ENERGY EFFICIENCY AND SAVING POTENTIAL ANALYSIS OF THE HIGH INTENSITY PROTON ACCELERATOR HIPA AT PSI*

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Abstract

High power proton machines consume a large amount of energy. Thus, the energy efficiency of grid to beam power conversion is particularly important for the overall power consumption of such facilities [1]. In this study, we analyse the energy efficiency of PSI's cyclotron-based HIPA facility, which presently delivers a maximum of 1.4 MW beam power. The total power consumption of the entire facility is 12.5 MW at 2.2 mA beam current (1.3 MW). Main power consumers are: RF systems, electromagnets, water cooling and auxiliary systems including infrastructure, each consuming 5.3 MW, 3.6 MW, 1.65 MW and 1.95 MW, respectively. HIPA's grid to beam efficiency is 18.3% when considering only those parts of any subsystems (RF components, magnets, cooling, and auxiliary systems), which are minimally required to produce a full 1.3 MW beam. The dependency of individual subsystems on beam power was also studied. These findings serve as a basis for further optimizations of the HIPA facility and give a reference of the efficiency estimate for the cyclotron-based high power machines.

INTRODUCTION

The HIPA cyclotron-based facility commissioned in 1974 is a high intensity accelerator that presently produces a 1.3 MW proton beam. The two isochronous separated sector cyclotrons Injector-2 and Ring form the facility's core (Fig. 1). The 2.2 mA beam is extracted from Injector-2 at 72 MeV, and then accelerated to the final kinetic energy of 590 MeV in the Ring. After extracting from the Ring Cyclotron the proton beam is guided to experimental areas and production targets for secondary particle generation (pions, muons and neutrons) [2]. The facility's consumption was previously estimated to be roughly 10 MW. It was long desired to verify this estimate by measurements and system-wide power analysis.
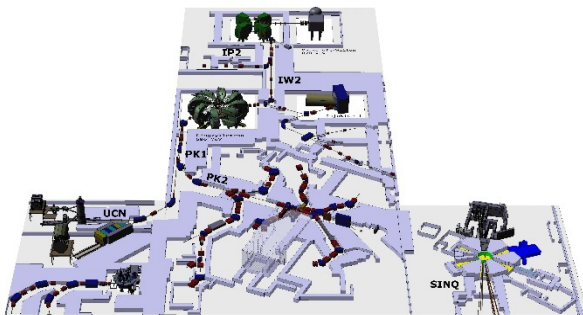

Figure 1: Schematic view of the HIPA facility.

The EnEfficient network of the EuCARD-2 integrated activity project focuses on the energy and cost efficient utilization of accelerator facilities. Following these principles, the present study extensively analyses the power consumption of high intensity accelerator facilities on the example of HIPA at PSI. Knowing exactly where and how electricity is consumed is the very first step in the optimisation cycle of a facility.

DISTRIBUTION OF POWER

Figure 2 reveals the power consumption of every subsystem as well as the total 12.5 MW power consumption of the facility. At a full load HIPA accounts for more than the half of PSI's ca. 20 MW of total power consumption. It shall be emphasised that reaching the consumption of 12.5 MW requires all experimental areas (IP2, UCN, SINQ, and all secondary beamline experiments) to run concurrently.
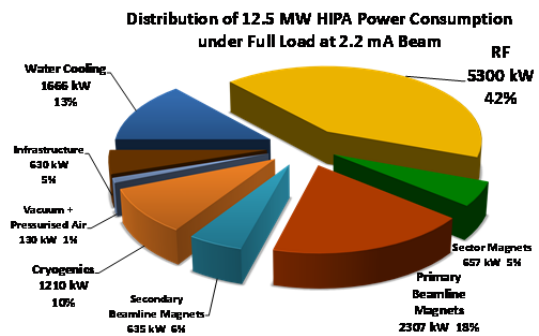

Figure 2: Distribution of 12.5 MW HIPA power consumption under full load at 2.2 mA beam current.

