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An Electromagnetic Calorimeter for the Solenoidal Tracker at the Relativistic Heavy Ion Collider

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Project Description:
**An Electromagnetic Calorimeter for the
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1. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) will allow the study of the collisions of up to 100 GeV/nucleon Au nuclei, which will result in baryon and energy densities possibly resulting in a short-lived plasma of quarks and gluons. This state of matter is believed to have existed some microseconds after the Big Bang, and may possibly exist in the interiors of some stars. RHIC offers the unique opportunity to study in the laboratory the properties of hot hadronic matter and the possible quark gluon plasma (QGP) state.

In the absence of definitive theoretical signatures for the QGP, it is imperative that many different observables be available from each experimental event. This information must also be as complete as possible, including the measurement of both charged and neutral particles in a geometrically efficient device. The STAR detector (Solenoidal Tracker At RHIC) is such a device, and will search for signatures of QGP formation and investigate the behavior of strongly interacting matter at high energy density.

The present configuration of the STAR apparatus consists of a large room-temperature solenoidal magnet, a time projection chamber (TPC) for charged particle tracking, and trigger counters (vertex position detectors, central trigger barrel, and others). Momentum measurements will be made at midrapidity ($|\eta| < 2$) with full azimuthal coverage by the TPC. Particle identification is possible for $|\eta| < 1$. An overall layout of the STAR experiment (including detector systems that are not presently funded) is shown in Figure 1 [1].

Figure 1. Schematic drawing of STAR showing the various subsystems.

In the presently funded configuration of STAR, no measurement of neutral energy is possible. An electromagnetic calorimeter (EMC) would markedly increase the sensitivity of experiments using the STAR apparatus by providing basic and important information to the experimenter at the trigger level and during offline analyses.

The EMC must function over a wide dynamic range. At the one extreme is the need to measure many particles, each with relatively small energies. In such an event, there may be 3000 π 's with typical energies of 200 MeV, with an otherwise unknown fraction of these being π^0 's. At the other extreme is the measurement of jets, which may have energies on the order of 50 GeV. Each of these classes of events may contain signatures of novel phenomena, via unusual isospin abundances in the former, or the extent to which the jets are quenched in the latter.

In this document, we outline a proposal to the National Science Foundation (NSF) for the construction of an EMC for STAR that fulfills these requirements. This proposal creates the opportunity for the NSF to make a major impact on the experimental program at RHIC by providing a crucial, but defensibly omitted, component of the STAR experiment as approved.

2. PHYSICS ENHANCEMENTS WITH THE PROPOSED EMC

The detector, as proposed below, will provide fast trigger and refined off-line information on the energies and spatial distributions of photons, leptons, and jets with good spatial resolution and efficient EM/hadron separation. The capabilities of STAR including an EMC are thus significantly enhanced, allowing:

- the measurement of neutral energy, which comprises on the order of 30% of the total energy in the event and which cannot be measured otherwise. The measurement of the total and differential transverse energy, E_T , is needed for the basic understanding of the collision dynamics in terms of the transfer of energy to midrapidity. The uncertainty in the measurement of E_T is decreased to $\sim 2\%$ given the information from an EMC.
- the search for events with significant isospin fluctuations or spatial fluctuations in pseudorapidity and/or azimuthal angle (η, ϕ), which may signal novel phenomena.
- the search for events with anomalous entropy, which may also signal novel phenomena.
- the measurement of gluon distributions in nuclei, which are necessary inputs for estimating the incident gluon flux in nucleus-nucleus collisions.
- the study of jets in p+p, p+A, and A+A collisions. Jets are penetrating probes and are sensitive to the incident gluon flux.
- the testing of perturbative quantum chromodynamics (QCD) via the participation of STAR in the spin physics program at RHIC.

The EMC for STAR will also add vital triggering capabilities. Listed below are sensitive trigger conditions for STAR, which can be formed on-line only with an EMC:

- thresholds on the total and differential EM energy in the calorimeter, e.g. the total transverse energy, E_T , which allows the selection of events with large energy densities.

