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WAYS TO SCATTER THE μ

Various ways to do the μ-scattering experiment at the PS have been discussed in the last weeks. The discussions are summarized in the present paper and the conclusions we have reached are presented.

We will separate the problem of the beam from that of the experiment.

A. Ways to conduct the experiment

These are illustrated schematically in Fig. 1.

I. Elastic scattering in hydrogen in a momentum analysed beam

The following quantities are measured :

1. incident momentum with spark chambers on either side of a bending magnet, see below (C1α);
2. scattering angle with spark chambers;
3. recoil angle with spark chambers.

The latter spark chambers are arranged on either side of the hydrogen target. As an elastic event is described by two elements, we dispose of the one redundant element and the coplanarity to discriminate against inelastic events. The incident flux required is about $5 \cdot 10^4$/burst[1] for 0.7 events/h in a band of momentum transfer of 1 GeV/c ± 10%.

This corresponds to our original proposal[2].

4753/NP/sb

II. Elastic scattering in hydrogen in a wide momentum band beam

Again the incident particle as well as the scattered particle and the recoil proton are detected in spark chambers. This time the secondary particles are momentum-analysed. We measure :

1. the scattering angle
2. the recoil angle
3. the momentum of the scattered particle
4. the momentum of the recoil proton.

The magnetic field is provided by a double magnet, proposed by Morpurgo, and shown schematically in Fig. 2. It surrounds the hydrogen target and a set of spark chambers on either side of it. More spark chambers are provided at some distance outside the field. It has been found[3)] that the momenta and angles can easily be measured with a precision of a few %. The acceptable range of momentum transfers and incident momenta remains to be investigated.

The intensity required is higher (about $5 \cdot 10^5$/burst) because of the restricted solid angle accepted by the magnet. This flux can be obtained, since there is no primary analysis in this case (see below C1β).

This scheme has been proposed by Prof. Bernardini. It seems superior to the similar Brookhaven scheme, where only the two angles and the proton energy (by range) are measured. Here more elements are measured and with greater precision.

III. Scattering in other substances

In this case only two quantities would be measured :

1. the incident momentum
2. the scattering angle.

The comparison with electron scattering can still be done if sufficiently detailed information about the elastic and inelastic scattering of electrons in the same substance is available. Since this is not the case at the present moment, this method is not of interest for the immediate future although this may be the way to go to higher momentum transfers ultimately, in view of the higher density of nucleons in substances other than hydrogen. Measuring also the momentum of the scattered particle would cost much intensity and require in principle the same kind of electron comparison data, although over a narrower range.

All schemes have in common an absorber with a counter behind it in the scattered μ-beam. This arrangement[1] helps to discriminate against π-mesons ($\sim$ factor 100, limited by π-decay in flight).

B. Comparison of the experiments

Experiment I has the advantage that one quantity, the incident momentum, is restricted to a narrow range. This facilitates the triggering, the analysis and the comparison with electron data.

Experiment II has the advantage of providing an extra element, and of eliminating the need to do the magnetic analysis in the intense incident beam.

We conclude, that experiment II is preferable.

C. Ways to produce the beam

Various systems have been considered. They all have some requirements in common, namely

a) A high intensity π-beam. Since no slow ejection scheme is available in the near future, this must be obtained from an internal target suitably placed inside a PS magnet[4].

Some focusing device must be put as near to the target as possible in order to intercept a large solid angle.

b. An unobstructed decay path of at least 30m, preferably 50m.

The various system are sketched in Fig. 3.

1. Quadrupole channel[5)]

The focusing element at the entrance of the channel is a pair of quadrupole lenses. Similar lenses, with a spacing of about 3m, are distributed all over the decay path. They permit the transport of a wide momentum band of π-mesons and the μ-mesons generated by π-decay. The decay path is followed by an absorber. This is made of light material (lithium, the first part possibly of carbon) to minimize multiple scattering. Focussing is provided also in this part, by either inserting the absorber into quadrupoles, or by passing a current through the lithium metal.