POWER CONSUMPTION OF SUB-SYSTEMS

Efficiency of the RF System

The Injector-2 and the Ring cyclotron each have their own amplifier chains for every cavity and resonator. During the analysis process power consumption was studied on the example of the Ring machine. RF is the single largest power consumer with 42% of all HIPA power. Each of the four accelerating cavities of the Ring machine has a chain of four tetrode tube amplifiers. The first step in the energy flow is AC-DC rectification, with an efficiency of about 90%. Then DC voltage is fed to the amplifier chain, where RF power is produced. The combination of all amplifications stages has an efficiency of roughly 60%. The Ring cyclotron's RF system power consumption (and hence the forward RF power) are linear functions of the beam current in the operating region up to 2.4 mA. At 0 mA beam the system still has a minimal

consumption of approx. 2.2 MW from the grid. This 'base load' is required for running the system at its operational point and to keep it ready for producing RF power. The grid to RF efficiency stays approximately 55% in this region of operation.

Magnet Power Consumption

The total 2.3 MW consumption of the beam lines was measured using a dedicated program SLEEP (Table 1). The in-house developed energy saving SLEEP program was also designed to monitor the power consumption of beam lines in real time and to put beam lines into standby during outages with no beam longer than 30 minutes.

Table 1: Power Consumption of Beam Line Magnets

Magnets	Power (kW)
Magnets outside SLEEP	217
Cyclotron sector magnets	657
Secondary beam lines	635
IW2 beam line	358
IP2 beam line	59
P-channel	746
SINQ beam line	565
UCN beam line	125

The SLEEP program was commissioned in April 2016 and successfully ran over the year. The saving potential of primary beam line magnets was forecasted to be 980 MWh/annum. The SLEEP program has saved 1171 MWh in 2016. Taking inefficiency of power supplies into account as factor 1.1 (90% efficiency) the saving in 2016 on the primary beam line magnets was 1288 MWh.

For the next operational year the SLEEP program has been upgraded with an RF module. It notifies operators that cavities and resonators can be put to a power saving mode. It shall assist operators to make another 370 MWh of additional documented savings.

Water Cooling Circuits

A considerable power consumer is the water cooling at an average electrical power of approx. 1.67 MW, which is roughly 11-14% of its cooling capacity. There are 3 different cooling methods used: water cooling from the river Aare, ground water cooling and forced air cooling. Most of HIPA is cooled with water from the Aare through heat exchangers. The cooling system has 3 levels of cooling circuits. The primary open loop cooling circuit circulates river water, whereas secondary and tertiary circuits are closed loop and are exposed to radiation.

Primary ground water, river water and forced air cooling circuits (Fig. 3) only consume a total of 18% (300 kW). Secondary and tertiary circuits require the remaining 1.4 MW (82%).

The power required for cooling showed very light dependency on the produced beam power: only a 5% increase in power between a 1.2 and a 2.2 mA beam. This

can be justified by the large fixed load in the form of magnets.

The primary cooling circuit is highly dependent on inlet and outlet river water temperature, which varies notably with seasons 4+°C in winter 25+°C in summer. This translates to an up to 50% fluctuation in primary pump electrical power.
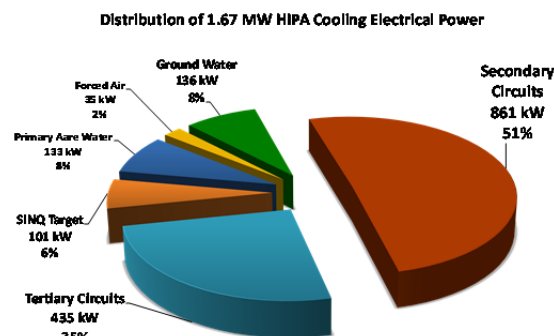

Figure 3: Distribution of cooling electrical power.

