STAR Upgrades

Daniel Brandenburg (Shandong University / BNL-CFNS)

→ for the STAR Collaboration

Initial Stages 2019

June 24-28, 2019

Columbia University, NY
STAR Upgrades : Outline

- STAR Upgrades for BES II
  - Upgrade of the Inner TPC
  - Event Plane Detector
  - Endcap Time-of-Flight
- Forward Rapidity Physics
- The STAR Forward Upgrade
  - Tracking
  - Calorimetry
- Looking Forward
- Summary
STAR Detector Upgrades

- Inner TPC upgrade
- Endcap Time Of Flight
- Event Plane Detector
- Forward Tracking & Calorimetry (Not Shown)
Inner TPC Installation

Installation

• East Side Sectors Complete 09/26/18
• West Side Sectors Complete 10/25/18

The testing and commissioning plan was developed ~ 2 years ago, and updated following the fall DOE NP review - Includes hardware testing

**Important components were:**

- Tests at SDU
- Test at BNL pre-installation
- Final inspection at installation time
- Post Installation checkout
- Cosmic data taking

**2019 Schedule followed:**

- Jan 18 - Feb 4: Cosmic data with forward Full Field
- Feb 4: Change Magnet polarity
- Feb 4 - ~Feb 18 Cosmic data with reverse full field
- Feb. 11: cool down of 2nd half of blue ring begins
- Feb. 14: beam in blue ring starting with the day shift
- Feb. 19: cool down of 2nd half of yellow ring begins
- Feb. 20: beam in yellow ring starting with the day shift
- Feb. 20: 1st collisions in STAR overnight at injection energy
- Feb. 21-27: Physics setup
**iTPC Performance**

- Excellent performance in bench test for MWPC:
  - Gas gain uniformity < 1.5% (RMS)
  - Energy resolution ~ 20% (FWHM)
  - Good stability under X-ray irradiation test

**iTPC (one sector) performance in 2018 isobar collisions:**

- Maximum hits number per track: 45 → 72
- Lower transverse momentum threshold of 60 MeV/c
- η coverage extended by 0.4 units.

**Diagram:**
- Counts vs. number of hits for iTPC sector and regular sector.

**Inner TPC Upgrade**

- Replace all inner TPC sectors → continuous pad rows
  - Doubled the readout channels. Using SAMPA chip developed for ALICE

**Graph:**
- Counts vs. number of hits for iTPC sector and regular sector.

**Event display:**
- Replace all inner TPC sectors → continuous pad rows
  - Doubled the readout channels. Using SAMPA chip developed for ALICE
Inner TPC Upgrade

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- Increase mid-rapidity coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$
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- Replace all inner TPC sectors → continuous pad rows
  - Doubled the readout channels. Using SAMPA chip developed for ALICE
  - Improved dE/dx Resolution (15%-30%)
  - Increase mid-rapidity coverage from |η| < 1.0 to |η| < 1.5
Excellent performance in bench test for MWPC:

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- Energy resolution ~ 20% (FWHM)
- Good stability under X-ray irradiation test

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Inner TPC Upgrade

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  - Doubled the readout channels. Using SAMPA chip developed for ALICE
- Increase mid-rapidity coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$

Improved dE/dx Resolution (15%-30%)

- Improved Momentum Resolution
- Decrease minimum $p_T$ threshold from $p_T > 125$ MeV/c to $p_T > 60$ MeV/c
Inner TPC Upgrade

Hitmap with “old” inner TPC (≤2017)
Inner TPC Upgrade

Hitmap with “old” inner TPC (≤2017)

Only one inner TPC sector upgraded (2018)
Inner TPC Upgrade

- Hitmap with “old” inner TPC (≤2017)
- Only one inner TPC sector upgraded (2018)
- All inner TPC sectors upgraded (2019)
Inner TPC Upgrade

Successful, on-time & under budget completion of the iTPC upgrade

2019 Event Display: Au+Au 19.6 GeV
Full tracking with all iTPC sectors
Event Plane Detector

- Replaces Beam-Beam Counter (BBC)
  - Improved triggering capabilities
  - Extend $\eta$ coverage
  - Improve event plane resolution

- Smooth installation
  - **Completed in 2018**
  - Already used in analysis of 2018 data

**Added coverage from EPD**

→ Allows measurement of $v_1$ over ~10 units of $\eta$!

