EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN/AT-MA/91-24

CONSTRUCTION AND TEST OF A MODEL OF A PULSED HIGH GRADIENT,
FINAL FOCUS QUADRUPOLE

M. Modena, P. Sievers
A.D. Chernyakin, I.G. Silvestrov, INP, Novosibirsk

Presented at the 12th International Conference on Magnet Technology
Leningrad, 23-28 June 1991

Geneva, Switzerland
September 1991

Construction and Test of a Model of a Pulsed High Gradient, Final Focus Quadrupole

M. Modena, P. Sievers, CERN, Geneva, Switzerland
A.D. Chernyakin, I.G. Silvestrov, INP, Novosibirsk, USSR

Abstract - Quadrupoles with gradients of well above 10^3 T/m are required for the focusing of e^-/e^+ colliders to achieve the required luminosity. Among other solutions, pulsed single conductor quadrupoles could provide such high gradients. In order to evaluate technical designs, a series of different model quadrupoles with full apertures of 10 mm, about 5-10 times the finally required size, was constructed at CERN. Electromagnetic tests of these models were carried out in the pulsed regime at the INP, Novosibirsk, where the magnetic fields, gradients, energy consumption and required voltages were measured. Some of the results are compared to computations achieved with a finite element computer code, taking into account the transient skin effect regime. By scaling the results to finally envisaged apertures and gradients, design values are obtained which allow to assess further the feasibility of pulsed final focus quadrupoles.

I. INTRODUCTION

High magnetic fields of well above the saturation of steel at 2 T are readily provided today by superconducting magnet technology. However, in particular cases where constraints like small available space or high levels of radiation prevail, it will be necessary to revert to high current carrying conductors at ambient temperature. Here, the challenge is the required large current density of the order of kA/mm^2 , similar to that attained in superconducting cables, creating problems associated with the pulsing of the currents necessary to reduce the average power, and the removal of the average power dissipated in the conductors.

In particular, pulsed final focus quadrupoles could be used in e^-/e^+ colliders, such as CLIC [1] and VLEPP [2]. Besides small aperture, high gradient quadrupoles made of permanent magnets [3], a pulsed device has been considered in Ref. [4], where the current leads are formed of liquid metal. Here, the technical feasibility of an alternative solution, water cooled copper conductors, has been assessed and will be described below. Many of the results are, however, also relevant for other applications involving pulsed currents.

II. PARAMETERS AND DESIGN OF A MODEL QUADRUPOLE

The good field region in the final quadrupoles of the CLIC focus system [5] should be contained within a radius of 0.1 mm. For the safe passage of the opposite beam, however, a much larger half aperture A of about 1.5 mm is required at least in the horizontal direction. The gradients considered at present are of the order of 10^3 T/m. Due to the small aperture size and the elevated fields, the magnetic structure considered here is made of only four single, axial conductors, arranged in iron free space symmetrically around

the quadrupole axis with currents passing through the four conductors in alternating direction.

In order to assess the electrical parameters of the quadrupole in the pulsed regime, such as peak current and voltage as well as dissipated energy per pulse, a model quadrupole was built at CERN with an enlarged half aperture of $A = 5$ mm and a length of 250 mm. Since tests were made only with single pulses (as opposed to the 1.7 kHz repetition rate foreseen for CLIC) and low currents, no cooling water was required. Moreover, no particular effort was made at this stage to maximise the good field region by shaping the conductor cross-section appropriately. The parameters measured on this model quadrupole were scaled afterwards to that required for CLIC, but can of course be used for any aperture and gradient, as required.

