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Simulations of an Induction Linac with Realistic Field Configuration

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Introduction

In terms of the basic beam dynamics, it has been shown [1] that an induction linac could be used to correct the energy spread of the muon beam in a Neutrino Factory, before the cooling stage. However the field configuration of the linac was based on idealised fields, where the electric field was only along the beam axis and did not vary with radius. Furthermore the transverse focusing was provided by a constant longitudinal field as an approximation to the real solenoids that would be present in the induction linac cells.

For this note the magnetic field has been introduced from a series of current sheets to approximate the field distribution from superconducting solenoids inside the induction linac cells, while the electric field configuration has been taken from electrostatic calculations using POISSON.

Finally the approximate power consumption of the linac will be presented and power saving factors (with certain compromises with respect to the beam dynamics) will be discussed.

Linac Parameters

The simulations presented in [1], used an induction linac capable of providing a gradient up to 2 MV/m and used a focusing field of 1.46 T. The total structure length was 50 m and the clear radius of the beam was required to be 30 cm. The electric field needs to be held for at least 300 ns.

In order to limit the switching of the high voltage to 500 kV, it was decided to use linac sections of 25 cm. In each cell the magnetic core and the solenoid windings are allowed over 15 cm, leaving 5 cm for the vacuum vessel and 5 cm for the high-field gap.

The resulting induction linac cell is shown in Figure 1, with the corresponding electric and magnetic field plots in Figure 2 and Figure 3 respectively. Furthermore, the magnitude of the magnetic field variation along the cell length can be seen in Figure 4. The design of the magnetic and electrostatic systems was in no way optimised for the beam dynamics.

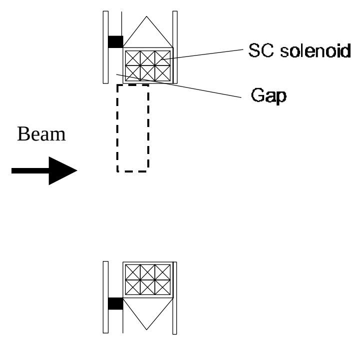

Figure 1. One cell of the induction linac. Cell length is 25 cm and the inner diameter is 60 cm. The dashed box illustrates the area over which the electric field is given below.

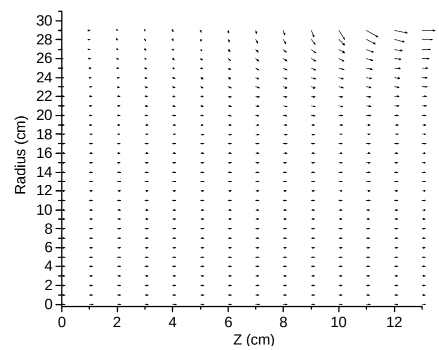

Figure 2. Electric field plot of one quarter of a cell. The right hand side corresponds to the mid-plane of the accelerating gap.

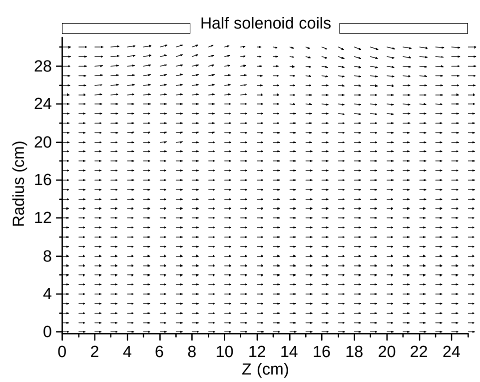

Figure 3. Vector plot of the magnetic field. Right and left hand planes correspond to mid-point of the solenoid coils.

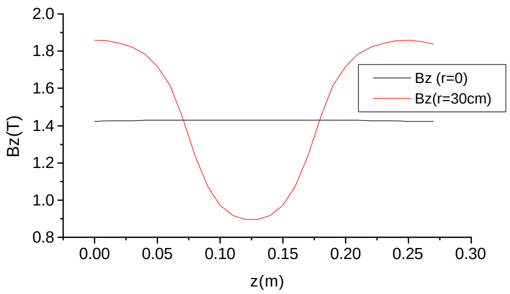

Figure 4. Bz component of the magnetic field at r=0 and r=30cm (beam maximum radius).

