Semi-Analytic Model of JLEIC Particle Identification Resolution

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I describe a parametric treatment of the resolution of hadronic particle ID for the Jefferson Lab Electron Ion Collider (JLEIC) full acceptance detector. The central region includes DIRC and TOF detectors. The ion-side endcap includes TOF and dual-radiator (aerogel and C_2F_6 gas) RICH detectors. The electron-side endcap includes TOF and modular aerogel detectors.

CONTENTS

I. Introduction 1
  A. Detector Coordinate System 2
  B. JLEIC PID Detectors 2
  C. PID Resolution, Purity, and Mis-Identification 2

II. Tracking 3
  A. Central Region 3
  B. Track Momentum Resolution 4
  C. Forward Region 5

A. Parameter Summary 6

References 6

I. INTRODUCTION

These notes describe a parametric model of the hadronic particle identification (PID) performance of the Jefferson Lab Electron Ion Collider (JLEIC) full acceptance detector design. This describes a C code that can be used as a fast Monte Carlo analyzer of the output of event generators, such as PYTHIA.

A. Detector Coordinate System

The detector coordinate system is defined by the $+z$-axis *opposite* the direction of the incident electron, the $+y$-axis opposing gravity, and the $+x$-axis chosen to create a right-handed coordinate system. The nominal incident ion momentum $\mathbf{P}$ is in the direction specified by polar and azimuthal crossing angles θ_C and ϕ_C, respectively:

$$\mathbf{P} = |\mathbf{P}| \left[\hat{z}\cos\theta_C + \sin\theta_C \left(\hat{x}\cos\phi_C + \hat{y}\sin\phi_C\right)\right] \tag{1}$$

The nominal values are $\theta_C = 50$ mrad, $\phi_C = \pi$.

B. JLEIC PID Detectors

The central detector is defined by the following regions:

- Electron-downstream endcap. $\pi + \tan^{-1}\left[(1.0\text{ m})/(-1.6\text{ m})\right] < \theta < \pi - 30$ mrad. Hadronic PID is accomplished by an array of modular (aerogel) RICH and Time-of-Flight detectors. Electrons and gamma-rays are identified by a central $PbWO_4$ crystal array, a large angle Shashlyk, and a Hadron Blind Detector (HBD) which is essentially a proximity focussed threshold Cherenkov detector detecting UV light from CF_4 gas.

- Solenoid Barrel: $\tan^{-1}\left[(1.0\text{ m})/(2.4\text{ m})\right] < \theta < \pi + \tan^{-1}\left[(1.0\text{ m})/(-1.6\text{ m})\right]$. Particle ID is accomplished by DIRC, TOF, and EMCal (Shashlyk) detectors.

- Ion-downstream endcap: $\theta < \tan^{-1}\left[(1.0\text{ m})/(2.4\text{ m})\right]$, excluding the Forward Region In the ion-side endcap, particle ID is accomplished by a dual radiator RICH, TOF, EMCal (Shashlyk), hadronic calorimeter (HCal) and muon tracking chambers.

- Forward-ion region:
  The forward region is defined by a cone of half-opening angle 80 mrad centered on the downstream ion beam. Dipole-1 is a 6 mrad outbender (2 Tesla for $P/Z = 100 GeV/c$), with nominal field boundaries at $z = 5.5$ and 6.5 m. Optimistically, the endcap dual RICH will provide hadronic PID in the forward region, excluding a 'race-track' oval region of 10 mrad opening angle around each beam pipe. Electron/gamma detection is provided by a forward $PbWO_4$ array between Dipole-1 and the first ion FFQ, subtending an annular range around the downstream ion beam 10 mrad $< \theta <$ 80 mrad. TOF, if useful, can be added in front of the $PbWO_4$ array.

C. PID Resolution, Purity, and Mis-Identification

For each charged particle species $f = \pi$, K, p of three-momentum $\mathbf{p}$, each PID detector (j) is described by a mass resolution

$$\sigma_f^{(j)}(\mathbf{p}; \text{par}) \tag{2}$$

The parameter set 'par' for each detector is described in the following sections. The parameter list and nominal values are summarized in Table I in Appendix A.

For a particle transiting several PID detectors, the cumulative mass resolution σ_f^{Tot} is determined by

$$\frac{1}{\left(\sigma_f^{\mathrm{Tot}}\right)^2} = \sum_j \frac{1}{\left(\sigma_f^{(j)}\right)^2} \tag{3}$$

For each particle of species f generated by a MC simulation, the PID mass histogram *hPID_f* is incremented by a random deviate u chosen from the gaussian distribution:

$$P_f(u) = \frac{1}{\sqrt{2\pi\left(\sigma_f^{\mathrm{Tot}}\right)^2}} \exp\left[-\frac{(u-m_f)^2}{2\left(\sigma_f^{\mathrm{Tot}}\right)^2}\right] \tag{4}$$

Let $\mathcal{P}_{j,j}$ denote the purity: fraction of particles identified as type j that were truely of type j. Let $\mathcal{P}_{j,k}$ denote fraction of particles identified as type j that were actually of type k. The purity and mis-identification probabilities, for the specific MC event sample, are obtained by applying PID cuts to each of the histograms *hPID_f*.

