

# High-Intensity Proton Beam Facilities

OECD Global Science Forum Workshop on Strategic Policy Issues

Paris, September 25/26, 2000

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## 1. BACKGROUND

During the next 10-15 years, a number of OECD countries will need to make decisions about significant investments in one or more of the following areas of basic and applied research:

- ◆ Neutron spallation sources for research in the physical, chemical, and life sciences, for materials irradiation, and for isotope production.
- ◆ Radioactive beam facilities for fundamental nuclear physics research.
- ◆ Accelerator-driven sub-critical devices for transmutation of nuclear wastes.
- ◆ Particle physics facilities that use muons for colliding-beam experiments, or for producing beams of neutrinos.

Decisions in the above areas will involve distinct needs, constituencies, costs and timescales. However, the successful implementation of any of the facilities will depend on the ability of scientists and engineers to design and operate High Power Proton Accelerators<sup>1</sup> (HPPA) with beam energies in the Giga electron-volts (GeV) region, and power levels ranging from 1-5 megawatts for some applications to 50 megawatts for others. In several critical areas, the needed levels of performance greatly exceed the state of current knowledge and technological capability (e.g., ion sources, microwave accelerating structures, beam transport, high-power targets, control systems).

HPPA-based facilities are under active consideration in many countries, and there are many formal and informal technical consultations. This report focuses on general policy considerations that governments need to know about and discuss to make informed decisions during the coming years. A review of the ensemble of applications sheds light on the current state and future potential of international co-operation and co-ordination, and on possible synergies that could be realised via multipurpose facilities.

The OECD Megascience Forum Working Groups on Neutron Sources (1996 – 1998) and on Nuclear Physics (1996 – 1999) found that, given the diversity of application areas and the formidable R&D challenges, there is a distinct need for constructive interactions among persons who are responsible for advanced planning, both at national and international levels. The lack of such contacts could lead to costly duplication of effort, neglect of certain promising directions of research, and inefficient planning due to lack of knowledge about existing or planned work in other domains or other countries. Because the needed consultations should occur at the policy-making, planning and priority-setting levels, they are particularly appropriate for sponsorship by the OECD Global Science Forum. Accordingly, delegates to the Second Meeting of the Global Science Forum in January 2000 authorised a workshop based on a proposal from the delegations of France and the United Kingdom.

The workshop took place at the OECD headquarters in Paris on September 25/26, 2000. Dr. Peter Tindemans chaired this meeting of 53 representatives<sup>2</sup> from 13 OECD countries, plus representatives of the European Commission (EC), South Africa, the European Organisation for Nuclear Research (CERN), the International Atomic Energy Agency (IAEA), the OECD Nuclear Energy Agency (NEA), and the International Union of Pure and Applied Physics (IUPAP). The workshop lasted one and one-half days. Each topic was reviewed by a distinguished expert. The subsequent discussions among the participants (government officials and scientists) revealed the current status and the perspectives of the field. They are summarised in this report.

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<sup>1</sup> A non-technical introduction to the subject can be found in Appendix C.

<sup>2</sup> A list of attendees and the agenda can be found in Appendix A and Appendix B.

## 2. APPLICATIONS

### 2.1 Spallation Neutron Sources

The advantages of neutron beams for the study of the structure and dynamics of condensed matter are well known<sup>3</sup>, with numerous applications across a broad spectrum of basic and applied research: fundamental physics, condensed matter physics and chemistry, biotechnology, materials science, engineering, geosciences, and other fields. Neutron science is recognised as an important component of any well-balanced strategy for maintaining and promoting scientific excellence, technological innovation, and economic competitiveness. Neutron beams are complementary to synchrotron radiation, nuclear magnetic resonance, and other techniques.

The world currently has some two dozen major facilities for neutron scattering research, of which five are based on proton accelerators, and the remainder on nuclear reactors. The OECD Working Group on Neutron Sources, which brought together scientists and funding agency officials to develop findings and recommendations for governments, recognised that with a continuing and increasing need for neutron beams, a "neutron gap" would develop during the coming 5-15 years, when many older reactor-based sources will be shut down. The Working Group therefore recommended that, where appropriate, existing sources should be supported and, if possible, upgraded, while attention should be given to the provision of a new generation of high intensity spallation sources. The Working Group developed a global scenario comprising three major regional<sup>4</sup> sources (America, Europe, Asia-Oceania) supported by a network of smaller facilities.

Since 1998, two important reactor sources (Brookhaven and Risö) have been closed, and the construction of the FRMII reactor is well under way. The construction of the Spallation Neutron Source (SNS) has begun in the US, and a major new initiative is close to final authorisation in Japan. In Europe, the European Spallation Source (ESS) is the subject of a design study, and will require action at the political level<sup>5</sup>.

The 2 MW Spallation Neutron Source is being built at the Oak Ridge National Laboratory in Tennessee. It features a 335 meter-long linac with superconducting cavities in the high-energy section of the accelerator<sup>6</sup>. Total project cost is approximately \$1.4 billion, of which the linac and its front end constitute 26%. Scientific operations will begin in 2007. The target station will be surrounded by an initial complement of 10 "best in class" instruments. In addition to numerous technical challenges, the SNS project involves important organisational issues, since it is a collaborative effort among six independent DOE-funded laboratories: Argonne, Brookhaven, Lawrence Berkeley, Los Alamos, Oak Ridge, and the Jefferson Laboratory.

