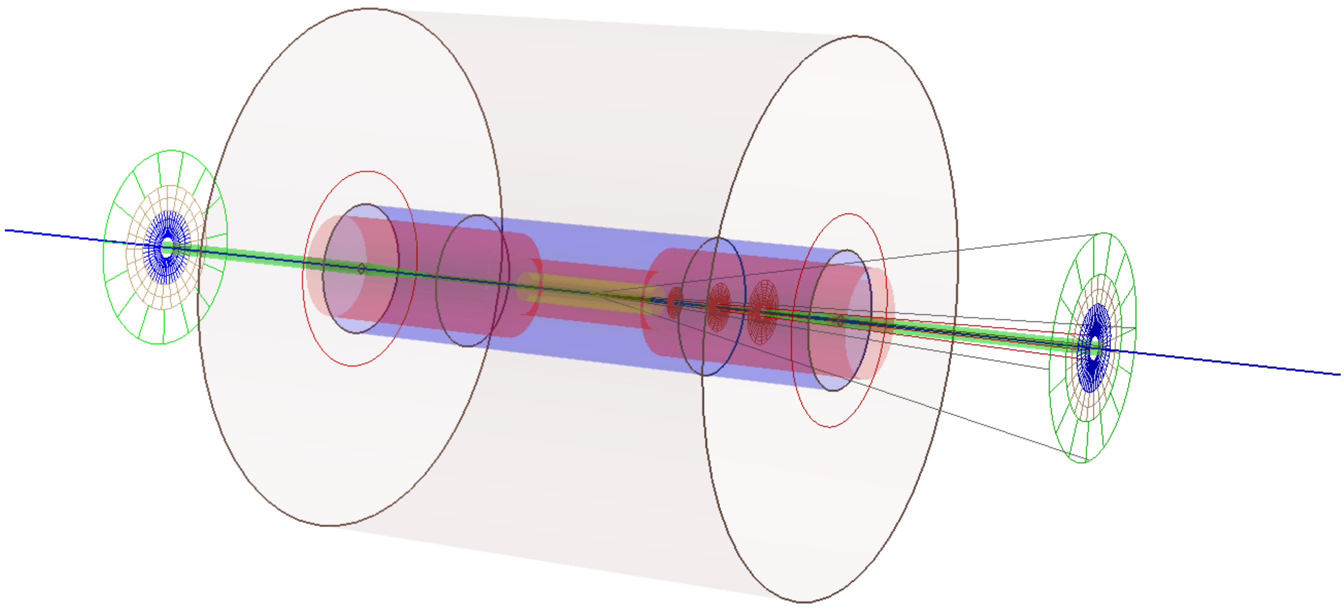
STAR R&D Proposal for an Event Plane and Centrality Detector for BES II



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1 Physics Motivation

The beam energy scan (BES) program at RHIC started in the year 2010 with the goal to find signatures for a QCD phase transition and critical point [1]. So far, STAR has taken data at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, and 62.4 GeV in the BES program. Furthermore, it is planned in the year 2014 to take data at $\sqrt{s_{NN}}$ = 15 GeV. With this last run, the BES phase I will be completed. BES phase II is anticipated in the years 2018-2019 and will cover an energy range from 5 to 20 GeV in collider mode and even lower energies in fixed target mode.

The beam transverse size at the lowest RHIC energies was significantly broader compared to $\sqrt{s_{NN}}$ = 200 GeV. This caused a lower luminosity, but also reactions of Au ions with either beampipe or supporting structure materials. At $\sqrt{s_{NN}}$ = 7.7 GeV 80-98% of the triggered reactions came from such kind of beam on beampipe collisions. Since the overall reaction rate was still relatively low, all triggers could be recorded. The situation will change with the installation of an electron gun, which will be used to cool the heavy-ion beams. With the additional stretching of the beam bunches, a total increase in luminosity of about a factor 10 is expected []. With such a high luminosity, it is essential to trigger on all good Au+Au collisions, which happen in the central part of the TPC.

