Proceedings of the 14th International Conference on Cyclotrons and their Applications, Cape Town, South Africa

PROBLEMS AND ACCOMPLISHMENTS OF SUPERCONDUCTING CYCLOTRONS

H. BLOSSER, D. JOHNSON and J. SCHUBERT

National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48823-1321, USA

As the Cyclotrons '95 Conference convenes, superconducting cyclotrons are clearly a main stream component of present cyclotron evolution. In particular: 1) six large superconducting cyclotrons (Chalk River, MSU K500, MSU K1200, Texas A&M, AGOR, and Catania) provide forefront capabilities for nuclear physics research (including, from the K1200, the highest energy CW beams available from any accelerator of any type in the world), 2) a K100 superconducting cyclotron at Harper Hospital in Detroit provides intense neutron beams for cancer therapy, 3) a major proto-type cyclotron, the Tritron, is being commissioned at Munich, 4) nine small (K12) superconducting cyclotrons, manufactured by Oxford Instruments, are in operation at sites around the world providing short lived isotopes for medical diagnostic procedures, 5) one new K500 research cyclotron project is beginning at Calcutta, 6) use of superconducting cyclotrons for proton therapy has been proposed (and is under serious consideration), and 7) a K500/K1200 coupling project to make a major leap in beam intensity has been proposed at the NSCL and construction has started on the first phase of this project. This paper principally reviews design features of the existing superconducting cyclotrons with emphasis on varying design choices which were made by the several design groups to avoid problems and how these choices appear in retrospect. Finally, the paper considers thoughts as to the possible future evolution of these highly efficient accelerators.

1 Introduction

It is now twenty years since "Superconducting Cyclotrons" (SC) first appeared as an invited paper topic at this series of conferences[1] and thirteen years since the first of these cyclotrons came into operation[2]. Overall, the accomplishments of this class of cyclotrons can only be characterized as enormously impressive. At the present moment three of these machines, at Chalk River[3], MSU[4], and Texas A&M[5], carry a major portion of the intermediate energy heavy ion research program of the world, and two additional large SC's, namely the Catania K800[6] and the Orsay-Groningen K600[7], are just entering the regime of routine operation in nuclear physics research; as these two important facilities come into operation, the role of superconducting cyclotrons in intermediate-energy, heavy-ion nuclear research will further greatly expand; one of the presently operating research cyclotrons, the K1200 at MSU, also stands as the highest energy CW (constant wave) accelerator of any kind in the world. The three major operating accelerators all produce a wide variety of beams basically fully covering or exceeding their originally contemplated working regime. In addition a new "Coupled Cyclotron Project" at MSU[8] is expected to carry the superconducting cyclotron into a major new, particle-microamp, intensity regime. This project at the time of writing has been partially approved and construction of the building has started; full approval is expected in late 1995.

The major advantage of the superconducting cyclotron comes from the large reduction in the quantity of magnet steel needed to achieve a given degree of bending of the particle beam. This advantage originates in a simple scaling law, namely that the flux contained in the cyclotron beam pancake varies inversely as the field strength for given maximum Bρ of the magnet. Figure 1 shows this feature quite dramatically; iron weight for cyclotrons of 100 MeV and higher (as indicated in the "Data Sheets" section of the proceedings from the previous conference in this series – Vancouver '92) is plotted vs. the maximum bending power of the cyclotron's magnet – superconducting cyclotrons (plotted as solid circles) are clearly a separate family with magnet weight reduced by more than an order of magnitude relative to the room temperature cyclotron group. This, plus overall reduced size, gives a large saving in the quantities of materials required; much of this saving is offset by increased complexity, but a factor of two is typically cited[9] as the approximate final cost advantage of superconducting vs. room temperature cyclotrons. In the tight budget mileau of the 1990's, a factor of two cost advantage is very compelling, and many major projects have therefore selected the superconducting approach.

In a recent paper reviewing the status of superconducting cyclotrons, Schreuder[10] grouped these cyclotrons into the categories "first generation", "second generation", and "unconventional". He placed in the first category the Catania K800, the MSU K1200, the Chalk River K520, and the Texas A&M K520; in the second category, the Orsay-Groningen K600 (AGOR); and in the unconventional category, the Munich K85 (Tritron) and the Oxford Instruments K12's (OSCAR). To minimize confusion, we adopt the Schreuder classification, but add a "third generation" category for discussion of likely characteristics of a superconducting research cyclotron entering the design/construction phase at the present time.

2 Characteristics of Present Superconducting Cyclotrons

Table 1 is a summary of major characteristics of the existing superconducting cylotrons. In this Table the entries not enclosed in square brackets are taken from the "Data Sheets" appearing in the Proceedings of the 1992 Vancouver Cyclotron Conference. Data in parentheses (especially the last column for the Triton) are taken from selected other publications and/or direct contact with the facility. The line following the page number in the Table gives the "generation" of each facility according to Schreuder's assignment. The MSU K500 and the Harper Hospital K100 were omitted from Schreuder's review – the K500 clearly is first generation based on it's status as the first of the superconducting cyclotrons to come into operation, and we have assigned the Harper K100 to the second generation, since it and Agor share the key characteristic of being the first machines to move away from the security of a cryogenically stable main coil structure (as discussed further in a later section).

Viewing Table I as a whole, the entries first of all clearly reflect both a broad range of basic goals in the various projects and a variety of varying judgements as to how to most effectively handle many sensitive design issues. A primary focus of this paper is to review and compare performance effectiveness and/or problems resulting from these different choices so that designs of future superconducting cyclotrons can benefit from the earlier experience.

Considering the entries in Table I, we see first of all in the "purpose" row that six of the projects share the common purpose of providing beams for nuclear physics research; these six cyclotrons also have the highest K values, namely 500 MeV or higher, reflecting the interest of nuclear research in high energy projectiles. The remaining three columns in the Table, cyclotrons with K's of 100 and lower, have varied purposes namely: 1) in the case of the Harper Hospital cyclotron to provide neutron beams for cancer therapy, 2) in the case of the Oxford Instruments cyclotrons, to provide isotopes for medical diagnostic procedures, and 3) in the case of the Munich cyclotron, to demonstrate the feasibility of the Separated Orbit Cyclotron (SOC) concept (with also the secondary goal in the long range, of providing a five fold increase in the energy of the beams available for the nuclear physics program at Munich). It is also important to note that four of the research cyclotron projects, namely the K800 in Catania, the K500's at Texas A&M and NSCL, and the K1200 at NSCL, have the feature of having been designed in their early formative states by a closely coupled MSU/Milan group[11]; these four cyclotrons then have many common features.

