THE ENERGY EFFICIENCY OF HIGH INTENSITY PROTON DRIVER CONCEPTS*

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Abstract

For MW class proton driver accelerators, the energy efficiency is an important aspect; the talk reviews the efficiency of different accelerator concepts including superconducting and normal conducting linacs, rapid cycling synchrotrons, and cyclotrons. The potential of these concepts for very high beam power is discussed.

INTRODUCTION

High power proton driver accelerators are used to generate secondary particles at high intensities, such as neutrons, muons, pions, kaons or neutrinos. The applications of these facilities have a broad spectrum in the fields of particle physics and condensed matter physics. On the other hand, the production of megawatt-class proton beams implies the consumption of large amounts of electrical energy. New projects and operating facilities must focus on improving the energy efficiency with a higher priority. This is especially true for linear accelerators suggested for Accelerator Driven Subcritical (ADS) Reactors, which may have to deliver >10 MW beams. Existing facilities are typically optimized for lower energy consumption, but are continuously upgraded for the new experiments, which demand higher beam power, and therefore, higher energy consumption. Recently, further energy consumption optimization became one of the important goals of society creating additional requirements for the big facility operations. Funding agencies initiated comparative analysis of electric energy consumption of accelerator research facilities – see, for example, [1,2]. Note that specific acceleration technology and operation mode – pulsed or CW - are determined primarily by the facility purposes, which demand in turn specific properties of the proton beam – energy, timing structure, beam quality. Different accelerator concepts have different energy efficiencies. On the other hand, big accelerator facilities are developed gradually, and some concept decisions are made in different historical situations, which do not allow maximizing the overall facility's power consumption efficiency. In addition, some critical subsystems may be designed under time, budget of environmental or other specific restrictions, which also do not allow optimal energy consumption. However, for a given type and "boundary conditions", efficiency is a crucial factor. Typically, three different accelerator concepts are used recently for the megawatt-scale proton drivers providing GeV-scale beams:

- Cyclotrons;
- Linear accelerators;
- Rapid-cycle synchrotrons (RCS).

The promising concepts, for example, Fixed Field Alternating Gradient accelerators (FFAG) [3] are developing also.

The goal of this paper is to consider the whole power conversion chain for all these types of accelerators from the grid to the beam, delivered to the experiments. In addition, important auxiliary systems of proton drivers are covered, such as vacuum systems, cooling and cryogenic facilities, but not office power consumption. Three operating accelerators for GeV- energy scale, MW beam power scale facilities are considered:

- Cyclotron of the High Intensity Proton Accelerator Facility, PSI [4];
- Superconducting RF (SRF) Pulsed Linac of the Spallation Neutron Source, ORNL [5];
- RCS and Main Ring of the Japan Proton Accelerator Research Complex, J-PARC [6].

The power consumption breakdown will be shown for three facilities, in order to understand the major energy efficiency drivers. It is difficult to introduce a single basic criterion of the efficiency for different types of accelerators based on the experience of existing accelerator facilities considered above. However, it is possible to consider a fraction of grid power converted to beam power, i.e., the ratio of the delivered beam power over the accelerator power consumption, including RF, magnetic system, cooling/cryogenics, but neglecting auxiliary systems and experimental facilities. Note, that if the application and parameters are well-defined – e.g., ADS - the accelerators and facilities should be optimized in a similar way. One may carefully scale the power consumption of considered accelerators to required parameters, estimate resulting efficiency, compare possible types of accelerator and select the most suitable, taking into account, of course, all other criteria.

The paper is based on the result of the Proton Driver Efficiency Workshop [7] organized by EuCARD[2].

