# STAR Calorimetry

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**Abstract**. The main STAR calorimeters comprise a full Barrel EMC and single Endcap EMC plus a Forward Meson Spectrometer. Together they give a nearly complete coverage over the range -1 < pseudorapidity < 4 and provide EM readout and triggering that help drive STAR physics capabilities. Their description, status, performance and operations (and a few physics anecdotes) are briefly presented and discussed.

## 1. Introduction and overview

Many thanks to the organizers for the invitation to this excellent conference held on this occasion in a lovely/historical setting (and with lots of great food and discussions!).

STAR is one of two large experiments sitting on the RHIC rings at Brookhaven Laboratory located on Long Island in New York. RHIC (the Relativistic Heavy Ion Collider) as its name suggests, provides collisions of heavy ion species with center-of-mass energies up to $\sqrt{s_{NN}} = 200$ GeV. It also provides polarized proton beams, with a capability for either transverse or longitudinal polarization at the experiments, with collision energies $\sqrt{s} = 200$ GeV, and in future years 500 GeV.

The main STAR operating calorimeters (pictured in figure 1), are the Barrel EMC (BEMC), the Endcap EMC (EEMC) and the Forward Meson Spectrometer (FMS). Taken together they provide nearly compete EM coverage for pseudorapidity $-1 \leq \eta \leq +4$. They total ~ 6800 "towers", ~ 43,000 "SMD" and ~7000 "Pre- and Post-Shower" readout channels. There are other smaller calorimeters at STAR, notably the Zero Degree Calorimeters (ZDC), used for monitoring collider luminosity, and versions of a Forward Pion Spectrometers (FPD) preceding FMS, that won't be discussed further here.

Unlike the configuration planning of many of the other detector projects we have heard presented at this conference, the BEMC, EEMC and FMS calorimeters at STAR were not among its "baseline" detectors. This accounts for a somewhat different "modus operandi" we have followed with incremental installation, commissioning, calibration, upgrade and maintenance activities. As well, the various calorimeters were driven by different physics interest subgroups: the BEMC designed largely for heavy ion studies with full tracking coverage from the Time Projection Chamber (TPC); the EEMC driven primarily according to spin physics (and having only partial TPC coverage but additional tracking envisioned); and the FMS which addresses some "heavy ion" issues along with emphasis on future spin physics. The first BEMC patch install was in 2001, with full install/all

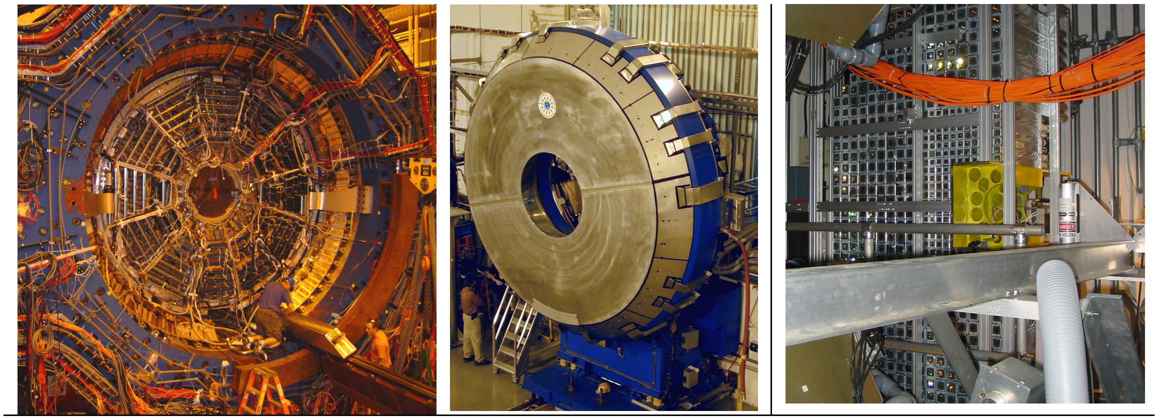

**Figure 1.** The operating STAR calorimeters as discussed herein: (left) the Barrel EMC shown during insertion of one of the 60 modules/side around the TPC, (center) the Endcap EMC as seen removed from STAR via the west poletip/carriage and (right) the Forward Meson Spectrometer which views the interaction region through the opening in the EEMC/poletip.

