30 YEARS OF SUPERCONDUCTING CYCLOTRON TECHNOLOGY *

H. Blosser, NSCL/Mich. State Univ., East Lansing, MI 48824-1321, USA

Abstract

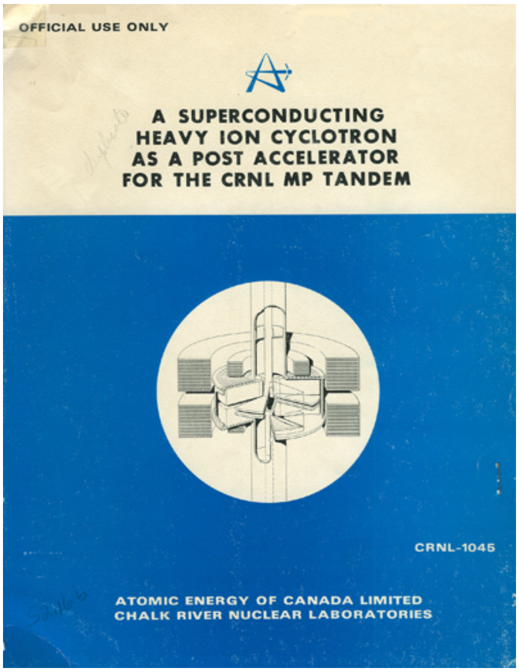
High field superconducting techniques were utilized in the late 1960’s in several large bubble chamber magnets (J.Purcell etal, Argonne National Laboratory, ANL/HEP 6813). Utilizing this technology, in Feb 1974, a group at the Chalk River Nuclear Laboratories submitted a proposal for “A Superconducting Heavy Ion Cyclotron…”(CRNL-1045). Similar proposals quickly followed from groups at MSU and Milan and in Aug. 1982 first accelerated beam from such a cyclotron was achieved in the K500 cyclotron at NSCL/MSU. In following years 8 more “Superconducting Cyclotrons” have come into operation (Chalk River, NSCL(two), Harper Hospital, Texas A&M, Groningen, Milan /Catania, Oxford, and Munich(Tritron)) and 4 are under construction (RIKEN, Calcutta, & ACCEL Inst. Gmbh (two). This paper reviews the significant steps in the development of this sequence of important cyclotrons.

INTRODUCTION

Techniques for using superconducting NbTi wire to build 5 Tesla bubble chamber magnets were developed in the 1960’s by groups at Argonne in the US and Saclay in France. This work was largely ignored by the cyclotron community until 1972, where the Proceedings of the Sixth International Cyclotron Conference refer to the use of superconductivity on page 24 of the volume “Cyclotrons 1972”. This well known reference (in a paper by the present author) says “Superconductivity then seems unlikely to make a contribution to cyclotrons in the foreseeable future….”. In contrast to this 1972 statement, at the 1975 Cyclotron Conference in Zurich, enthusiastic papers on the use of superconducting techniques to construct smaller, less costly cyclotrons were presented from Chalk River, Canada and Milan, Italy, and also from the author’s laboratory in East Lansing, Michigan USA (MSU). From that point forward, papers on “Superconducting Cyclotrons” have been a standard item at International Cyclotron Conferences. This paper gives a historical review of major steps in developing the technology on which this important class of cyclotrons is based.

THE EARLY YEARS

A widely circulated Chalk River report [1] (with an impressive cover – Fig. 1) started the wave of Superconducting Cyclotron enthusiasm noted in the Introduction. In this beginning phase, many important technical details needed to be resolved and a free exchange of technical information between all the groups was standard practice. The groups from Chalk River and East Lansing had monthly one day meetings at the Toronto Airport, and later, when funding was delayed for work in Italy, F.Resmini, the leader of the Italian group, moved to MSU with several coworkers and this group played a central role in the development of both the K500 and K1200 cyclotrons at MSU.