In Japan, two projects, independently proposed to two ministries, have been merged in the JAERI/KEK Joint Project, which will be built at Tokai. The neutron source, which should begin operations in 2007, will be part of a multipurpose facility for nuclear physics, research on nuclear waste transmutation, and high-energy physics. A 400 MeV room-temperature linac will inject protons into a 3 GeV synchrotron. These will then be incident on a spallation target. A superconducting extension to the linac will produce a 600 MeV proton beam for transmutation studies.

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<sup>3</sup> *Scientific Prospects for Neutron Scattering with Present and Future Sources*, European Science Foundation, 1996.

<sup>4</sup> In this report, the word "region" is used in the sense indicated in this sentence.

<sup>5</sup> The key technical parameters of new HPPA-based neutron sources are given in Table 1.

<sup>6</sup> SNS will be the first proton linac with superconducting cavities.

In Europe, the design of ESS is in the hands of the ESS Council - a collaborative effort of thirteen laboratories and research institutions from ten countries<sup>7</sup>. Its goal is to prepare a consensus design in time for a political decision in 2003 (including selection of a site), and an operational facility in 2010. Three options are being considered for the accelerator<sup>8</sup>, and two options for the spallation target stations<sup>9</sup>. The Council plans to select a preferred target station configuration by the end of 2001, and to choose among the accelerator options in mid-2002.

Those concerned with the design and construction of future neutron sources are well linked internationally. The major laboratories have close interactions in R&D activities, and sponsor the International Collaboration on Advanced Neutron Sources (ICANS) which meets regularly to exchange information and to promote collaborative projects. Scientific requirements are addressed at the biannual international conferences on neutron scattering research.

### **Conclusions**

Neutron scattering promises to deliver exciting, important results that will complement those obtained by synchrotron radiation and other techniques. Large regional spallation sources, equipped with a new generation of advanced instruments, will be among the most productive components of the global research infrastructure. High-flux reactors and smaller neutron sources will continue to play an important role. In the United States and in Japan, governments have responded vigorously to the threat of a shortage of research neutrons during the coming 10-20 years. The construction of the SNS is well under way at Oak Ridge, Tennessee, and the proposal for the joint JAERI-KEK project is now in the last stages of funding approval. It is believed that neither project will encounter insuperable technical difficulties, and that necessary R&D work can proceed in step with construction.

The situation in Europe is less advanced, and there remains a series of important questions regarding the future of neutron scattering in that region. Decisions will have to be made concerning funding arrangements, site selection, access policies, etc. While the current supply of neutrons is satisfactory<sup>10</sup>, long lead-times and high costs require that the decision-making process not be delayed too long. The size of the European neutron scattering community (estimated<sup>11</sup> at 4500) justifies planning for a multi-megawatt facility. However, scientific infrastructure policies in Europe should be based on stronger coherence among national actors. The renewed debate on this subject, linked to discussions about the next EC Framework Programme, may provide a good opportunity for undertaking a constructive round of discussions on the future of neutron sources. The difficulties should not be underestimated, on the administrative as well as technical levels, as borne out by the American and Japanese experiences.

## **2.2 Radioactive Nuclear Beams for Nuclear Physics**

The fundamental goal of nuclear physics is to understand the properties of nuclear matter, atomic nuclei, and how nuclei are built up from elementary constituents. Nuclear physics involves the study of diverse phenomena at vastly different scales, from the interaction of elementary entities (quarks and gluons) inside

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<sup>7</sup> This is the status as of the time of the workshop, and participation continues to grow.

<sup>8</sup> The accelerator options are: (1) a conventional linac neutron source, (2) a linac-based multipurpose facility that, in addition to neutron beamlines, could include facilities for nuclear physics, transmutation, irradiation, and high-energy physics, (3) a superconducting linac neutron source.

<sup>9</sup> A 5 MW short-pulse option is anticipated for all possible configurations. In addition, a second target station is being investigated, with either a 1 MW short pulse, or a 4.5 MW long pulse.

<sup>10</sup> Europe is the site of the world's leading reactor- and accelerator-based sources for neutron scattering research: ILL in Grenoble and ISIS at the Rutherford Appleton Laboratory.

<sup>11</sup> *Survey of the Neutron Scattering Community and Facilities in Europe*, ESF/ENSA, 1998.

nucleons or nuclei (including physical phenomena “beyond the Standard Model”), to the synthesis of elements in stellar interiors and supernova explosions, to fundamental interactions during the birth of the Universe in the “Big Bang”. In pursuit of an understanding of the complex interactions that occur at the nuclear level, physicists produce and study exotic unstable nuclei, or generate nuclear states of extreme density and temperature. Nuclear physics has produced an abundance of applications that benefit members of society in areas such as medicine, environmental science, and energy generation.

The OECD Working Group on Nuclear Physics proposed a globally co-ordinated vision of the future of the field, emphasising the importance of the balanced implementation of four kinds of facilities:

- ◆ radioactive nuclear beam facilities;
- ◆ multi-purpose hadron facilities with a wide variety of secondary particle beams;
- ◆ high-intensity electron-beam facilities;
- ◆ facilities for heavy ion collisions at very high energies.

High-intensity proton accelerators are vital components of the first two categories of facilities, where high intensities are needed to study processes that have very small production rates.

