Silicon Vertex Tracker for PHENIX Upgrade at RHIC:

Capabilities and Detector Technology

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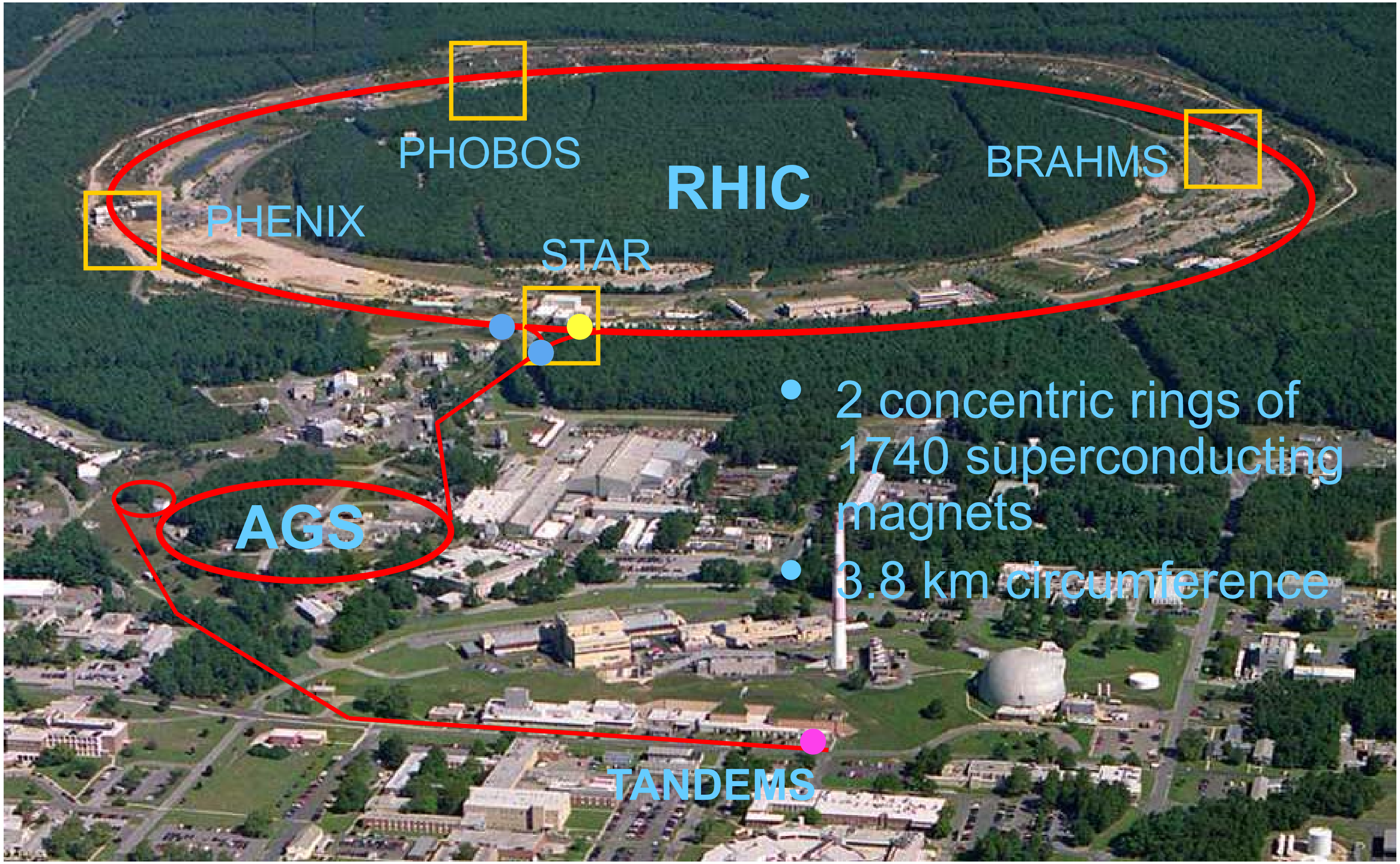
for the PHENIX Collaboration

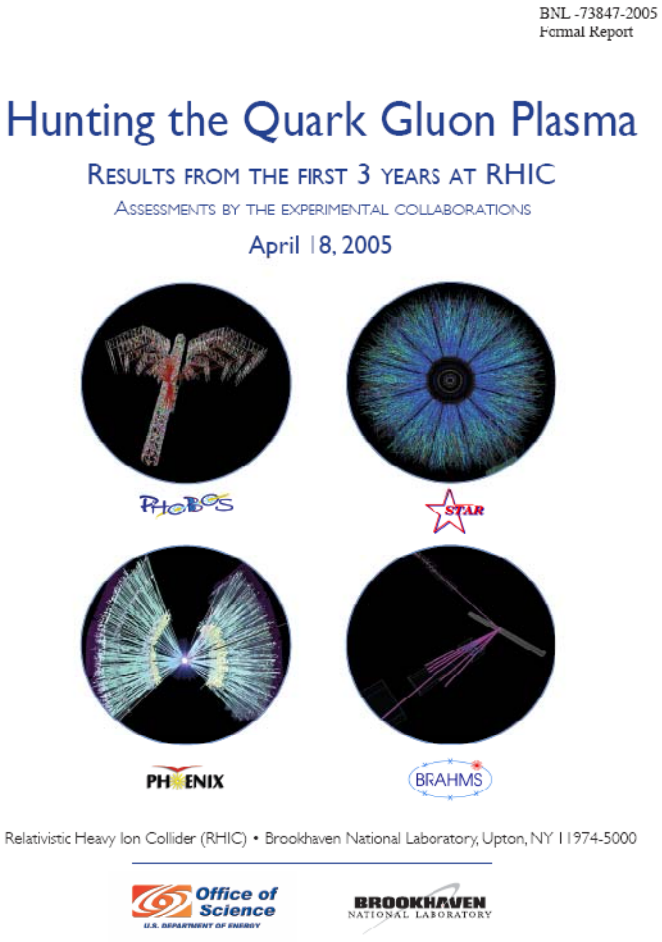
Relativistic Heavy Ion Collider (RHIC)



- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference

A=1~200, $\vec{p}\vec{p}$, pA, AA, AB; $\sqrt{s_{NN}}$: 20-200 GeV (AA), $\sqrt{s}$:48-500 GeV (pp)

Physics Motivations


BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

The Collaboration of the four experiments: PHENIX, BRAHAMS, PHOBOS and STAR at RHIC

CONCLUDE

that highly interacting medium have been discovered in most central Au+Au collisions at 200 GeV

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

In the press

Science Iran Daily April 20, 2005 4

Early Universe Liquid-Like

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence, AP reported.

By revising physicists' concept of the early universe, the new discovery offers opportunities to better learn how subatomic particles interact at the most fundamental level. It may also reveal intriguing parallels between gravity and the force that holds atomic nuclei together, physicists said Monday at a Tampa, Fla., meeting of the American Physical Society.

"There are a lot of exciting questions," said Sam Aronson, associate director for high energy and nuclear physics at Brookhaven National Laboratory, which is located on Long Island about 65 miles east of New York city.

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider, known as RHIC, repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Everything was so hot then that quarks and gluons, which are now almost inextricably bound into the protons and neutrons inside atomic nuclei, were thought to have flown around like BBs in a blender.

But by reproducing the conditions of the early universe, RHIC has shown that unconstrained quarks and gluons don't fly away in all directions so much as squirt out in streams.

"The matter that we've formed behaves like a very nearly perfect liquid," Aronson said.

When physicists talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity, a friction-like property that affects a fluid's ability to flow and the resistance to objects trying to swim through it. Honey has a high viscosity; water's viscosity is low. A perfect liquid has no viscosity at all, which is impossible in reality but useful for theoretical discussions.

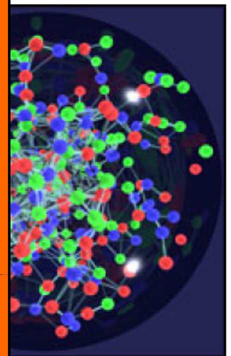
Theoretical physicists have recently proposed that material swallowed by black holes might also have extremely low viscosity. That notion, based on a branch of mathematical physics known as string theory, has led some physicists to hypothesize that there might be a deeper connection between what happens in a black hole and what goes on when two gold nuclei collide at RHIC.

When physicist talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity

New State o ... e'

Physicists ...
Laboratory annou...
created what appe...
out of the building...
and gluons. The r...
findings--which co...
composition of the...
big bang--today in...
American Physica...

There are four col...
PHENIX, PHOBO...
Brookhaven's Rela...
(RHIC). All of them...
interacting beams...
another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."



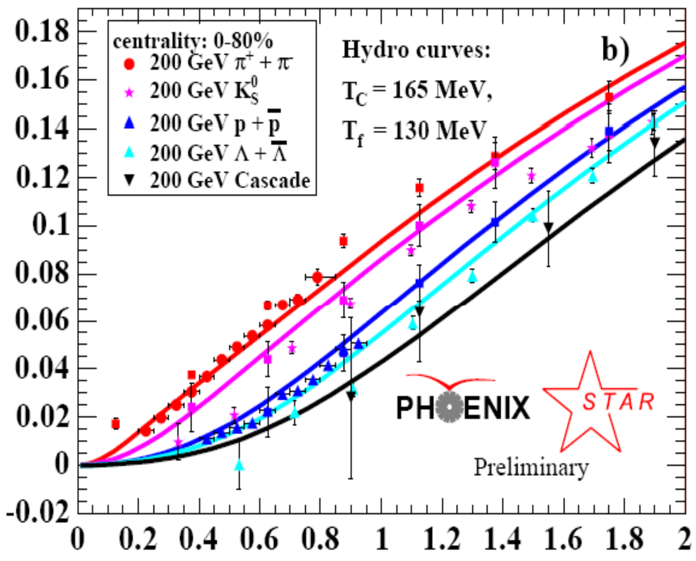
...s of matter that is more strongly interacting than predicted

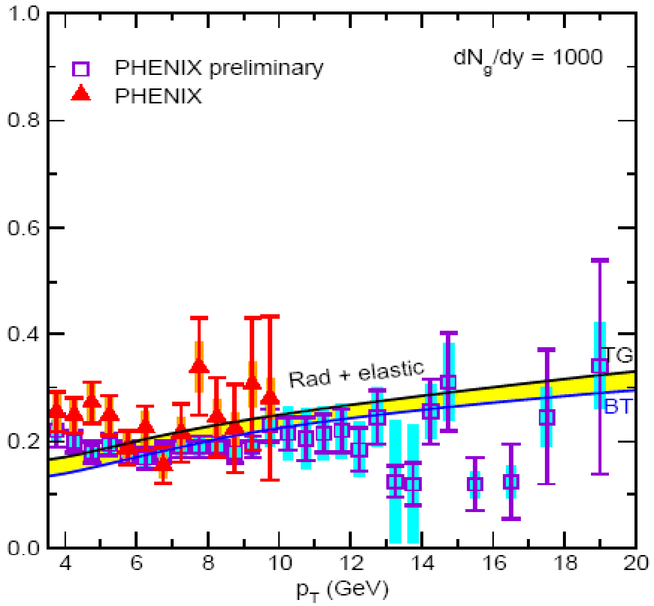
Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

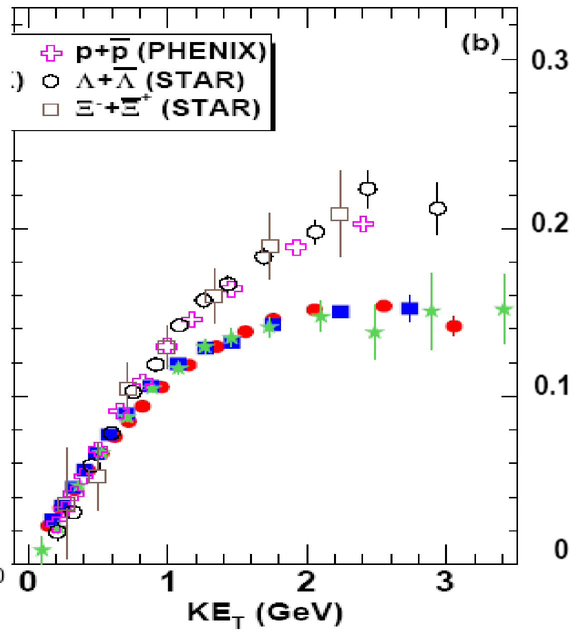
The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

Experimental Evidences

Elliptic Flow of Hadrons	Suppression of High-Energy Pions	Quark-Number Scaling
$v_2(p_T,m)$	$R_{AA}(p_T)=(spec)_{AA}/(spec)_{pp}$	$v_2(KE_T,n_q)$







Collective Expansion:
ideal hydrodynamics
(QGP equation-of-state)

Quark Energy-Loss:
perturbative QCD
(gluon radiation)

Hadronization:
quark coalescence

rapid thermalization, "perfect liquid" $\Rightarrow$ strongly-interacting QGP !?

What Next?

- Detailed study of the properties of the produc atter
  - Does energy loss mechanism depend c k mass?
  - Does flow strength depend on mass mass
  - ➔ Identify heavy flavors (charm ar om)
  - How is the jet correlation modi large solid angle?
  - Jet shape recoiled against c hoton
  - ➔ Measure charged partic arge solid angle

- Detailed study of nuc ucture
  - A_{LL} of charm an n production
  - ➔ Identify cha bottom
  - Direct pho t measurement to constrain parton level kinema
  - ➔ Me ecoil jet in large solid angle

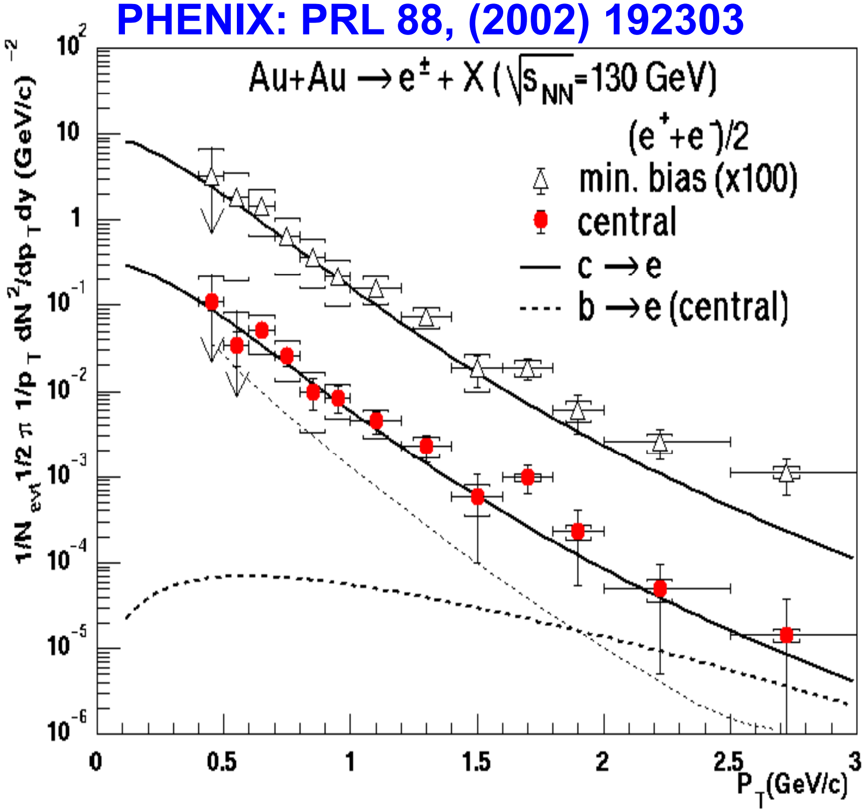
Key word = Heavy Quark production

PHENIX

Heavy-Quark Probes at PHENIX

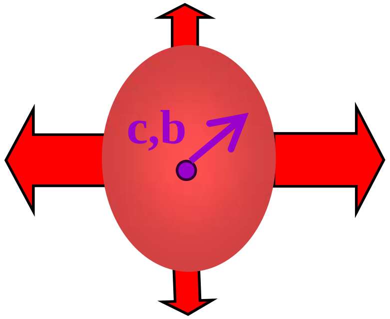
- **Present PHENIX**: Access signal from heavy quarks via single electron measurement