GENERAL

The entire power consumption of a proton driver is determined by the beam power, the power necessary for maintaining the accelerating RF field, beam bending and

* Work supported by EuCARD[2] co-funded by European Commission under Capacities 7th Framework Program, Grant Agreement 312453
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focusing, and power necessary for auxiliary systems including cooling and refrigeration. The grid power necessary for RF is determined to a considerable degree by the RF source and HV source efficiency, which is important for all the considered accelerators. The RF power necessary for acceleration contains overhead for control and compensation of loss in the feeding line and the RF cavity. The cavity RF losses are significant for normal-conducting cavities of cyclotrons and for RCS especially where low Q cavities are employed, and negligible for SRF ones. On the other hand, for SRF cavities operating pulsed regime, additional RF power is necessary for the cavity filling; for considerable low beam loading an additional overhead may be necessary for compensation of the cavity detune caused by ponderomotive forces of the electromagnetic field (Lorentz force Detune). In the CW regime of the SRF cavity operation an additional power may be required for mitigation of the cavity detune caused by mechanical vibrations ("microphonics"). Additional power from the grid is necessary for the cavity and RF source cooling and for refrigeration of the SRF cavities. The power necessary for the beam bending and focusing elements is determined by the power dissipated in the magnets and by the power source efficiency, which also require ~~also~~ power from the grid for cooling. The power consumption breakdown for the facilities mentioned above shows the critical elements providing major losses, and thus, gives the clue for efficiency improvement for future projects of MW-scale proton accelerators.

PSI Cyclotron of the High Intensity Proton Accelerator Facility.

The Proton Accelerator Facility of the Paul Scherrer Institute [4] is a high intensity facility which supports a wide spectrum of experimental programs including neutron and muon experiments. The Facility overview is shown in Figure 1. It consists of the ECR proton source, the 870 keV Cockcroft-Walton type pre-accelerator, and a chain of two isochronous sector cyclotrons, the 80-turn, 72 MeV Injector 2 and the 186-turn, 8-Sector Ring Cyclotron, which provides routinely the CW proton beam of up to 1.4 MW at the energy of 0.59 GeV. The beam current is 2.4 mA.

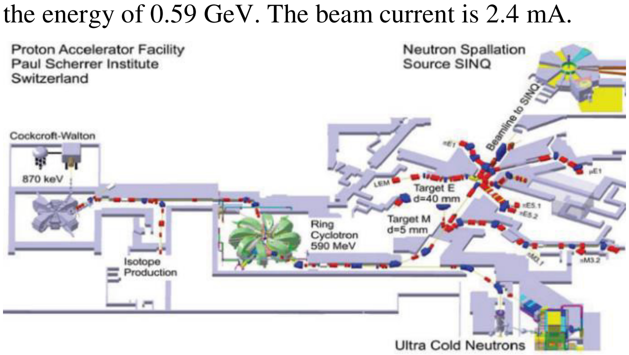

Figure 1: Overview of the PSI high intensity proton accelerator facility.

The Ring Cyclotron is shown in Figure 2. It has four 50.6 MHz copper cavities, see Figure 2. Each cavity has a high quality factor of 48,000, maximal voltage up to 1.2 MV (presently 0.85 MV) and delivers 400 kW of power to the beam. A third harmonic flattop resonator is used to compensate the curvature of the resonator voltage with respect to time.

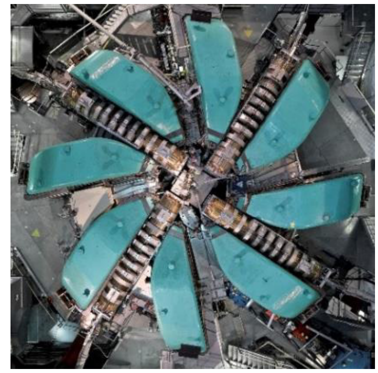

Figure 2: The Ring Cyclotron layout. The eight sector magnets and four RF cavities are shown.

The RF power consumption breakdown is shown in Figure 3 [8].

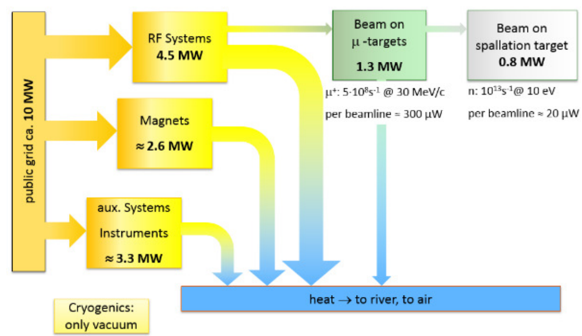

Figure 3: The RF power consumption breakdown the PSI high intensity proton accelerator facility.

