NUCLEAR ENGINEERING

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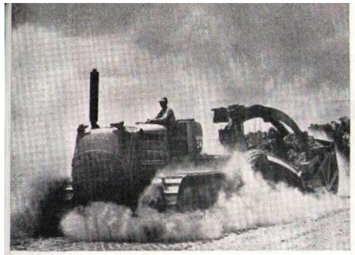
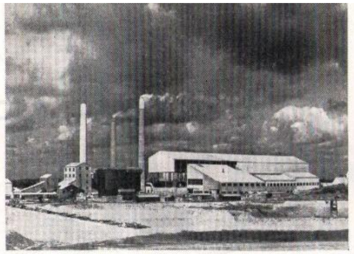

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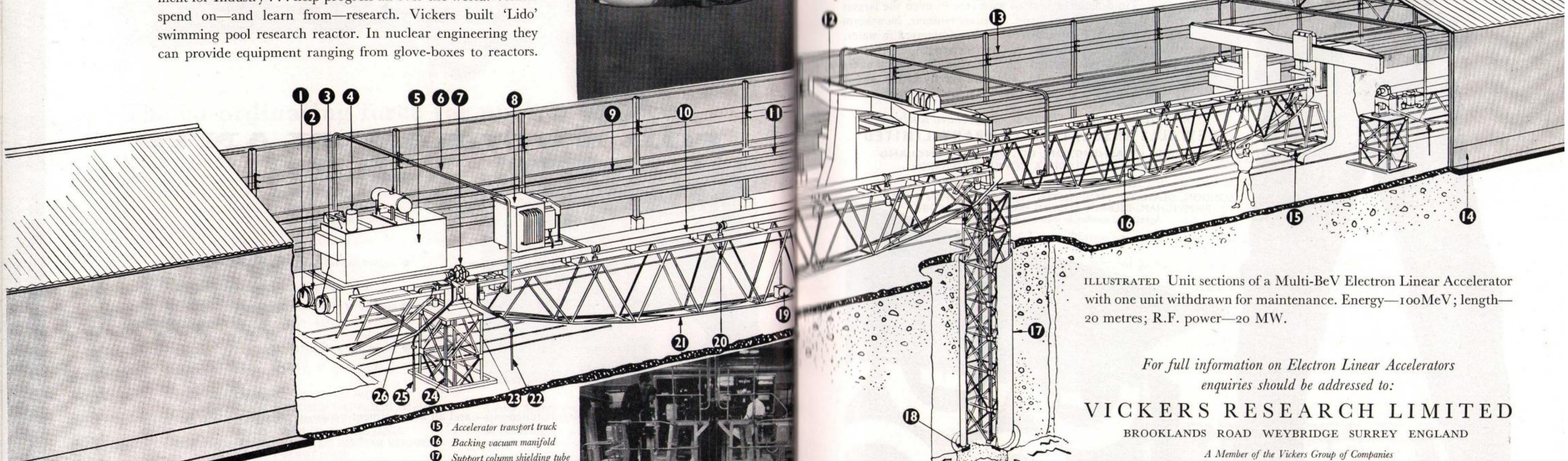

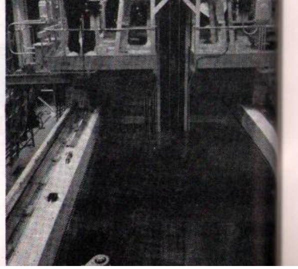

1. *Water main outlet*
2. *Lagging*
3. *Water main inlet*
4. *Klystron*
5. *Klystron Modulator Unit*
6. *Sub accelerator R.F. feed*
7. *Steering coil*
8. *Sub accelerator power supply*
9. *R.F. drive line*
10. *Accelerator tube*
11. *Supply and control cable rack*
12. *Travelling hydraulic hoist*
13. *Hoist power supply*
14. *Steel framed asbestos clad accelerator building*
15. *Accelerator transport truck*
16. *Backing vacuum manifold*
17. *Support column shielding tube*
18. *Bitumen seal*
19. *Rotary vacuum pump*
20. *Diffusion pump*
21. *20 metre sub accelerator*
22. *Water outlet*
23. *Support alignment jack*
24. *Support column*
25. *Water inlet*
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NUCLEAR ENGINEERING VOL. 4 NO. 37 APRIL, 1959

AEA RE-GROUPED

MAJOR reorganizational changes have been announced by the Atomic Energy Authority. The Authority will now comprise four groups instead of three, the previous Industrial Group having been divided into a Development and Engineering Group and a Production Group. The Authority's announcement states that, at the same time, the full-time technical Members will again assume executive responsibility for particular groups, in addition to their functional responsibilities and general duties as members of the Board.

Sir William Cook, with the title of Member for Development and Engineering, will be executive head of the Development and Engineering Group, and will in addition retain corresponding functional responsibilities throughout the Authority. Sir Leonard Owen will have the title of Member for Production (Designate) and will be executive head of the Production Group. Sir William Penney, whose appointment as Member for Scientific Research was announced a few weeks ago, will in addition become the executive head of the Research Group, while retaining his functional responsibility for scientific research throughout the Authority. The appointment of a Member for Weapons Research and Development has still to be announced.

The responsibilities of the new Engineering and Development Group are classified as development, design and construction of reactors and associated plant (with the exception of certain development work which will continue to be undertaken by the Research Group); engineering consultant work for the electricity authorities, overseas organizations and industry; general engineering design and construction of all major building projects. The Group will have headquarters staff at Risley and will control the Dounreay Experimental Reactor Establishment, the Culcheth Laboratories and the R. and D. organizations at Capenhurst, Windscale and Springfields.

The Production Group will be responsible for the operation of the Authority's factories including Calder Hall and Chapelcross and the research and development directly associated with the factory processes. It will also take over the commercial activities of the existing industrial power branch. The headquarters staff for the Group will remain at Risley.

In part the reorganizational changes fall directly in line with the recommendations made in the Fleck reports. It was felt with the existing organization, uncertainties were inevitable in the allocation of final responsibility for the running and organizing of plant that was predominantly experimental in character. The division also falls more into line with usual industrial practice where development and operation are considered as two quite separate functions. It is important to note that DFR and the AGR experiment at Windscale will come under the direct auspices of the Development and Engineering Group. This should ease considerably the planning of the experimental programme and should ensure that the reactors are operated in such a manner as to give the maximum information. On the other hand, the production reactors of Calder Hall and Chapelcross come firmly within the scope of the Operations Group, who will not be embarrassed by competitive demands for experimental facilities.

