ECONOMICAL CRYOGENIC PULSED SYNCHROTRONS FOR VERY HIGH ENERGIES

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I. Introduction

Cryogenics appears to be essential to any major advances in economical designs of super energy accelerators. High magnetic fields make feasible non-inductive designs of new machines with energies to several TeV, but also permit economical conversions of, or additions to existing machine complexes, such as auxiliary rings or even second machines in existing tunnels.

In 1966 the authors proposed and explored in depth the use of a separated function or "beam transport" lattice for the second generation of alternating gradient machines. The many possibilities resulting from its inherent flexibility during both the construction and operation of a machine complex is now widely recognized, and almost all recently proposed designs use the separated function lattice. It was pointed out from the beginning that economical, compact, ambient temperature dipole magnets are limited by low current density rather than by iron saturation. Useful fields at least 50% higher than those in room temperature magnets could be obtained with moderately high current density superconducting or pure metal coils inside an iron frame.

The aberrations would be somewhat higher than earlier machines, but widely distributed non-linear control magnets were desired independently for high intensity effects at injection, extraction, etc. Finally, looking further to the future, high field air core type magnets must withstand very large magnetic pressures. It was pointed out that the structural symmetry resulting from having single multipolarity magnets is an appreciable advantage. The possibility of vertical injection and extraction with a separated function lattice frees one to consider vertical to horizontal aspect ratios of unity. Circular apertures are attractive for small cryogenic magnets.

On the basis of useful vertical to horizontal aperture aspect ratio of unity the authors continued to develop window frame dipoles with moderately high current density cryogenic coils. Basic parameters of saturation and aberrations were first explored by only doing in Li$_2$N$_2$ to fields greater than 40 kG. Fig. 1 shows the cross section of a typical magnet with ~ 2-in. diameter aperture. The essential features are (1) the aberration produced is predominantly sextupole and can be compensated, (2) the amperes turns are reduced to ~ 1/3 that of its air core equivalent amperes turns so that it is feasible to consider coils of high purity aluminum at cryogenic temperatures as an alternative to superconductors, and (3) the field inside the coil is sufficiently parallel to the aperture field that bulk ribbon coils, whether Al or superconductor offer attractive simplification.

During recent years great progress in stabilization of superconductivity has been made by the approach of Smith et al, using non inductively coupled strands, or "Litz Wire". This approach has been widely used for the stabilization of low frequency superconductors, and dc conductor material of this type is now operational with reasonable charging rates. Appreciable work is going on in pushing this technique, by using very fine strands up to conventional accelerator frequencies. This involves making non-inductive conductors of sizeable amperes turn capacity and then holding them in position by some technique such as potting, which precludes motion and yet provides sufficient thermal conductivity to permit adequate cooling.

Most workers in the field have considered only air core type magnets either with or without iron image shields. The field shape is determined by a cosine current distribution, and there is little or no saturation to cope with. While this is very attractive in principle, the cosine magnet is mechanically more complex and for economical pulsed small bore magnets the window frame circuit has some very attractive mechanical and cryogenic features. From the viewpoint of conductors, only the "Litz Wire" approach is suitable to cosine type pulsed magnets. The window frame circuit can use either "Litz Wire" or bulk ribbon conductors. Extensive study has been made with high purity Al ribbons. Tests on NbTi and Nb$_3$Sn ribbon coils have been made, as well as hybrid combinations which are flux and therefore stabilized by combining superconductor and Al ribbons.

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structural viewpoint the forces are outwards on the four conductors located about 60° from the horizontal midplane. The two conductors located at the midplane have forces inward away from the main coil, which require special constraints. Alternatively, one can visualize superimposing a dipole layer of width equal to the midplane sextupole conductor running the full vertical extent of the primary coil and just inside it. If this layer is connected in series with the original sextupole winding with equal $j$ of opposite sign, the resultant is a hole or zero $j$ at the location of the midplane sextupole conductors. Physically the resultant is easily constructed, and provides identical sextupole correction plus a few percent additional dipole field aiding the primary. This variation has all forces horizontally outward. This geometry has been tested experimentally and computed with precision. The six conductors of the sextupole loop plus the two conductors of an auxiliary dipole loop have been combined into eight conductors, two of which are located in each corner and all of which carry current in the same direction as the neighboring primary coil. This combined auxiliary coil can be further condensed into a single area of conductor in each corner, or a "Helmholtz" correcting coil pair producing dipole aiding the main coil and sextupole opposing it. However some loss of sextupole symmetry requires larger total amperes turns and higher $j$ in this simpler correction geometry.

