Review of the Neutrino Factory Muon Front End

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Abstract

Three major facilities have been proposed for the precision study of neutrino oscillation parameters, the Neutrino Factory, the Betabeam and the Superbeam. Of these, the Neutrino Factory offers the high precision measurement of oscillation parameters [1]. The Neutrino Factory generates neutrinos by firing protons onto a target in order to produce pions. The pions decay to muons which are captured before being accelerated to 25 GeV and stored in racetrack storage rings where they decay to neutrinos. In this note the longitudinal drift, adiabatic buncher, phase rotation system and ionisation cooling system that make up the Neutrino Factory muon front end are reviewed.

THE NEUTRINO FACTORY

The baseline design of the International Design Study (IDS) is shown in Figure 1. 4 MW proton bunches with length in the range 1-3 ns are fired at energies in the range 5-15 GeV onto a target where pions are produced. The intensity of the beam may be sufficient to destroy non-moving solid targets; moving solid or liquid targets are under investigation. Pions are captured in a 20 T solenoid which is adiabatically tapered along the accelerator axis. Pions decay to muons with a large energy spread. The beam is transported through a long solenoid in order to enable a energy-time correlation to develop and then the muons are bunched and the energy spread reduced using phase rotation. The beam is subsequently cooled using ionisation cooling to increase the number of muons that are accepted by the accelerating system. The beam is then accelerated as fast as possible, to minimise decay losses, in a series of 3 linacs. In order to re-use equipment, the latter two linacs each have recirculators that return the beam for multiple passes through the same cavities. Next, a high acceptance Fixed Field Alternating Gradient machine (FFAG) is used to take the muons up to 25 GeV. Finally the muons are stored in a large aperture racetrack-shaped storage ring where the muons decay to neutrinos.

MUON FRONT END

The muon front end is the section of the Neutrino Factory concerned with capturing the muon beam [2]. This corresponds to the longitudinal drift, adiabatic buncher, phase rotation and ionisation cooling system.

The basic muon front end design presented here was developed as part of the so-called Feasibility Study 2A [3] and subsequently adopted as the baseline for the International Scoping Study. A modified version of this design [4] was adopted in April 2010 as the IDS baseline and is the lattice that is planned to be taken forward for engineering in the Interim Design Report (IDR) of the IDS. It has the advantage that the overall system is shorter, presumably making it cheaper, and it produces a shorter bunch train making the storage ring and FFAG kicker system easier. Both the ISS design and the IDR design are reviewed in this note.

SIMULATION CODES

The majority of the modelling of the baseline described here is performed using version 3.10 of the ICOOL code [5]. ICOOL is a tracking simulation code designed for ionisation cooling channels. It enables the calculation of realistic RF and solenoidal field maps together with a realistic model of physics processes undergone by charged particles in material, namely ionisation energy loss and multiple Coulomb scattering. ICOOL is used for the majority of the modelling in this study as it is well known to the community and has been previously verified.

Particle production at the target has been studied in version 15 of the MARS simulation code [6]. MARS has been used previously and hence enables this work to be readily compared with previous studies.

G4MICE [7] version 2-1-0 has been used to perform some simulations of the front end. This code was designed for use by the Muon Ionisation Cooling Experiment, a protype muon ionisation cooling channel, and hence will be compared in detail with experimental data when it becomes available. In the meantime, it provides a different physics model for studying electromagnetic processes in material. In addition, G4MICE has additional capabilities for studying beam optics that is not available in other codes.

