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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

ACCELERATOR R&D TOWARD MUON COLLIDER AND NEUTRINO FACTORY

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Over the last decade there has been significant progress in developing the concepts and technologies needed to produce, capture, accelerate and collide high-intensity beams of muons. At present, a high-luminosity multi-TeV muon collider presents a viable option for the next-generation lepton–lepton collider, which is believed to be needed to fully explore high-energy physics in the era following LHC discoveries. Such a collider can offer superb energy resolution, smaller size, and potentially cost and power consumption compared to multi-TeV e^+e^- linear colliders. This article briefly reviews the motivation, design and status of accelerator R&D for Muon Collider and Neutrino Factory.

В настоящее время мюонный коллайдер с высокой светимостью на энергию в несколько ТэВ представляется одной из привлекательных возможностей для изучения физики высоких энергий. Такой коллайдер будет иметь преимущества перед линейными электрон-позитронными коллайдерами в энергетическом разрешении, размерах и, возможно, стоимости. Приводятся параметры мюонного коллайдера, и дается обзор разработок его ускорительных подсистем.

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INTRODUCTION

Lifetime of the muon $\tau_0 = 2$ μs is just long enough to allow acceleration to high energy before the muon decays into an electron, a muon-type neutrino and an electron-type antineutrino ($\mu^- \to e^- \nu_\mu \overline{\nu}_e$). Over the last decade there has been significant progress in developing the concepts and technologies needed to produce, capture and accelerate muon beams with high intensities of the order of O(10^{21}) muons/year. This prepares the way for (i) a multi-TeV Muon Collider (MC) in which μ^+ and $\mu^-$are brought to collision in a storage ring and (ii) a Neutrino Factory (NF) in which 4–25 GeV muons decay within the straight sections of a storage ring to produce a beam of neutrinos and antineutrinos, directed toward large neutrino detectors located 100's to 1000's km away.

Muon Colliders were proposed by Budker [1] in 1969 and later conceptually developed by a number of authors [2, 3] and collaborations [4, 5], most recently by the Muon Collider Collaboration [6] and Fermilab Muon Collider Task Force [7]. At present, an international accelerator community works on feasibility proof of an MC needed to fully explore the physics responsible for electroweak symmetry breaking that requires a center-of-mass energy ($\sqrt{s}$) of a few TeV and a luminosity in the 10^{34}–10^{35} cm$^{-2}\cdot$s^{-1} range. Figure 1, *a* presents a layout of such an MC which has the following parts: a high-power proton driver based on «Project X» SRF-based 8 GeV H-linac [8]; pre-target accumulation and compressor ring(s) where

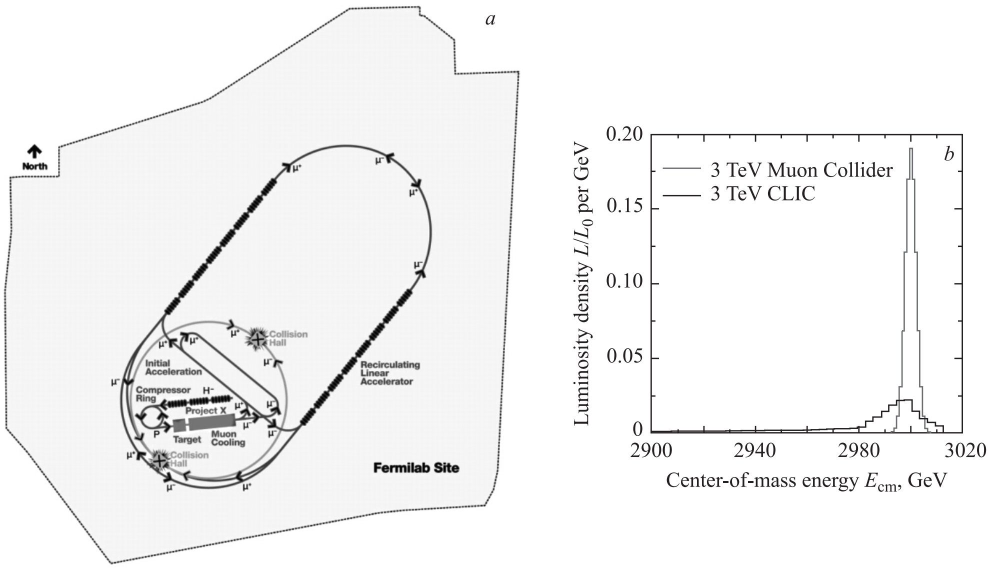

Fig. 1. a) Schematics for a 4 TeV Muon Collider on FNAL site. b) Comparison of the energy spreads for 3 TeV $\mu^+\mu^-$ and e^+e^- Collider (CLIC)

very high intensity 1–3 ns long proton bunches are formed; high-energy protons hit liquid mercury target after which muons with an energy of about 200 MeV are being collected and cooled in the multistage ionization cooling section with the goal of reducing the transverse and longitudinal emittances and creating a tight beam; that is followed by a multistage acceleration (initial and main) system — the latter employs Recirculating Linear Accelerator (RLA) to accelerate muons in a number of turns up to 2 TeV using SRF technology; finally, counter-propagating muon beams are injected into a Collider Ring located 100 m underground where they live and collide for 1000–2000 times.

