FERMILAB-CONF-09-442-APC

Report on

Workshop on Future Directions for Accelerator R&D at Fermilab

May 11-13, 2009 - Lake Geneva, WI

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Accelerator R&D has played a crucial role in enabling scientific discovery in the past century and will continue to play this role in the years to come. In the U.S., the Office of High Energy Physics of DOE's Office of Science is developing a plan for national accelerator R&D stewardship. Fermilab undertakes accelerator research, design, and development focused on superconducting radio-frequency (RF), superconducting magnet, beam cooling, and high intensity proton technologies. In addition, the Lab pursues comprehensive integrated theoretical concepts and simulations of complete future facilities on both the energy and intensity frontiers. At present, Fermilab (i) supplies integrated design concept and technology development for a multi-MW proton source (Project X) to support world-leading programs in long baseline neutrino and rare processes experiments; (ii) plays a leading role in the development of ionization cooling technologies required for muon storage ring facilities at the energy (multi-TeV Muon Collider) and intensity (Neutrino Factory) frontiers, and supplies integrated design concepts for these facilities; and (iii) carries out a program of advanced accelerator R&D (AARD) in the field of high quality beam sources, and novel beam manipulation techniques.

Possibilities of AARD along the third thrust, aligned with Fermilab's underlying capabilities, were presented and discussed at the *Workshop on the Future Directions of Accelerator R&D at Fermilab*. The charge to the Workshop includes:

1. Solicit and evaluate ideas that could be incorporated into a possible accelerator R&D program based on the ILC Test Accelerator in the New Muon Lab (NML) at Fermilab, which is currently under construction. The Workshop will also solicit ideas for improving and refining the current NML design to further enhance its R&D potential.
2. Solicit and evaluate advanced accelerator R&D proposals specific to enhancing the potential of ongoing and planned Fermilab R&D efforts, including Project X, ILC, and Muon Collider. Special emphasis should be placed on efforts that are synergistic between these programs and/or utilize currently existing or planned facilities.
3. Solicit and evaluate ideas for future accelerator applications of great potential but not yet part of the current Fermilab planned program such as medical accelerators and accelerator driven systems (ADS), including those based on the currently envisioned Project X facility.

The ideas presented and discussed at the Workshop are coalesced into this report, intended to be presented to Fermilab Management, which can then be used as the basis for a substantive R&D proposal for NML and the basis for further augmentation of the Fermilab accelerator R&D program. The report reviews the motivation, relevance, and uniqueness of each component:

1. Accelerator R&D opportunities at the SRF Test Accelerator at the New Muon Lab (NML)
2. High intensity beams R&D, collimation and RF
3. Accelerator driven sub-critical assemblies (ADS)
4. Medical accelerators

The main conclusions and recommendations of the Workshop are marked in **bold.**

The Workshop agenda, list of participants, and the organizing committee names can be found in appendices at the end of this report.

Additional information can be found on the Workshop web page:
http://apc.fnal.gov/ARDWS/index.html

1 Accelerator R&D Opportunities at the SRF Test Accelerator at the New Muon Lab (NML)

1.1 Background

The first use of the NML facility will be to test, both with and without beam, superconducting RF cryomodules for potential use in both Project X and ILC. A 40 MeV injector will provide an electron beam to a string of up to six 8-cell cryomodules. This injector will be capable of producing ILC-like bunch intensity (>3 nC/bunch), bunch length (<300ps), bunch train length (3000 bunches at 3 MHz), and repetition rate (5 Hz). The cryomodule string will produce beam energy up to ~1500 MeV with beam power up to 80 KW. Initial beam operation is scheduled to begin in 2012. This facility is being built with added floor space and infrastructure to accommodate additional test beam lines at both 40 MeV and 1500 MeV to support an AARD program. In particular there will be adequate floor space in the high energy test area to accommodate a ~10 m diameter storage ring.

Sixteen different speakers gave presentations in three broad categories: status of other AARD facilities (certainly not a complete list), overview of specific AARD research fields (certainly not a complete list), and specific proposals and suggestions for experiments at NML.

1.2 Other U.S ARD facilities

The AARD program at SLAC is extensive, mature, and continuing to develop. The newly approved FACET facility will use high intensity, small emittance 25 GeV e^- and e^+ from the main linac to explore beam-driven plasma acceleration concepts and beam-driven dielectric acceleration techniques. These techniques are potentially capable of providing acceleration gradients of ~1 GV/m to a ~10 GV/m, and their utility for future high energy colliders is obvious. Other active facilities at SLAC are: Injector Test Facility (ITF) – used for the development of RF guns and the study of beam manipulation techniques for LCLS; Accelerator Structure Test Area (ASTA) – used to test TW acceleration structures, with an electron gun to be added in the future; E163 Facility – to be used to test laser driven acceleration with dielectric structures; NLCTA – used to test X-band RF structures and power sources.

The BNL Accelerator Test Facility is the only proposal-driven, advisory committee-reviewed user facility in the world for AARD. Experimenters from national labs, universities, industry, and small business participate in research here. ATF is a high brightness 85 MeV e^- linac with 4 user beam lines and a high brightness x-ray source. A unique feature of this facility is a high power (terawatt) CO_2 laser (currently being upgraded to 10 TW), and the local expertise to operate and develop it. This laser is used to power an inverse free electron laser (IFEL) and other beam experiments. The use of an IFEL was recently demonstrated to be critical to preserving emittance during bunch compression at the LCLS. Successful experiments in plasma wakefield acceleration, inverse Thomson scattering, inverse Compton scattering (for possible use for a polarized e^+ source or possible use as a compact 100 fs x-ray source), and generation of ion beams with a 10 μm laser have been performed here, to name just a few experiments.

The Advanced Wakefield Accelerator (AWA) at Argonne National Lab is a 15 MeV e^- high brightness RF photoinjector capable of up to 150 nC single bunch charge. It has recently received funding to upgrade to 75 MeV. This facility is primarily dedicated to testing advanced accelerating structures and concepts – dielectrics, photonic band gap, solid state PASER, and others. It is a user facility, with participating experimenters from national labs, universities, and small business.

