Generation, Transport & Diagnostics of High-Charge magnetized Beams (MagBeam)

PERSONNEL

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  - Aaron Fetterman, Northern Illinois University (graduate student, beam dynamics, data acquisition and analysis)
  - Joseph Gubeli, Thomas Jefferson National Laboratory (diagnostics)
  - Christopher Marshall, Northern Illinois University (graduate student, beam diagnostics will be more involved in run III)
  - Philippe Piot, FermiLab Northern Illinois University (operation, data acquisition, analysis)
  - Jinhao Ruan, Fermilab (laser setup, operation, data acquisition)

PURPOSE AND METHODS

Background information

This project explores the formation, acceleration, and manipulations of electron beams with significant canonical angular momentum (CAM) often referred to as CAM-dominated or "magnetized" beams. Such beams are foreseen to be used as "cooling" beams in high-energy electron-cooling schemes for future electron-ion colliders.

Scientific or technical motivation and purpose

In its present phase (FY19-20), the project focuses on the formation of high-charge magnetized beams with parameters consistent with requirements associated with the JLEIC project at Jefferson Lab. The project also investigates the transport (manipulation in focusing system, acceleration), halo formation, and possible beam-degradation in a new straight-merger concept. This research is performed collaboratively between Fermilab, Jefferson Lab, and Northern Illinois University (NIU).

The project also leverages on past research (FY17-18) on flat beam generation at the FAST-IOTA injector and earlier at the A0 photoinjector. The original project objectives (as listed in our proposal to DOE) are:

1. The generation and characterization of a 3.2-nC magnetized electron bunch

2. The transport and halo formation in magnetized beams
3. The investigation of a straight merger concept

Objective (1) was partially accomplished during Run I [1] and the current run II proposal aims at taking all the data associated with objective (1) and working on objective (2). During run III we expect to produce all the deliverables associated with objective (2). **We presently do not believe FAST will be able to support objective (3) and are coordinating with our DOE program manager to relocate this task to an alternative facility.**

Experimental methods

Expected results and sources of uncertainty

The expected outcome is to produce and characterize a high-charge bunches ($Q = 3.2$ and 1.6 nC) with drift and cyclotron emittances consistent with the JLEIC project. The data acquire during run I and II will also be included in Mr. Fetterman's and Mr. Christopher Marshall's MS thesis (both will defend in the late Summer 2020) and the work they have done so far was presented at the NAPAC19 conference; see Ref. [1, 2].

Five shifts were allocated to this experiment during run I, the experiment obtained some preliminary results on magnetization but the quality of the data was limited by (i) the non-homogeneous laser transverse distribution, (ii) the poor calibrations of the ICT (some ICTs downstream of the injector were measuring higher charge that ICT2), (iii) the lack of reproducibility in the single slit-scan [we could not scan the slit in a reproducible way and had to rely on multislit technique for emittance measurement (which has a very limited dynamical range)], and (iv) poor focusing of CCD at X109.

It is our understanding that all these limitations were addressed during the summer shutdown. Therefore we believe this experiment has a high-chance to produce the required high-quality data.

BEAM CONDITIONS

The table below summarizes the range of operating parameters for the FAST injector. In the first series of shifts (dedicated to reproducing the condition of Run I) the beam will be run up to X124 (low-energy absorber). In the second set of shift (transport of magnetized beam), the beam will be run through the cryomodule (with cryomodule turned off) and diagnose at a downstream YAG screen.

It is worthwhile to note two "special" settings compared to the nominal injector setting:

- The bucking and main solenoids will be operated such to produce a variable magnetic field on the cathode surface. When tuning the solenoids one should keep the field on cathode constant around 0.05 T. The field on the cathode [in Gauss] is given by

$$B_c(I_b, I_m) = -4.1114 I_b + 0.9768 I_m, \quad (1)$$

  where I_b and I_m are the currents (in Ampère) associated with the bucking and main solenoids. A PYTHON knob is available to automatically adjust I_b while varying I_m so to provide a programmed B_c.

