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TITLE TOWARDS AN ADVANCED HADRON FACILITY AT LOS ALAMOS

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Towards an Advanced Hadron Facility at Los Alamos

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1. Abstract

In the 1987 workshop, it was pointed out that activation of the accelerator is a serious problem. At this workshop, it was suggested that a new type of slow extraction system is needed to reduce the activation. We report on the response to this need. The Los Alamos plan is reviewed including as elements the long lead-time R&D in preparation for a 1993 construction start, a menu of accelerator designs, improved losses at injection and extraction time, active participation in the development of PSR, an accelerated hardware R&D program, and close collaboration with TRIUMF. We review progress on magnets and power supplies, on ceramic vacuum chambers, and on ferrite-tuned rf systems. We report on the plan for a joint TRIUMF-Los Alamos main-ring cavity to be tested in PSR in 1989. The problem of beam losses is discussed in detail and a recommendation for a design procedure for the injection system is made. This recommendation includes taking account of single Coulomb scattering, a painting scheme for minimizing foil hits, and a collimator and dump system for containing the expected spills. The slow extraction problem is reviewed and progress on an improved design is discussed. The problem of designing the accelerators for minimum operation and maintenance cost is briefly discussed. The question of the specifications for an advanced hadron facility is raised and it is suggested that the Los Alamos Proposal of a dual energy machine - 1.6 GeV and 60 GeV - is a better match to the needs of the science program than the single-energy proposals made elsewhere. It is suggested that design changes need be made in all of the world's hadron facility proposals to prepare for high-intensity operation.

2. Welcome to our International Guests

I would like to take this opportunity to welcome our international guests to the second AHF accelerator workshop. We have a large group here from TRIUMF and another from the European Hadron Facility including both the Italian and German parts of the collaboration, two from the Japanese Hadron Facility, ISIS (Rutherford-Appleton Lab, England), and one each from SIN, and CERN. We have the special pleasure of hosting two guests from the Institute for Nuclear Research, Moscow, USSR, and one from the Institute for Atomic Energy, Beijing, Peoples Republic of China.

From the United States, we have a group from Brookhaven National Laboratory and another from Fermilab. There is also a representative of the SSC Central Design Group from Berkeley California. Finally, I would like to welcome the large number of Los Alamos participants from AT-, INC-, MP-, P-, and T- Divisions, many of whom are not normally involved with the advanced hadron facility.

3. Review of 1987 Workshop

I think that many of you will remember Pete Miller's enthusiastic introduction to the 1987 workshop and his invitation to attend the groundbreaking of AHF in the Fall of 1992. There were two other important outcomes of this meeting. Baconnier reminded us of the experience of present-day machines, which are operating near the maximum level of activation which is tolerable for "hands-on" maintenance. Baconnier's paper clearly documented the problems that the designers of the new high-intensity machine must solve. Teng, in his conference summary, pointed out that the traditional methods of slow extraction are not adequate for the high-efficiency extraction required in a kaon factory and that an invention is needed to improve the extraction efficiency. Both of these speakers presented a challenge to the audience. We will see some of the responses to their challenge in this workshop.

There are a number of problems discussed at the 1987 workshop which are still with us. At the PSR, there is a 2% beam loss which has bothered us for the past year. This problem has been explained by Macek in his talk earlier today. There is also the unexplained transverse instability of the PSR, the need to design an efficient collimation system for PSR and the kaon factories, and the problem of choosing an architecture which minimizes the lifetime cost of a kaon factory. I expect that all of these problems will receive some attention at this workshop.

4. The Los Alamos Plan

Our plan is based on preparing for a construction start in FY-1993 after CEBAF is complete and RHIC is well underway. We are redesigning LAMPF II to include a spallation source, to improve the losses at injection and extraction, and we plan to take advantage of all that has been learned from the PSR commissioning. Our near-term goal is to fill in a menu of accelerator designs with preliminary technical designs and cost estimates so that there will be some options for use during the political and scientific discussions surrounding the funding of an AHF. We also are increasing the pace of hardware development. You will see examples of the work on ferrite-tuned rf, on ceramic vacuum chambers, and on magnets and resonant power supplies at this workshop. We will collaborate with all of the other kaon factories for this development work. We plan to work particularly closely with the TRIUMF group during the next few years, as is discussed below.

