SURVEY ON THE PERFORMANCE AND DEVELOPMENT OF EXISTING PROTON LINACS

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Abstract

A survey of the present and past performances of proton linacs is presented. Developments which brought improvements are described. Present work and future goals are discussed. Special emphasis is put on considerations concerning beam loss and beam loading.

Introduction

This survey covers only existing proton linacs. However, as most of these machines also accelerate other particles, like H^-, d and light or heavy ions, they are included too. One exception has been tolerated: the FMIT, a machine that is designed to accelerate deuterons but which is not quite finished. This linac is very special and its inclusion in the survey, for reasons of comparison, is very instructive. Thus, data in the subsequent tables are sometimes presented for protons and sometimes for H^- or other particles. Data are missing on some tables or graphs because the information was not available or because it was not relevant in this context.

First, we shall discuss the performance and characteristics of the machines as they are now, then, some developments over the last years and finally a selection of future plans will be presented.

Present Performance and Characteristics

Beam Characteristics

Fig. 1 shows design and construction dates of the present machines. As one can notice there was a certain boom in the construction of linear accelerators around 1970.

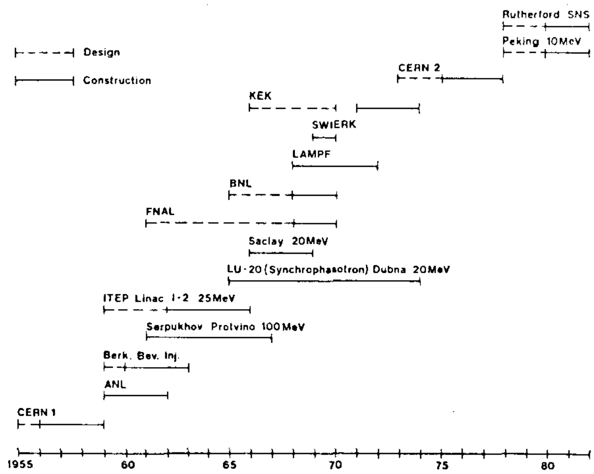

Fig. 1 Design and Construction Dates

rates vary from 1 Hz to 120 Hz. There is a corresponding wide range in duty cycle, beam power and beam mean power.

Fig. 2 presents a scatter diagram of beam currents versus pulse lengths.

The relationship between preinjector current and linac output current is shown in Fig. 3. There is a big difference between most machines and the FMIT which is designed for practically 100% beam transmission. CERN's linac 1 is nearest to this

TABLE I
MACHINE CHARACTERISTICS

LINAC	BEAM CURRENT mA	PULSE LENGTH μs	ENERGY MeV	REP. RATE Hz	DUTY CYCLE (max)	BEAM POWER MW	BEAM MEAN POWER kW
ARGONNE (H^-)	12	50	50	30	1.5×10^{-3}	0.6	0.9
BEIJING (p)	60	50-150	10	12.5	1.9×10^{-3}	0.6	1.1
BNL (p)	100	100	200	10	$1.\ \times10^{-3}$	20.	20.
BNL (H^-)	30	600	200	5	$3.\ \times10^{-3}$	6.	18.
CERN 1 (p)	80	100	50	1	$1.\ \times10^{-4}$	4.	0.4
CERN 2 (p)	150	150	50	2	1.5×10^{-4}	7.5	1.1
FNAL (p)	300	5	200	15	$6\ \times10^{-4}$	16	9.6
FNAL (H^-)	35	20-60	200	15	$9\ \times10^{-4}$	7.	6.3
ITEP	160	30	25	1	$3\ \times10^{-5}$	3.9	0.12
JINR (p)	50	500	20	1	$5\ \times10^{-4}$	1.	0.5
KEK (p)	130	5	20.5	20	$1\ \times10^{-4}$	2.7	0.3
LBL (p)	25	800	19.3	2	1.6×10^{-3}	0.5	0.8
LANL/LAMPF (p)	14	875	800	120	1.1×10^{-1}	11.2	1200.
LANL/FMIT (p)	100	CW	20/30		1.	2/3	2000/3000
RHEL/SNS (H^-)	78	500	70.4	1	$5.\ \times10^{-4}$	5.5	2.8
SACLAY	17	400	20	1	$4.\ \times10^{-4}$	0.34	0.1
SWIERK	1	800	9.6	12.5	$1\ \times10^{-2}$	0.01	0.1

