**Tracking Working Group Summary**

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**Introduction**

Kaon and muon experiments at Project X have challenging tracking requirements. In addition to excellent position resolution, requirements will include: extremely high rate capability (potentially up to 1 MHz/mm2), extremely low mass (<< 1% X0) and in some cases good timing resolution (< 1 ns). This working group undertook to survey tracking requirements of potential Project X experiments and the capabilities of available technologies, with the goal of identifying high priority areas for R&D.

The activities of this working group consisted of presentations in parallel sessions that were then followed by scheduled discussion sessions on subsequent days. The parallel sessions were divided approximately equally between silicon tracking and gaseous detectors. Attendance of the parallel sessions was typically about 15 persons. The discussion sessions had lower attendance, at least in part because some of the presenters were no longer present at Fermilab.

A list of the parallel session presentations follows:

Session 1 (Saturday June 16 morning)

* Tracking Requirements in Rare K Decay Experiments – Jack Ritchie
* Mu2e Tracker – Aseet Mukherjee
* Straw Tracking for g-2 – Hogan Nguyen

Session 2 (Saturday June 16 afternoon)

* Low Mass, High Speed Silicon Tracking – Ron Lipton
* The NA62 Gigatracker – Bob Velghe

Session 3 (Monday June 18 morning)

* The ORKA Drift Chamber – Toshio Numao
* Multi-anode Straws – Seog Oh
* Silicon Tracker for μ - Fritz DeJongh

Session 4 (Monday June 18 afternoon)

* Tracking for nnbar – Mike Snow
* Low-mass Tracker Mechanics – Bill Cooper
* Low-mass Monolithic Active Pixel Detector for STAR at RHIC – Leo Griener

**Benchmark Experiments**

Processes that impose challenging tracking requirements on future (and in some cases current) experiments include decay modes such as K+→π+×Ø, KL→μe, KL→π0ee, μ. These decays provide benchmarks that are useful in identifying the requirements that can be expected for Project X rare process experiments.

Time available during this workshop did not permit new studies to be carried out. Reviewing previous experiments and also on-going experiments can provide some guidance. For instance, the proposed ORKA experiment has a conceptual design for a very low-mass drift chamber, based on a chamber built for previous experiments at the Brookhaven AGS. The NA62 experiment, under construction at CERN, provides an interesting point of reference. The NA62 Gigatracker has very aggressive goals for providing good resolutions in both position and time using a low-mass silicon pixel detector. The experience gained from NA62 will be important for future experiments. NA62 and the Fermilab mu2e experiment illustrate the need for some detectors to operate in vacuum. In both cases, straw tracking is the chosen technology.

While some conclusions can be drawn by looking at past and current experiments, determining the tracking requirements of experiments at Project X will require detailed simulations that include realistic beam assumptions and specific detector geometries. None of this work has been done. Therefore, one clear priority is to begin work on such simulations.

**Low-mass Silicon Tracking**

Silicon tracking detectors can provide micron-level precision and excellent time resolution. This combination will be needed in experiments like ->e or NA 62, where background rejection depends on precise track reconstruction and accurate timing. NA62 reported time resolution below 200 ps in this workshop and the SLAC/JLAB heavy photon experiment has achieved 2ns using multiple sampling with standard 300 micron thick silicon detectors read out with the CMS APV chip. However combining excellent time and position resolution with low mass and low power is a challenge. The Heavy Flavor Tracker (HFT) group is producing a CMOS MAPS-based vertex detector for STAR at RHIC which is designed to achieve better than 5 micron resolution in a detector thinned to 50 microns with a readout time of ~100 microseconds. The ladders are air cooled and have a total radiation length of less than 0.3% per ladder. The time resolution is limited by charge collection by diffusion rather than drift and is zero suppressed but does not utilize sparse readout.

