SPACE CHARGE DOMINATED, LOW V/C ACCELERATORS

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Acceleration of space charge dominated ion beams in the energy range from 1keV/amu to 1 MeV/amu can be done with dc columns followed by Induction linacs or rf-linacs like Wideroe[1], Meqalac[2] and RFQ[3]. Choice and design of the accelerator structure depend on the beam energy, the radial and longitudinal emittance, the brilliance and the time structure required. Features and technical and physical limitations of the different accelerator schemes and specific applications are discussed.

Introduction

The actual development of accelerators is concentrating on higher energies or higher gradients and higher beam current. The improvement of the brilliance of the beam is especially important for ion beams, where phase space damping can be achieved only in cooler rings. Emittance conservation asks for minimum emittance and emittance growth in all parts of the chain of accelerators.

The optimization very soon leads to increased requirements for the synchrotron injectors normally being a linac and for the linac injector part which is the bottleneck in current capability and emittance conservation. This linac injector part is the region between the ion source and the first high energy accelerator structure e.g. an Alvarez[4].

In most high energy accelerator systems this part is the Cockroft - Walton[5] injector accelerating from the ion source to the Alvarez. The limiting performance is appr. 250mA beam current (protons) and 750 kV voltage in a short pulse of $\tau \sim 10\mu$sec (1Hz) and a emittance of $\varepsilon_N < 1.\pi\mu$m.

Higher duty factors reduce the applicable voltage and higher beam currents degrade the emittance.

For voltages up to 150kV the beam current can be as high as several Amperes which is the case in neutral beam heating (NBH) of plasmas. But these beams have cross sections well over 100 cm^2.

Limitations are only set by the size of the power supplies and economical constraints.

For higher beam energies as possible with existing DC injectors, for heavy ions, for the application of polarized beams and for the use of sources for highly charged heavy ions the restrictions imposed by the existing injectors are strong.

There are a number of proposed solutions for this parameter range. RFQ and Meqalac use rf-acceleration and electric focusing starting with very low energies. Dc and pulsed dc (induction linac LIA) schemes apply electrostatic quads and static acceleration and also use multiple "beamlets" for further increase of the beam current.

Beam dynamics considerations

Low energy ion accelerator development has been initiated by the early work of Wideroe, Van deGraaf, Cockroft and Walton and Alvarez. Beam currents have been restricted to very low values before AG focusing has been introduced for linacs too[6,7]. Nonintercepting strong transverse focusing has led to linacs with increased current capacity with little beam losses and good emittance control. The use of magnetic (drift tube) quadrupoles imposes limitations on the low energy injector part of the accelerator.

One solution was the increase of DC injector voltages which was only possible for limited currents. So improvement of transverse focusing at high ion beam current with conservation of the beam emittance is the major field of linac development.

The balance between focusing forces and emittance together with internal space charge or defocusing forces is decribed by the well known Mathieu equation which describes the movement of an individual particle in the periodic focusing fields of an accelerator:

$$d^2x/dt^2 + [\,\Theta^2\cos(2\pi t + \Phi) + \Delta\,]\,x = 0$$

Assuming a stable solution the movement will be approximately a harmonic oscillation around the beam axis:

$$x = X_0\cos(\sigma t + \delta)$$

The oscillation frequency is proportional to the restoring forces characterized by the focusing gradients and the periodicity length of the system[8].

$$\sigma^2 = \Theta^4/8\pi^2 - \Delta_{SC}\ , \quad \Theta^2 = \frac{q}{m}\,\frac{U(L_Q N)^2 X}{a^2}, \quad \Theta^2_{magn.} = \Theta^2 \times a\beta c$$

The focusing must confine the beam which has a finite emittance inside the aperture and must work against a possible rf-defocusing and the space charge repulsion.