It is important to distinguish two types of radioactive nuclear beam facilities:

- ◆ In an ISOL (for “Isotope Separation On-Line”) or “Two Accelerator” facility, a beam of charged particles (often, protons) is incident from a “driver” accelerator onto a thick target, producing a wide range of radioactive nuclear species. These diffuse out of the target at low speed and are collected, ionised and accelerated by a “post-accelerator”, after which they are studied using specialised, low-to-medium energy instrumentation. A classification of ISOL facilities is given in Table 2 according to the type of accelerators used for the driver and the post-accelerator.
- ◆ In an “In-Flight” or “Fragmentation” facility, heavy ions are accelerated to high energies and are incident on a thin target. The produced exotic nuclear species leave the target at high speed. They can be separated in flight by appropriate arrangements of electromagnetic fields and energy absorbers, and studied via specialised instrumentation. These radioactive nuclear beam facilities use accelerators that are optimised for heavy ions rather than protons.

There is a consensus in the scientific community that these two types of facilities are complementary, and that a balanced programme of nuclear physics research includes next-generation facilities of both kinds at the national and/or regional levels. Although the present report is concerned with the ISOL technique only, it should be noted that there are near- and mid-term plans for three regional new Fragmentation machines: the soon-to-be-completed NSCL in East Lansing, Michigan, the RI Beam Factory currently under construction at RIKEN in Japan, and proposed major upgrades to the facility at GSI Darmstadt in Germany.

The proposed Rare Isotope Accelerator (RIA) project in the US would combine ISOL and Fragmentation. In this machine, intense heavy-ion beams of typically 400 MeV per nucleon would be directed at a thin target. The exotic fragments would then be passed through a separator and slowed down in a gas ion-catcher. The stopped fragments would be re-accelerated for nuclear structure and astrophysics studies. The accelerator could also produce protons with energies up to 730 MeV. This beam could be used to irradiate thick targets in an ISOL mode. In the RIA, the beams would essentially be continuous, and the driver accelerator optimised for heavy ions, not protons.

Another important innovation is being studied in the European EURISOL project. A 1 GeV proton beam would be exploited at two power levels: up to a few hundred kW, the protons would be used directly for

(mainly neutron-deficient) isotope production; up to 5 MW, the protons would produce spallation neutrons which, in turn, would induce fission in appropriate targets for the production of neutron-rich nuclear species.

The required R&D work is similar to that for neutron spallation sources. Since the radioactive nuclei emerge from the target via slow thermal diffusion, the timing information is lost, and there is no need for the accumulator/compressor rings that are required for spallation neutron sources (see Appendix C).

### ***Conclusions***

Advanced ISOL and Fragmentation facilities should be implemented on a regional and/or national basis. Advisory bodies are communicating their needs to funding agencies, and plans are maturing in a number of venues. World-wide, there is active collaboration between the different facilities, and common R&D programs are carried out. However, no joint project among the three principal regions has been proposed.

Advanced ISOL facilities are under active consideration, including those that use high-intensity proton accelerators as drivers. The option of combining ISOL with other applications (notably, spallation neutron sources) deserves serious attention. This will be implemented in the JAERI/KEK Joint Project, and is being considered in the EURISOL study. The nuclear physics and the neutron scattering communities can co-exist at the same facility, provided they can make suitable arrangements for sharing the available beam.

There are important technical problems that must be overcome for implementing next-generation ISOL facilities, but these tend to be centred on sub-systems that are downstream from the driver accelerator: high-intensity target/ionisation assemblies, efficient post-accelerators and advanced instrumentation. An ISOL-type nuclear facility can, in principle, be added to an existing HPPA without causing major disruptions.

### **2.3 Transmutation of Nuclear Wastes**

The disposal of nuclear wastes is a major concern for countries with active nuclear power programmes. It is also a preoccupation for public authorities of developing countries, whose rapidly rising energy needs in this century will coincide with a period of vigorous economic and population growth. The nuclear option is also being re-examined by energy planners who contemplate the environmental effects of burning fossil fuels.

Power reactors (those, for instance, of the light water type) do not extract all of the energy contained in their uranium (or uranium/plutonium) fuel. Spent fuel contains radioactive isotopes of various elements: heavy elements created via nuclear reactions (actinides such as plutonium and americium), and lighter fission products (such as strontium and technetium). Some of these isotopes remain radioactive for many thousands of years. Most countries are committed to a programme of long-term geologic disposal, that is, stabilisation of the radioactive material and burial in specially-designed receptacles and repositories. These plans continue to solicit the concern of some experts and many members of the public.

As an alternative to long-term storage, it has been proposed that the long-life isotopes be converted to shorter-lived ones through exposure to neutrons, a process dubbed transmutation (or, colloquially, burning). The transmutation reaction can be induced by neutrons produced in nuclear reactors or by spallation neutrons produced in much the same way as in the facilities described in Section 2.1. A desirable feature of "Accelerator-Driven Systems" (ADS) is that the transmutation reaction will not sustain itself once the proton beam is switched off. This would preclude any uncontrolled chain reaction leading to a dangerous

release of energy and radioactivity. It has also been proposed that such reactors could evolve into major sources of energy, since they could be fuelled with the abundant element thorium.