Contrary to the recommendations of the Fleck committee is the decision to ally the responsibilities of the Members of the Atomic Energy Authority with duties as executive heads of the various Groups. At one time it appeared that the Authority had accepted the Fleck recommendations when Sir John Cockcroft resigned from the directorship of Harwell. It should be noted, however, that, taking the Research Group as an example, Dr. Schonland remains as the director of AERE and Mr. Fry as the director of Winfrith (answering to Dr. Schonland). The dual responsibilities need not include detailed administration work nor need the Members be involved in day-to-day running of the establishments. The new arrangement can, in fact, allow them greater access to all establishments and greater power in organizing and co-ordinating the work of individual divisions. It has yet to be seen, however, whether the opposite will not result, particularly as regards research activities throughout the Authority, and that the valuable work of co-ordination, that Sir John Cockcroft started, will not be wasted.

Certainly the Industrial Group was becoming too large to be manageable and too diverse in its activities. It seems unfortunate, nevertheless, that these moves could not have been made twelve months ago as repeated upheavals in the Groups' organization are most unsettling to staff. Let us hope that we can now look forward to a long period of stability once final details have been settled.

Nuclear Engineering

REFERENCE SHEET No. 1 PARTICLE ACCELERATORS*

SYNCHROTRONS

Table I. **Proton Synchrotrons**

Current No.	Energy GeV	Location	Designation	Institution	Status	Cost	Focusing type	Orbit radius	Mean radius	Sectors No.	Field max k-gauss	Power Input kW	Weight of Iron tons	Storage system	Rise Time sec	Weight of Copper tons	Aperture Width	Aperture Height	Pulse Rate	Output part./pulse	Injector System Type	Input to RF kW	Frequency Mc/s	Shielding
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	50	Leningrad, U.S.S.R.	50 GeV Synchrophasotron	Research Institute for Electro Physical Equipment	Completion date 1961	—	strong, a-g	167 m	—	120	12	100,000	22,000	flywheels	3·8	—	20 cm	12 cm	6 per min	—	linac	—	2·6–6·1	—
2	30	Long Island, U.S.A.	Brookhaven Alternating Gradient Synchrotron	Brookhaven National Laboratory	Completion date 1960	$29,000,000	strong, a-g	421·45 ft.	Magnet radius 280 ft.	240	13	—	4,000	—	1	400	6 in.	2⅜ in.	3 per min	—	linac	—	1·5–4·5	earth and concrete
3	25–28	Geneva, Switzerland	CERN 25-GeV Proton Synchrotron	European Organisation for Nuclear Research (CERN)	Completion date 1960	Sw.Fr. 100,000,000	strong a-g	70·08 m	100 m	100	12–14	27–32,000	3,400	flywheel	1	Al 130	14 cm	7 cm	1 per 3-5 sec	5×10^{9}	linac	16×6	3–10	baryte concrete 5·5 m
4	10·6	Canberra, Australia	ANU 10-GeV Proton Synchrotron	Australian National University	Design study 1953	—	weak, c-g	4·8 m	6·4 m	4	80	500,000	0	homopolar generator	0·7	80	22 cm	22 cm	1 per 10 min	—	cyclotron	60	1–7·5	—
5	12·5	Lamont, U.S.A.	ZGS (Zero Gradient Synchrotron)	Argonne National Laboratory	Completion date 1962	—	edge	71 ft.	87 ft.	8	21·5	~100,000	4,000	flywheel	1	65	32 in.	5¼ in.	1 per 4 sec	$\sim10^{12}$	linac	80–100	4·2–14	earth 20 ft. above 100 ft. sides
6	12	Oak Ridge, U.S.A.	Southern Regional Accelerator	Oak Ridge National Laboratory	Model tests began 1957	—	strong, a-g	142 ft.	213 ft.	32	10	700	1,200	condenser-choke	1/120	180	13 cm	6 cm	60 per sec	20 μa	AVF fixed frequency cyclotron	~1000	98–115	Vacuum chamber oval, 2·5×6·5 in.
7	10·6	Canberra, Australia	ANU 10-GeV Proton Synchrotron	Australian National University	Design study 1953	—	weak, c-g	4·8 m	6·4 m	4	80	500,000	0	homopolar generator	0·7	80	22 cm	22 cm	1 per 10 min	—	cyclotron	60	1–7·5	—
8	10	Dubna, U.S.S.R.	10-GeV Synchro-phasotron	Joint Nuclear Research Institute—High	Completion date 1957	—	weak, c-g	28 m	30·5 m	48	13	140,000	35,000	flywheels	3·3	2,700	150 cm	40 cm	5 per min	10^{9}–10^{10}	linac	—	0·19–1·45	—
9	7	Harwell, England	7-GeV Proton Synchrotron	Rutherford High Energy Laboratory	Completion date Dec. 1961	—	weak, c-g	18·78 m	23·63 m	8	14	100,000 kVA	7,000	flywheels	0·7	250	36 in.	9 in.	25–30 per min	10^{12}	linac	80	1·4–8·02	concrete and earth
10	7	Moscow, U.S.S.R.	7-GeV Synchro-phasotron (Model for 50-GeV)	Thermotechnical Institute	Completion date 1959 (?)	—	strong, a-g	40 m	—	98c and 12x	9·5	—	2,700	—	1·5	—	11 cm	8 cm	12 per min	—	linac	500	0·65–8·5	—
11	6·2	Berkeley, U.S.A.	Bevatron	University of California Radiation Laboratory	Completion date Feb. 1954	$9,700,000	weak, c-g	50 ft.	63 ft.	144	16	100,000	9,700	flywheel	1·85	347	112 cm 44 in.	25 cm 10 in.	11 per min	—	linac	25	0·36–2·46	concrete 5–10 ft.
12	≥2·5	Aif-sur-Yvette, France	Synchrotron à protons "SATURNE"	Commissariat à l'Energie Atomique	Completion date Aug. 1958	6,000,000,000 francs	weak, c-g	8·42 m	~11 m	4, and 284 blocks	15	24,000 kVA	1,080	flywheel	0·8	55	between pole tips 52·75 cm	between pole pieces 17·54 cm	duration 3·2 sec	10^{10}	electrostatic generator	15	0·78–8·41	concrete
13	3·0	Upton, U.S.A.	Cosmotron	Brookhaven National Laboratory	Completion date 1952	$7,000,000	weak, c-g	30 ft.	30 ft.	4	13·8	26,000	2,000	40-ton flywheel	1·0	70	28 in.	6 in.	12 per min	10^{10}–10^{11}	Van de Graaff	50	0·33–4·18	concrete
14	3·0	Princeton, U.S.A.	3-BeV High Intensity Proton Synchrotron	Princeton University and University of Pennsylvania	Completion date Jan. 1960	$9,000,000	weak, c-g	30 m	40 m	16	13·8	3,000	400	capacitors choke	25×10^{-3}	25	7 in.	2¾ in.	20 per sec	$1{\cdot}5\times10^{11}$	Van de Graaff	300	2·5–30	concrete 240 lb., 15 ft.
15	1	Delft, Netherlands	Delft Proton Synchrotron	Technical University Accelerator Division	Completion date Jan. 1959	—	edge	3·25 m	—	4	17·5	3,000 kVA	—	none	0·8	—	25 cm	10 cm	1 per 2 sec	—	cyclotron	—	—	—
16	1	Birmingham, England	The Birmingham Proton Synchrotron	University of Birmingham	Completion date July 1953	—	weak, c-g	5 m	16·5 ft.	—	—	—	—	—	—	—	—	—	5 per min	10^{10}	Cockcroft-Walton	60	0·3–9·6	concrete, 2 m pyrite loaded on lab. side
17	200 (650) MeV	Leningrad, U.S.S.R.	Model Synchro-phasotron (Model for 7-GeV)	Research Institute of Electro-Physical Instruments	Completion date 1958	—	strong, a-g	5 m	—	34	5 (10)	—	—	—	<1	—	13·9 cm	7·8 cm	4 per min	—	—	—	—	—

