HIGH FIELD PULSED MAGNETS FOR A BUBBLE CHAMBER BEAM

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Summary

To facilitate the production of hyperon-enriched beams for bubble chamber experiments, a range of pulsed magnets has been developed,[1 2] featuring 20-40 cm-long bending magnets with peak fields up to 13T, and 30-60 cm-long quadrupoles having gradients as high as 500T/m; apertures are typically 2-6 cms. Such parameters lend themselves to beam lines capable of kinematic analysis and focusing in very short distances, with consequent minimised decay losses.

All magnets are air-cored and water-cooled, with goemetries tailored to suit particular experimental requirements. Of singular importance are the measures taken to distribute in-pulse loads and minimise fatigue so that lifetimes may be stretched to at least 200,000 shots. Special attention is paid to the cooling of otherwise-limiting components of clamping assemblies, permitting the pulsed beamline to operate at machine rates of 25 ppm, and even to double-pulse if necessary.

Σ^- Beamline Layout

Figure 1 illustrates an arrangement designed to provide enhancement of Σ^- hyperon-content in a 3m-long negative beam for the CERN 2m Hydrogen Bubble Chamber. Secondaries are produced by collision of a well-focused beam of 21 GeV/c protons with a 10 cm tungsten target let into the upstream dipole. A combination of two 20 cm-long 10-13T pulsed bending magnets and a narrow slit in U_{238} absorber rejects all but those negative secondaries in the uppermost momentum range of 16-20 GeV/c, and so favours the heavier particles such as Σ^-. The hyperon to pion ratio is therefore increased, hopefully to the level at which the pion background is acceptable.

Secondary capture is improved by including a quadrupole doublet consisting of a vertically-focusing pulsed element with a 50 cm focal length, followed by a horizontally-focusing unit to limit divergence in the H-plane.

All magnets are energised in series by a 1-2 ms-long pulse of up to 130 kA peak amplitude derived from capacitor discharge. Magnet stands and busbar links are designed to give adequate flexibility and accommodate various momenta. Alignment is checked by a system of polaroid film-plate telescopes.

Current Source

An earlier, Λ°, experiment conducted at CERN was originally intended for use at the Rutherford High Energy Laboratory, where for reasons of time uniformity of field, pulses of the order of 2-3 ms length were required to accommodate 200-400 μS machine spills. A 20,000 μF capacitor bank charged to 4kV by a gated constant current thyratron-controlled supply and switched by ignitrons provided such pulses with peak amplitudes of 130 kA. Overswing is prevented by a simple crowbar circuit as described in earlier literature [3]; a typical pulse waveform is shown in Figure 2. Current has so far been carried to the magnets by as many paralleled low-loss co-axial cables as demanded by repetition rate.

Recent modifications to the power pack now permit each of two 10,000 μF banks to be charged to 6 kV, in order that a system like that described in the last section, but with elements twice as long (suitable for 50-100 GeV/c) may be double-pulsed to a peak 100 kA at a maximum repetition frequency of 27 ppm. for magnet-cooling reasons, the interval between pulse pairs should exceed 100 ms. Choice of pulse length and peak current represents a compromise between heating factors associated with effective operating frequency, and the maximum current that may be handled with reasonable ease and reliability.

Bending Magnets

History

For the first of an expected series of experiments an 8-turn 40 cm-long helical coil [3] machined from the solid copper, provided 7T to sweep aside all charged secondaries, leaving a zero-charged beam to enter the CERN 2m Hydrogen Bubble Chamber. Judicious choice of production angle increased the lambda to pion ratio. Designed for, and tested to at least 100,000 shots, one of the two magnets used in the experiment survived 300,000 shots without damage; during tests, another operated at 10T for 20,000 pulses without failure, but using excessive power. Fig. 3a shows such a coil.

More recent dipoles have geometries shrunk around the beam to economise on power, and permit more units to operate from a not-much-altered current source, and at higher bending strengths. Moreover, coils are now shorter to 'fit' the trajectories and provide requested acceptance without unduly increased aperture.

'Σ' Coil

The 8-turn coil of Figure 3b, shown during manufacture from a solid billet of cadminum copper, has already provided 9T over 23 cm for 90,000 shots, and shows no signs of fatigue. Vertical aperture is 2 cm, with a bore depth of 8 cm.

