NOVELTIES IN SPECTROMETERS

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I INTRODUCTION

Since the time for development, fabrication and tune-up of a spectrometer is about 3-4 years one can report on truely novel concepts or the proven success of the various recent design.

It is true however, that during the last 5 years there have been many new design ideas, some of which have been realised or will be realised soon. This is borne out by the fact that about a dozen or may be two spectrometer installations are operational or will be built up at low or intermediate energy accelerators. The basic reasons for this "boom" in new spectrometers are manifold:

No other detection system can handle extremely high fluxes of particles and at the same time single out weak groups with high resolution in the presence of very strong groups. Thus it is ideal for singles and coincidence experiments. Many of the new spectrometer designs are astoundingly flexible, e.g. the same basic design is used for a spectrograph at a Tandem accelerator and only slightly modified for a medium energy cyclotron or a meson factory. Magnetic spectrometers are still the main tools for spectroscopy.

This report covers only conventional magnetic spectrometers and leaves out instruments for mass spectroscopy recoil or beta spectrometers and similar 'spectrometer' installations. The objective of this paper is to describe the development which lead to the present spectrometers. A few specific examples considered as 'landmarks' serve the purpose to outline the trends of basic ideas, innovations and the technical realisation of modern spectrometer installations. Two representative examples are briefly discussed.

II SPECIFICATIONS OF SPECTROMETERS

The experimental physics programme may differ vastly from one laboratory to the other, but nevertheless the common design goals of an instrument for the momentum analysis of charged particles are
-High resolution-
-Large solid angle-
-Wide momentum acceptance-
Later the sum of these specifications will be referred to as the figure of merit. There are, however, additional requirements:
-Flexibility, to match the spectrometer favourably to the primary beam (emittance momentum dispersion) and to compensate effectively the broadening due reaction kinematics.
-Large angular range, preferable from 0°-180° (coincidence experiments) and a high angular accuracy.
The extreme magnetic rigidities of the particles determine the size of the spectrometer, which in turn is limited by technical and budget considerations.

This summary of specifications is necessarily incomplete. Particle identification and the choice of detectors have important consequences on recent spectrometer designs: With the advent of heavy ion beams and their use as spectroscopic tools, usually the mass and charge of the reaction product has to accompany the momentum analysis. Time of flight, dE/dx and residual energy measurements of the particles have to be made in the worst case. This involved matter cannot be discussed in a short report, instead it is referred to the review of Hendrie[1], the minutes of a workshop meeting on particle spectrometers held at the GSI at Darmstadt[2], or the more recent proposal for a spectrograph for the VICKSI accelerator at Berlin[3].

III EVOLUTION OF SPECTROMETERS

To a growing extent the quoted specifications -and some more- could be met during the last years. How this evolved is shown in fig.1. Seven spectrometer layouts are sketched schematically. The single magnet Browne Buechner and Elbek spectrometers were at first installed in 1956 and 1963, respectively. In 1966 a new double magnet spectrometer with a common set of coils the Enge split pole furnished the first spectra. All these instruments have been very productive and successful which is borne out by the fact that 23 split pole spectrographs are in operation.

Only three or four other types of spectrometers have been built up during this decade (Green, Parkinson). The beginning of a boom starts in 1970 and as 4 representative examples the Berkeley spectrometer the Heidelberg - München QDDD spectrograph, the EPICS π channel and spectrometer installation at LAMPF and the BIG KARL spectrometer from Jülich are shown (fig.2D-G).

At first sight it may be noticed that
(i) the number of elements increases,
(ii) starting with flat dipole magnets with simple straight or circular edges progress apparently demands more complicated curvatures as exemplified in the EPICS spectrometer.
(iii) new kinds of elements appear in increasing number:
a) classical quadrupoles (denoted by Q)
b) electrostatic deflectors (denoted by ED).

