Summary of Beam Cooling and High Brightness

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Abstract. We summarize the contributions and the outcome of the discussions in the session on 'beam cooling and high brightness'.

INTRODUCTION

The many challenging beam cooling projects at high energies are the driving force behind the remarkable progress in modeling and experimental verification reported during the workshop. At FNAL the 4.3 MeV electron cooler is presently being installed in the Recycler [1]. Electron cooling at very high energies (55 MeV) is proposed for the RHIC upgrade (RHIC-II) [2]. Electron cooling up to 8 MeV is required for the proposed HESR [3] as part of the FAIR project at GSI [4]. Optimization of the proposed cooling scenarios, including studies on rf manipulations, stochastic and electron cooling, intrabeam scattering, gas scattering, as well as other processes, requires not only accurate but also fast numerical models. On the other hand, existing electron cooler storage rings, like CELSIUS at Uppsala [5], COSY at FZ Jülich [3], and ESR at GSI [6], operate at relatively low electron energies below 300 keV. To make reliable predictions for the cooling dynamics at medium to high energies one has to critically check existing theoretical models. Also, experimental results obtained at the existing cooler rings for the equilibrium beam parameters and for intensity limits can be used to benchmark theoretical models at low energies. At high energies, intrabeam scattering theory for Gaussian beam can be checked with high accuracy in RHIC and in the Tevatron.

Here, we categorize the topics addressed during the workshop into four sections: intrabeam scattering, electron cooling modeling, other heating and cooling processes, and intensity limiting effects.

INTRABEAM SCATTERING (IBS)

IBS refers to two-body, small-angle multiple Coulomb scattering processes between the beam particles. The evaluation of IBS emittance growth or exchange rates consists of calculating the scattering rate in the beam rest frame based on the Rutherford scattering cross section, transformation to the laboratory frame, and averaging over phase-space and time. A number of different approximations are used to obtain IBS rates for Gaussian beams, examples are the model by Piwinski [7], its extention by Martini [8], the formulae by Bjorken-Mtingwa [9] and by Wei [10]. The different approximations can differ by factors of 2, depending on the application. In order to describe the detailed evolution of the bunch density profile and also the beam loss, direct analytical or numerical solutions of the Landau collision term, which has a Fokker-Planck structure, can be obtained [12, 14, 13, 11]. Within the presented theoretical approaches one usually averages over these fast oscillations. However, one must keep in mind that for sophisticated kinetic effects, like transverse beam echoes observed recently in RHIC [16], accurate IBS modeling requires the analysis of the Vlasov-Fokker-Planck equation, without averaging. But in most cases the averaging is justified because of the much longer IBS time scales. In case of the synchrotron motion the averaging is performed also in nonlinear rf wave forms [14, 11]. Remarkable agreement between 1D Fokker-Planck simulations and the observed IBS driven bunch profile evolution in RHIC has been achieved [15]. Electron cooling in combination with IBS results in non-Gaussian beam distributions. The kinetic description of cooling dynamics requires at least 1D and preferably 3D kinetic IBS models. The 3D "IBS map" approach [12] might be a way to include kinetic IBS in tracking codes. However, for long-term kinetic simulations of electron cooling scenarios reduced 1D Fokker-Planck models are still required. In summary, the theory behind IBS for "hot" beams (far away from crystallization) is considered as well understood. Molecular dynamics simulation results on IBS rates in ultra-cold beams are presented in Ref. [15]. Experimental results on 1D crystalline beams obtained in

the ESR can be found in Ref. [6].

Pertaining to IBS in "hot" beams, the following tasks are identified:

- Fast solvers for IBS rates including transverse coupling and arbitrary rf wave forms
- Fast numerical IBS models for simulations of kinetic cooling scenarios
- 3D kinetic IBS solvers using macro particle methods
- Benchmarking of kinetic IBS solvers with high resolution experiments, using beam echoes or other kinetic beam phenomena

