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DEVELOPMENT OF AN ALUMINIUM LENS

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DEVELOPMENT OF AN ALUMINIUM LENS.
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Abstract: For the upgrading of the antiproton source as part of the CERN Antiproton Collector (ACOL) project, strong lenses are required to focus a 26 GeV proton beam onto the antiproton production target as well as to collect the liberated antiprotons. Pulsed lithium lenses with gradients of 500 to 1000 T/m have been developed for this purpose [1]. Presented here is a novel and cheaper type of lens made of aluminium which might become an interesting alternative. Gradients of 1500 T/m are expected, making possible a very short and compact lens and thus avoiding excessive absorption of the beam particles by the lens material. The problems caused by the skin effect are overcome by a subdivision of the lens into three mutually insulated concentric tubes connected in series through electron-beam welded return tubes. The characteristics of this lens, like the distribution of the penetrating current, and the resulting field distributions, as well as the ohmic temperatures and the magnetic and thermal stresses have been computed. The design of the lens and the present state of this development are described.

Introduction

The aluminium lens, like the lithium lens, consists in principle of a cylindrical conductor powered with an axial current pulse. The resulting tangential magnetic field is proportional to the radius and therefore constitutes a perfect focussing lens for particle beams. Until now lithium, the lightest existing metal, has been used for a minimum of beam absorption and scattering. The lithium lens developed at CERN for the ACOL project has a conductor radius of 10 mm and creates a field gradient of 750

T/m using a current pulse of 462 kA amplitude and 600 μ sec duration. The lens material has to stand high magnetic and thermal stresses caused by the high current and field. Because of its low mechanical strength and its chemical reactivity the device needs a sophisticated container to keep the lithium compressed and to channel the current and the cooling water. It is interesting to make an equivalent lens of a light and conducting material which is strong enough to stand the stresses and which can easily be handled and machined. An aluminium lens has been calculated and designed. It has a reduced length to keep the beam absorption and scattering similar to that of the lithium lens and the gradient has therefore been increased to a maximum, determined by the fatigue strength of the material.

The skin depth

A homogeneously distributed current, can only be obtained with a direct current but the ohmic heating would destroy the conductor. A fast pulse reduces the ohmic heating at the expense of a worse field linearity due to the skin effect. The influence of the length τ of a half sine current pulse has been calculated with a computer program [2] based on the thermal finite element program DOT using the equivalences between the Maxwell equations and the thermal diffusion equations in two dimensions. The results for a cylindrical aluminium conductor of radius $r_0 = 10$ mm are shown in Table 1 for three different pulse lengths. The current amplitude I has been adapted every time to obtain the same gradient $G_2 = 1500$ T/m at the working point where the field gradient is most homogeneous. The shorter the pulse, the worse this homogeneity but the lower the ohmic

Table 1. The solid lens properties, calculated for three different relative skin depths. The underlined numbers were imposed. The stresses are calculated for a free bar (axial force zero) using a Poisson ratio of $\nu = 0.3$.

Solid aluminium lens, radius $r_0=10$ mm					Dimensionless results, any material any radius						
			Relative skin depth δ_r						Relative skin depth δ_r		
			0.37	0.52	0.74				0.37	0.52	0.74
Variables		Units				Variables					
<u>Half sine current pulse</u>											
Pulse length	τ	μ s	1000.0	2000.0	4000.0	$\tau/(r_0^2\gamma\mu)$		0.215	0.43	0.86	
Current amplitude	I	kA	1071.0	854.5	779.0						
<u>Field at max. current</u>											
Peak magn. field	B	T	21.4	17.1	15.6	$B/(\mu I/r_0)$		0.159	0.159	0.159	
Average gradient	G_1	T/m	1361.0	1359.0	1453.0	$G_1/(\mu I/r_0^2)$		0.101	0.127	0.148	
St. deviation of grad. $\Delta G/G_1$		%	41.9	15.5	4.1	$\Delta G/G_1$		0.419	0.155	0.041	
Time of peak	t_1	μ s	500.0	1000.0	2000.0	t_1/τ		0.5	0.5	0.5	
<u>Field at working point</u>											
Most homogeneous grad.	G_2	T/m	1500.0	1500.0	1500.0	$G_2/(\mu I/r_0^2)$		0.111	0.140	0.153	
St. deviation of grad. $\Delta G/G_2$		%	7.5	2.1	0.6	$\Delta G/G_2$		0.075	0.021	0.006	
Time of working point	t_2	μ s	810.0	1380.0	2400.0	t_2/τ		0.81	0.69	0.60	
<u>Ohmic heat/pulse</u>											
Energy	Q	kJ/m	69.2	73.6	110.1	$Q/(\mu I^2 l)$		0.048	0.080	0.144	
Peak temperature rim	ΔT	$^{\circ}$ C	224.0	161.0	180.0	$T/(\mu I^2/\rho c r_0^2)$		0.037	0.042	0.056	
<u>Max.stresses from pulse</u>											
Magnetic stress	σ_m	N/mm ²	207.0	140.0	121.0	$\sigma_m/(\mu I^2/r_0^2)$		0.0144	0.0153	0.0159	
Thermal stress	σ_t	N/mm ²	303.0	171.0	127.0	$\sigma_t/(\mu I^2 E \alpha/\rho c r_0^2)$		0.0311	0.0275	0.0246	
Total stress centre	σ_c	N/mm ²	262.0	191.0	167.0	σ_c		$\sigma_m+0.18\sigma_t$	$\sigma_m+0.30\sigma_t$	$\sigma_m+0.36\sigma_t$	
Total stress rim	σ_r	N/mm ²	387.0	235.0	181.0	σ_r		$\sigma_t+0.41\sigma_m$	$\sigma_t+0.46\sigma_m$	$\sigma_t+0.44\sigma_m$	