From here on, the continuation of the system depends on the type of experiment chosen.

α. If a momentum analysis is desired (Exp.I.) there will be a spark chamber, a bending magnet, another spark chamber, two gas Cerenkov counters and the scattering target. The functions of these various elements are the following. The magnet eliminates physically the greater part of μ-mesons of undesired momentum. Together with the spark chambers it permits an accurate momentum measurement on individual particles. The Cerenkov counters, of which one is in coincidence, the other at a lower pressure in anticoincidence, define for the μ-mesons a momentum band, which can be varied by changing the gas pressure in the counters. In a test run, a momentum band of $\pm$ 5% at half height with 100% transmission for the central momentum has to be obtained. Together with a higher momentum cut-off, which the magnet can provide, the Cerenkov counters also can provide a discrimination against π-mesons. The Cerenkov counters can be included into the trigger requirement for the spark chambers used for the momentum analysis of the incident beam. The beam intensity obtained in this case is estimated[4)] to be $9 \cdot 10^4/10^{11}$ protons for a 50m decay path. The estimate is uncertain (and probably pessimistic) since the loss of beam caused by a magnetic analysis behind the absorber, and therefore with a poor geometry beam, has been guessed very roughly to be a factor of 10 in the pass band. More accurate calculations will be made.

Quadrupole lenses will be inserted between the Cerenkov counters to minimize loss of beam.

The operation af the spark chamber before the bending magnet at full beam may present difficulties. This problem remains to be studied. It is to some extent common to all schemes we describe.

β. If a momentum analysed beam is not required (Exp.II), the absorber will be immediately followed by the two Cerenkov counters, again placed between quadrupole lenses. They are followed by the spark chamber, which forms the entrance to the scattering set-up.

The Cerenkov counters have two functions. Used as a narrow band momentum filter as in the previous case, they permit an investigation of the momentum spectrum of the particles emerging from the absorber. Included in the triggering requirement of the spark chamber, they give the angular distribution of the beam in a narrow momentum band. The knowledge of these two distributions is essential in order to be able to pass from a number of scattered particles to a cross-section. In the actual experiment, the pass band of the Cerenkov counters is chosen to be wide. However undesired particles can still be eliminated, e.g. particles below a certain momentum, which would contribute many large angle, low momentum transfer scatterings. The Cerenkov counters, used as a wide band device, do not contribute to a discrimination against pions, and more absorber will have to be used to produce a purity equivalent to that of Exp. 1α.

In this case we expect to have about $10^6\mu/10^{11}$ protons. This estimate is less uncertain than that under 1α.

2. An optical system without absorber. Such a system, based on the principle of the SC μ-channel, and with more bending magnets and Cerenkov counters to reach the desired purity, is being considered, but cannot be counted on for the immediate future.

3. A system using van der Meer beam guides[6] instead of quadrupoles is possible, but has not yet been studied in sufficient detail by us. It is interesting mainly in view of the possibility to make it very long.

4. A system proposed by Prof. Bernardini as an intermediate solution and worked out by Morpurgo[7]. It focuses the π-mesons from the target on to a point at the end of the decay path, using a pair of quadrupole lenses. The μ-mesons are allowed to spread out due to their finite decay angle. At the end, a large lens, made of iron, intercepts the μ-mesons. The lines of force are concentric circles round a wire passing along the axis of the system. They run in iron everywhere. The excitation is chosen such, that the iron is saturated everywhere. This device can focus all incident μ-mesons down to a small exit area. They come out under large angles, because of the initial large spread in space, and mainly because of multiple scattering in iron (see below). The purification is partly by the iron itself, partly by other absorbers, which can be interleaved with the iron. The intensity in this case has not been worked out in any detail, but is expected to be perhaps similar to that obtained from 1β.

In order to use most of the beam, the possibility of a primary analysis would have to be sacrificed. In this case the shape of the incident spectrum and the angular distribution as a function of momentum, which are essential for a measurement of a cross-section, can only be inferred from scattering data (e.g. at low momentum transfer), treating the cross-section as known. This presents the disadvantage, that an important check is lost, and that the spectrum is only known after many thousand scattering events have been measured, i.e. many weeks after a long run. Also there is no way of limiting the momentum spectrum or of modifying it during the run.

