# INTERIM REPORT OF THE TECHNICAL WORKING GROUP ON ACCELERATOR DRIVEN SUB-CRITICAL SYSTEMS

October 12, 1998

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## 1.— DEFINITION OF THE MANDATE OF THE TECHNICAL WORKING GROUP (TWG)

The Research Ministers of France, Italy and Spain have recently decided to set up a Group of Advisors [2] on the definition of a common R&D European platform on Accelerator Driven Sub-critical systems (ADS). Their recommendations at the end of their first meeting can be summarised as follows:

1.- The concept of Accelerator Driven Sub-critical systems (ADS) seems to possess remarkable potentialities, notably for what concerns the transmutation of the long lived waste, as to warrant a serious industrial effort.

2.- The construction of a demonstrator facility of significant power in the order of 100 MWatt (thermal) on a 10 years time schedule, is a necessary step for the development of the industrial strategies which will eventually lead to the actual exploitation of the concept. The facility will be in itself an important part of the R&D effort.

3.- To reach such an objective a serious R&D effort is required, for which a co-ordinated joint action of governmental research agencies and of industrial bodies is called for, with ad hoc allocated human and financial resources.

4.- The scale of the demonstration facility is that of a *regional facility.* European collaboration is therefore crucial. Governments should rise immediate action in order to seek (i) interest of other European partners in the programme; (ii) EU support within the 5th-Framework programme. During the R&D phase, collaborations are recommended with (i) USA, where a similar programme is being pursued and (ii) Russia where important know-how on the technology of lead-bismuth coolants exists.

5.- In addition and as a necessary requirement for an inter-government action, an *appropriate industrial platform* should be created, with as initial step a long range agreement among interested European partners, including the settlement of intellectual properties issues.

The Advisors Group on ADS recommend a ≈ 10 years European demonstration programme, divided roughly in three time phases:

1.- Creation of a European partnership, both among research agencies and at the industrial level and in particular setting up of the Technical Working Group.

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2.- R&D programme is performed, leading to the final design of the demonstration facility, according to point 2 of the recommendations

3.- The demonstration facility is constructed and operated.

In order to identify the critical technical issues in which R&D is needed, a Technical Working Group (TWG) has been established, initially constituted by three representatives from each country, plus a chairman and a secretary. In particular some of the issues to be considered have been indicated. The list, by no means comprehensive, includes:

-Accelerator technologies
-(beam) window technologies
-Liquid metal technologies
-Material testing
-Fuel cycles
-Safety and site licensing.

In addition to identifying critical issues and building a coherent programme toward the above goals, the TWG should give a cost estimate for the necessary, related activities, namely both the generalised R&D and the demonstrator according to directives above. A comprehensive TWG report is expected by the end of 1998.

The initial expenditure rate for 1999, awaiting a more comprehensive estimate by the TWG, has been recommended to be not less than 10 MECU/country "in order to keep the necessary momentum".

## 2.— MODUS OPERANDI

The primary task of the TWG is the definition of the demonstrator's programme for Europe. The members of the Technical Working Group (TWG) are aware of the fast pace of progress expected from them. However, there are at least two main reasons why statements at this stage are necessarily provisional:

1.- the forthcoming partnership in the TWG of additional European countries;

2.- the definition of an appropriate European industrial platform.

It has therefore been agreed that a first, preliminary report will be issued by the middle of October, to be followed by a more comprehensive report by (soon after) the end of the year, under the assumption that the final constituency of the TWG will be set up in time to complete the work within the indicated deadline.

A large amount of R&D on ADS is already going on or is in preparation in France, Italy Spain, and in other European countries as well as elsewhere (USA, Japan, Russia etc.). Therefore the first task of the TWG has been a first comprehensive review of such activities and especially those in our three countries in order to

1.- propose an optimised co-ordination amongst separate actions and

2.- reach a convergence toward a common European initiative for the demonstrator.

In this respect, it has been agreed that the TWG shall concentrate primarily on ensuring the realisation of those research items which are directly relevant to the realisation of the demonstrator.

The present interim report will therefore make a first attempt to define the parameters of an European ADS demonstrator and those related items in which appropriate R&D work is needed, as a part of a coherent plan.

The Final report will further narrow down the relevant parameters and the extent of the associated R&D tasks and provide a first estimate of the related costs and time schedule. In the second report also the general organisation for the co-ordinated ADS programme will be presented, taking also into account the activities outside Europe and the possibility of a wider international collaboration.

The coordinated programme identified by the TWG could be considered as a proposal to be developed in connection with the 5$^{th}$ Framework Programme. In the TWG meetings, the goals and specifications of the key action *Nuclear fission* have been taken into account.

