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NIU@FNAL Source Development Laboratory

An Expression of Interest for the formation of a Collaborative Laboratory for Beam and Laser Physics Research toward the Generation, Acceleration and Manipulation of Bright Beams

Principal Investigator: P. Piot (FNAL/NIU-NICADD)

Collaborators/Interested people (as of 11/06/2009)

FNAL: W. Chou, M. Church, H. Edwards, J. Ruan, Y.-E Sun, J. Thangaraj
NIU: V. Demir (Electrical Engineering), B. Gaillard (Chemistry)

Table of Contents

Executive Summary

Northern Illinois University and the Northern Illinois Center for Accelerator and Detector Development propose the formation, development, and operation of a source development laboratory (SDL) at and, when appropriate, in collaboration with Fermi National Accelerator Laboratory (Fermilab).

The new laboratory represents an expansion of the NIU accelerator science program and serves Fermi National Accelerator Laboratory in areas of mutual interest, including the development and study of novel high-brightness electron beam sources. These research areas are of strong interest to the Northern Illinois University Beam Physics and Accelerator Group (BPAG), and are of high relevance to future Department of Energy research facilities such as the International Linear Collider (ILC) and in the shorter term to the NML facility in construction at Fermilab. Student involvement at both the M.S. and Ph.D. level is expected to be very strong and immediate.

Introduction

The next generations of electron accelerators are anticipated to have vast improvements over the present generation of machines, both in terms of the quality of the electron beam produced and the average power of that beam. These areas of improvement contain key challenges for the beam diagnostics essential for characterization and control of these new machines. Existing diagnostics, such as those for emittance (a measure of the quality of the beam), will require greater sensitivity and precision so as to be properly matched to the expected beam parameters. New diagnostics will be required to measure and monitor such features as beam halo, which become important as higher average beam currents and powers are achieved. As advanced beam manipulations (e.g. transverse-longitudinal emittance exchanges) are employed to obtain greater control over delivered beam properties, new diagnostics will be required to measure beam phase-space cross-sections in "non-traditional" projections, e.g. between the two-dimensional phase space. And, due to the very high average beam powers and the use of these beams in user facilities, the diagnostics must be both fast and non-intercepting.

Development of new tools for science such as light source technology is part of the core mandate of the US Department of Energy, Office of Science. Ideas developed in collaboration between NIU/NICADD and Fermi National Accelerator Laboratory researchers offer the potential to create compact accelerators that could lead to, e.g., high-brightness x-ray light sources. Such a machine will also have electron beam properties similar to those anticipated for facility-scale installations, but with a much smaller cost and footprint.

Training and support of students in accelerator physics is vital if the field is to continue to progress. Such training is greatly facilitated by encouraging student access to and participation in ongoing research at accelerator laboratories. This interaction is of great benefit not only to the student but also to the laboratory. The proposed laboratory will be on an ideal scale for student involvement: large enough to provide several interesting and current research topics, yet small enough that a single student may become involved with most aspects of laboratory operation.

Northern Illinois University/NICADD proposes a collaboration to establish a source development laboratory (SDL) at Fermi National Accelerator Laboratory, to be jointly operated . Such a laboratory would address the needs mentioned above. Northern Illinois University/NICADD and Fermi National Accelerator Laboratory have strong interest in the development of new beam diagnostics techniques, and new sources. Such a laboratory would, by its nature, provide for a wealth of projects for student involvement, across the complete spectrum of complexity and depth of research. The intent is for the facility to be jointly supported by Fermilab and NIU/NICADD to strengthen accelerator research between the two institutions.

There are several potential funding sources to support this new laboratory. Facility-scale accelerators either presently being built or planned by the Department of Energy, such as ERL-based light sources, x-ray free-electron lasers, and linear colliders, will need non-intercepting diagnostics with greatly improved resolution in order to operate effectively. The Department of Defense also has strong interest in compact, high-power accelerators for a variety of missions. The diagnostics and beam source development planned for the SDL will be directly applicable to these machines. The possibility of constructing compact, flexible, x-ray light sources should be of interest to a number of agencies, including the National Science Foundation, Department of Homeland Security, Defense Threat Reduction Agency, and DARPA, as well as DOE and DOD in general. Recently the Office of Naval Research, for instance, has repeatedly indicated interest in funding such research efforts relevant to its mission (Note that all DOD-related activities carried by the NIU group are non-classified). The SDL would also be appropriate for inclusion in the State of Illinois supported Illinois Accelerator Research Center (IARC).

