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PHENIX STONY BROOK UNIVERSITY U.S. DEPARTMENT OF ENERGY Office of Science U.S. Department of Energy BROOKHAVEN NATIONAL LABORATORY

The Impact of Adaptive Control on measuring the low-mass dilepton continuum in $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions with the PHENIX HBD at RHIC.

Manuel Proissl

IRTG Seminar: Development and Application of Intelligent Detectors
Physikalisches Institut
Heidelberg – Dec 10, 2010

This talk summarizes the accomplishments of the HBD HVC Upgrade for the PHENIX Collaboration. The work was performed primarily at Brookhaven National Laboratory and the Relativistic Heavy Ion Group at Stony Brook University in the years of 2006 to 2010.

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OUTLINE

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TO THE INTERPRETATION OF CONTROL

The word "control" is very often misunderstood and misused. In its **classical definition** we find that Control represents…

- the ***PROCESS*** in which the dynamic behavior of a physical or mathematical object is observed in respect to its **(pre-)applied** boundary conditions.
- the ***ACTION*** of implementing **(pre-)defined** decisions to vary a system's governing parameters such that its desired behavior is achieved.

In other words, control in the classical sense is understood as an abstract concept where governing system policies define actions at **expected** parameter values.

The **key concepts** of Control Theory can be found directly in Nature and include:

✓ **FEEDBACK** from applied control functions. The system's state or output of a control function determines future control functions.

✓ The need for **FLUCTUATIONS** of parameters of the system to study its dynamics.

✓ **OPTIMIZATION** of the control function by minimizing the cost functional.

TO THE INTERPRETATION OF CONTROL

In history, there have been different **approaches** to Control Theory:

- **FREQUENCY-DOMAIN APPROACH.** – **(Laplace, Fourier, Cauchy, etc.)**
  Appropriate for linear time-invariant systems. H.Black: negative feedback (**1927**); H. Nyquist: stability theorem (**1932**); H.Bode: gain, phase margin (**1940**); N.Nichols: Nichols chart, theory of servomechanisms (**1947**); Horowitz: quantitative feedback theory (**1967**).

- **TIME-DOMAIN ALGEBRAIC APPROACH.** – **(Newton, Leibniz, Bernoulli, Riccati, Euler, etc.)**
  Based on the theory of differential equations. [Stability] G.Airy: instability of closed-loop systems (**1840**); J.C.Maxwell: Watt's governor – system is stable if roots of its charact. funct. have neg. real parts (**1868**); A.Lyapunov: stability of nonlinear diff. equations (**1893**) [Optimal Control, Estimation] Optimality principles by J.Bernoulli, P.d.Fermat in optics, C.F.Gauss, J.d'Alembert, L.Euler, J.L.Lagrange, W.R.Hamilton and A.Einstein in mechanics. R.Bellman: dynamic programming principle to optimal control of discrete-time systems (**1957**); R.Kalman: Kalman filter (**1960**); Boyd el al.: LMI solvers (**1994**).

- **POLYNOMIAL-MATRIX-DOMAIN FREQUENTIAL APPROACH.** – **(Rosenbrock, Wolovich etc.)**
  Matrix-fraction description / polynomial equation design for m-input/p-output linear time-invariant systems, represented by a p x m – transfer matrix (**1974**). Blomberg, Ylinen: Polynomial Systems Theory (**1983**, **2003**).

TO THE INTERPRETATION OF CONTROL

- **GEOMETRIC APPROACH.** – **(Basile, Laschi, Marro, Wonham, Morse, etc.)**
  Based on Differential Geometry. (geom. approach of linear systems theory) Basile, Laschi, Marro: controlled, conditioned invariants (**1969**); Wonham, Morse: (A,B)- and (C,A)-invariants (**1970**); Basile, Marro, Schumacher: self-bounded controlled, self-hidden conditioned invariants (**1982/83**); Stoorvogel el al.: Linking Kalman control/filtering to geometric decoupling (**1992**, **1995**, **2002**).

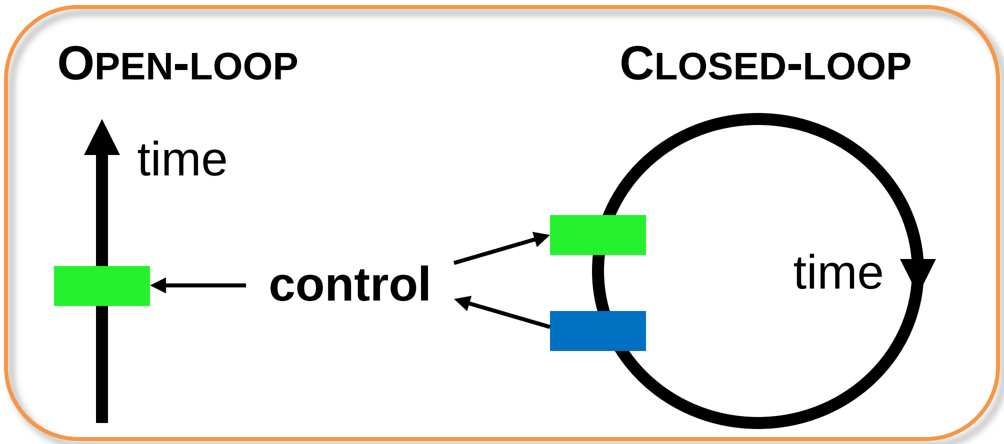
- **STRUCTURAL-DIGRAPH APPROACH.** – **(Andrei, Reinschke, Wend, etc.)**
  Based on structural methods for obtaining classes of feedback matrices with minimal structure. First considered for large-scale linear systems by Andrei (**1984/85**). The digraph consists of a number of nodes & edges associated to non-zero entries of the matrices of the system. Later also studied by Reinschke (**1988**) and Wend (**1993**).

All of these approaches have serious limitations, especially once applied to complex dynamic systems with a large number of degrees of freedom.

In addition, the description of systems, both in differential eq. and poly.-matrix freq. form, has numerical values of req. accurate knowledge; the algorithms for system analysis and controller synthesis are based on matrix manipulation without considering any particular structure of system or feedback.

TO THE INTERPRETATION OF CONTROL

What is the underlying **reason for these system limitations** and thus the applicability of Control Theory? – Let us naively resume the theory's mechanisms.



We distinguish between **external** or open-loop control and **intrinsic** or closed-loop control mechanisms.

+ Open-loop: fixed control structure

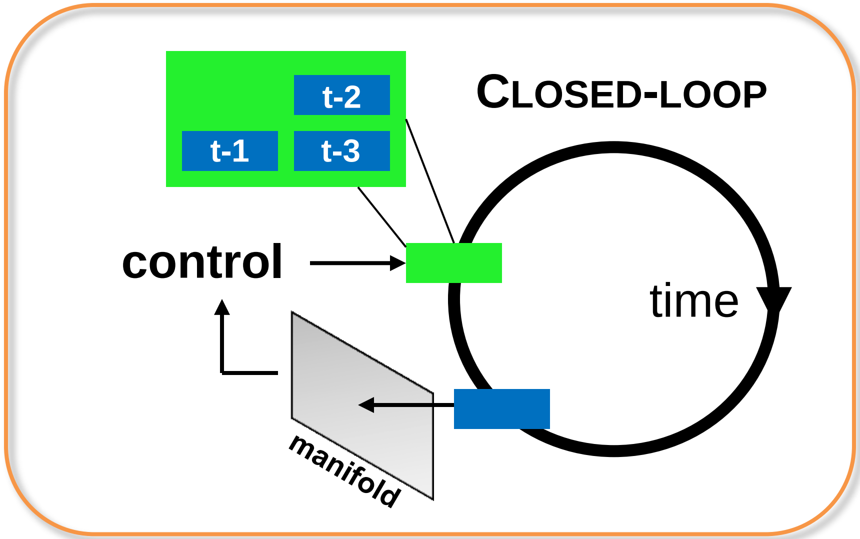
+ Closed-loop: adapted control

A **priori defined open-loop** control or "plan" for the dynamics of a system with a well-known initial condition **fails** for an immediately neighbored initial condition due to the induced instability of control trajectories in the state space. A **open-loop** control allows to **adjust measured deviations** ( ) of the nominal trajectory.

In any case, we always apply a **known governing structure** ( ), may it be a family of ordinary differential equations on finite dimensional smooth manifolds that determine the control response based on boundary **expectations** in the structure.

ON THE ADAPTIVENESS OF CONTROL

We are seeking a **universal theory**, a global mechanism, that allows us to *govern dynamic systems of arbitrary degree of complexity* and overcome the bond of the control structure to its initial form by introducing dynamic, **adaptive structures**.

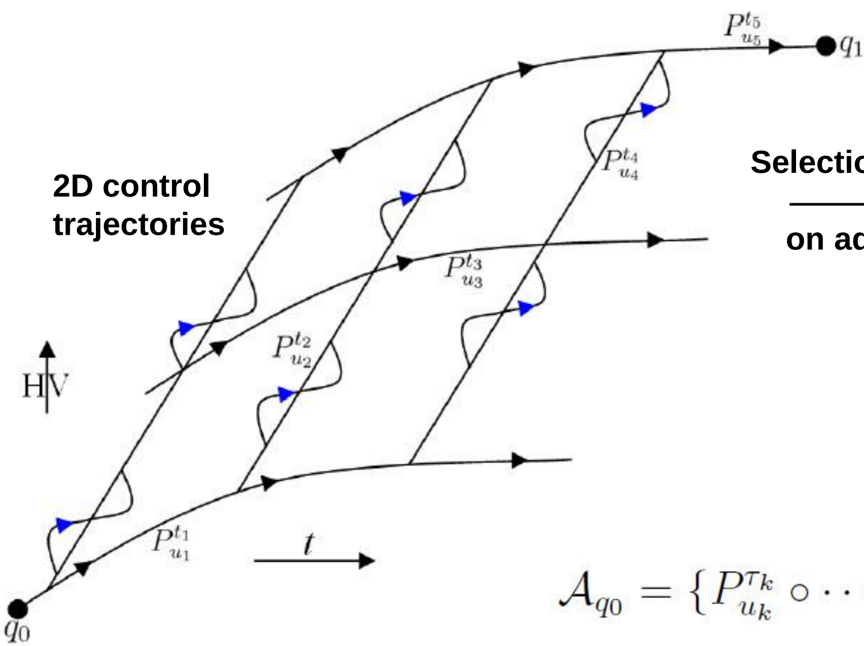


Each **control response** ( ) is being **embedded in the topological structure** of a compact **complex manifold**, which represents the "global" state space of the dynamic system. The control for the current state is then determined by solving the optimality problem on the "local" state space with the projected structure of similar states χ_{t-x} (conditions) from the "global" state space.

- The idea of adaptive control has been fundamentally enriched by an **iterative learning process** from dynamic complex systems, for which **unknown sequences** of control parameters states are **uncovered by reproducing patterns** of known parameter states over time and are embedded in the adaptive control scope for control actions thereafter.

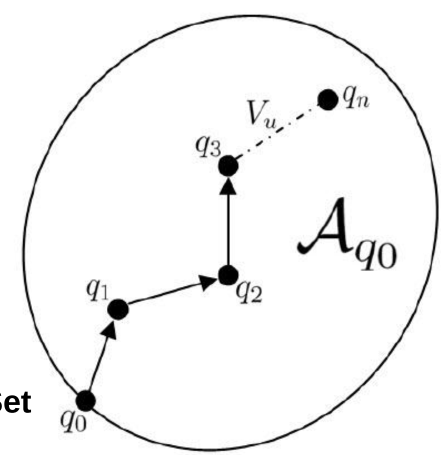
ON THE ADAPTIVENESS OF CONTROL

- This novel concept we call a **Theory of Dynamic Control (TDC)**, which incorporates **Modern Optimal Control Theory** and modern **Artificial Intelligence** concepts for High-Performance Computing (HPC) applications.
- As a result, we can apply this theory to not only classical control applications but moreover **learn from the intrinsic structure of our control subjects** and possibly uncover new dynamical properties. Since control theory finds currently most impact in engineering (e.g. aerospace), economics and mathematics, one may be able to utilize it more for research applications in the natural sciences.



Selection of sequence depends

on adaptiveness of control

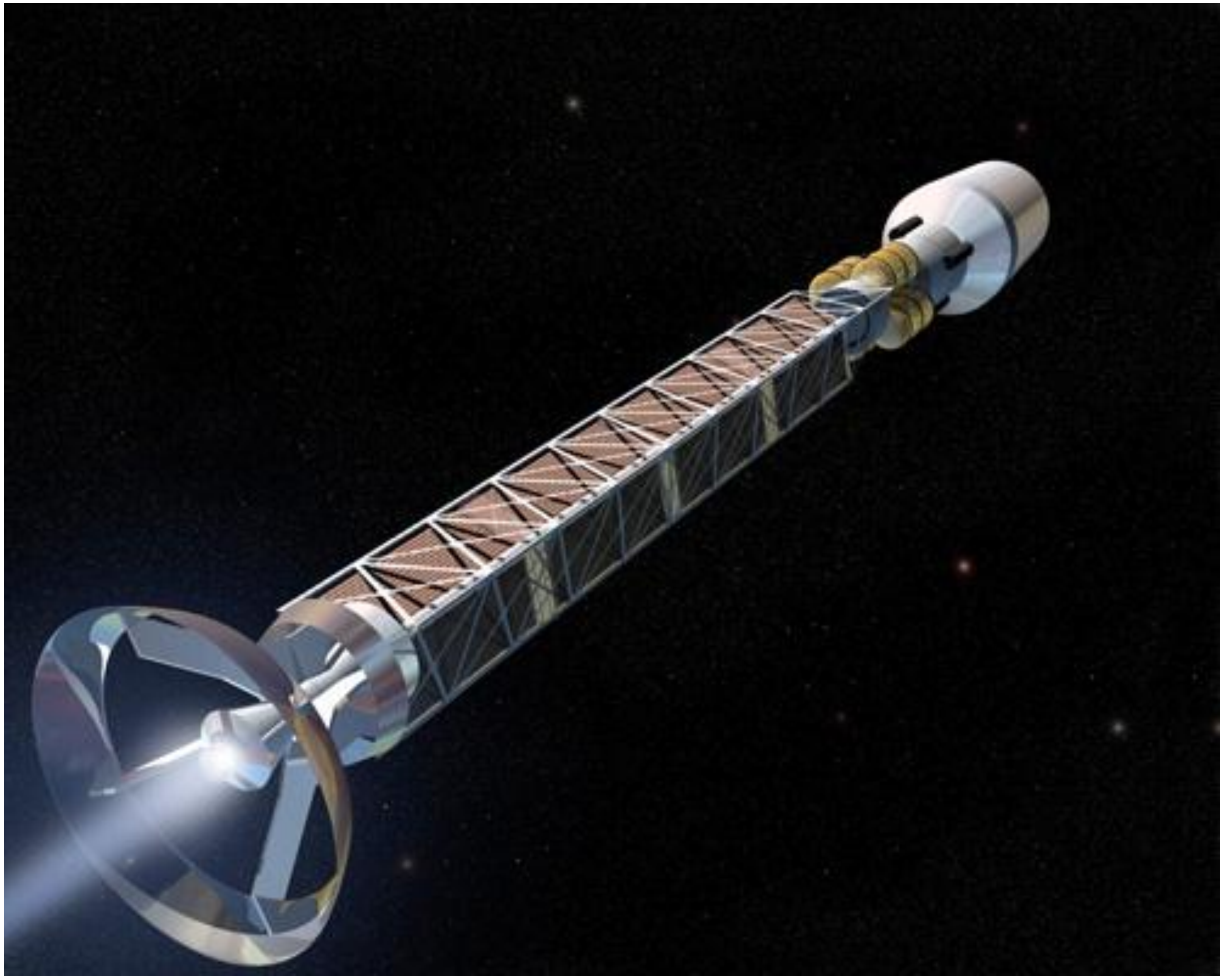


Attainable Set

$$\mathcal{A}_{q_0} = \{P_{u_k}^{\tau_k} \circ \cdots \circ P_{u_1}^{\tau_1}(q_0) | \tau_i \geq 0, \sum_{i=1}^{k} \tau_i = t, u_i \in U, k \in \mathbb{N}\}$$

A SNAPSHOT OF TDC HISTORY

- **1993:** This year marks the beginning of an originally independent study of a novel design of an **electric space propulsion systems based on controlled fusion**.



