HEAVY ION ACCELERATION USING DRIFT-TUBE STRUCTURES WITH OPTIMISED FOCUSING

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For the proposed lead ion accelerating facility at CERN various options for accelerating ions with q/A < 1/8 (relative to protons) from 0.25 MeV/u to 4.2 MeV/u, have been studied. At the preferred frequency of 202.56 MHz, the βλ drift-tube linac requires excessive quadrupole field gradients. However, starting with a 2βλ structure as reference, it is shown that a hybrid 2βλ/βλ sructure with quadrupole lenses separated by 4βλ or more has acceptable focusing characteristics.

In addition, this approach leads to a significant reduction in the number of quadrupoles and in the RF power, and yet retains well-behaved longitudinal and transverse acceptances.

Starting Conditions and Constraints

In order to study the focusing system the starting conditions are as follows.[1,2] The input beam is 30μAe of lead ions at 0.25 MeV/u with A = 208 and q ≥ 25, with normalised emittances 1 π mm mrad transverse and 1.6π 10^{-6} eVs longitudinal i.e. 117 keV° at 202.56 MHz. The linac output energy is 4.2 MeV/u and the operating frequency is 202.56 MHz.

Two tight constraints which have a major influence on the design optimisation are on the quadrupole pole-tip field (<1.3T) and on the peak surface electric field which is not to exceed 1.5 x the Kilpatrick limit, E_k where E_k = 14 MV/m at 200 MHz. Weaker constraints are on the peak RF power requirements (low duty cycle designs similar to Linac 2) and on the overall length.

Limitations of the 2βλ Structure

A feasibility study covering both RFQ and Linac at 200 MHz had demonstrated the difficulties of the quadrupole focusing when applying the drift tube structure to heavy ions at low energy.[3] The analytical formalism used in the latter study could be applied to the present starting conditions and a 2βλ structure was shown necessary to house the strong quadrupoles at 0.25 MeV/u. In the present study the initial comparisons between 2βλ structures and other structures were also made by this method but to get precise results a matrix treatment was necessary.

A linac design using the 2βλ structure from the outset can avoid the severe difficulties of low transit time factor which arise when a βλ structure is operated as a 2βλ structure (e.g. Linac 1 for deuterons, O^{6+} and S^{12+}). However the accelerating rate obtainable is still low, due to the reduced number of accelerating gaps per unit length if the RF breakdown limitation is respected. In fact, disturbing features of the 2βλ design between 0.25 and 4.2 MeV/u were the very large number of drift tubes (154 with quadrupoles) and to a lesser extent the overall length of the two accelerating tanks, 25m.

Analytical Design Equations

Important parameters when using the analytical method were the transverse (σ_T) and longitudinal (σ_L) oscillation phase advances over a complete focusing period Nβλ. The quadrupole focusing was approximated by the magnitude of the first harmonic in the Fourier analysis, and the RF defocusing was a smoothed value, both taken over the whole period. The equations are given in a non-relativistic form which compares more easily with the matrix formulation.

$$\sigma_L = N\left[\frac{2\pi H\lambda}{\beta c^2}\cdot ET\left|\sin\phi_s\right|\right]^{1/2} \quad \text{with } H = \frac{e}{m}\,\frac{q}{A}$$

Nβλ = focusing period length, e/m = charge to mass ratio of proton, E=mean electric field, T=transit time factor, ϕ_s=synchronous phase. The longitudinal acceptance approximates to an ellipse with semi-axes ΔW, Δφ :

$$\Delta W/W = \frac{\Delta\phi}{\pi}\cdot\frac{\sigma_L}{N}, \quad W \text{ is the energy and } \Delta\phi \approx |\phi_s|$$

For example with ET = 1.5 MeV/m, a longitudinal acceptance of 117 keV/u° (corresponding to a matched beam from the RFQ) is obtained when ϕ_s = -22.4°. The acceptance varies approximately as $\phi_s^{2.5}$.

$$\sigma_T^2 = B^2/8\pi^2 - \sigma_L^2/2$$

Adequate longitudinal acceptance implies some loss in focusing efficiency and if transverse stability is required over the range of phase excursions from 0 to $-2\phi_s$ then $\sigma_T > 0.7\sigma_L$. For a FODO focusing sequence :

$$B = 4\,\frac{(N\beta\lambda)^2}{\pi}\cdot\frac{HG}{\beta c}\,\sin\left[\frac{\pi l q}{N\beta\lambda}\right]$$

As the quadrupole length, l_q = 1.5βλ,

$$\sin\left[\frac{\pi l_q}{N\beta\lambda}\right] \doteq \frac{\pi l_q}{N\beta\lambda} \quad \text{for } N \geqslant 4 \text{ giving}$$

$$B = 4(N\beta\lambda)\,\omega^2 l_q \quad \text{with } \omega^2 = \frac{HG}{\beta c},\ G = \text{quadrupole gradient}$$

$$\beta_{max} = \frac{N\beta\lambda}{\sigma_T}\cdot\frac{1 + B/4\pi^2}{1 - B/4\pi^2}$$

This method was a good approximation when the focusing schemes involved quadrupoles in various polarity configurations but filling the whole focusing period evenly, and when the rf defocusing though discrete was in evenly spaced impulses. In this paper we compare results of this treatment with the more precise matrix treatment which used hard-edged quadrupoles (of the correct length) and the rf defocusing represented by thin lenses in the correct positions.

