LUXE Technical Note

Electromagnetic calorimeter

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First Student, First Postdoc
Second Postdoc, First Professor
(include people who contributed to this note)

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Contents

Abstract

ECAL is designed as an electromagnetic sampling calorimeter using GaAs or silicon sensors and tungsten absorber plates. ECAL will measure the number of positrons and their energy spectrum in e-laser and γ_B-laser interactions. In addition, ECAL will be used for the calibration of the energy scale of the tracker. In the following the mechanical structure of ECAL, the sensor options, the Front-end electronics and the DAQ are described. Monte Carlo simulations using the *Geant*4 package are used to estimate the performance in terms of energy and position resolution, of the number of positrons, and of the reconstruction of the positron spectrum. First results on the sensor performance measured in an electron beam are given.

1 Introduction

ECAL is foreseen to measure independently the number and the energy spectrum of positrons produced in e-laser and γ_B-laser interactions. It is designed as a sampling calorimeter. Tungsten absorber plates of 1 X_0 thickness are interspersed with detector planes of less than 1 mm thickness. Pad sensors are made of n-type silicon or GaAs of high resistivity GaAs. The pad size is 5x5 mm^2. High compactness, i.e. a small Moliere radius, is an essential prerequisite to measure positrons on top of a widely distributed low energy background. In addition, the fiducial volume is kept small. The technology for highly compact electromagnetic calorimeters was developed by the FCAL collaboration [**?**], a R&D collaboration to design, build and test prototypes of the luminometers, denoted as Lumical and BeamCal, for experiments at future electon-positron colliders, e.g. the International Linear Collider (ILC) and Compact Linear Collider (CLIC). Challenges here are very good position and energy resolutions, and efficient electron identification on top of a widely-spread background produced by beamstrahlung. These requirements and the relatively small available fiducial volume aim for a small Moliere radius. The existing prototype of LumiCal is a sampling calorimeter composed of 20 layers of 3.5 mm ($1X_0$) thick tungsten absorbers and silicon sensors placed in a 1 mm gap between absorber plates. This prototype was tested at DESY with an electron beam in the range of $1-5$ GeV and the resulting effective Molière radius at 5 GeV was determined to be (8.1 ± 0.1 (stat) $\pm$ 0.3 (syst)) mm, a value well reproduced by the MC simulation, (8.4 ± 0.1) mm. The electromagnetic calorimeter, ECAL, of the LUXE experiment will be based on these technologies.

2 Requirements and challenges

Positrons, originating from interactions of bremsstrahlung with laser photons or inverse Compton scattering with subsequent pair production, will be measured downstream from the IP, first by a silicon pixel detector, and followed by the ECAL. ECAL is designed as a highly granular and compact electromagnetic calorimeter. It will allow to measure independently of the tracker the number of positrons, and their energy spectrum. These measurements will be robust, since they use the total deposited energy by positrons, and are hence not affected by background particles of low energy. Essential for the performance of ECAL are high granularity to ensure very good position resolution, compactness, i.e. a small Moliere radius, to ensure a high spatial resolution of local energy depositions, and good energy resolution e.g. to measure the energy of positrons. The latter will be in addition important for the absolute energy calibration of the tracker.

[HA: Need to copy in expected rates and energy distributions of the positrons; maybe including backgrounds]

3 System Overview

Provide a short general overview of the system.
[HA: HA+WL will provide this part, with input from Yan's excel file]

4 Expected performance

Demonstrate the performance that can be achieved with the design chosen based on full simulation and/or tests in the lab/test beam.
[This section does not exist for the infrastructure and accelerator sections.] **[HA: HA and Shan will take care of this part]** Halina, in the following a few proposals what we may report.

4.1 Energy and Position Resolution for Single Showers

4.2 Determination of the number of Positrons and the Positron Spectrum for Medium Positron Multiplicities

4.3 Determination of the number of Positrons and the Positron Spectrum for High Positron Multiplicities

4.4 Impact of background

***can be added also in the previous subsections.

5 Technical description

Here now add sections specific to the system, including mechanics, readout on and off detector, hardware calibration system,...

