# BEAM ACCELERATION IN THE SINGLE-GAP RESONATOR SECTION OF THE UNILAC USING ALTERNATING PHASE FOCUSING

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*Abstract*

In the heavy ion linac Unilac a group of 10 single-gap resonators serves to obtain any desired ion beam energy in the range of 3.6 to 13 MeV/u from several discrete Alvarez cavity output energies. The routine time-shared, pulsed operation with varying ions and energies had been complicated by the fact that the chain of quadrupole magnets in the resonators could not be powered in a pulsed manner as well. With the recent introduction of beam acceleration at alternating rf phases – effecting weak transverse and longitudinal net focusing – the need of quadrupole focusing was eliminated. The beam behaves in the resonator group nearly like in a drift space. Calculations and operational results are presented.


## 1 INTRODUCTION

The technique of alternating phase focusing (APF) has been proposed for the design of short low beta structures, because its inherent focusing capability could eliminate the need of external transverse focusing by drift tube quadrupoles. Applications were discussed for protons [1]–[3], light [4]–[6] and heavy ions [7], [8] and fullerene molecules [9]; but only a few linacs have been built.

The use of APF in one section of the drift tube linac Unilac is not a typical application: a. It is applied to an existing long structure (9 m) of only ten individually phased single-gap resonators. b. The input velocities are rather high (beta of 0.09 to 0.15). c. The synchronous phase is relatively small (30°) and changes its sign in each gap. d. The ion beam will not be matched to the periodicity of the gap fields.

This application uses the fact that with acceleration at alternating phases the gap focusing effects nearly cancel out in each phase plane, allowing a drift like motion of the beam. The property of periodic focusing is not essential here.

## 2 THE SINGLE GAP RESONATORS

The section of single gap resonators (SGR), as the last part of the Unilac linac, is located downstream of a 5 cavity Alvarez accelerator that provides 7 discrete beam energies in the range of 3.6 to 11.4 MeV/u. Any intermediate energy can be obtained by further ac(de)celeration in some or all of the SGR. The field amplitudes and phases in the resonators are separately controlled, supporting the Unilac time share mode of acceleration of several beams from three ion sources to individual energies on a 50 Hz-basis [10].

The geometry of a cavity corresponds to that of a single Alvarez-cell and resonates in the E010 mode. Technical data are given in Table. 1

Table 1: Data of the Single-Gap Resonator Group

| | | |
|---|---|---|
| Number of single gap resonators | 10 | |
| Type of resonator | drift tube loaded $E_{010}$-cavity | |
| Diameter of resonator | 1500 | mm |
| Length of resonator | 888 | mm |
| Drift tube diameter | 160 | mm |
| Gap width | 100 | mm |
| Bore diameter | 40 | mm |
| Resonance frequency | 108.48 | MHz |
| Max. r.f. power (pulse) | 170 | kW |
| Shunt impedance | 8.8 | MΩ |
| Peak gap voltage | 1.8 | MV |
| Alternating phases for acceleration | $-30^0$/ $+30^0$ | |
| Alternating phases for deceleration | $-150^0$/ $+150^0$ | |
| Input beam velocities | 0.088 to 0.155 | c |
| Transit time factors | 0.74 to 0.88 | |
| Focusing strength at maximum gap voltage | 0.47 to 0.086 ($Ne^{7+}$)<br>0.13 to 0.029 ($U^{28+}$) | $m^{-1}$ |
| Input beam energy | 3.6 to 11.4 ( 7 steps ) | MeV/u |
| Required energy tuning range and accuracy | -1.0 to +1.0<br>down to 0.005 | MeV/u |

Originally, the SGR group was designed as a N=1 drift tube linac (DTL) with d.c. quadrupole magnets and acceleration at a phase angle of –30° (Fig. 1). For the multiple beam operation of the Unilac the beam rigidity bandwidth was limited and the required variable input and output matching over a wide range of Twiss parameters - even for simple beam transport – proved to be tedious.

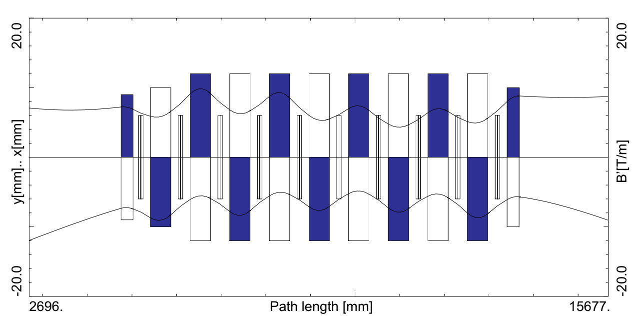


Figure 1: Transverse focusing scheme of the single gap resonator group in the original design as a drift tube linac. The height of the bars represents the quadrupole gradients and the equivalent gradients of the defocusing gaps (vertical scale in T/m). Dark bars denote focusing in the corresponding plane. A nearly matched beam envelope is sketched. Drift tube half aperture is 20 mm.