4.1. Collaboration with TRIUMF

In the Fall of 1987, an agreement was made that the TRIUMF and Los Alamos groups would work together on the R&D for a next generation hadron facility. In particular, it was agreed that a single main-ring cavity will be developed that will meet the tuning range and voltage requirements of both the TRIUMF and Los Alamos main-rings. The Los Alamos group will build the cavity and provide the basic rf-power system. The TRIUMF group will provide the driver amplifier and the feedback control system. This cavity will be tested in the PSR starting with the 1989 running period. In addition to testing the performance of the hardware, the test in PSR will provide information about beam loading, 50-MHz bunching, longitudinal and transverse painting, coupled bunch instabilities, and synchrotron-betatron oscillations. The information obtained will be valuable for all of the proposed kaon factories.

As a part of this agreement, the present Los Alamos booster cavity and 4 of the 6 existing ferrite toroids will be sent to TRIUMF for further research and development. The TRIUMF group was invited to participate in PSR development program and provided some staffing for all of the development runs of PSR in 1987. TRIUMF has also agreed to build a new beam-position-monitor control chassis for

PSR that will process information in parallel with the existing controller. We are looking forward to a productive collaboration no matter which direction the funding of kaon factories goes in the near future.

4.2. Menu of Accelerator Options

We propose to fill in a menu of accelerator options so that there will be flexibility when the time comes for a funding decision on AHF. For the high-energy machine, there are basically 3 options, namely:

a) Full size Booster and Main-ring;

b) Half-Size Booster, Half-Size Collector and Main-ring;

c) Third-Size Booster, Full-Size Collector and Main-ring.

For each of the three options, we must decide whether a stretcher is needed. We must also choose the proper injection energy for each design. For this workshop, we have prepared a preliminary design for each of the three options assuming that no stretcher is needed and that the injection energy for each is 1.6 GeV.

The compressor ring for the spallation source and neutrino source shares the LAMPF linac and any afterburner linac. For the purposes of this workshop, we have generated a preliminary compressor design based on 1.6-GeV H^- injection. We chose a 50-MHz rf system for this compressor ring in order to share rf technology and a front-end rfq with the higher energy machines.

5. Tentative Linac Front-End Design

The front end of the linac must generate a 50.3-MHz bunched beam for the advanced hadron facility. The simplest solution is to build a new ion source and a 50.3-MHz rf quadrupole (rfq) to inject the existing 201.25-MHz drift tube linac for LAMPF. If this design is reasonable, then it could be shared with the EHF and SSC which also need a 50-MHz bunched beam with 50 mA/4 current (one of four 201.25-MHz or one of eight 402.5-MHz bunches filled). I would like to ask the linac working group to study the problem of the rfq, the ion source, and matching to the LAMPF drift-tube linac. In particular, this group should consider the necessary modifications to LAMPF and make provision for a polarized ion source.

6. Expanded Hardware R&D Program

We are attempting to increase the pace of our hardware R&D effort. This expanded effort is described in the sections which follow:

6.1. Magnets and Power Supplies

The proposed advanced hadron facility is based on rapid-cycling (6-60-Hz) magnets The main-ring magnets raise the most problems as they must provide a 2.1-2.2-Tesla field in order to fit the 60-GeV accelerator into the LAMPF site. Calculations are being presented in the hardware working group which show an initial design of a suitable high-field dipole and quadrupole. In order to eliminate eddy-current losses in the coils, a stranded, indirectly cooled conductor should be used in these magnets. This conductor is similar to that discussed by Prof Sasaki at the 1987 workshop and will be discussed in the hardware working group.

The Los Alamos group has done the pioneering R&D on the dual-frequency magnet power supply suggested by Praeg. The proof-of-principle power supply has now been thoroughly tested. We have demonstrated that it is possible to build a dual-frequency supply with adjustable length flattop and flatbottom. The final report of this work will be presented in the hardware working group. In the next year, we plan to work on the question of precision control and regulation of a multi-unit power supply. This work will be done for us by Prof. George Karady of ASU. For this study, we will work with a 1/10 size scaled version of the necessary power supplies.

