IPAC'26 Preliminary proceedings (edited version): MOP7179

PRELIMINARY POWER BALANCE ASSESSMENT OF THE PERLE ENERGY RECOVERY LINAC[*]

F. Bouly[†], M. Baylac, Univ. Grenoble Alpes, CNRS/IN2P3, Grenoble INP, LPSC, Grenoble, France
R. Abukeshek, M. Ben Abdillah, S. Blivet, S. Chance, P. Duchesne, P. Duthil,A. Fomin, W. Kaabi,
A. Lermitage, B. Mercier, J. Michaud, G. Olivier, G. Olry, L. Perrot, D. Reynet, R. Roux, H. Saugnac,
A. Stocchi, D. Till, Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
H. Abualrob, An-Najah National University, Nablus, Palestinian Territories
On behalf of the PERLE collaboration

Abstract

The PERLE project aims to build a high-power electron Energy Recovery Linac (ERL) demonstrator (5 MW) to develop and apply the energy recovery technique in a multi-turn configuration. In an initial intermediate phase, PERLE will operate in a single-turn mode with a 5 mA beam at 89 MeV. In its final layout, the machine will run in a three-turn mode, delivering a 20 mA electron beam at 250 MeV. These challenging parameters make PERLE a unique multi-turn ERL facility operating in an unexplored power regime, enabling the study and validation of a broad range of accelerator phenomena and paving the way for future, larger-scale ERLs. The principal advantage of ERLs lies in their ability to return the power of a spent beam to the RF system. This recovered power can then be used for acceleration with practically no losses, thereby improving the sustainability of high-power machines. One of PERLE's goals is to assess the overall sustainability of a multi-megawatt ERL. In this work, we present the current status of the studies carried out to evaluate the total electrical power consumption ("plug-to-grid") of the accelerator and relate this consumption to the average beam power delivered at the interaction point. The power balance of a high-power multi-turn ERL is discussed and its efficiency is compared with that of conventional accelerator types (e.g. linacs). The impact of configuration (single-turn and multi-turn) is also briefly discussed.

CONTEXT

Efficiency and Power Consumption

The sustainability of research infrastructures is a multi-dimensional challenge. It is not limited to electrical energy consumption alone, but also encompasses issues related to the management of cooling and cryogenic systems, including water and helium consumption, as well as the use of critical materials and component lifecycle management. Nevertheless, for many accelerator-based facilities, reducing electrical power consumption has become a primary concern and an important factor to optimise operation.As a first example, one could consider CERN. Its annual electricity consumption is approximately ~1.3 TWh. During accelerator shutdown periods, this consumption decreases by about ~60 % [1, 2]. These figures highlight the sustainability challenges for future large-scale facilities, such as high-power superconducting (SC) linacs like ESS (European Spallation Source) or SNS (Spallation Neutron Source). For the latter, the overall efficiency (see Eq. 1) has been measured to be around 10 % [3] : the linac requires more than 16 MW of electrical power to deliver an average beam power of 1.4 MW. Nearly half of this consumption originates from the RF power systems (high-voltage modulators + klystrons), which are also one of the most failure-sensitive subsystems [4]. To reduce these risks and improve efficiency, several approaches can be considered. One option is the modernisation of existing facilities using more efficient technologies. For example, the Swiss Light Source aims to reduce its energy consumption by ~30 % through the use of permanent magnets, upgraded cooling pump systems, and more efficient RF amplifiers (solid-state based) [5]. Efficiency also depends on beam availability and, consequently, on subsystem reliability. In some cases, fast fault-compensation strategies and retuning procedures [6–8] can help ensure sustainable operation and maximise beam availability. For applications that are non-destructive or only minimally perturb the beam, alternative accelerator concepts have been developed. Energy Recovery Linacs (ERLs), based on well-established technologies, enable the recovery of beam power and thereby allow a substantial reduction in overall energy consumption [9].

ERL POWER CONSUMPTION

PERLE & Linac

The aim of this study was to provide a first estimate of the overall power consumption of the PERLE facility and to assess the efficiency gain of an ERL relative to a conventional SC linac. In this context, a first comparison was performed between the PERLE ERL configuration and a SC linac delivering the same electron beam at the interaction point: 20 mA at 250 MeV (i.e. 5 MW) in continuous wave (CW) mode (cf. Fig. 1). The metric used to quantify efficiency is the ratio between the beam power at the interaction point (i.e. the power transferred to the beam, ΔP_b) and the electrical power drawn from the grid (P_{grid}):

$$\eta = \frac{\Delta P_b}{P_{\text{grid}}}. \qquad (1)$$

---

[*] Work supported by the Agence Nationale de la Recherche via its program ANR-24-RRII-0001 and by the European Union's program EU HORIZON-INFRA-2023-TECH-01-01 under GA n°101131435.

