

REVIEW OF LINAC UPGRADE OPTIONS FOR THE ISIS SPALLATION NEUTRON SOURCE

C. Plostinar, C. Prior, G. Rees, STFC/ASTeC, Rutherford Appleton Laboratory, UK

Abstract

The ISIS Spallation Neutron Source at Rutherford Appleton Laboratory has recently celebrated 30 years of neutron production. However, with increasing demand for improved reliability and higher beam power it has become clear that a machine upgrade is necessary in the medium to long term. One of the upgrade options is to replace the existing 70 MeV H^- injector. In this paper we review the ongoing upgrade programme and highlight three linac upgrade scenarios now under study. The first option is to keep the existing infrastructure and replace the current linac with a higher frequency, more efficient machine. This would allow energies in excess of 100 MeV to be achieved in the same tunnel length. A second option is to replace the current linac with a new 180 MeV linac, requiring a new tunnel. A third option is part of a larger upgrade scenario and involves the construction of an 800 MeV superconducting linac.

ISIS UPGRADES

Over the last three decades, the ISIS spallation source has been delivering neutrons to generations of scientists from all over the world, creating a key centre for physical and life sciences research at Rutherford Appleton Laboratory in the UK. The accelerator consists of a 70 MeV H^- injector and an 800 MeV synchrotron delivering a total of ~ 200 kW beam power to two target stations. The injector starts with an H^- ion source, followed by a three solenoid low energy beam transport line (LEBT) and a 665 keV, four-rod RFQ operating at 202.5 MHz. A Drift Tube Linac (DTL) accelerates the beam to 70 MeV. The DTL consists of four tanks which have been recycled from previous high energy physics projects. Tanks 2 and 3 were commissioned in the 1950s for the RAL Proton Linear Accelerator, while tanks 1 and 4 were copies of the Fermilab DTL built in the 1970s, originally intended for the Nimrod accelerator, but first used in ISIS [1], [2].

While ISIS has been the most successful pulsed neutron spallation source in the world, it is also one of the oldest and the necessity for an upgrade has been made clear for some time. This involves not just maintaining or improving the current machine reliability, but also increasing its capabilities. With new facilities like the SNS in the USA and J-PARC in Japan now delivering MW class beams, a major power upgrade for ISIS has become a key strategic goal in the medium to long term.

Small upgrades are already taking place aimed mainly at improving the machine reliability and maintaining the current level of performance. A programme designed to improve the ion source lifetime, beam current, pulse length and reliability has been successfully taking place

as part of the Front End Test Stand project [3]. The old Cockcroft-Walton linac injector was replaced a few years ago with a 665 keV, 202.5 MHz RFQ, the structure of choice for most modern proton injectors, while efforts are now underway to replace the fourth DTL tank, a structure soon to celebrate its 60th anniversary. In the ring, the installation of a dual harmonic system has taken place. By employing a combination of harmonic numbers two and four RF cavities, the stable area of longitudinal phase space can be lengthened, allowing more beam to be injected and accelerated, thus overcoming the old machine intensity space charge limit of $2.5 \cdot 10^{13}$ protons per pulse. Beam powers of ~ 240 kW have already been demonstrated [4].

In terms of major upgrades, the addition of a second target station at the end of 2008 saw the machine capabilities and user base greatly expanded. However, for power upgrades, the construction of new accelerators is necessary. There have been several proposals for a power increase ranging from injector to synchrotron upgrades, as well as for a multipurpose facility where a high power proton accelerator would be used both for a spallation source and as a driver for a neutrino factory [5].

Regarding linac developments, it has become clear that a major upgrade will be necessary. While plans for a new machine are welcomed, any proposal has to take into account several factors, of which two are essential. The first requirement is that any upgrade work should consider the high likelihood of a phased upgrade. This simply means that any design choice should be made as part of a broader, long term plan, such that later upgrade efforts are not hampered by early choices. The second requirement takes into account the wider context of neutron science in Europe. With several experimental reactors due to be retired and with ESS not being fully operational for another decade, ISIS remains the main source of neutrons. Indeed, demand for beam time is at an all time high. This makes machine availability the dominant user requirement and as a result, potential upgrades with minimum user disruption should be proposed. In this context, three linac upgrades routes will be further outlined.