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 219-225

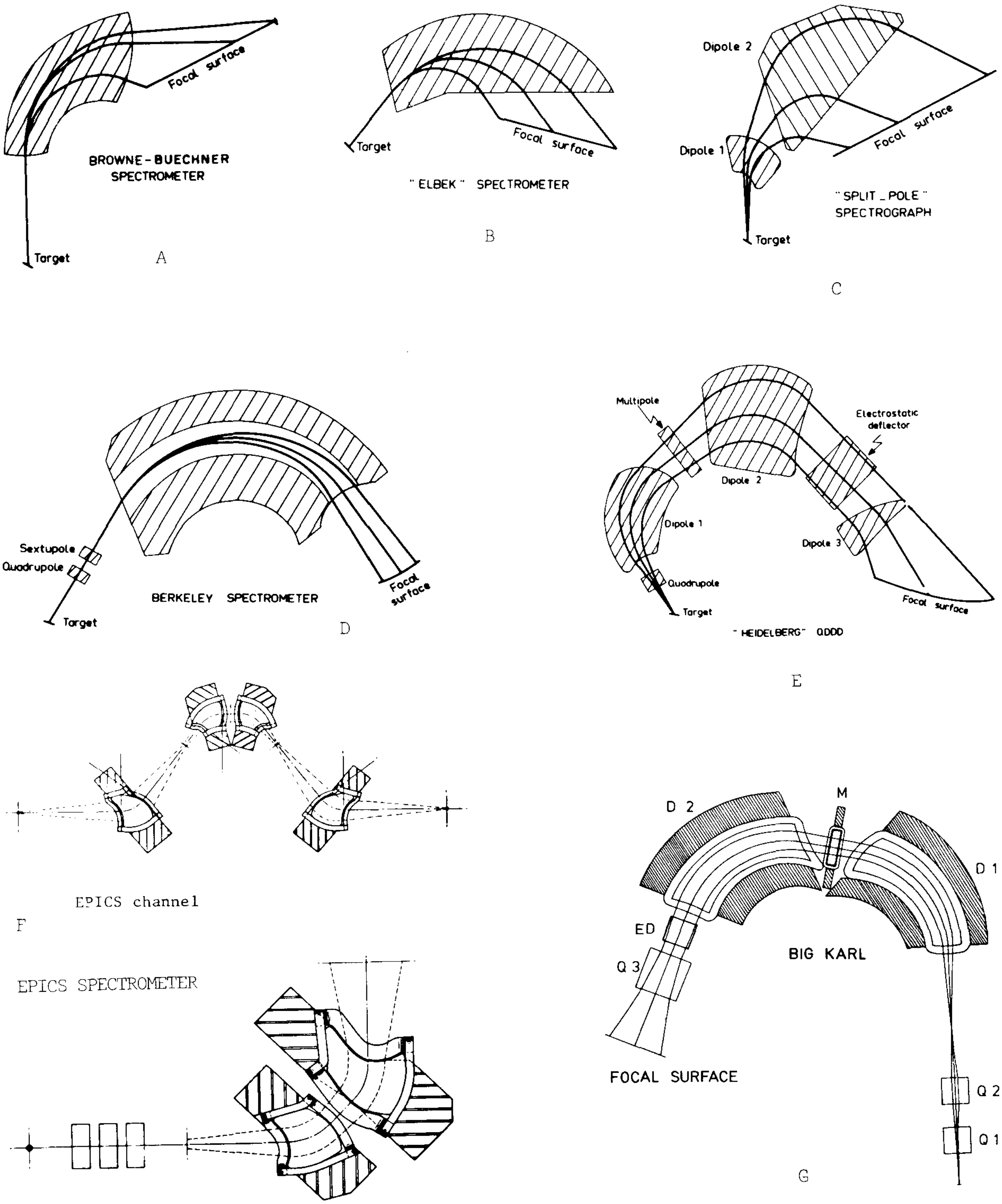

Fig.1 Schematic layouts of spectrometers.

c) rather complicated elements summarized as multipoles (denoted by M) which furnish a more or less complicated superposition of n-pole fields -up to n=5.

(iv) More recently a modification of the well known surface coils so called H_t windings, which are basically conductors embedded in the pole pieces are proposed. They are provided for EPICS and BIG KARL and are thought to eliminate local field imperfections due to mechanical tolerances and in some instances to create multipole components. After tedious investigations the EPICS group decided not to use them, and instead changed the ion optics and inserted separate multipole elements after the magnets had been assembled.

