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OPTIMISING A HIGH-CURRENT INJECTOR TO INCORPORATE A FAST BEAM KICKER

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Introduction

In addition to the requirement that the beam current limit imposed by space charge forces be as high as possible, provision should also be made in the injector for fast switching of the high-power beam. The intolerableness of beam losses in a high-current linear accelerator, such as proposed for the German spallation neutron source (SNQ) project[1], requires that the beam switching occurs cleanly between the beam bunches. The method of accomplishing this technically demanding beam switching is limited by the constraints on the injector chain such as the final energy and operating frequency. These boundary conditions, plus the choice of ion source voltage also come to bear on the current limit in the injector. In the SNQ the injector is asked to supply 200 mA of protons at 200 MHz at an energy of 2 MeV, while the ion source voltage has been chosen to be 50 keV[2].

In order to satisfy all the constraints on the injector and at the same time deliver the maximum current, a frequency jump becomes necessary. The requirements for rf power efficiency in the high-energy linac also demand that all rf buckets be filled. A funneling scheme has been proposed[3] for the SNQ where this can be achieved by doubling the current and bunch frequency from a pair of injectors operating at half the frequency. A new technique is also put forward in this paper for debunching a beam at an intermediate energy between two RFQ accelerators allowing an arbitrarily large frequency transition to be made between the two RFQ's and raising the current limit even further.

Beam Line for the Kicker

The layout of the kicker line is designed to incorporate a certain length of deflection elements that can kick the beam sufficiently to separate it from the envelope of the undeflected beam. The deflection elements must be incorporated between the focusing elements in the beam line which are there to both counter the space charge divergence of the beam and to transform the phase space separation of the beam in the deflectors into an optimal spatial separation. The product of length, L, and voltage, V, of the deflector elements determine the maximum emittance that can be just resolved by the kicker system. Simple models have been developed[4] which, neglecting space charge, allow this critical emittance to be expressed as

$$\varepsilon_n = \frac{\pi q V L}{4 m_0 c^2 \gamma \beta} \quad (1)$$

The deflection voltages that can be attained are limited by the risetimes of the pulse amplifiers, so that extrapolating the data from pulsed beam choppers presently in operation[5], about ±1000 V would be available for chopping a 100 MHz beam and ±500 V for a 200 MHz beam. In view of the beam emittances expected for SNQ and allowing some margin for the simplifications in eqn.(1), the length of the deflector at a beam energy of 2 MeV for a 100 MHz beam line has to be at least 1.2 m and for a 200 MHz beam line 2.4 m.

The length of the deflectors clearly exceeds the space available between the focusing elements in the beam line, requiring therefore a beam line design in which deflector modules can be distributed in the lattice. This can be done if the deflector units are placed at positions separated by a 180° focusing phase advance so that the deflected beam receives an extra kick each time it recrosses the beam line axis.

The close spacing of the focusing elements is necessary to transport the high current in the SNQ and is determined largely by the severe aperture limitations of the longitudinal focusing elements, or rebuncher cavities. Nonlinearity of a rebuncher limits its longitudinal aperture to about ±30° of rf phase and the transverse aperture is limited to a size of about $\beta\lambda/10$ above which the longitudinal-transverse coupling in the gap becomes significant. These constraints can be met in a FODO lattice of quadrupoles in which a rebuncher cavity is placed in every second drift space. The alternate drift spaces are occupied by the kicker modules and beam collectors. The beam line, shown in fig. 1, is tuned to a phase advance of 90° per cell so that the envelope separation is optimum at the position of the beam collector and allows a kicker to be placed in every second cell. The design shown is for a cell length of 1 m with 10 cm long quadrupoles (field gradient ~8 T/m) so that 40 cm is available for the deflector plates per cell. Six cells are therefore required to make up the 2.4 m of deflector necessary to fully separate the beam. Together