tower readout/trigger in ‘06 (full electronics in ‘07). Similarly the EEMC test install occurred in ‘02, with full install/all tower readout/trigger in ‘03 (full readout in ‘05). The FMS on the other hand, went quickly from final prototype to full detector installation and readiness for run 8, although the first FPD prototype (a section of an EEMC test module) was deployed already in ‘02.

The point of this brief chronology is to emphasize the incremental nature of the efforts and note also the small group involved in the various activities from installation to commissioning. As well, one should add that the “politics” of such an implementation demands that there be an increased capability and physics output for each yearly running period. In fact the latter was accomplished on a pretty regular basis starting with measurement of the forward $\pi^0$ inclusive single spin asymmetry and cross section from ‘02 pp running (FPD prototype); ‘03 $\pi^0$ inclusive cross section from d+Au, ‘03-4 polarized pp inclusive jet results for $\Delta G$, ‘04 Au+Au heavy flavor x-sec (all with 1/2 BEMC), ‘06 polarized pp di-jet “Sivers” with EMC trig data (full EEMC/BEMC), and recently much more spin and heavy-ion physics. Presently the STAR EMC’s dominate triggering for spin physics as well as in recent years the heavy-ion data bandwidth; EMC data are now also becoming a major part of STAR physics analysis and output (recall STAR’s baseline “heart” is the TPC). Overall, things have gone well and the EMC performance/operations, driven by available money and manpower vs. physics output has worked (maybe not perfectly but) well. There certainly has been great productivity!

Before presenting details of the individual calorimeters in the next sections, it is useful here to mention briefly some common organizational aspects of EMC equipment, analysis and calorimeter support procedures we have found helpful at STAR. In particular for the BEMC and EEMC, while both are sampling calorimeters with similar structures and features, there are also differing implementations (some significant) and approach. These issues are brought together in a STAR EMC “operations and detector analysis” based group (EMC^2) for which I have had oversight and whose weekly phone meetings (and some collaboration meeting sessions) I have coordinated over the past ~ 3 years. Discussed issues include detector equipment support and detector performance; calibrations (all kinds); run status tables/data base of detector components (for physics replay); detector based analysis algorithm development (from physics work groups); software, including the EMC subsystems coordinators reporting to the STAR software group. This group-like structure of contributors with somewhat diverse yet common interest seems to have worked reasonably well.

For illustration, we take the tower FEE digitizer as a common hardware issue. Nominally the FEE comprises a 32-input 9U digitizer with a 12bit ADC per channel, 10 MHz beam crossing rate and pipeline architecture (for EEMC the "magnetic" noise suppression components are removed and higher PMT gain used on poletip); trigger section outputs high tower (HT) and trigger patch (TP) information. In early running and then subsequently, "ghost pedestals", n*256 noise, and header corruption were traced to clock issues (problem then jumped from EEMC to BEMC and back, etc.). Besides the "fix", this spawned many common diagnostic tools to monitor/catch these detrimental hardware behaviors. Separately, in another hardware related symbiosis, the EEMC's required remoted power supplies (due to the high poletip magnetic fields), were found to be the final real solution to serious and continued BEMC supply failures. There are many other examples of various types.

## 2. STAR barrel EMC

The Barrel Electromagnetic Calorimeter (BEMC) completely surrounds the STAR Time Projection Chamber (TPC), covering an area of nearly 60 m$^2$. Figure 2 highlights several BEMC components.

