TECHNOLOGICAL ASPECTS AND CHALLENGES FOR HIGH-POWER PROTON ACCELERATOR-DRIVEN SYSTEM APPLICATION

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Abstract

It is a generally accepted fact that construction of a high-power proton accelerator (HPPA) capable of driving a system of nuclear subcritical assembly for nuclear transmutation or energy amplification is feasible theoretically and conceptually. However, there are a number of technological challenges in several areas that need to be solved so ADS can become feasible. In this paper, we discuss the key requirements of ADS, available technologies and extension and/or extrapolation of today's technology to render the ADS practical. ADS technology would necessarily be an extension of the accelerator of the Spallation Neutron Source (SNS), which is under construction at Oak Ridge National Laboratory. A discussion on how to extend SNS technology to ADS technology is also provided. As both accelerator and target/reactor would operate in uncharted regions of performances, extending and integrating today's technology to the ADS realm would require many performance/requirements trade-offs between accelerator and reactor designers. The uncharted regime of performance includes two to three orders of magnitude higher beam power, improving the reliability of the accelerator to that of a similar range of reactor, and improving and controlling accelerator beam loss fraction to the 10^{-6} range in order to facilitate hands-on maintenance of the accelerator system. An opinion on a possible road map to achieve the ADS goals is also provided.

Introduction

Some 70 years ago, the first series of accelerator-based nuclear transmutation experiments were performed at Cavendish Laboratory using a Cockloft and Walton constructed 300-kV high voltage rectifier-accelerator. One of the most famous and important results was the discovery of neutrons by James Chadwick in 1932. Today's proposal for an accelerator-driven system (ADS) to change species of nuclei from one kind to another is a continuation of the work started by the Cavendish Laboratory team under the leadership of Lord Rutherford. The differences between then and now are accelerator energy, beam current and accelerator reliability. Chadwick counted neutrons with his 10 fingers, while ADS attempts to produce neutrons in units of kilogramme per year. To produce such a quantity of neutrons, an ADS accelerator requires a beam energy of 1 GeV or more, beam current of 20 mA to 100 mA, and should be operational for 24 hours a day, seven days per week with 100% reliability. For the purposes of discussion, it is assumed that 20 mA is the desired current.

Today's accelerator meets the energy and current requirements of an ADS system separately and not simultaneously. At a beam energy of 600 MeV or above, the beam current requirement must be improved by one to two orders of magnitude. The average current of 1 mA beam for 800-MeV proton acceleration was demonstrated by the LAMPF linac a few decades ago. A 1.4-mA, 1-GeV accelerator (SNS) is under construction, and an SNS upgrade plan to ~4 MW is proposed. In other words, the beam current goal is within striking distance. However, the question regarding the system reliability/availability requires fresh thinking by accelerator designers/builders, accelerator users, and accelerator managers. In other words, a paradigm shift is required for all parties interested in the ADS in order to obtain ~100% reliable accelerators.

Other challenges facing ADS include controlling potential beam loss throughout the accelerator system. Beam instability induced by varying beam dynamic conditions of the accelerator can initiate uncontrolled beam losses. Excessive beam loss produces hazardous environmental conditions. Past experience shows that a 1-W/m beam loss is tolerable for hands-on maintenance.

In this paper, a short description of a typical conceptual ADS facility and the technology needed to make the concept viable is presented in the next section, followed by a short introduction to "reliability engineering", which is given in order to explain what is needed to improve the facility reliability. A discussion on beam loss is provided to show the extent of extrapolation from today's practice. One method of extrapolating to the future is to expand the SNS technology to the ADS, and this is described in a section below. Possible R&D and a trade-off study are also described. Loss of one W/m for the SNS corresponds to a fractional loss of $\sim 1 \cdot 10^{-6}$/m. A reliable prediction of such a small fractional number by numerical or analytical computation is very difficult. The fractional loss requirement for an ADS machine is even smaller than that of the SNS. The requirement is smaller by one or two orders of magnitude depending on the required current of the machine.

