Initial Design of the EIC@JLab Interaction Region Beam Pipe

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I. Introduction

The EIC@JLab concept[1] has a detailed design of the detector-accelerator integration [2]. This note presents a concept for the central beam pipe, that can marry the physics goals with the mechanical and accelerator requirements.

II. Beam Pipe Design Criteria

Some of the criteria that are incorporated in this concept:

- Depending upon the ion velocity, the nominal Interaction Point (IP) will move up to ±7.5 cm along the electron beam. This is part of the solution to the synchronization problem.
- The nominal ion beam trajectory should never be closer than 2 cm to the beam pipe. This includes synchronization offsets.
- With the present upstream electron FFQ triplet, there should be a neck of radius 1.5 cm at $z = 1m$ on the upstream electron beam. This is a synchrotron radiation shield, as suggested by Mike Sullivan (SLAC) at the Oct 2015 MEIC Collaboration Meeting [3].
- All particles within the acceptance of the downstream ion FFQ triplet should be transported in vacuo from the IP to iFFQ3 exit. Particles also in the acceptance of the large downstream dipole (iD2) should be transported in vacuo to the exit of iD2.
- The -50 mrad crossing angle breaks the cylindrical symmetry of the detector and individual beam lines. To partially restore the symmetry, the beam pipe structure has a symmetry axis at -25 mrad in the full region where both beams are in the same structure. This spans the approximate region -1.5 m $< Z < 2.0$ m.
- The central vertex chamber is a cylinder, 3.2 cm in radius. This could be elliptical, with semi-major axis 3.2 cm in the horizontal plane and 2.5 cm semi-minor axis in the vertical direction. The PEP-II experience suggests that it is aggressive to make the semiminor axis less than 2.5 cm. Given the strength issues of an elliptical cross section, it is not clear that there really is advantage to an elliptical design.
- A particle that exits the beam pipe should not re-enter.

A. Ion Downstream Side

The beam pipe concept from the IP to the first downstream ion final-focus quadrupole (iFFQ1dn) and the upstream electron final-focus quadrupole (eFFQ1up) is detailed in Table I. The ion beampipe is circular. This accommodates the 6 mrad bend in the first Dipole even with a straight pipe.

TABLE I. Summary of Downstream (Ion-Side) Beam Pipe Design, from the IP to the first quadrupoles in either beamline. The detector coordinates XYZ are defined as follows: The Z-axis is along the solenoid axis, with the electron beam in the $-Z$ direction, and the nominal IP position at the origin. The nominal incident ion momentum $\mathbf{P}$ is in the XY-plane with $\mathbf{P} \cdot \hat{Z} > 0$ and $\mathbf{P} \cdot \hat{X} < 0$ Each element is rotated by angle Θ_y about the $+Y$-axis. Conical opening angles θ are the half-opening angle. Radii are the inner radii at the two ends of the element. If a single z coordinate is given, it is the offset of the center of the element; when two z-coordinates are given, they refer to the two ends of the element. In each case, the z-coordinate values are local, before rotation by angle Θ_y. Thickness is the radial thickness.

Item	Form	Material	Θ_y Rotation	θ Opening	Length	Radii	Offset z_0 or (z_1, z_2)	Thickness
			(rad)	(rad)	(m)	(mm)	(mm)	(mm)
Vertex Chamber	Cyl.	Be	-0.025	0	0.6723	32.2	0	1
Vertex Flare	Cone	Be	-0.025	0.0735	1.5817	(32.2, 148.7)	$(0.3362, 1.9179)$	$1 \to 2$
Vertex Taper	Cone	BeAl	-0.025	$-30°$	0.1266	$(148.7, 75.6)$	$(1.9179, 2.0445)$	2
Vertex Exit Window	Cyl.	Al	-0.025	0	0.0020	0	2.0445	75.6
$e^{\pm}$ Entrance Aperture	Cyl.	$\neg$Al	0.0	0	0.0020	0	2.0445	21.0
Synchrotron Rad. Shield	Cone	Cu	0	0.0107	1.700	$(15.0, 30.0)$	1.4000	2
Ion Exit Aperture	Cyl.	$\neg$Al	-0.050	0	0.0020	0	2.0445	25.2
Ion BeamPipe	Cone	Al	-0.050	0.0124	4.9306	$(24.2, 85.3)$	$(2.0445, 7.0)$	$1 \to 2$

B. Downstream Electron Side

The downstream electron side beam pipe concept is detailed in Table II. The flare of the central chamber has the same opening angle as on the ion side, but is only $\sim 60\%$ as long. These choices are somewhat arbitrary but are motivated by the following considerations:

- Necessary separation between the electron and ion beams
- This size flare subtends a convenient solid angle for a crystal EM calorimeter.

