	−	−	$Ne \cdot \Delta W/W_{\text{ion}}$
SPC	+	−	−	+	−	N
DD	+	−	+	+	+	N
SCM	+	−	−	−	−	$\sim N \cdot \Delta W$
SEM	+	o	+	−	+	$\sim N \cdot \mathrm{d}W/dx$
RGM	+	+	+	−	+	$\sim N \cdot p\Delta W$
NRM	+	o	+	−		
BCT	+	+	+	+	+	$\sim N\zeta e$

have to be applied. A typical example gives the slow extraction mode of synchrotrons, preferred by nuclear or atomic physicists in their experiments to avoid pile-up in the detectors. Considering a revolution time of the order of 1μs and typical currents of the order of 100 μA, an extraction time of 1s results in a current of 100 pA, which is too high for particle counting and too low for measurement with a beam transformer. Due to effects which are discussed later, even measurements of current with Faraday cups in the pA range can be problematic. Fortunately, there is always an overlap of the ranges of absolute methods with various indirect methods, which allows calibrating them. This is illustrated in Fig. 2.1, which gives an overview of the ranges of different detector systems used in the SIS of GSI.

2.1 Faraday Cups

In principle, a Faraday cup (FC) is a beam stopper, isolated from the beam pipe ground potential and connected to a current meter. The device is the one mostly used to measure beam intensities. Although non-destructive measurements with beam transformers or similar devices are preferred for continuous monitoring of a beam, the Faraday cup, stopping the beam completely and measuring the beam current at the same time, has its advantages, too. For example

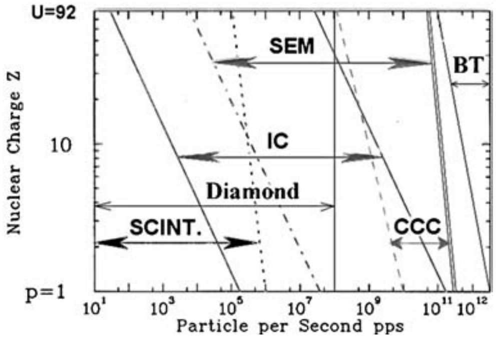

Fig. 2.1. Different detector systems used for slow extraction in the SIS at GSI. The numbers hold for different ions (scale on the left-hand side) with a kinetic energy of 1 GeV/u, an extraction time of 1 s and a beam spot size of 1cm^2. Here CCC stands for "Cryogenic Current Comparator" [31,32], and BT stands for beam current transformer. Due to the destructive character of Faraday cups, they are not used in this case

- if the beam has no time structure (dc-beam), a Faraday cup is the most versatile device for measuring the dc-current of the beam;
- during optimization of machine settings with respect to intensity, components of the following accelerator structures and beam transport system are automatically protected using a Faraday cup for intensity monitoring;
- beam stoppers, respectively, Faraday cups, are often used to stop the beam in case of emergency.

Normally, Faraday cups (FC's) are not provided to measure very fast signals, requiring a large bandwidth of the cup itself and the accompanying signal processing system. With a typical bandwidth up to about 10 MHz, FCs are suitable for measuring the current of dc-beams as well as the average current of pulsed beams having pulse lengths of the order of some microseconds to some milliseconds.

2.1.1 Faraday Cups for Low Power Beams

Due to the electrical insulation of a cup, heat transfer by conduction does not take place and also heat transfer by convection tends to zero in a vacuum system. To avoid heating up, the power loss on a noncooled Faraday cup should not exceed some watts. Cooling by radiation (see Chap. 3, Sect. 3.4) cannot be recommended because thermal emission of electrons arises according to Richardson-Dushmann's law [see (7.33) in Chap. 6, Subsect. 7.1.2].

Designing a non-cooled Faraday cup, the following effects have to be taken into account:

- emission of secondary electrons,

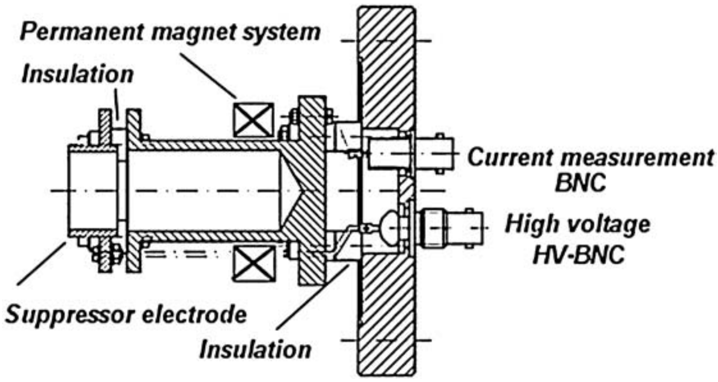

Fig. 2.2. Construction drawing of a simple Farady cup without cooling, mounted on a CF flange [33]

- leak currents arising due to sputtering and deposition of sputtered material onto isolating ceramic parts.

Secondary Electrons

The flux of secondary electrons is $\sim \cos\theta$, where θ is the angle of the electron trajectory against the beam axis. This implies $L_{\mathrm{Fc}} > R$ (L_{Fc} is the length of the open aperture and R is its radius), which is not always possible. Suppression of secondary electrons can be performed by

- an electric field
- a magnetic field
- a combination of both.

