THE ACCELERATORS CONSIDERED

FOR THE PROBLEM OF NUCLEAR WASTE

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1. Direct transmutation

1.1 Introduction

What is going to be refered to here as transmutation of nuclear waste is the transmutation of long lived isotopes coming out from industrial power reactors into short lived or stable ones. A distinction must be made beween actinides and fission products. Under a neutron flux, the former can either be transmuted, the result being an other actinide, or fissioned, hence producing energy and fission products. Transmutation only applies to fission products. It is likeky that actinides can be transmuted in reactors, either pressurized water reactors (PWR) or fast neutron reactors. The transmutation of fission products in nuclear reactors is more difficult because of their smaller cross section, and would require a high neutron flux. So the question may be raised : is there any hope that fission products coming out from industrial nuclear reactors can be transmuted with particle accelerators ? It is going to be shown that direct transmutation is quite unrealistic. Here direct transmutation means a particle beam shooting in a target made of fission products, possibly including a neutron multiplier material (beware of other radioactive nuclei produced by transmutations in this material), but no fissile material. Only proton beams will be considered, even if deuteron beams could bring some advantages. Electron beams producing photons for photonuclear reactions is an other possibility, but it will not be treated here since the energy balance seems to be worse with electrons than for protons.

1.2 Which accelerators would be needed for direct transmutation'?

Let us restrict ourselves to the most embarrassing fission products, that is to say the ones which have a long life and can enter into biological processes. One finds I-129, Tc-99 and Cs-135. The 50 or so French reactors produce roughly, by year:

1 ton of Tc-99

0.5 ton of Cs-135

1-129 will not be considered since it could possibly be dispersed in the oceans.

Let us now assume the very optimistic situation where :

. these fission products result from a perfect chemical and isotopic separation.

. one neutron can transmute one nucleus of Tc-99 or Cs-135 into a short lived or stable isotope with a 75°/0 efficiency.

It follows that 10^{28} neutrons per year are needed. Proof:

$10^{28} * 0.75 * 120/ 6.02 * 10^{23} = 1.5 * 10^{6}$ grams
where 6.02 * 1023 is the Avogadro number
and 120 is the average atomic mass for fission products

This corresponds to about 4% of the total number of neutrons produced per year in all the French PWR reactors :2.5 * 1029 neutrons per year. Proof:

each fission reaction yields 2.5 neutrons
if there are 1029 fission reactions per year in the 50 PWR
this is equivalent to 2 * 10^{27} fission reactions per year in one PWR
or 9.2 * 1019 fission reaction per second in one PWR working 6000 hours per year
since one fission yields about 200 MeV, or 200 * 10^{6} * 1.6 * 10-19 = 3.2 * 10-11 joule
then each PWR produces 9.2 * 10^{19} * 3.2 * 10^{-1}1 = 2.9 GW thermic or 1 GW electric.
This shows that 10^{29} fission per year is consistent with the total energy produced in the French PWR.

So to get rid of the most embarrassing fission products in an almost ideal situation we need all the neutrons produced in 4% of all the PWR reactors, or all the neutrons produced in 2 PWR.

Now let us imagine that these 10^{28} neutrons per year are to be produced by spallation with proton accelerators.

A 1.5 GeV proton accelerator will give about 33 neutrons per proton.
The number of needed protons per year is then :

3 * 102^{6} proton per hear or 1019 proton per second

which represents a current of 1.6 ampere or a total beam poweer of 2.4 GW and a power taken from the lines of the order of 5 GW (5 PWR).
The 1.6 ampere beam could come from 24 accelerators delivering each a 100 MW beam during 365 days per year, or more likely 35 such accelerators working only 200 days per year . . .

So we are arriving to the conclusion that direct transmutation can not be a general solution for the treatment of nuclear waste. Only partial applications could be contemplated.

2. Accelerators for hybrid reactors

2.1. Principle

Here the accelerator target is the core of a subcritical reactor. Depending on the level of subciticality, and also on the expected net power coming out of the plant, the needed proton beam power falls in the range of a few MW to tens of MW, continuous beam. Cyclotrons are proposed for a few MW, while linear accelerators are the only possibility for very high power.

There are two main concerns for the design of accelerators able to deliver such high power beams :

1. the power efficiency of the accelerating structures. The power delivered by the RF transmitters should go as much as possible to the beam. Losses in the cavity walls should be kept as low as possible. This RF power is one the key parameters for the design of such accelerators, since it has a strong influence on the capital cost and also on the operation cost.