1.3 AARD fields

Kwang-Je Kim (U. Chicago, Argonne) presented an overview of the current status of X-ray Free Electron Lasers (XFEL) and research opportunities in this field. Three new SASE XFEL facilities are scheduled to come on line in the near future; the Linear Coherent Light Source (LCLS) at Stanford in 2009; the Spring-8 Compact SASE Source (SCSS) in Japan in 2011; and the European XFEL in Hamburg in 2014. These facilities will be capable of producing x-rays with wavelengths as short as ~0.2 Angstrom. Some techniques for improving XFEL performance are under active investigation. The use of an RF photoinjector operated at ~1 pC/bunch and in the "blowout" regime could produce ultra-short pulses (~100 attosecond) in a very compact XFEL. Novel phase space techniques such as Flat Beam Transforms (FBT) and Emittance Exchange (EEX) may be useful in making a more compact XFEL. The concept of an XFEL Oscillator (XFELO) was first proposed in 1984 by Colella, *et. al.* and is now receiving renewed attention. An XFELO utilizes a multiple pass x-ray oscillator interacting with an electron beam in an undulator to produce fully temporally coherent x-rays (as compared to $\Delta\omega/\omega \sim 10^{-3}$ for SASE XFELs). It could have applications complementary to SASE XFEL – high resolution spectroscopy, Mossbauer spectroscopy, x-ray photoemission spectroscopy, and x-ray imaging with near atomic resolution. There exist many technical R&D challenges to developing an XFELO – the quality of the diamond crystals used as mirrors in the optical cavity, their angular and position stability, and stability under thermal stress; development of a low emittance CW injector (a thermionic cathode is suggested); and further development of emittance minimization techniques in electron beam manipulations.

Carl Schroeder (LBNL) presented an overview of the current status of laser driven acceleration and related research challenges. In principle it is possible to produce an accelerating gradient of ~100 GV/m in laser-driven plasmas of density ~10^{18}/cm^3. To date, good quality beams have been accelerated to 1 GeV (~200 MeV acceleration) in ~3 cm long capillary discharge plasma waveguides using Ti:Sa laser pulses ~10's of femtoseconds length and several joules energy. Single stage laser driven acceleration has been proposed as the driver for a compact (total length ~100 m) FEL operating in the XUV region or as a compact γ-ray source. Multiple (100) stage laser driven acceleration has been proposed as the basis for a 2 TeV e^+e^- linear collider as short as 1 km. The major remaining technical challenges are improving beam quality by better control of beam injection, and devising multiple stage acceleration strategies. The Berkeley Lab Laser Accelerator (BELLA) is planning to develop a dedicated 40 J, 40 fs, 1 Hz laser for these studies.

1.4 Potential NML experiments

More than 20 proposals and suggestions for experiments were made at this Workshop. We list and elaborate on a subset of these below. The Workshop organizers have selected these based partly on the maturity of the proposal, partly on their viability at NML, and partly on our own current interests. This list is only intended to be a sampling of possibilities and should not be deemed part of a "selection process."

Proposal	Motivation/Application	Description
optical stochastic cooling proof-of-principle (Valishev, FNAL)	possible use in μ storage ring; possible use in heavy ion storage ring	Concept: use wiggler as pickup and kicker for stochastic cooling at high frequency Requirements: ~750 MeV storage ring; λ=40 cm permanent magnet wiggler; Ti:Sa optical amplifier @ ~1 μm
test of integrable beam optics (Danilov, ORNL)	possible application to Project X and future proton storage rings	Concept: storage ring with highly nonlinear but stable betatron motion using nonlinear lenses Requirements: >300 MeV storage ring; flexible optics; 12.5 MHz RF
effect of power deposition in plasma on acceleration and focusing (Muggli, USC)	future linear collider	Concept: measure energy change and focusing of successive bunches in a plasma Requirements: 3.2 nC/bunch; 1.5 GeV; short bunches; 3 MHz bunch train; 20 μm spot size; 15 cm 10^{16}/cm^3 plasma; laser for interferometry
study ion motion in plasma (Gholizadeh, USC)	future linear collider	Concept: study ion motion in plasmas due to beam passage using Frequency Domain Holography Requirements: >2 nC/bunch; 1.5 GeV; 3 MHz bunch train; short bunches; ~20 μm spot size; 1 cm 10^{17}/cm^3 H plasma; 500 nm laser for holography

test of Image Charge Undulator (Piot, NIU)	compact x-ray source	Concept: study radiation from 2 parallel gratings Requirements: high peak current; short bunches; flat beam; emittance exchange for bunch train generation
test wakefield acceleration in dielectric slab structure (Piot, NIU)	test high gradient acceleration concept; extension of AWA work	Concept: study slab dielectric wakefields with bunch trains Requirements: high peak current; short bunches; ~20 μm spot size; flat beam (possibly); emittance exchange for bunch train generation
microbunching investigations (Lumpkin, ANL)	improve understanding of the fundamental phenomenon of microbunching; understand instrumentation effects;	Concept: compare microbunching between chicane and dogleg configuration; investigate microbunching phenomenon in regime of high charge and $60<\gamma<100$ Requirements: high peak current; short bunches; chicane and dogleg beamline configuration
Parametric Ionization Cooling lattice (Jansson, FNAL)	μ collider	Concept: build an electron model of a lattice suitable for μ cooling; investigate optics Requirements: adequate space in high energy beamline
test of 6-D μ cooling (Kaplan IIT)	μ collider	Concept: one of a number of cooling concepts can be investigated in a small μ storage ring; Requirements: ~300 MeV storage ring; e → μ production target
continuing emittance exchange experiment (Sun, FNAL)	development of beam manipulation procedures for broad application	Concept: transform longitudinal to transverse emittance with dogleg configuration and transverse mode cavity. Requirements: low energy test beamline with dogleg and 3.9 GHz deflecting mode cavity
microbunch generation from slits (Sun, FNAL)	generation of closely spaced bunch trains for broad application	Concept: use emittance exchange with slit mask to generate closely spaced bunch trains Requirements: low energy beamline with emittance exchange setup
electroproduction of μ's at 1.5 GeV (Striganov, FNAL)	improved measurement of cross section; useful for a broad range of applications	Concept: this region of μ production has not been adequately measured; incorporate results into MARS model Requirements: μ production target; 1.5 GeV beam
development of compact μ source (Striganov, FNAL)	cargo inspection for homeland security; medical imaging	Concept: produce a 10 MeV μ beam from 300 MeV e^- on 0.1 rad length tungsten target; Requirements: 1.5 GeV beam, μ production target; sweeping magnets; dump
FBT and EEX tests in support of MaRIE (Carlsten, LANL)	proof of principle experiments for beam manipulations for proposed XFEL	Concept: test performance of various FBT and EEX lattices at ~1 GeV Requirements: adequate space in high energy beamline.

