Proceedings of the CAS–CERN Accelerator School: Free Electron Lasers and Energy Recovery Linacs, Hamburg, Germany, 31 May–10 June 2016, edited by R. Bailey, CERN Yellow Reports: School Proceedings, Vol. 1/2018, CERN-2018-001-SP (CERN, Geneva, 2018)

Energy Efficiency

E. Jensen
CERN, Geneva, Switzerland

Abstract
Particle accelerators are precious tools, not only for high-energy and nuclear physics, but also for many other areas of science, medicine, and security. They do, however, have a substantial energy consumption, which makes it important to design them to make best use of the consumed energy. Maximizing the energy efficiency of an accelerator means minimizing not only the energy consumption and the environmental impact, but also allowing for smaller installations. The concepts and technologies developed to improve the energy efficiency of particle accelerators are not limited to accelerators, but will have a significant impact on energy systems generally. These developments include smart power grids and short-term energy storage devices, better energy conversion efficiencies for subsystems, efficient cryogenic systems, and, ultimately, the recovery of unused energy in more valuable forms than low-temperature heat. Energy recovery linacs are the prime example for good efficiency, since they accelerate, use, and decelerate a continuous beam, using the energy recovered during deceleration for acceleration.

Keywords
Energy conversion; exergy; efficiency; beam loading; Sankey diagram.

1 Introduction

1.1 Importance of energy consumption and efficient energy use

Humankind consumes about 160 PWh per year (or, on average, 18 TW or 2.4 kW per capita) for transportation, industry, nutrition, and comfort. More than 80% of this energy stems from fossil fuels (petrol, coal, natural gas), which are not abundant. Awareness of the scarcity of these natural resources arose in the 1960s (Club of Rome, 1968) and 1970s ([1], oil crisis 1973). Environmental concerns have increased since, relating global warming to greenhouse gas emissions and weather phenomena like El Niño to the incineration of fossil fuels. The 1997 Kyoto Protocol and the 2015 Paris Agreement document worldwide concern and underline the political will of many nations to reduce global warming.

Nuclear fusion and fission promise abundant resources, but have raised other concerns, either of public acceptance or economic feasibility. Renewable resources (wind, solar, hydro, geothermal) are not yet exploited to fully cover demand.

However, as illustrated using the example of the USA shown in Fig. 1, a large fraction of consumed energy is ‘wasted’ or ‘rejected’ rather than used for its purpose, and the term ‘energy efficiency’ is used here to denote the ratio between the useful output of an energy conversion system and the input. The goal of maximizing energy efficiency is synonymous to minimizing the amount of energy required to provide a requested service or product. Design towards higher energy efficiency will thus not only save energy but also allow a smaller installation, both for the supply of energy and for the disposal of rejected energy (typically cooling).

https://doi.org/10.23730/CYRSP-2018-001.421

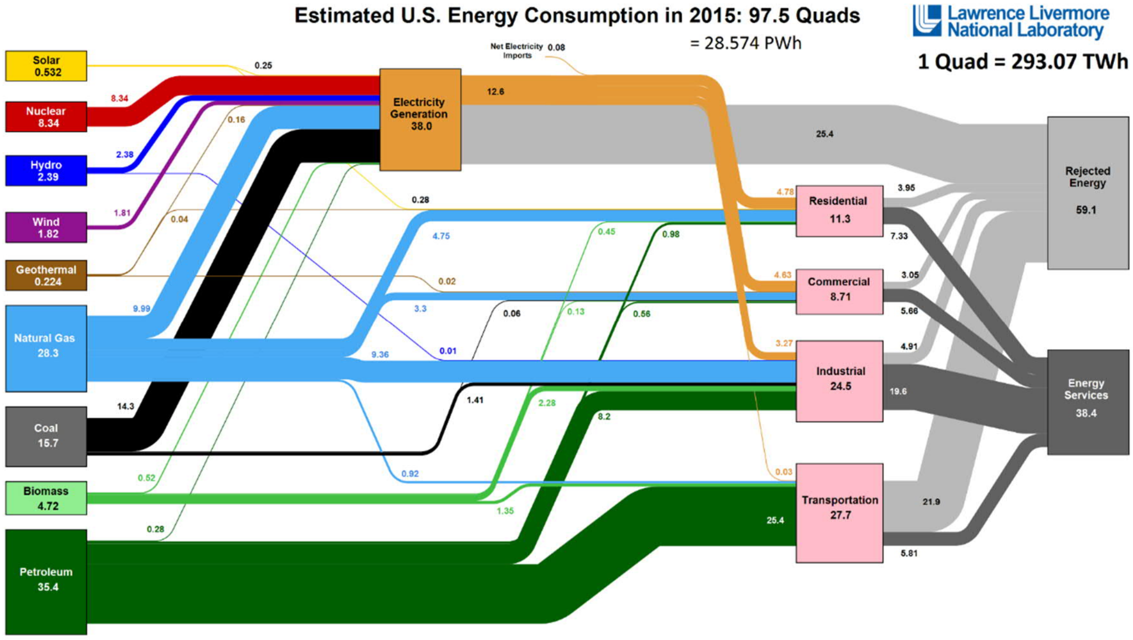


Fig. 1: Sankey diagram illustrating the different sources, forms, and uses of energy, using USA data for 2015 as an example [2].

1.2 Orders of magnitude

The total daily energy consumption of humankind is about 440 TWh or 60 kWh per capita (in Western Europe, 104 kWh). If we look at orders of magnitude for energy provision, storage, and use, we find the following.

1.2.1 1 kWh

This order of magnitude is the daily work delivered by a Tour-de-France race cyclist or one run of laundry in a household washing machine. A household freezer uses about 1 kWh per day, a laundry tumbler will require about 2 to 4 kWh for one run, an average Western European household uses 16 kWh per day per capita. The energy required to heat 1 m^3 of water by 1 K is 1.16 kWh. A window-mounted air conditioner unit running all day uses about 20 kWh. A mass of 37 t in 10 m height has a potential energy of 1 kWh in the Earth's gravitational field; a fully charged conventional lead car battery stores about 1 kWh. A Tesla Model S Li-ion battery holds up to 100 kWh for a reach of up to 540 km [3].

1.2.2 10 MWh

The order of magnitude 10 MWh corresponds to the electricity produced by a wind power station in one average day. Per year, an average household in Western Europe uses about 6 MWh electricity per capita, CERN's Linac4 consumes 10 MWh/day, CERN's PS-Booster or the Swiss Light Source require about 80 MWh/day. 1 MWh of electricity costs of the order of €100 (range €30 to €300). The energy stored in one ITER superconducting toroidal field coil is 11.5 MWh, about four times the energy stored in all 1232 LHC main magnets together at top energy.

1.2.3 10 GWh

The electrical energy produced per day by an average size nuclear reactor block is about 24 GWh. The 'Solar Star' photovoltaic power station in Southern California produces 4.5 GWh per day on average [4], the 'Alta Wind Energy Center' wind farm, with 320 wind turbines, also in California, about 7.3 GWh [5]. CERN's total daily electricity consumption on average is about 3.5 GWh; about half of this is needed for the LHC alone.

As indicated in Fig. 2, some proposals for post-LHC colliders will require RF powers alone of the order of 100 MW, or grid powers of hundreds of megawatts (translating to tens of gigawatt hours per day). It is clear that these large consumptions make the optimization of energy conversion efficiencies compulsory.

