Friday, June 16, 2017

PROPOSAL to eIC

To Develop the High Density Projective Shashlik Electromagnetic Calorimeter with improved energy, position, and timing resolution for eIC

Project Leader: S. Kuleshov

S.Kuleshov, Detector Laboratory of UTFSM, Valparaiso, Chile

J.Haggerty, E.Kistenev, C.Woody, Brookhaven National Laboratory, USA

A.Denisov, A.Durum, Institute for High Energy Physics, Protvino, Russia

A.Brandin, MEPHI, Moscow, Russia

J.Lajoie, Iowa State University, USA

Abstract
This is the directed R&D Proposal to develop High Density, Fully Projective Electromagnetic Calorimeter of Shashlik brand with improved Energy, Position and Timing Resolution for eIC. The specifications for EM Calorimetry in central region of a barrel eIC detector are well established in Proposal for a dedicated eIC detector and are mostly driven by particle identification needs in SIDIS and DVCS events where all or nearly all particles in the final state are detected. As eIC program develops the attention get shifted towards physics involving hard processes resulting in scattered jets in the central rapidity region which need jet tagging down to transverse momenta just above the average transverse momenta of particles produced in SIDIS events. The high quality total and electromagnetic energy measurements become of essence similar to charged particle measurements made by tracking. Calorimeters are expensive and very difficult to upgrade – opportunities missed by relaxed performance specifications are usually never recovered.
We also understand that living under current budgetary constraints may lead to funding delays and enhanced attention to the economy of physics experiment: detector cost and performance which was deemed “acceptable” and “sufficient” in the earlier years may sound too generous and run-time ineffective today.
All things together point toward the need in extending ongoing eIC Calorimetry R&D program towards improving EM calorimetry in central region (barrel in this proposal) in a way which contrary to usual happenings may alleviate both problems– cost and performance even in aspects which were not seriously considered in earlier R&D for eIC Projects like timing and position resolution in EM Calorimeter.

The proposed work is based upon many years of combine expertize in EM Calorimetry shared by authors as well as shared experience in industrialization of individual shashlik implementations for experiments like PHENIX, HERA-B, LHC-B and many others.

1. Physics Introduction to Calorimetry at eIC

QCD attributes the forces among quarks and gluons to their "color charge" which causes the gluons to interact with each other, generating a significant fraction of the nucleon mass and leading to a regime of matter, where abundant gluons dominate its behaviour. An Electron Ion Collider (eIC) is the new experimental facility proposed for quantitative study of the matter in this new regime. With its broad range of collision energies, its high luminosity and nearly hermetic detectors, the EIC could image the protons and nuclei with unprecedented detail and precision from small to large transverse distances.

The e+A program at an EIC will expand the eP studies to unveil the collective behaviour of densely packed gluons under conditions where their self-interactions dominate (gluon saturation), a regime where non-linear QCD supersedes "conventional" linear QCD.

2. Technical Introduction to Shashlik EM Calorimeters

The first Shashlik calorimeter was designed and manufactured at Institute for Nuclear Research (Moscow) [1] in 1991 for the experiment 865 [2] (Search for the Lepton Number Violating Decay $K^+ \rightarrow \pi^+\mu^+e^-$) at the BNL AGS. During the five-year high intensity run of the experiment, the Shashlik calorimeter was shown to be a very stable and reliable detector. Its features, together with its low cost and well understood method of construction, make this type of calorimeter a good candidate for other experimental projects. Similar calorimeters were built later for PHENIX experiment at RHIC (BNL) [3] and for HERA-B experiment at DESY [4]. A Shashlik calorimeters was also studied as a candidate for the CMS experiment at LHC (CERN) [5] by RD36 at CERN, the same team created modified calorimeter for COMPAS experiment at CERN and a smaller version of the calorimeter for NA-64 [6] experiment at CERN. Based on HERA-B experience, LHCb experiment [7] constructed a large area Shashlik calorimeter for the only fixed target experiment at LHC. ALICE experiment made one more version of such calorimeter [8]. All above mentioned calorimeters demonstrated 6-10% stochastic term and 0.8-2.% constant term in the energy resolution. KOPIO experiment team designed and constructed extreme "Shashlik" calorimeter with 3.-3.5 % stochastic term to the energy resolution [9].

The "classic" shashlik calorimeter is built as a stack of lead (absorber) and plastic scintillator (sensitive media) plates penetrated by ~1mm diameter WLS fibers for the light collection and either stainless steel straps or steel pins for fixing/aligning the stack as it is shown in fig.1. Only the inner calorimeter of HERA-B was done with tungsten plates. And tungsten absorber and LYSO scintillator crystal "shashlik" module was recently tested by ATLAS Collaboration.