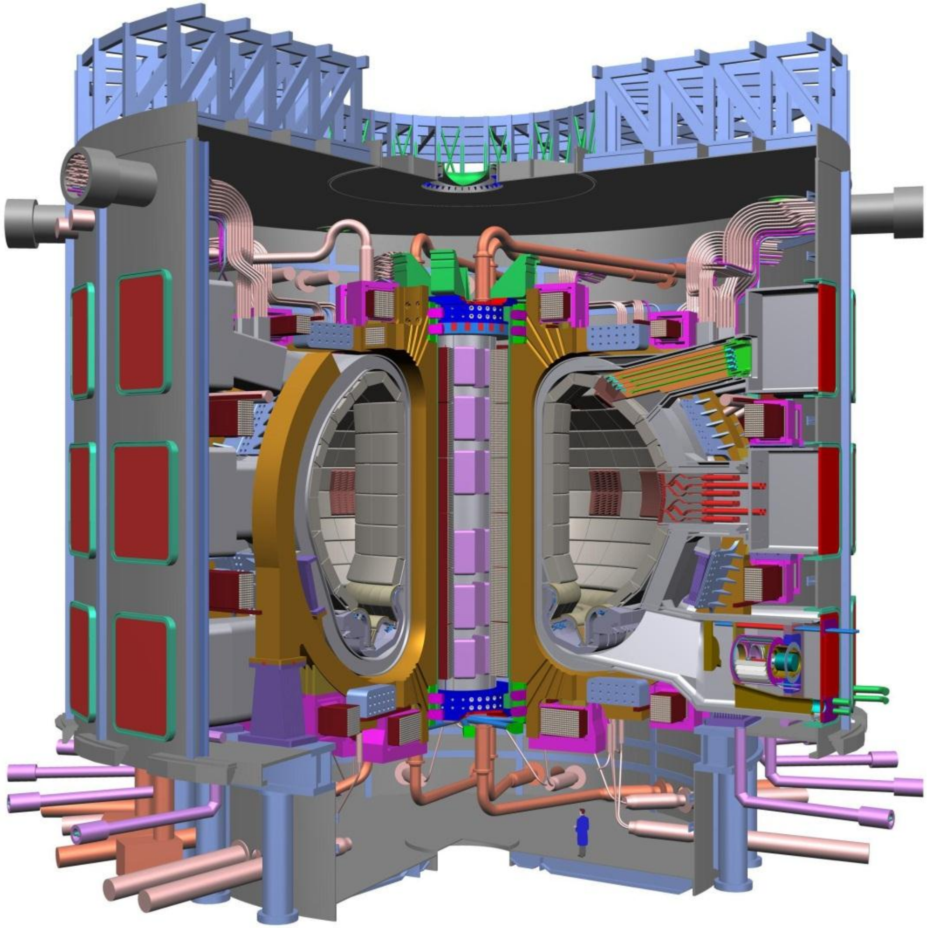
Actual design was based on controlled Deuterium and Tritium fusion with MHD boosters and a LINAC. (not in this fig.)

A SNAPSHOT OF TDC HISTORY

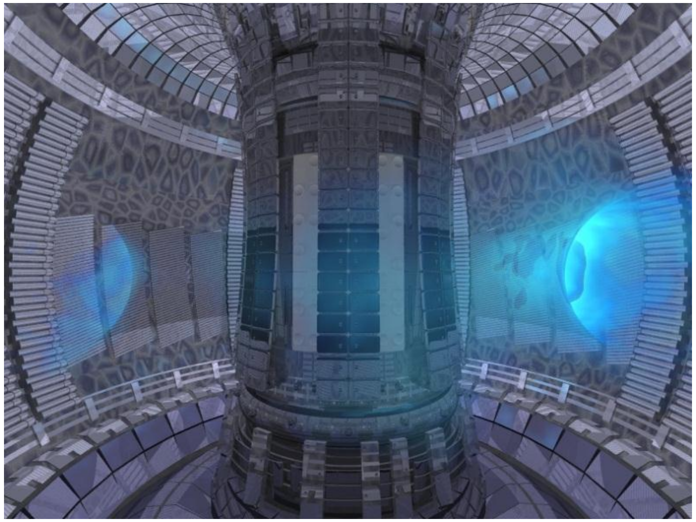
- **2000:** After 7 years of theoretical modeling, the design was first presented at Daimler-Chrysler Aerospace (today: EADS Astrium) and became soon part of an **international collaborative study** with physicists from NASA's Marshal Space Flight Center, Princeton Plasma Physics Laboratory, CERN, MPI for Plasma Physics and other institutions.

A SNAPSHOT OF TDC HISTORY

- **2002:** Soon it was found that not only this particular design but **any design** of fusion-based system for thrust generation will (at that time) **fail in the controllability of the continuous plasma flow.** Similar (but less complex) as in a Tokamak.



ITER project.



A SNAPSHOT OF TDC HISTORY

- **2003:** The project turned into a study of the **controllability of accelerated particle systems**. This marks the official explicit beginning of TDC development. Soon it involved the study of Riemannian geometry, and then Complex geometry with its interactions to various other fields such as differential, algebraic, arithmetic geometry, string theory, conformal field theory.

- **2004:** A vivid exchange with scientists within the **String Theory** community followed (IAS Princeton, MIT, Caltech etc.) due to **similar mathematical structures** found in TDC. This allowed to solve the embedding problem in TDC.

- **2006: It was time to test TDC** in its application to a challenging experiment, but with a relatively simple control parameter to easily validate the theory. (such as **high voltage**)

→ Pioneering implementation in the PHENIX Hadron Blind Detector (HBD) at the Relativistic Heavy Ion Collider (RHIC) – Brookhaven National Lab, NY.

FOR THE STUDY OF THE QUARK GLUON PLASMA.

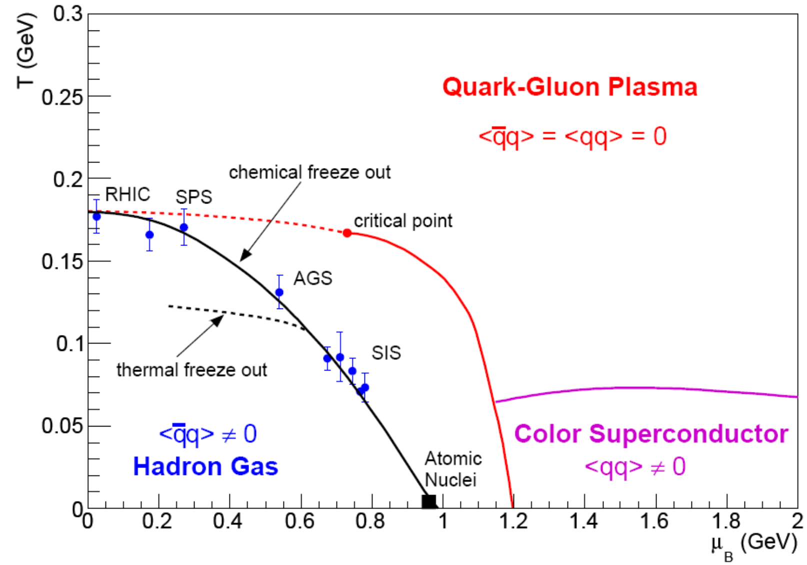
QUARK GLUON PLASMA AND RHIC

QCD: “Quarks are confined to hadrons in pairs of 2 or 3 and bound by gluons.“

+ at small distances → their coupling constant is small → quarks act as quasi-free particles
+ at large distances → their coupling constant increases → quarks are confined

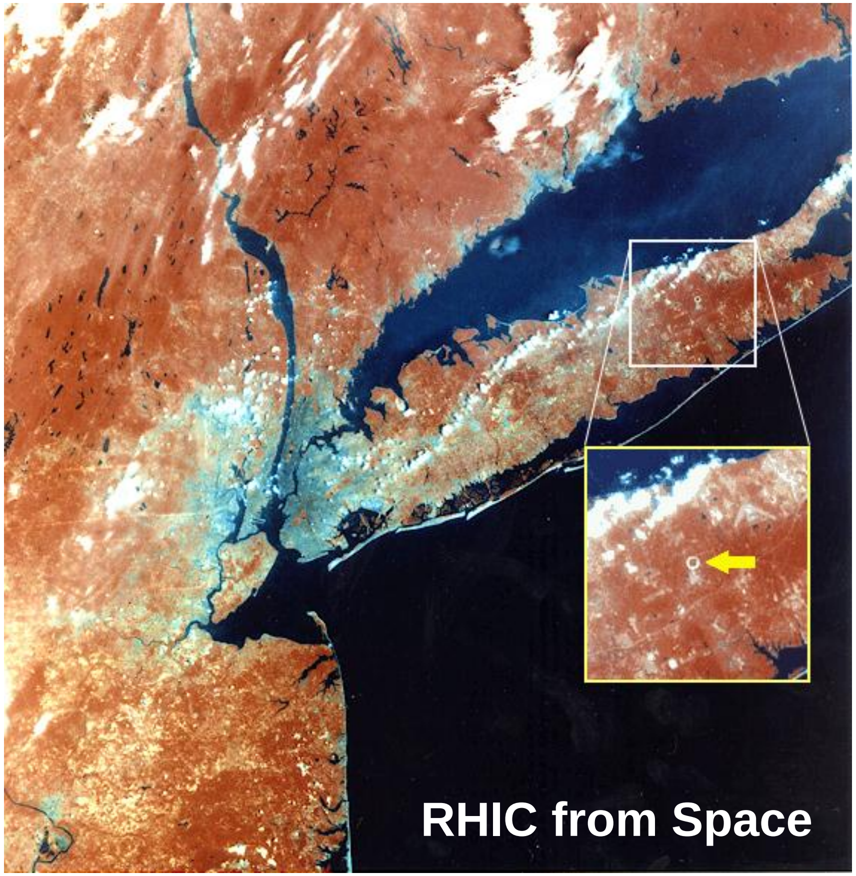
- A phase transition from a color-neutral hadronic state to a **new state** in which the degrees of freedom are the deconfined quarks and gluons, can be achieved at energy densities of $\varepsilon \approx 1\ \mathrm{GeV/fm^3}$ and a temperature of $T \approx 170$ MeV $\approx 10^{12}$ K – called …

QUARK-GLUON PLASMA (QGP)



- *Relativistic Heavy Ion Collider* (**RHIC**) allows to study a **QGP with low baryon densities** produced in d+*Au*, *Cu*+*Cu* or *Au*+*Au* collisions at center of mass energies up to 200GeV.

QUARK GLUON PLASMA AND RHIC



Aerial View of RHIC Complex

- RHIC consists of 2 independent rings with ions accelerated in one ring clockwise, in the other counter-clockwise and brought to collision at their 6 ring intersections, hosting 4 experiments.
- One of the 4 experiments is the Pioneering High Energy Nuclear Interaction eXperiment (**PHENIX**).

QUARK GLUON PLASMA AND RHIC

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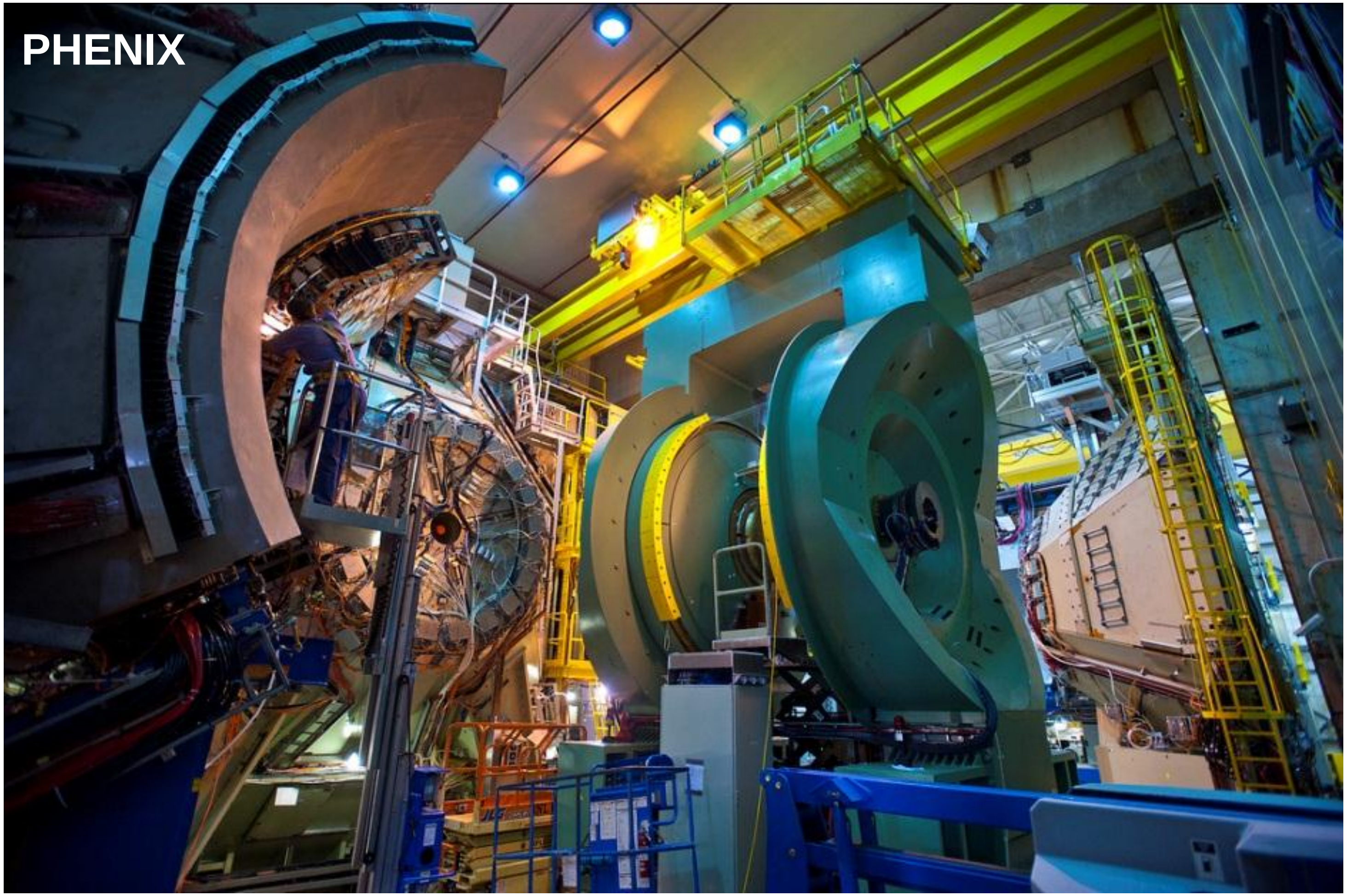
QUARK GLUON PLASMA AND RHIC



