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High-Intensity Muon Facilities for Neutrino Physics and the Energy Frontier

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Abstract.
An accelerator complex that can produce ultra-intense beams of muons presents many opportunities to explore new physics. This facility is unique in that it can present a physics program that can be staged and thus move forward incrementally, addressing exciting new physics at each step. An intense cooled low-energy muon source can be used to perform extraordinarily precise lepton flavor violating experiments and these same muons can be accelerated to be used in a Neutrino Factory or energy-frontier Muon Collider. In this paper I will give an introduction to muon accelerator facilities and their physics capabilities and then will discuss some of the limiting technologies that must be developed in order to make these concepts a reality.

Keywords: Neutrino Factory, Muon Collider
PACS: 29.20, 13.15

PREFACE

When he first heard of the discovery of the muon in 1936, Isidor Rabi asked, “Who ordered that?” At the time, the muon didn’t fit into the understanding of the subatomic world. We now know better. When some physicists argue that muon accelerator facilities should play an expanded role in future High Energy Physics facilities (such as a Neutrino Factory or Muon Collider), others question “Who ordered THAT?” or more directly, why? This paper will try to answer why.

INTRODUCTION

The physics potential of a high-energy lepton collider has captured the imagination of the high energy physics community for some time now. Understanding the mechanism behind mass generation and electroweak symmetry breaking, searching for, and perhaps discovering, supersymmetric particles and confirming their supersymmetric nature, and hunting for signs of extra space-time dimensions and quantum gravity, constitute some of the major physics goals of an energy-frontier lepton collider. In addition, experiments that can make very-high precision measurements of standard model processes open windows on physics at energy scales far beyond any forseeable direct reach. The Muon Collider provides a possible realization of a multi-TeV lepton collider, and hence a way to explore new physics beyond the capabilities of present colliders. A muon accelerator facility also presents the unique opportunity to explore new physics within a number of distinct programs that can be brought online as the facility evolves.

A schematic that shows the evolution of a muon accelerator complex which ultimately reaches a multi-TeV Muon Collider [1] is given in Fig. 1. The front-end of the facility provides an intense muon source that can perhaps support both a Neutrino Factory and an energy-frontier Muon Collider. The muon source is designed to deliver $\mathscr{O}\ 10^{21}$ low energy muons per year within the acceptance of the accelerator system, and consists of (i) a multi-MW proton source delivering a multi-GeV proton beam onto a liquid Mercury-jet pion production target, (ii) a high-field target solenoid that radially confines the secondary charged pions, (iii) a long solenoidal channel in which the pions decay to produce positive and negative muons, (iv) a system of RF cavities in a solenoidal channel that capture the muons in bunches and reduce their energy spread (phase rotation), and (v) a muon ionization cooling channel that reduces the transverse phase space occupied by the beam by a factor of a few in each transverse direction. At this point the beam could be used for low-energy muon experiments and also will fit within the acceptance of an accelerator system for a Neutrino Factory. However to obtain sufficient luminosity, a Muon Collider requires a great deal more muon cooling. In particular, the 6D phase-space must be reduced by $\mathscr{O}\ 10^{6}$, which requires a longer and more complex cooling channel. Finally after the cooling channel, the muons are accelerated to the desired energy and injected into decay rings for the Neutrino Factory or into a storage ring for the Muon Collider. In a Neutrino Factory, the ring has long straight sections in which the neutrino beam is produced by the decaying muons. In a Muon Collider, positive and negative muons are injected in opposite directions and collide for about 1000 turns before the luminosity becomes degraded due to the muon decays.

