LINAC POSTACCELERATORS FOR TANDEM MACHINES

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Summary

Linear accelerators as postaccelerators have become an accepted tool for increasing the final energy of tandem accelerators. This special application of linacs requires an extreme flexibility to cope with a wide velocity and specific charge range of ions while maintaining the excellent beam quality of the electrostatic machines. These requirements can best be fulfilled by choosing independently phased accelerator resonators of the spiral, splitring or quarter wave type in either normal or superconducting technology. Basic design considerations for postaccelerators are discussed and a survey about the major projects, operational or planned, is given.

Introduction

The electrostatic tandem accelerators have been among the most versatile and indispensable instruments of nuclear and atomic physics for more than a quarter of a century now. Their total number must have reached the one-hundred mark, and their development has culminated in such impressive installations as the 20-25 MV supertandems in Daresbury[1], Oak Ridge[2] and Jaeri[3]. Both the Daresbury and the Oak Ridge tandems now routinely provide heavy ion beams at terminal voltages of about 20 MV.

There are virtues of tandems, which must be maintained when considering boosting their final energy by the addition of any kind of postaccelerator. There is first of all the excellent transversal and longitudinal beam quality with an emittance of about 1 $\pi \cdot$ mm rad and an energy resolution of $\Delta E/E$ of typically $1 \cdot 10^{-4}$. Furthermore a tandem is intrinsically a DC machine, and its full energy variability, as well as the capability to accelerate any element which can be provided as a negative ion, make the tandem machines one of the most flexible accelerator systems available.

The mostly adopted solution to close the energy gap between the medium-size tandems with terminal voltages of around 12 MV and the supertandems was the addition of suitable linear accelerators as boosters.

General Requirements

The achievable final energy is only one important parameter in the design of postaccelerators. It is furthermore very essential that the combination of an electrostatic machine with an RF linear accelerator should maintain the excellent beam quality of the tandem, while being operational with a very high flexibility over as wide a mass range as possible. What this flexibility requirement means, having a tandem as an injector to a linac, is demonstrated in the diagram of fig. 1. Ion velocities as a fraction of the speed of light are plotted there vs. the ion mass as one finds them at a 12 MV tandem with a foil stripper in the terminal. As the charge states selected are always somewhere between the most probable ones and higher ones still compatible with intensity requirements, there is no unique curve but a whole band of possible velocity values, ranging from about 0.04 c at the highest masses to about 0.14 c at ^{12}C.

Besides the velocity of the ions, their specific charge q/A is an essential parameter which is further given in fig. 1 for those cases where the ions have been stripped to higher charge states in a final foil

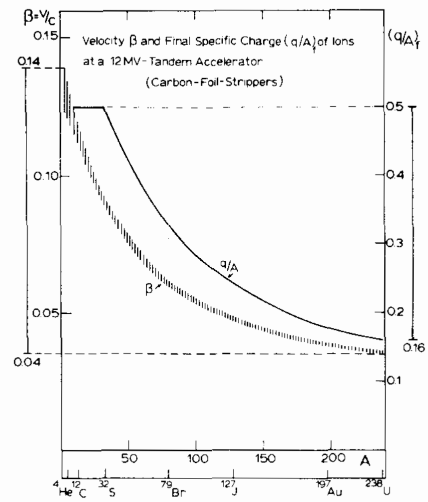

Fig. 1. Specific energy E/A and specific charge q/A of ions to be postaccelerated behind a 12 MV tandem accelerator.

stripper behind the tandem to enable a highly efficient postacceleration in the booster. Values for q/A range from 0.5 for light ions to 0.16 for the heaviest ones. So a linac postaccelerator had to have a high degree of flexibility in two respects: It had to provide acceleration voltage equally effective for ions varying in velocity at injection by more than a factor of three, while having at the same time quite different specific charges. These extreme requirements could not be fulfilled with long accelerating structures, where one specific velocity profile has been once and forever fixed during construction of the machine. The solution was a linac consisting of a multitude of short structures with as small a number of accelerating gaps per resonator as possible, and a truly independent phasing of the individual resonators. This way it would be possible to program almost any arbitrary velocity profile whatsoever[4].