Development of a joint source development laboratory provides clear benefits to both Fermilab and NIU. Our respective institutions have collaborated in many areas, but we lack a single dedicated laboratory with which to pursue our most challenging and interesting ideas. Given our separate strengths and areas of expertise, our past accomplishments in the relevant areas, and our commitment to moving forward as an integrated program, we believe that funding can be secured to continue pursuit of our mutual goals through the Source Development Laboratory.

Current Fermilab-NIU/NICADD accelerator collaboration

The Beam Physics and Accelerator Group (BPAG), headquartered in the Department of Physics at NIU and part of NICADD, has as its primary mission development of the premier university accelerator physics program in the State of Illinois while collaborating with and enhancing the major local accelerator research facilities at Fermi National Accelerator Laboratory (FNAL) and Argonne National Laboratory (ANL). The confluence of these major facilities makes northern Illinois an ideal location for accelerator research and development. One feature of the discipline of accelerator physics is its use of tools from a wide range of specialties. Consequently, new tools for accelerator physics likewise are generally useful in other specialties. Faculty members within the BPAG have also started a beam physics and accelerator technologies curriculum that presently consists of three new courses: PHYS 790C: “Introduction to Beam Physics” (spring 2006, fall 209), PHYS 483/583 (fall 2006, fall 2008) and 683 (fall 2007) “Beam Physics I and II”.

Similarly the NIU Department of Electrical Engineering has committed significant resources to the recently established program in RF engineering in collaboration with Fermilab, the program provides a Master's degree in RF engineering. As part of this program a new microwaves and RF laboratory has been established with the support of Department of Energy, and the electrical engineering curriculum is devised to include courses ELE670 "Microwave Circuits and Devices", ELE677 "Advanced Microwave and Millimeter Wave Engineering", ELE674 "Transmission Line Media and Wave Propagation", ELE675 "Antenna Theory and Design", ELE674 "Microwave Measurement and Beam Instrumentation Laboratory" as part of the program.

To supplement the theoretical research done at NIU, the BPAG has been collaborating with Fermilab. This strong link between Fermilab and NIU is exemplified with two joint appointments in Beam Physics and Accelerator Technology (P. Piot since 2005 and H. Podlech starting in 2010) along with several students involved in Fermilab projects. One of our graduate students, Tim Maxwell, works on the development of a new non-interceptive diagnostics based on electro-optical imaging at the A0 photoinjector and is sponsored via the FNAL-university PhD program. Another student, Christopher Prokop, recently joined the NML effort and will carry, as part of his dissertation research work, detailed numerical simulations to devise possible configurations of NML that could support tests of novel acceleration schemes (e.g. based on dielectric wakefield structures). Amber Johnson, a Fermilab employee, is currently a graduate student at NIU and her dissertation work will most probably concern the experimental demonstrate of novel phase space manipulations. All these students are pursuing Ph.D. degrees.

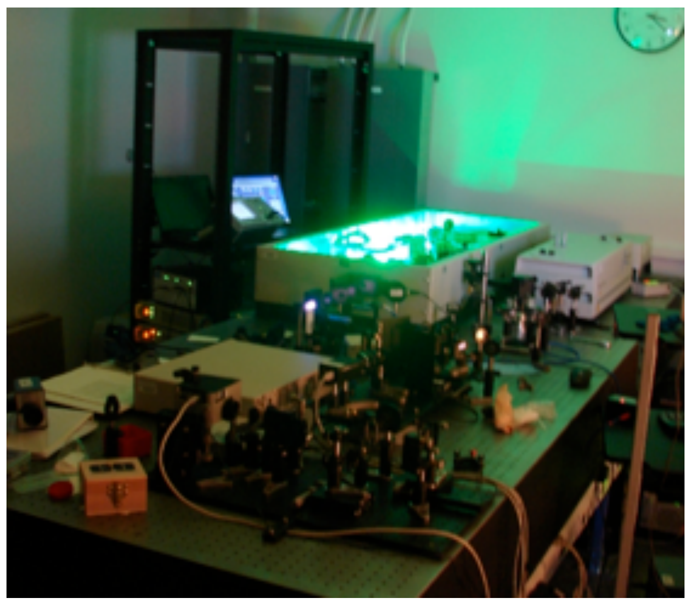

Figure 1: *Laser system that will be relocated at the A0 photoinjector beginning of CY2010. This work was sponsored by DoEd and the DOD's Office of Naval Research (ONR).*