1.5 Conclusions and Strategies

NML has the potential to be the largest general user facility for AARD in the U.S. It has potential for both directed AARD (aimed at specific applications) and generic AARD (furthering accelerator science for potential future uses). Judging from the attendance at this Workshop, there is extensive interest from the accelerator community in performing experiments at NML. There is also broad interest from FNAL scientists in participating in these experiments. **The high beam charge, short bunch length, and high repetition rate make this a unique facility.**

A dedicated department, with a broad range of talent, will be required to commission and operate this facility. Extensive laser expertise will be especially needed.

Most of these experiments will require significant resources to stage and carry out. A procedure for accepting, funding, and assessing NML experiments should be formalized. **Our suggestion is that Fermilab solicit written proposals for experiments and maintain a standing advisory committee (similar to the AAC) to assess proposals on a regular basis – both to judge ongoing experiments and evaluate new proposals.** Approval should be made at a level high enough to ensure adequate and continuing funding for the experiments. MOU’s with collaborating institutions should be established to define roles, responsibilities, and funding sources. Clearly, experimenters must bring students/postdocs to Fermilab to run the experiments and FNAL must provide full facility operation and support. Fermilab scientists should be encouraged to participate.

2 High Intensity Beams R&D, collimation, and RF

2.1 Background

In the next decade, the HEP community will explore the energy frontier by operating the Large Hadron Collider (LHC), designing its upgrades, and developing novel concepts and technologies necessary for the design of the next lepton collider. The community will also explore the intensity frontier by designing (and possibly operating) high intensity proton sources for neutrino physics and precision measurements in rare processes, and designing high intensity muon sources for neutrino physics, ie., neutrino factories. In both cases there is a need for theoretical calculation, simulation, and concept development to understand the limiting factors and develop mitigation techniques in the design of high-intensity both circular and linear accelerators. The most important physics processes affecting high-intensity accelerators are space-charge, electron-cloud, and impedance effects, and beam loss minimization by mitigation of these physics processes or by collimation are essential for a successful high-intensity accelerator application.

2.2 Space-charge effects

The role of space charge as a cause of particle loss and resonances has found adequate attention in recent years due to the increased interest in designing and operating high-intensity linear and circular accelerators. It is now accepted that space charge is not only the source of incoherent single-particle tune shifts moving particles into machine resonances, but that it can also directly drive coherent resonances. These resonances may be further enhanced by the free energy from beam anisotropy, and cause dilution of the phase space density and eventual beam loss. Important space-charge effects in very high intensity machines include:

a) Coherent synchro-betatron instabilities in rapid cycling synchrotrons: Because of the need for a high acceleration rate these machines have a high value of the synchrotron tune at injection. Coupled to a large space-charge tune shift, this leads to machine tunes just under integer numbers, which can excite low order coherent synchrobetatron resonances. The resonant mode is driven by external sources (for example betatron kicks from dispersion in RF cavities -- an effect which is thought to be causing such resonant behavior in the FNAL Booster). If the space-charge tune shift is high enough, coherent and incoherent spectra are separated, thus disabling Landau damping of the resonant mode.

b) Magnetic field errors in circular accelerators and storage rings: The effect of even small errors can accumulate and lead to instability if the betatron frequency of the machine has resonant values. Depending on the value of the tune, particle motion is sensitive to different components of the multipole spectrum of lattice errors, and since lattice errors are unavoidable, tunes must be set to values sufficiently far from resonances (low order resonances are the most important). This analysis is based on a single particle approximation for beam dynamics, in which space charge is treated only as a perturbation producing a shift in the single particle tunes (incoherent tune shift). Since the space charge force is defocusing, it decreases the value of the tune. Based on the resonance analysis outlined above, a standard criterion to limit the effects of incoherent tune spread is to impose a maximum tune change during acceleration of no more than 0.5, so that no resonance associated with gradient errors is crossed. This requirement restricts the amount of beam that can be accelerated in a synchrotron. Since a beam of interacting particles (space-charge) is a system which in general displays frequencies of oscillations that are different from the single particle tunes, it is imperative that we study this limiting criteria utilizing treatments that take into account the collective behavior of the beam. Unfortunately analytical calculation of the resonance conditions for a beam of interacting particles is far more complicated than for the case of non-interacting particles and can be carried out only for simplified modeling of the beam dynamics or with numerical simulations. It is thus imperative that the study of both incoherent space-charge driven structure resonances and the study of potential coherent effects is coupled with experimental measurements under controlled conditions. Such effects are even harder to describe in bunched beams, due to the coupling to synchrotron motion.

c) Intrinsic fourth order space charge resonances in linear and in circular accelerators: The fourth order difference resonance (”emittance exchange” or ”Montague” coupling-resonance) and the fourth order structure resonance lead to emittance degradation depending on the strength of space charge, the crossing rate through the resonance, and the lattice. Scaling laws have been calculated in the coasting beam limit in terms of simple power law expressions. Studying and understanding this scaling will be extremely important for the design of FFAGs. This includes the measurement of the geometric parameters that enter the power laws.

