Dipole Field Characterization by Floating Wire and Field Map Ray Tracing

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***Abstract*—The floating wire (FW) technique was applied to determine particle trajectories in three dipoles which form the magnetic spectrometer ANKE installed in the accelerator ring COSY Juelich. Methodical improvements of the well-known FW technique result in extended applicability and high accuracy. The FW measurements do compare well with field map based trajectory calculation using the GEANT code.**

I. INTRODUCTION

COSY Juelich is operating the magnetic spectrometer device ANKE (Apparatus for the Measurement of Nucleonic and Kaon Ejectiles) at the internal beam of the accelerator ring. Three dipole magnets, Fig. 1, are placed in one of the straight sections of the COSY ring. The magnet D1 deflects the proton beam by a certain angle φ onto the target in front of the dipole D2. D2 bends the beam by the angle 2 φ and D3 which is identical to D1 brings the beam back to the original orbit. D2 serves as the main spectrometer magnet in order to separate the ejectiles emitted with different momenta in forward direction. After this preselection the particles are further analyzed by a sophisticated arrangement of detectors. D1 will also be used as spectrometer for ejectiles emitted in backward direction. The magnets had to be characterized in view of their properties as spectrometer as well as in view of operating the accelerator. This task was done in a twofold way by calculating the trajectories based on measured and calculated field maps and by the "historic" floating wire technique which yields the trajectories directly. We report on the comparison of the results of both methods for D2 as spectrometer and for the D1–D2–D3 arrangement acting as a chicane in the COSY ring.

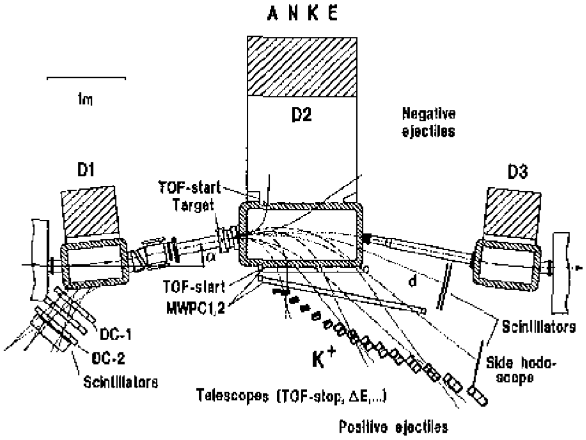

Fig. 1. The 3-dipole configuration of the magnetic spectrometer ANKE forming a 10.6 degree chicane in the cooler telescope straight section of COSY

II. FLOATING WIRE MESUREMENTS

The FW technique is based on the analogy that a flexible, current carrying wire, tensioned in a magnetic field takes up the position of the trajectory of a charged particle with a certain momentum [1].

$$F/I = 3.3356\,p \tag{1}$$

F is the tension force in Newton, I is the current in the wire in A, p is the particle momentum in GeV/c. The tension force is usually produced by running the wire over a well-balanced low friction pulley and hanging a weight of mass m from it, $F = g\,m$. With $g = 9.811$ m s^{-2}, our regional value (Aachen) of the acceleration of gravity, we get with m in gram the momentum p in MeV/c.

$$p = 2.9413\,m/F \tag{2}$$

A. Procedure for Ejectile Trajectories in D2

The spectrometer properties of D2 for positively charged particles were determined for the maximum field of about 1.57 T. In Fig. 2 is shown the arrangement which we used for determining ejectile trajectories at the magnet D2. One end of the wire is fixed at the position of the target. The wire is passed through the magnet, tracked over the pulley, and tensioned by the weight of a mass m . Applying a certain current, the wire can be made freely floating representing the trajectory of a particles with the momentum defined by current and weight. Moving the pulley a little alongside the magnet, the wire will find its equilibrium with a different entrance angle. Determining the position of such trajectories in the field free region outside the magnet by a set of rulers on a measuring table and extrapolating these straight lines until they cross, the focal point for a given condition of field strength B and momentum p is found. Repeating the procedure with various wire currents and appropriate positions of the pulley, foci in the interesting range of momenta are found. Since the wire length will have large variations, it is necessary to match it by a spool mechanism at the target