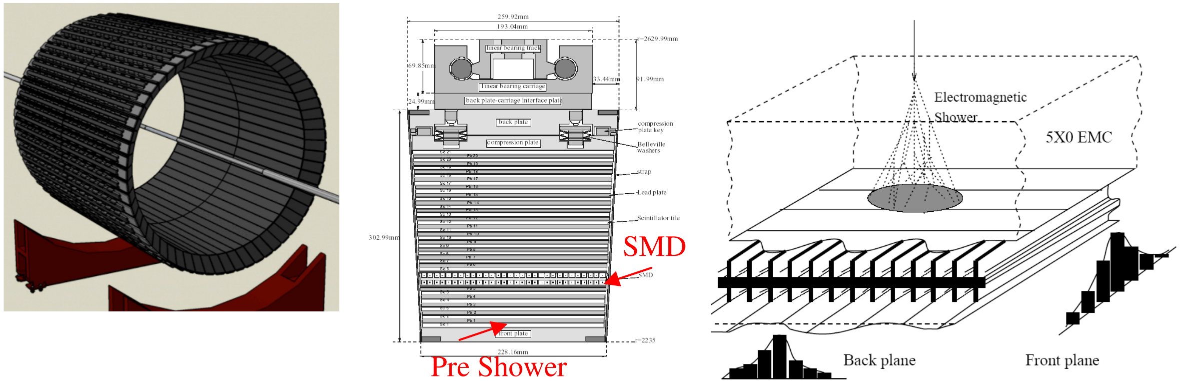

**Figure 2**. BEMC components: (left) schematic of 120 modules surrounding the beam pipe, (center) "end view" drawing of module cross section showing mechanical structure and location of the SMD and preshower, and (right) schematic of SMD detector response.

The nominal BEMC parameters are (see also reference [1]):

- $-1.0 < \eta < 1.0$; full azimuthal coverage; $dE/E \sim 14\%/\sqrt{E}$
- 4800 towers; 36k SMD strips; 4800 preshowers
- 120 modules (40 towers/module); 60 west and 60 east
- $(\Delta\eta, \Delta\varphi)$module ~ (1.0, 0.1); depth = 21 $X_\circ$
- $(\Delta\eta, \Delta\varphi)$tower ~ (0.05, 0.05)
- Shower Max Detector (SMD) at a depth 5 $X_\circ$
- $(\Delta\eta, \Delta\varphi) \sim (0.007, 0.007)$
- Preshower: first 2 scintillator layers (depth 2 $X_\circ$ ) combined/shared with tower readout

Overall the BEMC has worked performed well in producing lots of physics as mentioned above. However, of interest to this session of the conference are some details of operation. I have space to mention briefly only a few items from the talk regarding calibration and component performance next.

For pre-run checkout and online tower calibrations several techniques have been and still are employed. A LED pulser system can be used to adjust individual/aggregate HV for the tower tubes (for latter, e.g., moving all gains from 28 to 60 GeV full scale to match the EEMC for beginning of run 5). Slope equalization from minimum bias events is used at beginning of run to fine-tune the HV and is especially useful for getting new tubes/bases tuned in. This procedure is fast (turnaround in less than a day) but is only relative in the various $\eta$ "rings". During the run start, gains are checked using MIP's. Data production is requested in fastOffline mode and gives early confirmation that things are reasonable for the proper scale and triggering. For analysis and offline, the full calibration uses the STAR μDST framework. MIPs set relative gains for each tower; while electron E/p tracked with TPC are used to normalize $\eta$-rings. An artifact of particle isolation issues at the largest $\eta$ are presently corrected to a flat response as suggested by other calibration techniques. Beginning in 2006, additional statistics in the data sets allowed for a tower-by-tower electron E/p measurement. Currently higher $p_T$ electrons as well as calibration with $\pi^0$'s is being revisited.

