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TOWARDS EFFICIENT PARTICLE ACCELERATORS - A REVIEW*

M. Seidel†, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
and École Polytechnique Fédéderale Lausanne, Switzerland

Abstract

Sustainability has become an important aspect of all human activities, and also for accelerator driven research infrastructures. For new facilities it is mandatory to optimize power consumption and overall sustainability. This presentation will give an overview of the power efficiency of accelerator concepts and relevant technologies. Conceptual aspects will be discussed for proton driver accelerators, light sources and particle colliders. Several accelerator technologies are particularly relevant for power efficiency. These are utilized across the various facility concepts and include superconducting RF and cryogenic systems, RF sources, energy efficient magnets, conventional cooling and heat recovery. Power efficiency has been a topic in the European programs EUCARD-2, ARIES and the ongoing I.FAST project and the documentation of these programs is a related source of information.

INTRODUCTION

The environmental sustainability of research infrastructures (RI) has many aspects and includes not only energy consumption, but also issues such as water and helium consumption or the use of critical materials and life cycle management of components. For many accelerator-driven facilities, energy consumption and efficiency are the most important topics. In this paper the important aspects and power drivers will be reviewed for the classes of proton driver accelerators, lights sources and particle colliders. Technologies that are relevant for efficiency, for example RF power sources or superconducting (s.c.) resonators, are discussed where appropriate.

First of all we note that the purpose of all accelerator driven RIs is to produce secondary radiation for research. This can be tailored photon radiation in light sources or FELs, it can be neutrons and muons, or even exotic particles generated in the collisions of particle colliders. The power flow in all facilities can be divided in two main conversion processes. The first one uses grid power and converts it to the power of a primary beam, of course with properties that are dictated by the specific application. In a second step the primary beam power is converted into the desired secondary radiation. For certain facilities, including neutron-, muon-, neutrino-sources or lepton colliders, the performance is rather directly coupled to the beam power via the conversion chain. In these cases it is important to maximize the grid-to-beam conversion efficiency. For other facilities like hadron collider rings with superconducting magnets or pulsed free electron lasers with low beam power, the grid consumption depends less on the beam power and may be dominated by auxiliary systems. For all types of facilities it is often possible to improve the performance per grid power significantly by implementing an optimized scheme for generating the secondary radiation. This can be a low beta insertion for colliders, a low emittance lattice for light sources, a seeding scheme for an FEL or advanced target and moderator assemblies for neutron sources. A generic power flow for accelerator facilities is shown in Fig. 1.

PROTON DRIVER ACCELERATORS

Proton drivers are utilized for neutron, muon or neutrino sources for condensed matter research or particle physics. Often high beam intensity is needed and the conversion efficiency from grid to beam power is an important parameter. Today three megawatt-class proton driver accelerators operate worldwide which utilize different accelerator concepts: the J-PARC facility with a rapid cycling synchrotron, the superconducting linear accelerator of the spallation neutron source SNS and the PSI cyclotron based HIPA accelerator. In 2016 efficiency aspects of these facilities were discussed at a workshop [1] and a summary has been published at IPAC'17 [2]. The choice of concept depends primarily on the application. Here the perspective for high CW beam intensity operation of s.c. linacs will be discussed to show the potential of this technology. S.c. resonators operate with small losses, characterised by high quality factors Q_0. The dissipated power P_{dissip} in the cavity and the power transferred to the beam ΔP_{beam} are calculated using:

$$P_{\mathrm{dissip}} = \frac{U_a^2}{\left(\frac{R}{Q}\right) Q_0}, \; \Delta P_{\mathrm{beam}} = U_a I_b. \tag{1}$$

Here U_a is the cavity voltage, I_b the beam current and Q_0 the quality factor of the cavity. As an example, typical values for the high energy section of the planned PIP-II linac [3] are given in Table 1. Compared to normal conducting structures, the dissipated power is small, in fact three orders of magnitude lower than the power transferred to the beam. This fact supports the notion of s.c. technology being efficient. However, these few watts of heat are deposited at cryogenic temperatures and the cooling is quite inefficient at 1.8 K. As s.c. technology is increasingly used for magnets and resonators, it is worth to address cooling efficiency here.