The total power consumption of water cooling could be reduced by approx. 20% if pumps were upgraded to Variable Frequency Drive (VFD) equivalents. The estimated saving potential is 1.7 GWh. Note this is a rough estimation; to find the precise saving potential, it is advised to separately study the optimisation of the cooling system.

Consumption of Auxiliary Systems

Auxiliary systems include vacuum and pressurised air (130 kW), infrastructure (630 kW; ventilation, lighting, air conditioning, etc.) and cryogenic cooling.

The three cryogenic systems (1.21 MW) of HIPA are required for the cold moderators of both neutron sources, for a superconducting muon channel and for several experiment stations. Two out of the three Helium compressors will be upgraded to screw compressors technology in 2018 and hence their electrical power consumption is expected to reduce by from 780 kW to 624 kW (20%), resulting in a saving of 900 MWh per annum.

Saving Potential

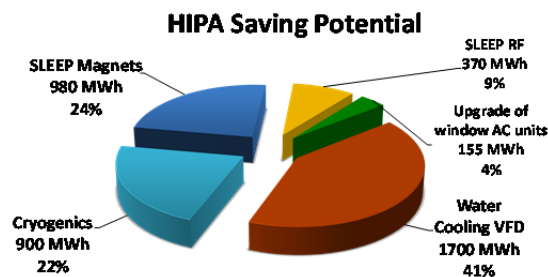The areas and amounts of saving potential were identified as shown in Fig. 4.

Figure 4: Distribution of 4 GWh HIPA's saving potential.

EFFICIENCY OF MINIMUM FULL BEAM

To evaluate the performance of a facility, it is oftentimes a good practice to look at its grid to beam conver-

sion efficiency. The grid to beam efficiency can be defined as a ratio of total power to the useful (beam) power:

$$\eta_{acc} = \frac{P_{useful}}{P_{total}} \qquad (1)$$

Under full-load conditions the grid to beam efficiency of the entire facility is $\eta = \frac{1.3}{12.5} * 100 = 10.4\%$. Although this is a good evaluation of the facility, it does not reflect the performance of the accelerator accurately. The branch-like beam line structure and the large number of experiment sites pose a considerably varying load on top of the accelerator power. In order to assess the accelerator's efficiency, the consumption of a minimum full beam has to be determined. A minimum full beam setup only includes those consumers, which are required to produce a 2.2 mA beam extracted from the Ring cyclotron.

Accelerator related consumers, including all RF components, the Cockcroft-Walton accelerator, Injector-2, the Ring cyclotron and the beam lines between the cyclotrons are shown in Fig. 5. The necessary cooling circuits need 379 kW of power. As far as infrastructure is concerned, ventilation and lighting are taken into account as the most significant consumers in terms of infrastructure.
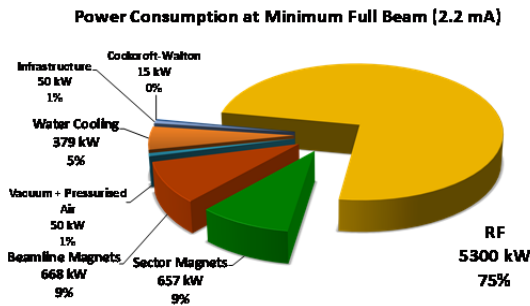

Figure 5: Power consumption at minimum full beam.

Hence, the minimum power consumption for a full beam is 7.12 MW. This in turn yields a grid to beam efficiency of $\eta = \frac{1.3}{7.12} * 100 = 18.3 \%$. The 7.12 MW requirements and the 18.3% efficiency can be used as the most accurate measurement on HIPA's performance so far.

