Advanced Beam Cooling
LoI to Beam Physics and Accelerator Education

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Beam cooling is intimately connected to the accelerator and beam phyiscs (ABP) grand challenges that have been identified in the recent DOE/HEP General Accelerator R&D roadmap exercise, particularly in the areas of beam intensity, quality and control. Just as a large number of accelerator facilities around the world have been enabled by innovations in beam cooling, modern hadron accelerators would greatly benefit from the realization of novel, advanced-cooling techniques that can provide a robust path toward higher luminosity and reliability of the colliders. Such techniques should be able to cool intense hadron beams at high energy, and they would counteract intrabeam scattering and control the emittance growth due to noise in the accelerator. They would also lower the transverse beam emittance in order for the beam to be focused in a tiny spot size at the interaction point. For instance, the electron-ion collider approved for construction at the Brookhaven National Laboratory in January 2020 needs strong hadron cooling to achieve the luminosity 10^{34} cm^{-2}s^{-1}. This cooling should work with the beam intensities up to 2×10^{11} particles per bunch at the proton energy up to 275 GeV.

There are two conventional cooling techniques for hadron and ion beams. The first one—the *stochastic cooling*—was invented by S. van der Meer at CERN in 1969. The second one—the *electron cooling*—was proposed by G. Budker in 1966 at the Institute of Nuclear Physics in Novosibirsk, Russia. These techniques found a broad application (about 20 electron coolers have operated in the world since 1974) and played a crucial role in many experiments, with the highest cooler energy reached at the Fermilab cooler project [1, 2]. However, they have their limitations. Stochastic cooling in the frequency range of several GHz is limited to relatively low-density beams. Electron cooling does not scale well to the proton energies above 10 GeV.

To overcome these shortcomings of the conventional cooling techniques, several new ideas have been proposed that have a promise to increase the cooling rate by orders of magnitude.

In 1993-1994, Michailichenko, Zolotorev and Zholents proposed the *optical stochastic cooling* (OSC) [3, 4] which conceptually is an extension of the conventional stochastic colling to the range of optical frequencies. The pickup and kicker are replaced by the wigglers, and instead of the RF signal from the pickup electrode the wiggler radiation carries the information about the position of particles in the bunch. The beam energy is modulated by the amplified radiation from the pickup in the kicker wiggler. Depending on the system configuration, the pickup radiation may be focused to a transverse spot size that is smaller than the particle beam, further increasing the granularity with which the beam's phase space is sampled and corrected and thereby enhancing the compatibility with higher-intensity beams. Furthermore, because OSC relies on synchrotron radiation as the means of measurement and feedback, in principle, its utility may extend beyond direct hadron cooling to applications in light sources, ring-based electron coolers and damping rings, for example.

In 2008-2009 Litvinenko and Derbenev came up with an idea of the *coherent electron cooling* (CeC) [5], in which the role of the pickup and modulator electrodes is played by an electron beam propagating with the same velocity and overlapping with the hadron beam. Between the modulator and the kicker the signal in the electron beam is amplified in a free electron laser at the frequency that can be as high as the optical frequency and many orders of magnitude higher than the traditional

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RF frequency of the conventional stochastic cooling. Further improvements of the CeC concept have been proposed under the name of the *micro-bunched electron cooling* (MBEC), wherein the narrow-band FEL amplifier in CeC is replaced by a broadband amplifier that uses a combination of space charge forces in the beam with the increased longitudinal slippage in magnetic chicanes [6]. More recently, another broadband amplification was proposed [7] based on the so-called *plasma-cascade amplification* mechanism (PCA).

Broad and sustained R&D is critical to successfully transition these concepts to operational technologies that could expand the performance and science reach of future DOE facilities; therefore, we propose a research program that will explore these new cooling techniques in theory, simulations and experiments.

While theoretical development over the last decade has firmly established the foundations for the new techniques [8–13], this development needs to be continued. It should provide a better understanding of the underlying mechanism of the cooling process, predict cooling rates in different scenarios, optimize various parameters of the cooler system and analyze the tolerances. These investigations are also important for the benchmarking of computer simulations.

Computer codes for simulations of the new techniques are critical for the final evaluation of cooling-system performance. As a rule, the existing in accelerator physics codes cannot be used for this purpose, because the cooling occurs on microscopic scales and requires extremely fine spatial resolution. In addition, cooling is a slow process that needs tracking of many revolution periods in the accelerator. New, dedicated codes should be developed [14] for this purpose.