An accelerator-driven nuclear waste transmutation system would consist of three major sub-systems:

- ◆ a proton accelerator with very high power (5 MW for a demonstrator, up to ~50 MW for an industrial burner);
- ◆ a burner reactor where spallation and transmutation would occur;
- ◆ a processing plant in which short-lived isotopes that could not undergo further transmutation would be removed for secure disposal, and where other isotopes could be recycled into new fuel assemblies for the burner reactor.

Unlike the other applications described in this report, ADS is aimed at producing a commercially viable operation, and thus:

- ◆ Stringent safety-related regulatory requirements would have to be satisfied.
- ◆ Acceptability would have to be achieved in a public environment that is dominated by negative attitudes towards new nuclear reactors, even when theoretical safety risks are low. In particular, the public has shown very little tolerance for accidents (even minor ones) in commercial and experimental nuclear facilities. It must be kept in mind that a transmutation burner would contain very large amounts of highly radioactive material.
- ◆ Economic viability would have to be established vis-à-vis anticipated prices of electric power, energy demands, and the cost of alternative energy sources. In this application, technological feasibility demonstration does not necessarily lead to industrial scale implementation.

Conceptual studies of ADS are under way in the three principal OECD regions. Regarding the proton accelerator component, attention is focussed on a linear accelerator with power levels well beyond those contemplated for other applications<sup>12</sup>. Pulsed operation can be envisaged for a demonstrator requiring moderate average beam power. However, only continuous operation is anticipated for an industrial installation. Since the instantaneous power level is approximately the same in a 50 MW continuous accelerator and a few-MW pulsed linac, the HPPA developments presently under way are directly applicable, provided the special issues of reliability and burner stability (as described below) are adequately addressed. Various accelerator/burner configurations can be considered, along with different scenarios for processing the radioactive materials. The diverse options entail different requirements for accelerator power and reliability. Theoretical calculations have to be accompanied by benchtop testing, and, at the appropriate stage, a dedicated demonstrator unit would need to be built and operated at an intermediate power level.

A "road map" for an experimental installation is being prepared by the European Technical Working Group. It is expected to conclude that an accelerator could begin operations in 2012 and, some three years later, it could be coupled to a burner. It could operate for 2-3 years at low power before the nominal 100 MW (thermal) level is reached.

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<sup>12</sup> Many accelerator experts are confident that a linac could achieve a power of several tens of megawatts, whereas cyclotrons are unlikely to exceed 10 MW. However, a multi-cyclotron industrial facility can be envisaged.

*Reliability.* Existing accelerators turn off (“trip”) often, usually for brief periods on the order of seconds. This is not a problem provided that the accumulated downtime does not unduly prolong the experimental programmes. Longer interruptions (of days or even weeks) are vexing to all, but they are rare: typical uptimes for accelerators of all types are in the 75% - 95% range. In the case of ADS, an interruption of the supply of protons for more than a second or so could have important effects on the burner which would be operating at very high power levels<sup>13</sup>. Thus, the dynamics of the very complex system have to be well understood under a wide range of conditions including unexpected interruption of the proton beam and other abnormal events. There is no *a priori* reason why very high reliability could not be achieved in a high-intensity accelerator (for example, through redundancy of critical sub-systems). However, this overdesigning might give rise to a considerable cost increase.

*Non-accelerator issues.* Although somewhat outside of the stated scope of the workshop, issues relating to the burner and to fuel processing were discussed, since there was agreement that the most challenging R&D issues lie in these domains, and that many alternative designs can be envisaged for various parts of a transmutation facility<sup>14</sup>. The burner would be a complex dynamic system whose behaviour would have to be well understood, but at this time there are unanswered questions regarding rates of various relevant nuclear processes. Therefore, interested countries should pursue measurements, computer simulations, materials studies, etc., and they should consider participating in existing or new international collaborations. At some point further progress will require construction of one or more pilot/demonstrator units.

Fuel processing technology also requires detailed analysis and R&D. A key question is the applicability of existing fuel reprocessing technology. Given the strict safety requirements that a commercial system would be subject to, and given the high sensitivity of the public, openness and close interaction with regulatory authorities are to be recommended at all stages of development of ADS.

## **Conclusions**

ADS is a promising technology whose potential benefits deserve the attention of policymakers in all countries that will have to contend with large amounts of spent nuclear fuel during the coming 50-100 years. Implementation of ADS on a significant scale would require a substantial commitment of resources over many years, with commercial systems coming online in the ~2050 timeframe. There do not appear to be any insurmountable scientific or technological obstacles, although a significant number of vital subsystems would have to be developed well beyond the current state of the art. The development of the ultra-high power proton accelerator would benefit from work undertaken for advanced spallation sources, as well as nuclear and high-energy physics facilities. The time scales for these projects are compatible with the ADS demonstrator road maps that have been presented in Europe, Japan and the United States. Accelerator-based applications share many technological challenges (e.g., ion sources, targets, high-reliability systems), and successes in any area could be shared by all. Existing international collaborations are valuable. Overall co-ordination can be pursued via existing international organisations, such as IAEA and NEA.

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<sup>13</sup> Proton beams of several tens of megawatts would be driving a burner that would operate at hundreds of megawatts; most of the energy produced in the burner would come from fission of the fuel. The protons merely produce the neutrons that make the fission possible.

<sup>14</sup> For example, there are at least two possible choices for the spallation target: liquid lead-bismuth or sodium-cooled tungsten, as well as various options for the burner coolant.

