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12 GeV CEBAF TRANSVERSE EMITTANCE EVOLUTION*

T. Satogata, Y, Roblin, M. Tiefenback, and D. Turner
Jefferson Lab, Newport News, VA 23606, USA

Abstract

We present commissioning results of measurements of beam phase space evolution of the newly commissioned 12 GeV CEBAF accelerator. These measurements range over two orders of magnitude in energy for a non-equilibrium beam, from near the photocathode to the diamond bremsstrahlung target for the GlueX experiment. We also compare these measurements to modeled beam evolution, and emittance growth expectations driven by synchrotron radiation.

INTRODUCTION

The Jefferson Lab CEBAF (Continuous Electron Beam Accelerator Facility) has been upgraded to double the peak beam energy from 6 GeV to 12 GeV [1]. The 12 GeV upgrade included the addition of 10 new "C100" cryomodules (each supplying 4x the gradient of original CEBAF cryomodules), a central helium liquefier upgrade, upgraded recirculation arcs, and the addition of a new 12 GeV experimental hall, Hall D. Beam [2] and RF [3] commissioning activities have been ongoing since 2013, including optics tuning and characterization of beam parameters for the new facility.

The upgrade parameters of relevance are shown in Table 1. Though the requirements of emittance and energy spread appear to loosen between 6 GeV and 12 GeV, the 12 GeV parameters are dominated by synchrotron-radiation (SR) driven emittance growth in higher energy recirculation arcs as discussed in the remainder of this paper.

Table 1: CEBAF 6 GeV to 12 GeV Parameters

	6 GeV Operations	12 GeV Design
Emittance at max energy (geometric rms): horiz, vert	(1, 1) nm-rad	(10, 2) nm-rad
Energy spread at max energy (rms)	$2.5\text{x}10^{-5}$	Halls A-C: $5\text{x}10^{-4}$ Hall D: $5\text{x}10^{-3}$

CEBAF 12 GEV OPTICS

Theory

For a relativistic electron beam traversing a 180-degree multi-cell bend of bend radius ρ, the rms geometric (unnormalized) emittance growth and energy spread due to SR are given by [4,5]:

$$\Delta\epsilon \approx 2 \times 10^{-27} \left(\frac{\gamma^5}{\rho[\mathrm{m}]^{\,2}}\right) \langle \mathcal{H} \rangle \qquad (1)$$

$$\sigma_{\mathrm{E}}^2 \approx 1.2 \times 10^{-33}\ \mathrm{GeV}^2 \left(\frac{\gamma^7}{\rho[m]^{\,2}}\right) \qquad (2)$$

where the traditional curly-H function is used.

The CEBAF tunnel geometry and dipole packing fraction preclude mitigation of SR-driven emittance and energy spread growth by increasing the bend radius. However, SR-driven emittance growth can be controlled in CEBAF by reducing curly-H in high-γ arcs, similar to standard practice in current-generation synchrotron light sources. This approach was taken in the original CEBAF design to meet 6 GeV program goals [6] but was more aggressively pursued in the 12 GeV era.

Other smaller sources of emittance growth in a recirculating linac such as CEBAF are transverse nonlinearities and coupling of longitudinal RF nonlinearity to transverse motion. Magnet measurements performed during the 12 GeV upgrade indicated that transverse nonlinear fields are acceptably small. Longitudinal nonlinearities are carefully managed with bunch compression in an injection chicane with tunable M_{56}, and monitoring of linac RF cresting.

CEBAF Optics Modifications

The recirculating linac design of CEBAF requires that each separate arc is matched to each linac through separate vertical beam spreader and recombiner sections. The spreader sections also include a dispersion-free matching straight to enable arc-by-arc transverse beam envelope matching using wire scanners and matching quadrupole scans. Matching performed in these regions, and in injector matching sections, provided emittances shown in later sections of this paper.

The arcs were originally configured as achromatic, isochronous, imaging, and FODO transport systems to minimize beam size while transporting beams transparently from spreaders to recombiners. For 12 GeV commissioning, the optics were modified to double-bend achromat (DBA) cells in arcs 6-10, providing a 30-40% reduction in curly-H and projected emittance growth. An example of DBA optics for the highest energy arc (arc 10) is shown in Figure 1.

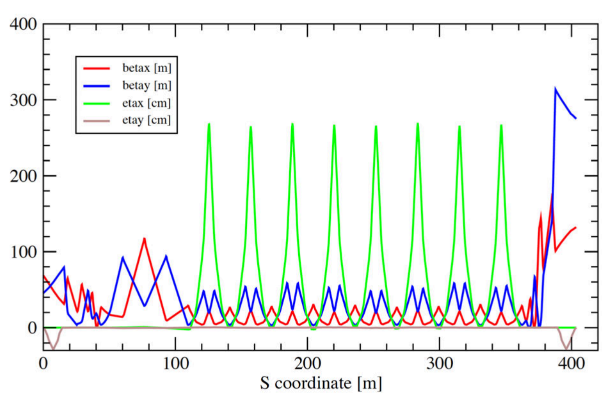

Figure 1: Arc 10 DBA optics for CEBAF SR-driven emittance growth reduction.