2.1 Magnet Features

All of the first and second generation superconducting cyclotrons use a basic magnet structure of the "Compact" type, ie. with circular main coils surrounding a cylindrical pole-base/pole-tip assembly with the magnetic flux from the acceleration region returned to the opposite pole by an outer, circumferential return yoke. The "unconventional" Tritron departs radically from this standard style by dividing the magnet into single turn sections with an individual exciting coil to produce the field for each turn and with the flux from that turn returned by yoke elements in the immediately adjacent space between that turn and its neighbors. This design 1) enormously reduces the required volume of iron, 2) allows selection of transverse focussing frequencies with considerable freedom so as to avoid serious resonances, and 3) provides positive longitudinal focussing (the need for, or benefit from, this last feature being however not of great significance). The Tritron, like any SOC, is dominated by the turn separation requirement and the very large accelerating voltages required to produce that separation. Finally the Oscar magnet design is a hybrid, dominantly air core structure, with iron pole tips inserted in the bore of an MRI style solenoid.

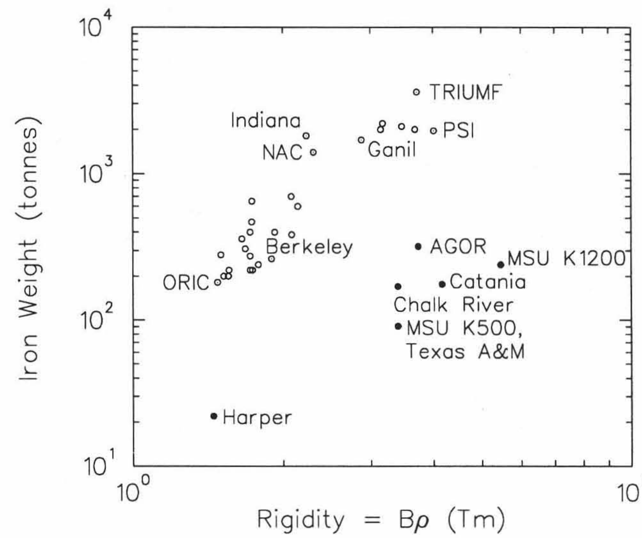

Figure 1: Iron weight in metric tonnes vs. maximum bending power in tesla meters for the large cyclotrons in the world. Numerical values are from the "Data Sheets" given in Proceedings of the Thirteenth International Conference on Cyclotrons and Their Applications, Vancouver 1992.

For the early group of cyclotrons, the superconducting coils were all designed to be "cryostable" which means that adequate cooling power (i.e. liquid helium) is provided in the winding such that if a section of conductor ceases to superconduct (due to temperature excursions from conductor motion, etc.), there is sufficient cooling to carry the resultng resistive power load with a residual margin which will recool the normal section of conductor and return it to the superconducting state. With this

Table 1: Characteristics of present superconducting cyclotrons (see text).

Facility Name	TASSC Chalk River	K800 Catania	AGOR Orsay Gron'gen	K500 Texas A&M	K100 Harper Hosp.	K500 NSCL MSU	K1200 NSCL MSU	Oscar Oxford Instru.	Tritron (Munich)
pg.#(Cyc & App 92)	781	806	817	841	843	844	845	862	
Generation (ref 10)	1st	1st	2nd	1st	(2nd)	(1st)	1st	Unconv.	Unconv.
Purpose	Nuclear Research	Nuclear Research	Nuclear Research	Nuclear Research	Cancer Therapy	Nuclear Research	Nuclear Research	Isotope Prod.	Prototype SOC
Dates:									
design	1973	1975-76	1986-89	1980	1981-84	1975-79	1976-86	1986-88	(1994)
construction	1978-84	1981-95	1988-92	1982-88	1984-89	1977-81	1980-87		
first beam	Sept 85	May 95	Apr 94	Jun 88	Apr 89	Aug 82	Jun 88	1990	
K bend (MeV)	520	800	600	520	100	520	1200	12	(90)
K focus (MeV)	100	200	200	160	50	160	400	12	(75)
Variable Energy	yes	yes	yes	yes	no	yes	yes	no	(yes)
Fe mass (Mgrams)	170	176	320	91	22	91	240	(1.5)	(1)
Stored Energy (Mjoule)	22	40	57	22	2	18	60	1	(small)
Cryostable	(yes)	(yes)	(no)	(yes)	(no)	(yes)	(yes)	(no)	(no)
Avg. J (A/mm^2	25	(35)	43/33	36	132	36	36/40	120	(120)
Rextract(mm)	650	867	910	670	300	670	1030	210	(1450)
Hill Gap min(mm)	37	86	70	64	38	64	76	29	(11)
Frequency-rf(Mhz)	31- 62	15- 49	24- 63	9-28	105	9-27	9-27	108	(170)
Acceleration Harmonic	2,4,6	1,2,3	2,3,4	1,2	3	1,2	1	3	(14-55)
Tuning Short	vacuum	air	vacuum	air	vacuum	air	air	vacuum	(cavity)
Dee volts(kv to grd)	100	100	110	80	33	100	160	33	(530)
dE/dn-max(keV/Q)	800	(520)	660	240	200	510	480	200	(3750)

type of structure, magnet quenches should not occur as long as the helium level in the coil is maintained at its proper level[a]; the magnetic stored energy will therefore never be dissipated in the coil and especially not in any local region of the coil where a destructive temperature excursion could easily result. The principle concern with this type of coil is its sensitivity to short circuits, since the cooling power criteria almost always requires bare conductor in direct contact with the helium bath; miscellaneous metal fragments can then easily lead to turn-to-turn or layer-to-layer shorts. To achieve cryostability at 4.5K, the current density must also be held at rather low values (below 40 amps/mm^2 average over the coil area) and the copper matrix in which the superconductor is imbedded must be quite pure (to lower the resistive heating in a normal section of conductor so that I^2R dissipation stays within the capabilities of the cooling bath).

An alternative superconducting coil design approach, in wide use in small superconducting magnets, is to give up on achieving cryostability and focus on eliminating frictional conductor motion heating by tight clamping and by fully impregnating the winding with epoxy to bond each turn into position. This type of winding is characterized as "instrinsically stable", a somewhat whimsical label referring to the fact that if the coil actually operates in a superconducting state, wire motion must have been fully suppressed.