**1st order Event Plane Resolution**

→ Significant improvement across all centrality
Motivation: Endcap Time-of-Flight Detector

➤ Extend STAR’s particle ID capabilities ($\pi$, $K$, $p$)
  - Complements the increased iTPC coverage $|\eta| < 1.5$
  - Essential for mid-rapidity particle ID in Fixed Target Program

➤ Allows “gap-less” scan of phase diagram with collider + Fixed Target Energies
  - Rapidity dependence of key bulk observables
  - Particle ID – needed for fluctuation measurements in the Fixed Target Program

➤ First streaming DAQ system at RHIC – important step towards the future

➤ Collaboration with CBM Fair phase 0

➤ Full eToF installation: completed Nov 22, 2018
ETOF Performance in 2019 Running

Region in red lines: extended coverage added by eTOF for identified protons

Particle bands are clearly distinguished over large momentum range.
Achieved target time resolution → Calibrated time resolution ~ 85 ps
STAR Physics Program after BES II

➤ STAR Upgrades for BES II → provide **unique** opportunities at mid-rapidity in high energy A+A, p+A, and p+p

<table>
<thead>
<tr>
<th>Mid-rapidity -1.5&lt;(\eta)&lt;1.5</th>
<th>Forward-rapidity 2.5&lt;(\eta)&lt;4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A+A</strong></td>
<td><strong>p+A, p+p</strong></td>
</tr>
</tbody>
</table>

**Beam:**
- Full Energy (200 GeV) Au+Au

**Physics Topics:**
- a deep look into the properties of the QGP:
  - \(\gamma\) & e+e- pairs
  - Chiral symmetry restoration
  - Temperature and lifetime of hot, dense medium
  - Lower momentum \(\pi, K, p\) spectra
  - Hypertriton Lifetime Measurement
  - Precision measurements of direct photon yields and \(v_n\)

**Beam:**
- 500 GeV: p+p
- 200 GeV: p+p and p+A

**Physics Topics:**
- Improve statistical precision:
  - TMD measurements, i.e. Collins, Sivers, ...
  - Access \(s\) & \(\Delta s\) through Kaons in jets
    - Measurement of GPD \(E_g\) through UPC \(J/\Psi\)
    - First access to Wigner functions through di-jets in UPC
  - Gluon and quark vacuum fragmentation
  - Gluon and quark fragmentation in nuclear medium
  - Nuclear dependence of Collins FF

Forward Upgrades

- Forward Rapidity Physics \((2.5 < \eta < 4)\)
- The STAR Forward Upgrade
  - Tracking
  - Calorimetry
- A Look Forward
Forward Rapidity Physics at STAR

- Unique program addressing several fundamental questions in QCD
- Essential to RHIC cold & hot QCD physics mission + fully realize scientific promise of future Electron Ion Collider

Mid-rapidity -1.5<\eta<1.5

**Au+Au**

**Beam:**
Full Energy (200 GeV) Au+Au

**Physics Topics:**
- Temperature dependence of viscosity through flow harmonics up to $\eta\sim4$
- Longitudinal decorrelation up to $\eta\sim4$
- Global Lambda Polarization → Test for strong rapidity dependence

Forward-rapidity 2.5<\eta<4

**p+A, p+p**

**Beam:**
500 GeV: p+p
200 GeV: p+p and p+A

**Physics Topics:**
- TMD measurements at high $x$
  - transversity → tensor charge
- Improve statistical precision for Sivers through Drell-Yan
- $\Delta g(x,Q^2)$ at low $x$ through Di-jets
- Gluon PDFs for nuclei
- $R_{pA}$ for direct photons & DY
- Test of Saturation predictions through di-hadrons, $\gamma$-Jets
Forward Rapidity Physics at STAR

➤ Unique program addressing several fundamental questions in QCD
➤ Essential to RHIC cold & hot QCD physics mission + fully realize scientific promise of future Electron Ion Collider

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<td><strong>Beam:</strong> 500 GeV: <strong>p+p</strong> 200 GeV: <strong>p+p</strong> and <strong>p+A</strong></td>
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<td>▪ Global Lambda Polarization (\rightarrow) Test for strong rapidity dependence</td>
<td>▪ (\Delta g(x,Q^2)) at low (x) through Di-jets</td>
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<td>▪ <strong>Gluon PDFs for nuclei</strong></td>
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Unique program addressing several fundamental questions in QCD
Essential to RHIC cold & hot QCD physics mission + fully realize scientific promise of future Electron Ion Collider

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Global Hyperon Polarization

Sensitive to thermalization and viscosity

- Polarization increases with viscosity

Hydrodynamic calculations:
Li, Pang, Wang & Xia, PRC 96 (2017) 054908; (private comm.)