A typical facility for ADS and available technology

An accelerator of ADS is used to produce ~ kg of free neutrons per year in order to change nuclei of one bulk material to another. Such a quantity free neutrons without fission multiplication can produce a proton beam of an order of 100 MW striking a heavy element target. When the target system is a subcritical assembly, the beam power requirement is reduced by a large factor depending on the criticality condition. Thus one can conjecture an ADS facility should be able to handle a beam power of ~20 MW. Since the SNS has a designed beam power of 1.4 MW, the required beam power of ADS is one order of magnitude higher than the performance today's technology can facilitate.

The SNS uses both room temperature and superconducting radio-frequency (SRF) technology, which supplies 80% of the beam energy. The room temperature portion is used to accelerate the beam to energy of less than 200 MeV, where particle velocity is less than 0.5 of light velocity, and rapidly varying. The SNS chooses to use the room temperature technology in this region purely due to the lack of time to develop. Figure 1 shows a schematic layout of the SNS linac. The linac operates with a beam duty factor of 6%. The changes or improvements required to evolve an SNS-type linac into an ADS linac are discussed later.

Figure 1. Schematic layout of the SNS linac

A typical accelerator for ADS would have a beam energy of 0.6 to 1.5 GeV, a beam current of 20 to 100 mA, and a duty factor of 100%. The layout would be similar to Figure 1 except that DTL and CCL could be replaced with cryogenic structures. The DTL could be replaced with an IH structure being developed in Frankfurt, and CCL could be replaced with spoke cavities or elliptical cavities. Current technology meets the required beam energy and current separately and not simultaneously. A challenge is to operate at high energy and high current with infinitesimally small beam loss and closed to 100% reliability. In the past, accelerators were never required to be as reliable as reactors. Improving accelerator reliability requires a different design/construction philosophy.

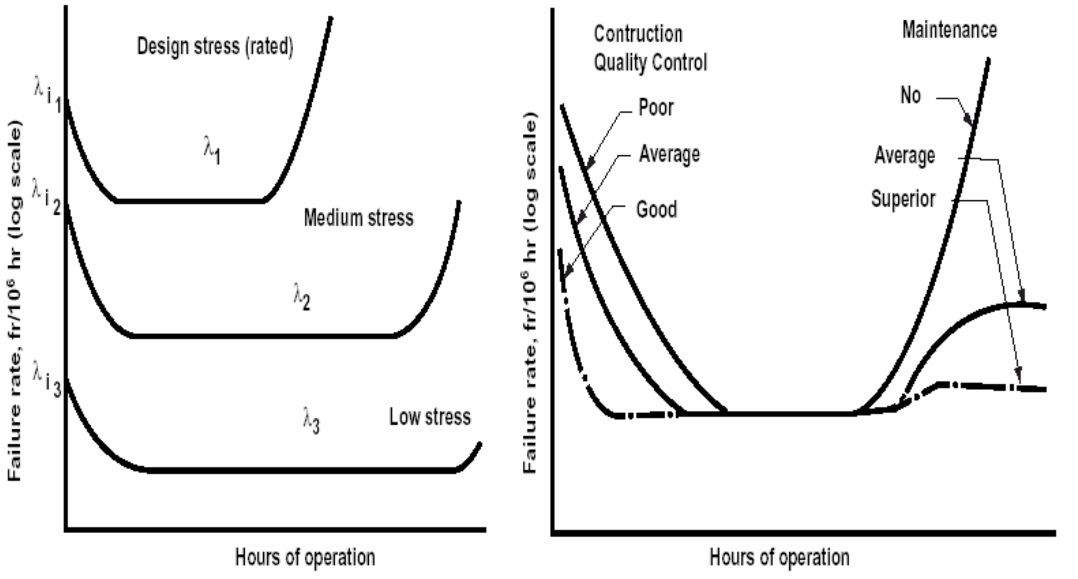
Reliability engineering

Since the invention of accelerators from the 1930s to the 1950s, almost all accelerators were used for nuclear/particle physics experiments to discover new nuclei, new particles, new phenomena and to measure fundamental numbers. The nuclear/particle physics community in the past would rather have higher-energy particles than higher current or higher-energy particles than high accelerator reliability. There were a number of reasons for these preferences. The probability of a discovery of a new particle or phenomenon is higher at higher energies. Typical particle/nuclear physics experiments run about a week, a few months, or years, and therefore an accelerator availability of 80% or so is acceptable to this community as long as the state of the accelerator has an energy frontier.

