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PROPOSAL OF A PULSED ECR-SOURCE FOR SYNCHROTRON INJECTION

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Summary

The ECR-source uses magnetic confinement of the plasma by a Minimum B configuration. The number of confined ions depends on the volume and on the density of the plasma.

If a large amount of stored ions could be extracted during about 100 μs the pulsed current would be increased considerably-compared with continuous operation. By installing a pulsed solenoidal coil inside an enlarged plasma chamber of a standard ECR source, the magnetic bottle can be opened and the charged particles - ions and electrons - are accelerated towards the extraction hole by the "Fermi force".

A test setup is under construction at GSI to check that idea.

It is confirmed by some calculations, that "high particle current" and "high charge state" is not necessarily a contradiction.

Dependence of current limits on q/A

The formulas for transversal and longitudinal beam current limits of RFQ structures are derived in ref. 1. It is assumed that the particle pulses have ellipsoidal shape and a homogeneous charge distribution.

This chapter summarizes results from investigations which are described in more detail in ref. 2. The main goal is to demonstrate that high q/A-values out of an ion source are also attractive to build up high current accelerators.

Assumptions about RFQ parameters used in the current limit formulas:

- Limits of longitudinal and transversal phase advances without space charge[3]:

  $\sigma_{ol}, \sigma_{ot} < 90°$

- Limits of longitudinal and transversal space charge parameters[4]:

  $\mu_l, \mu_t = 0.85$

- Choice of the structure parameters in such a way, that the sparking limit is approached; this gives maximum beam current. The dependence of the maximum field strength on the distance between the electrodes[5] is regarded in the calculations.

- The current limit of an RFQ is defined at the bunching section, where the synchronous phase is changed continuously from - 90° to the final value used in the accelerating section.

For the calculation we use:

$m = 1.3$, $\Phi_s = -60°$, $a/\beta\lambda = 0.1$ resp. 0.12.
m:= modulation parameter of the RFQ vanes;
a:= aperture radius

- The kinetic energy of the ions at the investigated position depends on the charge state q, on the source potential V_s and on the effective rf voltage gain V_{rf} of the ions:

  $W = q \cdot (V_s + V_{rf})$

  In case of high q-values it is favourable to use a low value for V_s because it is more complicated to bring that type of ion sources up to high potential.
  Instead of V_s the rf voltage gain during the bunching process can be much higher for high q-values and high rf frequency, because the bunching section can consist of much more unit cells in that case as the length of the structure is not a serious problem.

Results

Table 1 shows the electrical current limits I_l and I_t and the resulting particle current limit I_p in dependence from q/A and rf frequency.

Fig. 1 shows the dependence of the current limits on the mass number of the particle beam. The graphs correspond to the parameter sets in line 1, 2, 6 and 7 of table 1.

q	ν MHz	a/βλ	$\beta \cdot 10^3$	a mm	$E_s \cdot 10^{-7}$ V/m	σ_{ot} deg	σ_{ol} deg	I_t emA	I_l emA	I_p pmA
28	108	0,1	10	3	2,8	39	28	117	150	4,2
28	54	0,12	8,7	5,8	2,3	66	44	212	218	7,6
20	54	0,12	7,4	4,9	2,5	60	42	156	173	7,8
10	54	0,1	5,2	2,9	2,8	59	34	76	67	6,7
10	27	0,12	5,2	6,95	2,2	76	47	152	142	14,2
2	27	0,1	2,3	2,6	2,8	52	32	28	28	14
2	13,5	0,12	2,3	6,1	2,2	67	45	59	59	29,5

Table 1: Dependence of the particle current limit I_p on the charge state q of ^{238}U and on the rf frequency ν.

Interpretation:

- The current limit is inverse proportional to the resonance frequency. At a given resonance frequency the current limit is independent from the q/A-value as long as σ_{ot}, σ_{ol} don't approach the stability limit of 90°.

- By using ion sources for high charge states one can adjust the q/A-ratio for the whole mass region to the optimum value - this means operation of the RFQ at maximum electric field strength. This makes the dependence of the current limit on the mass number of the particle beam very weak (fig. 1).

- If an ion source for low charge states and one or more stripping processes along the Linac are used[6], the resulting current out of the Linac is lower than in the case of ions out of an ion source for high charge states.

- If ion sources for high particle current and high charge states are available the accelerator structures for heavy ions will become much more simple, compact and efficient.