PION PRODUCTION SIMULATION

In the baseline configuration 2, a proton beam crosses a 1 cm diameter Hg jet of 20 m/s velocity at about 33 mrad angle. The jet angle to the horizontal axis is about 100 mrad and the proton beam angle to the axis is about 67 mrad [1]. The pion production as a function of the beam angle to the Hg jet and the beam entry position has been studied [8] for different beam energies using MARS [6] simulation code. The beam and target geometry optimum parameters have been defined according to the results of these simulations. The pion/muon capture performance has been studied using two field maps with different field tapers (Fig. 3). Results from past studies gave a 10% increase in the muon collection for the FS2a field map. The results from the current MARS simulation give for proton beam energies between 5 and 15 GeV less than 5% increase (Fig. 4) in the muon yield at 50 m downstream of the target for muon kinetic energies of 40-180 MeV. For the purpose of this simulation only the relative yield for one field map compared to the other was considered. Other simulations with different software exhibit a difference in the overall yield not discussed in this document. In addition, data from the HARP [9] experiment, studying the pion production in a fraction of the momentum-angle phase-space interesting for the muon front-end, will be published soon for targets of one interaction length and will help simulation codes agree in the future.

Secondaries from a proton beam with energy of 8 GeV with the FS2 solenoid taper are simulated in subsequent sections. 8 GeV was chosen as it is close to the centre of the IDS parameter range and also may be the energy of a future proton driver at Fermilab.

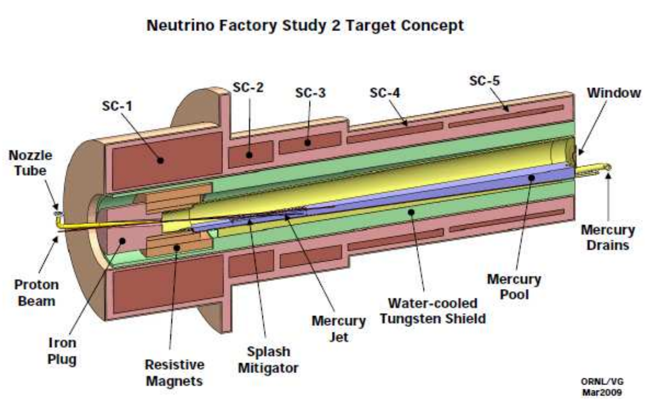

Figure 2: Layout scheme of the mercury target.

LATTICE DESCRIPTION

The magnetic lattice is described in Table 1. Magnets are all superconducting solenoids. Near to the target, current densities in the superconductor are relatively low, which will be beneficial in what is likely to be a high radiation environment. In the cooling channel, current densities are

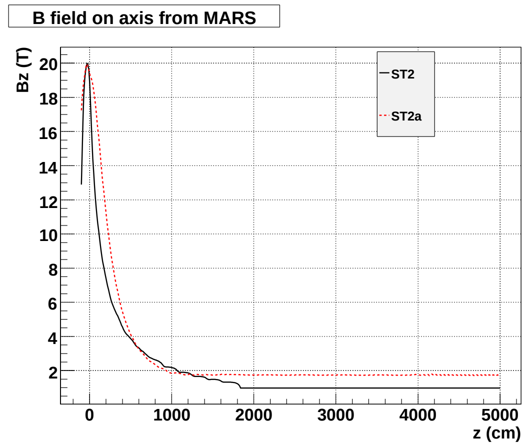

Figure 3: FS2 and FS2a field configurations.

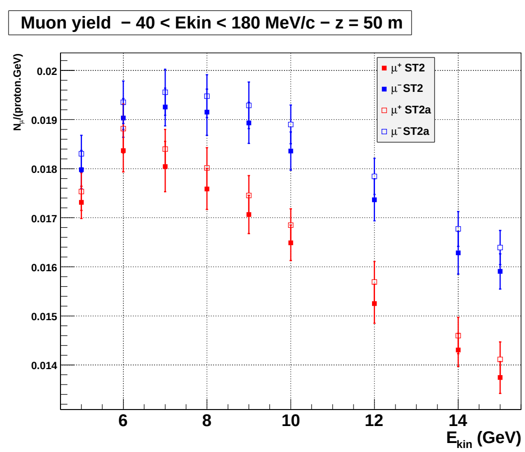

Figure 4: Muon yield per proton and per power as a function of the proton beam kinetic energy for FS2 and FS2a field configurations, with kinetic energies in the range 40 - 180 MeV.

rather higher and alternate coils have opposite polarity so that the field is sine-like.