On the other hand, over the past 20 years, accelerator builders for spallation neutron sources and synchrotron light sources have implemented a marked improvement in accelerator availability. For example, the Rapid Cycling Synchrotron (RCS) and its associated neutron-generating target system of the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory have a 20-year average availability of better than 95%. The availabilities of the Advanced Photon Source (APS) and the European Synchrotron Radiation Facility (ESRF) have achieved 98% over the past several years. A very high availability is required for structural analyses research using neutron scattering or synchrotron radiation. The requirement comes from the following facts: 1) users of such facilities usually prepare samples to be exposed to neutron or photon beams, 2) such sample preparation may take two weeks or more, 3) the sample lifetime with or without beam exposure could be as short as a few hours, and 4) if the sample misses the beam exposure due to machine unavailability, then the user must start the sample preparation over again. The requirement for high availability from scientific users was instrumental in the improvement implemented in light sources and neutron sources. It is reasonable to conjecture accelerator builders of ADS would improve the reliability of the machine.

It may be instructive to review the basics of “reliability engineering” described at the first meeting of this series of workshop held in Mito, Japan [1]. The frequency of system or hardware failure or trip is described with failure rate, l, which is the inverse of mean time between failure (MTBF). Though the failure rate is constant over a shorter time range, the failure rate increases as the system becomes older. The failure is also higher during a “breaking in” period soon after construction. This time variation of failure rate has the shape of a bathtub, and is known as a failure rate bathtub curve amongst reliability engineering professionals. Figure 2 shows a series of bathtub curves indicating the influence of design stresses, quality control during construction, and preventive maintenance during operations. As for design stress, it is preferable to design with low stresses as long as the budget allows.

Figure 2. Reliability bathtub curves as functions of various conditions



Thus the first task of designing a system is to make the MTBF of an integrated system as long as possible. The second task is to make the time required to repair the failed hardware as short as possible. The usual methods for shortening the repair time are to have redundancies or hot spares for hardware prone to fail and devising “quick connects and disconnects” to install and remove it from the system.

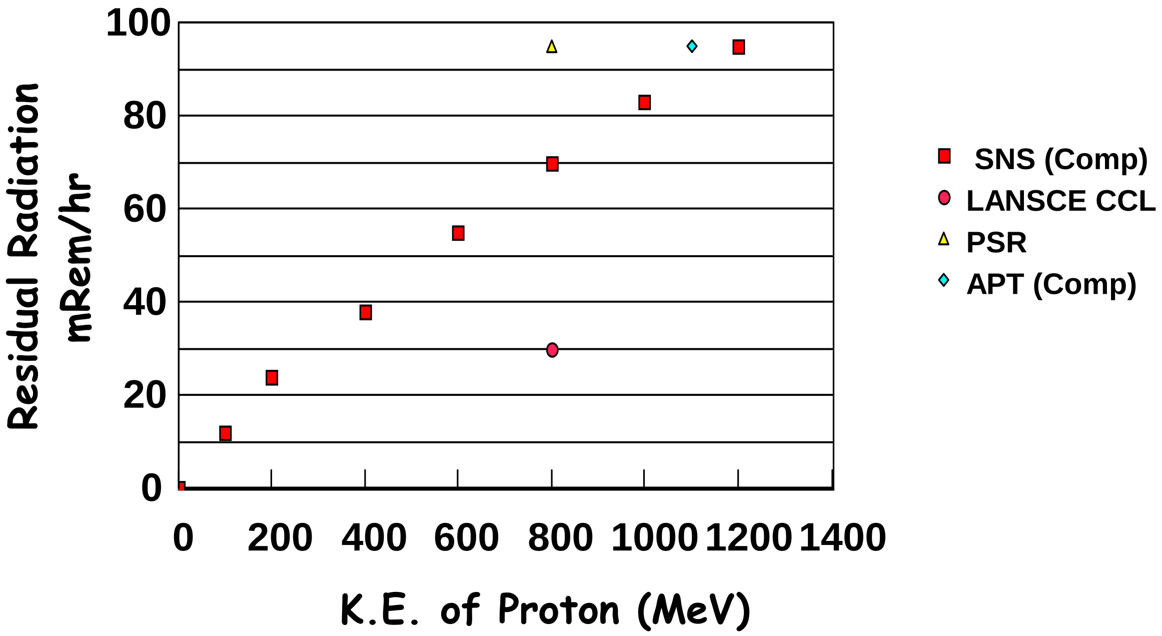
The superconducting portion of the SNS has a special feature of fault tolerance designed into the system in order to eliminate on-line repair time of cavity and its RF power supply failures. There are 81 cavities in the cold section and each cavity is powered by its own klystron. If one or two cavities fail, the linac can be retuned to operate without shutting down. This is a new feature of the SNS linac.