2. the beam losses. Accelerator physicists are used to avoid beam losses in their accelerators, mainly because lost beam is beam lacking for physics experiments. Here we are facing a different situation : a very small percentage of lost beam may produce an induced radioactivity gradually poisoning the accelerator, to the point of hampering the accelerator maintenance. We are not talking here of important beam losses which would result from failures quickly taken care of by adequat tripping systems.

This question of beam losses is linked to the formation of halo. It is believed that for very intense beams a sort of ring may surround the beam core. The classical emittance is no longer adequat to characterize such beams, and that part of accelerator physics is presently the subject of systematic studies at laboratories involved in high power beams. From a practical point of view, accelerator designers need answers to the following questions :

up to what distance from the core particle can escape ?

after a proper cleaning with suitable scrapers, at what speed do particles leak again?

2.2. RF power efficiency

If P_{RF} is the power delivered by the RF transmitters, P_W the power lost in the cavity walls and P_B the power given to the beam, then :

$$P_{RF} = P_W + P_B$$

In fact, the energy balance is a little bit more complicated than that, but we are assuming here that the cavity coupling factor is such that there is no reflected power.

The choice of the accelerating gradient follows from :

$$P_W = k * (\text{accelerating gradient})^2$$

where the k factor is large for room temperature cavities and very small for superconducting cavities.

So the RF efficiency, being defined as P_B / P_{RF} is acceptable with room temperature cavities only for high beam currents, while it is always excellent with superconducting cavities whatever the current. Incidently, one may remark that it is for this very reason that room temperature linear accelerators for physics are pulsed. The needed average beam current is rather modest, and room temperature cavities are poorly suited for such continuous beams. So the beam is pulsed : for the same average current, one gets a much better RF efficiency.

Practically speaking : room temperature cavities have an excellent RF efficiency for beam currents in excess of 100 mA. If it is a linac (the beam passes only once in the cavities), this means that the accelerator beam current should not be less than 100 mA. If it is a cyclotron where the beam passes N times in the cavities, N being the number of turns in the cyclotron, a good RF efficiency is achieved for beam currents of the order of 100/N mA.

2.3. Cyclotrons

From the above considerations, it follows very naturally that accelerators proposed for a few MW beam power are cyclotrons. More precisely, the accelerator consists of an injector, bringing the beam up to an energy adequat for injecting in the cyclotron. Cyclotrons are energy multipliers. As a rule of thumb, the mulplying factor is of the order of 10. So a final energy of 800 MeV means a 80 MeV injector. It would be very difficult that such a high current injector be also a cyclotron, because of space charge effects making high current beams very difficult to handle in low energy cyclotrons. This is the reason why proposed injectors are usually linacs, looking almost the same as the low energy part of a pure linear accelerator, except for the level of RF power. Of course one must accept the poor RF efficiency of this part of the accelerator.

The cyclotron itself is sometimes named sector focussed cyclotron, or spiral sectored cyclotron, or even fixed field alternating gradient cyclotron (FFAG) in order to draw the attention to the fact that its design is far from the classical compact cyclotron. Nevertheless, the principle of operation is the same. The beam trajectory is a sort of spiral in the horizontal plane. Vertical and radial stabilities are taken care of by a suitable shape of the magnet ridges. There is no longitudinal stability : the magnetic field must be carefully adjusted so that the accelerator is perfectly isochronous. It follows that the tuning of a variable energy cyclotron may be a difficult procedure, but since we are interested here in a fixed energy accelerator, one may take for granted that the isochronicity has been tuned once for all.

Each arm of the spiral in not an infinitely thin line. It does have a radial size, depending on the beam emittance, and also possibly on halo formation. It is of an utmost importance for a good beam extraction from the cyclotron that the radial beam size be substantially smaller than the distance between two successive arms of the spiral in the extraction region, which is classically called turn separation. Extraction in cyclotrons is not a natural process, as it is in linear accelerators. An extraction channel must be put in place to bring the beam outside of the magnetic field which would otherwise keep it spiraling. The first piece of this extraction channel is a septum, to be placed between the two last arms of the spiral. This septum is of course designed to be as thin as possible, but any particle hitting this septum will be lost (this is not the main point), heat the material (but abnormal losses is considered as a failure, see above), and also cause induced radioactivity. Scrapers can be placed at various places to limit the vertical beam size, but there is no mean to limit the radial size. Extraction is probably the weakest point of high power cyclotrons. This is why, in order to increase the turn separation, high power cyclotrons require a powerful RF system, providing a high energy gain per turn.