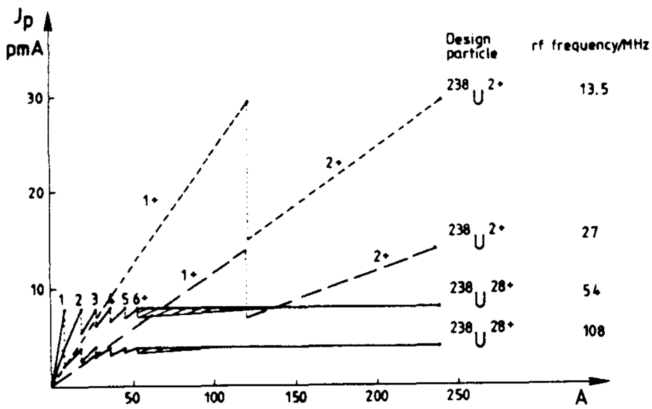

Fig. 1: Dependence of current limits in different RFQ-designs on the mass number of the particle beam.

Number of confined ions in an ECR-plasma

The ECR plasma is heated by the e^- in the zones where the condition for electron cyclotron resonance is fulfilled (eq. 1). Its maximum charge density is limited by reaching coincidence between rf frequency and plasma frequency (eq. 2).

$$B = 0.0354 \cdot \nu \; [T/GHz] \qquad 1)$$

$$n_e = 1.25 \cdot 10^{10} \cdot \nu^2 \; \left[\frac{1}{cm^3 \cdot GHz^2}\right] \qquad 2)$$

The rf heating times to reach the equilibrium densities for high charge states lie in the interval:

$$10 \text{ ms} < \tau \leq 30 \text{ ms} \qquad 3)$$

The e^--gas is not in thermic equilibrium[7]. The e^--energy is in the [keV]-range while the ions during their lifetime in the plasma are heated up by the e^- to kinetic energies in the [eV]-range only.

Using the data of analysed ECR-beams one can calculate the total number of ions confined in the plasma by the formula:

$$N = \frac{n_e \cdot V_{eff} \cdot I_{an}}{I_{ex} \cdot q} \qquad 4)$$

n_e := plasma density (eq. 2)
I_{an} := analysed electric current of the required ion type
I_{ex} := total electric extraction current
q := charge state of the required ion type
N := total number of ions of the required type
V_{eff} := effective plasma volume

The number of confined ions seem to be sufficient to form particle pulses of about 100 µs duration with analysed beam currents in the [emA]-range up to mass numbers above 100.

To reach this goal, three main problems have to be solved:

- A great portion of the confined ions has to be extracted during about 100 µs.

- The extraction voltage has to be increased up to about 100 kV.

- One has to analyse a pulsed extraction current in the [A]-range.

Pulsed extraction of the plasma ions

The force acting on charged particles in a magnetic mirror with axial symmetry around the z axis can be approximated by the following equation:

$$F_z = -\frac{W_t}{B_z} \cdot \left(\frac{\partial B_z}{\partial z}\right)_{r=0} \qquad 5)$$

W_t := kinetic energy of the charged particle perpendicular to z.

The formula is valid if the transversal distances from the z axis are not too big.

If the distribution of the magnetic field strength B_z in the ECR-source could be changed from curve 1 to curve 2 of fig. 2 the plasma would be moved towards the extraction hole.

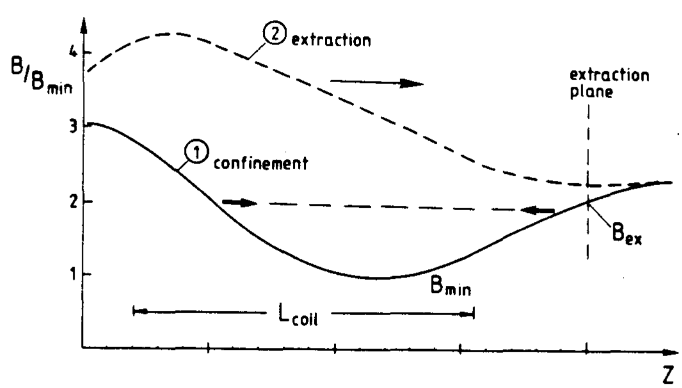

Fig. 2: Magnetic field strength B_z along the axis of the ECR-source:
1 := Distribution during heating and confinement of the plasma
2 := Distribution during ion extraction

To get an idea about the longitudinal energy which is gained by the particles during the extraction process we can use the following approximations in eq. 5):

$$W_t \sim W_{tot} \; ; \int_{z_1}^{z_{ex}} \frac{1}{B_z} \cdot \frac{\partial Bz}{\partial z} \cdot dz \lesssim 1 \; ;$$

$$\rightarrow \int_{z_1}^{z_{ex}} F_z \cdot d_z \leq W_{tot}$$

W_{tot} := kinetic particle energy.
B_{ex} := magnetic field strength at the extraction plane z_{ex}.

