Motivation and Framework: Proposed Project-X facility at Fermilab

The application horizon of particle accelerators has been widening significantly in recent decades. Where large accelerators have traditionally been the tools of the trade for high-energy nuclear and particle physics, applications in the last decade have grown to include large-scale multi-purpose accelerators like synchrotron light sources and spallation neutron sources. Applications like generation of rare isotopes, transmutation of nuclear reactor waste, sub-critical nuclear power, tritium production, radiation damage studies, studies of rare processes and generation of neutrino beams etc. are other areas of interesting investigation for accelerator scientific community all over the world. Such applications require high beam power in the range of few mega-watts (MW). One such high intensity proton beam facility is proposed at the Fermi national accelerator laboratory (FNAL), Batavia, USA, named as Project-X [1, 2]. This chapter gives a brief overview of historical development of accelerators and potential applications of high intensity proton or H\(^-\) ions accelerators. The main physics objectives of the Project-X facility and their global imprints on the scientific community are discussed. Layout of proposed accelerator complex for the Project-X facility is presented. Finally, the motivation behind the work and the thesis organization are described.
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1.1 Historical development of accelerators

Initial experiments in nuclear physics using charged particle scattering with a target was performed by E. Rutherford [3] in 1911 which resulted in a growth of relatively new science, the quantum mechanics. This experiment provided an idea to use charged particle beams as main instrument in the investigation of nuclear structure. Rutherford used alpha particles from a natural radioactive isotope and thus, the beam parameters were uncontrolled practically. The quest of providing highly intense, controlled beam and increasing the kinetic energy of charged particle motivated the physicists to design machine, named as accelerator, which could accomplish these requirements. The simplest way to increase the energy is to allow the particle beam to move through a high electric potential. Energy gained by a particle depends on potential difference between the two electrodes. Therefore, the initial development of particle accelerators was related to the design of high voltage generators. Van de Graaff generator [4] and Cockroft-Walton generator [5] are good examples of such high voltage generators. These high voltage generators are called electrostatic accelerators because voltage between the electrodes remains constant with time. The performance of electrostatic accelerators are restricted by maximum achievable voltage between electrodes which is limited by a high voltage break down.

![RF electric field between drift tubes](image)

Figure 1.1: RF electric field (shown by arrow) between drift tubes accelerate the particles.
1.1 Historical development of accelerators

In 1925 G. Ising [6] suggested an idea to use oscillating electric field to avoid the limitation of electrostatic accelerator and achieving further higher energy. The principle of using oscillating field for acceleration was first demonstrated by R. Wideroe [7] in 1927-1928. The basic idea of operation of the Wideroe accelerator is shown in Figure 1.1. A key component of Wideroe accelerator was metallic tubes which was aligned along the beam trajectory. Subsequent metallic tubes are connected to opposite polarities of a radio frequency (RF) source. Wideroe accelerator operates at π-mode. It means that at any instant electric field configuration between two successive gaps differ in phase by π. Ions are accelerated in a gap between the metallic tubes. When the field becomes decelerating the ions drift inside the tube where no field is applied to them. Therefore, these metallic tubes are also called drift tubes. To perform continuous acceleration the distance between centers of two subsequent gaps $L_n$ should satisfy the condition:

$$L_n = \frac{v}{2f};$$

(1.1)

where $f$ is the frequency of the RF source and $v$ is the velocity of particle. The particle velocity increases during acceleration and therefore, to maintain synchronization condition, distance between the gaps has to increase accordingly. Even though Wideroe established the principle that unlike an electrostatic accelerator, the voltage gain of the RF accelerator could exceed the maximum applied voltage but its performance was still limited for two reasons:

- For higher velocities the length of the drift tubes has to increase, which means that there was a natural practical limit for these machines. Especially for light charged particles the drift tubes would simply become too long.

- Operation at higher frequency results in reduction of drift tube length. But there is another limitation. Since these metallic tubes are not enclosed by a conducting boundary, the operation at higher frequencies means that the drift tubes were basically becoming antennas. With increasing frequency they radiate more and more of the RF energy instead of using it for acceleration, thus leading to a poor efficiency of the accelerator.