Table 1: Parameters of HB650 s.c. Cavities for PIP-II

U_a	(R/Q)	Q_0	I_b	P_{dissip}	P_{beam}
20 MV	609 Ω	$2 \cdot 10^{10}$	2 mA	33 W	40 kW

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† mike.seidel@psi.ch

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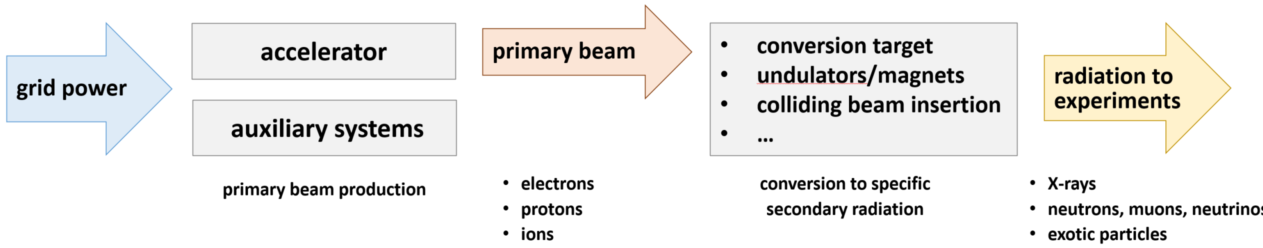

Figure 1: Accelerators for research convert grid power in two steps to the desired radiation. For several classes the conversion efficiency to beam power limits the performance, while for others the consumption is dominated by auxiliary systems.

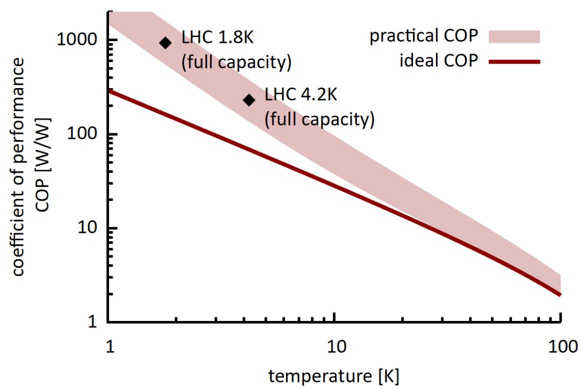

Figure 2: The ideal COP (Carnot efficiency) is shown together with an estimated range of practically achievable COP. The two points from LHC are taken from [4], a review of many refrigerators can be found in [5].

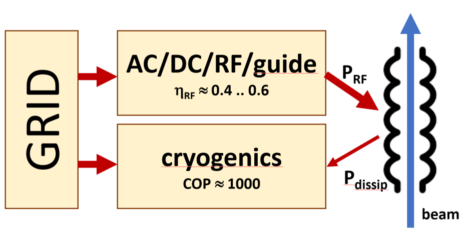

Figure 3: Essential powerflow for a s.c. linac. Grid power is converted to RF power that is fed to the cavity and finally transferred to beam power. The cryogenic power presents a significant limitation for the efficiency.

The refrigerator removes the heat Q_{in} from the cold mass by using the work W_c. It is the common to define a coefficient of performance (COP) that relates the latter one with the removed heat. From the laws of thermodynamics the maximum possible COP (see also Carnot efficiency) is given by $\mathrm{COP} = W_c/Q_{\mathrm{in}} = (T_0 - T)/T$, where T is the temperature of the cold mass and T_0 the one of the environment. At 1.8 K already the best possible value is in the range of 170, while in a real machine numbers of COP = 1000 are achieved. The overall cryogenic efficiency is further reduced by a factor if the cryogenic plant is not operated at the maximum power to keep some margin. Theoretical and practical thermodynamic efficiencies are shown in Fig. 2. For the example of the s.c. PIP-II cavity in CW operation we find that the power needed for cooling is in the same range as the power transferred to the beam. However, the cryogenic losses of s.c. cavities depend only on the field gradient and not on the beam current. The efficiency will be raising with higher beam currents. Besides the cryogenic load also the limited efficiency of RF generation has to be taken into account, Fig. 3. The total power needed is the sum of RF power including conversion efficiency from the grid and losses in the waveguides (η_{RF}), plus the cryogenic power.

$$\begin{aligned} P_{\mathrm{grid}} &= P_{\mathrm{cryo}} + P_{\mathrm{RF}} \\ &= \mathrm{COP} \cdot P_{\mathrm{dissip}} + \frac{1}{\eta_{\mathrm{RF}}} \Delta P_{\mathrm{beam}} \end{aligned} \tag{2}$$