100 MeV LINAC

A straightforward and by far the most economical upgrade is a new linac in the existing tunnel to replace the existing 70 MeV injector. By reusing the existing infrastructure, the civil engineering costs are dramatically reduced, the only constraint being the overall length restriction of ~ 50 m. By operating at a higher frequency, increased accelerating gradients and redesigning the RF structures for increased efficiency, energies in excess of 100 MeV can be achieved in the same length as the

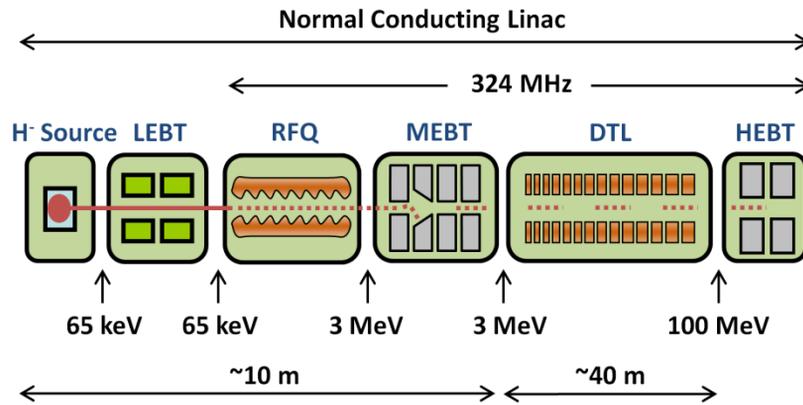


Figure 1: General layout of the proposed 100 MeV linac upgrade for ISIS.

current 70 MeV linac. Additionally, by adding a matching section with a chopper after the RFQ, mismatch and beam loss experienced in the current linac would be eliminated, ring injection losses would be reduced [6]. Considering that the FETS project is near completion, this assumes that FETS, or a FETS-like accelerator could be used as the linac front end. It is hoped that if such an upgrade is planned carefully, installation and commissioning could be completed with minimum disruption to neutron users.

The design of the new linac follows the same overall guiding principles as several modern linacs like SNS, J-PARC, Linac4, ESS, etc. It consists of a 3 MeV FETS-like front end followed by a DTL operating at 324 MHz which accelerates the beam up to 100 MeV. The repetition rate is 50 Hz and the peak beam current is 60 mA, more than double the current linac intensity. With beam pulse lengths between 0.1 and 1 ms, the linac will be capable of providing a range of operating regimes to match the ring injection requirements. The layout of the new linac is presented in Figure 1.

The front end starts with a Penning type surface plasma H⁻ ion source already operating routinely in FETS at parameters exceeding those required for the new linac. A three solenoid magnetic Low Energy Beam Transport Line (LEBT) matches the beam to a 4 m long, 4-vane, 3 MeV RFQ operating at 324 MHz. A Medium Energy Beam Transport Line (MEBT) employing the innovative

“fast-slow” chopping system [7] will transport and match the beam to the DTL [8].

The DTL section is ~40m long and accelerates the beam to 100 MeV in five tanks. Each tank is fed by a single 3.0 MW peak power Toshiba klystron with output energies of 23.5, 43.9, 63.8, 83.1 and 100.8 MeV. A ~20% margin has been maintained for the combined structure and beam power for each tank to take into account extra losses and leave sufficient control power.

From a beam dynamics point of view, a FODO focusing lattice is used throughout the linac which assumes permanent magnet quadrupoles. Working points are chosen such that resonances are avoided while maintaining inter-tank matching and a smooth evolution of the longitudinal and transverse phase advance. The average axial electric field is ramped from 2.9 to 3.3 MV/m in the first tank and then kept constant for the rest of the linac. Similarly, the synchronous phase angle is slowly increased from -35 to -25 degrees to enhance the longitudinal acceptance. Extensive beam tracking studies confirm the robustness of the design. RMS emittance growth in the DTL when assuming a 6D Waterbag distribution is less than 1% in all planes. End to end simulations indicate some deterioration in beam quality with a ~20% total transverse emittance growth mostly developed in the MEBT, but well within the linac safe operating limits.

