Accelerator driven systems: an application of proton accelerators to nuclear power industry

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Why accelerators can help nuclear energy

10 000 nuclear reactor-years of operation have witnessed 2 major accidents (Three Mile Island and Chernobyl) both caused by critical power excursions. It is clear *a posteriori* that this is too much for the public to neglect. It is certainly possible (at a cost) to decrease the probability of an accident to the 10^{-5} or 10^{-6} level, but this might not suffice to allay the fears and one has to seriously consider intrinsically safe reactors, in which by physical laws, serious accidents cannot occur. Another major (and growing) concern is that of the fate of long-lived radioactive nuclear waste.

Over this background, a small group at CERN led by Carlo Rubbia began in 1993 to look into novel solutions for nuclear energy based on the use of accelerators and developed the Energy Amplifier project. [Figure 1]

Proposals to use a particle accelerator as an adjunct to a nuclear reactor date back to the beginnings of nuclear energy, but at the time they were deemed unrealistic. The situation has changed largely because of the progress in key technologies in accelerator and computer technologies. The energy efficiency of accelerators has improved in the last thirty years from 0.1% to some 50% and their reliability is now at the industrial level (beam on 95 to 99% of the scheduled time). Also progress in computing power allowed to simulate in detail devices and processes which had never before been investigated at any degree of usable detail. These detailed simulations showed the necessity of discarding some schemes and of introducing new ideas.

Energy amplification, concept and experimental proof

In a sub-critical reactor, the number of neutrons originating from fission is not sufficient to overcome the losses (due to leaks and absorption of neutrons by some materials). Therefore, under no circumstances can a chain reaction be self-sustained and in order for the reaction to proceed, one needs to continuously supply neutrons from an external source. In an Accelerator Driven System, this external source consists of neutrons created by spallation when a medium energy proton beam reacts with a heavy target (usually Lead). The supply of neutrons is proportional to the proton intensity, which can be modified precisely and with a very short time constant. The proton beam plays the role of the control bars in a reactor, the difference being that it is proactive rather than reactive: if it fails, the reaction stops and it can never lead to an overheating.

In contrast to fission, spallation costs energy and the ability to steer the fission process will come at a cost, coming from the accelerator beam power needed, and that cost has to be minimized for the proposal to remain economical.

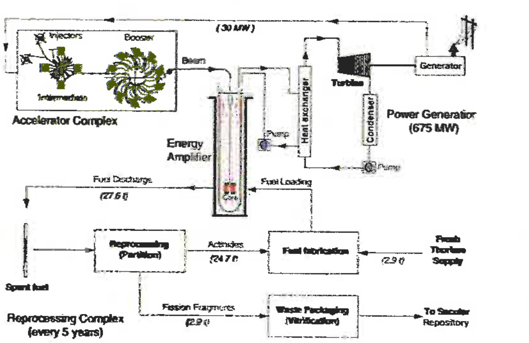

Fig 1: Closing the nuclear cycle with the Energy Amplifier, a sub-critical device with a Th $-^{233}$U fissile core fed with a supply of spallation neutrons. There is no criticality, no plutonium and no problem of actinide waste. At the end of the cycle, ^{233}U and the other uranium isotopes are recycled to serve as the initial fissile part of a new load of fuel. Thorium is an abundant resource (much more than uranium) and supplies could last thousands of centuries.

The energy of an incoming proton results – because it initiates nuclear fission cascades – in the production of a much larger energy. We say it is amplified (by fission) and call the device an Energy Amplifier (EA). The ratio between the incoming energy and the total energy is called the gain G of the amplifier. G is related to the neutron multiplication factor k.

$$k = \frac{\text{Production}}{\text{Absorption} + \text{Losses}}$$

For an efficient control of the reaction, it is enough for the EA to be weakly sub-critical. This is evident from figure 2, which compares the safety margin provided by delayed neutrons in critical reactors with that of a sub-critical device. We see that k=0.98 is sufficient to ensure that the EA is sufficiently far from criticality conditions. [Figure 1]