- thresholds on localized energy deposition from particles (e.g. π^0 's, γ 's) or jets with large transverse momenta P_T .
- the study of anisotropies in the spatial distributions of E_T , which are a sensitive measure of localized fluctuations in η and/or ϕ .
- triggering on the ratio of E_T and the (charged particle) multiplicity in the central trigger barrel, which can select events with significant isospin or entropy fluctuations.

The EMC is comprised of fast and simple detectors, so that good statistics can be gathered quickly on-line. This allows the rapid determination of the gating conditions needed to construct triggers to search for the interesting events discussed above.

3. DESCRIPTION OF THE ELECTROMAGNETIC CALORIMETER

In this section, the present design of the entire EMC system for STAR is described, although only the highest priority components of this system are the subject of this proposal. The EMC is a lead-plastic scintillator sampling electromagnetic calorimeter, and is shown in cross section in Figure 2. The complete STAR-EMC would consist of a barrel calorimeter (BC), barrel shower maximum detectors (BSMDs), two endcap calorimeters (ECs), and endcap shower maximum detectors (ESMDs).

Figure 2. A side view of the STAR detector showing the EMC. The beam line is along the bottom of this figure. The BC covers $|\eta| \leq 1.05$ and the ECs cover $1.05 \leq |\eta| \leq 2.0$.

The barrel of the EMC is located inside the STAR solenoidal magnet coil, and would cover $|\eta| \leq 1.0$ and 2π in azimuth, thus matching the acceptance for full TPC charged particle tracking. At $\eta \sim 0$, the total amount of material in front of the EMC is ~ 0.5 radiation lengths. The inner radius of the "barrel" is 2.2 meters and the overall length is 6.2 meters.

The conceptual design of the barrel EMC consists of 120 modules with 21 layers of 4-mm-thick plastic scintillator and 20 layers of 5-mm-thick lead plates, corresponding to a total of 18 radiation lengths in depth. Each module subtends 6° in azimuthal angle and consists of 5 pseudo-projective towers (see Section 8 for possible upgrades that will

increase the granularity of the device). The scintillator plates are read out by plastic wavelength shifting (WLS) optical fibers. Each WLS fiber is thermally fused onto longer clear fibers to transport the scintillation light to photomultiplier tubes (PMTs) located outside the magnet. The mechanical structure to support the alternating layers of scintillator and lead includes a 20 mm thick aluminum front plate, a 30 mm thick non magnetic stainless steel back plate, two 0.5 mm thick non magnetic stainless steel side sheets, all of which run the full 3.1 meter length of each module, two 3 mm thick end plates, and one 6 mm thick bulkhead at $\eta \sim 0.5$; see Figure 3. The “bathtub” structure can support the lead plates without the bending or “coining” that could damage the networks of delicate optical fibers. The total weight of the barrel EMC including the support structures is approximately 180 tons.

Figure 3. Side view of the framework of the barrel calorimeter with the side sheets removed.

At a depth of approximately 5 radiation lengths in both the BC and ECs, near the location of the maximum number of shower electrons for incident photons of 3-5 GeV, highly segmented “shower maximum” detectors (BSMD, ESMD) will be inserted. The purpose of these detectors is to allow the discrimination between direct photons and those from the decay of π^0 mesons having $P_T \leq 20$ GeV/c. A top view of a possible SMD configuration, including plastic scintillator slats and optical fiber readout, is shown in Figure 4.

In Figure 5, an end view of the BC is shown depicting the arrangement of the modules around the beam direction. The optical fibers are routed between the magnet coils to the outside of the magnet return iron, where the PMTs are to be located. There has been significant engineering effort to investigate the mechanical supports for the EMC, as well as the routing of the fibers, during the design stage of the STAR conventional magnet.

Each endcap calorimeter (EC) would be divided into two modules consisting of 26 scintillator layers and 25 lead sheets, corresponding to a total thickness of 23 radiation lengths. Each module would be segmented into 360 pseudo-projective towers with $\Delta\phi = 0.1$ radians and $\Delta\eta$ ranging from 0.05 at $\eta=1.1$ to 0.1 at $\eta=1.4$.

Figure 4. A schematic diagram of a plastic scintillator strip SMD, showing the routing of the optical fibers. This technology, as well wire/strip chambers, is being considered for the BSMDs and ESMDs.