As a consequence of constraints on current flow under oscillatory conditions, most of the energising current is conducted by the inner 3 mm skin of the coil [4]. Joule losses are accordingly higher than for DC conditions, and there is good agreement between calculation and measurement of both field and inductance.

Cooling

To dispose of the 30 kJ deposited in the coil during each pulse, demineralised water is forced at 10 atmospheres through copper tubes brazed on both sides of each turn before the coil is insulated between turns. Instantaneous temperature rises are in the region of 80°C, the mean copper skin temperature levelling at about 50°C during single-pulse operation at 27 ppm, and for 1 ms-long pulses. The temperature gradient through the copper turns is sufficiently high to avoid cooling water flashing to steam.

Forces

'Radial' in-pulse bursting forces are high - in the region of 120 tonnes on a side at 13T. Similar forces operate in the axial direction, but tending initially to crush the coil to reduce its bore. Moreover they are applied to a relatively small area of the interturn insulation as a result of the skin-effect; a massive backing assembly prevents early mechanical self-destruction.

Inter-turn Insulation

Peak inter-turn voltages are less than 400V, so provision of adequate electrical strength is no problem. However, the material must behave well under high instantaneous mechanical stress and thermal shock. Glass filaments are wound tightly around the coil bore before it is machined away, and the coil vacuum impregnated with a high temperature epoxy resin. Axial prestressing of the coil subsequently prevents the insulation going into tension during coil 'bounce' - a state in which it is more likely to fail.

Current leads

Current lead-ins are soft-soldered to an otherwise completed coil. They link the wide, low-loss busbars to the high current density coil turns in a very short distance, and are themselves water-cooled.

Clamping Assembly

To minimise movements likely to cause fatigue and early failure, the coil is clamped by an arrangement of stainless steel plates and bolts, with intermediate insulating load-distributing pads of epoxy-impregnated glass laminate. These limit differential movement arising from stress profiles, as well as overall coil movement; at the same time, they hold the steel components away from the regions of high stray field. Nevertheless, bulk eddy current losses account for 10 - 15% of total power used in these coils, so all bolts and plates are water-cooled to prevent gradual overheating, and in the axial direction, loss of prestress and subsequent insulation breakdown.

Figure 4 shows a partly dismantled Λ magnet assembly, whilst the photograph of Figure 5 is of the latest still-operational magnet.

Quadrupoles

Figure 6 shows the first test air-cored quadrupole and clearly indicates the conductor configuration; this is a version of the four line current geometry[5] well-known in plasma research for its 'cusp' fields, and yields good quadrupole fields. By laying 5mm square-section water-cooled copper conductors along a 3cm diameter cylinder with alternate current flow and return, a quadrupole field of quality sufficient to suit these purposes is provided over the central 2 cms of aperture. Energised in series with the dipoles of the previous section, a peak 130 kA corresponds to 500 T/m.

For the prototype, square section conductors brazed to massive current leads and bridging sections were mounted around a grooved hollow core of Permaglass -60% glass, 40% epoxy resin - the assembled coil being wet-wrapped with glass tape and the epoxy cured at 120°C. Conductors were cooled in parallel to provide the maximum heat transfer and to avoid flashing of cooling water to steam. This 50 cm-long magnet survived 85,000 shots at 400T/m before failure at one brazed joint, probably due to overheating as a result of cooling channel blockage by rubbish in the demineralised water supply.

Forces tend to partially cancel due to current disposition, leaving a total of only 10 tonnes per metre explosive force on conductors.

The second magnet of the doublet merely limits the beam divergence in the H-plane after the second of the two dipoles; the first quadrupole, described above, is sited between bending magnets. To accommodate increased beam width, 5 cms of aperture are required for this last active element, sufficient focusing power being provided by a 30 cm-long unit. A beam optics program, written by the Cambridge Bubble Chamber Film Analysis Group proposing the experiment, optimises the various parameters.

Operation of these lenses in series with the dipoles injects a certain inflexibility to the system, but a degree of tuning may be gained by shunting with suitable inductances. Alternatively, it is not unreasonable to consider preparing a selection of coils with conductors at a range of radii, and so offering different focal lengths.

Performance and Further Development

Tables 1 and 2 collect major parameters and performance figures of magnets operated to date, during both the Λ experiment and development tests for the Σ experiment.

