SLAC -PUB-2092
March 1978
(A)

RADIATION PARAMETERS OF ELECTRON LINEAR ACCELERATORS*

William P. Swanson

Stanford Linear Accelerator Center

P. O. Box 4349, Stanford, California 94305

March 3, 1978

ABSTRACT

Parameters of electron linear accelerators used in radiation therapy, industrial radiography, and for research and special purposes are compiled. Trends in accelerator development and implications for radiological safety are briefly discussed.

(Submitted for publication)

*Work supported by the Department of Energy.

During the preparation of a manual on radiological safety aspects of the operation of electron linear accelerators,(1) a worldwide survey was made to determine the relevant characteristics of these devices. After the results were compiled it appeared that this information would be generally useful in itself. These data provide an overview of the present status of electron linac development, as regards their uses, capabilities and radiological significance. A comparison of radiation parameters may provide a useful perspective on radiation-protection needs, and trends in accelerator development may be noted. In the design of new facilities, existing accelerator installations of comparable characteristics may be identified and their experience drawn upon.(2)

Table 1 shows data on electron linear accelerators introduced during the past decade for radiation therapy.(3,4) These are listed in the approximate order of introduction, but the parameters shown reflect recent specifications, if these are different from the original. Useful energies appear to be in the range 4 - 25 MV for photon treatment and 4 - 32 MeV for electron irradiation. There is a remarkable consistency among the parameters offered, reflecting a general consensus among manufacturers and users.

The maximum field sizes at 1 meter SSD or TAD are (30 x 30) to (40 x 40) cm2 for recent models. Even when physically achievable (as in electron therapy), dose rates higher than 500 rad min-1 m2 are not normally used for either photon or electron treatments because of regard for patient safety. The lowest dose rates reported are about 200 rad min-1 m2, still significantly higher than 60Co or 137Cs units normally provide. The amount of leakage radiation, as regards room shielding, seems standardized at about 0.1% of the useful beam at the same distance from the target, but is less than this in many cases. The leakage radiation in the patient plane is specified separately in some cases. Isocentric treatment capability is clearly desired. With some models, an unattenuated electron beam can be extracted for research or isotope production. The use of standing-wave accelerators has allowed economies in space utilization for some installations, and the possibility exists of installing higher-energy, higher-output units in rooms originally designed for less powerful equipment. In such cases and in cases where stationary field equipment is replaced by equipment capable of rotational therapy, the adequacy of existing radiation barriers must be evaluated. If equipment of energy above about 15 MeV is installed, the question of neutron streaming through the door and other penetrations should be considered, and adequacy of the labyrinth and door assessed.

Table 2 shows data on electron linear accelerators used in industrial radiography. Output for the standard models tabulated shows considerable variation (1.5 - 15000 rad min-1 m2). Leakage radiation, expressed as a percentage of useful beam at the same distance from the target, is higher in many cases than for the medical accelerators. In addition to the standard models, there are a number of custom-fabricated accelerators of higher energy and output which are not tabulated.

The high output of some of these models and the variety of physical accommodations in which they are employed mean that operating personnel must be carefully trained in their proper use. This is particularly true because these units are usually mounted to permit considerable freedom in positioning and beam direction. Because of the number of degrees of freedom available, limit switches sometimes cannot prevent irradiation in all unwanted directions, and careful administrative control must be exercised.

Table 3 shows parameters of research and special-purpose electron linacs.(5) Every installation known to the author has been listed, even though some information is incomplete, owing to lack of response at the time of writing. The data given should be considered "nominal;" several of the parameters can usually be varied over a considerable range.

Some characteristics that distinguish research accelerator facilities are uniqueness of design, high energy, high power, and variability in experimental setups and modes of operation. Radiation protection needs for this category of facility can most simply be portrayed in terms of electron beam energy and maximum beam power developed. The parameters given in the right-hand portion of Table 3 are intended to form a consistent, simultaneously achievable set, giving the highest electron beam power under continuous operation. Although many of such facilities operate at a greatly reduced beam power (say, for single-pulse operation), it would be conservative practice to plan the radiation protection needs for new facilities assuming that the highest values of both energy and beam power are simultaneously used. Figure 1 is a scatter diagram in which maximum continuously achievable beam power is plotted _vs_. nominal maximum beam energy. Accelerators used exclusively as injectors or for "industrial" purposes such as radiation processing or sterilization are omitted from this plot. From this figure, one may estimate the median energy and power to be around 50 MeV and 10 kW, respectively, but with great variation in both directions. That they tend to be grouped about the line reflects the fact that each increase in accelerator length or field gradient tends to augment the energy proportionately but may not affect the beam current significantly.

A great majority of the installations of Table 3 must have provision for handling activated components, and in some cases, activated cooling water. Some activity will be present at about 10 MeV; above about 20 MeV, the magnitude of these problems scales approximately as beam power.

Radiolytic decomposition of cooling water may be a problem where high-power beams are used. Where electron beams are transported in air, ozone production may also be a safety problem.