[†] frederic.bouly@lpsc.in2p3.fr

Type	Electrical Power [kW]	
	PERLE 3 Turns (250 MeV, 20 mA)	**SC Linac (250 MeV, 20 mA)**
Magnets		
Incl. Sol., Quads, Bends	**233.6**	**16.3**
Power Supply efficiency ~80%		
Injector	0.3	0.3
Merger	0.5	0.5
ERL or SC linac	232.8	15.5
RF Power		
Amplifier efficiency ~55%	**481.3**	**9741.0**
Margins for errors/attenuation : +5% in booster & linac, +10% in ERL		
Injector (Booster + Buncher)	278.8	278.8
ERL (4 cav.) or Linac (3×4 cav.)	202.5	9462.2
Cryogenic Systems	**192.4**	**427.2**
Cryomodule Booster		
Static load	21.75	21.75
Dynamic load	10.4	10.4
LHe (FPC)	8.3	8.3
ERL Cryomodule or 3 Linac Cryomodules		
Static load	17.9	53.8
Dynamic load	84.3	253.0
HOM (Static & Dynamic)	16.7	< 3
LHe (FPC)	8.3	24.9
Cryolines & Valves box	24.7	51.9
Diagnostics	~2.5	~1.5
DC Gun (HV, laser, laser room)	7.9	7.9
TOTAL	**917.8 kW (~1 MW)**	**10 194.0 kW (~10 MW)**
Power dissipated in dump	*140 kW*	*5000 kW*

Table 1: Preliminary estimate of the electrical power consumption of PERLE and comparison with a linac. Contributions from cooling circulation pumps and associated chillers, building facilities, control systems and datacentres, as well as vacuum systems and experiments, are not included. The beam dump power is indicated but not yet included in the total power balance.

It is assumed that the injector is similar for both accelerators, being composed of an electron gun [10], focusing solenoids, and a booster cryomodule with 4 cavities accelerating the beam up to 7 MeV [11]. The high-energy acceleration section is where the two configurations differ most. In the ERL configuration, only one 4-cavity cryomodule [12] is required, but a large number of dipoles and quadrupoles are needed for the recirculation arcs [13, 14]. By contrast, in the linac configuration, 3 cryomodules (12 cavities in total) are required to reach 250 MeV, while a reduced number of magnetic elements is used: 2 quadrupoles between each cryomodule and a few dipoles for injection.

Results of this preliminary study are presented in Table 1. As expected, the power consumption of the magnet systems is higher for the ERL due to the larger number of elements. The required power is calculated based on quadrupole and bending magnet design parameters [15], and a power supply efficiency of ~80% is assumed for the conversion to grid power.The most important contributions are from the RF and cryogenic systems. With the chosen coupling (Q_{ext}) for PERLE [12], beam recirculation allows the RF power per cavity to be reduced to~25 kW in the ERL cryomodule, whereas in the linac each cavity must be powered by an RF source of at least 410 kW (at optimal Q_{ext} [12]), with the number of cavities being tripled.

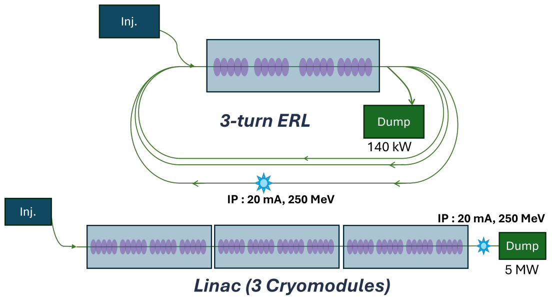

Figure 1: Compared machines structures

For cryogenic consumption, both static loads (without RF power) and dynamic loads (RF operation) have been estimated according to the cryomodule design, which operates at 2 K [16]. The dynamic load mainly originates from power dissipation in the cavity and scales with the accelerating voltage ($P_{\text{diss}} = V_c^2/(Q_0 \cdot (R/Q))$). Cryogenic efficiency (cf. Fig. 3) is derived from the coefficient of performance (COP), based on the Carnot efficiency (ideal) and an assumed cryoplant efficiency of ~20 % [17]. In addition, the fundamental power coupler (FPC) is cooled by a 5–300 K supercritical helium circuit, where efficiency is calculated from Exergy and expressed as a function of the mass flow rate (~33.3 kW$_\text{e}$/(g/s)). Another point of consideration is the cooling associated with higher-order modes (HOMs) [18] dissipation (as highlighted in cryomodule power balance of Table 1). These modes are excited by the beam, resulting in a power dissipation of approximately 130 W per cavity. More than 90 % of the HOM power is extracted by absorbers located between the cavities. The resulting heat load is evacuated through a cooling loop operating at 50–80 K. The remaining power (a few watts) is dissipated through dedicated couplers on the cavities and therefore at 2 K [18]. In the ERL case, HOM excitation is higher due to beam recirculation. However, because of the larger number of cryomodules, the overall linac power consumption is estimated to be roughly twice as high.

