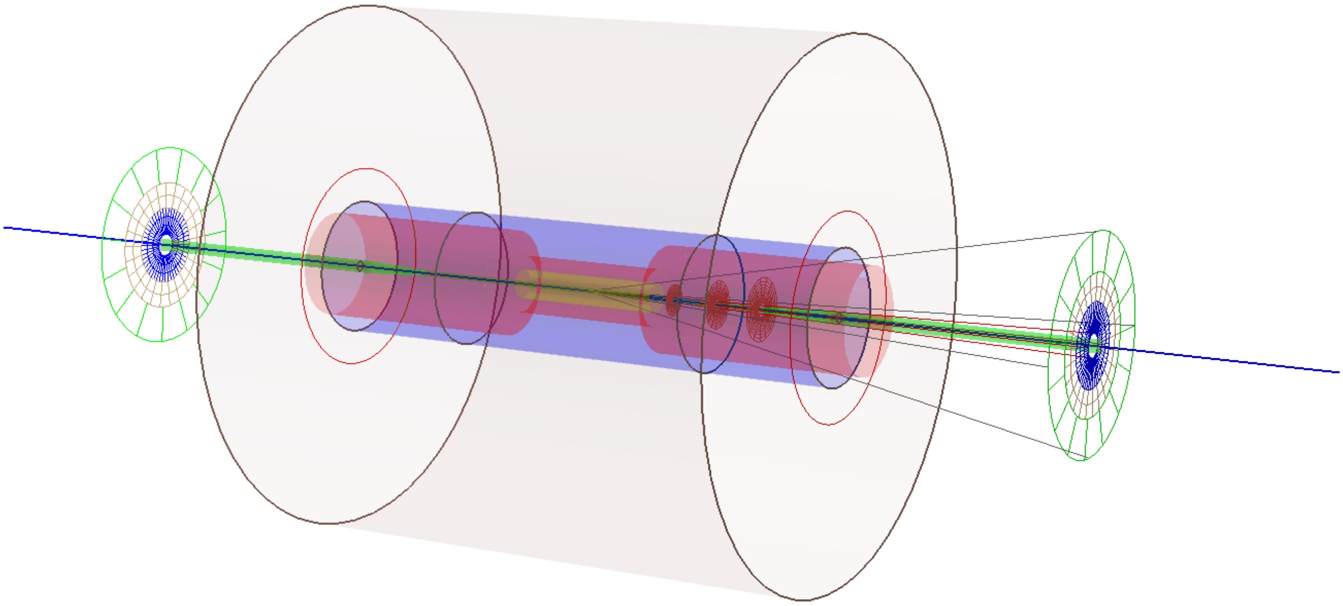
STAR R&D Proposal for an Event Plane and Centrality Detector for BES II



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1 Executive Summary

This document is a request for funds to carry out R&D to support a future proposal for a new, dedicated event plane and centrality detector in the forward directions of STAR for Beam Energy Scan (BES) phase II, which is anticipated for the years 2018-2019. The new detector will cover the pseudo-rapidity range between 1.8 and 5, with high radial and azimuthal segmentation. The current baseline detector design utilizes scintillators and silicon photomultipliers.

The proposed R&D activities will enable construction of a prototype detector to be ready for beam tests in 2016. The major proposed R&D activities are as follows:

- Study of light transport/collection simulations for various tile geometries
- Investigation of techniques for polishing, wrapping, installation of WLS fibers, and the connection of SiPMs and scintillators
- Development/integration of a STAR compatible readout system
- Construction of a demonstrator for basic trigger tests
- Building and integration of a two sector prototype to be installed and tested in the engineering run run in 2016

The R&D budget request is $75K, including overhead.

The R&D proposal is structured in the following way. In section 2 we elaborate on physics motivations and the need for the proposed detector. Section 3 summarizes the simulation results, in section 4 we elucidate the R&D needs and goals, and in section 5 we list the R&D costs.