The BEMC has had some significant component performance issues that have required effort to remedy. For example, for the towers, the original tower FEE crate design was a compact assembly including integrated power supply, controls and LV for the tower CW bases and etc. The solution to continued supply failures (as high as one every few weeks when running) was to remote the supplies to racks away from the magnet backlegs. As well the coupling of CW base LV to FEE power reduced flexibility and hard resets the CW when FEE's cycled following FPGA bit upset, so the solution here was to go to a completely separate supply as well as separate HV control functions. This separation has proven more flexible, reliable and easier on the components. For the towers themselves, as of 9/07 ~ 2% (96 towers) were not working with a plan to bring back about 40 towers (rest likely dead "forever" with broken optical fibers?). This to be compared to situation of '05 when 10-15% of the towers were dead! Similarly the SMD for the BEMC has taken some work to improve following initial damage due to a bad HV supply. The number of chambers lost during a running period has gone from 8-10/run for period '03-'05 to ~1 per run period the last few years. In all, a total of 53 out of 3600 (1.5%) anode wires have had to be cut permanently. The failure of SMD FEE cards remains fairly high (20-15 per run period) although recently reduced on the west side which has a different batch of storage capacitor array (SCA) chips; amplifier and shaper (15 chns) has a failure systematic on the top FEE card whereas SCA (150 chns) problems are systematic on east side. For the readout crates one had lost 50% by end of '05 run; now reduced to 1 (out of 8 total) at end in '07. For the preshower which uses similar electronics/crates, ~ 10-15% of channels not working at run 8 end … usefulness of signal in commissioning stage and being exploring in physics analyses at end of run 7 and into run 8.

## 3. STAR Endcap EMC

The Endcap Electromagnetic Calorimeter (EEMC) is mounted on the inside of the west STAR magnet poletip. The nominal EEMC parameters are (see also reference [2]):

- 2 half annuli – $1 < \eta < 2$; SS structure; 23 layers Pb/SS laminate; depth = 21 $X_0$
- 720 projective towers (comprising 24 layers)
  - 6° and 12° megatile; ~ 100% coverage
  - $(\Delta\eta, \Delta\varphi)$ tower ~ (0.057 to 0.099, 0.01)
  - $dE/E \sim 16\%/\sqrt{E}$
- Depth segmentation
  - 2 separate preshower (1,2) layers (1440 chns)
  - high position resolution SMD @ ~ 5 $X_0$
  - -- 6912 triangular-shaped scint strips; base 10 mm, height 7 mm
  - -- "u", "v" stereo planes in 30º sectors w/ overlap; ~ 280 cm to Interaction Region
  - postshower 24th layer (720 chns)

For the readout, of particular interest is the digitization of all individual channels of the SMD and pre-and post-showers. This is accomplished with an exceedingly compact design of Multi-Anode PMT