5.1 ECAL Frame and Tungsten Plates

A frame made of aluminum ensures the mechanical stability of the calorimter and allows the precise positioning of sensor planes and tungsten plates. The frame was manufactured in the workshops of JINR Dubna. A picture is shown in Fig. 1

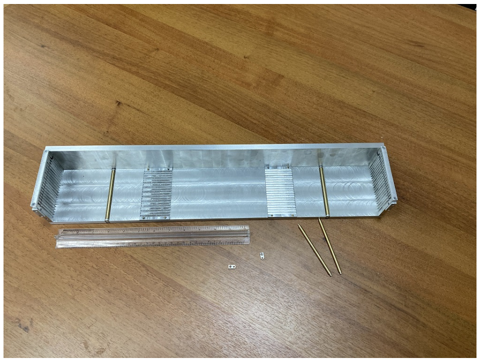

Figure 1: The mechanical frame of ECAL. The frame is made of aluminum. The bars, made of brass, allow the precise positioning of detector planes and tungsten plates.

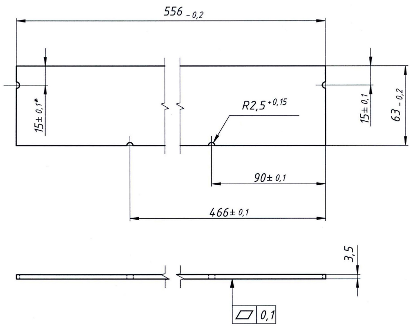

Figure 2: A drawing of the ECAL tungsten plate.

The requirements on the mechanical frame are: being able to insert 20 tungsten plates (556 mm x 63 mm x 3.5 mm) parallel to each other with a gap in between each plate equal to 1 mm, with a maximal deviation of $\pm 100 \mu m$ all over the tungsten plate surface. Silicon or GaAs sensors will be glued on the tungsten plates and fill the gaps. Hence, their thickness has to be lower than 1 mm. All materials used must be non-magnetic. The 20 tungsten plates will be moved in very precise aluminum combs, ensuring that the distance in between plates is equal to the reference distance ± 100 microns. In addition, 4 bars will use for precise positioning in the transverse direction. Tungsten plates are made of an alloy of 92.5%, tungsten, 2.25% copper, 5.25% nickel with density $17.4 g/cm^3$. A drawing of a tungsten plate is shown in Fig. 2

5.2 Sensor Options

5.2.1 Silicon Sensors

The silicon sensors are arrays of 5.5x5.5 mm^2, p+ on n subtrate diodes made of 320 um thick silicon with a resistivity of 3 kΩcm, and reverse bias voltage of about 200 V, without guard rings. Each sensor will have a total area of

89.7x55.3 mm^2, corresponding to 16x10 pads. Sensors of area 89.7x89.7 mm^2 have been produced by Hamamatsu Photonics for the CALICE collaboration (Fig. 3) and four of them were tested for LUXE purposes.