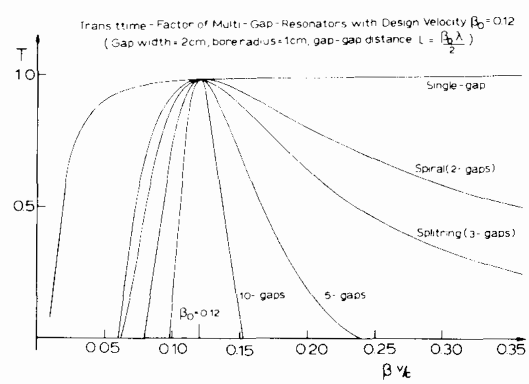

Fig. 2. Transit time factor T as function of particle velocity $\beta = v/c$ for resonators with 1, 2, 3, 5 and 10 gaps.

The parameter commonly used to describe the flexibility of a linac structure is the transit time factor T plotted in the diagram of fig. 2 for resonators with 1, 2, 3, 5 and 10 gaps as a function of the particle velocity for a design velocity of $\beta = 0.12$. Clearly the single-gap resonators would provide an ideal solution, as one type of resonator could be used for a complete machine. The two-gap resonator will maintain 70% of its efficiency in the beta range of 0.08 to 0.24, while a three-gap resonator has the same efficiency between $\beta = 0.09$ and $\beta = 0.19$. A further increase of the gap number clearly limits the useful beta range, so it is quite understandable that linac postaccelerators designed for highest possible flexibility make use of two- or three-gap structures almost exclusively. It is common practice, however, to install several groups of resonators identical in the design velocity following the velocity increase in the postaccelerator for a specific design particle.

Fig. 3 shows examples of two- and three-gap resonators used in postaccelerators.

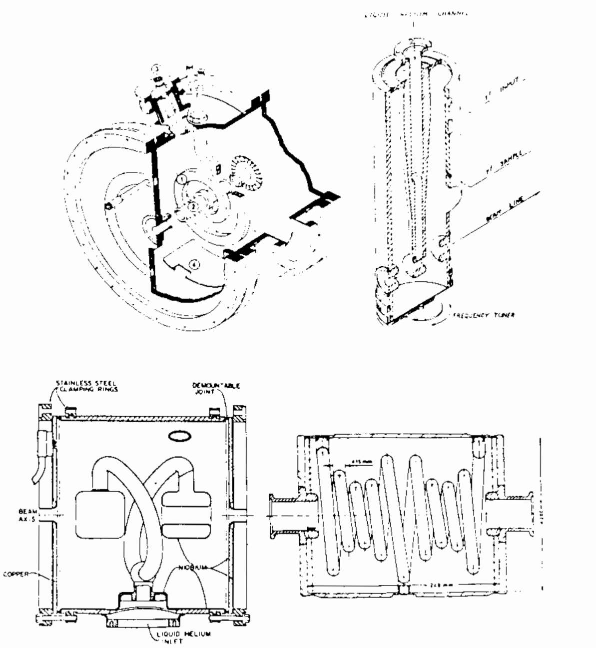

Fig. 3. Resonators frequently used in postaccelerators. a: spiral[6], b: quarter wave[9], c: splitring[10] and d: helix resonators[14].

The spiral resonator, a two-gap resonator originally developed by Dick and Shephard[5] as a superconducting device, is operating now in Heidelberg[6], Frankfurt[7], and Bucarest[8] in normal conducting machines.

The spiral element extending between the resonator tank and the drift tube, forming the two gaps a distance $L = \beta\lambda/2$ apart, is a quarter wavelength line.

A close relative to the spiral resonator is the superconducting quarter wave resonator of I. Ben-Zvi and J. Brennan[9]. Here the resonating element has been straightened, the number of accelerating gaps still being two. This resonator is mechanically extremely stable. If one exchanges the spiral element by a half wavelength line, one gets a splitring. The two drift tubes excited in push-pull form the three accelerating gaps. While the original development had been done in superconducting technique in Argonne[10] and Stony Brook[11], normal conducting species are being used in the Heidelberg[12] and Frankfurt[13] boosters. The last structure in fig. 3 has at first glance nothing in common with the ones previously discussed. The axial electric field of this helix resonator is however very similar to the one of a three-gap resonator, so also this structure, developed in Karlsruhe[14] and Saclay[15], for superconducting applications is a choice for a flexible postaccelerator.