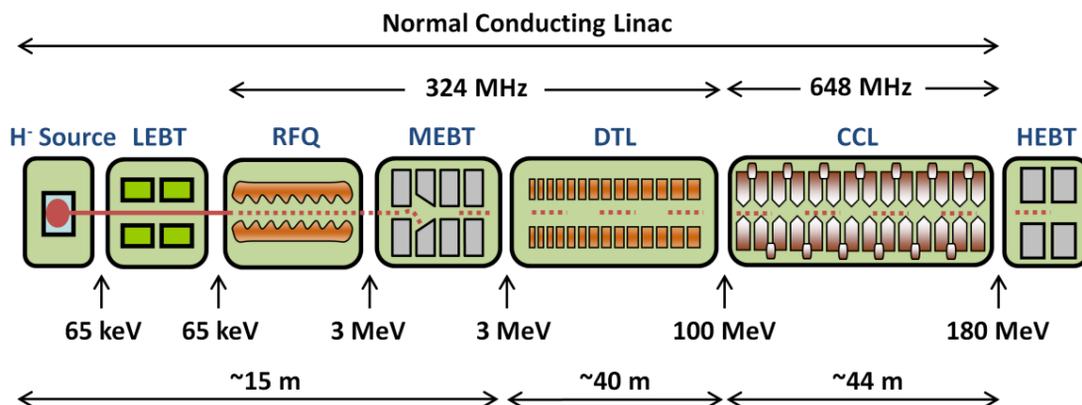


Figure 2: General layout of the proposed 180 MeV linac upgrade for ISIS.

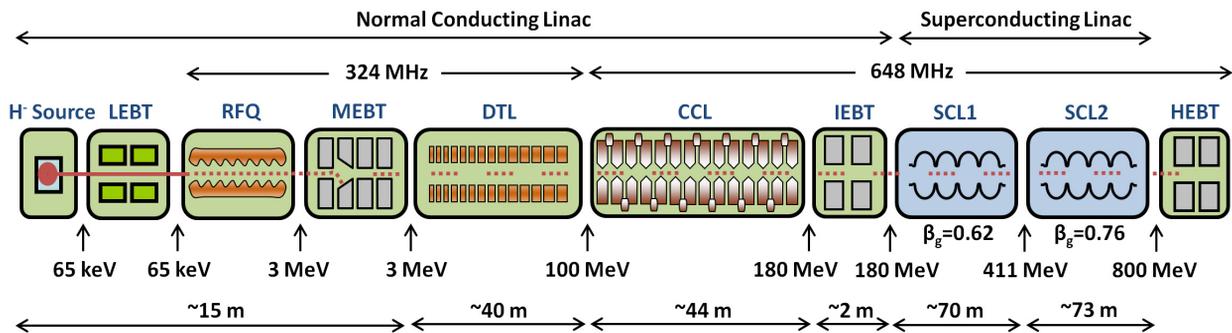


Figure 3: General layout of the proposed 800 MeV linac upgrade for ISIS.

180 MeV LINAC

A second linac option under development is a new 180 MeV normal conducting machine. This solution would require a new linac tunnel, which could be built in parallel with the current linac, thus minimising user disruption. By injecting at higher energy into the ISIS synchrotron, 0.5 MW power levels could be achieved, as the reduced space charge forces allow a higher current to be injected.

The new linac assumes the 100 MeV linac design described in the previous section as the initial stage and identical overall operating parameters. One major difference in the new design is the adoption of an improved chopper MEFT line. Above 100 MeV the Cell Coupled Linac (CCL) structure is adopted to improve the acceleration efficiency. The CCL operates at twice the DTL frequency with an overall length of ~44 m. A schematic of the new linac can be seen in Figure 2.

The front end uses the same layout as the 100 MeV linac, but is ~4 m longer. This is because of the adoption of a distributed chopper MEFT design which is longer, as the new linac does not have the same tunnel length restrictions. The new MEFT consists of a FODO-type lattice arrangement with re-bunching cavities and multiple fast and slow choppers. The choppers deflect the beam horizontally and vertically and are separated in phase advance such that their kicks are synergetic. This ensures maximum chopping efficiency, lossless operation and improved beam dynamics [9]. As a result, the RMS emittance growth at the end of the DTL is reduced to less than 8% transversally and 4% longitudinally.