AG Synchrotrons require very small random aberrations. In the design of the NAL 200 GeV synchrotron the tolerances on the horizontal and vertical relative displacement of the innermost turns of the two layer coil is 0.010-in. based on using 85% of full horizontal aperture for $\Delta B_{\text{aperture}}$ with $j_{\text{aperture}}$ of 10⁻⁴ A/m. Discontinuities in the location of inner conductors produce field errors proportional to $j_{\text{aperture}}$, falling as the absolute distance $r$ from the location. A 2-in. x 2-in. coil cross section shown in Fig. 1 still has tolerances of five times tighter for relative motion of the two coil layers, i.e., 0.002 in. The effect is somewhat worse since the aperture is smaller and one desires to approach closer to the coils. Some features of this question are treated elsewhere. The coil in Fig. 1 has a current density $j_{\text{aperture}}$ of $\sim 10$ kA/cm² at 4.2°K. However, current densities of $40$ kA/cm² are often desired in cryogenic magnets. Random motions of large portions of a coil must be considerably less than 0.001-in., unless one wastes appreciably expensive magnetic aperture. Systematic collective motion under magnetic pressure provides some compensation of low order multipoles.

Even with only 10 kA/cm² coil positional tolerances on the design of Fig. 1 are quite tight. The rectangular coil section is completely contained, with almost uniform pressure outward against the iron core. If a single layer ribbon were used from top to bottom, or if a two layer coil moved outward symmetrical, the tolerances are relaxed by about an order of magnitude. Computer calculations were made of various discontinuities of a two layer coil and also of uniform compression outward plus smooth distortions or rotations of a single layer coil. These confirmed that indeed the tightest tolerance is on random "bumps" on the inner coil surfaces. We are encouraged to believe that the window frame structure appears desirable mechanically where both tight tolerances and small apertures are desired.

III. Properties of High Purity Aluminum Conductors

The very high electrical and thermal conductivity of pure polycrystalline aluminum at low temperatures, even in the presence of strong magnetic fields, makes it an attractive and very stable cryogenic conductor material, or as a superconductor stabilizing material, to first approximation the resistivity in zero magnetic field, $\rho_0$ is the sum of the lattice defect and impurity contributions, plus a temperature dependent term due to scattering in the lattice. (Mattheisen's Rule). The latter term is negligible at $4.2\,\text{K}$ so the resistivity ratio (rr), $\rho_{0,0}/\rho_0$ is a measure of the temperature independent term. The lattice resistance varies as the fifth power of the temperature down to temperatures less than $20\,\text{K}$. Furthermore, the resistivity in a magnetic field, $\rho_B$ saturates to a constant times $\rho_0$, even though $\rho_0$ varies widely due to purity or temperature. (Koehler's Rule). A general background of $\rho_0$ properties is given in a summary article of Arp. To exploit the properties of this material a broad program encompassing small scale, material testing models through realistic prototypes was carried out. Initial testing was done to determine ac losses, low temperature material properties, etc. on a small 1-in. x 1-1/4-in. aperture dipole magnet 7-in. long (197). These studies were carried out at $4.2\,\text{K}$ with $\rho_0$, and from $16\,\text{K}$ to $20\,\text{K}$ with $\rho_B$. All conductor cooling was accomplished in the nucleate boiling mode. A second model was constructed having a 2-in. x 2-1/2-in. aperture and 24-in. long. The coils were wound in race track form from .015-in. x 1-in. (16000$\rho_0$) high purity aluminum. This magnet has been studied extensively at $16\,\text{K}$ to $20\,\text{K}$ with $\rho_B$ in the nucleate boiling mode. After ~7000 pulses at 40 kG and repeated thermal cycling to ambient temperature, these coils still show no degradation from short sample tests. Good heat transfer and accurate data on coil losses require cooling in the forced convection mode. A facility has been constructed to produce forced circulation cooling of the magnet. The 24-in. model was modified to permit forced circulation cooling and extensive tests both dc and ac in excess of 40 kG. In addition a 4.5-ft long magnet is being constructed specifically for forced convection cooling. This magnet has realistic saddle bent coils, Fig. 2. This magnet will ultimately be tested using supercritical helium gas at $\sim 10\,\text{K}$. The aluminum ribbon was degreased, acid cleaned, and anodized in a production set up. After anodizing the aluminum was annealed in air at $425\,\text{C}$ for one hour and furnace cooled. Anodizing the aluminum decreases the resistivity ratio of the material by $\sim 10\%$.