PHENIX: PRL 88, (2002) 192303



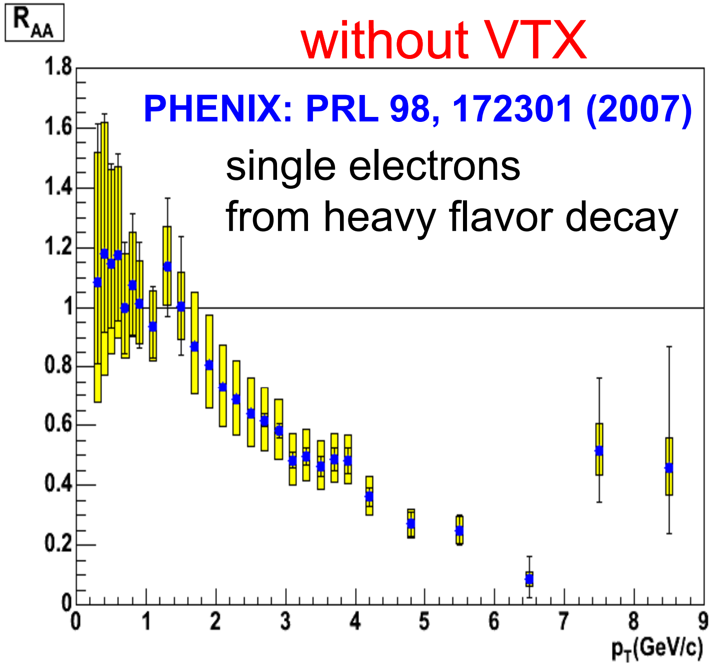
- **Precision of the measurement limited by systematic uncertainty because,**
  - Huge background contribution
    - – π^0 and η Dalitz decay
    - – γ conversion (γ -> e^+e^-)
- **Cannot Separate charm and beauty contribution model independently**
- **Lifetime (ct) of mesons with charm and beauty**
  - $D^{\pm}$ = 312 mm, D^0 = 123 mm
  - $B^{\pm}$ = 501 mm, B^0 = 460 mm
- **Secondary vertex identification allows us to suppress background on non-photonic electrons and will make it possible to distinguish if an electron originates from charm or beauty.**

Heavy-Quark Probes at PHENIX

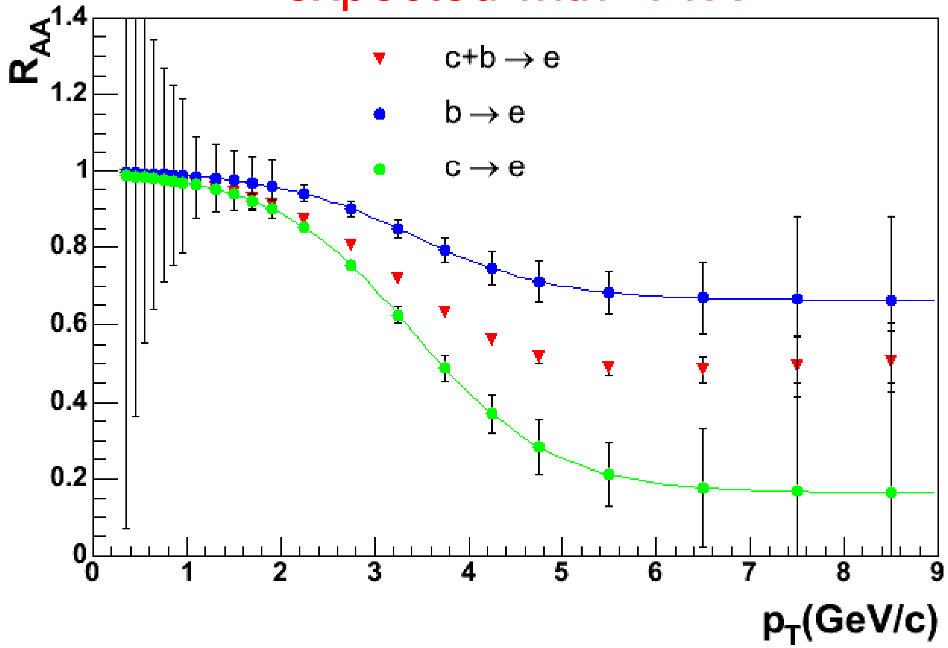


- m_{charm}=1.5 GeV, m_{bottom}=5 GeV >> T ≈ 300 MeV
- **sQGP:** energy loss, thermalization, v_2
- Experimental tool: electron spectra D,B → eX

Nuclear Modification Factor
without VTX



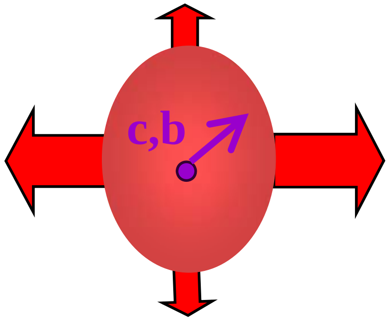
Nuclear Modification Factor
expected with VTX



- factor 4-5 suppression!
- perturbative QCD?

- VTX can separately measure R_{AA} of b→e and c→e

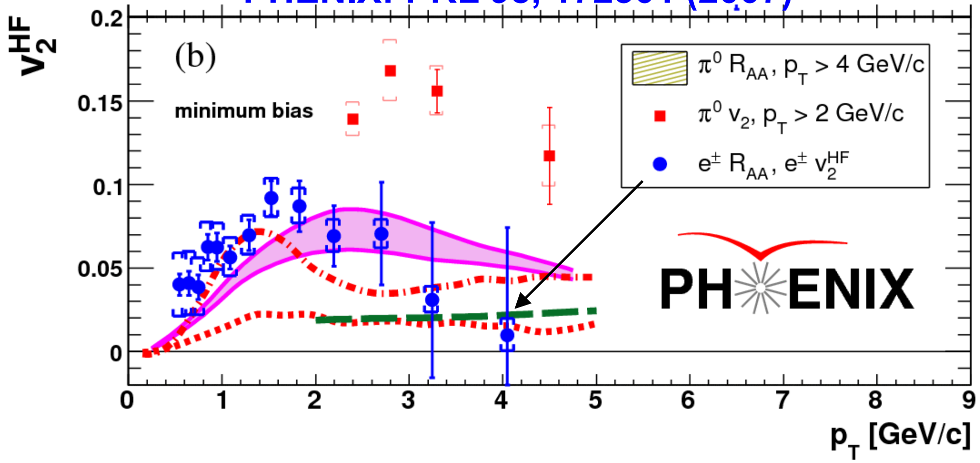
Heavy-Quark Probes at PHENIX



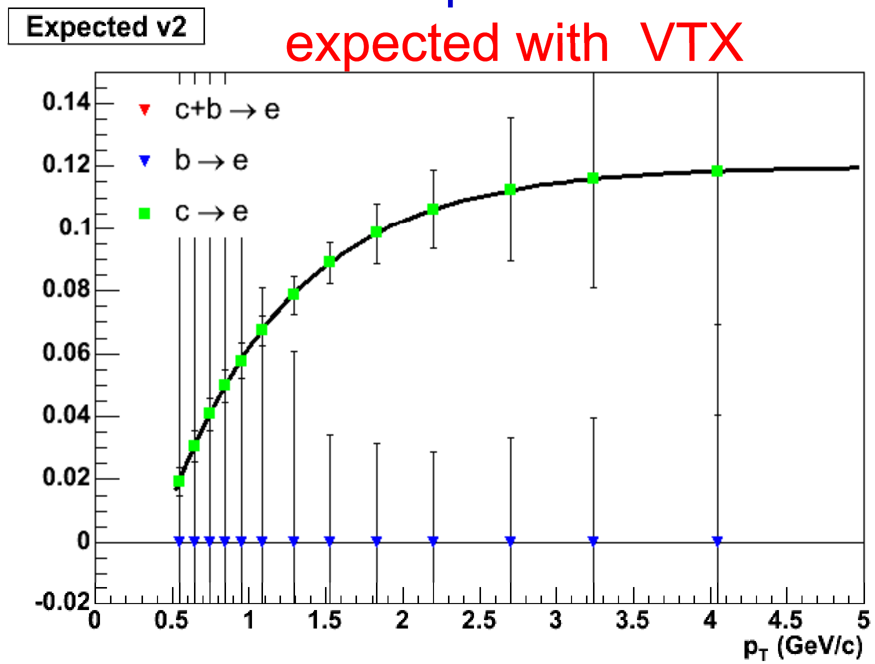
- **m_{charm}=1.5 GeV**, **m_{bottom}=5 GeV >> T ≈ 300 MeV**
- **sQGP:** energy loss, thermalization, **v_2**
- Experimental tool: electron spectra D,B → eX

Elliptic Flow
without VTX

PHENIX: PRL 98, 172301 (2007)



Elliptic Flow
expected with VTX



✪ substantial collectivity
✪ heavy-quark interactions?

PHENIX detector : present

✪ **P**ioneering **H**igh Energy **N**uclear **I**nteraction e**X**periment

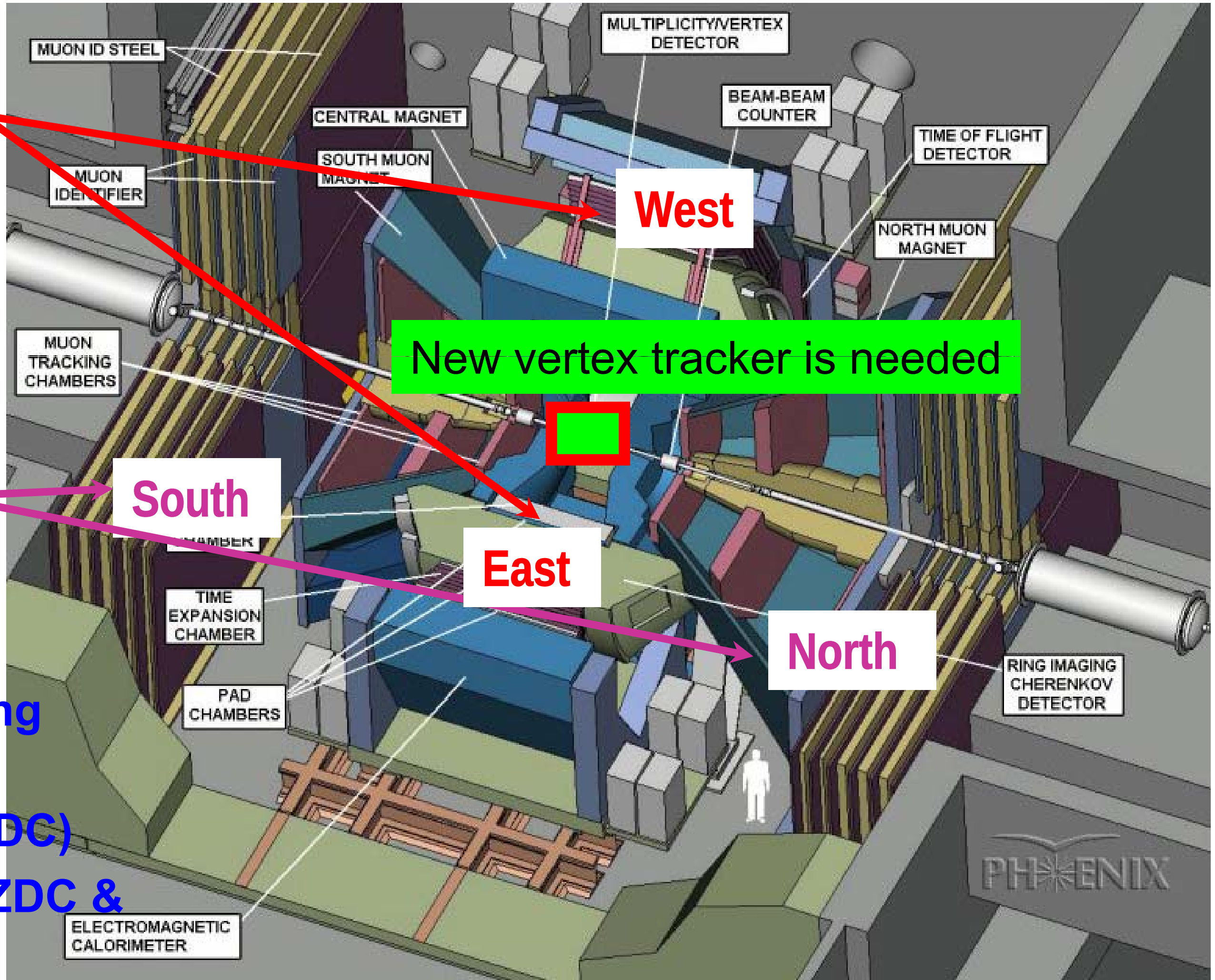
- **2 central spectrometers**

Photon, hadron, electron
$|\eta|<0.35$, $\Delta\phi=\pi$

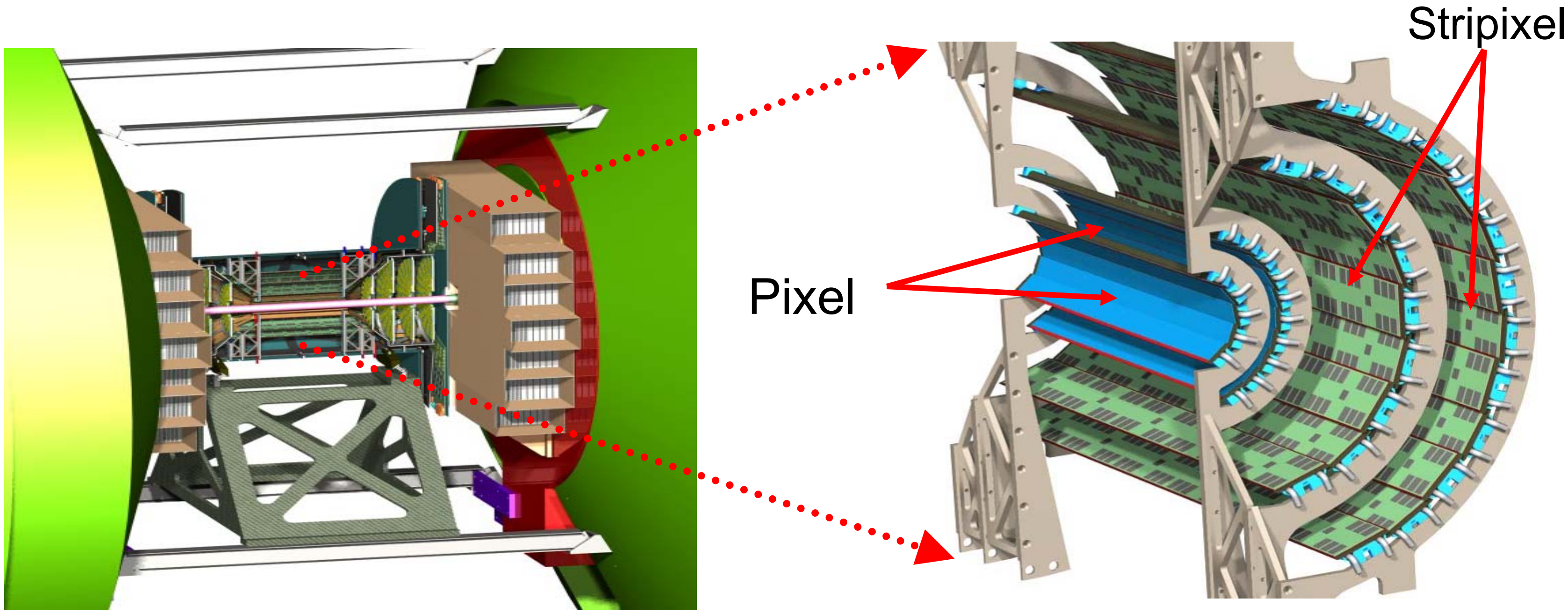
- **2 forward spectrometers**

μ detection
$1.2<|\eta|<2.4$, 2π in ϕ

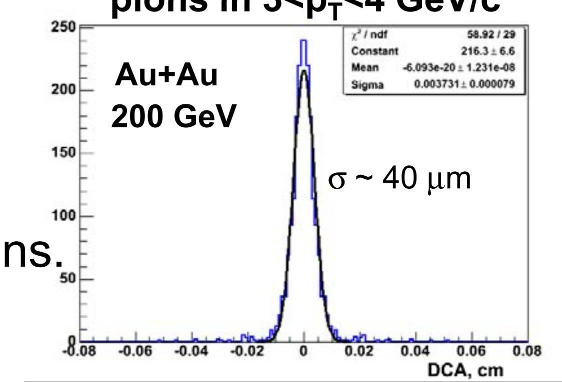
- **3 global detectors**
  - **Luminosity Monitoring (BBCN,BBCS)**
  - **Centrality (BBC vs ZDC)**
  - **Local polarimetery (ZDC & SMD)**