## 3.— ACCELERATOR DRIVEN TRANSMUTATION .

Recent advances in the field of particle accelerators have made possible the practical realisation of (i) beam powers in the MWatt range and of (ii) an energetic efficiency in the process which is in the vicinity of 50%, namely the beam power is as much as one half of the electric power needed to run it. These advances, coupled with the realisation that the so-called spallation reaction can be very neutron prolific ( ≈ 30 highly energetic neutrons for each incident proton of 1 GeV for a lead target) make the long sought idea of introducing the use of accelerators in the domain of nuclear technology more realistic. If all these ≈ 30 neutrons are used to induce fission in an appropriate element, a substantial energy will be liberated (≈ 0.2 GeV/fission), about 30 x 0.2 = 6 GeV, namely about 6 times the incident energy. Such an energy gain, G = 6, can be further increased if some of the secondary neutrons produced by fission are also interacting in the target producing additional neutrons. If k, the so-called multiplication coefficient, represents the probability for one fission neutron (via secondary neutrons) to cause fission again, the total number of neutrons is at the end increased by a factor 1/(1-k). In reality, fission is not the only open channel in the target, the other most important one being neutron capture with element transmutation. Therefore a more realistic formula for the energetic gain is G = 2.4/(1-k).

In all circumstances, the value of k must be substantially lower than 1, so that one deals always with proton initiated nuclear *cascades*, comfortably away from criticality, the operating conditions of a nuclear reactor, for which evidently, k = 1. The choice of k defines the relative role of the "external" source of neutrons, namely the accelerator, and the "internal" source, namely the fission process. Obviously, a too small value of k will result in a too large energetic burden on the accelerator, while a too large k will eventually reduce the controlling action on the reaction by the accelerator. In this sense, the accelerator has a controlling action of the process, in analogy to the "delayed" neutrons in the case of a reactor, which represent typically about one half of a percent of all neutrons in a LWR. A reasonable value is k = 0.95 ÷ 0.90, namely 5 ÷ 10 % of neutrons from the external source, which corresponds in practical circumstances to some 7 ÷ 15 % of the produced energy to supply the accelerator, the rest being used, for instance, to produce electricity.

Particularly interesting are schemes in which such ADS are used in association with conventional LWR's in order to alleviate the problems associated with nuclear waste and especially higher actinides. These elements, which constitute a major contribution to the long lasting radio-toxicity of the waste, are resilient to fission in a thermal neutron environment (≤ 0.1 eV) and accumulate in the waste. It is a fortunate circumstance that using fast neutrons instead (≥ 200 keV) these elements become fissionable again and become burnable fuel rather than waste. The most fission resilient elements are transmuted by neutron captures, the competing channel, and transmuted into other elements until fission occurs. A "secular chain" — similar to the one occurring naturally for radioactive decays — is established, leading to the progressive elimination of the unwanted species, accompanied by a substantial energy production. For instance, the complete elimination of 1 ton of waste, the approximate yearly production of neptunium, americium and curium of France, corresponds to the production of 1 GWatt of

thermal power over 940 days, independently of the length and structure of the chain. However, all along this chain, the fraction of fissions should be sufficiently large, in order to ensure the appropriate value of the multiplication coefficient k. Detailed calculations show that this is generally the case, provided fast neutrons are used.

The use of fast neutrons requires that the amount of low Z nuclei in the path of the neutrons is as small as possible. While this still permits the use of oxide fuels and eventually gas coolants, it requires a high Z diffusing medium. On the other hand, the best materials for the spallation target is lead, either pure or eutectic with bismuth. This has prompted the idea to use lead or bismuth also as the main diffuser of the Incinerator. The choice of lead vs. lead/bismuth is mainly related to the fact that while lead has a melting point in the vicinity of 327° C, the lead-bismuth eutectic mixture is liquid at a temperature very close to the one of sodium (125 °C vs. 98 °C), for which a vast experience exists. However bismuth produces more radioactive polonium. Use of such molten metals is not without problems, since they may become highly corrosive on some metals, including steel. It must be said, however, that experience exists in Russia on Pb/Bi (70 years of integrated operation), based on nuclear submarines (class alpha) and that such a know-how, to be largely complemented by additional R&D, could be made available to the project. The ultimate applicability of the molten Pb or Pb/Bi to ADS depends critically on the success of such an R&D.