6.2. Ceramic Vacuum Chamber

Ceramic vacuum chambers are needed for all of the rapid cycling magnets of AHF and of the TRIUMF Kaon factory. In order that the coupling impedance be minimized without interference with the ac guide field, these chambers must have conducting stripes to carry the image of the beam current (0.1 MHz-10 GHz). A capacitor at one end of each stripe assures a low impedance for these high frequencies while simultaneously providing a high impedance for the guide field (6-60 Hz). Our measurements of the coupling impedance of ceramic chambers show that the stripes must be on the inside of the vacuum chamber. In the next year, we plan to continue the development of these chambers in four steps. First, we will make a one-meter prototype with fixed flanges and internal stripes. This chamber will be fully vacuum tested but there will be no capacitors on the stripes. The second model will be a one-meter-long test of distributed capacitors. The third prototype will be a one-meter unit with capacitors and flanges. One of the two flanges will be demountable so that it will be possible to insert the vacuum chamber in a magnet without splitting the magnet in half. The fourth model will be a three-meter-long model which has all the features of the third unit. In addition, this long model will be curved to follow the beam without increasing the vacuum chamber dimensions to take care of the sagitta of curved magnets. Dr. Michael Featherby of SAIC is doing the ceramic vacuum chamber development under a contract with Los Alamos. Mike will report on the status of his ceramic vacuum chamber work in the hardware working group of this workshop.

6.3. Ferrite-Tuned rf

The Los Alamos group has been working on a ferrite-tuned booster cavity for several years. Just after the 1987 workshop, we achieved 140 kV on a single gap with 15% duty factor, 20% tuning range, and R/Q of 35 Ohms. This cavity was tested for the voltage and tune program required for the TRIUMF booster. The TRIUMF rf group determined that its performance is adequate for their application. After this test, we increased the duty factor to 50% at the same voltage. Unfortunately, we experienced a mechanical failure of two of the ferrite toroids during the higher-duty-factor test. It was possible to repair the broken section (1/6) of each toroid, but because there were no spares available, we were not able to run the cavity again until September. We are now working with the complete cavity and are making temperature measurements of the ferrite during high power operation. Carl Friedrichs will report on progress with this cavity during the hardware session.

In October 1987, we undertook the design and construction of a second-generation cavity in collaboration with TRIUMF. We chose a main-ring cavity because the smaller tuning range is more compatible with a planned test in PSR. A sketch of this cavity is presented in Figure 1. George Swain will be talking about the main-ring cavity during the hardware session of this workshop.

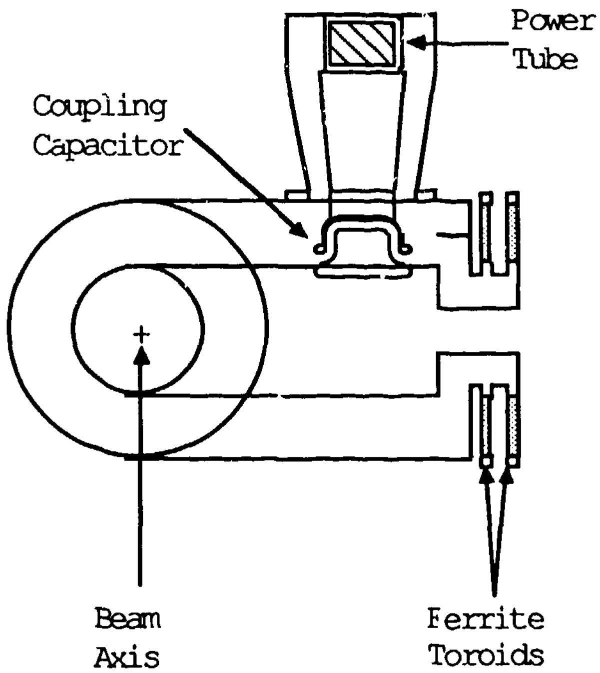

Figure 1. Sketch of proposed joint TRIUMF / Los Alamos main-ring cavity. The beam axis is normal to the plane of the paper. The ferrite is located in a separate tuner as shown. The power tube is located on the tuner rather than on the beam line so that it will be possible to mount several accelerators one above the other (as in the TRIUMF design) without mechanical interference with the power tube. This cavity is being prepared for a test in the PSR in 1989 as discussed in Section 4.1.

6.4. Other Necessary Hardware R&D

There are many other items requiring R&D in advance of construction. Foremost among these are the high-field magnets. We expect to start work on these magnets when we are confident of the required apertures. We should be ready to start work on the magnets in six months' or one year's time. Among the other accelerator components requiring R&D are beam diagnostics, controls, injection, and extraction hardware. We must wait to work on these items because of funding and manpower limitations.