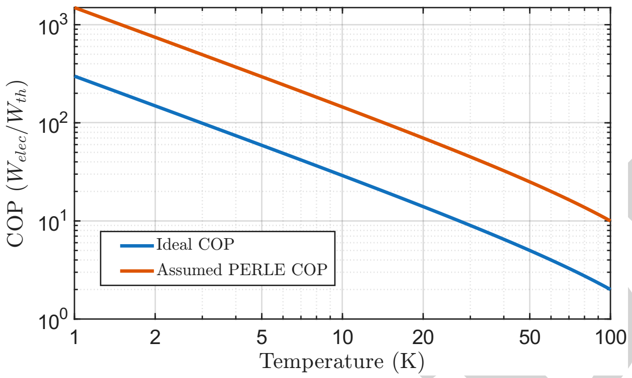

Figure 2: The ideal COP (Carnot efficiency) is shown together with the estimated practical COP for the PERLE cryoplant.

Finally, the total consumption for the ERL configuration is found to be higher than 0.9 MW ($\eta \approx 5.4$), compared with ~10 MW for the linac ($\eta \approx 0.49$). It should also be noted that the beam power to be absorbed in the beam dump is significantly lower in the ERL case, which greatly simplifies its design, as well as the associated cooling and radiation protection requirements. Nevertheless, this study remains preliminary and should be extended by including, for instance, the water cooling and chiller systems, which will in particular impact the ERL efficiency. A comparison with other accelerator configurations (such as ”racetrack” recirculating linacs) is also envisaged.

RF Efficiency Consideration

It is clear that one of the main advantages of an ERL is the saving in RF power consumption. Fig. 3 shows the evolution of the RF-to-beam efficiency (η_{RF}), here defined according to the RF power required for the injector ($P_{\text{RF inj}}$) and the ERL cryomodules ($P_{\text{RF ERL}}$), with cavity operation assumed at optimal detuning and chosen FPC coupling [12]:

$$\eta_{RF} = \frac{\Delta P_b}{P_{\text{RF inj}} + P_{\text{RF ERL}}}. \tag{2}$$

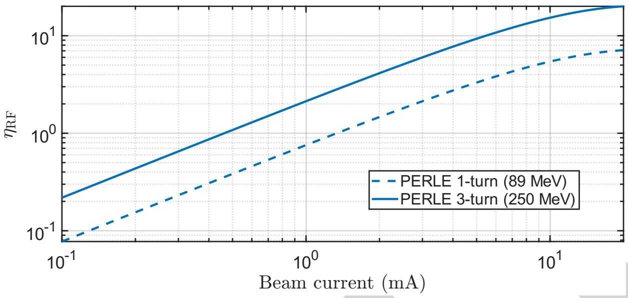

Figure 3: ERL RF-to-beam power efficiency as a function of beam current. Calculated at optimal detuning, assuming no tuning errors and Q_{ext} values given in [12].

While for a linac the coupling can be optimised for a given operating beam current, the coupling for ERL operation is optimised to minimise power consumption while ensuring a sufficiently large cavity bandwidth to guarantee stable LLRF control and operation [12, 19]. Assuming that, at an optimised coupling for a given operating current, the linac RF-to-beam efficiency is $\eta_{RF,linac} \approx 1$, it can be seen from Fig. 3 that the PERLE ERL becomes advantageous for average beam currents above ~2 mA. Furthermore, the efficiency improves with increasing number of recirculations and increasing average beam current.

CONCLUSIONS & PERSPECTIVES

A first estimate of PERLE efficiency has been performed and compared with that of a conventional SC linac; showing possibly ~ 10 times lower consumption for the 3-turn ERL configuration. However, these results remain preliminary, as only near-ideal operating conditions were considered, without accounting for tuning errors or additional effects that may lead to increased power consumption. Some consumption estimates still need to be improved, particularly for the magnetic elements, whose parameters depend on the final machine design. In addition, the power required for building utilities, cooling circulation pumps and associated chillers has not yet been evaluated, although it is expected to significantly impact the overall efficiency, especially for the ERL. The final objective of this work is to develop a model (applicable to PERLE and potentially other machines) including the transfer functions of all components, enabling efficiency studies as a function of beam current, duty cycle, errors and correction schemes [20], as well as evaluating the potential impact of technological choices (e.g. permanent magnets) or emerging technologies such as FE-FRT tuners or high-temperature superconducting materials.