Table II. **Electron Synchrotrons**

Current No.	Energy GeV	Location	Designation	Institution	Status	Cost	Focusing type	Orbit radius	Mean radius	Sectors No.	Field max k-gauss	Power Input kW	Weight of Iron tons	Storage system	Rise Time sec	Weight of Copper tons	Aperture Width	Aperture Height	Pulse Rate	Output part./pulse	Injector System Type	Input to RF kW	Frequency Mc/s	Shielding
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	7·5	Hamburg, Germany	Deutsches Elektronen-Synchrotron (DESY)	Deutsches-Elektronen-Synchrotron	Design study May 1957	—	a-g	31·70 cm	50·42 cm	48	7·89	1,800	600	resonant circuit	8 m	80	—	—	50 per sec	10^{11}	linear accelerator	400	499·67	earth equiv. direct 10 m, roof 2·50 m
2	6·0	Cambridge, U.S.A.	Cambridge Electron Accelerator	Massachusetts Institute of Technology and Harvard University	Completion date Jan. 1960	—	strong, a-g	85·8 ft.	118·3 ft.	48	8	1,200	350	capacitors choke	1/120 sec	55	6·0 in.	1·5 in.	60 per sec	1×10^{11}	electron linac	350	475·83	underground
3	4	U.S.S.R.	—	—	Model tests 1957	—	strong, a-g	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
4	1·5	Ithaca, U.S.A.	The Cornell 1·5 BeV Electron Synchrotron	Laboratory of Nuclear Studies, Cornell University	Construction start Jan. 1953	~$500,000	strong, a-g	12·5 ft.	12·5 ft.	16	13·5	250	20	—	1/100 i.e. 30 cycle	0·5	7 cm 3 in.	2·5 cm 1 in.	30	10^{9}	Van de Graaff	20	85–87	loaded concrete
5	0·75 (~1·3)	Tokyo, Japan	The INS 1-BeV Electron Synchrotron	Institute for Nuclear Study, University of Tokyo	Completion date March 1960	$640,000	strong, a-g	4 m	~5·5 m	8	6·25 (10·8)	140 (210)	53	condensers	$8{\cdot}4\times10^{5}$ gauss/sec	7·9	~15 cm	5·4 cm	21·5±2 per sec	3×10^{10}	linac	5 (50)	138·1	concrete
6	1 (1·2)	Roma, Italy	The INFN 1-GeV Electron Synchrotron	Institute Nazionale di Fisica Nucleare	Completion date Jan. 1959	~$1,500,000	weak	3·60 m	4·37 m	4	9·26 (11)	825	~95	capacitors	$\sim25\times10^{-3}$	~8	22·7 cm	8·6 cm	20 per sec	—	Cockcroft-Walton	30	42.6–43.7	Concrete and iron
7	1·2	Lund, Sweden	—	Department of Physics, University of Lund	Engineering design 1957	—	strong, a-g	3·65 m	5·30 m	16	11	200	32	condensers	—	6·5	6·0 cm	3·6 cm	12·5	—	microtron	5–10	402	—
8	1·4	Pasadena, California	Caltech Synchrotron	California Institute of Technology	Completion date Sept. 1956	—	weak, c-g	148 in.	—	4	13·4	8,500	—	flywheel	0·25	—	10 in.	3 in.	1 per sec	10^{10}–10^{11}	pulse transformer	40	37·6–4·0	lead 4 in. in median plane only. External shielding: wall concrete 3 ft., no roof
9	1	Moscow, U.S.S.R.	—	Atomic Energy Institute	Model tests 1957	—	—	0·34 m	—	—	100	—	—	—	—	—	—	—	—	—	—	—	—	—
10	0·6	Moscow, U.S.S.R.	—	Lebedev Institute	Construction started 1956	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
11	0·5	Bonn, Germany	500-MeV Elektronen-Synchrotron	Physikalisches Institut der Universität Bonn	Completion date 1958	1,300,000 DM	strong, a-g	1·70 m	2·63 m	9	10	75	12	condensers	8·5 m	4·8	—	—	50 per sec	—	Van de Graaff	2	161·45–163·08	—