Units operating well above the pion production threshold (about 140 MeV) may present the problem of high-energy neutron production. This neutron component dominates the radiation field outside of the shielding and, via "skyshine," is the major contributor to the population dose beyond the site boundary. At a few installations (above about 1 GeV), muon production must also be considered.

A recent trend in the area of research accelerators (6,7) is the use of short, intense pulses (on the order of 10 nanoseconds or less) for pulse radiolysis or for secondary particle energy determination by time-of-flight. Another trend is the development of high duty-factor machines (Amsterdam, Los Alamos EPA (standing wave), MIT, Saclay II). Superconducting technology (as exemplified by the Stanford SC Mark III accelerator) may offer the possibility of 100%

duty factor. In contrast to its popularity for medical accelerators, standing-wave technology is used by only two research facilities (Los Alamos EPA, now being installed in Ljubliana, and Geel BCMN). Klystrons of up to 40 MW peak power have been developed and some facilities with conventional facilities may choose to increase energy and power by upgrading their RF source. Another means of increasing beam energy is the SLAC Energy Doubler SLED, an arrangement by which energy can be approximately doubled while the duty factor is halved (yielding about the same average beam power). Such a system is currently being installed at SLAC.

New facilities are now under construction or undergoing major improvement for nuclear physics research (such as IKO in Amsterdam and Bates at MIT). However, in the realm of elementary particle research, the emphasis has shifted to the construction of new storage rings fed by existing accelerators (e. g., Cornell, DESY, Frascati, Novosibirsk, Orsay, SLAC). Interesting uses developed in the Soviet Union are the use of electron linear accelerators for mineral assay and bulk disinfestatation of grain.

Important trends not revealed by the data presented here are in the number of new facilities in the three categories being installed or planned. At the present time, there are about 600 medical linear accelerators and their number is increasing at an annual rate of about 15%.(4) The number of industrial radiographic installations is presently a small fraction of the medical installations (at most about 10%) but is also growing proportionately as applications of non-destructive testing are developed. The growth in the number of research and special-purpose electron linacs has definitely slowed, compared to the rate of construction during the preceding decade.

The author gratefully acknowledges the help of many individuals in providing the information summarized here. The manufacturers of electron linear accelerators were all extremely cooperative, as were individuals at the various installations contacted. I particularly wish to thank J. H. Bly, E. G. Fuller, T. F. Godlove, C. J. Karzmark, M. G. Kelliher, Iu. P. Vakhrushin, G. A. Loew, B. Mecklenburg, C. Nunan and J. Tanaka for providing information on installations or accelerator types which helped make the present tabulation significantly more complete.

REFERENCES

1. W. P. Swanson, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, International Atomic Energy Agency, Vienna (1978, in preparation).

2. A list of addresses of manufacturers and research linac installations may be obtained from the author.

3. Also see the useful paper by C. J. Karzmark and N. C. Pering, Electron linear accelerators for radiation therapy: History, principles and contemporary developments, Phys. Med. Biol. 18, 273 (1973).

4. See, for example, Bureau of Radiological Health (1975), The Use of Linear Accelerators in Medical Radiation Therapy, Overview Report No. 2, Market and Use Characteristics: Current Status and Future Trends, N.T.I.S. Report No. PB-246-226, Washington, D. C. (January, 1975).

5. J. S. Fraser and S. O. Schriber, Compendium of Linear Accelerators 1976, Atomic Energy of Canada, Ltd., Report No. AECL- 5615, Chalk River, Ontario (Sept., 1976).

7. See, for example, papers in: Proceedings of the 1975 Particle Accelerator Conference: Accelerator Engineering and Technology, held in Washington, D. C., March 12-14, 1974, IEEE Transactions on Nuclear Science, Vol. NS-22

(1975). Report No. PB-246-226, Washington, D. C. (January,

7. See, for example, papers in: Proceedings of the IXth International Conference on High Energy Accelerators, held at Stanford Linear Accelerator Center, May 2-7, 1974, N.T.I.S. Report No. CONF 740522, UC-28-Accelerators (TID-4500, 60th Ed.), Springfield, Virginia (1974).

FIGURE CAPTION

1. Beam power (kW) of representative research electron linacs plotted against maximum beam energy (MeV). The line represents the typical but otherwise arbitrary average current of 100 uA (corresponding to, e. g., I(peak) = 100 mA, DF = 0.1%).

