ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOAA004

ACCELERATOR DESIGN CHOICES FOR A COMPACT, ELECTRON-DRIVEN, PULSED NEUTRON SOURCE

L. M. Wroe, A. Latina, J. Olivares Herrador, S. Stapnes, W. Wuensch, CERN, Geneva, Switzerland
G. Kharashvili, F. Plewinski, DAES SA, Geneva, Switzerland

Abstract

Neutron scattering is an indispensable technique in material science research for providing solutions to important engineering challenges, including the ever-growing demand for more efficient batteries and fuel-cells. There are, however, limitations in the access and availability to the necessary neutron beams and this is worsening as nuclear research reactors continue to shut down. As a result, there appears to be market demand for an affordable, medium-flux, compact, accelerator-driven neutron source optimised for deployment in an industrial setting. In this paper, we present an overview of the beam specification and the high-level design choices for an electron linear accelerator that is optimised to drive such a facility.

INTRODUCTION

The use of neutron beams for neutron scattering measurements finds a broad range of applications in the field of material science [1]. In particular, neutron scattering techniques can be exploited to develop advanced battery and fuel-cell materials and manufacturing techniques [2–4], as well as to measure the material stresses and strains within material samples [5–7]. Such neutron scattering experiments and measurements are typically undertaken in large-scale facilities that utilise spallation sources (such as the Spallation Neutron Source at the Oak Ridge National Laboratory in Tennessee, US [8] and the European Spallation Source under construction in Lund, Sweden [9]) or nuclear research reactors (such as the High Flux Reactor at the Laue-Langevin Institute in Grenoble, France [10]).

However, the landscape of available neutron facilities is shifting as nuclear facilities continue to close despite the ever increasing demand for access to neutron beams [11]. Compact Accelerator-driven Neutron Sources (CANS) are a potential answer to this problem and, despite a reduced neutron flux at the sample compared to higher-end facilities, they offer a series of attractive benefits. These include, for example, the ability to develop and use advanced sample environments and instrumentation dedicated to focused topics, the provision of high ‘access agility’, the production of less radioactive waste, and the fact that nuclear licensing is not required [12].

Currently, there are no commercial-off-the-shelf CANS available to industry, universities, nor research centers. A collaboration therefore formed between DAES SA and CERN in 2023 to further develop the so-called VULCAN (Versatile ULtra-Compact Accelerator-based Neutron source) instrument that has been jointly developed between 2021 – 2024 by DAES SA, the Danish Technological Institute, and Xnovotech. VULCAN is a compact and affordable, non-destructive, CANS-based testing instrument that generates a cold neutron beam for neutron scattering measurements. It is purpose-built for implementation in an industrial setting and optimised for the in-situ analysis of battery and fuel cell electrodes, as well as for the measurement of internal stresses inside thick metallic and ceramic components.

Essential to the VULCAN design is its compactness. A conceptual visualisation of such a facility is shown in Fig. 1. The core parts are:

- Electron linac: A compact, pulsed electron-based linear accelerator that delivers 35 MeV electrons with an average beam power on the order of a kW to the Target-Moderator-Reflector (TMR).
- Radiofrequency source: A radiofrequency power source that drives the electron linac.
- Target-Moderator-Reflector (TMR) assembly: A compact setup optimised for the conversion of the incident electron beam into a cold neutron beam with the desired properties.
- Neutron guide: A neutron guide to provide time-of-flight measurements.
- Hexapod and detector: A hexapod on which to position the material sample and a detector with which to take measurements.

The collaboration between DAES SA and CERN has two aims. One is to benchmark the performance of a prototype TMR and the second is to develop a conceptual design of an electron linear accelerator optimised for VULCAN.

This paper focuses on the high-level design choices made for the electron linac design. We begin with a discussion of the electron beam specification and the accelerator design parameters that are to be optimised. The impact this has on the high-level accelerator design is then outlined.

ELECTRON BEAM SPECIFICATION

Table 1 provides the specification on the electron beam and accelerator design for the VULCAN facility.