Results of Simulations

Both the electrostatic and magnetic distributions were used as the field input for ICOOL 2.02 which was modified to ramp the magnitude of the electrostatic field as a function of time according to a 6^{th} order polynomial. (The magnetic field calculation was actually performed within ICOOL.)
Furthermore the final section of the decay channel (nominally a 1.46 T solenoid) was modified (with respect to [1]) to match the solenoid pattern of the induction linac in the last 6 m, in order to have a correct magnetic field transition.
The results of the simulations are given in Table 1, for the beam parameters that are affected by the introduction of the more realistic fields.
The results indicate that the more realistic fields patterns do not result in large changes in the muon beam parameters.
One important field still missing from the simulations is space-charge. However at present the timing schemes of the proton driver pulses is not fixed and therefore the muon beam current is not known.

Table 1. Pion to muon transmission efficiency and emittance (in mm.rad rms normalised) at the output of the induction linac. Column headings correspond to the field type that has has been introduced, while the other field type remains idealised. Column I has both E and B fields idealised. Only muons in a momentum region 180<P<220 MeV/c (at the linac output) are considered. Run with 5000 input pions.

	I	E	B	E+B
π->μ	31.5%	31.5%	31.5%	30.8%
Emit	18.4	18.7	18.8	18.7

Estimation of Power Consumption

The estimate of the needed magnetic core cross-section (A) is possible from the equation

$$V \cdot \Delta t = \Delta B \cdot A$$

where V is the required voltage to be held, Δt is the pulse length and ΔB is the magnetic field swing. Assuming Metglas 2714A (which has a low hysteresis loss and ΔB=1.1 T), we find A=0.136 m^2 to reach 1 MVm^{-1} for 300ns.
The power consumption of the linac can then be estimated from the following equations.

$$r_2 = \frac{A}{L_{mag}} + r_1 = 1.31\text{m}$$

$$Vol = \pi\left(r_2^2 - r_1^2\right) \cdot L_{mag} = 0.732\text{m}^3$$

$$P = w \cdot Vol \cdot R \cdot N_{cells} = 16.5\text{MW}$$

where r_2 is the magnet core outer radius, r_1 is the magnet core inner radius (40 cm), L_{mag} is the length of the core in the cell (15 cm), Vol is the core volume per cell, w is the energy loss per unit volume of the core (188 J/m^3 [2]), R is the rep-rate (50 Hz x 12 bunches) and N_{cells} is the number of cells required (200). This leads to a total power consumption of 16.5 MW. No consideration is given to the isolation required between the Metglas layers, required to reduce the Eddy currents. This will increase the outer diameter of the machine and increase the power consumption.

Various power saving techniques can be proposed. The output power after each of these is given as a percentage in parentheses.

1. Half the electric field duration and use a shorter decay/drift solenoid, resulting in a larger final momentum spread – (37%).
2. Half the number of proton bunches on the target (doubling the proton number per bunch) – (50%).
3. Half the machine gradient and double the length (capturing the same momentum range) – (73%).
4. Increase the core magnetic length to fill the entire linac length (not feasible but an indicator of the power gain) – (79%).
5. Reducing core inner diameter to 0.3 m with associated muon beam loss – (88%).

As is clearly seen the largest power savings are by reducing the electric field pulse duration (point 1) and reducing the number of proton bunches (point 2).
The effect of reducing the pulse duration will have to be studied on the muon yield and a compromise reached with linac engineering.
The present number of proton bunches (12) would also seem to be very difficult to provide [2] as so far multi-pulse schemes have been demonstrated only up to a factor of 4.
The other three possibilities do not lead to a significant power saving (but the saving of all three of the points together is still 50%).

Conclusion

It has been shown that the beam dynamics are not strongly affected by the use of idealised linear electrostatic and magnetic fields in the simulations of the induction linac. Therefore for the purposes of the feasibility study the idealised fields are sufficient for approximate values of transmission and emittances of the muon beam.
The power consumption has been estimated and can be seen to be high but several possibilities exist to reduce the power to levels that could be feasible. Simulations of these effects of these compromises on the muon beam need to be performed.
The induction linac scenario does not fit with the present proton beam time dynamics of the accumulator, i.e. a 12 bunch "burst" would appear to be too demanding on the power systems. Furthermore, the bunch spacing of the proton beam must be increased to keep the linac "off" for at least twice as long as the pulse length during the burst. This requires that the proton driver be reconfigured to give 900 ns between bunches or that the induction linac is re-simulated to result in a voltage pulse lasting for a shorter time (perhaps 150 ns).

References

[1] R Scrivens, Example Beam Dynamic Designs for a Neutrino Capture and Phase Rotation Line using 50 m, 100 m and 200 m Long Induction Linacs, CERN NF Note 14 or CERN PS/HP 2000-001 (2000).

[2] S. Yu, Private Comms.