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eRD16: Forward/Backward Tracking at EIC using MAPS Detectors

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Abstract:

We propose to continue development of tracking station concepts with silicon-sensors near the collision vertex to detect the hadrons and scattered electrons which are produced at forward and backward angles in e-A collisions. Disks of thinned-silicon sensors (MAPS) detectors will be laid out, including the conceptual design for the arrangement of electronics and conventional services (cooling, power, and readout) and their integration with the central barrel tracking subsystems. We will also continue R&D on low-mass cables that utilize aluminum traces.

1. Introduction and Motivation

The US Nuclear physics program plans to build an Electron Ion Collider to study the gluonic structure of nucleons and nuclei [1]. The facility will be built at Brookhaven National Laboratory as an upgrade to the Relativistic Heavy Ion Collider accelerator or at the Thomas Jefferson National Accelerator Laboratory as an upgrade to the CEBAF facility. The Electron Ion Collider is scheduled to be online in the late 2020s to 2030 timeframe. In this proposal, we propose to develop forward tracking instrumentation that is critical to the success of an EIC detector, building upon our experience in constructing Silicon vertex trackers for RHIC and the LHC.

The scattering region in the direction of the *electron* beam is of particular scientific interest. Specifically, this region gives access to the gluon-dense ("small-x") nuclear environment through the observation of leptonic and hadronic observables which have energies below the *electron* beam-energy. Tracking in this region is useful for both leptonic and hadronic momentum measurements but tracking in this region poses considerable challenges for the instrument designers due to the solenoidal fields that are under consideration for the central detectors. The momentum measurement, together with the energy measurement with electromagnetic calorimetry, is key to the identification of the scattered electron through the measurement of E/p. Unobserved losses of the scattered electron's energy, e.g. due to bremsstrahlung, introduce a bias in Bjorken-*x,* typically towards smaller *x* values. These considerations underscore the need for a well-integrated, low-mass tracker.

The scattering region along the direction of the *hadron* beam is of considerable scientific interest as well. Here, new insights are anticipated due to the partonic energy-loss mechanism(s) in cold nuclear matter. The observation of identified charmed hadrons in semi-inclusive processes would be qualitatively new and is likely to require topological reconstruction with a precision tracker.

Integral to the development of low radiation-length trackers are the use of low-mass conductors in the infrastructure for the delivery of power and for the readout of signal. It is important to use simulation guided design/optimizations to achieve the maximum results. In the sections below, we describe our progress to date in these areas for the proposed forward tracking stations and we give our response to feedback. This is followed by a proposed work plan for the upcoming period, key personnel, and our funding request.

2. Progress on aluminum conductor cable prototypes

Development of aluminum conductor cables was not the highest priority for eRD16, but the commonality with ALICE ITS interests gave rise to studies of mutual interest. We obtained Aluminum conductor cable prototypes with lengths between 21 and 48 cm from Hughes Circuit Inc. and from the Kharkov Institute of Physics and Technology. Dimensional and visual QA, preliminary electrical tests, and other tests have been performed, as described below. Very recently, the group has obtained new Aluminum conductor cable prototypes from the Kharkov Institute and from CERN with more elaborate designs and longer lengths up to 1.5 meters. The characterization of these cables is in progress. The material and work benefitted from synergies with the ongoing ALICE-ITS upgrade.

Hughes cables

Hughes provided three 26 cm long cables, named “HS1”,”HS2”,”HS3”, and three 48 cm long samples, named “HL1”,”HL2”,”HL3”, with different layouts, following the ALICE-ITS Upgrade TDR design. This design includes a power plane in the central section of the cable, named “central”, and two narrower power planes, named “analog”, one on each side. One of the two side power planes accommodates vias and pads for capacitors, named “caps” here. The other side plane is called “no-caps”. Figure 1 shows two of the cable samples.