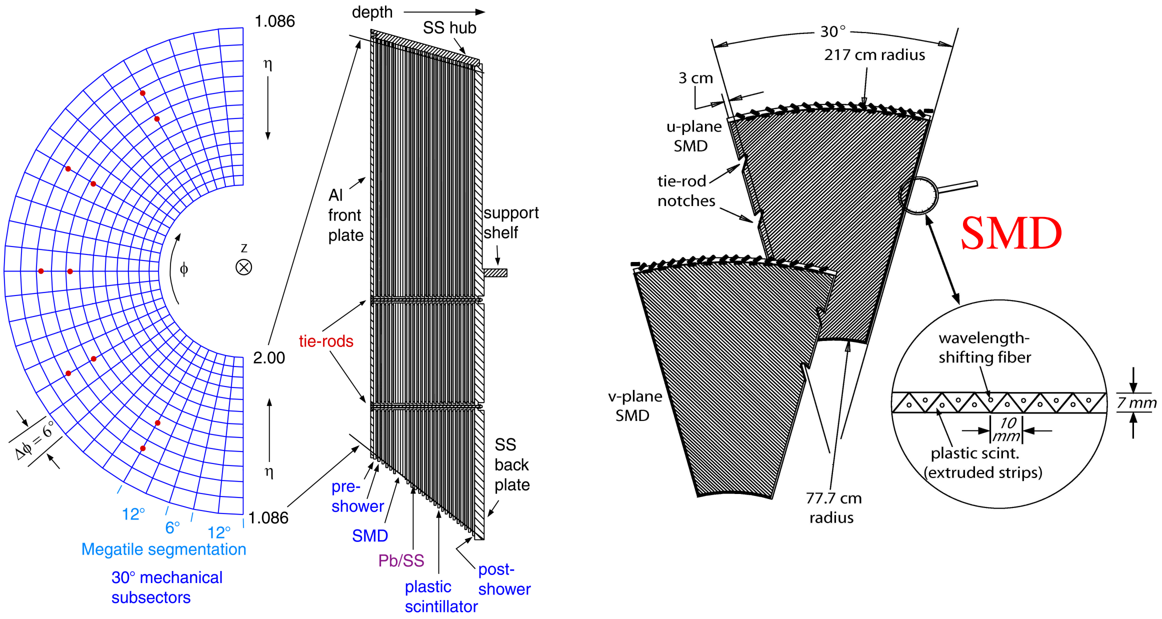

**Figure 3**. Schematic representation of EEMC components: (left) plan and elevation view of tower structure and layers, (right) illustration of stereo SMD planes of triangularly shaped scintillator.

(MAPMT) and associated CW base and FEE assembly (4 FEE cards with 4 chns x 12 bit ADC/each for every MAPMT). These assemblies are housed in magnetic shielding boxes, 12 assemblies = 192 chns/box. This has proved to be an elegant/robust system for individual readout of the ~ 9.2k channels.

In general the EEMC performance has been "remarkably good", but we can touch herein on only a few aspects. Regarding EEMC configuration and repair: as a special constraint, all PMT and FEE are located on back of the STAR west poletip in order to minimize light fiber pathlengh and localize electronics (only 54 fibers go to data collectors off the poletip). The ~ 1kG fields requires all the PMT's to be in shielding "boxes"; similarly, the MAPMT/FEE compact assembly as just described. In terms of maintenance, access to the poletip requires a manlift, and if running, the STAR magnet ramped down and locked out (e.g., latter means a minimum of a few hour turn around so rely mainly on scheduled/bi-weekly ~ 1 shift access periods for repairs/maintenance during runs). However, also during RHIC shutdowns, EEMC access limited when poletip is retracted for work on other systems (TPC, TOF, BSMD, etc.), hence, require ~ 2-3 weeks with poletip attached to do maintenance every year (the single box repair turnaround is ~ 1 day, which includes "piggyback" of box to neighbor box leaving light fibers attached). The good news is that EEMC electronics/readout failure rates are relatively low and declining! For the tower tubes and bases we have seen at peak ~ 1% /yr; for MAPMT it was 2% the first year but now <0.5%. The failure rate for MAPMT FEE boards is similarly declining to from < 1% to ~ 0.1%. Ancillary problems are with the HV controller units (ship for repair) and issues with the cooling for the MAPMT boxes (bubbles in the chiller and compressor fail/shutdown problems). A nuisance factor is that ~ 5% of the readout boxes require de-fibering for maintenance work due to fiber runs being miscalculated. Offline QA with pedestal monitoring catches many problems including complete failure, "fat pedestal" diagnostic, stuck bits, data base swap, etc. But, we have a recent example of low tower bits being stuck 50% of the time which eluded all diagnostics. The moral is to be always looking for the next problem which is presently ignored!

Calibrations for the Endcap at run startup are similar as described for the BEMC (slopes, etc.). However, a main difference is the fact there is only partial coverage by the STAR TPC tracking. In its place was "invented" a MIP identification using a SMD u x v plane hit isolation pattern