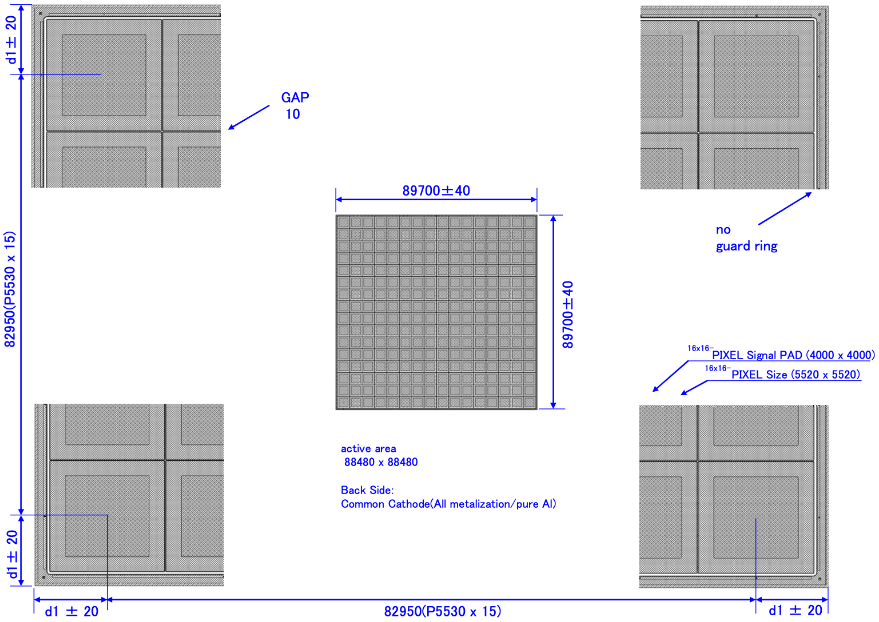

Figure 3: details of the geometry of the CALICE sensor.

For all pads of the four sensors the leakage current was measured as a function of the bias voltage. A typical result is shown in Fig. 4 In order to route the signal from the pads to the front end board, a flexible PCB has been designed.

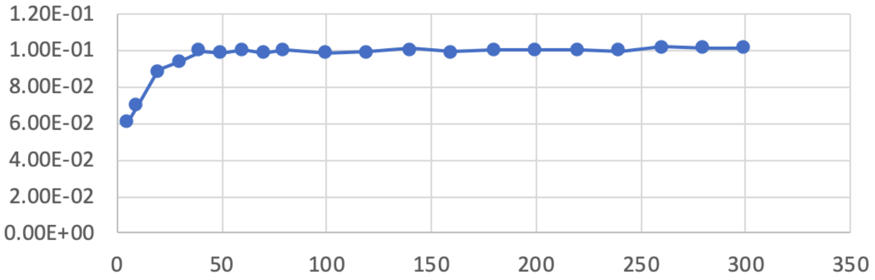

Figure 4: Leakage current (in nA) as a function of the applied voltage (in V) for a given pad.

It will be glued on the silicon sensors with a conductive glue or an an-isotropic conductive film. Another flexible PCB has been produced connect the bias voltage to the sensor back-plane.

5.2.2 GaAs Sensors

GaAs sensors are made of single crystals. High resistivity of 10^9 Ωm is reached by compensation with chromium. The pads are is 4.7x4.7 mm^2, with 0.3 mm gap between pads. Pads consist of a 0.05 μm vanadium layer, covered with a 1 μm aluminum, made with electron beam evaporation and magnetron sputtering. The back-plane is made of nickel and aluminum of 0.02 and 1 μm thickness, respectively. The sensors are 550 micrometer thick with overall sizes of 51.9×75.6 mm2. The active area is 74.7 x49.7 mm2 (15x10 pads) (no guard rings). The signals from the pads are routed to bond pads on top of the sensors by aluminum traces implemented on the sensor itself, avoiding the presence of a flexible PCB. The traces are made of 1 μm thick aluminum film deposited on the silicon dioxide passivation layer by means of magnetron sputtering. Prototypes of the sensors are shown in Figs. 5 and 6). The implementation of the aluminum traces is a new technology, and its performance with respect to cross-talk and noise will be measured in a test-beam. In case the results are not satisfactory, as a backup is considered the flexible PCB as in the silicon option above. **[WLO: do we have a leakage current measurement?]**

5.3 Assembled Detector Plane

Two different versions of an assembled detector planes are still under study. In the first the signals from the sensor pads are routed to the front-end (FE) electronics via copper traces on a flexible Kapton foil of 120 μm thickness. conductive glue or an-isotropic conductive film will be used to connect the copper traces to the sensor pads. In the second, thin aluminum traces are embedded directly on the GaAs sensors, routing the signals to the upper side of the sensor. There integrated bond pads are used to connect the traces to the FE electronics. The bias voltage is in both cases supplied to the back-side of the sensor by a 70 μm flexible Kapton-copper foil, glued to the sensor with a conductive glue.
A sketch of the structure of the detector plane using a Kapton fan-out is shown in Fig. 7 (a carbon fiber is used to protect the sensor but will not be glued in the ECAL).

