Prospects for an Accelerator Program in Mexico Focused on Photon Science

C. Hernandez-Garcia*, and M. Napsuciale**

*Jefferson Lab, 12000 Jefferson Ave, Suite 19, Newport News, VA 23606
chgarcia@jlab.org

** Departamento de Física, Universidad de Guanajuato Campus León, Lomas del Bosque 103, Fraccionamiento Lomas del Campestre, 37150, León, Guanajuato, México.

Abstract. Recent interest in developing Mexican expertise in Accelerator Science and Technology has resulted in several actions by the Division of Particles and Fields in Mexico, and by the electron accelerator community in the United States. We report on the very encouraging activities over the past two years which were aimed at developing a light source as the most effective starting point. We present a number of possibilities to initiate and grow an accelerator science program and present a path that would lead to building, commissioning and operating a third or fourth generation light source in Mexico.¹

1. Background
In March 2009, representatives of Mexican high-energy physics groups (theorists and experimenters) attended a meeting, hosted by the National Council for Science and Technology of México (CONACyT), to discuss the perspectives and prospects for their disciplines and to propose plans to develop them. Most of the participants were members of the Division of Particles and Fields of the Mexican Physical Society (DPyC-SMF). Among the conclusions of this meeting was the need to train people in “accelerator physics”. At present, the Mexican high energy physics community is involved in theoretical and experimental research (LHC, AUGER, FERMILAB) with expertise in data analysis and detector development. There are no Mexican physicists or engineers with accelerator science expertise.

In the summer of 2009 one graduate student from Universidad Autonoma de Sinaloa spent 8 weeks at Jefferson Lab’s Free Electron Laser (FEL) learning the basics of accelerator physics, and developing

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practical skills working with high voltage DC photoemission electron guns. Later in November of that year, the corresponding author presented a talk about the JLab FEL program at the XII Mexican Workshop in Particles and Fields, hosted by Universidad Autónoma de Sinaloa in Mazatlan, Mexico. In a meeting with members of the DPyC-SMF, the intentions amongst the particle physics groups to develop accelerator physics programs in Mexico were discussed, with the ultimate goal of building and operating a particle accelerator.

2. Some initial considerations

2.1. Why would México want to embark on developing an accelerator program?
Accelerators are very important tools in many scientific fields. These fields increasingly include medical, biological, material sciences, to name just a few, in addition to the traditional nuclear and high energy physics areas. This is exemplified by the growth in accelerator installations world-wide. One third of the 15,000 accelerators in operation worldwide are used in radiotherapy and almost two-thirds are used for industrial applications such as semiconductor production, sterilization, and materials preparation or in processes such as x-ray micro-machining. These few examples show the economic benefits of accelerators.

The development of an accelerator physics program trains a new generation of students, scientists, engineers, and technicians in this inherently interdisciplinary field and has the potential for economic stimulus for indigenous industry. For example, Klystrons, (used to accelerate particles and are expensive to develop), can be replaced by solid-state Radio Frequency (RF) amplifiers that can be built in Mexico by bringing expertise from the microwave telecommunications industry to a new technical field. Cooling water systems, control electronics and software and vacuum systems can be developed and constructed as a multi-institution and multi-disciplinary effort. Direct economic benefit comes also from manufacturing specialized equipment such as magnets and DC power supplies, from training and employing technicians, engineers, surveyors, etc. not to mention the civil construction of the accelerator enclosure and associated laboratory space and office buildings. All the research done by Mexican institutions is an additional stimulus along with the influx of international researchers looking for light sources.

2.2. What is the ultimate goal?
A Light Source, based electron accelerator technology, would be an ideal entry machine for Mexico to eventually do forefront photon science and become part of a worldwide accelerator-based light source community. A light source benefits a broader research community (e.g., materials, solid state, medical, biology, chemistry). In addition, light sources tend to be smaller installations than typical particle accelerators which are primarily nuclear and high-energy physics machines.