Making an accelerator complex as reliable as a reactor is going to be a challenge.

Beam loss consideration

Excessive uncontrolled beam loss in an accelerator complex brings not only a radiation hazard to personnel and environment but also prevents hands-on maintenance. Beams lost in a controlled fashion (controlled loss) usually collect in a catcher. Experience has shown a loss less than 1 W/m is tolerable for hands-on maintenance. Figure 3 shows calculated and measured residual radiation of accelerator hardware measured at 30 cm from the surface after a 4-hour cooling period following a shutdown under a continual loss of beam at a level of 1 W/m as a function of proton beam kinetic energy. The measured

Figure 3. Residual radiation vs. kinetic energy of proton beam under 1 W/m loss (computed and measured)



points are from LANSCE linac and PSR ring. The calculated values are from the SNS and APT. It is generally accepted that under a residual radiation of ~100 mRem/hr or less, hands-on maintenance can be performed [2].

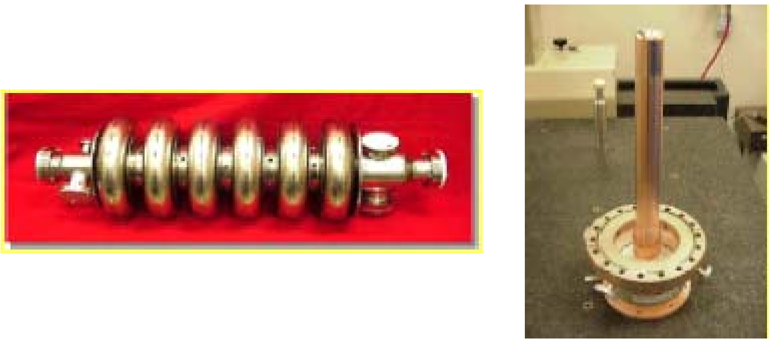
The challenge is making uncontrolled beam loss less than 1 W/m throughout the facility. If one takes a 20-MW beam power facility, the allowable fractional loss is $5 \cdot 10^{-8}$ /m. This kind of small loss is hard to predict because of imperfections in numerical calculations as well as incomplete input to the calculation. Accurate prediction and preventive measures are challenges that need to be solved. After construction completion, the measurement of beam losses at the SNS would show how easy it is to obtain required beam loss control at ADS.

From Spallation Neutron Source (SNS) to ADS

It is instructive to compare the SNS accelerator with a 20-MW ADS accelerator. There are many similarities and differences between the two. SNS was a warm machine and the design was changed to a cryogenic machine in 1999 based on available new technologies [3]: Cavity technology came from DESY which was developed in connection with the TESLA proposal and high-power power-coupler from KEK developed in connection with KEK-B-Factory. Figure 4 shows a picture of an Nb cavity and a power coupler. However, there is a remnant of room temperature technology in the SNS linac below 186 MeV as shown in Figure 1. The conversion took place two years after construction started, and the reason why the old technology was kept was lack of time to undertake the R&D necessary for the converting section below 186 MeV in 2000.

The SNS time-averaged beam current is 1.4 mA with a beam duty factor of 6% and RF duty factor of 7%. The peak current of the linac is about 25 mA. If the SNS linac were to operate in CW mode, the beam power becomes about 23 MW, which is an ADS beam power.

Figure 4. SNS niobium cavity (left) and power coupler (right)



Therefore, what are the changes necessary to build a CW 23 MW machine based on the SNS technology?

It is advisable to eliminate the warm section below 186 MeV. There are a couple of new technologies being developed around the world. One is the so-called spoke cavities being developed at ANL, LANL and Orsay, and the other is the IH structure being developed for GSI by the University of Frankfurt.

Since the idea is only to change the linac duty factor, the peak beam current of the machine does not change. Therefore it is important to note that beam dynamics associated with high current remains the same as that of the SNS. Beam stability criteria remain same.