Short sample measurements of $\rho_0$ and $\rho_B$ in an applied dc field were made in the temperature range from $4\,\text{K}$ to $21\,\text{K}$. For thin ribbon the zero field resistivity, $\rho_0$, has a sizeable correction at the lower temperatures due to surface effects, for example, a .015-in. ribbon with a $\rho_0$ measured of 11,000 at $4.2\,\text{K}$ corresponds to a $\rho_0$ bulk of 18,000. The 1/8-in. wire data is emphasized because it has only a very small size effect correction typically $10\%$ at $4.2\,\text{K}$. Fortunately, the cyclotron radius in Aluminum is such that the size effect correction is wiped out at a few kG, so that for practical magnet hardware the effective resistivity $\rho_B$ is not affected by these size considerations. The sample is contained in an isothermal "furnace" within the magnet aperture. Data is accumulated for different values of temperature and field. Fig. 3 shows $\rho_0$ versus temperature for a 1/8-in. wire and a .015-in. thick ribbon. The LH₃ points indicate that the large size correction for the .015-in. ribbon is slightly underestimated. The values of $\rho_0$ bulk are for $4.2\,\text{K}$. Fig. 4 shows in the usual Koehler form, for the 1/8-in. wire sample, the relation of $\rho_B$ to $\rho_0$ as a function of temperature. The curves at $16\,\text{K}$ and $21\,\text{K}$ were taken in subcooled $\text{LH}_2$. It can be seen that Koehler's rule is only accurate within a factor of two for high purity $\rho_0$ over a wide range of temperatures up to $21\,\text{K}$. At $21\,\text{K}$ $\rho_B$ is more than 80% due to ideal lattice scattering and $\rho_B$ saturates to a value approximately $6 \times \rho_0$. 
Saturation is slower and is not even complete at the highest point on the curve \(B_0 = 30\) kG. At the lower temperatures where \(\rho_{dc}\) is dominated by impurities and lattice defects \(\rho_{dc}\) saturates at a few kG to approximately three times \(\rho_{dc}\), as is expected. The deviation at the higher temperatures for very pure aluminum is consistent with the results of Fickett.\(^{10}\) The Koehler data for A2 ribbon is in good agreement with the wire data presented in Fig. 4. Less pure A2 with \(\rho_{dc}\) dominated by impurities even at 4.2K invests the other 30 kG. The deviations strengthen with the lower purity level of the material to its best advantage.

The Koehler data for AR highest point on the curve \(B_0 = 30\) kG). At the Lower higher temperatures for very pure aluminum is consistent in Fig. 4. Less pure AI with \(\rho_{dc}\) dominated by impurities even at 23K shows the characteristic saturation closer to 3. These results reveal that the highest purity materials should be operated at lower temperatures \(\leq 10^3\) K to achieve the predicted behavior. Even if Koehler's rule had been completely correct operation at \(\leq 10^3\) K was most efficient. The deviation strengthens the incentive to operate at temperatures which use the purity level of the material to its best advantage.

### IV Magnet Losses

Assuming pulsing to 40 kG with \(\rho_{dc} = 1.15 \times 10^{-9}\) and a coil cross section similar to Fig. 1 a resistive loss of 50 watts/kft occurs for a 40% duty cycle or 25% flat top physics duty cycle. Estimated auxiliary eddy current losses are small compared to resistance losses. The major additional loss is the hysteretic loss of the core which can be \(\sim 10\%\) of resistive losses for a suitable cycling rate. Relatively pure iron (USV Vitremetal 1) has cryogenic properties which more than compensate for its hysteresis loss. Enormous thermal "flywheel" results from its very large thermal capacity and conductivity. The core "flywheel" integrates heat load with a long time constant. With a good film coefficient the large surface area of the channels provides excellent heat transfer and a small \(\Delta T\) between the coil and core. This is very important since \(\rho_{dc}\) rises rapidly with temperature. With the coil and coolant tightly coupled to the core the iron core need only be refrigerated for the average load and one has considerable freedom in choosing other parameters since the capacity of the heat transfer does not determine \(\Delta T\). Table I shows the measured dc saturated resistivity \(\rho_{dc}\) as a function of temperature for the 1/8-in. diameter wire and 0.015-in. ribbon test specimen. The \(\rho_{dc}\) for the 24-in. magnet is the actual measured \(\rho_{dc}\) of its coils \((13,500 \text{ at } 4.2\) K\) multiplied by the Koehler factor (Fig. 4). To obtain a \(\rho_{dc}\) of 1.15 \times 10^{-9}, as shown in Table I, one must operate at \(\sim 10^3\) K with present materials, which will require the use of supercritical He gas at \(\leq 10\) atmospheres.