The magnet system consumes 2.6 MW, the entire consumption of the RF system is 4.5 MW. The Ohmic losses in the cavies are about 1.2 MW, losses in the RF sources are 1.5 MW, and losses in the rectifier are 400 kW. Cooling circuit efficiency is 94%. Thus, the entire efficiency is 18%. An entire power consumption breakdown excluding the auxiliary systems is shown in the Figure 4.

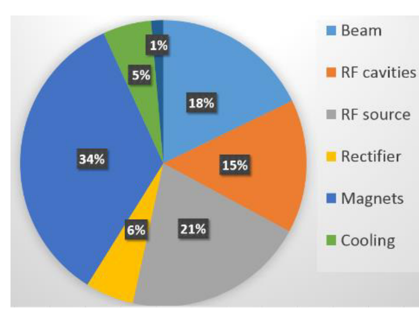

Figure 4: power consumption breakdown excluding the auxiliary systems.

Note that the beam current increase up to 3 mA leads to the beam loading increase and consequently, efficiency increase up to 24%. Further development of the to increase

ISBN 978-3-95450-182-3

the beam energy up to 1 GeV and the beam power up to 10 MW is considered in [9]. A number of concept improvements are suggested and realized, for example, utilization of the superconducting sector magnets. The world's first ring superconducting cyclotron is the 2.6 GeV cyclotron, which provides acceleration of a broad spectrum of ions up to Uranium. It is in operation at RIKEN Nishina Center [10]. Another development of the concept is a strong-focusing cyclotron [11].

Superconducting Pulsed Linac of the Spallation Neutron Source (SNS).

SNS is a pulsed neutron source, driven by a 1.4 MW, 1 GeV SRF proton accelerator. SNS is the leading facility for neutron scattering research, which provides 1.5e14 protons per pulse at the repetition rate of 60 Hz to the target. The macro-pulse duration is 1 msec, in the Accumulation Ring it is compressed to 700 nsec. The average macro-pulse H^- current in the linac is 26 mA. The SNS layout is shown in Figure 5.

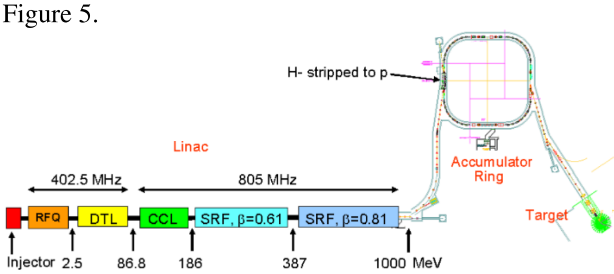

Figure 5: Layout of the SNS accelerator system.

The linac consists of the normal-conducting (NC) part operating at 402.5 MHz (DTL) and 805 MHz (CCL), which accelerates the H^- beam up to 186 MeV, and superconducting (SC) part operating at 805 MHz, which accelerates the H^- beam up to 1000 MeV. The macro-pulse structure is shown in Figure 6. The power losses are determined by the modulator efficiency, RF source efficiency, losses in the copper cavities for NC part, the cooling expenses for NC part and high-power RF system, and refrigeration expenses for the superconducting part.

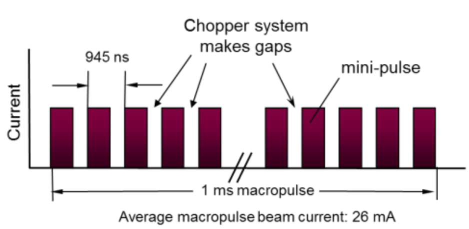

Figure 6: The macro-pulse structure.