What can be achieved with cyclotrons ? It is difficult to give a precise answer. However, one can refer to the present state of the art. Let us take as a reference the 600 MeV PSI cyclotron, near Zurich. It has been running for years with a 0.25 mA beam (150 kW). It is now being upgraded in order to reach 1.5 mA (900 kW). It seems very likely that these performances will be obtained, but will constitute the ultimate possibilities for this accelerator. Cyclotrons specially designed for high power beams could probably deliver more, let *us* say a few MW.

2.4. Linear accelerators

Beam guidance is much easier in linacs as it is in cyclotrons : there is no problem for injection and extraction (except for funneling, see below), transverse focusing can be adjusted at will while in cyclotrons focusing is sort of built in and can not be adjusted. Moreover, there is intrinsic stability of the longitudinal motion in proton linacs. Linacs can be designed so that transverse and longitunal stability is secured up to very high beam currents. Actually, projects have been made for 250 mA beams at 1.6 GeV (400 MW).

The state of the art is given by LAMPF, at Los Alamos. This accelerator delivers at 800 MeV a 1 mA (average) proton beam with a 6% duty cycle. That is to say that the current during the pulses is 17 mA. Losses in the linac are quite acceptable, and should be much less in a specially designed accelerator working with the same current for the two following reasons : first, most losses in LAMPF are believed to be the result of a poor matching at the entrance of some sections (since the time of the LAMPF design, the importance of a good matching has been better understood) ; second, at least half of the losses occur during the transients at the front end of the beam pulses, which is a problem disappearing for continuous beam linacs. But there is more : due to the fact that the high energy part of LAMPF uses 805 MHz cavities while low energy cavities work at 201.25 MHz, only one fourth of the available focusing capability is used, as far as space charge is concerned. So one should say that the experience gained with the operation of LAMPF gives confidence that beam behaviour, and beam losses, are well at hand for a 70 mA continuous beam. It seems reasonable to believe that with a design taking advantage of the development of accelerator physics since the design of LAMPF, and a better understanding of the formation of halo, a 250 mA accelerator is quite feasible.

Several projects have been studied in USA, Japan and former Soviet Union. The frequency ratio between high and low energy cavities is rather 2 instead of 4 as it is for LAMPF (e.g. : 700 and 350 MHz). Moderate power accelerators are pure linear accelerators, one half of the focussing capabilities of the high energy section beeing wasted. One starts usually with a 100 keV electrostatic pre-injector, followed by an RFQ section and drift tube cavities. Then the high energy section uses the coupled-cavity technique, e.g. the LAMPF side coupled cavities. Very high power accelerators usually use the funneling technique : there are two identical low energy accelerators, each accelerating half the required beam current. Then the two beams are mixed to be injected in the high energy part of the accelerator. The mixing is achieved with RF cavities working in a transverse mode so that bunches of particles coming from the two injectors at the 350 MHz frequency are intertwined to be injected in the high energy part at a 700 MHz frequency. Funneling allows a full use of focusing capabilities of both low and high energy parts of the accelerator.

An example for a medium power accelerator, without funneling, and using side coupled cavities for the high energy part could be :

final energy	700 MeV	:	beam power	56 MW
beam current	80 mA	:	RF power	79 MW
accelerating gradient	1 MV/m	:	power from the lines	134 MW

It must be noted that the choice of a 1 MV/m accelerating gradient is the result of an optimisation between capital cost plus operation cost of RF transmitters and the cost of accelerating structures.

2.5. What advantage would bring RF superconductivity to high power linacs ?

Of course RF cavities allow an excellent RF efficiency. Losses in the cavity walls (no more copper but niobium) are very low. But these losses are produced at very low temperature, and a costly cryogenic plant is needed to reject them at room temperature. But the main point is the following : the minimum cost for superconducting cavities allows to use much higher gradients, let us say 10 M'V/m instead of 1 MV/m. Even if superconducting cavities may be estimated twice as expensive per meter than copper cavities, a factor 5 is gained in the price since the linac is ten times shorter. All together it is estimated that a superconducting linac would save about 30°/0 on the capital cost and the same amount on the operation cost. But it must be said that there is no experience anywhere of the behaviour of superconducting cavities in high power proton linacs.

2.6. Related topics

The techniques involved for these high power linacs are common with two other applications for which the CEA has a strong interest : accelerators for tritium production, and also deuteron accelerators producing high flux of 14 MeV neutrons for fusion material research.