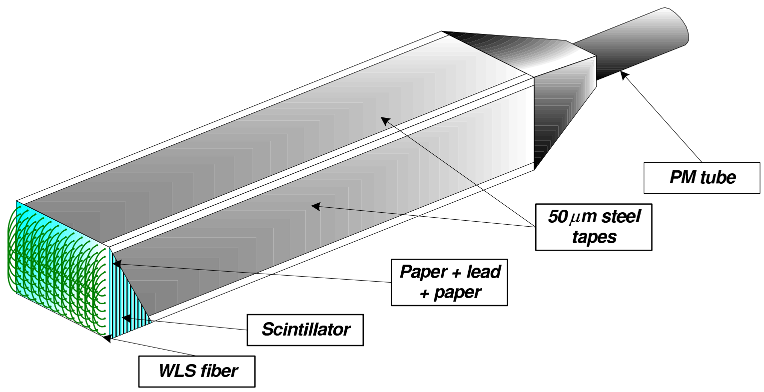


Fig.1 The “Shashlik” calorimeter of the KOPIO experiment.

Until recently the WLS fibers exiting individual towers were collected into a bundle and connected to PMT (cheap Russian phototubes with quantum efficiency 10-20% for 400-500 nm) with a Cockcroft-Walton (or resistive) base (Figure 2), which were the most popular.

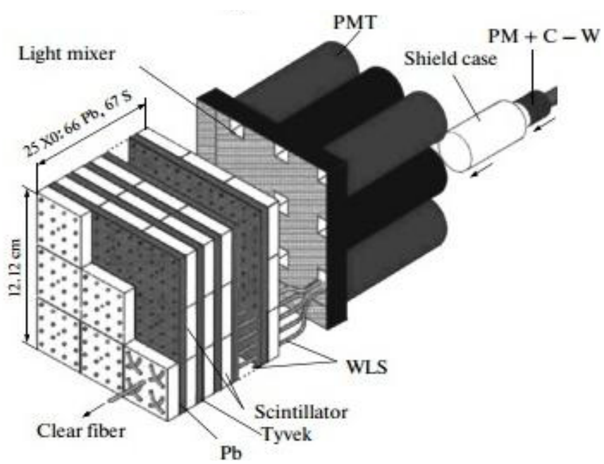


Fig.2 Schematic view of LHCb ECAL.

WLS fibers could be bundled on a distance comparable to tower size (typical ~50x50 mm^2), PMT adds another 100 mm and Cockcroft-Walton base length is about 100 mm. Thus, optical coupling between tower and readout can take about 250 mm which is close to 50% of the total space occupied by this kind of calorimeter and adversely affect the dimensions and cost and complexity of the system in collider experiments where space is at premium. The sensitivity of PMT to magnetic field is another limitation to this popular design.

It is exactly for this reason that RD36 and CMS studied the use of PIN diodes and APD in “Shashlik” operating in 4T magnetic field in collider geometry. Both PIN diodes and APD’s, which collect all charge deposited over the whole depleted silicon depth, respond to charged particles traversing them so the energy resolution get spoiled by the shower punch-through effect. Large pulses due to low momenta charged particles crossing photon sensors also result in degraded energy resolution and fake triggers in calorimeter based trigger electronics. Reaching expected performance required photon sensors with internal amplification or detector delivering much higher light output (or both) to suppress the electronics noise and punch-through effect. ALICE and CMS both selected PWO crystals viewed by APD's as an optimal price/performance solution (punch-through and consequently the trigger issues in APD based detector are fully resolved in a scheme with dual APD per tower).

Silicone Photomultiplier invented in 1990's was long expected "final" solution to a problem by applying essentially digital technology (signal is proportional to the ***number*** of individual amplification cells). New device provided an alternative to proportional ionization counters, open the possibility to overcome the noise/magnetic field related problems and solve the compactness/cost problem both for calorimeters and to a large extent the experiment as a whole.

A new Multi Purpose Detector (MPD) is now being constructed for the Heavy-Ion Collider at Dubna (NICA). Electromagnetic Calorimeter will operate in the magnetic field inside of limited space of MPD solenoid and expected to deliver good energy and space resolution in the energy range from ~100 MeV to few GeV. The calorimeter is "shashlik" sampling structure with the fiber readout by SiPM's. The design is similar to the calorimeter of KOPIO experiment except for the large area SiPM's (either 5x5 mm^2 or 3x3 mm^2) coupled to Winston Cone PMMA light guide [10]. SiPM's are temperature stabilized. A assembly of 9 towers is shown in figure 3.