Some typical results from tests on the 1D7 and 24-in. models are presented in Table II. \(R\) is defined by \(R = \frac{V}{Idt}\). \(R\) contains all losses including hysteresis. \(R\) is shown divided by the zero field magnet resistance \(R_0\) at the pool temperature prior to application of power. Shown for comparison is the ratio \(R_{dc} / R_{dc}\) for the same temperature as \(R_0\). The high current density 1D7 even at 22 kG had a \(25\%\) greater dissipation \(R_{dc}\) for a 4 sec repetition rate than for a single pulse. \(R\) decreased as the cycle rate decreased. After 9 seconds the steady state pulse value \(R_{dc} = 3\) occurred. The 24-in. model had slots in the core to provide more efficient heat transfer to the pool in the nucleating boiling mode. This magnet could be operated up 40 kG with no change in \(R\) for repetition rates as short as 4 seconds.

For dc excitation in LH (Nucleate boiling mode) both models went dramatically and reproducibly into film boiling above \(\sim 20\) kG. At high fields in the pulsed mode only the thermal "flywheel" of the core prevents film boiling. On the basis of standard heat transfer criteria the bottom coil (bottom surface cooled) should have much poorer heat transfer than the top coil (top surface cooled). AC and dc operation of both models, however, produce identical dissipation in both coils illustrating the excellent heat transfer from the coils to the iron. The data for nucleate boiling for unconstrained horizontal surfaces \cite{Kutateladze} will not be very useful in predicting the \(\Delta T\) in this situation. The magnet test data was taken with no direct monitoring of the coil temperature. We want to emphasize that power densities are quite high and in the case of the 1D7 data for pumped LH, the gas to liquid flow rate is 500-1500 sec\(^{-1}\), which gives in a very undesirable cooling mode. The ID7 at 33 kG and 15.2 K with the entire coil surface area transferring heat, would have a peak power density of 1 kW/cm\(^2\) which would lead to a \(\Delta T\) of 2.2 K according to the \(R\) correlation. The ratio of \(R_{dc} / R_0\) is 4.9 is surprisingly small if such temperature rises are occurring. Similarly, for the 24-in. model operated at 13.5 K, pumping every sec. to 35 kG with 40 kG/sec rise and fall rates gave \(R_{dc} / R_0 = 6.7\) \((\rho_{dc} = 0.44 \times 10^{-9})\). If the entire coil surfaces transferred heat the peak dissipation was 1.15 kW/cm\(^2\) and the predicted \(\Delta T = 2.2\) K which would lead to a \(\sim 35\%\) increase in \(R_0\).

The 24-in. nucleate boiling model, designed with large coolant channels and poor coil packing factors, has a factor of \(\sim 2\) higher power density than the equivalent forced circulation coil (Fig. 2) at a given temperature. Nevertheless, with no circulation completely reliable operation occurs even at repetition rates of \(\sim 5\) sec.

The modified 24-in. model was connected in series with a heat exchanger to provide subcooled LH in the forced convection mode. Fig. 5. At 17 K and 22 K, ac and dc testing was performed up to 46 kG. The power dissipated was high, typically an order of magnitude greater than the heat capacity per K of the LH mass flow, because of limitations of this model and the high operating temperature which in turn produced additional temperature rise. In dc operation at moderate power levels the temperature change \(\Delta T\) across the core was typically proportional to mass flow. The known heat capacity of the fluid checked with the power input, the pulsed losses were independent of flow rate, indicating "flywheel" transfer of heat to the iron core with its very large heat capacity \((-1\) joule/KKft.\)). For short duration very high dc operation the temperature difference between the coils and the LH remained small indicating excellent surface film heat transfer. The core temperature rose several degrees and then transferred heat to the pool of LH around the external core surface. The \(\Delta T\) of the fluid was almost independent of flow rate. If the LH pool temperature was held constant the actual heat transfer could be determined. The LH supply to the dewar pool however is the coolant channel discharge and the supply to the heat exchanger is siphoned from the pool. Since the thermal time constant of the pool is \(\sim 100\) times that of the magnet core it takes a considerable period of time for the pool to warm up appreciably. The results show the excellent heat transfer between the coil and the core.

