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Working Group II Report: Production and Dynamics of High Brightness Beams*

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Abstract. This paper summarizes the main discussions of the Working Group on the Production and Dynamics of High Brightness Beams. The following topics are covered in this paper. Proposed new electron sources and needed research on existing sources is covered. The discussions on issues relating to the description of phase space on non-thermalized electron beam distributions and the theoretical modeling on non-thermalized electron beam distributions is presented. Finally, the present status of the theoretical modeling of beam transport in bends is given.

INTRODUCTION

The physics of the production and transport of electron beams has seen renewed interest with the development of new high-brightness electron guns. Most of the previous work on electron guns and the transport of the produced beams have assumed thermalized electron distributions. Because of fundamental thermodynamic issues, the emittance of such beams after transport is significantly greater than the emittance of the initial electron beam distribution from the cathode. The high-brightness guns almost always produce non-thermalized phase-space beam distributions. However, these non-thermalized distributions have well-defined correlations in time or radius. If the beam then thermalized, the resulting emittance can be very large (factors of three or more). With an appropriate beamline design the correlations can be corrected, and the resulting

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emittance dilution can be significantly reduced. The study of the generation and transport of non-thermalized distributions is a very active field of research.

The same issues arise in the transport of high-brightness beams through a series of bends, such as a bunch compressor. In this case, the fields produced by the beam during transport through the bend can distort the 6-D phase-space distribution in either time (longitudinally) or x-y (transversely). Present modeling efforts do not adequately describe the effect of these fields on the beam phase space distribution to design a beam transport system for a high-brightness beam.

PRODUCTION OF ELECTRON BEAMS

Electron Sources

This section covers two new types of sources and then discusses issues concerning presently used photocathodes.

A new type of electron source, presented by Charlie Brau (Vanderbilt), is a single very sharp needle placed in a high electric field. As demonstrated in electron microscopes, very high current densities of extremely high brightness can be obtained from needle tips. Present experimental results indicate that pulse charges comparable to that required for accelerator applications (several nanocoulombs per micropulse) can be produced. An issue that need to be addressed is the effect from the very large dB/dt at the front and back of the pulse. Also, the beam must be transported form the needle tip to the accelerator. Since the absolute needle voltages are relatively low, the beam pulse length is short, and the beam radius is small, space charge effects will be the dominate contribution to the beam emittance.

Another new source, described by Tom Katsouleas (USC), is compatible with plasma-based accelerator designs. In this source, electrons are first produced in plasma potential wells and then accelerated from rest to relativistic energies in the plasma. Calculations show that several nanocoulombs can be trapped in each plasma period. This source appears to be ideally suited as an injector for a plasma wakefield accelerator since the same laser system that produces the electrons also provides the accelerator fields for the rest of the plasma wakefield accelerator. The main issues raised in the discussion was the emittance from this type of source. Even though the beam has a very small radius, the accelerating gradients are every high, on the order of GV/m. Maintaining linear transverse fields and keeping the transverse energy gain very small appears to be challenging.

Photocathodes, although used in many high brightness gun applications, still have a significant issue that needs to be addressed. The beam emittance at the cathode can be calculated from the photoelectron thermal temperature. The photoelectron thermal temperature has only been accurately measured for gallium arsenide and cesium antimonide photocathodes. Present guns, except for the polarized electron sources that use gallium arsenide, use photocathodes made of copper, magnesium, cesium telluride, and cesium potassium antimonide. Thermal temperature measurements need to be completed on these cathodes so that accurate predictions of the gun performance can be made.

Electron Gun Dynamics

The discussion on electron gun dynamics applied mostly to photoinjectors (photocathode in an rf cavity). However, the underlying physics issues apply to any gun system that relies on rapidly accelerating an electron beam and then introducing the beam to the main accelerator before the beam is thermalized.

Description of Beam Quality

Present descriptions of beam quality are not adequate to fully describe the performance characteristics of non-thermalized beams. These distributions have two characteristics. As mentioned in the introduction, photoinjectors produce beams with well-defined radial and longitudinal correlations. So, first, the correlations can be corrected to some degree by focusing element.