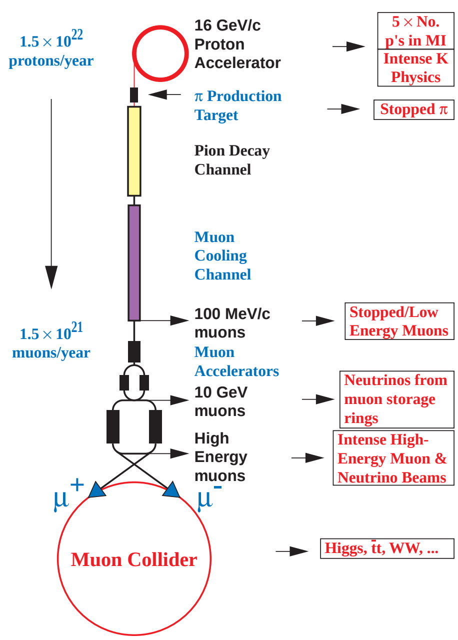


FIGURE 1. Schematic of a muon accelerator complex

LOW-ENERGY MUON PHYSICS

One of the first physics programs that a muon accelerator facility could support would be sensitive tests of charged lepton flavor violation (cLFV), such as what could be explored with a $\mu \rightarrow$ e conversion experiment. In the Standard Model this process occurs via ν mixing, but the rate is well below what is experimentally accessible. The rate (or limit on the rate) of this process puts very stringent constraints on physics beyond the Standard Model. For example supersymmetryic models predict the rate to be $\mathscr{O}$ 10^{-15}. The low-energy muon source of the muon accelerator facility provides a potential upgrade path [2] for the next round of cLFV experiemnts currently being planned. This upgrade path could extend their sensitivity by upwards of two orders of magnitude, exploring a mass reach to 4×10^4 TeV.

THE NEUTRINO FACTORY

In the Neutrino Factory [3], the neutrino beam is generated from muons which decay along the straight section of a race track-like decay ring and, since the decay of the muon is well understood, the systematic uncertainties associated with a neutrino beam produced in this manner are very small. In addition since the muon (anti-muon) decays produce both muon and anti-electron neutrinos (anti-muon and electron neutrinos) many oscillation states are accessible at a Neutrino Factory and the reach in the ν oscillation parameter space is extended. The oscillation processes accessible at a Neutrino Factory are given in Table 1.

TABLE 1. Oscillation processes in a Neutrino Factory.

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$	appearance (atm. oscillation)
$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	disappearance
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	appearance: "silver" channel

In the so-called "golden" channel listed in Table 1, the experimental signature in the neutrino detector is the presence of a muon with the "wrong" sign, a muon with the opposite sign to that which is stored in the decay ring. This requires that the neutrino detector be magnetized, but for Neutrino Factories with stored muons with energy of approximately 25 GeV, this represents standard neutrino detector technology [4]. It has been shown [5] that for a "magic" baseline of approximately 7500 km, the "golden" channel offers unprecedented sensitivity for the determination of the unknown mixing angle θ_{13} and the mass hierarchy. Adding a second detector at a baseline of approximately 4000 km adds sensitivity to the CP violating phase δ. Over the last decade there have been a number of studies [6, 7, 8, 9] that have explored the physics reach of Neutrino Factories to measure θ_{13}, determine the mass hierarchy and determine the CP violating phase, δ. The most recent study to be completed [10], the International

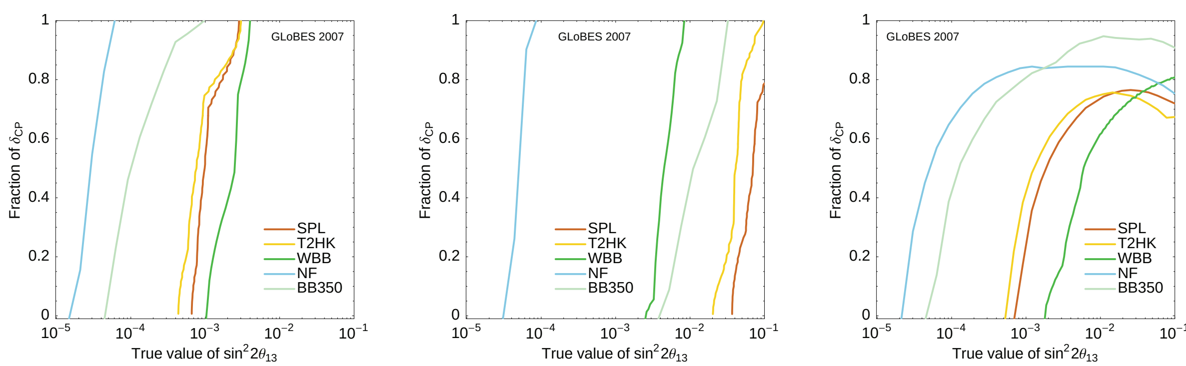
Scoping Study of a future Neutrino Factory and Super-beam facility (ISS), studied the physics capabilities of various future neutrino facilities: Super-beam, β-beam and Neutrino Factory.

