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# PROJECT LAESA FOR DEVELOPMENT OF AN ENERGY AMPLIFIER

*On January 21 in the SNE's "Jueves Nucleares" (Nuclear Thursdays), an interesting talk was given by Angel Pérez-Navarro, a researcher for 29 years in the former Junta de Energía Nuclear, today CIEMAT, subsequently Vice-Rector for Research at the Universidad Alfonso X el Sabio and currently General Director of LAESA.*

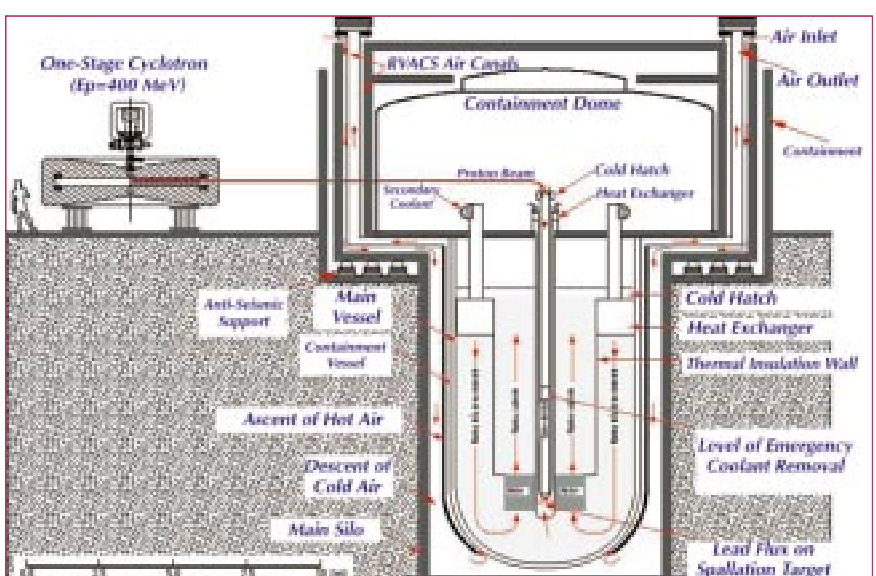
*Since development of the Energy Amplifier is what could be called a "boundless" issue, we have decided to publish the article in this international issue of Nuclear España.*

## INTRODUCTION TO THE ENERGY AMPLIFIER

The Energy Amplifier/Transmuter (AET) has been extensively described in an article published previously in this Magazine [1] and in the references cited therein. The AET belongs to the family of accelerator-maintained systems (ADS) and potentially appears as the most promising configuration for developing these systems.

Basically, the AET is a subcritical nuclear system maintained by neutrons generated by the impact of high-energy protons, in the range of hundreds of MeV, on a heavy material through the well-known phenomenon of *spallation*. After the proton impacts a nucleus of the heavy material used as the target, this process generates an intranuclear cascade that releases high-energy nucleons and leaves the nucleus in an excited state that results in the release of more nucleons and radiation, or in fission. The nucleons thus generated lead to a repetition of the phenomenon in an internuclear cascade, producing in the end a significant performance that is measured by the number of neutrons generated by the incident proton, which depends on the proton energy and the material used as a target. For an energy of 380 MeV and a lead target, this performance is of the order of 7 neutrons released per incident proton.

Along with the *fissionable* material, the subcritical assembly contains a *fertile* element in order to keep the fuel level, and thus the system reactivity, practically constant throughout long operating periods (in simulations, burn-ups of up to 160 GW·day/ton are obtained [2]), without requiring refuelings if the technical conditions of the fuel assemblies and structural elements of the AET so permit. It is possible to design AET for operation with a fast neutron spectrum or a thermal spectrum. In the case of a fast system, lead is used not only as the spallation target but also as a coolant for removal of heat generated in the core. The reasons for this choice are, on one hand, that the properties of lead are suited to each of these functions (high expansion coefficient, high density, negative vacuum coefficient, low saturation pressure, reduced activation, excellent radiation shielding, minimum effective absorption section, etc.), and on the other hand lead's low lethargy, which means that on every collision with lead nuclei the neutrons only lose 0.1% of their energy, thus permitting their energy to decrease from the level of 100 keV to 0.1 eV in such small steps that they are able to access the narrow resonances in the effective absorbtion section that most elements have in this spectral range. This increases the probability of these processes by up to five orders of magnitude and, as a result, significantly increases the performance of transmutation processes.