NIU through the Northern Illinois Center for Accelerator and Detector development also significantly contributed to the operation and experimental program of the A0 photoinjector from 2001 to 2005. NICADD/NIU owns the seed laser presently used in the A0 photoinjector (which will also be used in the NML photoinjector). BPAG is also developing laser components in its NIU optical laboratory in collaboration with Jinhao Ruan (FNAL/AD/A0); see Fig. 1. A laser system capable of producing ultra-short (100 fs) ultraviolet laser pulses will be installed at A0 in the next few months to support a unique experiment aimed at generating uniformly populated three-dimensional ellipsoidal bunches. These distributions are foreseen to significantly increase the brightness of electron beams. This uniform ellipsoid bunch proof-of-principle experiment is led by P. Piot and involves, besides Fermilab's people, personnel from UW-Madison (R. Legg) and from MIT's Nuclear Research laboratory (W. Graves).

Drivers for an NIU-NICADD beam laboratory at Fermilab

The A0 photoinjector will soon be decommissioned and most of Fermilab's electron beam research effort will shift toward NML. One of the primary goals for NML is to demonstrate the performance and reliability of superconducting accelerating modules for the ILC program and also address the technical challenge associated to Project-X. In addition, Fermilab has committed to eventually transform NML into a beam physics facility that should drive exciting beam physics experiments and novel acceleration and light source concepts. NIU/NICADD is a strong supporter and contributor to this program: presently one of our graduate students is involved in NML and we have pending proposals to possibly attract further funding and expand our contributions to the NML program.

Ultimately the performance of NML will be limited by the electron source, currently Fermilab does not plan to have a dedicated laboratory to continue R&D on electron sources. Persuing such an R&D program directly at NML will be very disruptive to the NML program. It is therefore of prime importance to pursue, in parallel to the NML program, a vigorous R&D program aimed at developing new concepts of electron sources; see Fig 2. This is precisely one of the research efforts to be conducted at the SDL. The R&D program will include the design and testing of improved radio-frequency gun cavities (probably in partnership with companies); the design and testing of novel electron sources based on, e.g., field emitter array cathodes; and the development of laser techniques needed to precisely control the six-dimensional phase space of photo- (or field-) emitted electron bunches. One of the emphases is the development of electron sources for next generation of laser-based accelerators (one of the requirements being the capability to produce electron bunches with atto-second duration). The laboratory would also support R&D on the beam diagnostics required to characterize the beams produced by these electron sources. Such research initiatives could have high education and research payoffs that could be directly transplanted to NML and to GeV-scale ultra-bright electron accelerator.

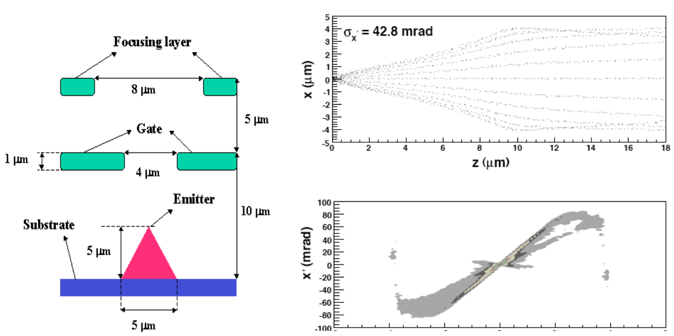

***Figure 2:** Geometry (left) of a field emitter cathode and associated electron trajectories (top right) and transverse phase space downstream (bottom right) of the field-emission cathode [D. Mihalcea and P. Piot, 2008]. This work was supported by the DOD/ONR Joint Technology Office.*

By teaming with Fermilab to install and operate this laboratory, both BPAG and Fermilab will benefit. First, locating the laboratory in Fermilab will give BPAG access to Fermilab-wide expertise in accelerator technology; this is a crucial element for the training of students and will also eventually enhance our Beam Physics and Accelerator Physics curriculum, e.g. by involving some of Fermilab personnel. BPAG could contribute both scientific full-time equivalent personnel (mainly faculty and graduate students), and with hardware, e.g., the already purchased RF power system will be needed to drive the initial beam source and the purchase of needed hardware to enable the operation of the facility. In return this unique accelerator laboratory will be a huge asset for increasing the scope of our NIU/NICADD BPAG program. . Placement of the facility at Fermilab allows the SDL to draw upon the local expertise and infrastructure available at Fermilab. Our facility will focus on high-brightness electron source development and will not require any superconducting cavity and associated infrastructure. It will however use (if available) the 1.3 GHz system already installed at A0 and the magnet and vacuum part that would not be relocated at NML.