The most promising measurements for the search of the critical point and the finding of signatures for a phase transition rely either on a centrality measurement (e.g. higher moments of net-protons [2]) or on an event plane (e.g. v_1, v_2, and azimuthal HBT). It turned out during the analysis of the BES I data, that neither the centrality nor the event plane determination was ideal for our purpose. The fluctuation analyses are sensitive to self-correlations between the centrality determination using TPC tracks and the actual measurement itself. It was tried to reduce those self-correlations by using different parts of the TPC for both measurements or by using different particle species. Both procedures are a workaround for a TPC independent centrality measurement and do not exclude self-correlations. The usable acceptance and granularity of the BBC detector, which has a large pseudo-rapidity gap to the TPC, is far from being suitable to be used as a centrality detector.

Indeed the decay of hadronic resonances such as the Delta and the rho meson etc. lead to correlations over roughly one unit of rapidity between the decay products. As a result, a centrality measurement based on the number of charged particles needs to be spearated by at least one unit of rapidity from the region where the cumulants are being determined. Otherwise, the tight cantrality selection required to minimize system size fluctuations will severely bias the fluctuations of the net-baryon (proton) number and the net-charge, and will likely shadow the dynamical fluctuations arising from a possible phase structure in the QCD phase diagram [3]. (Volker Koch)

Flow measurements suffer from similar limitations. It is well known that self-correlations in flow measurements, from now on called non-flow, are one of the main systematic effects. Non-flow can also be caused by resonance decays or from particle/EP-jet correlations. It can be reduced by increasing the pseudo rapidity (η) gap between the particles of interest and the event plane measurement. For identified particle elliptic flow measurements at the lower energies the TPC η-gap event plane is used. In order not to lose too much statistics, a typical η-gap is not larger than 0.1-0.5. A dedicated event plane detector at a pseudo rapidity of 4 would result in an η-gap of about 3 and thus limit non-flow effects to a minimum.

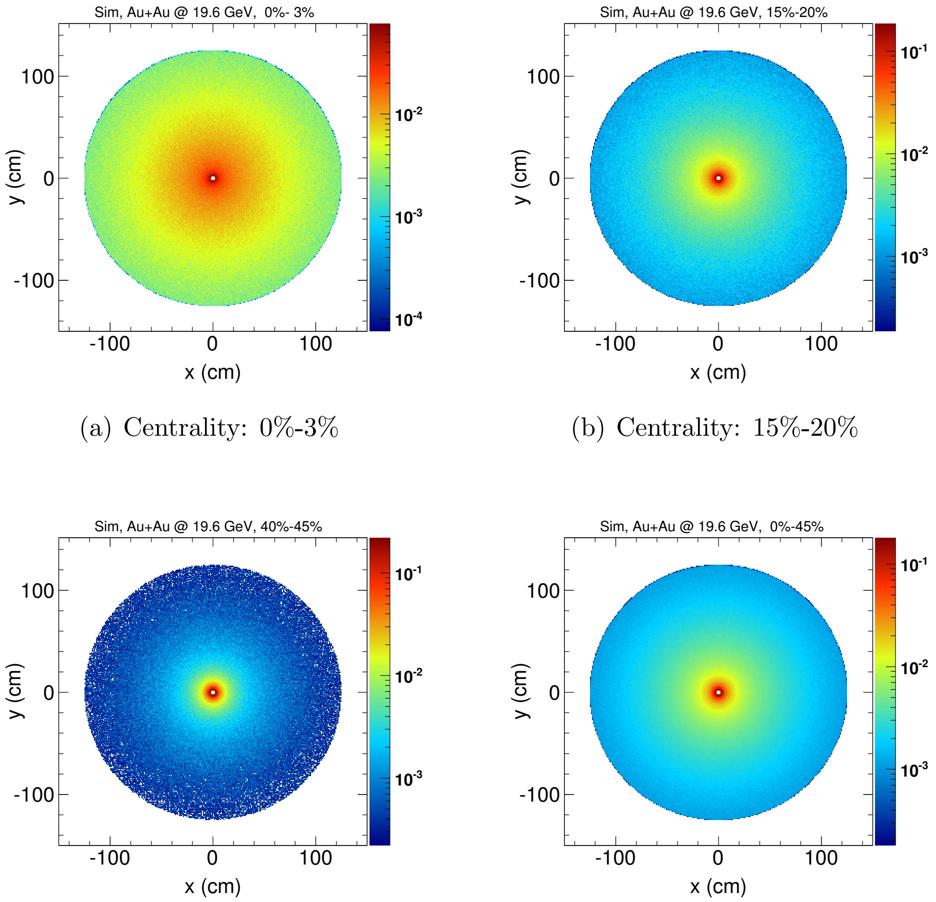
For directed flow (v_1) measurements, where the v_1 signal at mid-rapidity is small, a forward detector to determine the event plane is absolutely necessary. The double zero crossing of the dv_1/dy slope of net-protons is, together with the particle anti-particle v_2 difference [4, 5], one of the most promising results from the BES I program [6]. It could be related to the softest point of the equation-of-state and a first order phase transition. For this measurement, the BBC or ZDC/SMD event plane was used. It is evident that the ratio of produced particles to sheared off spectators in the acceptance of those detectors changes significantly with energy. This can bias the v_1 results exactly in the energy range of the double zero crossing of dv_1/dy. A forward detector with significant radial segments, which correspond to segments in η, can be used to study and limit such bias. It will be furthermore shown in the following section that the proposed dedicated forward detector has a significantly higher event plane resolution compared to the BBC, which will reduce the statistical error bars.