We can now define the grid to beam efficiency as the ratio of power transferred to the beam over the total power taken from the grid. Obviously the overall efficiency cannot exceed the efficiency of the RF generation.

$$\eta_{\mathrm{total}} = \frac{\Delta P_{\mathrm{beam}}}{P_{\mathrm{grid}}} \tag{3}$$

Using the numbers of the PIP-II design report with an amplifier efficiency of 45 % the grid to beam efficiency of such RF section is 30 %. To focus on the main effects for operation with high beam intensity all other power consumers of such facility are neglected. The high beta section of the linac is considered, which is particularly efficient. With further improvements and higher intensity, $\eta_{\mathrm{RF}} = 0.65$, $Q_0 = 3 \cdot 10^{10}$, $I_b = 4$ mA even 50 % efficiency could be achieved.

As the example shows, high grid to beam efficiencies are in reach with superconducting RF. A focus of ongoing R&D is the further improvement of cavity quality factors with optimized Nb cavity treatments, as described in [7]. For highest Q, flux trapping in the s.c. material during cool-down must be minimzed [8]. Another route for s.c. technology is the use of superconductors that can be operated at higher temperature. Nb_3Sn coated cavities show promising results [9, 10] and a factor 3 in cooling efficiency can be gained by operating at 4.2 K instead 1.8 K. RF sources are a very relevant part of the power conversion chain. Traditionally vacuum electronic devices, such as tetrodes, klystrons and inductive output tubes (IOTs) are used to generate continuous and pulsed RF power for accelerators. In recent years stronger efforts are undertaken at many accelerator labs to improve the efficiency of existing types of RF sources, but also R&D

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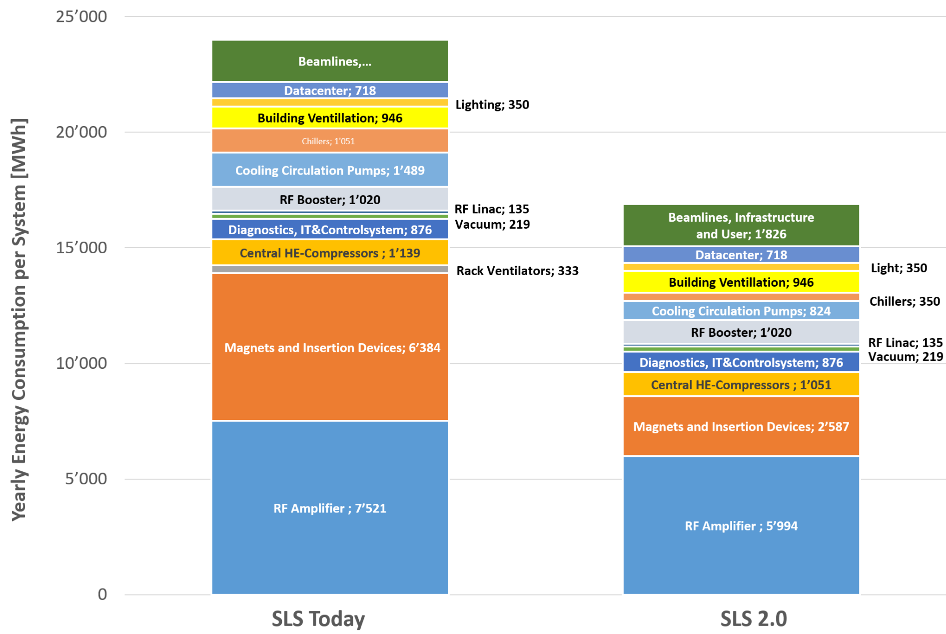

Figure 4: Breakdown of the energy consumption per year of SLS2.0 compared to the original SLS [6].

to make other types of sources available for accelerators. In particular solid state amplifiers are developed actively, and units delivering larger power become gradually available. Magnetrons provide high efficiency but were not used for accelerators as their phase stability and spectral purity was considered insufficient. However, studies on magnetrons at Fermilab and JLAB shows promising results, even for driving narrow band s.c. structures [11, 12]. Reviews of R&D on SSA and other efficient RF sources can be found in the documentation of dedicated workshops [13–15].