RF cavity parameters are listed in Table 2. All cavities are normal conducting and sealed by Beryllium windows. The Beryllium seal improves the cavity shunt impedance, gives a higher field on-axis and hence more efficient acceleration, and prevents field leakage enabling a more compact design. Muons tend to pass through the Beryllium with little emittance growth or even a small amount of ionisation cooling. The Beryllium is chosen to be as thin as possible; the thickness is determined by the need for a conduction pathway for heat to escape and to maintain structural integrity. In the case of the ionisation cooling channel, much thinner Beryllium can be used as Lithium Hydride absorbers provide structural integrity; a 25 micron thick coating is simulated.

In this design, RF cavities operate with large electric field gradients in strong magnetic fields, and as noted below this is some cause for concern.

	Drift[1]	Buncher and Rotator	Cooling
Number	54/136	142	Up to 135
Peak Field [T]	1.75	1.75	2.78
Length [m]	0.36	0.50	0.15
Inner radius [m]	0.43/0.32	0.65	0.35
Radial thickness [m]	0.10	0.10	0.15
Current Density [A/mm^2]	19.22/19.00	40.43	106.67

Table 1: Coil parameters for the ISS baseline of the muon front end lattice. Coils for matching and for the pion capture solenoid are not listed.

	IDR Baseline			ISS Baseline		
	Buncher	Rotator	Cooling	Buncher	Rotator	Cooling
Number	31	55	Up to 195	25	71	Up to 133
Peak Field [MV/m]	4.9-9.7	13.0	16.0	5.0-10.0	12.5	15.25
Length [m]	0.50	0.50	0.50	0.50	0.50	0.50
Frequency [MHz]	233.6-305.6	202.33-230.2	201.25	234.22-308.16	202.26-231.94	201.25
Phase [°]	0	5	35	5	6	40.

Table 2: RF parameters for the two muon front end lattices.

LONGITUDINAL PHASE SPACE

Longitudinal capture is achieved by an adiabatic buncher followed by a phase rotation system. Initially, RF is ramped slowly in order to capture particles into buckets. Moderately high frequency RF is used in order to get high accelerating gradients necessary for ionisation cooling, so it is not possible to capture in a single RF bucket. Instead, particles are captured into several buckets. The short proton bunch length means that the longitudinal phase space occupied by the muon beam is relatively small. The RF frequency is chosen such that particles stay in the same RF bucket despite a changing time offset between the high energy head of the macro-bunch and the low energy tail.

Once the micro-bunches are adiabatically captured, the phase rotation begins. The frequency and phase is chosen so that the head of the bunch sees a slight decelerating field while the tail of the bunch sees a slight accelerating field, leading to a reduction in total energy spread of the beam. In this way a large proportion of the beam, of both signs, can be captured.

The longitudinal phase space is shown in Fig. 5 at various points along the front end for the IDR baseline configuration. The evolution of the RF bucket can be seen clearly. The number of muons captured within two longitudinal acceptances is shown in Fig. 6. A large increase in the number of muons captured can be observed in the buncher and phase rotation system, and this corresponds to the development of a high density spot in the RF bucket. Subsequently some muons are lost from the RF bucket; this is partly due to a longitudinal mismatch between the phase rotation system and the cooling channel, and partly due to energy straggling in the Lithium Hydride.

The relative length of the bunch train is shown in Fig. 7. The IDR bunch train is about 25% shorter, which may make downstream kicker systems less demanding and enables a smaller storage ring design. The tail of the bunch train has a relatively low density and it may be desirable to chop the tail so that the beam can be injected and extracted more easily further down the accelerator chain.