The "cryostable" line in Table I, indicates that all of the first generation cyclotrons employ a cryostable coil design whereas the "2nd generation" and the "unconventional" cyclotrons use intrinsically stable coils. In coils of the later type, key parameters are the magnetic force density (the product of magnetic field and current density), which determines whether a wire will move, and the rate at which thermal energy spreads from a normal region, a rapid energy spread being helpful because fast expansion of the critical temperature boundary spreads the magnetic energy over a much larger sub-volume of the coil thereby lowering the "hot spot" temperature at any particular location. Another important safety issue in such coils relates to the internal high voltages which can be induced in a a quench due to the resistive IR drop which typically has a very different spatial distribution (because of the non-uniform temperature) than the inductive dI/dt voltage component; this difference can give internal voltages in the coil in the kilovolt range thereby possibly causing destructive layer-to-layer or layer-to-ground arcs in the coil even though the external terminal voltage is held at a modest value by the

[a]Any superconducting coil whether cryo-stable or intrinsically stable will of course quench if the temperature rises (such as from low helium level, etc.) – thus a quench occurred in the 400 Mjoule coil of the FermiLab 15 foot bubble chamber in its 15th year of operation, when a helium level warning failed leading the operators to bypass an interlock – the sonic blast from this quench caused the fire department to spontaneously respond assuming there had been a major explosion – in fact the coil survived without harm and continues to operate in its traditional way evidencing a degree of ruggedness frequently (but not always) observed in superconducting coils.

power supply and dump resistor. As an example, in a quench of the Harper Hospital coil, the estimated voltage to ground at the median plane coil-to-coil connection is approximately 4000 volts; this requires very careful procedures in designing and installing the coil-to-ground insulation system so that destructive arcs-to-ground cannot occur. Intrinsically stable coils are compellingly attractive in their insensitivity to miscellaneous metallic chips and in the fact that higher current density can be used, which reduces conductor cost. The appeal of this design approach is also reinforced by the fact that the intrinsically stable coils at both Harper and Agor have thus far performed well. (The Harper coil has been quenched on literally hundreds of occasions as various design limits were explored – the Agor coil has thus far been carefully operated so as not to experience a quench.)

Referring to the line "Fe mass" in Table I, another important design distinction is immediately clear, namely that the volume of magnetic material used in the various projects fluctuates markedly (as is also seen in the scatter of points in Figure 1). Judgements involved in selecting the magnet weight for the various projects are discussed further in the "Third Generation Cyclotrons" section of this paper.

2.2 Acceleration Systems

Present superconducting cyclotrons, with the exception of the pioneering Tritron at Munich, all use conventional room temperature resonators to produce the rf electric fields which accelerate the particle beam. Available space is crowded and successive orbits are closely packed together, relative to the much larger room temperature cyclotrons; designer's typically try to work near the upper limits of achievable electric fields in order to reduce the number of turns (and thus increase the separation between turns to make it easier to extract the beam). The rf system also accounts for most of the electric energy consumption of the cyclotron which can reach into the megawatt range (in the case of the MSU K1200), and for a large part of the unscheduled down time of the operating cyclotrons (electrostatic deflectors being typically the other large contributor to unscheduled downtime). All these factors then make the design of the rf system a particularly critical and sensitive aspect of the overall design of a superconducting cyclotron.

A first important rf choice is the selection of the "harmonic" number "h", (the ratio of rf frequency to orbital frequency). The orbital frequency is of course proportional to the charge-to-mass ratio (Q/A) of the accelerated ion, and cyclotrons which are intended to accelerate a broad range of ions, such as from deuterium to uranium, will need to handle a large Q/A range from 0.5 to around 0.1 (and up to 0.67 or to 1.0, if ^{3}He or bare protons are to be accelerated). If the energy is also variable, which is very important for nuclear physics, the rf frequency must be continuously selectable anywhere in the operating range, and the wider the required range of rf frequencies, the more difficult the rf design becomes. To reduce the span of rf operating frequencies, variable-energy multi-particle cyclotrons then customarily change harmonic numbers when the (n+1)th harmonic times the highest operating frequency equals n times the lowest operating frequency. The acceleration harmonics used or expected to be used at the various facilities are indicated in Table I.

An important choice with regard to the harmonic number is whether the lowest harmonic is h=1 as in the cyclotrons tracing to the MSU/Milan collaboration, or h=2 as in the Chalk River and Orsay/Groningen cyclotrons. Selecting h=1 as the lowest harmonic number is advantageous in the central region, because transit time effects are reduced making it easier to design electrodes which will accelerate an array of particles with different starting times into well-centered orbits. Also, the slip in phase between the beam and the rf caused by non-isochronous regions of magnetic field, is smaller for h=1 than for h=2, this being proportional to the product n*h where n is the number of turns and h is the harmonic number and the reduction in the number of turns due to increased energy gain in second harmonic is not large enough to balance the x2 change in the harmonic number. Designs based on h=2 have a very strong advantage in reducing the overall size of the resonator structure (the resonators being the dominant space occupying component of the h=1 cyclotrons) and the radial separation between successive turns is increased by the higher energy gain. Also, the minimum range of frequencies over which the rf must tune to have continuous energy variability is reduced from 50% in the case of h=1 to 33% for h=2. On the other hand, for given dee voltage, rf power is typically higher at the higher frequencies required by h=2, and the shorting stems tend to be too short to have space for insulators to bring the shorts out of the vacuum. This last is an advantage as well as a disadvantage since both the insulators and the sliding shorts are intricate, potentially troublesome components – omitting insulators is advantageous from the perspective of overall reliability but the dees are thereby considerably more susceptible to position errors due to the loss of mechanical support from the insulator, and the design of the sliding short is more difficult due to not having air as a cooling medium in close proximity to the sliding contacts. Summarizing, the comparative advantages and disadvantages of h=1 systems vs. h=2 are complicated and in many respects linked to the choice of beams to be emphasized at a particular cyclotron. If a new broad range cyclotron were being designed at the NSCL, we would clearly begin with a thorough study of an h=2 system because the advantage of compactness is very compelling; the study at an early point would evaluate the likely central region transit time problems for the heaviest ions since this was the consideration which, more than any other, led to selection of h=1 as the design choice for the group of cyclotrons based on the MSU/Milan design. (We note that the most recent MSU cyclotron construction proposal[12] – for a 250 MeV cyclotron for proton cancer therapy – almost immediately adopted an h=2 design, since acceleration of heavy ions, for which the central-region transit time would be of concern, was not a relevant issue.)

Turning to the mechanical features of superconducting cyclotron rf systems, we note that the first and second generation cyclotrons all use a traditional accelerating "dee" in each valley in order to provide the accelerating fields, and also, the quarter-wave shorted lines which form the resonant circuit are axial, to avoid median plane space restrictions from the main coil cryostat. The axial dee "stems" are usually paired i.e. two symmetrical stems above and below the median plane (to avoid axial electric fields) thus making the full resonator a half wave cavity.