LINEAR ACCELERATORS

Table III. **Proton Linear Accelerators**

Current No.	Energy MeV	Location	Designation	Institution	Status	Cost	Output Average μA	Beam Pulse μsec	Beam Dia	Injector System: Type	Injector System: Energy keV	Injector System: Output Average mA	RF System: Frequency Mc/s	RF System: RF Power kW	RF System: Power Units	RF System: RF Pulse Duration μsec	Tank Length	Tank Dia	Drift Tubes No.	Current No.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
1	9·99 39·95 68	Minneapolis, U.S.A.	Proton Linear Accelerator	University of Minnesota School of Physics	Completion date 68 MeV late 1955	$1,250,000	0·2 0·04 0·02	150	0·5 cm 1·0 cm 1·7 cm	60 × former	500	peak 3	202·55	600 2,200 3,200	Risnatron amplifiers	300	18 ft. 40 ft. 40 ft.	55 in. 60 in. 52 in.	42 38 25	1
2	50	Harwell, England	50-MeV Proton Linac	Rutherford High Energy Laboratory, NRNS	Completion date early 1959	—	—	rate 50/sec	—	Cockcroft-Walton	500	—	202·5	4,000	—	400	3 tanks 10, 20 and 20 MeV	—	—	2
3	50	Lemont, U.S.A.	Injector for the 12·5 BeV Synchrotron (ZGS)	Argonne National Laboratory	Completion date Jan. 1961	—	5,000	250	1 in.	Cockcroft-Walton	750	50	200	2,500	1 or 2	500	110 ft.	39 in.	124	3
4	50	Long Island, U.S.A.	Brookhaven AGS Injector	Brookhaven National Laboratory	Completion date 1959	~$2,000,000	> 1,000	—	~1 in.	cascade transformer	750	1 to 2 or more	200	2,500	triodes (TH-470)	200	110 ft.	3 ft.	124	4
5	40	Moscow, U.S.S.R.	—	Moscow Physical Institute	Completed before 1957	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5
6	31·5	Los Angeles, U.S.A.	32-MeV Linac	University of Southern California	Completion date Summer 1959	Original at Berkeley ~$2,000,000 + reinstallation cost $500,000	at 15 pps 0·2	400	1 cm divergence 10^{-3} radians	Van de Graaff	4 MeV	1·5	202·55	at 15 pps 20	10	600	inside 40·5 ft.	inside 48 in.	46	6
7	21	Kharkov, U.S.S.R.	—	Ukrainian Technical Institute	Completion date 1950	—	—	4/sec	—	Van de Graaff	1,700	—	—	—	—	250	12·4 m	—	—	7
8	20	Moscow, U.S.S.R.	(Injector for 7-GeV Synchro-phasotron)	Thermotechnical Institute	Construction started 1957	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8
9	10	Warsaw, Poland	—	Central Polish Nuclear Research Institute	In operation	—	—	—	—	—	—	—	—	—	—	—	—	—	—	9
10	9·9	Berkeley, U.S.A.	Bevatron 10-MeV Injector	University of California Radiation Laboratory	Completed Nov. 1953	$400,000	330	·500	½ in.	Cockcroft-Walton	400	total 10, protons 5	202·5	500	Eimac 3W 10,000	600	20 ft.	42 in. cavity	42 + two ½	10

Table IV. **Electron Linear Accelerators**

Current No.	Energy GeV	Location	Designation	Institution	Status	Cost	Output Average μA	Beam Pulse μsec	Beam Dia	Injector System: Type	Injector System: Energy keV	Injector System: Output mA	RF System: Frequency Mc/s	RF System: RF Power Peak kW	RF System: Power Units	RF System: RF Pulse Duration μsec	Acc. Length	Acc. Dia	Current No.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	45	Stanford, U.S.A.	"M" Electron Linear Accelerator	Stanford University	Design study 1956–1957	—	3	2	⅛ in.	electron gun	100	1,000	2,856	20,000,000	Klystrons	2	10,000 ft.	4 in. OD	1
2	1	Orsay, France	Accelerator Lineaire, D'Orsay	Laboratoire des Hautes Energies et de Physique des Solides	Completion date 1960	1,500,000,000 francs	1	0·1–1	1 cm	electron gun	40	peak 100	2,997·92	320	16 Klystrons	2	—	—	2
3	1	Kharkov, Russia	—	Ukrainian Technical Institute	Model tests 1956	—	—	—	—	—	—	—	—	—	—	—	—	—	3
4	700 MeV	Stanford, U.S.A.	Mark III Electron Linear Accelerator	High Energy Physics Laboratory, Stanford Lab.	Completion Spring 1952	$3,000,000	1	1	0·5 cm	pulsed	80	250	2,856	300,000	21 Klystrons	2	220 ft.	3·247 in. ID	4

* The information given in this Reference Sheet has been compiled in the main from ORNL Report No. 2644 (Nov. 7th, 1958) and represents an essentially complete record of all principal machines in each country throughout the world.