The ISS Physics Study

The ISS physics study [11] set out as a goal "to establish a strong physics case for the various proposed facilities and to find the optimum parameters of the accelerator facility and detector systems from a physics point of view." The study looked at Super-beam facilities, a β-beam facility and the Neutrino Factory. The 5 facilities that were studied are:

- a 4 MW facility at CERN (SPL) pointing to a 1 Mega Ton water Cerenkov detector at a baseline of 130 km (Super-beam).
- a 4 MW facility at JPARC (T2HK) pointing to a 1 Mega Ton water Cerenkov detector at baseline of 295 km (Super-beam).
- a 2 MW facility at FNAL (WBB) pointing to a 1 Mega Ton water Cerenkov detector at a baseline of 1300 km (Super-beam).
- a high-energy β-beam facility (BB350) pointing at a 1 Mega Ton water Cerenkov detector at a baseline of 730 km.
- a 4 MW Neutrino Factory pointing to two 50 kT magnetized iron detectors at baselines of 4000 and 7500 km plus a 10 KT magnetized emulsion cloud chamber at 4000 km.

Representative results from the study are shown in Fig. 2(a), 2(b) and 2(c) where 3σ exclusion contours are shown for the discovery reach in θ_{13}, the determination of the mass hierarchy and the CP violating phase δ, respectively.



(a) (b) (c)

FIGURE 2. (a) NF exclusion plot for θ_{13}. (b) NF exclusion plot for the mass hierarchy (c) NF reach in CP phase δ.

Neutrino Factory Design

The baseline Neutrino Factory Design from the International Scoping Study is shown in Fig. 3. It consists of a 4 MW proton driver with a 2 ns bunch structure, a Hg-Jet target for pion production, capture, drift and phase rotation sections, a muon ionization cooling channel sufficient to reduce the transverse emittance of the muon beam to level consistent with the accelerator system's acceptance, the accelerator system and two decay rings pointing to two detectors at baselines of approximately 4000 and 7500 km, as mentioned above.

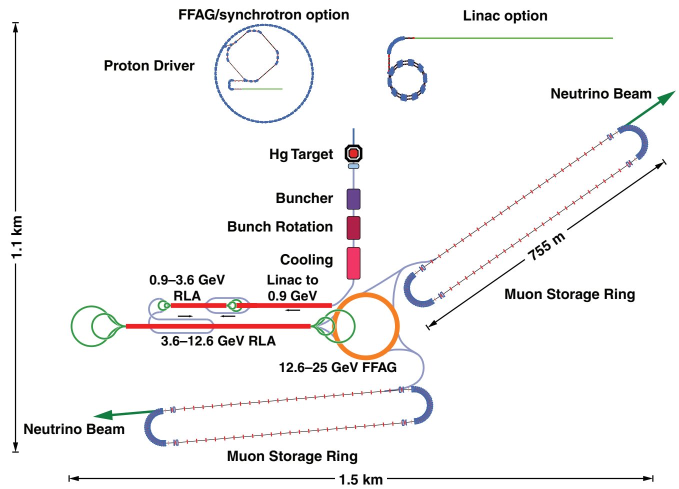


FIGURE 3. Neutrino Factory baseline design from the International Scoping Study.

THE ENERGY FRONTIER

The Muon Collider is the final step in the evolutionary process of the muon accelerator facility and it provides a very attractive possibility for studying the details of Terascale physics after the initial running of the LHC. If supersymmetric particles are observed at the LHC, then independent of the actual mass scale, the conclusions from the 2004 CLIC study [12] indicate that a multi-TeV collider would be needed for extended coverage of the mass range (that beyond which the ILC and the LHC can explore). The Muon Collider can study the same physics that electron-positron linear colliders address, but compared to these machines, a Muon Collider presents a very small footprint and contains fewer complex components as a result. It can easily fit on the Fermilab site (see Fig. 4), for example. In addition Muon Colliders may have a special role for precision measurements in that the machine potentially has a very small beam energy spread and thus allows for very precise energy scans without the beamstrahlung that exists at multi-TeV electron-positron linear colliders which can limit their ultimate precision. The Muon Collider also has a large advantage in s-channel scalar production due to the large cross section enhancement of approximatley 40,000 from the ratio: $(\frac{m_\mu}{m_e})^2$.