Based on these physics requirements we list the coarse specifications for the proposed **E**vent **P**lane and centrality **D**etector (EPD) in the following:

- Large rapidity gap to TPC to minimize non-flow and self-correlations
- Significant amount of radial (η) segments to reduce (EP) biases
- Large acceptance to maximize the EP resolution
- Symmetric in pseudo rapidity (east and west side) to determine an unbiased EP resolution and to measure as many particles as possible
- Large granularity (single hit determination) for good EP and centrality resolution
- Fast detector to be used as a trigger

We have to ensure that the new detector can fully replace the BBC. This includes the BBC's use for relative luminosity and local polarimetry measurements during RHIC beam operation with polarized protons [7]. To first order, this is achieved by ensuring that the acceptance of the Event Plane and Centrality Detector is larger than that of the existing BBC (inner) tiles, the design is top-down and left-right symmetric, with an improved segmentation. The segmentation in the radial and angular coordinates remains to be optimized, or at least demonstrated to be sufficient, for the anticipated instantaneous luminosities during future RHIC beam operation periods with polarized proton beams. In addition, the detector design will need to remain compatible with the trigger and 32-bit scaler subsystems.

We further want to study if the new detector can be helpful for the intended fixed target program for BES II. MORE TEXT TO BE ADDED.



(a) Centrality: 0%-3%

(b) Centrality: 15%-20%

(c) Centrality: 40%-45%

(d) Centrality: 0%-45%

Figure 1: Hit densities for simulated Au+Au events at $\sqrt{s_{NN}}$ = 19.6 GeV events at z = 375 cm for different centralities.

2 Simulations

We performed a series of Monte Carlo (MC) simulations to optimize the geometry of the proposed detector, based on the physics requirements. To minimize the overall size of the detector for a given acceptance, it would be good to place it as close as possible to the center of the TPC. The proposed detector will replace the BBC [8], which is currently located at z = ±375 cm. This position in z was also used for the simulations, since the available space in the forward direction even closer to the TPC is limited. The simulated detector has an inner radius of 4 cm and an outer radius of 125 cm.