HĲING with energy flow:
Deng & Huang, PRC 93 (2016) 064907

Model’s predict opposite Polarization trend with rapidity
→ Measurements at forward rapidity are key
Probing the Initial State in A+A

3 important questions:
- What are the nPDFs at low-x?
- How saturated is the initial state of the nucleus?
- What is the spatial transverse distributions of nucleons and gluons?

p+A@RHIC: unique kinematics

Observables free of final state effects:
- Gluons: $R_{pA}$ for direct photons
- Sea-quarks: $R_{pA}$ for Drell-Yan

Scan A-dependence prediction by saturation models

Accessible at forward rapidity
STAR Forward Detectors: FTS + FCS

Forward Tracking System

Silicon + small-Strip Thin Gap Chambers (sTGC)

Forward Calorimeter System

Preshower

EMCal

HCal
STAR Forward Upgrade Status

Associate Laboratory Director’s Review

- Reviewed on 19th, November 2018:
  - Physics requirements
  - Cost & Schedule for each subsystem
  - Readout & Triggering
  - Plan for integration and in-situ testing

- Positive Feedback & Recommendations
  - “Good progress has been made on an intriguing concept for a cold-QCD program to run in the near future in the forward direction at STAR”

NSF proposal submitted Jan 2019

- Funding for Forward Calorimeter systems
- Received very positive feedback
- Awaiting final response from NSF Division of Grants and Agreements - expect to be funded

STAR Forward Upgrade Institutions

Large project → **Dedicated manpower & expertise for each system**

- sTGC
- Silicon
- ECal
- HCal
- DAQ / Readout
- Software
- Integration
  - Calibration
  - Slow Controls
## Forward Tracking System

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum Resolution</td>
<td>A+A goals</td>
</tr>
<tr>
<td>&lt; 30%</td>
<td></td>
</tr>
<tr>
<td>Tracking Efficiency</td>
<td>A+A goals</td>
</tr>
<tr>
<td>&gt; 80% @ 100 tracks / event</td>
<td></td>
</tr>
<tr>
<td>Charge Separation</td>
<td>p+p / p+A goals</td>
</tr>
</tbody>
</table>

### Silicon mini-strip disks ×3
- Location: z = 90, 140, 187 cm from interaction point
- Build on and utilize STAR experience of successful Intermediate Silicon Tracker (IST) detector
- Minimal material (≤1% X0/layer) in the acceptance

### Small-Strip Thin Gap Chamber (sTGC) ×4
- Location: z = 270, 300, 330, 360 cm from interaction point
- Significant reduction in cost (compared to all silicon)
- Prototype at BNL, testing in STAR during 2019 run

# Forward Tracking System

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<table>
<thead>
<tr>
<th>Sigma of $p_T$ resolution</th>
<th>No ineficiency</th>
<th>10% inefficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA6 Simulation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Truth $p_T$ [GeV/c]</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation primary track 100% / 90% hit eff.</td>
<td></td>
</tr>
<tr>
<td>0.2 GeV/c</td>
<td>0.2</td>
</tr>
<tr>
<td>1.0 GeV/c</td>
<td>0.8</td>
</tr>
<tr>
<td>2.0 GeV/c</td>
<td>0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Log10(n tracks)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>1.5</td>
<td>1.0</td>
</tr>
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</table>

[Simulation](https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648)

We have demonstrated that the tracking performance of the Silicon and sTGC combined setup can achieve efficiencies of 80% out to 100 tracks/event and above 50% at 300 tracks/event. This level of performance satisfies the requirements from both the proton and HIC physics.
**Forward Calorimeter System**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Resolution p+p and p+A</th>
<th>Resolution A+A</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECal</td>
<td>$\sim 10%/\sqrt{E}$</td>
<td>$\sim 20%/\sqrt{E}$</td>
</tr>
<tr>
<td>HCal</td>
<td>$\sim 50%/\sqrt{E} + 10%$</td>
<td>—</td>
</tr>
</tbody>
</table>

**Electromagnetic Calorimeter**
- Reuse PHENIX PbSc
- New readout: SiPM

**Hadronic Calorimeter**
- Sampling iron-scintillator
- Uses same readout as ECal

**R&D in support of EIC**
- HCal development
- All readout electronics
- Balance Cost & performance

**NSF grant expected to provide majority of funds**

A. Kiselev (BNL)
T. Lin (TAMU)
D. Kapukchyan (UCR)
D. Neff (UCLA)
M. Sergeeva (UCLA)
B. Chan (UCLA)

6/26/19
Plan/Goals for Run 19

Forward Calorimeter System

✓ Fermilab test beam results completed
✓ Measured ECAL energy resolution $\sim 10% / \sqrt{E}$
  ○ HCAL energy resolution measured $\sim 75% / \sqrt{E} + 7%$
    ➢ Work on modified light collection to improve resolution
➢ 10-20 hours of Au+Au 200 GeV collisions
  ○ Test readout of calorimeters at $\sim 10$kHz rate
  ○ Finish commissioning of DEP (digitizer/trigger) boards with this data
  ○ Look at MIPS – use for calibration etc.