For low energy ions magnetic focusing is weak which can be seen by equating the focusing fields: $qE=qvB$. For $\beta=v/c=1\%$, which corresponds to an ion energy of T= 47keV/amu, the equivalent focusing fields are 3MV/m per Tesla. So in the low energy part of high current accelerators electric quadrupole focusing is advantagous.
In classical ion accelerators beam dynamics is dominated by the emittance of the beam and the rf- defocusing (low energy) while space charge defocusing and collective effectes can be neglected.
For high current accelerators space charge effects are dominating and the finite emittance of the beam has a minimum effect. Multiparticle calculations solve the Mathieu equation along the accelerator and take the defocusing coulomb interaction into account by stepwise solving the Poisson equation for an assembly of "macro-particles" numerically. The effect is a change of the radial oscillation frequency (tune shift) and changes of the particle distribuition and emittance.
The limiting current is given if the focusing and defocusing forces cancel.
Reiser[9] has given a first "formula" for the limiting current in a periodic focusing channel, which has been extended by numerous authors to give the current "transport" capability and the beam emittance as function of the beam and accelerator parameters also taking collective effects into account.
The practical design has to chose appropriate parameters (frequency, gradients, distributions, periodicities,) to achieve the necessary brilliance of the ion beam for the specific application.
At first electrical focusing is the choice for the energy range discussed. Secondly the aperture has to be as small as possible for the highest quadrupole voltages and focusing gradients possible technically (Sparking[10] will be the limit). The quadrupoles should be packed as dense as possible also on cost of accelerating efficiency, because in this energy range the problems are described sufficiently by the pure transport properties, the acceleration being a pertubation. The choice of operating frequency or focusing periodicity has also to optimize the acceptance and emittance of the channel and the ion beam current. Another solution is a multibeam arrangement by which the beam current can be directly multiplied. The ion beam emittance is bigger than the sum of the individual emittances which might be no problem if the following accelerators or the specific application is matched to such a beam.
The different accelerators can be classified by the maximum current, the emittance and brilliance of the beam and the beam energy. The average beam power that means the (possible) duty cycle, rf and power efficiency and possible energy variation are other important characteristics.

DC Accelerators

All accelerators start with a dc extraction and acceleration sytem behind the ion source. It basicly consists of a set of cylindrical electrodes to which dc potentials are applied to achieve a specific field gradient along the beam path for proper extraction, focusing and acceleration. Focusing action is achieved by change of velocity and a radial field which is proportional to the beam radius like in a Einzellens. Generally such a system is designed for a specific ion species and energy because the optical properties are changed with ion energy and matched to a special ion source or source emittance.
The ion source itself and the operational parameters have also to be optimized to give a specific beam current and emittance. The beam current is determined by the perveance P of the ion source extraction system: $I=PU^{3/2}$.
There is a upper limit for the perveance [11] so multiaperture systems are the natural solution for higher currents which have better emittance than a big single aperture.
The dc accelerator is characterized by the capacity of the electrode arrangement which has to be charged. The charges have to be brought to high potential by diodes, belts, chains or transformers. So for a given power of the primary source the current which can be draught from such accelerating electrodes will be inversely proportional to the voltage and beam energy. In addition there must be a resistor chain to maintain a defined gradient along the accelerator structure whose current is proportional to the voltage too. So also without nonlinear effects like coronas and discharges along the accelerator column the charging current is proportional to a higher power of U (e.g. $I\sim U^{-(2-3)}$) which shifts the problems to the power supplies.

An additional problem is sparking. The power in a spark is limited in a high impedance (low current) system. With increasing duty cycle and current the sparks which discharge the electrode capacity will cause more damage.
Sophisticated systems have been designed, which control the possible electron pathes and changes electrode and insulator materials. An active spark protection requires that power supplies must be capable of switching off the voltage and dump the energy very quickly.
Generally the beam current of dc systems which can be in the order of Amperes for 100 kV for example must be reduced significantly for higher potentials e.g. 50-100mA at 500kV at present. The dc sytem cannot be extended in energy lineary.

A new development which makes use of electrostatic quadrupoles in the dc column has the potential of extending the range of the dc systems[12]. High power accelerator modules (100 kV) which use the electrode potential for the quadrupoles too are stacked for higher energy. Tests of the first stages are in preparation and designs for 200mA and 800kV(CW) are proposed. Multiaperture systems for neutral beam heating shall deliver "Ampere beams" , thus making use of the inherently good power efficiency of dc systems together with energy variation and quadrupole focusing.