FI. Energy Amplifier/Transmuter Demo

TABLE I
Parameters Assumed for the Preliminary AE Demo Project

| | | |
|---|---|---|
| **GENERAL FEATURES** | | |
| Gross thermal power | 1 -- 250 MW | |
| Coolant | Molten Lead | |
| Subcriticality factor, k | < 0.98 | |
| Energetic gain | 60 | |
| Acc. electr.consumption | 10 | MW(elec) |
| **VESSEL** | | |
| Height | 10 | m |
| Diameter | 6 | m |
| Thickness | 2.5 | cm |
| Material | Steel | |
| **CORE** | | |
| Configuration | Hexagonal | |
| Number of hex. rounds | 7 | |
| Number of pins | 169 | |
| Total length | 1.5 | m |
| Flat to flat | 208 | mm |
| Pitch | 16 | mm |
| Initial fuel | (Th-U)O2 | |
| Fuel mass | 10 | Ton |
| Eq. inner radius | 0.29 | m |
| Eq. outer radius | 1.23 | m |
| Av. Core power density | 250 | W / cm$^3$ |
| Burnup GW.day/ton | 80 | |
| Max. fuel temperature | 910 | ºC |
| **PINS** | | |
| Outer diameter | 8.2 | mm |
| Cladding thickness | 0.35 | mm |
| Cladding material | HT-9 | |
| Active length | 120 | cm |
| Plenum length | 30 | cm |
| Fuel-cladding gap thickness | 0.1 | mm |
| Inner void diameter | 1.1 | mm |
| Max. Int. cladding temperature | 550 | ºC |
| **ACCELERATOR** | | |
| Configuration | Linac + Cyclotron | |
| Efficiency | ≥ 50 % | |
| Energy | 380 | MeV |
| Maximum current | 12.5 | mA |
| Nominal beam power | 5 | MW(elec.) |
| **PRIMARY COOLING SYSTEM** | | |
| Material | Liquid Lead | |
| Weight | 2700 | Ton |
| Pumping | Natural Convection | |
| Convection generated pressure | 0.08 | bar |
| Height convection | 6 | m |
| Heat exchangers | 4 x 62.5 MW | |
| Core input temperature | 400 | °C |
| " output " | 500 | °C |
| Lead speed in core | 0.7 | m/s |

A system based on the AET has two major applications [2]:

1) Radioactive waste transmutation, thus easing the storage requirements of this waste. Transuranides are used as the fissionable element in the fuel, and the neutron flux of losses is used for transmutation, by resonant absorption, of the fission products.

2) Nuclear energy production, with greater intrinsic safety and less waste production.

The scientific viability of the AET has been demonstrated in experiments carried out in CERN:

a) FEAT [3], which demonstrated the net energy gain by comparing the energy produced by fission with the energy consumed by the accelerator system, and

b) TARC [4], which proved the ability to transmute radioactive elements. The next stage in the development of this concept involves a demonstration of its technological and economic feasibility.

## INTRODUCTION TO LAESA

LAESA is a partnership that was created in Zaragoza in March 1997, for the purpose of industrially developing the AET as an element transmuter and energy producer.

LAESA's members include public institutions (CIEMAT, CRS4 (Cagliari, Italy), ACEGAS (Trieste, Italy), Instituto Aragonés de Fomento, etc.), enterprises (Abengoa, Ingesgrup/Technicatome, TAIM/TFG, Novotec, Confederación de Empresarios de Aragón, CAI, Ibercaja, etc.) and private parties from Italy, France and primarily Spain.

The company holds the exclusive worldwide rights to patent PCT/EP94/02467: *"Energy Amplifier for Clean Nuclear Energy Production Driven by a Particle Beam Accelerator"*, which covers the AET patented by this concept and a wide range of possibilities concerning spectrum, fuel, moderator, coolant, etc. for energy production. In addition, the CERN has granted to LAESA the right to use a second patent, PCT/EP97/03218: *"Neutron Driven Element Transmuter"*, covering the use of resonant absorption for radioactive element transmutation and radioisotope generation.

