FERMILAB-FN-XXXX-AD-APC

Design notes for an electron-lens test stand at CERN

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(Dated: June 24, 2016— DRAFT)

Abstract.

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CONTENTS

I. INTRODUCTION

Current research on electron lenses includes hollow electron beam collimation and long-range beam-beam compensation in LHC at CERN, nonlinear lattice experiments at the Fermilab Integrable Optics Test Accelerator (IOTA), tune-spread generation in the Fermilab Recycler Ring, and space-charge compensation in IOTA and at GSI (European ARIES project).

An electron-lens test stand has been considered at CERN with the following research objectives:

- demonstrate magnetized electron beams with currents up to 20 A;
- develop new cathodes in the shape of coaxial circular rings, interleaved with ring electrodes, in order to control the shape and modulation pattern of the electron beam by polarizing with relatively low voltages the corresponding ring electrodes;
- modulate the electron beam with frequencies up to 10 MHz;
- develop new instrumentation and diagnostics, such as an overlap monitor based on gas fluorescence, for imaging and discrimination between protons and electrons.
- explore the possibility of generating elliptical hollow beams for scraping in regions where the amplitude functions are not equal.

In this note, we address the preliminary design questions for such a test stand:

- What are the constraints on the cathode size?
- What is the required electron beam energy?
- What magnetic field is necessary for confinement and stability? Are resistive magnets sufficient?
- Should electron injection from the gun to the overlap region include bends, or can the test stand have a straight layout?

II. CATHODE SIZE

The cathode radius depends on mechanical constraints, on the details of the ring design, and on the achievable current density. For standard thermionic dispenser cathodes based on barium oxide, one can assume a current density of 4 A/cm^2 is achievable. The maximum current density j_0 on the axis of a

Gaussian beam with rms σ is $j_0 = I/(2\pi\sigma^2)$. For the ring cathode, we assume that the fraction of active area is $f = 0.5$. Therefore, the rms beam size at the cathode must be at least $\sigma > \sqrt{I/(2\pi j_0)/f} = 13$ mm. If the radius of the cathode has to cover 2.5σ, it has to be at least 31.5 mm. Here we choose a cathode radius of 32 mm. Although this implies a bulky electron gun design, the size of the vacuum chamber is still reasonable. In addition, the option of employing cathodes with higher current densities (scandium-based, for instance) is worth exploring.

For the European ARIES project (space-charge compensation), Gaussian electron beams with transverse standard deviation σ of 3–10 mm in the overlap region are needed. The magnetic compression (or expansion) factor $k \equiv \sigma_{\mathrm{gun}}/\sigma_{\mathrm{overlap}} = \sqrt{B_m/B_g}$, generated by the ratio of gun and main solenoids B_g and B_m, lies in the following range: $1.3 \leq k \leq 4.2$, or $1.6 \leq B_m/B_g \leq 18$. The minimum confining magnetic field is discussed in Section IV. This range of field ratios is generally reasonable, although only part of the required beam size range can be explored if only resistive solenoids are available.

III. KINETIC ENERGY OF THE ELECTRON BEAM

There are several factors affecting the required energy of the electron beam.

First of all, if the electron gun is operating in the space-charge-limited regime, the cathode-anode voltage V must be sufficient to extract the desired current I: $V > (I/P)^{2/3}$, where the perveance P depends on the geometry of the cathode, anode, and electrodes. Perveances up to 5 μperv have been achieved in electron lenses with convex cathodes. This translates into a voltage requirement $V > 25.2$ kV. It is desirable to design the electron gun with the highest possible perveance, therefore reducing as much as possible the average cathode-anode distance. In the case of convex cathodes, path length differences among electron trajectories are introduced, and one should verify with numerical simulations that the longitudinal structure of the electron beam is acceptable.

For long-range beam-beam compensation in LHC, the electron velocity β_e affects the current requirement. The required compensation strength is proportional to the number of circulating protons per bunch and to the number of long-range encounters. For HL-LHC, the maximum required strength is about $\mathscr{K}_{\mathrm{LR}} = 190$ A $\cdot$ m. (The effective strength is somewhat smaller, as present compensation scenarios are needed only in the middle of the physics fill.) Because both electric and magnetic fields play a role when using an ‘electron wire’ for compensation, the required electron-lens strength is reduced by a velocity-dependent factor: $\mathscr{K}_{\mathrm{elens}} = \mathscr{K}_{\mathrm{LR}} \cdot \beta_e/(1+\beta_e)$. For instance, $\mathscr{K}_{\mathrm{elens}} = 31.7$ A $\cdot$ m for $\beta_e = 0.2$, or $I = 10.6$ A for an overlap region $L_e = 3$ m. With these parameters, if we require that the electron lens current I be less than 20 A, we obtain $\beta_e \leq 1/[\mathscr{K}_{\mathrm{LR}}/(I \cdot L_e) - 1] = 0.462$, or $V \leq 65$ kV.

Of course, the maximum energy of the electron beam is also limited by the peak power $V \cdot I$ and average power $V \cdot I \cdot d$ (where d is the duty factor determined by the pulsing pattern) that can be dissipated in the collector. A depressed collector for energy recovery is probably mandatory, which also require a careful minimization of beam losses.