General beam characteristics of the machines are summarized in table I. There is a wide range of beam currents with a minimum just above 1 mA and a maximum of 300 mA. Pulse lengths range from a minimum of 5 μs to cw. The majority are in the few hundred μs range. Their energy is between 10 and 800 MeV. Repetition

performance due to the replacement of the conventional Cockcroft-Walton and its subsequent matching section to the Alvarez linac. The arrow on the graph means that the performance is not yet optimized and that a better one is expected in the near future.

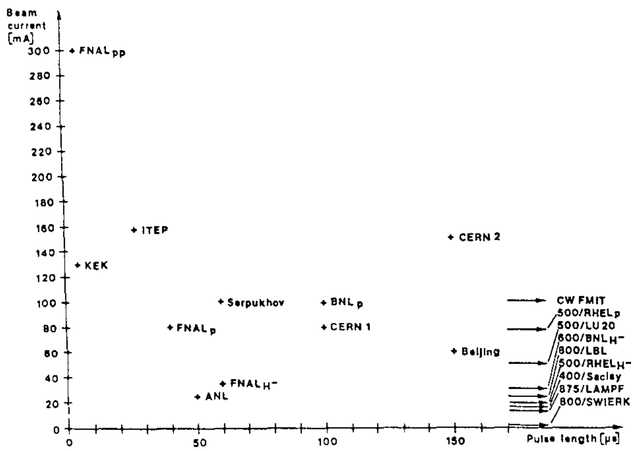

Fig. 2 Scatter diagram of beam currents versus pulse lengths

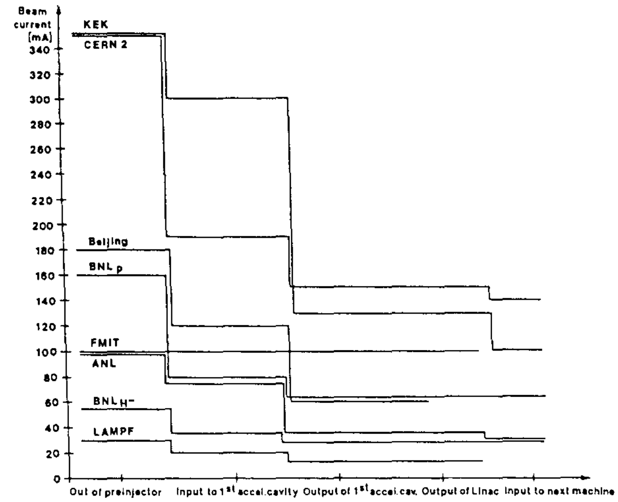

Fig. 4 Beam Current as a Function of Position in the Machine

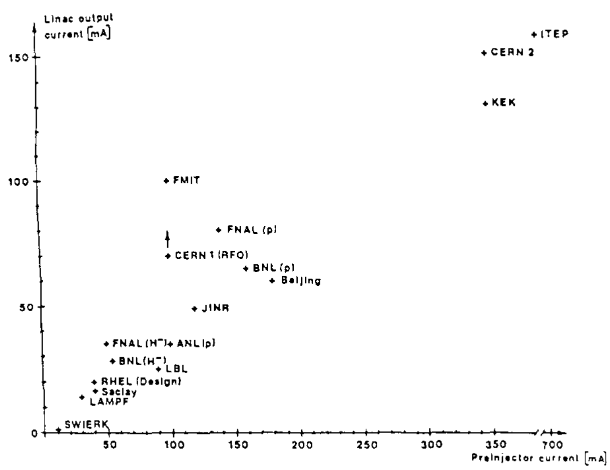

Fig. 3 Relationship between preinjector current and linac output current

Fig. 4 shows the development of the beam current as it passes through the accelerator. No major differences can be seen between the various machines, except for the FMIT. CERN's linac 1 lies in between.

Beam emittance data at the entrance and the exit of different linacs versus the input current are presented in Fig. 5. The points on the two curves show old data collected by C. Curtis[1]. The isolated points respresent new data which indicate a general decrease in the emittance values.