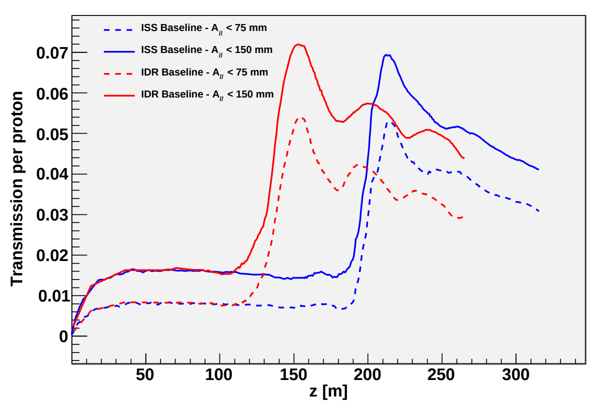

Figure 6: Number of particles captured in longitudinal acceptance of 75 and 150 mm and with z-momenta in the region of 100 to 300 MeV/c, for ISS and IDR baseline lattices.

TRANSVERSE PHASE SPACE

Particles from the target are captured into an adiabatically tapered solenoid before entering a constant solenoidal field. The constant field is used as it gives a large momentum acceptance and few aberrations, resulting in good

[1] The drift bore size changes along the drift, leaving the on-axis field invariant.

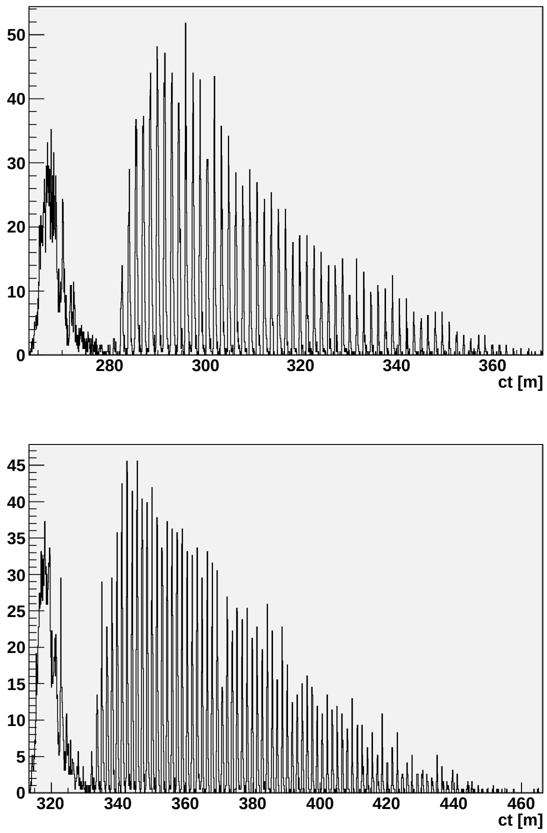

Figure 7: Length of the muon bunch train for (top) the IDR baseline and (bottom) the ISS baseline.

transmission for the entire beam. In the ISS baseline, a larger bore is required to fit RF cavities into the accelerator for the buncher and phase rotator. Matching sections are required to match between the two different bores.

Subsequently the beam enters the ionisation cooling channel. In ionisation cooling, muons are passed through material and lose energy by ionising atomic electrons. Subsequently the energy is replaced by RF cavities in the longitudinal direction only, resulting in an overall reduction of beam emittance. Stochastic effects, principally multiple Coulomb scattering and energy straggling, tend to spoil the cooling effect. The relative effect of the multiple Coulomb scattering can be reduced by using a beam with large transverse momentum, corresponding to a tightly focussed beam.