The CCL design has been optimised to accelerate a high current beam efficiently. A total of 32 cavities operating at 648 MHz are needed to reach ~180 MeV. Each cavity consists of 8 accelerating cells and 7 coupling cells, with an average axial accelerating gradient of 3.5 MV/m, a synchronous phase of -22 degrees and a total dissipated power of 7.2 MW. Assuming a configuration with four neighbouring cavities grouped together via bridge couplers, a total of 8 klystrons operating at 2 MW would be required. Alternative arrangements can also be considered for a different klystron power rating. The FODO lattice is also adopted for the CCL, with EM quadrupoles placed between cavity modules. Particular attention is paid to matching the beam from the DTL to

the CCL over a double frequency jump. The CCL RMS emittance growth when injecting the DTL beam is less than 3% in all planes. After the CCL, a high energy beam transport line will transport the beam to the ring.

800 MeV LINAC

An 800 MeV linac is proposed as part of a larger, long term upgrade scenario which would see the replacement of the entire ISIS accelerator chain and the addition of a new ring to increase the power to several MW [10]. A schematic linac layout is shown in Figure 3. The new machine, reuses entirely the 180 MeV linac described above and employs a new superconducting section to reach the final energy. A short matching and beam diagnostics line is added at the end of the CCL [11].

The superconducting elliptical cavities adopted operate at 648 MHz and have been designed for the same energy gain and beam power per cavity to facilitate cryomodule configuration and klystron development. Consequently, the accelerating gradient varies between 14 and 19 MV/m due to phase slips. Two cavity families are used with $\beta_g=0.62$ (SCL1) and 0.76 (SCL2) and a transition energy between the two at 411 MeV. A total of 34, five-cell cavities are needed for SCL1, with two cavities per cryomodule. For SCL2, 33 six-cell cavities are used, with three cavities per cryomodule. The synchronous phase is -22 degrees in SCL1 and -21 in SCL2 and the overall length of the superconducting section is ~143 m. After the SCL, an ~87 m long achromatic beam line will transport the beam to the ring.

The beam dynamics design approach is also maintained here, with a FODO doublet lattice employed throughout. Quadrupoles are located in the warm sections between cryostats. Transition matching is achieved by varying quadrupole gradients and cavity phases. Extensive multi-particle tracking simulations indicate a robust design, with very low emittance and halo growth rates [12].

CONCLUSION

An overview of current upgrade efforts on the ISIS linac was presented with particular emphasis on three new machines operating at 100, 180 and 800 MeV. The proposed linacs would not only increase machine reliability, but open the way high power operation up to multi-MW level.

REFERENCES

- [1] I. Gardner, "ISIS Status Report", Proc. of EPAC'94, London, UK, 1994.
- [2] D. Findlay, "Linacs at Rutherford Appleton Laboratory", RAL Report, Harwell, UK, 2004.
- [3] A. Letchford et al., "Status of the RAL Front End Test Stand", THPF105 in these proceedings, Richmond, VA, USA, 2015.
- [4] C. Prior, "Updates to the ISIS Spallation Neutron Source", Proc. of APAC'05, Indore, India, 2007.
- [5] J. W. Thomason et al., "Megawatt Upgrades for the ISIS Facility", Proc. of HB'2008, Nashville, TN, USA, 2008.
- [6] C. Plostinar et al., "Modelling the ISIS 70 MeV Linac", Proc. of IPAC'12, New Orleans, LA, USA, 2008.
- [7] M. Clarke-Gayther, "A Two Stage Fast Beam Chopper for Next Generation High Power Proton Drivers", Proc. of IPAC'11, San Sebastian, Spain, 2011.
- [8] C. Plostinar, "MEBT Design for the RAL Front End Test Stand", Proc. of IPAC'10, Kyoto, Japan, 2010.
- [9] C. Plostinar, "Design of a MEBT Line with "Fast-Slow" Distributed Choppers", RAL Report, Harwell, UK, 2009.
- [10] G. Rees, "Linac, Beam Line and Ring Studies for an Upgrading of ISIS", RAL Report, Harwell, UK, 2009.
- [11] C. Plostinar et al., "Conceptual Design of a New 800 MeV H^- Linac for ISIS Megawatt Developments", Proc. of IPAC'11, San Sebastian, Spain, 2011.
- [12] C. Plostinar et al., "Beam Dynamics Design Aspects for a Proposed 800 MeV H^- ISIS Linac", Proc. of LINAC'12, Tel-Aviv, Israel, 2012.