CYCLOTRONS

Table V. **Fixed-Frequency Cyclotrons**

Current No.	Particles	Energy MeV	Location	Designation	Institution	Status	Cost	Pole Tip Dia.	Field Gap	Field k-gauss	Weight of Iron tons	Winding	Coolant	D Dia.	D Aperture	D-D Gap	Oscillator Output kW	Ion Source	Shielding	RF Frequency Mc/s	Current No.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
1	Protons	850	Oak Ridge, U.S.A.	Southern Regional Accelerator (Injector)	Oak Ridge National Laboratory	Design study began 1957	—	—	—	22 max.	2600	—	—	—	—	—	—	—	—	—	1
2	Protons	400	Gainesville, Fla., U.S.A.	University of Florida Spiral Ridge Cyclotron	University of Florida	Design study June 1958	$5,000,000 (est'd.)	—	8 in.	10 max.	—	—	—	—	—	—	—	—	—	—	2
3	Deuterons Protons Alphas Heavy ions	15–60 7½–115 30–120 equiv.	Berkeley, Calif., U.S.A.	—	University of California Radiation Laboratory	Completion date July 1961	—	88 in.	7 in. min. 11 in. max.	17 average	258	hollow copper	water	40 in.	2 in.	4 in.	—	—	concrete 8 ft.	6–23	3
4	N^{3+} N^{4+} He^{+} $\frac{1}{2}D_2^{+}$	110 200 44 22	Zürich, Switzerland	ETH 300-cm Cyclotron Project	Swiss Federal Institute of Technology	Engineering design to start July 1959	—	300 cm	36 cm min.	centre 16	625	tubing	water	250 cm	10 cm	—	300	Oak Ridge	concrete 165 cm	—	4
5	Heavy ions	8–10	Dubna, U.S.S.R.	Heavy-Ion Cyclotron	Joint Nuclear Research Institute & Nuclear Reactions Laboratory	Construction started 1958	—	300 cm	—	—	—	—	—	—	—	—	—	—	—	—	5
6	Protons N^{4+} Heavy ions	1–75 4–100 >100	Oak Ridge, U.S.A.	Oak Ridge Relativistic Isochronous Cyclotron	Oak Ridge National Laboratory	Completion date 1960	$3,000,000	76 in.	7·5 in. centre	1·8–17 average	200	bar 1·13 sq. in. hole 0·75 in.	water	35·5 in.	1·87 in.	2 in.	500	Oak Ridge	concrete 7–8 ft.	7·5–22·5	6
7	Protons Deuterons Alphas	70 35 70	San Francisco, Calif., U.S.A.	NRDL Cyclotron	U.S. Naval Radiological Defense Laboratory	Completion date 1962	$1,515,000	—	~5 in. centre	B=17	—	hollow copper	water	—	—	—	—	—	concrete 5 ft.	—	7
8	Protons	25–50	Los Angeles, Calif., U.S.A.	The UCLA 50-MeV Cyclotron	University of California	Completion date 1959	$60,000 (excluding control desk)	44 in.	6 in. centre	26 max.	40	1 in. hollow	water	1½ in.	—	—	—	—	2 ft. iron all round	—	8
9	Protons N^{4+}	40 45	East Lansing, Mich., U.S.A.	Michigan State University 64-in. Cyclotron	Michigan State University	Completion expected June 1961	$1,500,000	64 in.	6 in. centre	17 max.	~75	—	—	62 in.	2 in.	—	—	—	—	—	9
10	Deuterons	15–40	Ann Arbor, Mich., U.S.A.	86-in. Spiral-Pole Cyclotron	University of Michigan	Model tests 1958	—	83 in.	—	—	342	hollow bar	water	—	—	—	150	—	—	—	10
11	Protons Deuterons Alphas	30 20 40	Boulder, Color., U.S.A.	University of Colorado 52-in. Cyclotron	University of Colorado	Completion date 1961	$750,000	52 in.	7½ in. centre	15 average	85	copper	water	24 in.	1½ in.	1 in.	80	hooded	concrete 7 ft.	7–23	11
12	N^{3+}	27	Oak Ridge, U.S.A.	The ORNL 63-in. Cyclotron	Oak Ridge National Laboratory	Completion date May 1952 (first beam)	—	63 in.	6 in. centre	15·5 max.	—	solid copper strip	circ. oil bath	25·5 in.	3·5 in.	2 in.	—	Oak Ridge	none, exclusion area	4·9	12
13	Protons	25	Oak Ridge, U.S.A.	The ORNL 86-in. Cyclotron	Oak Ridge National Laboratory	Completion date Nov. 1950 (first beam)	$700,000 (plus existing equipment)	86 in.	17·5 in. centre	9 max.	350	solid strip 3×0·4 in.	circ. oil bath	70 in.	6 in.	4 in.	250	Oak Ridge	concrete 5 ft.	13·4	13
14	N^{3+} Alphas	25 13·6	Leningrad, U.S.S.R.	—	Physical-Technical Institute	Completion before 1957	—	120 cm	—	—	—	—	—	—	—	—	—	—	—	—	14
15	Protons Deuterons Alphas Heavy ions	12 24 48 equiv.	Berkeley, Calif., U.S.A.	Crocker Laboratory 60-in. Cyclotron	University of California	Completion date 1939	—	72 in.	9¾ in. centre	19·7 max.	196	copper	oil	26½ in.	2⅜ in.	3 in.	250	capillary	water 5 ft.	12	15
16	Protons Deuterons Alphas	11 22 44	Gif sur Yvette, France	Cyclotron de Saclay	Centre d'Etudes Nucléaires	Completion date 1953	300 million francs	70 in.	11·8 in. centre	18 max.	252	hollow copper bar	deionized water	60 in.	6·7 in.	3·1 in.	60	Oak Ridge	underground, 6 ft. concrete	10·6	16
17	Deuterons	22	Stockholm, Sweden	The Stockholm 225-cm Cyclotron	Nobel Institute of Physics	Completion 1951 (first beam at full radius)	~$500,000 (excluding building) rough estimate	211 cm	34·8 cm centre	20 max.	370	28×25 mm bar 11 mm hole	water	190 cm	at centre 12 cm	12 cm	~180	moderately open arc	underground 2 m water on top	—	17
18	Deuterons Alphas Protons (H_2)	21·6 43·2 10·8	Lemont, U.S.A.	ANL 60-in. Cyclotron	Argonne National Laboratory	Completion date June 1952	$950,000 cyclotron $840,000 building and facilities	62 in.	14 in. centre	14·9 max.	265	aluminium	demineralized water	29½ in.	2½ in.	4 in.	70–100	hooded, arc, d.c. filament	150 lb. concrete 7 ft. walls, 4 ft. roof	11·2	18
19	Protons Deuterons Alphas	11 22 44	Seattle, U.S.A.	The University of Washington 60-in. Cyclotron	The University of Washington	Completion date October 1952	$900,000	60 in.	10 in. centre	19 max.	200	copper	oil	53 in.	2·4 in.	3·5 in.	100	graphite, enclosed with virtual cathode	sides 10 ft. earth or 4 ft. concrete; top 1 ft. concrete and 3 ft. water	11·6	19
20	Deuterons Heavy ions	22 100	Moscow, U.S.S.R.	Moscow 60-in. Cyclotron	Atomic Energy Institute	Completion date 1949	—	59 in.	7 in. centre	13·6 max.	330	—	air	—	—	—	130	slit	water 1 m	—	20
21	Protons Deuterons Alphas	7·5–15 15–21 30–42	Tanashi-Machi Tokyo, Japan	The UTINS 63-in. Cyclotron	Institute for Nuclear Study	Completion date Sept. 1957 (first beam)	$650,000	160 cm	25 cm centre	13·3 max.	243	solid strip 2×32 and 2·2×28 mm	oil bath	80 cm	7 cm	10 cm	120	Oak Ridge	concrete, 150 cm sides and 96 cm top	84–12·1	21
22	Deuterons	20	Orsay, France	Variable Energy Cyclotron	Laboratoire de Physique Nucléaires	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	22
23	Protons Deuterons Alphas Heavy ions	10 20 40 10/mc	Birmingham, England	The Nuffield Cyclotron	University of Birmingham	Completion date 1949	—	61·5 in.	10 in. centre	18 max.	250	strip	air	28·5 in.	5 to 3 in.	3 in.	100	hooded arc	concrete and water	—	23