For effective ionisation cooling, a large acceptance is required over a broad range of momenta. Additionally, absorbers placed in non-zero solenoidal fields can induce canonical angular momentum in the cooling channel that tends to introduce a mismatch. In the cooling section an alternating solenoid arrangement is used so that the induced canonical angular momentum is in the opposite sense in adjacent cells, resulting in no cumulative effect. In this situation, it is challenging to contain large transverse and longitudinal emittances. By packing adjacent coils closely, a good acceptance can be achieved together with a tight focus on the absorbers. Cooling is provided by Lithium Hydride absorbers. Lithium Hydride is chosen as it is a low Z material, and hence induces less multiple scattering per unit energy loss giving a better cooling performance.

The cooling performance of the lattice is shown in Fig. 8. Transverse emittance is reduced by a factor of nearly 3 both for the ISS and IDR baseline. It is difficult to distinguish between emittance reduction from ionisation cooling and transverse scraping, so the increase in number of muons in various transverse acceptances is also shown, and an increase of nearly a factor 2-3 in muon rate is observed.

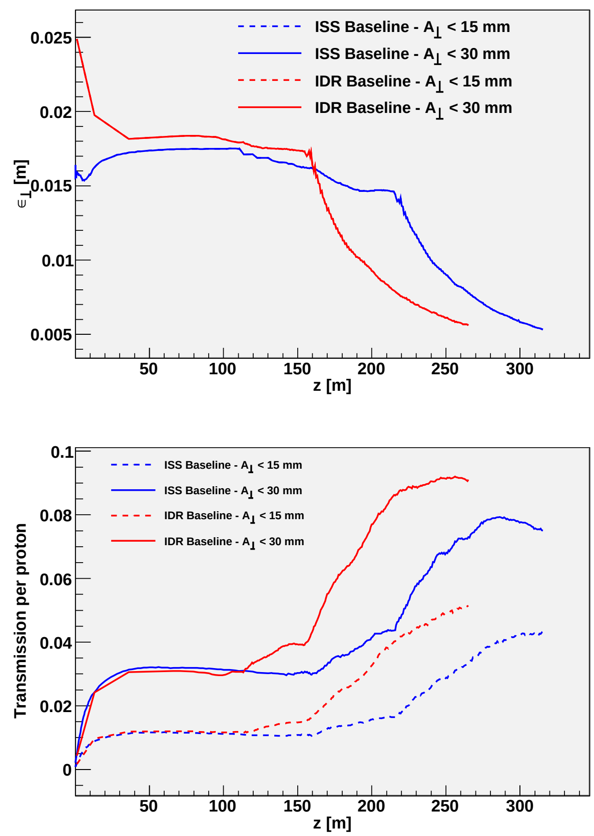

Figure 8: (top) Transverse emittance and (bottom) number of particles captured in a transverse acceptance of 15 and 30 mm with z-momenta in the region of 100 to 300 MeV/c, for ISS and IDR baseline lattices.

OVERALL PERFORMANCE

The overall improvement in muon transmission of the two lattices is shown in Fig. 9. In this figure the number of muons inside a minimum acceptance of the accelerator systems is shown as a function of position along the channel. The muon front end increases the muon rate by a factor of about 20 within the acceptance of the accelerator systems.

The ISS baseline and IDR baseline performance is similar. The main improvement between the ISS baseline and

IDR baseline is the shorter bunch length, which can reduce the storage ring length, and a shorter front end using less hardware, which makes the entire system less expensive.

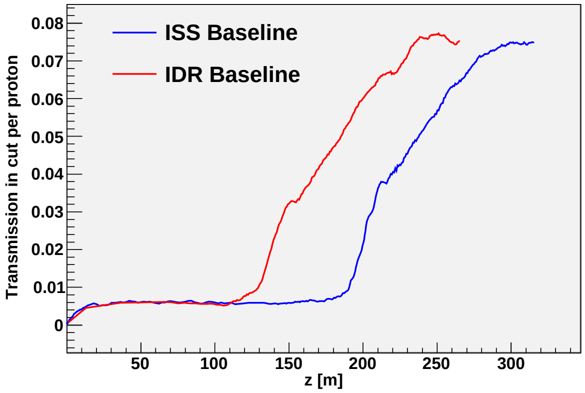

Figure 9: Number of muons within 30 mm transverse acceptance, 150 mm longitudinal acceptance and with z-momenta between 100 and 300 MeV/c.

