Energy Efficiency of High Power Accelerators for ADS Applications

M. Haj Tahar, F. Méot, S. Peggs , BNL, Upton, Long Island, New York, USA

Abstract

One important issue identified by the 2014 comprehensive nuclear fuel cycle Evaluation & Screening report [1] that was chartered by the US Department of Energy was the impact of the electricity required to operate the accelerator on the overall efficiency of an Accelerator Driven System (ADS).The objective of this paper is to contribute some understanding regarding that issue. Then, by looking at several options of existing and projected accelerator technologies for ADS, we evaluate the impact of the technology choice on the efficiency of a conventional ADS facility, in view of investigating the limitations and where there is room for improvement.

INTRODUCTION

Efficiency is an essential criterion for modern economic decision-making. Very often, though, incomplete accounting of efficiency occurs by externalizing costs. For instance, in nuclear energy, the costs of the nuclear waste disposal are externalized by passing them to the environment or to future generations. Externalizing the costs, generally considered a major market failure, can prove a very efficient way for the producer/seller to increase his profit and to result in prices that can satisfy the consumer. In this paper we address the question of energy efficiency of an advanced nuclear power plant that combines a particle accelerator with a nuclear reactor (ADS) in order to improve the fuel utilization and thus reduce the quantities of nuclear waste. A key question to answer is: How does the energy efficiency change in comparison with a conventional nuclear power plant where the problem of nuclear waste is not dealt with?

EFFICIENCY REQUIREMENTS FOR ADS

We first evaluate the overall efficiency of an ADS-Reactor facility by adding the cost of the accelerator beam. In [2], it is shown that the thermal power of the core of an ADS is given by:

$$P_{th,c}(MW) = E_f(MeV)I(A)\frac{N_0}{\nu}k_1S + P_{dh} \tag{1}$$

where

$$S = 1 + k_2 + k_2k_3 + k_2k_3k_4 + ... + k_2k_3...k_p + ... \tag{2}$$

k_i is the multiplication factor of the generation i, E_f the fission energy (≈ 0.208 GeV), E_p the proton energy, I the beam current, N_0 the number of primary neutrons injected in the core per proton, ν the number of neutrons released per fission ($\nu \sim 2.5$) and P_{dh} is the power of the decay heat (mostly due to the short-lived fission products). For simplicity, we will assume here that $P_{dh} \sim 0$, although this can represent up to 6% of the reactor power immediately after shut-down. It follows that:

$$\frac{P_{acc,grid}}{P_{th,c}} = \frac{E_p}{E_f}\frac{\nu}{N_0}\frac{1}{k_1S}\frac{1}{\eta_{acc}} \tag{3}$$

where η_{acc} is the wall-plug efficiency of the accelerator. Next, we compute the corrected thermal efficiency of an ADS [3]: this is essentially the net useful power output (a fraction of the electrical power is fed back to power the accelerator) divided by the total thermal power input:

$$\begin{aligned}\eta_{th} &= \frac{P_{el,c} - P_{acc,grid}}{P_{th,c}} \\ &= \eta_{th0} - \frac{E_p}{E_f}\frac{\nu}{N_0}\frac{1}{k_1S}\frac{1}{\eta_{acc}} \\ &= \eta_{th0} - A\frac{1}{k_1S}\frac{1}{\eta_{acc}}\end{aligned} \tag{4}$$

where η_{th0} is the uncorrected thermal efficiency of the installation.
For a 1 GeV proton beam impinging on a lead target, this yields $N_0 \approx 20$ so that $A \approx 0.6$.

The first spallation neutrons are the source of all forthcoming neutrons. Therefore, tailoring their spectrum in order to increase their importance *vis-à-vis* the fission process is important. If well mastered, this is very useful as will be discussed later on in this paper.
First, we assume that $k_i = k_{eff}$ for all i. Then, Eq. (4) becomes:

$$\eta_{th} = \eta_{th0} - A\frac{1-k_{eff}}{k_{eff}}\frac{1}{\eta_{acc}} \tag{5}$$

where k_{eff} is the effective multiplication factor. In most ADS proposals k_{eff} is chosen in the range [0.95:0.98] and has to accommodate for any possible accident, i.e for any possible positive reactivity insertion during the operation of the reactor, including the fuel loading stage. Figure 1 below shows a contour plot of the corrected thermal efficiency of an ADS system assuming an uncorrected reactor efficiency, $\eta_{th0} \approx 40\%$, consistent with a fast reactor concept. When k_{eff} is close to 1, the impact of η_{acc} is negligible: the reactor is very near the critical state, and the power drained by the accelerator to sustain the core thermal power is negligible. The same result is shown in Fig. 2.

