FEASIBILITY STUDY CONCERNING A POSSIBLE LAYOUT FOR A LEAD-ION INJECTOR FOR THE CERN ACCELERATOR COMPLEX

H. Haseroth, A. Lombardi, M. Weiss
CERN, CH 1211 Geneva 23, Switzerland

Abstract

A possible machine layout for acceleration of lead ions is presented, based on the experience gained with the successful - but painful - acceleration of oxygen ions in the CERN Linac 1[1].

The scenario consists of an ECR source, a RFQ and an Alvarez Linac. One has tried to optimize the parameters within the restrictions of the space available, keeping in mind the requirements and desiderata of the subsequent machines.

Introduction

After the successful acceleration of oxygen ions in the complex of CERN accelerators, an interest for acceleration of heavier ions is growing among the community of physicists[6]. As a reasonable step forward, one envisages the acceleration of lead ions, which are to be extracted from an Electron Cyclotron Resonance (ECR) ion source in a rather highly ionized state. The linear accelerators, which follow the ECR ion source must be designed for a charge to mass ratio $q/A^* \geq 1/7$, which means that one expects from the ion source Pb^{30+} ions.

The CERN Linac 1 accelerates now O^{6+} ions ($q/A^* = 0.375$) for the CERN accelerator complex and protons (or H^-) for the LEAR machine. We propose to separate these two operations: For the acceleration of lead ions a special Linac should be built, whereas Linac 1 (or rather its first tank only) would serve exclusively LEAR from another location. The new Linac (Linac 3) could be housed in the old building of Linac 1, extending the possible range of q/A^* from .375 to .144. The boundary conditions for Linac 3 are:

a) overall length $\leq$ 35 m
b) final energy/nucleon $\simeq$ 8 MeV/u (minimum energy for injection into the Booster)
c) operating frequency $\simeq$ 200 MHz.

These conditions are imposed by the existing space and by cost effectiveness obtained by using available 200 MHz RF equipmment.

General Considerations

To facilitate the choice of parameters for the Pb linear accelerator complex, we proceed as follows:

1) establish a "reference" layout by choosing some realistic main parameters;

2) analyze the reference design by applying approximate analytic formulae (smooth, linear motion) to see the interdependence of various parameters. Change parameters until a reasonable set of values is found;

3) Correct the reference layout for the new set of values.

The reference layout we start with is schematically represented in Fig. 1.

The ECR ion source will be of a similar type like the one used for O^{6+} [2], however, the magnetic field will be increased as well as the RF frequency (up to about 30 GHz). The source will then be capable to deliver currents of 30 to 40 μA of Pb^{35+} [3]. The extraction voltage will be pushed to about 100 kV to provide beams of 15 keV/u. In what follows, a normalized emittance $E_N = 1\pi$ mm mrad is assumed.

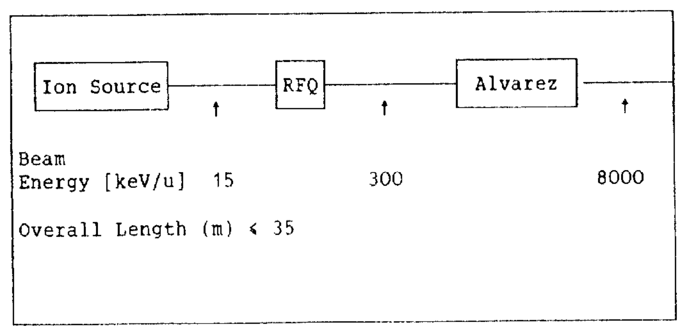

Fig. 1: Reference layout of the Pb Linac complex

The two accelerators which follow in our reference scheme are the RFQ and the Alvarez Linac. We analyze these accelerators with linear optimization programs, which contain essentially analytic formulae as shown in Table 1. With a low q/A^* ratio, it is not trivial to find acceptable acceleration and focusing parameters by keeping E_s and B_m in reasonable limits (see formulae (15) and (16)).