More detailed information concerning the entire EMC system can be found in the accompanying Conceptual Design Report (CDR) [2], and in Refs. [1, 3]. The contents of Ref. [2] include descriptions of the gain calibration of the detectors using ultraviolet lasers and radioactive sources, a conceptual design for the installation fixtures, prototype test models [4], et cetera.

4. DESCRIPTION OF WORK TO DATE

A conceptual design of an electromagnetic calorimeter for the STAR detector has been developed by the collaborating institutions [1, 2, 3]. This conceptual design drew heavily from experience with other colliding beam detectors and research for SSC detectors. The members of the present collaboration have contributed to the construction and successful operation of similar calorimeters for the CDF detector at FNAL, the HRS detector at PEP, the ZEUS detector at HERA, and the E814/877 spectrometer at BNL. Computer simulations of physics processes have also been performed to specify desired calorimeter properties. In this Section, a brief description of the most recent work on the development of an EMC for STAR will be presented.

Figure 5. End view of the barrel calorimeter showing the magnet structure and space for the routing of the optical fibers.

Measurements of the optical properties of the fibers and the optical readout chain were performed with the goal of optimizing the coupling of the optical fibers to the scintillator plates. A substantial amount of engineering was performed at Lawrence Berkeley Laboratory (LBL, integration with other STAR components and electronic and mechanical components for the EMC), Argonne National Laboratory (ANL, basic calorimeter mechanical design, some electronics design, and integration with the magnet), and Brookhaven National Laboratory (BNL, integration with the magnet). There is particularly strong coupling of the mechanical support for the barrel calorimeter and the conventional magnet design. A mutually compatible design for the mechanical support structures and the routing of the optical fibers has been developed, with minimal impact on the overall performance of the EMC and the magnet.

During the development of the conceptual design, a number of different technologies for the mechanical structure of the calorimeter were seriously considered. The location of the EMC inside the magnet immediately removed a number of promising technologies from consideration, and led to the adoption of optical fiber readout. Finite

element calculations of the long-term stresses in the lead plates showed that the "creep" of the lead over long time periods would be significant. The "bathtub" mechanical support for the lead, shown in Figure 3, was therefore the technological choice for the barrel EMC modules. The mechanical structure of the ECs shown in the Conceptual Design Reports [1, 3] was also adopted.

Two remaining technology choices will be decided by the beginning of 1994. Both are related to the shower maximum detector; one is the method of construction (either scintillator strips, wire chambers, or micro-strip detectors) and the other is the layout of the associated electronics. The shower maximum detector electronics may be identical to the electronics for the STAR TPC or silicon vertex tracker. These electronics are quite inexpensive per channel. In this case, it may be possible to instrument up to 30,000 channels of shower maximum detector for the barrel EMC at a cost on the order of 500 k\$. A considerable amount of design, prototype construction and testing for the shower maximum detector has already occurred at IHEP, Protvino, and further work is in progress.

5. PROPOSED DETECTION SYSTEM

The barrel EMC would provide unique measurements of neutral energy and important trigger quantities for STAR. This apparatus, coupled with the rest of the STAR detector, would provide excellent capabilities for studying the full range from p+p to Au+Au collisions at RHIC. We propose to construct the barrel calorimeter for STAR including the following components:

- 120 modules covering $|\eta| \leq 1$ and 2π in azimuth (full barrel).
- 600 channels of tower electronics (full barrel).
- BSMD hardware (but no electronics).
- Data acquisition (DAQ) and computing facilities.

The projected costs of the barrel electromagnetic calorimeter are based on engineering estimates from LBL and ANL and are in FY1993 dollars. These two estimates were done independently, and were consistent to ~10%. The cost estimates given below have been refined since the submission of the STAR Conceptual Design Report [1], because the design of many items has become more fully developed.

The cost estimates have been treated using the standard methodology adopted by STAR, namely accounting for all aspects of the cost (both labor and materials) according to U.S. industry or national laboratory costs. Savings from the effort of permanent staff, especially during the construction of components of the EMC, the use of inexpensive university machine shops, and the substitution of effort with low-cost student labor are listed separately as contributions from the collaborating institutions in Section 6.

