DESIGN OF A RAPID CYCLING SYNCHROTRON FOR THE FINAL STAGE OF ACCELERATION IN A COMMON PROTON DRIVER FOR A NEUTRINO FACTORY AND A SPALLATION NEUTRON SOURCE BASED ON MEGAWATT UPGRADES TO ISIS

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Abstract

Potential upgrades to the ISIS accelerators at RAL in the UK to provide proton beams in the few GeV and few MW range could be envisaged as the starting point for a proton driver shared between a short pulse spallation neutron source and the Neutrino Factory. The accelerator chain for the spallation neutron source, consisting of an 800 MeV H^- linac and a 3.2 GeV rapid cycling synchrotron (RCS), is currently being designed and optimised. The design of the RCS for the final stage of acceleration, which would increase the final beam energy of the dedicated pulses to feed the Neutrino Factory pion production target is presented. The feasibility of the final bunch compression to the necessary nanosecond range is also discussed.

INTRODUCTION

Currently, neutrino oscillations are the only confirmed physics beyond the Standard Model and the Neutrino Factory (NF) is the proposed future facility aiming for the precision measurement of this phenomenon including the verification of the existence of CP violation in the leptonic sector. The International Design Study (IDS-NF) is currently performing a detailed conceptual design for the NF. The Interim Design Report was accomplished this year [1] and the Reference Design Report is expected to be accomplished by the IDS-NF collaboration in 2013.

The NF will produce a high quality neutrino beam using muons decaying in the storage ring, but in its heart it must contain a high intensity proton driver to feed the pion production target. The requirement for the efficient production and capture of a high intensity pion/muon beam set severe constraints on the parameters of the proton driver. This machine needs to be in the multi-GeV energy range, the required beam power reaches as high as 4 MW and the repetition rate is set to 50 Hz in the baseline scenario. By far the most ambitious figure is the final proton bunch length at the pion production target, which needs to be as short as 1-3 ns rms, the pulse being typically subdividing into 3 bunches. This requires a dedicated bunch compression scenario to be developed to counteract the strong space charge forces. The current scenarios for the NF proton driver include solutions based on a superconducting H^- linac followed by dedicated accumulator and compressor rings, or ones where the majority of acceleration is performed using RCS technology.

The Rutherford Appleton Laboratory (RAL) is home to ISIS, the world's most productive spallation neutron source. A broad range of applications for neutrons exists, making them an essential tool for discovery and understanding in modern science and technology. A spectrum of reasonable upgrade routes for ISIS that will provide a major increase in beam power has been envisaged [2, 4]. In some scenarios the beam power may reach 4-5 MW, the figure, which is comparable to the power needed for the NF.

This opens a possibility to realise a common proton driver [3, 4], creating a facility capable of delivering the high power proton beams for both neutron production target of the spallation source and the pion production target of the NF, simultaneously. Such a proton driver, together with the NF could fit onto the RAL site and the conceptual design for this scenario has been created [4]. In a common proton driver scenario, based on multi-MW ISIS upgrade with an 800 MeV H^- linac and a 3.2 GeV RCS, both facilities have the same ion source, RFQ, MEBT, linac, H^- injection and acceleration to 3.2 GeV. At 3.2 GeV, part of the beam may be send to the neutron production target, but in order to meet the requirement of the NF baseline a dedicated RCS or FFAG booster must be added to accelerate the NF bunches, which need to be compressed before the pion production target. This paper describes the preliminary design of such a booster based on the RCS technology.

RCS DESIGN

General Principle

Based on the current parameters of the ISIS upgrade and the NF baseline many scenarios for equal or unequal power splitting between the neutron source and the NF can be envisaged [4].

The particular scenario currently assumed for the design of the RCS booster is based on the following arguments:

- The proton beam for both facilities shares the same accelerators till reaching 3.2 GeV, where the beam power is 4 MW.
- The 0.8-3.2 GeV accelerator operates at harmonic number 9, so 9 bunches are extracted at 50 Hz repetition rate.
- 6 bunches are sent for neutron production, which delivers a total beam power of ~2.66 MW to the spallation source.

- 3 bunches are injected to the dedicated RCS booster and needs to be further accelerated to 9.6 GeV to produce the 4 MW required.
- 3 NF bunches will be compressed before sending them sequentially to the NF target.

