ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB077

RESULTS FROM THE CBETA FRACTIONAL ARC TEST

C. Gulliford, N. Banerjee, A. Bartnik, J. Crittenden, P. Quigley
Cornell University, Ithaca, NY, USA
J. S. Berg,
BNL, Upton, Long Island, New York, USA,

Abstract

This work reports on results of experiments performed during the CBETA Fractional Arc Test (FAT) [1]. These include the recommissioning of the Cornell photoinjector, the first full energy operation of the main linac with beam, as well as commissioning of the lowest energy matching beamline (splitter) and a partial section of the Fixed Field Alternating gradient (FFA) return loop featuring first production Halbach style permanent magnets. Achieving these tasks required characterization of the injection beam, calibration and phasing of the main linac cavities, demonstration of the required 36 MeV energy gain, and measurement of the splitter line horizontal dispersion and R_{56} at the nominal 42 MeV. In addition, a procedure for measuring the tune per cell in the periodic FFA section via scanning the linac energy and inducing betatron oscillations around the periodic orbit in the fractional arc was developed and tested.

INTRODUCTION

The Cornell-BNL Energy recovery linac Test Accelerator (CBETA) [2], a 4-pass, 150 MeV ERL utilizing a Non-scaling Fixed Field Alternating-gradient (NS-FFA) permanent magnet return loop [3,4], is currently under design and construction at Cornell University through the joint collaboration of Brookhaven National Lab (BNL) and the Cornell Laboratory for Accelerator based Sciences and Education (CLASSE). The spring of 2018 saw the first major commissioning period for CBETA. Known as the Fractional Arc Test (FAT), this experiment bought together for the first time elements of all of the critical subsystems required for the CBETA project: the injector [5, 6], the Main Linac Cryomodule (MLC) [7, 8], the low energy (S1) splitter line which includes several new electromagnets, a path length adjustment mechanism, and a new BPM system, as well as a first prototype production permanent magnet girder featuring 4 cells of the FFA return loop with its own corresponding vacuum system and BPM design [9].

MEASUREMENTS

Figure 1 highlights the portions of the CBETA machine installed and used during the FAT. The first goal of the fractional arc test was tune up of the injector for a 6 pC commissioning bunch charge. We note that while the design Twiss values are specified at the end of the main linac, their only direct measurement is located in the EMS in the diagnostic line, which is equivalent to a measurement at the entrance to the first main linac cavity. Figure 2 and 3 display the measured beam sizes and emittances in the injector compared to the corresponding beam sizes and emittances computed using GPT.

After setting up the injector, the beam was then passed through the main linac, where the cavities required calibration. This was accomplished by measuring the time of flight of the beam after passes through a single cavity (all other voltages zeroed). The change in phase at a BPM downstream BPM takes the form:

$$\Delta\phi = \frac{\omega}{c}\int_{\text{cav}}^{\text{bpm}} dz\left(\frac{1}{\beta(V_c,\phi_b)} - \frac{1}{\beta(V_c,\phi_b=0)}\right), \quad (1)$$

Inversion of Eq. (1) in the least squares sense provides a simple way of determining the cavity energy gain calibration V_c, as well as the initial beam energy entering the cavity E_0 (if not known) from the measured BPM phase change $\Delta\phi$ for each cavity. Scanning the cavity phase ϕ_b (the on-crest phase is found by including it as another fit parameter) provides significant measured BPM phase change $\Delta\phi$, particularly when decelerating the beam. Using this method, each main linac cavity was calibrated by first setting the voltage to a fixed value of roughly 2-4 MeV, and then slowly changing the cavity phase from 0-360°. An example set of data for the first main linac cavity is shown in Fig. 4. In the figure, the trend for the best fit energy calibration is shown, along with energy gains 5% higher and lower, to give a sense of the measurement sensitivity. From the random error in the BPM phases, we estimate an error of approximately 0.4% for the final cavity calibrations. Assuming this represents the most significant source of error, this implies an overall error in the total main linac energy gain of roughly $\sqrt{6}\cdot 0.4\% \approx 1\%$ for any given machine setting.