The lengths and widths of the cables and the paths were measured and found in agreement with the design. The thickness was found to vary by about 40 μm across the cable, between 330 and 371 um. The measurement distribution dispersion is compatible with the expected aluminum layer thickness tolerance, therefore the Hughes prototype cables appear to be acceptable from this point of view.

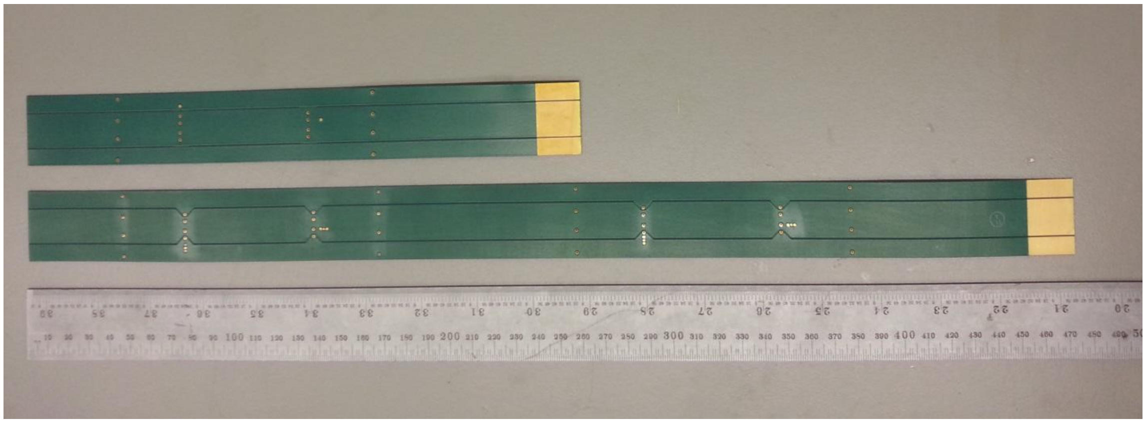

Figure 1: Aluminum conductor cable samples from Hughes Circuit, Inc.

The Hughes samples were inspected visually and found generally compliant with the ITS Upgrade TDR design. As is shown in figure 2, several imperfections were found on some of the cables by inspecting the cables with a microscope: there are bridges between the different power and ground conductor sections. Subsequent tests confirmed, in at least two cases, that these caused shorts between planes reported later. The vias are gold plated and plated through. Etching flaws were noted around the thermal reliefs on the via connections to the planes of the conductor.

Figure 2: One of the imperfections, circled in red, found on several of the Hughes cable samples.

The solder-ability of the cables was tested by soldering the wires needed for the circuit used to characterize the cables: we found that the solder adheres properly to the gold plated sections and the bonds appear to be reliable. Soldering to vias is also straight-forward and reliable. Soldered connections were checked with a continuity meter and found to be in contact. As part of subsequent tests, the Hughes power bus was soldered onto a Flexible Printed Circuit (FPC) prototypes received from the ALICE group in Torino. Via-to-via ground connections show solder all the way through the vias. Via-to-pad power connections show useful connections to the pads, but care is needed to establish reliable connections since surface tension seems to keep solder, fed from the top, from penetrating reliably to the pad.

Electrical continuity was verified between the different power and return paths (different planes) with a DVM. Shorts were found in 4 of the cables. From an inspection with an infrared camera, the shorts (hot regions) appear to be located in correspondence to vias in at least two of the cases. The resistance as a function of the path-lengths, measured for the fully functional power and return paths, is shown in figure 3 and exhibits good linearity.