Comments:

1) To obtain the system's average efficiency, one normally averages the output over a period of time and divide it by the average input over the same period of time. However,

ISBN 978-3-95450-147-2

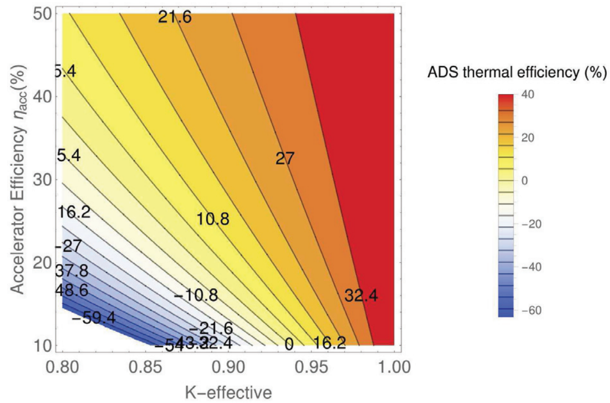

Figure 1: Corrected ADS thermal efficiency as a function of the effective multiplication factor and the accelerator efficiency.

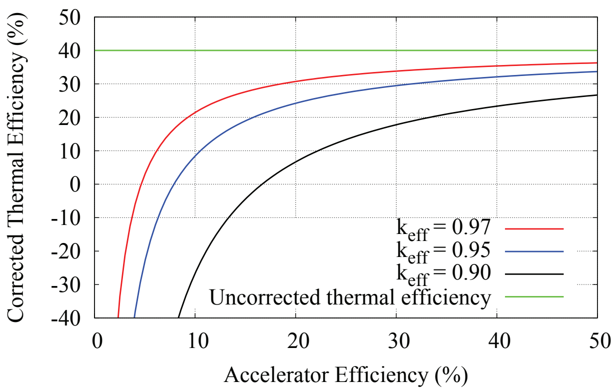

Figure 2: Corrected ADS thermal efficiency as a function of the accelerator efficiency η_{acc} for various values of the effective multiplication factor k_{eff}.

this is not entirely true for a complex system such as ADS, especially when system failure occurs. Beam trips longer than few seconds induce a reactor shut-down which requires several hours to restart the reactor during which the facility is still running in the background.

2) Reliability conflicts with efficiency: for instance, ADS reliability improves through redundancy. The main challenge is to improve the integrated efficiency over a long period of time with a fault-tolerant design.

3) The previous calculation assumes that $k_i = k_{eff}$ for all i. In reality, given that the spallation neutron spectrum is decoupled from the fission neutron spectrum, different neutron generations have different multiplication factors. The history of the spallation neutrons in the core is the most important parameter for an ADS, because these are the source of all forthcoming neutrons. This can be turned into advantage provided one can tailor their spectrum. For instance, suppose that $k_i = k_{eff}$ for all $i > 1$. Then, from Eq. (4),

$$\eta_{th} = \eta_{th0} - A\frac{1-k_{eff}}{k_1\eta_{acc}} \tag{6}$$

Figure 3 illustrates the impact of the first neutron generation on the overall efficiency of an ADS. It can be easily seen that k_1 plays the same role as η_{acc}. In other words, improving the importance of the first generation neutrons (by optimizing the design of the target) has the same energy efficiency impact as improving the wall-plug efficiency of the accelerator.

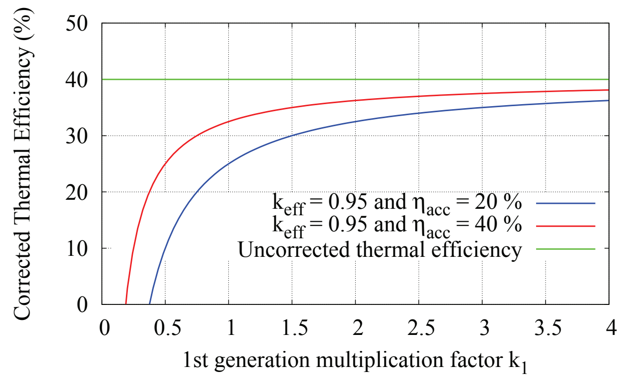

Figure 3: Corrected ADS thermal efficiency as a function of the 1st generation multiplication factor k_1 for various values of η_{acc}.

ACCELERATOR EFFICIENCY

It is important to identify the different steps of the energy transformation from input to output. One can identify three main transformations:

1. AC current is the most efficient way to deliver the electrical power. However, most of the electronic devices require DC power to function. Thus the 1st transformation requires an AC to DC converter. We refer to the conversion efficiency as η_{DC}. This is typically in the range $80-90\%$. For PSI and SNS, $\eta_{DC} = 90\%$.

2. DC to RF power conversion. This transformation takes place in a RF amplification system such as triodes, RF tubes or klystrons. The most commonly used for linacs are klystrons for frequencies above about 300 MHz [4]. We refer to the conversion efficiency as η_{RF}. Klystrons typically achieve 40% for pulsed operation and almost 60% for CW operation, suitable for ADS. Only a few high power klystrons offer $65\%+$ efficiency.
For the PSI main ring cyclotron, $\eta_{RF} \approx 64\%$ while for the SNS superconducting linac, $\eta_{RF} \approx 30\%$. At this stage, one could also include the magnet power conversion efficiency. However, it is best to leave this for later.