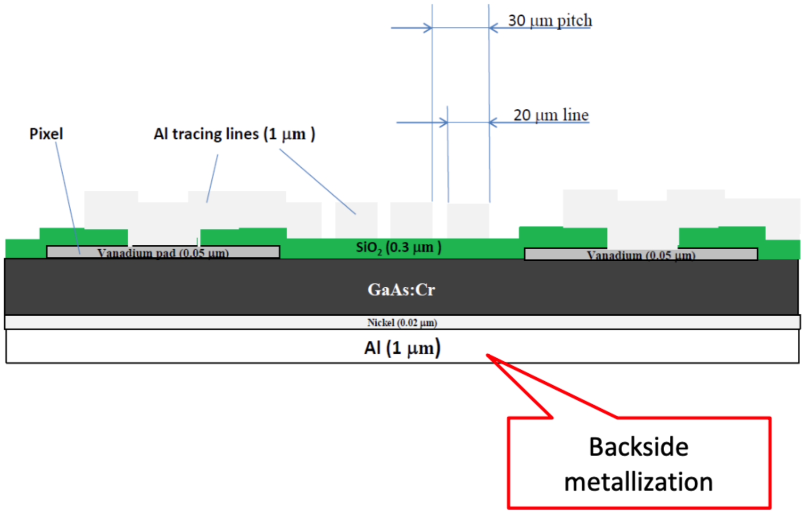

Figure 5: Schematic cut of the GaAs sensor. One the side of the pads, on the top of the passivation layer, the traces.

5.4 Front-end Electronics

Each detector plane will be readout by front-end ASICs called FLAXE (**F**ca**L** **A**sic for **X**fel **E**xperiment), mounted on a PCB and positioned on top of the calorimeter frame. Connectors on top of the PCBs are foreseen for cables to transfer digital signals from FLAXE ASICs to FPGAs installed at a larger distance. The FLAXE front-end electronics is based on existing readout ASIC called FLAME (**F**ca**L** **A**sic for **M**ultiplane r**E**adout), designed for silicon pad detectors in the LumiCal calorimeter of a future linear collider. The main specifications of the FLAME ASIC are shown in table 1 (left). A block diagram of FLAME, a 32-channel ASIC designed in TSMC CMOS 130nm technology, is shown in Fig. 8. FLAME comprises an analog front-end and 10-bit ADC in each channel, followed by a fast data serialiser. It extracts, filters and digitises analogue signals from the sensor, performs fast serialisation and transmits serial output data. As seen in Fig. 8, the 32-channel chip is designed as a pair of two identical 16-channel blocks. Each block has its own serializer and data transmitter so that during operation two fast data streams are continuously sent to an external data acquisition system (DAQ). The biasing circuitry is common to both 16-channel blocks and is placed in between. Also the slow control block is common and only one in the chip. During standard operation, the 10-bit ADC samples the front-end output at a rate of up to 20MSps. The analogue front–