Fermilab has several machines in its accelerator chain that can be used for very interesting measurements. The Booster (which has already provided very interesting data) could be a very important lab for studying effects such as synchrobetatron resonance, emittance growth and halo creation, scaling laws, and possibly mitigation prescriptions such as utilization of chromaticity and higher order multipoles. In this latter case it will be very interesting to study the interplay between coherent effects (fast losses) and incoherent effects (slow loss, halo creation). Mitigation techniques can help incoherent effects but may worsen coherent effects. **It will be important to plan for dedicated study time and include improvements of the beam diagnostics, especially turn-by-turn information on beam shape parameters. In addition, the Main Injector could be used for studies when Project-X relevant beam currents are available. Also, a low energy electron ring at NML could provide relevant information for lifetime and space-charge measurements, as long as the energy is low enough so that synchrotron radiation is not dominant.** Finally, all these studies benefit from numerical simulations. Fermilab already has much experience with the development and application of simulations capable of modeling 3D space-charge and other collective effects. Continuing to develop codes which can take advantage of massive computing resources and employ many physics models in the same simulation will be very beneficial.

2.3 Space-charge compensation

Over the past decade the electron lens has been developed at Fermilab. This new device employs the strong space charge forces of a magnetized beam of 10 KeV electrons which acts on 1 TeV (anti)protons. The technology necessary for electron lens applications is proven and available at Fermilab. It requires high field (>6 T) superconducting solenoids with very uniform B-field lines and correctors on all transverse phase-space planes. It requires the ability to generate magnetized electron beams with a variety of transverse profiles for the electron beam by utilizing thermionic cathodes. Currently this device is being studied at the Fermilab Tevatron for its effectiveness in beam-beam compensation and it could be used potentially for this purpose in the LHC. It was suggested that an electron lens application could be used for space-charge compensation, but the current thinking is that a variation of the same concept, the electron column, would be more effective. In this particular application, instead of uniformly distributing low concentration electrons around the ring, a high-concentration of electrons will be employed for a small fraction of the ring circumference. It is believed that this design would provide better stability of the transverse motion of the system, allow for good dynamic matching of the transverse beam charge distribution, and possibly allow for longitudinal compensation for not-flat proton bunches.

The development of electron columns is at the very beginning of the R&D phase. **Fermilab is in an excellent position to support this R&D by providing support and beam time to achieve the following technical goals:**

1. **Understand and characterize electron dynamics in e-columns (Linac Lab and TEL), especially tune shift and coherent instability.**
2. **Simulate improvement of slow extraction from Debuncher with e-lenses/columns (mu2e experiment)**
3. **Develop “stand-alone” superconducting solenoid technology for use in non-superconducting accelerators (cryocoolers)**
4. **Build an electron column or electron lens prototype for FNAL Main Injector and perform studies with highest available bunch intensity**

2.4 Electron cloud

The accumulation of spurious electrons inside an accelerator beam pipe (“electron cloud”) can interact with the positive beam to cause beam loss, emittance growth and an increase in the vacuum pressure. This is a very important effect in high intensity accelerators, relevant to both the design of intensity and energy frontier machines. It is essential that we have a good understanding of both the cloud buildup and its effects on beam dynamics. Primary electrons are generated by several different processes and their number is amplified by beam-induced multipacting on the vacuum chamber walls. The exact details of the secondary emission depend on the geometry and material of the surface. The models that are used for predicting these effects are based on phenomenological analysis of experimental data. It is thus essential to measure the electron cloud development to further constrain the models in order to make valid predictions. In addition, accurate calculations of the effects of the cloud on beam dynamics are impossible in the general case (without approximations), thus utilization of numerical simulations is necessary. These simulations are very time consuming, and in the current state-of-the-art they use simplifying approximations for the description of the non-electron-cloud dynamics of the accelerator. It is thus important to continue developing these numerical simulations in order to achieve accurate representation of the beam dynamics.

At Fermilab there is a very active program on electron cloud effect studies, focused on measurement and simulations of Main Injector configurations. This is very relevant to the proposed Project-X upgrades, that call for the machine running at 3E11 protons per bunch at 540 bunches, compared to the current state of operation at 1E11 with a smaller number of bunches. The current simulation studies and the measurements focus on characterizing and understanding the generation of the cloud, and how it is affected by the presence of external magnetic fields and the machine fill pattern. There are a few beam dynamics studies, employing a simplified lattice description and only modeling a single bunch. Experimentally both retarding field analyzer (RFA) detectors and the microwave propagation technique have been used to quantify the electron cloud generation in the Main Injector, with poor agreement between the two techniques so far.

The electron cloud program at Fermilab is synergistic to the necessary studies required by LARP for the proposed upgrade of the LHC proton driver, the PS2, and synergistic to the CESR-TA experimental program. **Regarding the future of the electron cloud R&D program at Fermilab, recommendations are:**

- **Make coherent tune shift measurement in the Main Injector using a witness bunch technique. Such a measurement performed at CESR-T showed good agreement with simulation, at least for the transverse phase-space coordinates, where details of the ecloud field have been taken into account**
- **Continue the development and deployment of instrumentation, both RFA and microwave, and test experimentally different mitigation techniques (beam pipe coating, bunch spacing, etc).**
- **Continue both experiment and simulation development in order to understand the discrepancy between RFA and microwave measurements.**

2.5 Collimation

Beam collimation is mandatory at any high-power accelerator and hadron collider. Only with a very efficient beam collimation system can the uncontrolled beam losses be reduced to an acceptable level, protecting machine components, detectors and personnel against excessive irradiation, maintaining operational reliability over the life of the complex, providing acceptable hands-on maintenance conditions, and reducing the impact of radiation on environment. Fermilab has a well established program on the design of collimators and the development of new collimator technology, and is responsible for the design of collimation systems both for Fermilab accelerators and other laboratories. In addition, an experiment on crystal collimation is conducted at the Tevatron (T-980).