3. RF power to beam power. We refer to its efficiency as η_{beam}. In a superconducting cavity, nearly all of the RF power goes to the beam. A parameter that measures the effectiveness per unit power loss for delivering energy to the particle is the shunt impedance, $Z = V_0^2/P$, where V_0 is the peak RF voltage in the gap and P is the average RF power loss, so that $\eta_{beam} \propto Z$. Superconducting technology is more

ISBN 978-3-95450-147-2

suitable for a high intensity accelerator. However, the situation is non-trivial in the presence of beam loading. For a superconducting cavity, the efficiency of the cryogenic system needs to be included as well.

In conclusion, the wall-plug efficiency of an accelerator is given by:

$$\eta_{acc} = \eta_{DC}\eta_{RF}\eta_{beam}\eta_{other} \tag{7}$$

where η_{other} is the additional contribution of the other sources of power consumption aside from the RF cavities, and is defined by:

$$\eta_{other} = \frac{AC}{AC + magnet + cryo + ...} \tag{8}$$

For instance, an additional source of power consumption for the PSI cyclotron comes from the magnets, while for the SNS superconducting linac, the cryogenic system lowers the overall efficiency of the linac. Table 1 below shows the current data for PSI and SNS which are the world leading accelerators in terms of average beam power produced. These data are not intended to make any comparison between the different technologies, but solely used here to identify the major sources of power losses that can be further reduced.

	PSI-HIPA	SNS	
		SC Linac	NC Linac
$\eta_{DC}(\%)$	90	90	90
$\eta_{RF}(\%)$	64	30	41
$\eta_{beam}(\%)$	55	87	17
$\eta_{pulsed}(\%)$	100	70	80
$\eta_{other}(\%)$	79.3	62.5	100
$\eta_{acc}(\%)$	19.4	6.8	

Table 1: Table of efficiencies for the PSI's high intensity proton cyclotron ($P_{beam} \approx 1.3MW$) [5] and for the SNS linac ($P_{beam} \approx 1MW$) [6], as of 2010. The two transformations where there is room for improvement are the DC to RF power and the RF to beam power transformations.

PROJECTED ACCELERATOR EFFICIENCY FOR ADS

For high intensity accelerators, most of the power is used for the high frequency RF cavities ($\eta_{other} \approx 100\%$). Therefore, the overall accelerator efficiency increases with the increasing beam current.

Based on the SNS numbers, one can estimate that for a CW linac with superconducting RF, an achievable efficiency in the MW range would be:

$$\begin{aligned} \eta_{acc} &= \eta_{DC}\eta_{RF}\eta_{beam}\eta_{other} \\ &\approx 0.9 * 0.6 * 0.87 * 0.62 \approx 29\% \end{aligned} \tag{9}$$

where the klystrons conversion efficiency assumed for CW beam is $\eta_{RF} = 60\%$. This is only an estimate and more detailed information about the state of the art of the klystron technology can be found in [7]. The two key transformations where there is room for improvement are the DC to RF power transformation, and the RF to beam power conversion.

For the PSI high power accelerator, an empirical law which relates the grid power to the beam power is given by [8]:

$$P_{grid}(MW) \approx 8MW + 0.81MW I(mA) \tag{10}$$

This yields the projected accelerator efficiency for PSI-HIPA at 5 mA, suitable for ADS: $\eta_{acc} \approx 24.5\%$.

Based on the current state of the art, the accelerator efficiency for high power machines lies in the range $20\% - 30\%$. This implies that the corrected thermal efficiency of an ADS would lie in the range $24\% - 29\%$, representing $25\% - 40\%$ downgrade of the uncorrected thermal efficiency of the power plant. For this particular reason, an ADS facility aiming at producing energy cannot compete with a conventional nuclear power plant unless its efficiency is optimized.

CONCLUSION

An energy efficiency as high as $\eta_{acc} \approx 50\%$ is possible. However, this goal should be considered in the preliminary design phase of the accelerator. Further development on the target side is a condition *sine qua non* to demonstrate that ADS can compete with other advanced reactor concepts.

REFERENCES

[1] R. Wigeland et al., "Nuclear fuel cycle evaluation and screening-Final report: Appendix B, Comprehensive set of fuel cycle options", Idaho National Laboratory Technical Report INL/EXT-14-31465 (2014).

[2] M. Haj Tahar, F. Méot and N. Tsoupas, "Beam Stability Analysis for ADS", AccApp15, Washington, USA (2015).

[3] F. Heidet, N. Brown and M. Haj Tahar, "Accelerator-Reactor Coupling for Energy Production in Advanced Nuclear Fuel Cycles", Reviews of Accelerator Science and Technology, Vol 8 (2015) 99-114.

[4] T. P. Wangler, "RF linear accelerators", WILEY-VCH Verlag GmbH & Co.KGaA, Weinheim, pp.171 (2008).

[5] M. Seidel, "Energy efficiency of particle accelerators", 2nd workshop Energy for Sustainable Science (2013).

[6] J. Galambos, Private communication.

[7] C. Lingwood, "Klystrons", Proton Driver Efficiency Workshop, Zurich (2016).

[8] M. Seidel et A.C. Mezger, "Performance of the PSI High Power Proton Accelerator", International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, Vienna (2009).

ISBN 978-3-95450-147-2