## 2.4 Muon and Neutrino Facilities for Particle Physics

Three application areas make use of high-intensity proton accelerators:

- ◆ Conventional neutrino beams produced when protons are incident on a small-diameter target, producing pions and K mesons which decay into muons and muon-type neutrinos.
- ◆ “Neutrino factories” in which muons (produced as above) are accelerated and then confined in constant-energy storage-rings. Muons decaying in long straight sections produce collimated beams of electron-type and muon-type neutrinos.
- ◆ Muon/anti-muon colliders which would be follow-ons to electron/positron colliders (SPEAR, PEP, TRISTAN, LEP, SLC, possibly NLC).

The first application can make use of existing proton accelerators (see Table 3). These conventional neutrino beams are already being realised on a national and regional basis, but it is possible that future facilities could be proposed based on dedicated high-intensity proton accelerators operating in the few-GeV energy range. The second two applications are ambitious and would probably require dedicated accelerators and the combined resources and expertise of all countries with active high-energy physics programmes. The eventual implementation of muon colliders would depend on results obtained at current and soon-to-be-completed facilities such as the FNAL Tevatron and the CERN LHC. Ideally, a global consensus strategy will emerge regarding such facilities. To this end, informal consultations by scientists are already well under way, with a measure of co-ordination through ICFA, ACFA and ECFA. In addition, contacts have been established among representatives of funding agencies via the OECD Global Science Forum Consultative Group on High Energy Physics.

The primary physics goal using conventional neutrino beams is to study the transformation of muon-type neutrinos into the electron- and tau-type varieties. This allows (among other things) a measurement of the neutrino mass<sup>15</sup>. Typically, neutrino interactions are measured near their source, and at a second, distant detector. Neutrino energies of interest are in the 10-20 GeV range which requires protons of many times that energy. Linacs of such energy are simply too long, so circular accelerators are favoured. Neutrinos interact very weakly with detectors and so maximum proton intensity is needed. A compendium of projects that are under active development or consideration is given in Table 3.

The principal challenge in designing and building neutrino factories is to accumulate a sufficient number of muons into a storage ring with an energy of ~50 GeV. The muons must be accumulated and accelerated quickly since they decay rapidly at low energies. Studies to date have focussed on proton synchrotrons in the 10-50 GeV range, and linacs with energies up to 5 GeV.

Muon colliders could directly produce rare particles (for example, the Higgs boson) at greatly enhanced rates relative to equivalent electron/positron colliders. They also have an advantage in that energy losses in the beams due to synchrotron radiation are much lower during acceleration and storage. Thus, a muon collider could, some day, be the logical choice for a globally-funded and globally-organised front-line high energy physics facility. The implementation of a muon collider would, however, be significantly more difficult than a “neutrino factory” that uses stored muons, since the energy of the muons would have to be some 100 times higher, and the beams would have to be concentrated (“cooled”) by many orders of magnitude so that they can be brought to a very sharp focus at the interaction point(s).

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<sup>15</sup> Strictly speaking, the measurements are of the differences between the squared neutrino masses. Since the mass of the neutrino is zero in the Standard Model, this is a way to explore deeper theories of fundamental interactions, for example, Grand Unified Theories (GUTs).

Experiments using conventional neutrino beams are well under way. If results warrant, the FNAL and CERN beams could be increased in intensity, although considerable investments would be needed.

### ***Conclusions***

Conceptual design studies for neutrino factories of a wide range of accelerator/detector combinations are appropriate and useful. Co-ordination can be provided by international scientific bodies. It appears likely that the proton accelerator component will not present the most difficult technical challenges, and that its cost in a final system would be less than 10% of the total hardware cost. If and when an R&D phase is reached, a number of existing proton accelerators could provide the needed test beams. It is conceivable that, some day, an upgraded existing proton accelerator would constitute the first stage of a neutrino factory facility. In general, however, neutrino factories and muon colliders will require dedicated facilities that are unlikely to be compatible with “service” applications such as producing neutrons for small- and medium-scale experiments.

Muon colliders are beyond the current horizon for the next generation of high energy physics facilities, but they deserve to be studied by accelerator physicists. At this time, bilateral inter-laboratory arrangements, and multi-laboratory MOUs, are the most effective method for exploring potential designs and solutions.

### **3. MULTIPURPOSE FACILITIES**

There is no simple or unique answer to the question of whether different applications of high-intensity proton accelerators can be combined at a single facility. The prospect of economies of scale and other cost savings have to be weighed against potential design compromises, operational complications, and delays in planning, authorisation and funding. Among the factors that must be taken into consideration are the following:

*Sharing of the available beam.* In some cases, technical measures can be used to change the time structure of beams to optimise them for particular applications. Total available intensity must be considered. Clearly, there are limits to the ability to share a finite proton flux, however large, among users who require maximum intensity for their experiments. In addition, acceleration of negative ions and of protons may have to be supported in the same accelerator.

*The needs and characteristics of the user communities.* The size and operating modes of user communities are important factors in deciding whether a shared large facility is warranted. In general, dedicated, longer-term projects cannot be easily combined with those where scientists from many disciplines come to the facility to perform short experiments (as is the case for many users of neutron sources). Some applications (most notably, ADS) may have special safety and regulatory constraints that would pose particular organisational problems at a shared facility. In some cases, especially for those machines that are at or beyond the state of the art, accelerator physicists would need frequent access to the machine, with unscheduled downtimes and frequent modifications.