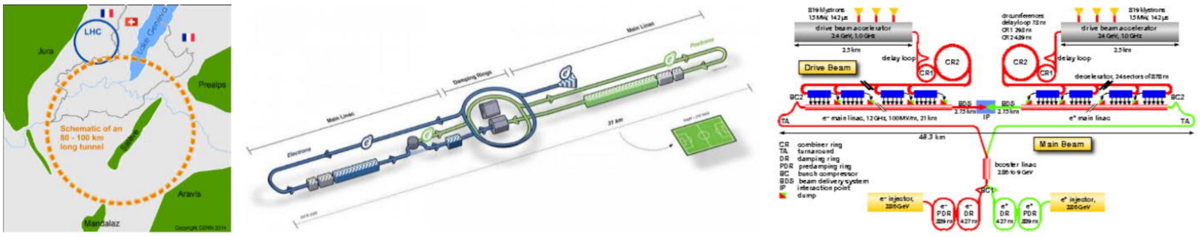


Fig. 2: Some major high-energy physics collider proposals for the post-LHC era. Left-hand side: FCC-ee circular collider, 90–350 GeV, 0.8 GHz continuous wave, total RF power: 110 MW. Centre: ILC (International Linear Collider), 0.5 TeV, 1.3 GHz, total (average) RF power: 88 MW. Right-hand side: CLIC (Compact Linear Collider),3 TeV, 1 GHz, total (average) RF power: 180 MW.

Regarding these examples, it is clear that large particle accelerators are in the size range that matters, both for the acceptance of accelerator projects by the public and because the technology developed to improve efficiency in particle accelerators may well be relevant for other areas of science and technology and thus may have a large societal impact.

Energy storage for this order of magnitude is difficult—the energy stored in all German hydroelectric energy storage plants together is of the order of 40 GWh.

1.2.4 1 TWh

France presently runs 19 nuclear power plants (58 reactor blocks) with a total power of 66 GW or 1.6 TWh per day. Germany uses about 1.6 TWh of electricity per day—humankind about 53 TWh. Energy storage does not really scale to this order of magnitude—the total energy that can be stored in all existing hydroelectric plants probably sums up to about 1 TWh. The annual electricity consumption of CERN is 1.2 TWh, that of the canton Geneva is 2.9 TWh; the whole of Switzerland uses 60 TWh, Germany 584 TWh.

The total solar energy (sunshine) on the Earth's surface is 3,000,000 TWh = 3 EWh every day.

1.3 Definition of energy efficiency

It is clear that it is important to define 'useful' in order to define energy efficiency. If, for example, we consider the purpose of heating an apartment, very clearly the purpose is to keep a certain comfortable temperature, which requires some heating if the outside temperature is lower. Large energy efficiency here certainly has to do with good thermal insulation—perfect insulation would not require any heating at all! One easily finds that all heating power is eventually required only to heat the environment through the apartment's imperfect thermal insulation, and good efficiency directly translates to avoided consumption of primary energy.

If we are looking at a subsystem that converts or transports energy, the definition of 'useful' is again relatively straightforward—the losses here are conversion or transmission losses and the efficiency very clearly is

$$\eta = \frac{\text{useful}}{\text{consumed}} = 1 - \frac{\text{lost}}{\text{consumed}} = \frac{1}{1+\text{lost}/\text{useful}} \; .$$

Also, note that the consumed energy is given by

$$\frac{\text{lost}}{1-\eta} = \frac{\text{useful}}{\eta} \ ,$$

and so both lost and consumed energy are reduced when η is maximized (indicated by the height of the blue boxes in Fig. 3, clearly smaller on the right-hand side). This, of course, means that the size of the installation and the cooling and ventilation systems can be designed to be smaller.

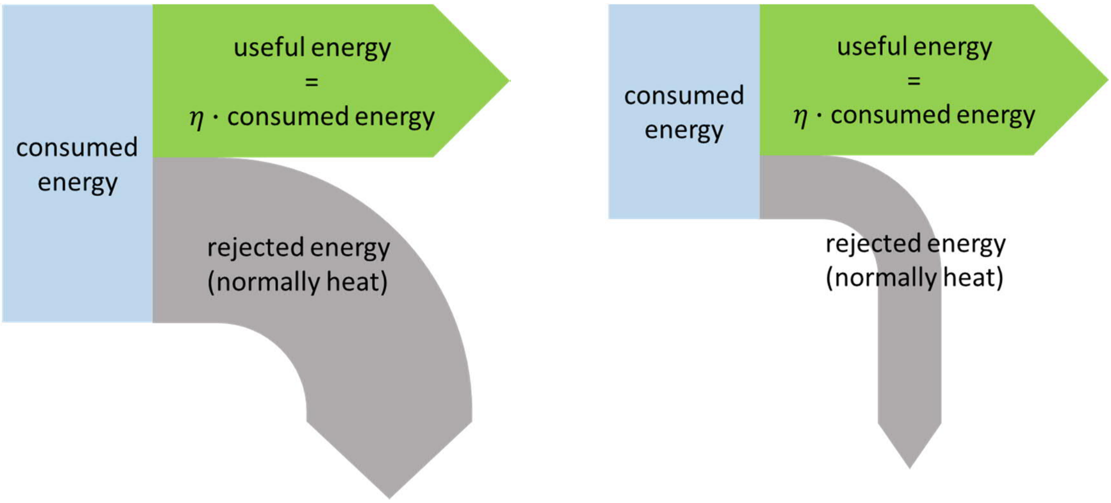


Fig. 3: Sankey diagram of the definition of efficiency as a ratio of useful energy to consumed energy. Note that the illustration of small efficiency (left-hand side) and large efficiency (right-hand side) is scaled to show identical 'useful energy' for the two cases (green), and that a larger efficiency also means a smaller installation for both the power supply (blue) and the cooling and ventilation (grey).

The fact that larger efficiency leads to less consumed energy allows us to coin the term 'avoided consumption', which can, in fact, be considered as a resource gained by increasing efficiency. Looking again at the example of Fig. 1, comparing the 'rejected energy' with the resources on the left, one realizes that this new resource can be of significant size.

2 Power flow in an accelerator

It is useful to look at all components of a particle accelerator that contribute to the energy conversion efficiency to identify at which point improvements pay off the most. Typically, one starts from the electricity grid at high voltage (400 kV) or medium voltage (18 kV) with large transformers. These feed so-called power converters that feed magnets, cryogenic installations, RF power generators and amplifiers, particle detectors, computers, and ancillary systems.

In the example given in Fig. 4, the RF system, magnet system, and scientific instruments share the consumed energy in almost equal parts, but this should not be generalized. A linac will certainly use more energy for RF than for magnets; the LHC uses the largest part for the cryogenic system to allow using only very little for the superconducting magnets themselves. In all cases, however, the energy of the beam is an important intermediate quantity that allows efficiencies of the accelerator subsystems to be quantified. In subsequent sections, we will look at these subsystems' efficiencies in more detail.