Table 1. Radiation parameters of medical electron accelerators introduced since 1965.[a]

Approx. Date of Introduction	Model	Manufacturer	Beam Energies[a] in Modality: Photons (MV)	Beam Energies[a] in Modality: Electrons (MeV)	Type of Mount or Motion	Limit of Rotation (degrees)	Accelerator: Total Length (m)	Accelerator: Type of Structure	Microwave Generator	Magnetic Beam Deflection (degrees)	Photon Therapy (at 1 m FSD): Maximum Dose Rate (rad/min)	Photon Therapy (at 1 m FSD): Maximum Field Size[b] (cm^2)	Photon Therapy (at 1 m FSD): Nominal[c] Leakage Radiation (per cent)
1964	LUE 5	Efremov	5	---	Isocentric 100 cm SAD	±120	2.3	TW	1.8 MW Magnetron	90	300	18 X 18	0.03
1965	SL 75/10	Philips MEL	7 - 10	4 - 10	Isocentric 100 cm SAD	370	2.25	TW	2 MW Magnetron	95	600 0.3 kW electrons at 8 MeV[d]	30 X 30	0.1
1967	LUE 25	Efremov	10, 15	10 - 25	Stationary: rotational & vertical positioning	-30,+45	6.5 2 Sections	TW	20 MW Klystron	90	1000	18 X 18 20 X 20[b]	0.03
1967	Therac 40 Saggitaire	CGR-MeV AECL	10, 25	7 - 32 (40)	Isocentric 105 cm SAD	±105 (370 with pit)	6.0 2 Sections	TW	9 MW Klystron	+37, -37, +37,-127	400 (1000) 2 kW electron beam[d]	38 X 38	0.1 0.3[c]
1967	LMR 13	Toshiba	10	8 - 12	Isocentric 100 cm SAD	±210	1.6	TW	4.8 MW Magnetron	105 Approx.	400	30 X 30	0.1
1968	Clinac 4	Varian	4	---	Isocentric 80 cm SAD	360	0.3	SW	2 MW Magnetron	Straight Beam	224	40 X 40	0.1 0.3[c]
1969	Mevatron VI	Applied Radiation	6	---	Isocentric 100 cm SAD	370	1.0	SW	2 MW Magnetron	261 Achromatic	300	40 X 40	0.02
1969	Mevatron XII	Applied Radiation	8, 10	5 - 11	Isocentric 100 cm SAD	370	1.3	SW	2 MW Magnetron	261 Achromatic	300	40 X 40	0.1
1970	ML-15MIIB	Mitsubishi	12	8 - 15	Isocentric 100 cm SAD	390	1.7	TW	5 MW Klystron	110	500	30 X 30	0.1
1970	Therapi 4	SHM Nuclear	4	---	Stationary: rotational & vertical positioning	365	0.35	SW	2 MW Magnetron	Straight Beam	220	40 X 40	0.1
1970	Clinac 35	Varian	8, 25	7 - 28	Isocentric 100 cm SAD	360	2.25	TW	20 MW Klystron	+57, -90	1000 5 kW electron beam[d]	35 X 35	0.1
1970	Dynaray 4	Radiation Dynamics	4	---	Isocentric 100 cm SAD	370	0.75	TW	2 MW Magnetron	266 Achromatic	300	30 X 30	0.1
1971	Therac 6 Neptune	CGR-MeV AECL	6	---	Isocentric 100 cm SAD	370	1.1	TW	1.7 MW Magnetron	262 Achromatic	250	40 X 40	0.1
1972	Dynaray 10	Radiation Dynamics	8	3 - 10	Isocentric 100 cm SAD	370	2.3	TW	2 MW Magnetron	266 Achromatic	300	35 X 35	0.1
1972	LMR 4	Toshiba	4	---	Isocentric 80/100 cm SAD	420	0.3	SW	2 MW Magnetron	Straight Beam	225	40 X 40	0.05
1972	LMR 15	Toshiba	10	10 - 16	Isocentric 100 cm SAD	420	1.7	TW	4.8 MW Magnetron	105 Approx.	350	30 X 30	0.1
1973	Therac 20 Saturne	CGR-MeV AECL	10, 18	6 - 20	Isocentric 100 cm SAD	370	2.3	TW	5 MW Klystron	270 Achromatic	400	40 X 40	0.1
1973	SL 75/20	Philips MEL	8, 16	5 - 20	Isocentric 100 cm SAD	360	2.5	TW	5 MW Magnetron	95	400 0.9 kW e^- at 10-15 MeV[d]	30 X 30	0.1
1973	ML-4M	Mitsubishi	4	---	Isocentric 80 cm SAD	380	0.3	SW	2 MW Magnetron	Straight Beam	224	30 X 30	0.1
1974	Clinac 18	Varian	10	6 - 18	Isocentric 100 cm SAD	360	1.4	SW	5 MW Klystron	270 Achromatic	500	35 X 35	0.1
1974	Dynaray 18	Radiation Dynamics	6 - 12	5 - 18	Isocentric 100 cm SAD	370	2.3	TW	5 MW Klystron	266 Achromatic	350	35 X 35	0.1
1974	ML-3M	Mitsubishi	2.8	---	Isocentric 80 cm SAD	380	0.25	SW	2 MW Magnetron	Straight Beam	100	30 X 30	0.1
1975	Clinac 12	Varian	8 (6)	6 - 12 (4 - 9)	Isocentric 100 cm SAD	360	1.2	SW	2 MW Magnetron	270 Achromatic	350	35 X 35	0.1
1975	Clinac 6X	Varian	6	---	Isocentric 80 cm SAD	360	0.3	SW	2 MW Magnetron	Straight Beam	192	40 X 40	0.1
1975	SL 75/5	Philips MEL	4 - 6	---	Isocentric 100 cm SAD	420	1.25	TW	2 MW Magnetron	95	350	40 X 40	0.1
1976	Therac 10 Neptune	CGR-MeV AECL	9	6 - 10	Isocentric 100 cm SAD	370	1.2	SW	2 MW Magnetron	262 Achromatic	300	40 X 40	0.1
1976	Dynaray 6	Radiation Dynamics	6	---	Isocentric 100 cm SAD	370	1.0	TW	2 MW Magnetron	266 Achromatic	300	35 X 35	0.1
1976	LUE 15M	Efremov	15	10 - 20	Isocentric 100 cm SAD	±120	2.6	TW	9 MW Magnetron	270 Achromatic	300 1.5 kW electron beam[d]	30 X 30 20 X 20[b]	0.1 0.2[c]
1977	Mevatron XX	Siemens	10, 15	3 - 18	Isocentric 100 cm SAD	370	1.3	SW	7 MW Klystron	270 Achromatic	300	40 X 40	0.1
1977	Clinac 6/100	Varian	6	---	Isocentric 100 cm SAD	360	0.3	SW	2 MW Magnetron	Straight Beam	200	40 X 40	0.1
1977	Clinac 20	Varian	15	6 - 20	Isocentric 100 cm SAD	360	1.6	SW	5 MW Klystron	270 Achromatic	500	35 X 35	0.1
1977	EMI FOUR	EMI Therapy	4	---	Isocentric 100 cm SAD	360	0.3	SW	2 MW Magnetron	Straight Beam	220	40 X 40	0.1
1977	EMI SIX	EMI Therapy	6	---	Isocentric 100 cm SAD	360	0.3	SW	2 MW Magnetron	Straight Beam	220	40 X 40	0.1
1978	LUE 5M	Efremov	4 - 5	4 - 5	Isocentric 100 cm SAD	±120	0.6	TW	3 MW Magnetron	Straight Beam	200	30 X 30 20 X 20[b]	
1978	SL 75/14	Philips MEL	8, 10	4 - 14	Isocentric 100 cm SAD	360	2.25	TW	2 MW Magnetron	95	350	40 X 40	0.1

