SYNCHROTRONS IN CYCLOTRON TERRITORY [*]

D. J. Clark and R. A. Gough
Lawrence Berkeley Laboratory
1 Cyclotron Road, Berkeley, CA 94720, U.S.A.

Summary

Synchrotrons and cyclotrons have an overlap in their particle and energy ranges. In proton radiotherapy, synchrotrons are proposed at 250 Mev, an energy usually served by cyclotrons. Heavy ion therapy has been synchrotron territory, but cyclotrons may be competitive. In nuclear science, heavy ion synchrotrons can be used in the cyclotron energy range of 10-200 Mev/u. Storage rings are planned to increase the flexibility of several cyclotrons. For atomic physics research, several storage rings are under construction for the energy range of 10 Mev/u and below.

Introduction

The advantages of synchrotrons over cyclotrons are their lower construction costs for high energy machines and their capability for fast energy or particle changes on a pulse-to-pulse basis. The disadvantages of synchrotrons are that they usually have considerably lower average currents, their duty factor is less than 100% and they are often more complex to build and operate. For some applications there has been considerable interest recently in the design and construction of synchrotrons and storage rings operating in energy ranges traditionally served by cyclotrons. Fig. 1 shows the particle and energy ranges required by several types of accelerator applications. In this figure "Cyclotron Territory" is defined by the performance of cyclotrons that are either operating or under construction.

Radiation Therapy

A workshop in ion therapy was held in January 1985[1]. In the field of light ion (proton and α-particle) radiation therapy, beams of 250 MeV/nucleon have enough range to penetrate 30 cm into the human body. Intensities of up to 10^{11} ions/sec are useful. Synchrocyclotrons have been used in this energy range for many years, including those at Uppsala, Berkeley, Harvard, Gatchina and Dubna for protons and the Berkeley machine for α-particles. Some of the new sector cyclotrons are using or planning to use proton therapy, including those at NIRS in Japan, the SIN injector, Lacassagne Center at Nice, and NAC in South Africa.

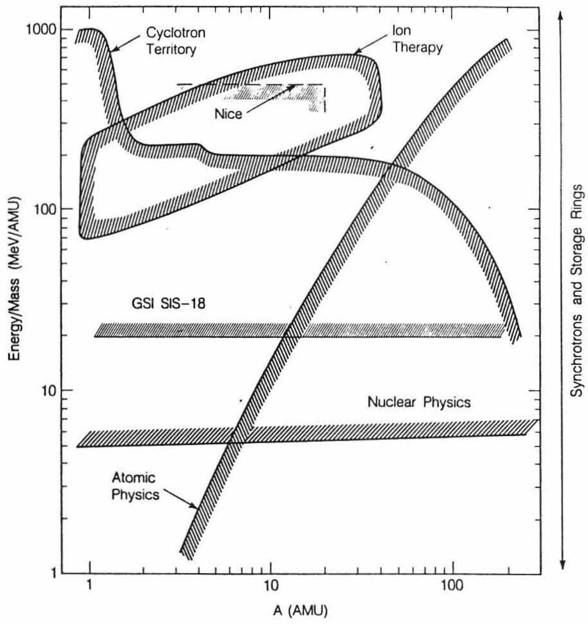

Fig. 1. Energy and mass ranges which are required for some accelerator applications, and which are available from synchrotrons and cyclotrons that are presently operating or under construction.

Recently synchrotrons have been proposed for this application. In some designs their magnets are room temperature, and in others they are superconducting. The ions are H^+ or H^- and injectors include pelletrons and RFQ linacs. Some of their characteristics are shown in Table 1. Recent interest has centered around the design of a 250 Mev proton machine as indicated by the first four entries in Table 1. A typical

---

[*] This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics and by Nuclear Sciences of the Basic Energy Sciences Program of the U.S. Department of Energy under Contract DE AC03-76SF00098.