Machine Characteristics

RF (table II). Most accelerators work at around 200 MHz, except the side-coupled part of the linac at LAMPF and FMIT. The majority use Thomson Houston tubes, whereas the large American accelerators are using RCA tubes, with the exception of the FMIT which uses an EIMAC tube. Most tubes are cooled by water or boiling water, except for the JINR which uses air-cooling.

TABLE II
SOME RF PARAMETERS

	FREQUENCY	RF POWER TUBE	COOLING OF TUBE	RF STABILITY		WINDOW	POSITION OF WINDOW
ARGONNE	200	RCA 7835	water	.5%	1°	ceramic	waveguide
BEIJING	201.25	TH 116	water	1%	1°	alumina	in tank
BNL	201.25	RCA 7835	water	.25%	.5°	ceramic	tank
CERN 1	202.56	TH 470/516	boil.water	now as CERN 2		teflon	coax. line
CERN 2	202.56	TH 170	water	1%	1°	ceramic	coax. line
FMIT	80	Eimac	water	1%	1°	ceramic	prior to coupl.loop
FNAL		RCA 7835	water	.3%	.2°	ceramic	in press.feeder line
ITEP	148.5	GI-27A	water/air	0.8%	0.5°	glass epoxy	middle of resonator
JINR	146	?	air	1%	?	teflon	in feeder line
KEK	201	TH 516	boil.water	?	?	alumina	tank wall
LAMPF	201.25 (805)	7835	boil.water	.2%	.2°	Rexolite Beryllia	near tank wall
LBL 200 MeV	199.3	TH 515	boil.water	?	?	--	near tank wall
RHEL/SNS	200	TH 116	water	?	?	cross-linked polystyrene	vacuum side of loop
SACLAY	200	TH 515	boil.water	1%	--	teflon	coax. line
SWIERK	193	?	air	?	?	teflon	in feeder line

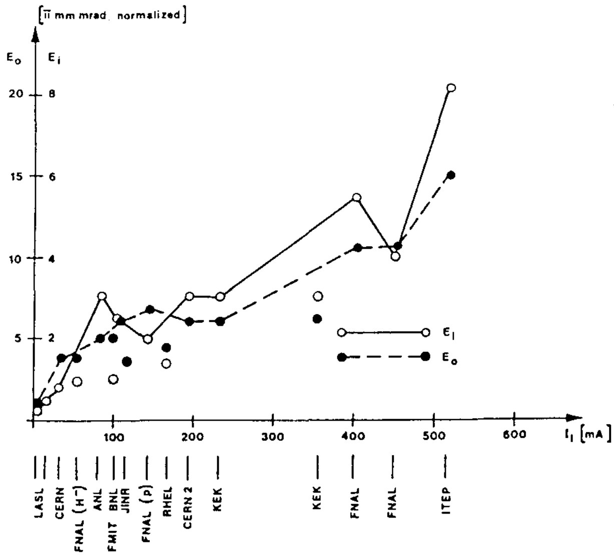

Fig. 5 Beam Emittances at Entrance and Exit of linac

The RF stability is in the range between 1% and 1° and .2% and .2°. High duty cycle and high energy linacs have a tendency to use the tighter tolerances. Ceramic is dominant as window material and is usually placed in the feeder-line.

Vacuum. Tables III and IV present some general vacuum characteristics. Oil and mercury diffusion pumps become scarce. Some cryo pumping is being used, but the majority are ion and turbo-molecular pumps. Pumping speeds are between a few hundred ℓ/s and 10 k ℓ/s. Higher pumping speeds are required for H^- preinjectors and for high duty cycle machines.

Pressures in the preinjectors and LEBTs range between 10^{-8} and 10^{-4} mbar. In the accelerating structures they lie between 10^{-8} and 10^{-6}. Pressures in the HEBT are similar.

Beam Measuring Equipment

Table V shows how many beam transformers, position monitors, spectrometers and emittance measuring devices are installed in the different machines. Other special instrumentation includes beam loss monitors, profile monitors, monitoring equipment in the secondary beams (related to the characteristics of the primary beam), capacitive pick-up electrodes for measuring the RF phase of the beam and destructive fast probes for measuring longitudinal bunch density distributions.