OFFICIAL USE ONLY

A SUPERCONDUCTING HEAVY ION CYCLOTRON AS A POST ACCELERATOR FOR THE CRNL MP TANDEM

CRNL-1045

ATOMIC ENERGY OF CANADA LIMITED
CHALK RIVER NUCLEAR LABORATORIES

Fig. 1 – the cover of the report CRNL-1045. This report circulated widely and led to the design and construction of the large number of superconducting cyclotrons which are in use today.

The pioneering studies presented in CRNL-1045 made Chalk River the early leader in the rush to build an operating cyclotron, but funding for construction of such a cyclotron in Canada was delayed to 1978 while decision makers considered the importance of the project relative to other fields of science. In the meantime MSU adopted a novel funding strategy, namely to request funds to construct the superconducting magnet with the proviso that the magnet would be moveable, with the final site to be determined in a standard scientific review process. The “moveable magnet” concept made it possible to organize a cluster of Universities and Laboratories supporting the project and a grant to construct the superconducting magnet was then officially awarded to MSU in June of 1975. (This exercise in what might be considered the “politics of science” clearly moved MSU into a position of advantage in the race to build an operating superconducting cyclotron.) In due course the moveable magnet came into operation (in May 1977) – technical difficulties described in following paragraphs were overcome -- a proposal to make the “movable” magnet into a cyclotron sited at MSU was submitted and approved – and in Aug 1982 the first external beam was extracted from the K500 cyclotron. The age of Superconducting Cyclotrons had become a reality!

The title of this paper refers to "30 years of Superconducting Cyclotron Technology" -- using superconducting magnets in a cyclotron led to events classed in this paper as "unexpected technical problems" – finding solutions to the "unexpected problems" is the key step in developing a new technology so several examples are described in some detail. (Examples of unexpected problems in this paper are taken mainly from the MSU experience since these are the problems best known to the author.)

A first central technical question in designing the main superconducting coils was whether the superconducting coils should be fabricated as a stack of double pancakes or as a continuous helical winding. J. Purcell, the leader of the group at Argonne, had used double pancakes for two very large superconducting coils for hydrogen bubble chambers [2-3], but Purcell was also interested in trying a helical winding. He thought the helical winding might be more efficient, and also the coil group at Saclay had used helical windings with good results in an early test magnet known as the "BIM" magnet. In the end, Chalk River and Milan used pancakes and MSU used the helix and both winding styles worked well.

The first unexpected problem with the MSU K500 coil came about as a result of a machining error in fabricating the stainless steel wall of the K500 helium vessel. The manufacturer made an error in aligning the welded rolled plate structure in the lathe where the oversize plates were to be machined to final dimensions. The result was that a region of the welded plate structure was out of position relative to the design inner wall dimension so that wall ended up after machining with an un-machined region, i.e. a region of missing metal relative to the design drawings. The transverse area of this region was approximately 300 x 500 mm in extent and with a maximum depth of about 5 mm. The manufacturer could have been required to replace the entire vessel, but virtually always in such a situation, there is a strong urge to avoid the delay involved in remaking the vessel. The defective component was therefore used (based on a crude stress analysis of the effect of the error) and in the end this has proved to be a good choice – now 40 years later, the K500 coil with the missing steel continues to operate reliably and the machining defect has been forgotten by all but a small few.

The K500 coil also experienced a "quench" in one of its early full field tests (a quench being a rapid transition from superconducting to normal conducting in the coil – resistive heating of the non-superconducting region rapidly vaporizes the liquid helium, causing the pressure limiting discs in the magnet safety system to rupture and vent the gaseous helium at high velocity). In conversation, the author describes this event as akin to having a large ocean liner blow its whistle just behind his back. The author also acknowledges that he personally caused this event – it was late in the evening -- the helium level gauge showed a low reading – the author declared this reading to be due to a faulty level gauge – this small misjudgment proceeded to produce a very large boom! Fortunately, damage to the coil proper was minor -- one internal instrumentation circuit had been torn apart by the high velocity gas, but the circuit was of marginal importance and was deemed not worth the extensive work that would have been required to open the 4K vessel and make a repair. It is also interesting to note that a similar event occurred in the 15th year of operation of one of the large bubble chamber magnets built for Fermilab by the Argonne group [3]. The stored energy in this magnet was 400 Mega-joules (compared to 18 in the K500 coil) – as in the K500 event the bubble chamber operator concluded that a helium level gauge was defective and entered an override – the resulting quench gave off an explosive sound and a plum of vapor that caused the fire department 3 miles away in West Chicago to spontaneously respond assuming there had been a major explosion on the Fermilab site.)