Forward Tracking System

➢ Silicon Detectors
  ○ Complete the design of detector module in June 2019
  ○ Build the first complete prototype module in Summer/Fall 2019
  ○ Fully test the prototype module in Fall/Winter 2019
➢ sTGC Detectors
  ✓ 30x30 cm prototype installed in STAR on June 5th, 2019
  ✓ Test in STAR DAQ with C10 (90% argon + 10% CO2)
  ○ Test performance with various gas mixtures at Shandong University in full size (60 x 60 cm) prototypes

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Looking Forward

Measurements planned for 2021+ with the STAR forward upgrade → Address important topics in hot & cold QCD

**p+p and p+**

- Transverse polarization effects in the proton: Twist-3 and TMDs
- Transversity, Collins, and Interference fragmentation functions
- Access $\Delta G$ through dijets with p+p at $\sqrt{s} = 500$ GeV
- Probe initial state with p+A collisions

**A+A**

- Correlation measurements in hot and dense nuclear matter
- Precision measurements of long range correlations
- Temperature dependence of the viscosity through flow measurements at $\eta \sim 4$

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Delivered Luminosity</th>
<th>Scientific Goals</th>
<th>Observable</th>
<th>Required Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p @ 200</td>
<td>300 pb$^{-1}$</td>
<td>Subprocess driving the large $A_N$ at high $x_F$ and $\eta$</td>
<td>$A_N$ for charged hadrons and flavor enhanced jets</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
</tr>
<tr>
<td>p+Au @ 200</td>
<td>1.8 pb$^{-1}$</td>
<td>What is the nature of the initial state and hadronization in nuclear collisions</td>
<td>$R_{pAu}$ direct photons and DY</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
</tr>
<tr>
<td></td>
<td>8 weeks</td>
<td>Clear signatures for Saturation</td>
<td>Dihadrons, $\gamma$-jet, h-jet, diffraction</td>
<td></td>
</tr>
<tr>
<td>p+Al @ 200</td>
<td>12.6 pb$^{-1}$</td>
<td>A-dependence of nPDF, A-dependence for Saturation</td>
<td>$R_{pAl}$: direct photons and DY</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
</tr>
<tr>
<td></td>
<td>8 weeks</td>
<td></td>
<td>Dihadrons, $\gamma$-jet, h-jet, diffraction</td>
<td></td>
</tr>
<tr>
<td>p+p @ 510</td>
<td>1.1 fb$^{-1}$</td>
<td>TMDs at low and high $x$</td>
<td>$A_{UT}$ for Collins observables, i.e. hadron in jet modulations at $\eta &gt; 1$</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
</tr>
<tr>
<td>p+ p@ 510</td>
<td>1.1 fb$^{-1}$</td>
<td>$\Delta g(x)$ at small $x$</td>
<td>$A_{UL}$ for jets, di-jets, h/\gamma-jets at $\eta &gt; 1$</td>
<td>Forward instrum. ECal+HCal</td>
</tr>
</tbody>
</table>

Summary of STAR Upgrades

Crucial Upgrades for Beam Energy Scan II:

- **Inner TPC**: Successful, on-time & under budget completion, excellent performance
- **Event Plane Detector**: Excellent uniformity + delivered expected improvement in the event-plane resolution
- **Endcap Time of Flight**: Fully installed, commissioning and data taking are ongoing 2019

➤ **Upgrades provide unique opportunities at mid-rapidity in high energy A+A, p+A, and p+p**

**STAR Forward Rapidity Upgrade:**

➤ Essential to RHIC cold & hot QCD physics mission & to realize scientific promise of future Electron Ion Collider

➤ **Forward Tracking System**
  ➤ **Silicon mini-strip detectors**: build on STAR expertise from previous IST detector
  ➤ **Small strip thin gap chambers**: reduced cost, already testing prototypes in STAR now

➤ **Forward Calorimetry System**: **Preshower + ECal + Hcal**
  ➤ In-situ testing at STAR now, received positive funding feedback from the NSF