2 Physics Motivation

The beam energy scan (BES) program at RHIC started in the year 2010 with the goal of finding evidence 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 phase I program. Furthermore, it is planned in the year 2014 to take data at $\sqrt{s_{NN}}$ = 14.6 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 ions in the beam halo 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, which will result in a several kHz trigger rate at the highest BES energies. To exploit this, it is essential to trigger on all good Au+Au collisions with a reconstructible vertex.

The most promising measurements in the search of the critical point and 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 femtoscopy). Analysis of the BES I data showed that neither the centrality nor the event plane determination was optimized for this purpose. Fluctuation analyses are sensitive to physics correlations between the centrality determination using TPC tracks and the actual measurement itself. These correlations can be reduced by using distinct regions of the TPC for both measurements or by using different particle species. Both procedures are only an approximation to a TPC-independent centrality measurement and do not in practice exclude physics correlations. The following statement emphasizes the need for a TPC-independent centrality measurement:

"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 separated by at least one unit of rapidity from the region where the cumulants are being determined. Otherwise, the tight centrality 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)

The usable acceptance and granularity of the currently installed Beam Beam Counter (BBC) detector, which is separated from the TPC by a large pseudo-rapidity gap, is far from optimal to be used as a centrality detector. The BBC has 18 inner and 18 outer hexagonal tiles with diameter of 9.64 cm, and 38.6 cm respectively. Those tile sizes are too large to provide single hit determination, as will be shown in section 3. Furthermore some inner and outer tiles share the same photomultiplier channel and therefore lower the centrality and event plane resolution. The outer tiles are, for several reasons, usually not used for heavy-ion analyses. Therefore, the usable acceptance of the BBCs is reduced to the inner tiles, which cover about 25 cm in radius.

Flow measurements suffer from similar limitations as the fluctuation measurements. It is well known that physics 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 jet correlations. Non-flow can be reduced by increasing the pseudo-rapidity (η) gap between the particles used for the correlation measurement and the event plane measurement. For identified particle elliptic flow measurements at lower energies, the TPC η-gap event plane is used. To preserve adequate 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 units of pseudo-rapidity 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 high radial segmentation (which corresponds to high segmentation in η) can be used to study the η dependence of the reconstructed event plane and limit such biases. It will be furthermore shown in the following section that the proposed dedicated forward detector has a significantly higher event plane resolution than the BBC, which will reduce statistical error.

Elliptic flow (v_2) measurements for inclusive charged hadrons and identified particles were the first results published from the BES I program [4, 5, 7]. With the high luminosity runs of BES II we will be able to reveal the flow behaviour of multi-strange particles, like Ω and ϕ at the lowest energies. The new detector will guarantee a v_2 measurement of those particles with a forward event plane, which limits non-flow, and a sufficient event plane resolution.

The majority of femtoscopic analyses at STAR have provided measurements of correlation lengths (femtoscopic radii, R_i) which are integrated in azimuth. The first mature measurements of *azimuthally differential* radii, $R_i(\phi)$, are now headed to publication. This analysis, which measured $R_i(\phi)$ with respect to the second-order event plane, provides the average fireball eccentricity at kinetic freeze-out. The next step in the STAR azimuthal femtoscopy program is a first harmonic measurement. Such efforts could reveal a *tilt* of the fireball–in the reaction plane–away from the beam direction. The tilt angle at different momentum scales is linked to the freezeout distribution at different times [8], making it the only proposed experimental observable for probing the *space-time* evolution of the freeze-out shape. Finding the tilt angle depends on precise determinations of the first few Fourier components of the $R_i(\phi)$, but it is exactly this kind of signal that is smeared out by poor event plane resolution.