This is clearly a less satisfactory way to run the experiment. We therefore conclude that for the moment the quadrupole channel scheme 1 gives the beam which is most suitable. It can be used for experiment I, II and later III, and can be adapted to other uses of the beam.

E. Time Scale

The prerequisites for any μ-beam are listed under B. In our opinion they can only be obtained in the East Area without disturbing many other experiments. So the zero of the time scale is the moment when straight section 64 is made accessible by exchanging two magnets.. For the lenses we could use 1m or 50 cm lenses before, and 50 cm or SC lenses behind the absorber. Enough such lenses will be available by April, according to M. Ašner.

The delivery situation of the special analysing magnet is still under investigation; the lithium can be delivered at short notice. All detection equipment should be ready by January. The Cerenkov counters have already been tested.

Should a situation arise, where a target in the machine and machine time is available, while there is not yet a sufficient number of lenses, then this time can be spent very usefully in studying elastic and inelastic scattering of π-mesons in the momentum and angular range we are interested in. The published data are insufficient to estimate the competition from these events.

D. Comparison of the beams

Beam 4 has the advantage of requiring little beam transport.

In order to compare the beam obtained from scheme 1 and scheme 4, we have to look at table 1, where, for a typical incident π-momentum of 6 GeV/c, the energy distribution and the multiple scattering angles are worked out for various substances. The notation is explained in the table.

The following assumptions may be controversial.

The Fe-C case corresponds to a rather extreme "dilution" of the iron, since in this case only $^1/_8$ of the volume is iron.

The attenuation length has been assumed to be twice the collision length. This is based on measurements by the Hyams group[8)], who find a pion attenuation length of 130 gcm^{-2} (= 2.15 collision lengths) for C at 10 GeV. Should the attenuation length at our energy be a little smaller that 2.0 collision lengths, then the figures in the table change somewhat, but the conclusion would not be altered.

We have arbitrarily assumed, that all μ-mesons below 1 GeV are rejected. If one puts this cut-off lower, say, then the band of accepted μ-mesons ($E^1 - E^2$) becomes larger for the heavy materials, but at the same time the scattering angles become still larger. If one raises the limit, the accepted band would shrink very seriously.

Inspection of table 1 shows : 1) the momentum band accepted from a heavy absorber is narrower; 2) the rms. multiple scattering angle from the iron lens would be about 3 times bigger than from Li. This means, that, if one uses the Cerenkov analysis of the incident beam as described under 1β, only about 10% of the beam will be transmitted, since 2m lens spacing is just about adequate to accommodate angles emerging from the Li. It is not feasible to reduce the lens spacing any more because of the dimensions of the Cerenkov Counters.

F. Finances

Standard equipment already ordered will not be counted.

The Li absorber will cost between 15 and 30 kFr.

The special magnet costs about 250 kFr. It can be made by modifying existing standard 2m magnets. In this case about 100 kFr would be required. We are convinced that it will prove useful for other experiments.

The iron lens would cost about 30 kFr.

The installation of a beam in the East Area is an object which is difficult for us to estimate. It is not normally included in the cost estimate of an experiment.

Should it prove possible to install the beam of type 4 (with iron lens) in the South Hall, then the beam 1 (with quadrupoles) can equally well be installed there. So beam 1 and 4 cost about the same; experiment II has the extra cost of the analysing magnet which seems money well spent.

G. Conclusions

We would like to go ahead with the erection of the quadrupole channel in the East Area as soon as possible. Even before the arrival of all lenses essential work could be done there, as soon as a magnet 64 is exchanged against a magnet with the yoke inside and a target is provided in magnet 63. Detailed power estimates etc., will be given in a separate note.

We would strongly prefer to do the experiment with the special analysing magnet. As long as this is not available, we will work with analysis on the primary beam only.