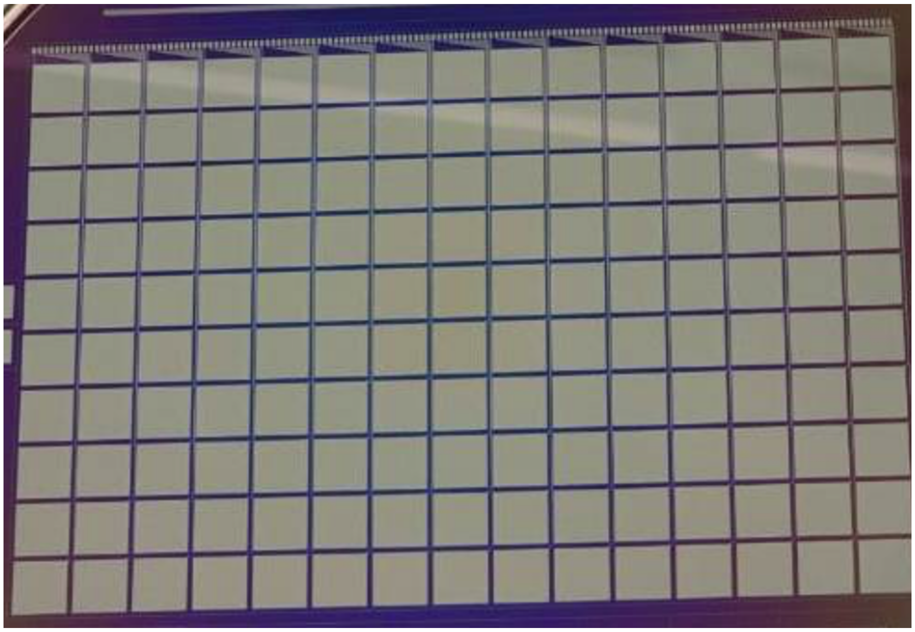

Figure 6: Picture of the GaAs sensor. On the top of the sensor the bond pads are visible.

end consists of a variable gain preamplifier with pole-zero cancellation (PZC) and a fully differential CR–RC shaper with peaking time $\sim 55\,\mathrm{ns}$. The shaper includes also an 8-bit DAC for precise baseline setting. The analogue front-end consumes in total $1-1.5\,\mathrm{mW/channel}$. The ADC digitises with 10-bit resolution and at least $20\,\mathrm{MHz}$ sampling rate. The power consumption is below $0.5\,\mathrm{mW}$ per channel at $20\,\mathrm{MS/s}$. In order to ensure the linearity of the ADC, the input switches are bootstrapped, reducing significantly their dynamic resistance.
The architecture of FLAXE ASIC will be very similar to the existing FLAME design. In particular the same analog signal processing scheme will be kept. A few modifications are needed, mainly in the digital part. The fast data transmission components will be replaced by a simpler and slower data transmitter to reduce the complexity and the cost of the subsequent FPGA-based back-end and DAQ system. This is possible, since the data rate and data volume is much less than for LumiCal. In addition, zero suppression will be implemented in the chip to decrease further the data volume. Depending on the sensor type which will be used in the experiment, small adjustments in analog front-end (e.g. charge-to-voltage gain) may be also needed. **[WLO: some information on the dynamic range might be helpful here]**

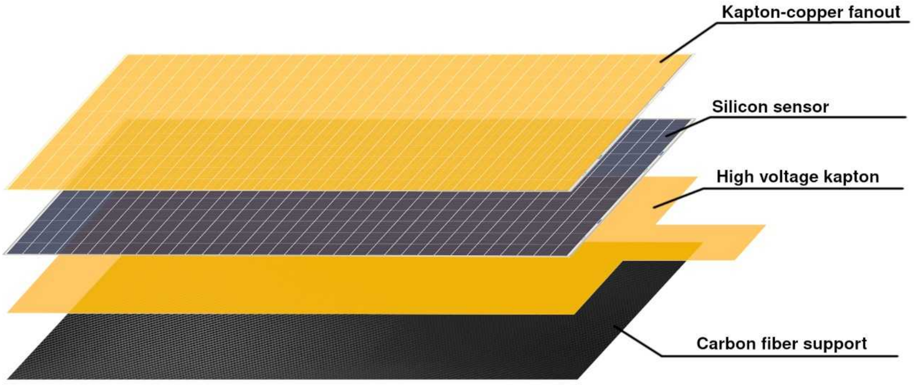

Figure 7: The structure of the assembled detector plane using a Kapton fan-out for the signal routing. The total thickness of the plane is about 650 μm for silicon sensors and 850μm for GaAs sensors .