After setting up the injector and main linac correctly, detailed measurements of the single particle dynamics through the rest of the experimental set-up were performed. The first of these was Measurement of the orbit response matrix provides as this provides a basic verification of various magnet

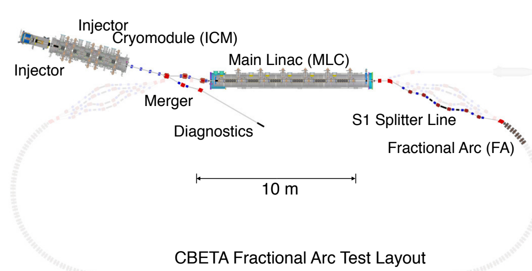

Figure 1: Schematic of the CBETA machine highlighting the components installed for Fractional Arc Test.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB077

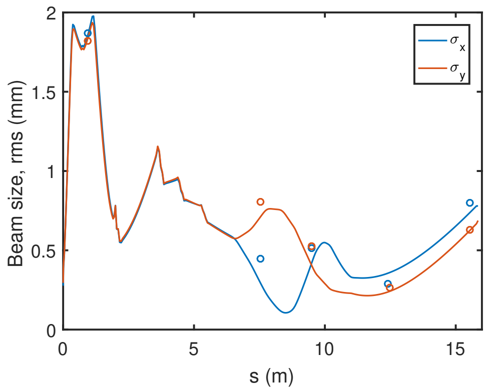

Figure 2: Comparison of measured horizontal/vertical beam size (blue/orange) to GPT beam sizes in the injector and diagnostic line.

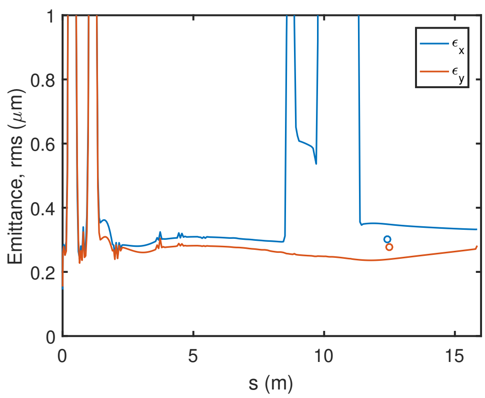

Figure 3: Comparison of measured horizontal/vertical normalized emittance (blue/orange) to GPT emittances in the injector and diagnostic line.

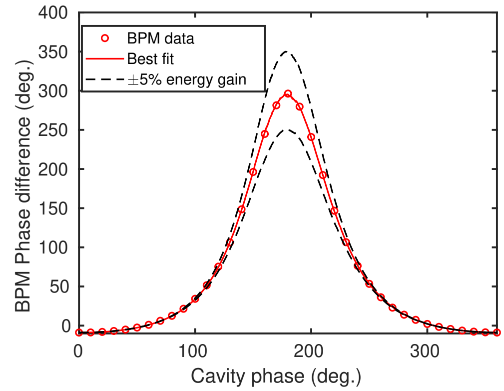

Figure 4: Change of the arrival time of the beam (shown as a phase change with respect to the RF clock) as a function of main linac cavity 6 phase set-point at a constant cavity gradient. Measured points are shown compared to the best fit model, and models that have ±5% energy gain.

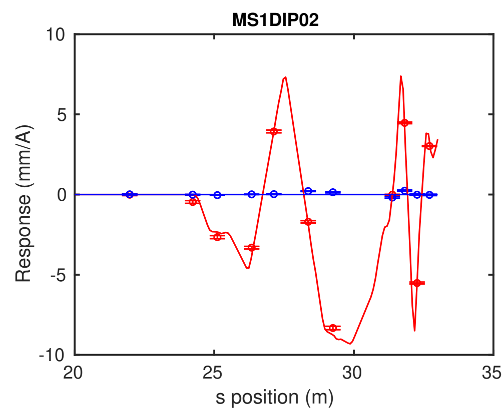

Figure 5: Example comparison of the measured horizontal orbit response from one of S1 dipoles to the simulated response (red line).