At present, tentative plans are in hand for running at 50 GeV/c and 100 GeV/c into the 15 foot chamber at NAL. Two 40 cm-long dipoles and double the quadrupole strengths would be required; otherwise only slight modifications to the general designs are envisaged. Eddy current losses in the dipole clamping assemblies may be reduced by increasing thicknesses of load-distribution pads to carry steel components further from the coil, whilst total restraining bolt area may be increased without major re-arrangement of other components.

Quadrupole lengths would probably be left at 50cm maximum for cooling reasons, since it is a simple matter to link twice as many already-tested and proved units in series. The transition from current lead-ins to active conductors can easily be strengthened to give longer life, and the use of finer coolant filters will prevent undue local overheating.

With such minor modifications, minimum lifetimes of the order 200,000 shots are expected, permitting the confident planning of a wide range of experiments.

Complete bending magnet assemblies will cost in the region of £1000, replacement dipole coils £300, and quadrupoles £200. Mounting apparatus already tested and used in the Λ° experiment permits rapid exchange of damaged items.

It is planned to chart both dipole and quadrupole field regions in detail, mostly to confirm predictions based on both simple mathematical models and the output of a program yielding field configurations for various conductor geometries.

Acknowledgements

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References

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4. T.Lammeraner, M.Stafl, 'Eddy Currents', Iliffe Books Limited, London.

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Table 1 Σ Quadrupole

Major Parameters and Performance to Date

length	50 cm
no. conductors	4
aperture	3 cm diameter
inductance	1 μH
peak current	100 kA
peak gradient	400 T/m
pulse length	1.5 ms
rep rate	27 ppm
lifetime	85,000 shots

Table 2 Dipoles

Major Parameters and Performances to Date

	Λ Dipole	Σ Dipole
Length	40 cm	23 cm
turns	8	8
aperture	6x12 cm²	2x8 cm²
Inductance	12 μH	4 μH
peak current	130 kA	90-100 kA
peak field	7 T	9-10 T
peak integrated field	3 Tm	2.1-2.3 Tm
pulse length	3 ms	1.5 ms
rep. rate	25-30 ppm	27 ppm
Lifetimes 1	40,000 shots	55,000 shots
2	100,000 survived	40,000 "
3	150,000 survived	90,000 survived
4	300,000 survived	