Variable	Specification
Technology	TSMC CMOS 130 nm
Channels per ASIC	32
Power dissipation/channel	$\sim 2\ mW$
Noise	$\sim$1000 e^-@10 pF + 50e^-/pF
Dynamic range	Input charge up to $\sim 6pC$
Linearity	Within 5% over dynamic range
Pulse shape and	T_{peak} $\sim$50 ns
ADC bits	10 bits
ADC sampling rate	up to $\sim 20\ MSps$
Calibration modes	Analogue test pulses, digital data loading
Output serialiser	serial Gb-link, up to 9 GBit/s
Slow controls interface	I^2C, interface single-ended

Table 1: Summary of the specifications of the FLAME ASIC.

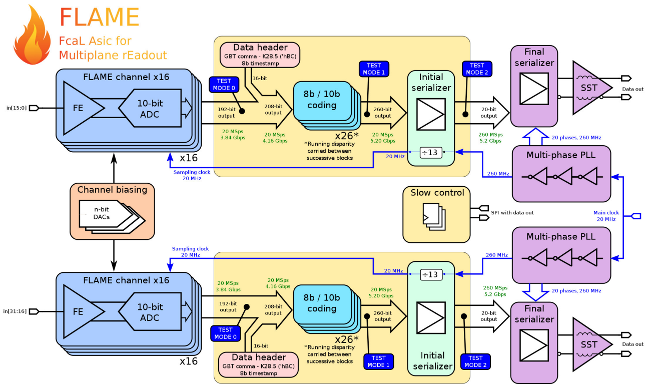

Figure 8: Block diagram of 32-channel FLAME ASIC

6 Interfaces and Integration

Discuss how this part is integrated with the rest of the LUXE experiment, e.g. the DAQ, the cooling, the timing synchronisation, .. **[WLO: Jakub and Yan please add was is new compared to the CDR]**

6.1 Trigger

For the normal operation of ECAL, the trigger will be provided by the Trigger Logic Unit (TLU) (figure 9).

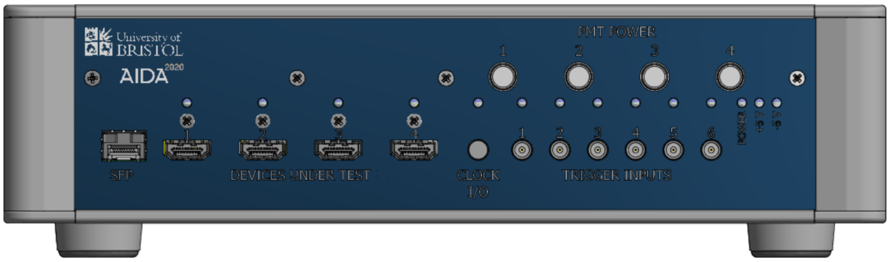

Figure 9: Schematic view of the TLU

The TLU will distribute to all the sub-detectors the trigger signal comming from:

- the electron beam with as frequency of 1 Hz
- the laser beam (interaction with the electron beam) with a frequency of 0.1 Hz

these trigger signals will be send to the ECAL FEBs via ?? (need help from Marek/Jakub)
during the construction construction of the ECAL at DESY, a cosmic muon trigger will be installed. It will consist of two scintillators and PMTs, connected to NIM modules to create the logic. This will provide a asynchronous trigger.

6.2 Data Acquisition

The five detector planes in each ECAL layer will be equipped with five front-end boards (FEB). The signals from the FEBs will be send to an FPGA board. One FPGA board will manage ten FEBs, comprising 2 calorimeter layers. The signals from the FEBs to the FPGA are fully digital, hence the FPGA boards can be positioned at a larger distance from the calorimeter, e.g. near or in the calorimeter rack. The communication between the FPGA boards and the DAQ computer is done through the user datagram (UDP) protocol. All FPGAs and the computer will be connected with a switch (1 Gb/s) located in the calorimeter rack.