Figure 2.2 shows the important parts and typical dimensions of an end Faraday cup, provided for measuring beam currents with low intensity and low beam energy. As a consequence, neither water cooling nor a large thickness of the stopper plate is required. Since most of the emitted secondary electrons are in the energy region below 200 eV, a suppressor voltage of about −500 V is sufficient. Nevertheless, the efficiency of the electrical secondary electron suppression should be checked by measuring the current dependent on the high voltage applied. A permanent magnet system can improve the efficiency of the electric field, especially if the condition $L_{\mathrm{Fc}} > R$ cannot be fulfilled due to spatial limitations. Figure 2.3 is an example of the design of a magnetic suppressor showing also the measured magnetic field strength along the x, y, z-axes. Referring to Eq. (7.74) (Chap. 6, Sect. 7.1.2), the bending radius of a secondary electron with kinetic energy W_{kin} is

$$\rho_{\mathrm{e}} = \frac{\sqrt{2m_{\mathrm{e}}W_{\mathrm{kin}}}}{eB} \approx 3.37\frac{\sqrt{W_{\mathrm{kin}}[\mathrm{ev}]}}{B[\mathrm{mT}]}[\mathrm{mm}] \,. \tag{2.1}$$

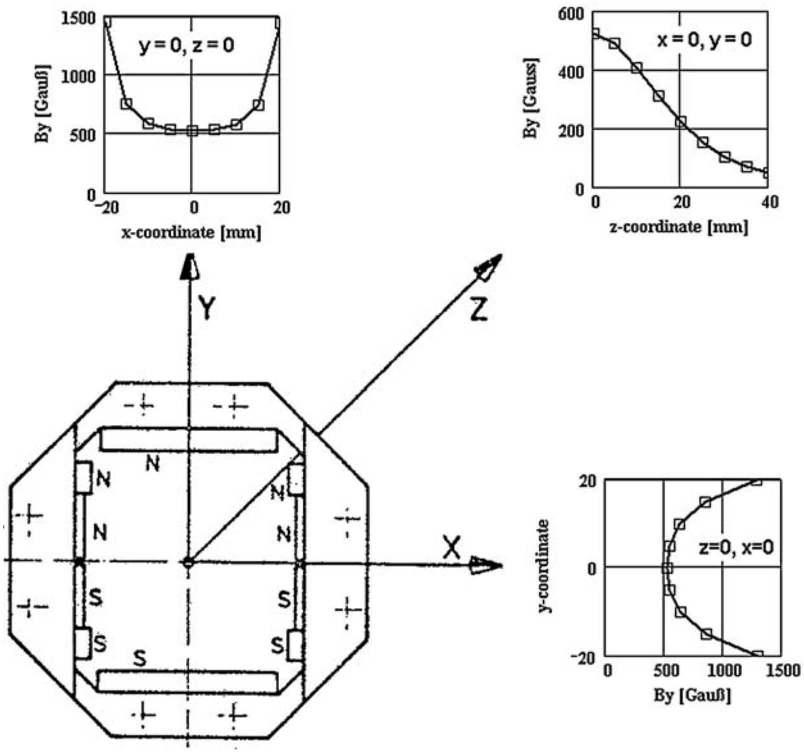

Fig. 2.3. Arrangement of cobalt-samarium permanent magnets in the yoke of a magnetic secondary electron suppressor and the magnetic field strength achieved along the three axes ($1\,\mathrm{Vs/m^2} = 1\mathrm{T} = 10^4\,\mathrm{Gau}\beta$)

For typical field strengths of permanent magnets, bending radii of the order of some millimeters result.

Sputtering

By the sputtering process, atoms of a material hit by energetic particles are removed and deposited elsewhere. Therefore, deposition of sputtered conductive material on electrical insulation can result in leak currents leading to falsification of beam current measurements. The number of sputtered atoms per incident ion depends on many parameters. Measured sputtering rates for a 45-keV Kr beam show relatively high differences between various materials. Table 2.2 gives the sputtering rates [34] for construction materials used mostly in the design of beam intercepting devices such as Faraday cups, and slits.

Table 2.2. Measured sputtering rates for some typical construction materials with a 45 keV Kr beam [34]

Material	C	Al	Ti	Fe	Cu	Mo	Ta	W
Atoms/Ion	2.3	< 1	2	4	12	3	3.1	5

With a sputtering rate of N atoms per incident ion, the amount of material that will be removed can be derived easily from the following relations:

$$\frac{\textit{Number of projectiles}}{\textit{Area}} = \frac{i\,t}{F\zeta e} \tag{2.2}$$

$$\frac{\textit{Number of sputtered atoms}}{\textit{Area}} = N\frac{i\,t}{F\zeta e} \tag{2.3}$$

$$\frac{\textit{Number of Atoms}}{cm^3} = \frac{N_\mathrm{A}\rho}{A}, \tag{2.4}$$

where, A = atomic weight, ρ = density [g/cm^3] of the bombarded material i/F = beam current density [mA/cm^2], ζ = charge state of the incident ion, and $N_\mathrm{A} = 6.022\times10^{23}$/mole is Avogadro's number. The thin layer of removed material comes out as

$$R_\mathrm{s}\,[\mu\mathrm{m/h}] = \frac{0.36\,N\,A\,i}{\zeta\rho F}\ . \tag{2.5}$$

To avoid deterioration of the isolating material, the designer should provide appropriate shielding for the isolating parts.

2.1.2 Faraday Cups for High Power Beams

Contact Cooling

If the average power loss in a Faraday cup becomes higher than some watts, contact cooling may be a solution. This can be performed by using an isolating material of relatively high heat conductivity between the cup body and a part, which can take away the heat to the beam pipe by water cooling or via heat conductivity. Experience has shown that beryllium oxide (BeO) and aluminum nitrite (AlN) (especially Shapal M, [35]) are suitable materials with high heat conductivity and low specific electrical resistance. The heat conductivity of BeO and AlN as a function of temperature is shown in Fig. 2.4. Taking the poisoning factor of beryllium into account using AlN is recommended (especially Shapal-M) as isolating material; it can be machined to a certain extent. A practical example is shown in Fig. 2.5. The drawing shows the main parts of a contact cooled Faraday cup provided for the following beam parameters: