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LOW β ION ACCELERATION WITH THE FOM MEQALAC-SYSTEM

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Abstract: The FOM MEQALAC (Multiple Electrostatic Quadrupole Array Linear ACcelerator) system in which four He^+ ion beams of 2.2 mA are accelerated from 40 to 120 keV is discussed. The cavity has a modified Interdigital H structure (TE111). In between the 20 acceleration gaps electrostatic quadrupole lenses are placed to achieve radial stability of the beams. Some fundamental considerations concerning the design of MEQALAC systems are presented. Furthermore, parameters for plasma diagnostics and ion implantation accelerators are given.

Introduction

A possible way to increase the total beam current in accelerators is to use a MEQALAC system [1], in which instead of a single beam a large number of small parallel beamlets is accelerated simultaneously by means of RF fields. Electrostatic quadrupole lenses are placed in between the acceleration gaps to oppose a space charge induced blow-up of the beams. Furthermore, they counteract the radial defocusing effect of the acceleration field. By increasing the number of acceleration channels the total current is increased. Note that the individual beamlets are effectively shielded from one another by the quadrupole elements.

Design considerations

The maximum current I_{max} which can be transported through a periodic focusing channel scales with the particle velocity β, the channel radius a_Q, cell length L, so-called (zero current) phase advance per cell μ_o, particle mass number A and particle charge state Z as [2]

$$I_{max} \sim \frac{A}{Z} \; \beta^3 \; \mu_o^2 \; \left(\frac{a_Q}{L}\right)^2 \qquad (1)$$

The cell length L is defined as

$$\tfrac{1}{2} L = l + g \qquad (2)$$

where l is the length of a quadrupole singlet lens and g is the distance in between successive singlets. The phase advance per cell μ_o is described in first approximation by the relation [2]:

$$\mu_o \approx \frac{ZU}{A} \frac{l^2}{a_Q^2 \beta^2} (1 + g/l) \qquad (3)$$

The quadrupole voltage is denoted as U. To avoid dangerous beam instabilities [3] μ_o has to be smaller than 90°. Relation (1) shows that a small cell length L is favourable for increasing the maximum current density. The influence of fringe fields in a quadrupole singlet lens, however, increases strongly with decreasing $1/a_Q$. Using relation (2) with a minimum gap distance g, we find that L and a_Q cannot be chosen independently. A working rule is

$$a_Q \leqq 0.1 * L \qquad (4)$$

Equation (1) and (4) imply that the maximum obtainable value of I_{max} is independent of the channel radius a_Q. The channel radius has to be chosen as small as possible to increase the current density of a MEQALAC system. On the other hand, the emittance of the ion source has to be smaller than the acceptance α of the quadrupole channel. This parameter scales as [2]

$$\alpha \sim a_Q^2/L \qquad (5)$$

This implies that a first limit to the minimum channel radius a_Q is set by the ion source. Furthermore, to keep μ_o at a constant value, the quadrupole voltage U has to be kept constant for decreasing a_Q and constant ratio $1/a_Q$ (equation (3)). The breakdown voltage, however, decreases with decreasing a_Q. Finally, the alignment and mechanical stability of the quadrupole array are critical at small values of a_Q. At present $a_Q = 2\text{-}3$ mm seems to be a practical lower limit for the channel aperture radius. The corresponding lower limit for the cell length is L = 20-30 mm. Note that this distance is occupied by two gaps and by two quadrupole singlet lenses.

The large capacitive loading in the MEQALAC resonator allows a representation of the resonator by a lumped-circuit model. The resonance frequency fo is related to the inductance L_R and capacitance C_R of the resonator cavity,

$$fo = (4\pi^2 L_R C_R)^{-\frac{1}{2}} \qquad (6)$$

L_R is proportional to the square of the cavity diameter D and inversely proportional to the total cavity length L_C:

$$L_R \sim D^2/L_C \qquad (7)$$

The resonator capacitance C_R can be described in terms of structure dimensions:

$$C_R \sim \frac{F}{d} \frac{L_C}{L} \qquad (8)$$

where F and d are the gap surface and width, respectively. Moreover, $2L_C/L$ equals the number of gaps. For a fixed resonance frequency fo the so-called parallel resonance resistance R_{po} scales as

$$R_{po} \sim C_R^{-3/4} \; L_R^{3/4} \; L_C^{5/2} \; L^{-2} \qquad (9)$$

At a given resonator frequency, a large cavity diameter D is favourable for having a large R_{po} value, which is in turn favourable for minimizing the RF power losses in the cavity.

Experimental set-up

A schematic picture of the FOM MEQALAC experiment is shown in fig. 1. From a bucket ion source four He^+ ion beams are extracted. A low energy beam transport section (LEBT) transports the ions from the high pressure ion source region to the low pressure RF acceleration region. The first five lenses (matching section) can be tuned individually to match the beam extracted from the ion source to the acceptance of the LEBT section. Halfway the LEBT section the DC beams are bunched by means of a two gap buncher [4,5,6].

Fig. 2 shows a schematic of the modified Interdigital H resonator. On opposite sides of a cylindrical cavity two hollow rectangular boxes (1,2), which carry fingerstructures, are mounted. The quadrupole elements (3) are placed inside the fingers. The RF magnetic

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field, flowing around the boxes, provides a strong coupling of the cells.

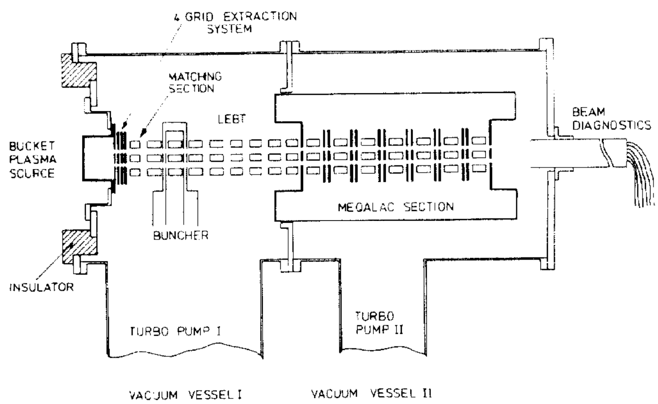
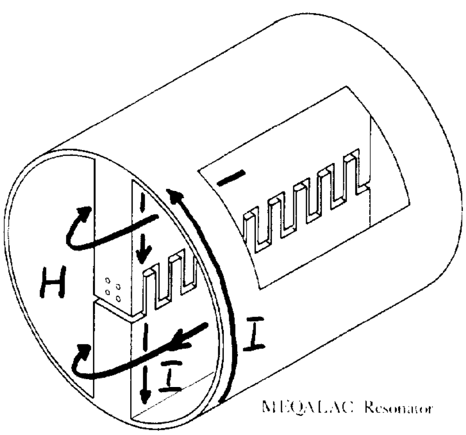


Fig. 1. The experimental set-up. For details, see text.



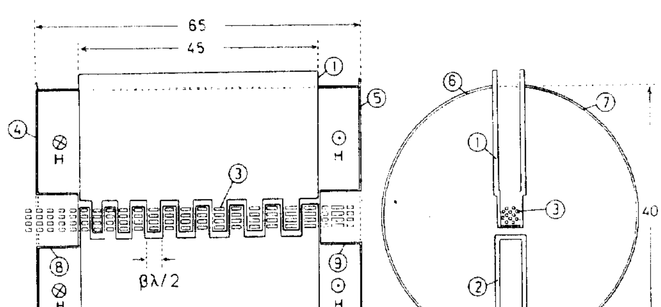


Fig. 2. The MEQALAC acceleration structure. All dimensions are in cm.

Measurements

RF measurements

Low level perturbation ball measurements show that the RF field distribution is flat within 7%. The resonance frequency is 40 MHz, the R_{po} value 16 MΩ and the unloaded quality factor 1800.