Symbols: γ = el.conductivity, μ = magn.permeability, l = length, ρ = spec.weight, c = spec.heat, E = Youngs modulus, α = therm.expansion coeff.

energy. At very short pulses the latter no longer decreases so much whereas the peak temperature T in the skin increases again. A good compromise is found by tuning the pulse length to near 2000 μsec corresponding to a relative skin depth of $\delta_r = (1/r_0)(2\tau/\gamma\mu\omega)^{0.5} = 0.5$. Here the standard deviation of the gradient at the working point is about 2% for a field gradient of 88% of that expected at full direct current. A dimensional analysis shows that the results of the calculation for aluminium can be generalised and dimensionless variables introduced with values which depend only on the relative skin depth (see Table 1). They are valid for any material and any radius and useful for the calculation of any pulsed conductor. It is interesting to note that the electrical conductivity is not an explicit parameter; it only determines the pulse length necessary to obtain the desired relative skin depth.

The stresses

The stresses determine whether the conductor will survive or not. First there is the stress caused by the magnetic body forces $f = j \times B$. These stresses can be estimated quite well by assuming the full current homogeneously distributed in the conductor. The stress pattern is then equal to that of a centripetal force field and the maximum found in the centre, $\sigma_{eq} = \mu I^2(3-4\nu)/16(1-\nu)\pi^2 r_0^2$, is slightly higher than the magnetic stress in Table 1 (Tresca criterion is used throughout). The magnetic stress is inherent to the functioning of the lens. It can be reduced by about 50% by restraining the longitudinal expansion of the lens ($c_z = 0$) but this increases the thermal stress. Secondly there is the thermal stress from the adiabatic ohmic heating. The worst stresses are found in the time interval between the peak current and the working point. These stresses diminish for longer pulse lengths (Table 1) where the temperature distribution becomes more homogeneous but the temperature levels increase. Thirdly there are the thermal stresses caused by the beam heating and fourthly those caused by the temperature offset due to repeated pulsing and which depend on the cooling efficiency. These last two types of stresses show both a high temperature in the centre and a low temperature at the rim and although the resulting stress pattern increases the hydrostatic pressure in the material, it diminishes the equivalent stress of the magnetic field and of the ohmic heating. It does therefore not endanger the stress situation unless it creates equivalent stresses beyond those of the magnetic stresses which would then be determinant after the pulse. There is finally a fifth stress originating from the magnetic force on the radial current leads which cause an axial pull in the conductor thus increasing the equivalent stresses. To avoid this, the current leads should be made rigid enough to bear this pull without transmitting it to the central conductor.

The candidate materials

It is interesting to compare the ultimate performance of lenses of different candidate materials like Mg, Be, Al, and Ti to that of lithium, all at the same skin depth of $\delta_r = 0.5$ (see Table 2). The current amplitudes have been adapted to each case to obtain a magnetic stress equal to the estimated fatigue strength of the particular material. The table also shows the lengths of the lenses necessary to obtain the same field integral as that of the lithium lens and it gives the corresponding conductor resistance, the (inner) inductance, the beam absorption and the scattering angle for 3.5 GeV beams. The last two include an estimated overlength of $1.5r_0$ for the current leads (and the titanium windows for the

Table 2. The properties calculated for lenses of different materials. Lens radii $r_0 = 10$ mm. Relative skin depth $\delta_r = 0.52$. The underlined numbers were imposed. Stresses calculated for a free bar, Poisson ratio $\nu = 0.3$.