Second, the electron distribution typically appears to have a halo, although the distribution is continuously varying in density. A typical x-x' phase space plot is shown in Figure 1. Most of the distribution is tightly grouped, however very diffuse wings can be also seen. The rms emittance ellipse shown in Figure 1 is much larger than what might be expected because a small number of particles have a very large spread in x' and x. Figure 2 demonstrates the effect of clipping the longitudinal distribution equally from both ends of a micropulse. The emittance drops much faster than the loss of charge. The reason for the non-linear dependence of emittance and charge can be seen in Figure 3. The beam is only "matched" for the center portion of the micropulse. As long as the beam does not mix longitudinally, then the effective beam emittance is more accurately represented by the emittance of the middle portion of the micropulse.

The same non-linear dependence of emittance can be exhibited radially. In fact, by a judicious choice of initial beam parameters, focusing solenoid setting and placement, and accelerating gradient, the radial component can have the dominant emittance effect.

The present figure of merit used to describe the beam quality, the rms emittance, does not adequately quantify the beam characteristics in these high-brightness guns. As a result, we need a new figure of merit to compare experimental results with simulations and to provide appropriate beam parameters for the application designers.

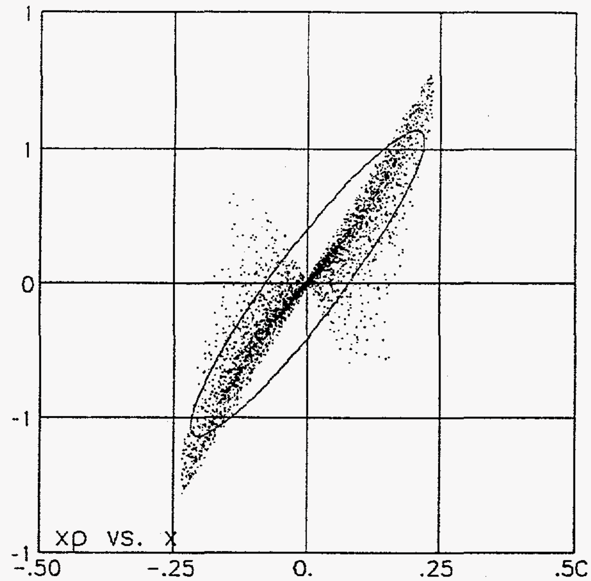

Figure 1. Sample x-x' distribution for a square input laser pulse incident on a photocathode.

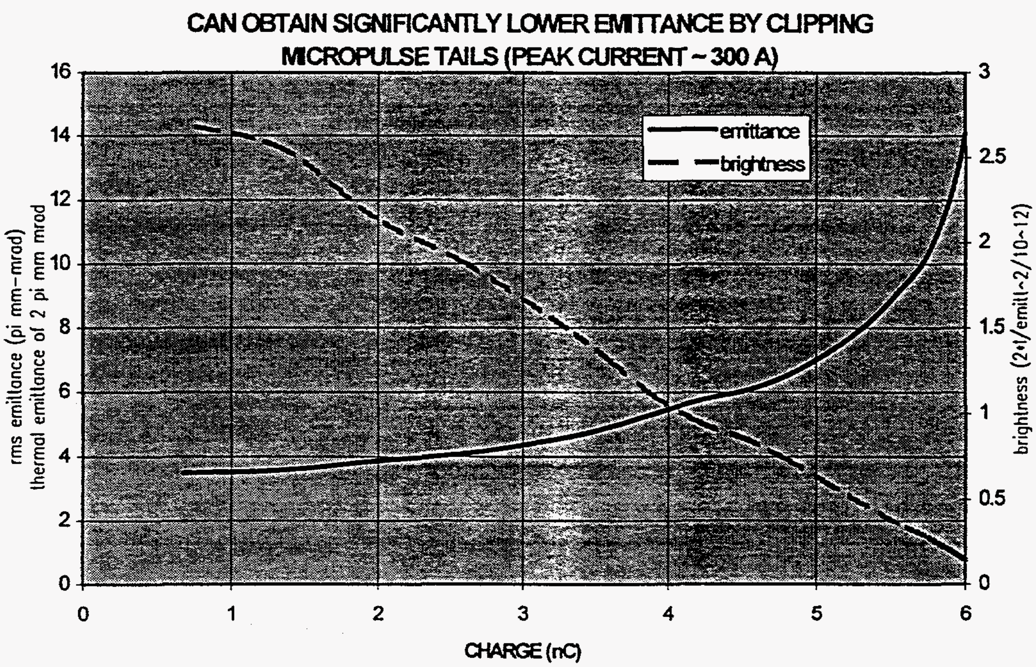

Figure 2. Clipping longitudinal distribution simultaneously from both ends of micropulse for the triple-gaussian input laser pulse.