A solution was proposed by Louis Alvarez [8], who put the Wideroe linac into a volume enclosed by conducting wall. This solved the problem of radiated energy at
higher frequencies. Figure 1.2 shows the principle of the Alvarez linac. It can be noticed that in the Alvarez linac the field, in all gaps, points in the same direction. Synchronism with the RF demands that the RF phase changes by $2\pi$ while the particles travel from one gap to the next. Thus, distance between centers of two subsequent gaps $L_n$ is:

$$L_n = \frac{v}{f}; \quad (1.2)$$

Trajectory of a particle through Alvarez and Wideroe accelerators was linear so these are called linear accelerators (linac).

In 1929 E.O. Lawrence [9] invented circular accelerator where charged particle moves in spiral trajectory under the influence of uniform magnetic field. As particle moves in circular or spiral orbit, particle can pass through an accelerating gap many times. Over the period of times Lawrence circular accelerator has been developed into synchrotron for the acceleration of particles up to the energy in tera electron volt (TeV). Large hadron collider (LHC) at CERN is a synchrotron accelerator which accelerates proton beam up to the kinetic energy of 3.5 TeV.

Initial development of accelerators was based on acceleration of heavy ions. For the acceleration of electron which becomes relativistic at relatively low energy, new accelerating structures were developed. A traveling wave could be used to accelerate relativistic particles. A cylindrical waveguide propagates waves with phase velocities greater than the speed of light. Since the charged particles must be traveling at less than the speed of light, they will not obtain any net acceleration, because they can not
keep in phase with the wave. If the waveguide is loaded by putting some obstacles, the phase velocity of the wave can be slowed down to a usable value. The particles may then “surf” along the wave with a phase yielding an accelerating force.

A traveling wave structure, closed at both ends with metallic walls, will yield multiple reflections on the end walls until a standing wave pattern is established. This type of accelerating structures are called standing wave accelerating structures. While the longitudinally open traveling wave structure allows all frequencies, additional boundary condition in longitudinal direction for standing wave structure results in an existence of discrete frequencies. If one feeds RF power at a different frequency, the excited fields will be damped exponentially. Thus, these structures can be excited only for certain loss free electromagnetic modes. Standing wave structure is commonly known as resonant cavity or resonator and frequency of operation is called resonant frequency. Resonators are widely used for both ions and electron acceleration at all energies while traveling wave structures are used only for relativistic beam i.e., $\beta(=\frac{v}{c}) \sim 1$ with $c$ being the velocity of light.

In modern accelerators variety of accelerating structures are used to accelerate the beam for kinetic energy ranging from few KeV to several hundred GeV. On the basis of the particle velocity accelerating structures are divided broadly in two groups.

- Low velocity accelerating structures : $\beta < 0.5$.
- Medium and high velocity accelerating structures : $0.5 \leq \beta \leq 1.0$.

Drift tube linac (DTL) which is a modified Alvarez accelerating structure, cavity based on coaxial transmission wave guide such as half wave resonator (HWR), quarter wave resonator (QWR) and spoke resonator (SR) are commonly used as low velocity accelerating structures. Normal conducting DTL, coupled cavity drift tube linac (CCDTL) and coupled cavity linac (CCL) are used in linac for spallation neutron source (SNS)\textsuperscript{10} facility at Oak Ridge while HWR are used at ATLAS facility. Rare isotope facility (RIA) consider HWR for the acceleration of beam at low energy \textsuperscript{11}.

Over the period of time cylindrical shaped cavity has been evolved into a elliptical shaped cavities for acceleration of intermediate and high velocity particles. These are significantly efficient and provide high accelerating gradient. Multi-gaps elliptical shaped superconducting cavity are used in modern accelerator to maximize net acceleration over the length of accelerator.
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1.2 Requirement of high intensity proton or H$^-$ ion beam

Scientific perspectives of accelerator facilities based on high intensity proton or H$^-$ ion beam acceleration are discussed below.

- **Spallation neutron source:** The neutrons are produced when an ion beam of energy typically in the range of 1 GeV to 3 GeV hits a target of heavy nuclei (lead, bismuth). Excited nuclei decay into stable states by releasing neutrons, gamma rays and electrons.

  Distinctive properties of neutrons make them ideal probes for investigations of condensed matter, which are summarized below [12]:

  1. The absence of the charge and the small cross-section of interaction allow investigating bulk materials in the form of thick targets.
  2. Scattering on nuclei allows hydrogen “imaging” and identifying isotopes.
  3. Neutron magnetic moment allows us to examine magnetic parameters at the micro-level.
  4. The wavelength of thermal neutrons at inter-atomic distances allows us to determine the crystalline structure and the arrangement of atoms in a lattice.