The features (i) - (iv) may be attributed in general to the two main design goals, the increase of 1) the figure of merit and 2) the flexibility of the spectrometer system.

ad 1) A greater figure of merit, by improving on resolution, angular or momentum acceptance causes spherical and chromatic aberrations. As in normal optics. a larger number of lenses with complicated surfaces - in our case the entrance and exit edges of dipole magnets - may be used favourably to reduce aberrations. In addition however this effect has to be independent of the induction -for the range of field values for which the spectrometer has been designed- and secondly has to be highly reproducible. This is accomplished by shaping the pole profiles to the exact Rogowski contour or at least taper it close to it and the use of field clamps, mirror plates, "snakes" or other special shims, mounted in front of the pole piece edges. These limit the extension of the field, avoiding mutual influence of the magnets or other magnetic material. In addition they are used to correct imperfections of the assembled spectrometer.

ad 2) In contrast to these hardware provisions, which are static, active elements serve the purpose of adapting the spectrometer to those conditions which vary considerably from one experiment to the other: The emittance of the primary beam and kinematic effects. Naturally the tune-up of the beam line plays here an equally important role.

The basis for the evolution in spectrometers and the increased number of spectrometers during the last 3-5 years lies in a parallel development of computational tools. Since 5-6 years computer programs such as TRANSPORT or OPTICS have existed together with sufficiently large computers. First and second order imaging properties may be easily calculated and optimised using the matrix representation for the beam and the elements. Higher order aberrations are then studied with codes like RAYTRAC or ORBITE which determine individual particle trajectories through assumed fields. The variation of curvatures at the pole edges and addition of multipole fields may lead to the desired optimum. This tedious task cannot be accomplished by computer fitting but rather the skills in trial and error attempts of an expert. (Recently A.Thiessen at LAMPF has developed the computer code MOTER, which should 'replace' this expert. It is not yet currently available.)

The final optical concept has to be translated into hardware, which is not always simple. Mechanical tolerances, material properties etc. are determined by the status of current technology and of course the budget. Also there is no computer code yet available which calculates the magnet field distribution for a given three dimensional 'arrangement' of iron and coils. If pole piece profiles or curvatures cannot be specified, according to previous experience, the set-up and field mapping of scaled down models are advisable. The same holds true for special elements or provisions like H_t windings.

Where has the trend to more complicated instruments led us so far as the system performance is concerned? Before this discussion, however, fig.2 shows the layout of two spectrometers, which follow a different trend. The SPES II spectrometer in SACLAY will be operational in 1975, the GSI spectrometer for the UNILAC accelerator at Darmstadt is funded and will be ready in 1977.

SPES II and its offspring SUSI at SIN are designed to reconstruct the particle trajectories with the aid of three detectors in the spectrometer. One is close to the target behind the quadrupole, one close to the focal surface and one behind it. Once the fields distribution is known after a careful mapping of the magnets the particle positions in these detectors are used in a computer analysis to determine the momentum. Finite position resolution and straggling effects however impose limitations on the resolving power of the system. Also limitations due to excessive counting rates may occur.

On the other hand the ion optics are much simpler. Higher order aberrations are negligible - the 'elementary cone' for one particle due to straggling effects and the finite position resolution of the detectors has a solid angle of only 20 μsr in the SUSI spectrometer. Consequently hardware design and shimming problems are alleviated. And finally the time needed to get the spectrometer operational from the design stage as well as the costs are very favourable. This holds true for the GSI spectrometer, which is also shown in fig.2. Here a few more elements are employed. For details of the ion optics the reader is referred to ref.4.

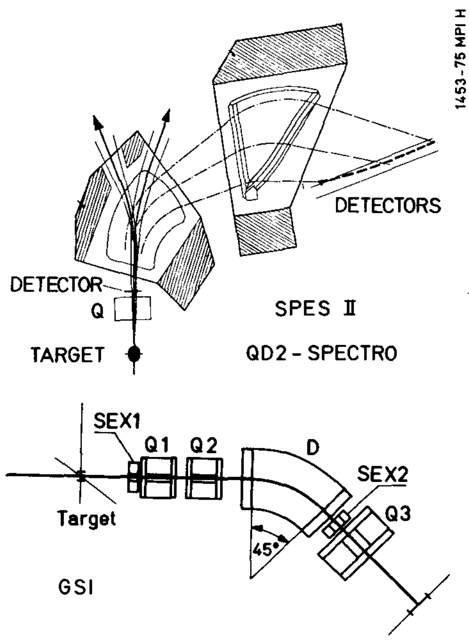

Fig.2 Schematic layout of the SPES II spectrometer (A) at SACLAY and the proposed spectrometer facility at GSI (B) (Darmstadt)

The main advantage of this system is the possibility of correcting large kinematic effects. A great degree of flexibility is provided, since all elements except the dipole magnet are standard elements - some already existing at other labs. They can be assembled anew with other elements for a different spectrometer if that is needed in the future.