Table 1. Synchrotrons for Ion Therapy

Group	Ion	Energy (Mev/u)	Ions/s	Injector	Status
Fermilab[3]	p	70-250	10^{11}	Pelletron /RFQ	Study
Brobeck[4]	p	70-250	10^{11}	RFQ	Study
Argonne[5]	p	2-250	10^{10-11}	Pelletron	Study
(H$^-$ accel. for easy extraction; α or p option)					
Harvard[6]	p	-250	10^{11}	RFQ	Study
Tsukuba[7]	p	-250	10^{11}	Linac	Oper.
(500 Mev beam degraded, KEK booster synchrotron)					
ITEP[7]	p	70-200		Linac	Oper.
(10 Gev synchrotron)					
Bevatron[8]	α-Ar	-700	10^{9}	Linac	Oper.
Bevatron Upgrade[8]	α-Ar	-700	10^{11}	Linac	Study
NIRS[9]	α-Ar	-600	10^{9-10}	Linac	Const.
LBL[10]	α-Ar	-800	10^{7-9}	Linac	Study

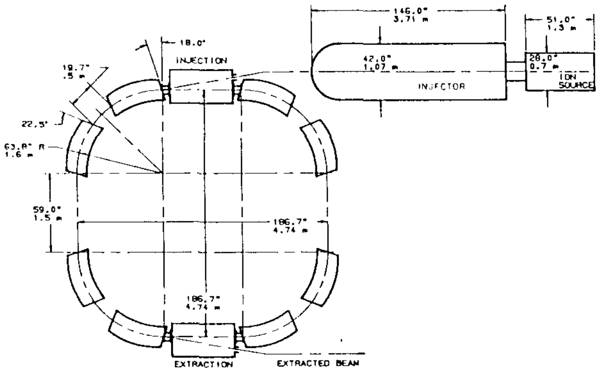

Fig. 2. A design of a 250 Mev proton therapy synchrotron by Fermilab for Loma Linda University[3].

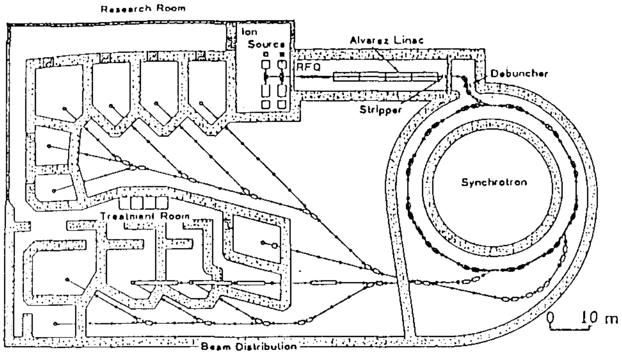

Fig. 3. The heavy ion therapy synchrotron being built by NIRS, Japan[9].

design is shown in Fig. 2. On the cyclotron front, Michigan State University has studied[2] a superconducting synchrocyclotron for this energy. It has a 2.4 m yoke outside diameter and uses a degrader for energy variation. This size is compact compared with the 5-14 m diameters of the proposed synchrotrons. At high energy synchrotrons at Tsukuba and ITEP, medium energy beams are used for radiotherapy programs. Also the use of injector linac proton beams for therapy has been considered at several high energy physics labs, including Fermilab and Argonne[12].

For radiotherapy with heavy ions (heavier than α-particles) several synchrotrons are operating or planned. The Bevatron at the Lawrence Berkeley Laboratory has an active therapy program with ions up to argon as indicated in Table 1; higher intensities would be available after a proposed conversion to strong focusing[8]. On the basis of the promising results obtained here a new dedicated heavy ion therapy synchrotron with beams up to 800 Mev/u argon has been proposed at Berkeley[10]. A dedicated heavy ion machine with energies up to 600 Mev/u argon has been approved for construction at the National Institute of Radiological Sciences in Chiba, Japan[9], Fig. 3. The energy range of these synchrotrons, 600-800 Mev/u heavy ions, has traditionally been the territory of synchrotrons, but several groups have considered the possibility of using superconducting cyclotrons here. The Michigan State group[2] has suggested a superconducting cyclotron accelerating neon to 340 Mev/u, extending the technology of the K800 machine. The group at the Lacassagne Center[11] at Nice, France is undertaking a study of a superconducting cyclotron for beams up to neon at 500 Mev/u, using the K=60 cyclotron as an injector. Thus cyclotrons may enter synchrotron territory in the heavy ion therapy field, as suggested in Fig. 1.