Example of Possible Specific Collaboration Topics

There are a number of topics in accelerator physics that are of common interest to both the BPAG and Fermilab. Examples include:

- Electron beam source development:
    - Photo-injector development: the SDL facility could be used to continue developing and commissioning new variants of the rf-gun(s) for the NML facility.
    - Novel photo-emission and field-emission electron sources: NIU is currently a subcontractor on an Argonne grant funded by the Department of Defense. The work entails developing a novel field-emission electron source capable of producing extremely bright electron beams. If successful, this project could lead to very short-wavelength coherent light sources, e.g., based on the free-electron laser principle. In the short term, this should lead to a M.S. thesis project. In parallel NIU is collaborating with MIT on the development of a compact X-ray light source. The collaboration include Akintude's group whose expertise resides precisely in the development of nano-structures. Similar expertise is present at NIU (in the chemistry laboratory) and could be developed further.
- Beam dynamics
    - Optimization, modeling and benchmarking of simulation codes for photoinjectors: In particular the NIU version of Impact-T, and possibly later simulations based on Vlasov solvers. The beam dynamics of high brightness beam are intricate due to the beam self-fields. Many tools have been developed to integrate the equations of motion and study the evolution of the properties associated with charged particle bunches. There is however, a lack of detailed benchmarking of the various simulation programs available to the beam physics community. Both Fermilab and BPAG are interested in pursuing such modeling validation using experiments carried at the SDL.
    - Phase space manipulations and beam tailoring
- Beam diagnostics
    - Low energy beam halo diagnostics (both intercepting and non-intercepting): Some beam applications require very high average current accelerators. In this type of accelerator the presence of an unwanted halo can result in significant radiological activation of, or physical damage to, some of the accelerator components. The development of an extremely sensitive diagnostic to detect halo is essential. BPAG received some preliminary funding to pursue R&D on this diagnostics. This is an important topic which is of interest for intense proton accelerators and high average electron linacs used for driving high power free-electron lasers (FEL). FELs are currently being explored by and are of interest to the DOD.

  - Measurement of beam phase space in non-traditional projections, e.g. x-pz: Most phase-space measurements are used to measure correlations and distributions within a single correlated plane, e.g. x-px, z-pz. With the advent of advanced beam manipulation techniques (e.g. flat-beam transform, transverse-longitudinal emittance exchange, crab cavities for short-pulse x-ray generation), measurement of new projections of phase space becomes important to the successful operation of machines based upon them. These measurements are relevant to experiments being planned as part of the NML AARD program and would be eventually integrated in NML.
- Novel proton/ions sources for medical therapy: SDL program will include laser system(s) which could eventually be upgraded to produce TW-peak power. Such a laser could be used to foster new R&D program such as the generation and acceleration to ~250 MeV/a.u. proton or ion beam to support next generation of compact proton/ion therapy centers. This activity could attract funding from the NIH agency.