EFFICIENCY AND BEAM POWER

The grid to beam efficiency η_{acc} can be further expressed via RF efficiency and dissipated power as:

$$\eta_{acc} = \frac{P_{useful}}{P_{total}} = \frac{P_{beam}}{P_{loss} + P_{beam}/\eta_{RF} + P_{aux}} \qquad (2)$$

where η_{RF} is the overall efficiency of the amplifier chain and P_{loss} are the ohmic wall losses in the cavities P_{aux} represents the base load required for magnets, vacuum, and conventional systems etc. The beam power P_{beam} scales with the maximum extracted beam current I_{max} and the kinetic energy E_{kin} of the particles q:

$$P_{beam} = \frac{I_{max} \cdot E_{kin}}{q} \qquad (3)$$

The wall losses are proportional to the square of the peak voltage U_{acc} of the cavities, where R is the impedance given by the cavities' geometry and material parameters:

$$P_{loss} = \frac{|U_{acc}|^2}{2\,R} \qquad (4)$$

According to the empirical law of Joho [3] the maximum beam current that can be extracted from the cyclotron scales with the acceleration voltage to the cube:

$$U_{acc} = \frac{E_{kin}}{q} \cdot \sqrt[3]{I_{max}/c} \qquad (5)$$

Substituting (5) into (4); and then (4) and (3) into (2) yields:

$$\eta_{acc} = \frac{I_{max} \cdot E_{kin}/q}{\frac{(I/c)^{\frac{2}{3}} \cdot E_{kin}^2}{2 \cdot R \cdot q^2} + \frac{I \cdot E_{kin}}{q \cdot \eta_{RF}} + P_{aux}} \qquad (6)$$

The relationship between the beam current and accelerator efficiency (Fig. 6) reveals that the efficiency could be further improved, however a limit is posed by the fact that ohmic wall losses scale with the square of the accelerating voltage, whereas the maximum current scales with the cube of the accelerating voltage [3]. At the present operation point HIPA's accelerator efficiency is 18.3%. A 3.0 mA beam will theoretically be feasible after the upgrades of Injector-2, the Ring cyclotron's flattop cavity, SINQ, and beam dump.
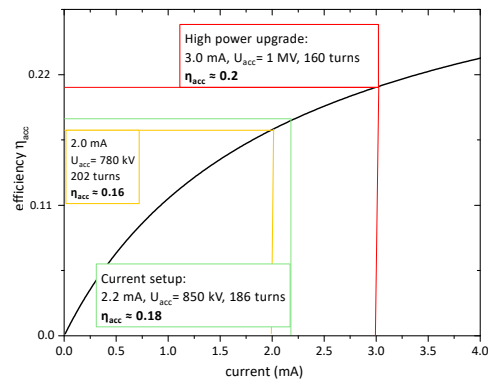

Figure 6: Accelerator efficiency vs. beam current [4].

CONCLUSION

The energy consumption of the HIPA facility was analysed. By evaluating each sub-consumer of the HIPA facility (RF, electromagnets, water cooling and auxiliary) and by summing up their power consumption, the 12.5 MW full-load power and the saving potential of the facility was identified. The power consumption of a minimum full beam setup was also found to be 7.12 MW and hence the 18.3% accelerator efficiency was calculated.

REFERENCES

[1] M. Seidel, R. Gehring, E. Jensen, T.I. Parker, P.J. Spiller, and J. Stadlmann, "Improving the energy efficiency of accelerator facilities", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, paper WEXC3, pp. 2428-2433.

[2] M. Seidel *et al.*, "Production of a 1.3 MW proton beam at PSI", in *Proc. 1st Int. Particle Accelerator Conf. (IPAC'10)*, Kyoto, Japan, May 2010, paper TUYRA03, pp. 1309-1313.

[3] W. Joho, *Proceedings of the 9th International Conference on Cyclotrons and their Applications*, Caen, France, 1981, pp. 337-347.

[4] J. Grillenberger and M. Seidel, "Energy Efficiency of Cyclotrons", presented at the 21st Int. Conf. on Cyclotrons and their Applications, (Cyclotrons'16), Zürich, Aug. 2016, paper THA01, unpublished.