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HEAVY ION LINAC BOOSTERS FOR ELECTROSTATIC TANDEMS

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Résumé. — Nous donnons une revue des activités concernant l'augmentation de l'énergie des ions provenant des installations de Tandem existantes, par l'addition d'accélérateurs linéaires à haute fréquence. Deux exemples, le post-accélérateur de Munich avec une structure interdigitale en H et le linac de Heidelberg utilisant des résonateurs en spirale indépendants en phase sont discutés avec plus de détails. Un sommaire des autres post-accélérateurs à linac est présenté.

Abstract. — Activities concerned with the upgrading of final ion energies at existing Tandem facilities by the addition of high frequency linear accelerators are reviewed. Two typical examples of the normal conducting linacs, the Munich booster with an interdigital H-structure and the Heidelberg linac using independently phased spiral resonators, are discussed in more detail. A summary of further linac booster projects is given.

1. Introduction. — Already in the late 1960's, when electrostatic Tandems of the FN and MP type were providing the experimental basis for heavy ion physics in many laboratories, plans were considered to boost the final energy of the heavy ion beams by a combination of the Tandems with other accelerators as cyclotrons [1-3], high frequency linear accelerators [4] or even electrostatic machines themselves [5]. None of the projects of that time was realized, but design work and prototype tests were continued at different laboratories, and it seems in the meantime, that linear accelerators are the machines of choice for a Tandem booster, since eight such machines, either superconducting or in conventional technology, are under construction or at least in an advanced design or prototype stage. This contribution will be limited to reviewing examples of the normal conducting variety, while the following presentation [6] is devoted to the superconducting postaccelerators. The Munich fixed velocity profile booster and the Heidelberg linac using independently phased spiral resonators are discussed in detail.

2. Requirements for a linac booster. — In table I requirements for the properties of a linac booster ⁽¹⁾ are listed. As stated in point 1, the final energy of postaccelerated ions should be at least 6 MeV per nucleon, « the coulomb barrier for uranium », for the particles of interest up to mass $A \cong 100$. The total

TABLE I

*Requirements for properties
of heavy ion linac boosters*

1. Final energy 6 MeV/N for ions up to $A \cong 100$.
2. Beam intensity $I \sim 100$ particle nA at $A = 100$.
3. *Tandemlike* beam quality
 - a) $\varepsilon_r \sim 5 \pi$ mm mrad
 - b) $\Delta W/W \sim 2 \times 10^{-4}$
 - c) Continuous wave (CW) performance.
4. Variability of final ion energy.
5. Flexibility to accelerate varying ion velocities.

effective postacceleration voltage necessary is dependent on the type of Tandem accelerator as well as on the number and kind of strippers used in the terminal and behind the Tandem to postaccelerate most effectively with the booster. The first figure shows the necessary booster voltages to obtain 6 MeV/N ions as a function of Tandem terminal potential with ion mass as a parameter. Curves are drawn for ^{32}S , ^{58}Ni and ^{120}Sn for one post-Tandem foil stripper and a choice of either gas or foil stripper in the terminal. For each stripper maximum intensity charge states have been selected [7].

As can be seen for an FN type of Tandem, the voltage necessary for ^{58}Ni ions lies in the range of 14 to 17 MV depending on the type of terminal stripper, while for ^{120}Sn between 27 and 35 MV are required. The corresponding values for an MP Tandem are 22 and 28 MV respectively. As foil lifetime specially at injected currents of typically 5 μA tends to be a severe problem for masses higher than $A \cong 40$ even at termi-

⁽¹⁾ For terminology and detailed theory of linear accelerators see *Linear Accelerators* (eds. P. M. Lapostolle, A. L. Septier; North Holland Publishing Company Amsterdam), 1970.