(a) Year introduced and original manufacturer are shown. If changes in specifications have subsequently been made, table shows revised values. Data in parentheses are non-standard options offered by manufacturer.
(b) Where two field sizes are given, the first refers to photon beam therapy, the second to electron therapy.
(c) Averaged over 100 cm^2 at 1 m. Where two values are given, the first refers to patient plane, the second to room shielding.
(d) Primary electron beam extracted in research mode (beam power in kW).

Table 2. Radiation characteristics of electron linear accelerators for industrial radiography.

Manufacturer	Model	Nominal Beam Energy (MeV)	RF Power Source (Magnetron or klystron)	Maximum X-Ray Output (unflattened) (rad min^{-1} m^2)	Maximum Field Size (at 1 m) (cm)	Nominal Photon Leakage Radiation (per cent of useful beam at 1 m)
CGR MeV	Neptune 6	6	M	750	50 (diam)	0.1
CGR MeV	Neptune 10	10	M	2000	50 (diam)	0.1
Efremov	LUE-15-1.5	15	M	10 000	30 (diam)	1.0
Efremov	LUE-10-1D	10	M	1800	22 (diam)	1.0
Efremov	LUE-10-2D	10	M	5000	25 (diam)	1.0
Efremov	LUE-15-15000D	15	M	15 000	40 (diam)	1.0
Efremov	LUE-5-500D	5	M	500	35 (diam)	0.2
EMI Therapy	Radiograf 4	4	M	500	26 x 35	0.5
Mitsubishi	ML-1 R II	0.95	M	20	30 (diam)	0.1
Mitsubishi	ML-1 R III	0.45 0.95	M	1.5 15	30 (diam)	0.1 0.1
Mitsubishi	ML-3R	1.5	M	50	30 (diam)	0.3
Mitsubishi	ML-5R	3	M	300	30 (diam)	0.3
Mitsubishi	ML-5 RII	4	M	350	30 (diam)	0.3
Mitsubishi	ML-10R	8	M	2000	30 (diam)	0.2
Mitsubishi	ML-15 RII	12	K	7000	30 (diam)	0.1
Radiation Dynamics	Super X 600	4	M	600	30 (diam)	0.1
Radiation Dynamics	Super X 2000	8	M	2000	30 (diam)	0.1
Radiation Dynamics	Super XX	12	K	6000	30 (diam)	0.1
Varian	Linatron 200	2	M	175	77 x 77	0.02
Varian	Linatron 400	4	M	400	39 x 39	0.1
Varian	Linatron 2000	8	M	2000	55 (diam)	0.1
Varian	Linatron 6000	15	K	6000	27 (diam)	0.1

Table 3. Radiation Parameters of Research and Special-Purpose Electron Linear Accelerators.