strength calibrations, and allows for comparison with the online simulation model. Additionally, use of the response matrix features prominently in various feedback routines such orbit correction. The procedure for measuring the orbit response on each BPM begins by scanning the corrector and dipole currents over a broad range (the full range in the case of correctors), and recording the beam position and intensity on all downstream BPMs. For each BPM, the data was truncated to include only those points within a small region around the BPM center, to best avoid BPM nonlinearity, and with intensity above a user defined BPM specific thresholds, to avoid cases of lost or partially scraped beam. The slope of each line yields the corresponding orbit response in [mm/A]. Figure 5 shows an exmample response function measurment, along with the prediction from the CBETA online model.

In addition to measuring the orbit response to dipole magnets, the dispersion through the splitter line and the R_{56} enter the fractional arc were also measured. This was accomplished by scanning the last main linac cavity voltage. Figs. 6 and 7 show the resulting measured dispersion as well as comparison to the CBETA online model. To get this level of agreement required adjusting the quadrupole settings in the model by a few percent.

The last day of beam running during the FAT saw data taken in the fractional arc as a function of energy by scanning the energy gain from main linac. In order to determine the phase advance per cell in the frational arc, the beam was kicked using two linear combinations of the last two S1 splitter dipoles and the last two vertical correctors energies ranging from 38 MeV to 59 MeV. These linear combinations were chosen to correspond to a betatron oscillation with a maximum amplitude at the FFA BPMs of 1 mm. The two linear combinations were chosen to give betatron oscillations that were 90° apart in betatron phase. For each setting, the beam position on the four FFA BPMs were recorded. This procedure was automated and tested with the online CBETA Virtual Machine [10] before use. In Fig. 8 the dashed lines show the corresponding prediction for the tunes, determined by tracking particles through 3D fieldmaps of the FA magnets and solving for the closed orbit, and displays good quantitative agreement. The agreement between the experimental

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB077

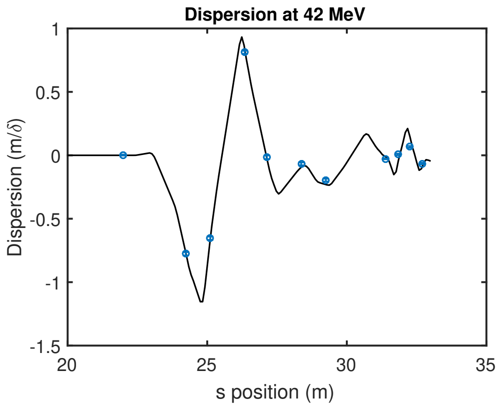

Figure 6: Comparison of the measured dispersion (points) to the online model (line) through the S1 splitter line and fractional arc.

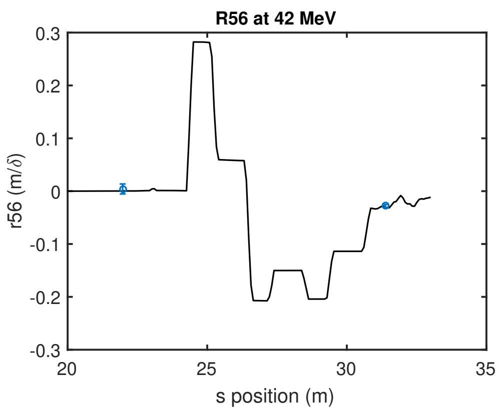

Figure 7: Comparison of the measured R_{56} (points) to the online model (line) through the S1 splitter line and fractional arc.

results and simulation data is quite good. A close inspection of the simulation and measured curves indicates even better agreement is possible if one allows for a systematic scaling of all the measured energy values by 1.02, indicating there may be an overall systematic discrepancy between the simulated quadrupole fields and/or the energy, and the measured data.