FIG. 1. — Booster voltage U_B required for 6 MeV/N ions as function of terminal voltage with kind of terminal stripper and ion masses as parameters. Post-Tandem stripper is a foil stripper.

nal voltages of 12 MV and above, the values for a gas stripper must be taken into account. As the necessary voltage goes approximately with the mass of the ions and as providing 20 MV effective acceleration potential is not a minor effort, the limiting mass will lie somewhere around $A = 100$ for the medium size Tandems like FN or MP. One objection against these curves might be, that selecting just the maximum intensity charge states is a too conservative approach. Deviating from the maximum value by two charge states in both strippers would reduce the required voltage for ^{58}Ni ions at an MP from 13.9 to 11.4 MV.

Figure 2 shows however, that this method certainly is problematic from intensity reasons. Here the combined charge state fraction for a Tandem-linac combination with two strippers is plotted *versus* the ion mass for a 12 MV Tandem. For light ions still about 30 % of the transmitted ion beam will be available when selecting the maximum intensity charge states. This value decreases however sharply with A , reaching below 5 % at mass $A=100$. In the above example for higher charge states of ^{58}Ni the available fraction will drop from 7.3 % to 2.1 %. The right scale in the diagram just gives the particle nA behind the linac booster for the following assumptions : source current 5 μA , Tandem-linac transmission 30 %. So at higher masses the available target currents are below 100 pA, requirement 2, table I.

FIG. 2. — Charge state fraction F_s and current I_B available from a linac booster behind a 12 MV Tandem as function of ion mass.

As already a Tandem without second stripper and booster is generally not a high intensity machine, it is to the author's opinion the better way to design the Tandem-linac combination for as high intensity as possible and to have the selection of higher charge states only as an option, provided the linac can cope with the higher charge to mass ratio and velocity effectively.

The third requirement in table I is the most decisive one: The combination Tandem-linac booster must maintain the excellent beam quality a Tandem can deliver, which is typically a radial emittance of $\varepsilon_r \sim 5\pi\text{mm.mrad}$ and an energy spread of $\Delta W/W = 2 \times 10^{-4}$.

The requirement concerning the radial property is usually not too severe, if the positions of the post Tandem stripper and possible other foil strippers are selected in a radial cross over of the beam, and if the linac radial acceptance can be maintained typically a factor of 10 larger than the beam emittance of the Tandem [8].

For the requirement concerning the energy resolution a bunching into a small longitudinal phase space around synchronous phase and nominal energy is essential.

The area of the longitudinal ellipse to be injected is completely determined by the energy spread of the Tandem beam behind the second stripper and by the phase acceptance of the bunching system used to match the beam to the linac. Matching for the case of 132 MeV ^{79}Br ions is achieved at the Heidelberg booster for an upright ellipse of $\Delta W = 0.7\text{ MeV} \times 5^\circ$. It is however not just the area of the ellipse but the adjustment of the correct shape that ultimately determines the final energy resolution. Figure 3 and figure 4

$\Delta W \cdot \Delta \phi$ Phase Space Diagrams of Heavy Ion Linac Booster
28 Spiral-Resonators 108 MHz - $^{79}\text{Br}^{21+}$

FIG. 3. — Calculated injection and ejection $\Delta W \Delta \phi$ phase space diagrams of the Heidelberg heavy ion linac booster.

show, how critical this shaping of the injection ellipses is.

These figures are results of beam dynamic calculations which have been performed for the Heidelberg booster with modified computer codes from GSI [9, 10] that include non-linear coupling between transverse and longitudinal phase space. On the left side of figure 3 the $\Delta W \Delta \phi$ injection ellipses are distorted from the $0.7 \text{ MeV} \times 5^\circ$ case to $\Delta \phi = \pm 10^\circ$ and $\Delta \phi = 20^\circ$ ellipses keeping the area constant. The resulting ejection phase space diagrams are shown on the right side. It is quite evident, that although the areas at injection are equal, a match to the linac, resulting in a compact, similar area at ejection, is only achieved in the first case.