		Materials				
		Li	Mg	Be	Al	Ti
Variables	Units					
<u>Pulse</u>						
Length τ	μs	590	1160	1779	2000	111
Amplit. I	kA	455	645	1117	883	1529
<u>Max. cur.</u>						
Field B	T	9.1	12.9	22.3	17.6	30.6
Grad. G_1	T/m	726	1029	1783	1409	2440
St.dev $\Delta G/G_1$	%	15.5	15.5	15.5	15.5	15.5
Time t_1	μs	295	580	890	1000	56
<u>Work. point</u>						
Grad. G_2	T/m	800	1135	1965	1553	2690
St.dev $\Delta G/G_2$	%	2.1	2.1	2.1	2.1	2.1
Time t_2	μs	407	800	1228	1380	77
<u>Ohmic heat</u>						
Energy Q	kJ/m	21	42	125	78	235
Temp. ΔT	$^{\circ}\text{C}$	61	123	169	173	536
<u>Max. stress</u>						
Magn. σ_m	N/mm ²	40	80	240	150	450
Therm. σ_t	N/mm ²	11	95	398	182	328
Centre σ_c	N/mm ²	43	111	359	205	548
Rim σ_r	N/mm ²	29	131	506	250	535
<u>With length adjusted for equal integrated field:</u>						
Length l	mm	130	92	53	67	39
Resist. R	$\mu\Omega$	37.0	13.5	5.1	5.8	60.0
Induct. L	nH	6.5	4.6	2.7	3.4	2.0
Absorp. $\Delta\phi/\phi$	%	17	20	17	23	20
Scatter. θ	mrads	3.9	3.5	1.8	3.9	4.9

lithium lens). Of these materials, Mg creeps at high temperatures, Be causes a health hazard, and Ti becomes extremely hot. Aluminium is attractive as a well known constructional metal but the expected maximum stress is far beyond the fatigue strength of about 150 N/mm² of high strength alloys. In addition, the peak temperature of 173 $^{\circ}\text{C}$ is near the annealing temperature of most of the aluminium alloys. A valid solution would be to make a longer lens and reduce the current accordingly but this costs an increased beam absorption and scattering.

The laminated lens

The problem of the high temperatures and thermal stresses in the aluminium due to the ohmic heating has been solved by laminating the cross-section in the form of mutually insulated concentric tubes electrically connected in series. This drastically reduces the pulse duration necessary for a complete current penetration in each tube and as a result lowers the temperatures and the thermal stresses. Such a design makes it possible to obtain equivalent stresses which are hardly higher than the magnetic stresses alone. Another advantage is that by choosing the number of laminations, the current amplitude and the duration of the current pulse can be tailored to that of the lithium lens which improves the interchangeability. A lens has been calculated consisting of three concentric cylindrical conductors of equal cross-section (radii 0-5.5 mm, 5.75-8.0 mm, 8.25-10.0 mm) separated by 0.25 mm thick layers of insulation. The results are given in Table 3 for three different relative skin depths of the central conductor. It shows the important reduction in ohmic energy, in peak temperature and in thermal stress. The latter hardly enhances the magnetic stress.

Table 3. The three fold laminated aluminium lens properties, calculated for three different relative skin depths. The underlined numbers were imposed. The stresses were calculated considering the assembly to behave like one solid bar with free ends. Poisson ratio $\nu = 0.3$.

Laminated alumin. lens ($r_0 = 0-5.5/5.75-8/8.25-10$ mm)				
		Rel. skin depth δ_r		
		0.336	0.475	0.672
Variables	Units			
<u>Half sine current pulse</u>				
Pulse length τ	μs	250	500	1000
Current amplitude I	kA	356	276	246
<u>Field at max. current</u>				
Peak field B	T	21.4	16.6	14.7
Average gradient G_1	T/m	1837	1517	1478
St.deviation grad. $\Delta G/G_1$	%	40.5	18.4	4.8
Time of peak t_1	μs	125	250	500
<u>Field at working point</u>				
Most homog. gradient G_2	T/m	<u>1500</u>	<u>1500</u>	<u>1500</u>
St.deviation grad. $\Delta G/G_2$	%	12.0	4.9	3.3
Time working point t_2	μs	203	345	570
<u>Ohmic heat/pulse</u>				
Energy Q	kJ/m	26.9	21.0	27.3
Peak temp. rim ΔT	$^{\circ}C$	105	53	53
<u>Max.stresses from pulse</u>				
Magnetic stress σ_m	N/mm ²	224	138	112
Thermal stress σ_t	N/mm ²		64	
Total stress centre σ_c	N/mm ²	241	154	124
Total stress rim σ_r	N/mm ²	236	121	87

The field linearity suffers only little from the lack of current in the insulation and the less homogeneous current distribution. The resistance and internal inductance increase with a factor of 9. Figure 1 shows the current distribution at different time intervals for the case where $\delta_r = 0.475$ in the central conductor. The resulting magnetic field and the ohmic temperature are shown in the same figure.