II. TRACKING

A. Central Region

The central assumes a uniform solenoidal magnetic field B_0 in a central tracking region of radius $R_0 = 1.0$ m and total Length $L_0 = 4.0m$. The solenoid center is offset from the Interaction Point (IP) by an amount $z_0 = -0.4$ m. In this model, the central tracker is assumed to extend from $z_e = -1.6$ m to $z_i = +2.4$ m.

PID detectors such as the DIRC and RICH detectors are sensitive to the uncertainty in both the magnitude and direction of the track momentum. The track multiple scattering is based on a thickness X/X_0 (Table I, post vertex-tracker). Since the tracker precedes PID detectors, I assume the out-going track angle is determined by the second half of the tracker. Consequently, the direction uncertainty of the track, projected onto each of two perpendicular planes containing the local track (momentum p) is:

$$\sigma(\theta_{x,y}) = \frac{13.7\ \mathrm{MeV/c}}{\beta p}\sqrt{\frac{1}{2}\frac{L(\mathbf{p})}{R_0}\frac{X}{X_0}}\,, \tag{5}$$

where $L(\mathbf{p})$ is the track length in the tracking region.

The bending radius of the helical track in the solenoid field (assuming unit charge) is:

$$r_{\mathrm{track}} = \frac{p_\perp c}{eBc} = \frac{pc\sin\theta}{eBc} \tag{6}$$

At any coordinate z, the track length from the IP is

$$L(z;\mathbf{p}) = z/\cos\theta. \tag{7}$$

There are three cases for the totat tracking length $L(\mathbf{p})$ in the central region:

- $2r_{\text{track}} < R_0$
  The track spirals until it reaches either the electron- or ion-side endcap.

$$L(p,\theta,\phi) = \begin{cases} z_i/\cos\theta & \text{for} \quad \cos\theta > 0 \\ \infty & \text{for} \quad \cos\theta = 0, \text{ ignore track} \\ z_e/\cos\theta & \text{for} \quad \cos\theta < 0 \end{cases} \tag{8}$$

- $2r_{\text{track}} > R_0$, but the track still spirals until it reaches one or the other endcap.
  Let $\varphi_{\text{track}}(z)$ denote the azimuthal rotation around the z-axis of the track. The chord length of the track (in the $x \otimes y$ plane) is

$$c_{\text{track}} = 2r_{\text{track}} \sin\left(\varphi_{\text{track}}/2\right) \qquad \text{and} \quad r_{\text{track}}\varphi_{\text{track}}(z) = z\tan\theta. \tag{9}$$

  The conditions under which the track reaches an endcap are:

$$\text{For } \cos\theta > 0, \text{ if } \frac{2r_{\text{track}}\sin^{-1}\left(R_0/(2r_{\text{track}})\right)}{\tan\theta} > z_i \qquad \text{then} \quad L = \frac{z_i}{\cos\theta}$$

  and

$$\text{for } \cos\theta < 0, \text{ if } \frac{2r_{\text{track}}\sin^{-1}\left(R_0/(2r_{\text{track}})\right)}{\tan\theta} < z_e \qquad \text{then} \quad L = \frac{z_e}{\cos\theta} \tag{10}$$

- $2r_{\text{track}} > R_0$ and the track ends in the barrel region.
  This occurs if both of the previous conditions fail. Then

$$L(p,\theta,\phi) = \frac{r_{\text{track}}\varphi_{\text{track}}}{\sin\theta} = \frac{2r_{\text{track}}\sin^{-1}\left(\frac{R_0}{2r_{\text{track}}}\right)}{\sin\theta} \tag{11}$$

In all three cases, the azimuthal angle of the track helix is $\varphi_{\text{track}} = L(p,\theta,\phi)\sin\theta/r_{\text{track}}$.