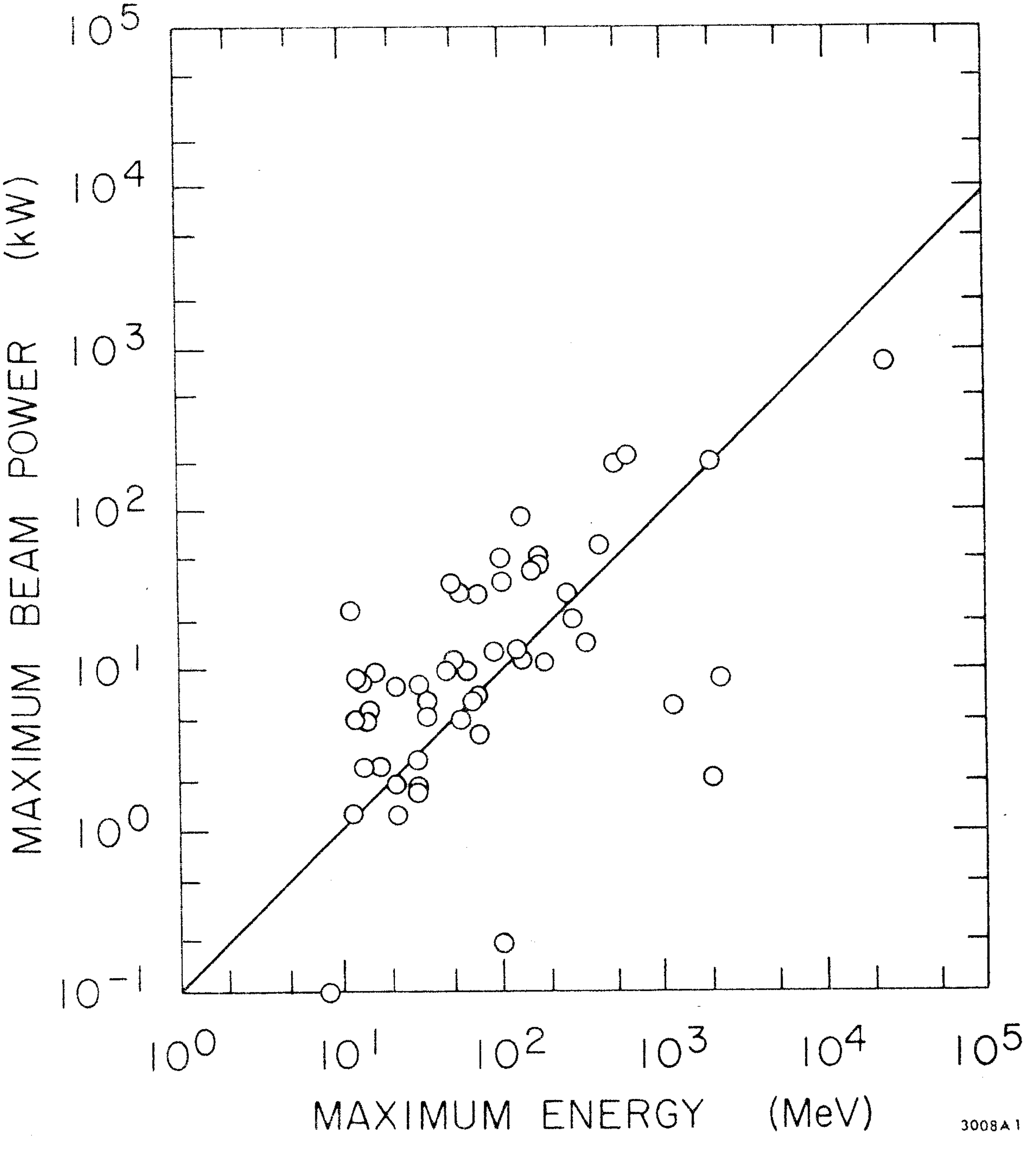
		Installation Location	Nominal Peak Energy (MeV)	Machine Purpose Description	Special Capabilities	(a) Number and Type of Sections	(b) RF Source: Number and Type	RF Source: Peak Power (MW)	Typical High-Power Operation (Approx.): Peak Current (mA)	Energy (MeV)	T_P (us)	Pulse Rate (Hz)	Duty Factor (%)	(c) Electron Power (kW)	
(d)	1	Amsterdam IKO	500	Nuclear physics Nuclear chemistry	n(0 - 500 MeV) Large duty factor	25 TW (S)	12 K	(1-4)	10	250	50	2500	10.	200	1
	2	Argonne	22	Nuclear physics Nuclear chemistry	n(2 - 20 MeV) 250 A in 35 ps at 800 Hz	2 TW (L)	2 K	(20)	2500	14	10	120	0.12	45	2
	3	Bariloche	30	Neutron physics Radiation research	10-100 ns pulses at 100 Hz	1 TW (S)	1 K		300	25	1.2	200	0.024	1.8	3
	4	Bedford RADC	12	Radiation research		1 TW (L)	1 K	(10)	550	10	4.3	180	0.08	5.0	4
	5	Berlin BAM	35	Activation analysis Neutron radiography Radiation protection		2 TW (S)	1 K		180	30	4	300	0.12	6.5	5
	6	Berlin HMI	18	Pulse radiolysis	Nanosecond pulses	1 TW (L)	1 K	(10)	800	12	5	50	0.025	2.5	6
	7	Bethesda AFFRI	55	Radiation research	High current	6 TW (S)	4 K		1000	30	1.0	1000	0.1	30	7
	8	Boeing (Seattle)	30	Radiation research		3 TW (S)	1 K		1100	11.5	5	30	0.015	1.9	8
	9	Bologna	12	Radiation chemistry Radiation biology Radiation physics	Selectable pulse width High current 11 Amps in 10 ns pulse	1 TW (L)	1 K	(10)	1400	6	5	300	0.15	12	9
	10	Bonn	35	Synchrotron injector		1 TW	1 K	(25)	800	20	1	50	0.005	0.8	10
	11	Cornell	246	Synchrotron injector		6 TW	3 K		100	150	2.5	60	0.015	2.3	11
	12	Daresbury	43	Synchrotron injector		4 TW	2 K	(30)	500	43	0.73	53	0.004	0.8	12
	13	Darmstadt DALINAC	70	Nuclear physics	(ee') resolution 30 keV	2 TW (S)	1 K		60	70	5.5	150	0.08	4.0	13