RFQ

$$\sigma^2_{OL} = \frac{\pi^2\, qe\, AV\, |\sin(\varphi_s)|}{A^*\, m\, \beta^2\, c^2} \quad (1)$$

Alvarez

$$\sigma^2_{OL} = \frac{2\pi\, qe\, ET\, \lambda\, N^2 |\sin(\varphi_s)|}{A^*\, m\, c^2\, \beta} \quad (2)$$

$$\sigma^2_{OT} = \frac{B^2}{8\pi^2} - \frac{1}{2}\, \sigma^2_{OL} \quad (3)$$

$$B = \frac{\lambda^2}{c}\, \frac{qe\, N^2}{A^*\, m}\, \chi\beta G \quad (5)$$

$$B = \frac{\lambda^2}{c^2}\, \frac{qe}{A^* m}\, \frac{\chi V}{a^2} \quad (4)$$

$$+ - : \quad \chi = \frac{4}{\pi} \sin\left(\frac{\pi}{2}\Lambda\right) \quad (7)$$

$$\chi = 1 - AI_0\left(\frac{\omega}{\beta c} a\right) \quad (6)$$

$$++-- : \quad \chi = \frac{8}{\sqrt{2}\,\pi} \sin\left(\frac{\pi}{4}\Lambda\right) \quad (8)$$

$$V = \chi V + AV\, I_0\left(\frac{\omega}{\beta c} a\right) \quad (10)$$

$$+++--- : \quad \chi = \frac{8}{\pi} \sin\left(\frac{\pi}{6}\Lambda\right) \quad (9)$$

$$a = \left[\frac{N\, \lambda\, E_n}{\sigma_{OT}} \cdot \frac{(1 + B/4\pi^2)}{(1 - B/4\pi^2)}\right]^{1/2} SF \quad (11)$$

CH2387-9/87/0000- PAC1987 © IEEE

$$\frac{\Delta W}{\Delta z} = \frac{\pi\, qe\, AV \cos(\varphi_S)}{2A^{*}\ \beta\lambda} \qquad (12)$$

$$\frac{V^2}{a} \leq 5\ .\ 10^{-2}\ [(MV)^2\ cm^{-1}] \qquad (14)$$

$$\Delta W = \frac{q}{A^{*}}\, e\, \bar{E}T\ \ L \cos(\varphi_s) \qquad (13)$$

$$E_s = \frac{L_c}{g}\, \bar{E}\ .\ EF \qquad (15)$$

$$B_m = G\ (a + 1\ mm) \qquad (16)$$

σ_{OL}...sync. phase advance/period
σ_{OT}...betatron phase advance/period
V.....intervane voltage in RFQ
A.....acceleration factor in RFQ
χ.....focusing factor
B.....focusing parameter
a.....minimum aperture radius
E_N....normalized beam emittance
I_O....zero order modified Bessel function
Λ.....quad. filling factor

N.....number of $\beta\lambda$/period
E.....mean acc. field
T.....transit time factor
B_m....magn. flux density at pole type ($\leq$ 1.3 T)
L.....accelerator length
L_c....cell length
g.....gap length
E_s....maximum surface field ($\leq$ 25 MV/m)
SF....safety factor (1.25)
EF....enhancement factor (1.5)

Analysis of the RFQ

We start analyzing the RFQ: low phase advances per period, σ_{OL} and σ_{OT}, are chosen because of the low q/A^*. However, we try not to descend below $\sigma_{OL} = \sigma_{OT} = 10°$. The breakdown criterion which is applied is a semiempirical one (formula (14)), derived from [4]).

The results of computations are presented in Table 2. Several frequencies have been considered, but it is the 200 MHz which interests us mostly. In fact, with σ_{OT} and σ_{OL} below 15°, solutions can be found. It is interesting to see which portion of the intervane voltage V is needed for acceleration (AV) and which for focusing (χV): it is the latter which predominates; compare formulae (1), (4), (10).