LIGHT SOURCES

A significant number of synchrotron light sources are operated worldwide, as well as several free electron lasers, to enable research with application tailored X-ray radiation. Although the energy consumption of light sources is moderate compared to high intensity proton drivers or colliders, it is nevertheless important to optimize also light sources in this regard. The grid power needed for the operation of synchrotron light sources below 1 km circumference is at the level of 5 MW, or below. For the typical labs operating these facilities, the grid energy cost is still a significant part of the operating budget. Fortunately the performance of synchrotron light sources is not strongly coupled to the beam intensity, which in turn had a direct impact on grid power. In fact enormous advancements are presently achieved for light sources by upgrades and by implementing multi-bend achromat lattices (MBA), resulting in 1-2 orders of magnitude improvement for the X-ray brightness. This is often achieved with a ring geometry fitting in the same footprint. These lattice based upgrades result in a huge improvement of the energy efficiency, i.e. the performance per grid power, as the power consumption is not much affected by implementing such lattices. It may be even possible to reduce the total grid power by utilizing the latest technologies for accelerator subsystems. An efficiency related figure of merit for a ring light source is the radiation power for experiments, that is the radiation generated in undulators for beamlines, per total grid power. In several light sources damping wigglers are used to reduce the beam emittance. Compared to implementing MBA lattices this concept is less efficient as the fraction of unused SR and the total grid power are increased.

In this context accelerator magnets using permanent magnet material are to be mentioned [16]. Although the primary motivation for using that technology is to realise bending fields with a longitudinal variation of strength and compact magnets, as a side effect this technology eliminates electrical powering. Other advantages include the absence of heat deposition and active cooling, which is associated with vibrations. Another technology with potential for efficiency savings are solid state amplifiers (SSA) that replace more and more the classical klystron based sources. Grid-to-RF efficiencies of 60% or higher can be achieved. As an example the breakdown of the power consumption of the Swiss Light Source SLS [17] is shown before and after the planned upgrade in Fig. 4. While the average grid power of the operating SLS amounts to 3.3 MW, the new facility will consume roughly 30 % less and the yearly energy consumption will be reduced from 24 GWh to 17 GWh. The main savings are achieved for the subsystems magnets (-59%), RF sources (-20%) and conventional cooling (-45%).

In an FEL process the conversion from electron beam power to photon beam power is particularly efficient as the coherent radiation power scales with the number of particles squared within a coherence length. In single experiments at low energy record efficiencies of 30% were demonstrated by using a seed laser and strongly tapering the undulator [18]. However, for practical applications at Angstrom wavelength

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the fraction of energy converted to laser radiation may be in the range of a few per mill. The power consumption of X-ray free electron lasers is dominated by the linear accelerator that is used to generate a pulsed electron beam in an energy range of roughly 5 to 20 GeV. Similarly as for synchrotrons the total consumption may be below 5 MW, while a beam power of a few hundred watts is sufficient for the application. Grid to beam conversion efficiency is thus not a priority, and the designs are rather optimised to achieve high quality beams in terms of phase space density and stability. To give rough numbers for PSI's SwissFEL as an example, grid power, beam power and photon beam power are respectively: 3 MW / 100 W / up to 0.2 W [19]. The picture changes a bit with the utilization of superconducting linacs for long bunch trains (EXFEL) or even CW operation (LCLS-II). For such facilities consumption may exceed 10 MW due to cryogenic cooling. For the superconducting EXFEL rough numbers for grid power, beam power and photon beam power are: 10 MW / 40 kW / up to 40 W [20]. For future superconducting FELs, the aforementioned R&D on high-Q cavities or operation at higher temperatures offers a good perspective for optimising power consumption.

PARTICLE COLLIDERS

A performance leap is targeted for the next generation of particle colliders, both for luminosity and for energy reach. Concepts and technologies of the different types of colliders vary. The performance is strongly coupled to the grid power consumption, ranging from roughly 100 MW to more than 500 MW, making sustainability a high priority aspect.