The actinide content of the LWR's spent fuel, with or without MOX cycles, is made of uranium which can be recycled, of plutonium which is readily fissionable and of minor actinides (Np, Am and Cm) which are fissionable with fast neutrons but not with thermal neutrons. Further action on these elements necessarily requires Reprocessing of the spent fuel. It is generally agreed by the TWG that the Minor actinides should be burnt in the ADS, while for plutonium the choice exists of either (i) burning it in the LWR's, but with a substantially increased stockpile of Minor actinides or (ii) sending it directly to the ADS. It is a fortunate circumstance that the general design of the ADS is substantially independent from the fuel choices and therefore both procedures are possible essentially within the same device.

When compared to ordinary reactors dedicated to energy production, incineration of actinides through fission demands high power densities, in order to be performed in a reasonable time. Indeed, as already pointed out, the elimination of 1 ton of fissile material leads to the side production of 1 GWatt (thermal) for 940 days. If elimination is to be performed in < 15 years, it requires > 170 Watt/g, significantly higher than in Superphenix (SPX).

In addition to the actinides, the spent fuel contains the fragments from the fission process, many of which are radio-active. Particularly worrisome are some of the long lived species, and in particular $^{99}Tc$ and $^{129}I$, which, though much less radioactive than the actinides, may in the long run diffuse in the biosphere and be selectively absorbed by living organisms. Therefore the ADS programme foresees also the possibility of transmuting these potentially offending elements into stable species using captures of some of the extra neutrons produced by the fissions (fortunately this transmutation produces little extra energy). Therefore an important aspect of the ADS programmes addresses also this task.

## 4.—THE NEED FOR A DEMONSTRATOR

The scientific feasibility of ADS has already been proven in experiments such as FEAT and TARC. There is no need for more experimental evidence concerning the central ideas of ADS and ADT (Accelerator Driven Transmutation). However, more experimental accuracy is needed both in *nuclear physics* and in *Energy technology physics.* For the former it is worth underlining the need for better and more comprehensive data of neutron cross sections in a large variety of nuclei. Current discrepancies in neutron integral parameters and neutron flux functionals are much higher than 1% depending on the nuclear libraries used, and this value could be reduced by appropriate experiments. For the latter, material corrosion and material endurance in operating conditions must be known better for a proper choice of reactor and target materials.

A considerable amount of R&D is on-going in many countries on subjects specific to ADS. The underlying basic physics processes have been investigated in many Laboratories in Europe and elsewhere. Most of these activities relate mostly to separate aspects of the programme and have been performed only at a laboratory scale. It is now necessary to proceed to a global demonstration of the operation and safety of the complex as a whole, under all possible operation regimes and at a sufficiently large scale to become the precursor of the industrial, practical scale transmuter. This device could become the focal point of a wider, co-ordinated effort on an European basis.

The demonstrator programme should be of a sufficiently large breath to permit to explore and eventually master most of the critical issues associated with the technology of the ADS concept. However the demonstrator is not yet the prototype of the industrial device, although most of the problems of the latter should be explored separately and solved in realistic conditions by the demonstrator. The realisation of a demonstrator is deemed inevitable to make real progress in the field. In addition, the practical realisation of a unique European demonstrator constitutes the fastest and most cost effective way to conclusively assess the potentialities and the feasibility of a full-scale industrial programme based on ADS. Hence a European demonstrator is along the "critical path" of the programme and should be realised as soon as possible: we shall use for it the name of ASAP_DEMO.

The main parameter of ASAP_DEMO is the maximum produced thermal power $P_{max}$. This has already been indicatively set by the Advisors Group to be of the order of 100 MWatt. The TWG believes that the choice $P_{max} \approx 100$ MWatt is indeed close to its optimal value. (For $P \approx 100$ MWatt the incineration rate will be of 38.8 kg/year). A much larger power (for instance $P_{max} \geq 250$ MWatt) would substantially complicate the realisation and the operation of the complex and increase its costs. Conversely, a much smaller power (for instance $P_{max} \leq 10$ MWatt) has significant problems. For a given fuel mass, a lower power will reduce both the fraction undergoing transmutation and the power density, which may indeed become insufficient to attain a significant, integrated effect on the fuel, in a realistic time.

There is no specific need at the first ASAP_DEMO stage to make secondary use of the produced heat and the produced 100 MWatt are to be "thrown away". A relatively low operating temperature can be used for the fuel and in the successive heat extraction process.

An important part of the programme is the investigation of the transmutation capabilities of the ASAP_DEMO for long lived fission fragments, and in particular $^{99}Tc$ and $^{129}I$. An appropriate set-up at the periphery of the core should be planned and operated in parallel with the rest of the demonstrator.

