Accelerator physics

https://doi.org/10.1038/s41567-022-01933-0

# A route to greener Big Science

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By recovering energy from a relativistically accelerated electron beam in a multiturn configuration, a reduction of radiofrequency power has been demonstrated. This is a milestone toward more efficient and better performing accelerators.

Linear radiofrequency particle accelerators (linacs) produce beams of charged particles at ultrarelativistic energies. Today, linacs accelerating beams of electrons are deployed widely in diverse areas of industry and medicine, in addition to the more obvious large scientific facilities such as light sources and high-energy physics machines. Owing to the prohibitively large amounts of electric power needed, large-scale linacs can operate only at low current. This issue has become particularly pertinent as Big Science receives progressively more scrutiny from society to ensure that its operations are environmentally sustainable — and the European energy crisis of 2022 has intensified this. A potential solution to this conundrum is the energy recovery linac (ERL). Now, writing in *Nature Physics*, Felix Schliessmann and colleagues have realized an ERL in a multiturn configuration, recovering 87% of the energy imparted to the beam while achieving higher beam currents[1].

In applications that require beams with energy greater than a few tens of megaelectronvolts, linacs are nearly always combined with storage rings to achieve high energy. This is because it is much cheaper to accumulate beam from a low-current injection linac, then accelerate the full current to the energy needed over a large — typically

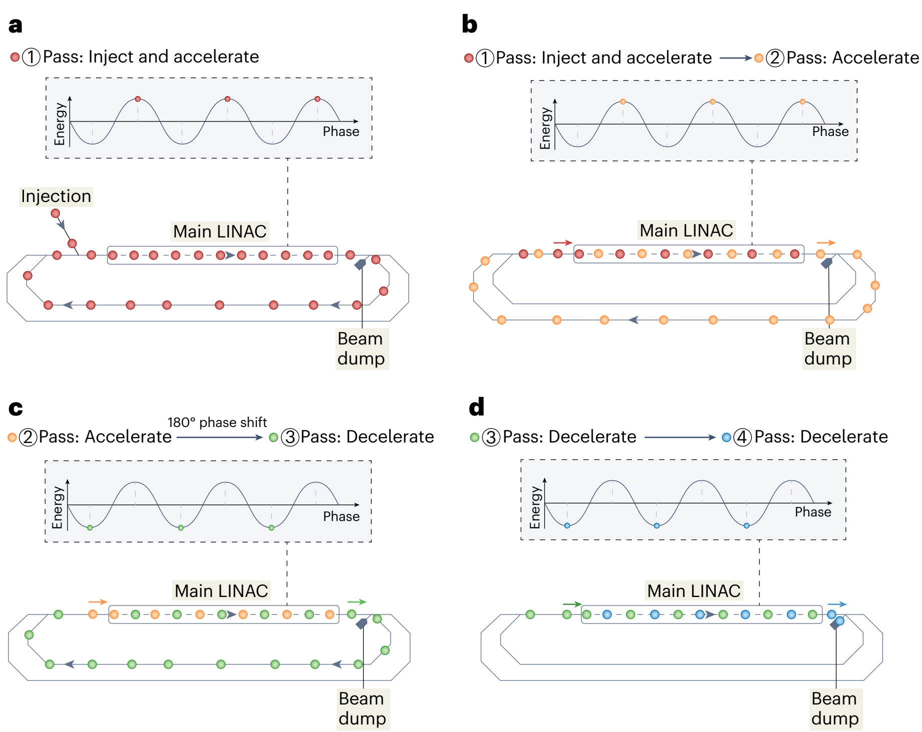


**Fig. 1 | Illustration of the multiturn energy recovery linear accelerator.** Two accelerations through the same linear accelerator (linac) structure were followed by two decelerations, resulting in an energy recovery of 87% of the energy imparted to the beam[1]. **a**, In the first stage, an electron beam (red) is injected and accelerated in the main linac. The energy versus phase diagram illustrates whether the electrons experience acceleration (on the crest of the waveform) or deceleration (in the trough of the waveform). **b**, When the electron beam enters the linac a second time, as indicated by the red arrow, it is accelerated again (orange) and bent on the outer loop. **c**, For the third pass, a phase shift of 180° alters the time when the electron beam enters the linac — the electrons (green) now experience a decelerating field. **d**, In the fourth and final pass, the electrons are decelerated again in the linac (blue), meaning that their energy equals the energy of the injected electron beam, and then the beam is stopped in the dump.

$10^{10}$ – number of turns through an accelerating structure embedded within a ring. Once full energy is reached, the beam is stored for many hours or even days as it is exploited.

Exceptions to this scheme are few, but have included the Stanford Linear Collider, and one favoured candidate for the next large high-energy physics machine: the International Linear Collider to be based in Japan. Indeed, the expense of such a large linear collider has led to many delays and false dawns in the 20 years since the baseline for the International Linear Collider was published; there is still no financial commitment to realize the project.