Central Silicon Vertex Trackers "VTX"



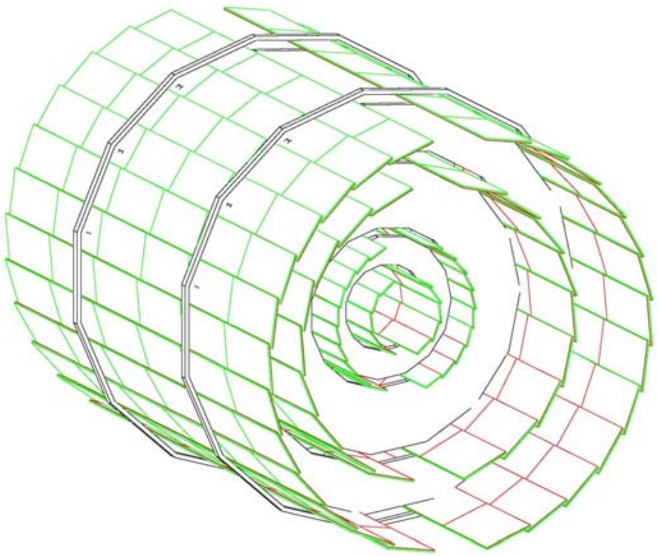
Expected DCA resolution



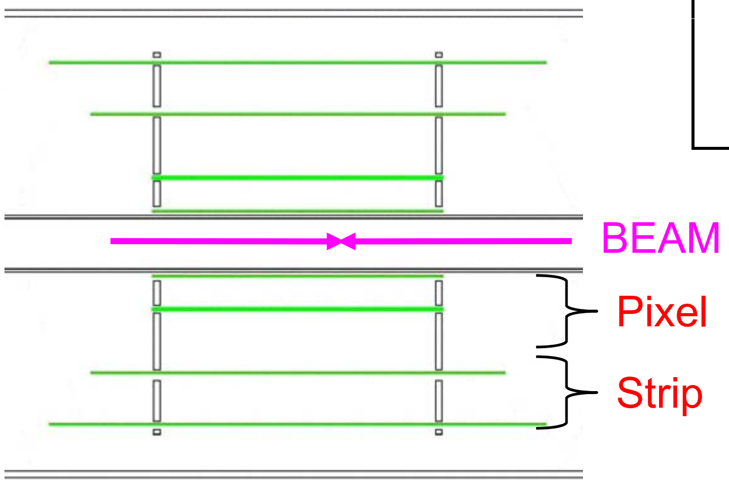
- **Specifications:**
  - Large acceptance ($\Delta\phi \sim 2\pi$ and $|\eta| < 1.2$)
  - Displaced vertex measurement $\sigma < 40$ μm
  - Charged particle tracking $\sigma_p/p \sim 5\%$ p at high pT
  - Detector must work for both of heavy ion and pp collisions.
- **Technology Choice**
  - Hybrid pixel detectors developed at CERN for ALICE
  - Strip detectors, sensors developed at BNL with FNAL's SVX4 readout chip

Barrel VTX Parameters

Pixel detector   Strip detector



VTX	Layer	R1	R2	R3	R4
Geometrical dimensions	R (cm)	2.5	5	10	14
	Δz (cm)	21.8	21.8	31.8	38.2
	Area (cm²)	280	560	1960	3400
Channel count	Sensor size R × z (cm²)	1.28 × 1.36 (256 × 32 pixels)		3.43 × 6.36 (384 × 2 strips)	
	Channel size	50 × 425 μm²		80 μm × 3 cm (effective 80 × 1000 μm²)	
	Sensors/ladder	4 × 4		5	6
	Ladders	10	20	18	26
	Sensors	160	320	90	156
	Readout chips	160	320	1080	1872
	Readout channels	1,310,720	2,621,440	138,240	239,616
Radiation length (X/X0)	Sensor	0.22%		0.67 %	
	Readout	0.16%		0.64 %	
	Bus	0.28%			
	Ladder & cooling	0.78%		0.78 %	
	Total	1.44%		2.1 %	

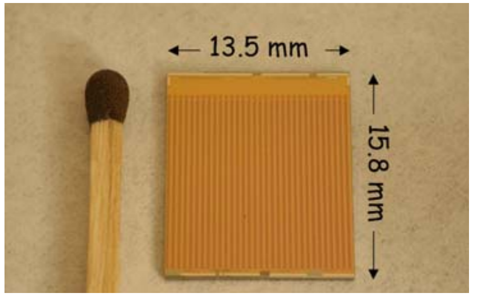


Layer	radius	Detector	Occupancy in Central Au+Au collision	
Layer 1	2.5 cm	Pixel	0.53 %	
Layer 2	5.0 cm	Pixel	0.16%	
Layer 3	10.0 cm	Strip	4.5 % (x-strip)	4.7 % (u-strip)
Layer 4	14.0 cm	Strip	2.5 % (x-strip)	2.7 % (u-strip)

Silicon Pixel Detectors

ALICE1LHCb readout chip:

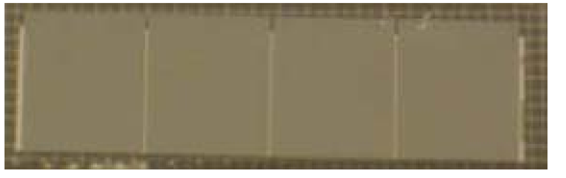
- Pixel: 50 µm (f) x 425 µm (Z).
- Channels: 256 x 32.
- Output: binary, read-out in 25.6µs@10MHz.
- Radiation Hardness: ~ 30Mrad

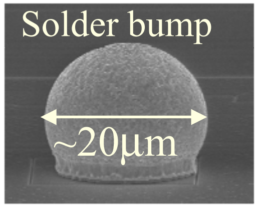


active area
ΔrΦ
1.28 cm = 50mm x 256
Δz
1.36 cm = 425mm x 32

Sensor module:

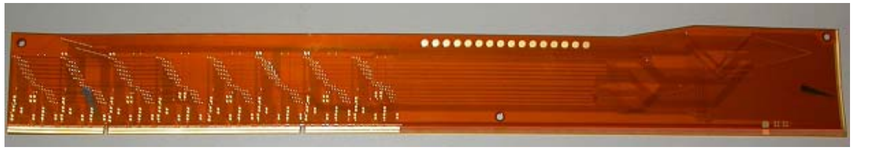
- 4 ALICE1LHCb readout chips.
- Bump-bonded (VTT) to silicon sensor.
- Thickness: 200 µm
- Thickness: r/o chips 150 µm





Half-ladder (2 sensor modules+bus)

- 1.36 cm x 10.9 cm.
- Thickness bus: < 240 µm.

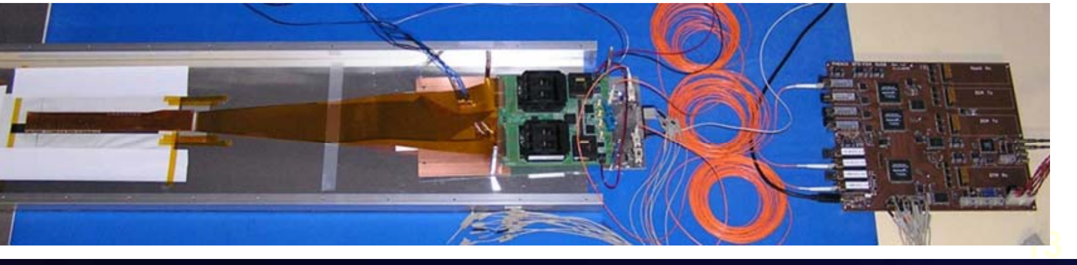


SPIRO module

- Control/read-out a half ladder
- Send the data to FEM

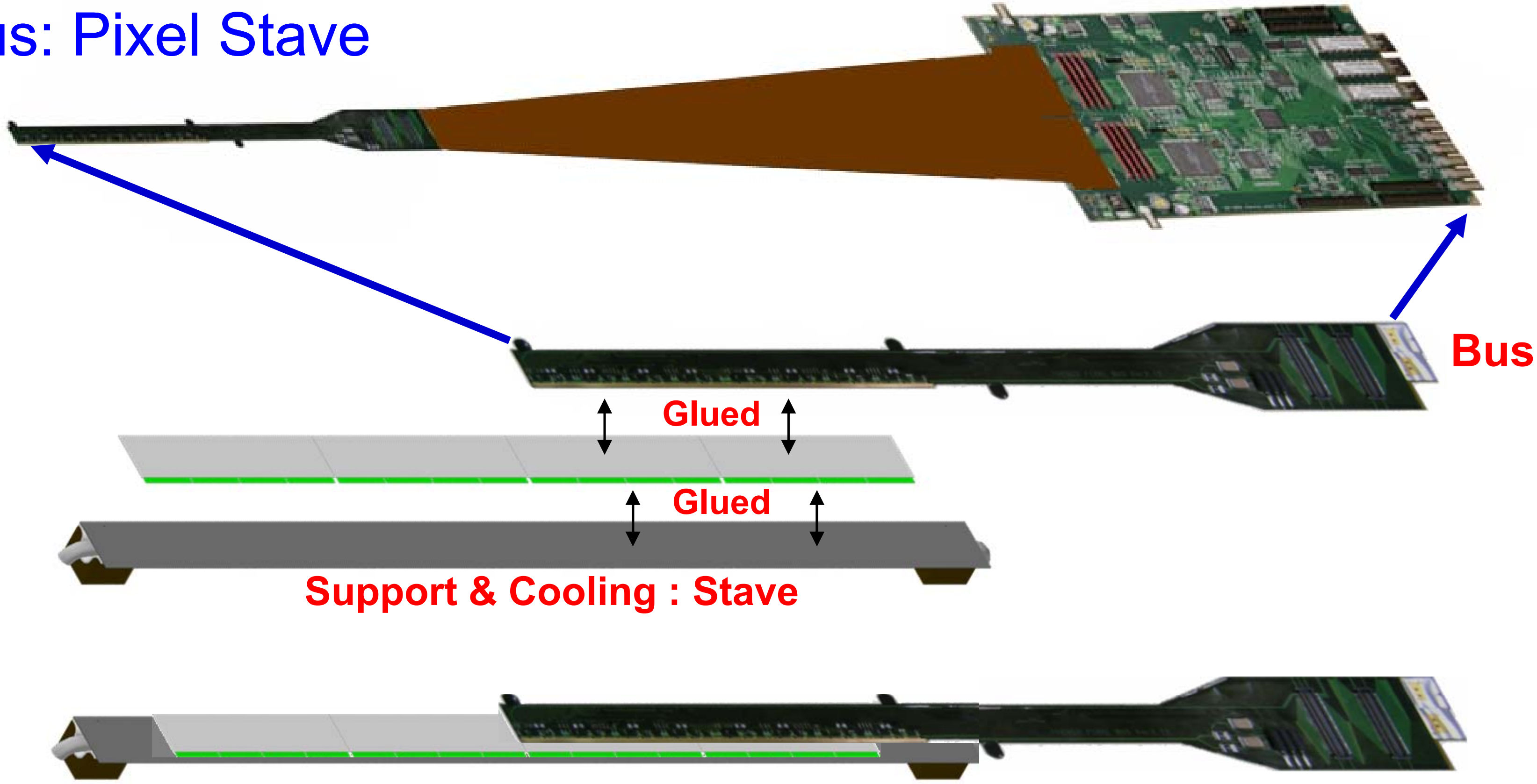
FEM (interface to PHENIX DAQ)