The mission of the ASAP_DEMO can be summarised as follows:

(i) operability of the accelerator/spallation target/Tank complex in realistic conditions and with a sufficient power (100 MWatt). The initial fuel could be an existing U-Pu oxide, like for instance the second, unused load of SPX or an equivalent high reactivity fuel of commercial availability;

(ii) innovative Fuels and fuel cycle qualification and operation;

(iii) demonstration of the capability to transmute various actinide fuels and

(iv) assessment of the capacity to transmute long lived fission products.

An ADS facility can be split in different basic subsystems or components that could be studied separately. The coordinated R&D programme can take this feature into account and a few *experimental facilities* could be devised to study a given problem (f.i., reactor cooling) with different options. Those experimental modules could help reduce the time needed to make the final choice for the ASAP_DEMO design and must therefore be defined within the coordinated programme. It is worth emphasising that *internal coherence* of the ASAP_DEMO is a fundamental requirement. Hence the modularity can be a tool to ease R&D, though it is not an objective per se and the modular research activities must be properly integrated.

Although uncertainties are still significant for some properties (f.i., corrosion rates and material damage) very complete numerical simulation studies could be carried out for some ASAP_DEMO conceptual designs. This point seems in agreement with some considerations of the 5$^{th}$ Framework Programme action for "Nuclear fission" studies.

## 5.—THE BASIC COMPONENTS OF THE ASAP_DEMO.

### *5.1.- General considerations.*

Of primary importance in the definition of the general components of the ASAP_DEMO are the critical safety functions:

(i) *Safe shutdown.* The multiplying medium must operate in a sub-critical mode at all times, controlled by the accelerator (power excursions and fuel evolution, etc.). Redundant and diversified accelerator beam switch off mechanisms must be provided to shutdown the ASAP_DEMO. Shut-down rods are also to be considered.

(ii) *Decay heat removal.* Redundant and diversified means must be provided for the removal of the produced heat. Consideration should be given to decay heat cooling with natural circulation.

(iii) *Radioactivity confinement.* Containment barrier (structural and confinement to radio-active releases) to be guaranteed in all plant conditions. Containment isolation on penetrating lines must be provided on demand.

Whenever related to our configuration, design criteria and requirements are mainly to be derived from the European Utility requirements (EUR), as the most updated set applicable to the next generation of reactors.

The physics of ADS shows several degrees of freedom that can be managed in the design of the ASAP_DEMO. Additionally, physical interconnection among the ASAP_DEMO variables must be taken into account in order to reach a coherent, flexible and useful design. In the following, the ADS degrees of freedom are taken into account setting up the ASAP_DEMO parameters.

Once the power is set, the next most important parameter for the ASAP_DEMO is the operating range of multiplication coefficient $k_O$[3]. Evidently, the limit $k_O = 1$ corresponds to an ordinary critical reactor. During the ASAP_DEMO phase it should be possible to explore values of $k_O$ sufficiently close to 1 ($k_{max} = 0.98$), although the limit $k_O \approx 1$, which corresponds to a critical reactor, is not to be attained. This implies a licensing procedure which is in practice not too dissimilar to the one for a critical reactor.

The choice of $k_{min}$, the minimum value of $k_O$ for a given produced power $P_O$ determines the required neutron yield from the spallation target and therefore the parameters of the accelerator. With such configurations[4], for a given total power in the device, it would be

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[3] $k_O$ is defined by the relation $N_{tot}/N_{acc} = 1/(1-k_O)$, the ratio between total number of produced neutrons $N_{tot}$ and the accelerator supplied neutrons, $N_{acc}$.

[4] For a specific fuel composition, the value of $k_O$ is determined tuning the mass of the fuel (buckling). If for instance this mass is reduced, $k_O$ will drop and, with it, the produced total fission related power. However the neutron flux is only slightly reduced, since it is boosted by the higher transparency of the less fuelled medium. This is the so-called TARC effect. Hence, contrary to power, the specific power is only a weak function of fuel mass and therefore of $k_O$ for a given accelerator performance. It is therefore

possible to greatly boost (i) the neutron flux, (ii) the specific power and (iii) the burn-up rate, but at the price of a higher beam power. The smallest value of $k_o$ which seems appropriate for Pmax =100 MWatt is $k_{min}$ = 0.80. Even lower values could be achieved, but at a power $P_o$ smaller than $P_{max}$.