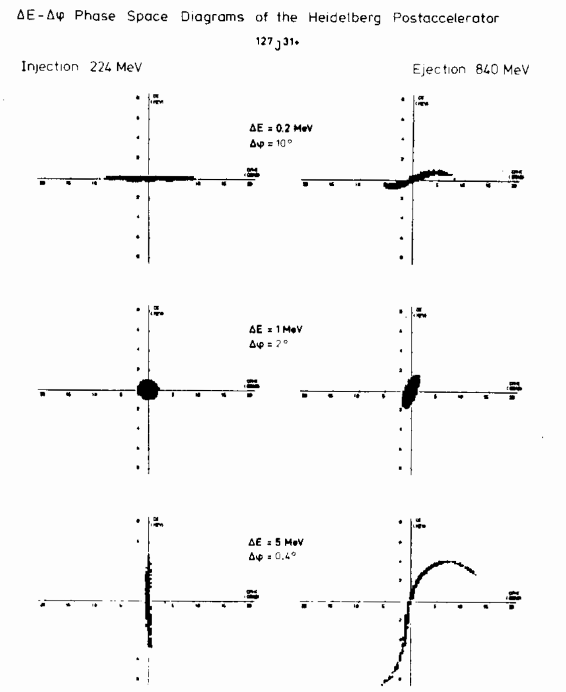

Fig. 4. Computer simulation of the postacceleration of a 224 MeV $^{127}J^{31+}$ beam in the Heidelberg booster[16].

That an array of independently phased short booster resonators does indeed maintain the beam quality of a well-bunched and properly matched tandem beam can be seen from the computer simulation of a run at the Heidelberg booster[16]; see fig. 4. It shows the postacceleration of 224 MeV $^{127}J^{31+}$ ions to a final energy of 840 MeV. The same longitudinal emittance determined mainly by the two stripping processes involved has been formed by the buncher in front of the linac to three injection ellipses of equal area: 2 MeV x 10 degrees, 1 MeV x 2 degrees and 5 MeV x 0.4 degrees. Operating frequency is 108.48 MHz, synchronous phase is $\phi_S = -20$ degrees. It is evident that, although the areas at injection are equal, a proper match to the linac resulting in a compact and undiluted phase space is only achieved in the second case. Debunching this compact ellipse after the machine is routinely done to restore energy resolutions in the 10^{-4} range.

Resonator Technologies

Three examples of technologies used in the realization of independently phased linac boosters will be discussed.

An example of normal conducting machines is the Heidelberg MP-Tandem Postaccelerator combination, the first one to use the independent phasing principle in a booster application as early as 1977[17]. The resonators installed there are spiral and splitring resonators. An example of the former type can be seen in fig. 5 which shows an opened spiral resonator, so its main components can be clearly identified: the spiral element with the active drift tube, the grounded drift tubes, coupling loop and the capacitive tuning plate. The inner tank diameter is 35 cm. The resonator tank and flanges are made of solid copper; the surface finish is obtained by mechanical grinding and polishing. The spiral itself is formed from a hollow copper profile bent in one piece around the drift tube and back. After fabrication it is high-quality electroplated.

The characteristic data of these resonators are summarized in table Ia, while the data for the newer

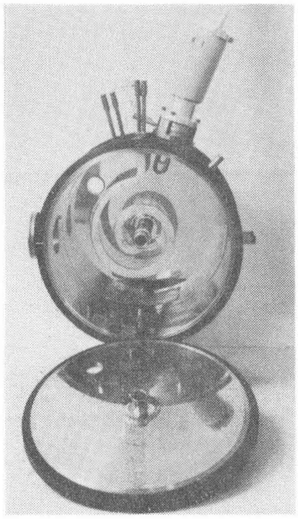

Fig. 5. View into an opened spiral resonator of the Heidelberg design.

TABLE IA

CHARACTERISTIC DATA SPIRAL RESONATORS

Frequency f (MHz)	108.48
Quality factor Q	3500
Design velocity $\beta = v/c$	0.06-0.08-0.10
Shunt impedance Z (Mohm/m)	40 to 30
Maximum voltage U (MV)	
(20 kW CW)	0.33
(80 kW 1:4)	0.66

TABLE IB

CHARACTERISTIC DATA SPLITRING RESONATORS

Frequency f (MHz)	108.48	
Design velocity $\beta = v/c$	0.12	0.04
Quality factor Q	4500	4300
Shunt impedance Z (Mohm/m)	33	57
Maximum voltage U (MV)		
(20 kW CW)	0.52	0.46
(80 kW 1:4)	1.04	0.92