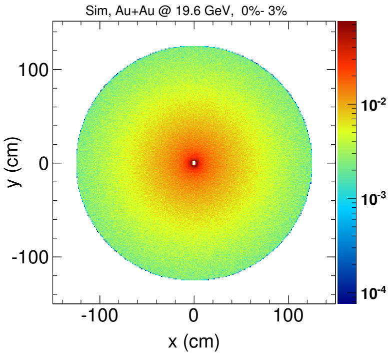
Based on these physics requirements we list the essential specifications for the proposed **E**vent **P**lane and centrality **D**etector (EPD) in the following:

- Large rapidity gap relative to the TPC to minimize non-flow effects and physics correlations
- Significant radial (η) segmentation 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
- Fine granularity (single hit determination) for good EP and centrality resolution

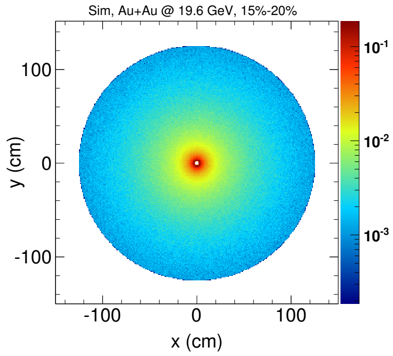
We have to investigate if the new detector can fully replace the BBCs. This includes the utilization of BBCs for relative luminosity and local polarimetry measurements during RHIC beam operation with polarized protons [9]. To first order, this is achieved by ensuring that the acceptance of the Event Plane and Centrality Detector is larger than that of the existing BBCs (inner) tiles, and that the design is up-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 must be 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. For that program, a gold target will be installed inside the beampipe at 2 m from the center of the STAR detector. This is to optimize the rapidity region which the TPC can cover in the boosted fixed-target center-of-mass reference frame. For the energy range of the BES II program, fixed-target center-of-mass will be boosted to rapidities ranging from 1.0 to 2.3 units. In the coordinate frame of the target, the EPD detector has coverage from $\eta = 2.3$ to 5.0 units. For the highest energies of the fixed target program, the TPC will cover from target-rapidity to mid-rapidity while the EPD covers from mid-rapidity to beam-rapidity giving STAR full rapidity coverage. For the lower energies of the BES II program, the EPD will cover projectile rapidities and can be used for triggering and centrality determination through the measurement of the number and distribution of spectator protons (the only particles in this rapidity region are protons and light nuclear fragments. The protons can be distinguished from the fragments using the amplitude of the signal). The physics goals of the fixed target program are similar to that of the rest of BES II program, i.e. searching for signatures of the first order phase transition through evidence of a softening of the equation of state. The most promising experimental signals are the directed and elliptical flow. The EPD will be crucial for these measurements by allowing for an independent determination of centrality and reaction plane. A similar benefit would be provided for a p+A BES II run which is currently under discussion.

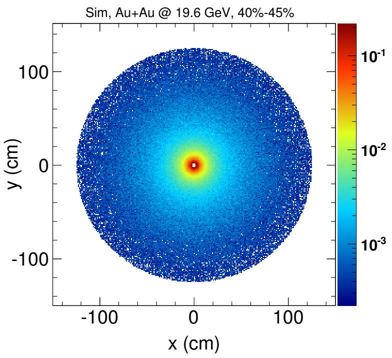
3 Simulations



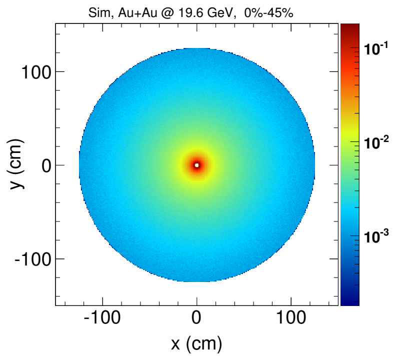
(a) Centrality: 0%-3%



(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.

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 [10], 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 $dN/d\eta$ [11] 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 directed flow (v_1) for each track was assumed to scale linearly 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 $\phi - \Psi$ between a particle and a randomly oriented event plane was finally sampled from the following distribution:

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

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 transverse 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 $\sqrt{s_{NN}} = 19.6$ GeV 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.