Each conductor consists of a single copper rod with a rounded surface at the aperture and with three arrays of comb-like cooling fins along the opposite side (see Fig. 1). Various sets of conductors with different cross-sections and pitches of cooling fins, as shown in Fig. 1, were used in order to assess the parasitic current passing through this array at various pulse durations, i.e. skin depths. Each of the four conductors is contained in its T-shaped stainless steel bar as shown in Fig. 2. To avoid excessive parasitic currents flowing along this bar in parallel with the copper rod, the steel is slotted laterally over the cross-section with an axial pitch of 10 to 20 mm, leaving untouched only 2 mm of the material immediately around the copper conductor and its cooling fins which provides the duct for the axially flowing cooling water. The different pitches of the slots in the steel were selected to measure their influence on parasitic currents at various skin depths. The size of the pitches in the stainless

Fig. 1 Various types of axial copper conductors, with different cross-sections and pitches of cooling fins arranged along the side opposite the aperture.

Fig. 2 Copper conductor inserted into its T-shaped, slotted stainless steel support, providing a closed duct around the cooling fins for the axially flowing cooling water and simultaneously minimizing axial parasitic currents.

Fig. 3 Cross-section of the fully assembled quadrupole. A: Copper conductor, B: Water cooling channel, C: Continuous part of the stainless steel support, D: Slotted part of the stainless steel support, E: Ceramic spacers, F: Steel frame.

steel supports can be much larger than in the copper conductors since their dimensions scale with the electrical resistivity of the two metals. The units of copper conductor-steel support are assembled thereafter inside a steel frame. Fig. 3 shows the cross-section of the assembled quadrupole. The precise relative positioning of the four conductors is readily achieved by perpendicular reference surfaces inside the frame and by precisely machined insulating vetronite spacers. These will, however, be made later of ceramics, because of its good radiation resistance. This assembly technique is particularly suited for future, smaller magnets since only the precise machining of parallel and perpendicular surfaces is involved. The four conductors were connected electrically in series by low inductance copper bridges bolted to the ends of the conductors (not shown in Fig. 3).

III. ELECTRICAL AND MAGNETIC MEASUREMENTS

The electromagnetic measurements were made at the INP-Novosibirsk where a suitable pulser (condenser bank, thyristor switch, matching transformer) and a computer controlled scanning table equipped with a miniaturized search coil with a diameter of 1 mm was available. To assess the influence of the conductor cross-section, of the cooling fins and of the stainless steel support, the following conductor configurations were used:

- I: Width 2 A, height 1.1 A (ideal minimum conductor).
- II: Width 2 A, height 1.7 A.
- III: Conductor II, equipped with an array of cooling fins.

- IV: Conductor III, including the stainless steel skin fitted around the array of cooling fins.
- V: Conductor IV fitted with the slotted stainless steel T-piece, representing a completed unit including the high performance cooling circuit.

The following parameters were measured: peak current, peak voltage, gradient, energy per pulse via the energy lost from the condenser bank. This corresponds to the energy loss in the total circuit and represents thus an upper limit for the loss in the quadrupole proper, which could be lower by 20%. Some energy measurements were also made by integrating the product of current and voltage across the quadrupole over time, which gave, however, results of similar precision. Thus, only those from the previous method are quoted. A full set of parameters was measured for pulse durations τ of 30 μ s, 100 μ s, 210 μ s, 450 μ s, 950 μ s by varying the size of the capacitances covering a range of skin depths in the copper of 0.5 - 2.5 mm. This is of particular importance in order to investigate the influence of the pulse duration and thus the current distribution across the complex structure of the conductors on the efficiency of the quadrupole (maximum gradient for minimum current, voltage and energy per pulse). The peak currents, peak voltage across the quadrupole and the energy loss per pulse versus skin depth δ (defined as $\delta = [2 \tau / \mu_0 \pi \sigma]^{1/2}$) are shown in Fig. 4 for the various conductor configurations.

In view of the application of this type of quadrupole for CLIC, all values have been scaled to a magnet of 1 m length, a half aperture A of 1 mm and a gradient G of 1000 T/m.

Fig. 4 Peak current I_0 , peak voltage V_0 and energy loss/pulse W versus skin depth δ/A for various conductor configurations (See text). The measured values have been scaled to a quadrupole with a half aperture A of 1 mm, a gradient of $G = 10^3$ T/m and a length of 1 m.