	14	DESY II	400	Synchrotron injector	e+(250 - 380 MeV) DORIS storage rings PETRA storage rings(d)	14 TW	14 K	(25)	200	500	2	50	0.01	10	14
	15	I	50	Second injector		5 TW	5 K	(6)	70	50	1	50	0.005	0.2	15
	16	Frascati CNEN	450	Storage ring injector	e+(60 - 320 MeV) ADONE storage rings	12 TW (S)	6 K	(20)	100	400	3.2	250	0.08	40	16
	17	Geel BCMN	150	Nuclear physics	10 Amps in 3 ns pulse	1 SW (S) 2 TW (S)	3 K		1500	90	0.1	900	0.009	12	17
	18	Ghent	90	Nuclear physics	e+(10 - 40 MeV)	2 TW (S)	2 K	(20)	250	70	2.5	300	0.075	13	18
	19	Giessen GILB	65	Nuclear physics	Mono-E photons(8-35 MeV)	2 TW (S)	1 K		200	65	2	250	0.05	6.8	19
	20	Glasgow I	130	Nuclear physics	n(0 - 10 MeV)	12 TW (S)	3 K	(25)	300	93	3.5	150	0.05	14	20
(d)	21	Glasgow II	30	Nuclear physics	Common beam distribution	2 TW (S)	1 K	(20)	400	19	3.5	240	0.08	6	21
	22	Hammersmith MRC	8	Radiation physics		1 TW	1 M	(2)	25	7	2	300	0.06	0.1	22
	23	Harwell I	55	Nuclear physics	n(0 - 10 MeV)	7 TW (S)	7 K	(8)	500	30	2.0	200	0.04	5	23
	24	II	136	Nuclear physics	n(0 - 30 MeV)	8 TW (L)	4 K	(20)	1000	60	5.0	300	0.15	90	24
	25	Hebrew University (Jerusalem)	8	Pulse radiolysis	Nanosecond pulses	1 TW	1 M		1400	8	0.01	460	0.0005	1	25
(e)	26	Hokaido	45	Neutron diffraction Pulse Radiolysis		3 TW (S)			100	45	3	200	0.06	5	26
	27	Karlsruhe	22	Food preservation		1 TW	1 K		100	16	4	300	0.1	2	27
(e)	28	Kharkov I	500	Nuclear physics						300					28
	29	II	2000	Particle physics		49 TW	51 K	(20)	20	1600	1.2	50	0.006	2	29
(e)	30	Kurgan	8	Product sterilization	Magnetic scanning system	1 TW (S)	1 M	(9)		8				5	30
	31	Kyoto (Osaka)	46	Neutron production	n(0 - 14 MeV)	2 TW (L)	2 K	(10)	500	25	4	180	0.07	10	31
(e)	32	Leningrad	8	Radiation chemistry Product sterilization	Magnetic scanning system	2 TW (S)	1 M	(9)		8				5	32