*The timescales of the various scientific programmes.* Long-range plans for the applications discussed at the workshop are in various stages of maturity at national and regional levels. Besides the difficulties of adding yet another level of co-ordination, there is the simple observation that each field should proceed according to its own optimum pace, which may not be compatible with the concept of multipurpose facilities.

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The notion of combining several HPPA applications at one facility deserves serious attention, with a realistic appraisal of the needs, benefits, and difficulties. Intermediate options are worth considering, viz., a single site with more than one accelerator and shared infrastructure such as power distribution and cooling systems, or office space. Opportunities for joint R&D should be exploited whenever possible, even when separate facilities are in order. The discussions during the workshop highlighted many common challenges that confront designers of high-intensity machines and other relevant equipment (such as ion sources and high-intensity spallation targets).

The European countries, Japan, and the United States have examined the issue of multipurpose facilities to ensure optimum solutions based on their long-range plans, requirements and resources. The KEK/JAERI Joint Project in Japan is a notable example of consensus decision-making at the national level. In the United States, separate facilities are favoured. In Europe, where scientific communities are very active in all relevant fields, efforts are under way to study the prospects for a multipurpose facility that could, possibly, be implemented in connection with a large new spallation neutron source.

**Workshop Participants**

Chairman	Dr. Peter Tindemans
Australia	Dr. Claudio Tuniz
Austria	Dr. Wolfgang Reiter
Belgium	Prof. Jean Sacton, Prof. Jean Vervier
CERN	Dr. Kurt Hübner
Denmark	Dr. Jørgen K. Kjems
EC	Dr. Serge Paidassi
France	Dr. Pascal Colombani, Dr. Bernard Frois, Dr. Daniel Guerreau, Dr. Jacques Joffrin, Dr. Jean-Louis Laclare, Dr. Philippe Leconte, Dr. Alex C. Mueller, Dr. Christian Ngo, Dr. Jean-Baptiste Thomas
Germany	Dr. Hermann-Friedrich Wagner, Prof. Dr. Walter F. Henning, Dr. Kurt Clausen, Prof. Dr. Dieter Richter, Prof. Ingo Hofmann, Dr. Dieter Proch, Prof. H. Lengeler
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Japan	Dr. Shoji Nagamiya, Dr. Isao Tanihata, Dr. Yujiro Ikeda
NEA	Dr. Claes Nordborg, Mr. Luc Van den Durpel
Netherlands	Dr. Hans Chang, Dr. A.J. Koning
South Africa	Prof. John Sharpey-Schafer
Sweden	Dr. Gunnar Leman, Dr. Waclaw Gudowski
Switzerland	Dr. Jean-Pierre Ruder, Dr. Erich Steiner
United Kingdom	Dr. George Stirling, Dr. Ian Francis Corbett, Dr. Andrew Taylor
United States	Dr. Harold Jaffe, Dr. Frank J. Goldner, Dr. Stephen Steadman, Dr. George W. Dodson
OECD	Dr. Stefan Michalowski, Mr. Kenji Sudo, Dr. Michael Osborne, Mr. Daniel Malkin

**OECD Global Science Forum Workshop on Strategic Policy Issues  
Concerning Future High-Intensity Proton Beam Facilities**

**Agenda**

**Monday 25 September 2000**

1. Introductory remarks by the Chairman.  
*Peter Tindemans*
2. Review and approval of the agenda.
3. Introduction/Overview.  
*Pascal Colombani, CEA, France*
4. Radioactive ion and hadron beam facilities for nuclear physics research.  
*Walter Henning, GSI, Germany*
5. Accelerator-driven sub-critical reactors for radioactive waste transmutation and energy production.  
*Carlo Rubbia, ENEA, Italy*
6. A global perspective on accelerator-driven waste transmutation.  
*Waclaw Gudowski, Royal Institute of Technology, Sweden*
7. Spallation neutron sources for research on condensed matter and irradiation of materials.  
*George Dodson, Spallation Neutron Source, United States*
8. Neutrino and muon facilities for elementary particle physics research.  
*Kurt Hübner, CERN*
9. Multipurpose facilities.  
*Shoji Nagamiya, JAERI/KEK, Japan*

**Tuesday 26 September 2000**

10. A Scientific Perspective.  
*Burton Richter, IUPAP*
  11. General discussion, to include interventions by national delegations and others as appropriate.
  12. Elaboration of consensus findings.
- Recommendations for follow-on actions.

## An Introduction to Proton Accelerators

A proton accelerator produces beams of protons with properties (energy, intensity, repetition rate, polarisation, collimation, momentum spread, etc.) that are suited for one or more applications. The development of proton accelerators has a long history, and these machines exist today in a wide variety of sizes and configurations, from small (0.5 meter radius) low-energy cyclotrons for medical treatment, to the giant high-energy Tevatron synchrotron at FNAL which has a radius of 1000 meters. Thus, there is a wealth of experience and expertise regarding their design, construction and operation. The reason why the issue is important now is that the applications discussed here require accelerators with power<sup>16</sup> levels that are at or beyond the state of the art and thus pose considerable challenges to accelerator physicists, and impose special constraints on the operation of the machines. In the application areas described, the proton accelerator, while an essential component of the overall facility, is just one part of a complex ensemble and will not, in itself be the main focus of attention of the scientists that come to use the facility. The high-intensity proton accelerator thus plays a “service” role, delivering protons which are then used to make other particles of greater interest: neutrons, other hadrons (such as pions), muons, neutrinos, and exotic nuclei.