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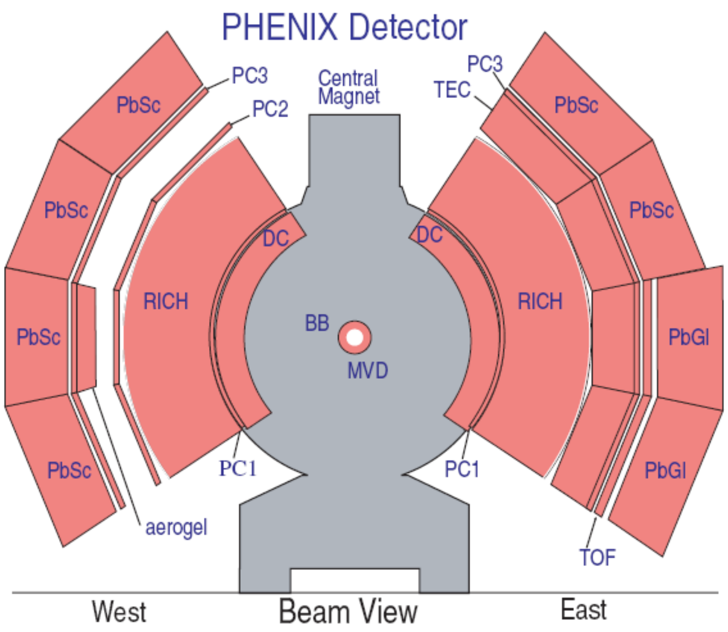
PHENIX & LOW-MASS DILEPTON CONTINUUM

- PHENIX allows high precision measurements of hadrons, leptons and photons with an **excellent mass resolution**. It represents a collection of advanced detector systems.

- One of its primary goals: study of **low-mass e^+e^- pairs**, which allow to gain insights to **QGP characteristics** as *chiral symmetry restoration* and *deconfinement.*

- CERES results have shown large enhancement of dilepton yield below Φ meson mass, which can be derived from **in-medium modifications** of the **light vector mesons** ρ, ω and Φ.



carry same quantum numbers as photon

$$\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$$

THEIR STUDY AT RHIC

- ✓ Collision energies at RHIC are sufficient to study the dielectron continuum
- ✓ However, multiplicity from collisions at RHIC is extremely high, hence dN/dy ~ 650

PHENIX & LOW-MASS DILEPTON CONTINUUM

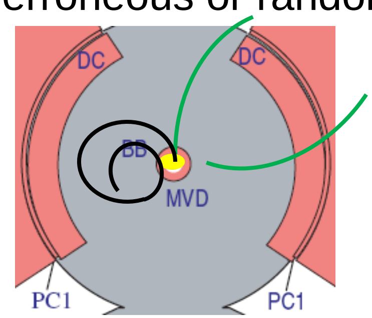
- The *key challenge* of this measurement is to significantly reduce the **combinatorial background** primarily resulting from **uncorrelated pairs** formed by tracks from **π^0 Dalitz decays** and γ **conversions**:

$$\pi^0 \longrightarrow e^+ e^- \gamma \qquad\qquad \gamma \longrightarrow e^+ e^-$$

$$e^+ e^-$$

from light vector mesons

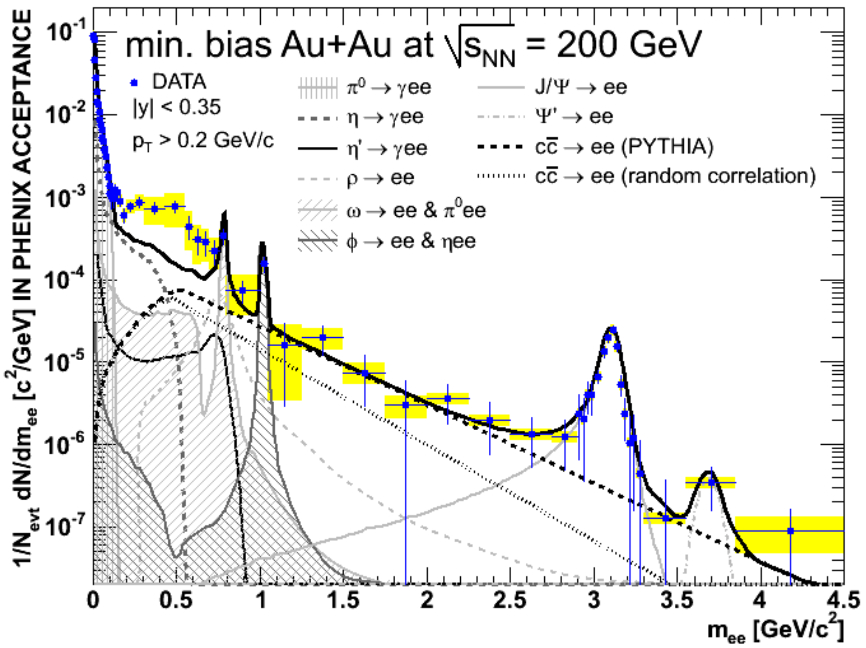
- The recognition and rejection of background pairs is especially exacerbated by the **incomplete azimuthal acceptance** of PHENIX → allows a low-momentum electron from dielectron pair and its spiraling track in magnetic field to become unrecognized by Central Arm detectors, while its counterpart contributes to background through erroneous or random combination of detected positron from a separate pair.

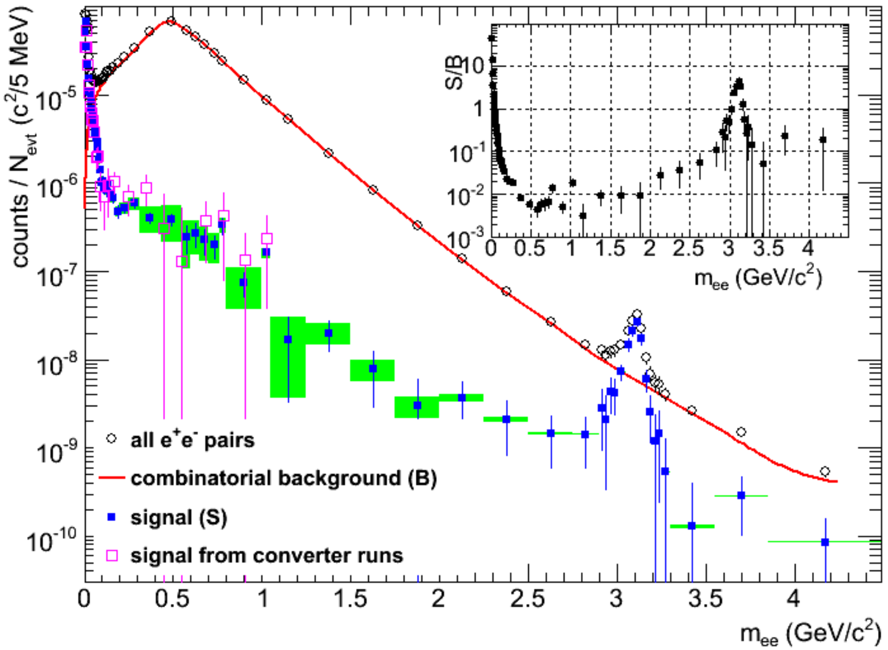


Acceptance: **$|\Delta\eta| \leq 0.35$** in pseudorapidity and **$\pi/2$** in azimuthal angle

PHENIX & LOW-MASS DILEPTON CONTINUUM

- **Consequence: S/B ~ 1/500** at invariant mass $m_{e^-e^+} \approx 500\text{MeV/c}^2$, making it **very difficult for PHENIX to measure the low-mass dilepton continuum.**





- Upgrade Solution for PHENIX to address this issue: the **Hadron Blind Detector (HBD)**

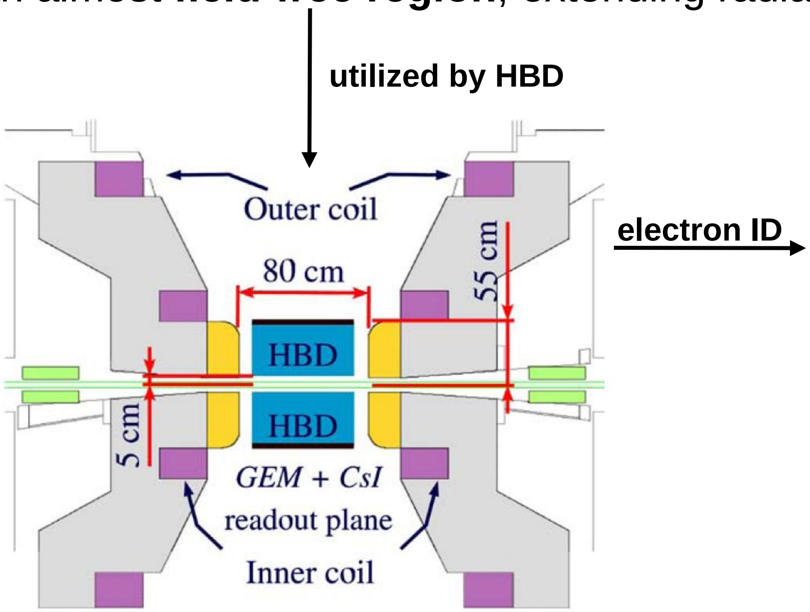
HBD: DESIGN AND IMPLEMENTATION

The HBD concept takes advantage of the …

FUNDAMENTAL OBSERVABLE TO IDENTIFY BACKGROUND PAIRS

The **opening angle** of pairs from γ-conversions/π^0-Dalitz decays is considerably ***smaller*** than of pairs originating from light vector meson decays!

- In order to preserve straight particle trajectories and the corresponding opening angles of pairs, the PHENIX Central Magnets are operated in (+ –) configuration, which creates an almost **field-free region**, extending radially out to ~ 50-60cm from beam axis.



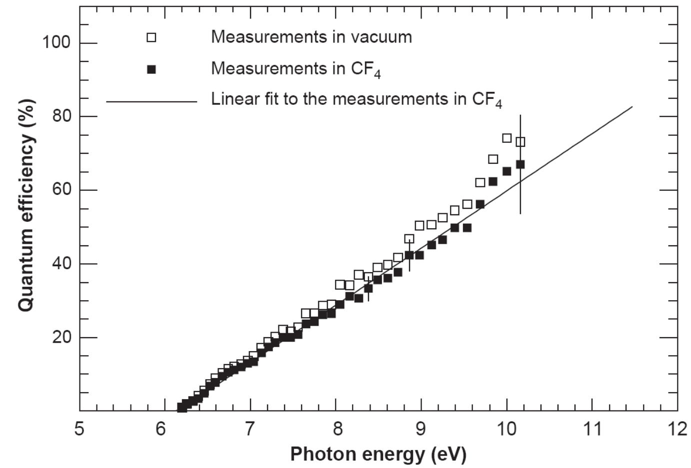
Design Challenges

- ✓ Fit into region about collision vertex R< 60cm
- ✓ Detect single UV Cherenkov photon, but still be blind to all transversing ionizing particles
- ✓ PHENIX geometry prevents design with focusing mirrors (RICH)
- ✓ Radiation budget < 3% of radiation length → windowless configuration!

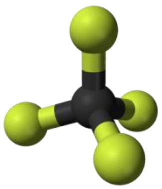
HBD: DESIGN AND IMPLEMENTATION

MAJOR DESIGN COMPONENTS

- **CsI** as photocathode, allowing an absolute quantum efficiency of about 80% in UV



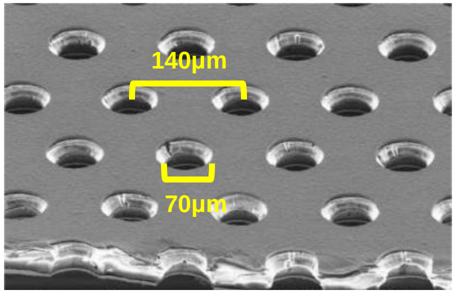
- **CF_4** as radiator and detector gas

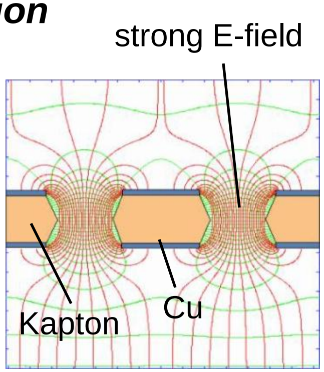


  - ✓ Large figure of merit $N_0 \approx 822\ \mathrm{cm}^{-1}$ (no. of photons emitted by electron over 1 cm path length)
  - ✓ *High ionization potential*; strongly ***E***-field dependent to generate an electron-F^+ pair

- Gas Electron Multiplier (**GEM**) as amplification unit
  - ✓ A thin, metal-clad polymer foil with high density of equidistant narrow holes
  - ✓ **Principal of Operation:** Based on ***Electron Avalanche Multiplication***

Each hole represents **prop. amplifier**: electrons close to GEM surface drift into holes, multiply in avalanche and transfer into next region