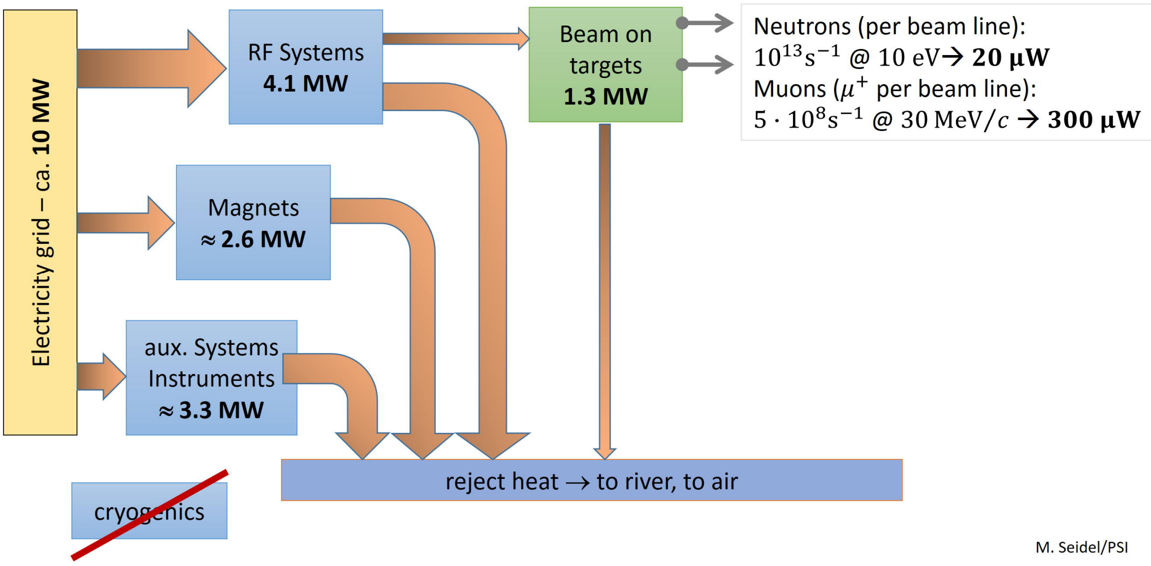
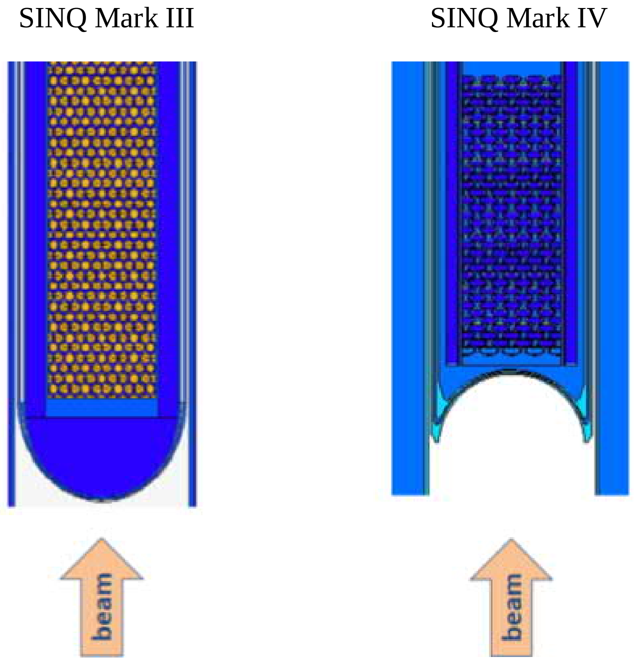


Fig. 4: Typical power flow in an accelerator (example PSI [6])

Conversely, it is equally important to assure that optimum use is made of the beam energy! The luminosity upgrade project of the LHC at CERN, ‘HL-LHC’, is an example aimed at increasing the luminosity (the number of physics events) by a factor of ten, while the beam intensities are increased by (only) a factor of two. This is achieved by squeezing the two proton beams even further (decreasing β^* from nominally 65 cm to below 20 cm). To avoid spurious collisions that would then result from head-on collisions requires, however, increasing the crossing angle, which can only be achieved by enlarging the aperture of the final focus magnets. A larger crossing angle with reduced β^* would, however, lead to incomplete overlap of the colliding bunches and thus a geometric luminosity reduction. Crab cavities will enable correction for this geometric aberration, allowing again for the same luminosity as in head-on collisions.

Another example for optimizing the use of the beam energy is presented in Fig. 5, which indicates a series of steps that led to the more efficient use of the incoming proton beam in a spallation neutron target, increasing its neutron yield by a remarkable factor of 1.42 [7]. This was achieved by using zirconium cladding, arranging the target rods to be closer together, the usage of lead reflectors, and reshaping the calotte for the incoming beam from convex to concave. Note that a yield increase by a factor of 1.42 is equivalent to a reduction of the used energy by the same factor!



Improvements

Zr cladding instead of steel	+12%
Compaction of rod bundle	+5%
Pb reflectors	+10%
Inverted entrance calotte	+10%
Total gain	+42.3%

Fig. 5: Improvements of a spallation neutron target for better neutron yield [7]

It is often difficult to quantify what exactly the 'best use of the beam energy' is, since it is, a priori, not known how much energy consumption is required for a physics discovery, but certainly one can make comparative studies, as in the two examples above, at least if the physical processes involved are understood.

In some cases, where a large beam energy is required continuously but the beam structure is not 'destroyed' in the process (for example, if electrons create light in a wiggler or undulator, or if electrons interact in an electron–ion collider), the 'best use' of the beam energy could be its recovery, for example, in an energy recovery linac (see Section 8 below).

3 Is everything lost?

Looking at the typical numbers in the previous examples it seems that—apart maybe from a few microwatts in neutrons or muons—virtually all energy is converted to waste heat. The obvious question arising is, 'Can we recover the heat in a more valuable form of energy?'

According to the second law of thermodynamics, one can distinguish forms of energy of different 'qualities': heat, for example, is a form of energy, which has value only in the presence of a temperature difference. Otherwise, in so-called thermodynamic equilibrium, it cannot be converted into another form of energy—in particular, it cannot do work. Other forms of energy can do work directly (potential, electric, to some degree kinetic) and thus have a higher value. Energy that can do work is often also referred to as *exergy* [8].

Heat in the presence of a temperature difference can do some work, and in spite of the former statement on heat as a form of energy of lower 'quality', it is practically involved in most energy conversion processes, from the steam engine via most power plants to nuclear reactors. The efficiency of the heat engine, the process of converting heat to work, is, however, strictly limited to the Carnot efficiency [9], which is given as $\eta_{\max} = 1 - T_C/T_H$, where T_C and T_H are the cold and hot temperature in kelvins, respectively. This is illustrated on the left-hand side of Fig. 6 in a Sankey diagram, while the Carnot efficiency of a heat engine operating in an ambient temperature of 20 °C is shown on the right-hand side. It is clear that that this efficiency becomes zero with vanishing temperature difference and reaches only 50% when $T_\mathrm{H} = 2\,T_\mathrm{C}$, which means that, with an ambient temperature of $T_\mathrm{C} = 20\,°\mathrm{C} = 293\,\mathrm{K}$, the efficiency reaches only 25.4% for $T_\mathrm{H} = 100\,°\mathrm{C} = 393\,\mathrm{K}$. Substantial efficiencies can be reached only at much larger ΔT.