After conditioning the structure, a CW RF power of 4 kW, which is limited by the power supply, is coupled into the resonator without problems. At this input power the gap voltage is calculated to be of the order of 13 kV, where the before mentioned value for R_{po} is used. This corresponds to an electric field of 7 MV/m in each gap. Under normal operating conditions the RF power ranges from 0.5 - 2.0 kW. During long periods of operation the increase in temperature of the half-cylinder shells and the endplates is 10°C per kW of RF power. Note that only the structure itself is water cooled. The shift in resonance frequency which is induced by this temperature increase is 5 kHz per °C. The RF regulation system follows this shift without problems. Further parameters of the accelerator are given in table 1 (column 1).

Beam accelerating experiments

The transverse periodic focusing structure of the LEBT section [7] is continued in the accelerator. The quadrupole lenses are placed in between the 20 acceleration gaps. The length of the quadrupole elements increases proportionally to the anticipated particle velocity. This way the focusing forces remain constant for a given quadrupole voltage $U_{q,m}$. The space charge limited current for one channel is calculated to be of the order of 3 mA for a quadrupole voltage $U_{q,m} = \pm 2.4$ kV and an RF input power of 700 W. For this calculation it is assumed that the injected current is matched perfectly in the radial as well as in the longitudinal plane.

The first acceleration measurements have been done with a 8.5 mA beam [7], which is ~ 3 times larger than the space charge limited current. Thus, a large fraction is expected to get lost. Therefore the experiments were carried out with one beam line only. The beam current is measured with a Faraday cup. The exit energy of the bunches is determined by means of a time of flight method. In figure 3 the accelerated current I_{cup} is shown as a function of the resonator input power P. The buncher is not excited. The measurements are done for different values of the accelerator quadrupole voltage $U_{q,m}$. The LEBT quadrupole voltage $U_{q,l}$ is kept constant at $U_{q,l} = \pm 2.4$ kV ($\mu_o = 60°$). Therefore, a certain radial mismatch has to be taken into account when $U_{q,m} \neq U_{q,l}$. The accelerator current I_{cup} in fig. 3 is observed to increase with increasing RF power P for small values of

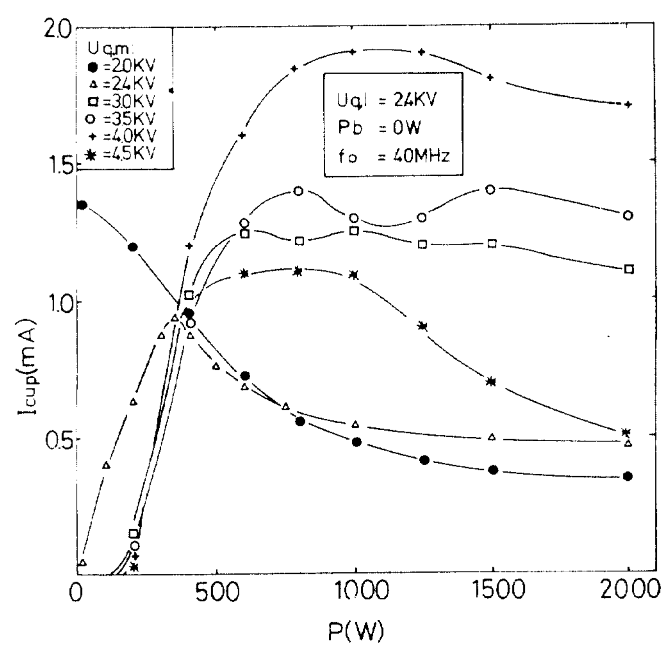


Fig. 3. The accelerated current I_{cup} as a function of the resonator input power P for different quadrupole voltages $U_{q,m}$. The injected current is ~ 8.5 mA/beamlet. The buncher is not excited.

P. In this region we expect that the current is "longitudinally limited". Above a certain value of P the radial defocusing space charge forces are expected to become dominant and to determine the limiting current. This implies that the current is constant for a further increase of P. This is seen in fig. 3. It is also seen that the maximum current which is accelerated drops dramatically for quadrupole voltages $U_{q,m} > 4.0$ kV. A possible explanation for this reduction is on one hand the increasing radial mismatch and on the other beam instabilities [3] predicted for quadrupole voltage which correlate with phase advances $\mu_o \geq 90°$. Note that a quadrupole voltage $U_{q,m} = 4.0$ kV corresponds already to a phase advance per cell of 110°. For quadrupole voltages $U_{q,m} \leq 2.0$ kV and a small input power non-accelerated particles are observed to travel through the resonator. For $P \geq 300$ W all particle bunches are accelerated to the design energy of ~ 120 keV. The accelerated current increases with 10% - 30% when the buncher is excited. A maximum current of 2.2 mA/beamlet is accelerated when the buncher and resonator cavities are excited with 100 W and 1 kW, respectively. In this case the quadrupole voltage in the accelerator is $U_{q,m} = 4.0$ kV.