EFFECT OF REDUCED RF GRADIENTS

There is some impirical evidence that suggests that magnetic fields overlapping RF cavities, as present in the Neutrino Factory front end, may induce breakdown in the cavities. The performance of muon cooling using a reduced field has been explored [10] using G4MICE [7] and ICOOL codes. The interaction of muons with material such as LiH are modelled differently in both codes, thus leading to different cooling performances (Fig. 10). Both simulations indicate that above 8 MV/m the number of muons captured by the cooling channel is roughly linear as a function of peak field gradient.

SUMMARY

The muon front end has been reviewed. The capture efficiency of the target system has been studied and the muon rate as a function of beam energy has been examined for two different field tapers. The FS2a field taper gives slightly better performance but requires a much more demanding magnet system.

The longitudinal capture and ionisation cooling performance has been evaluated for the ISS and IDR baseline. The performance of the two lattices is broadly similar, but the IDR baseline requires less hardware and is less demanding on systems downstream of the front end.

Additionally, the effect of reduced RF on the cooling systems has been examined. The cooling performance has been found to be roughly linear with RF cavity peak field.

Several studies remain to be undertaken to support this work. A full engineering design of the lattice is required, including design of instrumentation, RF, magnets and absorbers. A study of the effect of transmission losses and

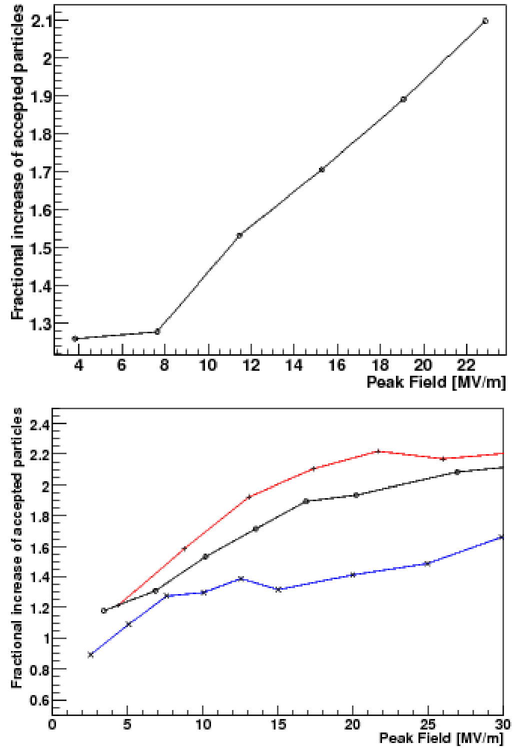

Figure 10: Fractional increase of accepted particles as a function of the peak field gradient, simulated in ICOOL (top) for 45° off-crest phasing, and G4MICE (bottom) for 30° (blue), 40° (black) and 60° (red) off-crest phasing.

heating from transmission of secondaries originating from the target, together with a design for collimation and associated systems must be undertaken. Further studies on the effect of proton bunch length, particle production model and comparison with experimental data should be performed. Additionally civil engineering requirements must be understood, and the costs evaluated.

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REFERENCES

[1] S. Berg *et al.*, RAL-2007-23 (2007).

[2] The Muon Front End website is hosted at `http:`

//www.astec.ac.uk/groups/beams/users/rogers/Front_End/

[3] Ed. S. Geer and M. Zisman, Neutrino Factory and Beta Beam Experiments and Development (aka Feasibility Study IIa), Technical Report BNL-72369-2004, 2004.

[4] D. Neuffer, M. Martini, G. Prior, C.T. Rogers, C. Yoshikawa (co-author), Muon Capture in the Front End of the IDS Neutrino Factory, Proceedings of the 1st International Particle Accelerator Conference, 2010.

