FERMILAB-CONF-06-331-AD

Summary of “beam quality diagnostics and control” working group

John Lewellen[*] and Philippe Piot[**]

[*] Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439
[**] Northern Illinois University, DeKalb, IL 60115 and
Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510

Abstract. The working group on beam quality, diagnostics, and control at the 12*th* Advanced Accelerator Concepts Workshop held a series of meetings during the Workshop. The generation of bright charged-particle beams (in particular electron and positron beams), along with state-of-the-art beam diagnostics and synchronization were discussed.

Keywords: charged-particle beam sources, charged-particle beam diagnostics
PACS: 52.59.–f , 52.59.Sa

GENERAL COMMENTS

Working Group 5 covers beam sources, controls, and diagnostics. This wide range of topics yielded an interesting and varied series of sessions. As a result, our Group did not have a central theme underlining and unifying the week; our summary reflects this, and the reader is encouraged to see the individual talks and papers for greater detail. Unless otherwise specified, references within the text are to the papers and presentations given at this Workshop.

INJECTORS

The field of beam source development is quite varied, as reflected in our session, even if restricted to electrons and positrons.

Subjects of Research

Injectors, in and of themselves, are interesting (and, sometimes, somewhat frustrating) objects for study. Our working group heard about several exciting developments in injector design and characterization, spanning a wide range of accelerator technology, particle sources, and even particle species.

One of the Workshop plenary talks, by J. Luiten, discussed the possibility of combining two novel—to high-brightness injectors—techniques to obtain ultra-low emittances. A key to this technique is the generation of 3-D ellipsoidal bunches with uniform charge density, i.e., “waterbag” distributions. There are several potential approaches to obtaining such a distribution [1,2]. One method is to start with an approximately 2-D distribution, and allow it to evolve into the desired 3-D distribution via space-charge-induced "blowout" [1,2b]. An advantage, with respect to photoinjectors, is that the temporal shape of the drive laser pulse is largely irrelevant, so long as it is short; the distribution is set in the transverse plane by relatively straightforward optical manipulations to obtain the desired 2-D intensity pattern. This method was recently tested [3] at the SPARC photoinjector test facility [4]. Although more work remains, the initial measurements are consistent with the desired bunch blowout regime and provide an exciting initial confirmation of the theory.

Another desirable drive laser distribution, and the one upon which most of the emittance-compensation theory was based, is the "beer can" beam: a right circular cylinder, with uniform intensity distribution. Generating such a distribution has proven to be quite problematic in practice, mostly in the longitudinal plane. Techniques such as frequency shaping have tended to work in the infrared to provide reasonably uniform longitudinal distributions. Metal and some semiconductor photocathodes[1] require UV light, however, and the needed laser frequency upconversion process usually degrades the pulse profile significantly. An alternate approach is to "stack" Gaussian UV pulses in time to form the desired flattop; complications include the need for alternate polarization of the stacked pulses to reduce potential interference effects. This technique is being explored at Fermilab [5] with excellent results to date.

Once one has a good way of generating a desired electron beam distribution, high-gradient, high-brightness photoinjectors promise the ability to generate a beam with good emittance and high bunch charge at moderate energy. There are many potential applications, ranging from Compton backscatter x-ray sources to THz-range free-electron lasers (FELs), to pulse radiolysis and electron diffraction. One challenge to the construction of a compact system is the arrangement and simplicity of the required injector. A "split" type injector typically requires a power divider and phase shifter to power the gun and capture linac section. "Integrated" injectors need only one rf power source, but are prone to the typical problems of many-celled standing-wave (SW) cavities. A novel approach being taken by UCLA is to combine a standing-wave cavity (the cathode and full cell similar to a typical "split" injector gun) with a traveling-wave (TW) energy booster in a single structure [6,7]. This approach is amenable to the use of long TW portions (helping to reduce the overall rf power requirements) and can be tuned to allow several interesting modes of operation. In particular, the beam can be induced to self-compress as it transits the traveling-wave portion of the injector, leading to peak beam currents in the kA range at the exit of the structure, with good transverse emittance. These performance characteristics make the design interesting both as a standalone accelerator, and as a potential source for higher-energy machines.