Manuscript received September 17, 1999.
This work was supported in part by the Russian Ministry of Sciences, the DFG grant 436 RUS 113/430, and the BMBF grant RUS-649-96.
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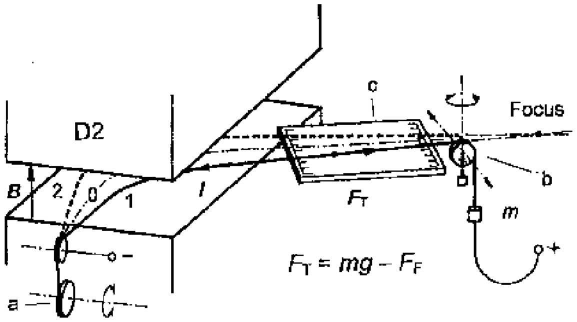

Fig. 2. Principle of the floating wire set-up at the dipole D2. (a) wire length spool mechanism, (b) pulley with pendulum, (c) wire position measuring table with rulers.

position. The choice of the wire is a primary problem. We got a 40 μm gold plated tungsten wire which perfectly fulfilled our requirements in view of electrical resistance, breaking strength, and flexibility. With weights of about 10 and 20 g and currents between 90 and 210 mA the interesting momentum range from 140 to 600 MeV/c for the maximum field of 1.5729 T was covered.

Negligible friction in the pulley can be achieved by the air bearing principle. Fig. 3 shows a cross-sectional view of our pulley. It is a closed axially symmetric construction. Clean, pressurized air is axially blown into the inner cylinder, radially distributed into the 0.05 mm split between inner and outer cylinder and leaving the pulley at the ends. 1...2 bar air pressure were appropriate to carry the weights of the outer cylinder (70 g) and the tension force weight (up to 30 g) without blocking the pulley due to Bernoulli forces at the air outlets.

For low momenta the D2 geometry does not allow to put the measuring table between magnet and focus. It is well-known that if the focus is in front of the pulley the wire will not be stable. As theoretically discussed by Kosodaev [2] and experimentally proved by Bounin and Milman [3], an unbalanced pulley acting as a physical pendulum solves the problem. The procedure to find the equilibrium for the wire is a bit more complicated because the wire length has to be precisely adjusted to get the pendulum back into its natural zero position to be determined before without the wire. We attached a weight of 0.8 g at the periphery of the pulley wheel and got stability for all investigated cases. This zero point, observed by a 80 mm long pointer, was reproducible within ± 0.2...0.3 degree corresponding to a ± 4 mg uncertainty of the weight. This uncertainty was not only due to the reading error but also caused by small slow oscillations of the pulley. These are a combination of a rest of friction and an intrinsic moment of rotation due to the air flow. Since these effects are largely compensated by the pendulum restoring force, it is advantageous to use the unbalanced pulley in any case. In addition, the reproducibility is better because variations of the pulley radius can be excluded. In earlier tests we had identified a 90 degree sector of the pulley where the radius is constant within ± 0.02 mm. Considering all these error sources, including accuracy of the current measurement and stability of the current power supply, we determine the momentum error to be $\Delta p / p \leq 10^{-3}$.

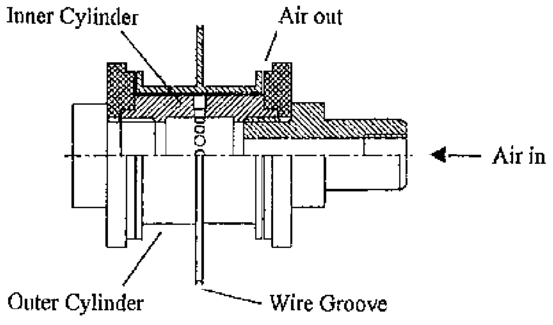

Fig. 3. Cross-sectional view of the air bearing pulley made of low permeability stainless steel. At the groove for carrying the wire the diameter of the pulley is 60 mm.