The underlying reasons behind this electron beam specification are:

- Beam energy and spread: The neutron yield per unit of electron beam power incident on a tungsten target increases rapidly between 7 – 30 MeV. Bremsstrahlung processes produce more photons with energies that have a significantly larger cross-section for exciting the giant

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOAA004

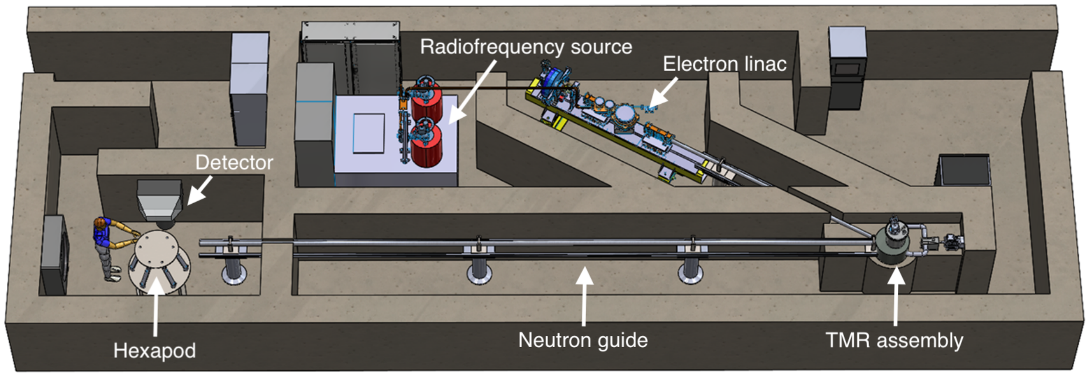

Figure 1: A conceptual visualisation of the VULCAN facility.

Table 1: Specification of the electron beam and accelerator design required for the VULCAN facility.Derived quantities are calculated assuming a train frequency of 100 Hz.

	Parameter	Value	Unit	Symbol
Electron Beam Requirements	Energy	35	MeV	E_{e^-}
	Energy Spread	< 5	MeV	ΔE_{e^-}
	Transverse Size	< 5	mm	σ_{e^-}
	Transverse Jitter	< 2	mm	Δr_{e^-}
	Train Length	< 1	µs	τ_t
	Train Frequency	~ 100 – 200	Hz	f_{rep}
Accelerator Design Parameters to Optimise	Average Beam Power	> 1	kW	P_{ave}
	Accelerator Length	< 10	m	L_{acc}
	Accelerator Cost	< 5	M€	C_{acc}
Other Derived Electron Beam Parameters	Duty Factor	< 0.01	%	D
	Peak Beam Power	> 10	MW	P_{pk}
	Train Charge	> 290	nC	Q_t
	Average Beam Current	> 29	µA	I_{ave}
	Peak Beam Current	> 290	mA	I_{pk}

dipole resonance in the target nuclei and producing photoneutrons [13]. Increasing the electron beam energy to at least 30 MeV therefore provides a significantly greater yield of neutrons relative to the increased RF power needed to accelerate the electrons to 30 MeV. An electron beam energy of $E_{e^-} = (35 \pm 5)$ MeV is therefore specified as the design goal for the VULCAN electron linac.

- Transverse beam profile: A 1 cm (~1 Molière) radius, 3 cm long cylindrical target is chosen to maximize the photoneutron yield. The transverse electron beam profile is therefore required to have a small enough size ($\sigma_{e^-} < 5$ mm) and jitter ($\Delta r_{e^-} < 2$ mm) to be sufficiently centred on the target and satisfy this optimum.
- Longitudinal beam profile: The energy resolution of a pulsed, time-of-flight neutron source is a key figure of merit and is dominated by three factors: the initial pulse length in time of the neutron beam as it exits the TMR, the physical length of the neutron guide, and the energy and time resolution of the detector. Minimising the fluctuation in the production time, maximising the length of the neutron guide, and maximising the resolution of the detector in turn maximises the energy resolution of the time-of-flight instrument because the arrival time of the individual neutrons at the sample is maximally correlated with their individual energies.
The TMR of VULCAN is optimised to limit the moderated neutron pulse to a FWHM of ~20 µs. This allows for a compact neutron guide length of ~10 m to achieve the necessary energy resolution at the sample. In order to achieve this initial pulse length, the length of the electron pulse (or train) incident on the tungsten target must be $\tau_t << 20$ µs and so $\tau_t < 1$ µs.[1]
We note that there are no constraints imposed on the longitudinal profile of the electron beam below the scale of the train. The bunch structure of the electron beam is therefore a variable that can be freely changed without drastically altering performance and it also means there are no specific requirements for the RF frequency, bunch length, or bunch charge.