We expect to start the experiment proper in April or May 1963.

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4753/NP/sb

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Fe-C	corresponds to a mixture of 50% Fe and 50% C by weight.
Z	atomic number
A	atomic (resp. molecular) weight
$L_{coll.}$	collision length (geometric)
$(dE/dx)_{min}$	specific energy loss at minimum
X_o	radiation length
x	absorber required for an attenuation of 10^5. The attenuation length is taken to be twice the collision length. This means 23 collision lengths for 10^5.
ΔE	energy loss in x, assuming 1.15 times minimum ionization.
E_1^{in}	highest μ-meson energy before the absorber. The μ mesons are supposed to be generated by 6 GeV π mesons.
E_1^{out}	energy of the same μ mesons after the absorber = $E_1^{in} - \Delta E$.
E_1^{av}	geometric mean of E_1^{in} and E_1^{out}.
ϑ_1	r.m.s. multiple scattering angle of highest energy μ mesons in the absorber. Follows from $15/E_1^{av} \times \sqrt{x/X_o}$ mrad. E_1^{av} in GeV
E_2^{in}	Lowest useful incident μ energy. This is 0.6 times E_1^{in} (kinematic limit) unless after subtraction of ΔE less than 1 GeV is left after the absorber. In this case, E_2^{in} follows from 1.00 + ΔE GeV.
E_2^{out}	etc., as above.
ϑ_2	largest r.m.s. scattering angles occurring.
$E_1 - E_2$	useful band of μ mesons, if mesons below 1 GeV are rejected.
E_c	centre of the μ band = arithmetical mean of E_1 and E_2.
ϑ_c	these r.m.s. scattering angles are the most representative ones.

Table 1

Behaviour of μ-meson beam in various absorbers.

	Substance	Fe	Fe-C	C	Li	LiH	H	
	Z	26		6	3		1	
	A	56		12	6.94	7.94	1	
	$L_{coll.}$	100	75.3	60.4	50.4	45.2	26.5	g cm^{-2}
	$(dE/dx)_{min}$	1.48	1.67	1.86	1.72	2.03	4.14	MeV g^{-1} cm^2
	X_o	13.9	21	42.5	77.5	74.4	58	g cm^{-2}
	x	2300	1730	1390	1160	1040	610	g cm^{-2}
	$\sqrt{x/X_o}$	12.9	9.1	5.72	3.87	3.74	3.24	
	ΔE	3.90	3.32	2.98	2.30	2.43	2.90	GeV
	E_1^{in}	6.00	6.00	6.00	6.00	6.00	6.00	GeV
	E_1^{out}	2.10	2.68	3.02	3.70	3.57	3.10	GeV
	E_1^{av}	3.55	4.01	4.26	4.71	4.62	4.31	GeV
	ϑ_1	55	34	20	12.3	12.1	11.3	mrad
	ϑ_1	3.15	1.95	1.15	0.71	0.69	0.65	°
	E_2^{in}	4.90	4.32	3.98	3.60	3.60	3.90	GeV
	E_2^{out}	1.00	1.00	1.00	1.30	1.17	1.00	GeV
	E_2^{av}	2.21	2.08	2.00	2.16	2.05	1.98	GeV
	ϑ_2	88	66	43	27	27	25	mrad
	ϑ_2	5.05	3.78	2.46	1.55	1.55	1.43	°
Width of μ momentum band	$E_1 - E_2$	1.10	1.68	2.02	2.40	2.40	2.10	GeV
	E_c^{in}	5.45	5.16	4.99	4.80	4.80	4.95	GeV
	E_c^{out}	1.55	1.84	2.01	2.50	2.37	2.05	GeV
	E_c^{av}	2.90	3.08	3.18	3.46	3.37	3.19	GeV
Average r.m.s. multiple scattering angle	ϑ_c	67	44	26	16.8	16.7	16.2	mrad
	ϑ_c	3.84	2.52	1.49	0.96	0.96	0.87	°