---

[1] Mg and Cu are the most popular choices for metal cathodes and S-band guns, while Cs_2Te is more commonly found in L-band gun systems.

A perennial problem for photoinjectors has been cathode quantum efficiency, or electrons produced per photon deposited on the cathode. For many applications, such as single-shot linacs, quantum efficiencies in the range of 10^{-5} are acceptable. For future applications, such as ampere-class energy-recovery linacs (ERLs), the use of metal cathodes would require a MW-class drive laser. Semiconductor cathodes such as CsKBr have much higher quantum efficiencies and operate well at green wavelengths, but are extraordinarily sensitive to vacuum conditions. Researchers at Brookhaven National Laboratory have proposed a solution to the need for high-quantum-efficiency cathodes: the diamond secondary emission enhanced photocathode (SEEP) [8]. A SEEP cathode is actually a miniature accelerator in itself and consists of a photocathode, a small gap, and a diamond amplifier surface. Electrons are emitted from the photocathode and are accelerated across the vacuum gap. When they impact the diamond, the electrons generate many secondaries; these secondary electrons are pulled through the diamond by an externally applied field (say, the rf field in a GHz-range or lower frequency photoinjector cavity). The SEEP cathode therefore increases the effective quantum efficiency of the photocathode by the ratio of secondaries generated per primary electron; further, during the transport through the diamond the secondaries are thermalized, leading to a very low intrinsic emittance beam. Good progress has been made on the development of the SEEP cathode, with the latest results demonstrating secondary generation transport through a diamond plate, and ejection into vacuum in DC test beds. Progress has also been made on the design and fabrication of an encapsulated cathode for use with superconducting rf guns. While presently an object of study in and of itself, the hope is that the SEEP cathode will become an enabling tool for accelerator development.

Enabling Tools for Research

High-brightness injectors and novel applications of other existing technology are increasingly being used as beam sources for other experiments or tools, as opposed to direct objects of study themselves. The SPARC photoinjector, for instance, is serving as the driver for a single-pass FEL project [4], as well as a platform for high-brightness source-related research. The requirements for the overall project have led to a very careful study of the SPARC injector performance, including phase-space evolution in the drift region following the injector.

The ability to use high-brightness sources as tools for, as opposed to objects of, research has been strongly correlated with the development of improved beam sources (e.g., drive lasers and cathodes) and diagnostics. We have also seen modern computing power and simulation techniques applied to “classic” beam sources, with some very interesting results.

A good example of the latter is the electron lens system in use at Fermilab [9]. The proton and antiproton bunch trains experience tune shifts at the interaction point and during parasitic crossing that depend on a bunch’s particular position within the bunch train [10]. This also leads to a tune spread within the bunch that results in a reduction of luminosity. Since typical beamline elements cannot respond quickly enough to compensate for the different focusing force each bunch receives, two electron lenses were constructed. These lenses use high-current DC guns, whose current can be varied at the bunch train rate, to provide bunch-specific compensation for the beam-beam interaction. By adjusting parameters such as the cathode and extraction electrode geometry, as well as adjusting the relative bias between the electrodes, a number of different beam profiles can be generated, for instance flat-top with "hard" or "soft" edges, and Gaussian profiles. Modern design tools and computing platforms allow the exploration of the large parameter space for optimized configurations of the transport line as well as the gun, permitting the system as a whole to be optimized.

A Compton backscatter source presently being developed at the University of Tokyo [11] has several unique features. It is a very compact system (footprint is 5m × 5m). The beam source is an X-band thermionic-cathode rf gun and linear accelerator structure, for a final beam energy of 35 MeV. An alpha magnet between the gun and linac provides bunch compression and energy filtering. The gun is a somewhat unusual design, incorporating 3.5 cells, an on-axis coaxial rf power feed, and a π-mode cell configuration; nominal peak field at the cathode is 150 MV/m. The backscatter laser is a Q-switched YAG, providing up to 2-J pulse energy in 10-ps pulses at 1064 nm, or 1.4 J per pulse at 532 nm. The beamline is arranged such that the laser pulse interacts with many separate bunches from the gun. Downstream collimation can provide quasi-monochromatic x-rays at energies around 21.9 keV (using 1064-nm light) or 43.8 keV (using 532-nm light). At present the gun is being commissioned.