The MC simulation input is based on PHOBOS $dN/d\eta$ [9] and STAR v_1 [6] measurements. We first sample a number of tracks based on STAR reference multiplicity distributions. Those are scaled to the PHOBOS $dN/d\eta$ distributions in the STAR acceptance. For the measured PHOBOS centralities from 0%-45% we sample the η values for each track. The p_T values are sampled from a Boltzmann distribution, which are adjusted to the mid-rapidity slopes from STAR. The direct flow (v_1) for each track was assumed to scale linear with pseudo-rapidity and the overall scale was also adjusted to measured data from STAR. We also included an elliptic flow v_2 component based on published STAR data from the BES [5]. A 5% Gaussian smearing for v_1 and v_2 was applied to account for fluctuations. The relative angle of the particles to a random event plane angle was finally sampled from the following function:

$$\frac{dN}{d(\phi - \Psi)} \sim 1 + 2v_1 \cos(\phi - \Psi) + 2v_2 \cos(2\phi - 2\Psi). \tag{1}$$

A total of 1M events was simulated for $\sqrt{s_{NN}}$ = 19.6 at z = 0 cm. The simulated particles were tracked through the (full) STAR magnetic field. Simulations for the STAR forward tracker in the same acceptance have shown that multiple scattering is a negligible effect for the event plane reconstruction. The hit density per cm^2 was calculated based on the intersection points of the tracks with the detector planes. The two dimensional hit densities for various centralities for $\sqrt{s_{NN}}$ = 19.6 are shown in Fig. 1. In the upper panel of Fig. 2, we show the hit densities as a function of the radius. An interesting and important feature of the distributions is that the hit density is higher for peripheral events at small radii compared to central events. The pattern switches with increasing radius due to the changed ratio of produced particles to sheared off spectators.

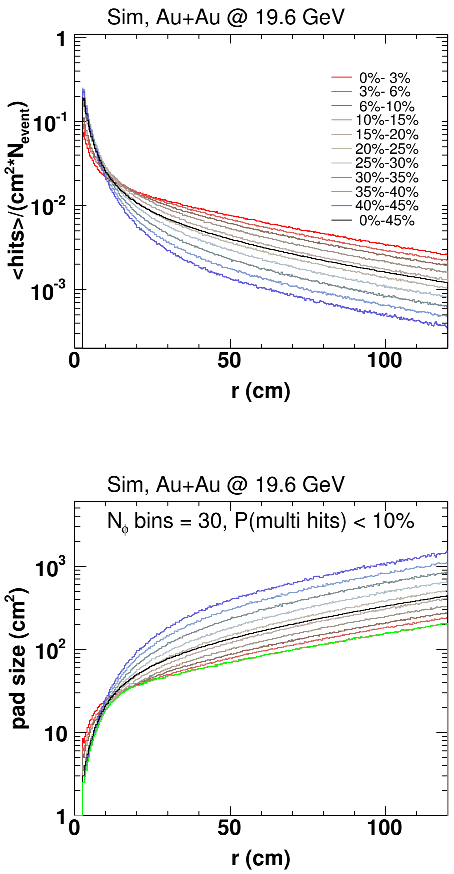


Figure 2: Upper panel: Charged particle hit density from simulated Au+Au events at $\sqrt{s_{NN}}$ = 19.6 GeV events at z = 375 cm as a function of the radius to the beam axis for various centralities. Lower panel: Maximum pad size as a function of the radius to the beam axis for a multi hit probability of $\leq$ 10% and 30 segments in azimuthal direction.

Based on the azimuthal symmetry of the system, we used a pie sliced detector layout. The geometry is defined by a number of equally sized azimuthal segments and radial segments, which can vary in Δr. For a given energy, the size of the pads is fully determined for any radius by choosing a number of azimuthal segments and a maximum double hit probability per pad. With those two parameters and the known hit density distribution, one can calculate the optimal pad size as a function of the radius. An example is shown for various centralities for $\sqrt{s_{NN}}$ = 19.6 GeV in the lower panel of Fig. 2. The minimum over all curves in Fig. 2 defines the optimal pad size for any centrality, as shown by the green curve. A possible geometry based on the calculations is shown in Fig. 3 with 20 radial segments and a multi-hit probability $\leq 10\%$. Such kind of setup would result in about 500 tiles per detector plane.