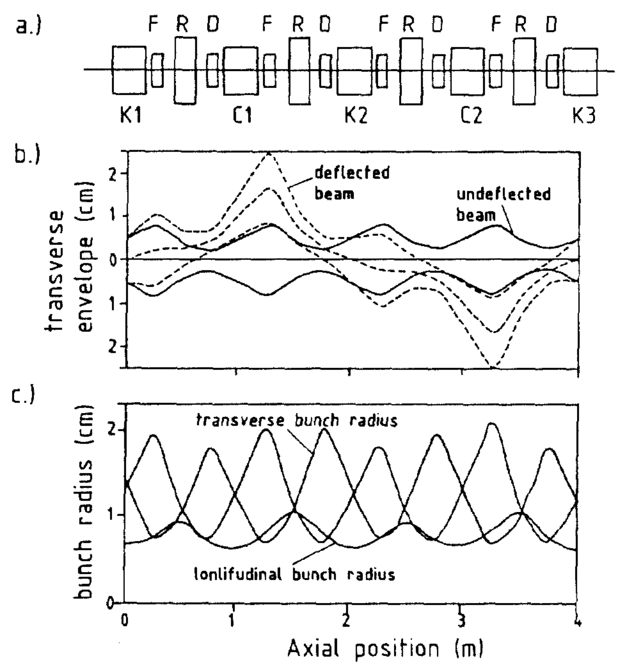

Figure 1

a. Layout of a beam line to incorporate kicker modules (K) and beam collectors (C) in a FODO lattice of quadrupoles (F and D) with rebuncher cavities (R) in every second drift space.

b. Transverse beam envelopes of the deflected and undeflected beams in the above lattice indicating that the envelope separation is maximum at the positions of the beam collectors, and that the kickers are positioned at points where the beam recrosses the axis.

c. Actual beam bunch dimensions calculated to include space charge for a 200 mA beam of 2 MeV protons at 200 MHz.

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with the six beam collector units in between the deflectors, this makes the total beam line 12 m long.

The beam envelopes have been calculated to include the effects of space charge using the programs MIRKO[6] and ENVELO[7], but further multiparticle calculations are needed to check that emittance growth is not excessive in spite of the precautions taken with the degree of tune depression and the beam bunch dimensions in the rebuncher cavities. If such calculations show, for example, problems with envelope resonances as a result of the 90° phase advance per cell being too high, the lattice can also be chosen to operate at a 60° phase advance. In that case the 180° phase advance between kickers is reached after three cells so that the total beam line becomes correspondingly longer. The main advantage of this design remains, though, that the length of the system can be indefinitely extended to meet the requirements imposed by the beam emittance and the limitations to the voltage from the pulse amplifiers.

Scaling Relationships and Current Limits

From eqn.(1) it can be seen that for a given beam emittance and deflection voltage the length of deflector necessary scales with the particle velocity, β. It is useful to know, therefore, how the other components in the beam line can be scaled so that the same current can be transported and with the same beam quality. In fact, only one beam envelope calculation need be used for all situations if the scaling is based on the following restraints: The zero-current focusing phase advance should stay constant (in this case $\sigma_{ot}=90°$) and the space charge factor $\mu=(\sigma_{sc}/\sigma_o)^2$ (both transverse and longitudinal) should stay constant. Using a model for linear space charge forces in an ellipsoidal bunch (see, for example, ref.[8]), this means that the transverse defocusing due to space charge

$$\sigma^2_{sc} = \frac{-3q\lambda I(1-M_z)\ S^2}{8\pi\varepsilon_o cm_o c^2\gamma^3\beta^2 r^2 b} \qquad (2)$$

must remain constant. An equivalent expression can be found for the longitudinal case that differs only in the constant terms.

If the length of the system, S, is scaled in proportion to β, as for the kicker, then μ will remain constant as desired if the bunch dimensions, r and b, are held fixed. If, however, the phase width of the bunch is to remain constant to stay within the linear operating region of the buncher, then the bunch length, b, must also scale with β. A constant μ is only then achieved if S changes in proportion to $\beta^{3/2}$. If the same degree of longitudinal-transverse coupling is also to be maintained in the rebuncher cavities then the bunch radius, r, must also scale with β so that μ is then only constant if $S\propto\beta^{5/2}$. If the length of the quadrupoles is also to scale with S then their gradients must scale as $B'\propto\beta/S^2$.