TABLES III and IV
VACUUM CHARACTERISTICS

	PREINJECTOR				LEBT			
	NO.	TYPE	SPEED (ℓ/s)	PRESSURE (mbar)	NO.	TYPE	SPEED (ℓ/s)	PRESSURE (mbar)
ARGONNE	2	turbo	1500	$2x10^{-4}$	4	cryo	1000	$2x10^{-6}$
BEIJING	2+1	ion,	1500,1600	$2x10^{-5}$	1	turbo		
		sputterion				sputterion	450/200	$2x10^{-6}$
BNL	2	turbo/ion	750/1500	$2x10^{-7}$	3/5	turbo/ion	160,1500	$2x10^{-2}$
CERN 1	6+2	turbo, ion	450/1500	$2x10^{-5}$, $1x10^{-6}$	0	--	--	--
CERN 2	4	turbo, ion	1500, 500	$2x10^{-5}$	3	turbo, ion	450	$5x10^{-7}$
FNAL	2	ion,turbo	2400,250	$3x10^{-6}$	0	--	--	$3x10^{-6}$
ITEP	18	Ti.dischge.	220	$2x10^{-6}$	-	--	--	--
JINR	1	oil diff.	5000	$1x10^{-6}$	0	--	--	$1x10^{-6}$
KEK	1+3	turbo, ion	650/5000	$2x10^{-4}$, $1x10^{-7}$	1+15	turbo, ion	1000,140	$2x10^{-4}$, $2x10^{-8}$
LANL/LAMPF		ion	400/5000			ion	400/5000	
LANL/FMIT	1	oil diff.	10 000	$2x10^{-6}$	1	cryo	2000	$1x10^{-6}$
LBL	3	turbo	1200	$2x10^{-6}$	1	turbo	800	$5x10^{-7}$
RUTHERFORD	2	turbo	2200	$1x10^{-5}$	1	turbo	330	$2x10^{-6}$
SACLAY	1	merc.diff.	2000	$1x10^{-5}$	1+1	turbo, ion	450, 200	$5x10^{-7}$
SWIERK	2	oil diff.	1000	$8x10^{-6}$		--	--	--

VACUUM CHARACTERISTICS

	TANKS				HEBT			
	NO.	TYPE	SPEED (ℓ/s)	PRESSURE (mbar)	NO.	TYPE	SPEED (ℓ/s)	PRESSURE (mbar)
ARGONNE	7	ion	2000	$3x10^{-7}$	3	turbo	270	$1x10^{-6}$
BEIJING	6	turbo,ion	450/1000	$1x10^{-6}$				
BNL	54	ion	1500	$1x10^{-7}$	15	turbo	150-1500	$1x10^{-7}$
CERN 1	6	turbo	1500	$2x10^{-6}$	2	ion	450	$1x10^{-7}$
CERN 2	(6	turbo)	(450)					
	10	ion	1000	$1x10^{-7}$	6	ion	450	$1x10^{-7}$
FNAL	52	ion	1000	$5x10^{-8}$	7	ion	600	$1x10^{-7}$
ITEP	34	Ti. discharge	220	$5x10^{-6}$	16	Ti. dis.	220	$2x10^{-6}$
JINR	11	oil diff.	5000	$5x10^{-7}$	2	oil diff.	5000	$2x10^{-6}$
KEK	12	ion	1000	$4x10^{-7}$	6	ion	400	$1x10^{-6}$
LANL/LAMPF		ion	400/5000	$1x10^{-7}$		ion	400/5000	
LANL/FMIT	4+2	ion	3500	$1x10^{-6}$	4	cryo	2000	$1x10^{-6}$
LBL	4+7+1	cryo,ion,turbo	500, 1500, 800	$2x10^{-7}$	2	turbo	1200	$4x10^{-6}$
RUTHERFORD	13	turbo	2200	$1x10^{-6}$	3+2	turbo,ion	270,2200,400	10^{-6} / 10^{-8}
SACLAY	2+4	turbo, ion	1500,1000	$5x10^{-8}$	8,11	turbo,ion	450, 200	$5x10^{-7}$
SWIERK	34	oil diff.	5000	$1x10^{-6}$	1	oil diff.	800	$1x10^{-5}$