This particular choice of assumptions relaxes the space charge tune shift at injection into the 0.8 GeV RCS and diminishes the longitudinal space charge forces at the final compression by boosting the final energy for the NF, which may also be beneficial for the NF target. The disadvantage of that particular solution is the need for very large RF gradient in the RCS for the operation at 50Hz repetition rate. The overall cost for the booster RCS is also higher with respect to any lower energy solution.

Lattice Design

The lattice design for the booster RCS was focussed on achieving the necessary acceleration and bunch compression with proven, cost-effective technology, e.g. dipole magnets with a maximum field of 1.2 T, and an RF system similar to the second harmonic one used currently at ISIS. It incorporates long straight sections for injection, extraction, RF and collimation. Based on the injection from the particular design of the 3.2 GeV ISIS upgrade RCS with 5 superperiods, the booster RCS design assumes RF with harmonic number 17. The RCS has six superperiods with six FDF triplet cells each, uses only three quadrupole families and allows for a flexible choice of gamma transition. The optical functions are shown in Figure 1 and the main RCS parameters for this design are summarised in Table 1.

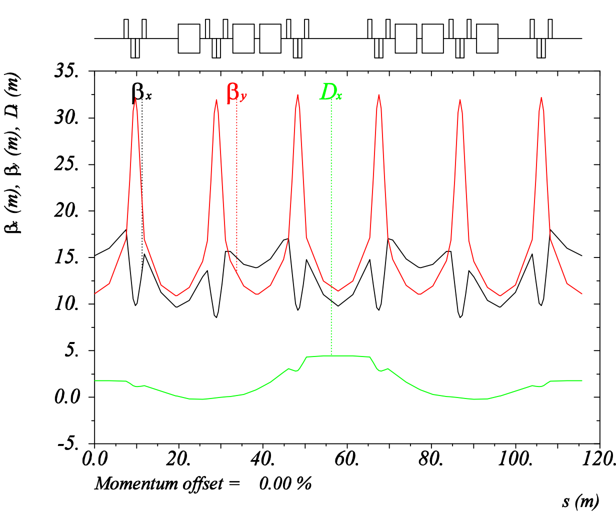


Figure 1: Betatron functions for one superperiod of the 3.2-9.6 GeV RCS booster for the Neutrino Factory.

BUNCH COMPRESSION

RF Program

In order to optimize the longitudinal muon capture in the muon front-end of the Neutrino Factory, the proton bunch at the target needs to be compressed to 1-3 ns length. Several methods have been proposed including adiabatic compression during acceleration or compression by rapid phase rotation, most often in the dedicated compressor ring. The scenario adopted here assumes the adiabatic compression in the RCS, which would remove the needs for fast changes

Table 1: Main parameters for the 3.2-9.6 booster RCS for the NF.

Parameters	Values
Circumference	694.352m
Number of Superperiods	6
Injection/Extraction Energy	3.2/9.6 GeV
Gamma transition	13.37
Harmonic number	17
RF frequency	7.149-7.311 MHz
Bunch Intensity	5.208×10^{13} protons
Number of Cavities	91
Energy gain per cavity	40.4 keV

In order to facilitate the bunch compression, the gamma transition in the booster RCS design was chosen to be 13.3, which avoids crossing transition and should provide margins for longitudinal stability at extraction. The RF voltage program was developed in order to obtain the required bunch compression, which can be seen in figure 2. It needs to be noted, that the sequential extraction of 3 bunches in the RCS with distance between extractions of the order of ~100 μs has a disadvantage of introducing an unequal energy between bunches. This effect and its role in the target operation needs to further studied.

ESME Program

Longitudinal beam dynamics in RCS Booster was simulated using the code, ESME [5]. ESME is a one-dimensional Fortran based computer program that calculates the evolution of a distribution of particles in energy and phase as it is acted upon by the radio frequency system of a synchrotron or storage ring. It provides for the modelling of multiple rf systems, feedback control, space charge, and many of the effects of longitudinal coupling impedance.

An initial, elliptical particle distribution, rf, ring parameters and a table with the magnet ramp data were input into ESME.

