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IMPROVING THE ENERGY EFFICIENCY OF ACCELERATOR FACILITIES*

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Abstract

New particle accelerator based research facilities tend to be much more productive, but often in coincidence with higher energy consumption. The total energy consumption of mankind is steeply rising and this is mainly caused by quickly developing countries. Some European countries decided to terminate nuclear power generation and to switch to sustainable energy production. Also the CO2 problem gives rise to new approaches for energy production and in all strategies the efficiency of utilization of electrical energy plays an important role. For the public acceptance of particle accelerator projects it is thus very important to optimize them for best utilization of electrical energy and to show these efforts to funding bodies and to the public. Within the European accelerator development program Eucard-2 [1] we organise a network EnEfficient [2] that aims at improving the energy efficiency of accelerators. In this paper we give some background information on the political situation, we describe the power flow in accelerator facilities and we give examples for developments of efficient accelerator systems, such as magnets, RF generation, heat recovery and energy management.

ENERGY – THE POLITICAL SITUATION

Over the history of mankind the consumption of energy shows a steep growth with the industrial revolution. Especially in the last few decades the growth is dramatic and many people see this development critically. Massive burning of fossil energy carriers causes high CO_2 emission, one of the causes for global warming and climate change. Nuclear power has other problems and is disputed. But even if one believes in technical advances, the development shown in Fig. 1 looks unhealthy and one might suspect that the growth rate cannot stay intact for long. The mentioned problems have caused a higher awareness on energy related issues around the world. Especially in Europe some countries try to change their energy generation schemes away from coal and nuclear power, in favour of sustainable energy production like wind and solar. In all strategies a high efficiency of electrical power utilization is of utmost importance. When a new research facility is proposed, its energy consumption is thus a critical aspect for the successful public and political acceptance. Statistical information on existing accelerator facilities can be found in [3]. In those countries with a larger fraction of renewable energies we observe also a technical impact of new energy strategies. While coal and nuclear power plants provide continuous base power, wind and sun are strongly fluctuating. Already today, spot market prices of energy vary by an order of magnitude. In extreme cases prices go even negative, when additional consumers are needed to avoid a breakdown of the grid. Energy storage systems could solve this problem. At present only limited technical solutions exist, which allow storing significant amounts of energy. As a result we observe fluctuations in availability of cheap electrical energy.

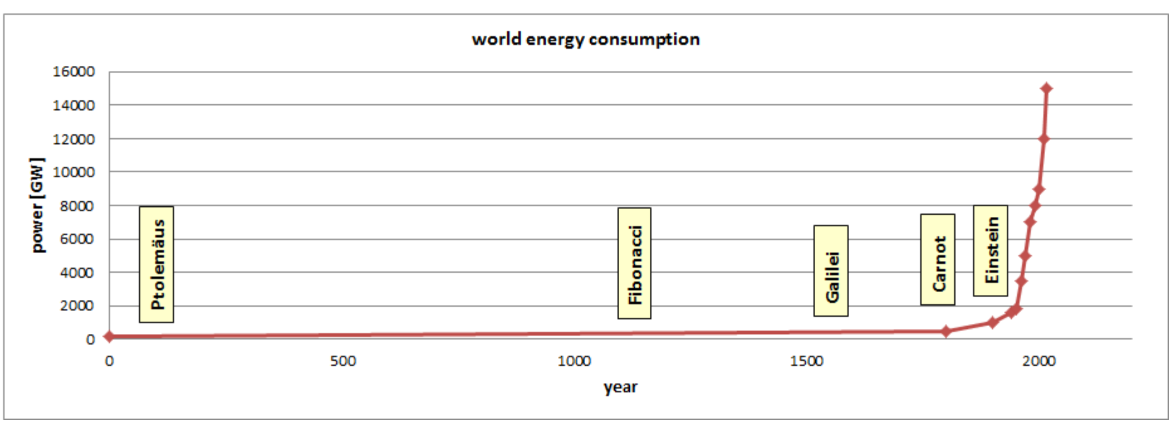

Figure 1: The world energy consumption shows a steep increase in the last 100 years. (Data before 1800 is estimated by scaling consumption in proportion to world population.)