Future experiments with different beam currents ($1 \text{ mA} \leq I \leq 15$ mA) and other diagnostic equipment will allow for a more quantitative discussion of the results.

MEQALAC designs

A list with the characteristic parameters of three MEQALAC systems is given in table 1. The designs are meant for different applications as plasma diagnostics (column 2) or modification of metal and semiconductor surfaces (column 3 and 4). The design of a 6 MeV, 100 mA Li^- MEQALAC system had already been presented at the 1984 Linac conference [6]. The parameters of the present MEQALAC experiment are given in column 1 for comparison. All designs are a first approach.

In the accelerator given in column 2, a 190 mA D^- ion current is accelerated from 80 keV to 1 MeV. This system can be used for plasma diagnostics [8]. The same system can be used for the acceleration of 95 mA H^- current from 40 keV to 500 keV.

The accelerators in column 3 and 4 are primarily designed for implantation of nitrogen ions into metal surfaces [9]. They can be used for the acceleration of a 110 mA N_2^+ ion current from 80 keV to 2 MeV (3), or for the acceleration of a 102 mA N^+ ion current from 40 keV to 1 MeV (4). Those accelerators can also be used for implantation of for instance P^+ or B^+ ions into a semiconductor surface. The required beam current is in the μA range [9], so that only one channel of the accelerator has to be used.

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Table 1. Characteristic properties of a MEQALAC design for plasma diagnostics (2) and modification of a metal/semiconductor surface (3 and 4). The parameters of the present experiment are shown in column 1. The subscripts L and T denote the longitudinal and transverse dimensions, respectively. The acceleration efficiency is defined as the fraction of the total RF power which is converted into particle power.

Parameter	1	2	3	4	Dim.
Particle	He^+	D^-	N_2^+	N^+	-
Injection energy	40	80	80	40	keV
Exit energy	120	1000	2000	1000	keV
RF frequency	40	80	27	25	MHZ
Synchronous phase	-38	-30	-20	-20	°
Gap electric field amplitude	2.6	12.0	14.2	12.0	MV/m
Width RF gaps	0.2	0.4	0.5	0.4	cm
Number of gaps	20	23	33	24	-
Number of channels	4	25	36	64	-
Overall beam dimensions	4	35	35	65	cm^2
Length resonator	65	150	200	170	cm
Diameter resonator	40	40	100	80	cm
Quality factor	1800	2500	3700	2800	-
Parallel resonance resistance R_{po}	16	28	110	38	MΩ
$R_{po,eff}$	8.1	17	79	27	MΩ
$\beta\lambda/2$ first cell	1.75	1.95	1.60	1.81	cm
$\beta\lambda/2$ last cell	2.80	6.10	6.50	7.40	cm
Quad spacing/length; g/l	0.75	0.95	1.30	0.81	-
Channel radius	0.30	0.30	0.25	0.30	cm
Quadrupole voltage $\pm U$	2.6	6.3	6.7	3.3	kV
Zero current μ_{oT}	60	60	60	60	°
Zero current μ_{oL}	19.8	27.6	30.5	35.8	°
Depressed μ_T	24.0	24.0	24.0	24.0	°
Depressed μ_L	7.9	11.0	12.2	14.3	°
Channel acceptance α_T	108 π	97 π	95 π	104 π	mm mrad
Channel acceptance α_L	270 π	112 π	100 π	130 π	mm mrad
I_T time averaged	2.9	7.7	3.1	1.6	mA
I_L time averaged	3.1	7.6	3.2	2.3	mA
Total current	11.6	190	110	102	mA
Acceleration efficiency	54	78	83	74	%