➤ **Unique program addressing several fundamental questions in QCD**
Calorimeter Current Status

- Fermilab test beam results
  - HCAL 16 channels, ECAL 16 channels
  - ECAL energy resolution measured $\sim 10\% / \sqrt{E}$ - meets requirement
  - HCAL energy resolution measured $\sim 75\% / \sqrt{E} + 7\%$
  - Work on modified light collection to improve resolution
    - Promising results - ongoing development, but does not affect design

- Installation and in-situ testing at STAR
  - 64 (8x8) EMCAL installed
  - 16 (4x4) HCAL installed
  - 1 layer (9 slats) Pre-shower (former FMS Post-Shower detector)
  - New generation of digitizer/trigger boards for ECAL/HCAL/Preshower readout

- Currently commissioning in STAR with beam
  - Operating pedestal, LED, and physics runs

- Online + slow controls + offline software being developed

6/26/19

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Looking Forward

Future A+A Measurements with the STAR forward upgrade

<table>
<thead>
<tr>
<th>Detectors</th>
<th>Physics Measurements</th>
<th>Acceptance</th>
<th>Longitudinal de-correlation $C_n(Δ\eta)$, $r_n(\eta_a,\eta_b)$</th>
<th>$\eta/s(T)$, $\zeta/s(T)$</th>
<th>Mixed flow Harmonics $C_{m,n,m+n}$</th>
<th>Ridge</th>
<th>Event Shape and Jet-studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Calorimeter (FCS)</td>
<td></td>
<td>2.5 &lt; $\eta$ &lt; 4 (photons, hadrons)</td>
<td>One of these detectors necessary</td>
<td></td>
<td></td>
<td>Good to have</td>
<td>One of these detectors needed</td>
</tr>
<tr>
<td>Forward Tracking System (FTS)</td>
<td></td>
<td>2.5 &lt; $\eta$ &lt; 4 (charged particles)</td>
<td>Important</td>
<td></td>
<td>One of these detectors necessary</td>
<td>Important</td>
<td></td>
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Addresses important topics in hot QCD:
- Ridge in p+p, p+A, and A+A
- Correlation measurements in hot and dense nuclear matter
- Precision measurements of long range correlations
- Temperature dependence of the viscosity through flow measurements at $\eta \sim 4$
the material. The Si-disks are combined with four small-strip Thin Gap Chamber (sTGC) wheels following the ATLAS design. These extremely cost effective sTGCs can also be seen as an alternative tracking detector technology to the planned GEM-trackers in the forward arms of current EIC detector designs. The Si mini-strip disks will be placed in the region $z = 140 - 187$ cm. The 4 sTGC wheels would be placed 30 cm apart starting from $z = 273$ cm. The Si-Disks readout is based on APV chips, which allows us to reuse the readout chain of the IST, which was part of the STAR HFT. For the sTGC the plan is to read it with the TPC electronics just unmounted TPX electronics.

3.4.1 Status

The June 2018 PAC recommended the FCS and all other STAR forward upgrade components be ensured to have a sound technical basis, hold to the estimated cost, and be ready to be installed and commissioned without beam for a 500 GeV RHIC polarized pp run to begin mid-August 2021. To this end the BNL ALD for NPP convened a cost and schedule review in November 2018. The outcome of the review can be summarized as: "A five-member review panel (S. Boose, C. Miraval, G. van Nieuwenhuizen, A. Tricoli, and chaired by G. Young) conducted a review of the resource requirements for the proposed forward upgrades to the STAR detector on November 19, 2018. The panel noted good progress on the proposed concept for a cold-QCD experiment to run in late FY2021 at RHIC, with plausible plans for funding and conservative designs for all detector components, electronics, and support infrastructure. The panel opined that the major project risks are identified and that the experiment appears positioned to be ready for first operation in 2021."

Figure 56: The organizational structure for the STAR forward upgrade.
**Forward Tracking System**

**Current Status**

**Silicon Detector**
- Silicon strip sensors ordered from Hamamatsu
- Detector module design and prototyping in progress
- First complete prototype module for test in Fall/Winter 2019

**sTGC Detector**
- 30x30 cm prototype delivered to BNL in January 2019
- Module tested in test-stand using cosmic rays + scintillator pads for trigger
- Connected to STAR Data Acquisition system – first test data being analyzed now
- Installed in STAR on June 5, 2019
- Full-size 60x60 cm prototype being produced at Shandong University

Prototype in STAR Clean Room, On the Mounting Structure