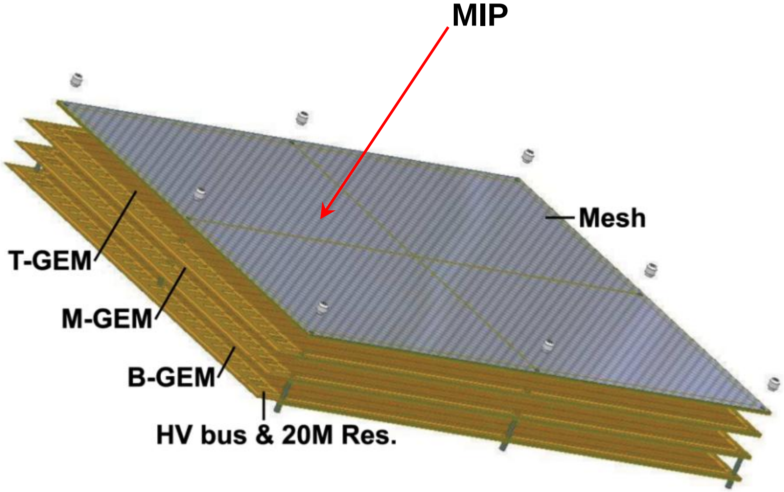


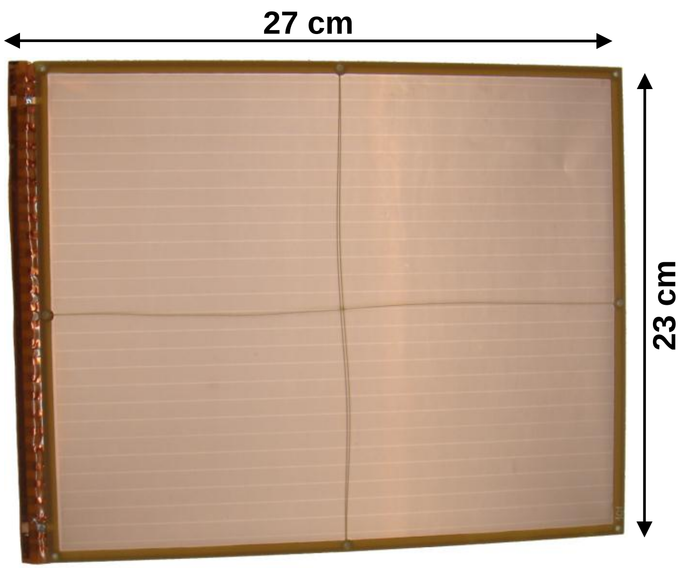


HBD: DESIGN AND IMPLEMENTATION

MAJOR DESIGN COMPONENTS

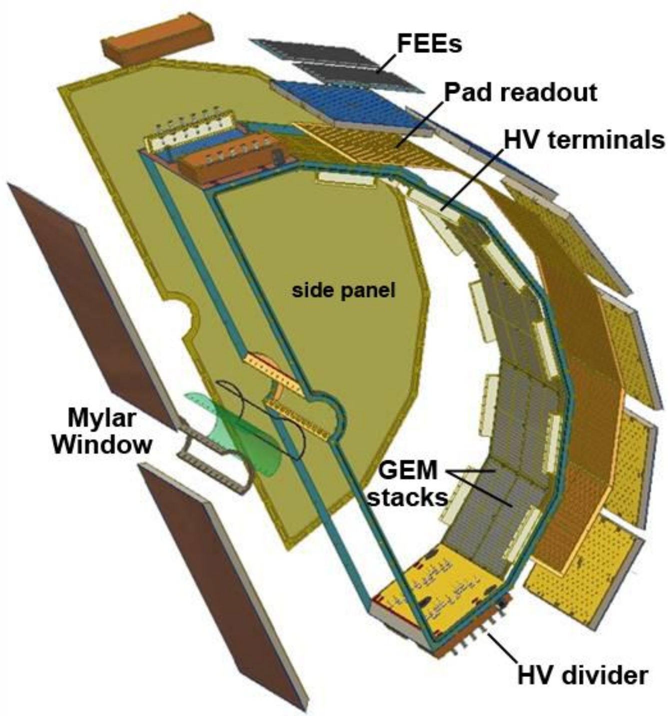
- Cascade three GEM foils to a **triple-GEM stack** to achieve *higher gains* and more *stable operation* (1.5 mm gaps in-between)
- Reduce the stored energy during discharges by segmenting foil in 28 strips with **20MΩ resistor** soldered to HV bus of top electrode
- Convert **Top GEM** into **photocathode** by evaporating a ~ 300nm layer of CsI onto its top surface
- Generate drift field to reject Minimum Ionizing Particles (MIPs) above Top GEM with a stainless steel **Mesh** of ~ 90% transparency
- Power GEM detector appropriately!

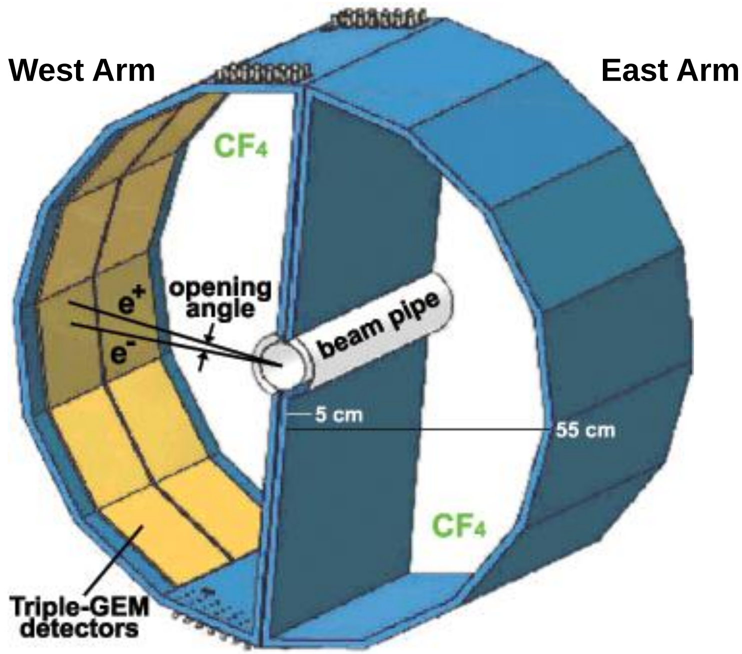




HBD: DESIGN AND IMPLEMENTATION

MAJOR DESIGN COMPONENTS





Each arm consists of 2 large front and 8 small back panels made of layers of FR4 / Honeycomb / FR4 (250µm/19mm/250µm) glued to rigid FR4 frame, while 2 side panels are mounted with plastic screws. The 5 inner panels are mounted with 2 Triple-GEM detectors with underlying readout plane, consisting of 96 hexagonal pads.

HBD: ELECTRON ID PRINCIPLE

The electron ID principle is illustrated using the following conventions:

- **Drift** with field $\mathbf{E_D}$ — gap between Mesh and Top GEM
- **Transfer** with field $\mathbf{E_T}$ — gap between GEMs
- **Induction** with field $\mathbf{E_I}$ — gap between Bottom GEM and pad readout PCB

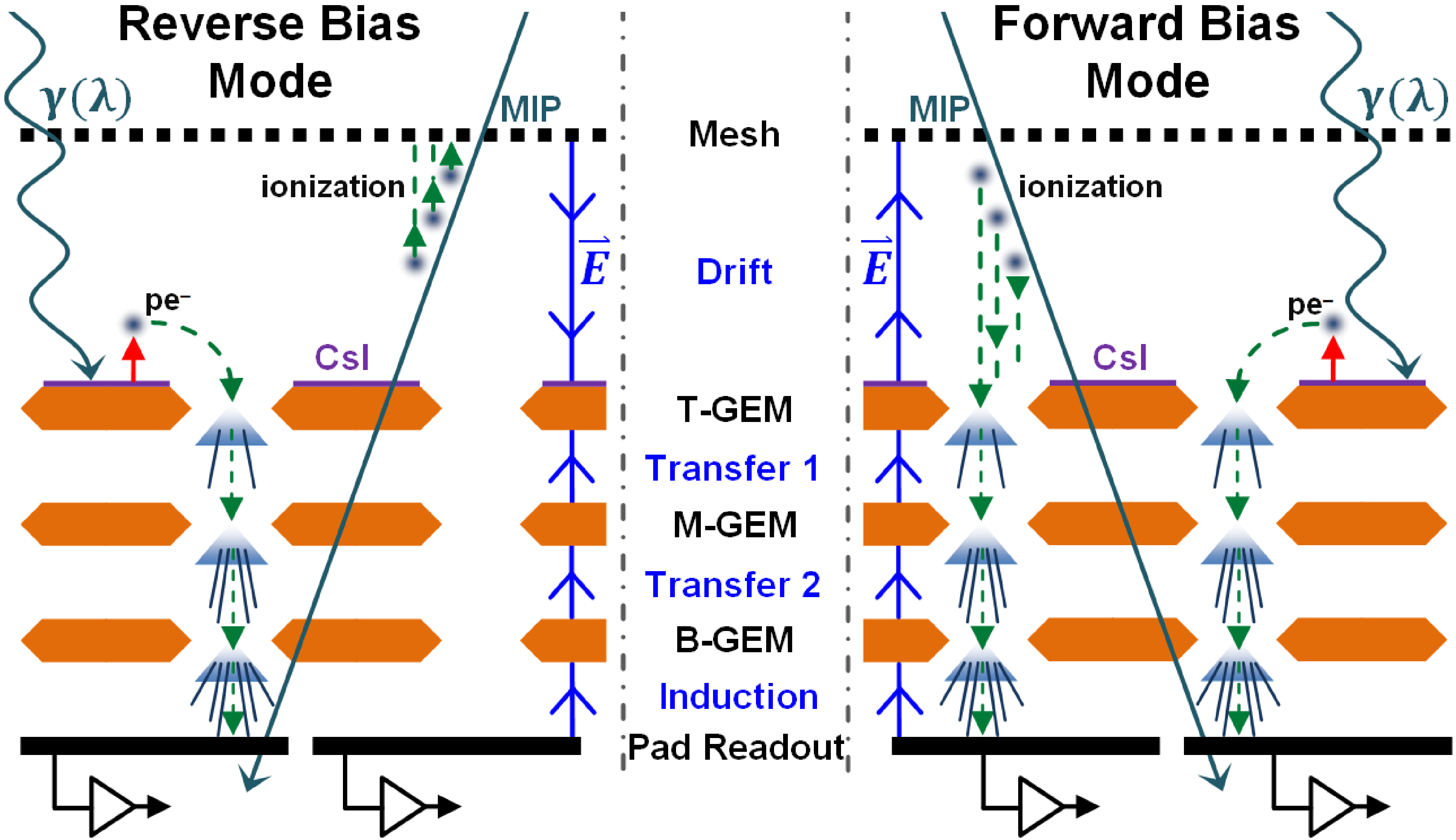
- **dV** — magnitude difference between potential on Mesh and Top GEM

- **pe⁻ extraction efficiency** — probability to extract a photoelectron from CsI surface
- **pe⁻ transfer efficiency** — probability to transfer an extracted photoelectron into GEM hole
- **pe⁻ collection efficiency** — ration of number of photoelectrons (pe⁻) collected/amplified by GEM to number of pe⁻ produced for given quantum efficiency of CsI

The HBD can be **operated in two different modes**, depending on its drift field configuration:

Reverse Bias	**Forward Bias**
negative dV	**positive dV**
→ **HADRON BLIND MODE**	CALIB. MIP REJECTION

HBD: ELECTRON ID PRINCIPLE

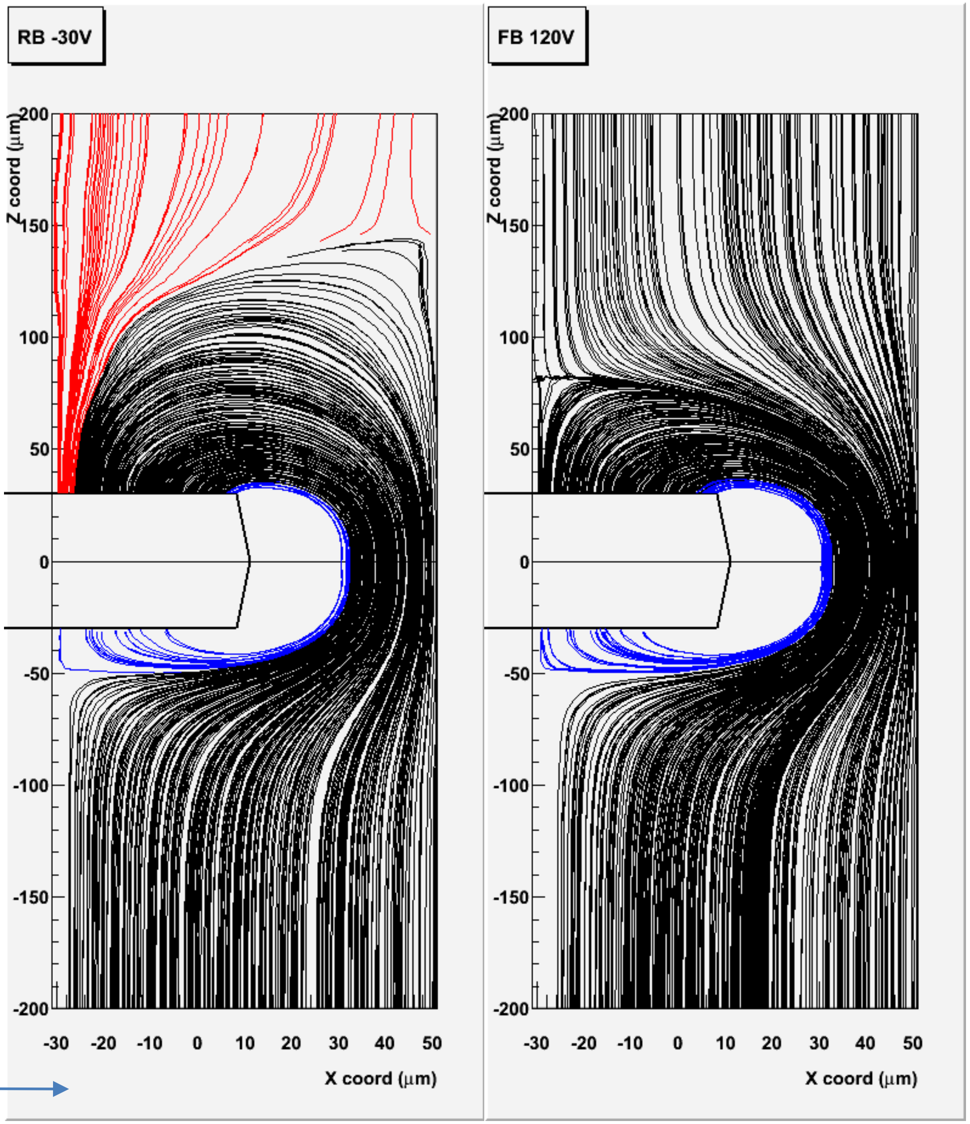


HBD: ELECTRON ID PRINCIPLE

- Simulations have shown that electrons within a volume defined **~ 150µm above the Top GEM surface**, meaning photoelectrons and ionization charge, are transferred into the GEM holes.

- In Reverse Bias, ~ 91% of electrons from GEM surface drift into next region, ~ 3% are swept towards the Mesh and ~ 6% are lost on bottom electrode.

→ this means that about 90% of charge in drift gap (1.5mm in height) is collected by Mesh.