7 Installation, commissioning and calibration

Discuss the plans for installation, including contingency plans, and the commissioning and in-situ calibration strategy.
[WLO: Yan and Jakub to review] Should also discuss decommissioning at the end of lifetime of LUXE.

7.1 Installation

[HA: Copied from material sent to Louis - to be properly formatted with added text if necessary]
Prior to ECAL installation, it will be calibrated in an electron test-beam, using at least one fully equipped ECAL tower. Apart from a function test of all subsystems and the DAQ, the energy resolution will be measured as a function of the electron energy, and the energy scale will be calibrated.
Just before placing ECAL in the area, the subsystems of the complete ECAL will firstly be tested in the laboratory and secondly a full system test will be done. This will allow to document the status of all subsystems just before installation, and potentially faulty components might be replaced.
For the final installation in the area the services have to be prepared in advance, i.e.

- The table placing the ECAL is ready
- All LV, HV and data cables are installed to connect the ECAL subsystems with the rack in the

The the following actions will be done in the given time and number of people :

- Move the ECAL to the area and place it on the table (rough weight: 50 kg, need crane); time: 1 day; person power: 1 technician (DESY), 2 physicists.
- Move the electronics racks to the area next to the ECAL (time and personpower included in the previous item.
- Survey, to define the position of ECAL precisely; time: $\frac{1}{2}$ day; person power: experts from DESY/XFEL survey, 1 physicist.
- Connecting the cables between ECAL and the rack; time: 1 day; person power: 1 electronics engineer, 1 technician, 1 physicist.
- Tests of HV, LV and data connections; time: 1 day plus 2 days reserve for potential replacements; person power: 1 electronics engineer, 2 physicists.

Hence for the installation of the ECAL in the area between 3.5 to 5 days are needed. The action will be performed by 2 physicists, 1 electronic engineer and 1 technician (partly provided by DESY), and the DESY survey team.

7.2 Commissioning

[WLO: Yan and Jakub]
After Installation, the full system test will be repeated. Low voltage settings and currents drawn by the sensors and the FE ASICs will be checked. With a special trigger pedestal data will be taken, and the pedestal values and width monitored, as a proof of stability and readiness for operation.

7.3 Calibration Strategy

In order to calibrate the energy response of the calorimeter, a measurement in an electron beam at several beam energies in the relevant range is foreseen. For these measurements at least one ECAL tower has to be fully instrumented with sensor planes and read-out electronics. The energy response and the energy resolution will be measured in steps of 1 GeV electron energy, and a comparison with the results of a *Geant4* simulation.

7.4 Decommissioning

[WLO: to be written by WL] The decommissioning of the ECAL will be done by the laboratories having developed and build the ECAL, i.e. JINR Dubna, the Tel Aviv University, The Tomsk Sate University and the AGH-UST Cracow. About a potential further use of the ECAL, or a dismantling, the involved parties will decide before the end of the experiment. In case of a dismantling, each laboratory will take back the components delivered by them. The time needed for decommissioning depends on a potential activation of the material, e.g. near the beam line. About a potential intermediate storage at

DESY the parties will propose an agreement with DESY before the end of the experiment.

8 ORAMS: Operability, Reliability, Availability , Maintainability and Safety

Discussion of challenges and approaches related to these five aspects for the system. **[WLO: HA will look into it]**
The number readout channels ECAL is about 25000, orchestrated by 5 FPGAs. Since readout frequency during normal data taking is 10 Hz, there should be no problem with the speed of readout and data transfer. The radiation dose for sensors and FE electronics is relatively low (we should give a number here), hence radiation damage is not expected. Solid state sensors are devices of high reliability. There will be no danger of overvoltage break-through or sparks. The change of the leakage current due to temperature changes will be kept small by air conditioning of in the area, with a maximum temperature drift of $\pm 1K$. The ECAL is modular. In case of malfunctioning of a detector plane it can be replaced by a spare part within a few days of access. For the replacement of faulty FE ASICs or FPGAs less than a day will be needed. The same holds for the Low Voltage and High Voltage power supplies. The bias voltage for the sensors will be around 100 V. High Voltage connectors and cables will be used matching the safety requirements.

