A NEW GENERATION OF HEAVY ION FACILITIES

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Introduction

We have observed during this present decade the emergence of heavy ion science from an embryonic stage, pursued at a few outposts, to a field of major significance commanding its own sections in scientific journals, its own sessions in scientific meetings, a large fraction of the research effort performed at accelerators, and now a significant commitment of money and manpower resources by many countries throughout the world.

From a science with beginnings largely in adaptations of existing light ion accelerators--notably the advent of high power Penning sources for cyclotrons, heavy ion negative sources for electrostatic machines, and the remarkable linking of the bevatron to the HILAC--we have now reached the start of a generation of accelerators designed specifically for heavy ion production.

To be sure, there were pioneers that preceded this decade; - the Oak Ridge nitrogen cyclotron in the late 1950's and the HILACS at Yale and Berkeley, and the heavy ion cyclotrons at Dubna and Orsay in the 1960's. But the modern age of dedicated major heavy ion accelerator facilities starts with the present decade. The cut through accelerator performance space that is most frequently used to describe heavy ion facilities is shown in Fig. 1. The portion of this space adjacent to the ordinate has been intensively investigated through many orders of magnitude beyond the energies shown here. Only recently have we begun to push out along the abscissa into the realm of macroscopic phenomena.

Fig. 1. Ion energy capabilities for major heavy ion facilities operating (solid lines), under construction (dashed lines) and proposed (dotted lines).

The region of nuclear studies begins at roughly 5 MeV/nucleon where we have particle energies sufficient to overcome the classical coulomb barrier. The region up to 30 MeV/nucleon will provide new opportunities to study the behavior of large nuclear systems under the stresses induced by these heavy ion collisions. This is also a region of ion energies where interesting new atomic systems can be produced for study. Above 30 MeV/nucleon we enter a domain where totally new phenomena may unfold. Collision velocity here will exceed the theoretical velocity of sound in nuclear matter and we may no longer treat nuclear matter as an incompressible fluid obeying Fermi statistics. A region where the exclusion principle may be violated in bulk material will be an exciting area for future research.

This paper will not review the existing facilities. The most elegant example of those now operational (perhaps the most elegant for some time to come) is the UNILAC facility at GSI in Darmstadt. A report on this facility appears later in these proceedings.

This report will center on the status of major heavy ion accelerator projects that are funded and under construction and a few still in the proposal state. This is a look, then, at those new facilities that we can expect to become operational between now and the mid-1980's that will push us towards these regions of possible new scientific phenomena. What are the major directions being pursued by this next generation of machines and what new features are being introduced?

The "Super-Tandems"

One of these directions is that of the "super-tandems," tandem electrostatic accelerators designed to operate at terminal potentials of 20 MV and above. (Recall that the present generation of large tandems, produced by HVEC and NEC are operating at upper voltages in the range of 12 to 14 MV.) In England, at Daresbury, a large tandem is now under construction designed to operate initially at 20 MV on terminal with later upgrading designed to reach 30 MV. In the U.S., at Oak Ridge, a large tandem is under construction designed to operate at 25 MV on terminal.

A cutaway drawing of the Daresbury tandem is shown in Fig. 2. This machine has a conventional configuration in that low energy negative ions enter at one end, in this case the top, and the accelerated ions exit the other. Slightly less conventional is the use of an inner potential shield. To give you a perspective of the physical size of the machine, the pressure vessel is 45 m high and 8.2 m in diameter. The column structure is about 2.5 m in diameter. This size column and pressure vessel yield reasonable voltage gradients for operation at 20 MV. The intermediate shield will be required to obtain reasonable gradients at 30 MV. This figure also illustrates some of the additional complexity introduced to these traditionally "simple" accelerators by the increased size and design considerations for accelerating heavy ions. We see more pumping of the acceleration tubes within the machine, more active beam optics elements

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Fig. 2. Cutaway view of Daresbury accelerator.

within the column, and complex terminal equipment for diagnostics and charge state selection.