To place the photon science relevance in perspective, during the past five years, the United States Department of Energy has organized 10 Workshops with more than 1,500 participants from academia, industry and national laboratories through its Basic Energy Sciences division to make a case for the century’s Science Grand Challenges. The report, “Directing Matter and Energy: 5 Challenges for Science & the imagination” by Graham Fleming and Mark Ratner (chairs) [1], presents the following challenges:

1. How do we control materials processes at the level of the electrons? *Pump-probe and time dependent dynamics*
2. How do we design and perfect atom- and energy-efficient synthesis of new forms of matter with tailored properties? *Pulsed Laser Deposition, photochemistry, X-Ray Spectroscopy.*
3. How do remarkable properties of matter emerge from the complex correlations of atomic and electronic constituents and how can we control these properties? \textit{Pump-probe time dependent dynamics and X-Ray Spectroscopy}

4. How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things? \textit{Pump-probe time dependent dynamics and X-Ray Spectroscopy}

5. How do we characterize and control matter away – especially very far away – from equilibrium? \textit{Non-linear dynamics, ultra-bright photon sources.}

These challenges are not unique to one nation and provide the impetus for the construction of third generation light sources in Australia, Spain, Brazil and France and for the construction of fourth generation light sources by the U.S., China, Japan, and a collaboration of European countries. The fundamental physics and technological challenges involved in developing accelerators capable of meeting the stringent requirements for producing X-ray beams with unprecedented brightness, fluence and pulse length, while maintaining temporal and special coherence are just being explored by the international accelerator and photon science communities. There are many opportunities for a new generation of scientist and engineers to contribute to the field.

3. Accelerator R&D

We focus on electron beams due to the fact that electron beams are best suited to generate light. Some of the multi-disciplinary areas involved in accelerator physics are briefly described below.

\textit{Beam physics} studies the behavior of a group of charged particles, known as a charged particle bunch, subject to internal forces of the bunch itself, as well as applied external electric and magnetic fields. The fundamentals of beam physics can be studied with an understanding of relativity, electromagnetism and calculus. Often the beam physics design of an accelerator, from beam generation through beam acceleration and transport, requires no hardware other than a computer for simulations since the collective effects of all particles composing the electron bunch are far too complex to be treated analytically.

\textit{Beam generation}. The beam is generated under vacuum conditions at the cathode, and typically accelerated in the range of 10keV to 2 MeV in what is known as an electron gun or injector. The most common type is the thermionic gun similar to that found in cathode ray tubes (CRTs). An electrically heated element such as oxide coated metal filaments or Hexaborides, emit electrons that have overcome the potential barrier (work function) by thermal energy. Electrons gain kinetic energy by means of a suitably biased the cathode. In photoemission electron guns, the electrons are generated in a photosensitive material, the photocathode. When a laser pulse illuminates the photocathode surface electrons are emitted due to photoelectric effect. The actual photoemission process consists of three main steps: photon absorption, electron transport to the surface, and emission into the vacuum. Once the electron bunch is generated, it is quickly accelerated to relativistic energies in order to reduce the transverse beam size spread due to the Coulomb repulsion of electrons within the bunch. In DC guns, an electrostatic accelerating field is generated with the cathode biased at 10-500 kV with respect to grounded anode which is placed a few centimeters from the cathode. An aperture in the anode allows the electron beam to exit the gun. In RF guns, the longitudinal component of an alternating electromagnetic field inside a specially shaped cavity accelerates the beam to ~2 MeV. If the cavity is made of copper, the gun is known as normal conducting radio frequency (NCRF) gun. If the cavity is made of cryogenically cooled Niobium, the gun is known as superconducting radio frequency (SRF) gun. Technical challenges such as ultra-high vacuum, very high voltage, cryogenics and RF high power are intertwined with the physics of beam generation for all types of electron guns, offering a multitude of training opportunities, R&D and career specialization.
Beam transport. The generated electron beam, composed of a train of electron bunches, exits the gun and travels in evacuated beam pipes. The transverse size of the beam is manipulated by electromagnetic elements mounted around the beam pipe to prevent beam scraping at the walls, which results in beam loss and generation of undesired radiation in the form of neutrons, x-rays and gamma radiation. Some elements such as solenoids and quadrupoles focus the beam, dipole magnets bend the beam and air-core coils provide vertical and horizontal steering. DC power supplies energize the magnets and high power magnet coils are cooled down with low conductivity water recirculation systems instead of air.