A large amount of work must be done on experimental-area equipment. The target cells and remote-handled equipment needs many years of advance work. There must be a serious effort devoted to the cold-neutron source and to the neutrino source. RF separators will be required for the beam lines. These should be superconducting devices, which require a large amount of R&D. None of this work has as yet been started because of funding and manpower limitations. Because no new work has been done recently, we have not included experimental areas in this workshop.

7. H^- Injection

Our work on H^- injection is based on the PSR commissioning effort. Because this work is included in the paper of R. Macek, only the conclusions are summarized here. Macek pointed out that the present 2% losses (0.6 µA) are the maximum which can be tolerated for hands-on maintenance of the machine components. He also concludes that that the slow beam losses of PSR can be explained by single and multiple scattering in the stripper foil. The injection system of PSR (with an H^0 stripper magnet and resulting mismatch) nearly fills the aperture at the moment of injection. Two-thirds of the beam loss is due to multiple Coulomb scattering of beam that is near the edge of the acceptance. The remaining one-third of the losses are explained by single Coulomb scattering of beam that is injected near the center of the aperture. Inclusion of energy loss (dE/dx) is unimportant for the PSR losses for normal extraction, although it must be included to explain the losses seen if an attempt is made to store the beam for many milliseconds.

7.1. Losses due to Interactions with the Stripper Foil

The important losses from a new accelerator will be those resulting from single Coulomb scattering as long as there is a sufficient aperture to contain the small-angle multiple Coulomb scattered beam. The large-angle scatters can be computed from the formalism in many textbooks. Our favorite reference is Jackson. The integrated projected angle distribution is given by

$$2\int_{\theta}^{\infty} P_s(\theta')d\theta' = 2\pi Nt\left(\frac{zZe^2}{pv}\right)^2 \frac{1}{\theta^2}$$

This equation is taken from Jackson (equation 13.114), where $P_S(\theta)$ is the projected scattering angle distribution, Nt is the number of atoms per unit area, z and Z are the charge of the projectile and atom, respectively, p is the momentum of the projectile, and v is the velocity of the projectile. The factor of two in this equation takes into account both positive and negative scattering angles.

There is another phenomenon which must be considered for the design of the next-generation machines. This is nuclear scattering. The nuclear scattering can be represented by a total cross section because the angle of scattering is large compared with Coulomb scattering. The angle of scattering is so large that it is unreasonable to contain the nuclear-scattered beam in the acceptance of an accelerator or storage ring. The stripping cross section is nearly independent of energy for energies of 800-MeV and higher (note that stripping is a process like dE/dx, which has a minimum value near velocities near 0.9c). A stripper foil of 250 μgram/square centimeter will have a 95% efficiency for conversion of H^- into H^+ at 800 MeV. Because the total cross section is also approximately independent of energy, we note that the fraction of beam which interacts with the stripper foil is roughly 6×10^{-5} per hit. The single Coulomb and nuclear interaction probabilities are shown in Figure 2.