IV DEVELOPMENT OF SYSTEM PERFORMANCE

So far only phenomenologically the evolution of spectrometers has been discussed. Fig.3 shows the development in system performance.

One should mention that for the full momentum band and the maximum solid angle the best resolution plotted here cannot be obtained. It is difficult to quantitatively describe the effect of trading off solid angle against resolution or momentum band for all spectrometer types consistently. Therefore, the decision was to present figures which are characteristic for the operation.
The dashed lines are a subjective interpretation of the trends over the years.

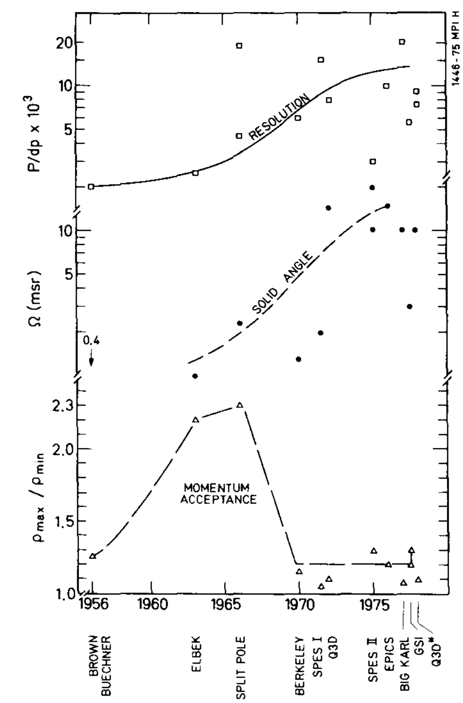

Fig.3 Momentum resolution (□), solid angle (●) and momentum acceptance (△) for different spectrometers built since 1956. Below the time scale, the spectrometer types are denoted.

(i) Momentum resolution is presently at the 20-50 ppm level. There are spectra from SPES I, where in a ^{208}Pb (p,p') experiment 95 keV (FWHM) has been obtained for the 3^- level with the 1 GeV beam from the Saturne accelerator at Saclay. Spectra with 2 keV resolution for 30 MeV are standard at MSU.

(ii) Solid angles have increased to 15-20msr. It can be expected that eventually, for special purpose systems, this figure will be increased by an order of magnitude, with however, at least the same reduction in resolution and a small momentum band of probably 5%.

Thus, for normal spectrometers, this figure will stay constant the more so since it is probably one of the most expensive specification for a given bending radius. There are however ion optical concepts - for instance the BIG KARL spectrometer at Jülich -where for 10 msr solid angle and a 14m flight path the particle envelope never becomes more than 4cm axially, which saves enormously in magnet costs.

(iii) The reduction of the momentum band coincides with the availibility of on-line focal plane detectors replacing nuclear emulsion plates.

Current detectors have a position resolution of 0.3 - 1 mm (FWHM); for the best resolution 3-4 points should determine the line shape in a spectrum. Assuming a momentum resolution of p/dp=5000 the dispersion has to be 5-20 cm/% momentum. Focal planes of 2m are still reasonable as far as the detector length and the system costs are concerned. Consequently the momentum acceptance comes down to 10-40 %. If the resolution of fast on-line detectors cannot be improved considerably also in the future, the momentum band will be rather restricted.

V EXAMPLES

Some more details are shown for two representative examples. In fig.2 a layout of the BIG KARL spectrograph at Jülich, which will be mounted in 1976, is shown. In fig.4 an aritst's view is reproduced. Intensive studies of various designs have led to a QQDDQ design. The deflection radius was chosen to be close to 2m, in order to deflect tritons up to E = 180 MeV. The solid angle for a momentum band of 6% varies between 6 and 20 msr. The design goal was a momentum resolution of p/dp = 20 000 for a solid angle of 5 msr. Scaling up a Q3D spectrograph would have meant a cost increase by a factor of more than 5 and a weight of 800 tons, which both was prohibitive. Thus the magnets had to be as small as possible while retaining a good figure of merit. This could be accomplished by a narrow gap (6cm) which in turn could be optically realized only by providing in each center of the two dipole magnets a waist in the axial direction and a focus in between them. With the full beam from the cyclotron, even for large kinematic shifts, a resolution of $p/\Delta p$=6300 is predicted. Details will be given in Reich's contribution on this conference (D 23).