A "fire department" event also occurred in the early days of operation of the K500 magnet. In this case, a so-called "dump resistor" was being tested and a design error caused the resistor to melt exposing the coil and its 18 mega-joules of stored magnetic energy to an open circuit. In this circumstance, the inductance of the magnet causes the voltage to rise to whatever level is needed to provide a path for the current to continue to flow. The path the current found in this case was inside the magnet power supply where the arc continued to move and dance for many minutes and this behavior was undeterred by either the H2O or the CO2 used by the fire department after their arrival. But again the coil proper sustained no significant damage and the K500 magnet was back in operation in a few weeks with a replacement power supply, and a rebuilt dump resistor.

Another "unexpected technical problem" came up as the author was showing a faculty group the process used for "centering" the coil. This process involved turning up the magnet current in steps and, at each step, recording the forces on the 9 epoxy-impregnated-glass-fiber links (this structure being designed to hold the coil at the desired position with minimum heat flow into the 4K vessel). At a certain point the author had finished reviewing the data from the preceding step and had decided the force balance could be improved with a small adjustment, and made the adjustment. About 30 seconds thereafter a very loud bang occurred (allegedly causing at least one member of the observer group to jump from his chair with a shout). The loud sound was high-pitched like a hammer hitting an anvil and on inspection it was determined that one of the epoxy/glass filament support links had broken allowing the 4K vessel to accelerate in the radial direction until it hit the 300K steel wall of the cryostat-magnet structure. Again the coil proper showed no evidence of harm and in a period of about one week, a new support link had been installed and the magnet was ready to operate. Also an additional operating rule was introduced namely "*ramp the magnet to zero current before making a link adjustment*".

Overall much MSU "good luck" can be inferred from the rather minor damage caused by each of the above events. The author however believes that this good luck should more appropriately be credited to the long experience of John Purcell and the fact that he was almost always available on the telephone with sage advice, when problems occurred. In comparison with MSU, Chalk River and Milan had many fewer "unexpected technical problems". Perhaps these groups were smarter, or perhaps both learned from the MSU experience, and, being later to reach the stage of first operation, were clever enough not to repeat any of the MSU mistakes.

THE MIDDLE YEARS

In the "middle years" group of superconducting cyclotrons, we include the entry of two important new superconducting cyclotron centers, a K500 at Texas A&M and a K600 at Orsay/Groningen respectively. Construction of two additional superconducting cyclotrons at MSU, the K1200 research cyclotron and the K100 cancer therapy cyclotron, are also assigned chronologically to the "middle years" category. (The author acknowledges that the set of chronological categories is largely inserted to provide subdivisions for the discussion without any more substantive defining purpose.)

Chronologically, the first of the above listed important events came at Texas A&M University where construction of their K500 superconducting cyclotron started in 1982 and first external beam was achieved in June 1988. The Texas A&M magnet is very like the MSU K500 magnet, the superconducting coil and the room temperature correction coils all having been fabricated by A&M personnel working at MSU and using the MSU winding machine. The cyclotron is though also designed to work in a coupled mode with the existing Texas A&M 88" cyclotron which led to changes (and improvements) in the radio-frequency system to achieve the required frequency matching between the two cyclotrons. Also the Texas A&M cyclotron has from the beginning operated with an axially injected beam from an ECR ion source.