A complete cost estimate for the entire EMC is presented in table 6B-1 in the EMC Conceptual Design Report [2]. This estimate assumes 1200 channels of tower electronics in the barrel and 720 channels for the endcap EMC. The barrel EMC as

proposed corresponds to roughly half the cost of the complete system. The design of the barrel calorimeter is such that it can be implemented initially with fewer towers, while preserving the complete azimuthal coverage by simply bunching the optical fibers onto fewer phototubes.

Although the conceptual design of the BC modules allows for the installation of the modules with the TPC in place, many TPC cables would have to be moved and the EMC optical fibers would have to be carefully routed to the outside of STAR during installation. Because of the great complexity with installing the shower maximum detector hardware after the barrel calorimeter modules are installed in STAR, it is proposed to construct and install the BSMD hardware. The BSMD electronics are not presently requested, but are listed as an upgrade path in Section 9.

The costs to construct a complete, *fully functional*, barrel calorimeter for STAR are:

<u>Item</u>	<u>Cost (k\$, FY1993)</u>
Barrel hardware and EDIA	4680
BSMD hardware	900
Barrel front end electronics	690
BSMD front end electronics	0
(funding to be requested as an upgrade)	
Computing, DAQ, trigger electronics	450
Full scale prototypes, fixtures	1070
Subtotal	7790
EDIA already funded	300
Total	7490

Table 1. Summary of the costs for proposed EMC consisting of a full barrel calorimeter.

The average contingency is ~25% and is included for the numbers shown above. The item labeled "EDIA already funded" in the table above represents Engineering, Design, Inspection and Administration funds already spent from STAR/RHIC R&D moneys and from the ANL High Energy Physics Division. Additional details may be found in the accompanying CDR for the EMC [2]. We distinguish the "full scale" prototypes listed above from a smaller prototype calorimeter, which is intended for immediate studies of the performance of the present design in test beams. Funds for the development and construction of a small prototype have been requested in a separate proposal [4].

6. COST REDUCTION OPTIONS

A significant cost savings is possible through the use of contributed resources. For example, the mechanical structure represents roughly half the cost of the barrel calorimeter. This includes the lead plates and all the hardware needed to support the lead and scintillator and to install the calorimeter. Significant savings may be realized by using the machine shops at several collaborating institutions, primarily Wayne State University, the University of Texas at Austin, IHEP, Protvino, and MEPI, Moscow.

Larger parts of the calorimeter will be purchased from commercial concerns as either custom or standard parts whenever possible. Any large items that cannot be obtained in this way can be made at the MSU/NSCL and ANL machine shops.

Another large cost is the assembly labor. In terms of total time, the biggest portion is in the preparation of the scintillator plates and the optical fibers, and the construction of the optical readout chain. A large fraction of this labor could be handled by students at the various collaborating institutions. The students would be supervised by experienced technicians. Finally, the cost of the shower maximum detector hardware would also be reduced considerably (~400 k\$) if constructed at IHEP, Protvino.

The overall cost savings from these and other sources is conservatively estimated to be ~1.5M\$. An additional cost savings of ~300 k\$ is expected from STAR/RHIC R&D moneys and ANL High Energy Physics Division resources in FY1994. Listed below is a funding scenario based on the assumption that these cost saving measures have been implemented.

<u>Item</u>	<u>Cost (k\$, FY1993)</u>
Barrel hardware and EDIA	3360
BSMD hardware	500
Barrel front end electronics	690
BSMD front end electronics	0
(funding to requested as an upgrade)	
Computing, DAQ, trigger electronics	450
Full scale prototypes, assembly, fixtures	700
Total	5700

Table 2. Summary of costs for proposed EMC consisting of a full barrel calorimeter taking into accounted projected savings from collaborating institutions.

Figure 6. Proposed yearly budget profile for the STAR EMC.

7. FUNDING PROFILE AND SCHEDULE.

A possible funding profile that would allow most of the barrel electromagnetic calorimeter modules to be completed before STAR begins running in 1999 is shown in Figure 6. Any remaining uncompleted modules would be installed in the first scheduled STAR shutdown.

A proposed work schedule for the construction of the EMC during the calendar years 1994 to 1999 is presented in Figure 7 at the end of this document. In this Figure, the open boxes correspond to design work, the dark boxes to fabrication, and the light boxes to installation. One can see from this Figure that work should begin soon in order to have the EMC installed before RHIC begins operation. The EMC project is sufficiently advanced that work could begin immediately.