A major upgrade required would be a cryogenic plant. Due to the change of RF duty factor from 7% to 100%, the dynamic heat load would increase by a factor of 15 from that of the SNS. For a given final energy of a linac, dynamic heat load is proportional to accelerating gradient; therefore a trade-off optimisation between gradient and costs of construction and operation should be performed in order to minimise the costs.

One of the SNS subsystems which would not function properly is the beam diagnostic system. Since the beam is CW rather than pulsed, the frequency response of the diagnostic system should be in the 200 MHz range, which is the bunch frequency of the beam formed at the initial RFQ. The frequency response of the SNS could be much lower because the pulse repetition rate is 60 Hz. An additional complication and intriguing challenge is how to commission or turn on the linac after shutdown.

When an accelerator is turned on for commissioning or after a shutdown, the beam trajectory is unknown because there are too many parameters which influence the trajectory, and these parameters are imperfectly known. A mis-steered beam can destroy the machine and present a hazard to people and the surroundings. To find the trajectory one needs a beam intense enough to provide signals in the diagnostics, and weak enough not produce a radiation hazard or destruction of hardware even if the beam is mis-steered. For a pulsed machine like the SNS, the condition just described is achieved by reducing repetition rate to, say, 1 Hz or less and reducing the beam pulse length from 1 msec to, say, 10 μsec while maintaining the pulse peak current. In this example the intensity reduction is 6 000 times less. In a CW machine, these features are not available, and one has to design the commissioning mode from the beginning by either providing a different set of diagnostics or providing pulsed or chopped beam operations.

Perhaps the most difficult extrapolation from the SNS to ADS is that of the beam loss prediction and control. Under the 1 W/m allowable loss criteria, the ADS beam loss has to be 15 times smaller than that of the SNS.

Interface between accelerator and reactor

The presently conceived interface between the ADS linac and the reactor is to insert the horizontal beam from the linac into the reactor vertically using a set of bending magnets situated above the reactor. This bend region would contain elaborate sets of charged beam and neutron diagnostics. The Nb surface of the linac accelerating structure is at a cryogenic temperature of 2 K, while the reactor is at a high temperature due to nuclear reactions and possibly emitting fission product gases. When the Nb surface is contaminated the performance of superconductivity could be degraded.

One of the challenges is to design and construct the bend region such that it can accommodate quick service to the beam transport and the reactor diagnostics. All existing spallation neutron sources except SINQ at PSI, Switzerland have horizontal beam delivery systems. Experience by SINQ on the vertical beam delivery system maintenance, inspection and other services could be helpful in designing future vertical delivery systems. The bending magnets in this area should be made of inorganic materials so that radiation damage to the magnets is minimal.

Another challenge is the windowless vacuum isolation between the accelerator and reactor. It is reasonable to assume that existing materials would not withstand this kind of radiation environment, and it is conjectured that either new technology or new materials are needed for the window and/or isolation. It is noted that there are a number of papers addressing “window” issues in this workshop.

R&D and trade-off

The ADS will advance accelerator and reactor technologies together, interfacing the two toward an uncharted regime. Therefore it can be expected that a number of difficulties will have to be faced. Some of the difficulties could be mitigated jointly by accelerator builders and reactor builders by trading difficulties and complementing each other. This is called “sharing difficulties” or “sharing pains” between subsystems.

Since no high-energy accelerator has been as reliable as a reactor, the question remains as to what kind of reliability the ADS reactor can tolerate. A HPPA can be made as reliable as a reactor with a large sum of additional costs. On the other hand, if a reactor can be designed to tolerate some amount of unreliability of an accelerator, there could be cost savings in accelerator construction. Such R&D efforts should be carried out in an iterative manner between accelerator builders and reactor builders in the “sharing pains” manner.

The diagnostics concerning the beam delivery system and reactor area would be in an uncharted domain. Developing equipment which does not intercept the beam, yet measures the beam profile and/or position, is essential. Furthermore, these instruments are likely to be situated in an area where back-streaming neutrons certainly cause radiation damage to the equipment. Additional requirements include a long MTBF and quick reparability. Redundancies and spares may or may not useful because of the extremely high level neutron radiation in the area. It is a challenge. As the expertise regarding radiation damage resides with reactor designers, this topic would also benefit from a joint effort between accelerator and reactor experts.