Figure 4 shows the corresponding projections on the ΔW and $\Delta \phi$ axes. The $\Delta W/W$ varies from 5×10^{-3} to 1.6×10^{-2} ; the $\Delta \phi$ corresponding to 0.2 ns in the first two examples. Only the first case can efficiently be debunched to obtain a final energy resolution of $\sim 3 \times 10^{-4}$.

The next important requirement in table I connected with beam quality is that for a continuous wave (CW) operation of the linac, essential for coincidence experiments.

It is further necessary to vary the final energy of the ions continuously while maintaining the beam quality. All properties required till now should also hold, point 5-, for the broad range of ion masses and velocities at injection, that is typical for normal Tandem operation. This requirement of flexibility basically means, that all rf-phases and amplitudes must be in all parts of the acceleration process under full control.

ΔW and $\Delta \phi$ Projections $^{79}\text{Br}^{21+}$ 340 MeV

FIG. 4. — ΔW and $\Delta \phi$ projections of the ejection phase space diagrams.

The quantity best suited to judge this flexibility of an rf-structure is the transit-time factor T .

$$T = \frac{\int_0^L E_z(z) \cos \frac{2\pi z}{\beta\lambda} dz}{\int_0^L E_z(z) dz} \quad (1)$$

with $E(z)$ being the axial electric field, $\beta = v/c$ the ratio of particle velocity to the velocity of light, L the length of the resonator and λ the free space wavelength. The transit-time factor thus is a dimensionless quantity which gives, normally plotted as a function of β (see Fig. 10) the fraction of the installed rf-voltage, that can actually be used in the acceleration. As the particle traveling through the resonator sees a time varying field, T is always ≤ 1 . How wide the β range is, in which T still is close to 1, is the decisive property, which determines the flexibility of the structure to accelerate ions of the large variety available at electrostatic Tandems.

It is worth while discussing this for two extreme kinds of structures to be called *long* or fixed velocity profile structures and *short* or independently phased structures.

In the *long* structure a number n of accelerating gaps follow each other in one common resonator in distances determined by the increase of velocity for a given charge to mass ratio and accelerating potential across the gap. Only for particles with the design input velocity β_0 and the correct charge to mass ratio the total installed acceleration potential can be used. For higher charge to mass ratios however the voltage across the gaps has to be lowered, and it especially makes no sense to select higher charge states for a given ion to get to higher final energies.

If the input velocity differs, the ions get out of phase fast depending on the β -difference. Plotting T versus β for a long structure results in a very narrow-band curve around the design velocity β_0 that approaches zero width with increasing number of gaps.

Nevertheless there are important advantages of such a long structure, the main of which are the low number of rf-components per MV of usable voltage like transmitters, regulation systems and critical

power coupling ports, as well as the generally high shuntimpedance Z

$$Z = \frac{|\bar{E}|^2}{N/L} \quad (2)$$

, $\bar{E}$ being the accelerating field averaged over the length L of the structure and N the input power.

The short or independently phased structures use resonators which ideally contain only one gap or from practical considerations two accelerating gaps in the distance $l = \beta\lambda/2$. All resonators are independently powered and phased, so that even for deviating velocities the ion never passes more than one extra gap before a rephasing can be done. Just plotting the transit-time factor in this case shows a very wide-band curve (Fig. 10).

The advantage of a linac constructed from independently phased resonators is obvious: a sufficiently wide range of ion velocities and charge to mass ratios can be handled at full installed accelerating gradient. Only with these structures Tandem like beam qualities can be obtained.

The disadvantages are clear: The higher number of rf-components results in higher costs and inevitably a somewhat lower reliability of the system.