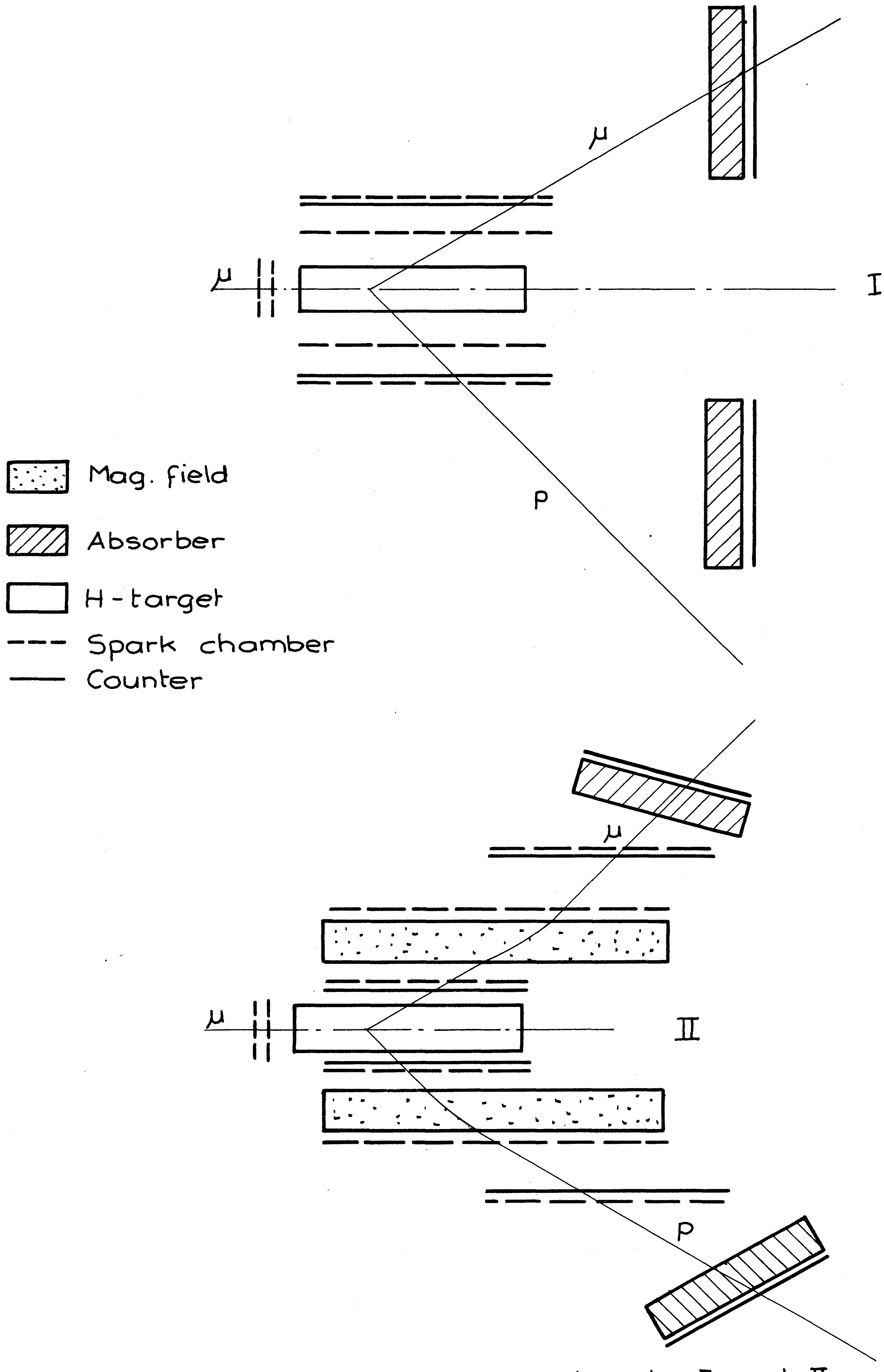

Fig.1 Principles of experiment I and II.