- **Generation of neutrino beam:** Our present understanding of elementary particle physics is based on the Standard Model (SM) of particle physics. Neutrinos are elementary particles which have no charge and virtually no mass according to the SM. In the past decade tremendous progress has been made toward the better understanding of neutrinos but there are still lot of open questions about their absolute masses, neutrino oscillations and possibilities of charge-parity violation. In recent years, serious evidences follow from the experiments on neutrino that were carried out in Gran Sasso (Italy) [13] and Kamioke (Japan) [14] about the existence of physics that does not fit the framework of the SM. The question whether neutrino has or has not mass became decisive for justification of principles of the theory of weak interactions, and, on the other hand, it is decisive for solving problems in Astrophysics. The experiments with electron neutrino $\nu_e$ from the Sun, and also with $\nu_e$ and $\nu_\mu$ from the space in the atmosphere showed
1.2 Requirement of high intensity proton or H\(^-\) ion beam

that it is quite possible that neutrino oscillates between the \(\nu_e\), \(\nu_\mu\) and \(\nu_\tau\) states. At least two of these neutrinos have masses different from zero.

Precise measurements of neutrino mass and evidences for new physics related with them require high flux neutrino beam. A high intensity proton (or H\(^-\)) beam is bombarded on high atomic number \((Z)\) target which results in production of \(\pi\) mesons as one of secondary particles. These \(\pi\) mesons decay into muons when they pass through a long channel. Primary modes of \(\pi\) meson decay are:

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ + \nu_\mu \\
\pi^- & \rightarrow \mu^- + \bar{\nu}_\mu \\
\pi^0 & \rightarrow 2\gamma
\end{align*}
\]

Thus, \(\mu^+\) and \(\mu^-\) are generated using these decay modes. As \(\mu^\pm\) live 100 times longer than \(\pi^\pm\), a linear muon decay channel would need to be few tens of kilometer long. To avoid this difficulty, muons are injected into a storage ring with long straight section. Accumulated beams of \(\mu^+\) are the sources of electron neutrino \((\nu_e)\) and muon anti-neutrino \((\bar{\nu}_e)\) neutrino, and beams of \(\mu^-\) mesons generate electron anti-neutrino \((\bar{\nu}_e)\) and muon neutrino \((\nu_\mu)\). Decay modes of muons are given as follows:

\[
\begin{align*}
\mu^+ & \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\mu^- & \rightarrow e^- + \bar{\nu}_e + \nu_\mu
\end{align*}
\]

This approach to neutrino production in storage rings forms the basis for circular \(\mu\)-colliders where center of mass energy in the regime of 10 TeV can be achieved.

- **Transmutation of nuclear wastes:** Power reactors do not extract all of the energy contained in their uranium (or uranium/plutonium) fuel. Spent fuel contains radioactive isotopes of heavy elements such as plutonium and americium and fission products. Some of these isotopes remain radioactive for many thousands of years. The disposal of nuclear wastes is a major concern for countries with active nuclear power program. Most countries are committed to a program of long-term geologic disposal, that is, stabilization of the radioactive material and burial in specially-designed receptacles and repositories. These plans continue to solicit the concern of some experts and many members of the public. As an alternative
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to long-term storage, it has been proposed that the long-life isotopes be converted to shorter-lived ones through exposure to neutrons. The transmutation reaction can be induced by spallation neutrons. An accelerator-driven nuclear waste transmutation system would consist of three major sub-systems [15]:

- A high intensity proton accelerator with beam power of 5 MW for a demonstration, up to ∼ 50 MW for an industrial operation.
- A burner reactor where spallation and transmutation would occur.
- A processing plant in which short-lived isotopes that could not undergo further transmutation would be removed for secure disposal, and where other isotopes could be recycled into new fuel assemblies for the burner reactor.