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For the operation of accelerator facilities the fluctuations of wind and solar energy result in large variations of energy cost. If it was possible to interrupt operation at times of low supply, significant savings could be achieved and a positive impact on the public grid situation could realised. Accelerators are complicated devices and generally it is considered a success to make them function at all. Interrupting the operation of an accelerator brings significant difficulties and it was out of the question to do this for energy savings. In context of the mentioned extreme fluctuations of availability and cost we might have to change our view on this and work out schemes to adapt the operation more flexible to the situation on the grid [4].

POWER FLOW IN ACCELERATORS AND FIGURE OF MERIT

Most accelerator facilities are built to produce secondary radiation with specific properties. This could be synchrotron radiation in light sources and FEL's, neutrons in neutron sources and ADS reactors, muons, neutrinos or exotic particles in particle physics facilities. Specific desired properties of the secondary radiation, such as energy bandwidth, coherence, emittance, brilliance could make it necessary to filter out a small fraction of the secondary radiation, leading to a further reduction of efficiency. The goal of high efficiency is clearly to maximize the intensity of the desired radiation with specific parameters per electric power from the grid.

Particle accelerators consist of individual subsystems that consume energy. Some systems are needed for an auxiliary function (cryogenic facility), while others are part of the power flow chain from grid to beam (RF system). Especially for high intensity beam accelerators the efficiency of individual steps converting grid power to RF power, to beam power and finally to the desired secondary radiation are important. Figure 2 shows an example of the power flow in the PSI HIPA facility that generates a significant proton beam power of 1.3 MW. The graphs in Figure 3 show example numbers of power conversion from grid to the desired secondary radiation. One observation from these numbers is that generally the primary particle beam can be produced with efficiency in the percent range, while the last step of producing neutrons, muons, exotic particles or photons with specific properties is least efficient. One could argue that the largest improvement factors are feasible for this final step. Indeed a large part of the physics design work is focused on this aspect. Examples for the different types of accelerators are the design of neutron production targets including moderators, beam demagnification systems in the interaction regions of particle collider facilities, low emittance lattices for synchrotron light sources or muon capture optics to maximize the rate of muons for certain applications.

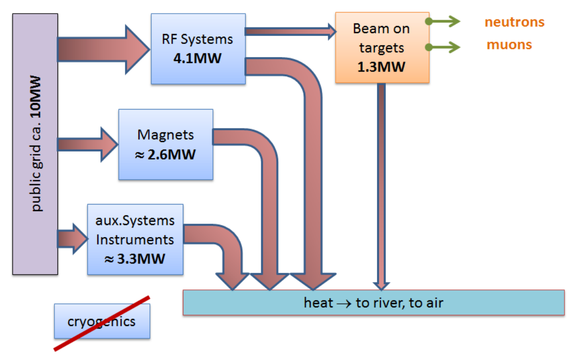

Figure 2: Example of a power flow in PSI's high intensity proton accelerator HIPA.

Within the Eucard-2 effort we focus efforts on the technical aspects in a power conversion chain, such as RF efficiency. However, one should always keep in mind that the relevant figure of merit in an accelerator based research facility is the rate of secondary radiation available for the user and not necessarily the intensity of the primary beam. Over the history of accelerators huge qualitative jumps in the efficiency were achieved by applying new physics concepts for the conversion to secondary radiation.

ENERGY MANAGEMENT

The high power high brilliance accelerators used in leading edge scientific projects usually consume high amounts of electrical energy. Together with the infrastructure of the experiments and the science facilities which are hosting them they tend to put significant loads on the local power grids.