[5] R. Fernow *et al.*, Nuclear Physics B. (Proc. Suppl.), Vol. 149 p. 274 (2005).

[6] N.V. Mokhov *et al.*, Fermilab-Conf 04/053 (2004).

[7] C.T. Rogers R. Sandstrom (lead author), Simulation of MICE using G4MICE, Proceedings of the 10th European Particle Accelerator Conference, 2006.

[8] X. Ding, NUFACT09 Conference Proceedings, AIP (2009).

[9] M. G. Catanesi *et al.*, NIM A Vol. 571 Issue 3, pages 527-561 (2007).

[10] C.T. Rogers and G. Prior, Muon Ionisation Cooling in Reduced RF, Proceedings of the 23rd Particle Accelerator Conference, 2009.

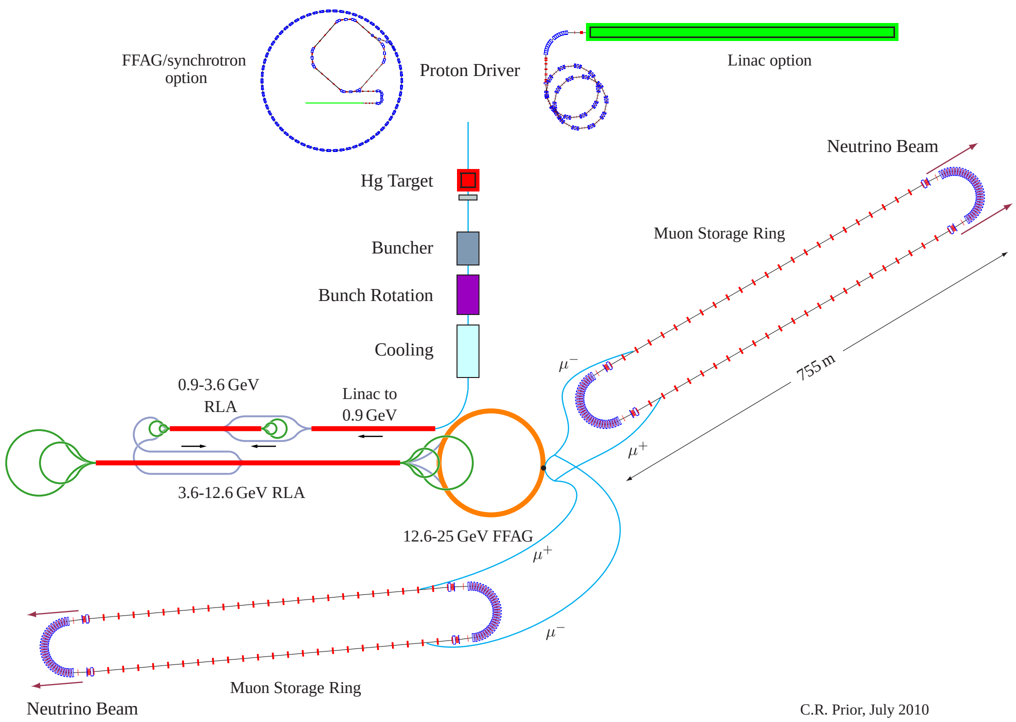

Figure 1: Schematic of the IDS Neutrino Factory.