		Installation Location	Nominal Peak Energy (MeV)	Machine Purpose Description	Special Capabilities	(a) Number and Type of Sections	(b) RF Source: Number and Type	RF Source: Peak Power (MW)	Typical High-Power Operation (Approx.): Peak Current (mA)	Energy (MeV)	T_P (us)	Pulse Rate (Hz)	Duty Factor (%)	(c) Electron Power (kW)	
	33	Livermore LLL	180	Nuclear physics	e- (10 - 180 MeV) Mono-E photons (5-70 MeV) n (0 - 30 MeV)	5 TW (S)	5 K	(15)	650	75	3	300	0.1	45	33
(f)	34	Los Alamos EPA	27	Prototype for protons	Large duty factor Standing-wave	SW (S)	2 K		17	20	500	120	6	20	34
	35	Mainz	320	Nuclear physics	Mono-E phtns (10-100 MeV) n (5 - 150 MeV) Nanosecond pulses	8 TW (S)	8 K	(25)	150	270	3	150	0.04	15	35
	36	Manchester (Paterson Labs)	12	Radiation biology Radiation chemistry	6 Amps in 10-ns pulse	1 TW	1 K	(20)	500	10	5	50	0.025	1.3	36
	37	MIT Bates	400	Nuclear physics	Large duty factor High-res. spectrometer	22 TW (S)	10 K	(4)	10	400	15	1250	1.8	60	37
	38	Monterey NPGS	100	Nuclear physics		3 TW	3 K		30	105	1	60	0.006	0.2	38
(e)	39	Moscow	5	Radiation chemistry	Magnetic defocusing lens	1 TW (S)	1 M	(1.8)		5				0.7	39
(e)	40		8	Product sterilization	Magnetic scanning system	1 TW (S)	1 M	(9)		8				5	40
(e)	41-43	(3 accelerators)	8	Radiation chemistry Product sterilization	Magnetic scanning system	2 TW (S)	1 M	(9)		8				5	41-43
(e)	44		22	Activation analysis	High-intensity brems. Recirculated beam	1 TW (S)	1 M	(9)		22				1.5	44
	45	Moscow Kurchatov	60	Nuclear physics	Neutron production 50 ns pulses at 900 Hz	6 TW	6 K		1000	60	5.5	150	0.1	55	45
(e)	46	Moscow MIFI U-27	10		Neutron production	1 TW (S)	1 M		330	10	3.5	400	0.15	5	46
(e)	47	U-28	11			1 TW (S)			400	11	4	400			47
(e)	48	U-17	30			TW (S)				30					48
(e)	49	Moscow RTI I	60	Nuclear physics			6 K	(25)		60	5.5	50	0.027		49
(e)	50	II	30	Neutron spectroscopy	10A in 10 ns pulse	2 TW	2 K	(15)		30					50
	51	Natick NARADCOM	15	Food preservation Radiation chemistry	Multiple beam ports	2 TW (S)	2 K	(5)	500	10	5	180	0.09	5	51
(e)	52-53	Navoi (2 accelerators)	8	Activation analysis	25000 rad min-1 brems.	1 TW (S)	1 M	(9)		8				7	52-53
(e)	54		15	Activation analysis	25000 rad min-1 brems.	1 TW (S)	1 M	(9)		15				4	54
	55	NBS (Washington)	160	Nuclear physics Radiation standards	n (0 - 20 MeV) e+ (10 - 40 MeV)	9 TW (L)	12 K		250	100	5	360	0.18	40	55
	56	NPL (London)	22	Radiation metrology	5 Amps in 5-ns pulse	2 TW	1 K	(20)	750	15	3.2	240	0.07	8	56
	57	NRC (Ottowa)	35	Nuclear physics	Neutron production	4 TW (S)	1 K		250	35	3.2	180	0.06	5	57
	58	NRL (Washington)	60	Radiation research	Neutron production	3 TW	3 K		450	50	1	360	0.04	10	58
	59	Oak Ridge ORELA	178	Nuclear physics	Nanosecond pulses	4 TW (L)	4 K		15000	140	0.024 K	1000	0.0024	50	59
(e)	60	Ohio State	6	Pulse radiolysis	Nanosecond pulses	1 TW	1 M		325	6	0.01	550	0.0006		60
	61	Orsay	2300	Particle physics	e+ (- 1.3 GeV) Storage rings ACO, DCI	39 TW	39 K	(20,25)	60	2000	1.5	50	0.008	9	61
	62	Raychem (Copenhagen)	17	Product irradiation	High current	1 TW	1 K		1100	10	6	200	0.1	10	62
	63	Rensselaer	100	Radiation research	n (0 - 30 MeV) 6 Amps in short pulse	9 TW (L)	9 K	(10)	300	45	4.5	720	0.32	50	63
	64	Rio de Janeiro	30	Nuclear physics		3 TW	1 A, 1 K		100	28	3.3	360	0.1	2.8	64
	65	RISØ (Roskilde)	14	Radiation research	Nanosecond pulses High current	1 TW	1 K	(17)	1100	10	4	200	0.08	8.8	65