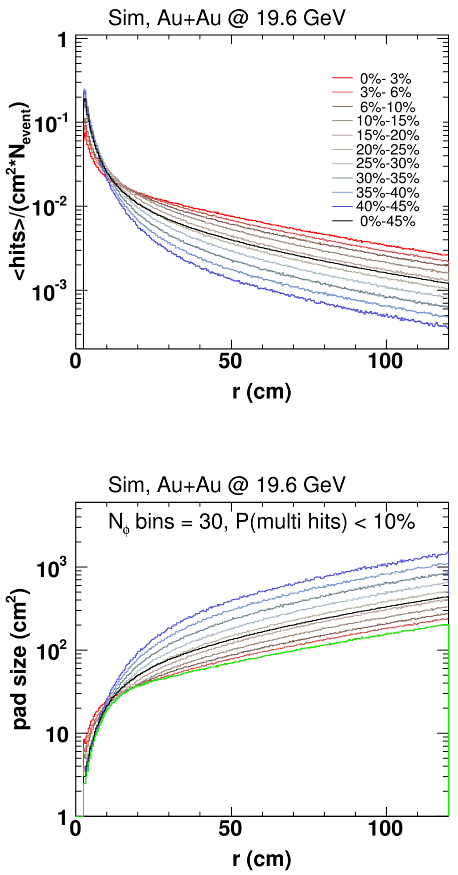


Figure 2: Upper panel: Charged particle hit density from simulated Au+Au events at $\sqrt{s_{NN}} = 19.6$ GeV events at z = 375 cm as a function of the radius to the beam axis for various centralities. Lower panel: Maximum pad size as a function of the radius to the beam axis for a multi hit probability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

Based on the azimuthal symmetry of the system, we used as a starting point a pie sliced detector layout. Such a layout is optimal to select different pseudorapidity regions, but other geometries, like hexagonal tiles, will be studied too. 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 multi-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 $\leq 10\%$. This kind of setup would result in about 500 tiles per detector plane. For the final detector we will minimize the number of different tile geometries.

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.

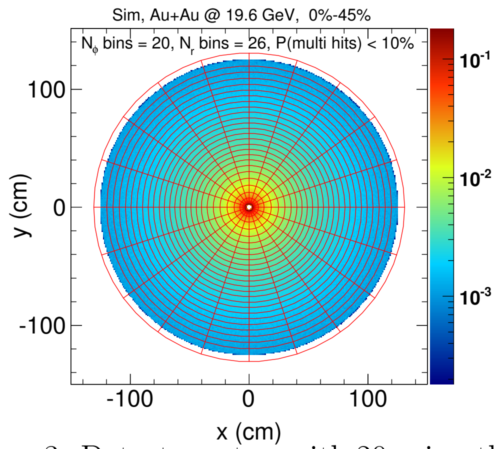


Figure 3: Detector setup with 20 azimuthal segments and for a multi hit probability $\leq$ 10%.

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.

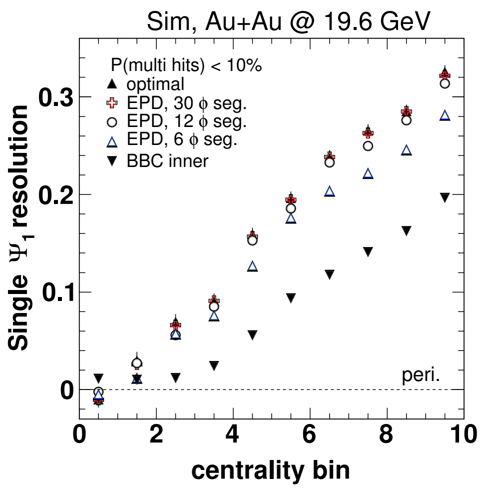


Figure 4: First harmonic (Ψ_1) event plane resolution as a function of centrality for different detector setups. Most central events are on the left, the most peripheral bin shown corresponds to 40%-45%. The resolution for the EPD setup with 30 azimuthal segments coincide with the optimal resolution.