TABLE I. Nominal accelerator settings for magnetized-beam generation consistent with JLEIC requirements. All phases are referenced to the maximum-energy-gain phases.

parameter	symbol	value nominal	value range	unit
laser rms duration	σ_t	~ 3	NA	ps
laser rms spot size	σ_c	1.15	[0.8, 1.5]	mm
bunch charge	Q	3.2	≤ 3.2	nC
magnetic field on cathode	B_c	0.0468	[0, 0.7]	T
bucking solenoid current	I_b	191.8	tbd	A
main solenoid current	I_m	321.5	tbd	A
laser/gun launch phase	φ_g	0	–	deg
E field on cathode	E_g	40	–	MV/m
SRF cavity 1 phase	φ_1	0	± 15	deg
SRF cavity 1 peak E field	E_1	28	≤ 28	MV/m
SRF cavity 2 phase	φ_2	0	± 15	deg
SRF cavity 2 peak E field	E_2	28	≤ 28	MV/m

- The CC1 field will be reduced to avoid over-focusing and ensure full transmission/transport of the magnetized beam (the beam has a larger effective emittance and is more difficult to transport compared to the nominal non-magnetised beam)

APPARATUS

This experiment will extensively use the beam-profile monitor's image from various CCD and beam position monitors. The data acquisition is done directly from the CLX cluster and a preliminary analysis is performed online. Data are eventually transferred to another cluster for detailed analysis. For the flat-beam generation, we will use an online optimization tool.

RUN PLAN

During run II we do not require any hardware to be installed and will use diagnostics nominally available in the FAST photoinjector. We expect the run to be spit in two phases each with a set of dedicated shifts organized as follows

Phase I: magnetized beam generation & characterization

The first phase of our studies in run II will essentially attempt to reproduce the conditions of run I and take a better set of data (with improved beam diagnostics and photocathode laser). This part of the run will use FAST in the "injector mode" (directing the beam to the LE absorber). We plan on using a nominal charge per bunch of $Q = 1.6$ and 3.2 nC with a cathode radius $r_c \simeq 2.3$ mm. The expected shift plan is:

- Shift 1 (8 hrs): propagate magnetized beam with nominal magnetization $\mathscr{L} \simeq 19$ μm up to the end of the injector

1. Verify the 1.6 nC and 3.2-nC beam is fully transmitted (check ICT do work properly).
2. Calibrate the CCD cameras and slits with a non-magnetized beam with $B_{z,cathode} = 0$
3. Measure magnetization using single-slit scan (to infer the correlated and uncorrelated emittances) using slits X106 and X118.
4. Measure beam size evolution along with the injector for various settings of solenoids (while maintaining require B_c field on the cathode).
5. Measure energy spread
6. Record emittance and beam size data for different laser-radius on the cathode (repeating steps 1-4 above)

- Shifts 2-4 within the same week (3×8 hrs): Direct measurement of beam eigen emittances via mapping into flat beams

1. Reestablish beam with same conditions/settings as during Shift 1
2. Measure magnetization using a single-slit scan using slits X106 and infer beam parameters upstream of Q106.
3. Set the skew quadrupole triplet (Q106, Q107, Q111) to produce a flat beam at X111 and X118
4. Measure beam emittance using scanning slit at X118
5. Repeat steps 1-3 for different solenoid currents (while maintaining require B_c field on the cathode).

Phase II: magnetized beam transport & characterization

- Shift 5-6 (2×8 hrs): Magnetized beam propagation to X505

1. Reestablish beam with same conditions/settings as during Shift 3
2. Measure magnetization using a single-slit scan using slits X106 and infer beam parameters upstream of Q106.
3. Transport the beam up to X505 with cryomodule on. Progressively lower cryomodule field and tune quadrupoles to fully transport beam up to X505
4. Use Quadrupole magnets Q441, Q442 and Q443 to generate a flat beam downstream of the ccryomodule and measure emittance using quadrupole scan. Ultimately this measurement will be performed in run III with a scanning slit as part of the JLab halo diagnostics.

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[1] A. Fetterman, et al., "Generation of High-Charge Magnetized Electron Beams Consistent With JLEIC Electron Cooling Requirements," in proceeding of NAPAC19, paper TUPLM20 (2019).

[2] C. Marshall, et al., "Design and Analysis of a Halo-Measurement Diagnostics," in proceeding of NAPAC19, paper TUYBB5 (2019).