The classical concept of a high energy electron/positron circular collider (CC) is studied in a version of FCC-ee [21] and CEPC [22]. CC's efficiently use the beam particles by recirculating them until they eventually undergo an inelastic reaction. But the light particles generate synchrotron radiation (SR) losses that have to be compensated using grid power, and that scale as IE^4/R for a ring with radius R, current I and energy E. The FCC-ee study limits the SR losses at 50 MW per beam for varying collision energy. The maximum attainable beam intensity is reduced towards higher energies as E^{-4}, Fig. 5. The luminosity for Gaussian beams with collision frequency f_c and N particles per bunch is given by:

$$\mathcal{L} = \frac{f_c N^2}{4\pi\sigma_x\sigma_y} \propto I_b \frac{\gamma\xi_y}{\beta_y^*}. \tag{4}$$

The vertical beam-beam parameter ξ_y is introduced here to indicate beam dynamics limitations for the bunch charge. With that the luminosity is proportional to the beam current, and in turn to the SR losses, causing the main part of the grid power. To be efficient the specific luminosity per beam current must be optimized as best as possible. The planned crab waist scheme is a conceptual measure to increase the specific luminosity, but also several IPs help to better exploit grid power. Technological efficiency measures include twin aperture n.c. bending magnets [23], efficient klystrons [24] and s.c. Nb/Cu cavities operating at 4.5 K. The use of magnets with high temperature superconductors (HTS) is another route to reduce consumption. The strong scaling of grid power with beam current provides flexibility for dynamic operation and grid load balancing.

For the operating 7 TeV hadron collider LHC, SR losses are negligible due to the strong dependence of the radiation on the particle mass. The LHC uses s.c. magnets and the significant grid power is dominated by the cryogenic plant and the static heat load in the magnets. In practice, the electron cloud instability contributes also a noticeable dynamic heat load. For the 50 TeV machine under study, FCC-hh, SR from protons become relevant. Although the SR power per beam is comparably low with 2.5 MW, the deposited heat has to be removed at low temperatures with a corresponding COP factor. Using a smart beam screen design it is planned to absorb the SR at intermediate temperature of ≈ 50 K, while the magnet coils in the same cryostat are kept at 2 K. The scheme results in a grid consumption of ≈ 100 MW out of the total 580 MW for the removal of the SR induced heat.

In order to avoid SR losses for lepton colliders, the concept of the linear collider (LC) has been developed to reach energies at which CCs become inefficient. Two concrete proposals are well worked out: the superconducting ILC [25] and CLIC with high frequency copper structures [26]. Similarly to the superconducting proton driver, the power consumption of ILC is dominated by the heat load at low temperature. It depends quadratically on the cavity gradient but is independent of the beam intensity. The linac will be operated at high gradients in pulsed mode. The base version of ILC with $E_{\mathrm{CM}} = 250$ GeV will use relatively moderate 111 MW to generate 2×2.6 MW beams, and variants for higher energy go up to 300 MW. For CLIC at $E_{\mathrm{CM}} = 380$ GeV the consumption of 252 MW is dominated by the power conversion chain from the grid to the 2×2.8 MW beams. It contains an involved drive beam concept to generate the RF power. At the highest CM energy of 3 TeV 50% of 582 MW grid power is needed for RF generation in this concept.

In an LC the beams collide just once, and to achieve high luminosity the beams are squeezed to extremely small size at the IP. In fact such small beam sizes cannot be realised in a synchrotron as that develops an equilibrium emittance distribution, resulting for example in significant bunch length. It is instructive to compare optimised bunch parameters in Table 2 for an LC and a CC at the cross-over point of collision energy, where both concepts have roughly the same performance (Fig. 5). In the example the circulating beam power is 350 times larger than the beam power of the LC. With an energy rococery linac (ERL) it is possible to recirculate the power rather than the particles, and benefit from advantages of both concepts. Just recovering the spent beam power in an LC would gain only a few percent. However, by operating this "Energy Recovery Collider" with beam parameters that cannot be realized in a LC or CC, significant gains are possible. V. Telnov [27] proposes a modification of the superconducting ILC. It foresees deceleration of the spent beam in an additional s.c. linac, recovering the beam

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Table 2: Bunch Parameters of the Proposed CC FCC-ee at 365 GeV [21] and the LC CLIC at 380 GeV [29]

	σ_x [nm]	σ_y [nm]	σ_z [μm]	**N** [10^9]	$\mathbf{f_c}$ [kHz]
FCC-ee^{365}	38’000	68	2’500	230	144
CLIC^{380}	150	3	70	5.2	17.6