Given that proton beams are the most efficient to produce spallation neutrons in a target of high Z (see Sect. 5.4), the choice of the main characteristics of the beam, that is its energy and its intensity, is mostly influenced by two physical quantities: the neutron production rate in the target per proton and per GeV and the fraction of beam energy deposited in the entrance window of the target. As implied in Sect. 4 the first quantity reaches its optimum value for protons of energy equal to or higher than 1 GeV. The second quantity is a decreasing function of the beam energy (see Sect. 5.3). Finally, for a given number of spallation neutrons (as required by the characteristics of the chosen sub-critical core) higher energies imply smaller intensities and therefore a reduction of both the technical challenge and the mechanical and thermal stresses on the target window.

Thus, aside from technical, cost and construction time considerations, the physics of spallation and of energy deposition favour the choice of an energy of the order of 1 GeV or more. In Sect. 5.2 we discuss some aspects of the technical issue and we defer the cost analysis to a future report.

Once the values or at least the required range of variability of $P = P_{max}$ and $k_{min} < k_o < k_{max}$ have been identified, we can work out the current $i_{acc}$ of the accelerator for a given (proton) kinetic energy $T_p$. Let us assume for instance for the chosen nominal power P = 100 MWatt and $k_o = k_{max} = 0.98$; we find i = 1.75 mA at the PSI cyclotron energy Tp = 600 MeV and i = 1.35 mA at the LAMPF LINAC energy, $T_p$ = 800 MeV. Alternatively, the condition ko = 0.98 could be achieved for instance at $T_p$ = 1.0 GeV but at about half of the present PSI current, $i_{acc}$ ≈ 0.82 mA. Therefore as long as $k_o$ ≈0.98, the requirement of the accelerator are within existing accelerator performances. In the case of ko = kmin = 0.75, again for P=100 MWatt we find respectively $i_{acc}$ = 22 mA ($T_p$ = 600 MeV), $i_{acc}$ = 10 mA ($T_p$ = 1 GeV). In these conditions the neutron flux and therefore the specific incineration rate (per unit of fuel mass) are incremented by a factor about 7.

In order to prepare for the two examples described in Sect. 5.2.2 it is worth noting the consequences of an increase of energy beyond 1 GeV on the intensity requirements. For instance, if we consider a proton kinetic energy of 1.5 GeV, the accelerated current required for $k_o$ = 0.98 is extremely conservative, $i_{acc}$ ≈ 0.55 mA. For lower $k_o$ values the current is correspondingly larger, but still within reasonable values. For instance for $k_o$ = 0.95, 0.90, 0.80 the corresponding values are $i_{acc}$ = 1.36 , 2.73 , 4.1 mA, respectively.

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possible to realise limiting configurations in which high power densities are produced and which make use of (i) an intense proton beam, (ii) a smaller amount of fuel with (iii) a very modest k-values.

### *5.2.- The accelerator.*

*5.2.1 -Technical options.* One meeting of the TWG has been dedicated to a critical discussion on the accelerator choices, to which several European experts in the field have been invited and whose cooperation we wish to acknowledge. Two alternatives, based on well established technologies, can be envisaged in order to fulfil the indicated requirements for the accelerator:

1.-super-conducting cavity LINAC's, for which a vast experience exists in Europe, including on the industrial production of the cavities and of the associated RF sources, especially as a consequence of the realisation, now fully operational, of LEP200[5] at CERN and of the work at DESY (Germany) and elsewhere (Italy, France) in association with the TESLA[6] programme.

2.-Isochronous cyclotrons, for which the world reference with respect to the ADS question is PSI (Switzerland). In the countries presently involved in the TWG, there is also a strong experience accumulated at the GANIL (France), CAL(France) and LNS (Italy) facilities. The guiding magnetic field can be produced either by ordinary magnets (PSI, GANIL, CAL) or super-conducting coils (LNS).

*5.2.2.- Two possible schemes.* It is not the aim of the present document to provide even a modest coverage of the number of options which can be considered based on the present state of the art of the high intensity accelerator technology and on reasonable expectations concerning its evolution. We shall only sketch two examples which illustrate how the LINAC and cyclotron options could be implemented.

1.- *Option for a high energy facility.* The TWG has taken note with interest that the LEP200 accelerating system (both cavities and RF sources) may become available at the end of operation of the LEP200 Collider, which is expected to occur by about 2001. The possible re-deployment of this accelerator system for a future proton LINAC on the ASAP_DEMO site has been investigated at CERN and elsewhere (Italy) and it appears promising. However the system as such needs some modifications since protons, unlike electrons, are not relativistic, especially in the early stages of acceleration. In short, the shape of the elementary cavity volumes must be altered: from an original spherical shape they must become roughly elliptical in order to cope with the slower speed of the protons maintaining of course the same resonance frequency[7]. Prototype cavities with these properties have been successfully tested at CERN.