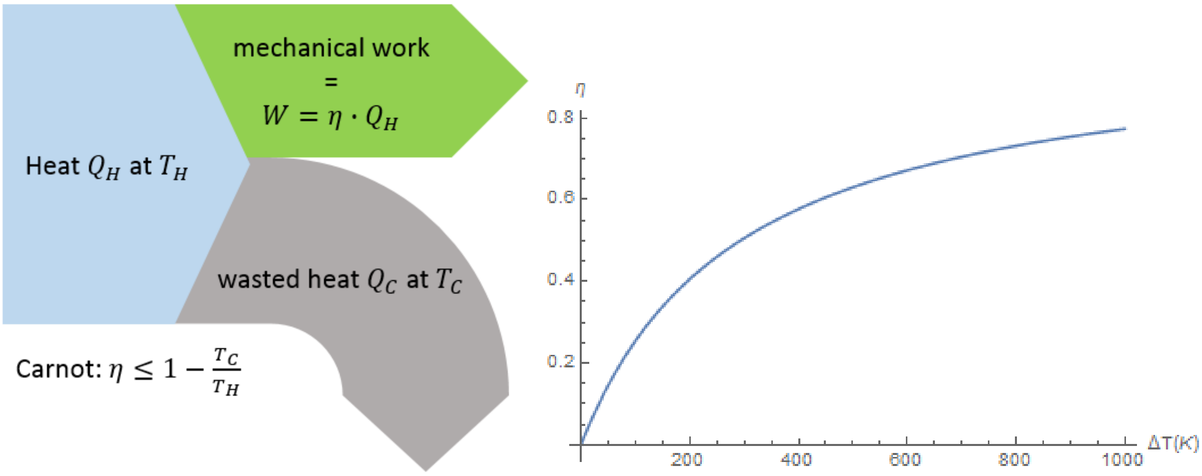


Fig. 6: Left-hand side: Carnot efficiency as the limit for the conversion of heat to work. Right-hand side: Carnot efficiency of a heat engine as a function of ΔT for $T_C = 20\,°\mathrm{C}$.

From this consideration, it should be clear that the recovery of waste heat to exergy is not efficient and works better at high temperature. Please consider that the Carnot efficiency is the theoretical limit, while measured efficiencies are always lower because of friction and other imperfections.

Before directly rejecting waste heat into the environment, one may of course consider injecting it into a heating plant, but this should be considered only for the unavoidable remaining waste heat after all other processes have been optimized to minimize consumption.

4 Optimizing magnets

In principle, no energy is consumed to generate a DC magnetic field—a prominent example for the use of permanent magnets in accelerators is the Fermilab Recycler storage ring [10]. Permanent magnets, however, are limited in both field strength (neodymium magnets reach $\approx 1.4\,\mathrm{T}$) and homogeneous field region. The downside of permanent magnets is, of course, the lack of tunability. An example showing how permanent magnets can also be made tuneable is illustrated in Fig. 7, which shows a permanent quadrupole studied for CLIC, which is tunable in a range from $15\ \mathrm{T/m}$ to $60\ \mathrm{T/m}$ by displacing parts of the magnetic circuit mechanically by a stroke of 64 mm.

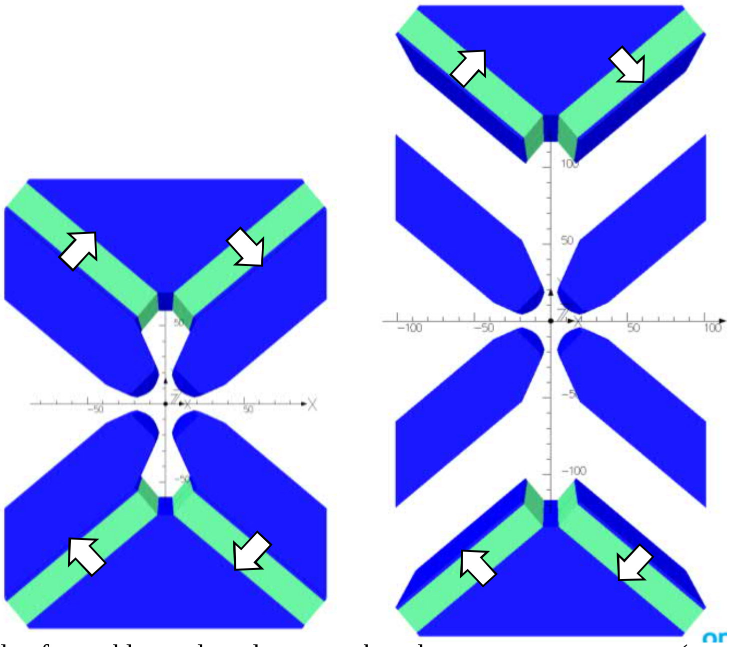


Fig. 7: Principle of tuneable quadrupole magnet based on permanent magnets (green) [11]

For the LHC, the main dipole magnets use NbTi superconductors up to 11.6 kA operated at 1.9 K to reach fields of the order of 8.33 T to guide the 7 TeV proton beams on the LHC curvature [12]. Thanks to superconductivity, the ohmic losses in the magnet coils are zero but, of course, energy is consumed to establish and maintain the cryogenic conditions, treated in Section 7 below.

5 RF power generation

Figure 8 shows the Sankey diagram for the FCC-ee as an example with optimistic but not untypical numbers for the energy conversion efficiencies involved. It should be noted that (i) the most significant conversion efficiency in the example is the generation of RF power and (ii) a large amount of energy is required to operate the cryogenic plant required to keep the cavities superconducting, which will be treated in Section 7 below.