Table 2

RFQ Parameters (W_{in} = 15 keV/u; W_{out} = 300 keV/u).

	f_r (MHz)	A	B	a (mm)	χV (MV)	AVI_O (MV)	V (MV)	V^2/a ($MV^2\ cm^{-1}$)	L (m)
σ_{OT}=15° σ_{OL}=15°	200	.39	2.8	3.2	.09	.06	.15	6.8	2.9
	150	.46	2.8	3.7	.06	.06	.12	4.2	4.1
	120	.52	2.8	4.2	.05	.06	.11	3.0	4.9
σ_{OT}=10° σ_{OL}=10°	.200	.24	1.9	3.8	.09	.03	.11	3.2	6.3
	150	.29	1.9	4.4	.06	.03	.09	1.8	8.6
	120	.34	1.9	5.0	.05	.03	.08	1.2	10.3

Analysis of the Alvarez

The situation is more complicated with the Alvarez. In order to fit into the available space, the Alvarez length should be $L_A \leq$ 25 m. This gives for the accelerating field $\bar{E}T \approx$ 2.5 MV/m (φ_S is taken as -30°).

The length of the period of betatron motion depends on the type of focusing: it is N$\beta\lambda$, with N = 2 (+-), 4(++--) or 6(+++---). The last type of focusing is unusual, but it has also been tried out.

The period of the synchrotron motion is $\beta\lambda$; however, the phase advances σ_{OL} quoted in following tables refer to the same length as σ_{OT}.

With $\bar{E}T$ = 2.5 MV/m one gets $\sigma_{OL} \approx 30°$; the result for various σ_{OT} and types of focusing are presented in Table 3. To facilitate the comparison of results, one has always kept the filling factor $\Lambda = \frac{1}{2}$ and the ratio $g/\beta\lambda = \frac{1}{4}$.

Table 3

Alvarez parameters for f = 200 MHz (W_{in} = 300 keV/u, W_{out} = 8 MeV/u, $\bar{E}T$ = 2.5 MV/m, L = 25m).

	σ_{OT} (deg)	a (mm)	G_{in} (Tm^{-1})	B_m (T)	E_s (MV m^{-1})	T_{in}
+ −	30	3.4	616	2.7	18.9	.79
	25	3.7	552	2.6	19.2	.78
	20	4.1	482	2.5	19.7	.76
$\sigma_{OL} \simeq 30°$	15	4.7	432	2.4	20.5	.73
	10	5.6	392	2.6	22.1	.67
++−−	50	4.3	352	1.9	20.0	.74
	40	4.6	315	1-8	20.5	.73
	30	5.2	282	1.7	21.4	.69
$\sigma_{OL} \simeq 60°$	20	6.2	256	1.8	23.2	.63
	10	8.5	2.38	2.3	29.0	.51
+++−−−	60	5.3	217	1,37	21.5	.69
	50	5.6	202	1.33	22.1	.67
	40	6.2	188	1.35	23.1	.65
$\sigma_{OL} \simeq 90°$	30	7.0	177	1.41	24.9	.60
	20	8.4	168	1.59	28.7	.52

From Table 3 we see that with W_{in} = 300 keV/u none of the solutions is satisfactory, although we came close with +++--- focusing. The situation would improve going to higher injection energies, but then the RFQ gets too long and complicated.

The same calculations are repeated for a lower frequency (150 MHz) and the results presented in Table 4.

Table 4

Alvarez parameters for f = 150 MHz
(W_{in} = 300 keV/u; W_{out} = 8 MeV/u; ET = 2.5 MV/m;
L = 25 m)

	σ_{OT} (deg)	a (mm)	G_{in} (Tm^{-1})	B (T)	E_s ($MV m^{-1}$)	T_{in}
+ − σ_{OL} = 36°	30	4.0	357	1.8	18.3	.81
	20	4.8	293	1.7	18.9	.79
	10	6.6	248	1.9	20.6	.72
++−− σ_{OL} = 72°	50	5.0	211	1.27	19.1	.78
	40	5.5	192	1.24	19.4	.77
	30	6.2	175	1.26	20.1	.74
	20	7.4	162	1.36	21.5	.69
	10	10.3	153	1.73	26.1	.57
+++−−− σ_{OL} = 108°	60	6.3	133	.97	20.3	.74
	40	7.35	118	.99	21.5	.69
	20	10.0	108	1.20	26.	.57
	10	13.9	106	1.59	34.8	.43

As expected, with the +++--- focusing one is now comfortably within the limits imposed on B_m. The frequency could be raised somewhat, staying beetween 150-200 MHz.

