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Beam Loading Computation for the IDS-NF FFAG

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Abstract

I accumulate the information we have for the current baseline design for a neutrino factory to determine the maximum current we can expect at the final FFAG accelerating stage. I then determine the energy extracted from the RF cavities in the FFAG, and from that determine how much time there must be between bunch trains to restore the energy to the RF cavities so that each bunch train has the same energy at the storage ring. I also estimate the amount of energy variation from the head to the tail of the bunch train.

Key words: beam loading, neutrino factory, proton driver

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1. Beam Current from Front End

From the ISS accelerator report [1], the total number of muons per proton per GeV of proton kinetic energy is approximately 0.017. In [2], the maximum production of mesons up to a point before the cooling channel is approximately 0.035 mesons per proton per GeV of proton kinetic energy. From [3], the ratio of this merit factor to the same factor into the neutrino factory acceptance at the end of a cooling channel is approximately 1.92. Thus, this figure corresponds to a number of muons per proton per GeV of proton kinetic energy of approximately 0.019. From the data underlying those calculations, it seems that the precise number is closer to 0.020 [4]. We assume that we have 3 pulses every 20 ms and a 4 MW proton driver. Taking the largest figure for the muons per proton per GeV, we find a number of muons in each bunch train at the end of the cooling channel going into the accelerator acceptance of

3.3×10^{12} .

2. Decay Losses in Acceleration

Decay losses in the earlier acceleration stages will reduce the current seen in the FFAG. There are three acceleration stages preceding the FFAG: a linac and two recirculating linear accelerators (RLAs).

The linac consists of three sections, with the following parameters [5,6]:

Lattice cell length (m)	3	5	8
Lattice cell count	6	8	11
Cavities	1	1	2
Cells/cavity	1	2	2
Energy gain/cell (MV)	11.25	12.75	12.75
Power input/cell (kW)	490	508	508
RF pulse length (ms)	3	3	3

The RF phase decreases from 72° to 0° approximately linearly down the channel [7]. Note that the energy gains appear to have no correction for the reduction in transit time factor at lower velocities.

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For these calculations that can be treated as being folded into the phase.

To compute decay losses, one must integrate the simultaneous equations

$$\frac{dN}{ds} = -\frac{mc^2 N}{c\tau\sqrt{E^2 - (mc^2)^2}} \quad (1)$$

$$\frac{dE}{ds} = qV(s) \cos \phi(s) \quad (2)$$

where N is the number of muons, E is the muons' total energy, s is the longitudinal position, m is the muon mass, τ is the muon lifetime at rest, and c is the speed of light. The result is 94.4% transmission.

The RLA designs [5] appear to have 3 m half-cells containing a single two-cell cavity with an energy gain of 25.5 MV per cavity. See the linac table for the corresponding power parameters. The first RLA has 26 such cells, the second has 88 such cells. The first RLA arc appears to be 130 m long for an energy of 1.2 GeV. The lengths of subsequent arcs are assumed to scale with the momentum. Each RLA accelerates in 4.5 passes.

Decay losses are computed by taking

$$N = N_0 \exp\left(-\frac{mc^2 L}{c\tau\sqrt{E^2 - (mc^2)^2}}\right) \quad (3)$$

in the arcs and

$$N = N_0 \left(\frac{E + \sqrt{E^2 - (mc^2)^2}}{E_0 + \sqrt{E_0^2 - (mc^2)^2}}\right)^{-\frac{mc^2}{c\tau qv}} \quad (4)$$

in the linacs. Zero subscripts indicate initial values, L is the length of the arc, and v is the accelerating gradient in the linac. The transmissions in the two RLAs (treating the transfer line as a fifth arc) are 89.0% and 89.2% respectively.

Thus, with the decay losses, we expect 2.5×10^{12} muons to reach the FFAG in each bunch train.

3. Energy Extracted from RF Cavities

From the Study II report [6], superconducting cavities were proposed that had a maximum energy gain per cavity of 25.5 MV and an input power of 1016 kW. In our likely configuration, a triplet with 5 m drifts, the beam will make 12 passes through some of the cavities.

Therefore, assuming the maximum energy gain, the 2.5×10^{12} muons extract 122 J from each cavity in 12 passes. To replenish that energy will at the input power rate available for the cavity will require 120 μ s.

The stored energy in the Study II cavity [6] was 2008 J. On each pass, the bunch train extracts 10.2 J from the cavity. Thus, the last bunch in the train sees 65 kV less RF voltage than the first bunch, receiving 0.25% less energy gain than the first bunch. Therefore, the last bunch in the train will finish the acceleration cycle with an energy 31 MV lower than the first bunch in the train.

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