Comparison of Focusing Periods by the Matrix Method

For the further analysis of focusing periodicities at 0.25 MeV/u another constraint is introduced which affects transverse and longitudinal optics, and the rf structure efficiency viz. transit time factor, TTF>0.65. If g is the gap between drift tubes, assuming g/βλ=0.25 and TTF=0.65, then the aperture radius, a = 6mm which is the value retained for subsequent analysis at 0.25 MeV/u. In particular the quadrupole aperture is now fixed at 7mm and the pole field limit becomes G<186 T/m.

The aim of the optimisation is to find focusing periodicities which minimise the number of quadrupoles whilst retaining good transverse and longitudinal acceptance. As will be shown later this has implications for the rf dissipation, the mechanical arrangement and the alignment tolerances. The matrix method was needed to test focusing arrangements in which 2βλ cells containing quadrupoles are separated by one or more βλ cells containing empty drift tubes. Thus if the period is Nβλ long there will be two drift tubes containing quadrupoles in 2βλ cells and (N-4) "empty" drift tubes in βλ cells (Fig. 1).

To find σ_T and β_{max} (β_{min}), (N+6) 2x2 matrices are multiplied together to find the overall transfer matrix between the middle of a focusing (defocusing) quadrupole and the middle of the next focusing (defocusing) quadrupole. There are four types of matrix representing drift spaces, rf defocusing, half a focusing quadrupole and half a defocusing quadrupole respectively.

Drift space $M_s = \begin{vmatrix} 1 & s \\ 0 & 1 \end{vmatrix}$

for N>4, s takes two values, $s_1 = \beta\lambda - l_q/2$ and $s_2 = \beta\lambda$.

rf defocusing $M_r = \begin{vmatrix} 1 & 0 \\ \Delta_r & 1 \end{vmatrix}$

The rf defocusing term in the matrix acts like a thin lens at the gap centre and is given by

$$\Delta_r = \frac{N}{N-2} \cdot \frac{\pi\, HET|\sin\phi_s|}{(\beta c)^2} = \frac{N}{N-2} \cdot \frac{\beta\lambda}{2} \left[\frac{\sigma_L}{N\beta\lambda}\right]^2$$

Note that to obtain proper comparisons of linacs with the same accelerating rate the rf defocusing term has to be stronger and the surface fields greater, for small N.

Focusing quad. $M_f = \begin{vmatrix} \cos\theta & \frac{\sin\theta}{\omega} \\ -\omega\sin\theta & \cos\theta \end{vmatrix}$

Defocusing quad. $M_d = \begin{vmatrix} \cosh\theta & \frac{\sinh\theta}{\omega} \\ \omega\sinh\theta & \cosh\theta \end{vmatrix}$

With $\omega^2 = \left[\frac{eq}{mA}\right]\frac{G}{\beta c}$, $\theta = \omega l_q/2$ and $l_q = 1.5\beta\lambda$ throughout.

Taking N=6 as an example, the overall matrix is

$$M_{FDF} = M_f M_{s1} M_r M_{s2} M_r M_{s1} M_d M_d M_{s1} M_r M_{s2} M_r M_{s1} M_f$$

$$M_{FDF} = \begin{vmatrix} \cos\sigma_T & \beta_{max}\sin\sigma_T \\ \frac{-\sin\sigma_T}{\beta_{max}} & \cos\sigma_T \end{vmatrix} \quad \text{if } |\cos\sigma_T| \leq 1$$

this gives σ_T and β_{max}. Similarly, M_{DFD} gives σ_T and β_{min}.

The beam envelope maximum and minimum are given by $x_{max} = (\beta_{max}\epsilon_n/\beta)^{1/2}$ and $x_{min} = (\beta_{min}\epsilon_n/\beta)^{1/2}$, ϵ_n is the normalised emittance.

If x_{max} < a (6mm), β_{max}< 0.83 but a 25% safety margin is often allowed between x_{max} and a.