The wire positions in the reference system of the magnet were determined in two steps. First, the wire position above the measuring table and second, the position of the table relative to the magnet. Looking through a magnifying glass, transparent 0.5 mm scale rulers with mirrors below enabled a parallax free reading with ± 0.1 mm precision. The special construction of our pulley allowed to cut the air flow just in the moment when the pendulum pointer was moving through zero. Once the pulley oscillations were stopped, precise and reproducible readings were possible. The position of the table was determined by standard surveying techniques using a high-precision theodolite [4] and optical markers placed on the table, the magnet, and the target point. The holes for placing the penta-prisma markers on the table were manufactured in distances of 610 ± 0.05 and 360 ± 0.05 mm. They were reproduced within 0.1 ± 0.04 mm. Also the distance of the two marks at the D2 magnet was reproduced within 0.1 mm. Therefore, we assume the absolute position of a crossing point of two trajectories to be accurate within 1 mm.

B. Procedure for a COSY Trajectory through D1–D2–D3

The FW technique was also applied for the simulation of the COSY beam through all three magnets in the φ = 10.6 degree position over the whole momentum range, Fig. 4. D1 and D2 are assumed to be identical and are supplied by a single power supply. The task was to determine the power supply currents $I_{D1,D3}$ and I_{D2} for which the chicane is balanced, i.e. the beam entrance angle in front of D1 and the exit angle behind D3 are zero under the additional condition that the target between D1 and D2 is also hit. The geometry was defined by two measuring tables. The reference for input and output angle was determined by stretching a flexible thread between the fixpoint at the D1 table and the pulley. Short rulers on rods between the magnets were used to measure the wire position in order to determine the individual deflection angle of a single magnet. To get the necessary

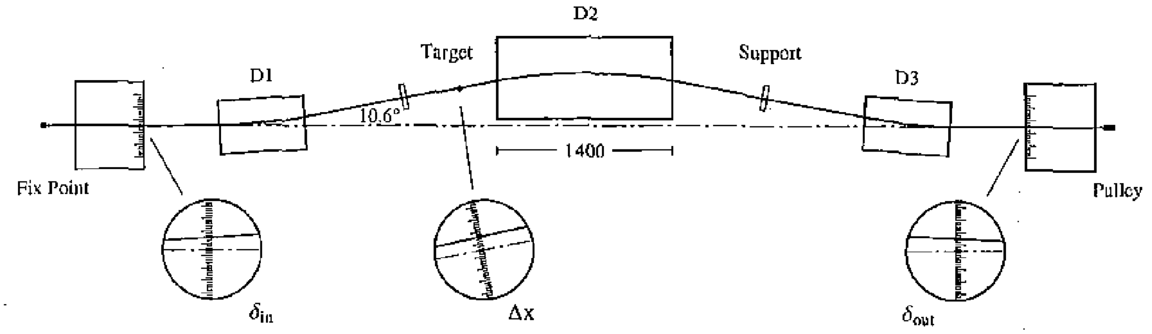

Fig. 4. Arrangement of magnets and measuring tables to determine the necessary magnet currents for D2 and D1, D3 to simulate a 10.6 degree COSY beam trajectory by the floating wire technique.

currents with the – due to safety regulations – restricted power supply voltage of 60 V, a 80 μm tungsten wire was used. Obtainable momenta were 295 MeV/c with 308 mA up to 1987 MeV/c with 45.78 mA wire current for a weight of 30.765 g. Due to the 8.5 m long and heavier wire it was necessary to introduce two supports between D1–D2 and D2–D3 which reduced sagging from 30 to about 4 mm. These supports were made of anodized and polished 8 mm diameter Al tubes. The influence of transverse friction of the wire on these supports was minimized by exiting oscillations prior to the reading of wire positions. This friction is of the Coulomb type causing a linear damping of the oscillation. The reproducibility in the equilibrium state observed at the target point was within ± 0.2 mm.