3. The Munich Heavy Ion Booster. — The typical example selected for a fixed velocity profile linac is the interdigital H-structure [11-15] used for the heavy ion postaccelerator at the MP-Tandem in Munich [16-17]. The Munich group just lately succeeded in testing their booster with a ^{32}S beam. The principle of the structure can be understood from figure 5. The IH-structure is a cylindrical resonator, — the figure shows a radial and an axial cut —, that is excited in a transversal TE_{111} mode. In a resonator with the drift tubes not yet installed there would be no axial E -field, but just a transversal depicted on the right side of the figure. The voltage amplitude varies along the resonator like a sin-function. If the drift tubes are installed on stems attached to the opposite sides of the tank, adjacent drift tubes are charged oppositely and the gap voltages can be used for particle acceleration. The main reason for selecting just this structure was the expected high shunt impedance which was deduced from model measurements to be above $100 \text{ M}\Omega/\text{m}$.

Figure 6 shows a simplified assembly drawing of the

FIG. 5. — Schematic representation of an IH-structure [17].

FIG. 6. — Simplified assembly drawing of the Munich IH-postaccelerator [16].

Munich booster. It is constructed as a 5 m long, 1 m diameter steel tank consisting of the two watercooled halfshells and an also water cooled middle part. All three parts are electrolytically copper plated. The middle part is carrying the conduction cooled drift tubes from solid copper. This drift tube configuration can be changed for different velocity profiles by sliding the drift tubes on the middle part and selecting the right length for the energy gain designed. When doing so one also changes the resonance frequency of the structure; the typical range is 55-80 MHz. Data for setting up the correct drift tube spacing at the resulting frequency have been obtained in the model measurements. The rf-power from a 50kW, 50-100MHz transmitter is inductively coupled into the tank through a ceramic vase; the resonance frequency of the tank is controlled in the range of 10^{-3} by sliding a copper cylinder to places of different magnetic field strength. Figure 7 shows a close-up view of the drift tubes mounted on the middle part. Drift tubes and their way of movable mounting can be clearly seen. Figure 8 shows the open booster at its final position in the beam line with a quadrupole doublet each at injection and ejection. As can be seen from the last two figures, the Munich booster has no internal focussing elements. According to Mc Millans criterium [18] longitudinally stable acceleration results for synchronous phases $\varphi_s < 0^\circ$ in a radial defocusing

$$\Delta \dot{r} = - \text{const. } U_0 T \omega r \frac{\sin \varphi_s}{\beta^2} \quad (3)$$

with U_0 the accelerating voltage across the gap and ω the frequency of the rf-voltage. The Munich booster will be operated with a synchronous phase φ_s close to 0° , thus avoiding the radial defocusing at the expense of longitudinal acceptance which will be quite

FIG. 7. — Close up view of drift tube assembly of the Munich postaccelerator. (Courtesy Dr. E. Nolte).

FIG. 8. — The opened booster at its final position in the beam line at the MP-Tandem. (Courtesy Dr. E. Nolte).

limited as the phase acceptance for a long linac is connected to the synchronous phase via

$$\Delta \varphi \gtrsim z |\varphi_s| \quad (4)$$

Computer simulations [17] show however, that for a structure with just 20-30 gaps like this IH-accelerator,

the injected ions perform only one third phase oscillation on their way through the linac, so that between 12 % and 17 % of the injected DC-beam should be stably accelerated. A buncher 20 m before the linac, operating at the linac frequency, will increase this fraction to over 50 %. The energy resolution calculated for operation with the buncher is $\sim 8 \times 10^{-3}$ for a ^{58}Ni beam while the corresponding value for unbunched beams is around 2×10^{-2} . The Munich booster has until now been tested extensively with α -particles from a source under full 50 kW power and with a Tandem beam of ^{32}S . The very promising results are summarized in table II. The expected high shunt

TABLE II
Results of α -particle and ^{32}S beam tests at the Munich booster

Particles accelerated	Z_{eff} (M Ω /m)	N (kW)	U_{eff} (MV)	ΔW (MeV)	E (MV/m)
α	117	50	5.4	10.8	1.08
^{32}S	92	40	4.3	60	0.86

impedance of the structure could successfully be demonstrated, the values 117 M Ω /m and 92 M Ω /m are the highest ones obtained in any heavy ion linac so far and the power consumption is accordingly low. The effective accelerating voltage U_{eff} for $^{32}\text{S}^{14+}$ ions was 4.3 MV, boosting the particles by $\Delta W = 60$ MeV to a final energy of 160 MeV. The usable accelerating field was around 1MV/m averaged over the length of the cavity. The tests with this IH-booster will continue, so that information not yet obtained about the critical and interesting questions of energy spread and transmission will be available soon.

