Superconducting Free Electron Laser Undulators for γγ Colliders

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This Letter of Interest builds upon the synergistic collaboration of two labs with world class expertise in accelerator magnets. Fermilab's High Field Magnet Program (presently part of US-MDP) has been developing Nb_3Sn superconducting (SC) magnets, materials and technologies for present and future particle accelerators since the late 1990s, culminating with its recent world record field for accelerator dipole of 14.5 T. Argonne National Laboratory (ANL) has been investing in SC NbTi undulators since the early 2000s after decades of experience in permanent magnet undulator technologies for light sources. By joining forces, the two labs recently concluded a phase of short model magnet R&D using Nb_3Sn undulators for the Advanced Photon Source storage ring by reproducibly achieving the SC short sample limit in these models [1-4].

The 2014 P5 strategic plan for U.S. HEP, echoed by the 2015 HEPAP subpanel review of the General Accelerator R&D (GARD) program, endorsed continuing a world leadership role in superconducting (SC) magnet technology for future Energy Frontier facilities, while cautioning against the excessive focus on project-driven R&D. The subsequent low funding level of the Magnet Development Program (MDP) may partially explain why the Fermilab's dipole record came 23 years after the previous record of 13.5 T at LBNL for an accelerator quality magnet.

We propose to merge the specialized know-how and expertise of HEP and BES labs in the design of SC free electron laser (FEL) undulators for γγ colliders. These proposed colliders have a long history [5, 6], are a rich multidisciplinary field, and since the late 1980s have been considered a natural part of all linear collider proposals. For e+e- colliders which use their beams only once, high energy photons with a brightness comparable to that of the electron beam are generated through Compton backscattering of laser light focused onto the incoming electron bunch just before the interaction point [7]. The fractional energy transfer from the electron beam to the photons goes from 46% at the 45 GeV beam energy typical of Z factories, up to 80% at 250 GeV beam energy. The photons with the maximum energy are produced in the direction of the electron beam. One laser pulse per bunch transfers energy from both electron beams into photon beams which would collide in the interaction point (IP). eγ collisions also occur between each photon beam and its opposite electron beam. When the scattering is designed to occur at a minimal distance from the IP, the photon spectrum is more monochromatic. The center of mass (c.m.) energy in the electron-laser photon interaction determines the maximum possible fractional energy transfer, and the polarizations of the electron and laser beam control the produced photon energy and polarization distribution. By using circularly polarized laser beams it is possible to produce highly circularly polarized photon beams at the maximum energy.

The fundamental design criterion for a photon collider laser is that it should supply enough laser light that every electron bunch has sufficient (>60%) electrons undergo a primary Compton backscatter. For an individual laser pulse, the pulse width should to be ~ 1 ps, and the pulse energy ~ 2 to 10 J. The specifications of the laser itself depend on the choice of accelerator parameters, which include the time structure of the electron beam, the electron beam energy, and the electron bunch length. Over the whole spectrum of proposed e+e- colliders, the average laser power per beam spans from 33 kW for the 500 GeV ILC stage, to 89 kW for a 500 GeV CLIC, to 239 kW for HFiTT [8], and up to 1000 kW for SAPPHiRE [9]; the laser energy per bunch train from 5 J for SAPPHiRE and HFiTT, to 1770 J for a 500 GeV CLIC, and up to 6600 J for the 500 GeV ILC stage.

FELs have several attractive advantages as a source of laser photons for a photon collider. Picosecond bunches are inherently simpler (unless one wants to shorten the FEL) because the laser pulse width is inherently the same as the electron bunch width, and it is possible to produce the required photon wavelength of ~ 1 μm. As experience at DESY and Sincrotrone Trieste show, synchronization of the two beams is straightforward. However, FELs for γγ colliders have to be specifically designed to generate very high pulse energies in helical undulators to provide the correct circular photon polarization. ANL has extensive experience with SC bifilar helical coil configurations [10] for the undulator magnets, and the design of SC FEL undulators would include, in addition to the magnets, also phase shifters, focusing magnets and precise electron beam position monitors.

Electromagnetic undulators wound with superconducting NbTi wires have opened a new era in undulator technology [11]. Superconducting undulators (SCUs) offer higher magnetic fields for a given period length and magnetic gap as compared to permanent magnets or hybrid undulators. In addition, the SCU technology can be successfully employed for building undulators of different types including planar, helical and universal devices. The SCU magnetic field can be further enhanced with use of more advanced superconductors such as low-temperature Nb_3Sn, as demonstrated at ANL. Fermilab has recently added to its portfolio [12] the development of dipole magnets made of high temperature Bi2212, which comes in the form of an isotropic round multifilamentary wire. The know-how accrued in the next few years on Bi2212 within the US-MDP will be of great value for this proposed research during the medium term.

The physics case for γγ colliders starts from the lowest energy options all the way up to the multi-TeV concepts. Importantly, the γγ approach eliminates the challenges of building a powerful positron source and subsequent fast damping ring. At the lowest end of the energy spectrum, a γγ collider with 12 GeV c.m. energy based on the 17.5 GeV SC linac of the European XFEL [13] would make uniquely possible the study of γγ physics in the $b\bar{b}$ region. The discovery of a Higgs-like boson at 125 GeV in 2012 renewed interest in a dedicated electron linac-based Higgs factory from γγ collisions. The proposed SAPPHiRE [9] would use recirculating electron linac technology to create 80 GeV electron beams to produce γγ collisions at 125 GeV c.m. Similarly, HFiTT [8] proposed to use the Fermilab's Tevatron tunnel to accelerate up to 80 GeV two electron beams for γγ production at 125 GeV. Studies of the physics of γγ and eγ collisions using a 500 GeV ILC stage include Higgs boson searches in the direct production mode γγ ––> H° and single gauge boson production. Using a 1 TeV linear collider to produce colliding photons is possible at the cost of a reduced luminosity [14]. In that case, the unique physics that could be performed includes: hadron physics through the study of the photon structure W_γ; purer high energy QCD processes, such as diffraction, total cross section; multiple production of gauge bosons; the detailed structure of the electroweak theory with 0.1% accuracy through processes such as γγ ––> WW, eγ ––> νW, and γγ ––> ZZ; strongly interacting scalars beyond the Standard Model thanks to the machine high monochromaticity.

The white paper will present a conceptual design study of the FEL SC undulators that would be required, if cost-effective, for existing concepts of γγ colliders with up to 1 TeV c.m. energy.

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