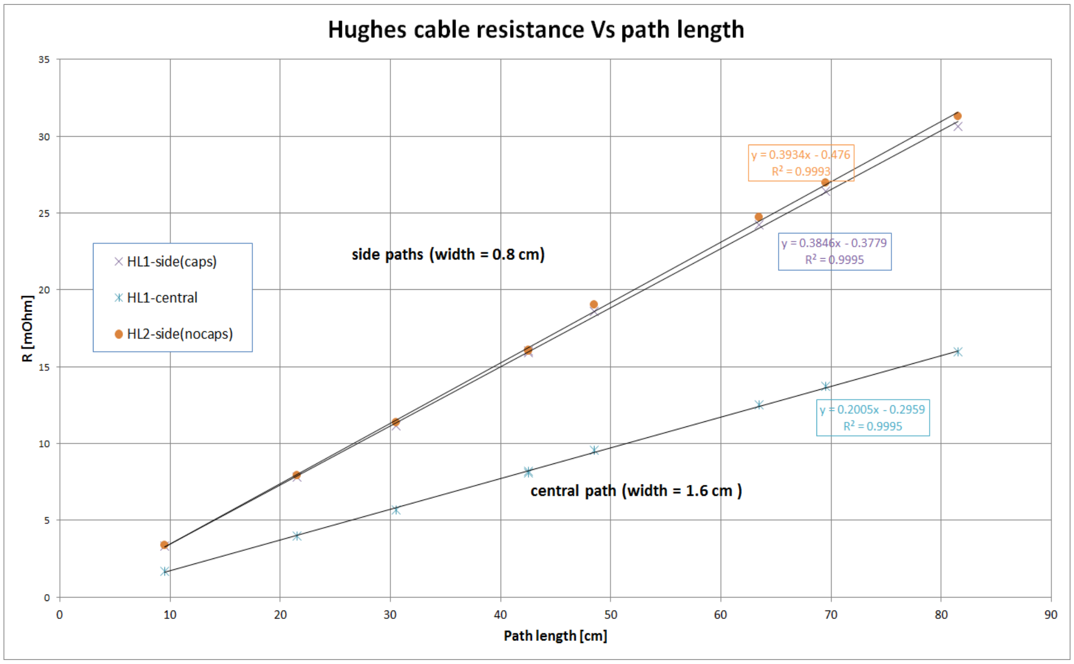

Figure 3: Resistance versus path-length measured for the functional Hughes cable samples.

Kharkov cables

Two prototype cables with tab-bonded tabs are shown in figure 4; with lengths of 21 cm ("KS1") and of 42 cm ("KS2"). These cables were obtained from the Kharkov institute.

Figure 4: The aluminum conductor cable samples obtained from the Kharkov Institute.

The Kharkov cables include tabs that are intended to be folded onto the top of the power cable and bonded to the FPC during stave assembly. The tabs are connected to the power planes via tab-bonding, and they appear to provide a robust and reliable connection. The cable structure appears generally more fragile than the Hughes samples. No visible flaws were found and the cables appear to be compliant with the design specifications. The thickness was found to vary by about 45 μm across the cable, between 311 and 357 um. The measurement distribution dispersion is compatible with the expected aluminum layer thickness tolerance. The full tab thickness is ~115 um.

The bonding pads, both on the cable and on the tabs, are not gold plated. This, combined with the more fragile design, makes the soldering and assembly process more involved. A number of suggestions were passed on to the Institute for subsequent designs. A satisfactory data set was obtained for the purpose of determining the voltage drop across the cables. These results are shown in figure 5.