The power P_R dissipated in the output resistor of the modulator is also a factor, and it can be mitigated by modulating the extraction electrodes with a bias that is a few percent of the full cathode-anode voltage. For each pulse, the gun and cable capacitance C is charged and discharged, and the dissipated power in the resistor is equal to twice the stored energy times the modulation frequency f_{mod}: $P_R = C \cdot V_{\mathrm{mod}}^2 \cdot f_{\mathrm{mod}}$. For instance, for $V_{\mathrm{mod}} = 1$ kV and $f_{\mathrm{mod}} = 10$ MHz, one obtains $V_{\mathrm{mod}}^2 \cdot f_{\mathrm{mod}} = 10$ W/pF. Typical gun capacitances are about 50 pF, and cables capacitances are approximately 100 pF/m. It is critical to minimize gun capacitance, to set up the modulator as close as possible to the gun, and to keep the bias voltage low.

Because it takes a finite time for the electrons and protons to propagate in the electron lens, the electrons must have a minimum velocity in order to fill the overlap region with a different value of the current within the time interval between circulating bunches. For bunch spacing τ_s and full bunch length τ_b, one must have $\beta_e \geq (L_e/c)/(\tau_s - \tau_b)$ for the case of co-propagating electrons and protons. In the counter-propagating case, the condition is more stringent: $\beta_e \geq (L_e/c)/(\tau_s - \tau_b - L_e/\beta_p/c)$. Under certain circumstances, these conditions may be impossible to satisfy, and trailing bunches only experience a partial change of the electron-lens intensity. For the LHC, $\tau_s = 25$ ns, $\tau_b = 1.5$ ns ($6 \times$ rms), and $L_e/c = 10$ ns ($L_e = 3$ m). This implies $\beta_e > 0.426$, or $V > 53.8$ kV in the co-propagating case (and $\beta_e > 0.742$, or $V > 251$ kV in the counter-propagating case). *Is the co-propagating case the only possibility in LHC for bunch-by-bunch modulation? What about the enhancement factor for LRBB?* This condition does not have to be strictly satisfied for a test stand, but it must be taken into account for long-range beam-beam compensation in LHC.

Because of the space-charge potential, electrons near the axis are slower than those at the edge of the beam. As the current increases, so does the potential depression, and at some point this effect limits the maximum current than can be transported through a beam pipe of radius b. For long, cylindrically symmetric beams with constant current density up to radius $a < b$, a self-consistent relativistic model can be developed. Under these conditions, the minimum relativistic factor γ_e necessary to propagate current I is $\gamma_e > \left[\{(I/I_0)\left[1 + 2\ln(b/a)\right]\}^{2/3} + 1\right]^{3/2}$, where $I_0 \equiv (4\pi\varepsilon_0) \cdot m_e c^3/e = 17$ kA is the characteristic electron current. Assuming $a = 4.24$ mm, $b = 40$ mm, for $I = 20$ A we obtain $\gamma_e > 1.0524$, or $V > 26.8$ kV. This limit needs to be verified with numerical simulations for the case of finite Gaussian beams.

In the case of beam compression, there is also a current limit arising from the longitudinal component of the self electric field. A simplified analytical model was developed, and it was verified with particle-in-cell simulations. *Add quantitative estimates.*

IV. SOLENOIDAL TRANSPORT AND CONFINEMENT

The axial solenoidal fields that are used to transport the electron beam must be strong enough for confinement (Larmor radius much smaller than the beam size) and to impede the space-charge evolution of the electron beam profile.

The Larmor radius is usually not an issue. For magnetic fields larger than 0.1 T, assuming a conservative transverse energy of 10 eV, the Larmor radius $r_L \equiv p_\perp/(eB)$ is smaller than 0.11 mm.

Because of the combined action of the radial electric self field $E(r)$ and of the axial solenoidal field B, the centers of gyration rotate around the beam axis ($E \times B$ drift) with azimuthal velocity $v_D = E(r)/B$. For uniform beams with radius a, the maximum electric field is $E_{\max} = n_e a/2\varepsilon_0$, where n_e is the charge density. The maximum drift velocity is $v_D^{\max} = n_e a/(2\varepsilon_0 B) \equiv \omega_D a$, which defines the diocotron angular frequency ω_D. To limit the space-charge evolution we require that the difference in rotation angle between particles on the axis (zero radial electric field) and those at the maximum field be less than one revolution: $\omega_D \cdot \tau < 2\pi$, where $\tau = L_e/v_e$ is the propagation time along the electron lens. In terms of the average axial magnetic field, this condition is equivalent to $B > n_e L_e/(\beta_e c)/(4\pi\varepsilon_0) = I L_e/(\pi a^2)/(\beta_e c)^2/(4\pi\varepsilon_0)$. For typical parameters under consideration, $I = 20$ A, $a = 4.24$ mm, $L_e = 3$ m, $\beta_e = 0.45$, we obtain $B > 0.524$ T.

These estimates should be checked with numerical simulations, as they are sensitive to the choice of beam size and velocity.

It seems possible to transport such an intense beam with resistive solenoids ($B \leq 1$ T). However, care must be taken in mitigating the sources of azimuthal asymmetries, as they will evolve under space charge. The range of achievable compression factors is also limited.

V. BEND EFFECTS

Describe two main effects: orbit displacement and profile distortion.

VI. CONCLUSIONS

Summarize cathode design considerations.

Summarize beam energy limits.

Summarize magnetic field requirements.

Bend implementation is recommended. A progressive approach starting with a straight setup, with a later addition of bends, is discouraged due to the cost of redesigning the vacuum system.