- Read/control two SPIROs
- Interface to PHENIX DAQ

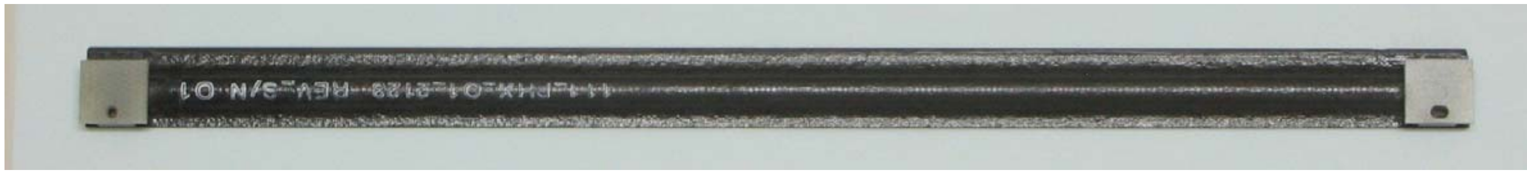


Silicon Pixel Detectors

Status: Pixel Stave

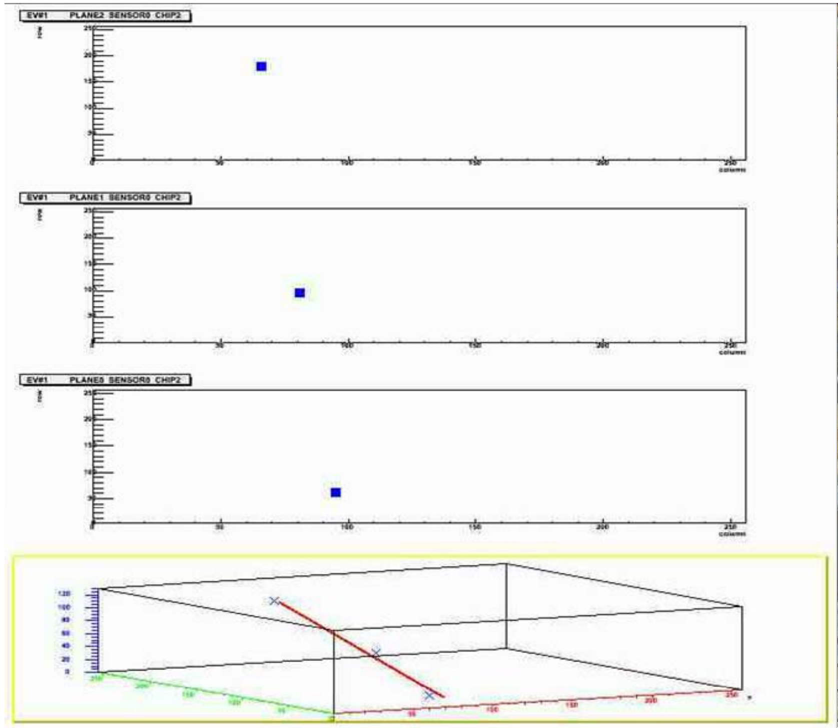


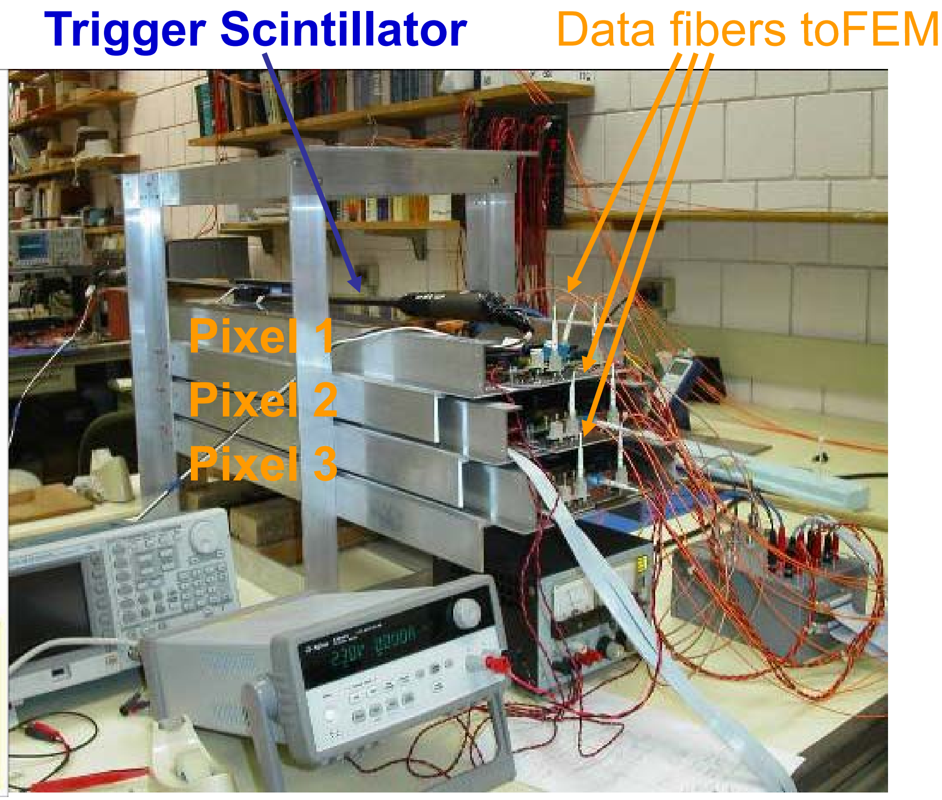
✪ Prototype stave has been delivered by HYTEC recently:



Silicon Pixel Detectors: Cosmic Ray

Test Results



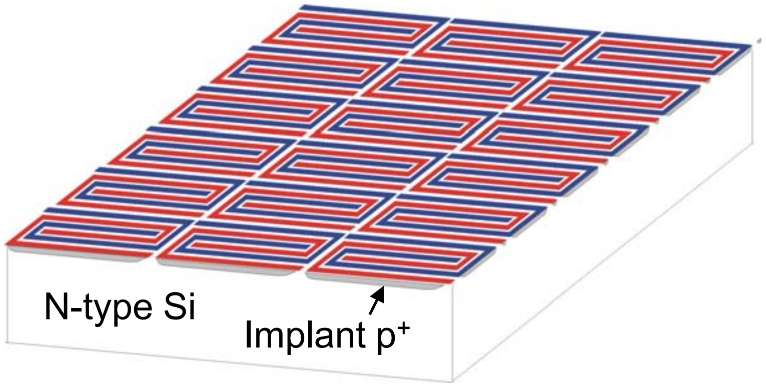


- 3 layers of pixel half ladders, read-out by a pixel FEM
- The spacing between the layers are ~ 6cm per layer.
- A half Ladder = sensor+ROC+bus+bus-extender+SPIRO

✪ **Second cosmic ray test using the final prototypes are underway at Stony Brook now**

Silicon Sensor Stripixel Concept

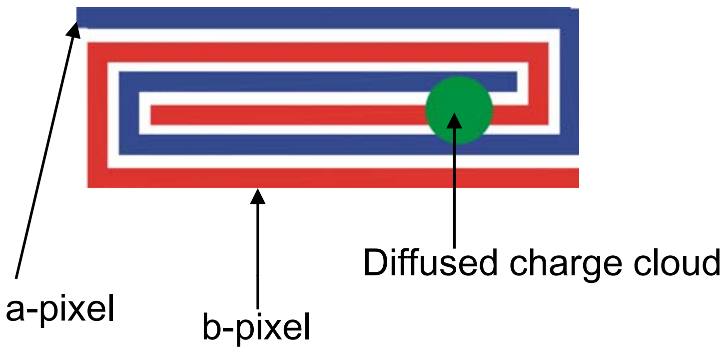
- Innovative design by BNL Instr. Div. : Z. Li et al., NIM A518, 738 (2004);
- R. Nouicer et. al., NIM B261, 1067 (2007).



- DC-Coupled silicon sensor
- Sensor is single-sided

- Pixel array : 80×1000 μm^2 pitch

Spiral p+ electrode :
5 μm line, 3 μm gap, 5 turns

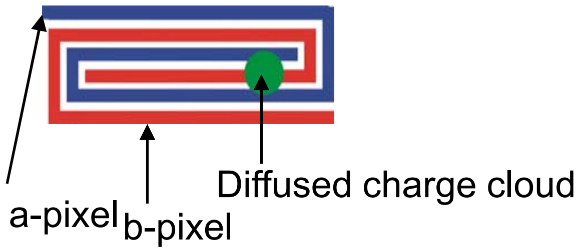


- A pixel is formed by two independent interleaved (a and b) implants
- 2-dimensional position sensitivity by charge sharing

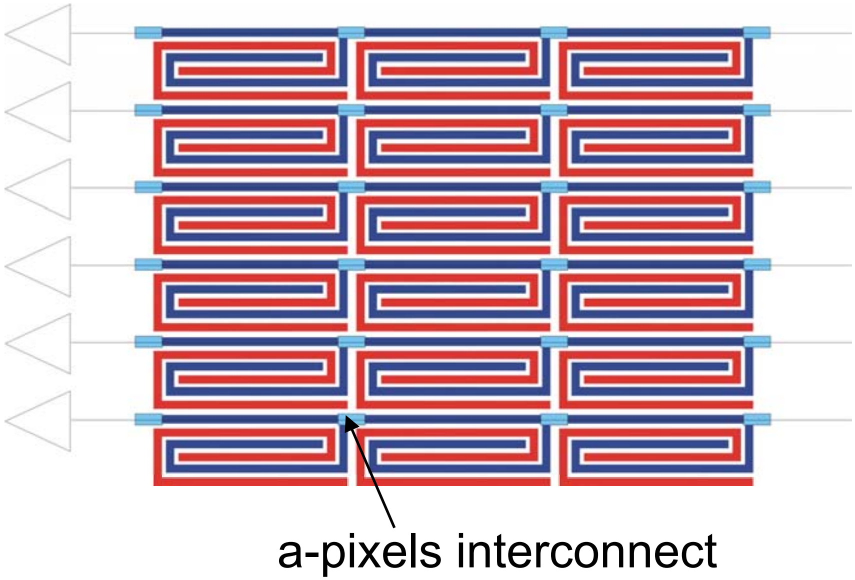
Silicon Sensor Stripixel Concept

- a-pixels are connected to form X-strips, and b-pixels are connected to form stereo-angled (4.6^o) U-strips

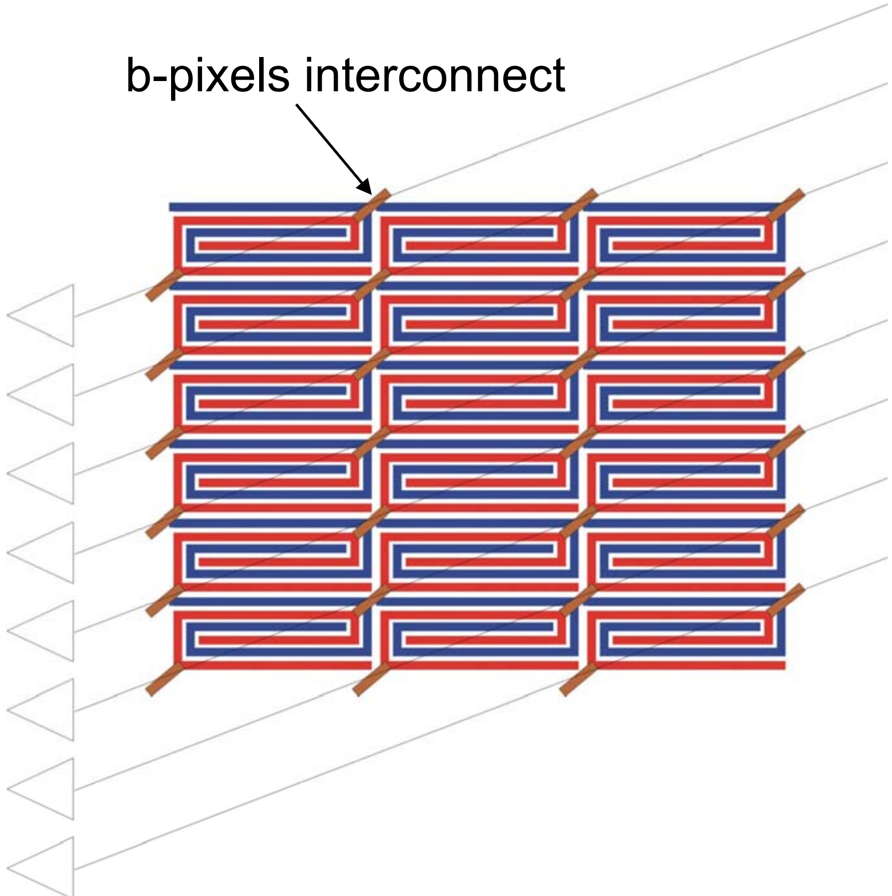
  - Pixel array : 80×1000 μm^2 pitch



X strips (connect a-pixels)



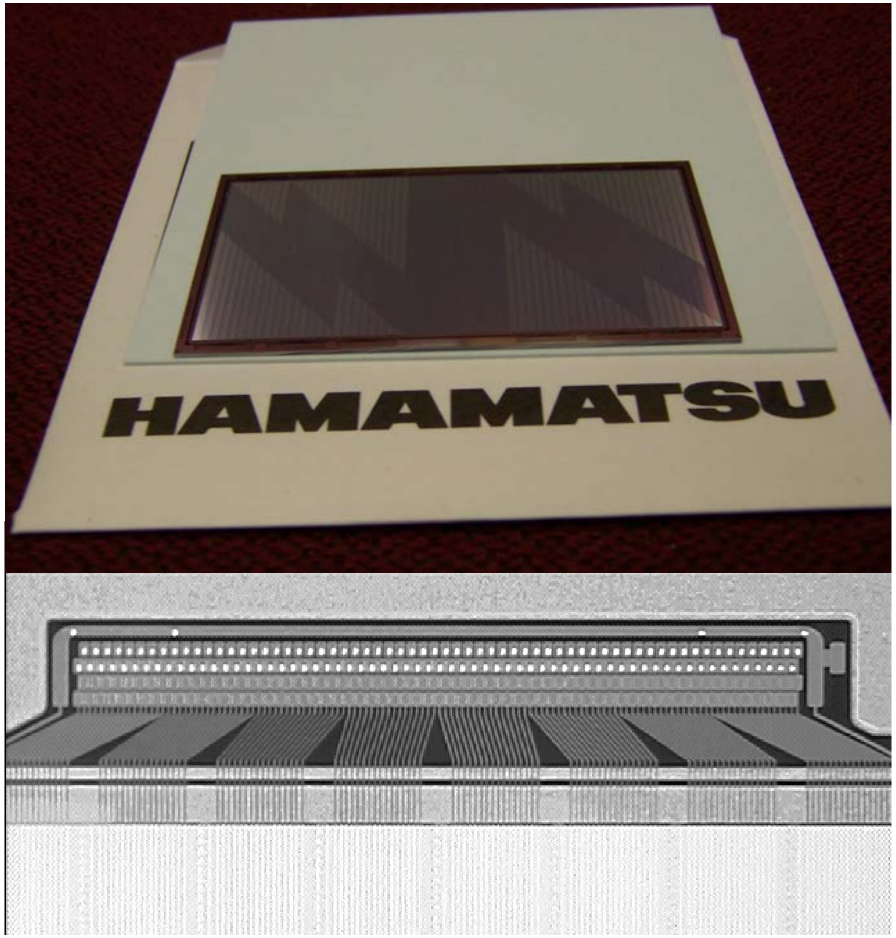
U strips (connect b-pixels)



Silicon Sensor Characteristics

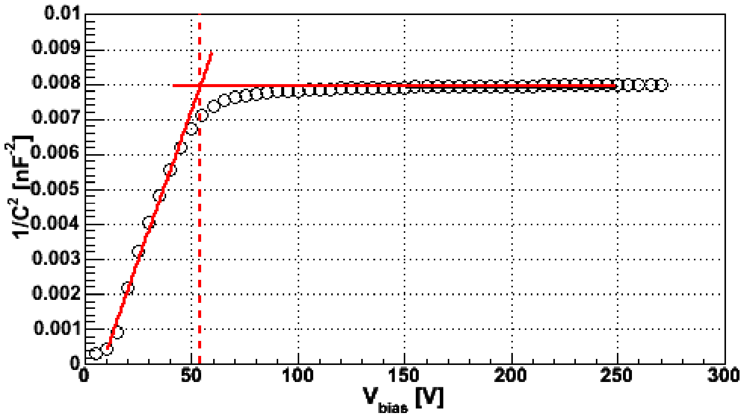
- ✪ Sensors produced by HPK
- ✪ Point symmetric structure of readout lines wrt the center of the sensor
- ✪ Readout pads in longer edges for ladder structure design
- ✪ No dead space in the middle
- ✪ Sensor size : 3.4×6.4 cm^2
- ✪ Pixel array : 80×1000 μm^2 pitch
- ✪ # readout strip
  - x-strip : 128×3×2
  - u-strip : 128×3×2
  - Total : 1536 channels/sensor

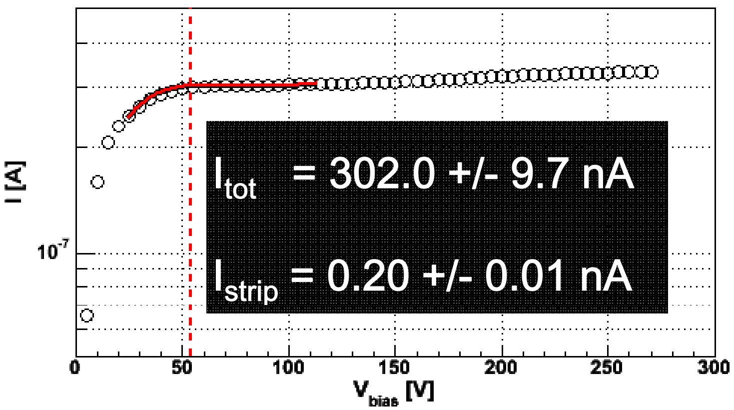
✪ Note: Stripixel sensor technology, including the mask design and processing technology has transferred from BNL to HPK.