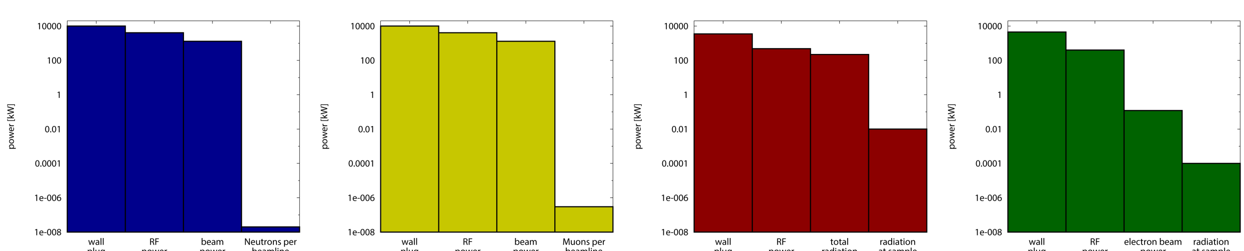

Figure 3: Main power flow including order of magnitude secondary radiation per beamline in the different PSI accelerators, left HIPA for neutrons, muons. right: synchrotron light source SLS [5], free electron laser SwissFEL [6].

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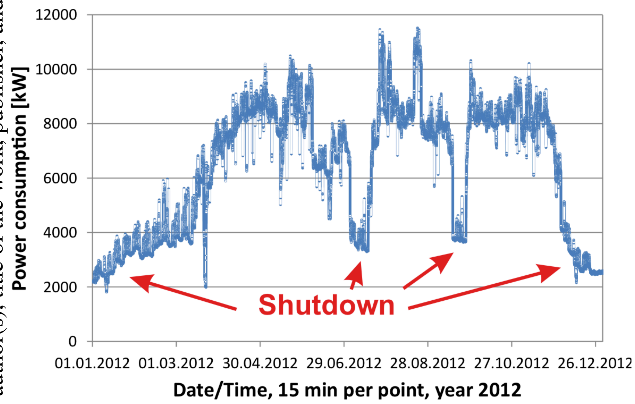

Figure 4: Power consumption of GSI Darmstadt over one year. Fluctuations are between 2 to 4 MW average load in shutdowns and between 6 to 10 MW during operation of the accelerator facility.

A survey within this EnEfficient network aims at identifying fluctuations in the power consumption of different facilities (see example in Fig. 4). These fluctuations hold the potential to reduce the dynamic load on the public grid. This can and has been done on a long term scale with planning shutdowns during times of high external energy demand (e.g. winter shutdown at CERN due to high electricity demand for heating). If it is possible to identify power consumers or modes of operation which influence the short term power use with no or low impact on the science output of the facility the research centre can actively contribute to grid stability. Possible examples are reduction of refrigerator output or special machine cycles during short times of very high external power demand. Existing facilities, however, tend to be designed for maximum reliability, avoiding changing loads. Introduction of new technologies and changing of policies to adopt energy management is a new consideration for large scale research facilities. The financial benefit for existing research facilities for employing new technologies at higher risk and cost, maybe even temporarily sacrificing science output, must be significant. It can be encouraged by the energy market due to lower overall costs or by the availability of additional funds at least for the investment part (e.g. not research but environment, development or general infrastructure). For new facilities and upgrades it should be possible to at least design the machinery considering future upgrades if changing market conditions and availability of technologies render investments feasible.

HEAT RECOVERY

Aside from negligible amounts consumed in nuclear processes, the energy used in accelerator facilities generally ends up as waste heat. In fact, depending on the individual processes and local climate, facilities may be adding heat from the ambient air. Therefore, accelerator facilities tend to generate large amounts of waste heat. If this heat could be re-used in a way that replaces other energy use, then a significant portion of the negative impact from the energy use of the facilities could be offset [7].