It shows that the peak currents for $\delta/A > 0.2$ do not depend much on the skin depth, since in this regime the current density is already quite uniform across the conductor [6]. The appearance of parasitic currents, flowing in parallel through the cooling fins (geometry III) and the steel structure (geometry IV, V) can clearly be seen. The rise of I_0 for the geometry V at small δ/A is attributed to the increased influence of the eddy currents in the steel structure. The peak voltage depends strongly on the skin depth in the range $\delta/A \leq 0.2$, while above it becomes rather flat and independent of the conductor configuration. For the energy per pulse, rather constant distributions were found around $\delta/A \approx 0.2$,

the absolute values depend again on the conductor configuration. The additional dashed curves shown in Fig. 4 for geometry II have been obtained by a detailed computational analysis which was made for this quadrupole and which is described in Ref. [7]. Satisfactory agreement is achieved for the peak currents and voltages, bearing in mind the estimated overall precision of these measurements of about 10%. Concerning the energy per pulse, larger differences between the measured and computed values are found. These can be attributed partly to the systematic shift of these measurements as mentioned earlier, but also to the fact that for the computation a pure half-sine current pulse shape was assumed, while in reality a damped half-sine occurs. Moreover, the limited mesh size and the post processing introduce a further error of about 10% into the computed values. The above results show that a reasonable compromise among the parameters I_0 , U_0 and W is achieved for $\delta/A \approx 0.2$ for which the values are given in Table 1 for different half apertures and gradients. Considering only the single pulse mode, limitations to extreme gradients or larger apertures will stem obviously from limits to the currents and voltages but finally also from the magnetic forces on the conductors [7]. Considering the operation of this quadrupole in the repetitive pulsed mode, an additional limit comes from the average power dissipated in the conductors.

TABLE 1
PEAK CURRENT, PEAK VOLTAGE, ENERGY LOSS PER PULSE AND AVERAGE POWER (1.7 kHz PULSE REPETITION RATE) FOR A 1 m LONG QUADRUPOLE WITH VARIOUS HALF APERTURES, GRADIENTS AND CONDUCTOR GEOMETRIES. THE VALUES HAVE BEEN EXTRACTED FROM THE MEASUREMENTS WITH $\delta/A = 0.2$.

Conductor geometry	Half aperture [mm]	1	1	1.5	2
	Gradient [T/m]	1000	2000	1000	1000
I	Peak current [kA]	3.5	7.0	7.9	14
II		4.0	8.0	9.0	16
III		4.25	8.5	9.6	17
IV		4.6	9.2	10.4	18.4
V		5.3	10.6	11.9	21.2
I	Peak voltage [kV]	2	4	2	2
II		2	4	2	2
III		2	4	2	2
IV		2	4	2	2
V		2	4	2	2
I	Energy/pulse [J]	4.4	17.6	22.3	70.4
II		4.4	17.6	22.3	70.4
III		6.2	24.8	31.4	99.2
IV		6.6	26.4	33.4	105.6
V		9.8	39.4	49.6	156.8
I	Average power [kW]	7.5	29.2	37.9	119.7
II		7.5	29.2	37.9	119.7
III		10.5	42.2	53.4	168.6
IV		11.2	44.9	56.8	179.5
V		16.7	67.0	84.3	266.6