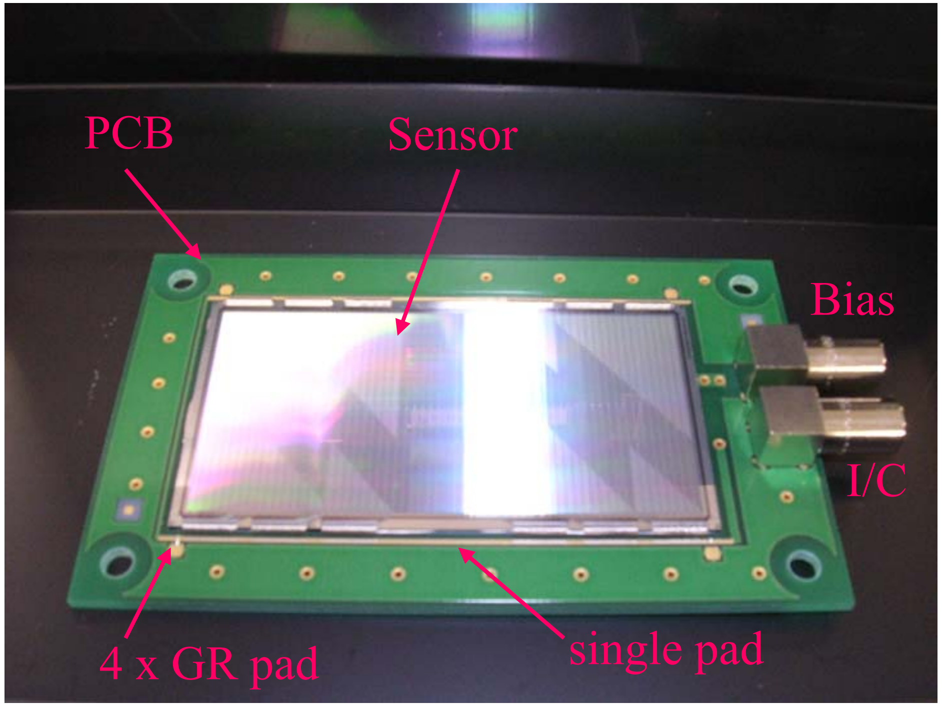


Total Leakage Current Measurements

- Measure total leakage current of 1532 strips (I_{tot})
- Define $I_{strip} = I_{tot}$ / #strip, where #strip = 12 x 128 = 1,536



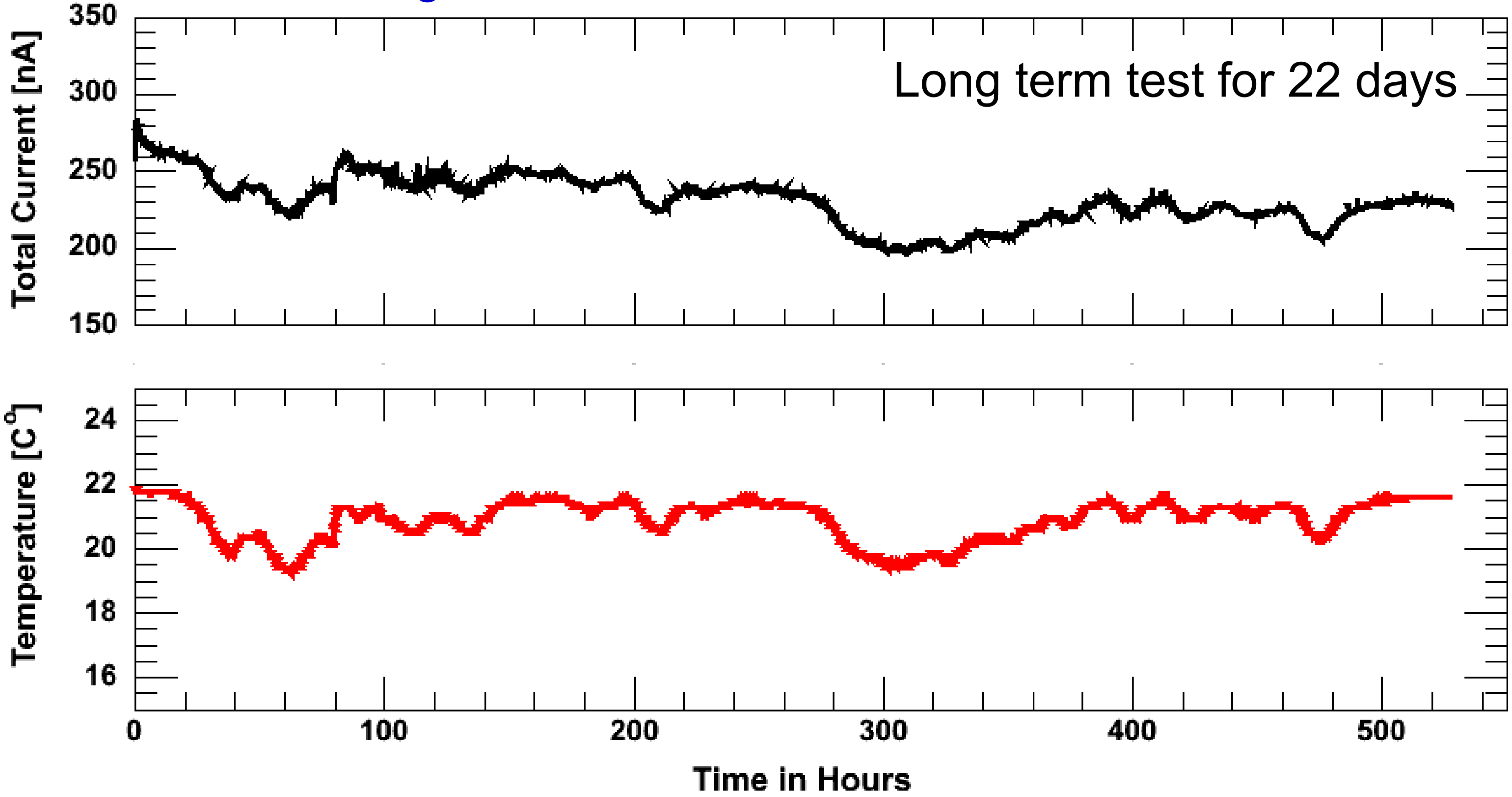




The 625 μm sensors bonded to the SVX4 chip; leakage current : 0.4 nA/strip well below the saturation limit of the SVX4 chip: 15 nA/Strip.

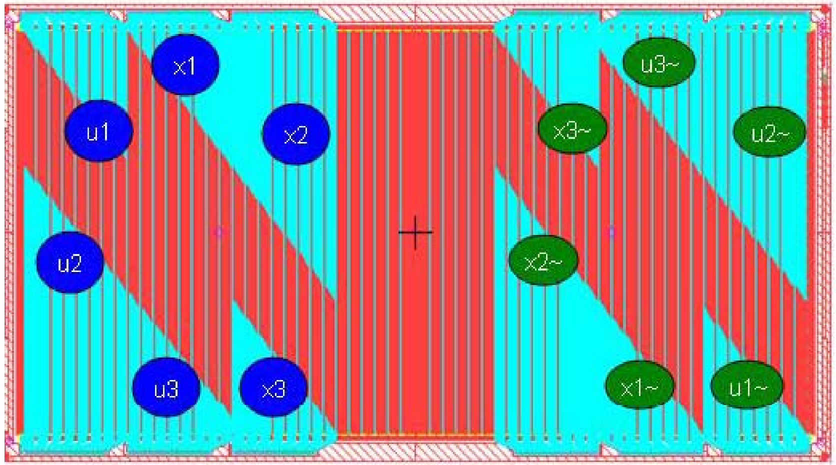
Stability of Leakage Current vs Time

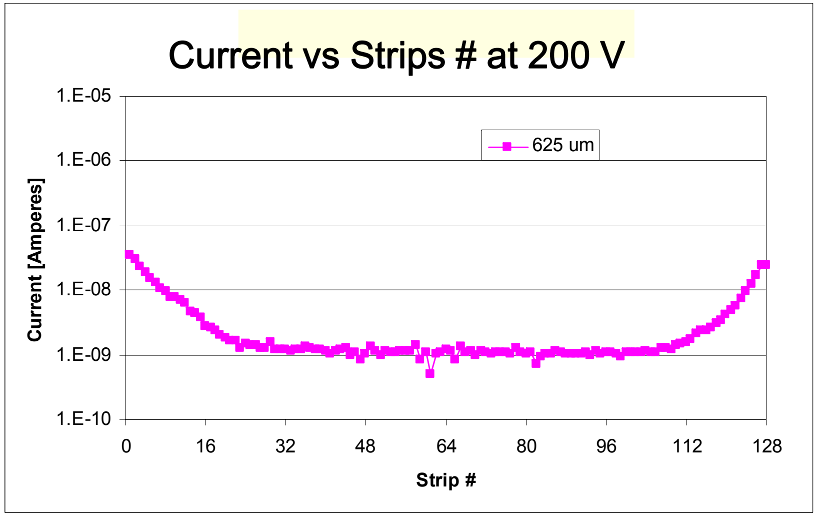
- Leakage current measurements from stripixel sensor biased at 120 Volts for 22 days
  - Good correlation between current and temperature
  - Leakage current is stable

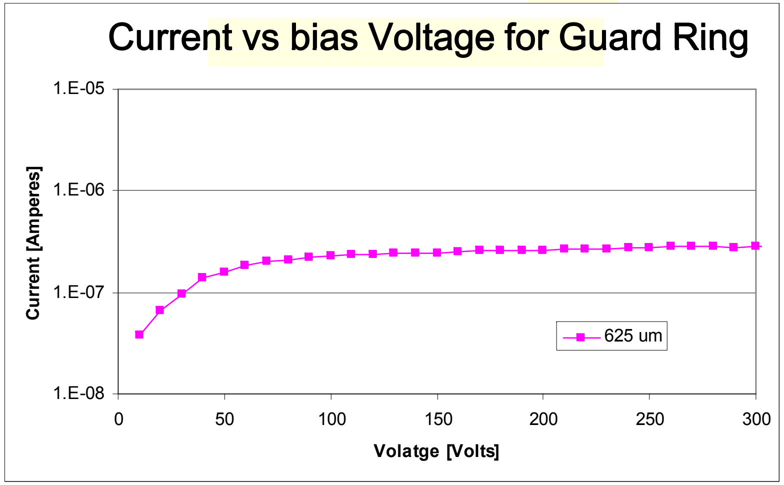


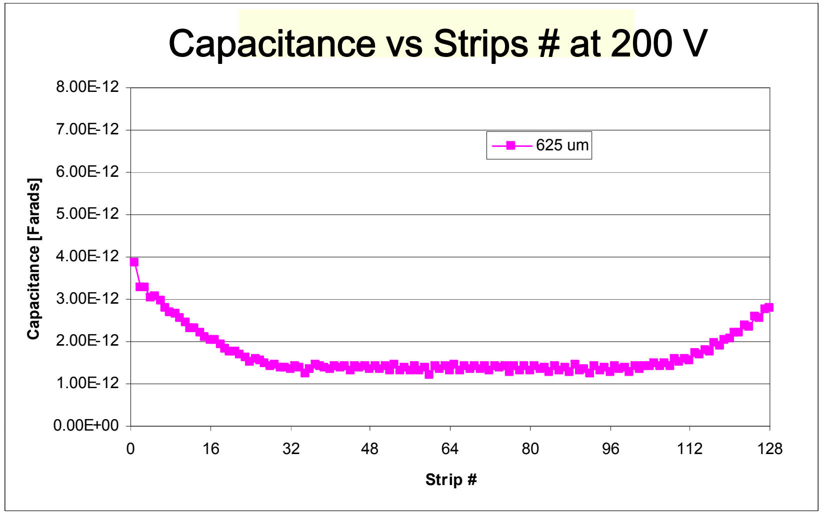
Details Measurements: Q/A Tests

- Inspection
- Diodes tests
- Guard Ring test
- Strips tests





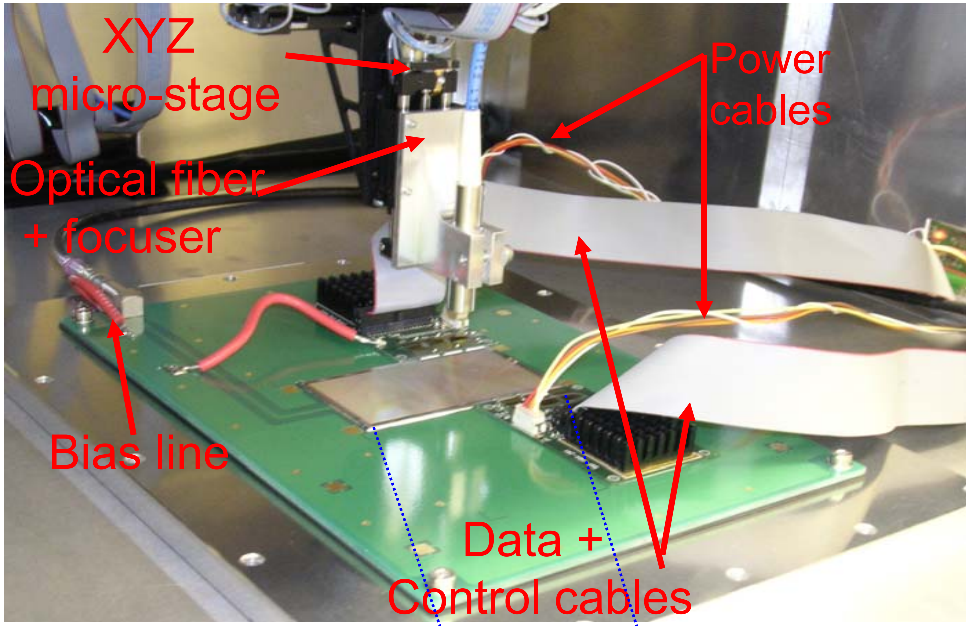




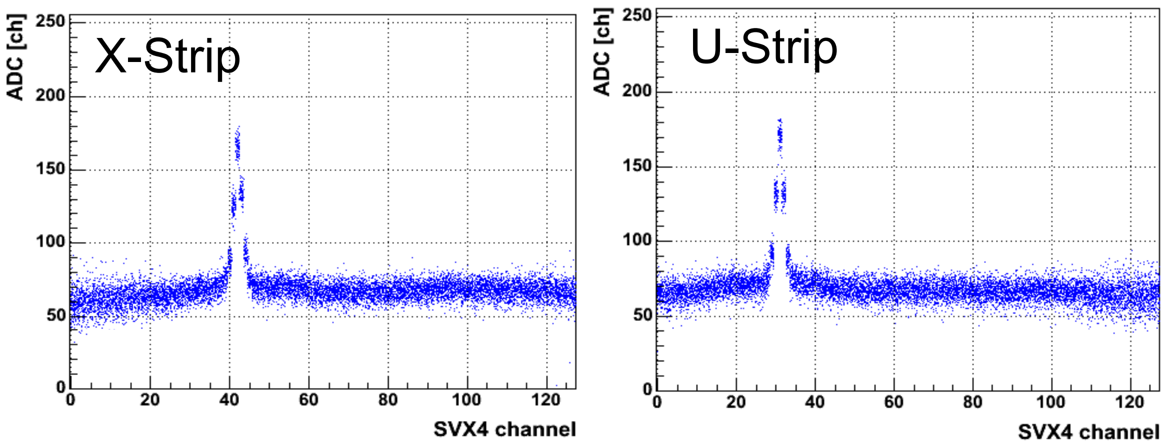
IR Laser Tests Results

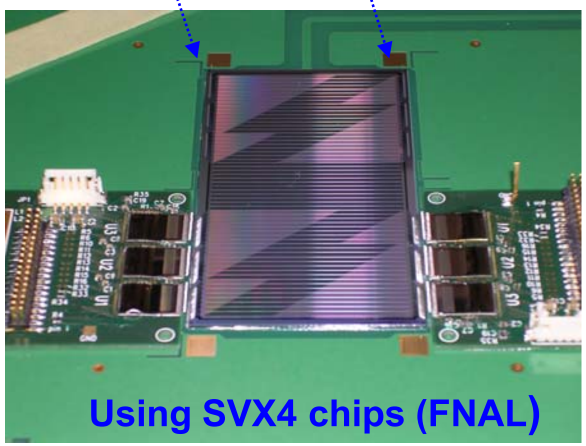
✪ Silicon module Prototype

- **S/N ~ 20:1 for 625 μm thickness**
- **Charge-sharing test w/ IR laser pulse injection**
  - **Large spot size in the present setup**
  - **Focusing length (8 mm) was too short to shine only one pixel in 625 μm thick sensor.**
- Planned: possible solution is to use a radioactive source, cosmic rays and beam.