TABLE II. Summary of Upstream (Electron-Side) Beam Pipe Design, from the IP to the first quadrupoles in either beamline. The detector coordinates are the same as in Table I. The Vertex Chamber is included for completeness, it is redundant with Table I.

Item	Form	Material	Θ_y Rotation (rad)	θ Opening (rad)	Length (m)	Radii (mm)	Offset z_0 or (z_1, z_2) (mm)	Thickness (mm)
Vertex Chamber	Cylinder	Be	-0.025	0	0.6723	32.2	0	1
Vertex Flare	Cone	Be	-0.025	0.0735	0.9490	(32.2, 102.1)	$(-0.3362, -1.2852)$	$1 \rightarrow 2$
Vertex Taper	Cone	BeAl	-0.025	$-30°$	0.0798	$(102.1, 56.0)$	$(-1.2852, -1.3650)$	2
Vertex Exit Window	Cylinder	Al	-0.025	0	0.0020	0	-1.3650	56.0
$e^{\pm}$ Exit Aperture	Cylinder	¬Al	0.0	0	0.0020	0	-1.3650	21.0
Ion Entrance Aperture	Cylinder	¬Al	-0.050	0	0.0020	0	-1.3650	21.0
Ion BeamPipe	Cone	Al	-0.050	0.0124	4.9306	$(20.0, 30.0)$	$(-1.3650, -3.5948)$	$1 \rightarrow 2$