We evaluated the event plane and centrality resolution for various detector geometries. The optimal pad sizes were calculated for 6, 8, 10, 12, 20, and 30 ϕ segments and for multi-hit probabilities per pad smaller than 10%, 20%, 30%, 40%, or 50%. As references we use the optimal event plane resolution within the detector acceptance and the BBC (inner tiles) event plane resolution. In contrast to reality, we assume for latter that every inner tile has its own read out channel and that every particle hit can be counted. A single hit counting (pulse height measurement, ADC) was also assumed for the EPD detector. Figure 4 shows the event plane resolutions for different detector setups as a function of the centrality bin.

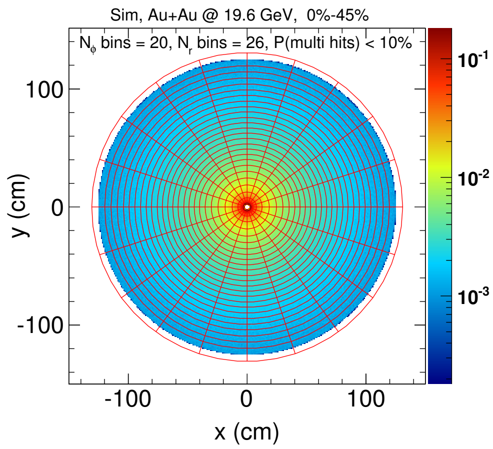


Figure 3: Detector setup with 20 azimuthal segments and for a multi hit probability $\leq$ 10%.

There is a significant difference ($\sim$20%) in the EP resolution between the EPD detector layout with 6 and 12 azimuthal segments, whereas more than 12 azimuthal segments do not contribute much more to the EP resolution. For 30 azimuthal segments we reach the optimal resolution. The r-segmentation has a much smaller impact on the EP resolution. The improvement compared to an optimal (see above) inner BBC setup is up to a factor 5 for the most central events and still 60% for the centrality bin 40%-45% . The corresponding improvement for an elliptic flow analysis using the first harmonic event plane would be even larger.

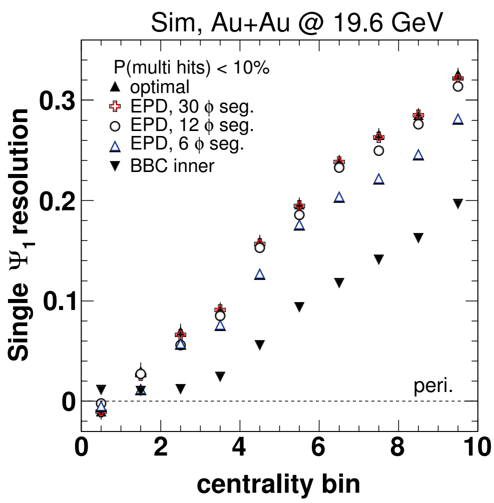


Figure 4: First harmonic (Ψ_1) event plane resolution as a function of centrality for different detector setups. Most central events are on the left, the most peripheral bin shown corresponds to 40%-45%. The resolution for the EPD setup with 30 azimuthal segments coincide with the optimal resolution.