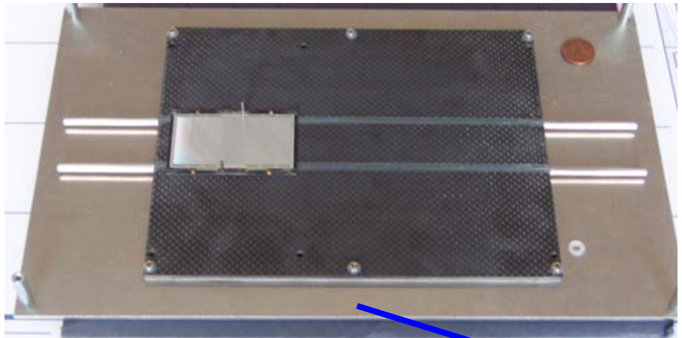
X and U strips are interleaved



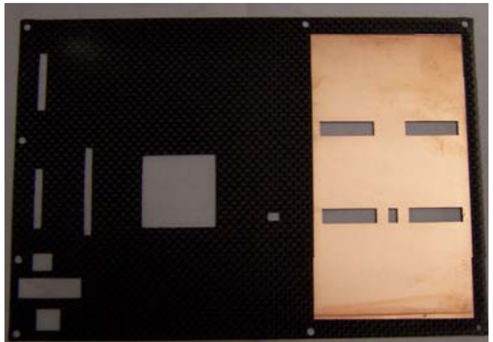


Status: Stripixel Detector Prototype

Step #1
Silicon sensor +CFC + cooling

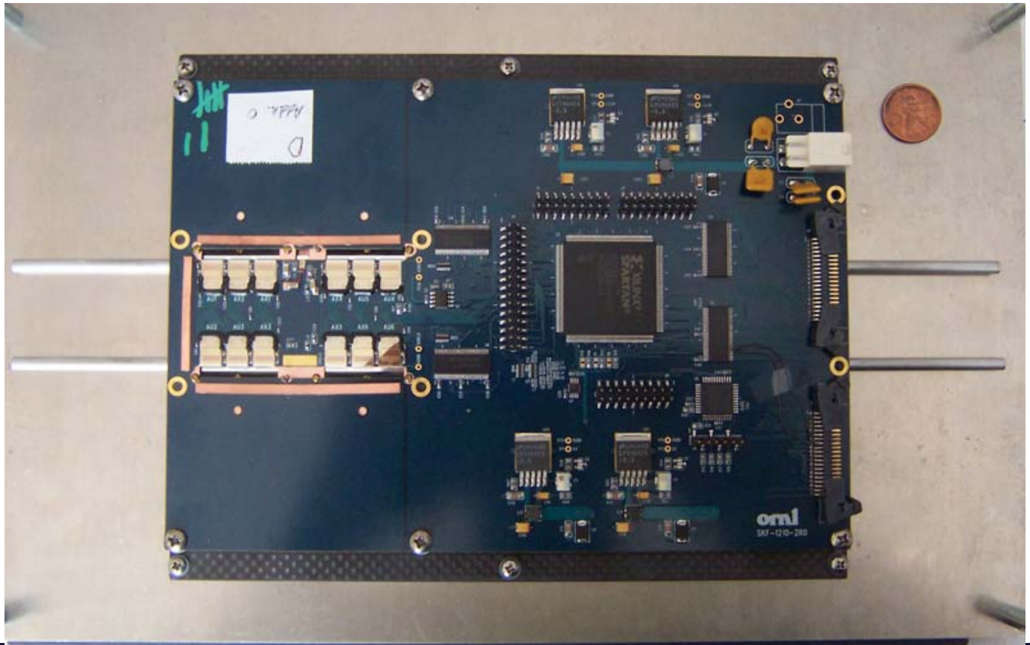


Step #2
CFC + Cu shielding



Step #3
Readout Card “ROC-2

Silicon Stripixel Module

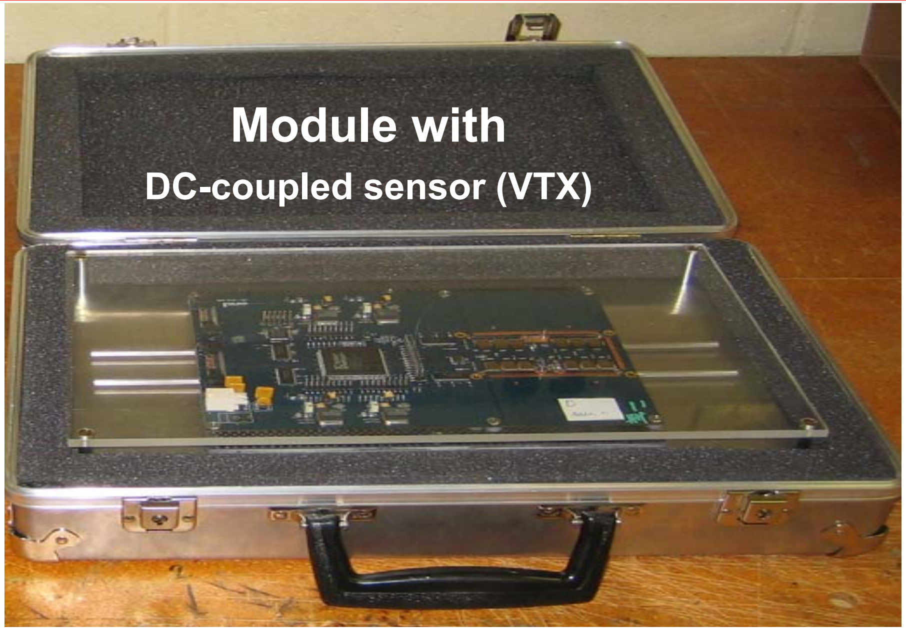


Status: Stripixel Detector Prototype

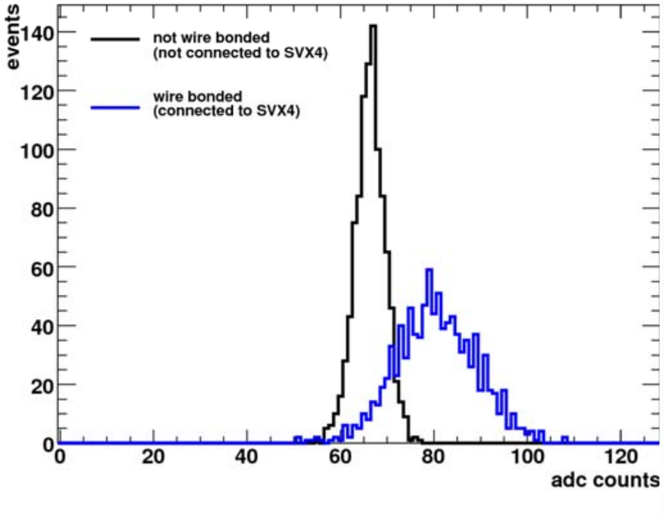
- Silicon Stripixel Module used ROC prototype