A solution where the 200 MHz frequency could be kept is to start with an Alvarez operating in the 2 βλ mode and returning to the βλ mode at a somewhat higher energy[5]. Such a hybrid structure has been analyzed as follows:

a) find lowest W_{in} for the βλ structure with +- and ++-- focusing; E_s = 20 and 25 MV/m, respectively. The bore hole radius a = 6 mm (a = SF x beam radius, SF = 1.25); g/βλ = ¼;

b) find lowest W_{in} for 2 βλ structure with +- focusing and other conditions as above;

c) repeat a) and b) with a = 7.5 mm and SF = 1.50. (It is a check how critical the choice of a and SF is.)

The results are grouped in Table 5 which shows several possible solutions for Linac 3, one of which is shown in Fig. 2.

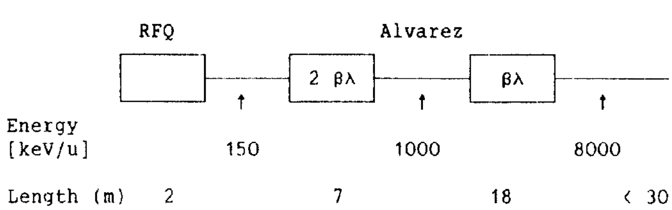

Fig. 2 : A Possible Pb Linac Layout

Discussion

The analysis which was carried out was only a feasibility study, from which it follows that a Pb^{30+} Linac could be built in the frame of conditions imposed. This analysis is in a certain respect complementary to ref. 5 where the effective shunt impendances ZT^2 for βλ and 2 βλ structures were considered. Due to our space limitations we have to find an optimum compromise between ZT^2 (RF power) and ET (efficiency of acceleration); this has not yet been done. However, ZT^2, also in the worst case (2βλ structure at injection), was kept > 10 MΩ/m.

Table 5

Parameters of the hybrid structure (W_{out} = 8 MeV(u))

	2βλ		βλ			
E_s ($MV m^{-1}$)	W_{in} (keV)	L (m)	foc.	W_{in} (keV)	L (m)	L_A (m)
a = 6 mm			SF = 1.25			
25	140	6.3	+−	950	17	23.3
	140	3.2	++−−	550	19	22.2
20	110	8.5	+−	850	21.6	30.1
	110	4.3	++−−	480	24	28.3
a = 7.5			SF = 1.5			
25	150	13.2	+−	1500	15.7	28.9
	150	5.4	++−−	700	18.5	23.4
20	120	15.8	+−	1300	20.2	36.
	120	6.4	++−−	600	23.5	29.9

To accelerate Pb ions in the CERN accelerator complex, only some minor improvements are necessary for the vacuum of the machines following the Linac 3, as PSB and PS.

It should also be mentioned that the feasibility study showed that q/A^* = 1/7 is not so critical and that one could go even lower. This is particularly interesting if one requires higher beam intensities which could eventually be supplied by other sources having a lower charge to mass ratio.

Acknowledgement

We thank P. Lapostolle and M. Vretenar for comments and help.

References

[1] H. Haseroth et al., "Ion Acceleration in the CERN Linac 1", Proc. of the 1986 Linac Acc. Conf. Stanford (USA), 1986.

[2] R. Geller et al., Proc. of the 6th Int. Workshop on ECR Ion Sources, Berkeley 1985, rep. PUB-5143, LBL Berkeley, 1985.

[3] R. Geller, CEN Grenoble, private communication.

[4] H. Daehne, "Sparking Experiments", Proc. of Acc. Aspects of Heavy Ion Fusion, Darmstadt, 1982.

[5] J. Ungrin and J. Klabunde, "A Heavy Ion Replacement for the First Tank of the Old CERN Linac, GSI, 1986.

[6] R. Stock, Univ. Frankfurt, R. Bock, GSI, "Heavy Nuclear Beams at CERN", unpubl.