Incorporating the kicker system at a lower energy, for example, results in the system being shorter, but the aperture restrictions of the rebuncher cavities means that the spacing between the focusing elements decreases faster than the length of the deflector plates. At lower energies a shorter kicker system can be built but it contains a greater number of kicker modules.

In view of these restraints in the kicker beam line the next point to consider is how the kicker system can be best configured with a RFQ injector accelerator. The maximum current in a RFQ is limited, amongst other things, by the choice of injection voltage, U_o, and the operating frequency, f. Combining the current limit formulae in ref.[8] with the Killpatrick criterion for maximum field strengths, it is possible to obtain a simple design formula for the current limit in a RFQ[9]

$$I \propto (E_m/E_k)^2 U_o^{1/2}/f \qquad (3)$$

where E_m is the maximum electric field and E_k the Killpatrick limit. In the case of the SNQ, a single RFQ would operate very close to its practical limits to deliver 200 mA at 200 MHz, so other configurations are also considered here.

Injector Configuration

A comparison of the various RFQ configurations considered here is made schematically in fig. 2. If both a low ion source voltage is desirable and a high operating frequency is necessary for the high-energy linear accelerating stage, then eqn.(3) dictates that high currents can only be handled if a frequency jump is made in the injector chain. One method of achieving this is to funnel the beams from two separate injectors so that the bunch frequency is doubled and also the current, as shown in fig. 2b. In order to ensure that the bunches entering the high-energy linac do not vary from one bunch to the next, the operating characteristics of the two injectors, in particular the two ion sources, must be very stable with time.

The scheme proposed in this paper uses instead a sequential connection of RFQ's and accomplishes a frequency transition by debunching the beam before it enters the next RFQ. Use is thus made of the very versatile nature of RFQ accelerators that are able to adiabatically bunch dc beams with very little beam loss. As a starting point, the situation shown in fig. 2c is considered, where the two RFQ's operate at a synchronous frequency, since this has some advantages for the kicker beam line.

The beam is accelerated to an intermediate energy by the first RFQ where it is further transported in a beam line incorporating the kicker system. The problem, as was already stated, for the kicker line at low energies is that the aperture limitations of the rebunchers require a very dense focusing lattice. However, if the beam is allowed to debunch in the kicker beam line these limitations disappear and the rebunching can be done in the more generous longitudinal aperture of the following RFQ. The advantage is that the kicker beam line is shorter and also simpler because it contains no rebuncher cavities. The bunches must not debunch beyond ±180°, otherwise the overlap would not allow clean switching of the beam. There are also some advantages for the RFQ since in the first RFQ the beam is not strongly bunched at the intermediate energy, so its current limit would be higher than that predicted by eqn.(3). In the second RFQ the voltage and aperture can be chosen to better suit the higher injection energy of the beam, so that its current limit is also higher than a single, uninterrupted RFQ.

A much larger increase in current limit can be achieved, according to eqn.(3), if the first RFQ is allowed to operate at a much lower frequency, as shown in fig. 2d. Fully debunching the beam at the intermediate energy allows it to be rebunched in the second RFQ at a higher frequency chosen to match the following high-energy linac. The first RFQ can now transport a much higher current, even for low ion source voltages, because its frequency can be chosen to be arbitrarily low, and as in the previous case the beam is only partially bunched in this RFQ. In the second RFQ the current limit is also much higher, even if the frequency is high, because the injection energy can be made correspondingly high. The kicker must now be placed again at the high energy end because the total debunching of the beam at the intermediate energy would no longer allow clean switching of the beam.

To take an example that would also satisfy the SNQ requirements, a 100 MHz RFQ could accelerate the beam from 50 keV to 200 keV where a transition would be made to a 200 MHz RFQ to accelerate the beam to 2 MeV. On the simple basis of eqn.(3) alone, the current limits in the two RFQ's would then be the same. The higher injection energy in the second RFQ implies that its electrical length will be greater, because a certain number of $\beta\lambda$ cells are necessary to adiabatically bunch the beam. At the same time the higher frequency reduces the physical length. In the above example, the second RFQ would have the same length as a single 100 MHz RFQ accelerating the beam from 50 keV to 2 MeV. If very high currents were required an RFQ cascade could be made, starting at very low frequencies, and making successive transitions to shorter λ's as β correspondingly increased, so that the length of the system did not run away.