The structure of the column is illustrated in Fig. 3. Inside the equipotential rings we see a structure of bulkhead plates separated by eight insulating posts. This figure also illustrates the "ladder-tron" charging chain developed by the Daresbury group.

This project was begun in 1974 and should become operational in early 1980. The status of building construction in December 1976 is shown in Fig. 4. The start of forming for the walls of the ion source room can be seen. The pressure vessel has been fabricated and is in place inside the tower.

The Oak Ridge machine is being constructed by National Electrostatics Corporation. A schematic view of this machine is shown in Fig. 5. Here a major departure has been made from the traditional tandem configuration. The machine will be a "folded" tandem with both the low and high energy accelerating tubes contained within the same column. Although originally suggested many years ago by Alvarez, in practice this configuration only becomes practicable when the accelerator is large. Above 20 MV, the column structure is large enough from electrostatic considerations, to accommodate the distance between the two tubes dictated

Fig. 3. Detail of Daresbury column.

Fig. 4. View of Daresbury facility construction.

by practical considerations of the 180-degree magnet in the high-voltage terminal. The column of the Oak Ridge machine is 3.3 meters in diameter. The pressure vessel is 30 meters high and 10 meters in diameter. There are no plans for an intermediate potential shield for this machine.

Some advantages to folding are the ability to locate the ion source in a more easily accessible location, reduction from two column structures to one, reduction in stored energy, reduced tank size, and reduced volume of insulating gas. Both this and the Daresbury accelerators will operate with SF_6 as the insulating gas. The amount required to operate the Oak Ridge machine at 7 atmospheres will be about 230,000 pounds.

As with the Daresbury machine there are a significant number of vacuum elements, beam optics elements, and diagnostic devices located inside the accelerator. Both machines will have a control system based on digital computers. This too is a break with the tradition of these machines and it will be interesting to follow this development of placing sophisticated electronic packages in the hostile environment of the large high voltage transients developed in these accelerators.

Fig. 5. Schematic view of Oak Ridge accelerator.

Fig. 6. Lower part of column structure for the 25 MV Pelletron accelerator.

A view of the column structure of the Oak Ridge machine is shown in Fig. 6. The column is approximately 70% assembled at the NEC plant. The column structure is the standard modular form pioneered by NEC. Bulkhead plates spaced at 2 ft intervals by 12 insulating posts separate each 1-MV section. Charging will be by means of NEC's "Pelletron" chain system and potential grading will be accomplished by means of closed corona tubes. Potential grading of the Daresbury machine will be done with fixed resistors. Most servicing of the accelerators will be by means of a lift inside the column structure.

Besides the two super-tandems I have discussed, a 20 MV folded tandem being constructed by NEC will be installed at the JAERI laboratory in Tokai, Japan. This machine is scheduled to become operational in 1979. An 18 MV linear tandem (the XTU) will be delivered by HVEC to the Legnaro Laboratory in Padua, Italy, and a 20 MV machine has been funded for Buenos Aires, Argentina. The vendor for this later machine, and whether it will be linear or folded, has not yet been decided.

At Oak Ridge, besides the construction of the 25 MV tandem, we are also modifying our existing cyclotron, ORIC, to serve as an energy booster. Figure 7 shows a profile section of the building and the relationship of the two accelerators. When operating in the coupled mode the tandem beam enters the ORIC through the back of the rf resonator, is bent by an inflection magnet so that the fringing field will bring the trajectory tangent to an acceleration orbit, and passed through a stripping foil located at the point of tangency. The resultant charge change on the ion provides the mechanism for capturing the ion into orbit.

Fig. 7. Profile section of the Oak Ridge facility.

Since some of the inflection loci require paths outside our existing dee structure, we have built a new dee and trimmer assembly which will accommodate these paths. At the first of this year, ORIC was shut down to install the new dee and trimmers and the supports for the inflection magnet. We expect to be operating with the new dee in about a month.