- Production of radioactive ion beam (RIB): Rare and highly unstable nuclei can be produced by bombarding heavy nuclei with proton beam or intense flux of spallation neutrons. These exotic nuclei are excellent means of studying fundamental interaction between nucleons. The two production methods are used in RIB facilities. One is commonly called Isotope Separation On Line (ISOL) and the other is called In Flight. In ISOL type facilities, radioactive ions are produced essentially at rest in a thick target, that is bombarded with energetic primary particles from a driver accelerator. After diffusion out of the target and ionization the radioactive ions can be accelerated in a post-accelerator. For the in-flight method an energetic heavy ion beam is fragmented while passing through a thin target. After mass, charge and momentum selection in a fragment separator the selected ions can be analyzed or stored for further studies. No post-acceleration is required. While the ISOL method allows good quality low energy RIBs to be produced, in-flight facilities are optimum for higher energy RIBs of short-lived nuclei. In order to move closer to the extreme limits of stability the available driver beam intensities have to be increased.

- Accelerator driven sub critical reactor system (ADS): ADS is a relatively new concept which is still needed to be demonstrated. The principal advantages of ADS over the critical reactors are twofold: greater flexibility with respect to fuel composition, and potentially enhanced safety. ADS are ideally suited for burning fuels which are otherwise problematic for critical reactor operation. Burning
1.2 Requirement of high intensity proton or \(H^-\) ion beam fuels such as \(U^{233}\) and minor actinide, degrade neutronic characteristics of the critical core to unacceptable levels due to small delayed neutron fractions and short neutron lifetimes. Additionally, ADS allows the use of non-fissile fuels (e.g. Th). ADS is based on spallation neutrons which are generated by high intensity proton accelerator under irradiation of the target made of a material with heavy nuclei. The deficiency of neutrons in the reactor operating in subcritical mode is compensated on the account of the spallation neutrons. The optimum energy of a proton beam compensating the deficiency of the neutron flux in the subcritical reactor is in the range of 1 to 3 GeV. ADS also provides enhanced safety due to the fact that once the accelerator is turned off, the system shuts down in the absence of spallation neutrons. Therefore, ADS seems to have the potential to provide an additional route to an efficient and economic nuclear power generation with the available uranium and thorium resources. The major sub-systems of ADS are [16]:

- **High power proton accelerator:** It is capable of accelerating the 10 - 30mA beam up to 1 GeV.
- **Spallation target:** Heavy elements such as lead, bismuth for 10 - 30 MW beam power.
- **Subcritical core:** Fast neutron system, thermal neutron system or a combination of fast and thermal neutron system.

Worldwide interest is increasing in high-current (>10mA), high-power (> 1 MW) proton accelerators. The main existing and proposed facilities based on high intensity linac all over the world are spallation neutron source (SNS) facility [10] at Oak Ridge National Laboratory (ORNL), Project-X facility at Fermi National Accelerator Laboratory (FNAL) [2], European Spallation Source (ESS) facility [17], European Isotope Separation On-Line Radioactive Nuclear Beam (EURISOL) facility [18], Japanese Hadron Project (JPARC) [19] and many more are still to come. SNS facility is already working successfully.

Most of the facilities are based on high intensity proton or \(H^-\) ion beam linear accelerators. Thus, development of high intensity ion linear accelerators provides benefits in the framework of a multipurpose facility.
1.3 Choice of linear acceleration for high intensity beam

All the proposed or existing high intensity ion beam facilities use linac for first stage of acceleration. The choice is made due to its capabilities for producing high energy and high intensity charge particle beams with high beam quality. Some attractive features of the linac are following:

- **High beam quality**: Linac is a single-pass machine. The beam traverses its path only once. Thus, repetitive error conditions causing destructive beam resonances are avoided which are common feature in circular accelerators where beam passes through orbit multiple times.

- **Capability of handling high current beam**: In comparison with synchrotron, linac can achieve high beam quality and have more distributed beam losses. Thus, linac can operate at higher duty factor, even at 100% (continuous wave mode), which results in acceleration of beam with high average current.

- **Easy injection and extraction**: Since nominal trajectory of beam through linac is a straight line, there is no need for special techniques for efficient injection and extraction of the beam.

- **Synchrotron radiation**: When a charge particle traverses a circular trajectory, it loses its energy in the form of synchrotron radiation. Synchrotron radiation is negligible in linac relative to circular accelerators. Therefore, linacs are efficient for acceleration even for charged particles with relatively smaller masses.

- **Reliability and maintainability**: Linac can be classified as an array of modules consisting of accelerating and focusing elements which are arranged in a straight line. It is easy to maintain and to replace failed elements in linac relative to circular accelerator as one needs to replace only the affected module with new one. Future upgrade of accelerator to higher energies is easier for linac by adding more modules at the end of linac.

