**Template JRA**

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| **Work package number** | WP24 | **Start date** | 01/06/2019 |
| **Activity Type** | Joint Research Activity | | |
| **Work package acronym** | JRA6-next-DIS | | |
| **Work package title** | Challenges for next generation DIS facilities | | |

1. Work carried out and overview of progress
   1. **Project objectives**

*[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]*

High precision Monte Carlo (MC) simulations of the physics processes are essential to design the interaction region,identify the optimal detector configurations and refine their parameters.

Modern time projection chambers (TPCs) used for charged particle tracking, are designed to operate at high collisions rates. Their main limitation is the amount of positive ions, created during the electron amplification processes that drift back from the readout detectors into the TPC's drift volume (ion back-flow, or IBF). Minimising this becomes a priority of TPC design.

Photon detectors for particle identification: the reconstruction of many reactions of interest depends on the ability to identify particles, which cannot be distinguished kinematically at high momenta, such as pions and kaons. In this kinematic regime, particle identification is most effectively achieved with ring-imaging Cherenkov (RICH) detectors, whose performance crucially depends on the photon detection.

The extremely high resolution required for vertex reconstruction in the EIC can be achieved using silicon pixel sensors and this WP proposes to develop a prototype for central and forward/backward tracking and vertexing, which will exploit the advantages of depleted MAPS technologies (DMAPS).

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]*

***Table 1.2: Progress made during the reporting period towards objectives***

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| ***Task 1: Monte Carlo Simulations*** |
| The deliverable for this task, namely a simulation study of exclusive processes at the Electron-Ion Collider, was completed and formed section 8.4 of the EIC Yellow Report (Nucl.Phys.A 1026 (2022) 122447).  In this reporting period, the focus has been on simulation for the EIC detector (ePIC) on two main aspects. On the one hand, simulations of exclusive processes have continued as they are instrumental for the optimization of the ePIC design. On the other hand, GEANT4 simulations of the Low-Q2 tagger based on the Timepix technology have continued at UGLASGOW in collaboration with the UK's Nuclear Physics Cross Community Support Group based at Daresbury Laboratory. |
| ***Task 2: Very low ion-back-flow detectors for high-flux TPC*** |
| The development and characterisation of a new hybrid MPGD (micro-pattern gaseous detector) detector with very low ion-back-flow (IBF) has been completed in 2023 with the publication of the results in Nucl.Instrum.Meth.A 1051 (2023) 168134. Results have shown that an hybrid structure Micromegas-GEM-micromesh can achieve IBF values as low as 0.2% for detector gains around 2000.  During this reporting period, the activities focused on the design, development and simulation of a cylindrical Micromegas layer for the tracking system of the EIC detector (ePIC). The ePIC silicon vertex tracker, developed in Task 4, will be complemented by layers of MPGDs to provide redundancy for tracking and patter recognition. An MPGD layer in EIC must be light in material budget, fit in a tight environment, work in high a magnetic field, and have 2D readout capabilities. Therefore, the activity focused on the upgrade of the 1D-readout cylindrical Micromegas technology developed for the CLAS12 experiment at Jefferson Lab: the choice of a 2D readout pattern and the resistive layer are being optimized for the ePIC needs. In March 2024, the design and the status of the R&D have been presented at the EIC Project Preliminary Design Review of the Tracking system. In parallel, a realistic description of the cylindrical Micromegas layer has been implement in the ePIC simulation framework: this allow for further optimization of the detector design. |
| ***Task 3: Photon detectors for particle identification using RICH*** |
| The main goal of this task is the implementation of a dual-radiator ring imaging Cherenkov detector (dRICH) for the hadron separation over the 3 GeV/c to 60 GeV/c momentum range, and the electron identification up to 15 GeV/c, for the EIC detector (ePIC).  In this reporting period, the small-scale prototype (D24.3, in the previous achieved in the previous reporting cycle) has been brought to beam test at CERN for further studies. In particular, it was equipped with eight improved photo-detectors and tested with various Aerogel samples and two gas radiators. The SiPM sensors have been operated at two working point temperatures of -40C and -20C. The temperature of the radiator chamber has been continuously monitored. In this beam test campaign a better separation of the Cherenkov rings has been achieved.  Also in this reporting period, careful studies of the geometry and the integration of the dRICH detector in ePIC have been made in strict collaboration with the EIC Project engineers: the complex and compact design of ePIC imposes constraints on the geometry and interferences with the other subsystems had to be resolved. |
| ***Task 4: Depleted MAPS for tracking*** |
| During the reporting period work towards the realization of the first EIC silicon detector, the ePIC Silicon Vertex Tracker (SVT), has been carried out on three topics.  **Sensor development** continued in collaboration with the ALICE ITS3 project to develop a new generation depleted MAPS sensor in 65 nm to satisfy the stringent requirements on vertex and tracking measurements at the EIC. During the reported period the ITS3 collaboration with contributions from ePIC institutes developed prototypes for technology exploration (MLR1 prototypes) and for learning of stitching methodology (ER1 prototype) towards the realization of the wafer scale sensor for ITS3 and ePIC. Within this effort, the University of Birmingham worked on the characterization of the analogue pixel test structures (APTS) prototype to assess the charge collection properties of the technology and hence its suitability for a production sensor. In particular, lab characterization with radioactive sources was performed on 14 different flavors of APTS. These were combinations of different pixel sizes, pixel designs and process parameters. They have been tested with signals injected via pulse generators and radioactive sources. Results highlighted how the optimizations in pixel design and process parameters achieve a larger depletion volume and shape the electric field lines leading to excellent charge collection properties with a pixel size in the order of 20 um, making the technology suitable to develop the sensor for the ePIC SVT. (More details are given in the deliverable report in 4.1)  In the **tracking and vertexing** context, work in Birmingham continued on the definition of the detector layout, the study of its performance, and the development of the associated tracking software with key contributions to the development of the ePIC tracker. The work proceeded through successive versions of the tracking detector and the evaluation of their impact on momentum and vertex resolutions. In particular: the position of the silicon vertex layers was optimized to maximize vertexing performance; trade-offs have been identified between redundancy and material for the silicon disk configurations in the forward and backward directions; the impact of the MPGD detectors in terms of their contribution to the tracker resolution and redundancy was investigated, highlighting their main role for track pattern recognition. Following up on work from the ePIC Background Task Force, first estimates of radiation levels and hit rates in the SVT were provided. In terms of more general contributions, Birmingham maintained an up-to-date parametrization of the vertex and momentum resolution of the ePIC detector at each new iteration of the geometry and contributed to the development of the track reconstruction software via benchmarking studies of realistic seeding versus truth seeding.    **Physics simulations** concentrated on expanding previous work on reconstruction of DIS kinematic variables with a reconstruction method developed in Birmingham. This uses a combination of knowledge of the cross-section for the kinematic variables x and y, and initial state radiation, with the detector resolution on the measured electron and hadron final states to improve the reconstruction. This method yields, in addition to the DIS kinematic variables, the energy of a possible photon radiated from the incoming electron beam which allows to get better resolution. Applying this method to ePIC simulated data showed its performance matches that of the best standard reconstruction method across the kinematic range. The method has been validated using with H1 simulation and data, showing good agreement. H1 simulations also show that hard ISR can be identified with good resolution and efficiency. Hard ISR results in a lower energy electron beam and extends the kinematic reach if identified. The distributions of reconstructed ISR in simulation and data also show good agreement. |