There are two major barriers to recycling waste heat, which may be summarized as quantity and quality. The quantity barrier is that there is not usually an established local use for the amount of waste heat generated. The notable exception is ESS, which is being built close to a district heating system that distributes around a TWh of heat per year, about four times what ESS will generate. However, there is also a temporal aspect to heat demand, as space heating demand varies with outdoor temperature and wind. Tap water heating demand is more stable.

Heat as an energy form contrasts with electricity in that it can be relatively easily stored, but not so easily transported. Short-term storage can be arranged in tanks. In district heating systems, these are referred to as accumulation towers. Conceptually, they are large thermoses. The heat can be stored in temperature layers, allowing storage of input and output temperatures for a cooling system to be stored in one facility.

Seasonal storage can be arranged in aquifers, such as drilled storage or rock caverns, if such are available. With seasonal storage, losses can be significant. The loss comes in the form of a loss of energy quality, temperature.

The second great challenge for heat recycling is the issue of quality. The quality of heat energy is simply temperature. At CERN, as one example, a possible use for about 10% of the over 1 TWh hour generated could be for heating the buildings on the extensive site. Buildings are currently heated with a site-wide district heating systems that employs gas boilers to distribute heat at around 120°C. Typical cooling temperatures for the cooling system, in contrast, are around 40°C. Such a gap could be bridged using heat pumps, but for such a large temperature gap, the electrical power use would be quite large, tending to exacerbate rather than mitigate the problem of the facility energy footprint.

For CERN's challenge, which is fairly typical apart from the magnitude of energy, a better solution than investing in heat pumps would be to make improvements in buildings to be able to use 40° for space heating. Such solutions exist both for floor heating and ventilation heating, and can be retrofitted. The challenge is not technical but financial. Even though such investments might be economically attractive, research facility financing mechanisms can be unwieldy in identifying and implementing even worthwhile investments in non-core activities.

The other side of the quality gap is the supply. Significant progress is being made in raising cooling temperatures. MaxIV and ESS will have separate high-temperature cooling loops, allowing direct cooling against the local district heat system, which requires 80° supply temperature and gives a 45° return. At PSI, the SwissFEL klystrons collector cooling system is at 80° and the heat used to heat up the site buildings [8] [9]. Tap water heating requires somewhat higher temperature than space heating, due to the risk of bacteria build-up.

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Heat can be use to produce work. The maximum work from a Carnot machine is given by $W_{\max} = Q(1 - T_0/T)$ where Q is heat, T_0 is ambient temperature and T is the temperature of the heat. An alternative to increasing T is therefore to find a low T_0, for example by locating a facility in a cold climate as several data centres have done recently in the arctic regions of the Nordic countries (although these so far simply use the free cooling directly).

HIGH EFFICIENCY RF GENERATION AND BEAM ACCELERATION

From the power grid to the accelerated particle beam, the product of three efficiencies is considered: the efficiency of the power converter or modulator, the electronic efficiency of the active element generating the RF power and finally the conversion efficiency RF power to beam power; we will focus here on the electronic efficiency of the active element (typically a significant contributor to the overall efficiency). While also solid state amplifiers and magnetrons can be considered, we limit ourselves here to klystrons and inductive output tubes (IOTs) to give account to recent R&D activities for these devices.

State-of-the-art klystrons reach electronic efficiencies in the order of 65% at saturation. To allow stable amplitude control however, they are typically operated below saturation, resulting in a useable efficiency of rarely above 50%. This efficiency is further reduced by the power consumption of the focussing coils and the cathode heater – these reductions are particularly significant in pulsed klystrons since heaters and solenoids are on even if no RF pulse is required. The use of permanent magnets can eliminate the focussing power but increases complexity of the tube.