TABLE V
BEAM MEASURING EQUIPMENT

	before + between					after linac				
	BT	PM	S	EM	OTHERS	BT	PM	S	EM	OTHERS
ARGONNE	3	-	-	-		3	12	-	-	
BEIJING	6	1	-	2		3	1	1	1	
BNL	15+2	8	-	7		16+4	7	1	1+1	
CERN 1	4	-	-	-		6	-	1	1	
CERN 2	6	(slits)	-	2	fastprobe	6	8	2	2	cap.prob.
FERMILAB	21	4	-	3		9+4	13+5	1	3 wire scan.	
ITEP	5	1	-	1		7	1	1	1	quartz plat.
JINR	1	--	--	--		6	--	1	1	
KEK	7	-	-	1	profile monitor	4+1	-	1	quad.+ prof.monitor	
LBL	1	3	1	1		1	3	1	2	3 profile
LANL (LAMPF)	50	100	-	7		8	19	1(1)	meas.profile	sec.channel
LANL (FMIT)	2	25	1	4		2	4	-	12	TOF
RUTHERFORD	6	-	-	1	loss monitor	5	14	1	-	8 loss monitors
SACLAY	1	1	--	1		8	15	1	1	
SWIERK	1	-	-	1	quartz plates	1	-	-	1	-

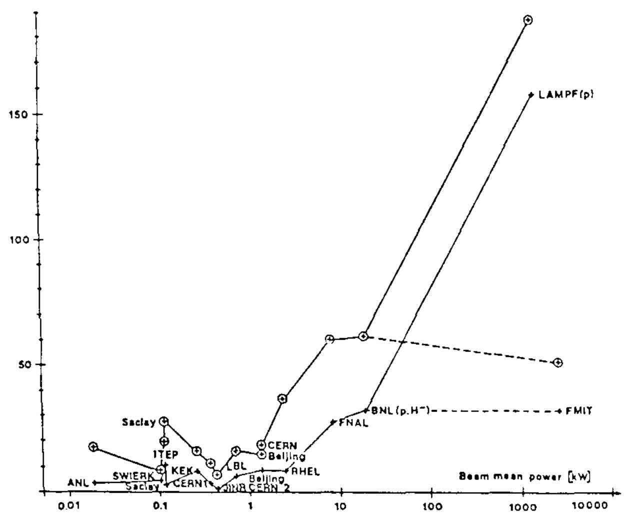

Fig. 6 Number of Beam Measuring devices versus Beam Mean Power

Fig. 6 shows the correlation between the number of beam measuring devices and the beam mean power for different machines. In this simple graph no attempt has been made to distinguish between more or less sophisticated instruments. The lower curve shows the number of beam measuring devices in and before the accelerator, the upper curve displays the total number including the devices in the high energy beam transport line. It seems there is a strong correlation with the beam mean power, which is comprehensible because beam mean power is a product of beam energy and beam mean current. The energy is obviously related to the length of the machine. The number of monitoring devices increases normally with the length and hence with the energy. The average beam current is responsible for beam damage and requires tighter tolerances for different parameters. This, again, yields a larger number of beam measuring devices. Therefore, the general trend of the two curves in Fig. 6 is understandable. The two points for the FMIT may indicate either some progress in understanding and controlling the accelerator beams, or simply the fact that this machine is not yet operational.

Operational Statistics (see table VI)

All machines are running for several thousand hours per year. Faulttimes range from well below 1% to 15%. There is a strong correlation with the complexity of the machine and with the number of "beam users". Of all subsystems the RF generally causes the highest percentage of downtime.