Pulse radiolysis also makes use of short, intense, moderate-energy electron beams. In this case, the intent is to use the electron beam as a pump for a material such as water or methanol; a trailing laser pulse can then be used to probe chemical reactions. The resolution of the measurement is theoretically set by the duration of the probe laser pulse; however, jitter between the electron beam and laser pulse arrival times is equivalent, when averaged over many shots, to a longer laser pulse [12]. Since processes of interest occur over timescales of 5 – 10 ps, a beam-to-laser pulse jitter of ~ 500 fs is desired. This has been achieved at the University of Tokyo pulse radiolysis facility via a combination of laser stabilization and overall temperature control to reduce both shot-to-shot jitter and long-term drift. Also in progress is the addition of a cathode loadlock and cartridge system to reduce downtime, allow the use of higher-QE photocathodes, and improve cathode lifetime by reducing system exposure to atmosphere.

Producing high-quality electron beams can be challenging in and of itself; producing high-quality, high-charge positron beams is more challenging still. The International Linear Collider baseline design assumes the use of polarized positrons; the nominal source design uses a 150-GeV electron beam and a 200-m wiggler to generate circularly polarized gamma rays; these are impacted on a target to generate polarized positrons. In contrast, by Compton backscattering CO_2 laser light from a 4-GeV electron beam, one can generate the 80-MeV photons required [13]. The interaction conditions have been tested at lower energies and have achieved record-breaking x-ray yields, with one x-ray photon per electron generated. By using advanced CO_2 laser technology (e.g., optical pumping) and a MOMPA (master oscillator, many power amplifier configuration), a series of optical interaction stations, each delivering 1-TW, 5-ps optical pulses, can be synchronized to maximize the gamma yield from a single electron bunch. This would allow the use of a 4-GeV driver linac for polarized positron production, eliminating the need to use the ILC main linac and a 200-m undulator for this task.

ACCELERATOR CONTROL AND FEEDBACK SYSTEMS

In a modern accelerator control system, the user does not control the accelerator. Rather, the control system runs the accelerator, and the user makes requests of the control system. In some accelerators this approach is limited to processes that take place too fast for humans to deal with, such as rf phase stabilization; in others, it encompasses tasks such as beam steering that humans can do, but which can often be better accomplished with a response matrix-based approach.

Regardless, for a control system to be effective it must incorporate both adequate diagnostics to determine (or allow the user to determine) the state of the accelerator, and it must be able to affect the parameters of the accelerator to obtain the result desired by the user. For control systems intended to autonomously adjust the operation of a machine (e.g., to stabilize beam position in a storage ring), the control system must, at some level, incorporate a model of the accelerator being controlled. This might take the form of a response matrix, a callable optimization routine linked to a simulation code, etc.

Modern high-current circular accelerators are routinely designed to operate above instability thresholds [14]. For instance, the Advanced Light Source storage ring has an instability threshold of 40 mA, yet has a design current of 400 mA. To run effectively, then, the control system must be able to detect and counter instabilities as they arise. In such a system, the control system effectively acts as a negative real impedance contribution to the storage ring impedance budget. Feedback systems can also be used to characterize the machine parameters; this can be done, for instance, by monitoring the actions taken by the feedback system after a brief interruption of the feedback process.

Many of the feedback techniques used in storage rings rely on the repetitive nature of the bunches in the ring; the same bunch will return to a given point on the circumference after one revolution. Thus, given fast enough processing electronics, it is possible to measure a bunch's properties (transverse offset, energy offset, etc.) on one pass and have sufficient time to calculate and prepare a correction by the time the beam has returned on the subsequent pass. Linear accelerators are intrinsically single-shot devices; each shot is different and measurements on a single shot cannot, with certainty, be used to predict what will happen on the next.