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The change to DBA optics also came with a cost. In particular, the four-fold periodic optics with 48 quadrupoles could not be adjusted to also preserve M_{56}=0, a previous aspect of CEBAF design arc optics. This complicated some higher-pass dispersion measurements and corrections during 12 GeV commissioning. Tradeoffs of DBA emittance reduction vs M_{56} and dispersion tuning are being evaluated for future 12 GeV runs.

Modeling Predictions

During 12 GeV design and commissioning, expected emittance growth and momentum spread were modeled at the injection chicane, for each arc, and for Hall D using elegant [7]. The results of this modeling are shown in Table 2. Note that the emittances shown here are geometric (unnormalized).

Table 2: CEBAF Momentum Spread and Geometric Emittance Growth from Elegant

Region	σ_p/p [x10^{-3}]	ε_x [nm-rad]	ε_y [nm-rad]
Chicane	0.50	4.00	4.00
Arc 1	0.050	0.41	0.41
Arc 2	0.030	0.26	0.23
Arc 3	0.035	0.22	0.21
Arc 4	0.044	0.21	0.24
Arc 5	0.060	0.33	0.25
Arc 6	0.090	0.58	0.31
Arc 7	0.104	0.79	0.44
Arc 8	0.133	1.21	0.57
Arc 9	0.167	2.09	0.64
Arc 10	0.194	2.97	0.95
Hall D	0.18	2.70	1.03

For 12 GeV operations, the injector/chicane beam energy is 123 MeV, and a linac pass before each arc and Hall D provides 1090 MeV energy gain. Arcs 1-5 are dominated by adiabatic damping, while Arcs 6-10 have DBA optics and are dominated by SR-driven emittance growth. There a 1090 MeV linac and vertical dogleg between Arc 10 and Hall D, providing small adiabatic damping in momentum spread and horizontal emittance, and some vertical emittance growth.

A comparison of Tables 1 and 2 shows that these design emittance predictions are a factor of 2-4 below 12 GeV requirements for Hall D operations, while momentum spread has considerably larger margin due to the expected tagger efficiency of the GlueX experiment in Hall D.

OPTICS MATCHING

Tools have been developed during 12 GeV commissioning to efficiently match CEBAF optics at each matching section before each arc as part of a broader effort to develop a model-driven machine configuration and optics improvement program [8,9]. These tools included improvements in measurements of Twiss parameters and emittances with single quadrupole scans and downstream wire scanner measurements. A single application, qsUtility, performed fast "zigzag" wire scans, calculated optics fits, propagated Twiss parameters upstream, and used elegant and a design optics database in CED [9] to calculate the new match. After design templates were established, each matching location could be transversely matched in under 1 hour.

Figure 2 shows scans of the MQA9S06 quadrupole and vertical beam size measurements to measure vertical beam size and Twiss parameters at the entry to Arc 9, before and after a single iteration of the matching procedure. Vertical emittances calculated from both measurements are consistent.

The calculated phase space at the entry to the MQA9S06 quadrupole for horizontal (Figure 3) and vertical (Figure 4) planes show the improvement of phase space matching with the improved matching procedure.

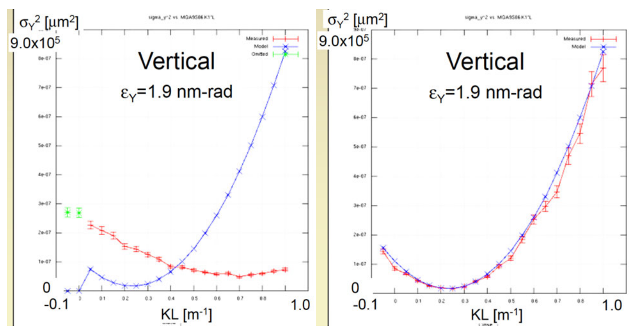

Figure 2: Vertical Arc 9 MQA9S06 quadrupole scan, before match (left) and after one match iteration (right). Blue points are model predictions; red points are measurements. Emittances displayed are calculated from a parabolic fit of the measured beam sizes.

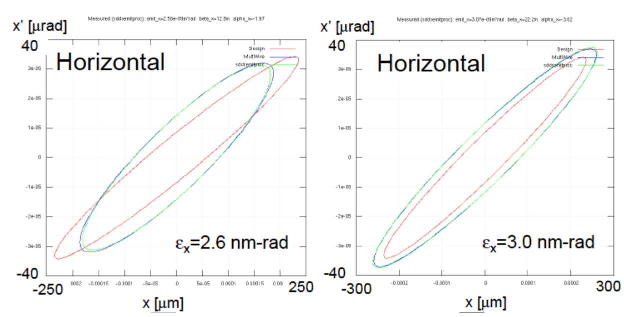

Figure 3: Horizontal Arc 9 spreader match phase space, before match (left) and after match (right). Blue/green are measurement, red is model, with measured horizontal emittance larger than model prediction.