In order to be able to handle the increased collimation requirements for the LHC and for future intensity and energy frontier accelerators new collimation techniques need to be developed, beyond the multi-stage collimators that are the state-of-the-art today. There are already plans and ongoing R&D for the upgrade of the LHC system that call for the replacement of the existing carbon composite collimators with metallic ones. There are other ideas for collimator technology evolution, such as rotating collimators, bent-crystal collimators for high energy machines (utilizing channeling), and new multi-strip crystals utilizing volume reflection (VR). VR radiation is very similar for both e+ and e-, and has large angular acceptance, thus it makes this option a good candidate for the collimation system for a linear collider. In addition, active elements for tail elimination, such as octupole doublets for nonlinear tail folding, and hollow electron lens collimators are being considered for different applications. The development of a hollow electron lens systems is very well suited for Fermilab because it builds on the expertise of the electron lens development for beam-beam compensation. This particular system may provide a good option for LHC collimation evolution:

- A non-invasive electron beam at a smaller radius can push halo out and can be used to eliminate loss spikes due to transverse beam motion and to increase the impact parameter of primaries collimators.
    - Halo particles as close as three sigma from the beam core could be effectively removed. No material used in conventional multi-stage collimators can survive to better than 5 sigma proximity to the beam core.
- The diffusion rate of halo particles would increase, which in turn would increase the impact parameter in the primary collimators, thus increasing efficiency.
- The increase in the impact parameter would allow for the primaries (and secondaries) to be placed at greater sigma, decreasing the impedance contribution of the collimators, an important consideration for the LHC.

In addition, since there is no matter-particle interaction, such an e-scraper can be just as effective with ions.

The R&D recommendations in this area of research include

- **Study hollow e-lens dynamics and build a prototype.**
    - **Technical goals :**
        - **Develop a 10-15 mm hollow beam electron gun (suitable for Tevatron e-lens), test it and measure its profile**
        - **Install in TEL2 and operate (beam studies) in DC regime**
        - **Design TEL2 modification with hollow cathode/collector and straight configuration for possible test at the end of Run II**
        - **Build an electron scraper for LHC, possibly test at RHIC, and possibly install in the LHC.**
- **Design and perform NML experiments on the beam folding technique with an octupole doublet.**
- **Continue T-980 crystal collimation experiment at the Tevatron through the end of (or even somewhat beyond) the collider Run II. (A new advanced goniometer, 3 new crystals and enhanced beam diagnostics are to be installed this summer.) Pursue the study of the volume reflection technique.**
    - **Design and perform experiment at NML on volume reflection radiation as an interesting possibility for e+e- beam collimation.**
    - **Study the potential of the technique at T-980 using Tevatron beam.**
- **A materials beam test facility, possibly using the Fermilab Pbar Source, will be very beneficial for ProjectX, neutrino factory, muon collider and ADSMW beam needs.**

2.6 Relevance/synergies with LARP

There are a number of of synergies between the LARP program and the topics discussed in the previous sections, especially with collimator technology development, space-charge studies (for the PS2 design), and electron cloud. In addition, LARP is interested in crab cavity development, which should be done in a wider context than just LARP, thus generating potential for future collaborations. The crab cavity R&D includes studies on beam dynamics including evaluating the merit for global versus local correction schemes, which must be done in conjunction with the collimator implementation choice. A very large component of the LARP program focuses on Nb_3Sn magnet R&D, attempting to explore and extend several operational limits (optics, field quality, beam loss/heat loading, and radiation damage). There is also a strong instrumentation R&D component (luminosity monitor, Schottky, AC dipole), where the potential for collaboration focuses on implementation, tests, and commissioning. Finally, laser stripping, which is of interest for Project-X, and laser wire emittance measurement, which could be tested at the FNAL linac, are other options for projects that could be done with major Fermilab participation.

2.7 RF

The need for an RF unit test facility (including CW) was discussed in depth at the Workshop. Potential tests and R&D directions include

- all components for fully dressed cavity and power distribution, modulators for phase and amplitude control
- replacement of gun (thermionic gun) to match Project X design parameters
- study individual tuning and power distribution to utilize maximum gradient per cavity
- study and optimize HOM absorption efficiency, design and prototype absorber for what is not absorbed, perform direct measurements in NML
- building and testing a prototype cavity BPM
- EM simulations of coupler and wakes
  - Design and study coupler kick reduction schemes and eventually test at NML
  - (LLRF studies) -- jitter stabilization

Most of these questions can be addressed by the new facility at NML.

3 Accelerator Driven Sub-Critical Assemblies (ADS)

3.1 Background

Accelerator Driven Sub-Critical Assemblies (ADS) have a long history. As early as the 1970s, a Canadian team led by Stan Schriber and others began the study of the transmutation of nuclear reactor waste by means of a high intensity proton accelerator. At about the same time, Bob Wilson at Fermilab suggested using high-energy protons to make neutrons, which would then be absorbed by fertile uranium or thorium to produce fissionable material that can be burned in a nuclear reactor. In the past three decades, a number of groups around the world (e.g. LANL USA, CERN Switzerland, and Gatchina Russia) were involved in the study of ADS and several projects were proposed (e.g. ATW, APT, AAA at LANL, CONCERT and EA in Europe). However, none of these projects were approved for construction. The reasons were complicated and varied from country to country. Consider the AAA project as an example. The project leader Richard Sheffield cited two principal reasons for its termination: (1) concerns of reactor designers about accelerator faults/trips; (2) a 1996 National Research Council study that was negative. While the latter could be based on faulty assumptions such as the requirement of eliminating the need for a High-level Waste (HLW) repository, the former remains of genuine concern today. This will be discussed in more detail below.