For three sector, dee-in-the-valley cyclotrons, 120 degree phasing is needed between the voltages on the respective dees, if harmonics other than 3, 6, 9, ... are to be used (and harmonic 6 gives no net acceleration if the gaps are spaced at the normal half-sector value of 60 degrees); 120 degree phasing originally gave some difficulty in the MSU K500 where it was first attempted, but has now become routine; a separate high power rf source is required for each dee, and an arrangement of shielding electrodes is required in the cyclotron central region to reduce capacitive coupling between the dees so that each dee receives its dominant drive component from its own amplifier. A low level phase sensing and feedback system is also necessary to continually compensate for drifts in phase in any part of any of the three amplifier chains.

The single particle, fixed energy cyclotrons (Harper Hospital and the OSCAR's) use a three-sector, three-dee, third-harmonic resonator system which makes the rf problem much easier since all dees are in phase (enforced by a galvanic coupling link joining the dees at the center of the cyclotron). The only tuning required in these systems is then a single adjustment to match the impedance between amplifier and resonator.

Many aspects of the accelerating system at Chalk River differ from the the design pattern described above, frequently in ways which are only applicable in a four sector magnet. Thus opposite dees in the four-sector, four-dee configuration are galvanically joined, the joining structures for the two pairs passing respectively over and under each other at the cyclotron center with each dee pair mounted on a single axial dee stem, the stem for one pair of dees going up and that for the other going down. This arrangement has the attractive feature of allowing all four dees to be driven by a single amplifier with either the in-phase or out-of-phase natural modes of the two resonator system being selected by setting the drive frequency to match the resonant frequency of the desired mode. In either mode opposite dees are always in phase (so there is no net acceleration on odd harmonics) and harmonics 2, 4, and 6 are used to cover the desired operating range.

The single high-power amplifier aspect of the Chalk River rf system is an important advantage, but in its present form is incompatible with a central ion source or with low energy injection because of the space required for the dee stem branches in the central region. The axial electric fields associated with the out-of-the-median-plane single stem resonator for each dee pair can also be troublesome in inducing harmful coherent axial oscillations in the beam and in producing rf fields inside the dee which can give problems with internal components (deflectors, stripping foils, cryopanels, etc.). A Chalk River like structure in which each dee has two symmetric dee stems, i.e. eight total, was a part of the recent MSU design study[12] for a 250 MeV proton therapy cyclotron. In this cyclotron study, coupling between one of the pairs of opposite dees was accomplished by a galvanic link in the median plane (thus maintaining the median plane symmetry of the system), and the two remaining dees (at plus/ minus 90 degrees from the driven, galvanically coupled pair) were excited by their capacitive coupling to the driven pair (provided by the central region electrodes). In this arrangement, the satellite dees have two natural modes (push-push and push-pull) relative to the driven pair and the desired mode (push-pull for h=2, push-push for h=4, etc.) can be selected by tuning the satellite to the desired resonance peak, just as happens at Chalk River for the undriven dee pair and in many earlier two dee cyclotrons as well[25]. (Both satellites must of course be tuned to the correct mode.)

The four nuclear physics cyclotrons growing out of the MSU/Milan joint design all bring the dee stems out into air to achieve better cooling of the sliding short system. At the time of this conference, the shorting-plane-in-vacuum designs seem somewhat more attractive, the early concern about difficulties with rf sliding contacts in vacuum not having materialized. (The body of experience supporting this conclusion comes mainly from the Chalk River cyclotron and the Harper Hospital cyclotron, both of which have been in use for a number of years; the experience is less extensive in terms of operating hours than that from the shorting-plane-in-air cyclotrons, but never-the-less clearly evidences the general feasibility and reliability of the shorts-in-vacuum approach.)

The Tritron accelerator at Munich undertakes to make a bold step forward in accelerating structures, namely, to use a system based on superconducting cavities to provide very high voltages across the accelerating gaps. Six of these cavities for example give an energy gain per turn of of about 4MeV/charge, and the cavities constructed for the Tritron have moreover proved to be quite rugged and reliable[14]. (Project delays have been dominately due to details of the magnet excitation and beam diagnostic systems.)

An interesting thought exercise is to consider whether Tritron style cavities could be utilized in conjunction with a more conventional cyclotron magnet such as for example the PSI main ring magnets. A major difficulty with this concept is the need to shield the cavities from the external magnetic fields of the sector magnets (which would quench the high Q of the superconducting rf mode). Combining superconducting cavities with conventional, rather than SOC type, sector magnets may well then be a direction for major future progress in cyclotron design, although clearly one where quite difficult problems will need to be addressed.

2.3 Extraction System

Extracting the beam from the "Unconventional" cyclotrons is trivial and not required for the cancer therapy cyclotron. Extraction is difficult for the remaining Table I cyclotrons because the extraction process in a cyclotron is almost always based on using a strong electric field (the "deflector") to partially offset the effect of the magnetic field; superconductors have greatly increased achievable magnetic field strengths (by a factor of at least 2.5), but no phenomena has yet been developed to comparably increase the strength of electric fields. Design of the extraction system for a high B, high Q/A cyclotron is then not inaptly characterized as a desperate battle in which the designer must use every available gain factor in order to achieve a workable system. Deflector fields of 100 to 150 kV/cm are usually needed and these are often the most limiting factor in the performance reliability of the complete accelerator. Programs aimed at improving performance of electrostatic deflectors are in process at several laboratories, with the depth of effort and overall accomplishments being particularly impressive at Chalk River[15].

In the higher energy cyclotrons the electrostatic deflector(s) fall well short of providing the incremental radius change needed to break the beam free of the cyclotron and magnetic channels are used to complete the extraction process. Magnetic elements are usually much stronger in bending power than the electrostatic deflectors and can also provide focussing forces to offset the undesirable effects which occur as the beam traverses the edge field of the magnet. The cyclotrons at MSU, Texas A&M and Catania use small assemblies of inert iron bars as magnetic channels with the magneto-motive-force for the bars coming from the main cyclotron field, (the magnetic channel assemblies being located in regions where the cyclotron field is still quite strong). The cyclotrons at Chalk River and at Groningen in contrast use active electro-magnetic channels (plus two inert iron bar assemblies at Chalk River); separate windings in the active channels allow the strengths of the focussing and bending field components to be separately selected giving considerably more ability to optimize the beam configuration as it passes along the extraction orbit. Agor in fact uses two such channels, one with room temperature coils and one superconducting. The room temperature channel operates at quite high power densities so that the electrical power required is a significant component of the total cyclotron power budget. Part of the coil configuration is arranged to reduce the effect of the electro-magnetic channel on the cyclotron internal beam (computations, including the iron with an estimated residual permeability, show that the effect of the channel is very accurately cancelled in the internal beam region). In the case of inert iron channels, the internal beam region can be similarly shielded by adding appropriate iron extensions to the channel assembly; in the fully saturated limit, these extensions behave as very high density current loops, and can nicely offset the effect of the channel on the internal beam region just as if active coils were used. The simplicity of the inert iron channels also allows replicating the channels in every sector if desired, so that imperfection field components are accurately cancelled; this approach has been used extensively and quite successfully in the MSU/Milan group of cyclotrons. The main gain from an active channel is then the ability to independently change the strength of both dipole and quadrupole components to give desired optical characteristics. (External magnets can also do this at much lower cost than required for an active internal channel, but with added difficulty because the beam will have expanded and experienced substantial non-linearities in that process.)