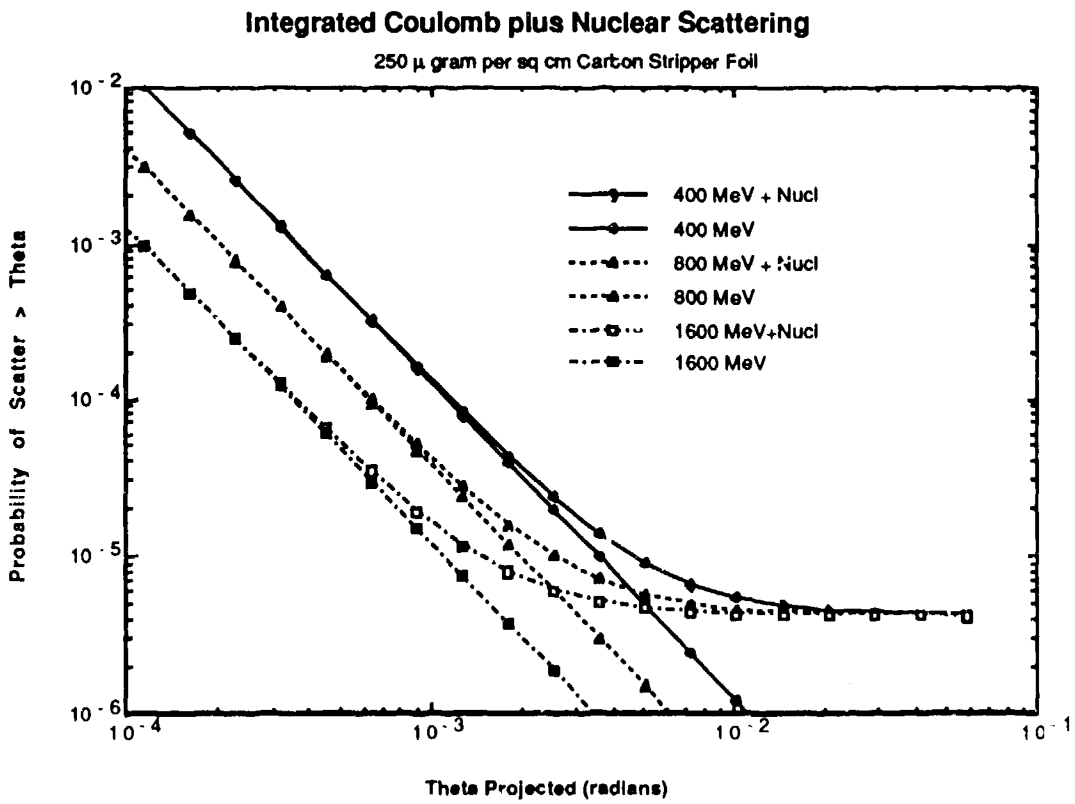

Figure 2. Integrated scattering probability for single Coulomb scattering as a function of angle. Also shown is the sum of single Coulomb scattering and nuclear scattering.

In previous design studies, insufficient attention was given to the interaction of the beam and the stripper foil. At PSR in development runs , there are more than 1000 foil hits per injected particle and a 3% loss. This is easily explained with a $1x10^{-5}$ loss probability (and a factor of 3 enhancement for multiple scattering) or an acceptance of about 2 milliradians.

The lesson is clear. We must keep the losses below 0.6 µA at 800 MeV. The stripper foil must be located at a low-beta double waist. Then the acceptance must be sufficient to accept scattering out to the angle at which Coulomb and nuclear scattering probabilities are approximately equal (2 mrad for 250 µg per square cm of carbon at 800 MeV). Even this may not be sufficient if a large number of turns of injection are required (as at PSR, the new AHF compressor, or the TRIUMF accumulator ring). In these cases, it is necessary to find a painting scheme that minimizes the number of foil hits. If the foil hits cannot be reduced sufficiently, the only alternative is to put a collimator in the downstream portion of the injection straight section to contain the spill. The region between the stripper foil and the collimator must be shielded, remote handling must be provided, and no active components should be located in this portion of the ring.

In designing the injection system, we must be careful not to forget the fraction of the beam which is not fully stripped or which misses the foil. For a 250 µgram per square centimeter foil, at least 5% of the beam will remain as H^o. At PSR, a 200 µgram foil is used. Our experience at PSR is that 10% of the beam is neutral and that up to 5% additional beam misses the foil and remains as H^-. It is absolutely essential to provide a dump for both the H^o and H^- beams which leave the foil. These dumps are not difficult to design since the phase space which must be contained is that of the injected beam, not the beam stored in the ring.

It is the opinion of the Los Alamos group that meeting all of the injection constraints simultaneously requires an accelerator designed to fit around the injection system and that the injection system cannot be simply inserted into a pre-existing straight section. For this reason, all of the new Los Alamos designs have a long injection-straight-section consisting of several cells. For the AHF booster, we favor a racetrack shaped ring.

7.2. Painting

At Los Alamos, Eugene Colton has made a preliminary study of the fraction of time that a particle hits the foil for several painting schemes. The results, which are presented in a contribution to this workshop, are tabulated in Table 1.

Table 1. Foil hits per particle per turn for several painting schemes. (Warning, results are very sensitive to the distance of the beam from the edge of the foil!).

Injection Scheme	Foil Hits per Turn
Fixed Brush (2D)	25%
X-Y Offset and Skew Quad	10%
X-Y Offset and Bumps	10%
TRIUMF Painting Scheme	8%
Combine 3). & 4). ?	6%?

In addition to meeting the criterion of minimizing foil hits, the painting scheme must result in a beam matched to the accelerator with the desired phase space and G factor. Meeting all of the constraints simultaneously may result in a larger number of foil hits. I have asked the injection and painting working group to consider this problem and report back on their findings.

