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### Proton Model of a Heavy-Ion RFQ Linac

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# <u>Summary</u>

The radio frequency quadrupcle (RFQ) structure has been accepted to be very well suited for the acceleration of light ions at high currents in the low energy range. In case of very heavy ions with low charge the structure is characterized by low r.f. frequencies in the 10 MHz range, and is therefore technically different. An RFQ accelerator at 13.5 MHz for the acceleration of  $U^{++}$  ions from 2.4 to 100 keV/amu has been designed. Problems like current transport capability, emittance growth, validity of calculations are presently studied using a 1:4 proton model.

#### Introduction

Radio-frequency quadrupole (RFQ) linear acceleration structures are recognized as a favourable and available link between d.c. preacceleration and conventional r.f. structures. At moderate injection energies, the beam is bunched, accelerated and simultaneously strongly focused. This is important for the acceleration of high beam currents with a good beam quality. Moreover, RFQ structures are relatively economic in terms of investment and operation costs.

A concept for proton acceleration has been developped by Kapchinskij and Teplyakov<sup>1</sup>, and has been brought to a high technical standard by the Los Alamos RFQ group<sup>2</sup>. An outstanding feature is the excellent agreement of the theoretical prediction with beam characteristics, especially with respect to the current transport limit.

There is a strong demand for intense and bright beams of very heavy ions of low charge (A/q  $\approx$ 100, as e.g. Bi<sup>++</sup>). Heavy ion drivers for inertial confinement fusion of D-T pellets require beams with a normalized brightness of the order of  $10^{13}$ A/m<sup>2</sup>, and electric currents of more than 10 mA. Injection into heavy ion synchrotrons is another possible application. Heavy ion RFQ structures operating at frequencies of about 10 MHz will fulfill these demands.

A cooperation of GSI, Darmstadt, and the University of Frankfurt, Institut für Angewandte Physik, has been initiated in 1979 to develop heavy-ion RFQ structures. A variety of different technical versions is being investigated analytically as well as experimentally. A crucial point being studied is the sparking limit of r.f. fields in RFQ geometries<sup>5</sup>. The most advanced part of our work is a 1:4 scaled-down proton model of a heavy-ion RFQ linac as proposed by one of the authors<sup>3</sup>. "Split coacial cavities" are used to excite an appropriate electrode system (see fig. 2). With slight modifications (a smaller beam aperture and stronger transverse focusing) this structure will be built at GCI for the acceleration of heavy ions up to U<sup>++</sup>, to be operationed in part in 1982. The topic of this report will mainly be the proton model.

# General design

The "spatially uniform focusing" scheme of Kapchinskij and Teplyakov<sup>1</sup> had been the main stimulation for our work. Use has been made in our design of older approaches to the RFQ technique, expecially of those of Lapostolle (reviewed by Boussard<sup>4</sup>). The technique of "focusing fingers" offers a good solution for the problem of proper electrode shaping, provided the fingers are long enough so that the quadrupol field components are not a small perturbation but the dominant term. We use a similar design (see fig.1). Generally the drift tubes will introduce non-uniformities into the quadrupolar-gradient distribution which result in additional coupling terms of the longitudinal to the transverse motion. Calculations have shown that these terms are completely irrelevant for emittance growth or other disturbing effects, if there is no resonance between both motions.

The drift tube rings completely solve the problem of deflecting field modes, allow a better transit time factor, and are easier to manufacture and adjust, if the system's clear aperture is kept constant.

The first 30 cm of the proton model have been designed in a manner similar to Kapchinskij's design: Short cylinders fixed on supporting bars, which are interconnected by annular yokes. At least at higher particle velocities the comparison of both techniques is in favor of the drift tubes and fingers, which is a more elegant technique if interconnections between opposite electrode pairs are needed.

### **RF** Cavities

The four-chamber H cavity (modified  $H_{211}$  mode) used in proton RFQ structures would have a diameter of 6 m at 10 MHz; smaller dimensions would require an additional load by capacities.

Any Wideröe type cavity (GSI Wideröe, IH structure, spirals,...) could serve as an alternative, but facing the high distributed capacity C' inherent to RFQ structures a solution with a better shunt impedance was developed, the "Split-Coaxial Structure". This structure can be looked at as a modification of the double  $\lambda/4$  - TEM cavity operated in the  $\pi$  mode, with the gap distributed along the inner conductor's length (see fig.2). The split coaxial resonator has remarkable properties: Compactness; high R<sub>p</sub> even with a high C'; good voltage flatness along the cavity even with a non-uniform C' distribution; mechanical stiffness; easy coupling with neighbouring cavities, thus preparing a continuous bed for the RFQ electrodes, and easy calculation once C' is known.

### Parameter layout

The subdivision of any RFQ linac equipped with adiabatic bunching features is shown in fig. 3; the shaper has been preliminarily omitted in our design.