SIS/R/4895

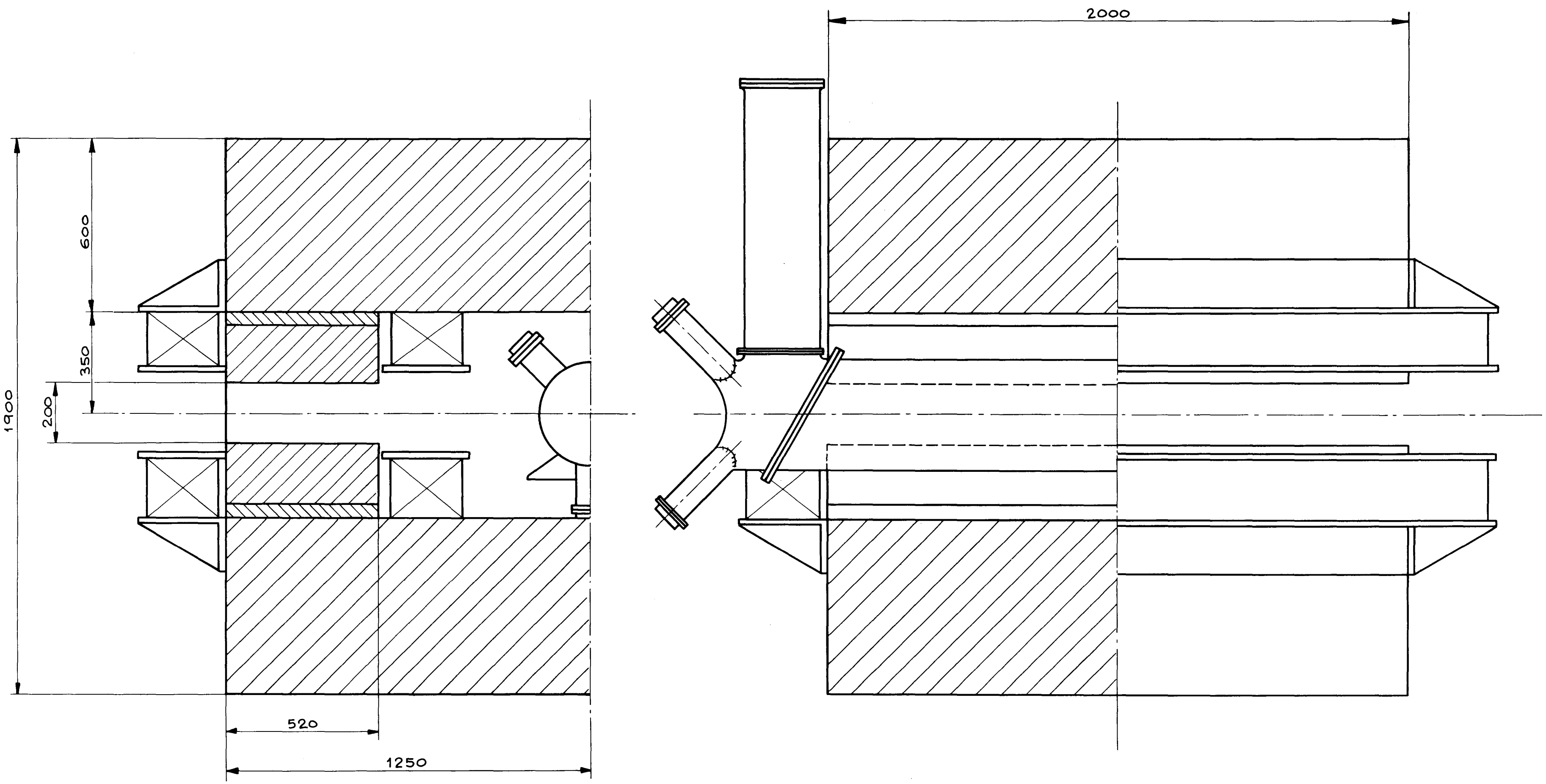

Fig.2 SPECIAL ANALYZING MAGNET

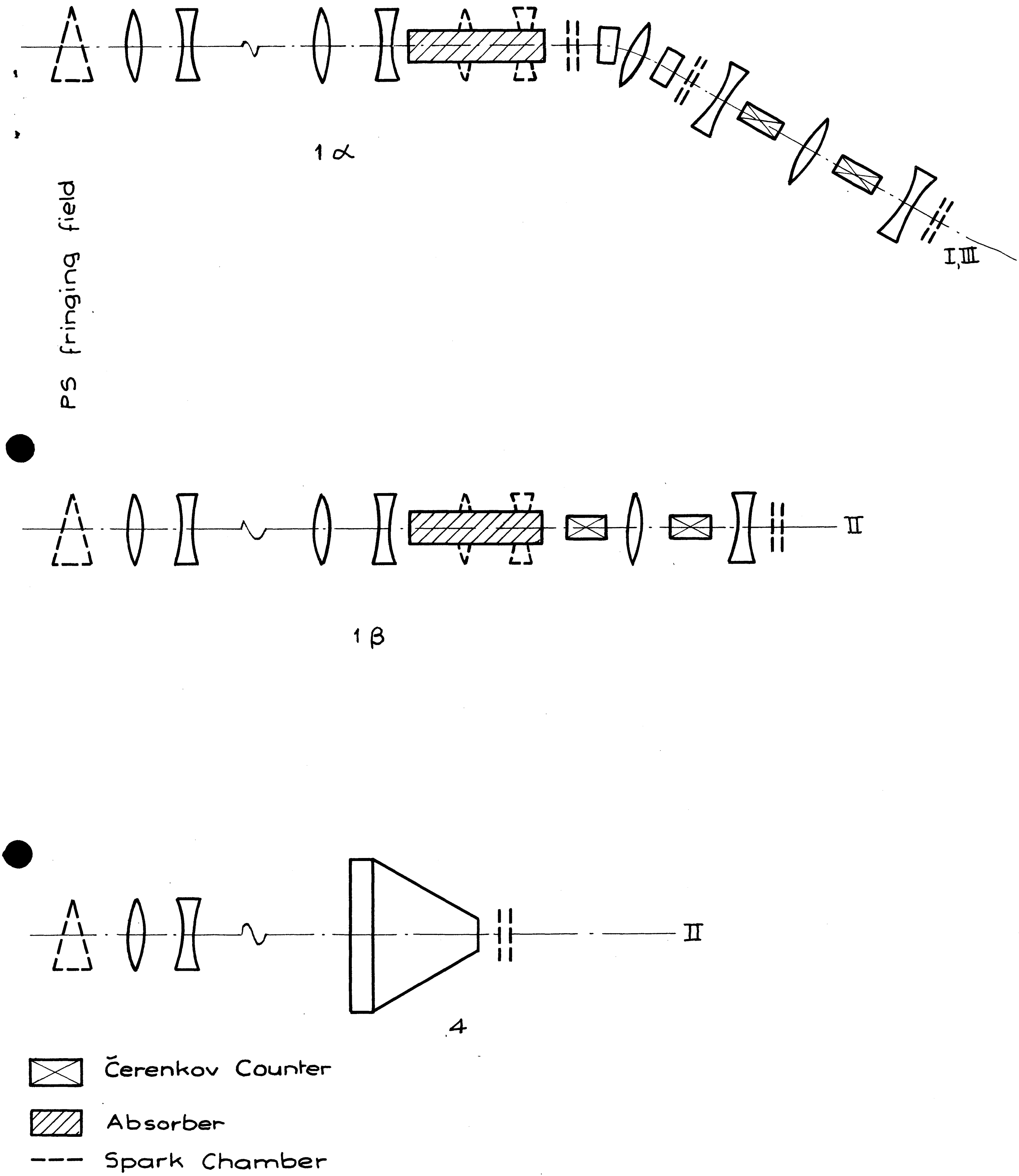

Fig. 3 Various μ-meson beams (schematically)

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