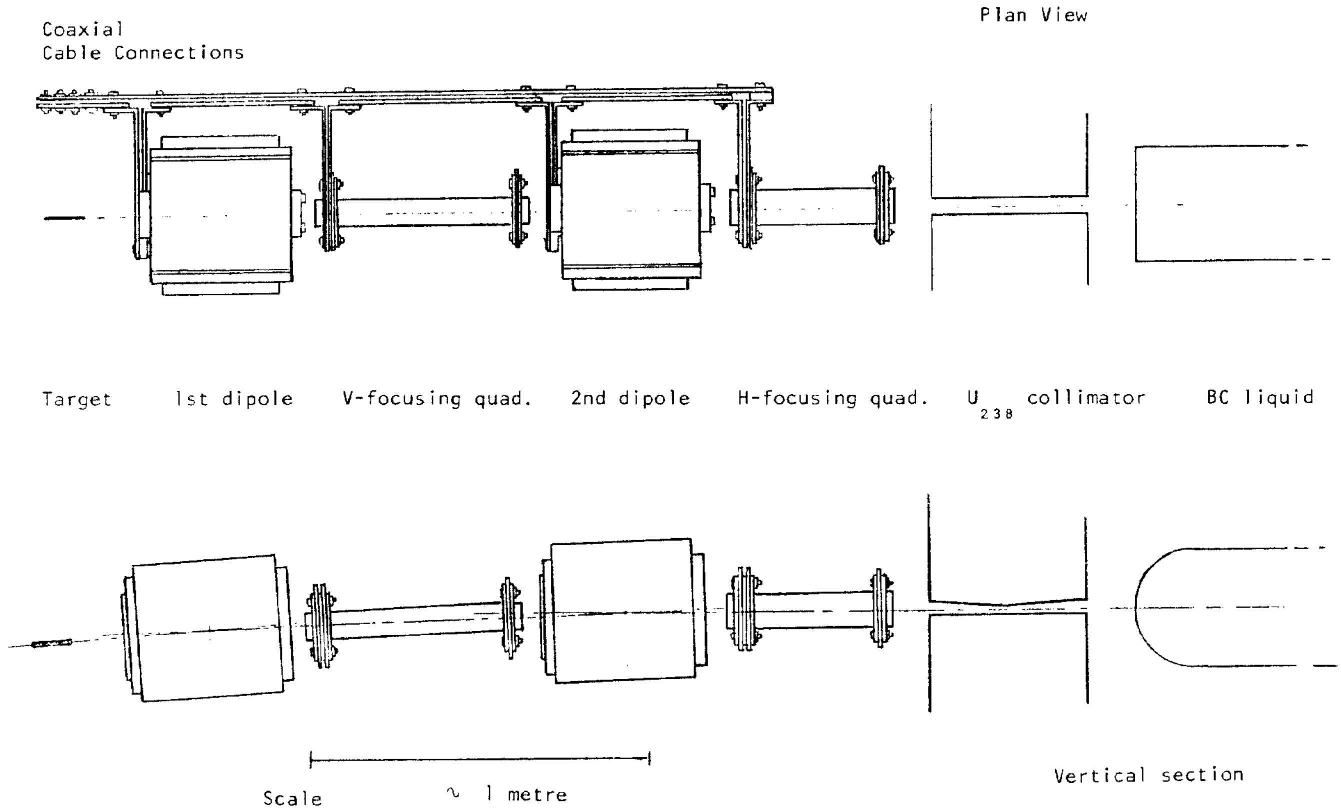


Fig. 1 General layout of a Pulsed Beamline as envisaged for a 20 GeV/c Σ^- Experiment at CERN

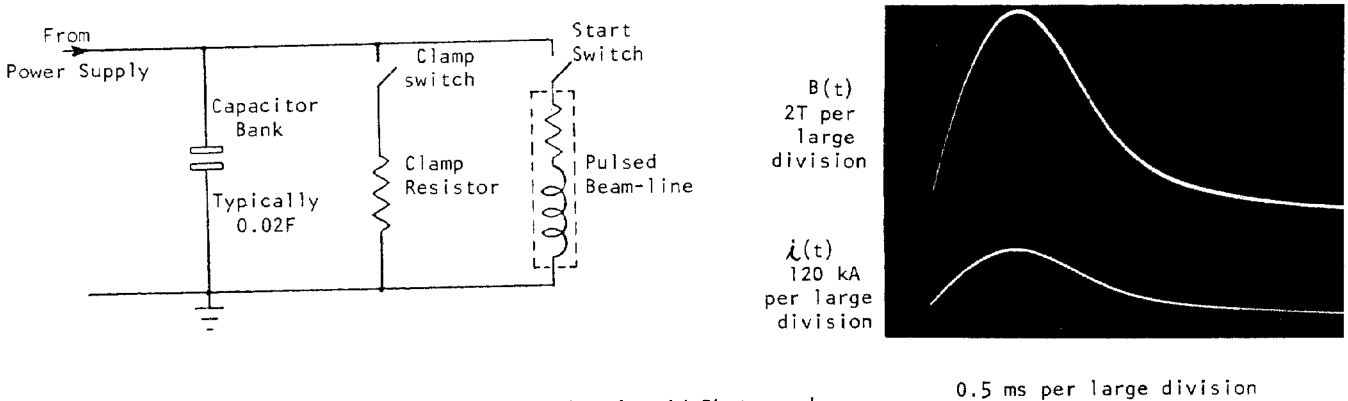
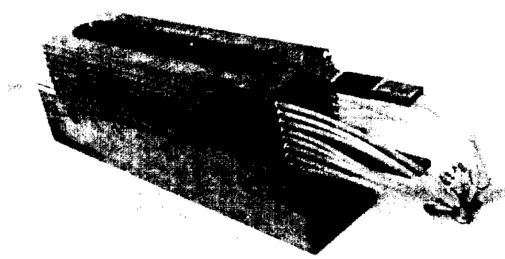
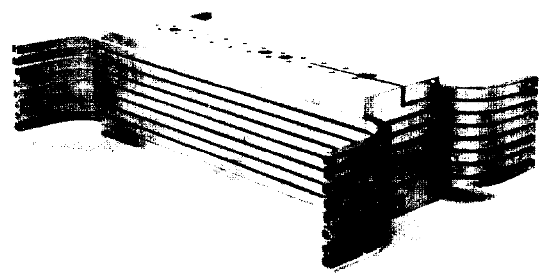


Fig. 2. Basic Circuit Diagram with Polaroid Photograph of Typical Waveforms



a) 40 cm Coil on Permaglass Pad



b) 23 cm Σ Coil during manufacture.