CONCLUSION

The CBETA fractional arc test provided invaluable experience testing and commissioning many of the most critical CBETA subsystems. Full beam commissioning of the main linac yielded beam energies up to roughly 60 MeV, nearly a factor of 1.6 times the 36 MeV necessary for the CBETA design. Reaching these energies required development of many important measurement procedures including a method for cavity energy gain calibration using BPM time of arrival. Similarly, commissioning of the low energy splitter line saw development of procedures for testing non-linearity correction of the splitter BPMs and the first successful test of the path length adjustment mechanism. Additionally, we successfully transported the beam through the main linac and splitter, and ultimately injecting the beam onto the periodic orbit in the fractional arc. We succeeded in measuring the phase advance per cell and the periodic orbit location in that arc over a broad energy range. The results in Fig. 8 represent a significant milestone for the CBETA project. Many of the measurement techniques developed in this work will be used for commissioning the full return loop. The FAT also proved extremely helpful in developing the CBETA Virtual Machine online modeling software. The simulation results here demonstrate its usefulness as a tool for not only displaying useful physics data to operators in real time, but also for debugging and testing measurement procedures before putting them to use in the real machine.

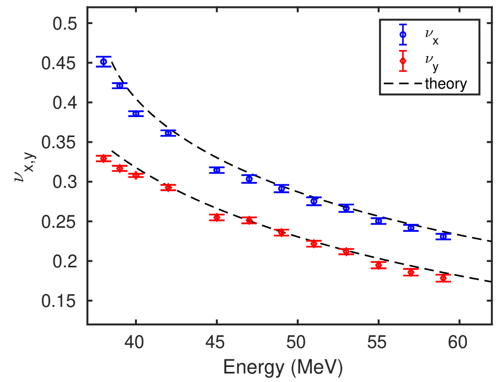

Figure 8: Comparison of the horizontal/vertical (blue/red) phase advance per cell in the fractional arc to the simulated values from tracking through 3D field maps.

ACKNOWLEDGEMENTS

This work was funded by NYSERDA, the New York State Energy Research and Development Agency. This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.

REFERENCES

[1] C. Gulliford *et al*, “Beam Commissioning Results from the CBETA Fractional Arc Test", https://arxiv.org/abs/1902.03370.

[2] G. Hoffstaetter *et al*, *CBETA Design Report, Cornell-BNL ERL Test Accelerator*, arXiv:1706.04245[physics.acc-ph]

[3] K. R. Symon, D. W. Kerst, L. W. Jones, L. J. Laslett, and K. M. Terwilliger, “Fixed-Field Alternating-Gradient particle accelerators", Phys. Rev. **103**, 1837 (1956).

[4] K. Halbach, “Design of permanent multipole magnets with oriented rare earth cobalt material", Nuclear Instruments and Methods **169**, 1 (1980).

[5] B. Dunham, *et al*, “Record high-average current from a high-brightness photoinjector", Applied Physics Letters **102**, 034105 (2013).

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB077

[6] C. Gulliford *et al*, “Demonstration of low emittance in the Cornell energy recovery linac injector prototype", Phys. Rev. ST Accel. Beams **16**, 073401 (2013)

[7] R. Eichhorn *et al*, “The Cornell Main Linac Cryomodule: A Full Scale, High Q Accelerator Module for cw Application", Physics Procedia **67**, 785-790 (2015).

[8] F. Furuta *et al*, “Performance of the Cornell Main Linac Prototype Cryomodule for the CBETA Project", *Proc. of the North American Particle Accelerator Conference*, October 2016, Chicago, IL, USA, paper MOPOB60 pp. 204-207.

[9] S. Brooks and S. Peggs and D. Trbojevic and J. Tuozzolo, *Technical Milestone 2: Assemble Prototype Girder*, BNL Technical Report, (2017).

[10] C. Gulliford, A. Bartnik, J. Dobbins, D. Sagan, J. Berg, and A. Nunez-delPrado, “Experience with CBETA Online Modeling Tools", in *Proceedings of the 13th International Computational Accelerator Physics Conference*, October 2018, Key West, FL, paper TUPAF10 E pp. 196-201.