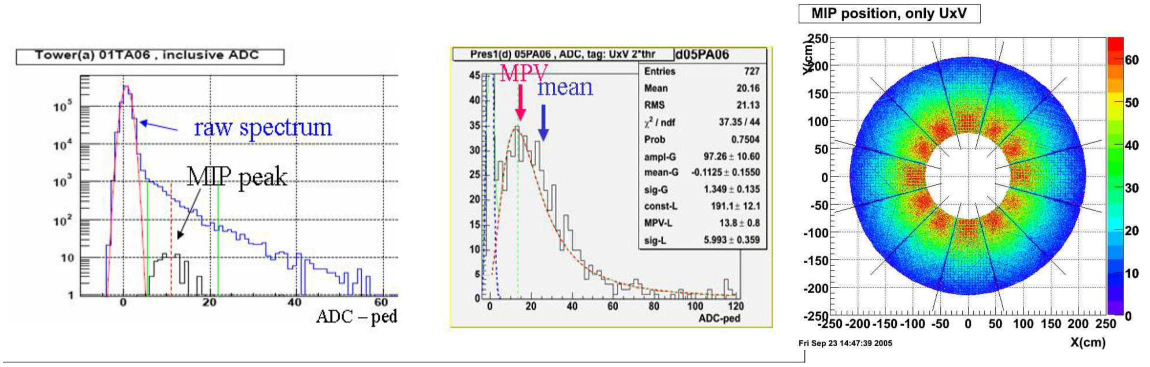

**Figure 4.** EEMC MIP calibration using SMD "tracking" isolation: (left) tower response, (middle) 1st preshower layer response, (right) SMD u x v MIP response. See text for details.

0000000 -- X[X] – 0000000 along with the MIP-like response of all the other the detector components (2 preshowers, tower and postshower). This 26-fold condition is highly selective and allows MIP calibration of the various EEMC components by excusing the detector components from the coincidence in turn. The ideal tower gains are set to 60 GeV $E_T$ for full scale (4096 chns); the RMS spread from this procedure is ~ 9%. We find from run 5 to 6 (for example) that the gains are stable to ~ 1%, so there is no indication so far of fiber, scintillator or PMT degradation for the EEMC.

A performance issue for the EEMC SMD is that of $\pi^0/\gamma$ separation for which the triangularly shaped scintillator strip design with individual readout were envisioned. The physics interest is in investigation of the gluon contribution to the proton spin, probed in γ-jet double spin measurements in longitudinally polarized pp collisions via partonic qg Compton scattering. The expectation was that a factor ~ 3 reduction of $\pi^0$'s was needed at $p_T$ ~ 10 GeV/c (more required to go down in $p_T$) for reasonable extraction of the direct γ-jet signal. Extensive analysis is ongoing with the limited run 6 data sample and includes use of SMD shower shape discrimination analysis (e.g., a maximum sided fit residual in both u and v planes) along with detailed response of the rest (e.g., and including both preshower layer energies) of the EEMC detector components. For the SMD we have found that the initial simulations are not realistic in producing details of the transverse shower shape. At present we have embarked on using a library of SMD response shapes of real photon showers indentified from η particle decay (shapes replace Monte Carlo according to SMD sector, φ, η and photon energy). First look at sided residual discrimination with these "data driven" shapes in pythia for background and signal slices look encouraging although there remains considerable work to do for a robust extraction.

## 4. Level 0 High Tower, Jet Patch and higher level triggering in STAR

The STAR calorimeters can trigger at Level 0 (L0) on High Tower (HT), Trigger Patch (TP) or Jet Patch (JP). Generally set HT: ≥ 1 (of 4800 BEMC or 720 EEMC) if tower ET > threshold; JP: ≥ 1 (of 12 BEMC or 6 EEMC) hard-wired jet patches (sum of several TP's) if total ∑ ET > thresh [note: there is also a minbias condition]. Triggering on something as large ($\Delta\eta$ =1; $\Delta\varphi$ =1) as a jet patch requires careful trigger signal processing to avoid noise issues. The tower digitizer trigger 12 bit ADC is reduced to 10 bits at the FPGA. A special "ped_4" (to put pedestal in range 16-31 channels is then subtracted). For the trig patch (already produces a 6 bit HT) the 2 least significant bits are dropped and Σ 8bits => Trig Patch sums without noise (single channel pedestals that sum in bigger jet patches for triggering). The above information is also passed on to a higher level 2 (L2) trigger that can accept or abort events. As example 2006 JP rate was ~ 150 Hz with L2 trigger used to fit limited bandwidth (~ 2.5 Hz for this trigger). Run 9 "DAQ1000" for the TPC will relax these rate limits – but data volume still a concern! Issues in running these EMC triggers are “hot towers”, particularly for low threshold HT (HI physics); for spin physics where the JP is a workhorse due to reduced trigger bias on jet type, the issues are keeping good pedestals, tracking stuck trigger bits on the digitizer boards, etc. For the upcoming run 9 we plan L0 wiring/FPGA upgrades => smooth out present trigger response in $\varphi$ and $\eta$.