Setting k=0.98, the neutron deficit, to be supplied by spallation is s=0.02

For each 100 neutrons, there will be 98

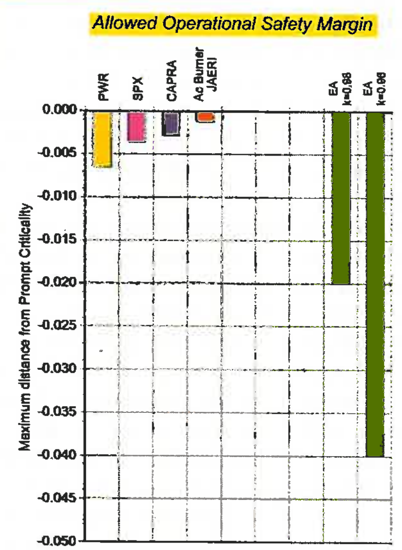

Fig 2: Even with k=0.98, the EA has a much higher safety margin than the one offered by b delayed neutrons. The fact is even more striking when one considers heavy actinides.

Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2000606

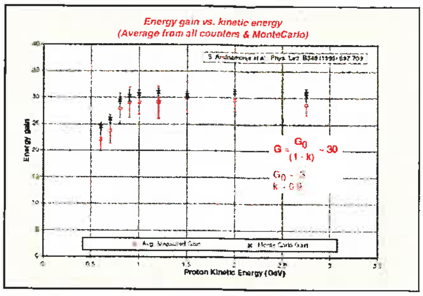

Fig 3: Variation of gain with incident proton energy. The gain is constant for energies larger than 1 GeV. The relevant figure is the beam power (GeV × mA) over 1 GeV.

fission and 2 spallation neutrons (each costing 30 MeV), in the mix. Only part of the neutrons (40%) will induce fission and bring 200 MeV of energy, the rest will be captured or leaked out. Therefore:

$$G = \frac{\text{Return}}{\text{Cost}} = \frac{200 \times 0.4 \times 98}{2 \times 30} = 130$$

The gain will be smaller (G≈50) if 5% of the neutrons comes from spallation and more generally, it can be shown to be:

$$G = G_0 \frac{1}{1-k}$$

This simple concept was first tested experimentally when a small number of protons 109 per pulse ie 10^{-4} of the total intensity of the CERN Proton Synchrotron was sent on an existing "pedagogical" subcritical assembly consisting of natural uranium rods (3.5 tons) immersed in water and known to have k=0.90. The energy produced (of the order of 1 Watt) was measured by determining the temperature elevation (millikelvins) in the insulated vessel, using very sensitive thermometers.

The energy gain was measured as a function of the proton energy ((Figure 3) and shown to be constant at energies larger than 1 GeV . As shown in Figure 4, only a small proportion of the energy produced by the Energy Amplifier (4 to 6%) will have to be recirculated into running the accelerator .

What accelerator?

It is within the possibilities of present-day technologies to build an accelerator for the EA (15mA@1GeV). There are two possible solutions: an isochronous cyclotron or a linac. Both technologies are well proven and would give 50% efficiencies. The cyclotron (an extrapolation of the machine running at the Paul Scherrer Institute near Zurich) has the advantage of being more compact and a simpler technology. The linac solution would presently be more based on the LEP-type superconducting cavities than on the Los-Alamos LAMPF, even though a superconducting linac would need a warm machine as an injector at some 400 MeV. The real advantage of the Linac is the possibility of going to much higher currents (say 30 to 50 mA) if they were needed. The cyclotron does not involve superconductive technology, takes less floor space and is therefore probably more adapted to industrial type applications.

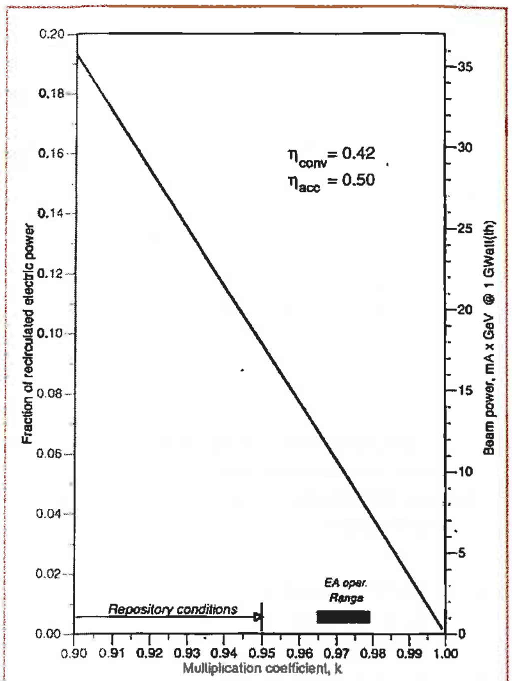

Fig 4: Fraction of energy recirculated to run the accelerator, assuming 42% energy conversion and 50% accelerator efficiency.