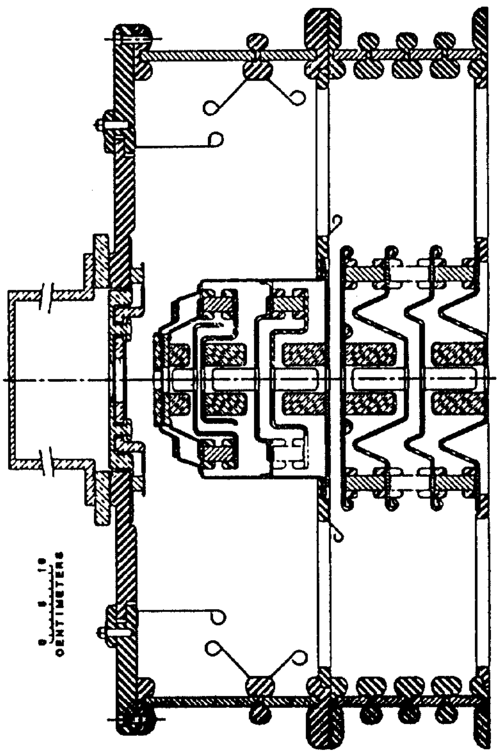

Fig. 1 CCVV Constant current variable voltage prototype (80mA, 200kV DC)

Induction Accelerator

The linear induction accelerator can be treated as a pulsed dc structure. It is mainly persued in LBL[13] and LLL and had been developed for high current electron acceleration. A capacity, e.g. a Blumlein line is discharged over a inductivity which can be made larger by having a ferrite or ferromagnetic load. As long as the current changes there will be an inductive voltage across the accelerator gap which is near the inductivity as shown in Fig.2. So flux change inducing a voltage in this 1:1 transformer gives potential free voltage for acceleration which can be stacked. The beam acts as secondary of the trafo and impedance matching will occur for currents similar to those flowing in the charging line, e.g. kiloamperes (pulse time $\tau \approx$ 50nsec, U $\approx$ 250kV), so application for bursts of electrons is attractive.

For low velocity ions the voltage has to be reduced to maintain the necesssary μsec pulse time, because the product $\tau \times U$ or the flux change is constant. Again acceleration in the induction linac is mainly a beam transportation. An electrostaticly focused multibeam arrangement is appropriate because the multibeam can be maintained also in the high energy end of this linac which is one feature of this driver for heavy ion fusion (Fig 3). In the test machine MBE4 for Cs^+ ions, four beams are accelerated from 200 to 750 kev in 16 LIA modules (length 16m)[14]. By applying special shaping of the voltage pulses (pulse former networks in the lines) the beam bunch will be compressed .

This type of accelerator is naturally suited for stacking and higher energy extension. The beam is not suited for injection into another more classical postaccelerator because of its size and effective emittance.

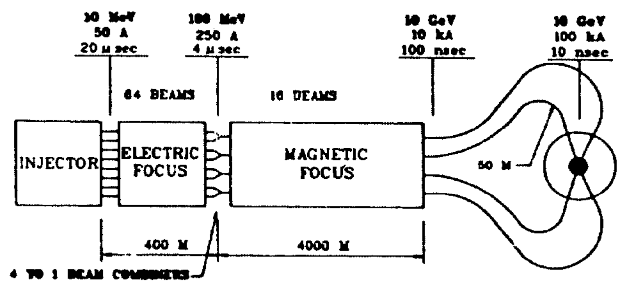

Fig. 2 Induction Linac Module

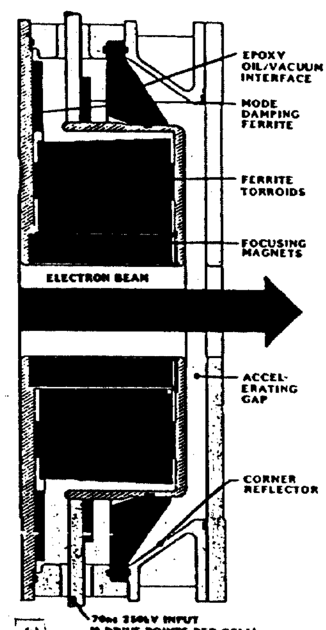

Fig.3 Induction linac driver for HIIF (Heavy Ion Inertial Fusion)

Meqalac

The Meqalac system proposed by Maschke[2] makes use of electrostatic quadrupole focusing and rf acceleration. The "current formulas" can be interpreted in a way that the beam current is independent of the channel diameter in a wide range. For narrow channels the necessary quadrupole voltages are low, so multibeam acceleration of a bundle of beams is a solution for high beam current with use of effective rf acceleration. Because of the high capacitive load the frequency is low and appropriate for ion acceleration.
A Meqalac prototype for He (40-120 keV) has been succesfully built at FOM, Amsterdam[15,16](Fig 4). Limits for the Meqalac are the matching to a multiaperture ion source and the power density (beam losses) and tolerance problems for small channel diameters. The minimum injection energy is given by the frequency and the cell (quadrupole) lengthes. The higher energy limit is given by the decreasing efficiency of the rf accelerator, which is a Wideroe type $\beta\lambda/2$ structure. The experimental results (four beams) show, that appr. 60 % of the theoretical current limit can be reached, that appr. 30% of the injected dc beam are accelerated and that the emittances agree very well with the calculated values. At FOM in a second stage a four-beam N^+ ion implanter (40keV-1MeV, 4mA, 25MHz) is beeing built for use as ion implanter.