ERLs are, in some senses, hybrids between linacs and storage rings. While each bunch transits the ERL once, the same beam will (in most ERL designs) transit the same accelerator cavity at least twice. In principle, therefore, at least some of the correction techniques used on storage rings could be used on ERLs.

BEAM DIAGNOSTICS

About half of the presentation in our Working Group concerned instruments and/or techniques for measuring given beam parameters or associated phase-space density distribution. We also had a joint session with the working group on electromagnetic structure pertaining to ultrafast diagnostics (that is, diagnostics with possible application to attosecond bunches, such as those generated in optical accelerators). From the given presentations, we infer that beam diagnostics R&D mainstream is two-fold. On one hand several groups are exploring quasi-noninterceptive techniques with emphasis on measuring "projected" beam parameters; on another hand other groups are developing/improving techniques capable of measuring the details of the phase-space distribution within the bunch. Ideally one would like to be able to measure these details in a noninterceptive fashion; however, this proves impractical. Therefore, most groups usually "just" measure the statistical properties of the phase-space distribution—typically first- and second-order moments (i.e., spot size and emittance). However, this type of measurement is not sufficient when trying to study the intricate beam dynamics associated with, e.g., space-charge-dominated beams.

Transverse Trace Space

Detailed measurements of the transverse trace-space distribution are possible via tomographic techniques. The method consists of measuring a series of beam profiles for different phase advances between the measurement location and a defined point upstream where the trace-space distribution is to be reconstructed. D. Startakis described the implementation of such a method in UMER [15]. Although the method has been previously used by several groups [16,17], the originality of Startakis' work was to develop a reconstruction algorithm that includes linear space-charge forces. This algorithm was validated using initial beam distributions provided by the WARP particle-in-cell tracking program to simulate the measurement technique. It was found, in the case of extremely space-charge-dominated beams, that the transverse emittance computed from the reconstructed trace space agrees with the emittance computed on the initial trace-space distribution generated by WARP within 15% or less. Such a good agreement provides confidence on the applicability of the technique to space-charge-dominated beams.

Another example of detailed measurement was presented by P. Musumeci in a talk pertaining to the SPARC facility photoinjector commissioning [4]. The injector beamline incorporates an axially movable single/multislit mask assembly. It is therefore possible to measure the transverse trace-space distribution evolution at various longitudinal positions downstream of the electron source. The apparatus was initially designed to study space-charge-dominated beam dynamics with the emphasis on trying to directly observe the transverse emittance oscillation(s) predicted by numerical simulations and theories. Musumeci illustrated the power of the system by showing the (x,x') trace-space evolution of a space-charge-dominated beam that clearly displays the expected laminar-type focusing typical of such beams, in contrast to the single-particle-dynamics crossover-type focusing.

A nonintercepting transverse diagnostic capable of measuring the beam's second-order moments was discussed by N. Barov [18]. The diagnostic consists of a standing-wave resonant cavity optimized for operation on the TM_{220} (quadrupole)-mode cavity. The prototype tested at NLCTA at SLAC operates at f=11.424 GHz. As the beam passes through a skew[2] cavity, it excites cavity modes. The power associated with the TM_{220} mode is extracted and provides information on the beam's second-order moments $\left\langle x^2 - y^2 \right\rangle$ if the beam is centered on the cavity axis. To distinguish between the beam's second- and first-order moments, it is proposed to have an assembly consisting of two dipole-mode (8.568 GHz) and one two-cell quadrupole-mode (11.424 GHz) cavities; this will enable both a measurement of beam positions and rms sizes. It is anticipated that micron-size beams could be resolved with this diagnostic. By using a series of six such cavities, separated by appropriate phase advances, the rms beam emittances can be determined. The performance of the diagnostic requires tight but achievable machining tolerances. Finally Barov dashed a possible direct trace-space measurement using a transformation that maps, e.g., *(x,x')* trace space onto *(x,y)* configuration space.