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[5] The LEP200 programme ultimately consists of about 3.6 GeV gradient for the continuous acceleration of relativistic electrons and positrons with a current of up to 7 mA.

[6] The TESLA programme aims at the realisation of advanced super conducting cavities, of high gradient and lower cost in order to open the way to the realisation of a Linear Collider in the 1/2 TeV range and eventually beyond.

[7] Of course the rest of the system, namely the general structure, the cryostat, wave guides, the RF source, controls etc. can be used without changes.

A preliminary study shows that directly using a large number (about 100) of LEP200 $\beta$ =1 cavities and adding only two different geometries, optimised for lower beta values, a large part of the accelerating system of LEP200 could be used to build a LINAC able to accelerate protons from about 200 MeV up to 1600 MeV, with the same current as that of LEP200, namely about 8 mA, though smaller currents are also possible. The energetic efficiency, i.e. the fraction of the mains power transferred to the beam, should be very high (of the order of 50%).
However, the LEP200 technology based on niobium sputtered copper cavities is not immediately suitable to accelerate protons of less than 200 MeV. Therefore a front end of a different type must be considered. The TWG is not yet in the position to indicate a precise choice, though several possibilities are under consideration, eventually to be used in cascade, namely: (i) Pure niobium cavities, as developed by TESLA, (ii) a standard (warm copper), commercially available Drift tube LINAC structure, (iii) a compact super-conducting cyclotron.
As of today, the possibility (i) is being developed in Italy in the frame of TRASCO programme. On the other hand, there is already a significant experience on option (ii) from the LANL facility which is already able to deliver a proton bunch intensity well above that required by the ASAP_DEMO. Coming now to the possibility (iii), it should be noted that the choice of frequency for LEP200 (352 MHz) is optimal since it permits to have a large beam hole, thus minimising halo losses. The cyclotron design allows the use of a sub-harmonic of such a frequency, f.i. 70.4 MHz. Therefore a relatively low energy proton beam accelerated with a cyclotron could in principle be subsequently injected in super-conducting LINAC structures. On the other hand, the experience on this type of injection is very limited. At any rate, it appears that a matching section will be required in order to adapt the transverse and longitudinal emittances between the two machines.
The TWG has also taken note of the vigorous on-going development work in France and elsewhere on suitable ion sources and the RFQ-structures necessary for the first few MeV in the full LINAC alternative (France and Italy).
In spite of the large physical dimensions ($\leq$ 1 km over-all length) and the somewhat oversized expected performances, the proton accelerator derived from LEP200 is a promising possibility for the ASAP_DEMO, since it will make use of the very large development work already done and it could be financially attractive because of the investments already made. The TWG recommends that the possibility of using the LEP200 cavities -- after the termination of the CERN programmes -- should be further pursued.

2.- *Option for a low energy facility.* Another possibility, reviewed by the TWG, is a sector focused cyclotron based on the parameters of the PSI cyclotron, successfully operated since about twenty years, but with significantly increased energy and/or current. This solution offers the possibility of a much more compact structure with a much smaller number of components and thus will offer an

attractive possibility for future "commercial" applications. However for the ASAP_DEMO it offers far less flexibility in the choice of running conditions than the one of the LINAC option. The optimum proton energy for this configuration appears to be in the range 600 ÷ 800 MeV, somewhat smaller than the one of the LINAC, with an accelerated current which can be ultimately of the order of 10 mA or slightly higher. It is not possible to reach the full energy in one single machine stage. Therefore the machine, like at PSI, is to be split into two parts, an "Injector cyclotron" of about 100 MeV, followed by the final "booster". The magnetic structure could be either normal or super-conducting, while the RF made with ordinary copper or aluminium cavities is adequate.

A relatively delicate element of the cyclotron is the extraction of the intense proton beam which must be performed with very high efficiency to minimise activation ($<< 10^{-3}$ relative losses). The PSI operates on a single turn extraction, which in turn requires a good orbit separation at the top energy. A more attractive method, which however needs to be further investigated, would consist in accelerating singly ionised hydrogen molecules ($H_2^+$) and to "strip" them into two individual protons (with the loss of the binding electron) at top energy, doubling the current and halving the magnetic curvature, before bringing them to the extraction channel.