The tower is now to the level of the base of the pressure vessel. The building, including the pressure vessel should be completed in early 1978. Installation of the tandem is scheduled to take a year so that full operation of Phase I is expected in late 1979.

Phase II and GANIL

At Oak Ridge we have continued to plan for extending the available range of ion energies. The Phase II performance shown in Fig. 1 is based on our proposal to add a K=400 separated sector cyclotron booster. Of the various options available, we continue to favor this concept. This machine is described in more detail elsewhere in these proceedings.² I would like to mention here an interesting design refinement made during the course of our recent model studies. The 0.15 scale model magnet is shown in Fig. 8. In order to minimize the trim coil power, we decided to pre-shape the magnetic field to have the appropriate contour to compensate for half the mass increase of the most relativistic ions (in this case 100 MeV/nucleon). The trim coils need then to only add or subtract field as needed from this base. This shaping was accomplished by means of a contoured slot in the pole tip. This correction can be seen in the exposed pole of the model. This contour slot provides a field isochronous for 50 MeV/nucleon final energy with no degradation in the orbit properties.

Fig. 8. View of the Phase II SSC model magnet.

The model studies at Oak Ridge have benefited from the participation of staff members from project GANIL. This accelerator facility to be located at Caen, France, is now funded and in the early stages of construction. This facility is based on a double cyclotron concept employing two K=400 separated sector machines. A recent plan view of the GANIL facility is shown in Fig. 9. Although not final, this layout illustrates the two cyclotron feature with the associated injectors and experiment areas. The projected performance is shown in Fig. 1. The schedule calls for the GANIL facility to become operational in 1981. It should be noted that, at the present time, GANIL is the only facility funded that has performance capabilities in the 100 MeV/nucleon class. If funded in 1979, the Oak Ridge Phase II will become operational in 1983.

A related facility to these is the VICKSI project at Hahn-Meitner Institute in Berlin. This facility is sort of a "mini" Phase II with a 6 MV single ended electrostatic accelerator injecting a K=120 separated sector cyclotron. This facility is just coming on line and is described elsewhere.³

Fig. 9. Plan view of the GANIL facility.

The Super-Conducting Cyclotrons

Another example of combining a tandem accelerator with a cyclotron is the project at Chalk River. Here, a superconducting cyclotron with an energy constant of 500 will be constructed to serve as an energy booster for their existing 13 MV MP tandem. The proposed layout is shown in Fig. 10. An interesting sidelight is that this configuration requires reversing the direction of the MP accelerator from the present setup.

Fig. 10. The CRNL Tandem/Super-conducting Cyclotron Facility.

The major innovation here is the superconducting cyclotron. This novel concept is being developed in parallel here and at the Cyclotron Laboratory of Michigan State University. More recently a third program is under way at the University of Milan. The essential idea in these machines is to combine the high field technology developed for superconducting coils, for bubble chambers, with the existing technology of isochronous cyclotrons. The actual superconducting elements are the main field coils with the remainder of the accelerator at room temperature. A cutaway view of the MSU magnet is shown in Fig. 11. The obvious result of using the high field generated by these coils is a reduction in physical size. Average

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Fig. 11. Schematic view of the MSU magnet yoke.

mean fields in excess of 40 kG are more than twice those obtained in conventional room temperature cyclotrons so that, for the same energy, the superconducting cyclotron is about half as large, promising savings both in construction and operating costs.

All three groups are funded resently for prototype magnet studies, the Chalk River and MSU prototypes being full size. The coil designs bear strong similarities. All have the superconducting main coil divided into two sections so that by shifting current between these windings the first order field shape required for a particular mass and energy of ion may be obtained.

The Chalk River machine will be four sectors, whereas the MSU machine employs three sectors to obtain a higher focusing limit. A picture of the MSU magnet is shown in Fig. 12. A view of the coil is shown in Fig. 13.