Another noninterceptive diagnostic, based on optical diffraction radiation (ODR), was described by A. Lumpkin [19]. Near-field measurements of ODR performed at the Advanced Photon Source (APS) facility at Argonne were reported. ODR is very similar to optical transition radiation (OTR): the field associated with the beam is diffracted by an obstacle (e.g., edge or slit) that does not intercept the beam. The experiment done at APS used a moving edge to generate diffraction radiation. Because of the high beam energy, 7 GeV, the radiation can be emitted in the optical regime for impact parameters larger than the beam size (typically the impact parameter was approximately 5-σ). Dependence of ODR intensity on beam size was established and correlated with corresponding OTR-based beam-size measurements at the same location. Although an exact measurement of the spot size via ODR was not possible in this proof-of-principle experiment, a cross calibration of the ODR signal with the OTR measurement suggests that ODR could serve, at least, as a noninterceptive beam size monitor, e.g., to continuously monitor the relative variation of beam size. The applicability of this diagnostic to high-average-current accelerators (e.g., ERLs), x-rays free-electron lasers, and linear colliders looks promising. The impact of the diagnostic on the beam (wakefield) remains to be quantified.

Finally V. Scarpine presented OTR measurements performed in the Tevatron complex at Fermilab [20]. Initial measurements were done in a transfer line with a 120-GeV

---

[2] Such a cavity has its transverse axes rotated with respect to the beam coordinate system, typically by 45°.

proton beam, and a two-turn measurement was performed in the Tevatron ring for an uncoalesced proton beam. An interesting observation reported by Scarpine was that the OTR intensity is much smaller both than predicted and when compared to an earlier prototype system with a different OTR foil. A possible explanation is related to the (still debated) formation depth associated with transition radiation phenomena being smaller that the metallic layer used as a radiator: in some of the presented measurements, the radiator consists of a thin (1000 Å) Al layer deposited on a Kapton film. This interesting hypothesis should be easily confirmed in smaller-scale electron beam facilities by performing a parametric study of OTR intensity radiated for different radiator thickness. This would be a first direct observation of the formation length effect associated with the transition radiation process.

In the joint session with Working Group 7, a novel transverse beam position monitor (BPM) was discussed by S. Banna. The BPM consists of, e.g., $N \times N$ metallic vertical posts bounded from above and below by two horizontal metallic plates [21]. In such a configuration, the beam offset from the horizontal symmetry axis is determined by measuring the backward radiation emitted by the beam as it traverses the array. More precisely, it was shown that the backward radiation angular distribution consists of two lobes, and a measurement of the lobes' asymmetry provides an indirect measurement of the beam offset. Assuming a perfect machining of the BPM, the resolution is limited by the noise equivalent power of the optical detectors used to measure the lobes' intensity.

Other transverse phase-space measurements, such laser wire scanners, are coming into increasing use but unfortunately were not discussed in our Working Group.

Longitudinal Phase Space

Frequency-based bunch-length measurement has become a very popular technique because of its simplicity and low cost. It is based on the coherent enhancement of electromagnetic radiation emitted by a bunch at wavelength comparable to the bunch length. Various radiation mechanisms have been used (e.g., synchrotron, diffraction, transition, Smith-Purcell radiation) but coherent transition radiation (CTR) is the most widely used. In its simplest form, the diagnostics consists of a detector measuring the coherent radiation within a certain wavelength window. Such a configuration can serve as a bunch-length monitor, e.g., to minimize the bunch length downstream of a bunch compressor by simply tuning the accelerator to maximize the radiated power [22-24]. More sophisticated setups, aiming at measuring the charge distribution, include a Michelson autocorrelator. The measured autocorrelation can be used to infer the radiation power spectrum (via the Wiener-Kitchine theorem), which can then be inverted using Kramer-Kroenig relations to provide a possible charge distribution. The technique is prone to the non-uniform frequency-response of the system, which distorts the calculated spectrum. For sub-mm bunch length (ps-regime), the low frequency part of the spectrum is generally suppressed due to diffraction effects, and the spectrum must be "completed" by some method before reconstructing the charge distribution [24,25]. The coherent radiation autocorrelation method is actually better suited to even shorter bunch lengths, e.g., optical regime measurements. In any case, the Kramer-Kroenig relations do not provide an unambiguous time distribution, and this remains one of the main limitations for reconstructing intricate (e.g., multi-peaked) charge distributions.