Other key R&D and trade-off studies include the isolation issue concerning the “beam window” to isolate the accelerator from the reactor, and vertical beam insertion to the reactor through a beam delivery system.

A road map for a high-power proton accelerator-driven nuclear system

The following is an opinion of the author regarding a possible road map leading to a high-power proton accelerator for an accelerator-driven nuclear system.

The Japan Proton Accelerator Research Complex (J-PARC) R&D plan on ADS work in Japan was presented at this workshop. The plan includes a "transmutation physics part" and a "transmutation engineering part." The facility to carry out the R&D is under construction, and will use a 200-kW beam (600 MeV, 1/3 mA) from J-PARC injector linac. A transmutation physics study planned requires only a 10-W beam.

My opinion is that the plan proposed by J-PARC is prudent, proper and a practical approach toward an ADS system. It is a wise plan to understand and attempt to solve ADS reactor physics and engineering issues with a modest beam power instead of starting with 10 s of MW beam. Since there may be number of unknown difficulties achieving 10 s of MW HPPA based ADS system, a graded approach may be a worthwhile option and should be considered. One natural graded approach is to start with 200 kW to 2 MW to 20 MW machines. In this chain of graded approach, the first two machines would exist within a few years at JAERI and ORNL, respectively.

Under the graded approach concept, every laboratory interested in an ADS system should join the J-PARC effort to learn and to solve reactor problems at 200 kW level internationally. In the same manner that EU-funded collaborative work exists in Europe, it seems natural for Asian countries to form a collaboration with JAERI. Putting resources together and eliminating duplications will expedite the programme with minimum expenditures for each collaborating laboratory. A model for such international collaboration is that of the TESLA Test Facility (TTF). Since 1992 the TESLA collaboration centred at DESY in Hamburg, Germany, consisting of some 50 institutions, has developed very high gradient (~40 MeV/m) superconducting cavities and built an initial linac of 300 MeV, and more recently of 1 000 MeV, using the cavities developed by the collaboration. The initial linac was to demonstrate a self-amplified spontaneous emission (SASE) free electron laser, and the latter linac is the driver for a VUV free electron laser user facility. As noted earlier, the SNS uses technology developed by TESLA.

The uniqueness of the TESLA collaboration is that each collaborator contributed their expertise and in-kind hardware. For example, cavity materials and construction from DESY, some RF power supplies and power couplers from FNAL, cryomodules from INFN, injector from CEA and Orsay, vacuum chambers for FEL from ANL, and so on. The results of these collaborative effort is an approved proposal to build an X-ray FEL at DESY as a European facility and a proposal to build a 500-GeV linear collider, which is under review by the International Committee on Future Accelerators. This model of international collaboration can be used to carry out developmental work for an HPPA-driven ADS. This proposal does not advocate discontinuing national institutional programmes in favour of the collaboration. However, national programmes can be tailored to complement the collaborative effort.

Summary

The technological aspects and challenges of employing a high-power proton accelerator to drive accelerator-driven nuclear system are discussed. There are a couple of requirements which where today's accelerators have not demonstrated. One is achieving a reactor-like reliability and the other is controlling beam losses to an unprecedented level. A trade-off between accelerator and reactor to mitigate these difficulties is proposed. A road map to achieve an ADS facility is also proposed.

If the SNS linac were to run in CW mode without changing the beam peak current as it was designed for the pulsed mode, the beam power would become 23 MW. This level of beam power is a desired level of the ADS system. The technology and performance of the SNS linac would guide the ADS linac design and performance. For example, if one finds the SNS beam loss is 10 times less than conjectured today, then the ADS linac should be able to facilitate hands-on maintenance.

The fault tolerant design implemented in the SNS linac should be tested to its full extent to determine whether such a system can be used to improve the reliability of an ADS linac in order to meet the requirement of only five trips per year.

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TECHNICAL SESSION I

Accelerator Reliability

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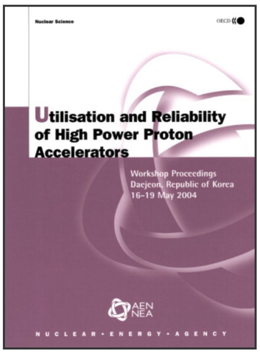

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