The Energy Amplifier: basic concept

Neutrons are created by spallation when a beam of protons coming from the accelerator interacts with a Lead target. Neutrons lose their energy and diffuse to interact with a sub-critical fissile core. The heat created by fission is evacuated from the core by natural convection in molten Lead, through a heat exchanger to a secondary circuit. The presence of Lead results in a harder neutron spectrum than is the case in usual, sodium-cooled fast reactors. As shown in Figure 6, this is opens up the very important ability of the device to fission practically all actinides with a reasonable probability.

The use of Lead as a heat carrying medium has important safety implications. In comparison with Sodium (which has been used extensively in critical fast reactors, Lead is chemically inert and it has a low vapour pressure even at a high temperature. Its high density allows the use of cooling by natural convection which avoids using pumps. This is a safety feature: no pumps, no failure. The nuclear properties are also remarkable: Lead being a doubly-closed shell nucleus (the nuclear equivalent of a noble gas, it has a very low absorption by neutrons. Together with its high mass, this makes for properties of slowing down of neutrons which we will discuss in the next section.

One safety problem which is specific to the EA and has been much talked about is the window separating the beam from the target. There is at CERN and other labs an extensive experience with proton beams of a fraction of a millimetre diameter and an average intensity of one microampere. The EA would admittedly involve beams of 10 000 times higher intensity, but then the beam spot would be of some 10 centimetre diameter so that the current density would actually be smaller. All this has obviously been included in the detailed simulation and there is a further plan to test experimentally at a lower proton energy (where the energy loss, going as 1/E is actually greater). One has therefore confidence that the window concept is sound. One cannot argue that the window would be a weak point in the barrier insulating the reactor core from the outside world. In

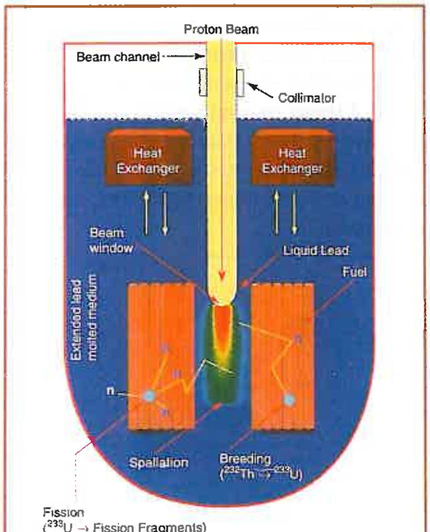

Fig 5: Schematic principle of the Energy Amplifier.

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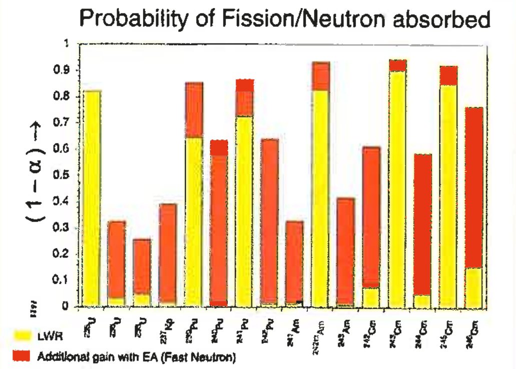

Fig 6: Because of the Lead neutron diffusing medium, all elements will fission to some degree, this opens the way to destroying actinide waste.

fact, should the window break, it would immediately be replaced by liquid lead flowing up the beam tube, preventing the beam from reaching the target and thus stopping fission processes occurring in the core.

Destroying long-lived nuclear waste

The EA can destroy long-lived waste coming from reactors.This is principally plutonium and higher actinide elements. Typical half-lives are 24000 years for ^{239}Pu and 6500 years for ^{240}Pu. As for fission products, after a few years of swimming pool storage, the vast majority of their radiotoxicity is carried by just two isotopes (^{90}Sr and ^{137}Cs with half-lives of about thirty years. In addition to the 30 year component, there are a few very long-lived fission products such as ^{99}Tc and ^{129}I with respective half-lives of 200000 and 15 million years. Even though not highly radioactive they are very worrying because some of them are soluble in water and can therefore easily migrate into the biosphere. We have demonstrated a possibility for the EA to transmute them into stable, innocuous products.