For our centrality studies, we used Glauber calculations, based on measured STAR data at $\sqrt{s_{NN}} = 19.6$ GeV, to get the correlation between the number of produced charged particles and the impact parameter b. Figure 5 shows the correlation for single hit counting (left) and for a multi-hit probability per detector tile of 50% (right). In this calculation it was assumed that multiple hits per tile cannot be distinguished. The projections

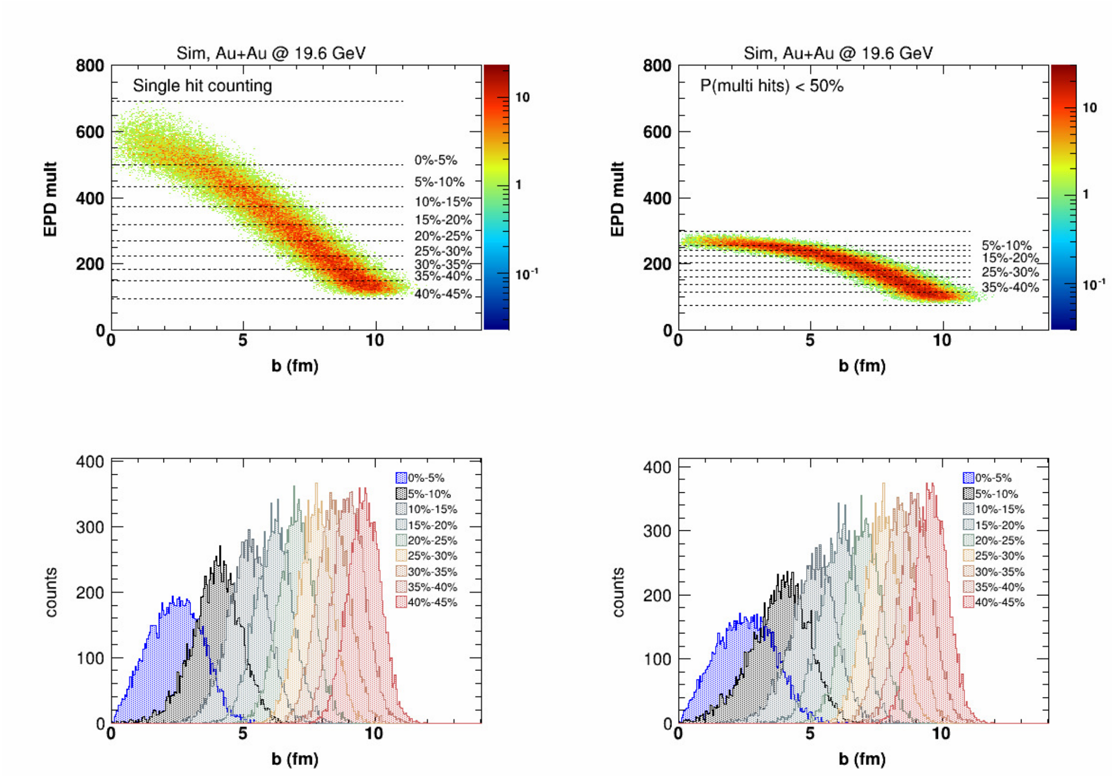


Figure 5: Upper panels: Multiplicity in the EPD acceptance as a function of the impact parameter b for single hit counting (left) and a multi-hit probability per detector tile of 50% (right). Lower panels: Projections to the impact parameter axis for different centrality selections.

for different centrality selections to the impact parameter axis are shown in the lower plots. A clear saturation/flattening effect is observed for increased multi-hit probabilities (larger tile sizes). Based on the b-projections we calculated the b-purity (90% confidence interval) for different centrality selections as a function of the multi-hit probability, as shown in Fig. 6. The purity for the most central collisions significantly drops with increased mulit-hit probability, whereas the purity is almost constant for peripheral centrality selections due to the lower saturation probability. For multi-hit probabilities $\leq 10\%$ we achieve almost the optimal b-purity.

It is also obvious that a limited granularity will be more sensitive to any kind of multiplicity fluctuations in the saturation region of high multiplicity events. We further want to point out that a significant amount of sheared off spectator particles mixes with the produced particles in the forward region at lower energies. It is unclear how this will affect the determination of the centrality, but we think it will be crucial to have the capability to distinguish different η regions. Therefore, a significant number of radial segments will be important. This would be another advantage compared to the BBC detector.