R. Marsh presented a somewhat different frequency-domain diagnostic based on the interbunch coherence (while the above diagnostics are based on intrabunch coherence) [26]. The 17-GHz accelerator at MIT was used to produce coherent radiation at harmonics of 17 GHz up to a high frequency cut-off given by the single-bunch Fourier transform. A measurement of this coherence cut-off frequency is therefore representative of the bunch duration. The process to produce radiation was either transition or Smith-Purcell radiation. The angular distribution of the coherent radiation produced by both processes was measured and found in agreement with simulations. A time-domain bunch-length measurement based on a pair of deflecting mode cavities [27] confirmed that a measurement of the coherence cut-off frequency correlates well with the bunch length.

J. Rosenzweig reported initial measurement of coherent edge radiation (CER) performed at the ATF at Brookhaven [28]. Edge radiation, which is produced while the beam crosses the boundary of a magnet, is very similar to synchrotron radiation but has a stronger intensity at wavelengths larger than the critical wavelength and it is radially polarized. The CER emitted by the bunch as it travels between the two last dipoles of a magnetic bunch compressor chicane was detected and analyzed. The CER signal was untangled from coherent synchrotron radiation (CSR) via polarization measurements. The CER angular distribution and polarization were measured and agree with numerical simulations based on a Liénart-Wiechert potential approach.

Time-domain measurement of short electron bunches using a TM_{110} (dipole) mode cavity was discussed by J. England [29]. In this scheme the incoming electron bunch traverses the cavity at the zero-crossing phase. The head and tail of the bunch are transversely deflected in opposite directions while the bunch center remains unaffected: the beam is streaked. A measurement of the transverse beam profile in the deflecting direction provides a direct measurement of the longitudinal charge density. An X-band (9.96 GHz) deflecting cavity was designed and installed downstream of a dogleg-type bunch compressor at the Neptune facility at UCLA. The cavity is presently being commissioned. England's analysis indicates an achievable resolution of approximately 50 fs in the Neptune setup. Given the cavity design (9 cell) and available power (50 kW) a transverse deflecting voltage of approximately 0.5 MV is possible. Finally it was noted that complementing this cavity with a spectrometer line orthogonal to the cavity deflecting direction provides a direct "projection" of the longitudinal phase space $(t,\delta E)$ onto the transverse configuration space (x,y).

Finally a novel idea for a frequency-domain bunch-length measurement was dashed by L. Schächter. The idea is based on the resonance of gas and somewhat related to the PASER principle [30]. It was shown that energy lost by a bunched pass through a linear resonant medium is dependent on the bunch transverse and radial sizes.

Although we did not hear about these techniques, it is worth mentioning that electro-optical imaging is also a very popular technique for measuring the bunch-charge distribution with sub-ps resolution [31].

PHASE-SPACE MANIPULATION

It is common in accelerators to manipulate the phase space: the emittance compensation scheme or longitudinal bunch compression in the magnetic chicane exemplify such manipulations within one degree of freedom.

Recently phase-space manipulation schemes capable of manipulating the beam in two degrees of freedom have emerged. An example that was discussed by Y.-E Sun is the round-to-flat beam technique first proposed by Derbenev [32]. The transformation was later adapted to produce flat beams (i.e., beams with large transverse emittance ratio) directly out of a photoinjector starting with an angular-momentum-dominated beam produced by immersing the photocathode in an axial magnetic field [33-35]. Sun reported on the first experiment performed at the Fermilab photoinjector aimed at studying the flat-beam generation. To date, an emittance ratio of approximately 100 was experimentally achieved, and scaling laws for the angular-momentum dominated and flat beams were verified to match the theoretical predictions [36,37]. The applicability of the flat-beam technique in the foreseen international linear collider (ILC) is still questionable since the required four-dimensional emittance needed to meet ILC specification is $\gamma\sqrt{\varepsilon_x\varepsilon_y} \approx 0.4$ mm-mrad for 3.2 nC, a value about one order of magnitude below what present sources can reliably achieve.