Heavy Ion Nuclear Science

In the field of nuclear science there are several operating or planned heavy ion synchrotrons whose energies span the range of 10-1000 Mev/u. This constitutes a large overlap with present or planned cyclotrons. Some typical machines are shown in Table 2. Some intensities are shown in the table for the cyclotron energy range for neon and uranium beams. The accelerator which pioneered the field of relativistic heavy ions for nuclear science is the LBL Bevatron[8]. Its beams are used for nuclear science from 100 Mev/u up to 1-2 Gev/u. The proposed upgrade[8] of the Bevatron, Fig. 4, will increase its intensity by a factor of 100-1000. At GSI, Darmstadt a new synchrotron, SIS-18, Fig. 5, is under construction. Its energy range is about the same as the Bevatron. Its injector, the UNILAC, will be greatly improved, resulting in final currents from SIS-18 of about 10^{12}/s, very competitive with heavy ion cyclotrons in this energy range. The Synchro-phasotron at Dubna is also in this energy range for heavy ions. It is weak focusing like the present Bevatron, with somewhat higher energy but lower current and mass range. The Saturne II machine was rebuilt with strong focusing and operates sucessfully at a somewhat lower energy and lower mass range than the Bevatron or SIS-18. A synchrotron and storage ring have been proposed recently at the Oak Ridge National Laboratory[13]. The synchrotron will be injected by the present tandem accelerator and would produce beams of lighter heavy ions up to 600 Mev/u and uranium up to 100 Mev/u. The fast cycling rate of 20 Hz produces high beam intensities, as shown in Table 2. Other heavy ion synchrotrons have been proposed, including the Numatron at INS, Tokyo and the Nuclotron at Dubna.

Several labs are planning to use storage rings injected by the synchrotrons. These can be used to increase the duty factor, increase the energy by stripping and reinjection into the synchrotron, store radioactive beams and provide multiple simultaneous experimental stations. The GSI SIS-18 will have a storage ring, the ESR shown in Fig. 5, and the Bevatron upgrade plans to add one later as shown in Fig. 4. The storage ring, a form of synchrotron, is becoming popular as a second stage at many accelerators, including cyclotrons. They can improve the beam quality available at a cyclotron facility by use of electron cooling. So they enhance the performance of the cyclotron rather than compete with it. Some of the cyclotron groups operating or planning storage rings are INS, Tokyo (TARN and TARN II), Indiana (Cooler), Julich (COSY) and Uppsala (Celsius). Many of these are described in this Conference.

Table 2. Nuclear Science Synchrotrons

Group	Foc Type	Dia. (m)	Ion	Energy (Mev/u)	Current Ions/s	Status
LBL[8]	Weak	38	Ne	200	3×10^9	Oper.
			U	100	3×10^7	
LBL[8]	Strong	43	Ne	200	2×10^{11}	Study
			U	100	2×10^9	
GSI[11]	Strong	66	Ne	200	2×10^{12}	Const.
			U	100	5×10^{11}	
ORNL[13]	Strong	38	Ne	200	2×10^{11}	Study
			U	100	2×10^{10}	

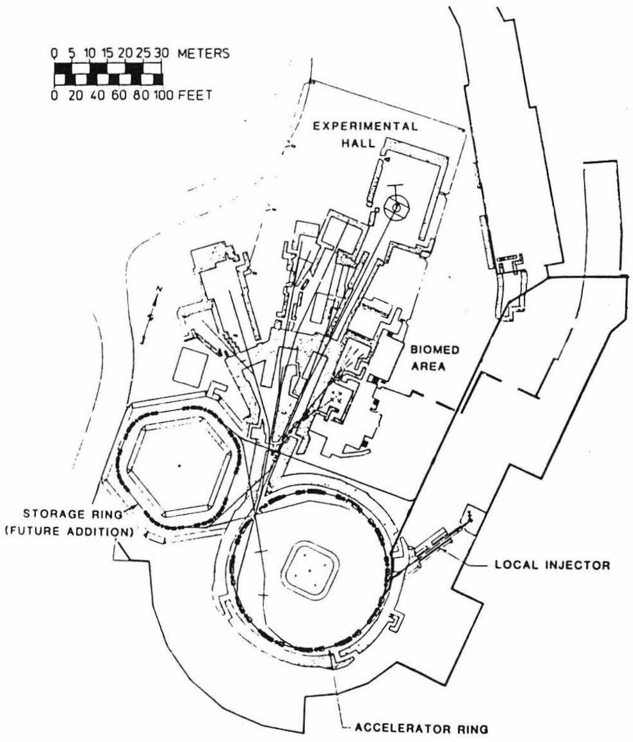

Fig. 4. The LBL proposed Bevatron upgrade with a strong focusing ring and future storage ring[8].