In addition, in the pulsed regime the losses are caused by the modulator rise time, the cavity filling time, LLRF/HVCM settling time, control margin, mismatching, etc. – see Figure 7. Cavity filling and discharge require additional power from the cryo-system [12]. The power consumption breakdown is shown in Figure 8. The linac power consumption is 16.3 MW at the beam power of 1.4 MW. Therefore, the linac efficiency is about 9%. However, the linac efficiency is very different between the NC part and the SC part, which is illustrated in Figure 9a for CCL module 4 and in Figure 9b for one of the SRF cavities.

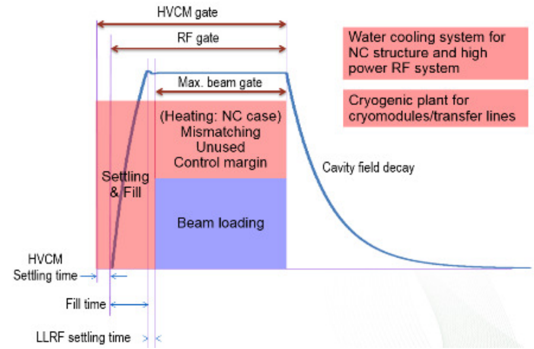

Figure 7: SNS pulse structure.

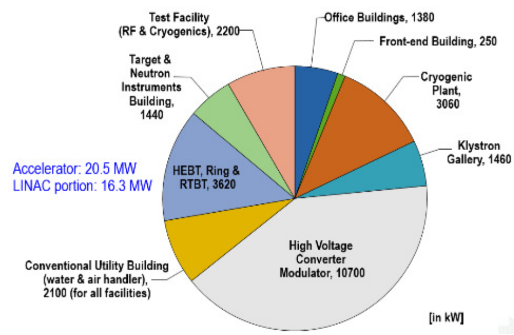

Figure 8: Breakdown of electric power consumption by systems during 1.4 MW operation.

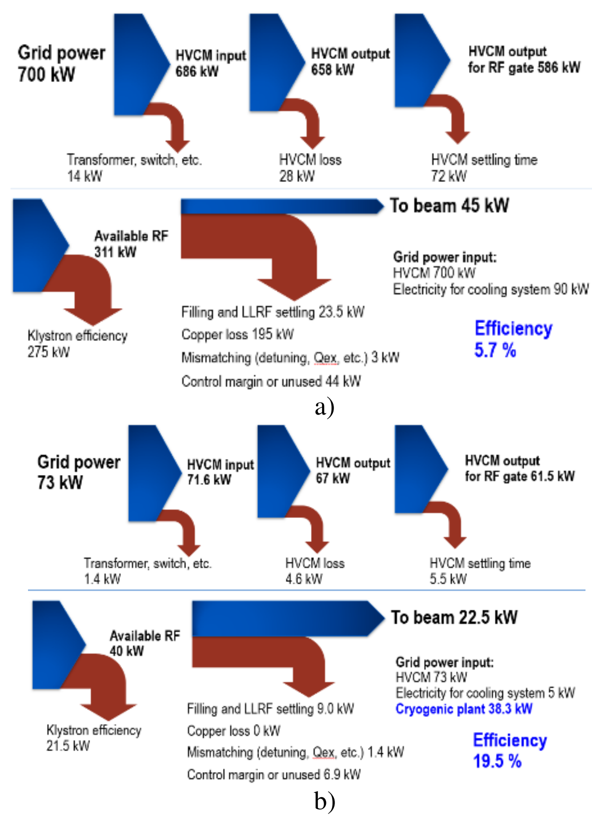

Figure 9: Power flow from grid to beam during 1.4 MW operation: a) CCL module 4, b) one of SRF cavities in the cryomodule 20.

The CCL module 4 consumes 700 kW from the grid providing 45 kW to the beam. The efficiency, therefore, is 5.7%. In contrast, for SC cavities the efficiency is much higher. The SRF cavity shown in Figure 9b consumes 73 kW from the grid providing 22.5 kW to the beam. The total efficiency is 19.5 %. The efficiencies of individual RF cavities during 1.4 MW operation are shown in Figure 10.A superconducting linac is more efficient for a MW class pulsed machine than a normal conducting linac. The SNS linac has room for improvements that are under consideration – especially for less scattering of accelerating gradients via cavity performance improvement since one high voltage convertor modulator feeds ten SRF cavities. It is also estimated that overall efficiency of the SNS SCL will be improved from 13% to 21% after an upgrade of the linac for the Proton Power Upgrade project, which results from higher beam loading and better utilization of the exiting cryogenic plant.