3 Third Generation Cyclotrons

Defining a third generation cyclotron-of-tomorrow, as one entering the design phase today, we first of all note the general truth that every group of designer/builders is most effective when they operate close to their own previous experience, so that the cyclotron of tomorrow in a given lab will surely very appropriately have strong elements of the local cyclotron(s)-of-yesterday. And an optimized design for any cyclotron will be heavily impacted by the goals which it is intended to achieve, i.e. is it another heavy-ion research cyclotron but with better optimized, less costly features? is it for light and heavy ion research at higher E/A? is it for proton therapy or radiography? is it a neutron factory to provide supplemental neutrons for safer power reactors? etc. It is also clear that any speculation as to future developments will be heavily biased by the past experience of the person(s) making the speculation. Having stated these caveats, we proceed to speculate!

3.1 Superconducting Separated Sector Cyclotrons

We first of all recall that a major design demarkation line arises just above an E/A of 200 MeV due to the "stop-band" associated with the NuR=3/2 focusing resonance in a three sector cyclotron. This "3/2 stopband" makes the three sector radial focusing oscillation catastrophically unstable over a wide range of energies and four or more sectors must be used to go higher in energy. (This resonance is strictly a velocity effect associated with the relativistic mass increase of the ions and therefore occurs at about the same E/A irrespective of the specific Q/A of the beam i.e. for any particle from protons to Uranium; the energy at which the stopband starts can be increased/decreased to some degree by reducing/increasing the three sector component of the azimuthal variation of the magnetic field.)

Not too far above 200 MeV/A, axial focusing also becomes a very difficult problem in a high field cyclotron, since the flutter is at a saturation level which can only be increased by lowering the total field, i.e. making the cyclotron larger (and thereby incrementally giving up the important weight advantage of the superconducting approach), or of adding sector coils on the poles, or of changing from the compact magnet structure used in present superconducting cyclotrons to a separated sector design. The latter approach is intriguing, and seems clearly required in the 500 MeV/A energy range. A sector magnet design, of course immediately implies an increased orbit length so that the weight advantage of high field, superconducting systems is weakened relative to the compact magnet systems, although raising the field by 50 to 75 per cent (cutting the orbit length by 1/3 to 3/7) will cut the flux by the same factor (1/3 to 3/7), and give an important, but not dominating, decrease in magnet weight.

Initial attempts at constructing a prototype sector magnet at two laboratories[16,17] have demonstrated the greatly increased difficulty of high field coils with non-circular geometry, and were overall rather discouraging. More recently, promising new sector coil arrangements have been suggested by Marti[18] and by Jungwirth[19], and a major new project at Riken[20] plans to use high-field superconducting sector magnets.

The event we of course all clearly want to see is an actual example of a working, superconducting, separated-sector cyclotron running at fields well above the levels achieved in room temperature magnets. This would greatly clarify both the difficulties and the advantages of high-field, separated-sector cyclotrons and would give a real basis for speculations as to the future role of this type of cyclotron – may such a project be in operation at the time of our next conference!

3.2 Third Generation Compact Superconducting Cyclotron

In this subsection we consider the probable design features of an optimized variable-energy, multi-particle cyclotron with energy in either the same range as the existing superconducting nuclear physics cyclotrons, or somewhat higher, up to perhaps 350 MeV/A, but below the relativistic range discussed in the previous subsection. It first of all, seems clear that a compact cyclotron could still achieve adequate axial focusing at 350 MeV/A without recourse to sector coils and without changing to a significantly lower magnetic field by using a smaller magnet gap and a tighter spiral than used in the MSU K1200. A four sector magnet seems the likely optimum choice, to avoid the 3/2 stopband while still providing net axial focusing at field strengths in the 5 Tesla range. Four sectors also offers the simplicity of a one amplifier rf system as at Chalk River (but almost certainly with the modification discussed in the rf subsection, to eliminate asymmetric dee stems and to provide the ability to operate from a central source or axial injection system). A four sector magnet, as is well known, has some difficulty with weak axial focusing near the center of the cyclotron – careful studies would be needed to see how effectively this difficulty could be offset by careful magnet design taking advantage of both electric focusing and magnetic field-fall-off focusing in the region preceeding the onset of adequately strong four-sector field components. It is of course likely that a large new cyclotron would use an injector cyclotron as in the MSU CCP project[8] in order to achieve high intensity and the injector cyclotron in such a coupled system could easily be a three sector cyclotron with good central focusing. Clark[21] has suggested a cyclotron with four sectors in the central region but transitioning to eight sectors away from the center where the flutter is adequate – three sectors transitioning to six would be another option, although this last would give up the one amplifier advantage of a four sector design. Summarizing, many options clearly exist for providing good low energy focusing in such a cyclotron system.

Another issue to assess relative to likely future directions for superconducting cyclotrons is the degree to which higher magnetic fields (in the 8 to 10 Tesla range) will be helpful and cost effective. Magnet weight will be

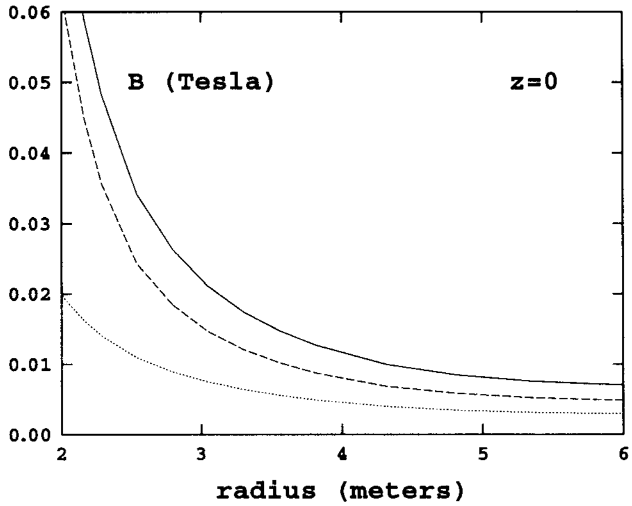

Figure 2: Poisson computations of median plane fringe fields for 1) the ' MSU K500 cyclotron as it now exists (the solid curve), 2) the K500 with an additional 10 cm layer of steel added on top, bottom, and outer periphery of the magnet (the dashed curve), and 3) with the further step of filling the coil support holes in the median plane and on the top and bottom of the cyclotron with iron (the dotted curve).