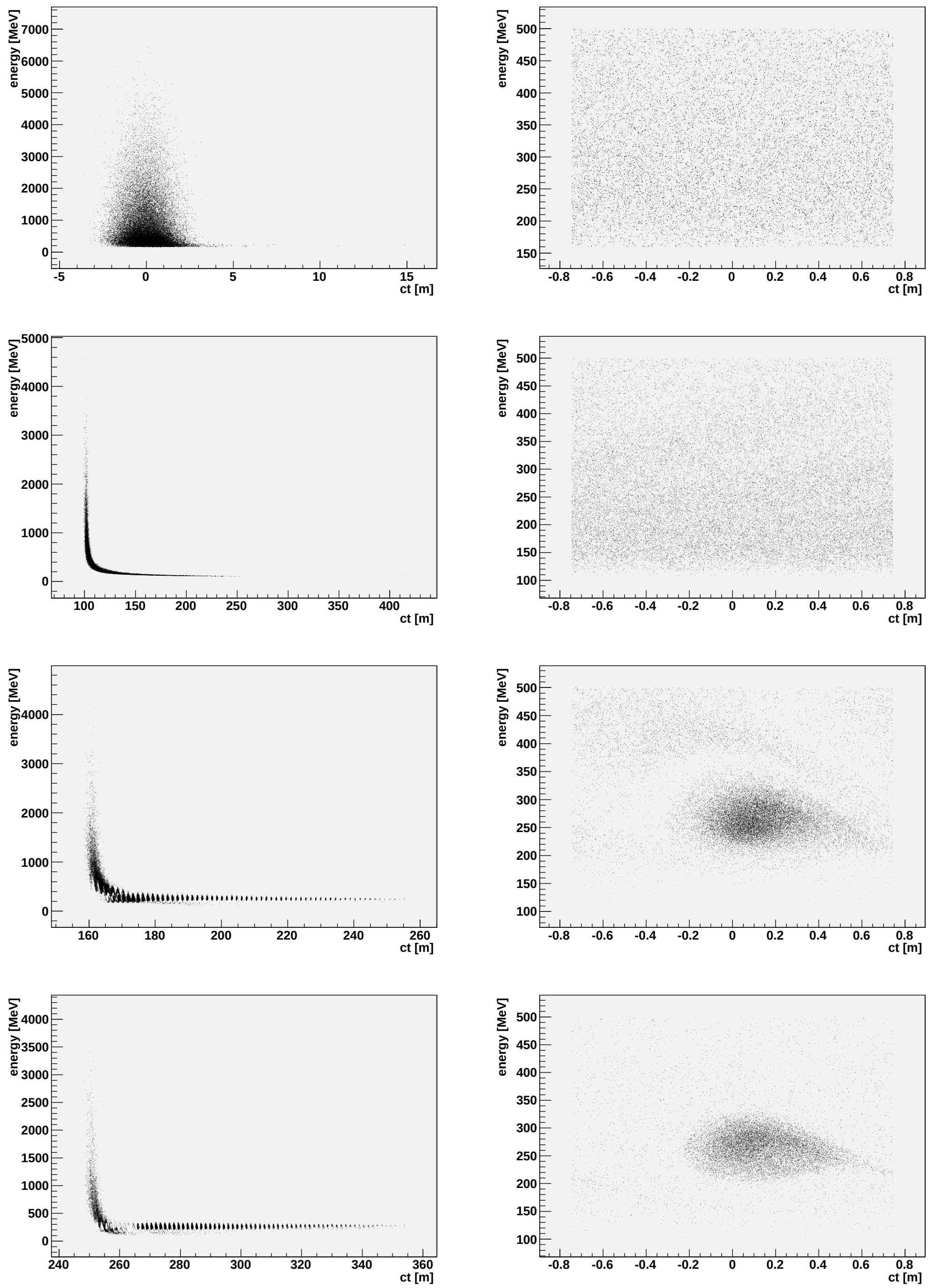

Figure 5: Evolution of the particle distribution in longitudinal phase space at (top) the target (upper middle) end of the longitudinal drift (lower middle) end of buncher and phase rotator and (bottom) end of the cooling channel. On the left hand side, the full distribution is shown; on the right hand side, the distribution is shown transformed to a 5 ns period (effectively the particle phase). In the top image, $\pi+$ are displayed; subsequently, it is assumed that the pions have decayed and so $\mu+$ are shown. Simulation was performed for the IDR baseline.