TABLE VI
FAULTTIME AND RUNNING TIME OF SOME MACHINES

	PI	RF	BEAM TRANSP.	VAC	OTHERS	TOTAL % OF RUNNING TIME	HOURS/ YEAR
ANL	30	40	10	10	10	1	4000
BEIJING	--	--	--	--	--	--	--
BNL	45.6	29.4	1.5	8.8	14.7	6.8	6003
CERN 1	--	--	--	--	--	1.	3000
CERN 2	11	45	29	0	15	.67	6618
FNAL	10	80	-----10------		--	2	7500/8000
ITEP	69	13	10	0	8	1.3	6260
JINR	?	?	?	?	?	1	4000
KEK	2.3	71.3	24.1	1.2	1.2	0.87	4000
LAMPF	20	35	----------45----------			15	3650
RHEL/SNS	--	--	--	--	--	--	--
SACLAY	50	50	--	--	--	10	2500

Power Consumption and Efficiency (see table VII)

The machine mains consumption ranges from .1 MW up to 18 MW and the beam mean power from .1 kW to 2000 kW. This results in efficiencies between 1 x 10^{-3} and .18. The higher efficiencies belong naturally to the machines with higher energies and larger duty cycles.

TABLE VII
EFFICIENCY OF MACHINES

	MACHINE CONSUMPTION (MW)	BEAM MEAN POWER (kW)	EFFICIENCY x 1000
ARGONNE	.45	.9	2.
BEIJING	.24	1.1	4.58
BNL (p)	2.08	20.	9.6
BNL (H^-)	2.08	18.	8.6
CERN 1	.3	.4	1.33
CERN 2	.30	1.1	3.7
FNAL (p)	1.2	9.6	8.0
FNAL (H^-)	1.2	6.3	5.3
ITEP	--	0.1	--
JINR	--	0.5	--
KEK	.3	0.3	1.
LBL	--	.8	--
LANL/LAMPF	18.	1230	68.
LANL/FMIT	11.0	2000	182.
RUTHERFORD	1.5	2.8	1.9
SACLAY	--	0.1	--
SWIERK	0.1	0.1	1.

Some Developments over the last Years

For practically all machines improvements in technology have brought along increases in beam current intensity and better stability for the RF. The latter holds especially for machines with higher beam mean power where beam losses are more dangerous.

On the vacuum systems diffusion pumps were frequently replaced by turbo-molecular pumps and some cryo pumps were substituted for ion pumps.

Argonne

After a conversion to polarized protons, the machine ran with these particles until 1979. Afterwards, the source was replaced by a H^- magnetron, the repetition rate increased from .25 Hz to 30 Hz and the machine served as injector for the intense pulsed neutron source (IPNS).

Brookhaven

This linac has also been converted to H^- operation using a H^- magnetron source and two preinjectors. A polarized H^- source has recently been installed, together with a RFQ, as a third pre-injector. Beam loss monitoring devices, using ionization chambers, are in regular use as warning system.

CERN Linac 1

As mentioned above, the mercury diffusion pumps on the preinjector and on the tanks have been replaced by turbo-molecular pumps. It is interesting to note that electricity and water savings, made due to this change, paid for the new installation after about 3 years.

The programmed RF beam load compensation introduced specially to make the long pulses necessary for the booster was replaced by a fast feedback system for level and phase on the low level part of the RF.

Quite recently, the old-fashioned electrostatic generators on the preinjector have been replaced by an RFQ capable of high intensity (80 mA) proton operation. This RFQ is mounted directly on tank 1 together with a longitudinal matching cavity which allows the correct matching of the bunch to the acceptance of the tank.

Beams of deuterons and alpha particles using the two $\beta\lambda$ mode have been produced well above the 10 mA level.

CERN Linac 2

No major improvements have been necessary. Some beam loss monitors were installed in the high energy beam transport line to keep the amount of beam induced radiation low. Deuteron beams have been produced exceeding 20 mA.

Fermilab

As this machine has to satisfy different user requirements, e.g. cancer therapy, it proved useful to run with H^- particles and to modulate the pulse length as appropriate. Two injectors were installed using H^- magnetron sources.

A beam loss monitor system using pairs of ionization chambers is installed after tank 4 and in the high energy beam transport line. In case of abnormal beam losses or matching problems this set-up proves extremely useful.

Some improvements were made to the RF modulators resulting in better stability. The control system was changed to micro-processors.

JINR

Beams of 16 mA deuterons and 1.2 mA alpha particles were accelerated. With a laser source 3 mA of Li, 4 mA of C, .5 mA of O and 1.5 of Mg of 5 to 10 us duration at 5 MeV/n (2 $\beta\lambda$ mode) are reported.