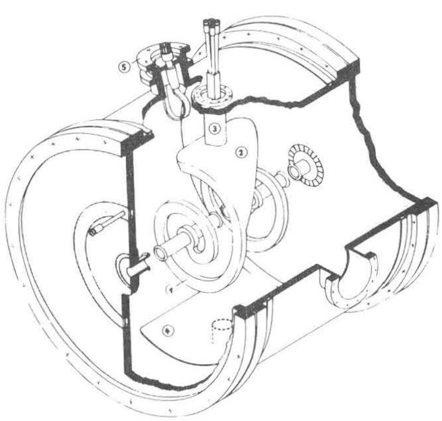

Fig. 6. Cut drawing of a $\beta = 0.12$ normal conducting splitring resonator.

development - the splitring resonator - are given in table Ib. Fig. 6 is a cut drawing of a splitring resonator; two spiral elements with one common leg form the half wavelength line with the two drift tubes. In the region of the current maximum the surface area has been enlarged to keep losses low. The Heidelberg machine uses all together 32 spiral and after the insertion of the new low-beta module 8 splitring resonators. In the pulsed operating mode the maximum acceleration voltage will be above 25 MV.

The resonators in all linac postaccelerators can normally be grouped in a modular fashion with external focusing elements like solenoids or quadrupole lenses only inserted after a certain number of resonators, typically two to four. This is possible, as the velocity of the ions to be accelerated is already quite high at a tandem and as the synchronous phase can be selected relatively small (typically 20 degrees) because the longitudinal beam quality of a tandem allows the bunching into a phase width of a few degrees. Fig. 7 shows a module of the Heidelberg machine consisting of four identical resonators. One quadrupole doublet is sufficient to compensate the radial defocusing in the acceleration gaps and to ensure an acceptance one order of magnitude larger than the typical emittance of an ion beam from the tandem.

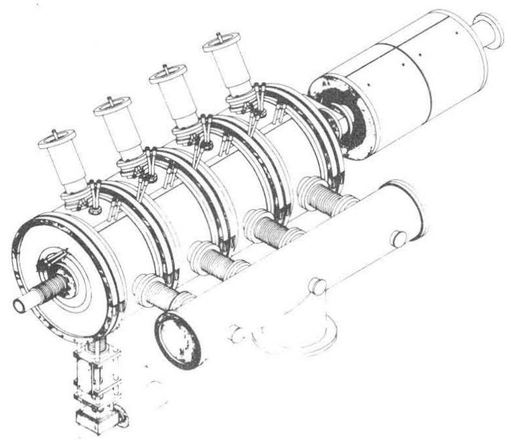

Fig. 7. Resonator module of the Heidelberg postaccel- consisting of four spiral resonators and one quadrupole doublet.

A very ingenious, high-efficiency, low-cost solution of a normal conducting postaccelerator has been designed and built by Morinaga and Nolte for the Munich postaccelerator[18]. This multigap IH structure has been in operation since 1977 at one beam pipe of the Munich tandem laboratory. It operates at 78 MHz, has an extraordinary shunt impedance of 150 Mohm/m and thus only needs 35 kW to produce 5 MV accelerating voltage. A second tank of double the frequency will be added in the future. There is a detailed description in a contribution to this conference[19].

Now turning to the superconducting solutions, table II summarizes some facts about RF superconductivity and the two materials used for resonators, niobium and lead.

Table II

RF - Superconductivity

Surface Resistance :

$$R_S(\Omega) = \text{const}_{BCS} \cdot \frac{f^{1.8}}{T} \exp\left(-1.9\frac{T_C}{T}\right) + R_0$$

f = 100MHz	T_C (°K)	B_C(4.2°K) (G)	R_{BCS} (Ω)	R_0 (Ω)	R_S (Ω)
Niobium	9.2	1800	$2.5\cdot10^{-9}$	$\sim10^{-9}$	$\sim5\cdot10^{-9}$
Lead	7.2	450	$\sim5\cdot10^{-9}$	$\sim2\cdot10^{-8}$	$\sim3\cdot10^{-8}$

$R_S(Cu) = 2.6\cdot10^{-3}\,\Omega$

Although DC resistance of superconductors disappears at the critical temperature T_C, there remains a residual RF surface resistance depending on frequency, temperature and critical temperature. While the first term, the BCS resistance, it not too different for the two materials, the preparation and treatment-dependent term R_0 is. The difference in the total surface resistance R_s is more than half an order of magnitude. Niobium obviously has the superior properties. Comparing the R_s values to the surface resistance of copper at room temperature, which is about 2.6×10^{-3} ohm, one sees that there is a tremendous improvement factor in the range of 10^{-5}. This of course is why superconductivity is so attractive; here is the promise for a considerable reduction in power cost which, including all efficiency factors as in the liquifier, might be as large as 5 in realistic applications.