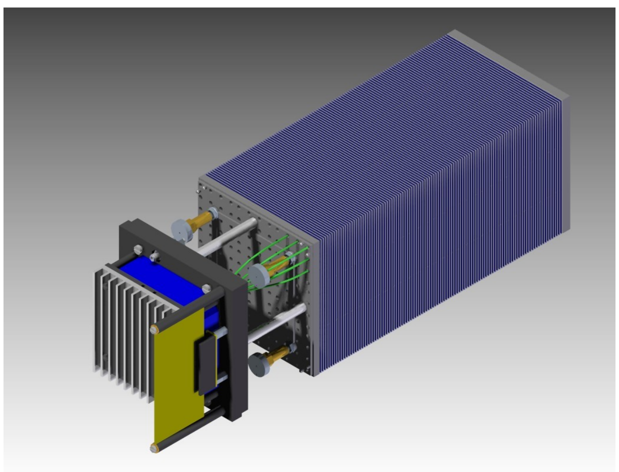


Fig.3 9-towers "Shashlik" module of MPD (NICA).
The MPD calorimeter have cylindrical structure and will be positioned in MPD at a radius of R = 1.78 m. The basic building block of the calorimeter will be a module (120x120 mm^2) consisting of 9 optically isolated towers which are read out individually. The light from each tower is collected by 16 longitudinally penetrating wavelength shifting fibers.

Space for MPD is allocated rather generously. The envelop depth for the active media is 400mm plus 150 mm for the light detection module. The module copies the best of KOPIO design optimized to the MPD conditions with a sampling cell of 0.3 mm Pb and 1.5 mm scintillator (14 X0 total). The estimated stochastic term in the energy resolution is 4.4% and the constant term is 1.0% . Tower response to MIP (3x3 MPPC with Winston Cone) is 900 pixels.

The estimates are optimistic, they do not account for non-uniformity of the light collection with WLS fibers, the punch-through effect from light mixer of WLS fibers and longitudinal energy leakage from rather thin calorimeter. Additional fluctuations are expected due to energy leakage through holes in scintillation plastic tiles and absorber plates and losses in or around aligning pins.

The combined effect of accounted factors will be a 5-7% position dependent non-uniformity in response to photons and electrons limiting stochastic term for energy resolution to values above 3% (KOPIO). It will also affects detector position resolution. Reaching x- and y-position resolution of the order of 1mm would require position dependent corrections, which usually are prone to autocorrelations. All those factors are illustrated in figures [4], [5] from LHCb collaboration. S-function position correction is shown on figure [6] and [7] by MPD (NICA)

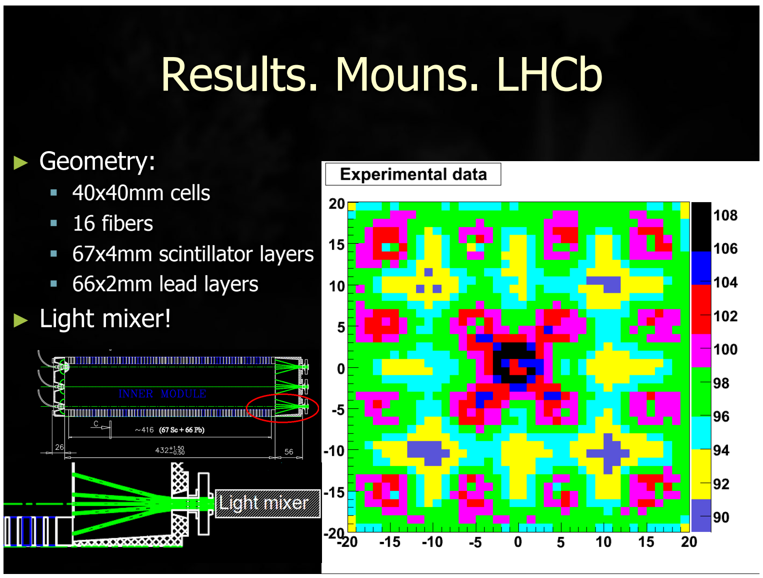


Fig.4 A scan of one tower of LHCb module with muons. The large response (108%) in the center of the module is from the light mixer (the punch -through effect), 4x4 peaks at level 100% are from WLS fiber regions, 2x2 peaks at the 90% level are from 4 stainless steel pins penetrated the tower. The structures in the range of 92-96% reflect variations in the thickness of the scintillating plastic(!) and losses in and around WLS fibers.