Beam acceleration. Typically, the beam leaving the gun/injector would be further accelerated. The final beam energy can be anywhere from 10 MeV for medical applications and up to tens of GeV for nuclear physics, high-energy physics, and light sources. The acceleration of electron bunches is achieved in either NCRF or SRF cavities, usually assembled in groups of 2-10 in larger, modular accelerator components. The traveling electron bunch is accelerated in a cavity by the longitudinal electric field (in the direction of beam velocity) component of an electromagnetic wave oscillating at radio-frequencies in the order of 500 to 1500 MHz coupled to the cavity. The RF power needed to accelerate the beam is provided by velocity modulation in electron tubes called Klystrons, and is transported to the cavities by waveguides or specially shielded cables, depending on the frequency and power. The module assembly is then transported to the accelerator enclosure for installation in the beam line, and then connected to the RF power systems, and in the case of SRF technology, it is also connected to cryogenic lines. There are a multitude of disciplines involved in the physics and engineering designs and in the construction of these modules, such as particle beam physics, material science, mechanical, electrical and cryogenics engineering. Also wide ranges of degrees and skills ranging from bachelors to doctoral degrees in science and engineering fields are needed to realize such accelerating modules from concept to the actual product.

Beam diagnostics. This is an area that offers a range of topics in disciplines such as electrical engineering, computer science, mechanical engineering, instrumentation & control and beam physics. There are two main branches in beam diagnostics: one provides information about the beam (bunch) properties and the other provides information about the beam position and timing as it travels through the accelerator. In beam position monitors, opposite and electrically isolated plates coaxial to the beam path register the image charge, the difference in charge between the plates gives a relative position of the beam. In pulsed mode, the electron beam transverse profile can be viewed indirectly by the coherent transition radiation when the beam collides with a thin foil inserted in its path. The beam energy spread can be inferred from synchrotron radiation imaged on CCD cameras as the beam path is bent in dipole magnets. Other devices such as moving wires and multi-slits are inserted into the beam path for measuring transverse emittance, helping characterize the transverse phase space properties at a particular location along the accelerator.

Other technical areas such as vacuum systems and beam loss detection by radiation monitoring, essential for personal safety and for machine protection systems, also present opportunities at various levels of proficiency. If SRF acceleration technology is chosen for the machine, scientists, engineers and technicians can be trained in cryogenic systems. Following the Light Source in Brazil example [2], insertion devices (undulators/wigglers) can be designed by a new generation of scientists and engineers, and built by specialized companies such as STI. A new generation of scientists and engineers could also develop the X-ray beam transport lines and user end-stations.

Mexican engineers engaging undergraduate and graduate students in specific projects can develop the control system for all of the machine sub-systems.

4. Developing a Mexican accelerator program
Successful projects have often been envisioned, planned and executed by a core group of people with a clearly defined goal. The formation of a “steering committee” would be essential to take the endeavor from the early stages to the ultimate goal. This is something that needs to be driven by Mexican institutions interested in both photon science and accelerator physics—necessarily multidisciplinary and multi-institutional. The committee will need to remain focused despite unavoidable hurdles (politics, resources, etc). A paramount task would be the creation of a nation-wide case for photon science towards building a national user community, which could potentially expand to the international photon user community and drive the development and construction of the first light source in Mexico. In parallel with lobbying at the government level for a science case, development of a foundation of accelerator scientists, students, engineers and technicians could be carried out by the means described below. The formation of the committee should not preclude the start of a training program, which in fact, has already started.

4.1. The photon science case: Organization of workshops will be essential in attracting potential users among diverse disciplines such as material and life sciences, applied R&D for industry and medicine towards developing a photon science case for building a Light Source. The idea is the establishment of a truly National Facility offering unprecedented research resources not only to Mexican institutions but also to U.S. and Latin American counterparts. Multi-national sources of funding can be explored if credible proposals with strong science are presented.

4.2. The student foundation: Training a new generation of students in beam physics theory and simulations can be started immediately by encouraging undergraduate students to seek universities with graduate programs specialized in accelerator physics such as Old Dominion University, Cornell, Berkeley, University of California Los Angeles, Stony Brook, Idaho State, and Northern Illinois University. These activities should be handled skilfully to foster a strong motivation for graduated students to return to Mexico for becoming the professors and the scientists who will lead the Accelerator Program.