Since its creation, the company's activities can be summarized in terms of three fundamental milestones:

1. Acquisition of the exclusive rights to the Energy Amplifier patent (March 1997).
2. Execution of the preliminary project for a 250 MW Demonstration Prototype (July 1998).
3. Approval by the Board of Directors and ratification by the Assembly of LAESA's development strategy (October 1998).

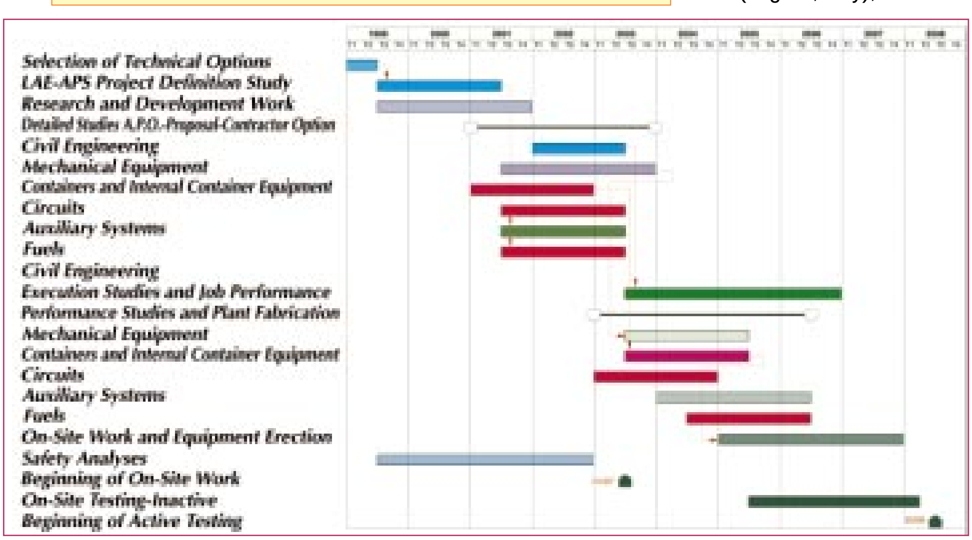
The first point is described hereinabove, and the other two are described in the following paragraphs.

## PRELIMINARY PROJECT FOR A ENERGY AMPLIFIER DEMO

By using the conceptual design of a 100 MW AET, extendable to 250 MW (Figure I), which was developed in EET-CERN by C. Rubbia and his collaborators and the basic parameters of which are summarized in Table I, LAESA has completed the preliminary project for a demonstration plant. To do so, nine engineering studies, commissioned and coordinated by LAESA, have been carried out. The fundamental conclusions of these studies, aside from the main component design, are as follows: a) the technologies required by the AET are available with current state-of-the-art, but R&D is required for almost all of them: reprocessing, fuel manufacture, accelerator, spallation target materials, molten lead corrosion, etc.; b) the cost of the Demo exceeds 70,000 millions pesetas (420 million euros); and c) the time required for execution is about 9 years (Figure II).

## LAESA'S STRATEGIC PLAN

The definition of a strategic plan to achieve LAESA's corporate aims has



FII. Schedule for Construction of the AET Demo accounted for the following:

a) AET's importance as a waste transmuter for nuclear power plants, as expressed in the favorable reports of several committees and agencies (EURATOM STC, NEA/OECD, IAEA).

b) The possible emergence of a European initiative to develop this concept, as evidenced by the existence of a tripartite committee requested by the Ministries of Research of Italy and France and the Ministry of Industry of Spain, which should define the lines of R&D required by the ADS and the methods for accomplishing it. This Committee recommends that construction of a Demo be included in this public research program and that it be based on an industrial platform [5].

c) Inclusion of Transmutation in the top priority actions within the area of nuclear fission of EURATOM's V Framework Program.

d) The need to find industrial solutions for two of the basic components of AET: accelerator and spallation target, as compared to the greater industrial development already available for nuclear components: pressure vessel, fuel, etc.

e) The search for greater possible social support in the region where LAESA's facilities are located, by creating a laboratory with multidisciplinary fields of application and covering areas that at present cannot be undertaken in our country due to a lack of suitable resources.

On the basis of these premises, a strategy has been approved for LAESA involving four consecutive phases as outlined in Figure III:

1. Creation of a Laboratory for studying the accelerator and other critical amplifier components, which would include a 380 MeV cyclotron and a spallation target.