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

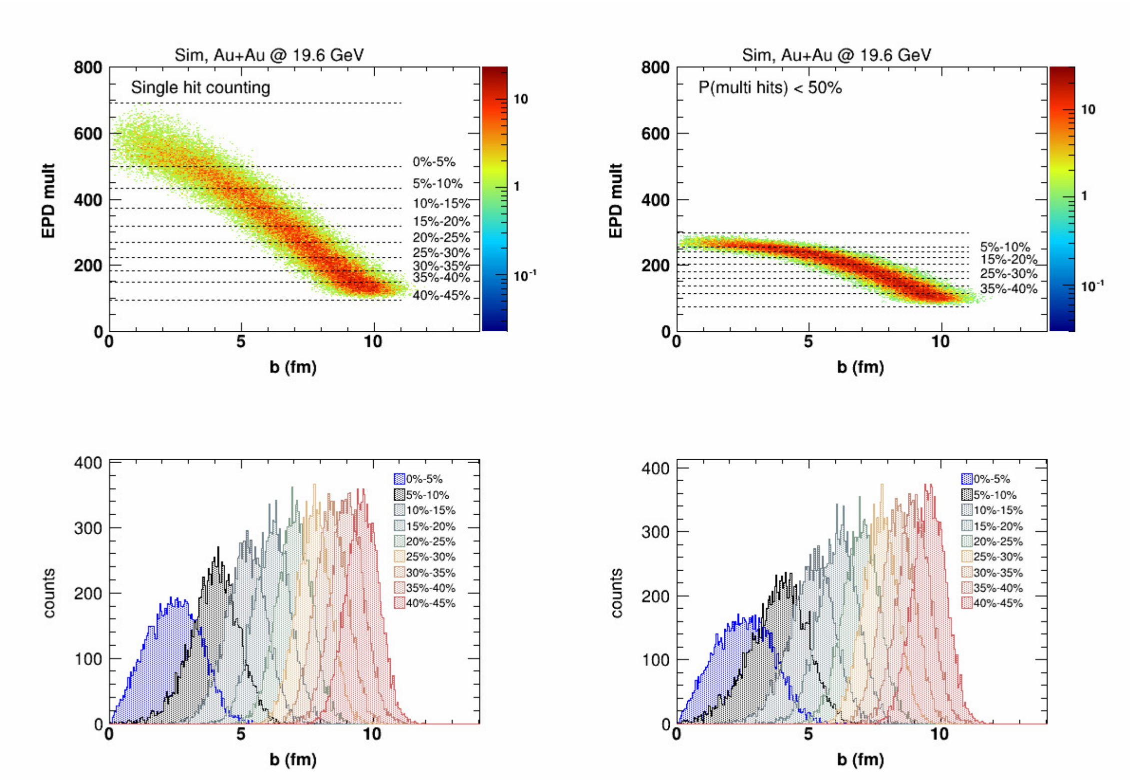


Figure 5: Upper panels: Multiplicity in the EPD acceptance as a function of the impact parameter b for single hit counting (left) and a multi-hit probability per detector tile of 50% (right). Lower panels: Projections to the impact parameter axis for different centrality selections.

cannot be distinguished. The projections 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 large number of radial segments will be important. This would be another advantage compared to the BBC detector.

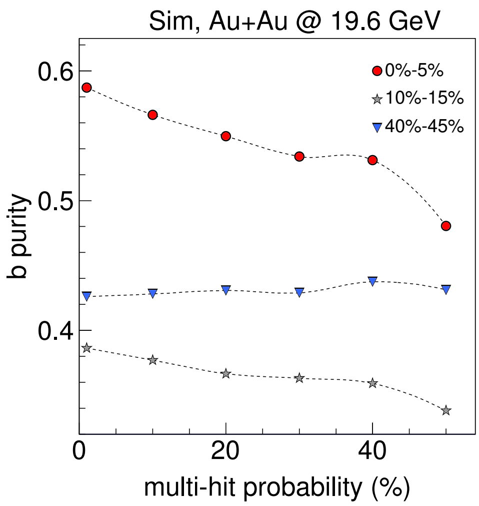


Figure 6: Impact parameter purity for simulated Au+Au events at $\sqrt{s_{NN}} = 19.6$ GeV as a function of the multi-hit probability per detector tile, for three different centrality selections.