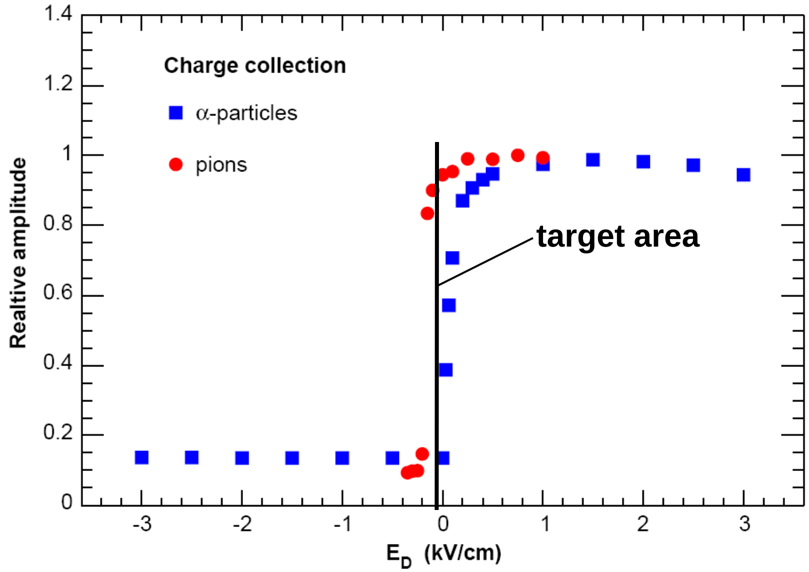


✓ Electron path follows ***E***-field lines
✓ Field line density does not correspond to field strength
✓ No diffusion and avalanche effects taken into consideration in plot

Field lines **to Mesh**, **towards pad**, **to Bottom electrode** of GEM

HBD: Electron ID Principle

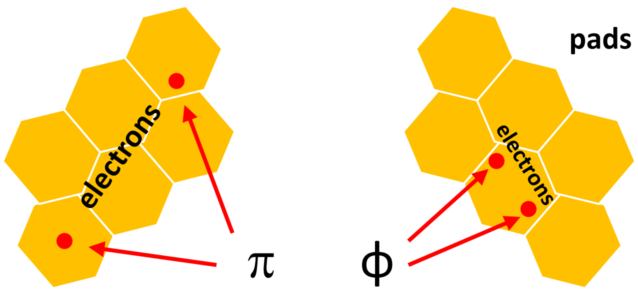
- The photoelectron collection efficiency is preserved at **slightly negative E_D field**, whereas the collection of ionization charge is suppressed!



Experimental studies have shown, the configuration of E_D needs to be achieved in a window of ~ 0.1 kV/cm

When powering a GEM stack with a divider and operational voltages in the order of 4kV, the **HV Control System needs to be capable of supplying voltage with ~ 0.1% precision to achieve the required dV to 4V**

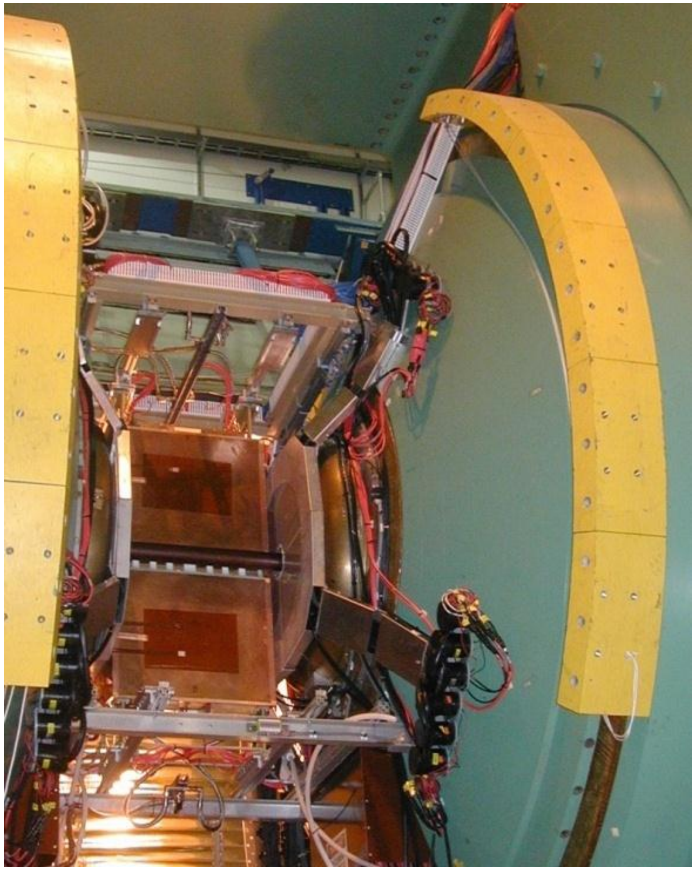
- Due to Cherenkov yield of ~28.4 in CF_4, pions with a momentum < 4GeV don't radiate photons.
- According to Monte Carlo simulations, a MIP may produce ~ 1 Cherenkov photoelectron and single primary electrons ~ 36 photoelectrons
- Identify background pairs by twice the number of photoelectrons produced by single hits (compare amplitudes for pads + angle cut → analysis algorithm)



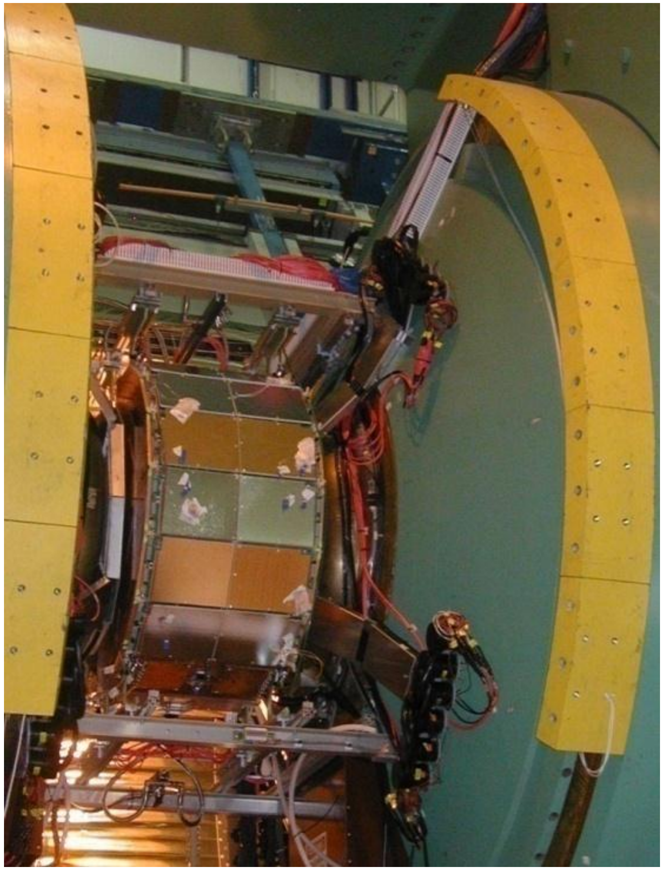
Gain crucial to determine single or double electron hits

RUN-7 OPERATION AND PERFORMANCE

- Both HBD arms were installed for their first run in 2007 and ...
  utilizing a <u>classical</u> HV Control System.



HBD West

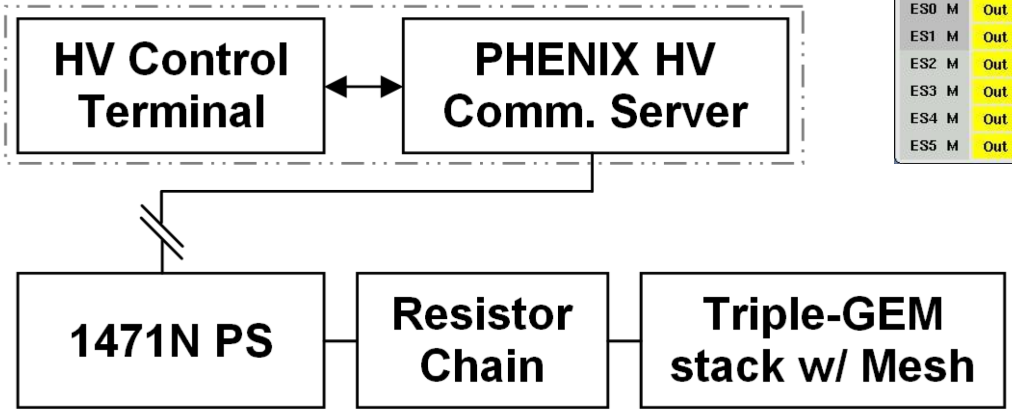


HBD East

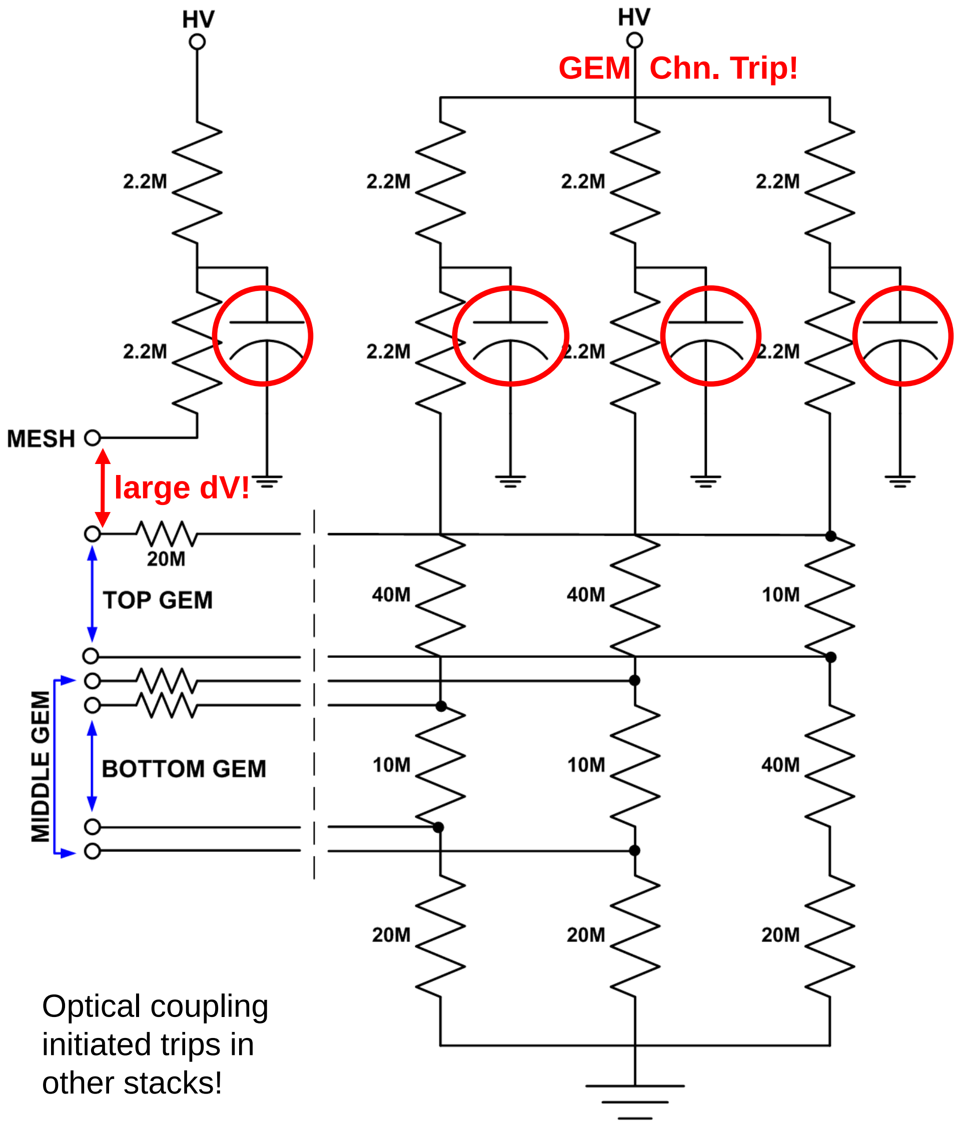
RUN-7 OPERATION AND PERFORMANCE

- Triple-GEM stacks were powered by LeCroy 1471N power supply modules, consisting of 8 independent channels
- One channel supplied voltage to the GEMs utilizing a three-branch resistor chain
- 1471N parameters, as demand voltages and trip currents, were set by a Terminal/Server based control software written in Perl
- Communication to the HV modules was established with the PHENIX HV Server/Client, which accesses the mainframe containing the 1471N supplies

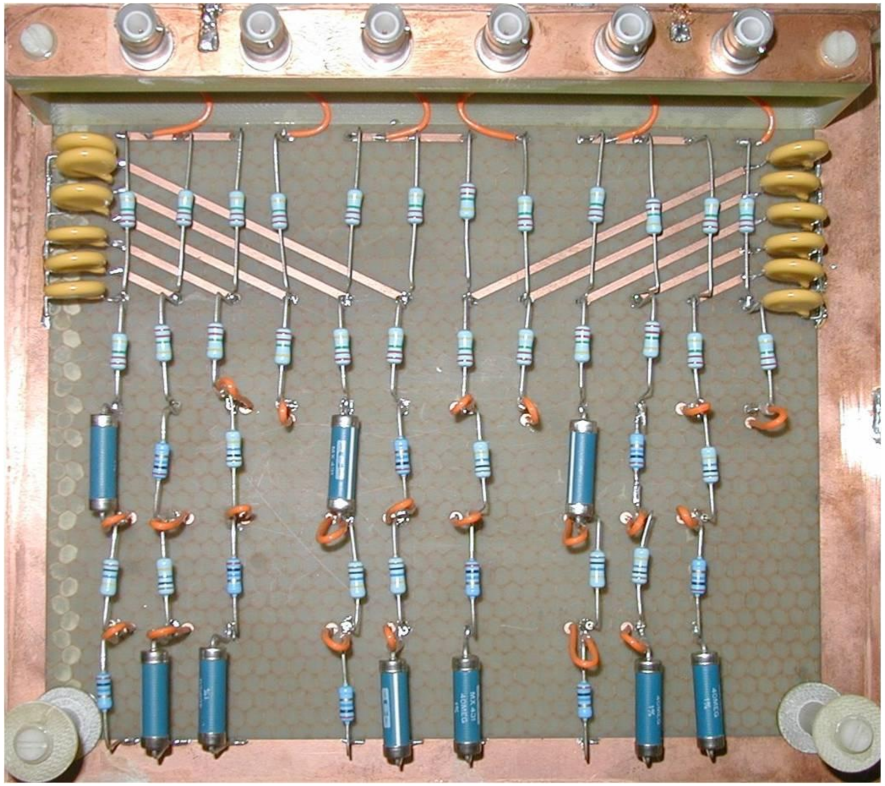
Name	In/Out	En/Dis	V	Dem. V	Peak I	Sta.	Set V	Name	V	Dem. V	Slow I	dI[%]	Sta.	Set V
WN0 M	Out	En	-3068.8	-3066.1	-0.411	1	-3066.1	G	-3101.2	-3100	-125.145	-0.20	1	-3100.0
WN1 M	Out	En	-2786.1	-2783.9	-0.399	1	-2783.9	G	-2799.5	-2800	-114.588	1.06	1	-2800.0
WN2 M	Out	En	-3066.1	-3066.1	-0.349	1	-3066.1	G	-3099.4	-3100	-125.853	0.56	1	-3100.0
WN3 M	Out	En	-3065.9	-3066.1	-0.393	1	-3066.1	G	-3102.2	-3100	-126.488	0.92	1	-3100.0
WN4 M	Out	Dis	0.2	0	-0.289	0	0	G	0.2	0	-0.005	--	0	0
WN5 M	Out	En	-3066.8	-3066.1	-0.334	1	-3066.1	G	-3101.2	-3100	-126.295	0.59	1	-3100.0
WS0 M	Out	En	-2972.7	-2972	-0.34	1	-2972.0	G	-3000.6	-3000	-122.473	0.92	1	-3000.0
WS1 M	Out	En	-2032.6	-2031.3	-0.388	1	-2031.3	G	-2000	-2000	-81.719	1.02	1	-2000.0
WS2 M	In	En	-1562.5	-1561	-0.402	1	-1561.0	G	-1499.6	-1500	-61.298	1.02	1	-1500.0
WS3 M	Out	En	-3159.7	-3160.1	-0.455	1	-3160.1	G	-3199.3	-3200	-130.935	1.15	1	-3200.0
WS4 M	Out	En	-3161	-3160.1	-0.399	1	-3160.1	G	-3200.9	-3200	-130.498	0.89	1	-3200.0
WS5 M	Out	En	-3066.4	-3066.1	-0.412	1	-3066.1	G	-3100.1	-3100	-127.124	1.42	1	-3100.0
EN0 M	Out	En	-2031.9	-2031.3	-0.299	1	-2031.3	G	-2001.3	-2000	-81.617	0.87	1	-2000.0
EN1 M	Out	En	-3068.1	-3066.1	-0.358	1	-3066.1	G	-3100.6	-3100	-125.731	0.17	1	-3100.0
EN2 M	Out	En	-2972.6	-2972	-0.423	1	-2972.0	G	-3001	-3000	-120.332	-0.85	1	-3000.0
EN3 M	Out	En	-3067.5	-3066.1	-0.356	1	-3066.1	G	-3100.9	-3100	-125.496	-0.07	1	-3100.0
EN4 M	Out	En	-2974.8	-2972	-0.405	1	-2972.0	G	-3004	-3000	-120.654	-0.80	1	-3000.0
EN5 M	Out	En	-3066.7	-3066.1	-0.351	1	-3066.1	G	-3101.8	-3100	-126.004	0.38	1	-3100.0
ES0 M	Out	En	-2785.5	-2783.9	-0.399	1	-2783.9	G	-2800.4	-2800	-114.643	1.27	1	-2800.0
ES1 M	Out	En	-2975.7	-2972	-0.387	1	-2972.0	G	-3002	-3000	-122.472	0.80	1	-3000.0
ES2 M	Out	En	-2972.5	-2972	-0.352	1	-2972.0	G	-3000.9	-3000	-121.585	0.19	1	-3000.0
ES3 M	Out	En	-2972.8	-2972	-0.375	1	-2972.0	G	-2999.5	-3000	-121.408	0.11	1	-3000.0
ES4 M	Out	En	-2972.2	-2972	-0.348	1	-2972.0	G	-3000.2	-3000	-122.931	1.26	1	-3000.0
ES5 M	Out	En	-3066.4	-3066.1	-0.365	1	-3066.1	G	-3100	-3100	-126.048	0.24	1	-3100.0