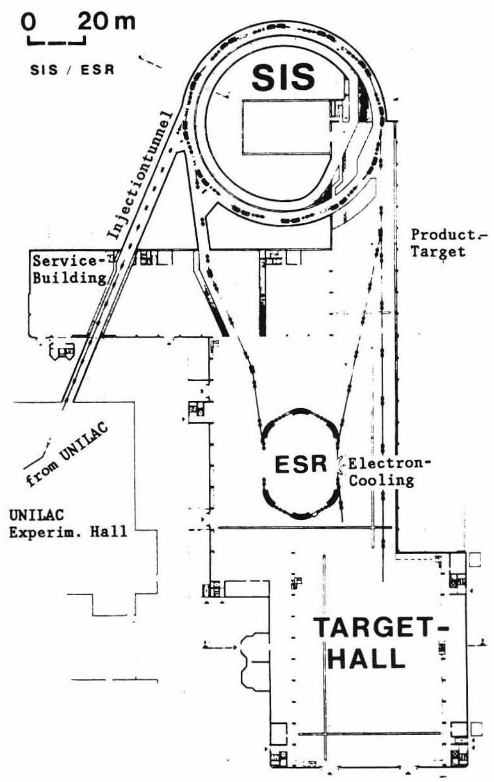

Fig. 5. The GSI SIS-18 heavy ion synchrotron and ESR storage ring, under construction[11].

Atomic Physics

In the field of atomic physics research, ion beams with all possible charge states are required. Many of these ions can be produced with high charge state ion sources, but the highest charge state heavier ions are produced by acceleration and stripping. So the energies required span a broad range from eV to hundreds of Mev/u to strip the heavist ions. The accelerators required are thus in the same range as for the nuclear science research applications mentioned above, as shown in Fig. 1. The addition of storage rings is an advantage for atomic physics just as it is for nuclear physics, opening up the possibility of high quality beams from electron cooling, and deceleration of highly stripped and radioactive secondary beams for studies in the lower energy ranges. Some of the groups building or planning storage ring facilities for atomic physics research are Heidelberg (TSR, 1.5 T m, const.), Stockholm (CRYRING, 1.4 T m, const.), Aarhus (ASTRID, 1.8 T m), and Oak Ridge (HISTRAP, 2.0 T m, study). In the list above the project name, beam rigidity in Tesla meters and status are given in parentheses. It happens that none of the rings listed above are injected by cyclotrons, but 3 are injected by tandem accelerators. Cyclotrons could also serve as injectors, making higher energies and thus higher stripped charge states available.

Acknowledgements

The authors wish to thank all of the correspondents who kindly supplied information for this paper and hope that it has been presented correctly.

References

1. Proc. Medical Workshop on Accelerators for Charged-Particle Beam Therapy, Fermilab, Jan. 1985.
2. H. Blosser, private communication, and Ref. 1, p. 109.
3. Conceptual Design of a Proton Therapy Synchrotron for Loma Linda University Medical Center, Fermi National Accelerator Laboratory, June 1986.
4. Proton Therapy System Status Report, Brobeck Corp., August 1985.
5. R. Martin, private communication.
6. B. Gottschalk, Ref. 1, p. 123.
7. B. Gottschalk, Ref. 3, Appendix.
8. The Bevalac Upgrade, PUB-5166, Lawrence Berkeley Lab., March 1986.
9. K. Kawachi, private communication.
10. The Heavy Ion Medical Accelerator, PUB-5122, Lawrence Berkeley Laboratory, June 1984.
11. K. Blasche, D. Bohne, B. Franzke and H. Prange, IEEE Trans Nucl. Sci. NS-32, 5 (1985).
12. F. T. Cole, Ref. 1, Summary.
13. Physics Division Prog. Rept., ORNL, Sept. 1985, p. 274.