REFERENCES

[1] M. Seidel, "Improving the Energy Efficiency of Accelerators," in *Journée Accélérateurs de la SFP*, Roscoff, France, 2019. `https://indico.ijclab.in2p3.fr/event/5423/contributions/18497/attachments/14412/17887/enefficient_seidel.pdf`

[2] J. Torberntsson, "Cooling Related Inventory," EuCARD-2 Consortium, Deliverable D3.1, 2014. EuCARD2-Del-D3-1-Final. `https://edms.cern.ch/ui/file/1325126/4/EuCARD2-Del-D3-1-Final.pdf`

[3] V. P. Yakovlev, J. Grillenberger, M. Seidel, S.-H. Kim, and M. Yoshii, "The Energy Efficiency of High Intensity Proton Driver Concepts," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 4842–4847, `doi:10.18429/JACoW-IPAC2017-FRXCB1`

[4] R. Geng *et al.*, "Reliability analysis of SNS SRF linac and perspective for future high-power proton SRF linacs," in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2349–2352, `doi:10.18429/JACoW-IPAC2023-TUPM066`

[5] M. Seidel, "Towards Efficient Particle Accelerators - A Review", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 3141–3146. `doi:10.18429/JACoW-IPAC2022-FRPLYGD1`

[6] B. Yee-Rendon *et al.*, "A Systematic Analysis of Cavity Compensations in the JAEA-ADS Linac Utilizing the LightWin Tool," presented at IPAC'26, 2026, paper WEP4621, this conference.

[7] A. Plaçais *et al.*, "Towards Automated Cavity Failure Compensation in the SPIRAL2 SC Linac," presented at IPAC'26, 2026, paper THP4019, this conference.

[8] A. Leduc, A. Orduz *et al.*, "Cavity Failure Compensation Study in Spiral 2 LINAC: Simulation and Experimentation," presented at IPAC'26, 2026, paper WEP5005, this conference.

[9] C. Adolphsen, K. Andre, D. Angal-Kalinin, M. Arnold, K. Aulenbacher, S. Benson, J. Bernauer, A. Bogacz, M. Boonekamp, R. Brinkmann, M. Bruker, O. Brüning, C. Curatolo, P. Duthill, O. Fischer, G. Hoffstaetter, B. Holzer, B. Hounsell, A. Hutton, E. Jensen, W. Kaabi, D. Kayran, M. Klein, J. Knobloch, G. Krafft, J. Kühn, B. Kuske, V. Litvinenko, F. Marhauser, B. Militsyn, S. Nagaitsev, G. Neil, A. Neumann, N. Pietralla, B. Rimmer, L. Serafini, O. A. Shevchenko, N. Shipman, H. Spiesberger, O. Tanaka, V. Telnov, C. Tennant, C. Vaccarezza, D. Verney, N. Vinokurov, P. Williams, A. Yamamoto, K. Yokoya, and F. Zimmermann, "The Development of Energy-Recovery Linacs," FERMILAB-PUB-22-509-AD, JLAB-ACP-22-3666, arXiv:2207.02095, 2022.

[10] M. Baylac *et al.*, "High current photogun for the energy recovery linac PERLE," presented at IPAC'26, 2026, paper THP2104, this conference.

[11] R. Roux *et al.*, "Status of the PERLE's Injector," presented at IPAC'26, 2026, paper WEP5090, this conference.

[12] F. Bouly *et al.*, "RF coupling choices, power requirements, and their impact on transients in the PERLE energy recovery linac," presented at IPAC'26, 2026, paper WEP6126, this conference.

[13] A. Fomin *et al.*, "Beam Dynamics Challenges and Optics Development for the PERLE Multi-Turn ERL," presented at IPAC'26, 2026, paper WEO5M01, this conference.

[14] J. Michaud *et al.*, "Status of the Beam Dynamics Studies for the PERLE Energy Recovery Linac," in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 702–705. `doi:10.18429/JACoW-IPAC2025-MOPS041`

[15] R. Abukeshek, "Magnetic Design and Beam Optics Optimization for PERLE," PhD thesis, Université Paris-Saclay, 2025.

[16] G. Olivier, S. Blivet, P. Duchesne, G. Olry, and H. Saugnac, "ESS Cryomodule Adaptation Design Report," Work Package 6.3, ISAS Project, August 2025.

[17] T. R. Strobridge, "Cryogenic Refrigerators: An Updated Survey," NBS Technical Note 655, National Bureau of Standards, 1974. `doi:10.6028/NBS.TN.655`

[18] C. Barbagallo, "Design and optimization of higher order mode couplers for the superconducting cavities of the PERLE energy recovery linac," PhD thesis, Université Paris-Saclay, 2024, HAL: `https://theses.hal.science/tel-04805279`

[19] C. Joly *et al.*, "RF system status for PERLE," presented at IPAC'26, 2026, paper WEP6146, this conference.

[20] R. Abukeshek *et al.*, "Linear Imperfection and Orbit Correction Scheme for the PERLE Accelerator," presented at IPAC'26, 2026, paper MOP1110, this conference.