III. FIELD MAPPING AND TRAJECTORY CALCULATIONS

Due to the size of the D2 we needed a large field mapping machine which fortunately could be provided by GSI Darmstadt. Its positioning mechanism could cover the area of about 3 x 1 m in one run without readjustment. The machine measures all three field components with a set of three Hall probes. The field was measured in five planes (the midplane and the vertical planes at $y = -7, -3.5, +3.5, +7$ cm) on a grid with steps of $\Delta x = 2$ and $\Delta z = 1$ cm, x ranging from -54 to $+40$ cm and z from -121 to $+144$ cm. The maps were measured at the four field values 0.1297, 0.9997, 1.2387, 1.5757 T determined in the center of the magnet. For comparing FW and field mapping results we used the midplane data and the effective length of the field which should be independent on calibration errors. In addition, a calibration of the central field value as a function of the magnet current was done by an NMR probe.

The measured field area covered the range necessary to determine the accelerator beam trajectory but was not wide enough for the calculation of the spectrometer trajectories. Therefore, using the MAFIA code [5], 3 D field calculations were carried out which cover the lacking area. The combined fields are then used with the GEANT code [6] to get the required trajectories.

IV. Comparison of Results

A. Spectrometer Trajectories

Fig. 5 displays results of spectrometer trajectories obtained with the floating wire technique. The six bundles of exit trajectories correspond to momenta in the range from 140 to 600 MeV/c. Each bundle represents the five input angles −10, − 5, 0, + 5, + 10 degree adjusted relative to an accelerator beam input angle of 10.6 degree. The crossing of the different trajectories in each bundle determine the focus line in the midplane of the magnet. In the shown scale the foci are well defined, only at the highest momentum of 600 MeV/c some aberration can be seen. Magnified views on the trajectory pattern around a focus demonstrate that aberration is clearly resolved by the measurement. As an example, a

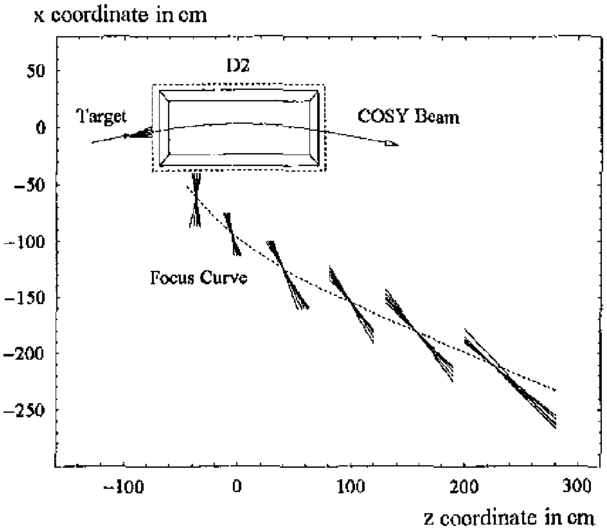

Fig. 5. Floating wire crossings for the six momenta 140.4, 207.4, 291.3, 400.2, 500.3, 600.4 MeV/c forming the midplane focus curve for the given target position, z = 296.7, x = 78.9 mm. The dashed line around the rectangular-type magnet represents the effective field boundary.

magnified view on the 291.3 MeV/c pattern is shown in Figure 6 (a).The width of the aberration is comparable to a momentum deviation of 1%. The single points indicate crossings obtained with trajectory calculations using the combined map of measured and calculated fields. The agreement is rather good. Another proof for the accordance of the results of both methods is shown in Figure 6 (b). 291.3 MeV/c trajectories were calculated backwards starting from the measured wire position. Within the line width all five trajectories cross in a point. The true target point is only 3 mm away in longitudinal direction. For the other momenta the result is not as perfect but the deviations are not more than 10 mm longitudinally and 2 mm transversely. It is interesting to note that comparable good results are obtained with the MAFIA field alone as long as the NMR calibration for the maximum field value is applied.