3 R&D and Goals

Based on the physics requirements and the area to be covered, we decided to use scintillators plus silicon photomultipliers (SiPM) [10] for the detector. SiPM technology is rather new and not many high energy experiments have used them so far. Therefore one part of the R&D process will be to determine the overall performance of SiPM and check if they are good enough for our purpose. This includes tests of the radiation hardness, noise level, and signal shape for MIPs and multiple hits per scintillator tile. So far it is unknown how much radiation is expected in the forward region for BES II. Those estimations have to be done in the near future. We further have to adjust the SiPMs for the scintillator light wavelength. This may include the installation of wave length shifting (WLS) fibers, which depends of the specifications of the chosen SiPMs. We already have some basic experience with the combination of scintillators and SiPM at RNC/LBNL, which will help to get first test results quickly [11].

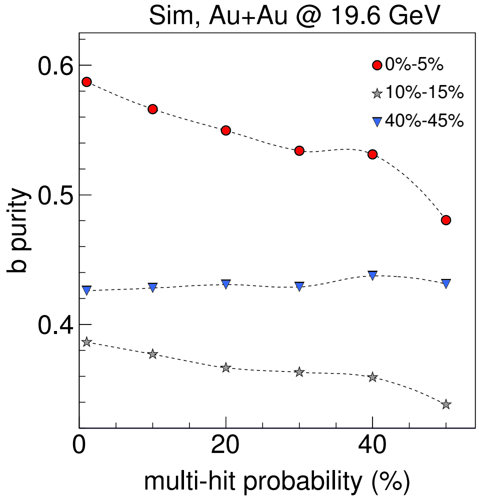


Figure 6: Impact parameter purity for simulated Au+Au events at $\sqrt{s_{NN}} = 19.6$ GeV as a function of the multi-hit probability per detector tile for three different centrality selections.

The arrangement and connection of SiPMs and scintillators has to be developed. We already started simulations to calculate the light emission and light collection in the scintillators and SiPMs. The simulations will cover several tile geometries, scintillator materials, and positions and quantities of SiPMs to get the detector response functions (DRF). Based on the results of those simulations, we will define the exact tile geometry and perform a series of experiments, which may include several arrangements as shown in Fig. 7. Emphasized in the figure is only the largest tile, which will be most problematic due to the small ratio of SiPM area to tile size, but similar tests have to be done for various tile sizes. One goal will be to validate the simulated DRF which will finally lead to the full detector design.

The polishing and wrapping of the scintillators has to be developed and tested. To reduce the amount of work and costs, a trapezoidal shape for the individual tiles will be used instead of having a curved surface. If WLS fibers are needed, a technique has to be developed to install them and to optimize the connection to the SiPMs.

The first tests will be done with commercial hard-, and software provided by the SiPM manufacturer. In this stage we will also perform basic trigger tests with cosmics and a two or three tile setup. We switch to STAR customized hardware and build a demonstrator once the basic tests are done and the optimal SiPMs and scintillators are selected. This may include modifications of the existing hard-, and software. MORE TEXT TO BE ADDED.

Item	**Costs in $**	**Overhead**
SiPM	XYZK	XYZK
Scintillators	XYZK	XYZK
Cables and connectors	XYZK	XYZK
Readout electronics and software	XYZK	XYZK
Workshop	XYZK	XYZK
Travel	XYZK	XYZK

Table 1: Requested R&D budget.

The result of the R&D studies should be answers to the following questions:

- Which combination of SiPM and scintillator is optimal?
- Is the radiation hardness of the chosen SiPM good enough for our purpose?
- What is the optimal pad geometry for different radii?
- Are waveshifters needed and if yes, how do we install them?
- What is the optimal connection between SiPM and scintillator?
- Can multiple hits be distinguished, and which kind of ADC is needed?

The final stage of the R&D will be building a prototype of two fully equipped sectors with about 16 channels each. Those will be installed on the west and east side of STAR in 2016 or 2017 and tested under realistic conditions with a full integration into the DAQ system. From this final test we can scale the performance and multiplicities to the fully equipped detector.