further decreased as field levels are increased, but the size of the cyclotron will also decrease, perhaps beyond the point of being helpful; power densities will increase in many components and the general crowding which is often classed as the major design problem of superconducting cyclotrons, will be even more severe. The clearest need for higher fields is in the specialized situation of very heavy ions – Uranium at 100 MeV/A for example. An 8 Tesla magnet with 1 meter radius would have a bending K of 3100 MeV and would give 100 MeV/A for uranium ions in charge state 43, which compares with the need stated in the MSU CSC proposal to have charge state 74 in order to reach 90 MeV/A in the K1200 cyclotron. To confirm the feasibility of 8 Tesla fields in cyclotron type structures, a small K85 magnet has been constructed and operated in a thesis project at MSU[22] – the coil uses conventional NbTi conductor in a potted, intrinsically stable winding cooled to 4.5K – performance of this magnet is in good agreement with design expectations – in a follow on thesis project, one of the authors (JS) has the goal of making this magnet into an operating cyclotron.

A more mundane question concerns the detail of how much steel to use in a high field cyclotron magnet. More steel, as in the AGOR design, reduces the external magnetic field produced by the cyclotron but with increased cost, and decreasing cost effectiveness of incremental additional yoke thickness. Figure 2 for example shows a recent study of the effect of adding an additional 10 centimeter layer of steel to the full exterior (top, bottom, and circumference) of the MSU K500. Such a change, with steel pricing of today, would cost in the vicinity of 30,000 US$. The 10 cm layer reduces the fringe field by a significant factor (20%), but whether this represents a good cost trade off in a future cyclotron project is a delicate design judgement which would need to take account of many aspects of the site of the prospective cyclotron and of its fiscal situation. The third curve in Figure 2 shows the effect of closing the holes in the K500 yoke that provide space for coil supports and other cryostat utilities; an improvement approximately equal to that produced by adding the 10 cm layer of steel is achieved; such a change is certainly feasible through redesign of the coil support system and would be less costly initially than thickening the yoke but with some increase in refrigerator load which would need to be evaluated. Another approach to fringe field reduction is to use active coils on the periphery of the yoke as in the OSCAR cyclotrons – such coils can largely eliminate external fields, but added cryostat expense for a large cyclotron would undoubtedly amount to a greater cost than adding additional iron. Also operating with steel at 4K as in OSCAR would give severe stress problems in large systems and long cool-down times.

Another interesting aspect of the Agor design is the use of an unusually tall coil distribution in order to provide a better main coil match to the shape of the isochronous fields, thereby reducing power consumption in the room temperature trim coil system, but at the cost of considerably enhanced Fe volume since each centimeter of coil height involves the extension of both the pole base and the outer yoke. Figure 3 shows air core fields for the Agor coil distribution and for the K500 coils. The field of the outer Agor coil falls with radius so that a nearly flat field results when it is summed with the inner coil with both at full current as shown in Figure 3. In contrast when the sum is made for the K500 coils, the resulting field rises by approximately 3%, but this is in fact also well optimized[23] since the contribution from the magnet steel falls with radius. To further clarify this point, an extensive comparison study would be needed involving fitting of the many operating points and with the actual distribution of magnet steel included since the iron field is also very important in determining total trim coil power[24]. (Such comparisons to the author's knowledge have not been made.)

Another important variable in lowering trim coil power is to allow the current in the outer coil to reverse for some operating points. This leads to a different stress distribution in the coil, but one which is not difficult to handle if reverse current operation is included as an aspect of the original coil design (the MSU K1200 coils were designed for reverse currents and have operated in this mode without problems for many years.) If reverse

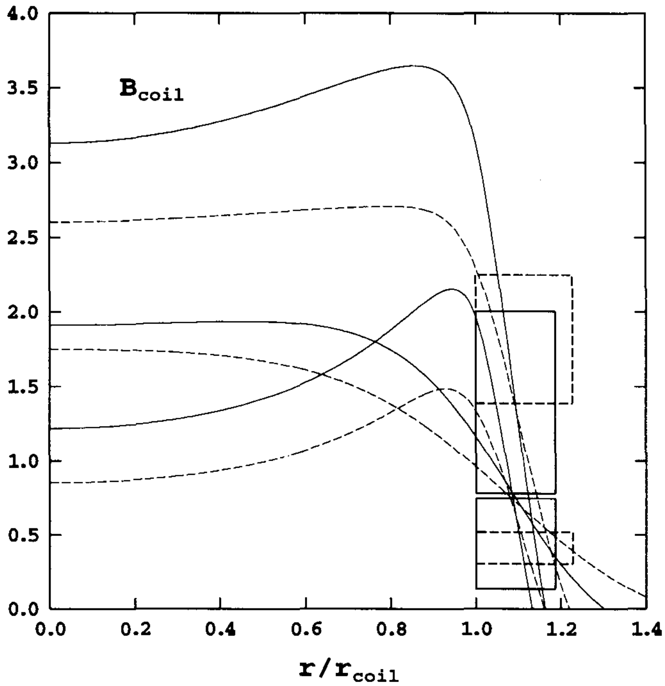

Figure 3: Air-core calculations of the magnetic field of the main coils of the Agor cyclotron (dashed lines) and of the MSU K500 (solid lines). The three curves are in each case for the individual coil and for their sum, with current in all cases at peak design vlaues. Dashed and solid boxes show the physical shape of the coils.

currents are allowed, the need for the tall AGOR coil structure disappears, and magnet weight is substantially reduced. Another step in the direction of reducing trim coil power is to divide the main coil into three independent windings; this involves the refrigeration cost of an additional set of coil leads and magnet maps would be needed over the three dimensional current grid, which would greatly expand the mapping effort, but the third independently adjustable current would clearly work in the direction of further lowering trim coil power and is an option which should be considered in designing a third generation superconducting cyclotron. The trim rod system at Chalk River, while cumbersome, is clearly the ultimate step in reducing trim coil power, and is in additiion compatible with very small magnet gaps.

