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A NOVEL METHOD OF CHARGING AN ACCUMULATOR RING

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A key problem for Heavy Ion Fusion is the rapid accumulation of megajoules of beam, which will subsequently be bunched and directed to a pellet. The two applicable methods of filling are by "multi-turn injection" of many turns from a linac, typically, or "box-car" stacking, typically done with a synchrotron injector. "Stacking" in momentum space, as is done in the CERN ISR, is not applicable here because the subsequent bunching required increases the momentum spread by a large factor (~ 10 -100, say).

For high power fusion applications, a circular accelerator for heavy ions is not likely to be competitive with a linear accelerator. This is principally because one requires rather high accelerator efficiencies, and quite large average power. We need efficiencies $\geq 10\%$, and perhaps 30-50 MW of average beam power. On the other hand, the linear accelerator can be built to satisfy these constraints, and in addition, it is ideally suited for multi-turn injection. A difficulty with multi-turn injection is that in typical application it is rather lossy. With care, and sufficient phase space dilution, one might hope to obtain $\geq 90\%$ injection efficiency, but even at these levels the large amount of beam power lost in the accumulator might have serious consequences for the machine operation. Therefore, it is desirable to be able to use "box car" stacking, which is essentially 100% without particle loss. What is proposed here is a method of operating the linear accelerator so that the output beam is of suitable instantaneous current to permit box-car stacking with the linac output.

Let us consider an example, in order to illustrate how the system might work. Suppose we want to fill the storage ring up to the 5 ampere level. If we have a linac capable of producing 40 mA of beam, we could fill the ring in 125 turns, via multi-turn injection. In order to fill the ring "box-car" fashion, we need high current "bursts" from the linac. Suppose this to be a 10 ampere burst, lasting for 40 ns. Assuming that we have a single burst injection system with a rise time ≤ 40 ns, we can arrange to time our bursts so that they occur sequentially spaced around the circular accelerator. For our example, if we keep to a 40 mA average current, with 10 amps in the burst, this means a 10 μ sec interval between bursts. If the revolution period of the ring was 9.92 μ sec, the next

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linac burst would arrive in the ring just 80 ns behind the initial burst, and so on until the ring was filled.

Now let us turn our attention to the problem of producing the appropriate current versus time structure in the linac. In normal operation, a linac is a constant current device. The usual situation that prevails is that space charge effects restrict the input current. However, as the energy of the particle increases, the space charge limiting current tends to increase. Therefore, we could imagine accelerating for a while, and then "bunching" the beam to a higher current, and going on again in the linac. Again, let's look at an example.

We suppose our linac starts out with a long pulse (for our example, the pulse length must be $\sim 125 \times 10 \mu\text{sec} = 1.25 \text{ ms}$) with no structure other than the normal linac bunch structure. At the appropriate energy, we use very fast rise time kickers to deflect the beam into 4 different transport channels at 40 ns intervals. The lengths of the 4 channels are arranged so that the beam can be brought back together at the same time. This is done with three lines with transit times of 40 ns, 80 ns, and 160 ns, say. Beams 1 and 2, and Beams 3 and 4 are combined, with a septum magnet to produce two beams of larger horizontal emittance. This can be done with virtually no beam loss, and a phase space dilution factor of about 1.5. The two beams are then combined in identical fashion in the vertical plane.

The net result of this procedure is that we have taken an essentially "DC" beam of 40 mA, and produced a "chopped" beam, containing 40 ns bursts of 160 mA at 160 ns intervals. The price we have paid is that our transverse phase space is 3 times larger. However, the momentum spread, i.e., the longitudinal phase space, has not been diluted. This is basically a method of exchanging transverse phase space density to obtain higher longitudinal phase space density.

As a practical matter, there is an effective dilution of longitudinal phase space which would occur as a result of each beam debunching by a different amount. This can be corrected by putting a "buncher" cavity at the midpoint between the two linac sections. Figure 1 shows a schematic of the process.

If the above process was repeated three more times, at appropriate energies, we would wind up with 10 ampere bursts, 40 ns long, at 10 μ sec intervals. The thing which allows this system to work is the fact that the stored energy in each linac tank is much greater than the energy removed by the burst. Typical values for a 200 MHz Alvarez structure give about 4 Joules/MV, and our burst removes about 0.4 Joules. The energy spread between the first and last bunches of the 40 ns burst can be compensated for by the intermediate buncher cavities, or by the debuncher cavity at the end of the linac.

Now let us look at space charge considerations. The longitudinal space charge forces scale in such a way that we have:

$$\frac{i_{LSC} A f}{\bar{e} E} = \text{constant} .$$

where $\bar{e}$ is the average electric field, E the energy of the particle, A the atomic weight, f the linac frequency, and i_{LSC} , the longitudinal space charge limiting current. The constant can be determined empirically by examination of existing linacs operating near the space charge limit. The AGS linac, with 100 mA at 0.75 MeV, assures us of a longitudinal space charge limiting current in excess of 25 amperes at 200 MeV.

The transverse space charge limit goes up even more rapidly with energy, and so will not be of limiting concern.

To complete our example, let us consider a linac starting at 10 MeV and accelerating Uranium to 40 GeV. We perform our current bunching operation at 56 MeV, 316 MeV, 1.8 GeV, and 10 GeV. If our final emittance is about $\epsilon = 10^{-4}$ at 40 GeV, our intermediate emittances are:

<u>Energy</u>	<u>ϵ</u>	<u>I</u>
10 MeV	0.8×10^{-4}	0.04 amps
56 MeV	1.0×10^{-4}	0.16 "
316 MeV	1.2×10^{-4}	0.64 "
1.8 GeV	1.6×10^{-4}	2.5 "
10 GeV	2×10^{-4}	10.0 "
40 GeV	1×10^{-4}	10.0 "

At 10 MeV, the transverse current limit is about 0.18 amperes for this value of emittance, and a charge 10 state. Therefore, we are well within the limit at the start, and things get better as we accelerate. The longitudinal space charge limit, using the FNAL linac as the benchmark, requires the frequency to be below 75 MHz. 25 MHz is a likely frequency choice for this early section, so that that should not present a problem.

There are many ways of achieving much the same result, and no attempt has been made here to obtain an optimum solution. For instance, our first "bunching" step could have consisted of putting together 4 2.5 μ sec long bursts of beam, at 10 μ sec intervals. This requires substantially longer drift distances, which would be accomplished by 3 ring transport systems of 7.5, 5.0 and 2.5 μ sec revolution period. Here, care would have to be taken that the bunches did not debunch so much as to overlap. This can always be arranged with the appropriate bunching cavities in the transport.

At the low energies, beam power is not a problem. Therefore, one might choose to do multi-turn injection to obtain the current multiplication. At the expense of throwing away beam, this could result in a substantially brighter beam at final energy. (We are talking about factors of 2 - 4 at most.)

For our example, the storage ring space charge limit for 40 GeV U^{10+} corresponds to a peak current of 17.5 amperes, which matches well with the average injected beam current of 5 amperes. The stored energy in the accumulator amounts to 200 kJ. 20 such rings would hold 4 MJ, and would require a single 25 ms linac pulse to fill all of them. Such a linac, if operated CW, would produce 160 MW of beam. This is enough to produce around 5-10 GW of net electrical energy.

FIG. 1