ELECTRON COOLING

For unmagnetized electrons the cooling force can be extracted from the theory of hot plasmas. The resulting formula by Budker [17] can be used as an order of magnitude estimate for the cooling rate. In a hot plasma the Coulomb logarithm is large (usually $\sim$10). A sufficiently strong longitudinal magnetic field greatly improves the cooling forces. Analytical expressions for the friction force on a single ion moving through a magnetized electron distribution have been published by a number of authors [18, 19, 20]. The cooling force estimations for the RHIC-II [21] project are based on the Parkhomchuk formula [22], which is an empirical generalization of the theoretical friction force for unmagnetized electrons. Magnetized electron cooling will be crucial for RHIC-II and also for the HESR in order to achieve the required cooling rates. Especially with regard to magnetized cooling at high energy, the existing theoretical cooling models are regarded as insufficiently accurate. Complications arise from the small Coulomb logarithm for magnetized cooling. Further analytical difficulties result from the fact that electron scattering by a heavy particle in a magnetic field does not have a general analytical solution and exhibits chaotic orbits (see e.g. [23]). Experimentally, the correction of field misalignments is a challenging technical problem. The precise knowledge of the residual field errors is required for accurate simulations of beam cooling. All these complication will make accurate (within a factor of 2) predictions for magnetized cooling very difficult. On the other hand, macro-particle simulation codes, like VOPAL [24], allow the calculation of electron cooling forces from first principles. Using the tabulated forces extracted from a large number of simulation runs or fitting parameters one might be able in the future to achieve the required accuracy. Such simulations need to account for the various practical cooler imperfections and also for collective electron-ion effects. In addition, understanding of cooling forces through measurements on the existing machines at low energies is important. Concerning the longitudinal cooling force a number of comparisons between measured forces and the theories were published in the literature [25, 26, 27]. It will be worth re-investigating such existing data under the light of the new project challenges. Transverse cooling forces are usually more difficult to measure. Recent results using kicked pencil beams in CELSIUS [5] look promising. Of special interest with regard to the new high energy cooling projects is also the scaling of the cooling force with the projectile charge number Z. Cooling forces calculations based on the binary collision approach or on the dielectric theory exhibit a Z^2 scaling law. Experiments [28] as well as theoretical studies [29] showed a scaling law $\sim Z^{3/2}$ for the longitudinal cooling force, which can be explained in terms of non-linear screening of the projectile ion by the electrons. Non-ideal plasma effects are another possible explanation [30] of the experimental results.

Pertaining to electron cooling, the following tasks are identified and questions raised:

- Large-scale simulation studies of magnetized cooling forces
- Measurement of magnetized cooling forces at low energy using existing machines with proper control of the relevant cooler and beam parameters.
- Are non-ideal or non-linear electron plasma effects important at high energy ? Do we expect deviation from the Z^2 scaling law for the cooling force at high energy ?

OTHER PROCESSES

Progress has been reported concerning the modeling of stochastic cooling especially on the fast numerical computation of the dispersion integrals [13]. It has been pointed out that the operational experience shows that electron cooling and stochastic cooling cannot be switched on simultaneously. However, stochastic precooling is routinely performed in storage rings [6]. Laser cooling in combination with electron cooling can result in very low momentum spreads. First results on laser cooling of C^{3+} ions were presented during the workshop [6]. For experiments with internal targets the achievable luminosity depends on the target density. For the high local densities in pellet targets the beam-target interaction can be the dominating beam heating mechanism that must be balanced by strong electron cooling. Hence, detailed models of beam-target interaction are essential for the design of future high energy storage rings [31]. The theoretical models should be benchmarked against measurements at low energies. Another beam heating process, called "electron heating" in electron cooler rings is

related to the nonlinear space charge field of the cooler electrons [32, 33].

Pertaining to topics in this area, the following tasks are identified:

- Fast solvers for stochastic cooling calculations
- Understanding of the negative operational experience that stochastic cooling and electron cooling can not co-exist – are there ways to effectively combine stochastic and electron cooling ?
- Benchmarking of beam-target interaction models
- Particle tracking studies of "electron heating"

INTENSITY LIMITS

Beam intensities in the existing cooler rings are mostly limited by various kinds of collective instabilities. Intensity limits discussed during the workshop were transverse coherent dipole oscillations [33], longitudinal microwave instabilities [34, 6] and two-stream instabilities induced by trapped ions [33]. The transverse dipole modes observed in HIMAC and COSY can be damped by feedback systems, whereas the longitudinal microwave instability must be avoided by all means. Above transition energy the negative mass instability can effectively limit the equilibrium beam parameters [6]. A lattice with imaginary γ_t is proposed for the HESR in order to enhance Landau damping to suppress longitudinal and transverse instabilities [34].

Pertaining to intensity limits, the following tasks are identified and questions raised:

- What is the driving impedance behind the coherent instabilities observed in HIMAC and COSY ? A detailed stability analysis taking into account electron cooling, space charge and the resistive wall will be necessary.
- More accurate threshold calculations for the longitudinal microwave instability in electron cooled beams are necessary. Is the microwave instability the main limitation for the achievable momentum spread in the proposed high energy cooler rings ?
- Comparison of the observed two-stream instability thresholds with theoretical predictions.
- What are the main intensity limitations with regard to high energy cooling ?

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