It is worth mentioning that a byproduct (and an extremely valuable one) of the L2 triggering is QA feedback from L2 trigger algorithms. In particular, L2 samples all events (STAR “online” just ~1% and random) and can easily be trigger sorted and/or other diagnostics performed and summarized. We typically monitor pedestal residual per tower, HT and TP frequency/trigger, di-jet correlations, etc. In fact in run 6 a physics measurement (“Sivers” $A_N$ measurement for di-jets [3]) was made directly out of L2 by identifying and triggering on 2 localized clusters, $\eta\Delta \times \phi\Delta = 0.6 \times 0.6$, with $E_T$EMC > 3.5 GeV, $|\phi\Delta| > 60°$ from which the cosine of the di-jets was reconstructed => sign of net $k_{Tx}$ for each event. Of course trigger data can be replayed (fast) offline to optimize cuts, etc. … a novel use of L2!

## 5. STAR EMC calorimetry operations & Procedures

In addition to (and complementing some of) the detailed comments in the above sections, we summarize here the main overall operational protocol and associated personnel:

- While the collider runs yearly there is generally a “summer” maintenance period (no running due to weather, electricity costs, etc.) during which the EMC priorities are sequenced for repair and upgrades directly impacting performance in next run period (mostly EMC expert).
- At run startup: collisions timing checks, pedestals (triggering), pulsers, etc. (EMC expert)
- With beam and starting with minbias trigger => QA detector response and initial calibrations; then activate EMC HT, JP, level 2 (L2) triggering and tune cuts, rates, etc. (EMC expert)
- Monitoring in running mode: online QA-plots (a fraction of events/all triggers) saved per run (shift crew and EMC expert); L2 trigger diagnostics and monitoring plots, ratios, etc. available few minutes after each run and saved to web (~ EMC expert)
- Problems: shift crew reset supplies, reload FPGA (from radiation upsets, etc.); EMC experts mask hot channels, deal with stuck trigger bits, and all other problems
- Special runs: minbias/fill for status tables; background (HT, JP w/o minbias); other special
- Access: ~ bi-weekly (1 shift); or on demand “under fill prep”/machine probs/emerg (.25-1hr)

## 6. Forward Meson Spectrometer (FMS)

The FMS is a hermetic electromagnetic calorimeter, built from finely segmented lead-glass detectors, positioned west of the interaction point at STAR. Some FMS attributes are:

- 2-m square, 1264 cell Pb-glass array at 7.5 m from center of STAR
- Small cells / 476 total: 3.8 cm square x 60.2 cm; $\pi^0$ vs. $\gamma$ to 60 GeV
- Large cells / 788 total: 5.8 cm square x 45 cm (Scott F2) $\pi^0$ vs. $\gamma$ to 40 GeV