RUN-7 OPERATION AND PERFORMANCE



Optical coupling initiated trips in other stacks!

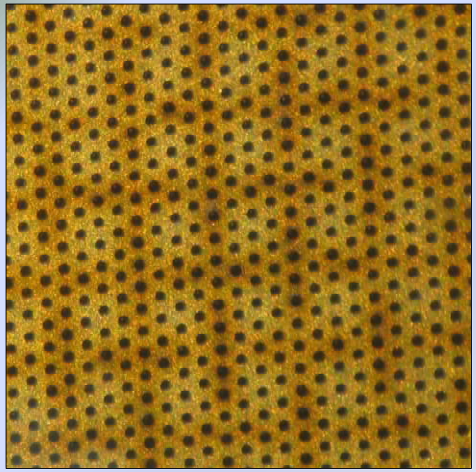


- 1471N was configured to trip when small current draw detected (micro-sparks)
  - → initiated an enormous dV, resulting in a large Mesh to Top GEM spark, which damaged the GEM foil

RUN-7 OPERATION AND PERFORMANCE

MAJOR PERFORMANCE ISSUES

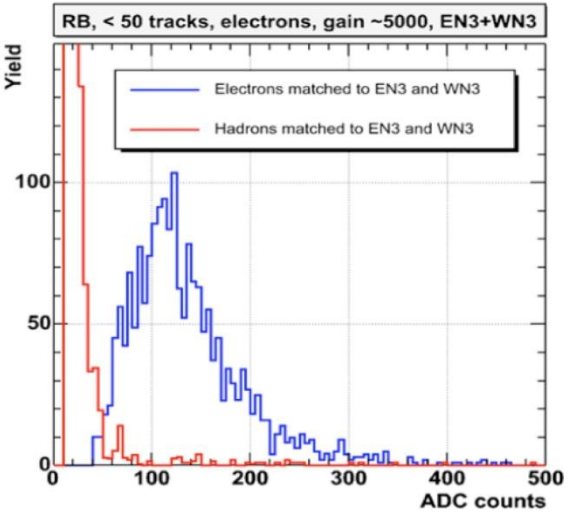
- dV between Mesh and Top GEM exceeds acceptable value during a trip condition and causes severe damages to the GEMs;
- Stored energy in filter capacitors of resistor chain contributes to energy in discharges in stack;
- Trip conditions of 1471N lead to stored energy in HV output filter capacitors that can only dissipate through detector
- Lack of calibration functions for true 1471N output voltage
- Instabilities in module gain due to P/T fluctuations
- Lack of true control structures in code of software and its conceptional design;
- Inadequate logging system of HV (control) parameters



Inspection after Run-7

- Clear separation between hadrons and electrons
- BUT no clear separation between single and double electron hits → insufficient active area to do Physics!

UPGRADE OF HBD HV SYSTEM NEEDED!!!



SUMMARY OF HV CONTROL CHALLENGES

The control of HBD yields several **unique design challenges** on the governing HV system:

- ✓ **HV precision** should be better than **~ 0.1% at 4 kV** in order to generate a slightly negative drift field within a 0.1 kV/cm window for optimal photoelectron collection and maximal MIP charge suppression.

- ✓ Due to strong pressure (**P**) and temperature (**T**) dependence of the **gas gain**, i.e.

$$\textbf{HBD gain} \propto exp\left({}^{P}\!/_{T}\right)^{3},$$

  gain variations due to P/T fluctuations have significant impact on operational characteristics of detector and may induce GEM sparking. Thus the **HBD gain has to be stabilized** and kept within nominal operating range of +/- 10% by counteracting with relative HV modifications.

- ✓ Stored energy in HV modules should be prevented from dissipating through the detector at trip conditions, while **trip decay** of GEM and Mesh channels has to be **synchronized**.

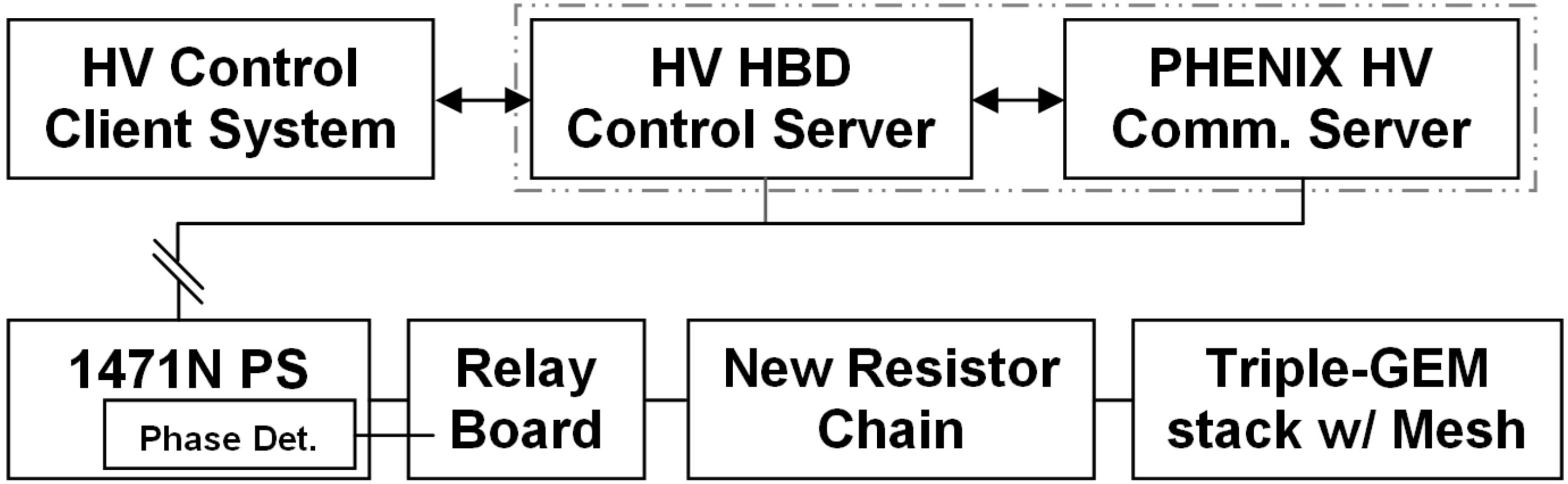
- ✓ Two independent HV **channels** power Mesh/GEM-stack → differentially coupled!

- ✓ Each **GEM module has to be treated as a dynamic control subject** requiring custom treatment based on single-GEM performance variations due to e.g. partial shorts.

GENERIC UPGRADE STRATEGY

Implement a **TDC-adapted Control System** and introduce 3 fundamental components:

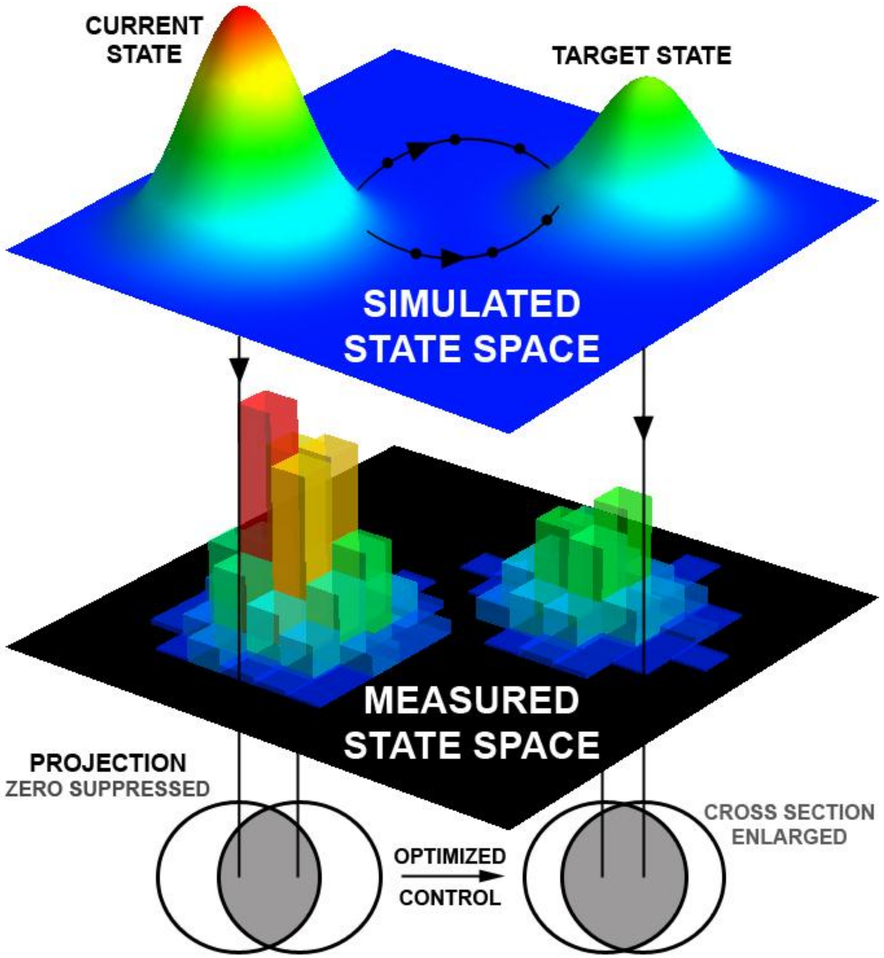
- **New Resistor Chain** with the goal to minimize the stored energy, synchronize the decay time of GEM / Mesh channel (keep dV under control), and optimize achievable gain without the need to increase the chain's input voltage.
- **1471N Phase Detector and Relay Board**, with the goal to monitor the voltage generation directly and ground GEM-stack and Mesh channel simultaneously, if either one appears to have a trip issued by the LeCroy.
- **HV HBD Control Server and Client**, with the goal to allow intelligent, stable, high-efficient, precision control of the detector and the dynamic self-improvement of control functions, if deemed necessary.



TDC-ADAPTED PRINCIPLE OF CONTROL

The **TDC-adapted High-Performance HBD HV Control and Monitoring System (HVC)** treats the detector's triple-GEM stacks as dynamical subjects of control.

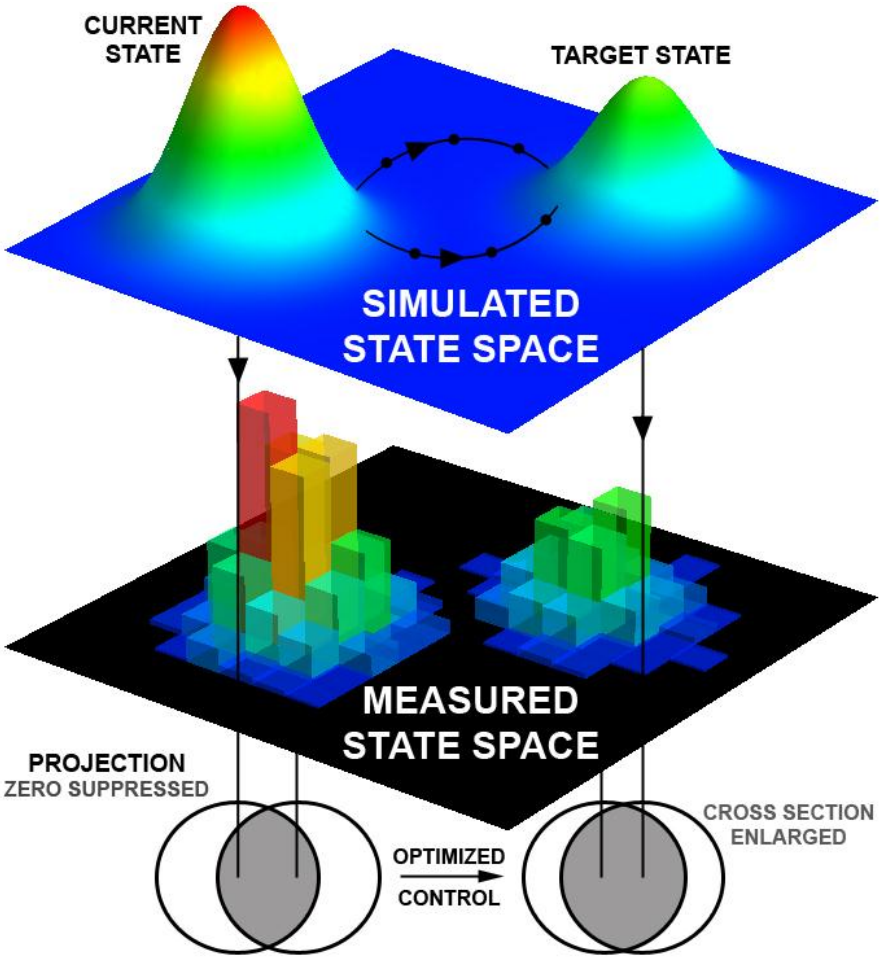
- The state space is defined on a **smooth Hausdorff para-compact topological manifold**.
- Generally speaking, the formalism combines *measured mainframe parameters* and *internal software control parameters* forming a certain structure or peak in a **"local" Simulated State Space**.
- Any behavior of control subject and response is permanently embedded in **"global" Measured State Space**.
- Iterative process: online simulations of actions with aim to **optimize system / detector performance** during each control loop.