4.3. The scientist and engineer foundation: Establish collaborations between Mexican and International Institutions to send recent PhD graduates to become post-doctoral fellows, visiting professors and visiting researchers to institutions with well established accelerator machines and programs such as Thomas Jefferson National Accelerator Facility, Cornell light source (CHESS), Lawrence Berkeley National Lab, UCLA Particle Beam Physics Laboratory, Brookhaven National Laboratory, Argonne National Light Source, University of Wisconsin Light Source (Aladdin) and Idaho Accelerator Center.

4.4. The technical expertise foundation: Establish collaborations with aforementioned institutions to send engineers and technicians to learn new skills on topics such as magnet design, construction and operation, Radio Frequency systems, Vacuum systems, DC power system, Low conductivity and cooling water systems, Cryogenics, Radiation control, Machine protection systems, Instrumentation and control, etc.

4.5. Small accelerators as training tools: There are many decommissioned medical and industrial accelerators that can be acquired as “educational loans” to be assembled and operated in university laboratories with minor infrastructure requirements. New Ph.D. students returning to Mexico could take on the lead in training students and technicians during the assembly and operation of such accelerators. Of special interest would be the formation of a committee to visit Idaho State University (ISU) to learn from their model. ISU has over 20 small accelerators and a very productive educational program. Other example is the Cyclotron Kids project [3] sponsored by Jefferson Lab, in which two high school students have spent the last two summers at Jefferson Lab working and learning from scientists, engineers and technicians who have enthusiastically worked on the project for free.
Materials such as 2 tons of steel for the magnet have been donated by local industries, vacuum equipment has been rebuilt from spare parts donated also by Jefferson Lab. RF amplifiers and electronics have been purchased at very modest prices through e-bay. This could be an ideal approach to train students and technicians in the technical and scientific aspects of an accelerator since the small cyclotron shares many of the same principles of operation as its larger counterparts. In addition, its small size allows it to be developed and operated in a typical university laboratory space, with minimal radiation shielding.

5. Suggested time line
2010-2015:
• Students start Ph.D. programs in Accelerator Physics
• Interested Mexican Universities establish connections with U.S. institutions and industries to acquire equipment by “educational loans” to build small accelerator for training and education
• Develop synergy between physics and light source community in Mexico to draft plans for workshops towards forming a photon science case

2015-2020:
• The first generation of students returns to Mexico and starts assembling and operating the equipment, while teaching basic courses to students and training technicians.
• At the end of the five year period, demonstrate successful operation of the first accelerator for educational and training purposes
• Continue training a second generation of students
• Continue physics and photon science workshops towards elaborating science case

2020-2025:
• Develop formal photon science case based on workshops and white papers. The document should also include a study of the economic benefit that an accelerator-based light source would have in the country, by training a new generation of highly skilled physicists, engineers and technicians who would eventually build, maintain and upgrade such a machine or use their acquired skills in industry or start their own enterprises.
• Establish a PhD program in Mexican Universities focused on accelerator physics, for the continuing training of a new generation of physicists and engineers.

2025-2030:
Begin design and construction of the accelerator-based light source, followed by commissioning and operation. This phase can be accomplished by taking a de-commissioned machine, or by designing and building a brand new one. The latter would be more difficult but will be the ideal case since the machine would be designed and built by the people who have actually been trained. In either case, the accelerator-based light source would be operated and maintained by a new generation of scientist, engineers and technicians that will be subject-matter-experts in many disciplines.

We would like to remark that the suggested time-line can be shortened to at most ten years if an aggressive plan to develop the accelerator program is supported by the Mexican funding agencies.

6. Resources and opportunities:
The United States Particle Accelerator School (USPAS) conducts graduate and undergraduate level courses at U.S. universities, holding two such programs per year, one in June and one in January. These courses, running 2 weeks in duration, take place at leading universities across the United States. By successfully completing the 2-week course requirements, which include forty-five contact hours as well as daily problems and examinations, students earn 3 semester hours of university credit. The course accreditation for students enrolled in Mexican Universities would have to be worked out
directly with USPAS. In Norfolk VA, Old Dominion University (ODU) Center for Accelerator Science grants Ph.D. in accelerator physics where students do their thesis work on projects under the guidance of JLab staff who are also ODU professors. The visit of one of the authors (M. N.) to Jefferson Lab in May 2010 generated genuine interest, willingness and cooperation - which can provide not only theoretical but hands-on experience for particle accelerators. Since JLab is a leading SRF facility and since SRF technology is favored for most future accelerators including the International LINAC Collider and fourth generation X-ray light sources, the lab's encouragement is fortunate. Students can potentially earn Ph.D. degrees not only at ODU but at other universities with accelerator physics programs.