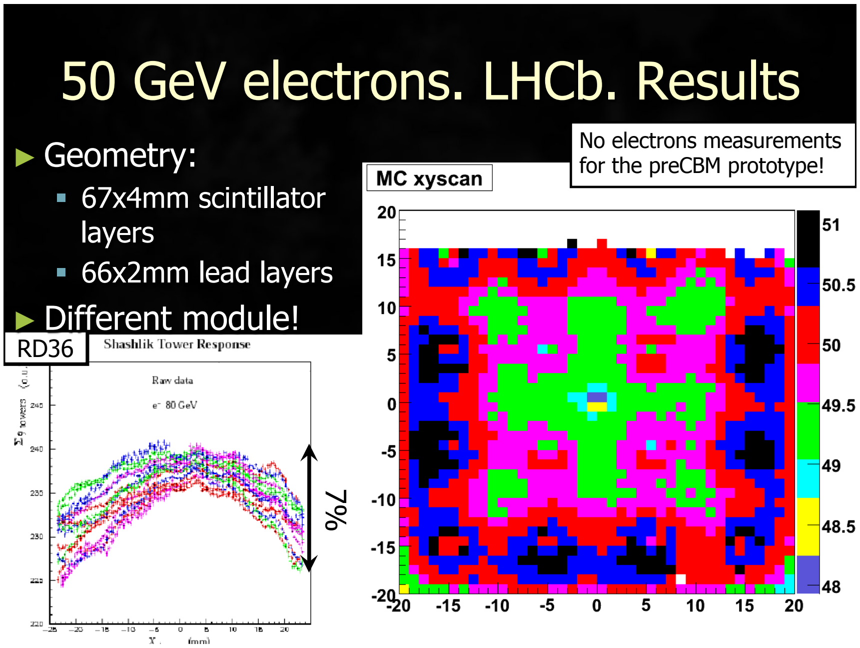


Fig.5 Results of scan of the tower from figure 4 with 50 GeV electrons and the same measurement from RD36 as a reference. The slide is from LHCb Collaboration.

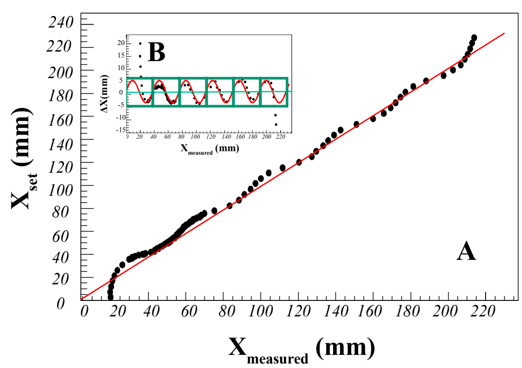


Fig.6 *Correlation between set and measured coordinates (A). Deviation of the measured coordinates from the linear dependence (B).*

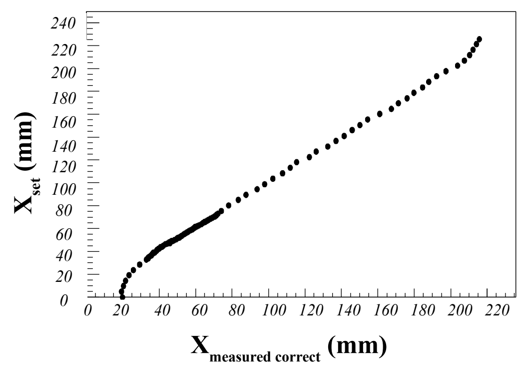


Fig.7 *Correlation between set and measured coordinates after correction.*

The “Shashlik” calorimeter designed and built by IHEP team for the COMPAS experiment is an example of rather successful attempt on minimizing those effects. Spiraling holes for WLS fibers were created using 4 slightly different tiles with hole patterns rotated around the tile centre by $2\pi/16$. Exiting fibers are bonded inside black plastic cookie with 16 holes spaced at 2 mm distance centre to centre (Figure 8). The same type of modules with 40 X0 depth is used by NA64.

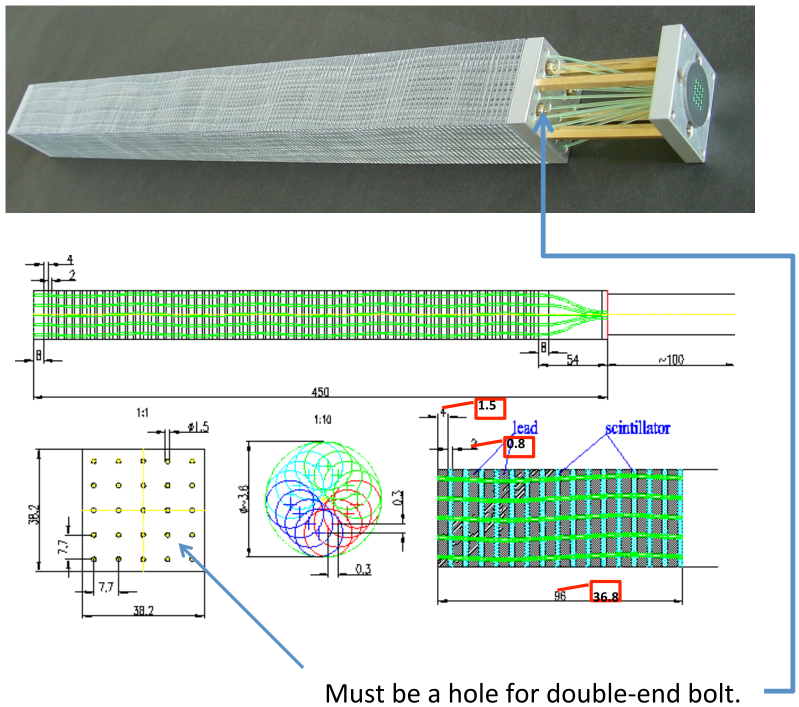


Fig.8 IHEP/COMPAS version of “Shashlik” calorimeter .