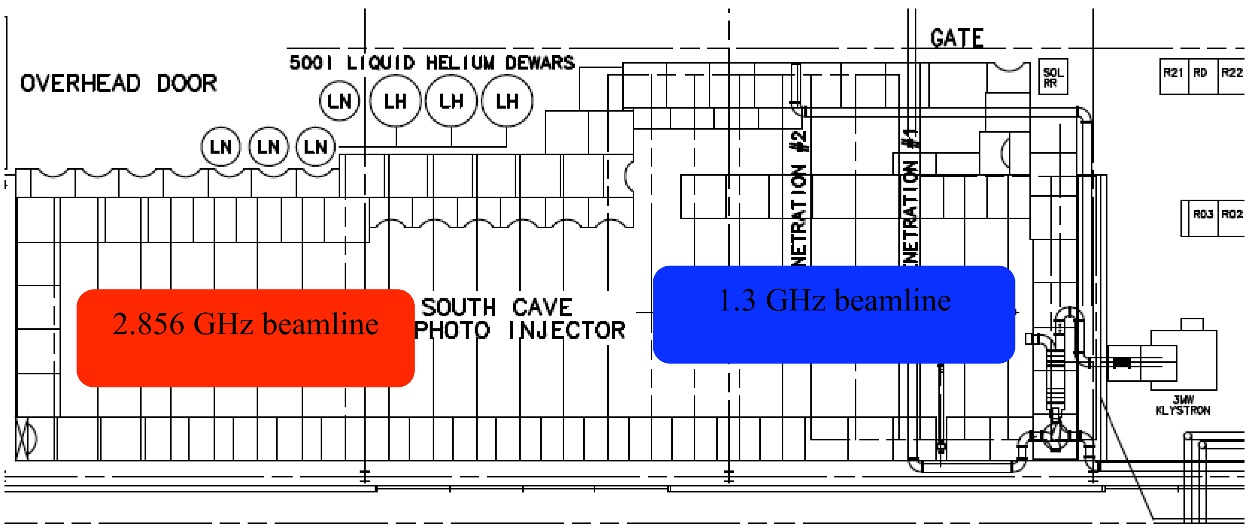

Figure 3: *Overview of the A0 bunker with proposed beamlines. The "1.3 GHz beamline" will include the present A0 photoinjector system (gun and magnets) while the "2.856 GHz beamline" will incorporate new elements (most of them already in hands at NIU). The "1.3 GHz beamline" will be used to carry R&D in direct connection with NML and ILC. The "2.856 GHz beamline" will be used to explore more advanced concepts (e.g. field emission cathode, production of shaped electron beam, etc…)*

Foreseen activities for the first two years

NIU already has in hand a 6 MW 2.856 GHz klystron with modulator (a turnkey system from Scandinova inc.), a Titanium-Sapphire sub-TW laser system (capable of serving as a photo-cathode laser), quadrupole magnets, ions pumps and other generic components needed to build an accelerator beamline. The only missing element is a 2.856 GHz rf gun but several guns are available at the APS and could be borrowed from Argonne.

Since the A0 gun, magnets, most of the vacuum parts (beamline and diagnostics), controls and support structure will not be needed for NML (and will remain in the A0 building), we would start by using the A0 gun and beamline (using our Titanium Sapphire laser as a photocathode laser), this would give SDL an electron beam from day one. We are currently not proposing the use of any accelerating cavity beside the rf-guns and assume the superconducting cavity currently installed at the A0 photoinjector would be removed from the beamline (as currently planned). We do not foreseen any use of superconducting cavities in the long term. In parallel we would start building a second beamline with a 2.856 GHz gun; see Fig. 4 for a possible configuration of the accelerator vault. The 1.3 GHz gun and beamline will be used for R&D directly related to NML or the ILC program while the 2.856 GHz beamline would be used for more advanced (and risky) R&D such as operation of field emitter cathodes in an RF-gun. Depending on the operational mode selected, the base configuration can provide single bunches up to 2 nC, or bunch trains to 1 A macropulse average current, and bunch durations down to ~ 100 fs.

Activities will include:

- A novel scheme to measure the halo with extreme sensitivity is being developed at NIU. Preliminary background test at Argonne were successful. The halo diagnostic will be installed at SDL for full test and improvement. This halo monitor is an important diagnostics for high average current linacs.
- Test of a 1.3 GHz PWT rf gun. Duly Inc. has a SBIR Phase II award and is supposed to deliver a new 1.3 GHz gun based on the PWT scheme. SDL could support the testing of this gun. The tests of this gun, if successful, could open new possibilities for producing spin-polarized electron beams.
- First test of field emission photocathode in an rf-gun, in collaboration with Vanderbilt University and or MIT. This effort will most probably include the participation of a student from Vanderbilt and/or MIT.

Opportunities beyond the Accelerator Sciences

The compact facility described above could also foster several non-accelerator sciences program. First the department of Biochemistry and Chemistry at NIU is interested in having access to a 5 MeV electron beam for radiolysis experiments. In addition the P. Piot, (NIU, Physics); B. Gaillard, (NIU Chemistray/Biochemistry); and V. Demir (NIU, Electrical Engineering), have recently proposed the construction of an accelerator facility for ultra-fast electron diffraction (with ~30 fs resolution); see rendition of the concept in Fig. 4. There is no doubt the SDL could support such experiments. Very recently J. Santners (NIU, College of