There are three major limiting effects in superconducting devices: 1. the thermal breakdown, 2. the electric one, where field electron emission leads to local heating and 3. the magnetic breakdowns, when the RF magnetic field surpasses the critical field of the superconductor. The remedies are the following: Use thin films of the superconducting material on well-cooled copper substrates, minimize the peak electric and the peak magnetic field per accelerating field. So by looking at the peak field ratios one can readily judge how well a certain resonator has been designed.

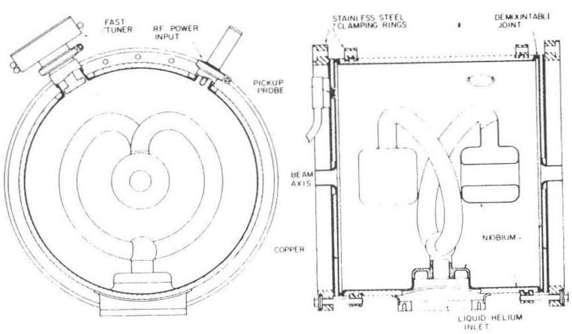

Fig. 8. Cut drawing of an Argonne type niobium resonator[10].

The technical realization of superconducting resonators will be discussed in the examples of the Argonne and Stony Brook splitrings. Fig. 8 shows cuts through the Argonne splitring. Whereas the splitring element is manufactured from solid niobium tubing, the housing is made from a compact copper-niobium material in which the niobium sheet is explosively bonded to the copper substrate, a material that allows pure conduction cooling, while the splitring is liquid helium cooled. To be recognized on the drawing are the fast tuner, the power input coupler and the pickup probe. The techninical details are summarized in table III. Argonne now operates 24 resonators, 11 low and 13 high beta ones. The total effective acceleration voltage is 21.6 MV. Also here resonators are grouped in a modular fashion, fig. 9 showing a cut through a cryostat filled with six

Table III

Lead plated Resonators Stony Brook / Caltech

Type	SRR	SRR	QWR
β_0	0.55	.10	.085
f (MHz)	150	150	(159)
Diameter (m)	0.36	0.38	0.76 (Length)
Length (m)	0.14	0.22	0.18 (Diameter)
E_p/E_a	5.5	5.5	4.2
B_p/E_a(G/(MV/m))	90	110	54
U (mJ) at 1MV/m	15	47	58
E_{max} (MV/m)	1.8	3.0	3.0 (Phase stabil.)
Voltage gain (MV)	0.25	0.67	(.54)
No. of resonators	16	24	—

Total operating Voltage 20.0 MV

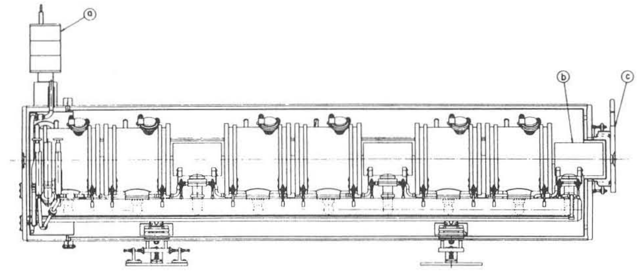

Fig. 9. Cryostat module of the Argonne postaccelerator, showing the resonators and the 7.3 T solenoid lenses[10].

$\beta = 0.105$ resonators. The modularity has been chosen to one solenoid of 7.3 T and 30 cm length per two resonators.

The Caltech-Stony Brook splitrings exist also in a low and high beta version of $\beta = 0.055$ and $\beta = 0.10$ operating at 150 MHz (table IV). Presently they can be run with the following fields phase stabilized: 1.8 MV/m at the low and 3.0 MV/m at the high beta resonators. The energy gain per charge state is 0.25 MeV and 0.67 MeV. All together there are 16 low beta structures grouped in modules of four in one common cryostat and 24 high beta ones in modules of three. Focusing is done by normal conducting quadrupoles between cryostat modules. The total effective acceleration voltage is 20 MV.