24	Deuterons	20	Long Island, U.S.A.	BNL 60-in. Cyclotron	Brookhaven National Laboratory	Completion date April 1951	~$950,000	62 in.	10 in. centre	15 max.	240	bar 2⅜×1½ in. Al strap	water	—	4 in.	3 in.	not measured	arc (hot cathode)	loaded concrete 4–5 ft.	11	24
25	Deuterons Alphas Protons	20 40 10	Cleveland, U.S.A.	NASA 60-in. Cyclotron	Lewis Research Centre (Nat'l. Aero. & Space Adm.)	Completion date July 1956	$1,000,000	60 in.	12 in. centre	17 max.	225	copper	water	not circular	4·37 in.	4·3 in.	400	Berkeley	concrete 13 in. earth 4 ft.	—	25
26	Protons Deuterons Alphas	10 20 40	Pittsburgh, U.S.A.	University of Pittsburgh Cyclotron	University of Pittsburgh	Completion date 1946	$200,000	47 in.	4½ in. centre	18 max.	—	copper strip	oil	23 in.	—	1½ in.	50	capillary arc	water and earth	11·8	26
27	Deuterons	16	Pretoria, S. Africa	The CSIR 44·5-in. Cyclotron	Nuclear Physics Div. Council for Scientific and Industrial Research	Completion date January 1958	£100,000	44·5 in.	5 in. centre	17·5 max.	73·8	hollow core 22×28 mm	distilled water	105 cm	5 cm	6 cm	6·5	open, spare filament	4 m earth and concrete	13·25	27
28	Protons Deuterons Alphas	8 16 32	Washington, U.S.A.	Dept. of Terrestrial Magnetism 60-in. Cyclotron	Carnegie Institute of Washington	Completion date 1944	$250,000	60 in.	12 in. centre	16 max.	200	copper	water	55 in.	6 in.	3 in.	—	hooded arc	earth and masonry	—	28
29	Deuterons Protons Tritons He^{3} Alphas	6–16 3–9 12 9–27 12–32	Los Alamos, U.S.A.	Los Alamos Variable Energy Cyclotron	Los Alamos Scientific Laboratory	Completion date December 1954	—	42 in.	4·5 in. centre	18·5 max.	70	copper	water	40 in.	1·9 in.	1·5 in.	70	similar to Oak Ridge	concrete 4–6 ft.	8·3–13·9	29
30	Deuterons	16	Cambridge, Mass., U.S.A.	Markle Cyclotron	Mass. Institute of Technology	Completion date (first beam) 1940	$100,000	42·5 in.	5·5 in. centre	17·4 max.	total 96	copper	water	40 in.	2 in.	2 in.	70	conventional capillary arc	concrete 4 ft. walls 3 ft. ceiling	13·1	30
31	Deuterons	16	Zagreb, Yugoslavia	—	Institut Ruder Bošković	Eng. design January 1958 Construction under way	$300,000 (including building)	140 cm	20 cm centre	18 max.	60	solid strip 5·6×0·34 cm	water tube pancakes	125 cm	9·6 cm	8 cm	80	similar to Oak Ridge	underground except front, 2 m concrete	—	31
32	Protons Deuterons Alphas	7·6 15·2 30	Kyoto, Japan	Kyoto Cyclotron	Institute for Chemical Research, University of Kyoto	Completion date January 1956	87,000,000 yen	105 cm	13·4 cm centre	17·5 max.	71·3	30×2·55 mm strip	oil bath	102·4 cm	4·8 cm	4 cm 2·6 cm between feelers	100	hooded arc	170 cm concrete, all sides and top	13·1	32
33	Deuterons Alpha particles Protons	15 30 7·5	London, England	MRC Cyclotron	Medical Research Council	Completion date July 1955	£150,000	50 in.	6 in. centre	15 max.	111	aluminium	water	50 in.	2½ in.	2½ in.	75	Oak Ridge carbon chimney	6 ft. concrete with 10 ft. lab. wall	11·3	33
34	Protons Deuterons Alphas Tritons	2·6–14·6 5·2–18·3 10·3–36 7·7–12·3	Livermore, U.S.A.	UCRL Livermore 90-in. Cyclotron	University of California Radiation Laboratory	Completion date February 1955	$1,000,000	228 cm 90 in.	305 cm centre 12 in. centre	9 max.	320	copper	oil cooled	198 cm 78 in.	6·35 cm 2·5 in.	one dee	380	Oak Ridge	concrete 5 ft. sides 2 ft. top	4·6	34
35	Protons Deuterons	8–15 11	New York, U.S.A.	Columbia University 36-in. Cyclotron	Columbia University Pupin Cyclotron Laboratory	Remodelled 1939–40	$28,000 (1937)	36 in.	5·875 in. centre	17·5 max.	—	copper strip	water	33 in.	1·5 in.	1·75 in.	30	Oak Ridge	water 4 ft.	—	35
36	Protons Deuterons Alphas	7·2 14 28	Zürich, Switzerland	ETH Cyclotron	Federal Institute of Technology, Physics Dept.	Completion date 1944	approx. $100,000	33 in.	8 in. centre	19·8 max.	60	copper	water	31 in.	1·8 in.	8 in.	50	w-fil., 800 V	1 m water, top none, 2 m concrete lab. wall	13–16·6	36
37	Deuterons	13·5	Kiev, U.S.S.R.	—	Ukranian Physical Institute	Completion before 1956	—	—	—	—	—	—	—	—	—	—	—	—	—	—	37
38	Deuterons	14	Moscow, U.S.S.R.	—	Thermotechnical Institute	Completion 1949	—	120 cm	—	—	—	—	—	—	—	—	—	—	water and boric acid, 1 m	—	38
39	Deuterons	12·7	Louvain, Belgium	Cyclotron du Centre de Louvain	Centre de Physique Nucléaire de l'Université de Louvain	Construction started 1949	—	101·5 cm	15 cm centre	18·1 max.	60	copper	air-cooled	36·6 cm	5·3 cm	5 cm	—	hot cathode arc discharge type	50 cm ordinary concrete on three, 100 cm concrete and 100 cm water on fourth	13·6	39
40	Deuterons Alphas	13 26	Heidelberg, Germany	Heidelberg Cyclotron	Max Planck Institut für medizinische Forschung	Completion First 1944 Second Sept. 1956	1,500,000 DM	101 cm	27 cm centre	17 max.	80	rectangular tube	distilled water	90 cm	6·0 cm	4 cm	80	hooded capillary arc or PIG type	1 m water; 0·5 m concrete	12·8	40
41	Deuterons Alphas	12·5 25	Sofia, Bulgaria	—	—	—	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	—	—	41
42	Deuterons Alphas	12·5 25	Peiping, China	—	Institute of Atomic Energy	Completion date 1958	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	—	—	42
43	Deuterons Alphas	12·5 25	Prague, Czechoslovakia	—	Institute of Nuclear Physics Research	Completion date 1958	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	—	—	43
44	Deuterons Alphas	12·5 25	Dresden, E. Germany	Festfrequenz-Zyklotron Type U–120–I	Zentralinstitut für Kernphysik	Completion August 1958	—	120 cm	17 cm centre	17 max.	105	2×336	distilled water	60·8 cm	2·5×1 cm	2·5 cm	150	capillary arc	concrete 2·5 m	—	44
45	Deuterons Alphas	12·5 25	Cracow, Poland	—	Institute of Nuclear Research	Completion date 1958	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	concrete	—	45
46	Deuterons Alphas	12·5 25	Bucharest, Rumania	—	—	—	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	—	—	46
47	Protons (H_2) Deuterons Alphas	6 12 24	Copenhagen, Denmark	—	Institute for Theoretical Physics University of Copenhagen	—	—	90 cm 35 in.	11 cm centre 4·3 in. centre	17·5 max.	35	solid strip 3×0·3 cm	oil bath	42·5 cm 17 in.	5–7 cm 2–2·8 in.	5 cm 2 in.	—	capillary hooded arc (spec.)	boron-loaded concrete 4·7 ft.	13	47
48	Protons	12	Delft, Netherlands	12 MeV Radial-Sector Fixed Frequency Proton Cyclotron	Technical University Accelerator Division	Completion (internal beam) January 1958	—	85 cm	12 cm centre	centre 14	—	hollow aluminium 2×2 cm	water	—	—	one dee	—	—	—	21·5	48