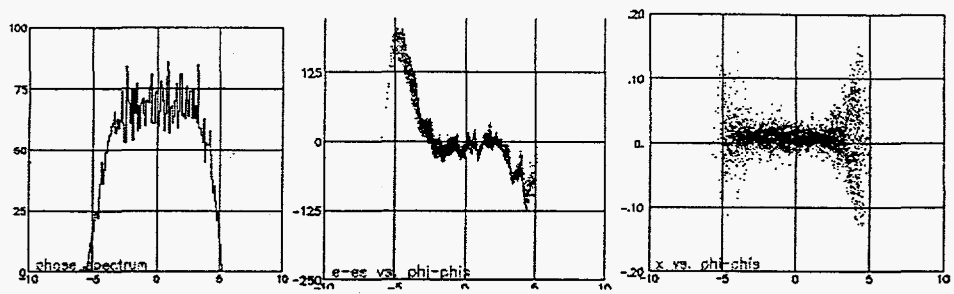

Figure 3. Beam characteristics downstream of the linac for a triple gaussian input pulse. The left is the temporal profile of the pulse, the middle is the energy versus phase, and the right is electron radius versus phase at the wiggler entrance. The horizontal scale is 5 degrees of 1.3 GHz per division. The vertical scales are particle number per bin, 100 KeV, and 0.10 cm for the left, center, and right figure, respectively.

Performance of Electron Beam Sources

The best experimental result to date is 2 mm-mrad rms normalized emittance at 1 nC. Based on present simulations, emittances of 0.5 to 1.0 mm-mrad per nanocoulomb can be expected in the near future.

Institution	key	gun type	KE (MeV)	Q (nC)	τ (FWHM, ps)	Δt (ns)	number of pulses in macropulse	normalized emittance (mm-mrad)
Duke	0	1 cell, S-band	1	.03	3			~ 4 measured
Northrup-Grumann	1	3-1/2 cell S-band	9	2	4-10	7	1000-1400	~ 4 measured
TJNAF (CEBAF)	2	350-500 KV DC+ 2SRF@ 1497 MHz	10	0.14-0.27	4	27	CW	4.4 modeled
BNL 3	3	1 MV DC over 1-2 mm	1	1	1000 (ps & fs planned)			10 modeled
TTF 1	4	1-1/2 cell 1.3 GHz	3.8	10	10	1000	800	15 modeled
BNL 1	5	1-1/2 cell S-band	4.5	0.04	0.37	NA	NA	0.5
Twente	6	4-1/2 cell, 1.3 GHz	3-7	<8	35-53	12	<1200	10 measured
Boeing	7	2 cell 433MHz + accel	20	3	55 to 9 after compression	37	224,324	9 before, 14.5 after compress
BINP (Novosibirsk)	8	150 KV, DC	0.15	4	2000			6 measured
BINP (Novosibirsk)	9	200 KV, DC	0.2	20	2000			<10 modeled
NLTCA (SLAC)	10	150 KeV DC, Xband buncher	83	0.25	1.2		1440	6 modeled

NLC (SLAC)	11	120 KeV DC+accel	80	3.2	15	1.4	90	50 modeled
SLAC	12	120 KeV DC	0.12	10	2000	61.75	2	10 measured
CTF2 (CERN) 1	13	2-1/2 cell S-band	7.1	13.4 of 21	8	0.333	48	62 measured
CTF2 (CERN) 2	14	1-1/2 cell S-band	4	1	8	NA	1	64 measured
LAL (CERN) 3	15	80 KeV DC	0.7	14		0.333	75	
BNL/SLAC/UCLA	16	1-1/2 cell	6	1	10	24.5	100	<1
TTF 1 (DESY)	17	250KeV	10	0.037	320 to 3.5 after compres	4.6	17300	3 to 4.5 after compression
APEX (LANL) 1	18	5.5 cell	8 (4-8)	1	20 to 1 after compress	9.4	2-20	5 to 16 after compression
AFEL (LANL) 2	19	10-1/2 cell	17 (12-20)	1	8	9.4	2000	2 measured
AFEL (LANL) 3	20	10-1/2 cell	17	6	20	9.4	2000	12 modeled (6 for 5nC,core)
CANDELA	21		2	1	2,8 @ 1.5m	NA	1	<10 measured
ANL		1 cell, 1.3 GHz	1.8	80	14	11	700	130 meas.
KEK		1, 2.86 GHz	0.9	3.2				
MIT		1.5, 17 GHz	2.5	0.1	0.5	11.9		0.5
TTF FEL 2 (DESY)		1.5, 1.3 GHz	81	1	7			3 modeled
CEA		1 cell, 144MHz	2	5	20-50			4@1nC,meas.