This report is primarily concerned with two types of devices: linear accelerators (“linacs”) and synchrotrons.

In a linac, protons from an ion source<sup>17</sup> follow a straight-line trajectory through a series of radio frequency (“RF”) cavities where energy is transferred to the particles from an electromagnetic field. It is useful to make a distinction between the “low-energy” (up to about 100 MeV) and “high-energy” sections of the linac. In the former, the velocity of the protons increases rapidly with energy, and this must be accounted for in the phase of the accelerating field in successive cavities. In the latter part of the linac, the velocity of the protons approaches the speed of light as their energy continues to rise. It is in this section that designers may choose to use superconducting cavities. In addition to RF cavities, linacs are equipped with focussing magnets of various kinds to control the position and size of the beam as it traverses the accelerator.

In a synchrotron, a low-energy linac is followed by a circular arrangement of electromagnets within which the protons make thousands of turns in an (approximately) circular path. During each turn, the protons gain

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<sup>16</sup> The power of an accelerator is the product of the energy of the protons and the beam current. The current, in turn, is the product of the electric charge of the protons in each bunch (for pulsed machines) times the number of bunches per second. Thus, in commonly used units,

$$\text{Power (in MW)} = \text{Proton energy (in GeV)} \otimes \text{Beam current (in mA), or}$$

$$\text{Power (in MW)} = 1.7 \times 10^{-16} \otimes \text{Proton energy (in GeV)} \otimes \text{Protons per pulse} \otimes \text{Repetition rate (in Hz)}.$$

Note that we are considering very high power levels indeed: an energy source with a power of one megawatt can boil three liters of water in one second. On the other hand, the total mass accelerated is modest. For example, the US Spallation Neutron Source, operating continuously for one year, would accelerate less than one gramme-worth of protons.

<sup>17</sup> In proton accelerators, it is usually more convenient to actually accelerate  $\text{H}^-$  ions, i.e., protons with two electrons attached. Following acceleration, both electrons are removed by sending the ion beam through a thin layer (“stripping foil”) of graphite or other material.

energy when they pass through a set of RF cavities. In terms of cost, the trade-off between accelerator types is straightforward: in synchrotrons, the advantage of being able to use the same cavities to accelerate the same protons many times is offset by the necessity of installing the magnets for deflecting the beam in a closed path.

Three general accelerator properties deserve special mention:

- In “continuous wave” (CW) linacs, the protons are (approximately) uniformly distributed along the accelerating structure, and thus exit the machine in a continuous flow. This type of linac is, in general, easier to design and build for very high power levels, and is thus the solution of choice for those applications where precise timing information is not needed (bulk neutron irradiation, nuclear waste transmutation, most nuclear physics applications)<sup>18</sup>. Pulsed linacs of very high peak power present challenging technical problems for the accelerator physicist and designers of the downstream equipment that the protons impinge on following acceleration. Pulsed beams require pulsed RF cavities which must be able to withstand the associated thermal and mechanical shocks. The same is true for spallation targets and other downstream components.
- Linac designers have to choose between superconducting and room-temperature RF cavities. The former produce higher accelerating fields and therefore result in shorter accelerators which, in addition, consume less electricity and have much smaller requirements for waste heat removal. On the other hand, superconducting cavities are more expensive to fabricate, and they require a significant investment for building and operating a liquid-helium production plant.
- High reliability and beam stability – greater than those achieved in the lower-power machines built to date – are critical parameters for the next generation of high-intensity accelerators. As the protons traverse the accelerator, it is imperative to keep the particles moving in a well-defined trajectory. Otherwise, stray particles collide with magnets, beam pipes, vacuum pumps, electronics and other components, making them radioactive. Unless such particle losses can be avoided, one may have to provide expensive robotic equipment for maintenance of the accelerator hardware. High reliability is especially critical for nuclear transmutation where, as described in the body of the report, interruptions in the proton beam can adversely affect the transmutation system.

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<sup>18</sup> In a pulsed linac, typical proton pulse widths are on the order of 1 millisecond. Even this is too long for neutron scattering applications, which require pulses of 1 microsecond or less. Special purpose “accumulator” or “compressor” rings are incorporated into neutron sources for this purpose.

**Table 1: Characteristics of the new generation of regional spallation neutron sources**

Name Location	Beam Power (MW)	Proton Energy (GeV)	Repetition Rate (Hz)	Protons per Pulse ( $\times 10^{13}$ )	Pulse width ( $\mu$ s)	Accelerator Configuration	Other Components	Status  Completion date
SNS Oak Ridge	2.0	1.0	60	20.8	1.0	185 MeV conventional linac 1.0 GeV SC linac	40m. radius compressor/ accumulator ring	Under construction. Operational in 2007
KEK/JAERI Joint Project Tokai	1.0	3.0	25	8	<1.0	400 MeV conventional linac with 600 MeV SC extension 3 GeV synchrotron 50 GeV synchrotron		Approved
ESS <sup>19</sup> Europe	5.0	1.33	50	46	1.4	1.33 GeV conventional or superconducting linac	Two 35m. radius compressor/ accumulator rings	Ongoing study
AUSTRON Austria	0.5	1.6	50	3.9	0.44	1.6 GeV synchrotron		Ongoing study
LPSS Los Alamos	1.0	0.8	60	12	1000	Upgrades to existing LANSCE conventional linac		Ongoing study

<sup>19</sup> This is only one of the possible configurations being studied. As mentioned in the text, an additional 4.5 MW, 2.5 msec reactor-emulation mode is also under consideration.