2. Construction of a low-power (≤10 MW) Reduced Demo.

3. Participation in construction of the European Prototype (≈ 100 MW).

4. Industrial exploitation of the concept.

Obviously, phases 2 and 3 are closely linked to a possible though still undefined international program and cannot be specified in detail at this time. However, LAESA has already begun phase 1, the main components of which – accelerator and spallation target – are detailed in the following paragraphs. The construction schedule for the Laboratory and its basic components, estimated to last five years, are shown in Figure IV, and its cost (around 8,000 million pesetas, or 50 million euros) is detailed in Figure V.

## ACCELERATOR

The proton accelerator is one of the critical elements of the AET, since an industrial plant of this type, in addition to current intensities in the beam of the order of tens of mA, will be required to have conditions differing greatly from those normally found in research laboratories or medical facilities. Specifically, its *use on a continuous basis* will be necessary, with a high degree of reliability, easy maintenance and modularity in construction allowing for fast component replacement and simple adjustment and operation, which permits plants operation by personnel not specialized in this field.

The cyclotron appears to be the most valid alternative for the AET from an industrial point of view. Compared to linear systems (Linacs), its advantages include smaller size and lower costs, by more than one order of magnitude. Linacs easily reach and exceed the intensities

**TABLE II**
**Comparison of Parameters of Existing Accelerators and the Ome Proposed by LAESA**

| Installation/Place | Type of Accelerator | Energy | Intensuty |
|---|---|---|---|
| Harvad Cyclotron Laboratory, USA | Sincrocyclotron | 160 MeV | 5 nA |
| Lawrence Berkeley Laboratory, USA | Sincrocyclotron | 932 MeV | - |
| Uppsala, Suecia | SF- Sincrocyclotron | 200 MeV | - |
| Dubna, Rusia | Sincrocyclotron | 680 MeV | - |
| San Petersburgo, Rusia | Sincrocyclotron | 1000 MeV | - |
| Clatterbridge, UK | isochronal Cyclotron | 62 MeV | - |
| Louvain-la-Neuve, Bélgica | isochronal Cyclotron | 85 MeV | - |
| Centre Antoine Lacassagne,Niza,France | isochronal Cyclotron | 65 MeV | - |
| Orsay, Francia | Sincrocyclotron | 200 MeV | - |
| NAC, Sudáfrica | Cyclotron | 66 MeV | 30 µA |
| Indiana University, USA | Cyclotron | 210 MeV | 1 µA |
| CNRS, Francia | Cyclotron | 34 MeV | 45 µA |
| Tsukuba, Japón | Synchrotron | 500MeV | - |
| Northeast Proton Therapy Center,USA | isochronal Cyclotron | 235 MeV | 1.5 mA |
| IPNS/Argonne, USA | Linac +Synchrotron | 50 MeV (Linac), 500 MeV (Sincrotrón) | 15 µA |
| KENS-I /KEK, Japan | Linac +Synchrotron | 40 MeV(Linac), 500 MeV (Sincrotrón) | 10 µA |
| ISIS /Rutherford Lab., UK | Linac + Synchrotron | 70 MeV(Linac), 800 MeV (Sincrotrón) | 200 µA |
| LANCSE / Los Alamos, USA | Linac + storage ring | 800 MeV | 60 (100) µA |
| SINQ /PSI, Suiza | Cyclotron | 590 MeV | 1.000 µA |
| LAESA | Cyclotron | 380 MeV | 2.000 µA |