The situation is changing rapidly in the 21st century. Clean energy and clean environment are the two of the top priorities in almost all developed and developing countries including the US, Europe, Japan, China, India, Korea. A sub-critical thorium reactor connected to a high power proton accelerator as an alternative energy source has received the attention of many government policy makers. Such a system has a number of important advantages:

a) In the thorium fuel cycle, there are no fuel or waste products that can be used as bomb material;
b) A sub-critical reactor is inherently incapable of causing a meltdown, i.e. it contains passive safety features;
c) Thorium does not require enrichment, which guarantees there is no proliferation risk;
d) Waste consists mostly of U^{233}, which can be recycled as fuel;
e) Waste material is radiotoxic for tens of years, as opposed to the thousands of years with today's radioactive waste;
f) Thorium exists in great abundance.

While a), c), d), and f) are advantages of thorium itself, b) and e) are possible only when an accelerator is used as the driver.

The Indian government has announced the construction of a thorium reactor. The Chinese government plans to establish a new research institute dedicated to an ADS study and considers spending as much as 2-3 billion yuans ($300-450M) for this study from 2011 through 2015. The Japanese government issued a national license to Kyoto University to conduct an ADS experiment using the KUCA reactor and an FFAG accelerator. Europe has begun the EUROTRANS project for waste transmutation, funded by the European Union's Seventh Framework Program (FP7). In the US Senate, Harry Reid and Orrin Hatch introduced a bill titled "*Thorium Energy Independence and Security Act of 2009*," which proposes investing $500M to a thorium study from FY2010 through 2014.

3.2 Accelerator requirements

There are four basic requirements for an accelerator to be used as an ADS driver:

1) High power

   A nuclear reactor usually produces thermal power on the order of 1 GW. Depending on the criticality factor k of the reactor, the energy amplification factor G (ratio between thermal power and beam power) ranges from several tens to several hundreds. Therefore, the required accelerator beam power is on the order of 10 MW. This is achievable using today's technology, either by a superconducting linac or by a cyclotron.

   For demonstration purposes, however, the requirement can be greatly relaxed. For example, for a 10 MW demonstration reactor, a 100 kW accelerator would suffice.

2) Medium energy

In an ADS, the accelerator acts as a spallation neutron source. A proton hits a target generating tens of neutrons, which are absorbed by Th^{232} and transform it to U^{233}, which is fissile. The goal is to generate the maximum number of neutrons for a given proton beam power. The yield (number of neutrons per proton) is a function of the proton energy and peaks at about 1 GeV. This is the optimal accelerator energy.

However, the peak is broad. If we lower the energy to, say, 800 MeV, the yield would decrease by less than 10%. This energy level is attainable by either a linac or a cyclotron.

3) Remote handling
This is a difficult issue since even a small loss in a MW accelerator leads to a high radiation dose to the machine components. For instance, if a magnet fails, one must use remote handling procedures to carry out the replacement, including the water and electric connections and the RF joints. Fortunately, some laboratories, such as PSI which operates the world's most powerful cyclotron at 1.3 MW, have accrued years of experience in remote handling.

4) Extremely high reliability
This is the most difficult and most challenging problem in designing, constructing and operating an accelerator for ADS. The requirement was set by reactor designers, i.e., beam trips longer than 1 second cannot be allowed. This requirement is based on the effect of transients on materials (target and windows), the effect of transients on fuels, the quality of electrical power delivered to the grid, and necessary periodic maintenance. The performance of existing accelerators has a long way to go to reach this goal. For instance, the typical duration of short trips in the PSI cyclotron is about 30 seconds.

However, it is believed this issue is soluble if we follow reliability guidelines during the accelerator design: strong component design (over-design); inclusion of redundancies in critical areas; and the enhancement of the capability of fault-tolerant operation. Besides, improvements in power storage devices and careful evaluation of the effect of transients on materials and fuels (at LANL) and on reactor structures (at JAEA) may lead to a relaxed specification on beam trips.

3.3 What can Fermilab do?

The US DOE Office of High Energy Physics assumes the stewardship of accelerator R&D and is organizing a workshop in late 2009 to examine the uses of accelerators throughout society and R&D efforts to meet the needs of accelerator users. Fermilab, as the principal HEP laboratory in this nation, will play a major role in this workshop. It is expected that energy will be a major topic. Although ADS is not yet part of the current Fermilab planned program, it is a future accelerator application of great potential.

- Fermilab has the nation's largest and strongest team in the highly specialized proton accelerator field;
- Fermilab's ILC and Project-X R&D program provide a natural link to the 1 GeV multi-MW CW superconducting proton linac needed by ADS;

- ADS is a logical extension to the Fermilab program when it positions itself on the intensity frontier;
- Fermilab and Argonne Laboratory are located near each other. Argonne has had many years of experience in the reactor studies required for ADS. A joint Fermilab-Argonne effort can provide a quick start to an ADS program.

We propose forming a joint task force with Argonne Laboratory and the University of Chicago (UC). The charge to this task force would be to work out a near-term and long-term R&D program for ADS. The funding can come from the Strategic Collaborative Initiatives between UC and Fermilab and between UC and ANL.

This joint task force will be the core for a collaboration that can subsequently be expanded. For example:

- Los Alamos Laboratory.
  LANL built a great device called LEDA (Low-Energy Demonstration Accelerator), which was mothballed after the termination of the AAA project. It is a 6.7 MeV, 100-mA CW proton RFQ and reached ~1 MW beam power in just 8 meters. It has advanced instrumentation for measuring beam halo, critical for understanding beam loss in a high intensity machine. Fermilab can make a request for relocating LEDA to Fermilab if we decide to launch a serious effort on ADS.
- The Institute of High Energy Physics (IHEP) in China.
  IHEP is joining forces with three other institutes in the Chinese Academy of Sciences (CAS) to form a new institute dedicated to an ADS study. Prof. Jiuqing Wang, deputy director of IHEP and leader of this study, is editing a special issue of the *ICFA Beam Dynamics Newsletter* with ADS as its theme. This issue is scheduled for publication in August 2009. Prof. Wang has indicated a strong interest in collaborating with Fermilab in an ADS study.
- The Research Reactor Institute of Kyoto University (KURRI) in Japan.
  Recently KURRI conducted the first “accelerator + reactor” experiment for ADS, albeit at very low power. The experiment leader, Prof. Yoshi Mori, has had a long-term productive collaboration with Fermilab under the umbrella of the US-Japan Accord. We can explore the possibility of expanding this collaboration into the ADS area.