The transverse scan with 70 GeV electrons results are shown in Fig.9. It could be compared with Fig.5 from LHCb.

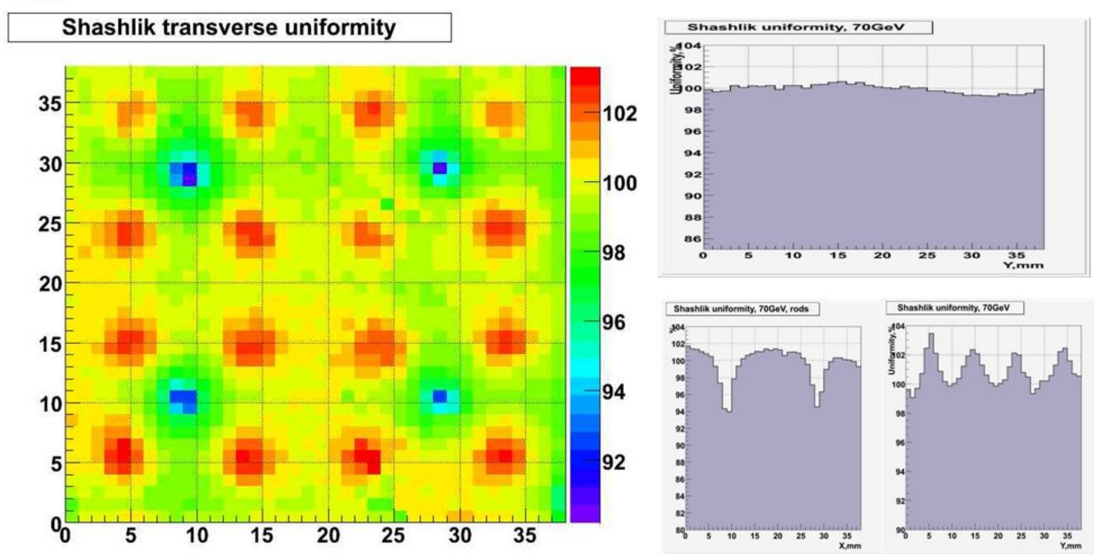


Fig.9 Results of transverse scan of IHEP/COMPAS calorimeter with70 GeV electron beam.

All components of "Shashlik" are produced using standard industrial equipment. Technology of assembling is relatively simple but needs trained technicians and sufficient tooling. Every step in production can be controlled. In general, mass production of modules can easily be industrialized.

"Shashlik"+PMT+CW stays well balanced price/performance solution for large calorimeters of particle physics experiments of last 2 decades, with price about 250$ per "Shashlik" tower, about 100$ per PMT and about 80$ per CW base. Including price of cables and DAQ the total amounts to about 500-600$ per the calorimeter tower.

It is the inefficient use of space by Shashlik+PMT+CW triad what creates a major drawback keeping Shashlik from being used in collider geometry - inefficient use of radial space (50%) in experiments where space is really at premium.

The silicone photomultipliers (SiPM) due to their performance, low price and ability to work in the magnetic field offer the opportunity for Shashlik to finally overcome this limitation. The SiPM's are not sensitive to magnetic field, has high internal (10^5-10^7) gain, good photodetection efficiency (20-40%) and in general does not need temperature stabilization. Its gain is reasonably stable and can be monitored and adjusted using LED or laser based feed back control of bias voltage. Even better source of monitoring data for scintillator based Calorimetry are ever present cosmic muons. Availability of SiPM's with pixel sizes around or below 15mkm and packaging efficiencies above 30% (packaging density high than $5x10^3$ pixels per 1 mm^2 of SiPM sensitive area) finally makes them fit to direct readout of light from WLS fibers with 1-2 mm diameter in analogue calorimeters without reaching optical saturation limit.

A combination of silicone photomultipliers with "shashlik" calorimeter with fiber density matching shower size (exponential fit to radial shape of the energy distribution in shower) which is ~5mm (one fiber per $1cm^2$ of calorimeter area) opens the path towards building detectors with near 100% efficiency of the space use, near ideally uniform response and tunable granularity. This granularity which is x10 higher compared to preshower granularity in STAR calorimeter and matches the granularities considered for W/Si calorimeters ($2x60mm^2$) will further enhance the physics reach of the device and reduce its mechanical complexity and total cost by making preshowers obsolete.

