Energy Efficiency of High Power Accelerators for ADS Applications

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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:

\[ P_{th,c}(MW) = E_f(MeV)I(A)\frac{N_0}{\nu} k_1 S + P_{dh} \] (1)

where

\[ S = 1 + k_2 + k_2 k_3 + k_2 k_3 k_4 + ... + k_2 k_3 ... k_p + ... \] (2)

\( k_i \) is the multiplication factor of the generation \( i \). \( E_f \) the fission energy (\( \approx 0.208 \text{ GeV} \)), \( E_p \) the proton energy, \( I \) the beam current, \( N_0 \) the number of primary neutrons injected in the core per proton, \( \nu \) the number of neutrons released per fission (\( \nu \approx 2.5 \)) 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 \( P_{th} \sim 0 \), although this can represent up to 6% of the reactor power immediately after shut-down. It follows that:

\[ \frac{P_{acc,grid}}{P_{th,c}} = \frac{E_p \nu}{E_f N_0 k_1 S \eta_{acc}} \] (3)

where \( \eta_{acc} \) 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:

\[ \eta_{th} = \frac{P_{el,c} - P_{acc,grid}}{P_{th,c}} = \eta_{th0} - \frac{E_p \nu}{E_f N_0 k_1 S \eta_{acc}} \] (4)

where \( \eta_{th0} \) 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 \( \text{vis-à-vis} \) 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:

\[ \eta_{th} = \eta_{th0} - A \frac{1 - k_{eff}}{k_{eff} \eta_{acc}} \] (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 \( \eta_{acc} \) 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,
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 \( k_1 = k_{eff} \) for all \( i > 1 \). Then, from Eq. (4),

\[
\eta_{th} = \eta_{th0} - A \frac{1 - k_{eff}}{k_1 \eta_{acc}}
\]

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 \( \eta_{acc} \). 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.

**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 \( \eta_{DC} \). 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 \( \eta_{RF} \). 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 \( \eta_{beam} \). 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, \( Z = \frac{V_0^2}{P} \), 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
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:

\[
\eta_{acc} = \eta_{DC}\eta_{RF}\eta_{beam}\eta_{other}
\]

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

\[
\eta_{other} = \frac{AC}{AC + \text{magnet} + \text{cryo} + ...}
\]

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.

<table>
<thead>
<tr>
<th>(\eta_{DC}(%))</th>
<th>PSI-HIPA</th>
<th>SNS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SC Linac</td>
<td>NC Linac</td>
</tr>
<tr>
<td>(\eta_{RF}(%))</td>
<td>64</td>
<td>30</td>
</tr>
<tr>
<td>(\eta_{beam}(%))</td>
<td>55</td>
<td>87</td>
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<td>(\eta_{pulsed}(%))</td>
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<td>(\eta_{other}(%))</td>
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<td>62.5</td>
</tr>
<tr>
<td>(\eta_{acc}(%))</td>
<td>19.4</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Table 1: Table of efficiencies for the PSI’s high intensity proton cyclotron \(P_{\text{beam}} \approx 1.3\,\text{MW}\) [5] and for the SNS linac \(P_{\text{beam}} \approx 1.0\,\text{MW}\) [6], as of 2010. The two 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]:

\[
P_{\text{grid}}(\text{MW}) \approx 8\text{MW} + 0.81\text{MW}\text{I}(\text{mA})
\]

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**