B. Track Momentum Resolution

The momentum of the track is obtained from the track radius:

$$p = r_{\text{track}}\left(eB_0c\right) \tag{12}$$

For $\varphi \leq \pi$, the track is also defined in terms of the sagitta:

$$s_{\text{track}} = r_{\text{track}}\left[1 - \cos\left(\varphi_{\text{track}}/2\right)\right] = r_{\text{track}}\left[1 - \cos\left(\frac{L(p,\theta,\phi)}{2r_{\text{track}}}\right)\right] \tag{13}$$

The relative momentum resolution of the tracking system is

$$\frac{\sigma(p_\perp)}{p_\perp} = \frac{\sigma(r)}{r} = \frac{\sigma(s)}{s(r,\varphi)}\,. \tag{14}$$

A comprehensive analysis of tracking resolution is presented by Gluckstern [1]. Here, I simplify the analysis, and assume a fixed sagitta resolution

$$\sigma(s) = 200\,\mu\text{m}. \tag{15}$$

If $\varphi > \pi$, then the total sagitta is not the useful measure of the track. On the other hand, this is low momentum particle, for which the momentum resolution will likely be dominated by multiple scattering. In this case, I define the tracking momentum as

$$\frac{\sigma(p_\perp)}{p_\perp} = \frac{\sigma(s)}{s(r,\pi)} = \frac{\sigma(s)}{r_{\text{track}}}. \tag{16}$$

In the central solenoid, $p = p_\perp/\sin\theta$. The complete momentum resolution is

$$\left[\frac{\sigma(p)}{p}\right]^2 = \begin{cases} \left[\dfrac{\sigma(s)}{r_{\text{track}}\left[1-\cos(\varphi_{\text{track}}/2)\right]}\right]^2 + \left[\dfrac{\sigma(\theta)}{\tan\theta}\right]^2 & \text{for} \quad \varphi_{\text{track}} \le \pi \\ \left[\dfrac{\sigma(s)}{r_{\text{track}}}\right]^2 + \left[\dfrac{\sigma(\theta)}{\tan\theta}\right]^2 & \text{for} \quad \varphi_{\text{track}} > \pi \end{cases} \tag{17}$$

C. Forward Region

Due to space limitation, tracking chambers will likely be in the field region, and thus the effective sagitta corresponds to just the field within the 1 m nominal length of the magnet. The effective bend angle for tracking is:

$$\theta_{\text{Bend}}(p_{\text{ion}}) = \theta_0 \frac{z_{\text{ion}} P_0}{p_{\text{ion}}} \qquad \text{with} \quad \theta_0 \approx 4 \text{ mrad} \tag{18}$$

and where p_{ion} is the total momentum of an ion fragment of charge z_{ion}, and ZP_0 is the incident ion (charge Ze) total momentum. The momentum resolution is

$$\frac{\sigma_p}{p_{\text{ion}}} = \frac{\delta s}{r_{\text{track}}\left[1-\cos(\theta_{\text{Bend}}/2)\right]} \approx \frac{\delta s}{r_{\text{track}}\theta_{\text{Bend}}^2/8} \tag{19}$$

The tracking parameters are

$$r_{\text{track}} = \frac{p_{\text{ion}} c}{z_{\text{ion}} eBc} = \frac{p_{\text{ion}}}{z_{\text{ion}} P_0}\frac{P_0 c}{eBc}, \qquad \text{with} \quad \frac{P_0 c}{eBc}\theta_0 = L_0 = 1 \text{ m}. \tag{20}$$

The tracking resolution within the dipole acceptance can be simplified to

$$\frac{\sigma_p}{p_{\text{ion}}} \approx \frac{\delta s}{(z_{\text{ion}} P_0/p_{\text{ion}})\, L_0\theta_0/8} = \frac{8\delta s}{L_0\theta_0}\frac{p_{\text{ion}}}{z_{\text{ion}} P_0} \approx (40\%)\left(\frac{p_{\text{ion}}}{z_{\text{ion}} P_0}\right) \tag{21}$$

The final numerical estimate comes from an assumed space-point resolution of 0.20 mm. For a 10 GeV/c fragment from a 100 GeV/c beam, the momentum resolution is projected as 4%. Since the forward particles are typically high momenta, a GEM or microMEGAS detector could possibly improve the resolution by as much as a factor of 4.

Appendix A: Parameter Summary

TABLE I. Parameter Summary and List of Nominal Values

Detector	Parameter	Label & Nominal Value
Central Tracker	Magnetic Field	$B_0 = 3$ Tesla
	Radius of Tracking Region	$R_0 = 1$ m
	Field boundaries	$z_e = -1.6$ m, $z_i = 2.4$ m
	Sagitta Resolution	$\sigma_s = 200\,\mu$m
	Thickness	$X/X_0 = 1\%$
DIRC	Intrinsic Cherenkov Angle Resolution	1 mrad
TOF	Timing Resolution	50 psec
Forward Ion	Ion Dipole-1	
	Magnetic Field	$(2T)P/(100$ GeV/c$)$
	Field Length	1 m
	Beam Bend Angle	6 mrad
	Tracking Region Bend	≈ 4 mrad

[1] R. L. Gluckstern, Nucl. Instrum. Meth. **24**, 381 (1963). doi:10.1016/0029-554X(63)90347-1