Up to now, these novel cooling ideas have not been demonstrated experimentally. Currently several proof-of-principle experiments are being prepared. An OSC development program is underway at Fermilab's IOTA facility where OSC will be explored with 100-MeV electrons and first results are anticipated within CY20 [15]. This R&D program attempts to demonstrate OSC for the first time, in both non-amplified and amplified configurations, and subsequently use the OSC concepts and technology as the foundation of new tools for beam control and sensing. Additionally, IOTA's demonstrated ability to reliably store and characterize an individual electron for multiple hours enables careful exploration of the fundamental physical proceses underlying OSC. An amplified-OSC development program is also underway at Cornell University's CESR storage ring with the expectation of tests with 1-GeV electrons within the next few years.

A CeC-PCA cooling experiment is being developed at BNL. It is aimed at the demonstration of the cooling of ions with 26.5 GeV/nucleon in a 4-cell PCA system at RHIC, with the first results expected in CY21-22.

On the experimental side, the coherent cooling needs development of high-current electron beams that have internal low noise after acceleration to the energy exceeding 100 MeV and transporting the beam in the cooler channel. This requirement is critical for the success of the cooling, as has been demonstrated in the CeC proof-of-principle experiments at BNL. Another critical element, common to both optical and coherent cooling, is the precise, sub-micron control of the path lengths for the beams, which may require the development of new feedback systems.

Realization of these high-bandwidth cooling architectures will provide the accelerator community with a new portfolio of technologies for increasing the performance and flexibility of future accelerator facilities. Furthermore, the physics and engineering challenges solved in the process will undoubtedly support numerous other areas in accelerator science and technology, as well as many early-career scientists, postdocs and graduate-student researchers.

[1] Sergei Nagaitsev, Daniel Broemmelsiek, Alexey Burov, Kermit Carlson, Consolato Gattuso, Martin Hu, Thomas Kroc, Lionel Prost, Stanley Pruss, Mary Sutherland, Charles W. Schmidt, Alexander Shemyakin, Vitali Tupikov, Arden Warner, Grigory Kazakevich, and Sergey Seletskiy. Experimental demonstration of relativistic electron cooling. *Phys. Rev. Lett.*, 96:044801, Jan 2006.

[2] S. Nagaitsev, L. Prost, and A. Shemyakin. Fermilab 4.3 MeV electron cooler. *Journal of Instrumentation*, 10(01):T01001–T01001, jan 2015.

[3] A. A. Mikhailichenko and M. S. Zolotorev. Optical stochastic cooling. *Phys. Rev. Lett.*, 71:4146–4149, 1993.

[4] M. S. Zolotorev and A. A. Zholents. Transit-time method of optical stochastic cooling. *Phys. Rev. E*, 50:3087–3091, Oct 1994.

[5] Vladimir N. Litvinenko and Yaroslav S. Derbenev. Coherent electron cooling. *Phys. Rev. Lett.*, 102:114801, 2009.

[6] D. Ratner. Microbunched electron cooling for high-energy hadron beams. *Phys. Rev. Lett.*, 111:084802, Aug 2013.

[7] V. N. Litvinenko, G. Wang, D. Kayran, Y. Jing, J. Ma, and I. Pinayev. Plasma-Cascade Micro-bunching Amplifier and Coherent Electron Cooling of a Hadron Beams. Technical report, February 2018.

[8] Gang Wang and Michael Blaskiewicz. Dynamics of ion shielding in an anisotropic electron plasma. *Phys. Rev. E*, 78:026413, Aug 2008.

[9] Alexander Zholents. Damping force in the transit-time method of optical stochastic cooling. *Phys. Rev. ST Accel. Beams*, 15:032801, Mar 2012.

[10] V. Lebedev. Optical Stochastic Cooling. *ICFA Beam Dyn. Newslett.*, 65:100–116, 2014.

[11] Andrey Elizarov and Vladimir Litvinenko. Dynamics of shielding of a moving charged particle in a confined electron plasma. *Phys. Rev. ST Accel. Beams*, 18:044001, Apr 2015.

[12] G. Stupakov. Cooling rate for microbunched electron cooling without amplification. *Phys. Rev. Accel. Beams*, 21:114402, Nov 2018.

[13] P. Baxevanis and G. Stupakov. Transverse dynamics considerations for microbunched electron cooling. *Phys. Rev. Accel. Beams*, 22:081003, Aug 2019.

[14] Jun Ma, Xingyu Wang, Gang Wang, Kwangmin Yu, Roman Samulyak, and Vladimir Litvinenko. Simulation studies of modulator for coherent electron cooling. *Phys. Rev. Accel. Beams*, 21:111001, Nov 2018.

[15] J. Jarvis, S. Chattopadhyay, V. Lebedev, H. Piekarz, P. Piot, A. L. Romanov, J. Ruan. Optical Stochastic Cooling Program at Fermilab's Integrable Optics Test Accelerator. *in Proc.*, North American Particle Accelerator Conference (NAPAC2019), Lansing, Michigan, Sept. 2019.