TABLE III - LAESA Cyclotron Parameters

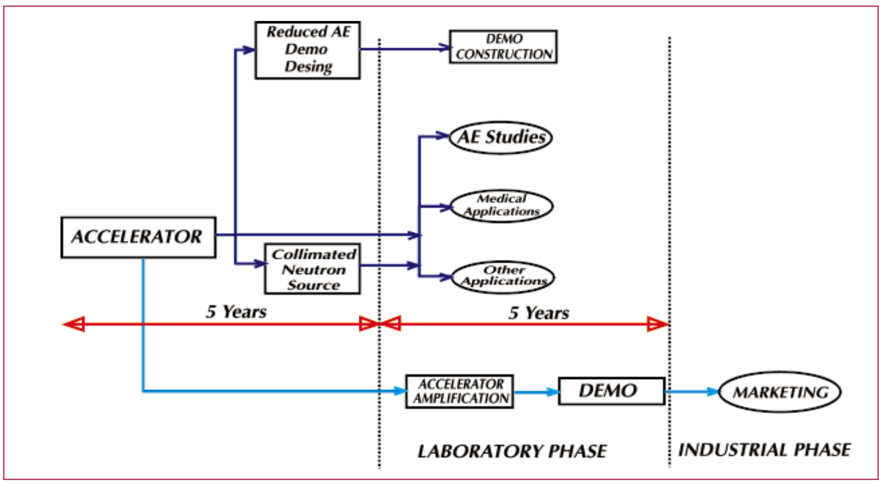
| Parameter | Magnitude |
|---|---|
| Injection energy | 20 MeV |
| Extraction energy | 380 MeV |
| Proton beam intensity | 10-15 mA |
| RF Frequency | 70.4 MHz |
| Harmonic | 10 |
| Outside diameter | 12 m |
| Number of sectors | 6 |
| Vertical gap between magnets | 0.06 m |
| Sector angle in lower/upper polar radius | 14.0/22.2 deg. |
| Spiral sector angle in maximum polar radius | 3.6 deg. |
| Total weight of iron | 1920 Ton. |
| Number of cavities | 4 |
| Type of cavity | Delta, 2 gaps |
| Voltage peak (Injection/Extraction) | 200, 600 kV |
| Radial gain per round (Injection/Extraction) | 45/18 mm |
| Total power required by accelerator | 10.02 MW |
| Total power for cavities (beam+wall losses) | 9.54 MW |
| Total magnetic power | 0.48 MW |

TABLE IV - Spallation Performances

| Energy (MeV) | Spallation (neut/proton) | Integral flux (n/s/mA) | Power for 3 10E16 n/s (kW) | Intensity for 3 10E16 n/s (mA) | Flux at r = 30 cm n/cm$^2$.s .mA) |
|---|---|---|---|---|---|
| 100 | 0.399 | 2.49 E+15 | 1203.0 | 12.03 | 6.55 E+12 |
| 200 | 1.788 | 1.12 E+16 | 536.9 | 2.68 | 2.93 E+13 |
| 300 | 4.156 | 2.60 E+16 | 346.5 | 1.15 | 6.82 E+13 |
| 400 | 6.939 | 4.34 E+16 | 276.7 | 0.69 | 1.14 E+14 |

TABLE V - Comparison of Spallation Sources

| Parameter | ISIS | AUSTRON | SINQ | ESS | FNEUT |
|---|---|---|---|---|---|
| Beam energy (MeV) | 800 | 1600 | 570 | 1334 | 380 |
| Proton current (mA) | 0,2 | 0,25 | 1 | 3,8 | ≈1 |
| Beam power (kW) | 160 | 410 | 600 | 5000 | 380 |
| Maximum current density (μA/cm²) | 10 | 18 | 25 | 90 | 3 |
| Operation | 50 Hz | 50 Hz | continuous | 50 Hz | Continuous |
| Pulse duration (μs) | 0,4 | 0,44 | - | 1 | - |
| Energy in a pulse (kJ) | 3,2 | 8 | - | 100 | - |
| Accelerator | Linac+RCS | Linac+RCS | Cyclotron | Linac+2 PCR | Cyclotron |
| Target | $(U^{238})$Ta | W5%Re | Pb(Zy-2) | Hg | Pb |
| Cooling | $D_2O$ | $D_2O$ | Pb($D_2O$) | Hg | Pb |
| Neutron flux (n/cm²/s) | $3x10^{13}$ | $\sim10^{13}$ | $1,5x10^{14}$ | $1x10^{15}$ | $\sim10^{14}$ |




FIII. Initial LAESA Development Phase.

required by the AET, but not cyclotrons, which need to increase current intensity also by almost one order of magnitude in excess of the values reached by currently operating cyclotrons (Table II). To achieve the energies needed in the beam required by the AET, a modular structure must be provided in which each stage accelerates the beam up to a certain energy by injecting it into the next one. This scheme involves a preliminary injector that brings the beam up to tens of MeV, followed by an intermediate accelerator that can reach several hundred MeV and a final accelerator that accelerates the protons up to almost 1 GeV.