6.1. Some of the steps already taken
In the Fall 2010, one graduate student from Universidad de Guanajuato was accepted into ODU’s Ph.D. program in accelerator physics. The student will develop his thesis work at JLab under the guidance of Dr. G. Krafft, Director of the Center for Advanced Studies in Accelerators. ODU’s physics department Chair, Dr. G. Dodge is looking forward to receiving more applications from excellent and motivated Mexican student to pursue their Ph.D. degrees. During Dr. Napsuciale’s visit to ODU, discussions about developing a joint degree program between ODU took place. Based on ODU’s experience with a French University, developing agreements for joint degrees seems extremely difficult. As an alternative, it was proposed that the student can hold dual degree, that is, both his/her academic Mexican institution and the U.S. institution would grant Ph.D. degrees. It is always a viable option for the student to enroll in graduate programs at U.S. Universities with assistantships from CONACyT. This is an area that will have to be resolved case by case by Mexican Universities.

Two undergraduate students from Universidad de Guanajuato and one from Universidad de Puebla spent 8 weeks during the 2010 summer at JLab participating in the Cyclotron Kids project [3]. The students experienced unique hands-on training on vacuum techniques and laboratory safety. They also designed, built and operated an ion source, and received basic concept training on accelerator physics. Imagine what can be accomplished with basic equipment in laboratories at Mexican universities in areas such as instrumentation & control, vacuum systems, electron guns, mechanical design & engineering, beam physics theory and simulations, etc. with modest, perhaps used equipment that could potentially be donated or loaned under special agreements by U.S. laboratories.

The corresponding author has discussed the prospects for training Mexican students in beam physics with USPAS director Dr. W. Barletta and with Dr. H. Winick (SLAC) who point out that Brazil and Australia have developed successful accelerator programs and built light sources and can be used as role models. Dr. Barletta reports that there are fewer students from Mexico attending USPAS compared to other countries in South and Central America. Quoting Dr. Barletta: “It was seem that USPAS could play an extremely valuable role in the enterprise…certainly the enthusiastic support and dedicated engagement of some notable users would push a project forward”. Dr. Barletta expressed also that he would be most enthusiastic to assist, both through the USPAS and through the American Physical Society [4].

7. Conclusion
The possibilities for developing an accelerator physics program in Mexico focused on photon science are plentiful and the commitment of talented and enthusiastic leading scientists in the U.S. is real and encouraging. The vision of developing, building and operating the first light source in Mexico as a true national facility has sparked enthusiastic discussions in the high energy physics group and can potentially open a brand new field for graduate students and future scientists.

The formation of a core group or committee should be seriously considered. The committee would have tasks such as establishing collaborations with international institutions, encouraging the
formation of a user group in Mexico which ultimately will drive and define the science case for an accelerator-based light source, organizing photon science and accelerator R&D workshops, organizing visits to other light sources in countries like Brazil, Spain, etc. In this way, a coherent and focused effort can be developed. For reference, it took about 10 years to build the Brazilian Light Source.

The immediate enthusiasm should perhaps be directed in sending students to earn their Ph.D. degrees in accelerator physics and to engage with the photon user community.

As Dr. Herman Winick, Assistant Director and Professor Emeritus SLAC National Accelerator Laboratory pointed out “…I think that lots of help is potentially available, but the lead must be taken by Mexico and Mexicans…” [5].

8. Acknowledgments
The authors wish to express their most sincere gratitude to Dr. Hari Areti (JLab) for his continuing enthusiastic support and guidance.

[1] www.science.doe.gov/bes/reports/list.html

[2] “The Brazilian Synchrotron Light Source”, P. F. Tavares and J. A. Brum, Proceedings of the 2005 Particle Accelerator Conference, Knoxville, TN, pp. 325-329.

[3] www.thecyclotronkids.org/archive/

[4] www.aps.org/

[5] H. Winick, private communication.