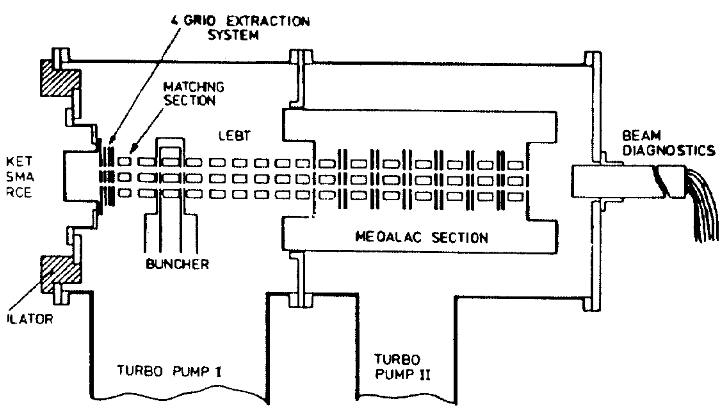

Fig.4 Experimental set up of the FOM Meqalac

RFQ accelerator

In the RFQ structure rf fields are used for acceleration and focusing. The spatial homegenous focusing[3,17,18] is the most densely packed quadrupole channnel in which mechanical modulation of the quadrupole electrodes as indicated in Fig. 5 and Fig. 6 is a periodic perturbation and produces the acceleration field. Application of gentle (adiabatic) bunching allows a nearly 100% capture and acceleration of low energy dc ion beams. The quadrupole structure is continoues and the cell length can be even smaller than the aperture.
That is the reason for the very low injection energy T_i respectivly high operation frequency of RFQs. Typical values are T_i= 10-50 keV and frequencies between 100 MHz and 500 MHz for protons and T_i= 30-300keV and frequencies between 5 and 110 MHz for heavy ions depending on the beam current.
The rf accelerator is a transformer producing the high gradients only on the electrodes so sparking will occur at higher voltages and there are no HV feedthrough problems. This allows very strong focusing and currents up to 150mA (protons) have been achieved. The high energy end is also given by the decreasing acceleration efficiency (~ $\beta\lambda/2$ structure)of the RFQ because the cell lengthes increase at constant electrode (gap) voltage.