**1.3 Highlights of significant results**

*[Include an overview of the project results towards the objectives in line with the structure of the Annex 1 to the Grant Agreement*.*]*

Task 4: Demonstration of the suitability of the selected 65 nm CMOS imaging process for the development of the wafer scale ePIC SVT MAPS sensor through the evaluation of prototypes.

1. Critical Implementation risks and mitigation actions

**2.1 Risk materialization**

*[Provide the information on the project risks described in Annex 1 to the Grant Agreement*.*]*

1. Little or no progress to reach approval for the EIC (low)

Whether the risk has materialized? (No)

During this reporting period, the EIC Project made huge progress. It was awarded CD-3a approval, and together with the ePIC collaboration, is moving towards the CD2/3 milestones that will mark the completion of the design phase and the beginning of the construction phase.

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**2.2 Risk-mitigation measures applied**

*[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period*.*]*

1. Developments within this WP will benefit near-future projects such as sPHENIX at BNL, upgrades to TJNAF and ALICE at CERN. The risk is low — the EIC has been through a large number of reviews with very positive results and the US National Academies assessment is expected imminently.

Whether the risk-mitigation plan was applied? No

A strict collaboration with the ALICE ITS3 development is already in place.

**2.3 Comments/new risk-mitigation measures proposed**

*[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above*.*]*

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

**3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package**

*[Explain the reasons for deviations, the consequences and the proposed corrective actions.]*

As explained in the two previous periodic reports, the objective of task 4, i.e. the development and characterization of a prototype depleted MAPS sensor for the ePIC SVT, was carried out in a different way than originally planned.