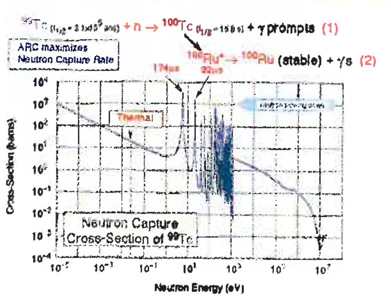

Fig 7: Transmutation of ^{99}Tc with a high efficiency using resonances.

In the EA, the transuranic elements (TRU) coming from the reprocessed spent fuel from an LWR will fission (producing energy) and the excess neutrons, captured on the fertile ^{232}Th will breed ^{233}U (which is in itself valuable, either as seed for an EA or as fuel for a critical reactor. To give some numbers, an EA of nominal power 1500 MW_{th} with a burnup cycle of 120 GW-day/t refilled after 2 years would incinerate 402kg of TRU per year, breeding at the same time 175kg per year of ^{233}U, which can itself power an LWR.

If we now turn to long-lived fission products, we shall take as an example ^{99}Tc which is the most worrying. By capture of a neutron and subsequent beta decay, it is transformed (after 15 seconds) into stable ^{100}Ru. In a reactor neutron energy spectrum that cross section is extremely low (if not, there would be no ^{99}Tc left !). Since we cannot envisage to leave ^{99}Tc in a reactor for hundred years or have a correspondingly high flux (people have tried), one has to find a better idea. At a slightly higher energy, the capture cross section of ^{99}Tc shows a series of resonances, the most important one being at 5.6 eV where the cross section is about three orders of magnitude larger than for thermal neutrons. Can we make use of that resonant property?

For that purpose, Rubbia has come forward with the concept of Adiabatic Resonance Crossing.

Let us assume a volume of Lead bombarded by 1 GeV protons which is large enough to contain the majority of the cascade. A number of neutrons are created and since Lead does not absorb neutrons, they will undergo a large number of elastic collisions and lose their kinetic energy in small decrements governed solely by the kinematics and the masses. This coefficient which is called lethargy results in the neutron losing at each step a fraction ($\approx$ 1%) of its actual energy. It is easy to see that in the region of the resonances, the actual energy losses are much less than the width of the resonance and therefore, a slowing down neutron cannot miss it. If the impurity to be destroyed is placed inside a volume where there is no competing absorbing material, it should be destroyed with a high efficiency.

This concept was successfully tested at CERN by an experiment (TARC) supported by the European Union.

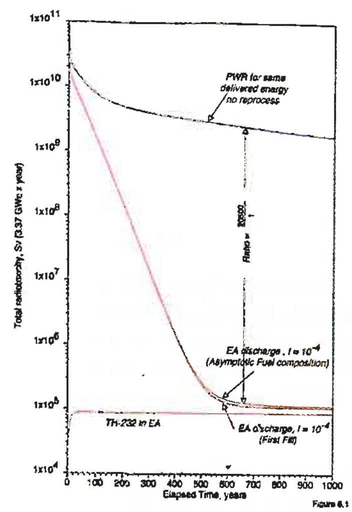

Fig 8: Comparison of radiotoxicity of nuclear waste of the EA and an ordinary reactor for the same amount of energy produced.

The results also served to validate the Monte Carlo simulation program so that one can now predict the performance of the EA in transmuting of ^{99}Tc and ^{129}I. A practical transmutation scheme would locate the technetium at a large distance from the strongly absorbing core– more precisely at a distance larger than the diffusion length of neutrons in Lead –. One can safely assume that neutrons that have travelled that far would have a negligible chance of diffusing back to the core. Therefore, one is using for transmutation neutrons which would otherwise be lost by capture on the wall. This means there is no penalty on energy production.

An Energy Amplifier would typically destroy without loss its own production of technetium (obviously coming from the preceding cycle). In order to transmute other species (for instance coming from LWR waste, one would have to accept a small loss of neutrons, hence of energy production.

Conclusion

There is presently a large and growing interest from the European Union and several countries (in Europe and elsewhere) to explore the possibilities of transmuting nuclear waste by Accelerator Driven Systems. It is likely that a demonstration prototype will be funded in the Framework Program 6. If the method shows promise, it would open a new and important field of application for high intensity medium energy proton accelerators.