The gentle buncher section needs more care since the synchronous phase varies. The acceleration rate and the  $\beta\lambda$  (z) profile should be chosen such that (a.) the longitudinal acceptance does not shrink; (b.) the product of the transverse oscillation frequency times the geometric bunch length, proportinal to the transverse current limit<sup>3</sup>, is constant. One possibility is to keep both transversal and longitudinal focusing frequencies, and hence also the mean geometric bunch length, constant<sup>1</sup>. However, this requires non-uniform apertures or non-uniform voltage distributions, and was therefore abandoned. Nevertheless the criteria mentioned above (a) and (b) have been fulfilled.

The parameters of our layout are given in table 1. At the beginning and at the end, radial matching sections are installed, both  $2\beta\lambda$  long. They provide a linear ramp of the quadrupole gradient and the r.f. potential on the axis which is considered to be very important for the conservation of the effective beam emittance.

#### Proton model experiments

Fig. 4 gives the scheme of the proton model. Loss power per section required for the nominal electrode voltage of 1900 V is about 20 W. Rough estimates yield space charge saturation corresponding to a proton beam of 0.5 mA with an emittance of 100 mm x mrad at an injection energy of 2.4 keV (0.23 mm x mrad normalized). So far the beam current injected into the RFQ acceptance space is still much lower, due to severe beam losses in the interface system.

Two of the five r.f. cavities are now in place at Frankfurt. The electric properties turned out as expected,  $R_p = 80...100$  kOhm per cavity,  $Q \approx 2000$ . Though the electrodes consist of brass and are partially soldered, multipactoring is no problem.

The beam diagnostic equipment is not yet complete. Particle energies are now measured with a reverse voltage cup incorporating a secondary electron suppression device. Due to the faulty display of a source power supply the injection energy was slightly lower than 2.4 keV, as can be seen from the spectrum (fig.5). The energy acceptance of the RFQ entrance is wide enough to tolerate this.

The preliminary results (figs. 5 and 6) indicate that the beam behaves as expected in the low - current case.

Fig. 5 shows some integral energy spectra measured with the reverse voltage method behind the first RFQ section. When the r.f. is completely turned off only a small fraction of the injected beam reaches the Faraday cup. When the r.f. voltage exceeds 1.2 kV the beam is already focused and consequently the transmission is increased. At the design voltage of 1.9 kV the transmission further increases, and no unaccelerated particles can be detected. At this r.f. level the differential energy spectrum shows very good agreement with the calculated spectrum (fig. 6). If the r.f. voltage is further increased the maximum of the energy spectrum shifts only slightly (see fig. 5).

Computations have been carried out at the HRZ, University Ffm. This work is supported by the Federal Ministry for Research and Technology, BMFT.

### References

<sup>1</sup>I.M.Kapchinskij, V.A.Teplyakov. Pribory i Tekh.Eksp. (1970), p 19-23

<sup>2</sup>R.H. Stokes, this conference.

<sup>3</sup>R.W. Müller, GSI report 79-7 (1979), GSI Darmstadt

<sup>4</sup>D. Boussard, in: Lapostolle, Septier (ed.), Linear Accelerators (1970) p. 1073, N.H. Publ. Co., New York, Amsterdam

<sup>5</sup>H. Klein et al., this conference

	Proton model	Full size for U <sup>++</sup> (Profile A)
RF frequency	54 MHz	13.5 MHz
Free aperture diam.	6 mm	24 mm
Normalized acceptance, $\alpha_{N} = \beta \alpha$	0.25·10 <sup>-6</sup> m	1.10 <sup>-6</sup> m
Injektion: βλ	1.25 cm	5.0 cm
End: $\beta\lambda$	6.1 cm	35 cm
Length	2.3 m	17 m
No. of $\beta\lambda/2$ cells	141	197
RF amplitude	1.9 kV	225 kV
Min. clearance	2.5 mm	10 mm
R per cavity	>80 kOhm	>160 kOhm
RF loss power per cavity	20 W	140 kW
RF loss power per m (av.)	40 W/m	70 kW/m
Aver.accel.gradient	25 kV/m	0.8 MV/m
Rod shape	Cylinders 4 shifted fo	cones, cone centres r larger $3\lambda$
Phase adv. o <sup>t</sup>	0.28-0.45	0.28-0.45-0.4
per cell o <sup>2</sup>	0.77-0.25	0.77-0.25-0.13
Beam current limit at nom. voltage	0.25 mA	30 mA

Table 1. - System parameters



Fig. 1: RFQ Electrodes (Section 4, 26.2 keV)



Fig. 2: Evolution of the Split Coaxial Cavity out of a double  $\lambda/4$  TEM Cavity in  $\pi/mode$ 



Fig. 3: Layout scheme of an RFQ accelerator



Fig. 4: Proton model







Fig. 6: Integral and differential spectra  $W_{in} = 2 \text{ keV}, U_{RFQ} = 1.9 \text{ kV}$