4. **The Heidelberg Postaccelerator.** — The structure which is the most widely spread example of a *short*, normal conducting, independently phased resonator, is the spiral resonator, formerly developed by Dick and Shephard in Pasadena and later investigated by groups in Los Alamos [20], Heidelberg [21-26], Knoxville [27], Frankfurt [28-31] and Seattle [32]. Figure 9 is a photograph taken on an opened spiral resonator of the Heidelberg design. The spiral element, that coined the name for this type of resonator, is resonating in a $\lambda/4$ mode at a frequency of 108 MHz. The leg of the spiral, — approximately the location of the current maximum —, is demountably fastened to the outer shell of the resonator, while the free end of the spiral, — location of the voltage maximum —, holds the drift tube between the two grounded tubes forming the gaps. These accelerating gaps are at a distance corresponding to half a rf-period at the design velocity. Coupling of 20 kW-CW or 80 kW duty cycle 0.25 rf-power is done by a turnable inductive loop extending into the resonator near the leg of the spiral. The resonance frequency of 108 MHz can be maintained by operating a servo loop controlled

FIG. 9. — Opened Heidelberg Spiral resonator showing spiral, drift tube, coupling loop and tuning plate. Tank inner diameter is 35 cm.

capacitive tuning plate with a frequency range of 0.6 MHz. Input power dependent frequency shifts are typically 12 kHz/kW. Just for completeness, all components of the resonator have been produced by conventional mechanical techniques in the institute workshop. The resonator tank is from E-copper while the watercooled spiral is soldered together from two square (9.3 $\times$ 9.3 mm²) Cu-profiles which are electroplated with copper for smoothing the surface. In table III the parameters of the Heidelberg spiral resonators, as verified in model measurements and numerous beam tests with ^{32}S and ^{58}Ni ions are

TABLE III
Parameters of the Heidelberg spiral resonators

Operating frequency (MHz)	108.48
Design velocity $\beta_0 = v/c$	0.06-0.10
Shunt impedance Z (M Ω /m)	40-30
Z_{eff} (M Ω /m)	35-29
Input power N_{CW} (kW)	20
N_{P} (kW)	80
Effective voltage ($\varphi_s = -20^\circ$) U_{CW} (MV)	0.32-0.36
U_{P} (MV)	0.6-0.7
Average axial field E_{CW} (MV/m)	1.8-1.7
E_{P} (MV/m)	3.6-3.4

listed. The design velocities were chosen from 0.06 to 0.10 giving shunt impedances of 30-40 M Ω /m. At a CW-power input of 20 kW an effective voltage of 0.32-0.36 MV can be obtained (depending on the β_0), a value that can be doubled under 1 : 4 pulsed operation at 80 kW. The corresponding average accelerating fields of $\bar{E} = 1.8$ to 1.7 MV/m and 3.6 to 3.4 MV/m compare quite favourably with other structures, the values of the today available superconducting split-rings not being higher. Further properties are just shortly listed:

1) The mechanical and electrical optimizations can be done independently from the specific requirements of the velocity profile. 2) The structure has by the curling of its resonating element small dimensions and can be stacked modularly thus allowing external focusing elements. 3) A very widebanded transit-time factor guarantees the desired high flexibility. This can be seen from figure 10, which shows the

FIG. 10. — Transit-time factor for a spiral resonator with design velocity $\beta_0 = v_0/c = 0.10$. The arrival phase in the first gap must be adjusted to the optimum phase [25] for maximum energy gain.