[1] Future studies are to further investigate the possibility of relaxing the requirement that $\tau_t < 1$ µs. This may reduce the benefit of incorporating a pulse compressor, as discussed in the next Section.

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOAA004

- Beam repetition rate: In a pulsed, time-of-flight neutron source, the individual neutron pulses must be independent from each other to prevent pile-up and the degradation of resolution. Maximising the repetition rate within this limit, however, should be taken to maximise the average neutron flux.
  In the VULCAN design, the slowest (~1000 km/s) cold neutrons take ~10 ms to traverse the ~10 m long neutron guide. The maximum repetition rate that maximises average beam power whilst limiting degradation from pileup therefore lies in the range of 100 – 200 Hz.

The above electron beam specification is the minimum requirement that the VULCAN electron linac must deliver to the TMR. Afterwards, the accelerator design is optimised for:

- Maximising the average beam power: Beyond an incident electron energy of 35 MeV, the neutron yield is linearly proportional to the incident beam power. A minimum average beam power of 1 kW is required for VULCAN in order to undertake the neutron scattering measurements on the required time scales. Maximising the incident beam power beyond this is desirable.
- Minimising the accelerator length: A key to the design of the VULCAN facility is its compactness. A total accelerator length of less than 10 m is desired so that VULCAN can be easily integrated into an industrial environment. Additionally, there are certain neutron scattering applications that may desire a degree of portability on the VULCAN instrument; an accelerator with a length scale on the order of a few metres may be beneficial for this.
- Minimising the accelerator cost: The VULCAN facility needs to have an attractive price point for the industrial market it is designed for. As such, the complete accelerator should cost less than 5 M€.

ACCELERATOR DESIGN CHOICES

To guide the optimisation of the electron linac design for the VULCAN facility, the following high-level design choices are made:

- Injector: Compared to a photoinjector or RF gun, a DC thermionic gun is a simpler, cheaper, and more robust electron source technology. Furthermore as there is no requirement on the beam at the level of the individual bunches of the electron train, a DC thermionic gun appears to be the superior choice for the electron source of the VULCAN linac.
  The optimisation study must determine whether the injector requires dedicated bunching cavities or if it is sufficient to incorporate a few bunching cells into the first accelerating structure.
- RF power source: High-gradient RF cavities powered by klystrons are the most suitable accelerator technology for attaining the desired compactness and high average beam power.
  The variation of the modulator cost with the peak klystron power is approximately linear whilst the variation of the cost of the klystron with peak klystron power is much more ‘gentle’ — that is the cost associated with doubling the klystron peak power is less than double. As the RF power source forms a significant cost of the VULCAN facility, accelerator designs are simulated that utilise a single klystron with peak powers in the 5 – 50 MW range.
- Accelerating structures: High-gradient, normal conducting, pulsed accelerating RF cavities have been designed that operate in the 3 – 12 GHz range [14–16].
  In the case of VULCAN being limited to a 1 μs train length, travelling wave accelerating structures are better suited than their standing wave counterparts because of their shorter fill-times and compatibility with a pulse compressor.
  In particular, the utilisation of a pulse compressor is key to the VULCAN electron linac design because it can effectively double, triple or even quadruple the peak power available from the klystron by compressing the ~5 μs RF pulse length to less than 1 μs. As a result, a greater electron current can be accelerated and a higher average beam power delivered to the TMR.

Having made the above high-level design choices, the VULCAN electron linac design can be optimised by utilising beam dynamics and electromagnetic simulation codes.

CONCLUSION

In this paper, the motivation has been outlined for the VULCAN instrument — a compact, affordable, electron-driven, pulsed, cold neutron source optimised for deployment in an industrial setting. The requirements of the electron beam incident on the target-moderator-reflector assembly have been identified and justified alongside the design criteria with which to optimise the overall accelerator design. The impact of such a specification on the high-level design choices of the VULCAN accelerator design are explained.

From here, beam dynamics and electromagnetic simulation software can be used to optimise the design of the electron linac for compactness, average beam power, and affordability within the necessary electron beam requirements.