Table IV

Niobium Splitring-Resonators ANL

β_0	0.06	0.105	0.163
f (MHz)	97	97	145
Diameter (m)	0.41	0.41	0.41
Length (m)	0.20	0.36	0.36
E_p/E_a	4.8	4.7	4.8
B_p/E_a(G/(MV/m))	129	182	145
U (mJ) at 1MV/m	69	147	159
E_{max} (MV/m)	3.4	3.0	(3.0) (working average)
Voltage gain (MV)	0.7	1.1	1.1
No. of resonators	11	13	(1)
Cooling requirem. (W)	4	4	4

Total operating Voltage 21.6 MV

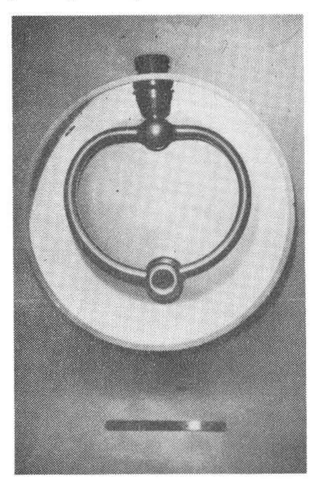

Fig. 10. Low beta lead-plated splitring resonator of the Caltech-Stony Brook design[11].

The quarter wave resonator also included in the table is at present, because of its high stability and well-optimized peak field ratios, however, the lead-plated resonator of choice and it is used in an increasing number of projects. Fig. 10 is a look into a lead-plated low-beta splitring resonator. Also here the tank is conduction cooled; the splitring is liquid helium filled. Fig. 11 shows a drawing of the first quarter wave resonator module at the Weizmann Institute. The four vertical cylinders are the quarter wave resonators[20].

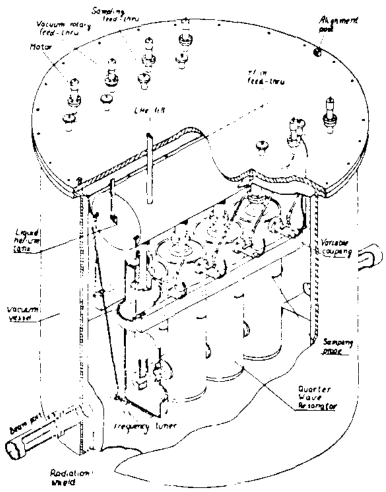

Fig. 11. Cryostat module with four quarter wave resonators for the Rehovot postaccelerator[20].

General Layout of Postaccelerator Facilities

Almost all tandem-postaccelerator combinations either built or planned have one thing in common: There is normally only limited building space available, and existing experimental setups must be served by tandem and by postaccelerated beams. There is one solution which has been adopted almost everywhere. It is explained at the example of the Heidelberg booster installation to be seen in fig. 12. The beam of the tandem (1) which is transported in normal operation via the analyzer and the switcher magnet to the experiment is deflected for the booster by a first dipole magnet from the tandem axis. Here one finds the energy stabilization slits and in the vertical direction the slits of the ns pulsing system. At the location (2) the foil stripper produces the desired high-charge states, which are then selected by a second identical magnet and focused on the axis of the linac (3). Five meters upbeam from the booster a spiral resonator bunches the still 1 ns wide beam pulses to the desired 100-200 ps at the linac injection. Presently the linac consists of nine accelerator modules depicted: 3 x 0.06, 2 x 0.08, 3 x 0.10 and 1 x 0.12 design velocity. Very shortly an additional splitring module with low beta resonators will be installed at the injection of the linac to match even the heaviest ions like Pb of Au to the existing machine. The back-transport of the beam starts with one 90 degree magnet - very helpful for calibration and spectroscopy purposes - and is continued by four smaller magnets (4) in between which four new experimental setups can be reached. Back on the tandem axis the beam comes to a spiral resonator working as a debuncher, which can manipulate the longitudinal beam properties to restore, for example, the energy resolution to tandemlike values. The analyzer magnet (5) of the tandem has been placed on a turntable and can be rotated into the position shown. It deflects the beam to the switcher (6), and thus to all existing experimental installations.

From the diagram of fig. 13 one can judge whether the three operating postaccelerators using independently phased resonators have achieved the goal of closing the energy gap to the 25 MV supertandem. It is the usual performance chart: specific energy vs.