β — dependence of the transit-time factor for a $\beta_0 = 0.10$ — resonator, T has its highest value of 0.98 at the design velocity and is at even double the velocity still above 0.7. So the spiral resonator is a very flexible structure indeed. How they are stacked in operational modules in the Heidelberg postaccelerator is shown in figure 11. Four resonators, here for $\beta_0 = 0.10$, build up one module giving a total effective voltage of 1.3 MV in CW, 2.6 MV pulsed. Always two resonators share one common middle flange carrying the grounded enddrifttubes. Extensive beam-dynamics calculations — examples of which were depicted in figure 3 and 4 — showed, that a quadrupole doublet for each module, with a typical gradient of 2.5 kG/cm is sufficient for setting up a periodic focussing array and compensating for the defocussing action of the linac. External installation of the quadrupoles has the decisive advantage of easy access and possibility of exact adjustment of the quadrupole-axis, essential for good transmission and conservation of the Tandem beam quality. Furthermore modules can easily be exchanged if necessary without interfering with quadrupole adjustment. The prototype module, very similar to the module in figure 11, is shown in figure 12 during assembly. It consists of three spiral resonators ($\beta_0 = 0.10; 0.06; 0.06$) and went into operation at the beam line of the MP-Tandem early in 1976 after a successful period of over 3 000 h of full power tests on the first resonator. This module is injected with the beam from the left side. The standard quadrupole doublet focusses the beam through a 35° analyzing magnet onto the analyzing slits. All essential parameters of the structures, performance and stability of the electronics, reliability of the commercially built FM-broadcast transmitters, and most important of all, feasibility of the independent phasing concept have been carefully tested and verified in many beam tests at this set up [25]. The spectrum obtained with this arrangement, when all resonator

FIG. 11. — Cut drawing of a postaccelerator module with four $\beta_0 = 0.10$ resonators and external quadrupole doublet.

FIG. 12. — Postaccelerator prototype module with three spiral resonators, quadrupole doublet and analyzing magnet during assembly.

phases were set for maximum energy gain, is to be seen in figure 13. A DC beam of 140 MeV $^{58}\text{Ni}^{21+}$ was foilstripped behind the Tandem to a charge state of 21^+ was injected into the module; the sum of power input into the resonators was 61 kW. As in a DC beam the particles arrive at random phases towards the rf-field, maximum acceleration and deceleration occurs, so acceleration to 159 MeV and deceleration to 122.2 MeV can be seen in one spectrum. From the width of the curve the effective used voltage can be deduced. The design velocities of all three resonators in this

FIG. 13. — Momentum distribution of postaccelerated 140 MeV $^{58}\text{Ni}^{21+}$ ions measured with a 35° analyzing magnet.

module were different from the velocity of the injected ions ($\beta = 0.072$), so the transit-time factor was not optimum in all three cases. Based on the successful tests of this module, a 3 MV/CW (6 MV pulsed) booster consisting of 10 $\beta_0 = 0.10$ resonators is under construction and will have the first beam tests end of 1977. The physical layout of the 3 MV section and the beam transport system is shown in figure 14. The transport system has been designed to fit the booster into the existing building of the MP-Tandem and to bring the postaccelerated beam to the experimental area already in a very early stage of installation. The resonators of the 3 MV test section are altogether 3 of the modules described before. The Tandem beam, after passing a chopper system at one 8^{th} of the linac frequency, a 60° analyzing magnet, stabilizing slits and the second stripper is deflected by the second 60° magnet with the desired charge state onto the axis of the booster. The rebuncher, 5 m upstream from the linac time focusses the beam into a phase space of $3.5^\circ \pi \times \text{MeV}$. Pulse widths of 70 ps or a factor of 3 better than necessary for matching the Tandem beam to the linac have been already demonstrated [33]. The postaccelerated beam is finally redeflected by two 90° bends through the debuncher onto the axis of the MP and, through the MP's 90° magnet, placed on a turntable, into the existing experimental area. The final energy, the 3 MV/6 MV section can produce for the