We want to point out that this project will definitely benefit from the experience of the FMS preshower development, as it is using similar technology [12].

4 Budget Request

Laboratory space for the test setup will be available at LBNL. Basic equipment, like oscilloscopes and power supplies will also be provided by the RNC group. The requested budget in table 1 includes the material for the basic tests to develop the needed techniques, and further the material for the demonstrator and the two prototype sectors. We further request some money for workshop related operations. We also request a travel budget, which will be mostly relevant for the last phase of the development where we install and test the prototype.

The LBNL overhead for BNL funded projects adds up to 23.91% and is added separately.

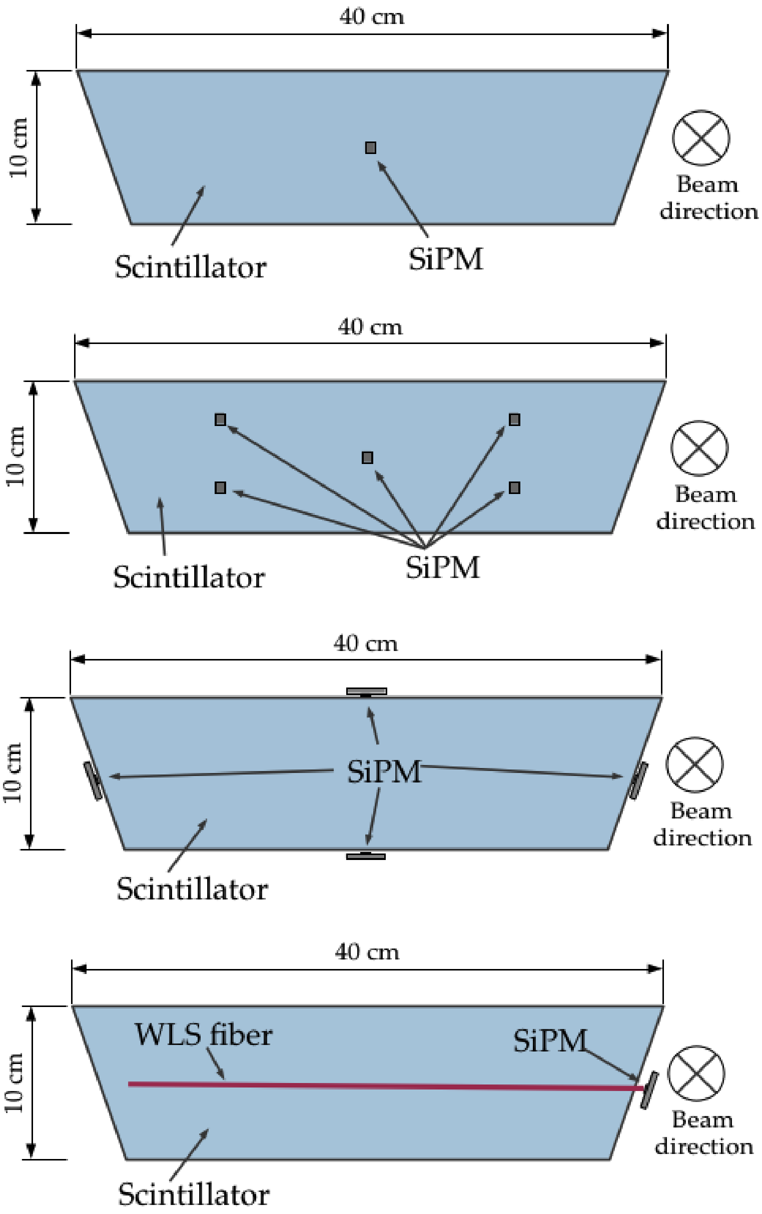


Figure 7: Drawing of a large scintillator tile and several possible arrangements of SiPMs, which have to be simulated and tested. The bottom drawing shows the additional installation of wave length shifting (WLS) fibers, which may be needed.

5 Acknowledgments

References

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