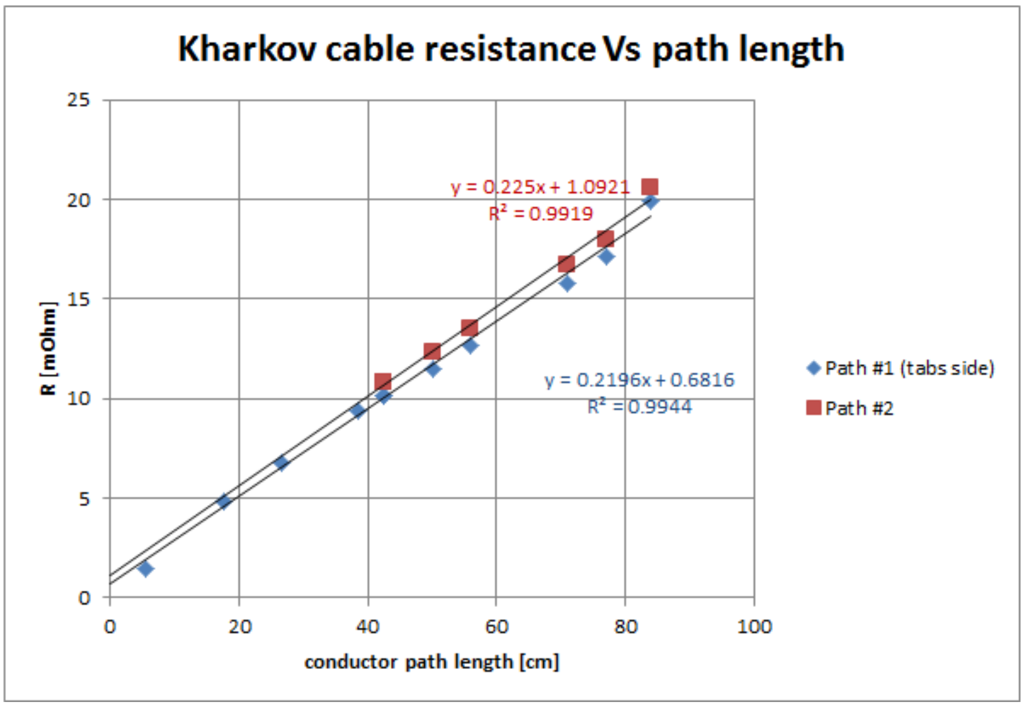

Figure 5: The linear dependence of the measured resistance on the length of the power and return path for the Kharkov cable prototypes.

3. Progress on simulations

Initial simulations have been performed to develop a conceptual layout/design of pixel tracking stations in the forward and backward scattering regions at a future EIC. This work was performed by LBNL staff with an undergraduate student (Velkovsky) and a toolset that was developed originally for ILC tracking studies [2]. This tool performs a simplified simulation of the detector, based on a helix track model and taking into account multiple scattering, followed by full single track reconstruction from digitized hits using a Kalman filter. A postdoctoral researcher (Lai) has now been hired, who will utilize the tools developed at BNL specifically for

EIC simulation. Lai will arrive in Berkeley later this summer. At the time of writing this report, we have performed a number of simulations for the 3 T solenoid of 2 m length and 1.2 m radius and the symmetric detector geometry of the forward and backward silicon disk trackers envisioned in the BeAST detector concept [3] using the ILC-tools. We have also performed simulations for a detector concept based on the 1.5 T BaBar magnet [4]. This concept, in its original form, relies on tracking with GEM disks of different radii. Figure 6 shows a side-view of one of the geometries, with 2 set of 10 disks, on either side of the collision point. This arrangement was used in the simulations.