The traditional way to increase the electronic efficiency of a klystron is to use a so-called depressed collector, i.e. to let the spent beam run against a decelerating DC voltage after the output cavity to recover part of its remaining energy; multi-stage depressed collectors (MDC) are often used in space-borne devices; they add complexity to the tube and have to be carefully designed to prevent the reflection of electrons back into the interaction region. A recent R&D proposal in the US is considering equipping an existing high-power klystron with an MDC for energy saving.

A more direct increase of electronic efficiency of a klystron results from the combination of the concept of "bunch core oscillations", the "BAC" method (bunch – align – collect) and the concept of "congregated bunches" – the combination of these ideas promise efficiencies in the order of 90% without depressed collector; with the help of the EnEfficient network this has created strong interest in the community [10]. Figure 5 tries to explain the concept of core oscillations [11]: while in conventional klystrons some particle trajectories arrive in the accelerating phase in the output cavity (outer trajectories, diagram on the left), the oscillating core allows those outer particles to approach and finally join the core at the decelerating phase (diagram on the right). A number of proof-of-principle devices in L-, S- and X-band are presently in construction.

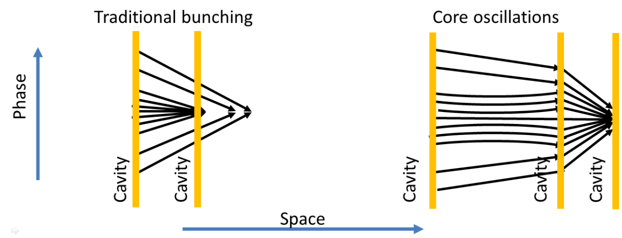

Figure 5: Illustration of the concept of "bunch core oscillations" (illustration by C. Lingwood).

While klystrons use velocity modulation of the electron beam, IOTs modulate directly the density of the electron beam using a grid, and thus can be much shorter. They can be operated at their maximum efficiency (presently around 70%) without the klystron-typical saturation. Another distinct advantage is the absence of a diode current if no RF is present. The disadvantages of IOTs are their smaller gain and their smaller output power of typically below 100 kW. ESS has embarked on an R&D program jointly with industry and CERN to evaluate the potential of MW-class multi-beam IOTs as high-efficiency, high power RF sources for large accelerator facilities. The RF to beam efficiency of normal-conducting, pulsed accelerators can be made very high at the expense of gradient, as demonstrated in the CLIC drive beam accelerator, which demonstrated >90% in CTF3 [12]. For superconducting accelerators, even the small wall losses lead to large power needs due to the efficiency of the cryogenic system (see above). For this reason, a global R&D effort to minimize the surface resistance R_s has recently resulted in some remarkable results: FNAL and JLAB have obtained significant reduction by almost a factor 4 of R_s by nitrogen and titanium doping [13] at the same temperature reducing the cryogenic power consumption by this same factor, while Cornell have demonstrated an small increase of R_s at significantly higher operating temperature [14], which equally resulted in reduced power need due to the improved cryogenic efficiency.

EFFICIENT MAGNETS

Most accelerators today guide and focus the beam using electromagnets that can be optimized. With cables of larger cross section in the coils, the resistive losses can be reduced while the field strength can be maintained. A good optimum can be achieved in the range of 2 to 3 A/mm^2. Of course these savings come at the expense of a larger magnet size and cost. A number of alternatives to classical electromagnets exist. Especially for permanent magnets (Fig. 6) significant development work has taken place. But also pulsed magnets, magnets with high saturation material and superconducting magnets can be energy effective under certain conditions. Presentations of the different concepts can be found at a recent workshop

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of EnEfficient [15]. For the purpose of this paper we summarize Pro's and Con's of different concepts in Table 1.