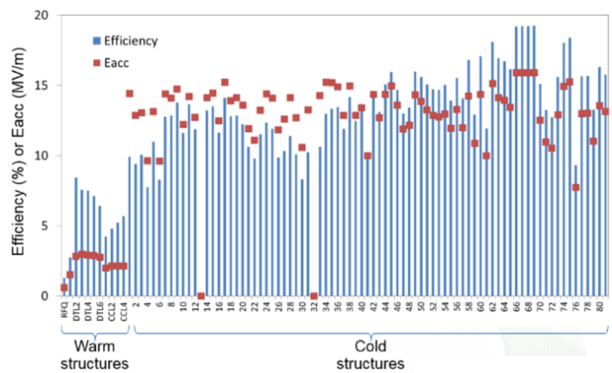

Figure 10: Efficiency of individual RF structures.

Japan Proton Accelerator Research Complex (J-PARC)

The J-PARC accelerator facility is a unique complex providing the pulsed proton beam for neutrino experiments as well as for a wide range of other applications, see Figure 11. The J-PARC facility contains a 400 MeV room temperature linear accelerator, and two synchrotron rings, a 3 GeV Rapid Cycle Synchrotron (RCS) and a Main Ring Synchrotron (MR) [13]

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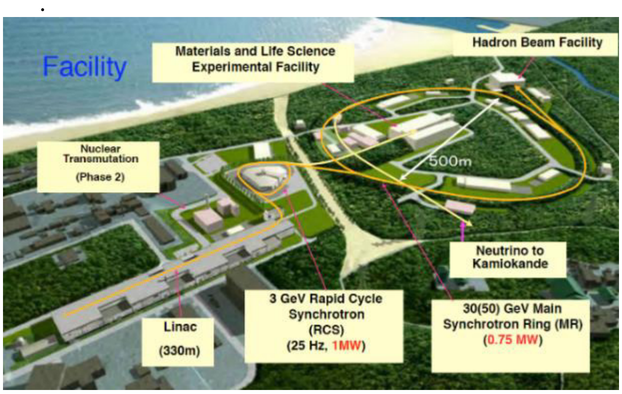

Figure 11: Japan Proton Accelerator Research Complex.

The Linac has many accelerating structures to accelerate a high intense H^- (negative hydrogen) effectively up to 400MeV of proton energy. The Linac consists of 20 accelerating cavity modules (RFQ, 3 DTLs and 16 SDTLs) in the low-beta linac section and 21 ACS cavity modules and 2 sets of the buncher and de-buncher in the high-beta linac section. RF sources use the 324-MHz klystrons for the low-beta section and the 972-MHz klystrons for the high-beta section. The linac has the following parameters:

- Accelerated particles: H^- (negative hydrogen)
- Energy: 400 M eV, SDTLs and ACS
- Peak current: 40 mA ~ 50 mA (for 1MW at 3GeV)
- Repetition: 25 Hz (additional 25 Hz for the future ADS application)
- Pulse width: 0.5 ms (beam pulse), 0.65 ms (for RF pulse)

The 3 GeV Rapid cycling synchrotron (RCS) is designed to accelerate a proton beam from the energy of 400MeV to 3GeV with a 25Hz repetition rate. The main magnets are excited with a DC-biased sinusoidal current waveform using a resonant circuit. The magnetic alloy loaded cavities were developed and adopted to achieve the high accelerating field gradient. The accelerating frequency changes from 1.23 MHz to 1.67 MHz with h=2 rf harmonics. The Q-value of the RCS cavity is selected 2, so that the RF cavity impedance covers both the accelerating and second-harmonic frequency ranges. Twelve RF systems are used for acceleration and bunch shape manipulation. RF sources at the final stage use two 600kW tetrodes operated in a push-pull. The 3 GeV Rapid Cycling Synchrotron (RCS) has the following parameters:

- Circumference 348.3 m
- Injection energy 400 MeV
- Extraction energy 3 GeV
- Repetition rate 25 Hz
- Output beam power 1 MW
- Harmonic number 2
- Accelerating peak voltage 420 kV

The main synchrotron accelerates the 3GeV proton of the RCS up to 30 GeV. The frequency changes only 3% from 1.67 MHz to 1.72 MHz with h=9 RF harmonics. Seven cavities for acceleration and two cavities for bunch manipulation are provided separately. RF sources use two tetrodes as well as the RCS RF source. Main Ring synchrotron parameters are shown below (a number in brackets shows an original design value):

- Circumference 1567.5 m
- Injection energy 3 GeV
- Extraction energy 30 [50] GeV
- Repetition rate 1/2.48s [1/3.64s]
- Output beam power 0.75 MW
- Harmonic number 9
- Accelerating peak voltage 280 kV

The synchrotrons have the following features:

- Transition free lattice: the missing bend structure
- RCS: high transition gamma
- MR: imaginary transition gamma
- Magnetic alloy loaded cavity:
- High field gradient > 20kV/m
- Multi-harmonic_feed-forward_beam-loading compensation

ISBN 978-3-95450-182-3

- MR: Slow and fast extractions for nuclear and particle physics experiments

The J-PARC operation cycle is 2.48 seconds or 5.52 seconds, which depends on the extraction mode. During the fast extraction mode of 2.48s cycle, the Linac/RCS generates 62 pulses of proton beam. Four pulses are ejected into the MR and another 58 pulses are delivered to the MLF facility. The power consumption breakdown is shown in Figure 12 when ~500kW beam delivery to the MLF and NU facilities. The Linac consumes 8.6 MW in total. The electrical demand of the Linac is almost constant. In the RCS, the Magnet system and RF system consume 9.6 MW and 7 MW, respectively. The consumption at the RF systems changes by an intensity of proton beam and the operation mode. The overall power consumption of the 3 GeV part (Linac and RCS) is 32.6 MW and the efficiency is about 3%. The RCS is favourable to provide a high power pulsed proton beam having the energy of exceeding GeV, though the overall efficiency is several % at most. Increasing a repetition rate of an accelerator is the way to effectively develop beam power, like the J-PARC MR approach to the beam power upgrade. To realize 0.75 kW output beam power with a proton beam energy of 30 GeV lower than the design value, the cycle of the MR aims to make short to 1.3 seconds or less. A number of improvements are in process of implementation [14]:

- New power supplies with capacitive energy storage for the main magnets are under development. The power variation at the electrical system keeps its present value even after the upgrade.

- High gradient RF cavities loaded with high performance magnetic alloy (FT-3L) cores started to be installed. The total loss with these cavities is half of that with existing cavities.

Replacement of all MR cavities was completed in the summer of 2016. Nine cavities are operated with 4-GAP configuration. The MR magnets and RF systems consume 10.3MW and 5.6 MW, respectively, when a 460kW proton beam is delivered to the neutrino facility. And, total power consumption is 21 MW in the MR (see Figure 12).

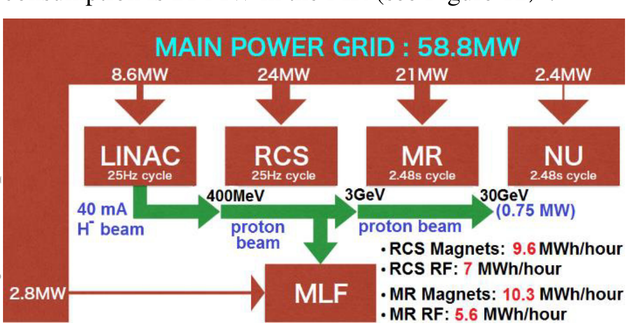

Figure 12: The RF power consumption breakdown for the J-PARC facility.