In the case of zero axial strain, the magnetic stress reduces considerably and the thermal stress increases and becomes predominant. The resulting maximum stress reduces from 154 N/mm² to 121 N/mm² ($\delta_r = 0.475$).

The stresses in the insulation are high ~ 175 N/mm² ($\delta_r = 0.475$) and will probably cause cracks. However by designing a sufficient thickness and by keeping the electrical field across sufficiently low, even a cracked insulation is expected to be acceptable.

The design

The design of the lens is shown in Figure 2. The three central conductors are connected in series through two cylindrical return paths. The current enters into body ref. 1, flows through the central conductor 2, is brought back by a return tube 6 to flow through the second intermediate conductor 3, is once more brought back by a return tube 5 to flow through the third outer conductor 4 of the lens and finally it is brought to the peripheral contact 7 by means of current leads in the form of four radial spokes. The insulation is obtained by hard anodising the aluminium pieces before assembly. The assembly starts with the innermost pieces and every subsequent piece is then added and welded by electron-beam welds. In order to keep the insulation compressed and to

Fig.1 The calculated current distribution, field distribution and temperature distribution for the three fold laminated aluminium lens ($\delta_r = 0.475$) at time intervals of 60 μs .

Fig.2 Cross-section of the three fold laminated aluminium lens (parts 8, 9, 11 and 15 are ceramic).

to ensure that the lens behaves like one solid piece, all the cylindrical elements are assembled by shrinkfitting. For the same reason, longitudinal tie bolts 13 clamp the body halves onto a central insulator 8. The lens is water cooled through channels 18 in one body. The 500 Watts of ohmic heating power diffuse quite well through the lens owing to the good contact from the shrink fitting and the expected temperature offset relative to the cooling water is about 40°C.

The beam heating

The energy deposited by the beam causes an instantaneous temperature rise with a peak in the centre. A FLUKA calculation predicts for a proton beam at 26 GeV, with an intensity of 2×10^{13} protons per pulse and a halfwidth of 5 mm, a peak temperature of 54°C in the centre and a thermal energy of about 20% of that of the ohmic energy. For a collecting lens downstream the target the average temperature rise is somewhat less but the peak temperature in the centre will be about 175°C. In that case a ceramic rod of 1.5 to 2 mm radius could be inserted in the centre of the lens to avoid local overheating of the aluminium and still maintain the stress condition of a solid piece; a central hole would cause a doubling of the stress in the material directly around the hole.

Tests

Several models have been made to optimise the dimensions and study the assembly. For the shrink fitting, the pieces are heated as homogeneously as possible to about 180°C in a specially designed oven in order to avoid damage to the insulation layer. Shrink fitting of the smallest central piece has to be done very quickly to avoid premature sticking. Its radial oversize has been limited to 0.0025 mm to obtain an assembly time of 0.4 sec. The thicker pieces allow for some more time, up to a few seconds before they stick and this makes it possible to position the pieces correctly relative to the spokes. As material the aluminium alloy 2219 has been taken for its good fatigue strength at elevated temperatures. Rotating beam tests showed fatigue limits of 150 N/mm² at 150°C, 130 N/mm² at 200°C and 110 N/mm² at 260°C (for 10^6 cycles). It is easy to weld and electron beam welding tests have been made to define the welding parameters and to check that the insulation does not suffer. This material is not so

suitable for hard anodising. Tests are under way but in parallel a second lens will be made from alloy 7075 which is more easily anodised. To test the behaviour of the aluminium oxide under ionising radiation, some insulated test cylinders have been shrink fitted and mounted in the proton accelerator for an irradiation test at 14 GeV. The construction of a complete prototype is on the way and will hopefully be pulsed before the end of the year.

Conclusions

An aluminium lens has been calculated and designed which could be a substitute for the lithium lens developed at CERN for the ACOL project. The length is reduced to keep the beam scattering and the absorption at a level similar to that of the lithium lens. The field has been increased accordingly to obtain the same integrated field. The high thermal stresses caused by the skin effect have been reduced by subdividing the lens into three concentric cylindrical conductors which are connected in series. As a result the supplied current has the same pulse length as that of the lithium lens and about half the amplitude. The outside diameter is the same as that of the lithium lens to allow assembly in the same current transformer. Tests have been done or are in progress concerning the shrink fitting, the electron beam welding, the hard anodising and the effect of the ionising radiation. A prototype is under construction and expected to be pulsed before the end of the year.

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