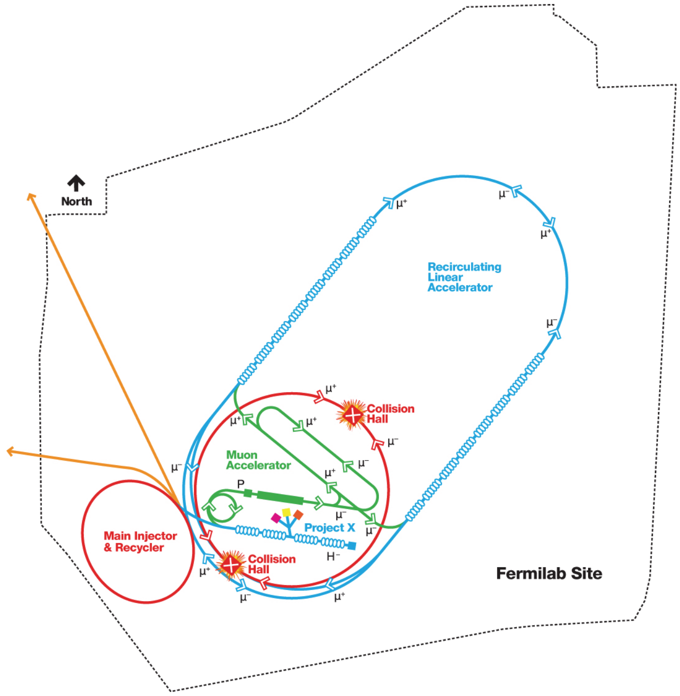


FIGURE 4. A 2 TeV center-of-mass Muon Collider schematic.

MUON COOLING

As was mentioned in the introduction, the phase space of the muons that are produced at the front end of a muon accelerator facility must be reduced (cooling) in order for the muons to fit within the acceptance of the accelerator system. For the Neutrino Factory, this means reducing the transverse phase space in each dimension by an order of few. Because of the muon's short lifetime (2μs), the only viable technique for cooling the muon beam is ionization cooling. In this scheme, the muons pass through an absorber of low atomic number (Hydrogen is the preferred material). They lose energy isotropically and are then re-accelerated longitudinally. This process needs to be done in a suitable magnetic lattice, however, for the cooling to take place. The evolution of the normalized transverse emittance is then given by [13]: $\frac{d\varepsilon^N}{ds} \approx -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon^N}{E_\mu} + \frac{1}{\beta^2}\frac{\beta_\perp(0.014)^2}{2E_\mu m_\mu L_R}$, where ε^N is the normalized muon-beam emittance, β is the muon velocity, $\beta_\perp$, is the betatron length at the absorber, $\frac{dE_\mu}{ds}$ is the muon energy loss per unit length in the absorber, L_R is the radiation length of the absorber material and m_μ is the muon mass. The two terms in the equation correspond to the cooling component (first term) and the heating component (second term) which is due to multiple Coulomb scattering. Optimizing the cooling channel requires a large $\frac{d\varepsilon^N}{ds}$, large L_R and strong focussing (small $\beta_\perp$). The equilibrium emittance is when these two terms are equal.

In addition to a very large reduction in the transverse emittance, the Muon Collider also requires reduction of the longitudinal emittance at various stages along the complete cooling scheme [14]. The 6-dimensional cooling is typically accomplished by using transverse-longitudinal emittance exchange where dispersion is introduced in the channel such that particles with larger energy follow a longer path-length trajectory through the absorber material, thus reducing the beam energy spread.