## 3 BEAM DYNAMICS

### *3.1 Transverse beam optics*

In the recently introduced alternating phase mode, the gap fields in the SGR accelerate alternatingly at –30° and +30° (or decelerate at –150° and +150°) and the main quadrupole group is turned off. The (de)focusing rf fields establish a weak focusing channel that modulates the beam envelope, shown in Fig. 2 for moderate gap focusing strengths of 0.14 $m^{-1}$. These depend strongly on the beam velocity ($\sim\beta^{-3}q/A$; see Table. 1 for some values), but in general, the modulations are smaller than shown in the figure, even at maximum rf gradients. Only for some low rigidity beams the accelerating fields should be reduced.

The outer pulsed drift tube lenses in the resonator group are used like beam transport elements. The beam envelopes through the SGR section can be rather uniform, independent of beam rigidities and of the number of actually accelerating resonators, demonstrated for a fully accelerated and a drifting beam in Fig. 2. The matching to the downstream beam lines simply scales with rigidity.

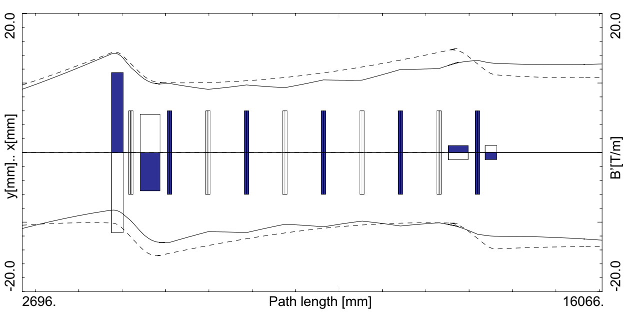


Figure 2: Transverse focusing scheme of the SGR group in the APF mode at +/-30° phase angles. Symbol meanings are the same as in Fig. 1. Envelopes of a drifting beam (outer lines) and of an accelerated beam are shown (12 emA $^{238}U^{28+}$, 11.4 MeV/u).

### *3.2 Longitudinal Beam Optics*

In APF designs the small longitudinal acceptance is generally of major concern. In the Unilac the problem is minor, because the SGR are only a short structure and the Alvarez section can provide bunch widths of about ±20°, adequate for a synchronous phase of 30 °.

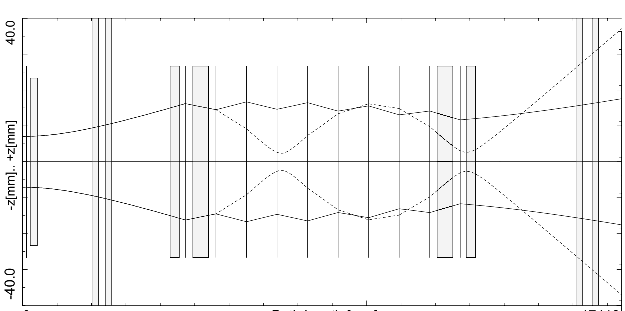


Figure 3: Calculated bunch width of an 11.4 MeV/u beam post-accelerated in APF mode (solid line) and in DTL mode (dotted line). The resonator gaps are indicated by vertical lines. The vertical full scale is ±35 ° at 108 MHz.

To first order, the bunch propagation under linear acceleration fields (gradients related to those of the transverse dynamics) looks favourable as the bunch width remains rather constant (Fig. 3).

However the bunching-debunching sequence in the APF mode does not rotate the bunch phase space effectively, and distortions due to the nonlinear accelerating fields are likely to occur. Particle tracking with the code Dynamion of a high current beam through the SGR revealed that the ion distribution develops a sickle like shape with a tail (Fig. 4). Bunching of the beam in the first gap can suppress these distortions.

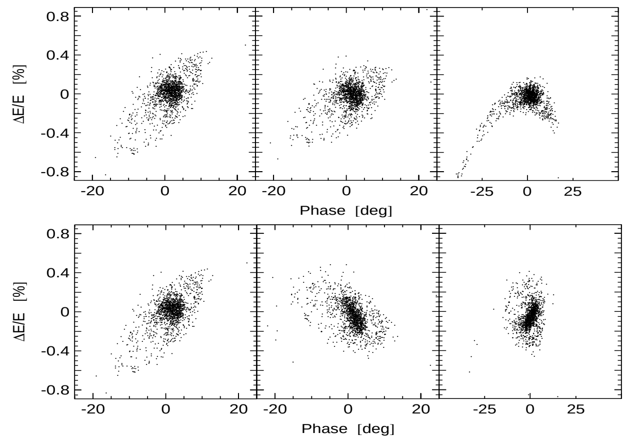


Figure 4: Simulated longitudinal particle distributions in a high current bunch (12 emA $^{238}U^{28+}$, 11.4 MeV/u). From left: before, after the first SGR and after 10 SGR. Top: the first SGR accelerates at –30°, bottom: acts as a buncher at –90°.