LAESA is considering a system with a 20 MeV injector and an intermediate 380 MeV cyclotron with a beam intensity of the order of 2 mA. This intensity makes it possible to achieve the powers required by the experiments in this phase and the second one, which are lower than 10 MW, and is within the range of values already obtained in other cyclotrons. This value could be increased by including a second injector and making suitable modifications in the cyclotron. The selected energy permits an acceptable performance for spallation and allows for use of this cyclotron as an intermediate unit for another final one, either based on a Linac with superconductor cavities such as those in the LEP at CERN, which would require a beam at input with an energy exceeding 250 MeV, or else on a conventional cyclotron that carries the beam up to a final energy approaching 1 GeV.

LAESA has developed the design for the intermediate cyclotron as part of the preliminary AET Demo project described in section 3. The parameters of this cyclotron (Figure VI) are included in Table III. An energy of 20 MeV is being considered for the injector, which would facilitate its use in medical applications, with several different alternatives: commercial Linac, conventional cyclotron, or superconductor cyclotron with molecular hydrogen at 40 MeV and stripping to obtain 20 MeV protons.

## SPALLATION TARGET

This system is based on the incidence of a proton beam on molten lead (or the lead-bismuth eutectic if operation at a lower temperature is desired). With the accelerator described in the preceding section, this would provide a collimated output of neutrons with an integral flux of $4 \times 10^{16} n.s^{-1}.mA^{-1}$. This target would be surrounded by a solid lead block measuring 4 m. around the edge (Figure VII). Its objectives are as follows:

1) Support R&D on the AET's spallation system components;

2) Help perform transmutation and radioisotope generation studies, and

3) Generate neutron beams for multidisciplinary applications.

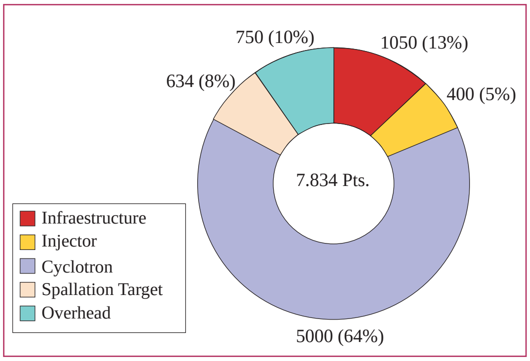
The conceptual system design has been based on the following premises:

1. The neutron source can be obtained by spallation on a lead (lead/bismuth) target of the proton beam from the accelerator proposed for this first phase of the Laboratory.

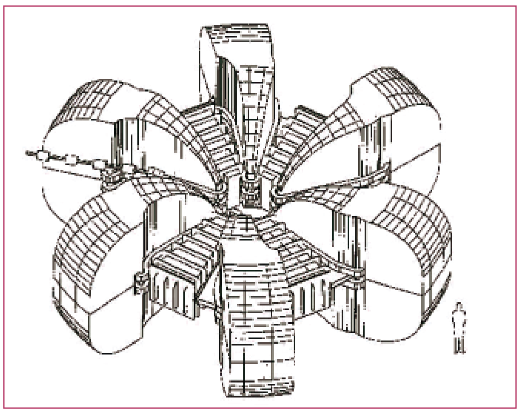
2. The source performance is strongly dependent, in terms of neutronic flux production per unit of current intensity in the proton beam, on the energy of this beam. Table IV contains theoretical estimates for these performances. An increase in the beam energy from 100 to 400 MeV increases performance by a factor of 17.

3. To obtain a flux similar to the one in a conventional power reactor, of the order of $10^{14}$ n/cm².s in positions at a distance of around 30 cm away from the beam incidence area, a current intensity of 1 mA is required in the case of a 400 MeV beam, and for 100 MeV it increases to 15 mA.