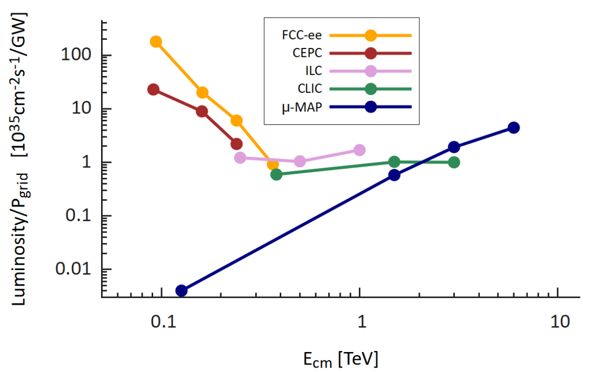

Figure 5: Luminosity per grid power for the future collider concept under discussion (data from design reports).

power in combination with recirculation of the beams at low energy. With a high duty factor the average beam intensity can be raised by a large factor, keeping grid power comparably moderate. Another proposal by Litvinenko *et al.* [28] is based on a modification of FCC-ee, and a 4-pass acceleration / deceleration in a ring-like tunnel is envisaged. Challenges of these concepts are related to the dynamics of the spent beam with long energy tails, to higher order mode losses in the s.c. cavities and the higher cost and complexity.

Realising a lepton collider with muons, 200 times heavier than electrons, reduces the emitted synchrotron radiation power and beamstrahlung during collision, thereby enabling high luminosity per grid power. The scaling of the beam power, impacting grid power, is derived from the requirement of fixed relative energy spread at the IP. With higher energy the absolute energy spread may increase, allowing reduced bunch length, and in turn smaller betatron functions. The scaling of the luminosity can be formulated as [30]:

$$\mathcal{L} \propto B \frac{N_0}{\varepsilon_n} \gamma P_{\mathrm{beam}} \tag{5}$$

Here N_0 is the initial number of muons, $\varepsilon_n = \gamma\varepsilon_{x,y}$ the normalised emittance, and the bending field B is included to show that a smaller ring leads to more collisions during the lifetime of the muons. The achievable luminosity per beam power is increasing with γ, an advantage over the classical linear collider at highest energies. On the downside a muon collider is a far more complex facility than the classical e^+/e^- collider and many technical and conceptual aspects including the detailed power consumption must be studied and optimized before such a facility can be realised.

While advanced ERL and muon accelerator concepts are attractive on a longer time scale, the classical ring collider is a pragmatic and already highly optimised solution for a next-generation facility. It excels through its relatively simple technical design and operation as well as its high performance in an interesting range of energies.

OTHER ASPECTS AND CONCLUSION

In an accelerator facility all grid energy is ultimately converted to heat. Heat is a low grade energy, but it can be reused for heating of offices and lab spaces. If the cooling loop temperature is not sufficient for heating, heat pumps can be used to provide heat at higher temperature with moderate additional grid power. Another trend at many research institutions is the installation of photovoltaic panels (PV) for energy production. A study on direct injection of DC PV power for accelerator subsystems has been launched [31]. Together with other efficiency related activities this is organised within the ongoing European I.FAST/WP11 project [32]. Since 2014 several projects aiming at efficient accelerators were organised and co-financed by the EC [33, 34]. These websites reference a number of related workshops and document efficiency related developments.

Sustainable sources of energy, wind and solar power, are introduced with high priority worldwide. This will lead to fluctuations in energy production, including significant surpluses at times [35]. Operating cost and impact on society of a research infrastructure consuming hundreds of megawatts of electricity will therefore vary depending on the grid situation. A mitigation measure is dynamic operation of such facilities. For e^+/e^- CCs standby modes can be implemented with near zero beam current. At times of high load grid power can be minimized, while an optimized machine setup is maintained to allow fast restarts.

Besides energy consumption also the carbon footprint caused by the construction of facilities must be considered. For applications that require lower beam power, advanced acceleration concepts with very high gradients may be used to create compact and thus sustainable facilities.

Today the importance of energy efficiency is recognised in the field of particle accelerators. Conceptual and technological R&D activities are ongoing and have triggered innovative ideas to boost the energy efficiency of accelerator driven research infrastructures. Superconducting technology has a high potential for significant future improvements across all types of facilities, and high priority should be given to related R&D. In particular the use of HTS materials, both for magnets and resonators, will allow their operation at higher temperature with much better cryogenic efficiency. For facilities that nevertheless need very large power for full performance, dynamic operation can be set up to take advantage of the expected fluctuations of future sustainable energy production.

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