Updated EIC machine parameters and evolving physics requirements resulted in more stringent requirements for the EIC vertex and tracking detector that could be met with a MAPS sensor in the originally proposed 180 nm CMOS imaging technology. The EIC project and ePIC SVT collaboration decided to move to a smaller feature size process (65 nm) available at the same foundry, exploiting similar project requirements and timescale with the ALICE ITS3 collaboration.

Delays due to the pandemic and the semiconductor industry crisis meant that the milestones (MS51) and deliverable (D24.4) associated to task 4 were delayed but have both been successfully achieved during the grant period.

The development of a prototype sensor for the ePIC SVT in 65 nm technology was merged with the ITS3 development and proceeded through two prototype submissions to validate the process and learn about stitching methodology for wafer scale sensor design. The University of Birmingham joined the larger ITS3 and ePIC characterization effort of the MLR1 and ER1 prototypes. The results of this effort led to the ongoing design of the full wafer scale, depleted MAPS sensor for the ITS3 and ePIC SVT projects.

**3.2 Deviations between actual and planned person months**

*[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]*

1. Deliverables and milestones tables

**4.1 Deliverables**

*[Please list all the deliverables due in this reporting period, as indicated in Annex I.*

*Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]*

***Table 4.1 List of deliverables***

| **Deliverable No.** | **Deliverable name** | **Lead Beneficiary** | **Nature** | **Dissemination level[[1]](#footnote-1)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D24.4 | EIC DMAPS prototype  and characterization | 42 - UOB | Demonstrator | PU | 58 | Yes | 58 |  |

*In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate “uploaded report” in correspondence of a deliverable*

**4.2 Milestones**

*[Please complete the table if milestones are specified in Annex I.*

*Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]*

***Table 4.2 List of milestones***

| **Milestone number** | **Milestone name** | **Lead beneficiary** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- |
| MS51 | First functional tests of the  EIC DMAPS chip | 42 - UOB | 46 | Yes | 46 |  |

**4.3 Deliverable Reports**

*[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]*

**D24.4 EIC DMAPS prototype and characterisation: Deliverable achieved.**

During the grant period Birmingham worked on the development of prototypes for the ePIC SVT depleted MAPS sensor. The activity focused on the characterization of prototype structures to assess the charge collection properties of the devices. In total 14 different flavors of analogue pixel test structures were characterized. Flavors differ by pixel size, pixel design and process parameters.

Figure 1 shows a schematic of the pixel cross-section for the three different pixel designs. Flavor (a) is the standard process as used in previous generation MAPS (such as the ALPIDE sensor), where the depletion region grows only around the n-well collection electrode. In flavor (b), the use of a deep n-well implant achieves full depletion of the pixel volume, extending the depletion region below the p-well containing the electronics. Finally, flavor (c) introduces a gap in the deep n-well between pixels to shape the electric field at the edges for a more complete charge collection in the entire pixel.

These three flavors come in up to four splits, where each split contains optimizations of the geometry and size of both the collection electrode and the electronics p-well to further enhance charge collection properties. The combinations of pixel design and splits are implemented on pixel sizes between 10 and 25 μm.



Figure 1: APTS pixel designs [1]. (a) standard process; (b) modified process with deep n-well; (c) modified process with deep n-well with gap.

Figure 2 shows the results of an example measurement with an 55Fe source. The plot on the left shows the results on sensors implemented in the standard process from split 1 and 4. The plot on the right shows the results on sensors implemented in the modified process with gap for all four splits. The pixel pitch is 15 μm. With the process modifications, the 55Fe spectra is clearly visible demonstrating the improved charge collection with respect to the standard process.

A screenshot of a computer screen

Description automatically generated

Figure 2: Comparison of different pixel designs and process optimisations (splits) for 15 μm pitch APTS sensors.

The results obtained in this study are publicly available as part of a publication currently on the arxiv and under review by NIMA [1] and have also been presented at an EIC UK meeting [2].

[1] <https://arxiv.org/abs/2403.08952>

[2]<https://indico.jlab.org/event/760/contributions/14248/attachments/10697/16836/ePIC_SVT_sensor_development_Long_NEW.pdf>

1. PU = Public

   PP = Restricted to other programme participants (including the Commission Services).

   RE = Restricted to a group specified by the consortium (including the Commission Services).

   CO = Confidential, only for members of the consortium (including the Commission Services). [↑](#footnote-ref-1)