Both e^+e^- and $\mu^+\mu^-$ colliders have been proposed as possible candidates for a multi-TeV lepton collider to follow LHC discoveries. Synchrotron radiation (proportional to the fourth power of the Lorentz factor γ^4) poses a challenge for multi-TeV e^+e^- colliders, which cannot be circular, but must have a linear geometry and, with practical acceleration schemes, be tens of km long. Furthermore, beam–beam effects at the collision point induce the electrons and positrons to radiate, which broadens the colliding beam energy distributions. Since $(m_\mu/m_e)^4 = (207)^4 = 2 \cdot 10^9$, all of these radiation-related effects can be mitigated by using muons instead of electrons. A multi-TeV $\mu^+\mu^-$ collider can be circular and therefore have a compact geometry that will fit on existing accelerator sites (see Fig. 1, a for a possible footprint of MC on the 6×7 km FNAL site). The c.o.m. beam energy spreads for 3-TeV e^+e^- and $\mu^+\mu^-$ colliders are compared in Fig. 1, b.

The parameters of the several MC options under study are given in the table. The first two columns are for MCs with higher and lower c.o.m. energies and small emittances which are believed to be achievable, the last column is for 2 TeV MC with beam emittances with no significant cooling [9]. The front-end of an MC, up to and including the initial cooling channel, is similar (perhaps identical) to the corresponding Neutrino Factory front-end [10].

However, in an NF the cooling channel must reduce the transverse emittances $(\varepsilon_x, \varepsilon_y)$ by only factors of a few, whereas to produce the desired luminosity, an MC cooling channel must reduce the transverse emittances by factors of a few hundred and reduce the longitudinal emittance ε_L by a factor O(10) — see Fig. 2, a.

Parameters	Low E	High E	High ε
COM energy, TeV	1.5	4	2
Luminosity, $\text{cm}^{-2}\cdot\text{s}^{-1}$	10^{34}	$4\cdot10^{34}$	$4\cdot10^{30}$
# of bunches	1	1	12
μ's/bunch, 10^{12}	2	2	0.1
Circumference, km	3	8.1	3
$\beta* = \sigma_z$, mm	10	3	5
dp/p, rms, %	0.1	0.12	0.01
Ring depth, m	13	135	13
PD rep. rate, Hz	12	6	60
PD power, MW	≈ 4	≈ 2	2.4
Tr-emm. ε_T, $\pi\cdot\mu$m$\cdot$rad	25	25	3000
L-emm. ε_L, $\pi\cdot$mm$\cdot$rad	72	72	25

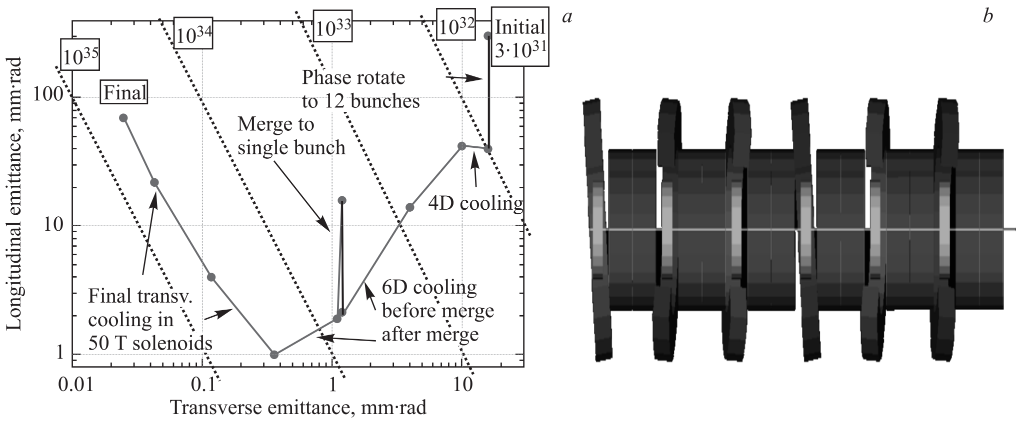

Fig. 2. a) Simulated 6D cooling path corresponding to one particular candidate MC cooling channel. The first part of the scheme (indicated by «4D cooling») is identical to the present baseline NF front-end. Dotted lines indicate approximate luminosity reach of a 3 TeV MC. b) Candidate scheme for 6D muon cooling («FOFO snake») which offers fast reduction of the beam longitudinal and transverse emittances for both signs of muons

RECENT PROGRESS TOWARD MC AND NF

It is specified in the «Project-X» design that it has to be upgradeable from initial proton beam power of 1 MW to 2–4 MW, so it can serve as a source for an MC. The design work on the following accumulation/(and) bunching ring(s) has just been started recently.