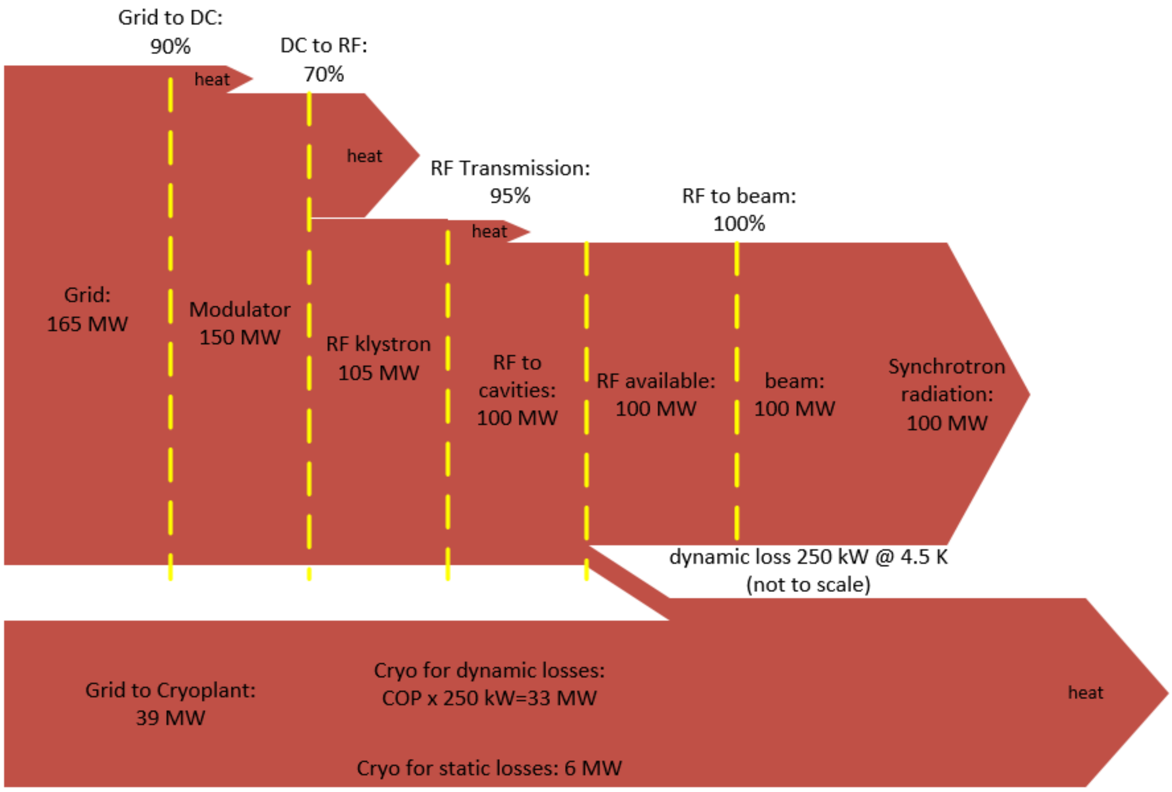


Fig. 8: Sankey diagram indicating energy conversion efficiencies for the FCC-ee circular collider RF systems and cavities. The generation of RF from DC is a significant contributor to the overall efficiency.

Active elements used for RF power generation are summarized in Table 1. Note that the frequencies, powers, and efficiencies given are merely meant to indicate typical orders of magnitude, while actual cases may significantly deviate. In particular, for solid-state power amplifiers, the attainable efficiency depends strongly on the frequency range and on the technology used to fabricate the active elements. The abbreviation IOT stands for 'inductive output tube', which is a hybrid between a tetrode and a klystron.

Table 1: Typical frequency, average power, and efficiency ranges of active elements for RF power generation

	Tetrodes	**IOTs**	**Klystrons**	**Solid-state power amplifier**	**Magnetrons**
f range	DC to 0.4 GHz	0.2–0.5 GHz	0.3–20 GHz	DC to 20 GHz	GHz range
P range	1 MW	1 MW	1.5 MW	1 kW	<1 MW
Typical η	85–90% (class C)	70%	50%	60%	90%
Remarks	Broadcast technology, widely discontinued		New ideas promise significant increase	Requires P combination of thousands	Oscillator, not amplifier!

5.1 The impact of improving the RF power generation efficiency

I will use the example of the FCC-ee study, sketched in Fig. 8, to illustrate the impact that an improvement of the klystron efficiency from 70% to 80% would have. Let us assume that the indicated 105 MW are given; in this case, the required power from the grid would decrease from 165 MW to 144 MW. All electrical installation on the primary side could thus be dimensioned 12.5% smaller. With an assumed annual operation period of 5000 h, the annual energy consumption would reduce by 105 GWh. With an assumed electricity cost of €50/MWh, this would reduce the annual electricity bill by €5.2 million, savings that could co-finance the R&D. The waste heat rejected to the environment would be reduced by 35% from 60 MW to 35 MW. This would also mean that the cooling and ventilation systems could be designed to be 35% smaller.

All of these savings are significant and make it worthwhile to invest in ideas that could lead to increased RF power generation efficiency and the development of better klystrons.

5.2 New concepts to increase klystron efficiencies

Klystrons are widely used in particle accelerators, in both pulsed and continuous wave operation. Conventional klystrons reach efficiencies of up to 70% in saturation and typically around 50% in standard operation. In a standard klystron, a DC voltage of typically 20–200 kV accelerates a continuous electron through a vacuum tube. A small RF voltage applied to the passing beam in an input cavity leads initially to a velocity modulation of the beam, which, after a drift region, leads to an intensity modulation (bunching). This density modulation gives rise to RF components of the electron beam, which can be extracted with an output cavity. In this simplest form of a klystron, consisting of just input cavity and output cavity, a maximum efficiency (extracted output power divided by DC voltage and beam current) of 58% can be reached. Additional passive cavities between the input cavity and the output cavity are often used; they are tuned slightly off the operating frequency or near its harmonics and help in the bunching process to reach larger efficiencies; this is how today's conventional klystrons reach approximately 70%.

Space charge forces limit the efficiency of a high-power klystron. Since short bunches are required for high efficiency and space charge forces counteract the formation of short bunches, this led to the invention of multi-beam klystrons, where the total beam current is divided into n smaller beams, reducing the space charge by a factor of n.

New ideas appeared in 2013, which fundamentally questioned the established methods of maximizing klystron efficiencies. One of these ideas is the core oscillation method, where the space charge is used to help the bunching rather than obstructing it [13]. Figure 9 tries to illustrate the core oscillation principle (bottom) by comparing it with conventional bunching (top). The plots on the left-hand side show the particle phase distribution (vertical axis) while travelling through the klystron, passing the different cavities (vertical grey lines). The particle distribution is sketched using two different colours to distinguish between those particles that arrive in the output cavity in a useful RF phase to contribute to power generation (light brown shading) and those that arrive in the wrong phase, i.e. particles that will actually be accelerated in the output cavity and thus reduce efficiency (grey shading). In conventional klystrons, the number of electrons arriving in the wrong phase is substantial—this leads to the limitation of efficiency.

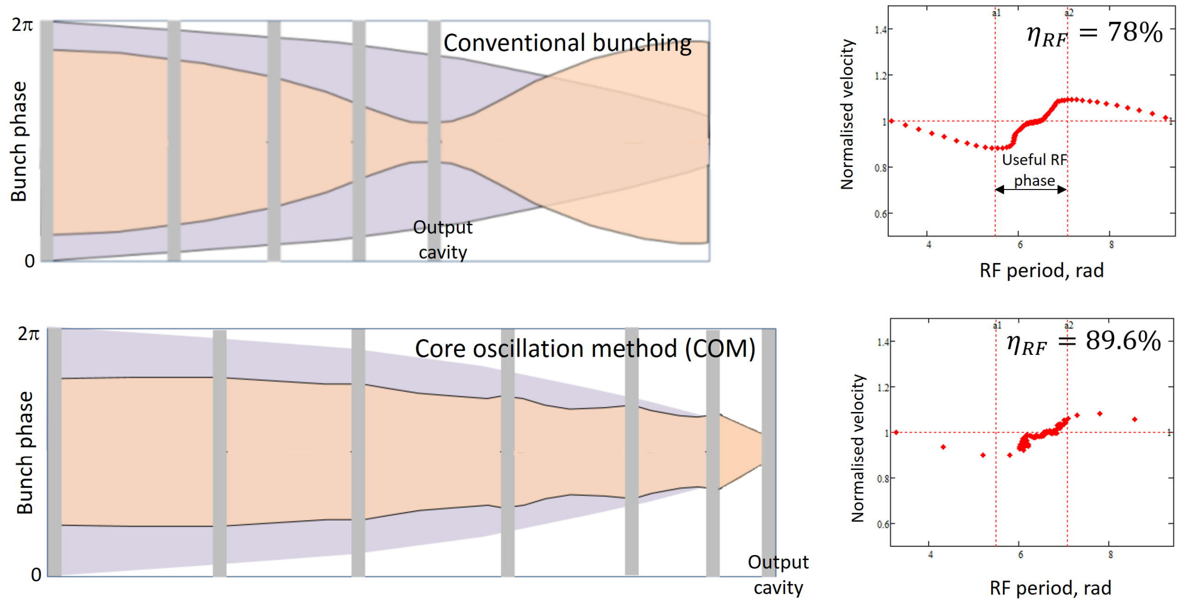


Fig. 9: Conventional bunching (top) compared with core oscillation method (bottom) to reach higher klystron efficiency.