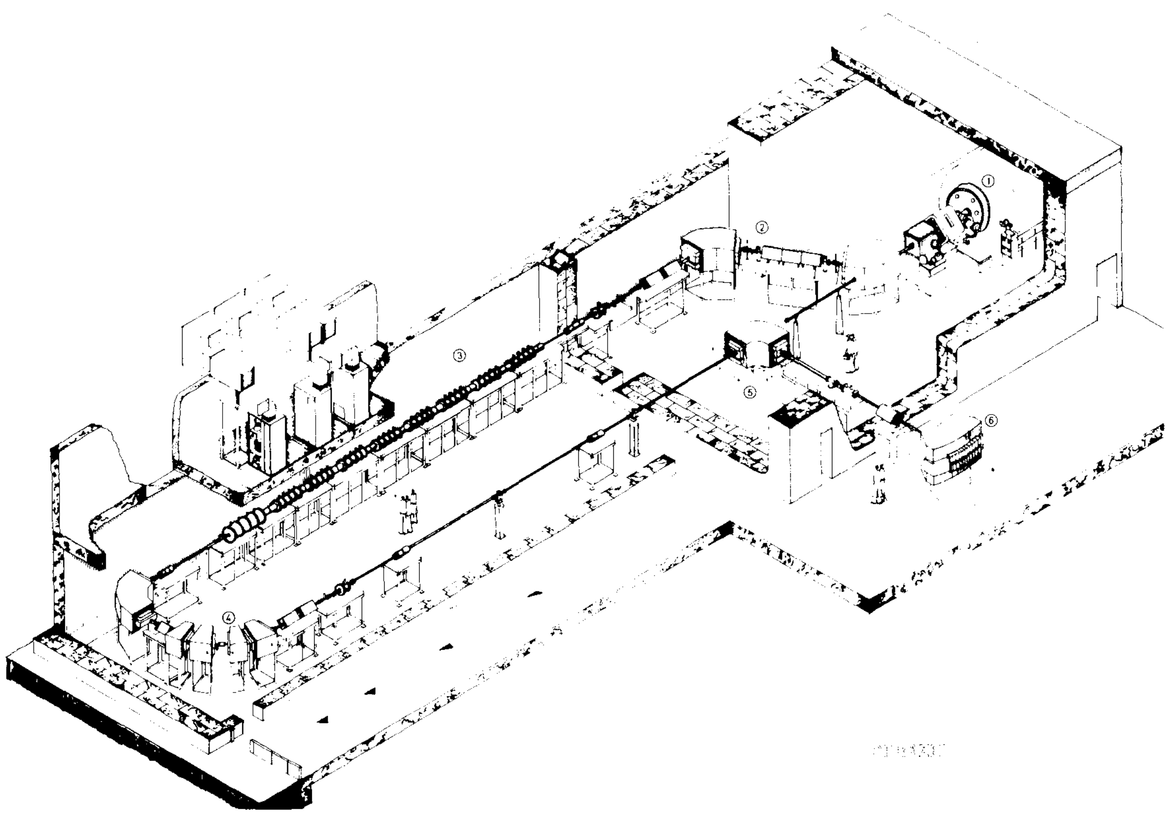

Fig. 12. The Heidelberg postaccelerator.

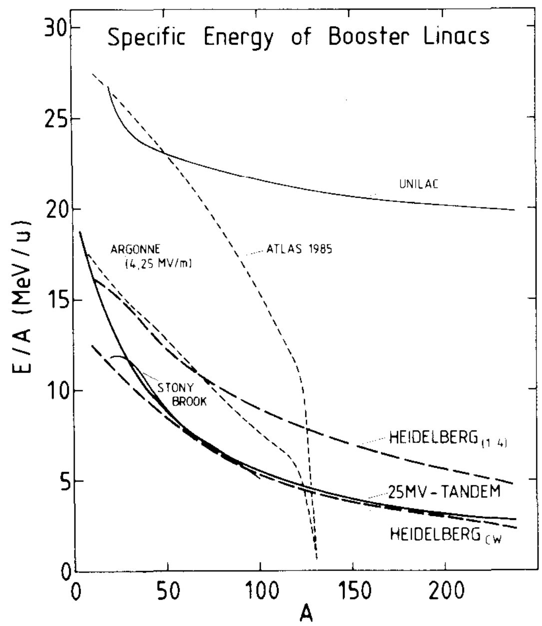

Fig. 13. Specific final energies of the postaccelerators in Argonne, Heidelberg and Stony Brook compared to the performance of a 25 MV tandem.