*5.2.3.- Comments and recommendations.* An important element for the accelerator of the ASAP_DEMO is a high reliability in continuous operation and in particular the absence of "beam glitches", namely of short interruptions of the beam current. While the LEP200 super-conducting LINAC has demonstrated a remarkable level of continuity of operation, since a single short glitch would imply the immediate loss of the colliding beams, at PSI some beam instabilities have been observed, due to discharges in the RF-feed through to the cavities. It is believed that this problem can be overcome with a more advanced design of such components[8], which are known to operate without such inconveniences in other installations (CERN).

It is expected that both accelerator schemes (LINAC and cyclotron) will have sufficiently low beam losses to permit "hands-on" maintenance of the bulk of the components, like it is the case for PSI today. Both solutions offer highly reliable and redundant methods to control the beam current and to switch it off extremely quickly (a few μs) and reliably if and when required by the sub-critical unit.

Therefore the TWG is of the opinion that an accelerator with the characteristics required by the ASAP_DEMO could be build successfully in Europe on a relatively rapid time scale. The TWG also recommends that the intense model work on the super-conducting cavities, on the RFQ front end and on the cyclotrons (both with normal and super-conducting coils) be vigorously pursued in order to make a final choice on the accelerator configuration in a near future.

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[8]New cavities are under development also at PSI.

### *5.3.- The beam window.*

The proton beam from the accelerator must penetrate in the sub-critical environment through a thin beam window. This window, or eventually a second window, must also be an element of the boundaries to the main containment volume. The window must present all guaranties of safe operation and indeed it represents per-se a major element of the R&D. Current practice (PSI, ISIS, CERN etc. ) indicates that power densities of the order of ≈ 20 $\mu A/cm^2$ for minimum ionising protons, (corresponding to 1.25 $10^{14}$ $p/cm^2/s$) offer mechanical stability and endurance to radiation damage of the order of one year. The energy losses due to this current density at minimum ionisation dissipate as well about 40 Watt/g actinide metal, about a factor three less than what is customary in the SPX fuel (120 Watt/g).

Since the radiation damage due to charged particles is a local phenomenon, higher current capability can be achieved using a wide beam spot at the window, which is realised with an appropriate optics (emittance blow-up and high-$\beta$). For instance a current of 5 mA will require an effective surface of as much as $5 \times 10^{-3}/2 \times 10^{-6} = 250\ cm^2$. High(er) currents, though conceivable in principle, become progressively harder because of the larger and more complicated window design.

For a given power and multiplication factor P and $k_o$ respectively, the specific energy loss and therefore the local radiation damage in the window is a rapidly decreasing function of the beam kinetic energy, since (i) the current needed to produce the required number of spallation neutrons decreases with $T_p$ and (ii) the specific ionisation losses is also significantly decreasing with $T_p$ (in the $T_p$ domain of practical interest). Therefore, minimising the beam load on the window requires the highest possible proton energy from the accelerator. Therefore the above choice of a high energy accelerator, in the region of $T_p \approx 1.5$ GeV is vastly reducing the demands on the window.

The beam window(s) are generally subject to pressure differentials, both continuous and accidental, depending on the configuration. For instance, a containment window between the vacuum of the accelerator and the rough vacuum region of the spallation target may be relatively thin since it is submitted to small differential pressures. A thick window, deeply immersed by a long tube in the molten lead, is instead subject to a continuous pressure of up to many tens of atmospheres. The dissipated beam power is proportional to the mass of the active part of the window, which in turn is a function of the pressure differential. While thin windows may be naturally cooled by radiation, thick windows require ad-hoc cooling devices, most likely the molten metal with which it is in contact. Multiple Coulomb scattering in the window material is by no means negligible with respect to the emittance of the beam and it must be carefully accounted for in the design of multiple window barriers.

### *5.4.- The spallation source.*

The performance of the spallation neutron source of the ASAP_DEMO is within the expected performance of several of the next generation, projected accelerator driven Neutron sources, amongst which we mention the ESS (European Spallation Source) and the

corresponding US (SNS) and Japanese (OMEGA) programmes. In these projects the characteristics of the required proton beam (i.e. *average* proton current and energy) are rather similar to the one presented here, except that their beam has to be pulsed[9] rather than being continuous, which adds further difficulties to the realisation of the target with respect to our application. Smaller projects are also on-going, amongst which is worth recalling SINQ ($\geq$ 0.85 mA[10] at 590 MeV) which is under realisation at PSI and the Austrian project AUSTRON. Finally , in the UK, the ISIS spallation source has been operated very successfully over the last several years with a (pulsed) proton beam of an average current of 0.75 mA[11] at a proton energy of 800 MeV. Therefore, a considerable amount of potential "cross-fertilisation" in the related R&D is available between these projects and the ASAP_DEMO.