For the core oscillation method, one allows the space charge to drive the forming bunches apart again and puts the next cavity further downstream. Bunches form again, are driven apart again by space charge and redressed again further downstream—this can be repeated several times, leading to 'core oscillation'. While this core oscillation takes place, the electrons that would otherwise arrive in the wrong phase in the output cavity see smooth focusing forces that allow them to drift also into the core of the bunch. This leads to a much more favourable electron distribution in the output cavity and thus significantly larger efficiency.

The disadvantage of the core oscillation method is the need for a much longer device, but other methods are the focus of recent studies to combine high efficiency with reduced length.

6 Conversion of RF power to beam power

Once the RF power is generated and transmitted to the cavity, where the interaction with the charged particle beam takes place, how much of this power can actually be transferred to the beam? How can one optimize this transfer of power to the beam?

In the early days of accelerators, the quantity optimized in the cavity design was the shunt impedance. This makes sense, since the shunt impedance R_{shunt} is defined as $|V_{\mathrm{acc}}|^2 = R_{\mathrm{shunt}} \cdot P$, i.e. maximizing R_{shunt} will result in the largest accelerating voltage given the input power. R_{shunt} can be expressed as the product of a factor R/Q, which depends only on the cavity geometry, and the quality factor Q, which is the number of RF periods, during which the stored energy decreases by a factor 535.5 ($= \mathrm{e}^{2\pi}$) if no RF power is replenished. A typical order of magnitude for the factor R/Q is 200 Ω; a typical order of magnitude for Q is 10^3 to 10^5 for normal-conducting copper cavities and 10^9 to 10^{11} for superconducting niobium cavities.

Note that the power P in this equation is the power lost in R_{shunt} and not the power transferred to the beam!

For the transfer of energy from the RF to the beam, however, optimizing the voltage by optimizing R_{shunt} neglects the effect of the beam current, which, if not small, is important for the energy transfer to the beam and thus for the conversion of RF power to beam power. Referring to Fig. 10, with the simplifying assumption that the cavity is in tune, such that L and C exactly compensate each other and can be neglected. In the absence of the beam ($I_\mathrm{B} = 0$), the generator current through R_shunt will create the accelerating voltage V_acc, as desired.

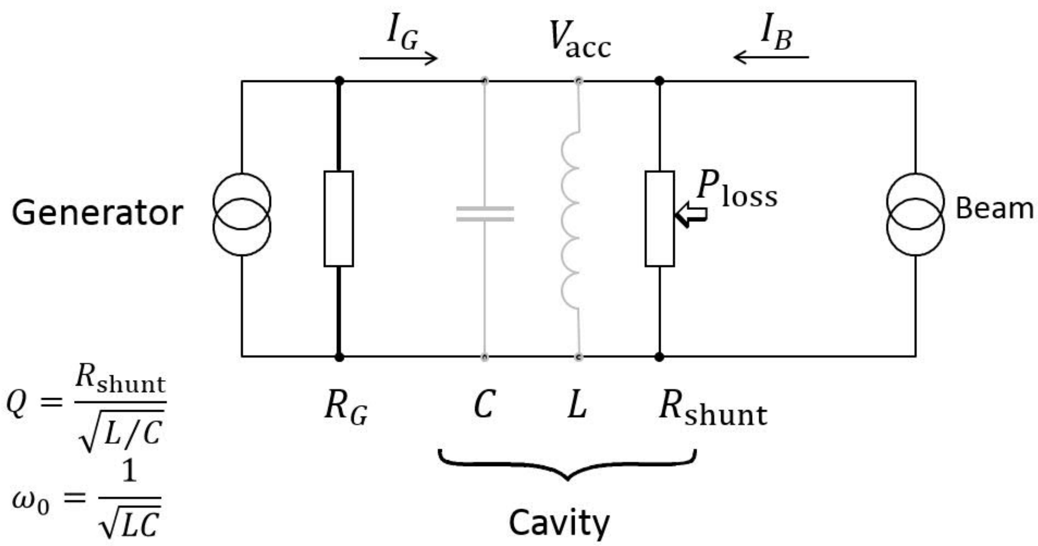


Fig. 10: Equivalent circuit for a single mode in an accelerating cavity

In the presence of the beam ($I_\mathrm{B} \neq 0$), the sum of I_G and I_B flows through R_shunt. When accelerating, with the arrow direction as chosen in Fig. 10, the beam current will, however, be in antiphase to the accelerating voltage ($I_\mathrm{B} < 0$) and thus counteract I_G, which means that the total current through R_shunt and thus V_acc will be reduced. This effect is generally referred to as 'beam loading'.

In a more general formulation, the currents and voltages in the equivalent circuit have arbitrary phases, best described as complex quantities, which also enables studying the cavity off tune and any beam phase. With the arrow direction chosen in Fig. 10, the power transferred to the beam is given as $-\Re\{V_\mathrm{acc} \cdot I_\mathrm{B}^*\}$, where $\Re$ denotes the 'real part' and the asterisk denotes 'complex conjugate'. This is the quantity to be maximized for best efficiency in the transfer of RF energy to beam energy. One can state that, to have a large energy transfer efficiency, the beam loading should be large.

If R_shunt is very large, as is the case for superconducting cavities, it can be neglected entirely in the equivalent circuit, and now the task of optimizing energy transfer is to match R_G to the equivalent beam impedance, $-V_\mathrm{acc}/I_\mathrm{B}$. If this matching is possible, the energy transfer efficiency can reach 100% in this limiting case.

Full beam loading can also be reached in normal-conducting accelerating structures, and was, in fact, reached in CTF3 in the frame of the CLIC study [14]. For the acceleration of the drive beam in a normal-conducting 3 GHz travelling-wave structure, an RF to beam energy transfer efficiency of 95.6% could be experimentally verified. On the downside, maximizing the efficiency reduces the accelerating voltage from the value that is reachable in the unloaded case. For full beam loading, this reduction is roughly a factor of two, as indicated in Fig. 11**.** This reduction is of no concern for a circular accelerator, but very important for linacs used in linear colliders. In the CLIC concept, full beam loading is used for the drive beam, but only 20% beam loading is chosen to accelerate the main beam, which is a trade-off between efficiency (36%) and a reduced accelerating gradient compared with the unloaded case (90%).