Multi-MW target R&D has greatly advanced in recent years and has culminated in the Mercury Intense Target experiment (MERIT [11]) which has successfully demonstrated a Hg-jet injected into a 15 T solenoid and hit by an intense proton beam from the CERN PS. A high-Z target is chosen to maximize $\pi^{\pm}$ production. Solenoid radially confines essentially all $\pi^{\pm}$ coming from the target. The Hg-jet choice avoids the shock and radiation damage related target-lifetime issues that arise in a solid target. The jet was viewed by high-speed cameras (Fig. 3) which enabled measurement of the jet dynamics. MERIT results suggest this technology could support beam powers in excess of 4 MW.

Significant efforts are presently focused on high-gradient normal conducting rf cavities operating in multi-tesla magnetic fields as required in the bunching, phase rotation, and cooling channel designs. Closed 805 MHz rf cells with thin Be have shown windows significant reduction of maximum rf gradient in 3 T field — 12 MV/m vs. 17 MV/m specified. Further R&D will explore possibilities of surface treatments, usage of high-pressure hydrogen gas, «magnetically insulated» or open cavities.

The present baseline 4D ionization cooling channel design consists of a sequence of LiH absorbers and 201 MHz rf cavities within a lattice of solenoids that provide the required focusing. International Muon Ionization Cooling Experiment (MICE [12]) at RAL (UK) is now at the initial stage, preparing to test an ionization cooling channel cell in a muon beam by 2011–2012. The MICE cell is adequate for an NF.

In the last few years several self-consistent concepts based on different technologies have emerged for the MC 6D cooling channel which plays central role in reaching high luminosity (see Fig. 2, a). To achieve desired mixing of transverse and longitudinal degrees of freedom, the muons have to be put onto a helical trajectory, e.g., as in «FOFO-snake» [13] shown in Fig. 2, b. The design simulations of the channels are not yet complete and the main challenges are attainment of large enough dynamic apertures, taking into account realistic magnetic fields, RF cavities and absorbers, optimization of the B fields in RF cavities and technological complexity. The design of the final cooling stages is particularly challenging as it requires very high solenoid fields (up to $\sim$ 50 T have been considered). The final MC

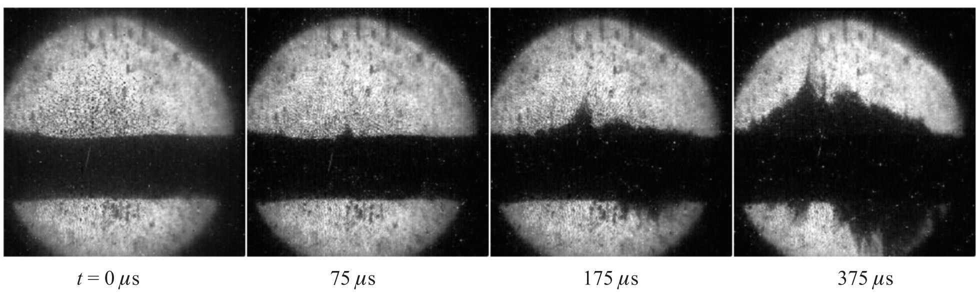

Fig. 3. Sequential images of a Hg-jet target hit by a 24 GeV beam pulse containing 1013 protons (MERIT). The jet was in a 10 T field (measurements have been made up to 15 T). At the timescales of $\sim$ 15 ms the jet re-establishes itself ready for next proton pulse

luminosity is proportional to this field. The MCTF has begun studying the viability of an HTS option for these solenoids.

Recirculating Linac with SC RF cavities (e.g., 1.3 GHz ILC-like ones) is a very attractive option for acceleration of muons from low energies in cooling sections to the energy of the experiments. It offers small lengths and low wall plug power consumption, but requires small beam emittances [14].

Recently, realistic collider ring beam optics has been designed which boasts a very good dynamic aperture for about $dP/P = \pm 0.5\%$ and small momentum compaction [15]. The distortions due to beam–beam interaction will need to be studied as well as practical issues of the machine-detector interface.

The NFMCC and MCTF have recently proposed a joint R&D plan for the next 5 years with the goal of delivering a «Design Feasibility Study» report. The study would include (i) an end-to-end MC simulation based on components that are either within the state of the art or could be expected to be developed within a few years, (ii) an evaluation of the MC performance and physics program, (iii) a first defensible cost estimate, and (iv) planning for the subsequent R&D that must be done before an MC could be built, including component development and proof-of-principle experiments. It is thought that, if the HEP community wishes to go down this path, an MC construction start in the early to mid-2020s is plausible. The next NF step, which has begun, is the so-called International Design Study (IDS) which hopes to deliver a «Reference Design Report» by 2012. By this time it is anticipated that all of the proof-of-principle tests will be completed. If the community wishes to proceed, after a few years of additional R&D, the NF construction could start as early as the late 2010s.

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