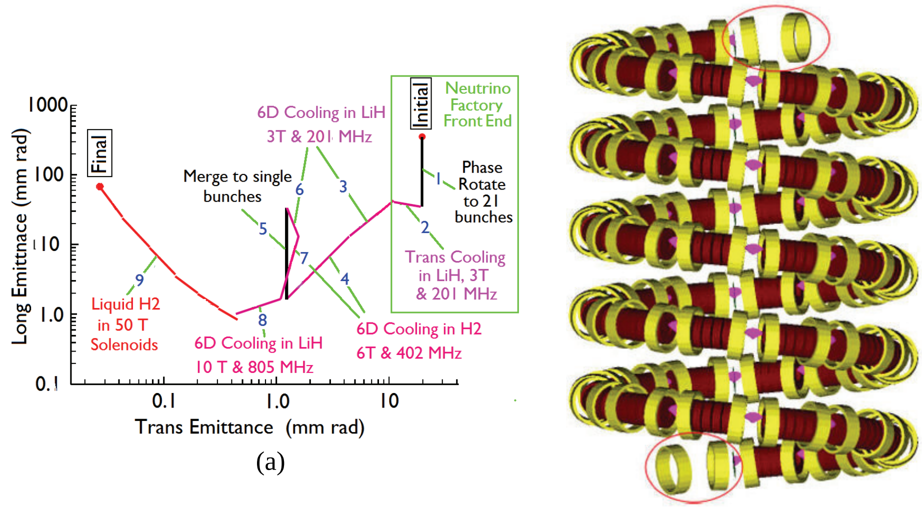
THE TECHNOLOGICAL CHALLENGES OF A MUON FACILITY

Many of the key technologies and components for a muon accelerator facility are currently under study. The MERIT experiment [15] has successfully tested the concept of the liquid Hg jet target and it has shown very promising results which indicate that this type of target system can operate at a power level of 4 MW and above. The Muon Ionization Cooling experiment, MICE [16], is preparing to perform a demonstration and engineering test of 4D muon ionization cooling utilizing 200 MHz RF and liquid hydrogen absorbers. The MuCool [17] program is investigating the operation of vacuum RF cavities in the presence of high magnetic fields, has made preliminary studies on liquid hydrogen absorbers and will also be studying the use of LiH absorbers as an alternative to using the liquid hydrogen absorbers in the muon cooling channel. The MuCool program focuses on component R&D and, in addition to the capability to test RF components at high power, will have the capability to test cooling channel components with a high-intensity proton beam from the Fermilab linac. The Electron Model with Many Applications (EMMA) [18] experiment will study the properties of FFAGs which are a potential candidate for part of the acceleration system at a muon facility.

Of all the underlying accelerator technologies that are required for the complex, it can be argued that RF technology is the single most important “Limiting-Technology”. It is of fundamental importance for these facilities in that it is needed in: 1. Muon capture, bunching and phase rotation, 2. Muon cooling and 3. Acceleration. Both normal conducting RF (front-end, 1 and 2 above) and superconducting RF (acceleration) are required. A crucial challenge for the front-end design and cooling channels is the operation of high-gradient normal-conducting RF (NCRF) in the presence of high magnetic field. This problem has been the primary focus of the MuCool program. What has been observed in MuCool is that the safe operating gradient limit degrades significantly when a NCRF cavity is operated in magnetic field, dropping by approximately a factor of 2 [19] at the B field needed for the cooling channel lattice. There are a number of models that have been developed that attempt to describe this phenomenon, but all involve field emission from emitters (surface field enhancements in the regions of high gradient) in the cavity. The interaction of the field emission with the magnetic field can cause surface imperfections on the cavity to break off which then produces a plasma under bombardment by the field emission current. The plasma then initiates a breakdown. In order to address this problem, three approaches are being investigated. These are: 1. Processing the cavities with superconducting RF or atomic layer deposition [20], 2. Using different materials (such as Be) for the cavity walls and 3. Operating the cavities filled with high-pressure hydrogen gas in order to use the Paschen effect to inhibit breakdowns. [21]

6D Muon Ionization Cooling

Intense 6D cooling for the Muon Collider is not yet under experimental study, but is being modeled, studied with theoretical and computation tools and an experimental program exploring some of the major component parts of the system is being developed. The Muon Collider design starts off with the Neutrino Factory front end (target, pion capture and decay, and initial muon cooling), but it requires far more ambitous cooling than is need for the Neutrino Factory as was mentioned in the introduction. At this point in time, we do not have a full end-to-end simulation for the cooling needed for a muon collider, but a self-consistent end-to-end cooling scheme has been developed and is shown schematically in Fig. 5 (a) [14]. This scheme utilizes the initial transverse cooling scheme from the Neutrino Factory Study 2a (up through step 2 in Fig. 5), the “Guggenheim” ring-FOFO and final cooling with 50T solenoids and liquid hydrogen absorbers.



