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Advances in bright electron sources

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ABSTRACT

In this paper, we review the status of bright electron sources. High peak current (up to kA) low emittance (<1 mm rad) electron beams have been one of the critical components in the development of XFELs. The outlook for the field is even more promising as progress in the understanding of photoemission physics, development of novel photocathode materials, gun and laser technology, enable further progress in advanced light sources as well as novel applications such as ultrafast electron diffraction and microscopy. We outline here the more recent research trends which pave the way for potentially orders of magnitude brightness improvements with respect to the current state-of-the-art.

Contents

1. Introduction

The performance of electron sources plays a key role in the widespread development of high brightness beam applications such as short wavelength high gain free electron lasers, ultrafast electron diffraction and microscopy, inverse compton scattering, injection into very high gradient advanced accelerators and high power THz generation [1–5]. The availability of very high phase space density electron beams is the result of two decades of progress during the 1980s and 1990s in studying and understanding the key aspects of beam generation, capture and evolution in high gradient photoinjector systems [6–10], which has permitted the production of intense, cold, relativistic electron beams with ultralow normalized transverse emittances (well below 1 um) with a lasting impact well beyond the field of high energy physics which these sources were originally developed for [11–13]. For example, the advent of X-ray Free-Electron lasers (XFEL) [14,15] would not have been possible without the low emittance and high current beams made available by the development of the high gradient radio-frequency (RF) photogun. In order to allow the growth of the FEL instability in the interaction of electromagnetic radiation and charged

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particles in the undulator, kAmp-class beams with sub-um emittances at GeV energies are required. This puts stringent requirements on the electron source to generate electron beams of sufficient quality, which in turn raises the demands on the beam transport, acceleration and bunch compression systems to preserve the initially very high phase space density. High brightness electron beams with up to a few MeV energy are also used directly in state-of-the-art electron imaging instrumentation—ultra-fast relativistic electron diffraction (UED) and microscopy (UEM) [16–22]. Compared to XFEL electron sources, these applications typically require lower beam charge (pC or less), and are critically dependent on beam emittance and bunch length, which directly affect the spatial and temporal resolution of the system. With bunch lengths close to or even shorter than 100 femtoseconds, these instruments yield detailed information about the behavior and structure of atomic-molecular systems at their characteristic spatial and temporal scales, permitting so-called ultra-fast four-dimensional imaging [23,21]. The fundamental limits in beam brightness set by quantum mechanics are still at least five orders of magnitude away from the performance of state-of-the-art pulsed electron sources [24], therefore presenting an optimistic view of the opportunities for significant improvements and further breakthroughs in the spectrum of bright electron beam applications. For example, in order for XFELs to lase at even higher photon energies, with higher efficiencies and shorter pulse lengths, the source brightness remains a critical parameter. Time-resolved single-shot TEM is limited to slow (>10 ns) acquisition times due to the relatively low peak brightness of the electron beams employed in standard microscope columns [25,26] and could take advantage of increased beam brightness from novel photoinjector sources [27,28]. Another up and coming challenge is related to the desire for higher average beam powers—many applications will benefit from significantly higher pulse repetition rate than what can be provided by peak brightness electron sources. These considerations drive most of the recent research efforts in this field. The development of electron sources enjoys decades of experience in accelerator and laser technology, detailed engineering development, and well benchmarked simulation models, and benefits from continuous investments over many years from different funding agencies. While all these elements have created a very mature field in which significant progress has to be necessarily measured in factors of two, rather than in order of magnitudes, there are a number of key reasons and novel elements that support the promise for breakthrough advances. In particular:

- The revolution introduced by femtosecond and sub-femtosecond techniques in ultrafast science has increased the demand for ultrashort electron and X-ray pulses, which in turn has driven the designs of electron sources towards ultrashort bunch lengths with relatively low charge per bunch. The accompanying progress in beam transport systems and ultimately detectors has also contributed to lowering the requirements for the range of relevant charges per pulse to 0.2–20 pC.
- With the help of material science and solid state physics, and a well concerted effort in testing and characterization, many advances have been made in our understanding of photoemission physics. These results, together with the development of important technologies such as high average power wavelength-tunable fiber lasers, as well as surface engineering can be used to develop advanced photocathodes systems with better performances.
- In the last few years there has been a steady and measurable progress in RF technology [29,30], both superconducting and normal conducting, leading to a better understanding of the breakdown process to the introduction of novel materials (or materials in novel regimes, such as cryogenic temperatures) and surface preparation techniques. This can be exploited in the construction of future electron sources with much larger accelerating gradients and therefore with the promise of much higher beam brightness.
- Other important contributions are the exponential gains in available computing power which permits massive, computationally intensive optimization algorithms and the development of accurate beam diagnostics schemes to characterize and fine tune the source performances.

In this paper we plan to review the research directions outlined in this introduction. The subject has been the focus of many recent workshops [11] and lies at the core of one of the main thrusts of the multi-institution Cornell-led Science and Technology Center, the Center for Bright Beams (CBB) [31]. A comprehensive review of the field is far beyond the goal of this paper. Instead, we aim to provide the scientific background and justification as well as highlight the novel approaches in the CBB Center activities. The structure of the paper shows the main areas where significant progress is expected in the next few years, starting from a presentation of the research trends in photocathode physics, then moving on to an outlook on the possibilities of increasing the injection field in the gun, a review of the progress in the beam diagnostics and ultimately a discussion of the ultimate limits in the brightness of photoemission sources (see Table 1).

1.1. Brightness scaling laws

A good starting point in framing the field of bright electron sources is the definition of beam brightness [32]. The term was first introduced by Ruska [33] to characterize the quality of beams in electron microscope systems. At the time, the concept of brightness came naturally from the observation that a larger divergence was required to focus the beam to a smaller spot leading to the identification of a figure of merit for the quality of the beam in the electron column as the current (I) per unit area and unit solid angle. The extension of this concept to relativistic beams (including proper relativistic normalization factors) directly translates into the so called 5D brightness $B_{5D} = 2I/\epsilon_n^2$, where $\epsilon_n = \beta\gamma\epsilon_g$ with ϵ_g being the geometric emittance which enters the Ruska definition. This brightness is the relevant quantity in many electron beam applications, and for example directly enters in the calculation of the ρ parameter which determines all of the important properties of an FEL amplifier such as efficiency, gain length and saturation power.

Beam compression systems can easily change the peak current in the beam by manipulation of the longitudinal phase space, so B_{5D} is not an invariant in modern linear accelerators. At least formally, a better figure of merit would be the 6D brightness, or the 6D phase space density, which is preserved for Hamiltonian transport systems by the Liouville theorem. Quantum mechanics, by way of the Pauli exclusion principle and the Heisenberg uncertainty relation, sets a hard quantum limit to the maximum 6D brightness achievable for an electron beam. No more than 2 (spin up, spin down) electrons can fit in each (normalized) quantum unit of phase space $(h/(m_0c))^3$. In SI units $B_{quantum} = 10^{25}$ C/m^3. Normalizing the beam brightness by the quantum limit beam brightness one can estimate the number of electrons in each fundamental quantum unit cell of phase space, which is called the quantum degeneracy factor of an electron source. In theory this number can never be larger than two. In practice best electron sources have quantum degeneracy factors of 1E−5 at best, leaving ample room for future improvements.

The scaling of 6D brightness with the various electron source parameters is more complex as it has strong contributions from intrabeam scattering effects (Boersch effect [34]) and has not yet been discussed in detail in the literature. Moreover, there are significant experimental challenges in the measurement of the longitudinal phase space [35] with resolution sufficient to assess with small uncertainty the area occupied by the beam, and even more when there are correlations with the other dimensions. Therefore, the 6D brightness finds at this time less practical relevance.

For systems with small transverse to longitudinal coupling (therefore excluding all emittance exchange manipulations) we can restrict the discussion to the transverse phase space and a commonly used well-defined quantity to characterize the quality of the electron source is the

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