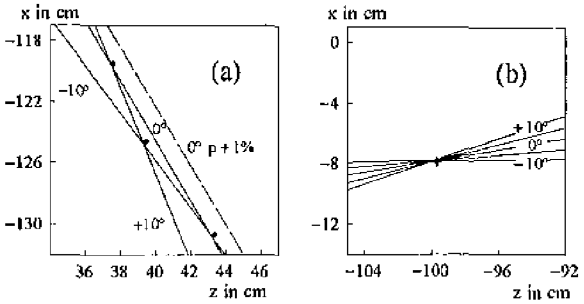

Fig. 6. (a) Comparison of measured and calculated trajectories in a magnified view for the 291.3 MeV/c focus pattern. (b) Backward calculated trajectories fall together in a point very close to the true target position.

B. Accelerator Trajectories

Fig. 7 shows a plot of the currents $I_{D1,D3}$ and I_{D2} versus the full momentum range possible for the 10.6 degree arrangement. The accuracy limits were $\vartheta_{in} - \vartheta_{out} \le 1$ mrad and $\Delta x_{target} \le 1$ mm. These limits should have been small enough to enable static orbits in COSY. As a crosscheck the currents were determined with the magnetic measurement data. For D1 and D3 we got good coincidence between the result of both methods. Random variations were within ± 0.5 mrad. A systematic deviation appeared for D2. The FW method gave a 2 mrad larger deflection at the same magnet current. The reason for this discrepancy is unclear but was not important because after having installed ANKE into the ring, a circulating beam at injection could immediately be obtained. Also acceleration worked. Dynamic effects due to eddy currents are being handled by the backleg windings of D1 and D3.

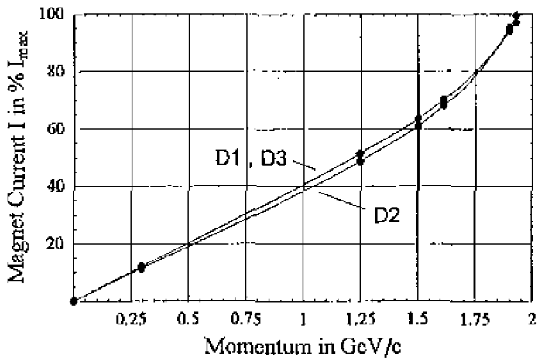

Fig. 7. D1, D3, and D2 magnet currents for a 10.6 degree trajectory in the ANKE chicane determined by the FW technique. The values derived from the field measurements are in good coincidence. Expressed in deflection angle, D1, D3 values agree within ± 0.5 mrad. . For the D2 appeared a systematic deviation such that the FW method generally yields a 2 mrad larger deflection at all except the highest momenta.

V. CONCLUSIONS

The comparison of the D2 ejectile trajectories determined by field map ray tracing and floating wire measurements reveals that 3 D magnetic field codes like MAFIA can provide reliable results. The floating wire technique was successfully applied also for the critical case "focus in front of the pulley" by using the principle of an unbalanced pulley. A further improvement is the method of "freezing in the wire", made possible by the design of our pulley. A momentum accuracy of $\Delta p / p \le 10^{-3}$ has been achieved. The precision and accuracy for position measurements can be obtained with the best surveying instrumentation available only nowadays.

Having at hand the well-developed FW apparatus it was possible to characterize the three ANKE magnets with sufficient accuracy in order to guarantee the circulation of the accelerator beam. Once this is achieved, the fine adjustment can be performed by the accelerator beam itself. Machine experiments at COSY are underway in this direction. They will also clarify the 2 mrad discrepancy between the FW and the field map result.

ACKNOWLEDGMENT

We cordially thank our colleagues from the GSI Darmstadt for the assistance with their large field map machine.

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