- Silicon Stripixel Module was wire-bonded at FNAL

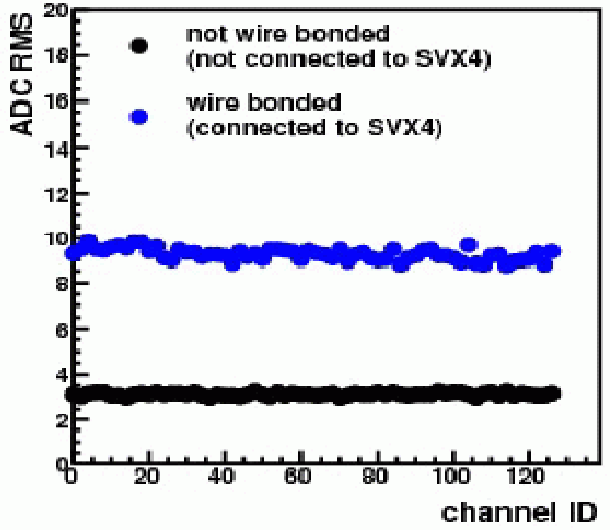
- Note: only outer pads are wire-bonded



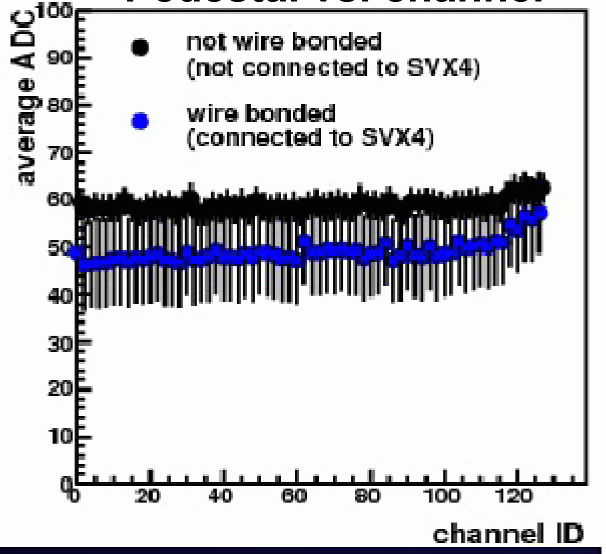
Pedestal for one channel



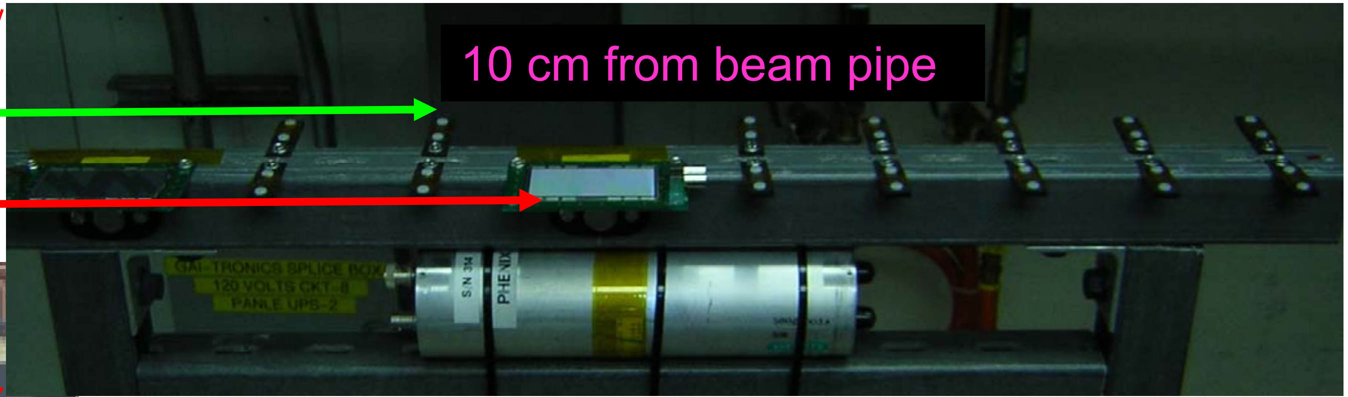
Noise vs. channel

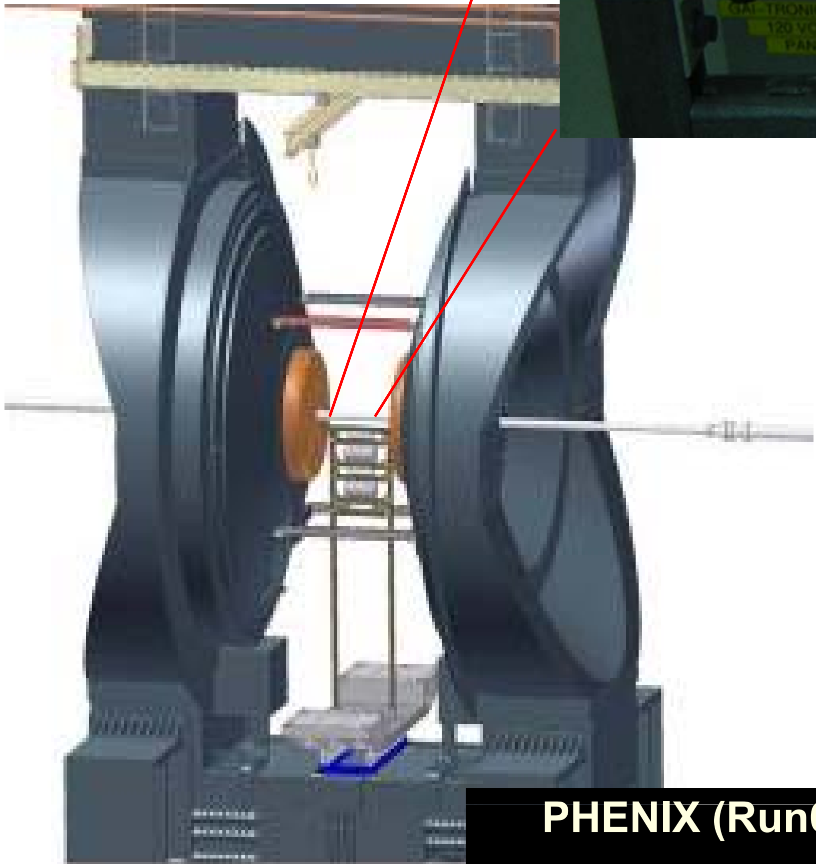


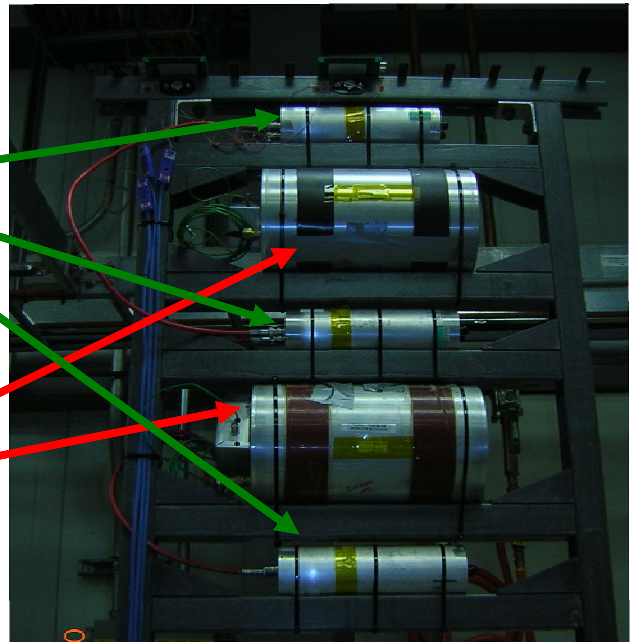
Pedestal vs. channel



Radiation Measurements in IR PHENIX: Run 6





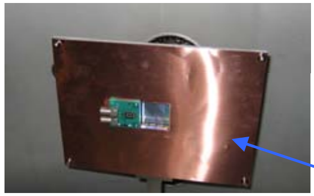


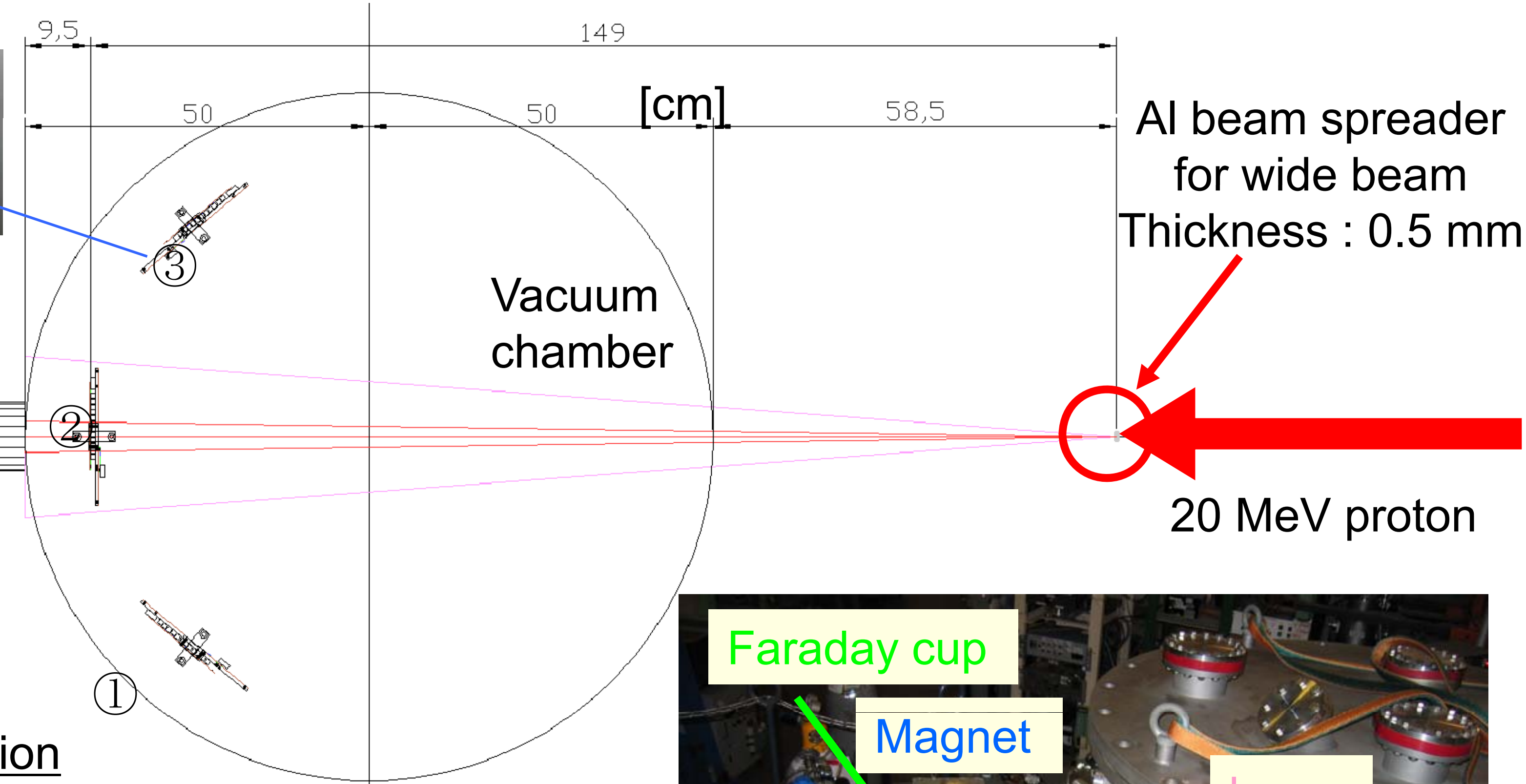
PHENIX (Run6: pp) : Dose/Luminosity at 33 cm = 1.5 Rad/pb^{-1}

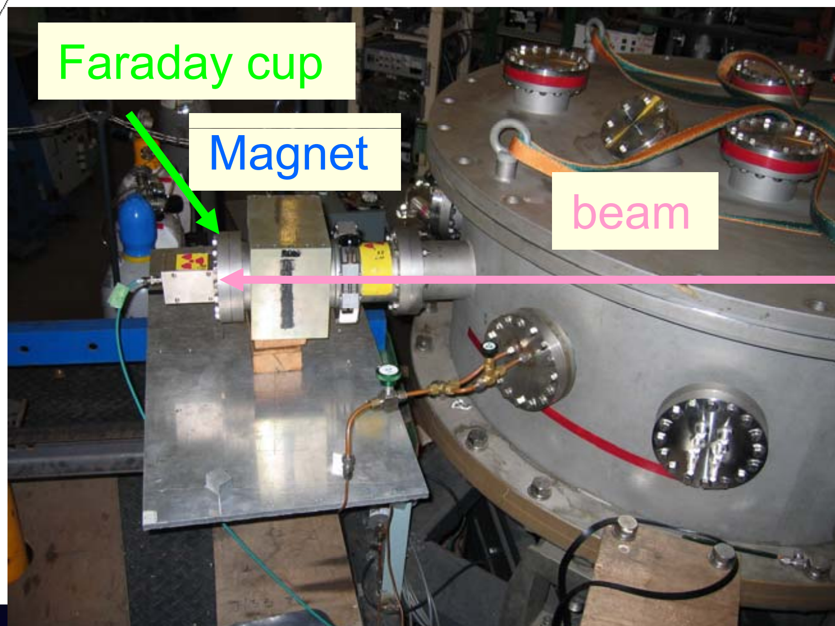
Total Luminosity delivered while that structure stayed in the IR: 12 pb^{-1}

total dose observed = 30 Rad

Radiation: 20 MeV Proton Beam at Tsukuba







3 setup rotation

1) Blank target : intensity measurement of beam
2) 625um sensor (low flux)
3) 500 um sensor (high flux)

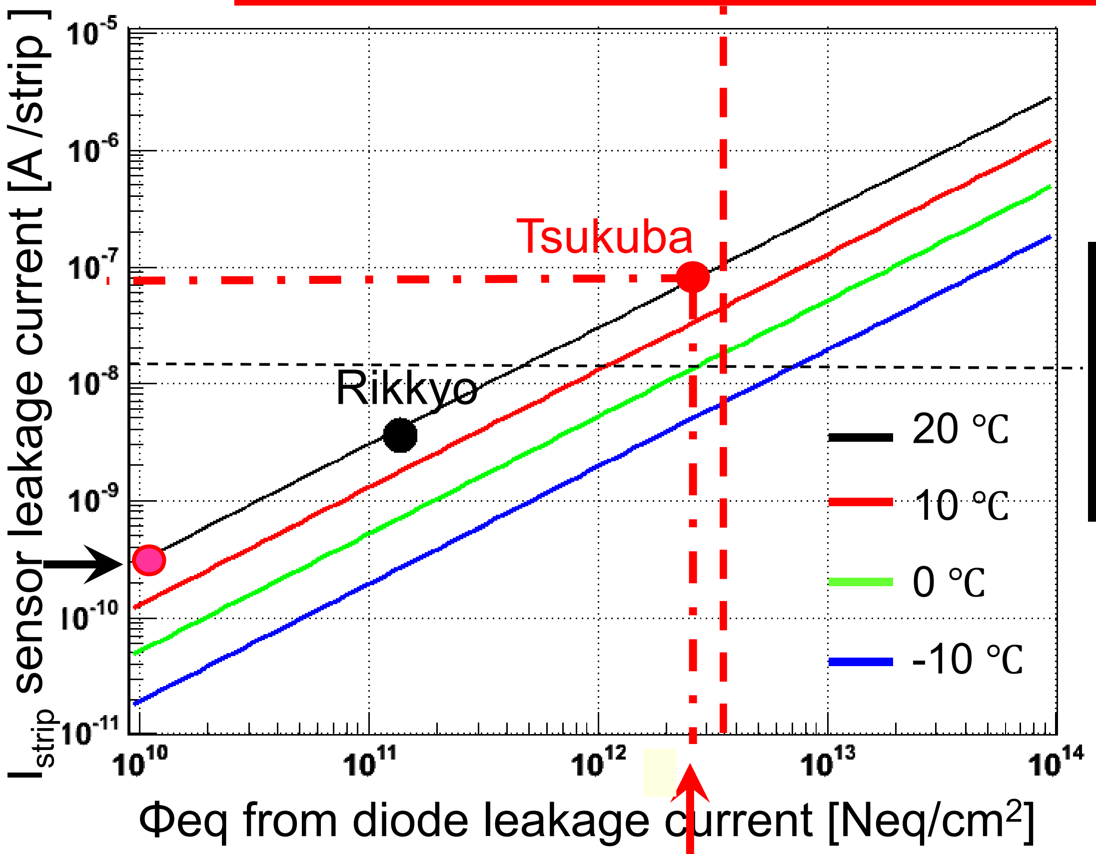
Leakage current of Stripixel sensor

3.3E+12 [N_{eq}/cm^2]

PHENIX in RHIC2 for 10 years

7.4x10^{-8} [A]

PHENIX IR



Saturation of circuit 15nA/strip

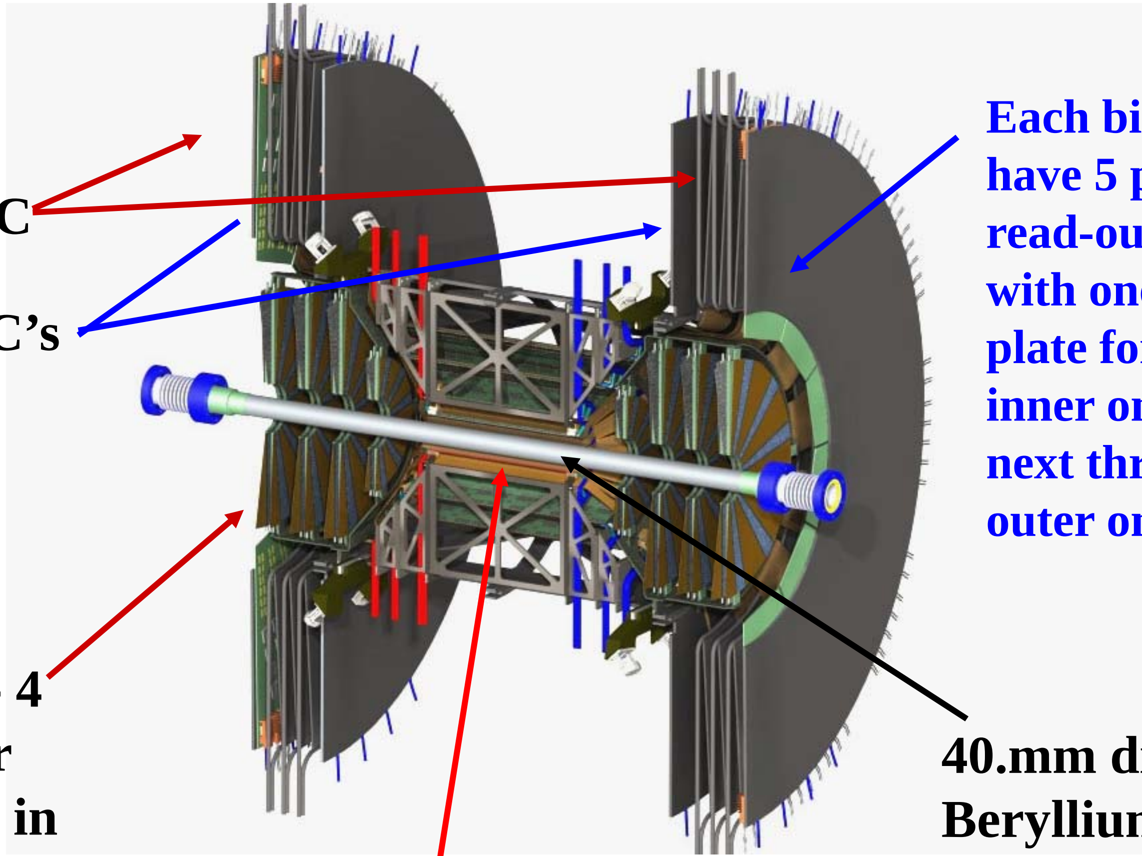
Φ_diode=2.43x10^{12} [N_{eq}/cm^2]

Conceptual Mechanical Structure (HYTEC Work)

Baseline design for the VTX and FVTX detectors;

FVTX-ROC

VTX ROC's



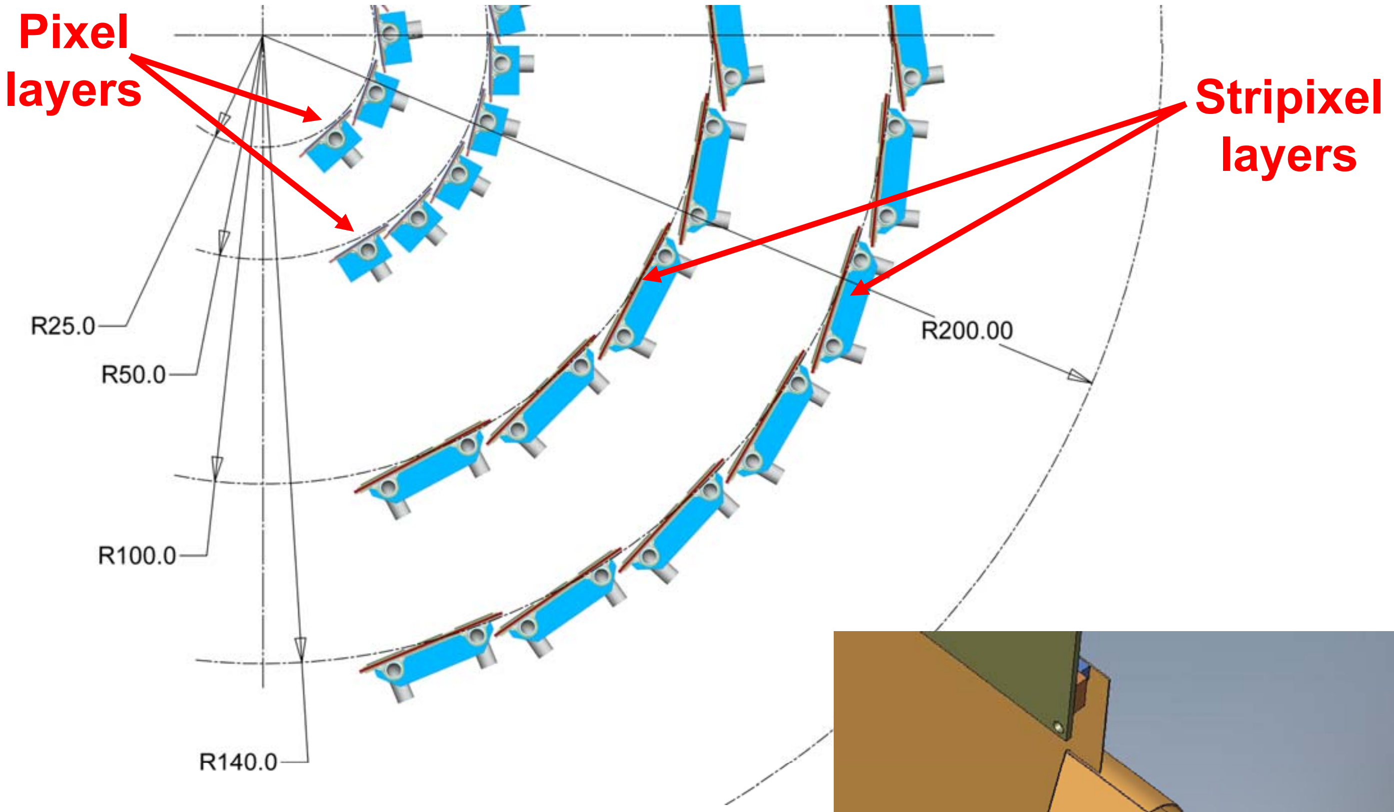
Each big wheel will have 5 planes of read-out electronics, with one cooling plate for each plane; inner one for strips, next three for pixels, outer one for FVTX.