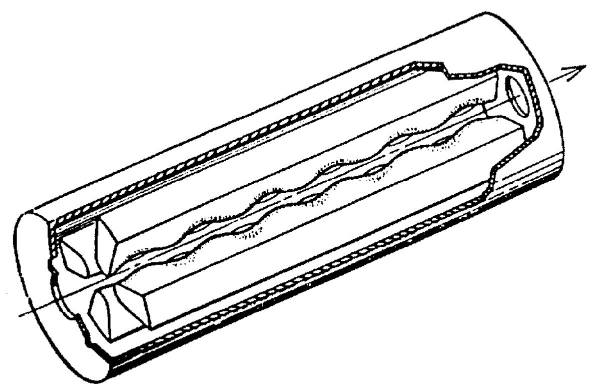

Fig. 5 Scheme of a 4Vane RFQ

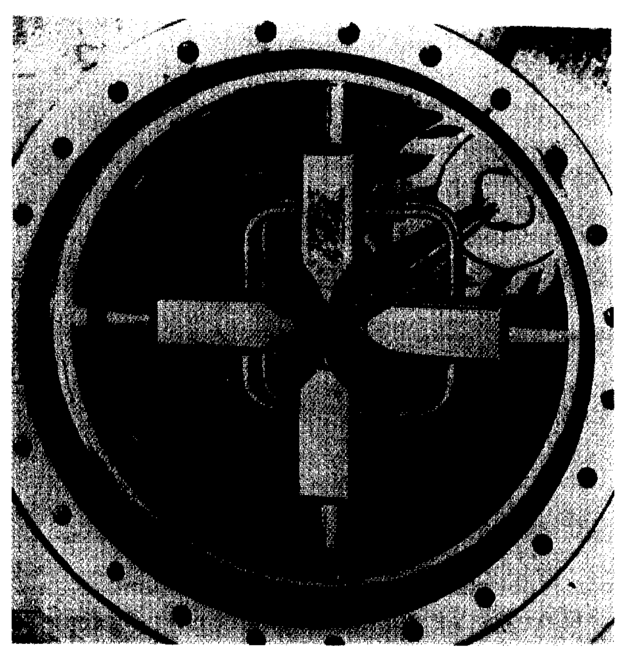

Fig. 6 View of the CRNL cw 4Vane RFQ

There are different rf-structures which are applied for heavy and light ion acceleration: the 4Vane[3] the 4Rod[19] (Fig. 7) and the Split Coaxial[20] (Fig.8) structures which are different in the way they produce the quadrupole fields. In the frequency range suited for space charge dominated heavy ion beams the 4Vane structure cannot be used, while for protons it is the most common structure which even is applied in CW operation tests. (FMIT[21]: 2MeV, 40mA, D^+, 80MHz ; CRNL[22] (Fig.6) : P^+, 0.6 MeV, 270 MHz, 70 mA)
There are also designs for "Ampere beams" with RFQs[23,24] for application in NBH of fusion plasmas which extend the current limits significantly even without using multibeam arrangements, which can be done using the 4Rod RFQ[25].

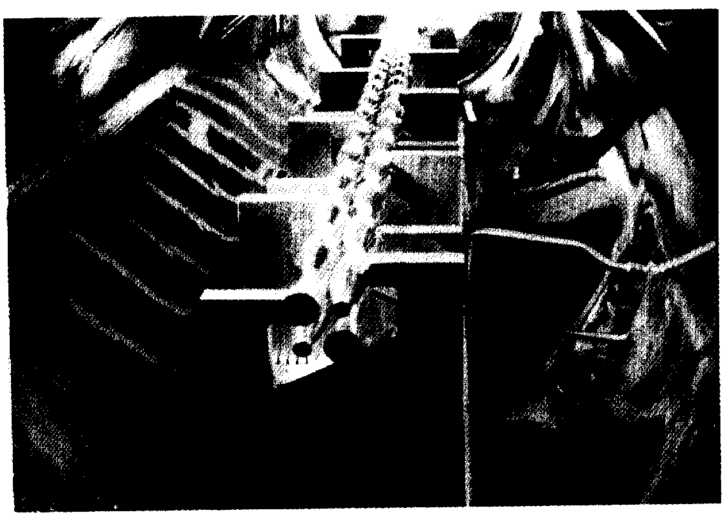

Fig. 7 View of the 4Rod RFQ

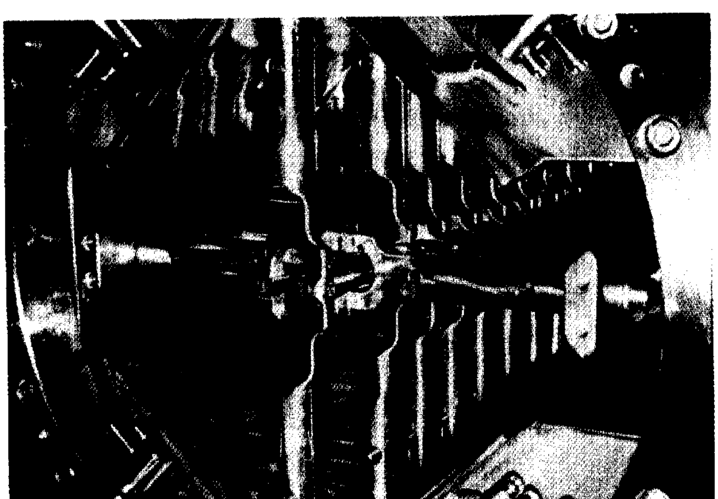

Fig. 8 View of the GSI Split Coaxial Heavy Ion RFQ for 13 MHz

Conclusions

The development for accelerators with space charge dominated beams has been mainly pushed by the need for high current injectors for high energy physics accelerators[26]. There the RFQs have replaced a large number of the existing dc injectors.
Now new applications like HIF [27], ion implantation[28], EHF/AHF[29], NBH [24], "esoteric applications"[30] and also "physics" heavy ion machines[31] have pushed the development furthermore. Along with the big progress in the theoretical description of space charge dominated beams the hardware has been developed too so that 100 mA, 1 MeV, 1. π μradm per beam (even cw!) are realistic numbers for ion beams, not only usable in computer codes.

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