The SiPM's unfortunately suffer radiation damage in intensive radiation field usually present in collider experiment. While this sensitivity is not prohibitive to device use in experiment, it may adversely affect the performance of the detectors with multiple SiPM's passively coupled to a common preamplifier. CMS and STAR both claim that comparative study of multiple devices subjected to similar exposures indicates the possible device dependent drift of Vbd with exposure. Technically the system with fixed amount of light distributed to individual devices connected to common amplifier is feasible (see sPHENIX hadron calorimeters) but will be technically very difficult to build for very dense electromagnetic calorimeter. Optically and electronically decoupled shashlik fibers in the detector with thin scintillating tiles could still be monitored using cosmic muons what in general will result in a system with minimal number of SiPM's attached to short and inexpensive WLS fibers and monitored with ever present cosmic radiation and stable performance in presence of radiation.

In summary we consider bundle-less shashlik with individual fiber readout as very promising and the only really new development in large energy range calorimetry today. Approving it for development as a back up solution for eIC Central Calorimeter may at the end modify and improve the detector design while keeping its cost under control.

3. **Feasibility of the Proposal and Prototyping.**

We propose to study "shashlik" calorimeter designed and constructed to work with SiPM based optical readout. In doing so we will also count on future and make use of most recent developments in SiPM technology and readout electronics. As an absorber we will use industrial brand of 80W20Cu material very popular for use in electrolysis technology as current delivering electrodes (because of its high density, chemical stability and ease to machine). We are relying on use of injection molded shashlik kind of scintillating tiles commonly produced at IHEP and/or UNIPLAST in Russia (injection molding kits for all kinds of tiles used over the world in the last 25 years are still available). We are also relying on use of readout electronics from BNL (configured to support calorimeter test-beam operations at FNAL) and SBND[11].

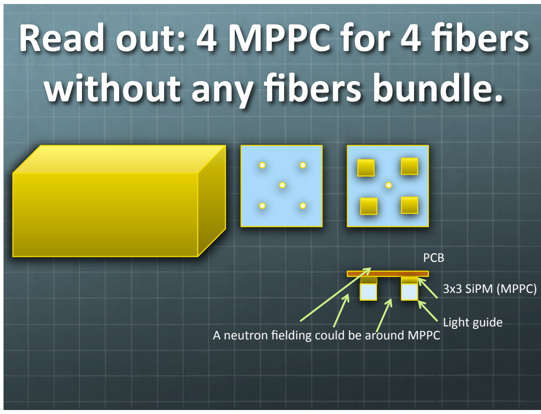
The feasibility assertion for successful completion of this R&D Program is based on the following observations:

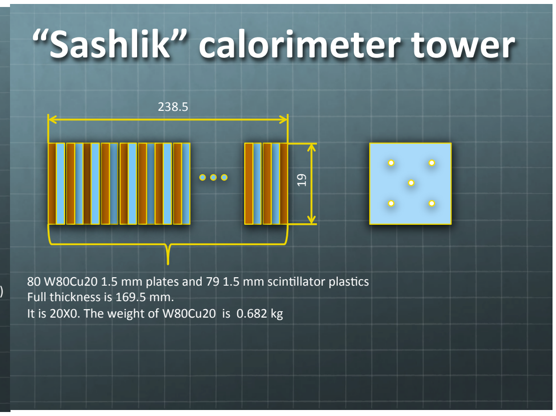
1. Large scale SiPM production by HAMAMATSU, SenSel and other companies is pushing device prices down. 1-4 mm^2 sensitive area devices in SMD package are now available at a cost of about $5 for device. Such cost is comparable to cost per 200-500 mm long 1mm diameter WLS fiber mirrored on the one end. Reading individual WLS fibers with individual or passively ganged SiPMs allows to tune detector granularity to needs of experiment without impact on compactness and cost of downstream detector components. The SiPM based shashlik calorimeter will retain its reputation of being low cost, high performance and easy to manufacture design, but its newly developed immunity to magnetic field and compactness will hopefully make it also a solution of choice in collider geometry. The solution is very attractive.
2. Implementation with as short as possible WLS fibers is free from punch-through effect and cladding light effect.
3. Adjusting (profiling) local thickness of scintillating tile in cold/hot regions will hopefully resolve the uniformity of response problem – the solution which is easy to implement and test with shashlik.
4. Individual readout for each SiPM will further allow to greatly improve the position resolution for photons, electrons and positrons and identification of hadrons thus eliminating the need in super costly preshower detectors. It will also reduce the systematics in position measurements compared to rectangular matrix of towers violating azimuthal symmetry of the device. It could discriminate low energy gamma from MIP particles what is the prerequisite for DIS measurements at central rapidities in eIC detector.
5. Shashlik with SiPM will have substantially lower cost compared to similar granularity W powder/scintillating fibers option for RCAL of eIC.