IV. COOLING OF THE CONDUCTORS

To investigate efficient cooling systems, a conductor of 2 mm x 2 mm, close to finally envisaged dimensions, has been built together with its comb-like cooling fins along one side (see Fig. 5). These fins have each a cross-section of 0.48 mm x 0.48 mm and a height of 5 mm. The machining was done by crosswise, diagonal wire spark erosion. For the power and cooling tests, a watertight plastic container was fitted around the conductor. With a d.c. current of 1.4 kA (a current density of 350 A/mm², more usually associated with superconducting cables), a water flow of 0.01 l/s axially through the array of fins and a pressure drop of 26 bar per meter, the power of 7.8 kW/m was evacuated from this conductor with a temperature difference of 17 °C between the copper and the water. This shows that average powers dissipated in all four conductors of the quadrupole, as stated in Table 1, seem to be feasible, provided technical solutions for the renewal of the water increasing in temperature by about 10 °C per 10 cm along the conductor can be found. It could be advantageous to pass the water across instead of along the array. An extreme solution might be to use liquid nitrogen as cooling liquid, which would considerably reduce the electrical resistance of copper and thus the power dissipation. This argument is, however, only valid for the nearly d.c. regime ($\delta/A > 0.2$).

V. CONCLUSION

The model work on a pulsed, single conductor quadrupole with a half aperture $A = 5$ mm has shown that gradients of $1 - 2 \times 10^3$ T/m with half apertures of $A = 1 - 2$ mm should be feasible, the limitations coming from the average power dissipation and the associated cooling system, when high pulse repetition rates of 1.7 kHz are required.

The design adopted for the $A = 5$ mm model can readily be applied to reduced sizes with $A = 1$ mm or below.

Obviously, additional material around an ideal minimum conductor is required for its precise positioning, support and cooling. This has to be paid with an increase of 40% in current and by a factor of 2 in the average power in order to achieve the same gradient as with an "ideal minimum" quadrupole.

For small repetition rates with low average powers and thus reduced cooling requirements, considerably higher gradients around 5×10^3 T/m and above should be reached, being limited finally by the current leads and the magnetic forces on the conductors.

Problems to be expected due to the pulsing of the quadrupole, like vibrations and thus errors of alignment as well as material fatigue at high pulse rates present an additional challenge and have not yet been addressed.

ACKNOWLEDGMENTS

The fabrication of the model quadrupole was entrusted to the workshops of the ST/MT Divisions of CERN and in particular to C. Vuitton, whose contributions are gratefully acknowledged. We should also like to thank G. Silvestrov of

Fig. 5 Side view (Insert: enlarged top view) of a single axial copper conductor with its array of cooling fins, machined out of the copper strip by wire spark erosion.

the INP, Novosibirsk, and his group for their help and for the many enlightening discussions. Finally, thanks are due to Mrs C.L. Jullien for her diligence in typing this article.

REFERENCES

- [1] W. Schnell, "The CERN study of a 2 TeV e^+e^- collider CLIC," Proc. 1991 IEEE Particle Accelerator Conference, San Francisco, May 1991, to be published.
- [2] V.E. Balakin, A.N. Skrinsky, "VLEPP Status Report," Proc. XIII International Conference on High Energy Accelerators, Novosibirsk, USSR, July 1986, vol. 1, p. 101.
- [3] K. Egawa, T.M. Taylor, "Conceptual design of a 5 T/mm quadrupole for linear collider final focus," Proc. 1989 IEEE Particle Accelerator Conference, Chicago 1989, p. 360.
- [4] G.I. Silvestrov, A.N. Skrinsky, T.A. Vsevolozhskaya, "Superstrong quadrupoles of liquid metal for final focusing at linear colliders," Proc. XIV International Conference on High Energy Accelerators, Tsukuba, Japan, 1989, pp. 1241-45.
- [5] O. Napoly, P. Sievers, T.M. Taylor, B. Zotter, "Progress on the CLIC final focus system," Proc. 1991 IEEE Particle Accelerator Conference, San Francisco, May 1991, to be published.
- [6] M. Modena, P. Sievers, "Computation of design parameters for a pulsed quadrupole in the 2D-transient skin effect regime," Proc. IEEE 8th Conference on the Computation of Electromagnetic Fields, COMPUMAG, Sorrento, Italy, July 1991, to be published.
- [7] M. Modena, P. Sievers, "Computation of design parameters and optimization of a pulsed final focus quadrupole in the transient skin effect regime," Proc. IEEE 12th International Conference on Magnet Technology, Leningrad, USSR, June 1991, to be published.