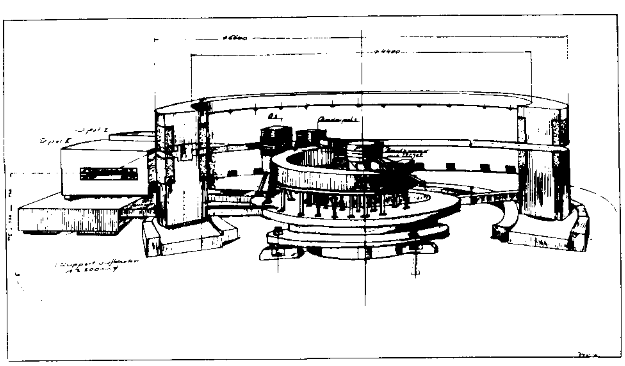

Fig.4 Artist concept of the Jülich BIG KARL spectrometer. The last quadrupole and the detector chamber have been omitted. Heavy shielding has to be inserted around the scattering chamber and behind the second quadrupole.

Orbit radii:	R_o=191 cm	R_{max}=197 cm R_{min}=185 cm
Angular range:	-10^o to 150^o continuous	
Solid angle:	6-20 msr	
Energy range:	E_{max}/E_{min} = 1.12	
Mass energy product:	$10 \leq m\cdot E/z^2 \leq 540$ $2\ kG < B_o < 17.4\ kG$	
Focal plane:	length 1m (straight) focal plane tilt angle 90^o	

First order ion optical properties

Magnification:	0.85 in radial direction 7.15 in axial direction
Momentum dispersion:	17cm/%
First order momentum resolution:	$p/\Delta p$ = 20 000

Tab.1 Some characteristics of the Jülich QQDDQ spectrometer.

Another example is the SUSI spectrometer at SIN, which will be operational still this year, and is shown in side-view (fig.5). The magnet arrangement is vertical in order to measure at far backward angles and for background reasons. The configuration is a QDD type. The ion optics are simple insofar as in the radial direction there is point to point focussing from a detector in front of the first dipole to the focal plane. Since the magnification is about 1, the image of 10x10 cm^2 detector would correspond to 3 % momentum resolution to first order alone, aberration would seriously decrease this figure.

Each point of the front detector 'defines' a different focal plane. With two additional detectors and on-line analysis, it is hoped to achieve a resolution of $p/\Delta p$ = 3000 for 20 msr solid angle and a momentum band of 30-35 %.

For the final tune-up of this spectrometer a "nonnormal" philosophy has been adopted. After the delivery of the spectrometer it was carefully mapped and the lengths and curvatures of the magnets determined. The next step should have been shimming the instrument to the original concept. Instead particles were traced with a computer program using the field maps. The results are fed into the on-line computer for the analysis of the expected pions.

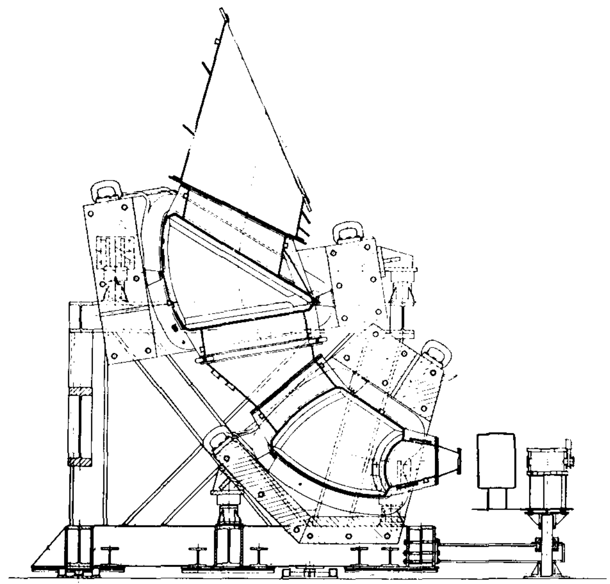

Fig.5 A side-view of the SIN π-spectrometer SUSI. The ion optical layout is similar to the SPES II spectrometer (fig.2B). Between the scattering chamber on the right side and the first detector at the entrance of the vacuum chamber of the lower dipole magnet, a helium bag will be provided.