1.4 High intensity beam facility at Fermilab: Project-X

Fermilab is one of the largest laboratory in Unites States for fundamental research based on high energy particle physics. Fermilab’s Tevatron was highest energy accelerator
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until LHC started operation in 2010. In recent times, focus of accelerator community is moving toward high intensity ion accelerators and Fermilab also decided to move toward high intensity frontier. A multi mega watt proton accelerator facility named as Project-X is proposed for construction at Fermilab \[1, 20\]. It is the centerpiece of the plan for future development of the Fermilab accelerator complex. Figure [1.3] shows proposed site for Project-X facility. It will be nicely tied with existing accelerator complex and will provide high intensity proton beam of different energies. Project-X will be a multiuser facility which supports many experiments simultaneously.

1.4.1 Physics goals of Project-X

The Main objectives of Project-X facility are following:

![Proposed Project-X site at Fermilab.](image)

**Figure 1.3:** Proposed Project-X site at Fermilab.
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- **A neutrino beam for long baseline neutrino oscillation experiments:** Most of the previous experiments on neutrinos were based on cosmic rays which resulted in excess of background and very low frequency of desired events. A high intensity neutrino source of a single flavour reduces backgrounds and its known energy spectrum and intensity could be decisive both for oscillation searches and precision measurement of the lepton mixing parameters.

- **Kaons rare decay experiments:** A neutral kaon decays into a neutral pion and two neutrinos, $K^0 \rightarrow \pi^0 + \nu + \bar{\nu}$. This process is a unique probe for study of the matter-antimatter asymmetry in our world and is a strong adjudicator of the existence of physics beyond the SM. The proposed Project-X accelerator would create enough beam power to pursue the kaon physics. Figure 1.4 shows schematic layout of proposed Kaon decay experiment. Project X facility, with a

![Kaon rare decay experiment: $K^0 \rightarrow \pi^0 \nu \bar{\nu}$](image)

Figure 1.4: Schematic layout of Kaons rare decay experiment.

50-picosecond pulse fired every 40 nanoseconds, is ideally suited for time-of-flight techniques that are needed to determine with high accuracy the momentum of neutral kaons before they decay in the vacuum chamber. The design of the photon detector is optimized to precisely measure the energy and direction of the two photons emerging from the decay of the neutral pion and a detector surrounding
the vacuum chamber will help identify background processes that can mimic a signal.

- **Advanced muon to electron (mu2e) conversion experiment:** Quarks transform into each other, and so do neutrinos. Scientists have never observed the charged leptons (electron, muon, and tau) change directly into each other, yet there exists a possibility that these processes may exist. Proposed experiment “Advanced muon to electron conversion” at Project-X facility will hunt for these processes. High intensity proton beam will produce huge number of muons in controlled environment. These muons are captured and then state-of-the-art beam cooling techniques would reduce the momentum range of the muon beam by a factor of 10 compared to current experiments. Combined with a high-precision electron detector, this low momentum spread, high-flux muon beam would allow scientists to explore the mystery of charged-lepton conversion in greater depth than ever before. Figure 1.5 shows schematic layout of muon to electron conversion experiment.
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1.4.2 Accelerator goals of Project-X

An overview of Project-X accelerator complex is shown in Figure 1.6. This facility is based on high intensity H⁻ linear accelerator. It will operate at continuous wave (CW) mode. The schematic of baseline configuration of the proposed 3 GeV superconducting CW linac is shown in Figure 1.7. Linac is capable to accelerate an average beam current of 1mA (average over > 1µs) and pulse peak beam current of 10 mA (average over < 1µs) corresponding to a frequency of 325 MHz. As shown in block diagram (Figure 1.7), ion source (H⁻ gun), radio frequency quadrupole (RFQ) and medium energy beam transport (MEBT) system operate at room temperature (RT) and rest of the linac is superconducting. These systems are described as below.

![Figure 1.6: Schematic layout of the proposed Project-X facility.](image)

![Figure 1.7: Acceleration scheme for 3 GeV SC CW linac of the Project-X.](image)
1.4 High intensity beam facility at Fermilab: Project-X

**Ion source:** Ion source for CW linac is capable of delivering direct current beam of H\(^-\) ions of magnitude up to 10 mA. A prototype of ion source has been designed and tested at LBNL \[21\]. Transverse emittance is measured for different currents ranging from 1 mA to 10 mA at various beam energies. Normalized root-mean-square (r.m.s) transverse emittances were found less than 0.2 \(\pi\) mm mrad, which met the specification for beam requirements. This beam is transported to the upstream of RF quadrupole using low energy beam transport (LEBT) system. It includes diagnostic devices and solenoids. A schematic of LEBT, also consisting of ion source, is shown in Figure 1.8.