8. HUMAN RESOURCES

The two lead institutions in the STAR calorimeter collaboration are Michigan State University (MSU/NSCL), and Argonne National Laboratory (ANL). The engineering and management of the project have already begun at these two institutions. The head of the STAR-EMC Collaboration and the EMC representative on the STAR Technical Committee is D. Underwood (ANL). The principal investigator for this proposal, and the person with the primary responsibility for NSF funding is G.D. Westfall (MSU/NSCL). If the calorimeter were funded through MSU/NSCL, a memorandum of understanding would be written with each of the other collaborating groups to perform various EMC tasks. These groups would in effect be sub-contractors on the project. The use of memoranda of understanding is customary within STAR for construction of the "baseline" detector. The division of tasks by institution is:

- Michigan State University/National Superconducting Cyclotron Laboratory would provide project leadership and management, R&D and construction of the optical components, construction of front end electronics, student assembly labor, and supervision of the assembly labor. The optical and radioactive source calibration systems will be developed. Machining of some mechanical components and assembly of the barrel EMC modules would also occur.
- Argonne National Laboratory would provide project leadership, mechanical engineering, technical support for construction, optics R&D, front end electronics design and construction, and construction of mechanical and full barrel EMC module prototypes. Large detector assembly facilities at Argonne will be used for construction of large sections of the EMC, and machining of some mechanical components would also occur.
- Brookhaven National Laboratory will provide simulations of the calorimeter performance.
- The Johns Hopkins University will provide computer simulations, and will contribute to the development of the BSMDs.
- Hope College will provide computer simulations of the calorimeter performance and small scale machining of parts for the calorimeter.

- Institute of High Energy Physics, Protvino, is expected to supply much of the SMD hardware, some machining, and extensive Monte-Carlo simulations of the calorimeter. IHEP funding may be via a subcontract through MSU/NSCL, and is expected to be on the order of 500 k\$ over the 6 year project.
- Rice University will contribute to the development of the front end electronics and the PMT bases.
- University of California at Los Angeles will contribute to the integration of the EMC components and systems with STAR, PMT testing and calibration, PMT base design and construction, and the development of slow control equipment.
- The University of Notre Dame will contribute to the development of the optical calibration systems.
- The University of Texas at Austin, Wayne State University, Detroit, and the Moscow Engineering Institute, Russia, will provide very low cost machining.

9. UPGRADE PATHS

The possible paths by which the proposed implementation can be upgraded in the future are listed below.

- The addition of the electronics for the BSMDs would increase the granularity of the device, allowing the study of direct photons as well as gluon distributions, at a cost of ~500 k\$.
- The kinematic coverage of STAR would be extended via the addition of one partially instrumented EC including the ESMD hardware, allowing the more complete study of direct- γ +jet and jet+jet events at an estimated cost of ~4 M\$.
- The granularity of the barrel would be increased by a factor of two in η or depth simply by redistributing the optical fibers to a larger number of phototubes without removing any of the calorimeter modules. This would improve the spatial resolution of the hits and allow studies of jet production in the collisions of heavier nuclei. Of these, the doubling of the η segmentation would be done first, at a cost of ~0.6 M\$. The subsequent doubling of the depth segmentation would cost ~1.2 M\$.

The total cost of all of these upgrades is ~6.3 M\$.

10. SUMMARY

This is a proposal for an electromagnetic calorimeter that will dramatically increase the capability and versatility of STAR for the study of p-A and A-A collisions at RHIC. More recently it has been recognized that RHIC also offers a unique opportunity to make fundamental measurements and tests of QCD in polarized p-p collisions. This RHIC spin program is currently before the Brookhaven PAC. The proposed configuration of the EMC for STAR would provide important trigger and offline information for both the polarized proton and heavy-ion programs at RHIC. Timely funding of this project would insure its successful completion.

11. REFERENCES

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Figure 7. The schedule projected for construction of the STAR electromagnetic calorimeter, assuming the funding profile shown in Figure 6. The open boxes correspond to design, the dark boxes to fabrication, and the light boxes to installation.

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