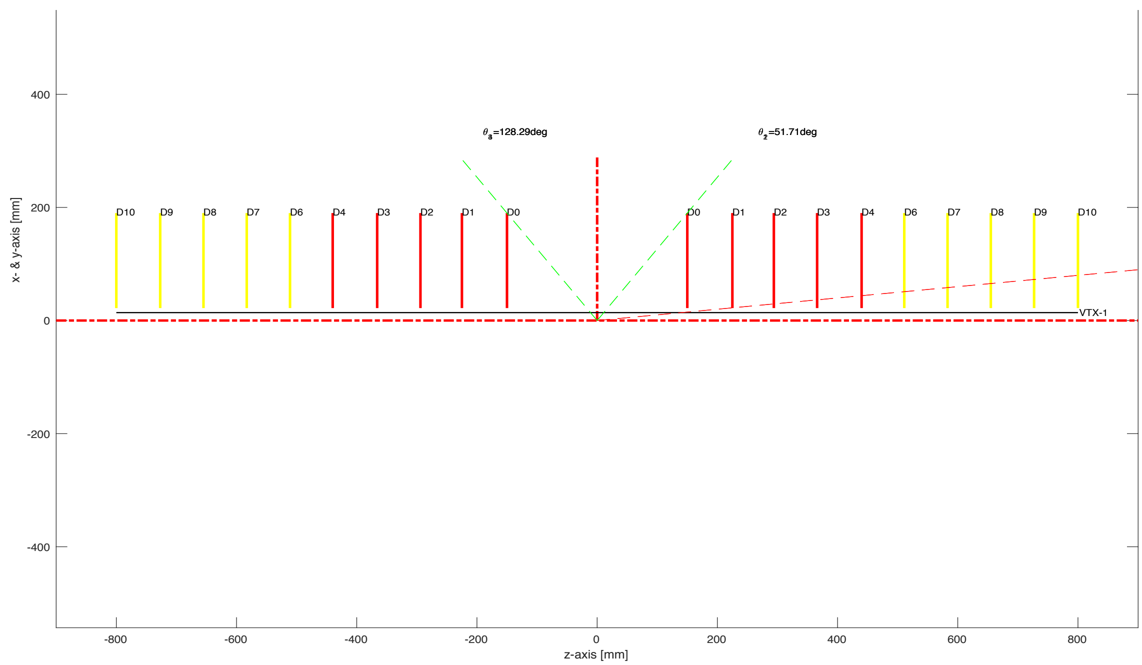

Figure 6: Sideview of a simulation geometry with 2x10 disks.

Figure 7 shows simulation results for the relative momentum resolution for charged pions as a function of (total) pion momentum. Both a 3T solenoidal field configuration with 2x7 disks, as in the BeAST model detector concept, and a 1.5 T solenoidal field with the 2 x 10 disk configuration shown in Figure 6 were simulated. In these simulations, the pixel size was chosen to be 20 um by 20 um and the hit locations were digitized accordingly. Charged pions were emitted at an angle of 5.6 degrees, corresponding to a pseudo-rapidity of 3. For these simulations, the tracking *only* made use of the disks. The disks are assumed to have a thickness corresponding to 0.3% radiation lengths. It should be noted that the positions of the disks along the beam direction were chosen to allow for a central silicon barrel tracker of the same length as the ALICE inner tracker that is currently being constructed. Such an inner tracker has been shown to fit inside the BaBar magnet and is under consideration for sPHENIX. The BeaST detector concept could accommodate something else, and this will be optimized in future studies.

The difference in performance for the two curves in the figure has its origin in the different values of the solenoidal field and, to a lesser extent, in the difference in path-lengths and the number of traversed disks (effects that partially compensate each other in this particular set of simulations).