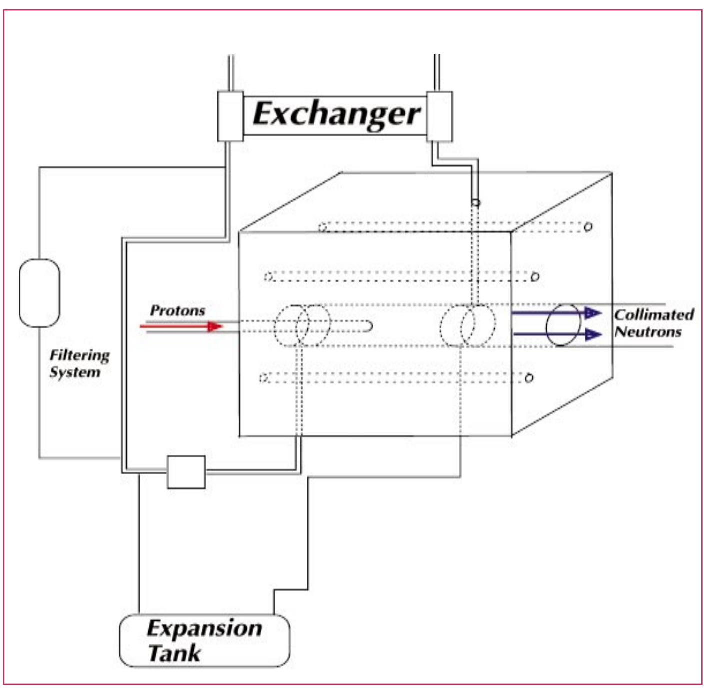

FIV. Schedule for Laboratory Development



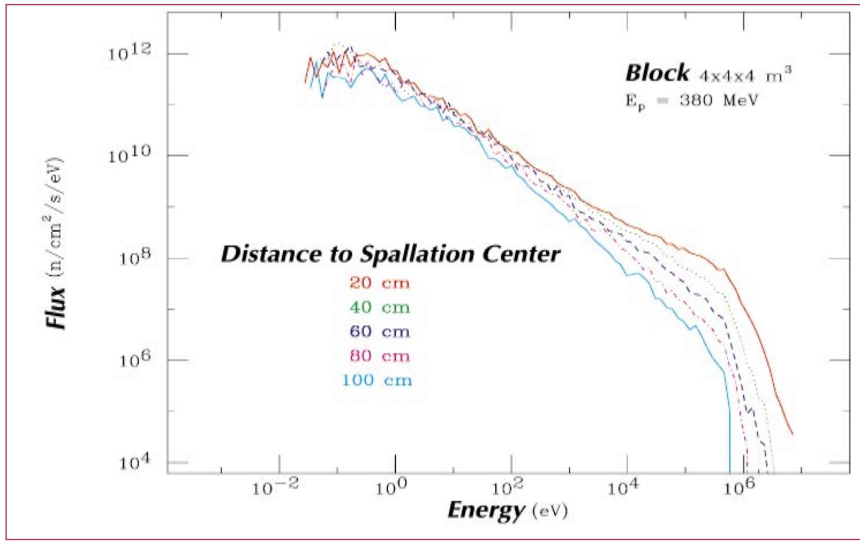

FV. Estimated Laboratory Cost



FVI. 380 MeV Cyclotron




FVII. Spallation Target




FVIII. Neutron Spectra on the Spallation Target

Obviously the flux decreases with the inverse of the square of the distance. Thus, with these beam intensities, very significant fluxes can be obtained in the experimental area ($3 \times 10^9$ n/cm$^2$.s in experiments located 50 meters away from the spallation target).

4. The powers with which the proton beam bombards the spallation target can approach values of the order of one MW. To ensure cooling and durability of the target after working continuously or during long intervals, it is advisable to use a molten lead (lead/bismuth) target which, with suitable circulation, can guarantee target cooling.

5. Having ensured the cooling and filtering of the spallation zone, it is possible to surround the target with a solid lead cover, in an arrangement similar to the one used in the TARC experiment, where the neutrons that are not initially propagated in the axial direction can be used for absorption studies on samples located in longitudinal canals in this assembly. It would be possible to perform transmutation and radioisotope generation studies with the indicated fluxes of $10^{14}$ n/cm$^2$.s. Preliminary studies carried out at LAESA indicate annual transmutation rates of 0.4% for fission products (99Tc, in particular) and 0.5% for transuranide fission.

6. The neutron spectrum emerging from this system depends on the distance between the beam incidence point and the free lead surface through which the collimated beam is obtained. As this distance increases, the spectrum's thermal component also increases (Figure VIII).

The spallation target thus defined would make it possible to have a neutron source comparable to the ones proposed in Switzerland and Austria, as shown in Table VI, and it would only be one order of magnitude less than the European Spallation Source that is pending construction approval.

## REFERENCES

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[5] C. Rubbia, Private correspondence.

## CONTRIBUTIONS

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