VI CONCLUSIONS

Concluding these remarks about novelties in spectrometers, the following statements about trends may be made:

1. The two or three last generations of spectrometers seemed mostly to be made on an assembly line: For example 23 split pole spectrographs were sold. Spectrometers of new generation are tailormade to the specific demands. For example, there are 4 different Q3D designs for the physics programs at 12 laboratories.
2. There is clearly a trend towards the many element systems which feature multipoles at positions where they are most effective. In addition the trend is towards more active elements, which make the systems more complex to operate. On the other hand, kinematic and beam line matching becomes possible for a wider range of initial conditions with a better figure of merit.
3. There are still spectrometers which are simple and where the difficult ion optical requirements are solved with the aid of detectors which allow the reconstruction of the particle trajectories.

Prerequisites for good performance of the spectrometer include careful tuning of the accelerator and the primary beam; This is completely neglected in this review. Many aspects of these problems will also be discussed during this conference.

References

1) D.L. Hendrie, Magnetic Detection of Charged Particles in Nucl. Spectr. and Reactions Part A, ed. J. Cerny, New York (1974)

2) P. Armbruster ed., GSI Bericht 73-3 (1973)

3) H.G. Bohlen, B. Gebauer, W.v. Oertzen, Vorschlag für ein Magnetspektrometer für VICKSI, HMI Bericht B 171 (1975)

4) Th. Walcher, Vorschlag für ein magnetisches Schwerionenspektrometer für die GSI, MPI Heidelberg, Bericht V 25 (1974)

DISCUSSION

H.G. BLOSSER: I think I should add a comment. The aberrations in the split pole are very much worse then the resolution which was 1 in every 40'000 in momentum and which was achieved with a very restricted aperture in the split pole. We wanted to show what would happen with a better spectrograph. The experiment revealed that the cyclotron and transport system can work at 1 in 40'000. The experiment was run with open slits and 1-2 μA on target. Dr. Miller will present details in his talk "Improved Energy Resolution with the MSU Cyclotron".

C.A. WIEDNER: I understand this was only possible with the aid of an "energy measuring device" in the focal plane of the MSU split-pole spectrograph plus the additional feedback to your cyclotron and beam handling system.

J. REICH: Just let me comment that in future one should add to the data on spectrographs, the transmission between accelerator and target, at least for cyclotrons, since even with present cyclotrons the over-all resolving power at a fixed transmission is influenced by the quality of the beam.

C.A. WIEDNER: This is very true, and certainly to run a spectrograph in an absolute mode with cyclotrons -- i.e. having a monochromator in the beamline -- means sacrificing something like 95% or more of the intensity. On the other hand spectrographs are running in the absolute mode with machines like tandems which have very good emittance and known energy.

F. RESMINI: Can you comment on the trend of energy resolution which you showed previously? Namely whether you think that presently achieved resolutions are close to a technological limit, or whether we would not have any use in physics for still better resolution?

C.A. WIEDNER: My personal opinion is that p/dp = = 50'000 can be reached at the present status of technology, and even probably more with the recently installed means of correcting mechanical imperfections. Naturally, other factors will then limit the resolution, e.g. the target thickness -- and one has to have a reasonable target thickness in order to study the wave intensity low cross-section and coincidence reactions -- or the energy spread due to reaction kinematics which can be corrected only partly for the full expected momentum band of the spectrograph. Also competing reactions with particles inside this momentum band have generally different kinematics which is not corrected and gives rise to a continuous background. This is a particular problem in heavy-ion physics.

K.V. ETTINGER: Some improvement in the energy spread of the extracted beam can be obtained by using the cyclotron as a spectrometer. The tuning of the RF system and magnet alone can reduce the energy spread to about 0.1-0.5%. It is vital that the phase acceptance at the source is fairly narrow. An extra improvement is also possible if an additional RF pulsing is applied to the extracted beam, thus making the useful phase region even narrower.

These of course are "poor man" approaches for those who cannot afford an expensive spectrometer.

C.A. WIEDNER: I agree that with an internal target the fringe field of the cyclotron separates particles of different momenta spatially. However, the recorded position depends on the producing angle as well and it seems difficult to see how figures of merit as the ones quoted can be obtained with this method.