ACKNOWLEDGEMENTS

The collaborative research between CERN and DAES is funded by the CERN Innovation Programme on Environmental Applications (CIPEA) under Agreement *KR5865/IPT/KT/ATS/EN185C*. The collaborative research between DAES SA, the Danish Technological Institute, and XnovoTech is funded by EUREKA-EUROSTARS under reference *EUROSTARS E! 115722 - VULCAN*.

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOAA004

REFERENCES

[1] J. Olivares Herrador *et al.*, "Performance of high-intensity electron linacs as drivers for compact neutron sources", submitted for publication.

[2] R. Tao *et al.*, "Insight into the fast-rechargeability of a novel Mo1.5W1.5Nb14O44 anode material for high-performance lithium-ion batteries", *Adv. Energy Mater.*, vol. 12, pp. 2200519, Jul. 2022. doi:10.1002/aenm.202200519

[3] O. Holderer *et al.*, "Fuel cell electrode characterization using neutron scattering", *Materials*, vol. 13, pp. 1474, Mar. 2020. doi:10.3390/ma13061474

[4] A. Senyshyn *et al.*, "In-operando neutron scattering studies on Li-ion batteries", *J. Power Sources*, vol. 203, pp. 126-129, Apr. 2012. doi:10.1016/j.jpowsour.2011.12.007

[5] M. Hosseini *et al.*, "Neutron scattering: A subsurface application review", *Earth Sci. Rev.*, vol. 221, pp. 103755, Oct. 2021. doi:10.1016/j.earscirev.2021.103755

[6] A. Nycz *et al.*, "Effective residual stress prediction validated with neutron diffraction method for metal large-scale additive manufacturing", *Mater. Des.*, vol. 205, pp. 109751, Jul. 2021. doi:10.1016/j.matdes.2021.109751

[7] P. J. Withers, "Mapping residual and internal stress in materials by neutron diffraction", *C. R. Phys.*, vol. 8, pp. 806-820, Nov. 2007. doi:10.1016/j.crhy.2007.09.015

[8] T. Mason *et al.*, "The Spallation Neutron Source in Oak Ridge: A powerful tool for materials research", *Physica B Condens. Matter*, vol. 385-386, pp. 955-960, Nov. 2006. doi:10.1016/j.physb.2006.05.281.

[9] S. Peggs *et al.*, "ESS technical design report", ESS, Lund, Sweden, ESS-doc-274, Apr. 2013.

[10] M. Johnson and G. Cicognani, "ILL annual report 2023", ILL, Grenoble, France, Dec. 2023.

[11] T. Gutberlet *et al.*, "Neutron scattering facilities in Europe: Present status and future perspectives", ESFRI Physical Sciences and Engineering Strategy Working Group, Neutron Landscape Group, ESFRI, Sept. 2016.

[12] G. Rossi *et al.*, "Low energy accelerator-driven neutron sources", LENS Ad-Hoc Working Group CANS, League of Advanced European Neutron Sources, Nov. 2022.

[13] F. Jallu *et al.*, "Photoneutron production in tungsten, praseodymium, copper and beryllium by using high energy electron linear accelerator", *Nucl. Instrum. Methods. Phys. Res. B*, vol. 155, pp. 373-381, Sept. 1999. doi:10.1016/s0168-583x(99)00487-5

[14] N. Shafqat *et al.*, "Design and high-power test of a short prototype of high gradient S-band accelerating structure for the FERMI free electron laser linac upgrade", *Nucl. Instrum. Methods. Phys. Res. A*, vol. 979, pp. 164473, Nov. 2020. doi:10.1016/j.nima.2020.164473

[15] D. Alesini *et al.*, "Design of high gradient, high repetition rate damped *C*-band rf structures", *Phys. Rev. Accel. Beams*, vol. 20, pp. 032004, Mar. 2017. doi:10.1103/PhysRevAccelBeams.20.032004

[16] X. C. Lin *et al.*, "Fabrication, tuning, and high-gradient testing of an X-band traveling-wave accelerating structure for VIGAS", *Nucl. Sci. Tech.*, vol. 33, pp. 102, Aug. 2022. doi:10.1007/s41365-022-01086-y