FVTX - 4 detector stations in each end

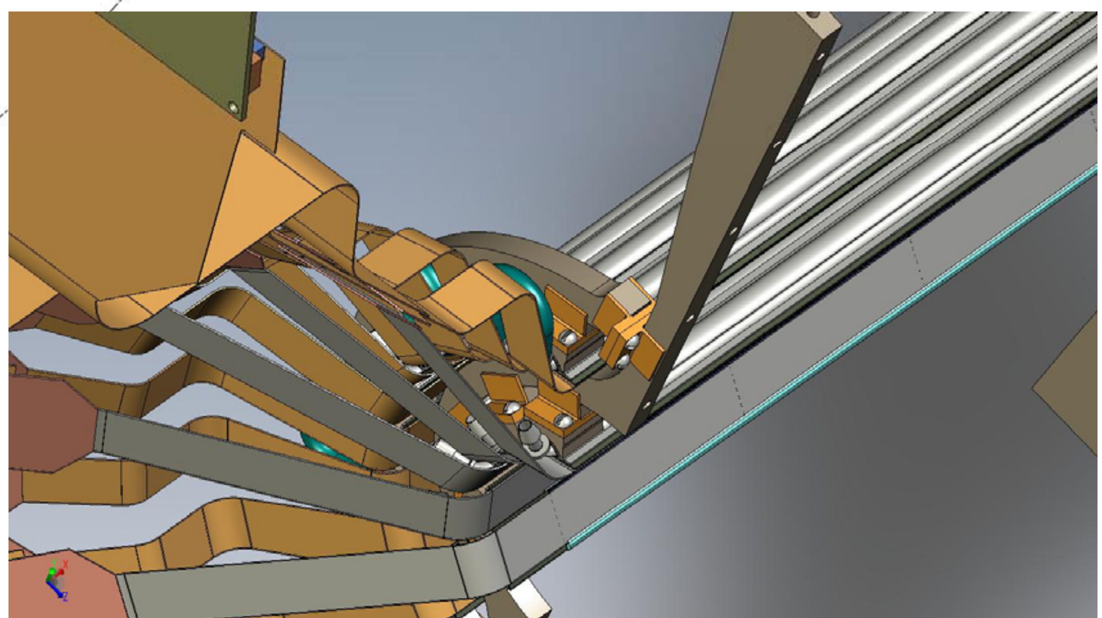
VTX – 4 layers ~ 2π

40.mm diameter Beryllium beam pipe

Conceptual Mechanical Structure (HYTEC Work)



End on view of VTX four layers



Summary

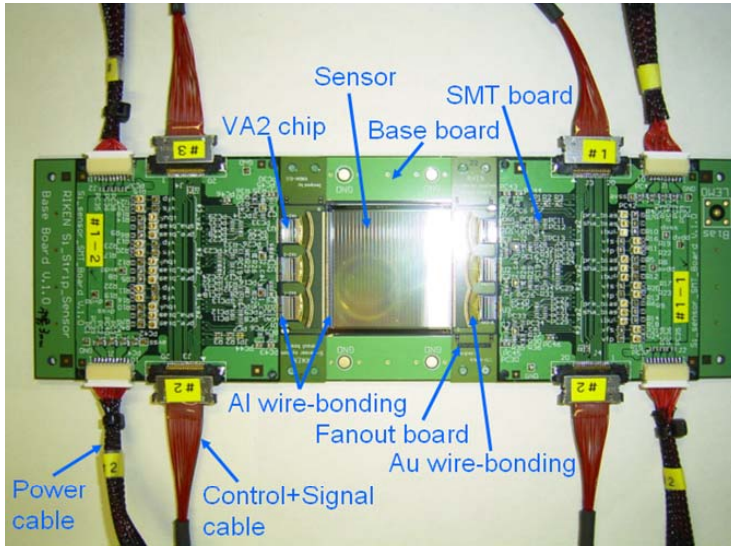
- ✪ The Silicon Vertex Tracker is an important upgrade of the PHENIX detector and will extend its physics capabilities to new observables for the physics at RHIC and the polarized proton program
- ✪ DOE approval for October'06 start of the project
- ✪ Pixel detector
  - Working on the first prototype ladder
- ✪ Stripixel detector
  - Working on the silicon module with ROC-V2/3
- ✪ Installation complete in fall 2009/2010
  - early partial implementation will be possible

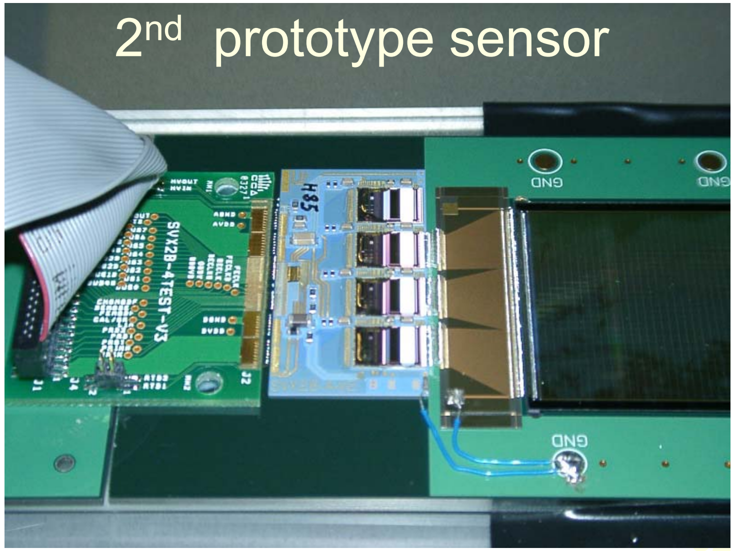
Auxiliary Slides

R&D : Prototypes Sensors

- 1^{st} prototype sensor
  - Spiral p^+ electrode : 8 μm line, 5 μm gap, 3 turns
  - Thickness : 400/250 μm
  - R/O chip: VA2 (analog multiplexer)
  - Tests w/ source & beam
    - S/N: 17:1 for 400 μm thickness
    - 2-D sensitivity need improvements.
- 2^{nd} prototype sensor
  - Spiral p^+ electrode : 5 μm line, 3 μm gap, 5 turns
  - Thickness : 400/500 μm
  - R/O chip: SVX4(CDF SVX4 hybrid)
  - Tests w/ nano-sec pulsed laser
    - S/N: 14:1 for 500 μm thickness
    - Laser signals were seen

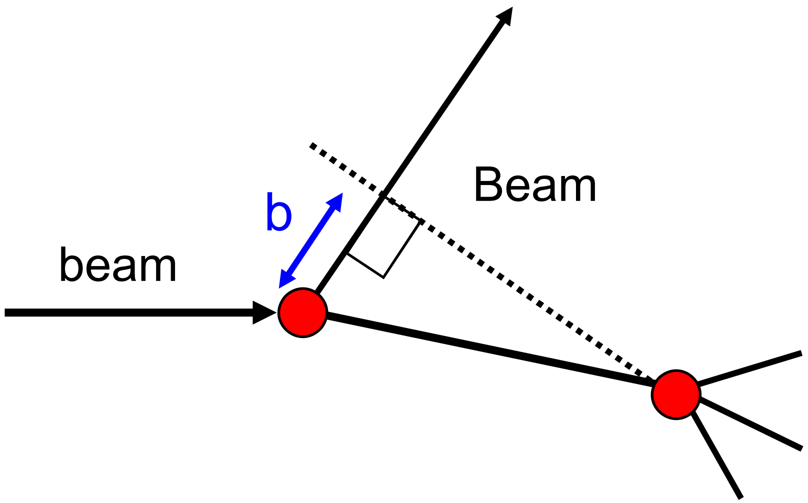
1^{st} prototype sensor





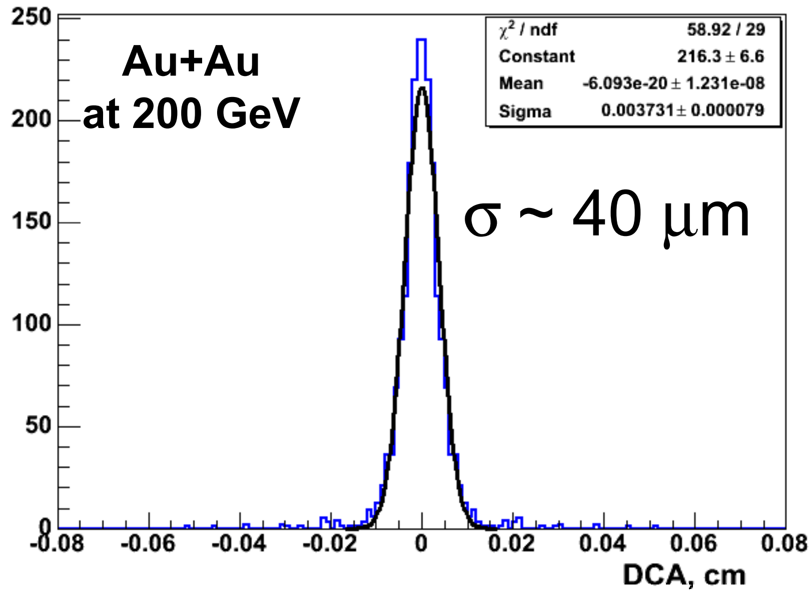
DCA

- What is measured?
  - Distance of Closest Approach (DCA)



b = distance of closest approach of a **reconstructed** track to the true interaction point

Expected DCA resolution of VTX

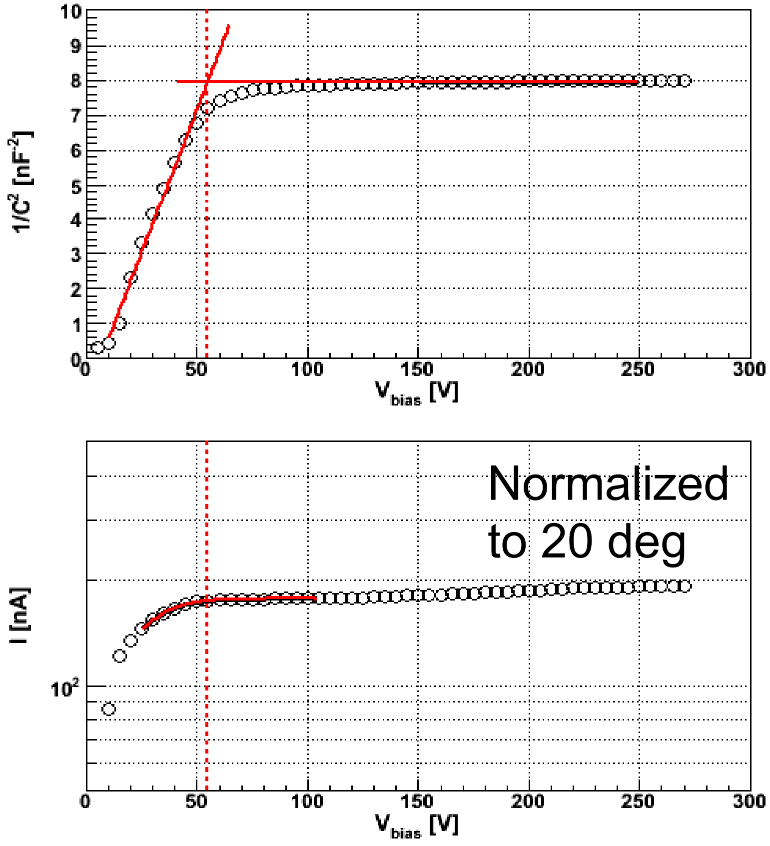


DCA distribution for single simulated pions in $3<p_T<4$ GeV/c. Simulation is done with 200 micron pixel layers and 650 micron strip layer. The passive material is 1.0% per pixel layer and 2.75% per strip layer.

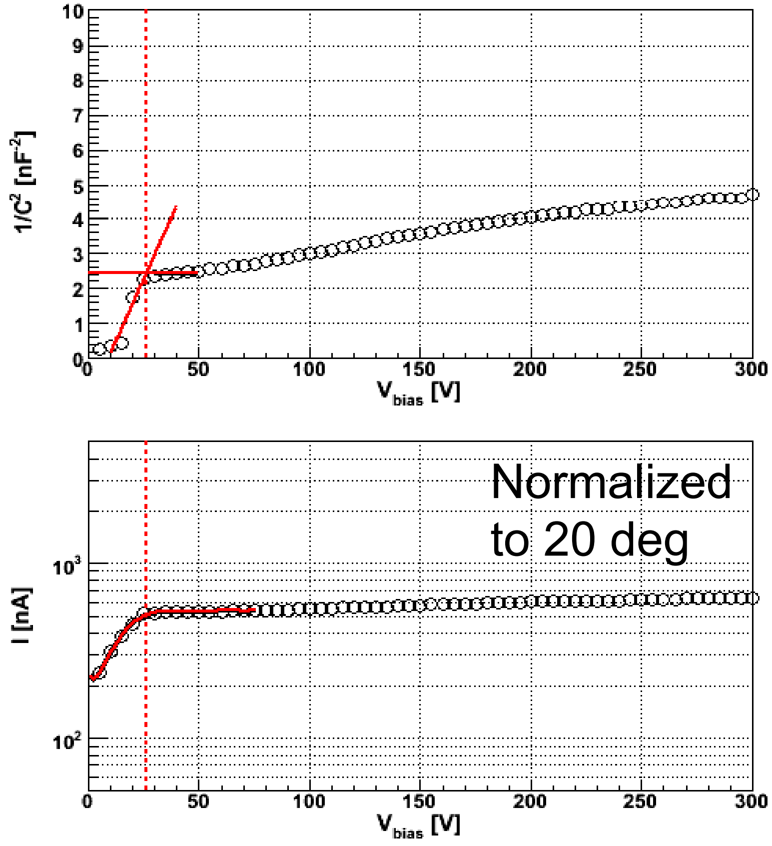
Radiation Measurements in IR PHENIX

✪ Measurement obtained from silicon stripixel sensor

Before irradiation



After annealing



V_{FD} = 54.820 +- 13.874 [V]
I_{FD} = 1.748e+02 +- 8.804e-01 [nA]

V_{FD} = 26.146 +- 18.765 [V]
I_{FD} = 5.083e+02 +- 1.083e+01 [nA]

Fluence of 625 μm Stripixel Sensor

- **$\Delta I/V = \alpha \Phi$ (Φ = fluence, 1 MeV neutron equivalent fluence)**

  α : proportionality factor (current related damage rate)

  - V_{total} = 3 x 6 x 0.0625 = 1.125 [cm^3]
  - ΔI_{total} (20℃) = 3.3 10^{-7} [A]
    - Calculating increase of single strip

      ΔI_{total}/1536=2.2 10^{-10} [A/strip]
  - α_{IR} = 3 10^{-17} [A/cm]
  - **Φ_{total} = 9.9 10^{+9} [N_{eq}/cm^2]**

- In the same way, fluences of diodes were estimated.

Silicon Sensor Stripixel Concept

- Cross section view of double meta; layout of Silicon Strip detector via contacts on *U sub-pixels*