TDC-ADAPTED PRINCIPLE OF CONTROL

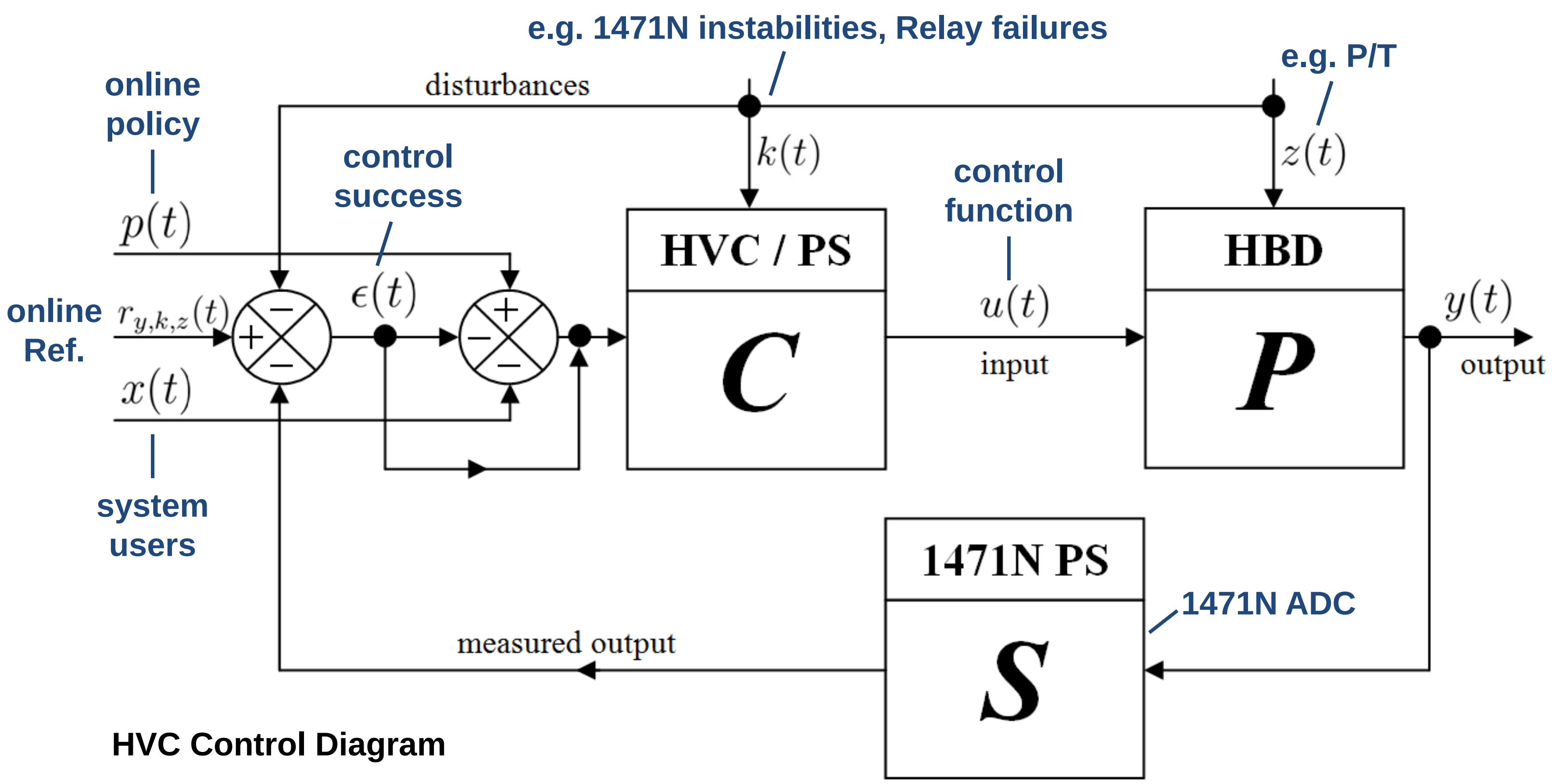
The **TDC-adapted High-Performance HBD HV Control and Monitoring System (HVC)** treats the detector's triple-GEM stacks as dynamical subjects of control.

- An optimal target state is simulated by evaluating all **achievable control trajectories** from an attainable set of operations (online policies) given by boundaries of the current state.
- In case a **similar target state was achieved in the past**, the system is able to reduce the deg. of freedom by incl. the corresponding structure in the global state space. Otherwise, an **interpolation method** is utilized.
- The final aim is to **maximize the projected cross section** of simulated and measured states.



TDC-ADAPTED PRINCIPLE OF CONTROL

Several **external parameters contribute** to the target state simulation, where the controller (***C***) or HV mainframe receives and applies control functions to the control plant (***P***) or HBD with the output signal (***S***) being measured by the 1471N's ADC and evaluated by the system.

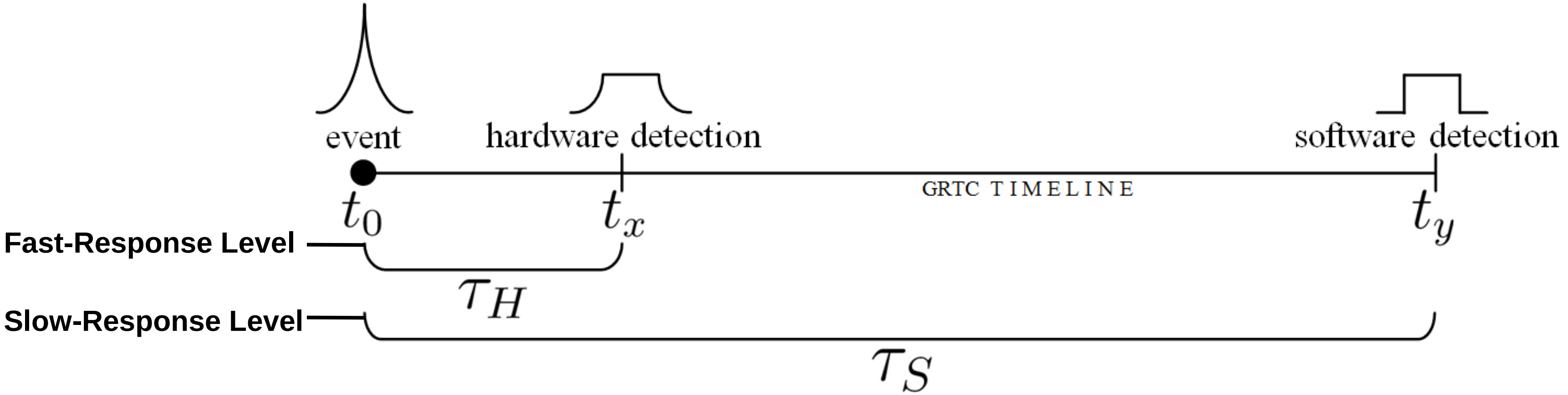


HVC Control Diagram

TDC-ADAPTED PRINCIPLE OF CONTROL

- The HVC Theory of Dynamic Control (TDC) introduces the **Global Response Time Constant** in order to realize optimal control over detector on hardware / software layer.

Definition: *A response time constant τ shall represent the time it takes from a measurable event at t_0 to be detected by a device and so its first ability to respond in appropriate control action if deemed necessary.*



- **Each hardware component represents a control system itself.**
- The software control is required to **incorporate the "knowledge"** of control actions on hardware level.

CONTROL ARCHITECTURE

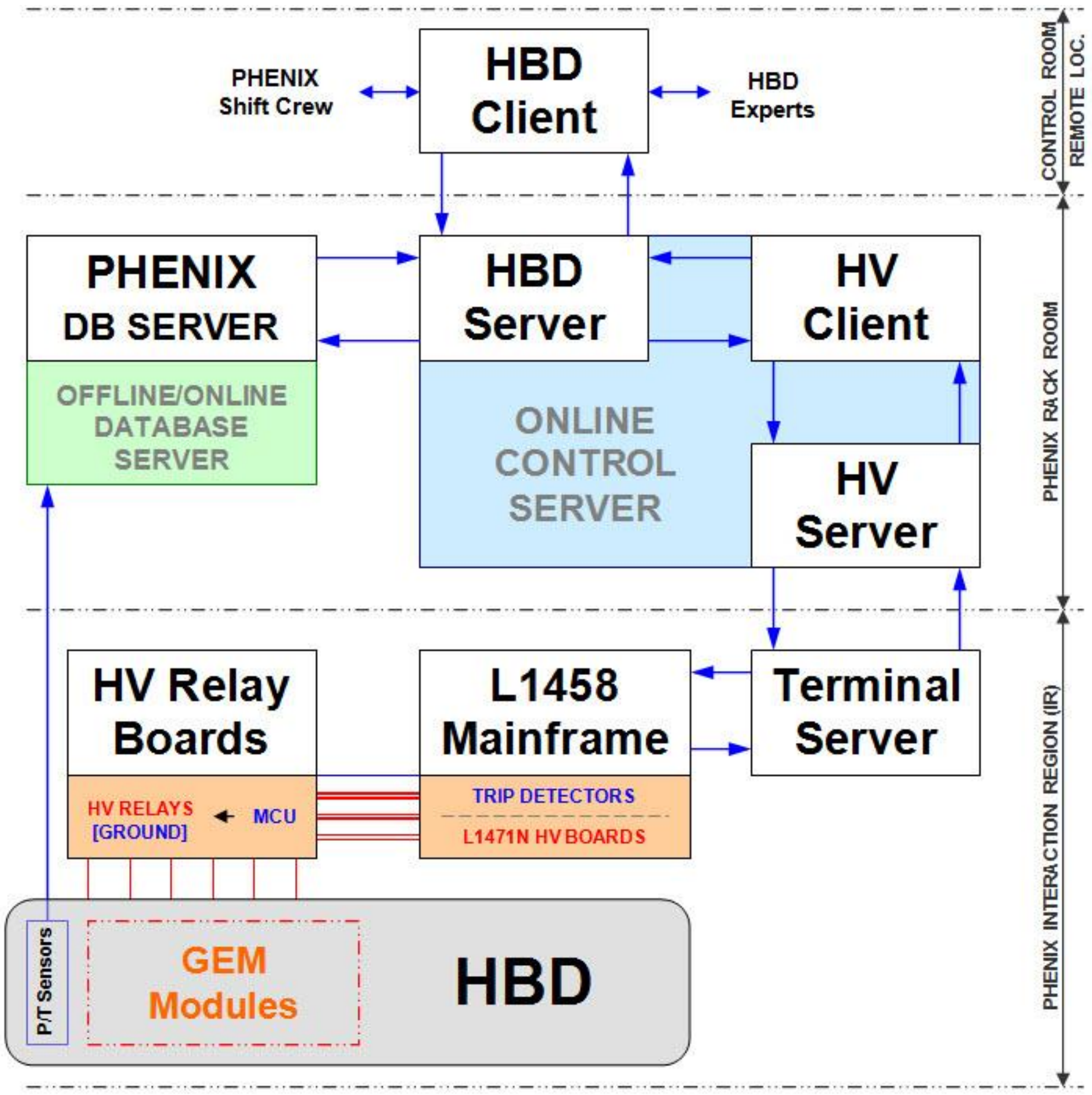
- The computational realization of a **real-time TDC faces** common data flow limitations induced by **delays** from quantization, conversions and saturated grid/multi-core outsourcing **along the processing and control response chain**.
- HVC Control Architecture designed to overcome these boundaries by **moving the "intelligence" to the controlling client's local memory**.
- The client inherits the **ENTIRE state space history embedded into the compactified topological structure of a complex manifold** → optimal target space simulation.
- **Low Memory Consumption** due to confinement of control subject's entire history (system's knowledge) locally on the client in compact manifold representation – depending on system environment, only slices of manifold could be moved to client.
- This yields a **significant improvement of processing performance and control response**, since the extraction of large data packages from databases and resulting network burden can be eliminated.

→ **Mechanism smoothly adapts and profits from the technological progress in high-performance computing (supercomputers etc.).**

CONTROL ARCHITECTURE

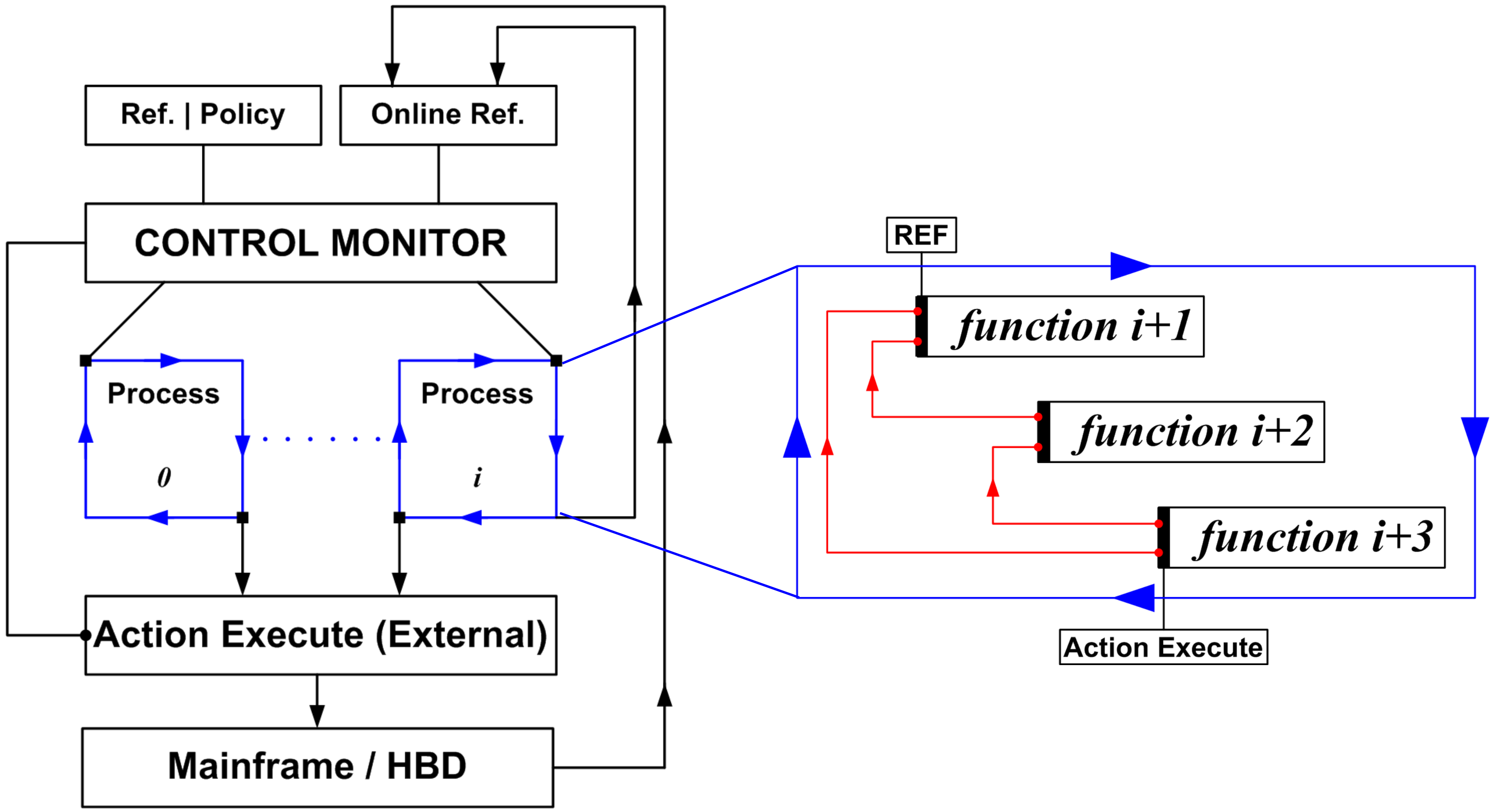
The HVC is built on a **true Client/Server (C/S) architecture** and comprises:

- ✓ LeCroy **1458HP MF** with six 8-chn. **1471N** HV modules suppl. Up to 200μA at 6kV
- ✓ 1471N's modified with **Trip Detection** and ext. **HV Relay boards** with pass-through HV outputs to **divider boards** powering each Mesh/GEM-stack of HBD.
- ✓ Control via software sector: distributed **rich-clients** and **HBD Server** that performs continuous data backup PHENIX DB and executes control functions via **PHENIX HC C/S**.