**Table 2: Classification of major existing, planned and proposed ISOL facilities<sup>20</sup>**

Driver	Post Accelerator	Facilities (and Driver properties)	Status
Cyclotron	Cyclotron	<ul style="list-style-type: none"> <li>Louvain-la-Neuve (Belgium) protons to 30 MeV, 300 <math>\mu</math>A</li> </ul>	Existing
		<ul style="list-style-type: none"> <li>SPIRAL at GANIL (France) heavy ions to 25 MeV/nucleon</li> </ul>	Commissioning
Cyclotron	Linac	<ul style="list-style-type: none"> <li>ISAC at TRIUMF (Canada) protons to 500 MeV, 100 <math>\mu</math>A</li> </ul>	Existing
Cyclotron	Tandem	<ul style="list-style-type: none"> <li>EXCYT at LNS (Italy) primarily heavy ions, considering 200 MeV protons</li> </ul>	Under construction
		<ul style="list-style-type: none"> <li>HRIBF at ORNL (USA) protons, deuterons, <math>\alpha</math> particles 50 – 100 MeV, 10 – 20 <math>\mu</math>A</li> </ul>	Existing
Proton Synchrotron	Linac	<ul style="list-style-type: none"> <li>REX ISOLDE at CERN (Switzerland) PS booster, 1.4 GeV protons at 2 <math>\mu</math>A</li> </ul>	Under construction
		<ul style="list-style-type: none"> <li>SIRIUS at Rutherford Appleton Lab (UK) 800 MeV protons at 100 <math>\mu</math>A from ISIS</li> </ul>	Proposed
Linac	Linac	<ul style="list-style-type: none"> <li>RIA at ANL (USA) Superconducting linac, protons up to 730 MeV, heavy ions up to uranium, 400 MeV/nucleon</li> </ul>	Proposed

<sup>20</sup> This table omits small, low-energy facilities, as well as reactor-based neutron beam ISOL facilities.

**Table 3: Conventional neutrino beam projects**

Name Country	Proton Synchrotron	Protons per pulse ( $\times 10^{12}$ )	Repetition interval (sec)	Near detector	Far detector  Distance	Status
K2K Japan	12 GeV synchrotron	6.5	2.2	at KEK	Super- Kamiokande  250 km.	Running
KEK/ JAERI  Joint Project	50 GeV	320	2.7	at JAERI	Super- Kamiokande  295 km.	~2007
BooNE USA	8 GeV	5	0.07	at FNAL		2002
NuMI	120 GeV	30	1.9	at FNAL	MINOS  730 km.	2003
CNGS CERN, Italy	400 GeV	48	6	not required	Gran Sasso  732 km.	2005

## GLOSSARY OF ACRONYMS

<b>ACFA</b>	Asian Committee for Future Accelerators
<b>ADS</b>	Accelerator-Driven Systems
<b>CERN</b>	European Organisation for Nuclear Research
<b>CW</b>	Continuous Wave
<b>DOE</b>	U.S. Department of Energy
<b>EC</b>	European Commission
<b>ECFA</b>	European Committee for Future Accelerators
<b>ENEA</b>	National Agency for New Technology, Energy and Environment, Italy
<b>ESS</b>	European Spallation Source
<b>EURISOL</b>	European Isotope Separation On-Line Radioactive Nuclear Beam Facility
<b>FNAL</b>	Fermilab National Accelerator Laboratory, USA
<b>FRMII</b>	Munich Research Reactor
<b>GSI</b>	Heavy Ion Research Center, Darmstadt, Germany
<b>GUTs</b>	Grand Unified Theories
<b>HPPA</b>	High Power Proton Accelerators
<b>IAEA</b>	International Atomic Energy Agency
<b>ICANS</b>	International Collaboration on Advanced Neutron Sources
<b>ICFA</b>	International Committee for Future Accelerators
<b>INFN</b>	National Institute for Nuclear Physics, Italy
<b>ISOL</b>	Isotope Separation On-Line
<b>IUPAP</b>	International Union of Pure and Applied Physics
<b>JAERI</b>	Japan Atomic Energy Research Institute
<b>KEK</b>	High Energy Accelerator Research Organisation, Tsukuba, Japan
<b>LEP</b>	Large Electron Positron collider
<b>NEA</b>	OECD Nuclear Energy Agency
<b>NLC</b>	Next Linear Collider
<b>NSCL</b>	National Superconducting Cyclotron Laboratory
<b>OECD</b>	Organisation for Economic Co-operation and Development, Paris, France
<b>PEP</b>	Electron positron collider at SLAC
<b>RIA</b>	Rare Isotope Accelerator
<b>RIKEN</b>	Institute of Physical and Chemical Research, Japan
<b>SLAC</b>	Stanford Linear Accelerator Center
<b>SLC</b>	Stanford Linear Collider
<b>SNS</b>	Spallation Neutron Source, Oak Ridge national Laboratory, USA
<b>SPEAR</b>	Electron positron collider at SLAC
<b>TRISTAN</b>	Electron positron collider at KEK