4 R&D and Goals

Based on the physics requirements and the area to be covered, our baseline design uses a combination of scintillators and silicon photomultipliers (SiPM) [12] for the detector. This combination is the most promising technology choice. A few important characteristics of SiPM are listed below, showing that SiPM can replace standard photomultipliers and have in addition a few advantages:

- Time of Flight coincidence resolving time ≤ 250 ps
- Gain in the order of 10^6
- Linear dependence of gain with bias voltage
- Total quantum efficiency $\geq 20\%$ (wavelength dependent)
- Cost on the order of 100$
- Supply voltage ~ 50V
- Not sensitive to magnetic fields

- SiPM are small devices, allowing for compact designs

Commercial SiPM technology as a replacement for standard photomultipliers (PMT) has been used for high energy experiments from 2005 on [13, 14]. Tests show a similar or even better performance compared to standard PMTs. Many experiments are currently planning upgrades using SiPM technology, e.g. the CMS HCAL upgrade for the high luminosity runs [18]. It is also planned to use SiPMs in the STAR EIC calorimeter and the FMS preshower detector, which is now under development [15].

A part of the R&D process will be to check which SiPMs performance is sufficient for our specific purpose. This includes the following measurements:

- Efficiency for single m.i.p. hits
- Uniformity of pulse area and efficiency as a function of position of hit on a scintillator
- Pulse shapes (rise time and fall time) for m.i.p.'s
- Gain vs bias voltage
- Timing resolution
- Temperature stability

We also have to ensure that radiation damage does not affect our measurements within the two years of BES II operation. So far it is unknown how much radiation is expected in the forward region for BES II with the electron cooled beam and the small beampipe installed. Based on neutron flux measurements in the STAR cave during the high luminosity p+p 510 GeV run [16], we can make an estimation for the expected radiation dose. The integrated number of neutrons for one run (100 days) with $E_{kin} \geq$ 100 keV is close to the beampipe at a distance of 6.75 m in the order of $10^{10}/cm^2$. Those can be compared to detailed radiation hardness measurements of several SiPMs for the JLab hall B calorimeter, which have been recently performed [17]. Preliminary estimates indicate that we should be aware of possible radiation damage effects during the BES II run. It will be a part of the R&D to investigate this issue in more detail by analyzing existing BBC data and doing radiation tests at RHIC in run 15.

We also have to adjust the SiPMs for the scintillator light wavelength. This may include the installation of wave length shifting (WLS) fibers, which depend on 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. SiPM modules with dimensions of 3×3 and 4×4 mm from two companies, sensL and AdvanSiD, were tested with a scintillator. Different setups, with and without optical fibers, were investigated and tested in a two paddle cosmic ray setup. By triggering on one paddle, there was almost 100% efficiency of seeing a count in the other paddle [19].

The geometrical configuration and the connection of SiPMs to scintillators has to be developed. Simulations to calculate light emission and collection in the scintillators

Achievement	Time estimate
Simulations for different tile geometries	mid of 2014
Basic tests with SiPM and scintillators	mid of 2014
Demonstrator for basic trigger tests	end of 2014
Polishing and wrapping technique developed	begin of 2015
Two sector prototype	mid of 2015
Integration of prototype into STAR + DAQ	end of 2015
Construction proposal	end of 2015

Table 1: Timeline and goals.

and SiPMs are underway. The simulations will cover several tile geometries, scintillator materials, and positions and quantities of SiPMs to determine the detector response functions (DRF). One goal is to find the most cost effective tile geometry and tile arrangement. We will also minimize the number of different tile geometries. 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 as an example for trapezoidal tiles 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.