KEK

A polarized ion source with a separate Cockcroft-Walton was installed. Alpha beams of .1 mA (preinjector: 1 mA) have been produced.

Los Alamos LAMPF

Continuous development of H^- beams, especially the replacement of the H^- injector, yielded a peak of 15 mA from the injector and 10 mA accelerated up to top energy. The transition region between the Alvarez and the side-coupled linac was replaced to permit independent matching and phase control of the two beams.

Los Alamos / FMIT

The operation of the RFQ with 240 kW in cw caused some minor problems due to local heating. For the same reason high pumping speeds are used and are necessary.

Berkeley

This machine was running since 1971 in the 2 $\beta\lambda$ mode for d, C and N ions with a charge/mass ratio of more than 1/3. Now, the tank has been separated into two different RF cavities with an intermediate stripper. The first is capable of coping with a charge/mass ratio down to 1/7, whilst the second can go to .36. The RF system was rebuilt using pieces from the old 50 MeV linac.

Rutherford

This linac has been converted into an injector for the spallation neutron source (SNS) by installing a Penning surface plasma H^- source and increasing the repetition rate from 1 Hz to 50 Hz. Graphite inserts are used in the first drift tubes of tank 2 to limit the beam loss downstream.

Saclay

The focusing system was converted from ++-- to +- by making use of the increased current capabilities of pulsed power supplies. Polarized particles (p, d) were accelerated with a set-up called Hyperion 1. Quite recently ions (up to 6 x 10^9 charges of e.g. N, C and Ne) were accelerated from Cryebis and via a special RFQ (Hyperion 2).

Some future Plans

Argonne

It is planned to upgrade the ion source and to increase the repetition rate to achieve 100 A average. Some thoughts are being given to a 200 MeV machine with larger duty cycle for a 4 mA average current.

Beijing

Some upgrading is foreseen for the repetition rate (up to 20 Hz) and for the current (up to 80 mA). The present 10 MeV energy will go up to 35 MeV. Later,the Cockcroft-Walton will be replaced by a RFQ.

BNL

RFQs will be substituted for all Cockcroft-Waltons. There are, at the moment, no plans to accelerate ions in the linac (the AGS will be supplied with ions by another machine).

CERN Linac 1

As the low energy antiproton ring (LEAR) requires H^- beams for machine setting-up and for physics experiments, the production of these beams is planned for the very near future (around 2 mA).

A project has been approved to accelerate O^{6+} beams up to 12 MeV/n and subsequent stripping to O^{8+}. These beams will be further accelerated by the CERN accelerator complex (PSB, PS and SPS)[3]. The design, manufacturing and installation of the ECR ion source, a special RFQ and the necessary upgrading of linac 1 will be done in a collaboration between CERN, GSI and LBL[4].

CERN Linac 2

Production of α beams is scheduled for the not too distant future, using the same technology[5] of stripping a He^{1+} beam developed for linac 1. Plans are being pursued for the replacement of the Cockcroft-Walton by a RFQ.

FNAL

Some thoughts have been given to the development of RFQs, to the increase of the linac energy and possibly its replacement by a higher frequency machine.

KEK

The introduction of a new multi-cusp H^- source is foreseen for 1985 together with the development of a RFQ. The increase of the output energy up to 40 MeV is also planned.

Los Alamos / LAMPF

The polarized H^- source will be replaced by a higher intensity one, either of atomic beam type or optically pumped.

The aim is to reach 25-30 nA with a peak current of 250 to 350 nA. These intensities are needed for the polarized neutron programme.

Los Alamos /FMIT

The replacement of large ion pumps by cryo pumps is planned because the latter are more effective for hydrogen pumping.

Conclusions

There has been a continuous development towards higher intensities, larger duty cycles and the application of more modern technologies.

Machines, originally foreseen for protons, are now accelerating H^- beams, polarized particles, deuterons, alpha particles and even heavier ions.

The installation of RFQ's on new facilities and the replacement of existing Cockcroft-Walton preinjectors by RFQ's is an ongoing development on most machines.

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