	Installation Location	Nominal Peak Energy (MeV)	Machine Purpose Description	Special Capabilities	(a) Number and Type of Sections	(b) RF Source: Number and Type	RF Source: Peak Power (MW)	Typical High-Power Operation (Approx.): Peak Current (mA)	Energy (MeV)	T_P (us)	Pulse Rate (Hz)	Duty Factor (%)	(c) Electron Power (kW)	
66	Saclay I	70	Radiation research	n(0 - 2 MeV) Mono-E photons(7-40 MeV)	4 TW (S)	4 K		100	70	2	500	0.1	7	66
67	II	600	Nuclear physics	Mono-E phtns(20-120 MeV) Large duty factor High-res. spectrometers (two) Muon, pion beams (20-100 MeV)	30 TW (S)	15 K	(12)	25	400	20	1000	2.0	200	67
68	St. Bartholomews (London)	15	Radiation physics Radiation biology		2 TW (S)	1 K	(20)	750	15	5	100	0.05	6	68
69	San Diego IRT	100	Radiation research	Nanosecond pulses e+(3 - 75 MeV) Mono-E photons(3-75 MeV)	4 TW (L)	4 K	(40)	700	60	4.5	180	0.08	35	69
70	S. Barbara EG&G	30	Radiation research	50-ps pulses	3 TW (L)	2 K		500	20	4.5	180	0.081	8.1	70
71	Sao Paulo USP	50	Nuclear physics		2 TW	2 K		10	50	1	120	0.01	0.05	71
72	Saskatchewan	250	Nuclear physics	n(0 - 150 MeV)	6 TW (S)	2 K	(18)	300	200	1.2	400	0.05	30	72
73	Sendai (Tohoku)	280	Nuclear physics	n(0 - 20 MeV)	5 TW (S)	5 K	(20)	100	280	3.3	300	0.1	20	73
	Stanford Univ.:													
74	HEPL Mark III	1200	Particle physics Pion therapy studies	e+(- 1 GeV) Pion condenser	31 TW	31 K	(20)	30	1200	1.3	120	0.016	6	74
(d) 75	HEPL Supercdg	2000	Particle physics Pion therapy studies Free electron laser	Superconducting linac Duty factor = 100% Recirculated beam	8 SW (L)	8 K	(0.015)	0.1	2000	CW	CW	100.	200	75
76	SLAC	22800	Particle physics	e+(- 15 GeV) Interlaced beams SPEAR storage rings Muon and meson beams Picosecond pulses Mono-E, polarized photons Polarized electrons Energies to 27-35 GeV (SLED) (d) PEP storage rings (d)	960 TW (S)	245 K	(20-40)	70	20000	1.6	360	0.06	800	76
77	Tokai JAERI	190	Nuclear physics	n(0 - 20 MeV)	5 TW (S)	5 K	(20)	350	100	2	150	0.03	11	77
78	Tokyo ETL	33	Nuclear Physics Solid-state physics	180o spectrometer	3 TW (S)	2 K	(7)	200	30	4	300	0.12	7	78
79	Tokyo INS	15	Synchrotron injector		1 TW (S)	1 K	(6)	200	13	1.2	21.5	0.0026	0.07	79
80	Tokyo NERL	35	Neutron Physics Pulse radiolysis	20 ps single pulse	2 TW (S)	2 K	(6.5)	200	35	4	200	0.08	6	80
81	Toronto	50	Nuclear physics	e+(10 - 25 MeV) n(0 - 20 MeV)	4 TW (S)	2 K	(20)	400	35	3.5	240	0.084	12	81
82	Warsaw	13	Pulse radiolysis Radiation research	Nanosecond pulses	2 TW	1 K		800	13	3	300	0.09	9	82
83	White Sands WSMR	48	Nuclear effects	Nanosecond pulses	2 TW (S)	2 K	(20)	600	48	10	120	0.12	35	83
84	Winfrith AEE	15	Radiation research		1 TW (S)	1 K	(10)	200	14	4.5	200	0.09	2.5	84
85	Yale	70	Nuclear physics	n(0 - 20 MeV)	5 TW (L)			700	40	4.5	250	0.11	30	85
(e) 86	Yerevan I	50	Synchrotron injector		2 TW (S)	2 K	(20)	200						86
87	II	480	Nuclear physics Solid state physics Synchrotron radiation	Iterative acceleration e+(- 200 MeV)	4 TW (S)	4 K	(20)	1500	120	8	100	0.08	140	87

(a) TW = traveling wave, SW = standing wave, S = S-band, L = L-band operating frequency.
(b) Number of klystrons (K), magnetrons (M) or amplitrons (A). Peak power rating per unit (MW) given in parentheses.
(c) Parameters simultaneously achievable giving highest electron beam power under continuous operation.
(d) Under construction or design parameters not yet achieved at time of preparation of table.
(e) Unconfirmed or incomplete information at time of preparation of table.
(f) Being installed at Josef Stefan Institute, Ljubljana, at time of preparation of table.

(2/27/78)



MAXIMUM BEAM POWER (kW)
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
MAXIMUM ENERGY (MeV)
3008A1

Fig. 1.