We also have to develop and test the polishing and wrapping procedures for the scintillators. 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. Once basic tests are done and the optimal SiPMs and scintillators are selected we will switch to STAR customized hardware and build a demonstrator. A goal of this proposal is to define the needed hardware for the readout chain in discussion with the trigger group. In order to fully replace the BBC detectors we need to consider the following points:

- A hit time measurement is needed to determine the z-vertex position
- An expansion of the existing readout system or a significant amount of preprocessing is needed

We furthermore want to investigate whether it is possible to significantly improve the timing resolution with the EPD setup compared to the BBCs, which could lead to new applications, like out of time rejections. Those studies could end in a follow up proposal in order to develop the needed readout system.

The timeline and goals of the R&D are listed in table 1.

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

- Which combination of SiPM and scintillator is optimal?
- What is the optimal pad geometry for different radii?

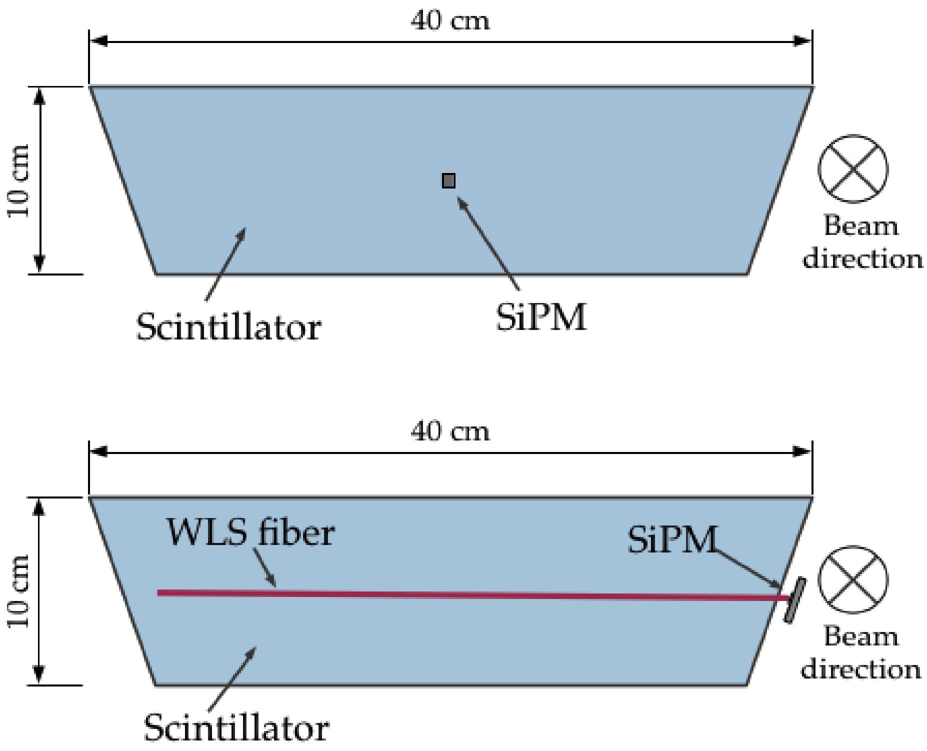


Figure 7: Drawing of a large scintillator tile and several possible arrangements of SiPMs, which have to be simulated and tested. The bottom drawing shows the additional installation of wave length shifting (WLS) fibers, which may be needed.

- 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 what kind of ADC is needed?
- What timing resolution can we achieve with the setup?
- How will the radiation damage influence the measurement?

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, just before the one year RHIC shutdown in 2017, and tested in an engineering run 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.

5 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 for the first tests in the lab. The requested budget in table 2 includes the material for the basic tests to develop the needed techniques, and the material for the demonstrator and the two prototype sectors. We further request funds for workshop-related operations. Travel expenses will be covered from other sources.

The LBNL overhead for BNL funded projects adds up to 23.91% and is included in table 2, which lists the individual items for the requested budget.

Item	**Costs including overhead**
SiPM	5K
Scintillators	5K
Power supplies	5K
Cables, connectors, miscellaneous	5K
Readout electronics and software	25K
Support structures, workshop & transportation	30K
Sum:	**75K**

Table 2: Requested R&D budget, including overhead.

6 Acknowledgments

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