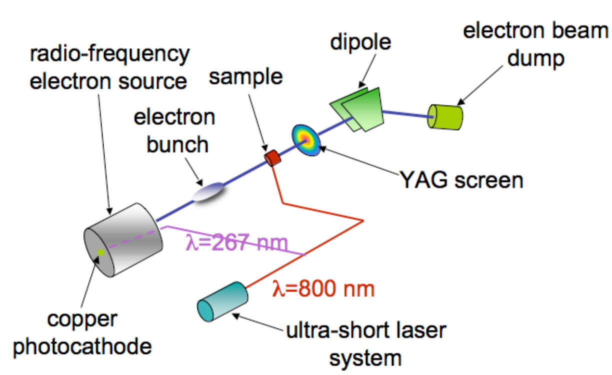

Figure 4: *Electron accelerator configuration for ultra-fast electron microscopy [P. Piot, B. Gaillard, V. Demir submitted to NSF (2009)].*

Engineering & Engineering Technology) contacted P. Piot to explore possible collaborative work on electron beam technology for waste treatment. Again SDL could be used to support early stage experiments on this topic.

Summary

A strong NIU collaboration with Fermilab would provide an experimental platform with local infrastructure and expertise that not easily available at NIU. Such a capability, along with the related accelerator facilities present at Fermilab, would provide a strong capable collaboration for future proposals and undoubtedly help in securing peer funding. The SDL would also be a natural component of the State supported IARC. Finally, the NIU/NICADD group and various Fermilab groups have many common interests and one common sponsor (DOE), making development of joint facilities and programs even more attractive from a funding-agent viewpoint.

Proposed facility location

We presently envision to construct the SDL in the A0 building in the south cave; see Fig. 5. The building currently hosts the A0 photoinjector facility and the proposed beam laboratory could benefit from infrastructure already in place there (e.g. the control room and the temperature-stabilized laser room). The accelerator vault and its adjacent racks areas, the laser and control rooms would be the required space to host SDL.

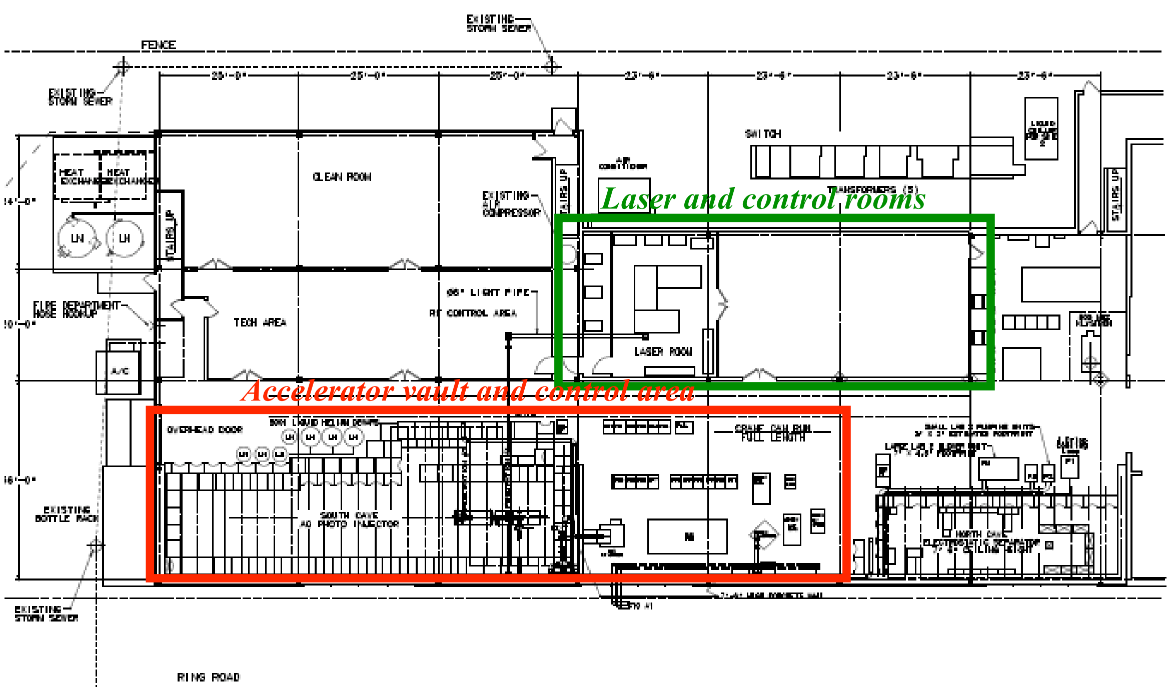

Figure 5: *The most natural (and cost-effective) location for the Source Development Laboratory is in the building A0 at the current location of the A0 photoinjector. Most of the A0 hardware would be reused (if available). The colored rectangles indicate areas that would be needed by the SDL.*