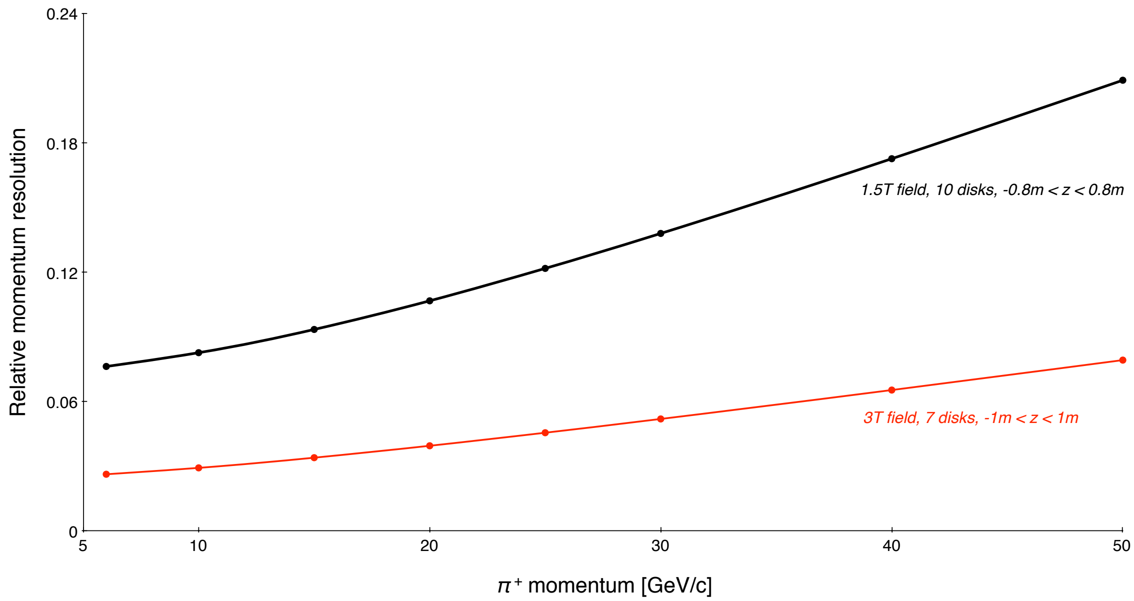

Figure 7: Expected (relative) momentum resolution for two solenoidal field values and forward disk configurations for secondary pions emitted at a pseudo-rapidity of 3, plotted versus charged pion momentum.

Figure 8 shows the anticipated effect from a change in pixel size in the range of 10 x 10 microns to 40 x 40 microns. The charged pion angle and other parameters are identical to those used in the simulations for figure 7. As the target momentum resolution is at the level of several percent for forward scattered electrons, a pixel size in this range is adequate. Combined with stand-alone assessment of EIC event-rates, this study supports the continued consideration of the ALPIDE sensors, which have pixels of 28 x 28 microns, as candidates for use at EIC.

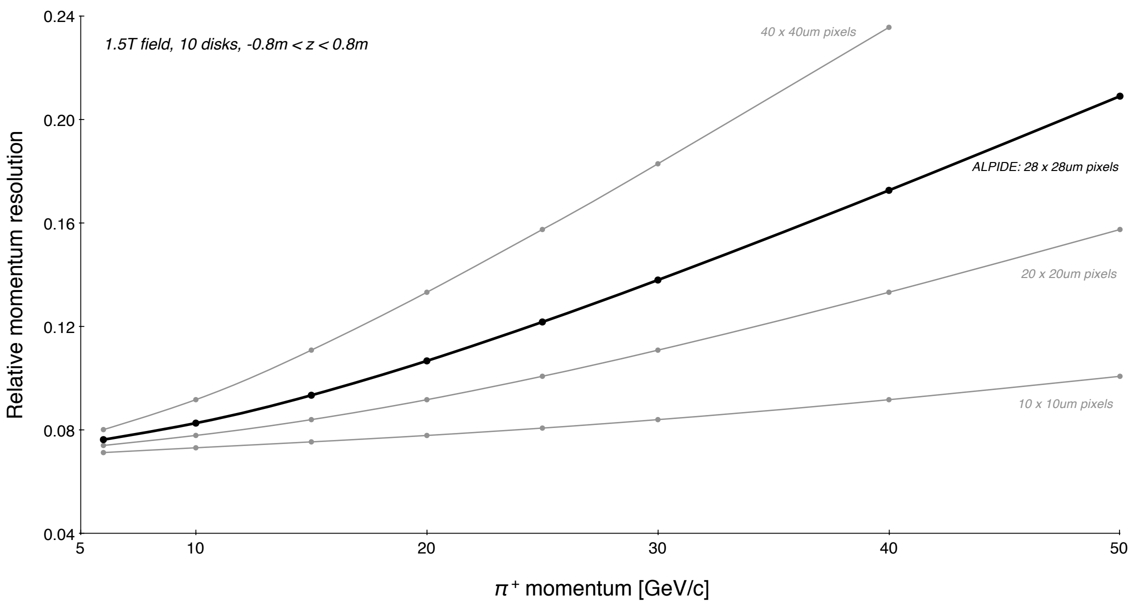

Figure 8: Forward momentum resolution versus pion momentum for different pixel sizes, as indicated.