Continuing chronologically, the second "Middle Years" event is the construction at MSU of the K1200 cyclotron. From the beginning of superconducting cyclotron work at MSU, site dependant two-accelerator options had always been under consideration with one accelerator injecting into the other using a stripper foil to increase the charge state and thus match the beam onto a centered orbit in the second cyclotron. In an arrangement of this type the second accelerator acts as an energy multiplier, and lacking a significant first cyclotron, the first MSU superconducting cyclotron proposals were to make two K500 cyclotrons, one injecting the other, an arrangement which would produce beams up to 100 MeV/nucleon. One day a theoretical physicist, Richard Shaeffer, a visitor from Saclay who was spending a year working with the MSU theory group, came into the author's office with a lot of excitement. Schaeffer was sure that increasing the energy up to 200 MeV/ nucleon would open very important new areas of Physics. But technically, the change that Schaeffer wanted was not easy to accomplish. In the Proceedings of the 1985 Cyclotron Conference in Tokyo, the author says "The K800 (i.e. K1200) is however at the same time a much more difficult technical challenge than the K500 due to the larger number of turns, the higher dee voltage, the tighter spiral, and the intrinsic proximity of the operating point to the 3/2's radial stopband". And much more difficult beam extraction should also have been added to this list. In the end Shaeffer's 200/MeV/nucleon was adopted by the Laboratory and in subsequent competitive reviews, the project received a "highest priority" rating. Based on this the official name of the MSU Cyclotron Laboratory was changed to "National Superconducting Cyclotron Laboratory" (NSCL), funding was increased, construction of the K1200 began in the fall of 1980, and first external beam was achieved in June of 1988.

The third "Middle Years" superconducting cyclotron event is the K100 superconducting cancer therapy cyclotron for Detroit's Harper Hospital. This cyclotron accelerates 50 MeV deuterons onto an internal Beryllium target. The neutron beam produced in this reaction passes out through a shaping collimator to the location of the cancer tumor. The cyclotron is mounted on a rotating ring system which allows it to move through a full 360 deg circle about a patient on the treatment couch, thus causing the neutron beam to hit the tumor from as many directions as the physician stipulates. Construction of this cyclotron started in 1984 and first external neutron beam was achieved in April 1989.

The fourth superconducting cyclotron which is placed in the "Middle Years" group is a joint project between the Orsay Laboratory in France and the Groningen Laboratory in the Netherlands. Construction of this AGOR (Accelerator Groningen Orsay) cyclotron started at Orsay in 1987, first external beam was achieved at Orsay in April 1994 and at Groningen in 1996. The cyclotron is a unique design with many novel features. A special design goal is to accelerate Q/A = 1 ions (i.e. protons) to 200 MeV, (the same energy as the K1200 would obtain if it was accelerating and disassociating an H2+ molecule, but the quality of the direct proton beam would certainly be much higherthan that of a beam from a disassociated molecule). The AGOR superconducting magnet uses an epoxy-impregnated coil (like the Harper K100) so coil short-circuit problems due to miscellaneous metal debris are eliminated. The extraction system involves two active magnetic channels one of which is superconducting. The dees are equipped with an unusually thorough array of beam diagnostic devices (see Fig.2). (Other novel features of the AGOR cyclotron regrettably go unmentioned in this paper due to the author's lack of Knowledge.)

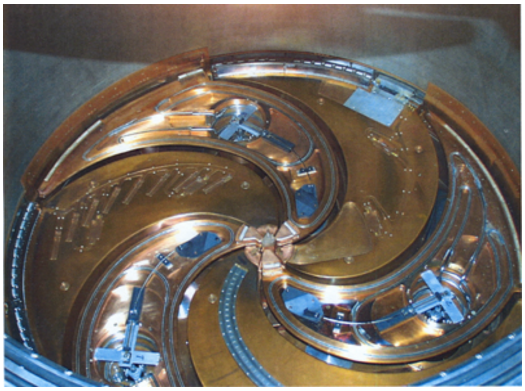


Fig. 2 – a view of the lower pole face of the AGOR cyclotron showing the copper covers of three poles. The pole at the bottom of the figure with a spiral track guides a full radius beam probe. Intricate mechanisms in the three lower dee's provide an unusually complete set of diagnostic devices.