Fig. 3. 8-turn Dipole Coils

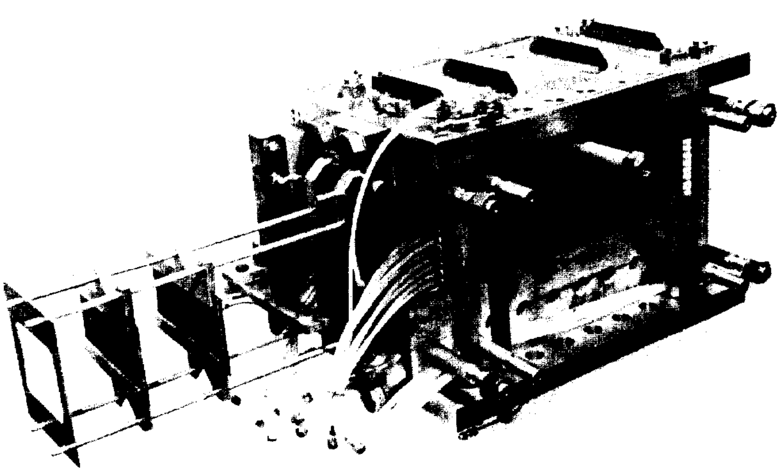


Fig.4 A Dipole Assembly partly dismantled to show restraining members, and with Polaroid film plate telescope fitted.

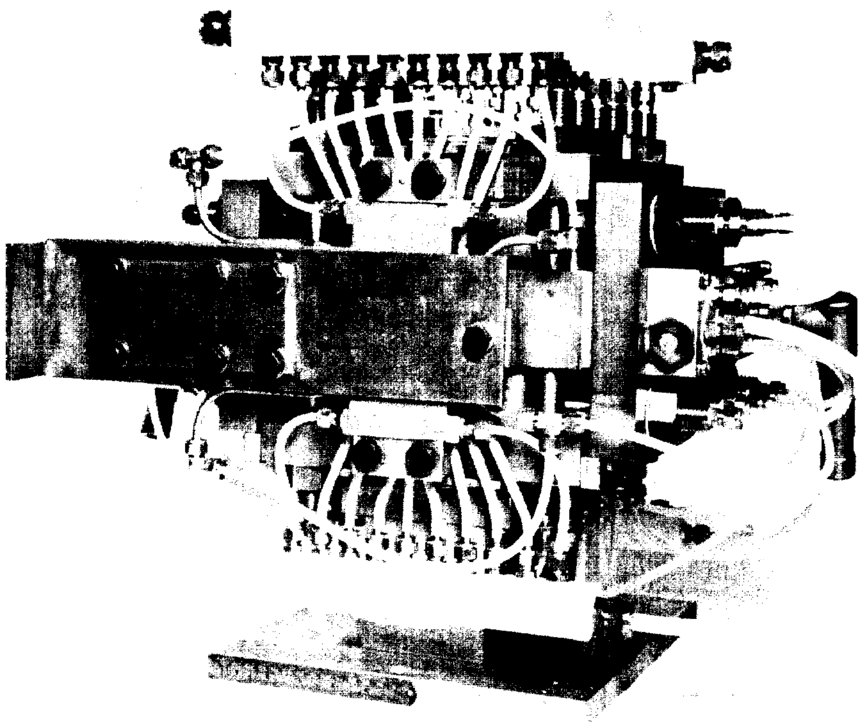


Fig. 5 Σ Dipole Assembly, viewed from beam-entry, current-lead end.

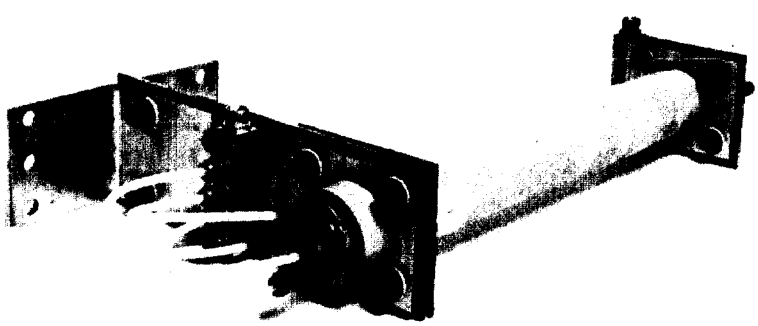


Fig. 6 60 cm-long Σ Quadrupole, showing 4 separately-cooled conductors.