![Figure 1.8: Ion source and LEBT-Schematic of beam propagation from ion source to the upstream of RFQ.](image)

**RF Quadrupole and Medium energy beam transport system:** RFQ is well suited for the acceleration of low velocity beam typically in the range of \(\beta = 0.01\) to 0.07. It also provides longitudinal bunching and transverse focusing of the beam. RFQ for Project-X CW linac is normal conducting and it operates at 325 MHz. It accelerates the beam up to 2.5 MeV. The RFQ is followed by MEBT section. Since the linac average beam current is 1 mA and the beam current at the ion source can be as high as 10 mA, up to 90\% beam has to be removed by chopper in MEBT section. The power of removed beam is quite high, of the order \(\sim 25\) kW, and thus it will require a dedicated beam dump. The beam energy of 2.5 MeV was chosen in part because it is below the neutron production threshold for most of the materials. Beam chopper provides beam time structure which is necessary to operate the different
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experiments simultaneously. MEBT operates at room temperature and it consists of matching section which provides beam matching between superconducting and normal conducting section of the linac.

**Superconducting (SC) linac:** The MEBT is followed by SC linac which is segmented into two sections: low energy part and high energy part. In present design low energy section (2.5-160 MeV) uses three families of SC single spoke resonators (SSR) i.e. SSR0, SSR1 and SSR2 which are operated at 325 MHz. The high energy section of the SC linac (160 MeV-3.0 GeV) uses two families of 5-cell, elliptical cavities which are designed for \( \beta G = 0.61 \) and \( \beta G = 0.9 \) where \( \beta G \) is the geometrical velocity. These cavities are operated at the frequency of 650 MHz.

3 MW beam at the end of CW linac will be divided between neutrino program and rare decay process program, using a pulsed dipole. Further, a RF beam splitter can deliver the beam to multiple (at least three) experimental facilities (shown in Figure 1.6). For the second stage of acceleration, a pulsed linac is used for the acceleration of 1 mA beam pulses with 1-5% duty cycle from 3 GeV to 8 GeV. A pulse linac is preferred over rapid cycling synchrotron due to its flexibility for further upgrade. This beam is injected to recycler which delivers 2 MW beam power at any energy between 60-120 GeV to support neutrino factory. Operation of many experiments simultaneously

![Figure 1.9: A 1-\( \mu \)sec period in the CW linac, with red pulses for the muon conversion experiment, blue for rare kaon decay experiments, and green for other experiments.](image)
require special beam time line. To achieve required time structure for bunches, broad band chopper \cite{22} removes selective bunches. It reduces beam average current from 10 mA to 1 mA. There are two time lines associated with beam chopping:

- Timeline for strip injection into the Recycler/Main Injector (MI).
- Timeline for the 3-GeV program.

The injection into the ring requires 1-5\% of the linac duty cycle. The total charge needed for injection is 26 mA-ms for every 0.7-1.4 seconds (determined by the MI ramp cycle). The required bunch chopping during this timeline is associated with the ring RF frequency (∼53 MHz) and with the kicker gap needed every revolution period (11 μs). The remainder of the duty cycle (> 95\%) is delivered to the 3-GeV experiments.

Distribution of beam in these experiments is not decided yet but a preliminary proposal has been made. The time distribution to different experiments at Project-X facility is shown in Figure 1.9. Using an RF separator running at 1.25 times of the bunch frequency i.e., 406.25 MHz, every other pulse is available to the muon experiment, so a burst of 17, 162.5-MHz bunches (∼100 nsec) of $11 \times 10^7$ particles per bunch can be provided. The other RF buckets are chopped and equally split between two other experiments to match the 20-30 MHz desired bunch spacing.

1.5 Motivation for present work

The main emphasis of this thesis is on the design of superconducting radio frequency (SCRF) cavities for intermediate and high energy sections of the Project-X linac and on the design of beam transport line (lattice) for CW linac.