Standard fully depleted silicon detectors analog power requirements are set by the analog power needed to achieve a given time resolution and signal/noise. This reflects directly in the mass budget for power delivery, cooling, and services. The time resolution can be approximated by t=trise/(Signal/Noise). Risetime and noise are in turn directly dependent on the current in the front-end amplifier. This sets fundamental limitations on power needed to achieve the needed time resolution for a given detector capacitance. In the workshop we explored these limits, as well as possible new technologies, such as silicon avalanche diodes integrated in two 3D layers to provide internal amplification (as in a gaseous detector) in combination with a 2 layer coincidence to defeat noise.

Low mass tracking also requires low mass supporting structures and cabling. This is an area of active work in the collider community. Examples of such structures from collider detector R&D, such as the low mass ladders for STAR, and carbon foam structures being studied by the PLUME collaboration were presented. Work from the SID ILC detector concept on techniques to build low mass systems utilizing high modulus carbon fiber was also presented. Another important area is improvement in the efficiency and mass burden of power delivery utilizing DC-DC converters, serial powering, and aluminum cables.

**Gaseous Trackers**

Gaseous tracking is a well-developed technology that has been used for many years. In many situations it continues to provide the best tracking solution, particularly when large volumes or large areas need to be covered. The requirements of different experiments can be quite different, so generalizations are difficult. For instance, a somewhat convention cylindrical drift chamber apparently meets the needs in the case of stopped K experiments, while straws are a more natural solution in decay-in-flight experiments. Also, straws provide a means to instrument an evacuated volume with large-area tracking detectors as in NA62 and mu2e.

The ORKA experiment, proposed to measure K+→π+×Ø, needs to achieve the best possible momentum resolution for the 205 MeV/c π+ from the K+→π+π0 decay, the main background source. The conceptual design for the drift chamber follows the “ultra-thin” design of the BNL E949 chamber. There are a number of open issues concerning possible improvements, such as the optimal cell size and shape, choice of gas, etc. It is also important to achieve good *z*-coordinate resolution, which was achieved in E949 with a separate outer straw tracker (using timing). For ORKA the trade-offs between different alternatives for an outer tracker need to be explored. Also, the need to minimize dead material inside the hermetic photon veto system leads to the novel ideal that possibly the drift chamber endcap could be an active material. In view of the timescale proposed for ORKA, the emphasis needs to be on optimizing the design rather than generic R&D.

Straws have proven to be a robust and capable technology in a number of experiments. The mu2e system illustrates the strengths of straws: the ability to economically cover a large area with reasonably good resolution and – critically – to operate inside a vacuum region. A similar application is part of the NA62 experiment. The New g-2 Experiment is also exploiting the ability of straws to operate in vacuum by instrumenting two of its calorimeter stations with straw tracking. Tracking information will enable studies of the beam profile and moments, pileup, and calorimeter stability, which will improve the understanding of the systematic errors in the measurement.

The material in a straw tracker is dominated the walls of the straws themselves. While planar geometries are natural for straws, in a cylindrical geometry it is mechanically complicated to include a stereo layer. An interesting idea that addresses both issues is multi-anode (i.e., multi-wire) straws. A prototype has been constructed at Duke University that has 12 sense wires per straw, providing an average of about three hits per straw for through-going tracks. Thus, the mass per hit is reduced by a significant factor. It also has been shown possible to rotate the end-pieces of the straws by 15 degrees to achieve a stereo arrangement of wires within the straws. Tracking with multi-anode straws represents a new idea for an otherwise stable technology and appears to be a favorable direction for R&D.

It would have been good to include consideration of other gaseous tracking technologies (e.g., GEM, MicroMega, …), but we were not able to do so during the June workshop.

**Conclusions**

Rare decay experiments at Project X are likely to require unprecedented performance from tracking detectors. Each experiment will have its own unique set of requirements. Simulation efforts are needed to define these requirements. Nonetheless, the general themes of low mass and excellent timing are shared among many concepts. In some cases the required performance may be achieved by extending and improving current generations of detectors, such as straw tubes and drift chambers. In others, new ideas are needed to circumvent fundamental limits in existing technologies. This workshop was a first step in exploring and extending the toolkit of detector technology to Project X.