(b)

FIGURE 5. (a) Cooling scheme for Muon Collider. (b) Schematic of the Guggenheim cooling channel

The Guggenheim channel uses a large-pitch helical lattice (see Fig. 5 (b)) in order to avoid the injection and extraction problems with a true Ring-FOFO [22]. The component parts of the Guggenheim are the same as that for the Ring-FOFO and include vacuum 201 MHz normal-conducting RF cavities, liquid hydrogen absorbers and solenoids (all of which are components that will be under test in the MICE experiment). This approach has been under study for a number of years, but much work remains to be done in order to study the effects of tapering (changing the RF frequency along the channel), implementation of realistic B fields and absorber parameters in the simulations and the effects of windows.

US ROADMAP TO THE FUTURE

A proposal that presented a R&D program aimed at completing a Design Feasibility Study (DFS) for a Muon Collider and, with international participation, a Reference

Design Report (RDR) for a muon-based Neutrino Factory has been submitted to the US Department of Energy as a joint proposal from US Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task Force [23]. The goal of the R&D program is to provide the HEP community with detailed information on future facilities based on intense beams of muons and give clear answers to the questions of the expected capabilities and performance of these muon-based facilities, while providing defensible estimates for their cost. This information, together with the physics insights gained from the next-generation neutrino and the LHC experiments, will allow the HEP community to make well-informed decisions regarding the optimal choice for new facilities

With regard to muon ionization cooling (or more generally speaking, the Front-End of the facility), the R&D plan will embark on both design and simulation and hardware efforts. The design and simulation work will study and optimize: 1. Pion capture and decay, bunching and phase rotation, 2. Precooling and 3. 6D cooling and final cooling. A full end-to-end simulation of muon production and cooling (through final cooling) with all interfaces between cooling sections will be a major component of the effort.

The hardware effort on cooling has 3 main objectives: 1. Established the operational viability and engineering foundation for the concepts and components incorporated into the Muon Collider Design Feasibility Study and the Neutrino Factory Reference Design Report, 2. Establish the engineering performance parameters of these components and 3. Provide the basis for a defendable cost estimate.

The most critical technical challenge for the Muon Collider is the demonstration of a viable cooling scenario. To this end, the R&D proposal will support the MICE experiment through all its phases and will strive to develop a single scheme for 6D cooling that is backed by rigorous component testing for this chosen scheme. We anticipate critical results from the RF tests in the first two years of our R&D program, at which time we will proceed with building a short cooling section for one cooling scheme. It is not envisioned that a 6D muon ionization cooling demonstration experiment will be performed within this program. Fig. 6 presents what we believe will be the Muon Collider Technical Foundation after a 7 Year program is completed, relative to where we believe the technology is today.

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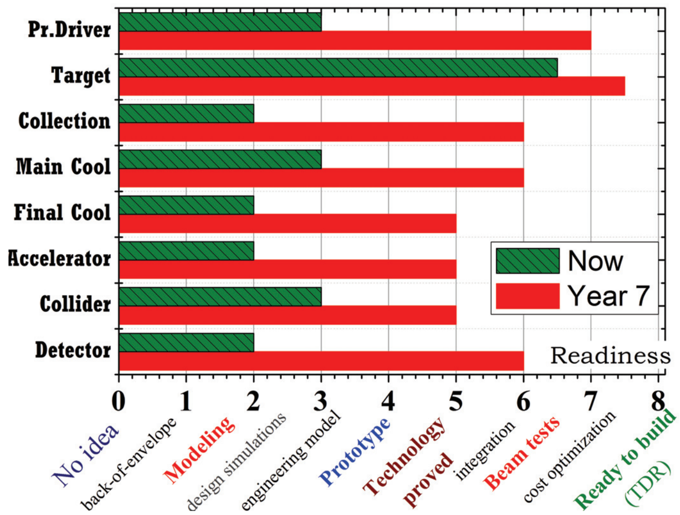

FIGURE 6. Technological foundation after 7 year R&D program.

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