The use of an elliptical cavity for particle acceleration has resulted as a consequence of a series of trade-off between different cavity parameters, ranging from RF to mechanics, and takes into account the constraints imposed due to cavity design technique and fabrication experience. It includes both fundamental as well as practical aspects. The fundamental aspects of cavity design comprise of choice of operating frequency, number of cells in multi-cell cavity, operating range of cavity etc. The practical aspects of cavity design include concerns from industrial production and technological constraints such as availability of auxiliary components (tuner, power coupler etc.)
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Shapes of $\beta_G = 0.90$ and $\beta_G = 0.61$ cavities for CW version of Project-X linac are optimized to achieve maximum acceleration and minimum power dissipation to reduce cryogenic losses. Field enhancement factors (i.e., ratio of peak surface electric and magnetic fields to accelerating fields) are minimized to increase the accelerating gradient while ratio of shunt-impedance to quality factor ($R/Q$) and geometrical factor for operating mode are maximized to reduce the power dissipation to the wall of cavity. Optimization of shape and calculation of RF parameters such as field enhancement factors, quality factor, shunt impedance etc. of cavity are performed using two-dimensional cavity design code SLANS. Higher order modes (HOMs) spectrum is studied for both cavities. The cavities are designed such that there are no significantly trapped HOMs. A systematic study is performed to understand the effects of excitation of resonance of HOMs on beam quality and resultant power dissipation. Analysis of HOMs provides better understanding of the requirements of HOM damper for these cavities.

Linac design of Project-X has evolved over recent years. Initial proposal of Fermilab’s Project-X facility, based on a pulsed linac, was considered for the acceleration of beam from kinetic energy of 420 MeV to 1.2 GeV in high energy section. These cavities are designed for $\beta_G = 0.81$, operating at a frequency of 1.3 GHz and initially included 11-cells to utilize existing design of cryomodule. In this thesis, the end cells of 11-cell cavity are optimized to avoid potentially trapped HOMs. Asymmetric design of end cells are used at both ends so that if any mode gets trapped from one end then it may propagate through other end. Although 11-cell cavity is well optimized but there were few concerns from the fabrication point of view. The presence of 11-cell makes the cavity more sensitive to fabrication errors and thus industrial yield is expected to be low. An alternative study is also performed in this work to design 9-cell cavity for the pulsed linac.

One of the most challenging tasks of Project-X facility is to have a robust design of the CW linac which can provide high quality beam to several experiments simultaneously. Hence a careful design of linac is important to achieve this objective. $H^-$ ion is non-relativistic at kinetic energy of 2.5 MeV and its velocity changes very rapidly with acceleration in Project-X linac. Thus, linac uses several types of accelerating structures which are optimized for different particle velocities to provide efficient acceleration. On the basis of energy, linac is segmented into three sections, i.e. low energy section, intermediate energy section and high energy section. Three families of spoke...
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Resonators are used in the low energy section of the linac, which are operated at a frequency of 325 MHz. These will be used to accelerate the beam from kinetic energy of 2.5 MeV to 160 MeV. This is followed by the intermediate energy section which consists of 5-cell, elliptically shaped cavities which will be operated at a frequency of 650 MHz. These cavities are designed for particles travelling with 61% of the speed of light (geometrical beta $\beta_G = 0.61$) and will be used to accelerate the beam from kinetic energy of 160 MeV to 500 MeV. High energy section also consists of 5-cell, elliptical cavities which will be operating at a frequency of 650 MHz, but, these cavities are designed for $\beta_G = 0.90$ to accelerate the beam from kinetic energy of 500 MeV to 3.0 GeV.