8. Slow Extraction: An Invention Needed

At the 1987 workshop, Lee Teng emphasized the need for an invention to improve the efficiency of the slow extraction system Present day slow-extraction systems spill on the order of 1% of the beam. The problem is 75 times worse than the injection loss problem because of the higher beam energy at extraction. Thus we must limit extraction losses to 0.008 μA, or 0.8x10-4 for a 100 μA machine Both the Los Alamos and TRIUMF groups are working on improved efficiency schemes. The Los Alamos proposal consists of locating a massless magnetic septum 90^{o} upstream of the electrostatic septum to reduce losses on the electrostatic septum. The TRIUMF alternative is a special thin (10-micron) and short (1-meter) electrostatic septum in place of the massless magnetic septum. It is expected that a reduction of the losses by an order-of-magnitude to 1×10^{-3} is possible by either of these techniques. Since this is insufficient to limit the extraction losses to the required level, it will be necessary to include a collimator in the extraction system to reduce the losses in the remainder of the ring by an additional factor of 12. I have requested that the slow-extraction and collimation working group study this problem and report back on their findings.

9. Consideration of Lifetime Cost

In the present set of designs for hadron facilities, only the LAMPF II design took account of the operation and maintenance of the accelerators. The design should account for the lifetime cost of the machine including R&D, design, construction, installation, operation and maintenance, and power. In a 30-year projected lifetime of an accelerator, the dominant cost is the operation and maintenance cost. This subject is discussed in the following section.

9.1. Operation and Maintenance Cost

The operation and maintenance cost of a machine is difficult to predict in advance. Among the factors which influence the result are the complexity of the design, the degree of standardization, the quality of the design and execution, and the desired beam availability. It is unlikely that we can make a quantitative estimate of all these factors. I asked Roy Billinge to use the experience of the PS division at CERN and make a subjective estimate of the expected manpower requirements. I then used the experience of Los Alamos ($145k/full time equivalent) to convert the manpower estimate into cost. The results are presented in Table 2.

Table 2. Estimated Manpower Cost for Several Designs

Design (TRIUMF Nomenclature)	People	Annual Cost
- D (Main-ring Only	60	$ 8.7 Million
- D+E	100	$14.5 Million
- B+D (LAMPF II)	130	$18.9 Million
- B+D+E	170	$24.7 Million
- B+C+D+E (EHF)	210	$30.5 Million
- A+B+C+D+E (TRIUMF)	260	$37.7 Million

In designing the accelerator, the operation and maintenance cost should not be the dominant consideration. Indeed, first priority should go to a conservative, reliable design which meets all the requirements of the physics program. Nevertheless, some weight should be given to simpler designs which will be cheaper to operate. In the 30-year lifetime of a typical machine, the difference in operating cost between the simplest and most complicated design in Table 2 is $870 million.

10. The Los Alamos view of the specifications for an advanced hadron facility

All of the existing proposals for hadron facilities discuss a beam power near 3 MW (100 μA at 30 GeV). Gerry Garvey explained why we believe that 60 GeV is a better choice for beam used for hadron spectroscopy. He also pointed out that 1.6-GeV is a better energy for neutrino physics. The 1.6-GeV beam energy is well matched to the needs of the neutron scattering community. Our proposal of 60 GeV at 25 μA with two additional 600 μA beams at 1.6 GeV results in a higher total power (3.5 MW) than the other proposed facilities and a better match to the needs of the users.

11. Summary and Conclusions

The Los Alamos plan consists of performing the long-lead-time R&D required to prepare for a construction start in 1993. To this end, we are preparing a menu of accelerator options, are actively engaged in the development of the PSR, and are accelerating the pace of hardware R&D. This work is being performed in close collaboration with TRIUMF, especially the development of a joint main-ring cavity that is being prepared for testing in PSR in 1989.

The PSR commissioning work has led to an understanding of the source of the observed beam losses. Single Coulomb scattering must be considered in the design of all of the next generation machines. A painting scheme which minimizes foil hits is also required. In order to keep the efficiency of the slow-extraction scheme high enough, it is necessary to use a pre-septum and to add a collimator to contain the residual losses. It is suggested that more consideration be given to an accelerator architecture that minimizes operation and maintenance cost. For these reasons, we believe that all of the proposed kaon factories should be redesigned for high-intensity operation.