FIG. 14. — Layout of the 3 MV test section and the beam transport system in the existing experimental hall.

two ways of operation — 20 kW CW or 80 kW pulsed power input per resonator — are shown in energy per nucleon as a function of the projectile mass in figure 15. At 20 kW ^{32}S can be accelerated over the Coulomb barrier of uranium, while in the pulsed mode Ca will be around 6 MeV/N. A typical behaviour of a booster with independently phased resonators, which can be seen from this diagram, is the

cyclotron like increase of energy with decreasing mass, quite in contrast to the linacs with fixed velocity profile. It is an obvious consequence of the high flexibility of the spiral resonators.

The shaded area indicates, where the further plans are likely to go: a possible extension to 10 MV CW by the increase of the number of modules to 8. This extension can be done, when enough operating experience will be available with the 3 MV test section. As the booster design is very modular and enough space is available in the transport system, the extension can be completed in a fast time schedule.

FIG. 15. — Energies per nucleon available at 20 kW CW and at 1 : 4 pulsed 80 kW operation of the 3 MV section compared with two relevant Coulomb barriers and the present MP-performance.

5. Comparisons of present booster plans. — Besides this more detailed discussion of two extreme varieties of boosters, all normal conducting linac booster projects have been summarized with their relevant parameters in table IV. Four laboratories operating MP or FN Tandems and one with a single stage upgraded CN machine have been included in the list. Interdigital H-structures and spiral resonators are used about equally often. The frequency is typically around 100 MHz, consequence of the similar β — range the boosters have to operate on. The number of resonators ranges from 1 to 5 for the long structures to more than 40 in the case of the independently phased spiral resonators (Seattle). The voltage gain lies between 2 and 20 MV — probably more, as the Seattle project will in three stage operation of the injector require a higher value to accelerate ^{238}U . The power requirement of the IH-structures is generally a factor of more than 6 less per MV-CW voltage gain which makes these structures a very attractive solution, where flexibility over a wide range of ion masses is not required. Besides pointing out to the remaining entries on focussing, maximum ion mass, linac length and status, it remains to be stated, that

TABLE IV
Comparison of present normal conducting heavy ion booster projects

Laboratory :	München [16]	Saclay [34]	Heidelberg [25]	Seattle [32]	Frankfurt [31]
Tandem :	MP-13.3MV	FN-8.5MV	MP-13MV	FN-3stg.	CN-7.6MV
Structure :	IH	IH	spiral	3-spiral ^(a)	3-spiral ^(a)
Frequency (MHz) :	55-80	100 (var.)	108.48	109	108.48
Number of resonators :	1	5	10 (30) ^(b)	41	2
Effective voltage U_{eff}					
CW (MV) :	5.5	16.8	3 (10)	... ^(c)	2
Pulsed (MV) :	...	...	6 (20)	...	...
Input power per resonator (kW) :	50	30	20/80	20/100	80
Input power per booster (kW) :	50 _{CW}	150 _{CW}	200 (600) _{CW}	820 _{CW}	160
Average field (MV/m) :	1.1 _{CW}	1.3 _{CW}	1.8 _{CW} /3.6 _P	... ^(c)	2.5 _{CW}
Focussing :	...	...	QP-doublet	QP-singulett	APF ^(d)
Heaviest ion (6 MeV/n) :	⁴⁰ Ca	⁵⁸ Ni	⁴⁰ Ca (⁷⁹ Br)	²³⁸ U	⁴⁰ Ar (1.9 MeV/N)
Length (m) :	5	25	5 (13)	32	1
Status :	In test	proposed	Under construction	proposed	Adv. design

(a) 3 spiral elements per resonator.

(b) Values in brackets refer to phase II of the project.

(c) Information not available.

(d) Alternating phase focussing.

average accelerating fields of up to 3.6 MV/m at the independently phased resonators can compete today with the fields of the superconducting boosters to come.

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