Further, a robust lattice is designed for reliable operation of CW linac which preserves beam quality and allows robustness in design parameters such as accelerating gradients in cavities, focusing gradient in magnets etc. Studies are performed for the baseline lattice to analyze beam trajectory and beam emittance in longitudinal and transverse plane using beam tracking codes, TRACEWIN and TRACK. An essential measure of a successful accelerator system is its ability to provide high beam availability and high reliability. The multiuser facility and further upgrade for higher current to test Project-X as a test facility of accelerator driven system requires minimum beam interruption for reliable operation of linac. To improve the reliability of linac, possibility of failure of beam line elements are included in the lattice design. Operation of the linac at CW mode puts stringent tolerances on beam transport elements, especially at low energy section, which increases the possibility of temporary or permanent loss of accelerating cavities and focusing magnets during the operation of linac. Failure of the beam transport elements like cavity, solenoid and quadrupole alters the focusing period of the beam, resulting in a mismatch of the beam with the subsequent sections. This, in turn, causes beam losses. Sensitivity of the linac performance to failure of elements also depends on the location of failed elements. In some cases, failure of the beam transport element results in huge beam losses and it becomes necessary to replace this element for nominal operation of the machine. To recover nominal performance of linac using traditional way involves replacement of a complete cryomodule (containing several cavities). It is required to warm up the cryomodule from operating temperature (usually 2K) to room temperature and after replacement cryomodule is again cooled down to the operating temperature. Furthermore, procedure to resume the nominal operation is identical as starting procedure and requires slowly ramping up the accelerator. Thus,
these beam interruptions reduce the beam availability to the different experiments for a long time. Lattice should be robust enough to have a capability that RF cavity or magnet failure may be compensated locally by using the neighbouring elements. The numbers of cavities and focusing magnets in a cryomodule are chosen in such a way that at least one failure of RF cavity or focusing magnet can be compensated locally.

SCRF cavities are complex and expensive and their fabrications involve lot of scientific and engineering efforts. A standard procedure developed for the fabrication of 1.3 GHz, 9-cell cavity at mass scale, is discussed in this work. Similar approach will be used for the fabrication of 650 MHz cavities for CW linac. Deep-drawing method is commonly used to fabricate niobium cavity. Quality of inner surface of cavity degrades during process of fabrication which may limit maximum accelerating gradient in cavity. Thus, it is passed through sequence of surface treatments in order to remove defects from production process. Surface treatments involve chemical etching (electro chemical polishing, buffer chemical polishing), high pressure water rinsing and heat treatment of cavity. After all treatments, performance parameters of cavity like accelerating gradient and quality factor are tested at 2K in the vertical-test stand (VTS) facility.

1.6 Thesis Organization

The thesis is organized in six chapters. A brief description of each chapter is given below.

Chapter 1 provides an overview of the proposed high intensity proton facility, Project-X at Fermilab, Batavia, USA. Physics objectives and a layout of Project-X facility are presented.

Chapter 2 reviews basics of beam physics necessary to discuss beam motion and fundamentals of lattice design for high intensity beam. This chapter also includes an electromagnetic description of cavity and its performance parameters such as quality factor, accelerating gradient, shunt impedance etc. In modern high energy accelerator, usually superconducting cavities are preferred over normal conducting cavities. A brief overview of superconductivity, superconducting material for cavity fabrication and their properties are presented.

Chapter 3 addresses the general design criteria for cavity such as choice of frequency and number of cells in a multi-cell cavity. A topology for geometry of elliptical cavity
is introduced. Influence of geometrical parameters on cavity performance, simulation tools for cavity design and limiting mechanisms in high accelerating gradient cavities are discussed. Methodology behind the design of 1.3 GHz $\beta_G = 0.81$ cavity for the pulsed variant of $H^-$ ion linac and 650 MHz, $\beta_G = 0.9$ and $\beta_G = 0.61$ cavities for CW variant of $H^-$ linac for the Project-X facility are presented. Higher order modes (HOM) coupler is an expensive component of accelerating structure. In order to determine the requirement of HOM coupler for 650 MHz cavities, analysis is performed to estimate power losses and emittance growth due to HOM in intermediate and high energy sections of CW linac.

Chapter 4 presents architecture of CW linac for the Project-X facility. Choice of accelerating structures, magnets, assumptions and limitations used for lattice design are discussed. Beam quality parameters such as emittance and halo parameters are analyzed for baseline lattice. Longitudinal and transverse acceptances are studied. Operation of linac in CW mode puts stringent tolerances on beam line elements especially at low energy. Failures of beam line elements at critical locations are studied and their local compensation scheme is demonstrated.

Chapter 5 introduces fabrication techniques for SRF cavity in context of fabrication of 1.3 GHz, $\beta_G = 1$ cavity. Fabrication processes include building of half cells from raw material sheets, electron beam welding to form single cell or dumbbells. Various techniques are described for surface cleaning such as high pressure water rinsing and post surface purification method such as baking. A single cell 1.3 GHz, $\beta_G = 1$ cavity is tested on VTS and results are presented.

Chapter 6 summarizes the main features from all the preceding chapters.
1. MOTIVATION AND FRAMEWORK: PROPOSED PROJECT-X FACILITY AT FERMILAB