Prototypes:

1. The minimal detector element will be a tower with internal position sensitivity – shashlik with every fiber instrumented with SiPM and individual readout for each fiber. The transverse size of tower may be as big as fits into azimuthal and/or rapidity segment which can be built keeping fiber to fiber spacing constant (precondition for the effectively constant sampling fraction everywhere) and not damaging the fibers when mechanically shaving the tower (required for pointing geometry in 1- or 2-dimensions). We will begin this Project using ~38x38mm^2 lateral size W/Cu plates currently available at UTFSM and modified Panda injection molds (IHEP) to produce appropriately sized scintillating tiles (38x38mm2 cells penetrated by 16 fibers each) at IHEP. As work will progress, we'll purchase W/Cu plates of ~10x10cm^2 size matching available KOPIO scintillating tiles to study shower development in the calorimeter with thin optically coupled scintillators. With this choice of absorber the Moliere radius of the tower will be kept low (<20 mm). Historically the scintillating plastic with thicknesses less than 1 mm had problem with scintillation light output. To avoid overburdening the project with optical studies, we prefer to work with 1.5 mm scintillator plastic (same as KOPIO). In this case 1.5 mm absorber built of 80W20Cu alloy (or 2.6 mm of lead) and painted TiO2 (diffuse reflectivity) is optimal. The price of 80W20Cu is 50-80 $ per kg depending on quantity. The 80W20Cu alloy could be machined without problems (tested in our Lab at UTFSM) and we prefer this material to lead.
2. The 50/50 volume mix of 80W20Cu and Scintillator will have radiation length of ~9.1 mm and Moliere radius of 18.4 mm The module of 20 X0 depth will constitute of 60 sampling cells and have depth ~180 mm. Safe estimate for energy resolution in such calorimeter is better than 12% (the stochastic term).
3. All prototypes will be 3x3 optically and mechanically separated towers. Mechanically the prototype structure will be designed to allow the high precision transversal scanning in at least the central mechanical towers. All towers will be instrumented with individual fiber read out on every fiber-SiPM pair (144 channels).
4. We are proposing to build 3 prototypes:
    a. Single tower technological prototype with Pb or W/Cu absorbers , with 16 fibers and single 2" PMT in direct contact with fibers for readout;
    b. 3x3 towers prototype with rectangular towers and 144 fibers with individual SiPM readout;
    c. 3x3 towers prototype with shaved towers to match proposed eIC RCal radius and pointing capabilities and 144 fibers with individual SiPM readout;

Time and funding permits we will also consider implementing readout with spiraling fibers for the central tower in our 3x3 matrix.





4. Beam and test bench studies

The research program requires access to the test beam at FNAL or/and NA64 CERN and cosmic ray test in Chile:

1. Scan with cosmic ray in horizontal and vertical positions. Response uniformity measurements. Detailed study of the uniformity of light collection and the punch-through effect level.
2. Create Geant 4 model of the calorimeter based on the cosmic test.
3. Measure energy resolution with an electron beam from 0.2 GeV to 30 GeV.
4. Make lateral scans with electron beam in the 0.5-30 GeV energy range.
5. Make lateral scan with muon beam.
6. Study hadron rejection with pion and electron beams.

Cosmic ray set up (in UTFSM, Chile) will require:

1. Scintillators hodoscope with 1 mm space resolution and working area greater then 38x38 mm^2
2. 2 scintillators hodoscopes with 200x200 mm2 working area and 5 mm space resolution.

The prototype (3x3 towers) will need 144 channels of SiPM biasing and readout. It’s a relatively humble number in modern world but even in modern world building it from the leftovers of the past experiments can be strenuous.

A solution to readout problems perfectly matching needs for calorimeter test beam readout was recently offered by commercialization of the A1702 FEB board developed by the Albert Einstein Center for Fundamental Physics of the University of BERN for readout of SiPM arrays used in veto system of the SBND Cosmic Ray Tracker. The FEB is designed as one module serving 32 channels and has the following functionality:

- provides bias voltage in the range 40-90 V individually adjustable for each of 32 channels;

- amplifying, shaping, discriminating and digitizing output pulses on all channels;

- providing basic coincidence of signals from any combination of channels;

- allowing for coincidences between groups of FEB's;

- data buffering.

It is supplied with rather advanced ROOT based data acquisition software easy to use and data storage in the form of ROOT trees.

For the purpose of this Project we propose to acquire and use 5 FEB's of SBND design and ask our students to modify its software to allow for advanced debugging of future prototypes in line with data accumulation.

5. Draft Schedule

The schedule of the work (3 years):

- Single tower technological prototype	July-September 2017
- Production of 3x3 towers rectangular prototype:	July-December 2017
- Production of hodoscopes:	July-December 2017
- Implementation of read out for hodoscopes	July-October 2017
- Implementation of the readout for calorimeters	July-November 2017
- Production of the rectangular (nonpointing) prototype	February 2018
- Assembling and testing cosmic ray setup	January 2018
- Cosmic ray test of technological prototype	February 2018
- Cosmic ray test of rectangular prototype	March-April 2018
- Production of the 2-D pointing) prototype	May 2018
- Cosmic ray test of the projective prototype	June-July 2018
- Delivery of prototypes to BNL	August 2018
- Test beam	2018 and 2019
- Publishing results	2020

UTFSM is formally beginning the project in June 2017.
The collaborating groups assume that project funds from BNL will be available starting October 2017.