Another phase-space manipulation that involved two degrees of freedom (derived in Reference [38]) aims to exchange one of the transverse emittances with the longitudinal emittance. K.-J. Kim presented a slight variant of the emittance, based on a double-dogleg beamline instead of a chicane beamline, which produces an exact emittance exchange. (In Ref. [38] the emittance exchange was approximate.) Kim described a possible linac concept for the Greenfield free-electron laser that makes use of both the round-to-flat beam transformation and the transverse-to-longitudinal emittance exchange. In this design a low-charge (20 pC) bunch is generated in a photoinjector and optimized to produce low longitudinal and transverse emittances, e.g., typically $\gamma(\varepsilon_x, \varepsilon_y, \varepsilon_z) \approx (0.23, 0.23, 0.07)$ mm-mrad. The beam is then accelerated and made flat: the emittance partition is changed to $\gamma(\varepsilon_x, \varepsilon_y, \varepsilon_z) \approx (9.9, 0.005, 0.08)$ mm-mrad. Finally the beam horizontal and longitudinal emittances are exchanged, resulting in the final beam emittance partition $\gamma(\varepsilon_x, \varepsilon_y, \varepsilon_z) \approx (0.08, 0.005, 9.9)$ mm-mrad. Although this is not an optimum operating point (one would indeed rather the final transverse emittance to be equal), this mode of operation is advantageous since the large longitudinal emittance makes the beam less prone to space-charge-induced microbunching instabilities while the low transverse emittances significantly reduce the FEL gain length [39].

THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER)

The UMER accelerator deserves special mention because it cuts across so many of the areas of interest to this working group. As a beam source, UMER is unique; it is a storage ring a few meters across, intended to operate at 10-kV beam energies and up to 100-mA beam current.

The beam parameters of UMER can be scaled to match, in equivalent effect, those of an ion beam at GeV energies and kA beam currents. This allows the study of severely space-charge-dominated beams in a small facility with minimal requirements for magnet size and power supply, radiation shielding, etc.

Due to the low beam energy and high space charge, UMER presents unique challenges to beam injection [40] and steering [41]. With 36 dipoles, UMER has a “complexity,” in terms of sector and bends count, commensurate with large-scale storage ring facilities. As an additional complication, the Earth’s magnetic field plays a significant role in determining the trajectory of the beam in the ring, and requires the use of best-approximation methods of adjusting beam steering. The injection procedure must be tuned not only for efficient injection of beam into UMER but also to permit closed-orbit transport around the ring once injection has been performed. Likewise, the steering must meet the requirements for first-turn (injection) as well as stored-beam steering.

In addition to the role UMER has in studying space-charge-dominated beam dynamics, it also provides an interesting window into the operation and optimization of complex accelerators, such as light sources, in a compact package. As such, it is not only an interesting source and a useful research tool, it is also an excellent resource for accelerator physics education.

REFERENCES

1. O. J. Luiten et al., Phys. Rev. Lett. **93**, 094802 (2004).
2. B.J. Claessens et al., Phys. Rev. Lett. 95, 164801 (2005); L Serafini, AIP Conf. Proc. **413**, p. 321 (1997).
2. J. Rosenzweig, “Dynamics beam profile creation in photoinjector: first results from SPARC experiments,” this proceedings.
3. P. Musumeci, “Commissioning of the SPARC photoinjector”, this proceedings.
5. R. Tikhoplav, “Laser pulse shaping and emittance studies,” this proceedings.
6. B. O’Shea, “Design of a SW/TW photoinjector,” this proceedings.
7. J. Rosenzweig, “The Hybird TW/SW photoinjector,” this proceedings.
8. J. Smedley, “Electron Amplification in Diamond Progress Toward a Secondary Emission Enhanced Photo-injector,” these proceedings.
9. V. Shiltshev, “Electron beam generation and control in Tevatron electron lens,” this proceedings.
10. V. Shiltsev, Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, (IEEE, Piscataway, NJ, 2001), 154.
11. F. Sakamoto et al., “High power experiment on X-band thermionic cathode rf-gun for Compton scattering X-ray source,” this proceedings.
12. A. Sakumi et al., “Photoinjector for sub-picoseconds pump and probe experiments”, this proceedings.