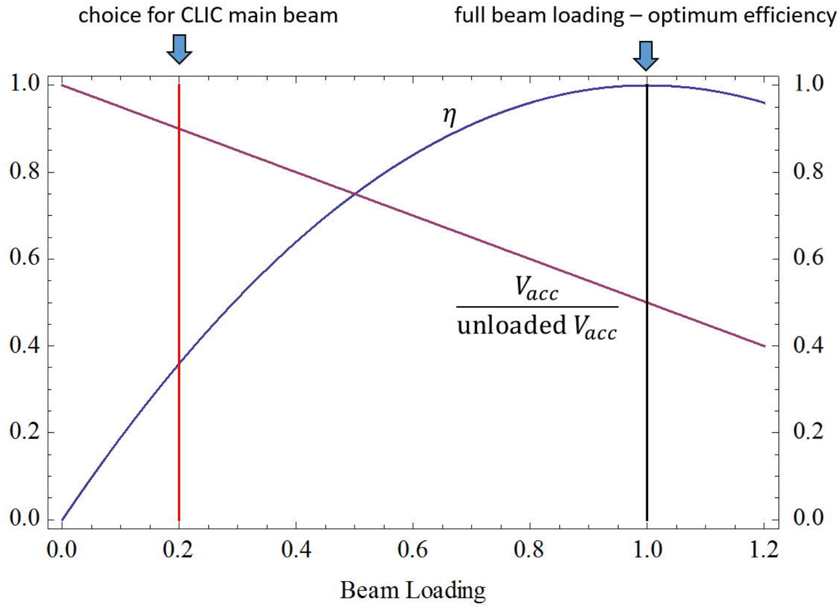


Fig. 11: RF to beam energy transfer efficiency as a function of degree of beam loading. For full beam loading, only about 50% of the unloaded gradient is reached; for partial beam loading, gradient and efficiency can be traded off.

7 Cryogenic system efficiency

The concept of the Carnot efficiency introduced in Section 0 above, limiting the efficiency of a heat engine, is also valid for other engines that transfer energy between heat and ordered motion, such as heat pumps or refrigerators.

Figure 12 illustrates a refrigerator, where mechanical work is done to extract heat at a low temperature—the basic principle of a cryogenic system. At the same time, this illustrates a heat pump, for which Q_H at T_H is the desired heating, extracting energy Q_C at the lower temperature T_C with the help of the mechanical work of the heat pump.

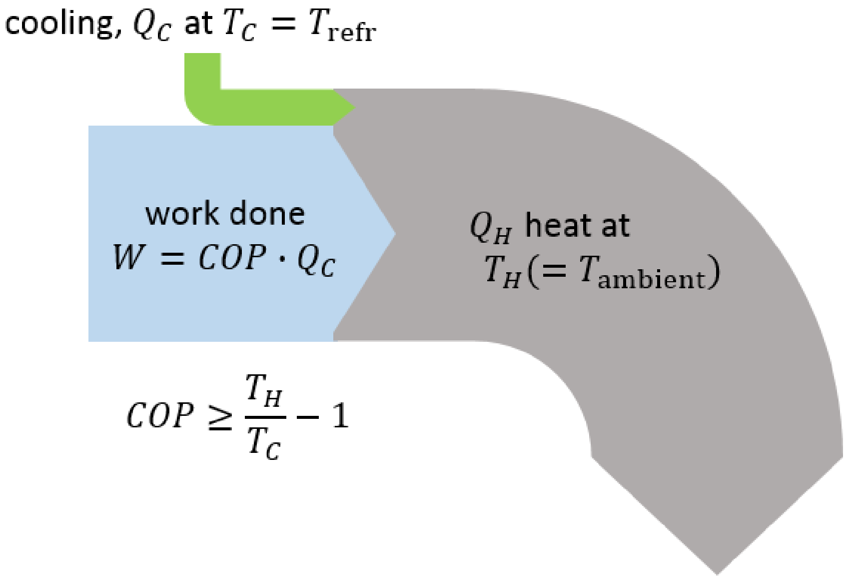


Fig. 12: Reversed Carnot cycle, illustrating the energy flow in a cryogenic system—the goal is to extract heat Q_c at T_c, which requires work $W = \mathrm{COP} \cdot Q_C$.

The established term used to describe the performance of cryogenic plants or heat pumps is the 'coefficient of performance', abbreviated COP. If we use our definition of efficiency as the ratio of 'useful' energy to 'used' energy, and define for a cryogenic plant the cooling power at low temperature, Q_C as the 'useful' energy, we could write $\mathrm{COP} = \eta^{-1}$. For a heat pump, where Q_H is the 'useful' energy, the efficiency is sometimes defined as $\eta = Q_H/W$, neglecting the used incoming heat Q_H, which leads to efficiencies well over 100%, limited by Carnot's principle to $T_C/\Delta T$.

For real technical installations, the COP obtained is much larger than the Carnot limit (Fig. 13). Based on consolidated experience with modern and large CERN cryogenic plants, the technically achieved COP is about 230 at 4.5 K and 930 at 1.8 K, much larger than the Carnot limits of 64.1 and 161.8, respectively (assuming an ambient temperature of 293 K).

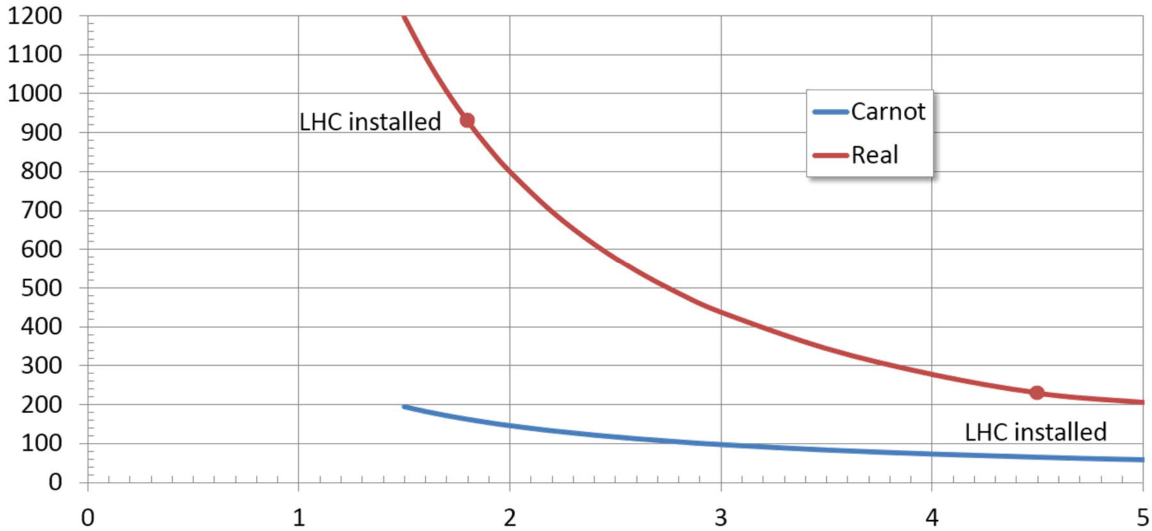


Fig. 13: COP obtained in large cryogenic systems as a function of temperature (P. Lebrun, private communication)

7.1 Optimum operating temperature for a superconducting RF system

When optimizing a superconducting RF system, as, for example, the one used as an example in Fig. 8, it is important to optimize the whole system and not just the subsystems. While superconducting cavities reach lower losses when operated at lower temperatures (see Fig. 14, left-hand side), it is clear that cooling to obtain those lower losses costs more energy, owing to the increased COP. Combining these two effects leads to an optimum operating temperature at which the energy consumption for the cryogenic system is minimized (see Fig. 14, right-hand side) [15].