This means that the gain in longitudinal energy during the magnetic extraction process ranges up to the original kinetic energy of a particle. As a consequence the e^- react much faster on the pulsed field.

If the extraction hole is big enough, a great amount of e^- are reflected back into the plasma by the extraction potential and neutralize the plasma till the ions are extracted.

Suggested test array

A 10 GHz Minimafios source, built by CEN Grenoble and recently installed at GSI will be modified to test this extraction principle.

A sketch of the geometry is shown by fig. 3.

The permanent multipole is placed inside the pulsed coil to get enough fieldstrength. A decapole geometry with its steep increase of field strength close to the plasma surface will be used because of the following reasons:

- The transversal magnetic field components, which hinder the pulsed extraction process are weak inside an extended region around the z axis.

- A transversal expansion of V_{eff} is expected. This effect would rise N (see eq. 4) and allow to feed bigger extraction holes with beam, compared to the present experience with sextupole devices.

Another advantage is the smaller outer diameter[8] of a permanent decapole which defines the inner diameter of the extraction coil (fig. 3).
The pulsed coil consists of two layers.
The end pointing towards the extraction is kept on source potential. At the opposite end the pulsed voltage is applied symmetrically between the inner and the outer coil layer. The permanent magnetic multipole will be enclosed in two housings, isolated from each other.
By that way, closed paths for the flow of eddy currents surrounding the plasma are suppressed.

The excitation of the pulsed coil has to be synchronized with the interrupt of the rf heating.

The magnetic pulse length will be flexible, the rise time is about 100 µs.

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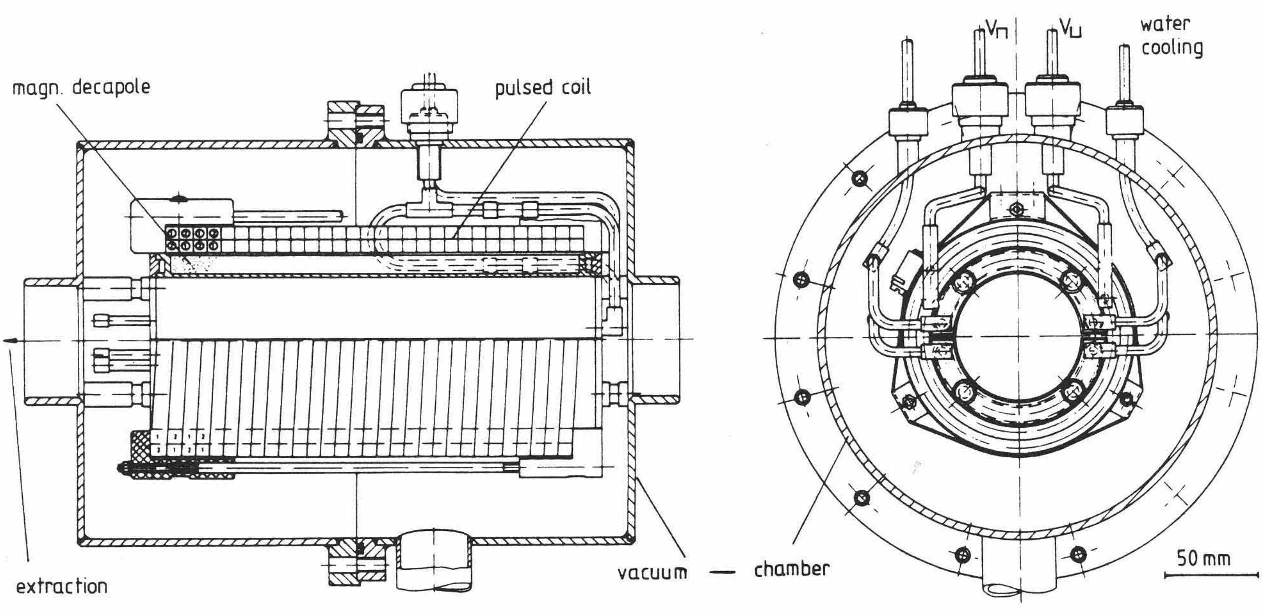

Fig. 3: Modified second stage chamber of a 10 GHz ECR source MINIMAFIOS.