4 Medical Accelerators

4.1 Background

Accelerators have three types of applications in the medical field:

1) Isotope production
   About 90% of today’s radioactive isotopes for diagnostic nuclear medicine are produced in reactors. The remainder are made in cyclotrons. However, these reactors are aging, becoming unreliable, and experiencing frequent shutdowns. Replacements are not in sight. In order to overcome this urgent problem, TRIUMF, teaming up with the medical isotope company MDS Nordion, plans to build a high power 50 MeV superconducting electron linac to replace the reactors as a major supplier of medical isotopes in North America. This linac will use the ILC SRF technology.

2) Medical imaging

   There are two important inventions in medical imaging. One is SPECT, single photon emission computed tomography. Another is PET, positron emission tomography. Both make use of accelerators. Since the radioactive tracers have very short half-lives, they must be produced on-site by a cyclotron.

3) Cancer therapy
   a) X-ray therapy

      Radiation therapy for cancer treatment began as early as the beginning of the 20th century when x-rays were discovered. This technology has been perfected by the Varian Company in Palo Alto, California. A modern x-ray machine is based on a compact electron linac. It can treat as many as 100 patients per day. There are about 5,000 units installed worldwide and they provide about 50 million treatments each year.

   b) Particle therapy

      In 1946, Bob Wilson published his seminal paper "*Radiological use of fast protons*." It opened up a new field for cancer treatment by using protons of several hundred MeV, which can be readily produced by an accelerator. Because the Bragg peak of protons in the human body is much sharper than for x-rays, the treatment can be localized, tumor targeting accuracy improved, and the irradiation of sensitive neighboring tissues and side effects reduced. Cornelius Tobias at Berkeley pioneered this technology. It was later extended to use fast neutrons, helium, neon and carbon ions. As of today, a total of about 50,000 patients around the world have been treated by particle therapy over the past several decades.

This Fermilab workshop focused its discussion on 3b). A good reference is Volume 2 of the journal *Reviews of Accelerator Science and Technology*, which is devoted to the topic of medical applications of accelerators and is scheduled for publication in late 2009. There was also a recent hadron therapy workshop at Erice (Sicily), Italy.

4.2 Accelerator requirements

The reason that the number of patients treated by particle therapy is several orders of magnitude smaller than that by x-ray therapy is obvious. For the time being, the facility required by particle therapy is much bigger, more complicated and more expensive than that for x-ray therapy. Despite its undisputable advantages against x-rays, only a few large hospitals or national laboratories can afford a particle therapy facility. To illustrate the difference, an x-ray therapy machine can easily fit in a hospital room, whereas a particle therapy facility needs a whole building. The newest, recently completed in Heidelberg, Germany, employs a gantry that has a rotating part as heavy as 570 tons with a diameter of 14 meters.

Therefore, the main challenge to accelerator people is how to make hadron therapy accelerators smaller, lighter, cheaper and more flexible so that every hospital could afford one, just like the x-ray machines. Recent R&D is making progress in reducing the physical size of such installations.

4.3 What can Fermilab do?

Fermilab has a glorious history in particle therapy. Not only was Wilson the founding father of this laboratory, but also Fermilab designed and fabricated the world's first hospital-based proton therapy accelerator, which was installed at the Loma Linda Hospital in the 1980s. This hospital is by far the most successful proton therapy center in the world and has treated more than 10,000 patients in the past two decades, about 20% of the particle therapy patients altogether. Fermilab operates a fast neutron therapy center that began treating cancer patients nearly three decades ago.

Medical applications are a very important part of accelerator applications with a deep impact on society. They provide an effective and easy-to-understand way to communicate the relevance of accelerators to the public, showcasing the large returns and important benefits of the investment in accelerator science and technology.

At this moment, medical accelerators are not yet part of the current Fermilab planned program. We propose to add them. Specifically, we propose to form an exploratory team consisting of accelerator physicists and engineers from the Accelerator Physics Center and the Accelerator and Technical Divisions. The charge to this team would be to develop an R&D program for compact proton accelerators in the range of 200-300 MeV for cancer therapy. The technology should not be limited to conventional RF acceleration and magnet bending but should also explore the possibility of using an intense laser beam for proton acceleration, a new technique that has been making extraordinary progress in recent years.

5 Appendices

5.1 Workshop agenda:

Monday, May 11

16:00 Reception

Introductory Session

Convener: V. Shiltsev

17:30 – 17:40 V. Shiltsev (FNAL)	Welcome and Workshop Goals
17:40 – 18:10 M. Tigner (Cornell)	AAR&D: Big Picture and Challenges
18:10 – 18:40 M. Church (FNAL)	Introduction to NML at Fermilab

Tuesday, May 12

Session 1a: NML experimental possibilities

Conveners: M. Church, P. Piot

8:30 – 9:00	K.-J. Kim (ANL)	Beam Tests for Novel FELs
9:00 – 9:20	S.Y. Lee (IU)	Possible IU Experiments at NML
9:20 – 9:40	A. Valishev (FNAL)	Possible Experiments with Electron Ring at NML
9:40 – 10:00	P. Muggli (USC)	Possible USC Experiments at NML