The detector is actually mixture of recycled/built parts (a very “green” detector!); e.g., Pb-glass from E831/FNAL (large) and IHEP + JLAB (small); bases and tubes also some borrowed/built. However, all the Pb-glass was re-wrapped and extensively QA/tested. There is a north-south split at the beam pipe and halves movable by carriage since at this forward position there is strong $x_F$ and $p_T$ correlation which can then be mapped. An advanced custom “QT” board readout for FMS cells was built. Salient features of these 32 analog input (~ 80 ns capture time), 12-bit ADC /channel boards, include 5-bit TDC / channel (5 ns time stamp background reduction) and five FPGA for data and trigger. For each trigger 32 bits of information are produced for each RHIC crossing and shipped on fiber to PCI receivers; DAQ is linux based. The trigger treats groups of 16 crystals: for HT trigger (implemented) – e.g., highest of 16 ADC values; for “overlapping patches”, select a contiguous group

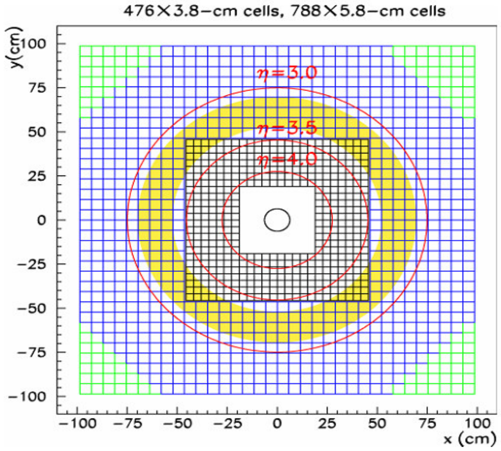

**Figure 4**. A schematic of the STAR forward meson spectrometer as seen from the interaction point. The Blue beam penetrates at the center of the matrices. The array is 'stacked for physics" in forward direction; the yellow shaded area represents a conservative fiducial volume used for detection of direct $\gamma$ candidates, with the remainder of the FMS used as a veto of photons arising primarily from  decay.

of 6 bits sum /6 bits HT => a dynamic clustering and ~ movable trigger patch (to be commissioned). Regarding initial Run 8 FMS performance and operations: using adapted shower shape codes from FPD, and preliminary calibration/efficiency, see clear evidence for $\pi^0$ events in both large and small tiles. Detector capabilities were commissioned as needed for dAu, then polarized pp running and included a LED gain tracking system. At runs's end there were only ~ 10 "problem channels" overall.

## 7. Future Directions and Developments for STAR Calorimetry

The need for better EMC operations and performance as well as the push to address new physics goals has defined a number of near and longer term tasks. A summary of the notable items by category is:

- Readout and Trigging: upgrades to trigger control/driver units => more EMC thresholds; continue with further development of EMC L2 and FMS trigger algo's for efficient triggering and monitoring; parts of EMC readout now slow! re: new TPC "DAQ1000" => rework barrel SMD/preshower RDO crate FPGA; all receivers to DDL transfer (ALICE) and PCI/linux
- Tracking: forward GEM tracker (FGT) => STAR upgrade plan for ~2010 (e.g., charge sign separation of W decay e's for flavor dependent spin PDF determination); optimize (meantime) forward tracking algo's and new DAQ hardware for maximum TPC reach
- Shielding, material and etc. Fight "extra" material associated with central tracking and other upgrades; tunnel shielding for remaining EMC "hot spots" => bandwidth/data integrity
- Calibrations, algorithm development and etc. improve tower calibrations (e.g., $\pi^0$'s and e's where possible) and other components for next tier of physics output; improve $\pi^0/\gamma$ and e/h discrimination algos ($\gamma$ -jets currently of interest for spin, HI and QCD)

## 8. Summary

STAR Calorimetry was installed and commissioned over several years and serves a variety of both heavy ion and spin physics needs At present, all EMC components are running well and increasingly contributing to STAR physics. Examples in triggering and EMC response analysis were presented and selected operations, procedures, component performance issues reviewed along with anticipated upgrades. We look forward to many future years of successful operations and physics output!

## References

[1] M. Beddo *et al.*, 2003 Nucl. Instr. Meth. **499**, 725.
[2] C.E. Allgower *et al.*, 2003 Nucl. Instr. Meth. **499**, 740.
[3] B.I. Abelev *et al.* 2007 PRL **99**, 142003.