4. Progress on feedback received

We have followed up on the committee's recommendation to establish contact and dialogue with the eRD6 and eRD3 Tracking consortia. We have focused more on eRD6 contacts, as we had anticipated that eRD3 would fold into eRD6. We have recently learned, however, that this may not be the case at the current time.

It is clear that silicon tracker endcaps will need to coexist smoothly with tracking in the central rapidity (i.e. barrel) region. As eRD6 has undertaken studies in support of a design for central region tracking, this is the right tracking consortium for us to work with. Coordination of designs is crucial to ensure hermeticity of tracking and appropriate overlap to optimize performance in the overlap region around η=2. At the same time the central and forward/backward trackers must coexist and the infrastructure for one must not interfere with the other. This will require excellent communication and cooperation in moving from first concepts to an actual design. To this end, we have discussed with the eRD6 collaboration the idea to merge our efforts on the timescale of approximately a year. It is too early to do this now, as we are still concentrating on initial conceptual design of silicon endcap trackers. The sensor layout will dictate the geometry for readout and cooling, and this information is key for integration with barrel tracker concepts.

In its January 2016 report, the committee correctly noted that LBNL has recently identified the EIC as a focus for near term strategic support. The committee encouraged us to consider this opportunity. We have pursued this opportunity in collaboration with colleagues from multiple divisions at the Laboratory and we are competing for strategic LDRD funds targeting EIC science and instrumentation. We note, in particular, that the proposed effort includes a comparative evaluation of HV/HR-CMOS and MAPS, and also includes studies of tracking in the very forward region that may develop closer synergies with the tracking for polarimetry than the forward disks considered here. The allocation of FY17 LDRD funds is anticipated to become known by late Summer of 2016.

5. Proposed work

Our proposed work for the coming fiscal year focuses, in large part on simulations. Specifically,

1. We will complete the set of simulations proposed for the last cycle within the BNL-developed simulation framework. Yue Shi Lai, a new LBNL postdoctoral researcher who is currently at CERN, moves to LBNL later this summer. In the fall, he will travel to BNL to work with Alexander Kiselev to learn the BNL simulation software. Lai will then implement the optimized disk geometry into the full simulation and further study its performance. To this end, the unspent travel funds from FY16 will be used, though the visit may not commence before October 1. The remaining postdoc funding from FY16 will cover a fraction of Lai's time, though not enough to carry out all the simulations which will be required. Consequently, we request new funds, as detailed below.

2. The current, independent, simulations will be pursued further with Velkovsky. Preliminary results indicate that the envisioned disk configurations with an equal number of equidistant disks for both the electron and hadron direction can be optimized further for the respective physics objectives. We propose to work this out and work out configurations that are asymmetric between the electron and hadron directions. Furthermore, we propose to pursue simulations of displaced vertexing capability in the hadron direction.

3. We propose to study in detail how disk and barrel tracking are best integrated, both with an eye to physics performance and actual feasibility. Particular attention is needed to the region of acceptance overlap with the detector barrel and the inner edge of the disks. This will require new simulation efforts by Lai.

4. The 4 μs effective integration time of the ALPIDE sensors appears manageable at EIC, at least with the repetition rates envisioned at BNL. We propose to develop simulations to quantitatively assess and specify the readout speed requirements, starting from the ALPIDE parameters.

Having ascertained in FY16 that the ALICE ALPIDE sensor has sufficient granularity and thinness for applications at the EIC, we propose:

5. To study how sensors with these geometries can be best laid out to construct an actual disk. Different layout possibilities will be investigated. The BeAST concept, for example, adopted vertical staves. Alternative configurations involve different trade-offs and may offer attractive advantages. Specifically, we will study alternatives, including trapezoidal wedges (which may enable "lamp-shade"-like configurations) and triangular base forms (which may offer "iris"-like design-flexibility). There is a major tradeoff inherent in changing the sensor shape, however the additional sensor development costs

may be warranted to maintain low mass in the forward tracking disks. Figure 9 contains an illustration of disk structures from trapezoidal and triangular base forms; the layout of sensors onto these forms is not shown.