Another important design question for a future variable-energy, multi-particle cyclotron is whether to reduce the hill gap by a substantial factor, following the design philosophy being employed by IBA in their 230 MeV proton therapy cyclotron project[25]. Benefits from reducing the hill gap to 1 or 2 cm include: a) making extraction much easier, b) increased flutter (stronger axial focusing), and c) higher energy from a given size coil and yoke system. As an example of the effect of such a change, Figures 4 and 5 show results from a preliminary brief study of the effect of reducing the magnet gap in the large radius region of the MSU K500 by a factor of 4 (from present 63.5 mm to 15.9 mm). With no change in the coil or the maximum coil currents (but with the 10 cm outer yoke extension of Figure 2 included in the calculation), the bending K increases to 560 MeV and the focusing K to 240 MeV. Figure 4 shows equilibrium orbit characteristics for the 200 MeV proton operating point; the orbital frequency and the radial focusing frequency are both well behaved, and the axial frequency is higher than needed, which could easily be corrected with an adjustment of the spiral angle (the dip to a negative NuZ value near extraction is due to the 3/2 stopband rather than to defocussing). With the reduced gap, extraction is very much easier as shown in Figure 5; a single 125 kV/cm deflector mounted inside the dee plus 5 inert magnetic channels extract the beam in a flight path of about 180 degrees, vs. two 133 kV/cm deflectors, 8 magnetic channels and 320 degrees for the present K500 magnet operating at the focusing limit.

3.3 Superconducting Separated Orbit Cyclotron

A final very difficult question as to the likely further evolution of superconducting cyclotrons is to envisage the future role of Tritron type systems. The small group of highly skilled and dedicated workers at Munich has taken many years to bring their first device to the commissioning stage and probably will need more years before the prototype reaches a level of reliability adequate for a reasonable nuclear physics program. Beyond that a much larger major working device is clearly needed in order to fully establish that a rugged and reliable technology has really been achieved. Funding for such a project in today's climate of fiscal restraint will be difficult to obtain, but the group at Munich is accustomed to overcoming difficult challenges and their prospects for overcoming the financial obstacles of a follow-on project should certainly not be discounted.

U. Trinks also foresees[14] an alternate major application of superconducting separated orbit cyclotrons, namely to provide very intense (10ma) beams at an energy of perhaps 1 GeV for producing supplemental neutrons to make safer nuclear power reactors. Trinks' arguments in these papers are reasonable in the aspect of a rational solution being available for each known problem, but there is also a significant weakness, or time mismatch, relative to the status of the competing solution, namely a large room temperature separated sector cyclotron based on the PSI technology. In particular, the PSI accelerator system has many years of solid performance at a point of parameter space very much closer to the expected requirements of a power reactor neutron

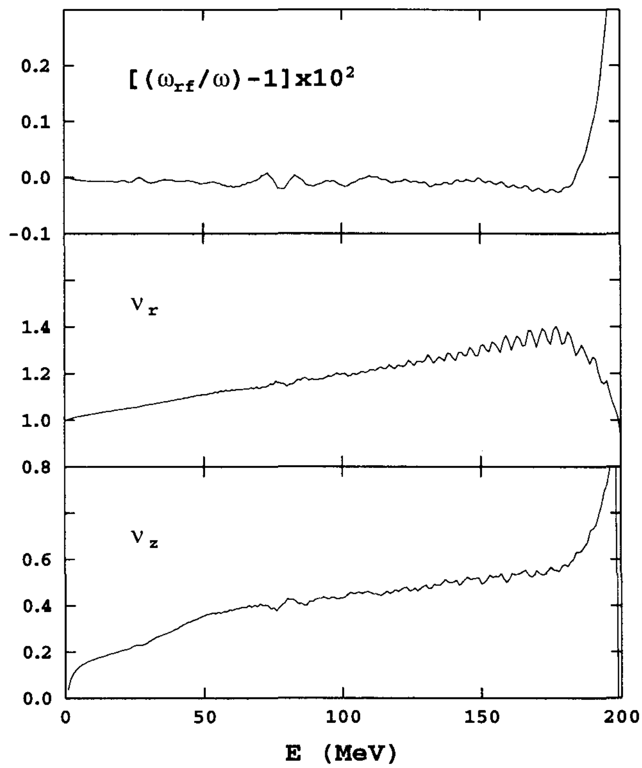

Figure 4: Orbital frequency and transverse oscillation frequencies for the 200 MeV proton operating point of an MSU K500 in which the magnet gap is reduced to 16mm near the magnet edge and the yoke has an additional 10 cm layer of steel (as in the dashed curve of Figure 2).

source, and with a very much larger group working on the concept. The missing element of a Tritron based technical solution is in the lack of years of operating experience and the great number of novel components which must all perform satisfactorily at the same time in order for the system to function as an effective industrial accelerator. To be competitive, the Tritron needs to catch up with the PSI style system and that will only happen if a very much larger group is funded to work on the problem which seems unlikely in the present fiscal climate.[b]

3.4 High Intensity Coupled Cyclotrons

The MSU Coupled Cyclotron Project (CCP)[8] is seemingly, as noted above, at the transition point from a future project to a present project, but at least a brief discussion of the project seems appropriate as a final item of this review. The primary goal of this project involves reactivating the original 1976 facility concept namely to operate the K500 and the K1200 as a coupled system with the K500 injecting into the K1200. This original plan was dropped in the mid 1980's because progress in ECR ion sources made it feasible to meet the beam goals of the nuclear physics program as then perceived, with an ECR injected K1200 operating in a stand-alone mode (the cost and reliability advantages of a one cyclotron system vs two being the attractive advantage in this judgement). More recently the nuclear physics program has evolved in the direction of radioactive beam physics, and the need for very intense beams in the particle-microamp range has become a major facility priority. Reactivating the original coupling plan, offers a quick and highly cost-effective way to meet this goal. The intensity gain from coupling follows from the natural intensity profile of the ECR's, namely, an intensity peak at low to medium charge falling off strongly as the charge increases to the fully stripped value. Thus 200 MeV/A Oxygen beam in the stand-alone mode requires a fully stripped 8+ ion from the source. In the coupled mode a 3+ ion with 500 times the intensity from the ECR is injected into the K500, accelerated to full radius, extracted and reinjected into the K1200 with a stripping foil to change the charge to 8+; some losses occur at each step of this process but a final intensity gain in the vicinity of 100 fold is typical for most ions. The coupling plan is also revised relative

[b]The Tritron group, noting a widely quoted 1972 assertion by the first author of the present paper as to the unlikely benefit of superconductivity to cyclotrons, are undoubtedly quite pleased by the unenthusiastic forecast given here, which on the basis of historical precedent can only be viewed as strong evidence for the likelihood of the opposite.