6. Total Funding Request to Collaborating Institutions in 2018-2020 (k$US)

Sub project	Years	Machining K$	Equipment K$	M&S K$	Manpower K$	Travel	Source Team / eIC
Base detector design and engineering	2018	0	-	2	4	4	6 / 4
Geant4 simulations	2018	-	2	-	6	6	10 / 4
Test bench for Prototype studies at UTFSM	2018	5	3		2		5 / 5
Cosmic ray facility in UTFSM	2018	6	10	5	6		20 / 7
Tooling. Assembly Lab for eIC shashlik at UTFSM	2018	6	-	6	5		10 / 7
Technological prototype	2018	2		5	6	4	10 / 7
Non-projective prototype	2018	4		5	4	4	10 / 7
Test beam experiment and related analysis	2018		10	8	**3**	**15**	10 / 26
Total 2018	**2018**	**23**	**25**	**31**	**36**	**33**	**81 / 67**
Light collection studies	2019	4	5	4	8		8 / 13
Projective prototype R&D	2019	3	0	0	4	6	6 / 7
Projective prototype construction	2019	8		10	4	**8**	10 / 20
Test beam experiment and related analysis	2019		4	6	**6**	**15**	10 / 21
Total 2019	**2019**	**15**	**9**	**20**	**22**	**29**	**34 / 63**
Light collection and uniformity studies	2020	6	4	10	**2**	**5**	15 / 12
Test beam experiment and analysis	2020		2	2	**6**	**10**	15 / 5
Total 2020	**2020**	**6**	**6**	**12**	**8**	**15**	**30 / 17**
Proposal Total		**44**	**40**	**63**	**66**	**77**	**290(145/145)**

7. eIC Funds Allocation (money matrix) 2017-2020 (k$US)

	Technological prototype and Assembly Laboratory (at UTFSM)	Geant4 simulation	Prototypes	Cosmic ray facility (in UTFSM)	Test beam experiment and related analysis	Total for each institution
UTFSM	31	4	9	20	5	69
IHEP	0	2	1	0	0	3
MEPHI	0	2	0	0	2.5	4.5
ISU	0	2	0	0	2.5	4.5
BNL	20	4	7	7	26	64
Total for subproject	51	14	17	27	36	145

We are also requested by Guidelines to consider three budget scenarios (nominal, -20% and -40%). We assume that these scenarios are for eIC funding only. Note that the tables above do show similar contributions to the Proposal from both the Collaboration (team) and that of eIC. We have all reasons to believe that "team" contribution will eventually dominate in this Proposal allowing to extend its scope. But this "team" contribution is coming not unconditionally. Members of our team are currently applying to funding agencies in their respective countries for grants which will include funds to cover their contributions to this Proposal. In general funding agencies in different countries follow the reciprocity principle in fund allocation. Grant requestors in international Projects is expected to show a certain (equal or larger) support level on part of host Country/Institution. As an example for this particular Project we rely heavily on additional funding from FONDECYT grant to Detector Laboratory at UTFSM in Valparaiso, Chile which constitute the dominant part of our institutional funding and is currently under considerations. In our opinion 20% reduction in eIC funding will at worst cause less ~6 month delays in prototype's readiness for beam testing while 40% reduction may trigger disproportional reductions to Institutional contributions and have a major adverse effect on the Proposal.

8. References

[1] G.S. Atoyan, et al., Nucl. Instr. and Meth., A 320 (1992) 144.

[2] R. Appel, et al., Nucl. Instr. and Meth., A 479 (2002) 349.

[3] L. Aphecetche, et al. [The PHENIX Collaboration], Nucl. Instr. and Meth., A 499 (2003) 521.
[4] G. Avoni, et al. [The HERA-B ECAL Collaboration], Nucl. Instr. and Meth., A 461 (2001) 332.
[5] J. Badier, et al. [RD-36 Collaboration], Nucl. Instr. and Meth., A 354 (1995) 328..
[6] D. Banerjee   et. al. [NA64 Collaboration], PRL 118, 011802 (2017)
[7] F. Muheim [LHCb Collaboration], Nucl. Instr. and Meth., A 462 (2001) 233.
[8] J.Allen, et al. arXiv:0912.2005v1 [physics.ins-det] 10 Dec 2009
[9] G.S. Atoyan, et al., arXiv:physics/030047v1 [physics.ins-det] 10 Oct 2003
[10] Igor Tyapkin et al. (The MPD Collaboration), PoS(PhotoDet2015) 053
[11] Igor Kreslo, FEB V3.0 technical description and operational manual, February 21, 2016.
CAEN 2016/2017 Product Catalog 2017, p 197.