10:00 – 10:30 Coffee break

10:30 – 11:00	V. Yakimenko (BNL)	AARD program at ATF and How NML Might Complement It
11:00 – 11:30	W. Gai (ANL)	AARD program at AWA and How NML Might Complement It
11:30 – 11:50	G. Schvets (UT)	Possible UT Austin Experiments at NML
11:50 – 12:10	J. Rosenzweig (UCLA)	Possible UCLA Beam Experiments at NML

12:30 – 14:00 Lunch break

<u>Session 1b: NML experimental possibilities</u>

Conveners: S. Nagaitsev, K.-J. Kim

14:00 – 14:30	T.Raubenheimer (SLAC)	Future Directions of AARD at SLAC
14:30 – 14:50	P. Piot (NIU/FNAL)	Possible NIU Experiments at NML
14:50 – 15:10	B. Graves (MIT)	Inverse Compton Source
15:10 – 15:30	A. Jansson (FNAL)	Possible Tests Relevant to Muon Collider R&D

15:30 – 16:00 Coffee break

16:00 – 16:30	C. Schroeder (LBNL)	Challenges and Opportunities of Plasma Acceleration Programs
16:30 – 16:50	D. Kaplan (IIT)	Possible IIT Experiments at NML
16:50 – 17:10	Y-E. Sun (FNAL)	A0 Photoinjector Program Extension to NML
17:10 – 17:30	B. Carlsten (LANL)	Possible LANL Beam Experiments at NML
17:30 – 17:50	S.Striganov (FNAL)	Photoproduction of muons at <1 GeV at NML

19:00 Workshop Dinner

Wednesday, May 13

Session 2: High Intensity Beams and New RF/Accel. R&D

Conveners: P.Spenztouris, M. Tigner

8:30 – 9:00	A.Burov (FNAL)	Overview of challenges and ideas toward very high intensity beams
9:00 – 9:20	V. Shiltsev (FNAL)	Space charge comp with e-beams/e-lenses/e-columns
9:20 – 9:40	V. Danilov (ORNL)	Test of the integrable optics accelerator idea at Fermilab
9:40 – 10:10	N. Mokhov (FNAL)	New collimation ideas:crystals,hollow e-beams,etc
10:10 – 10:30	E. Prebys (FNAL)	Accelerator R&D ideas for/at CERN LHC
10:30 – 11:00	**Coffee break**	
11:00 – 11:30	M. Furman (LBNL)	Issues with electron cloud for long-term R&D and possible beam tests
11:30 – 11:55	N. Solyak (FNAL)	Beam tests needed to explore new RF techniques
11:55 – 12:25	J.Hirshfield (Omega P)	Alternative concepts for a high-power proton driver

12:30 – 13:30 Lunch break

Session 3: Accelerator Driven Subcritical Assemblies (ADS) and Medical Accelerators

Conveners: S. Schriber, W. Chou

13:30 – 13:50	R. Raja (FNAL)	ADS: Issues and Ideas
13:50 – 14:20	S. Schriber (MSU)	Ideas for efficient beams for accelerator driven subcritical assemblies
14:20 – 14:40	J.Grillenberger (PSI)	Ultimate capabilities of high power proton cyclotrons: challenges
14:40 – 15:00	Y. Alexahin (FNAL)	D-T beam fusion ideas, why they don't work/review
15:00 – 15:30	R. Levy (Loma Linda)	Particle therapy and accelerator R&D needed to boost it
15:30 – 15:50	S.Peggs (BNL)	"Therapy&Thorea, FFAG & RCS: common challenges".

15:50 – 16:20 Coffee break

Session 4: Summary

Convenes: V. Shiltsev

16:20 – 16:45 Session 1

16:45 – 17:05 Session 2

17:05 – 17:25 Session 3

5.2 List of participants:

Name	**Affiliation**
Alexahin, Yuri	FNAL
Ankenbrandt, Chuck	Muons Inc
Burov, Alexei	FNAL
Carlsten, Bruce	LANL
Chou, Weiren	FNAL
Church, Mike	FNAL
Danilov, Slava	ORNL
Furman, Miguel	LBNL
Gai, Wei	ANL
Gholizadeh, Reza	USC
Grillenberger, Joachim	PSI
Hirshfield, Jay	Omega P
Holmes, Steve	FNAL
Jansson, Andreas	FNAL
Kaplan, Dan	IIT
Kim, Kwang-Je	ANL
Latina, Andrea	FNAL
Lee, S.Y.	Indiana U.
Levy, Richard	LLUMC
Lumpkin, Alex	FNAL
Mokhov, Nikolai	FNAL
Muggli, Patric	USC
Nagaitsev, Sergei	FNAL

Peggs, Steve	BNL
Piot, Philippe	NIU
Prebys, Eric	FNAL
Prost, Lionell	FNAL
Raja, Rajendran	FNAL
Rosenzweig, James	UCLA
Raubenheimer, Tor	SLAC
Schriber, Stan	MSU
Schroeder, Carl	LBNL
Seiya, Kiyomi	FNAL
Shiltsev, Vladimir	FNAL
Solyak, Nikolai	FNAL
Spentzouris, Panagiotis	FNAL
Stancari, Giulio	ISU
Striganov, Serge	FNAL
Sun, Yin-E	FNAL
Tigner, Maury	Cornell
Tollestrup, Alvin	FNAL
Valishev, Alexander	FNAL
Webber, Bob	FNAL
Wendt, Manfred	FNAL
Yakimenko, Vitaly	BNL
Yakovlev, Slava	FNAL
Yonehara, Katsuya	FNAL
Zwaska, Bob	FNAL

5.3 Web-sites:

http://indico.fnal.gov/conferenceDisplay.py?confId=2512

http://apc.fnal.gov/ARDWS/index.html

5.4 Organizing Committee:

Vladimir Shiltsev (FNAL, APC, Chair)

Michael Church (FNAL, APC)

Panagiotis Spentzouris (FNAL, CD)

Weiren Chou (FNAL, AD)

Margaret Bruce (FNAL, APC)

Synthia Sazama (FNAL, PPD)

Susan Weber (FNAL, PPD)