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Table 1. A chart of the present measured and calculated performances for electron beam sources.

Theory Issues

The gun theory discussion centered on the theoretical developments associated with emittance-compensated photoinjectors. The two theoretical physics issues raised were the frequency scaling and the scaling of present theories to include nonlinear effects.

The theoretical dependence of performance on linac frequency scaling needs to be definitively specified. Present theory states that the emittance is independent of frequency. This is obviously not the case. For example, a 100 nC micropulse charge is incompatible with a 30 GHz accelerator. Even if the charge could be accelerated, the emittance would be much worse than for a 50 MHz accelerator. Also, the effect of the cathode thermal emittance (emittance is proportional to the cathode radius) is not folded into the theoretical models.

The present theoretical models describe only the linear part of emittance compensation. To attain the very low emittances required for x-ray FELs, the present models need to incorporate non-linear effects. In particular, the theoretical models need to include non-linear transverse space charge forces, non-linear beam expansion, and halo formation due to over-focusing the beam wings.

BEAMS IN BENDS

Present Theoretical Understanding of Beam Physics

Since electron beams are getting brighter, effects that were not considered important just a few years ago can now limit the performance of electron machines. In particular, emittance growth of beams in bends is expected to be a significant issue in the next generation of electron beam machines. For example, in present designs for recirculating linacs, bunch compressors could have a factor of ten growth in emittance for beams entering at 1 mm mrad rms normalized emittance. This section covers the emittance degradation of beam propagating through bends.

Emittance degradation in bends is the result of several factors. First, the space charge force is modified. The fields due to the electron bunch varies in the plane of the bend since the potential fields are less dense radially outwards. This variation in density in the plane of the bend gives a transverse and longitudinal variation (longitudinal because the retarded times are not symmetric) in the potential fields experienced by the electrons during transport through the bend. If the bend is used as part of a buncher element, then as the bunch is compressed the forces experienced in a direction radially outward of the bend will not be corrected by a downstream bending element with a radius in the opposite direction. The non-asymmetry occurs because during bunching the beam field density is increasing, changing the potential field map due to the electrons own space charge fields.

The beam can also generate coherent synchrotron radiation (CSR) if the rms bunch length is on the order of the cut-off wavelength of the beam-pipe. CSR is particularly odious because the radiation and the emittance growth scale as the bend radius to the 1/3 power for a fixed bend angle. Simulations of CSR-driven storage ring instability look a lot like a microwave instability.

Both of these effects interact with dispersion to generate emittance degradation. The space charge effect leads to a longitudinal force that is both a function of radius and longitude; thus the slice emittance grows. The CSR effect leads to a purely longitudinal force and thus the slice emittance is unchanged.

Present theory is mostly limited to studies of CSR effects (with some work on the space charge effect). Several difficulties exist with the present models. Since the formulas cannot be solved analytically, the theoretical models make significant approximations. For instance, the models keep only the lower order terms, neglect transients, and ignore beam size effects. Also, nearly the canceling terms in the expansions are lowest order and very large in absolute value, giving the possibility for large errors in the results. This leads to difficulties in numerical simulations.

At present, although CSR is itself well-understood, its effects on emittance has not been experimentally observed. However, an experimental manifestation of the CSR is not expected in present experiments because the CSR is only expected to affect very-bright-beam based experiments, and those experiments are just coming on line now.

Future Directions

Simulation with Green's functions may be the best way to develop new models. For the modeling efforts to date, bunch size variation, transients, and realistic beam transport have proved too difficult to handle.

Several participants are confident that the effect can be significantly reduced with clever beam transport design (e.g. phase advances). However, our present understanding is not sufficient to produce such a design.

Experiments planned to occur in the next several years should observe effect (if it is really significant). Experiments are expected at Jefferson Lab IR FEL, BNL ATF, NLC test stand at SLAC, Tohoku University, Sunshine at Stanford, ANL, and DESY.

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