43	Deuterons Alphas	12·5 25	Prague, Czechoslovakia	—	Institute of Nuclear Physics Research	Completion date 1958	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	—	—	43
44	Deuterons Alphas	12·5 25	Dresden, E. Germany	Festfrequenz-Zyklotron Type U–120–1	Zentralinstitut für Kernphysik	Completion August 1958	—	120 cm	17 cm centre	17 max.	105	2×336	distilled water	60·8 cm	2·5×1 cm	2·5 cm	150	capillary arc	concrete 2·5 m	—	44
45	Deuterons Alphas	12·5 25	Cracow, Poland	—	Institute of Nuclear Research	Completion date 1958	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	concrete	—	45
46	Deuterons Alphas	12·5 25	Bucharest, Rumania	—	—	—	—	120 cm	—	14 max.	120	—	—	—	—	—	120	—	—	—	46
47	Protons (H_2) Deuterons Alphas	6 12 24	Copenhagen, Denmark	—	Institute for Theoretical Physics University of Copenhagen	—	—	90 cm 35 in.	11 cm centre 4·3 in. centre	17·5 max.	35	solid strip 3×0·3 cm	oil bath	42·5 cm 17 in.	5–7 cm 2–2·8 in.	5 cm 2 in.	—	capillary hooded are (spec.)	boron-loaded concrete 4·7 ft.	13	47
48	Protons	12	Delft, Netherlands	12 MeV Radial-Sector Fixed Frequency Proton Cyclotron	Technical University Accelerator Division	Completion (internal beam) January 1958	—	85 cm	12 cm centre	centre 14	—	hollow aluminium 2×2 cm	water	—	—	one dee	—	—	—	21·5	48
49	Deuterons	12	Birmingham, England	Radial Ridge Cyclotron	Birmingham University Dept. of Physics	Completion date April 1960	—	40 in.	3·25–4·25 in.	16 average	40	strip 1×0·2 in.	water-cooled rubber bags	41 in.	1·25 in.	single dee	45	hooded carbon arc	concrete, 4 ft.	—	49
50	Protons	11	Melbourne, Australia	Melbourne University Variable Energy Cyclotron (MUVEC)	Physics Dept., University of Melbourne	Completion (first beam) January 1957	£A35,000	39½ in.	6 in. centre	14 max.	42	1⅓×1×0·4 in dia. hole	degassed water	16 in.	2 in.	one dee	50	hooded arc	2–5 ft. brick and sand, 1·5 ft. water	19·9	50
51	Deuterons	9	Liverpool, England	Liverpool 37-in. Cyclotron	Nuclear Physics Research Lab. University of Liverpool	Completion June 1939	£8,000	88·2 cm 36 in.	19·6 cm centre 8 in. centre	18·5 max.	46	copper	water	33 cm 13·5 in.	4·9 cm 2 in.	3·7 cm 1·5 in.	20	hot cathode	4 ft. concrete to front	12·5	51