Table 1: Magnet Concepts for Beam Transport

permanent magnets Pro: no power required, reliable, compact	Con: tunability difficult, large aperture magnets limited, radiation damage
optimized electromagnet Pro: low power, less cooling	Con: larger size, cost
pulsed magnet Pro: low average power, less cooling, high fields	Con: complexity of magnet and circuit, field errors
s.c. magnet Pro: no ohmic losses, higher fields	Con: cost, complexity, cryo installation
high saturation materials Pro: lower power for same field, compactness and weight	Con: cost, gain is limited

ENERGY STORAGE SYSTEMS

Many accelerator systems operate in cycles, and thus the power load occurs in cycles as well. Examples are pulsed RF systems or synchrotrons that are ramped at a certain frequency. In such cases energy storage systems are needed to realise a uniform load on the grid. Pulsed magnets as mentioned in the previous section can use a storage system to recover a part of the field energy for the next cycle. In the context of energy management large capacity storage systems can be used to bridge times of high load on the public grid, or could simply act as an uninterrupted power supply. Typically accelerators have long start-up times, during which significant power is consumed but user operation is not yet possible. By avoiding unwanted interruptions from glitches on the grid, the overall efficiency of a facility can be improved.

The methods used for storage depend on capacity and cycle duration. At CERN a mechanical flywheel system has been in use for many years, and was then replaced by a capacitor bank. An interesting proposal for a large capacity storage system that nevertheless can overtake a load very quickly is the LIQHYSMES concept, proposed by KIT. It is a hybrid system of a superconducting storage magnet and a liquid hydrogen reservoir, realising the large capacity [16]. Although this system was proposed for very large capacity, it could possibly be used as medium time storage for large accelerator facilities.

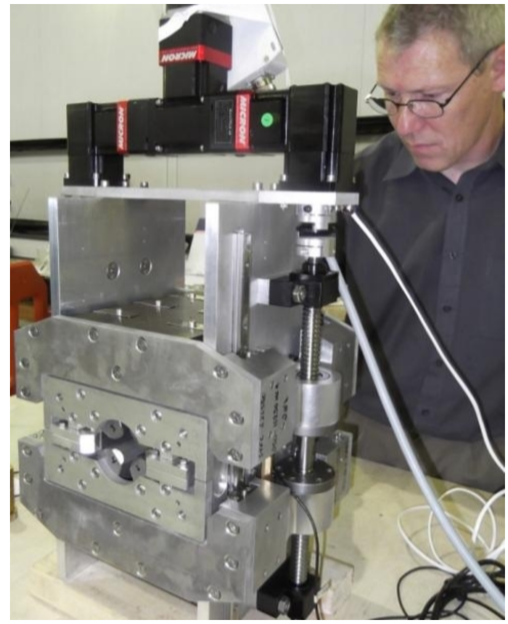

Figure 6: Permanent quadrupole with mechanical tune ability of the gradient between 15 and 60 T/m, developed for focusing of the CLIC drive beam [17].

CONCLUSION

Implicitly it was always the goal of accelerator development to optimize the efficiency of accelerators. Sophisticated layout of interaction regions for high luminosity in collider facilities or optimized low emittance lattices for high brightness of light sources are examples, where new physics concepts resulted in large qualitative improvements of the overall efficiency.

As a result of the worldwide scarcity of resources and increased awareness on resource problems it is mandatory today to optimize also the efficiency of each technical subsystem as best as possible and to reconsider the overall energy management aspects of large facilities. Technical developments in this direction are noticeable in many areas of accelerator technology. Within the Eucard-2 program, work package EnEfficient, we try to stimulate such technical developments by organising workshops on aspects of energy efficiency for accelerators. The reader will find documentation in the reference list of this paper.

Heat recovery is used in many facilities today. A key aspect for efficient recovery is the operation of cooling circuits at higher temperature level and one tries to implement this where possible. RF sources are reaching higher efficiencies beyond the 60% level and klystrons as well as inductive output tubes, both with multi beam concepts, can be mentioned in this context. A lot of development was done for permanent accelerator magnets which are even tuneable today and exhibit improved field quality. Pulsed magnets represent another efficient solution for beam transport. Energy management in the presence of fluctuating supply will an important topic for the future.

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