III. G4BeamLine

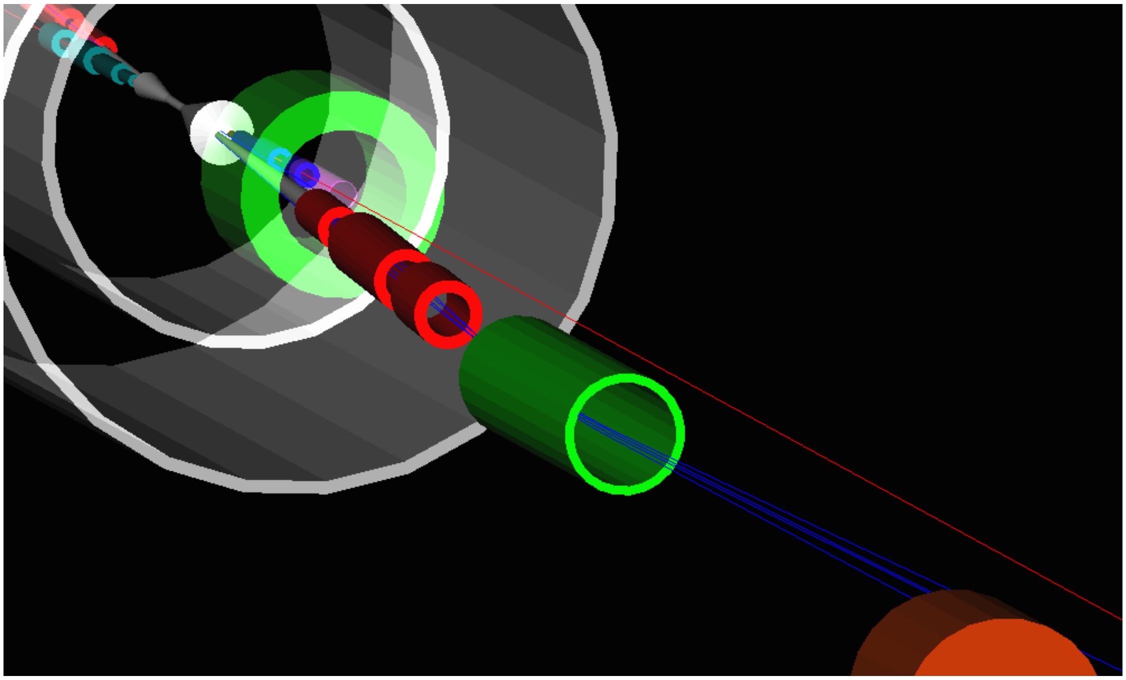

FIG. 1. Overview of the full interaction region beamline. Magnets in green are dipoles, the silver/grey outer cylinders are the coils of the dual solenoid. Magnets in red are ion beamline quadrupoles, magnets in blue (and blue/green) are the electron beamline quadrupoles. The violet cylinder is a flux exclusion tube for the electron beamline. The grey/silver 'rattle' shape is the IP vacuum pipe, with connections to the individual electron and ion beam pipes (shown only up to the first quadrupole of each beamline. The large rust/copper colored cylinder in the lower right is the ZDC (likely Cu, with scintillating and Cherenkov fibres).

I have implemented the proposed beam pipe in a `g4beamline` model of the Interaction Region optics, illustrated in Fig. 1. A zoomed-in view in wireframe visualization is shown in Fig. 2. There is an interference between the upstream ion beam pipe and the first two downstream electron quadrupoles. Likely a few mm of will need to be removed from the Fe yoke to allow a full 2 cm inner radius ion beampipe. The vacuum chamber alone, with the solenoid and first ion-downstream dipole removed is shown in Fig. 3.

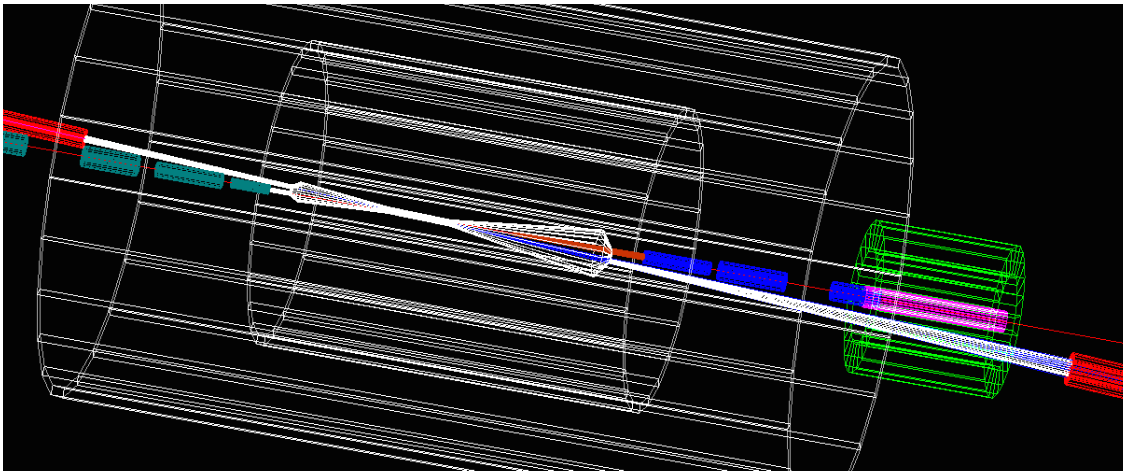

FIG. 2. Wire frame view of the Interaction Point. The central vertex chamber and its connection to the individual beampipes are clearly visible. There is a bundle of six proton trajectories (blue lines) in the downstream ion beampipe. The rust colored upstream electron beampipe is 2 mm thick Cu. This is a synchrotron radiation shield. It extends into the central beam pipe to a neck of 1.5 cm inner radius at $Z = +1.0$ m.