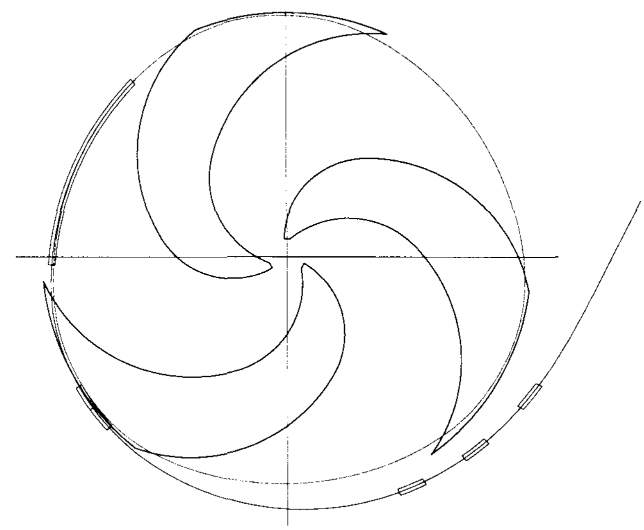

Figure 5: Extraction orbit of the modified MSU K500 at the 200 MeV proton operating point. The electrostatic deflector inside the dee at the upper right operates at 125 kv/cm and five magnetic channels of 6 degree length with a gradient of 32.7 T/m and 0.13 T dipole field i.e. the same values as present K500 magnetic channels.

to the original plan in a number of ways (2 to 1 harmonic ratio vs. 3 to 1 in the earlier plan which was based on a PIG source, a straight coupling line with a buncher vs an isochronous line, etc.) as is discussed elsewhere[8]. Assuming the funding profile is as presently anticipated, operation of the CCP facility for nuclear physics should start in the second quarter of the year 2000.

Acknowledgments

Work supported by US National Science Foundation Grant # PHY92-14992.

References

1. H. Blosser, D. Johnson, R. Burleigh, R. Niemann, and J. Purcell in *Proc. Seventh Int. Conf. on Cyclotrons and Their Applications*, (Zurich 1975), p.584.
2. M. Mallory, IEEE Trans. on Nuc. Sci. NS-30(1983)2061
3. H. Schmeing, B. Bigham, N. Bray, W. Davies, B. Greiner, C. Hoffmann, J. Hulbert, P. Hurley, H. Lindqvist, J. McGregor, R. Milks, G. Mitchel, J. Mouris, J. Ormrod, L. Shankland, E. Stock, L. Thomson, R. Tremblay, and X. Zhou, *Proc. Twelfth Int. Conf. on Cyclotrons and Their Applications* (Berlin 1989), p. 89.
4. P. Miller T. Antaya, F. Marti, D. Poe, B. Sherrill, J. Stetson, J. Winger, and J. Nolen, *Proc. Thirteenth Int. Conf. on Cyclotrons and Their Applications* (Vancouver 1992), p. 86.
5. D. May, R. Rogers, P. Smelser, and D. Youngblood, *Proc. Twelfth Int. Conf. on Cyclotrons and Their Applications* (Berlin 1989), p. 1.
6. F. Alessandria, G. Bellomo, A. Bosotti, C. DeMartinis, D. Giove, P. Michelato, C. Pagani, L. Rossi, L. Calabretta, G. Ciavola, G. Cuttone, M. DiGiacomo, S. Gammino, P. Gmaj, G. Raia, D. Rifuggiato, and J. Sura, *Proc. Thirteenth Int. Conf. on Cyclotrons and Their Applications* (Vancouver 1992), p. 90.
7. H. Schreuder, *Proc. Thirteenth Int. Conf. on Cyclotrons and Their Applications* (Vancouver 1992), p. 40.
8. The K500⊗K1200-A Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory, July 1994, Michigan State University, East Lansing, Michigan, MSUCL-939.
9. R. Burleigh, D. Clark, and L. Glasgow *Proc. Seventh Int. Conf. on Cyclotrons and Their Applications* (Zurich 1975), p. 604.
10. H. Schreuder, *Proc. 1995 Particle Accelerator Conference* (Dallas 1995), (in press).
11. H. Blosser and F. Resmini, Trans. on Nuc. Sci NS-26(1979)3653.
12. H. Blosser, C. Gelbke, D. Lawton, F. Marti, J. Vincent, R. York, and A. Zeller - Mich. State Univ. Internal Report MSUCL-874(1993).
13. W. Johnson - Proc. International Conf. on Sector-Focused Cyclotrons and Meson Factories, Report CERN 63-19(1963)p.279.
14. U. Trinks - The Superconducting Separated Orbit Cyclotron Tritron - *Proc. Fourteenth Int. Conf. on Cyclotrons and Their Applications* (Capetown 1995), (in press).
15. W. Diamond, C. Hoffman, G. Mitchel, and H. Schmeing, *Proc. Thirteenth Int. Conf. on Cyclotrons and Their Applications* (Vancouver 1992), p. 569.
16. U. Trinks, H. Daniel, G. Graw, G. Hinderer, E. Huenges, P. Kienle, H. Korner, H. Morinaga, F. Nolden, E. Nolte, H. Scheerer, U. Schneider, W. Schott, S. Skorka, W. Wilhelm, H. Willers, E. Zech, Proc. 1983 Particle Accelerator Conference p. 2108.
17. R. Oganessian, JINR, Dubna (private communication).
18. F. Marti, Proc. 1994 European Particle Accelerator Conf. p. 2304.
19. H. Jungwirth and J. de Villiers, *Proc. Thirteenth Int. Conf. on Cyclotrons and Their Applications* (Vancouver 1992), p. 709.
20. Y. Yano, A. Goto, T. Katayama, and RIBF Group - The RIKEN RI Beam Factory Project - *Proc. Fourteenth Int. Conf. on Cyclotrons and Their Applications* (Capetown 1995), (in press).
21. D. Clark, Proc. 1993 Particle Accelerator Conf. p. 1724.
22. J. Kim, An Eight Tesla Superconducting Magnet for Cyclotron Studies - PhD Thesis(1994)Michigan State University.
23. G. Bellomo and F. Resmini, MSU Internal Report MSUCP-31 "Trimming of the Magnetic Field for the K-500 Cyclotron at MSU(1980).
24. G. Bellomo and F. Resmini. Trans on Nuc. Sci. NS-26(1979)2095.
25. Y. Jongen, A. Laisne, W. Beeckman, J. Dufour, H. Marie, R. Verbruggen, N. Takahashi, S. Satoh, M. Sano, and T. Takayama, *Proc. Thirteenth Int. Conf. on Cyclotrons and Their Applications* (Vancouver 1992), p. 244.