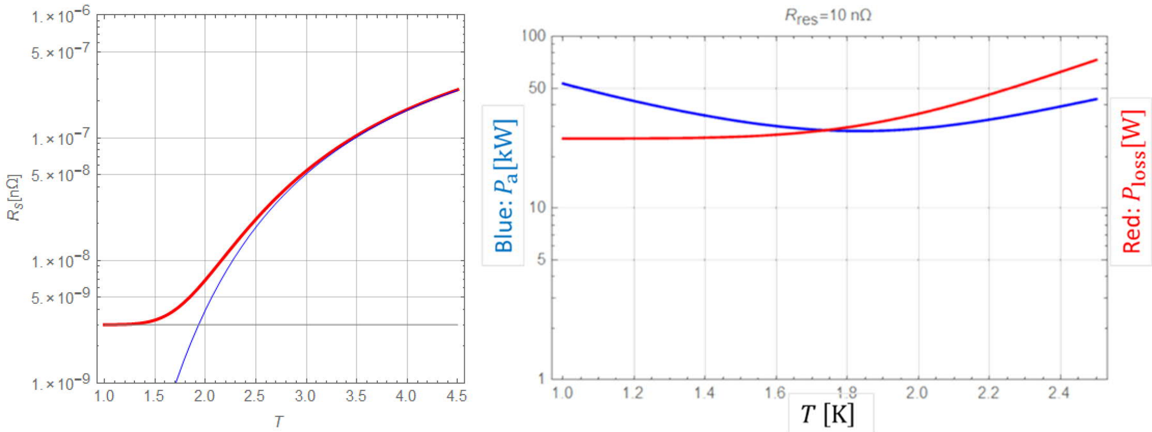


Fig. 14: Left-hand side: surface resistance in a Nb superconducting cavity as a function of temperature, according to the BCS model (blue) and real (red). Right-hand side: with the T dependence of both R_s and COP, an optimum operating temperature results. Red: cavity wall losses in watts. Blue: required cooling power at ambient temperature in kilowatts.

8 Recovering the beam energy

8.1 Beam energies and beam powers in synchrotrons and linacs

When we talk about ‘energy recovery’, we clearly mean the recovery of energy in a valuable form, preferably as exergy.

There is a substantial difference between synchrotrons and linacs concerning the beam power and beam energy: while a synchrotron is filled with a particle beam just once, which is then often kept for a relatively long period, linacs are constantly fed with a fresh beam which normally has only a single passage through it. In the following, we will illustrate this difference and its impact on the possibility and viability of beam energy recovery based on the examples of the LHC and CLIC.

The beam energy stored in the LHC at nominal parameters (2808 bunches of 1.15×10^{11} protons at 7 TeV) is 362 MJ or 100 kWh (small). This energy is distributed over practically the whole ring or 90 µs. This means that, when the beam is dumped, a 90 µs long pulse with a peak power of 4 TW will impact on the dump once. The recovery of this energy (just once) does not seem worth the effort.

Now consider a CLIC linac as an example: it is designed to operate at a repetition frequency of 50 Hz with pulses of 312 bunches of 3.72×10^{9} electrons, accelerated to 1.5 TeV, resulting in 278 kJ per pulse (more than a factor 1000 below the stored energy in the LHC!). But the repetition every 20 ms leads to an average beam power of 14 MW, which, of course, would be very interesting to recover (if it were not used to collide).

Looking at these beam powers and beam energies it is clear that—contrary to a synchrotron—it looks interesting to recover the (large average) beam power of a linac.

8.2 The principle of beam energy recovery

Looking again at the equivalent circuit in Fig. 10, note that the beam on the right-hand side is modelled as an ideal current source, which, with our choice for the arrow direction, consumes power for acceleration if $\Re\{I_\mathrm{B}\} < 0$. However, the equivalent circuit is equally valid for $\Re\{I_\mathrm{B}\} > 0$, which would describe the case that the beam delivers power rather than consuming it. This can, in fact, be reached simply by placing the bunches in the decelerating rather than the accelerating phase. Fig. 15 illustrates the principle, combining two equal accelerating structures in series, with the second phased such that the particles are decelerated. Neglecting losses, exactly the same RF power would be generated from the beam in the second accelerating structure that is used in the first structure for acceleration. The beam energy, which reaches a maximum after acceleration in the first structure, would be decelerated to exactly the injection energy after passage through the second.

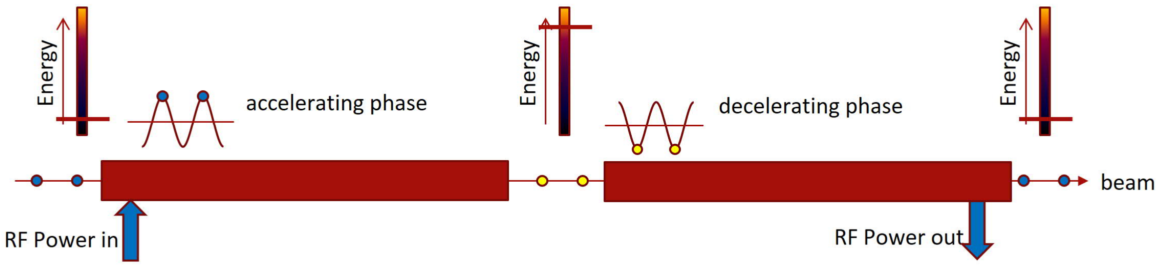


Fig. 15: Two equal accelerating structures with the same bunched beam passing through them. Depending on the phase of the beam relative to the RF in the cavity, the beam will be accelerated or decelerated.

This principle can be extended by adding arcs and thus feeding the same beam through the same accelerating structure again. This is the principle of an energy recovery linac, invented by M. Tigner in 1965 [16] and illustrated in Fig. 16.

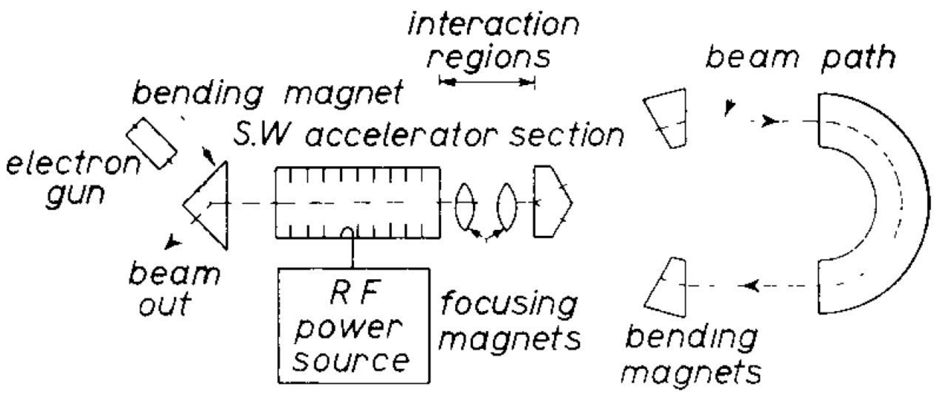


Fig. 16: The illustration in the original paper by Tigner [16], where the spent beam is passing through the same cavity again for deceleration to recover the beam energy (reproduced with permission from the publisher).

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