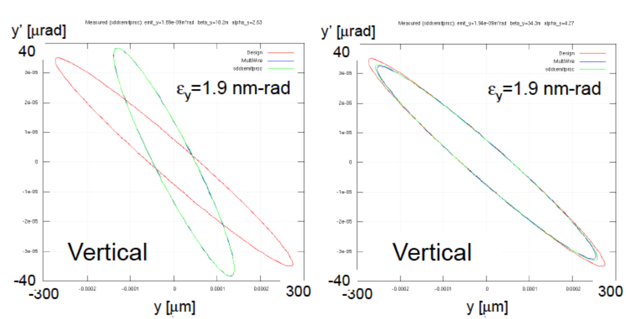

Figure 4: Vertical Arc 9 spreader match phase space, before match (left) and after match (right). Blue/green are measurement, red is model, with consistent emittance measurements.

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The optics tuning campaign provided reasonable emittance statistics over the course of the spring 2015 commissioning run at 11 GeV total machine energy. Similar measurements will be acquired in both dedicated and parasitic studies for the full 12 GeV CEBAF in fall 2015 and spring 2016 commissioning periods.

EMITTANCE MEASUREMENTS

Emittance measurements from the spring 2015 11 GeV run are tabulated in Table 3. A wire scanner was not available to install in the arc 7 matching section for this run, and the arc 5 wire scanner was in disrepair and could not be repaired during operations. All wire scanners will be returned to service for the fall 2015 12 GeV commissioning period.

Table 3: Model and Measured Emittances (11 GeV)

Region	Model $\varepsilon_x, \varepsilon_y$ [nm-rad]		Measured $\varepsilon_x, \varepsilon_y$ [nm-rad]	
Chicane	4.00	4.00	2.5±0.9	1.9±0.6
Arc 1	0.41	0.41	0.43±0.04	0.32±0.05
Arc 2	0.26	0.23	0.50±0.10	0.31±0.10
Arc 3	0.22	0.21	0.63±0.05	0.72±0.07
Arc 4	0.21	0.24	0.81±0.07	0.65±0.10
Arc 5	0.33	0.25	---	---
Arc 6	0.58	0.31	0.48±0.05	0.66±0.04
Arc 7	0.79	0.44	---	---
Arc 8	1.21	0.57	1.1±0.1	1.0±0.1
Arc 9	2.09	0.64	3.1±0.2	1.9±0.3
Arc 10	2.97	0.95	2.4±0.3	1.7±0.4

Table 3 shows that early machine emittances are lower than design, indicating that the CEBAF injector is well-tuned. High-energy measurements seemed to indicate a rounder beam than expected, with suspicion of sources of coupling in the spreaders and recombiners. The fall 2015 run will evaluate the full impact of SR on beam emittance, and faster emittance and matching measurements will permit systematic comparison of beams from different injector lasers destined for different experimental halls.

There are also several synchrotron light monitors installed in CEBAF that will be developed as parasitic beam quality and emittance monitors. Model-driven machine operations will also be improved with further optics measurements using LOCO [10] and RayTrace [11].

CSR SUPPRESSION EXPERIMENT

The flexibility of the arc optics, and the higher beam energy of the CEBAF 12 GeV complex, make it a natural test bed for SR and coherent synchrotron radiation (CSR) compensation lattices. The Jefferson Lab MEIC concent [12] also includes electron cooling from a high-power ERL that requires careful management of CSR and microbunching instabilities, motivating a strong Jefferson Lab interest in control and mitigation of CSR.

Yves Roblin is heading an LDRD project to evaluate feasibility of testing recent ideas of diMitri, Cornacchia, Borland, and Douglas [13] for CSR-compensation lattice designs with installation of a high-current (50-100 pC, 350 kV) gun in CEBAF. This would emable tests of extremes of SR- and CSR-driven emittance growth and energy spread [14].

CONCLUSIONS

The 12 GeV CEBAF accelerator has non-equilibrium beam emittances that are dominated by adiabatic damping at low energy to SR-driven growth at high energy. The SR-driven emittance growth is mitigated with new DBA optics in higher-pass recirculation arcs. Transverse matching and emittance measurement methods were improved to be routine during the spring 2015 11 GeV commissioning period, providing data for an emittance survey that shows existing emittances are near design, with some likely sources of coupling. 12 GeV measurements will be performed in fall 2015. Future experiments are also planned to use CEBAF optics flexibility to investigate CSR suppression lattice designs.

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