Results for β_{max} and σ_T as functions of G for N=4, 6, 8 and 10 are plotted in Fig. 2 with ET = 1.495 MV/m, ϕ_s = -40°, β = 0.02307 corresponding to σ_L = 12.5 N°. There are several ways to compare results with different periodicities.

a) As $\sigma_L \sim$ N then it is logical to compare results for $\sigma_T \sim$ N as the rf defocusing effect is a constant fraction of the total focusing effect :

N	σ_L°	σ_T°	G(T/m)	β_{max}	x_{max}(mm)	x_{min}(mm)
4	50	40	231	0.305	3.6	2.4
6	75	60	193	0.420	4.3	2.2
8	100	80	178	0.600	5.1	2.0
10	125	100	166	0.905	6.3	1.7

The envelope is acceptable (<6mm) for N = 4, 6 and 8 but only for N = 8 is the gradient below the 186 T/m limit.

The above matrix results can be compared with the analytical method results :

N	σ_L°	σ_T°	G(T/m)	β_{max}	x_{max}(mm)	x_{min}(mm)
4	50	40	236	0.300	3.6	2.4
6	75	60	206	0.375	4.0	2.1
8	100	80	196	0.478	4.6	1.9
10	125	100	192	0.628	5.2	1.6

For N=4 the agreement is good but as N increases the analytical method increasingly over-estimates G and under-estimates β_{max}.

b) Compare cases for constant G = 186 T/m :

N	σ_L°	σ_T°	G(T/m)	β_{max}	x_{max}(mm)	x_{min}(mm)
4	50	28.5	186	0.47	4.5	3.2
6	75	55	186	0.44	4.4	2.3
8	100	89	186	0.60	5.1	1.8
10	125	153	186	----	---	---

Only for N=10 is x_{max}> 6mm but the condition for transverse stability over the full range of phase excursions is not fulfilled for N=4 (σ_T=0.57 σ_L). For N=8 this condition holds down to G=170 T/m (where x_{max}=5.2mm).

c) If cases with β_{max} = 0.6 are compared, the required gradients for N=4 and N=6 are less than for N=8 but the transverse stability with phase oscillations is poor.

The advantages of the N=8 system for beam transport come mainly from the working point at σ_T = 80° where β_{max} varies slowly with G. But the main criterion for its choice must be that only 40% of the number of quadrupoles is required compared to N=4, assuming that both systems operate at the maximum allowable accelerating rate.

Results at Higher Energies

Having chosen N=8 by comparisons at 0.25 MeV/u, it is necessary to check the results at higher energies. One (safe) design assumption is that ϕ_s decreases from -40° at 0.25 MeV/u to -30° at 2 MeV/u with $\phi_s \sim \beta^{-0.28}$. Also the mean electric field rises linearly with distance (from 2.2 to 3.2 MeV/m) maintaining the peak surface field near E_K = 14 MV/m. Similarly, between 2 MeV/u and 4.2 MeV/u we assume E=2.8 MV/m and ϕ_s = -30° giving a maximum surface field of 17 MV/m. Given the variation of E with distance, and of ϕ_s and TTF with β in the two cavities, a preliminary linac design can be generated with simple algorithms and values of σ_L computed. At 2 MeV/u a change of periodicity to N=10 is foreseen as radial aperture can be increased to 9mm. All results in the following table are for σ_T = 80° and $l_q \leq 1.5\beta\lambda$. The required quadrupole focusing power ($\sim Gl_q$) diminishes approximately as $\beta^{-0.2}$ along the linac. There are 38 and 17 quadrupoles respectively required for the two linac tanks in the "safe" design. An "economical" design[2] aims to reduce the number of quadrupoles (to 34 and 14 respectively) by increasing the mean electric field to that corresponding to E_s=21 MV/m.

W (MeV/u)	$-\phi_s^\circ$	σ_L°	$l_q/(\beta\lambda)$	G (T/m)	x_{max} (mm)	x_{min} (mm)
0.25	40.0	100	1.50	178	5.1	2.0
0.50	36.3	85	1.06	159	4.9	2.0
1.00	33.0	80	1.06	108	4.8	2.0
1.50	31.2	70	1.23	76	4.7	2.0
2.00	30.0	66	1.30	62	4.7	2.0
N=10						
2.00	30.0	82	1.50	45	5.5	2.2
4.2	30.0	69	1.04	41	5.3	2.2

RF Design

Drift-tubes are usually dimensioned to contain quadrupoles so for this proposal there are two types, the larger of diameter 150mm, length about 1.75βλ, contains a quadrupole and the smaller of diameter 80mm, length about 0.75βλ is "empty". The latter 0.75βλ drift tubes establish the desired field distribution on the axis with much less rf losses than the larger ones would incur. The program SUPERFISH was used to establish the resonant dimensions of the cavity by choosing reasonable gaps at 0.25 MeV/u, finding the cavity diameter for resonance at 202.5 MHz, then keeping this diameter for a range of energies up to 2 MeV/u but adjusting the gaps for resonance. The process was repeated between 2 and 4.2 MeV/u. Computed shunt impedances (ZT^2 including support stems) range from 26 to 40 MΩ/m up to 2 MeV/u and >52 MΩ/m thereafter (cf. 16 to 32 MΩ/m up to 2 MeV/u for 2βλ structures).