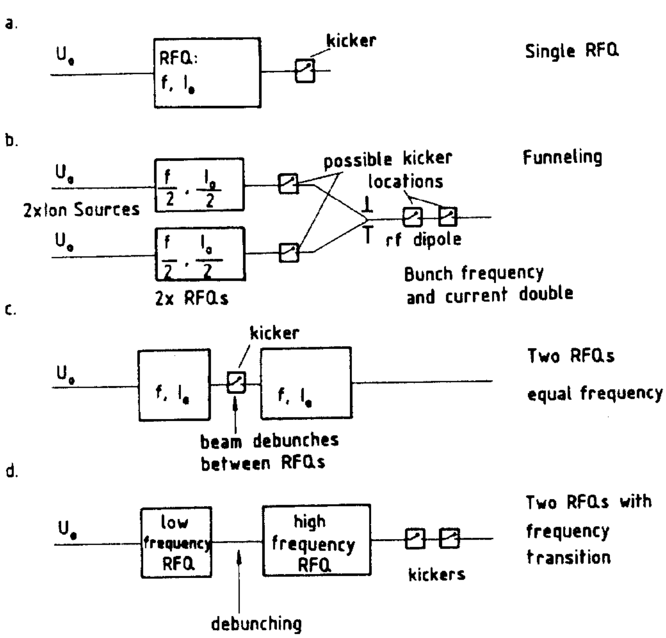

Figure 2

Comparison of high-current injector configurations where the boundary conditions are given by the ion source voltage, U_o, and the final energy, U_f, and frequency, f, of the beam. Position of a fast bunch kicker is also shown.

a. single RFQ whose current is determined by the above constraints.

b. funneling, in order to double the bunch frequency and current.

c. two RFQ's operating at the same frequency in order to incorporate the kicker at a lower energy.

d. two RFQ's with an arbitrary large frequency transition to achieve a higher current limit.

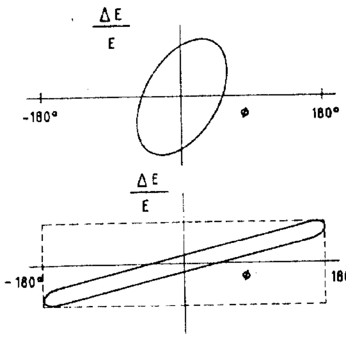

Figure 3

In the longitudinal phase space of a bunched beam it can be seen that if a bunched beam (top) is allowed to drift until it debunches into a dc beam (bottom), the effective emittance of the beam ellipse increases to the area of the rectangle shown.

Debunching and Longitudinal Emittance

If a bunched beam is allowed to drift until it debunches into a dc beam a mismatch in longitudinal phase space occurs which leads to a considerable dilution of longitudinal phase space. The situation is illustrated in fig. 3 where a bunched beam with energy spread ΔE and phase width $\Delta\phi$ is allowed to drift until its phase width extends to a full $\pm 180°$. The emittance of the bunched beam is given by the ellipse area $\pi\Delta E \cdot \Delta\phi$. The area of the ellipse stays the same as the beam debunches, but once the bunches extend beyond $180°$ and the beam is treated as a dc beam then the effective longitudinal emittance is given by the area of the rectangular region shown in fig. 3, namely $4\Delta E \cdot 180°$. The effective emittance increase is approximately the ratio $180°/\Delta\phi$.

In the RFQ configuration of fig. 2c proper longitudinal matching can in fact be done in the second RFQ because the beam does not fully debunch. However, in the configuration of fig. 2d the longitudinal matching must be done at the end of the first RFQ before the beam fully debunches. This is done by incorporating a debuncher into the vane profile of the first RFQ to rotate the lower ellipse in fig. 3 so that the energy spread is at a minimum. This technique is used in the Saclay RFQ[10] for example, to allow dc beams to be transported at the end of the RFQ.

It is important that the beam debunches between the RFQ's to the extent that intensity modulations at the lower frequency become negligible in the high frequency beam, as this may disturb the high-energy linac. Preliminary simulations[11] with PARMTEQ show that the low frequency bunch structure is rapidly blurred by the filamentation structure in the bunches.

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