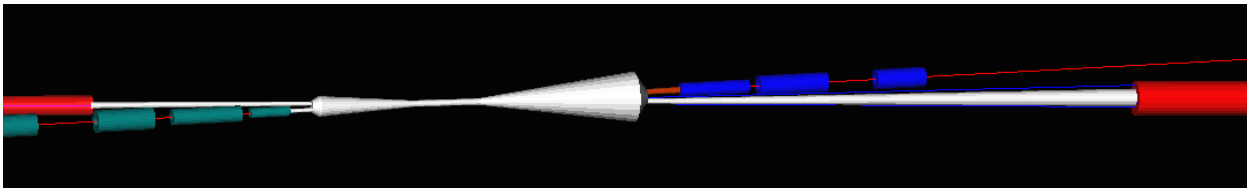

FIG. 3. G4BeamLine view of the Interaction Point vacuum chamber. The solenoid coils and the first dipole on the downstream ion beam line are removed for clarity. The central vertex chamber extends from $Z = -1.365$ m to $Z = 2.045$ m. As one integral unit, the vertex chamber plus beampipes spans 10.5 m from the upstream ion Final Focus Block to the downstream ion Final Focus Block.

A. Beam Pipe Materials, Mechanical Requirements, and Radiation Length

TABLE III. Young's Modulus E, Radiation Length X_0, Figure of Merit $X_0\sqrt[3]{E}$, and minimum wall thickness to radius ratio t/R for a circular vacuum pipe, for common materials used in accelerator beam pipes.

Material →		Be	CFC*	Al-Be	Al	Ti	Fe**	Air	RF mesh†
Parameter	Units								
E	GPa	290	200	193	70	110	210	—	
X_0	cm	35.3	27.1	25.3	8.9	3.6	1.8	$3.0 \cdot 10^4$	46.3
$X_0\,E^{1/3}$		2.34	1.58	1.46	0.37	0.17	0.11	—	
t/R	%	2.15	2.43	2.46	3.45	2.97	2.39	—	

* Carbon Fibre Composite

** Stainless Steel

†RADIOSCREEN$^{\mathrm{TM}}$, `www.lessEMF.com`: $X_0 = 23.13$ cm, Thickness 0.09 mm,
Areal density 0.0045 g/cm^2
By weight: 23.4% Cu; 10.9% Ni; 65.7% Polyester thread

1. Mechanical Requirements of the Beam Line Vacuum Pipe

The ion beam pipe is likely to be either circular, or conical with a small angular opening (of order of the 12 mrad acceptance of the FFQ optics). For a long cylindrical vacuum pipe, the required wall thickness t as a function of radius R (including ×2 safety margin) is ([4], Eq. 4):

$$\frac{t}{R} = 2\left[\frac{P_{\mathrm{atm}}(1-v^2)}{0.25E}\right]^{1/3}, \tag{A1}$$

where E is Young's Modulus of the material and v is Poisson's ratio of the transverse contraction strain to longitudinal stretch strain. The value of $1-v^2$ is generally close to 0.9 [4]. Values of E and t/R for common materials are listed in Table III. Over a broad range of materials, the required thickness to radius ratio is 2 to 3 %, including safety margin.

2. Multiple Scattering Figure of Merit

For a charged particle of momentum P, energy E, and charge ze exiting the vacuum at an angle α to the local plane of the pipe (of perpendicular thickness t), the rms multiple scattering angle is ([5], Chapter 32§3):

$$\theta_{m.s.} = z\frac{13.5\ \mathrm{MeV/c}}{p}\sqrt{\frac{t}{X_0\sin\alpha}}\left[1+0.038\ln\frac{z^2t}{X_0\sin\alpha}\right] \tag{A2}$$

where X_0 is the radiation length of the material. For different materials, the required thickness t scales as $E^{-1/3}$, as defined in Eq. A1. Neglecting the log term in the multiple scattering, the figure of merit (Table III) scales as:

$$\mathrm{F.O.M.} \propto X_0E^{1/3}. \tag{A3}$$

Table III illustrates the Be is the best material, almost a factor of two better than its nearest competitors, Carbon-Fibre-Composite (CFC) or Be-Al alloys. Use of a CFC beam pipe would require an inner coating of Al, or other conductive material. The RF skin depth of a conductor of magnetic permeability μ and resistivity ρ is (SI units):

$$\lambda = \sqrt{\frac{\rho}{\pi f \mu}}. \tag{A4}$$

The skin depth of Al at 100 MHz is $\sim 10\,\mu$m and at 1 GHz it is $< 3\,\mu$m. The light weight mesh listed in Table III has an RF attenuation rating of 50 dB from 20 MHz to 3 GHz.

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