9 Project Organisation

[WLO: WL will incorporate previously collected input, HA will add risk analysis]
Includes organisation of work at institutions, discussion of main technical milestones (e.g. internal or external reviews, test beam campaigns etc.) and interfaces to common services.
Also discusses which institution contributes how.

9.1 Human and financial resources

Estimate of human and financial resources required. For the financial resources the sources (e.g. company quotes, experience from previous work...) and uncertainties should be provided. For the human resources it should be clarified what type of people are needed.

9.2 Schedule and milestones

Describe here the schedule and the milestones. Normally we will try to be ready for installation by January 2024. There will be risks to that which we can treat as risks and the mitigation is to install later.

Table 2: Cost estimates for the various components. The comment discusses the source of the prize and its uncertainty where possible.

Component	Cost (kEur)	Comment

Table 3: Risk description, potential impact on cost and schedule, probability to occur and strategy on how to mitigate the risk.

Description	Cost	Schedule	Prob.	Strategy

The level of detail of milestones should be quite high but maybe we should put it partially into an appendix.

9.3 Risk management

Plain text that discusses the main risk factors, how/if they impact cost and/or schedule, their probability and how they are mitigated. **[HA: sensors, chip delivery for FE]** There are two dimensions, the impact and the probability. We separate the impact on the cost and the schedule and use the following terms for impact risks:

- Insignificant: Risk is easily mitigated by day to day process.
- Minor: Delays up to 10% of schedule. Cost increase up to 10% of budget.
- Moderate: Delays up to 30% of schedule. Cost increase up to 30% of budget.
- Major: Delays up to 50% of schedule. Cost increase up to 50% of budget.
- Catastrophic: project abandoned

For the budget, the denominator used is the budget of that area, i.e. if it is in the phase-0 laser area it is relative to the total phase-0 laser costs. In any case for the cost also the absolute numbers are given, so we can easily renormalize if the total cost changes.
For the schedule, the fraction is taken relative to 24 months, assuming a start in January 2022 and a readiness of January 2024.
The probability of a risk to be realized is quantified as, rare: ($< 3\%$), unlikely (3-10%), moderate (10-50%), likely (50-90%) or certain ($> 90\%$).
Table~3 shows a template for a summary of the risks.

9.4 Responsibilities

Discuss which institute takes responsibility for what aspect.

10 Further tests planned

Here we include future tests and studies still needed before being sure that the system will meet the requirements and can be installed etc.

Appendices

A Title of Appendix A

Can have appendices here, e.g. for very technical information that would disrupt the flow of the main note.

B Title of Appendix B

C All notes

This is the list of all notes and the lead editors:

- Technical infrastructure and beam instrumentation at LUXE: Louis Helary and Stewart Boogert
- Laser, interaction chambers and timing system: Matt Zepf et al.
- Laser diagnostics: Matt Zepf et al.
- Common aspects (Simulation, Data Acquisition, Data Quality and Computing): Matthew, Sasha, Federico et al.
- Pixel tracker: Noam Tal Hod
- EM calorimeter: Halina Abramowicz and Wolfgang Lohmann
- Scintillation screens: Matthew Wing and John Halford
- Cherenkov detectors: Ruth Jacobs
- Gamma Profiler: Marco Bruschi
- Gamma Spectrometer: Gianluca Sarri
- Backscattering calorimeter: Maryna Borysova
- physics performance: Beate Heinemann

.... (to be finalized)