Future applications of ultrarelativistic electron beams have beam quality requirements that well exceed those possible to achieve in a cost-effective manner in storage rings. When accelerated, ultrarelativistic charged particles emit radiation. Bending is of course such an acceleration, and the radiation thereby emitted is termed synchrotron radiation, as it was first observed as visible light shining out from the General Electric Synchrotron in 1947.

Synchrotron radiation also affects the properties of the emitting electron beam through radiation damping and quantum excitation. Damping is the adiabatic cooling of the beam, whereas excitation is the heating of the beam by recoil of the electrons against photons. At high energy, heating dominates, causing a large energy spread, thereby spoiling the statistical properties of the beam and limiting its utility.

Linear accelerators do not suffer from this limitation, so the Stanford Linear Collider (and a potential future International Linear Collider) displays much higher-quality beams. However, the drawback is their lower beam current, which is limited by the costs associated with the vast amounts of required electric power. By recycling the beam energy, ERLs offer a way to overcome this barrier. In beam dynamic terms, the ERL concept sits halfway between the pure linac and storage ring solutions. The beam once accelerated and exploited is directed back to the accelerating linac and decelerated by timing the transit at anti-accelerating phase. The beam energy is thus returned to the electromagnetic field within the linac and reused to accelerate subsequent bunches. This process allows it to reach – at high energy – much higher beam power than the radiofrequency power required to sustain it, while also banishing the quality limitation arising from stored beams. In short, the beam is not stored, but its energy is.

The concept of an ERL is not new, having first been proposed by Maury Tigner in 1962. However, the technology is only recently maturing. To store the energy, one needs superconducting radiofrequency linac structures with a high quality factor to minimize dissipation of the energy as heat due to induced currents within the cavity materials (on the timescale of microseconds). Additionally, the structure must not have a high quality factor for unwanted frequencies, which has proven technologically extremely challenging. Industrial maturity in superconducting radiofrequency manufacture is now at the level that ERL-based large facilities can be seriously considered.

Applications that would be enabled by successful deployment of ERLs are those that require beyond state-of-the-art electron beam quality at high average power. Examples include the creation of an interaction point at the Large Hadron Collider at CERN with high-quality 60-GeV electrons at the collider's bunch rate of 40 MHz; a narrow-band gamma-ray source with a high spectral flux for nuclear science and industry; or the generation of 100-kW-scale free-electron laser radiation in the extreme ultraviolet and soft X-ray regime. The latter could be used not only for scientific purposes, but also as a potentially revolutionary light source for photolithography semiconductor chip production.

There have been a number of superconducting ERL test facilities over the past 30 years – all performing one accelerate–decelerate turn. But only one such machine, the Jefferson Laboratory infrared free-electron laser and upgrades, has demonstrated operation at higher average beam power than radiofrequency power input[2]. In 2020, the Cornell Brookhaven National Laboratory ERL Test Accelerator achieved a major advance, becoming the first superconducting ERL to demonstrate multiturn operation with four accelerations followed by four decelerations[3]. However, the current was too low to be able to demonstrate substantial saving of radiofrequency power through beam energy recovery. Schliessmann and colleagues have demonstrated just this: a significant radiofrequency power saving in a two-turn energy recovery operation.

They achieved this at S-DALINAC, the Superconducting Darmstadt Linear Accelerator, which has operated in multipass linac mode for nuclear physics experiments since the 1990s. In the 2010s the Darmstadt group saw the opportunity to augment their beam transport with additional beamlines configured to enable a demonstration of multiturn energy recovery. The reconfiguration of the machine was completed in 2018 and one-pass energy recovery demonstrated in 2020[4]. The present results were taken in a series of dedicated runs in 2021. Two accelerations through the same linac were followed by two decelerations, with 87% of the energy imparted to the beam recovered back into the superconducting linac structures (Fig. 1). Control of the beam on the second decelerating pass is suspected to account for the inability to recover the remaining 13%. However, there are no fundamental reasons why 100% energy recovery cannot be achieved with the S-DALINAC parameters. Further runs will implement strategies to show how the last drops of energy can be squeezed out of the beam.

The demonstration at S-DALINAC is extremely timely. The 2020 European Strategy for Particle Physics emphasized the sustainability aspects of Big Science in the remainder of the century[5]. Five priorities for research and development in accelerators were therefore recommended to address the issue – one of which was ERLs[6]. Two European accelerator test facilities, bERLinPro at the Helmholtz Centre in Berlin[7] and PERLE at IJCLab, Orsay[8], are seeking support to continue the effort to establish ERLs as the method of choice to provide higher-power and higher-energy electron beams for the science of the future, without unacceptable burden on the environment. These results are a vital step along that road.

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Published online: 26 January 2023

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## Competing interests

The author declares no competing interests.