13. I. Pogorelsky, V. Yakamenko, “Polarized γ-source based on Compton backscattering in a laser cavity,” this proceedings.
14. J. Fox, “Beam Feedback - Examples from Instability Control, and Ideas for the Future,” this proceedings.
15. D. Startakis, “Phase Space Mapping and Emittance Measurement of Intense Particle Beams using a Tomography Technique,” this proceedings.
16. C.B. McKnee, P.G. O’Shea and J. Madey, Nucl. Instrum. Methods **A 358**, 254 (1995).
17. M. Geitz et al., Proceedings of the 1999 Particle Accelerator Conference, New York, NY, (IEEE, Piscataway, NJ, 2001), p. 2175 (2001).
18. N. Barov, “High-Efficiency Resonant Cavity Quadrupole Moment Monitor,” this proceedings.
19. A. Lumpkin, this proceedings.
20. V. Scarpine, “Optical Transition Radiation (OTR) Detectors for Intense Proton and Antiproton Beams at FNAL,” this proceedings.
21. S. Banna et al., Nucl. Instrum. Methods **A 555**, 101 (2005).
22. W. Kimura, “Ultrafast Diagnostic Techniques Used in STELLA-LW Experiment,” this proceedings.
23. C. Sears et al., “Ultrafast/Optical Scale Diagnostics for E-163,” this proceedings.
24. M. Useka, “CTR Bunch Length Measurement of Monoenergetic and Maxwellian Electron Beams from Plasma Cathode,” this proceedings.
25. D. Mihalcea, “Measurements of Longitudinal Electron Bunch Shape with Coherent Transition Radiation,” this proceedings.
26. R. Marsh et al., “Coherent Transition and Smith-Purcell Radiation Experiments on the HRC MIT 17 GHz Linac,” this proceedings.
27. J. Haimson in *Advanced Accelerator Concepts: Eleventh Advanced Accelerator Concepts Workshop*, edited by Vitaly Yakimenko, AIP Conf. Proc. No. 737 (AIP, New York, 2004), 95.
28. J. Rosenzweig, “Bunch compression and coherent edge radiation experiment at the UCLA-ATF chicane,” this proceedings.
29. J. England, “Experiment to measure ramped electron bunches at the UCLA Neptune Laboratory using a transverse deflecting cavity,” this proceedings.
30. L. Schächter, Phys. Lett. **A 205**, 355 (1995).
31. A. Cavalleri, Phys. Rev. Lett. **94**, 114801 (2005).
32. Ya Derbenev, University of Michigan Report No. UM-HE-98-04 (1998).
33. R. Brinkmann, Ya. Derbenev, and K. Floettmann, Phys. Rev. ST Accel. Beams **4**, 053501 (2001).
34. A. Burov, S. Nagaitsev, and Ya Debenev, Phys. Rev. **E 66**, 016503 (2002).
35. K.-J. Kim, Phys. Rev. ST Accel. Beams **6**, 1042002 (2003).
36. Y.-E Sun et al., Phys. Rev. ST Accel. Beams **7**, 123501 (2004).
37. P. Piot, Y.-E Sun, and K.-J. Kim, Phys. Rev. ST Accel. Beams **9**, 031001 (2006).
38. M. Cornacchia and P. Emma, Phys. Rev. ST Accel. Beams **5**, 084001 (2002).
39. P. Emma et al., submitted to Phys. Rev. ST Accel. Beams, preprint FERMILAB-PUB-06-256-AD/SLAC PUB 1000-86 (2006).
40. J. Thangaraj, “Beam Injection and Matching in the University of Maryland Electron Ring (UMER),” this proceedings.
41. M. Walker, “Beam Control and Steering in the University of Maryland Electron Ring (UMER),” this proceedings.