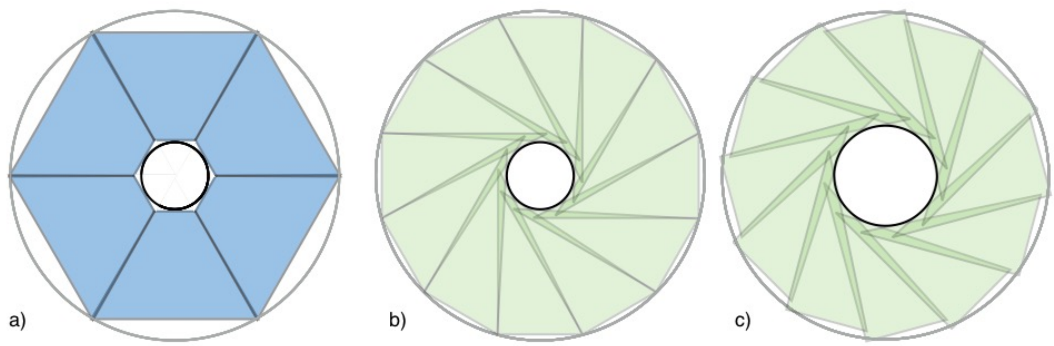

Figure 9: Disks constructed from a) trapezoidal base forms and b), c) triangular base forms.

This topic will be pursued with a combination of studies, including simulations.

We consider the pursuit of low-mass conductors a priority, in particular now that the ALICE-ITS upgrade is transitioning from R&D into the production phase, and the particular needs in disk configurations for the EIC are becoming clear. Following effort 5 above, we thus propose:

6. To build on our past collaboration with industry, specifically Hughes corporation, and attempt to develop a commercial option for aluminum conductor flex PCBs with a focus on disk configurations. In parallel, we will consider the capabilities of additional vendors.

This development process will necessarily be iterative. We will define sample flex PCB designs to demonstrate capability, and work with the vendor(s) to establish processes for progress toward meeting the design requirements. This will require procurement of test parts from the vendor. The cost, given the new processes to be developed, will be significantly higher than copper based PCBs and M&S is thus part of our funding request. We have had some initial successes with Hughes in the STAR Pixel detector development and ALICE-ITS, and we believe that pursuing this collaboration, and potentially collaboration with other industrial partners, will be beneficial for the EIC detectors as well as for the community at large.

6. Personnel

Forward disk conceptual design and simulation studies are led by Sichtermann. These efforts include several younger scientists. Summer student Ivan Velkovsky from the UC Berkeley Physics Department has been supported by eRD16 for conceptual design simulations. He carried out calculations and more detailed simulations of the concept under the supervision of Sichtermann. Velkovsky will continue this work during the 2016/2017 academic year. Postdoc Yue Shi Lai recently joined LBNL; he will work part time on detailed performance simulations after arriving in the U.S. and Berkeley in late summer or early fall. Aluminum cable characterization was carried out by Contin and Greiner.

7. Funding request

1.0 student (Summer support); to work on simulations
0.5 postdoc FTE; to work on simulations
$10k M&S; for continued cable prototyping purchases

Cost, including LBNL overheads:

50% postdoc	$ 83,616
student support	$ 8,276
M&S	$ 12,922
Total	$104,814

References

[1] D. Geesaman et al., The 2015 Long Range Plan for Nuclear Science.
[2] M. Regler et al., J.Phys.Conf.Ser. 119 (2008) 032034 and references therein.
[3] E.C. Aschenauer et al., arXiv:1409.1633 and references therein.
[4] A. Adare et al. [PHENIX Collaboration], arXiv:1402.1209 and references therein