Table VI. **Frequency-Modulated Cyclotrons**

Current No.	Particles	Energy MeV	Location	Designation	Institution	Status	Cost	Pole Tip Dia.	Field Gap	Field Centre k-gauss	Power kW	Weight of Iron tons	Winding	Coolant	D Aperture	Oscillator Input kW	Repetition Rate Pulse/sec	Ion Source	Shielding	Frequency Range Mc/s	Current No.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
1	Protons Deuterons	730 460	Berkeley, U.S.A.	184-in. Cyclotron	Radiation Laboratory University of California	Completion 1946/1957	—	188·75 in.	14 in. centre	23·3	old coils 900 aux. coils 1600	4,000	old coils ½×4 in. solid Cu; aux. coils 1⅜× 1¼ hollow Cu	old coils oil, aux. coils water	12·3 cm 4 $\frac{3}{16}$ in.	operating cond. 10	64	conventional	15 ft. concrete sides, 4 ft. concrete top	36–13	1
2	Protons	680	Dubna, U.S.S.R.	6-m Phasotron	Joint Nuclear Research Institute	Completion 1949/1953	—	—	60 cm centre	16·8	1,000	7,200	copper bar	air	—	arc 50	80	hot cathode	concrete 6 m, rear beam 6 m of iron	26–13	2
3	Protons	600	Geneva, Switzerland	600-MeV Synchro-cyclotron	CERN	Completion date Aug. 1957	10,300,000 Sw. francs (excl. building)	500 cm 197 in.	17·5 in. centre	18·86	680	2,500	38×50 mm bar 20 mm hole	water	12 cm 4·7 in.	12 max.	55	Penning	heavy concrete 13 ft., lab. wall 19 ft.	28·75–16·4	3
4	Protons	460	South Ellis, U.S.A.	170-in. Synchro-cyclotron	Enrico Fermi Institute for Nuclear Studies	Completion date 1951	$2,500,000	170 in.	18 in. centre	18·6	700	2,200	copper	water	4·5 in.	140 max.	60	d.c. hot cathode	10 ft. steel punching loaded concrete	28·5–11·3	4
5	Protons	440	Pittsburgh, U.S.A.	CIT 440-MeV Synchro-cyclotron	Carnegie Institute of Technology	Completion date May 1952	—	141 in.	156·2 in. centre	20·5	430 max.	1,460	copper	oil	4 in.	60	180–200	hot cathode	magnetic cement and 60% steel scrap; 12 ft. min. roof; 5 ft. reg. concrete	31·5–19·8	5
6	Protons	400	Liverpool, England	Liverpool 156-in. Synchro-cyclotron	Nuclear Physics Research Lab. University of Liverpool	Completion date 1954	£473,000	381 cm 156 in.	36 cm centre 41·1 in. centre	18·9	800	1,640	aluminium	treated water	9·6 cm 4 in.	2·9	110	hot cathode (cold cathode Sept. 1958)	sides, 6 ft. concrete and 12 ft. rock; front, 12 ft. loaded concrete, top, 6 ft. concrete	28·2–18·9	6
7	Protons	350	New York, U.S.A.	The Nevis Cyclotron	Columbia University	Completion date 1950	$3,000,000	164 in.	18 in. centre	18	550	2,000	copper	oil	5 in.	25	60	cold cathode	6 ft. concrete and 2 ft. pig iron; 8 ft. iron forward	29–17	7
8	Protons	240	New York, U.S.A.	130-in. Synchro-cyclotron	University of Rochester	Completion date 1948	$1,362,000	130 in.	13·6 in. centre	16·9	160	1,000	aluminium	water	3 in.	25	100–300	cold cathode	3 ft. concrete on top and back; 3 ft. copper on front	19·5–26·3	8
9	Protons	200	Uppsala, Sweden	Uppsala Synchro-cyclotron	The Gustaf Werner Institute for Nuclear Chemistry	Completion date Dec. 1951 (first beam)	$1,000,000	230 cm 90·5 in.	25 cm centre 9·8 in. centre	21·54	440	600	copper	water	8 cm 3·1 in.	25	240	pulsed arc	underground and iron-ore concrete	25·5–33·3	9
10	Protons	175	Harwell, England	110-in. Synchro-cyclotron	Atomic Energy Research Establishment	Completion date Dec. 1949	~£250,000	110 in.	12 in. centre	16·2	300	670	copper strip	oil	4 in.	21	180	d.c. filament arc	underground, 6 ft. concrete roof	26·3–18·9	10
11	Protons	168	Cambridge, U.S.A.	Harvard 95-in. Cyclotron	Harvard University	Completion date June 1949	$1,000,000 (approx.)	95 in.	11·7 in. centre	19	160	641	copper	water	2 in.	~10	0–280	hot filament pulsed arc	3 to 8 ft. concrete	26–30	11
12	Protons Deuterons	155 80	Orsay, France	Synchro-cyclotron de 150-MeV	Faculte des Sciences de Paris	Completion date June 1958	500,000,000 francs	280 cm	39 cm centre	16·26	400	650	Al 24×24 mm bar 13 mm hole water	water	20–8·5 cm	50	500	w-filament arc	concrete	25·2–20·2	12
13	Protons	100	Montreal, Canada	McGill Synchro-cyclotron	McGill University	Completion date 1949	not over $200,000	82 in.	7·5 in. centre	16·3	200	—	hollow Al bar	water	3·5 in.	—	400	cold cathode	12 ft. underground	25–20·6	13
14	Deuterons Alphas	35 70	Bonn, Germany	Synchro-cyclotron Bonn	Institut für Kernphysik Universität Bonn	Completion date May 1958	1,500,000 DM	186·5 cm	29·7 cm centre	14·5	70	220	copper	distilled water	10 cm	25	1,800	low voltage arc	concrete, 2 m	10·7–11·2	14
15	Deuterons	30	Buenos Aires Argentina	The Buenos Aires 71-in. Synchro-cyclotron	Comisión Nacional de la Energía Atómica	Completion date Nov. 1954	3,000,000 florins	71 in.	14 in. centre	14·56	240	180	aluminium	water	7·5 in.	24	1,950	arc or filament	concrete 31·5 in. and water 31·5 in.	10·46–10·88	15
16	Deuterons Alphas	28 56	Amsterdam, Netherlands	Philips' Synchro-cyclotron	Institute for Nuclear Research	Completion date Aug. 1949	—	180 cm	32 cm centre	13·72	90	170	solid strip	oil	18·2–15·7 cm	25	1,960	d.c. arc with filament	1 m concrete	10·05–10·43	16
17	Protons	21	Los Angeles, U.S.A.	UCLA 41-in. Cyclotron	University of California, Physics Dept.	—	—	41 in.	4·5 in. centre	16·6	60	80	copper	oil	1·5 in.	10	1,000	open d.c. arc	water wall and exclusion	22–25·6	17
18	Protons	20	Princeton, U.S.A.	Princeton FM Cyclotron	Princeton University	Completion date Jan. 1951	$180,000	35 in.	3·5 in. centre	19	20	40	copper strap	water	1·25 in.	6	2,000	hot filament	3 ft. heavy concrete all sides and top	25–28	18