As already pointed out, the most suitable target material is by far lead or eventually lead/bismuth eutectic mixture[12]. The power dissipated by the beam in the target is typically 825 kWatt[13] for $T_p$ =1.5 GeV and $i_{acc} \approx 0.55$ mA, corresponding to $P_o$ = 100 MWatt and $k_o$ = 0.98. For lower values of $k_o$ and for a constant fission power, the power dissipation grows like $1/(1-k_o)$ and it might be as much as a factor 10 larger for $k_o = k_{min} = 0.80$. Therefore the target must be made out of molten lead or Pb/Bi.

Two possible conceptual geometries are possible for the target with a penetrating downward going proton beam. In one alternative the coolant of the sub-critical medium (lead or Pb/Bi in this case) is also the spallation target for the proton beam. This method, which is the simplest, implies full mixing of the spallation products with the activation due to the fast fission neutrons. It also implies that the containment barrier must be crossed by the proton beam, through an appropriate window. The beam tube goes deep inside the molten coolant and the pressure on the window is high, of the order of several bars.

A more elaborated scheme would imply a separation wall between the spallation target, and the sub-critical medium in which it is imbedded. This removes mixing of spallation and other fragments and constitutes a first barrier of containment for the sub-critical volume. The separation walls will be exposed not to the proton flux, which will come to rest in the spallation target volume, but to the (fast) neutrons produced both by the target and the sub-critical medium. The radiation damage and therefore the structural lifetime of these elements will then be comparable to the one of the fuel cladding.

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[9] In order to realise the short time bursts required by the neutron source, protons must be stored in an accumulation ring, between the accelerator, in all cases a SC-LINAC, and the spallation target. Pulsing the beam typically at 50/60 Hertz produces thermal shock waves.

[10] Beam losses from a 1.5 mA beam at the pion production target. The present target is zircaloy. A lead or mercury target is foreseen, in order to increase the neutron yield.

[11] The ISIS repetition rate is 50 Hertz and the pulse duration is 400 ns. The average proton rate is 1.25 $10^{15}$ p/s, corresponding to an average dissipated power of 600 kWatt.

[12] Some of the spallation target projects are considering mercury as target material. In our case, in view of the strong neutron flux emitted by the sub-critical region, activation problems discourage the use of this target element.

[13] This figure is about 50% larger than the present operational level of ISIS and SIN-Q.

In the separate target alternative, the target volume can be filled with molten lead or Pb/Bi either fully or partially. If it is fully filled, the target window must go deep into the liquid and withstand substantial pressure as well as the passage of the beam. If the target is only partially filled, windowless geometries are possible, in which the beam hits the liquid top layer directly. In this case the region above the liquid will be primarily vapour at very low pressure though contaminated by volatile spallation fragments. Therefore the containment window can be far away from the spallation volume and it must withstand only very small pressure differential, assuming that the proton transport is performed in an evacuated pipe. The cooling of the spallation liquid can either be performed by circulation of liquid of by letting the liquid vaporise in the beam impact region, followed by cold trapping.

It is evident that a substantial amount of R&D is required also in this domain: important areas are amongst others, the cooling method, thermal shocks due to beam variations, radiation damage and spallation product containment.

The TWG believes that the spallation target assembly should be extensively tested with a suitable accelerator beam as a separate component, before coupling it to the sub-critical medium.

### *5.5.- The sub-critical system.*

*5.5.1- Functions of the sub-critical system.* The sub-critical system begins outside the spallation source region, and comprises the fuel and the associated handling devices if any, the coolant needed to extract the power and the associated components, the vessel which contains all these elements with the associated closing structures.

The main functions of this sub-critical system are the neutron multiplication, in the fixed range of k value, the power production (100 $MWatt_{th}$) and its extraction in normal, abnormal and accidental conditions, and the radioactivity containment together with the rest of the overall plant.

Nuclear wastes to be transmuted, both actinides and fission products, will be distributed in the sub-critical system. The actinides, together with other nuclear materials aimed at neutron multiplication, inside the fuel and the fission fragments probably as targets in the reflector.

It is agreed that in order to efficiently transmute minor actinides a fast neutron spectrum is needed.

*5.5.2.- Fuel.* Use of solid fuels allows to obtain very hard neutron spectrum, with large excess of neutrons. Such solid fuels based on oxide are very well known, at least with uranium and plutonium, in a wide range of temperatures and operative conditions including accidental transients. Such solid fuels have been currently used up to plutonium enrichment as high as 35%, and have been qualified together with their cladding. Enriched uranium up to 20% could be also used.

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