Measurements with a capacitive pick-up confirmed that a beam keeps its bunch structure under various accelerating and decelerating conditions (Fig. 5). Also shown for comparison: when accelerated at a constant synchronous phase, the bunch is rapidly spread out. This can be expected from Fig. 3 for a not matched beam.

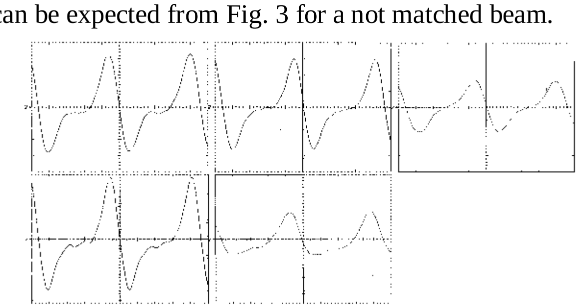

Figure 5: Bunch signals 25 m behind the SGR. A $^{40}Ar^{7+}$ beam of 3.6 MeV/u is (top, from left): not accelerated; accelerated to 4.8; decelerated to 2.55 MeV/u. Bottom: The beam is decelerated to 3.2 MeV/u in APF mode (left), in DTL mode (right). The bunch distance is 9.2 ns.

### *3.3 Matching*

As the quadrupoles in the Alvarez DTL are not pulsed, the emerging beams of varying ion species and energies differ in transverse phase advances and emittance orientations [11]. Matching of these beams to the SGR structure does not require to adjust the 6-dimensional emittance like for periodic structures. For the beam to quasi 'drift' through the section it is sufficient to provide the proper beam widths at the entrance and to focus to its end.

In the transverse planes, this matching can be achieved with a pulsed quadrupole doublet and two SGR entrance lenses for beams with phase advances from $10^o$ to $120^o$ (Fig. 6). In practice the calculated magnet settings are adjusted with the help of beam profile measurements at both ends of the SGR, and the last Alvarez drift tube lens (to the left in Fig. 6) is used additionally to correct beams which are not matched in the Alvarez structure. The beams move with similar envelopes through the resonators.

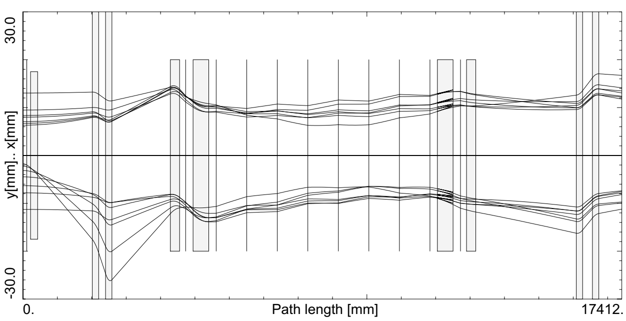


Figure 6: Transverse matching of beams with different phase advances emerging from the Alvarez section and transport through the SGR structure. The resonators are tuned to accelerate in APF mode.

The calculations have been based on 90%-emittances of 15 µm as measured on high current, space charge dominated beams. The acceptance of the SGR assembly is about 30 µm, which is by a factor of up to 5 smaller than the acceptance of the former drift tube linac structure, but corresponds to that of the beam lines to the target stations. Fig. 7 shows the irregular emittance shapes of a high current beam, that nearly filled the acceptance, after drift through the SGR.

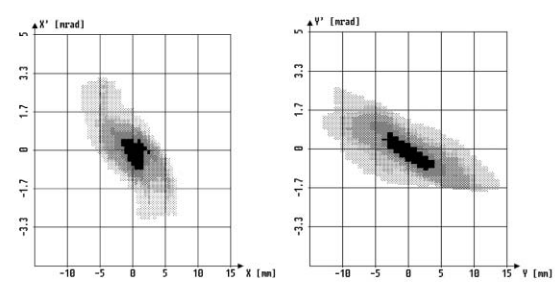


Figure 7: Horizontal (left) and vertical emittance of a 4.5 mA $^{40}Ar^{10+}$ beam at 11.4 MeV/u measured behind the SGR. The shown patterns for 95% intensity correspond to emittances of 14 and 18 µm. For the full beam, values of 19 and 25 µm were determined.

For the longitudinal motion, two bunchers in the Alvarez section are available for the adjustment of the bunch width of intermediate energy beams, and the last SGR is usually also employed as a buncher.

## 4 SUMMARY

Alternating phase focusing has been successfully introduced as the accelerating mode of the single gap resonator group of the Unilac. The operation has been simplified significantly in so far as:

- Input beam matching has been reduced to the control of beam widths, which can be examined visually.
- Output beam matching became obsolete.
- Output beams have become rather independent of the degree of acceleration. During successive tuning of the resonators the bunch signals and the beam profiles remain stable for observation.

## 5 REFERENCES

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