atomic mass number. One recognizes that the Stony Brook and the Heidelberg machine in CW are very close to a 25 MV tandem, the Heidelberg machine up to the highest masses, and it can be operated in the pulsed mode, reaching even higher energies between 16 and 5 MeV/u. The dashed curves are valid for the Argonne booster and its ATLAS extension to be operational in 1985, assuming in both cases an average acceleration field of 4.25 MV/m. At present the operating average of that booster is more around 3 MV/m, so that its curve actually shifts towards the Heidelberg CW line. It should be added that Heidelberg has been operating since 1977, Argonne since 1978 and Stony Brook since 1983.

One can safely conclude that all projects have well achieved their goal; existing medium-size tandems have been dramatically upgraded and this for considerably lower cost than the installation of large electrostatic machines. Two things have made this possible: technological breakthroughs in the development of low-beta accelerating cavities and, very important, the advancements in computer control that allow us to reliably operate accelerators with that high number of parameters as one finds them at machines with a large number of independently phased resonators[21].

Table V shows that all together there are now 15 postaccelerator projects in operation, under construction or in the state of approved proposals, some being further extended. There are three interdigital boosters and three normal conducting spiral splitring boosters in Heidelberg, Bucharest and Frankfurt in operation. The niobium splitrings can be found in Argonne and Tallahassee, the lead-plated splitrings in Stony Brook and Oxford.

The newly developed quarter wave resonator seems to be becoming the preferred solution; three projects already make use of it, Seattle, Rehovot and Canberra. Also the superconducting helix, that has become a stiff and reliable alternative, will produce around 25 MV in the Saclay postaccelerator.

TABLE V LINAC POSTACCELERATORS AT TANDEMS

LOCATION	TANDEM	RESONATOR-TYPE	TECHNOLOGY	NO. OF RESONATORS	TOTAL VOLTAGE (MV)	STATUS
MÜNCHEN[18]	MP - 13 MV	IH	Cu	1 (2)	5 (10)	IN OPERATION (UNDER CONSTRUCTION)
RISØ[22]	FN - 9 MV	IH	Cu	2	10	PROPOSAL APPROVED
TSUKUBA[23]	12UD-12 MV	IH	Cu	1	5	IN OPERATION
HEIDELBERG[12]	MP - 13 MV	SP-SRR	Cu	40	12.5/25^{++}	IN OPERATION
BUCHAREST[8]	FN - 9 MV	SP	Cu	20	6	IN OPERATION
FRANKFURT[7]	CN^{+} - 7 MV	SP-SRR-IH	Cu	3 (10)	2 (10)	IN OPERATION (PROPOSED)
ARGONNE I[10]	FN - 9 MV	SRR	Nb	24	22	IN OPERATION
ARGONNE/ATLAS	FN - 9 MV	SRR	Nb	42	>40	UNDER CONSTRUCTION
TALLAHASSEE[24]	FN - 9 MV	SRR	Nb	2 (12)	2.2 (13.2)	TESTSECTION (UNDER CONSTRUCTION)
STONY BROOK[11]	FN - 9 MV	SRR	Pb	40	20	IN OPERATION
SEATTLE[25]	FN - 9 MV	QWR	Pb	32	~26	PROPOSAL APPROVED
REHOVOT[20]	14UD-14 MV	QWR	Pb	4	2.2	CONSTRUCTION COMPLETED; TESTPHASE
OXFORD[26]	FD - 10 MV	SRR	Pb	9	6	UNDER CONSTRUCTION
CANBERRA[27]	14UD-14 MV	QWR	Pb	4 (48)	2.2 (20)	UNDER CONSTRUCTION (PROPOSAL TO BE SUBMITTED)
SACLAY[15]	FN - 9 MV	HX	Nb	48	~25	UNDER CONSTRUCTION

$^{+}$SINGLE STAGE $^{++}$CW/PULSE, D.F. = 0.25

IH INTERDIGITAL H-STRUCTURE QWR QUARTER WAVE RESONATOR Cu NORMAL CONDUCTING
SP SPIRAL HX HELIX Nb NIOBIUM-SUPERCONDUCTING
SRR SPLITRINGRESONATOR Pb LEAD PLATED-SUPERCONDUCTING

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