THE RECENT YEARS

Major superconducting cyclotron events in "Recent Years" include the giant step in process here in Japan, the K2500 SRC (Superconducting Ring Cyclotron) at RIKEN, the major reconfiguration of the MSU K500 and K1200 cyclotrons into a combined system, the initial operation of the K800 cyclotron in Catania, The commercial manufacture of two K250 medical superconducting cyclotrons by ACCEL Inst, of Bergisch-Gladbach, Germany, and the completion of the Separated Orbit Cyclotron Project at Munich. (The K12 superconducting isotope production cyclotron of Oxford Instruments has sometimes been included in these listings but is omitted from the discussion in this section.) Since most of the events above have also been reported on at this conference it seems unnecessary in this section to have more than a cursory review of these "Recent Years" events.

The RIKEN K2500 Superconducting Cyclotron is of course a huge project relative to any other project which has been undertaken in the field of cyclotrons. And at the same time, the SRC is itself only a component of the overall array of new facilities being constructed or about to be constructed at RIKEN. Fig. 3 gives a compact overview of the RIKEN plan.

The major reconfiguration of the K500/K1200 cyclotron system at MSU and the introduction of stripping extraction into the accelerator complex at Catania both have the purpose of achieving beams of much higher current than had been previously available at the respective cyclotrons. Clearly both of these projects show that new ideas in the field of Superconducting Cyclotrons are still happening and that these ideas still lead to important advances in our overall field.

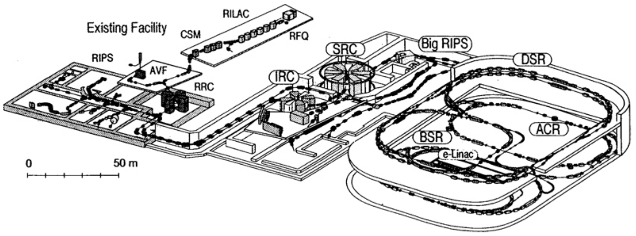


Fig. 3 – A 1998 conceptual drawing showing the set of accelerators, storage rings, beam transport lines, etc. as envisaged by the Riken group at that time

The termination of the Separated Orbit Cyclotron project in Munich [4] appears to tell us that we have not yet found an effective way to utilize superconducting radio-frequency structures in cyclotrons. It then remains an area of challenge to cyclotron builders where possible new concepts could be of great benefit

SUMMARY

Judged by the number of papers submitted for this conference, it is clear that activity in the field of Superconducting Cyclotrons remains high but growth is less rapid than in the conferences of 20-30 years ago (and possibly flat). The project at RIKEN is the clear leader in assaulting very difficult challenges and much progress has been achieved. Most of the major Laboratories continue forward toward challenging goals (except for the founding project at Chalk River, where the cyclotron based nuclear physics program has been terminated, and the K500 cyclotron cut into pieces and sent to the scrap metal depository). Commercially, Oxford Instruments has, after the retirement of key individuals, ceased to manufacture its K12 cyclotrons after a total production of approximately 10. The Oxford termination has however been more than offset by the rising sales of K250 cyclotrons for proton treatment of Cancer by ACCEL Gmbh, of Bergisch-Gladbach, Germany (two K250's in commissioning status, a third under contract).

REFERENCES

[1] J.S. Fraser and P. R. Tunnicliffe, " A study of a superconducting heavy ion cyclotron as a post accelerator for the CRNL MP Tandem", CNRL-1045, 1974.

[2] J. R. Purcell et al., "The superconducting magnet system for the Argonne 12-foot Bubble Chamber", ANL/HEP 6813, 1968.

[3] J. Purcell, H. Desportes and D. Jones," Superconducting magnet for the 15-foot NAL Bubble Chamber", ANL/HEP 7215, 1973.

[4] A. Cazan, P. Schutz and U. Trinks, "Commissioning of the first separated orbit cyclotron TRITRON", Cyclotrons'98, Caen, 1998, p. 323.