Fig. 12. View of the MSU magnet yoke and cryostat.

The final field shaping for the MSU design will be done with conventional room temperature trimming coils. A novel approach employed in the Chalk River design is the use of trim rods (Fig. 14). These rods are extracted into the pole tip to produce the required average field contours. Another important difference

Fig. 13. View of completed MSU main coil before closing of helium vessel.

in these two designs is that the Chalk River machine is intended only as a booster accelerator with no provision for an internal ion source. The Michigan State machine will from the start be designed for an internal source, but the cryostat is designed for conversion to accommodate injected beams if this becomes desirable. A design constraint here, of course, is to minimize the number and size of penetrations through the cryostat. Both designs use an accelerating electrode in each valley to obtain a maximum energy gain per turn. This high gain minimizes the path traveled by the accelerated ions and is needed to produce adequate turn separation for extraction. Both machines plan extraction systems based on electrostatic deflectors followed by magnetic elements.

Fig. 14. Schematic of the CRNL trim rod design.

Both of the full-scale magnets should become operational this year. First operation of the MSU magnet is projected for this spring with the Chalk River magnet scheduled for late fall. Both laboratories have proposed to follow magnet testing as quickly as possible with completion of an operating accelerator. Assuming no funding delay, the Chalk River facility would be ready to deliver beam in 1980. More details of the Chalk River accelerator will be discussed in later papers.^{4,5}

A proposal has been made by the University of Rochester to use the MSU machine as a booster for the NSRL MP tandem. This would provide a facility very similar to the Chalk River installation.

The Michigan State group estimates that they could achieve beam from their K=540 super-conducting cyclotron by late 1978. They have proposed that such

a machine be used as an injector for a K=800 superconducting cyclotron booster. The combination of these two machines yields the performance projected in Fig. 1. The potential savings made possible by the high fields of the superconducting main coils can be illustrated by noting a comparison between the proposed K=800 MSU design and the K=725 room-temperature cyclotron now under construction at Dubna. The pole diameter of the superconducting machine is 2 meters, half that of the Dubna cyclotron. The resultant savings on steel are large. The yoke weight for the superconducting cyclotron is estimated at 275 tons compared with 1770 tons for its room temperature counterpart.

Certainly the superconducting machines hold much interest for the future. How much this concept will impact the next generation of facilities should be more apparent within the next year with the completion of the prototype magnet studies.

Summary

One area that was not touched on here that is highly relevant to energy boosting of tandem accelerators is that of super-conducting linacs. Although there are not yet major facility proposals based on this technique, a number of laboratories are actively pursuing development studies. A review paper⁶ appears in these proceedings as well as several contributions in the session on linear accelerators.

Also not discussed was the Bevalac improvement which should provide beams in the upper portion of the region shown in Fig. 1 but with two to three orders of magnitude less intensity than the facilities that have been discussed. Even so, this will be an important member of our heavy ion accelerator arsenal for the next decade.

I have tried to summarize the major heavy ion facilities that we should look for through the first of the next decade. I want to end by returning briefly to the subject of the super-tandems. There is an interesting esthetic by-product to these large electrostatic machines. For years we have built horizontal accelerators, often in rather non-descript flat buildings - even tunnels and trenches. But for structural reasons the large tandems are vertical machines and now we have the opportunity to build towers - structures that have always captured mans imagination.

Fig. 15. Artists conception of the heavy ion accelerator building at Oak Ridge.

Certainly we had a lot of discussion about the form of our tower for Oak Ridge. (Fig. 15) One early suggestion of an architectural style most compatible with our existing buildings is shown in Fig. 16. I would remind you that, in a certain sense, this could be called the first accelerator building of modern physics. It is somehow pleasing to be again building towers and to be aware that we approach these new

Fig. 16. The tower of Pisa.

regions of scientific exploration by pursuing new knowledge following the precepts of the scientific method born at this tower at Pisa nearly four centuries ago.

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