SUMMARY

A number of MW class proton driver accelerators are in operation today. The used concepts are cyclotron, SRF linac, and rapid cycling synchrotron. Because it is challenging to introduce a single basic criterion of the efficiency for different types of accelerators considered above, we consider the fraction of grid power converted to beam power, over the accelerator power consumption, including only RF, magnetic system and cooling/cryogenics. The results are presented in Table 1. Note that all the considered accelerators have a lot of room for the power consumption improvements, see above. Energy efficient technologies are developed in the fields of superconducting technology including High Temperature Superconductors, SRF and Room-Temperature cavities with low losses and low RF power overhead, including high Q_0 and resonance control for SRF. The use of permanent magnets for beam transport systems would save power. Cycling accelerator components need efficient and reliable energy storage systems, for example capacitive energy storage for cycling synchrotron magnets. New or alternative ideas and approaches should be developed for both new and explored basic accelerator parameters. Prominent examples are the studies on fixed-field alternating gradient (FFAG) accelerators. Radio frequency sources are an important part affecting efficiency for all the considered accelerator concepts. Promising technologies include magnetrons, phase modulation, high-efficiency klystrons [15].

Table 1: The Energy Efficiency

	PSI cyclotron	**SNS linac**	**J-PARC linac and RCS**
Beam energy	0.59 GeV	1 GeV	3 GeV
Beam Power	1.4 MW	1.4 MW	1 MW
Power consumption	4.5 (RF) in total 10 MW	16.3 MW	32.6 MW
Fraction of grid power converted to beam power	~18-19%	~9%	~3%

REFERENCES

[1] J. Stadlmann, *et al.*, “Analysis of electric energy consumption of accelerator research facilities,”*IPAC’16*, Busan, Korea, May 2016, WEPMR043, pp. 2370-2372.
[2] Ph. Lebrun, “Why are particle accelerators so inefficient?” *The EuCARD² Workshop on Compact and Low-Consumption Magnet Design for Future Linear and Circular Colliders.* CERN, Oct. 2014.
[3] S. Machida, *et al.*, “Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA,” *Nature Physics*, v. **8,** March 2012, pp. 243-257.
[4] J. Grillenberger, *et al.*, “Status and further development of the PSI high intensity proton facility,” *Cyclotrons’2013,* Vancouver, Canada, Sept 2013, MOPPT004, pp. 37-39
[5] S-H. Kim, *et al*, “Overview of ten-year operation of the superconducting linear accelerator at the Spallation Neutron Source,” NIM, A 852 (2017), pp. 20-32.
[6] M. Yoshii, *et al.*, “Present status of J-PARC ring RF system,” *PAC’05,* Knoxville, Tennessee, May 2005, pp. 475-477.
[7] Ch. Densham, *et al.*,“The Energy Efficiency of Proton Driver Accelerators, Summary.” *The EuCARD² Proton Driver Efficiency Workshop,* PSI, Zurich, Feb 29-March 2, 2016.
[8] J. Grillenberger, “Cyclotrons,” *ibid.*

[9] Th. Stammbach *et al*., “The feasibility of high power cyclotron,” NIM, B 113 (1996), pp. 1-7.
[10] K. Yamada, *et al*., “Status of the superconducting ring cyclotron at RIKEN RI beam factory,” *EPAC'08*, Genoa, Italy, 2008, THPP069, pp.3518-3520.
[11] N.J. Pogue, et al., “Strong focusing cyclotron and it's applications,” IEEE Trans. On Applied Superconductivity, vol. 25, No. 3 June 2015, Art. ID 0600104.
[12] S-H. Kim, “Pulsed Proton Linac,” *The EuCARD^2 Proton Driver Efficiency Workshop,* PSI, Zurich, Feb 29-March 2, 2016.
[13] M. Yoshii, “Japan Proton Accelerator Research Complex,” *ibid.*
[14] Y. Morita, “MR upgrade and power management,” *ibid*.
[15] F. Gerigk, “Summary: RF systems,”, *ibid.*

ISBN 978-3-95450-182-3