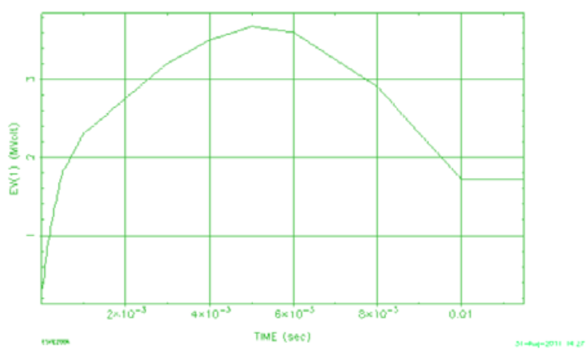
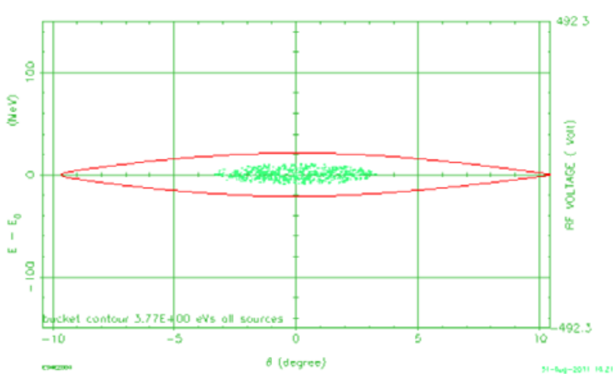
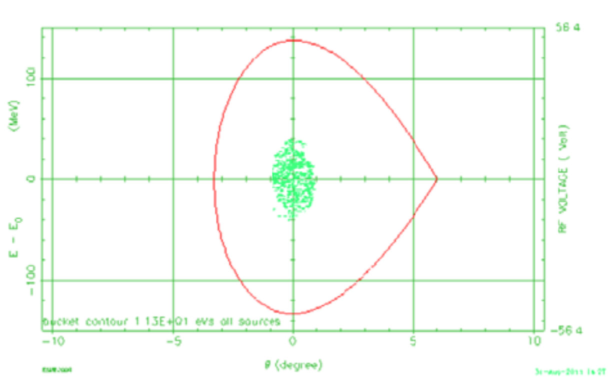


Figure 2: Voltage as a function of time in the dedicated 3.2-9.6 GeV RCS booster for the NF.

Figure 3 shows the initial, mid-point and ending longitudinal phase-space plots. The bunch is represented in green with the x-axis showing the phase extent of the bunch. The thickness of the bunch shows the energy spread (left axis). The rf bucket is represented by the red contour, the rf voltage appears on the right hand axis. The simulation demonstrated that the bunch has been successfully accelerated from 3.2 to 9.6 GeV and phase rotated from ~40 ns to ~8 ns absolute length (26.6 to 2.52 rms length).





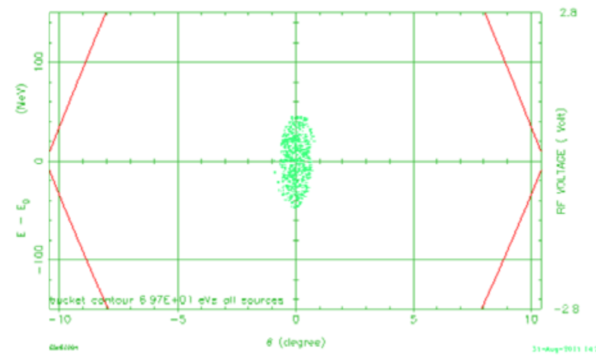


Figure 3: Showing the initial, mid-point and concluding longitudinal phase-space diagrams. The scale in degrees is divided by the harmonic number.

In order to obtain more realistic simulation results the longitudinal ring impedance needs to be estimated and input into ESME. To simulate a realistic beam, the simulation must be run with a large number of macroparticles, which is expected to be a computationally intensive operation.

CONCLUSION

The design of the dedicated booster RCS to deliver the beam to the NF pion production target in the framework of the common proton driver for the spallation neutron source and the Neutrino Factory has been proposed, using the reference scenario of the ISIS MW upgrade. In this scheme, the initial acceleration stages: ion source, RFQ, chopper, H^- linac, beam accumulation and acceleration to 3.2 GeV are identical for both facilities. This synergy would allow the creation of a multi-purpose facility for science and technology at Harwell site in a cost effective manner. The RF program for adiabatic bunch compression in the RCS has been investigated and the preliminary longitudinal simulations using ESME code were performed. The preliminary results show successful acceleration and phase rotation to the desired length. The work on the impedance model of the RCS machine, to be used in the simulations, has been initialized.

REFERENCES

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