Other Design Considerations

The quadrupoles can be scaled from the Linac 2 designs where the lamination form was specially optimised for high pole-tip field. There can be some simplifications relative to the Linac 2 mechanical design arising from the "empty" drift tube idea. As the beam envelope will be maximum in the quadrupoles, the necessary aperture in the "empty" drift-tubes can be less, which is equivalent to allowing larger alignment tolerances e.g. ±0.5mm radial compared to the normal ±0.1mm radial demanded for drift-tubes with quadrupoles. With the operating point and aperture we have chosen for the N=8 focusing, the beam centroid deviation due to misalignments is less than for the N=4 periodicity, due mainly to fewer quadrupoles. In addition, the proposed cavity diameters of 1.02m and 1.05m allow for somewhat easier drift tube installation than Linac 2.

Conclusions

A way to reducing both gradient and number of quadrupoles in a 202.5 MHz drift-tube Linac while retaining good focusing characteristics for heavy ion beams at 0.25 MeV/u, has been demonstrated. The provisional design detailed in Table 1 has safety margins in transverse acceptance, longitudinal acceptance and surface field, Es. Also this proposal retains many of the advantages of the conventional drift-tube linac, such as computable, adjustable and well-behaved structures, predictable beam quality and the availability of many proven beam dynamics programs.

Acknowledgements

I would like to thank M. Weiss for helpful discussions on the application of the analytical method and M. Vretenar for the "Superfish" results.

References

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Provisional Parameters of a 202.56 MHz Drift-Tube Linac

	Tank 1	Tank 2
Energy (MeV/u)	0.25 to 2.0	2.0 to 4.2
Tank length (m)	9.3	9.4
Tank diameter (m)	1.05	1.02
DT outer dia. (mm)	150 or 80	150 or 80
Aperture Rad. (mm)	6 to 8	9 to 10
DTs (with quads)	36 + 2x1/2	15 + 2x1/2
DTs (empty)	74	48
Ez (Mv/m)	2.2 to 3.2	2.8
Es/Ek (max)	1.0 to 1.0	1.2 to 1.0
ϕ_s°	-40 to -30	-30
TTF	0.65 to 0.73	0.83 to 0.82
Foc. Period	8βλ	10βλ
Quad. G(T/m)	178 to 62	45 to 41
RF Power (MW)	1.2	1.2

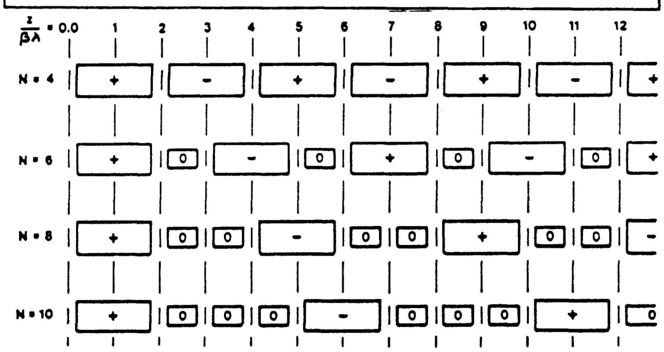

Fig. 1 : Focusing Periods with "empty" DT's; Nβλ is repeat length, + and - are quadrupoles, "O" is "empty" DT.

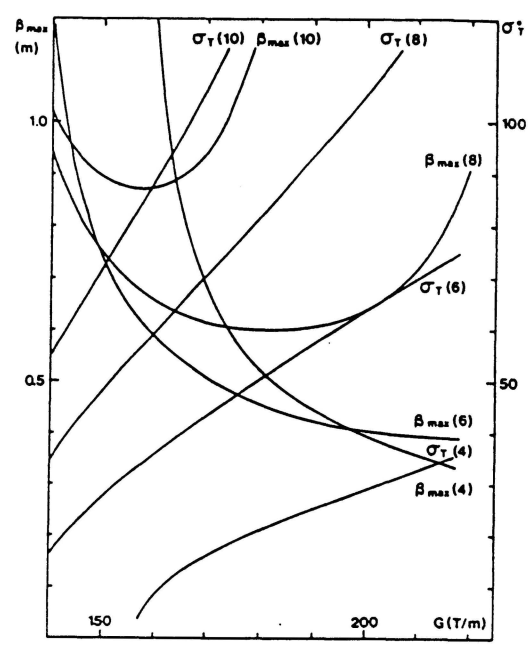

Fig. 2 : σ_T and β_{max} vs gradient; N = 4, 6, 8 and 10.