For pulsed operation to high fields, the effective resistance \(R\) was independent of flow rate and substantially below the resistance in dc operation. For example, 1000 amps (34 kG) pulsing at 17 K with \(\sim 40 kG/sec\) rise and fall rates gives the following results for 10 gpm and 20 gpm operation respectively. Coil temperature increases by 1.3 K and 1.1 K with the peak at the end of the applied power. The fluid outlet temperature increases by 0.68 K and 0.56 K with peak rise of 2.5 sec. and 3 K sec of the applied power. (the fluid transit times are 0.3 sec and 0.15 sec respectively). The coil and outlet fluid thermal pulses decayed with time constants of \(\sim 3.4\) sec and \(\sim 2.2\) sec respectively for the two flow rates as the fluid took heat from the core following the pulse. Note that the coil \(\Delta T\) changed negligibly with the flow rate. This is also shown by \(R\)}
which is independent of flow rate to a few percent accuracy. \( R \) is 7 the zero field value. The dc magneto resistance at 17°K is similar to the 21°K value (Fig.4), and predicts \( R/R_0 = 6 \). The factor of 7 includes temperature rise, auxiliary losses and magneto resistance. Note that the \( \Delta T \) between the coil and the outlet fluid is \( \sim 0.5^\circ \)K. Therefore, with the same coefficient and losses \( \sim 10 \) times less, the \( \Delta T \) between the coil and fluid would be very small.

Consider again 1000 amps. at 17°K, but with 15 second pulsed dc or flat top operation. After \( \sim 6 \) sec. both the coils and the outlet fluid reached maximum temperature for both 10 and 20 gpm flow. This was the "flywheel" time constant of the core. At the end of the power cycle the thermal recovery time constants were \( \sim 3 \) sec. and 5.5 sec. While the "flywheel" of the core is flow rate independent, confirming good heat transfer, the recovery rate is not, since it is determined by mass flow. Both the coils and fluid have \( \Delta T \) values about 5 times the pulsed case. For 10 and 20 gpm respectively, the coil \( \Delta T \) is 4.0 and 3.9°K, and the fluid \( \Delta T \) in 8.52 and 3.39°K. Again the temperature is almost independent of flow rates. The coil to fluid \( \Delta T \) is 0.5°K. This is 50% higher than in the pulsed case. The measured \( R \), however, is also 50% higher due to the greatly increased coil temperature. This linearity further confirms the film transfer behavior, and the fact that with 10 less power density the coil less power density the coil and fluid \( \Delta T \) would be quite small and there would be negligible coil temperature fluctuations. Fig. 6 shows the forced circulation LH set up.

### V Discussion

High \( \rho \) aluminum lends itself to large quantity production. Quality control improvement will bring the \( \rho \) of the present material to \( \sim 20-25,000 \). Large scale production of this material will lead to drastic price reductions, probably an order of magnitude. For a TeV machine the estimated cost per ft for a cryogenic magnet (dewar + magnet) is 4/3 of that of a conventional magnet. Although the "hot watts" of the refrigerator would be \( \sim 3 \) x that of a superconducting machine, considering practical factors such as cooldown power, transfer line losses, etc. other simplifications will affect the cost. This comparison is based on conventional duty cycles. If the future lies with ISR machines, then superconducting magnets are definitely superior. Hybrid coils containing high \( \rho \) aluminum and superconductors show great promise. Work is in progress on such hybrids in window frame magnets. The heat transfer studies in supercritical He will also consider \( \Delta T \) + Nb Sn.

### References

Fig. 1 Schematic Drawing of Model Magnet: 2-in. x 2-in. aperture.

Fig. 2 Winding fixture for fabricating anodized Alu-

minum ribbon coil.

Fig. 3 Bulk resistivity, $\rho_0$, of $\tau = 14,000$ Aluminum as a function of temperature.

Fig. 4 Koehler plot of high purity Aluminum.

Fig. 5 End view of 24-in. model magnet.

Fig. 6 Circulated LH$_2$ facility and magnet cryostat.