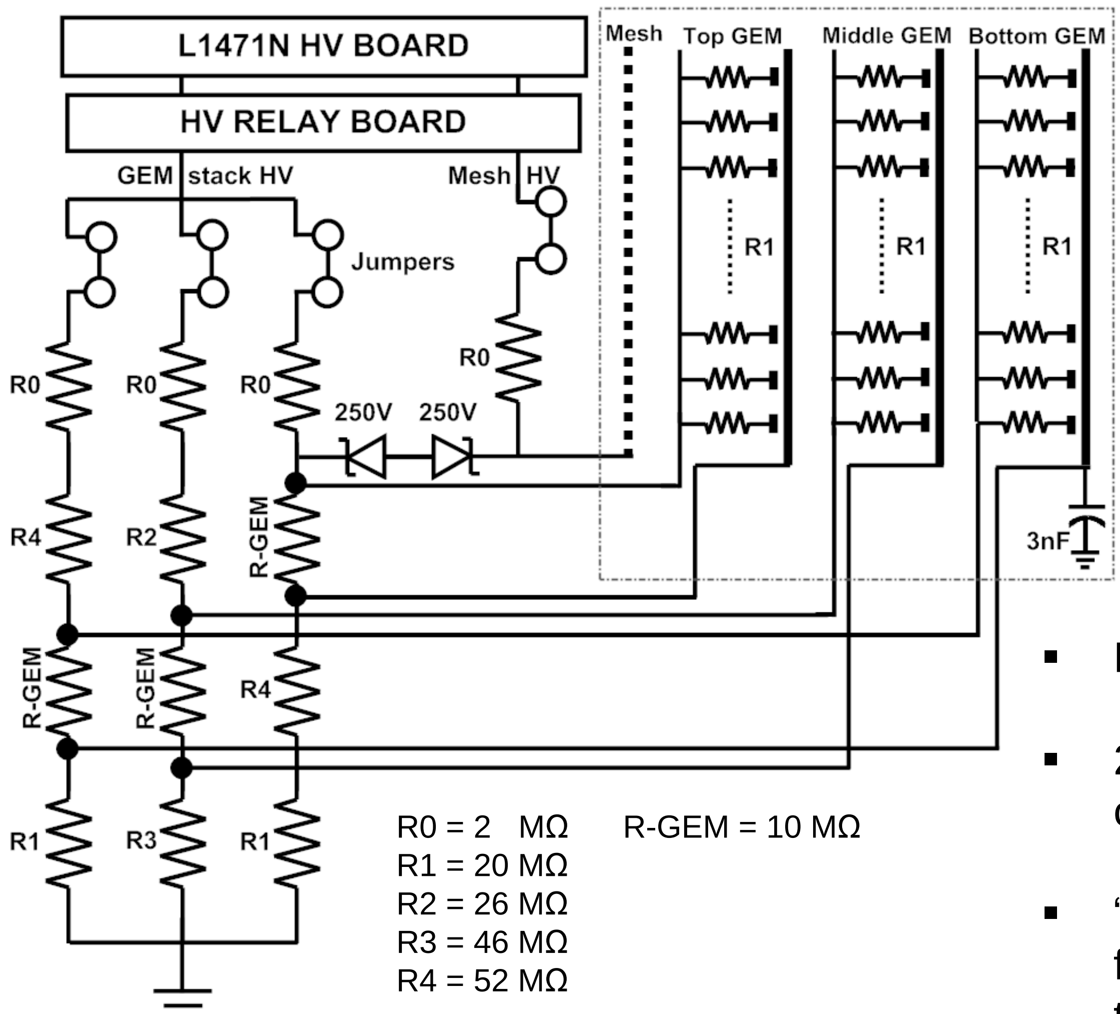


CONTROL ARCHITECTURE

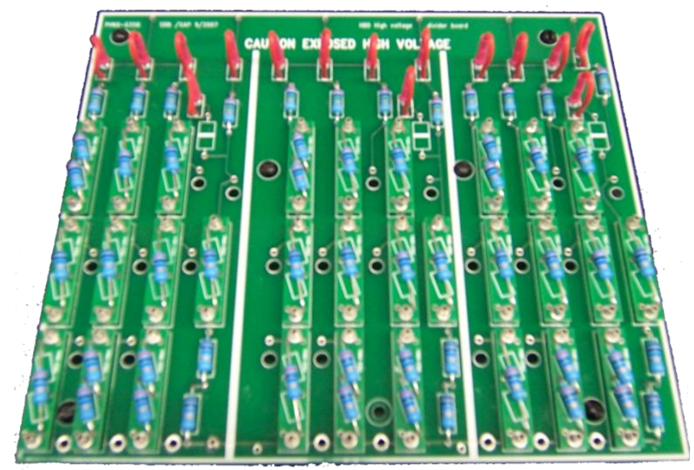
- TDC-implementation through a concept of **LEARNING PROCESSES**, where online parameter states of their functions are logged as reference for other concurrent and future processes.



VOLTAGE DIVIDER BOARD

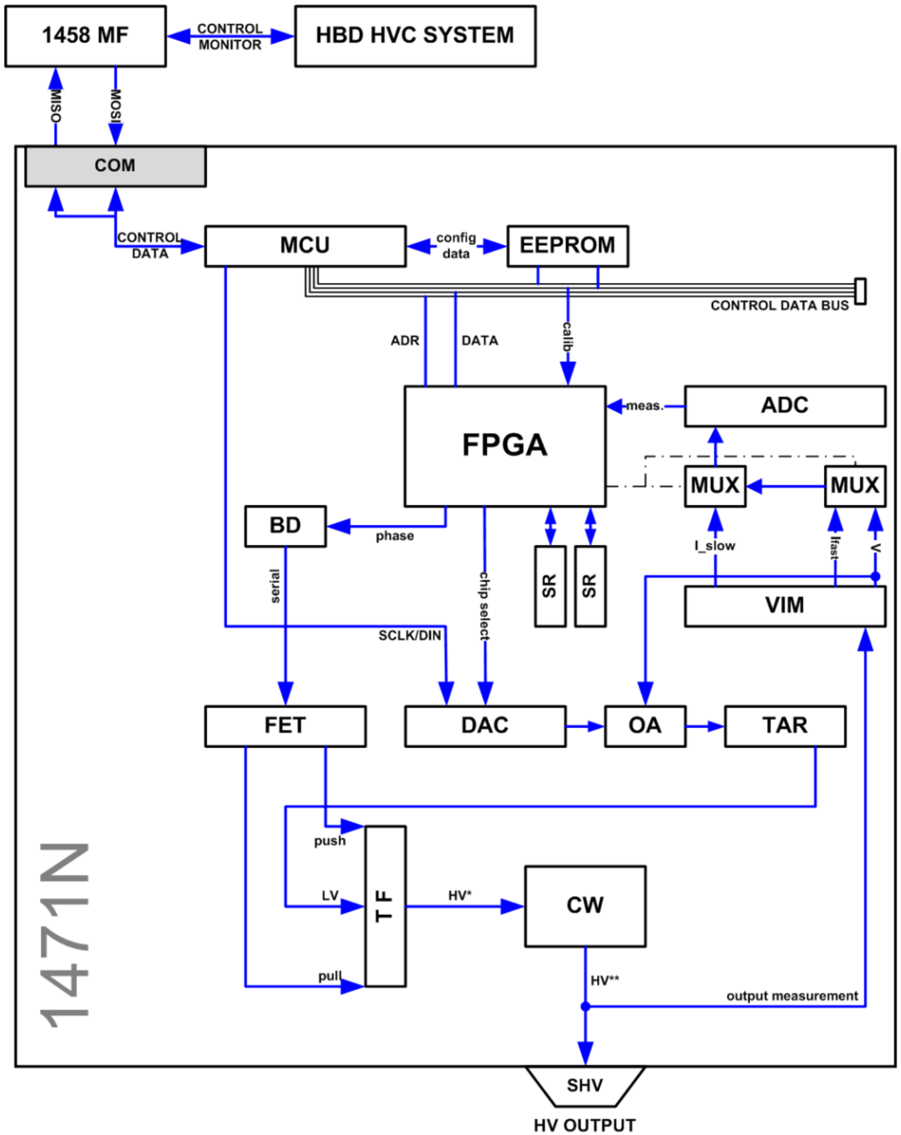


R0 = 2 MΩ R-GEM = 10 MΩ
R1 = 20 MΩ
R2 = 26 MΩ
R3 = 46 MΩ
R4 = 52 MΩ



- Exchangeable miniature resistor plates.
- 250V Zeners in back-to-back configuration for RB/FB modes
- “Free Gain” through increased transfer fields – higher resistance across transfer gaps in respect to R_{GEM}

1471N HV MODULE



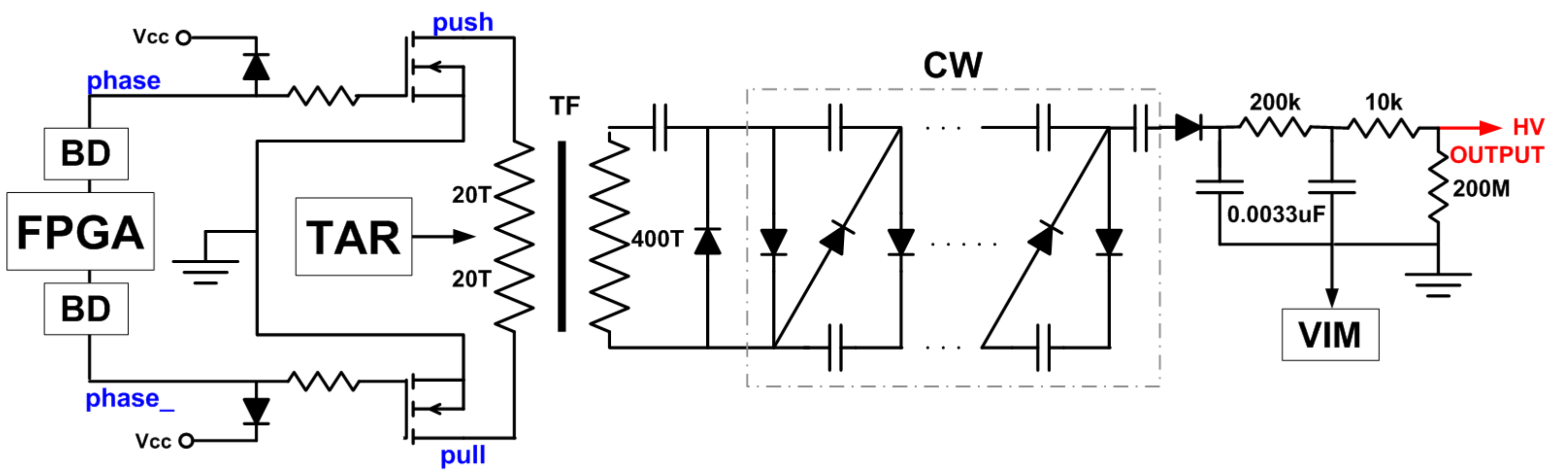
The 1471N represents its own closed-loop control system. Its control structure is implemented in HVC.

The 1471N consists of 6 basic units:

1. **Mainframe-Module Communication**
2. **Baseline Control**
3. **Operational Control**
4. **LV Generation**
5. **HV Generation**
6. **Measurement**

1471N HV Module: HV Generation

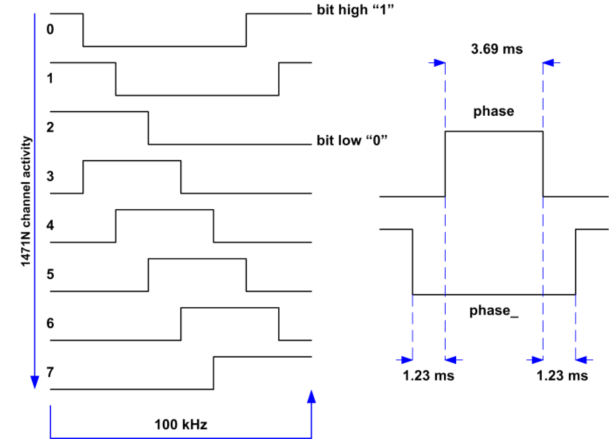
- The DC output of 1471N is based on a switching regulator technique with the ability of pulse-width modulation.
- Control over the output voltage is realized by using a current switch with a constant frequency and variable pulse duration *over period,* the *duty cycle.*
- A **push-pull topology** is chosen, where a DC-DC conversion is accomplished with a high-frequency transformer of fixed ratio and two switching Field-Effect Transistors (FET), one pushing current in one way, the other pulling it the other way.
- This method allows minimal power dissipated in the FETs and so keeps the operational temperatures low due to higher efficiency.



1471N HV MODULE: OPERATIONAL CONTROL

- The FPGA generates the two phases for each FET
- In order to prevent shorting out the power supply, a small deadtime of 1.23 ms is provided between FET activities

→ this results in an approximation of sinusoidal TF output



HV states	FET 1 (PUSH)								FET 2 (PULL)								
	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	init. reset (all low)
	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	init. / prepare routine
	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	
0	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	
1	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	0	
2	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	1	
3	0	0	1	1	1	0	0	0	1	0	0	0	0	0	1	1	
4	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	
5	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	
6	1	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	
7	1	0	0	0	0	0	1	1	0	0	1	1	1	0	0	0	

control band

800 kHz

phase generation 100 MHz

trip condition positive

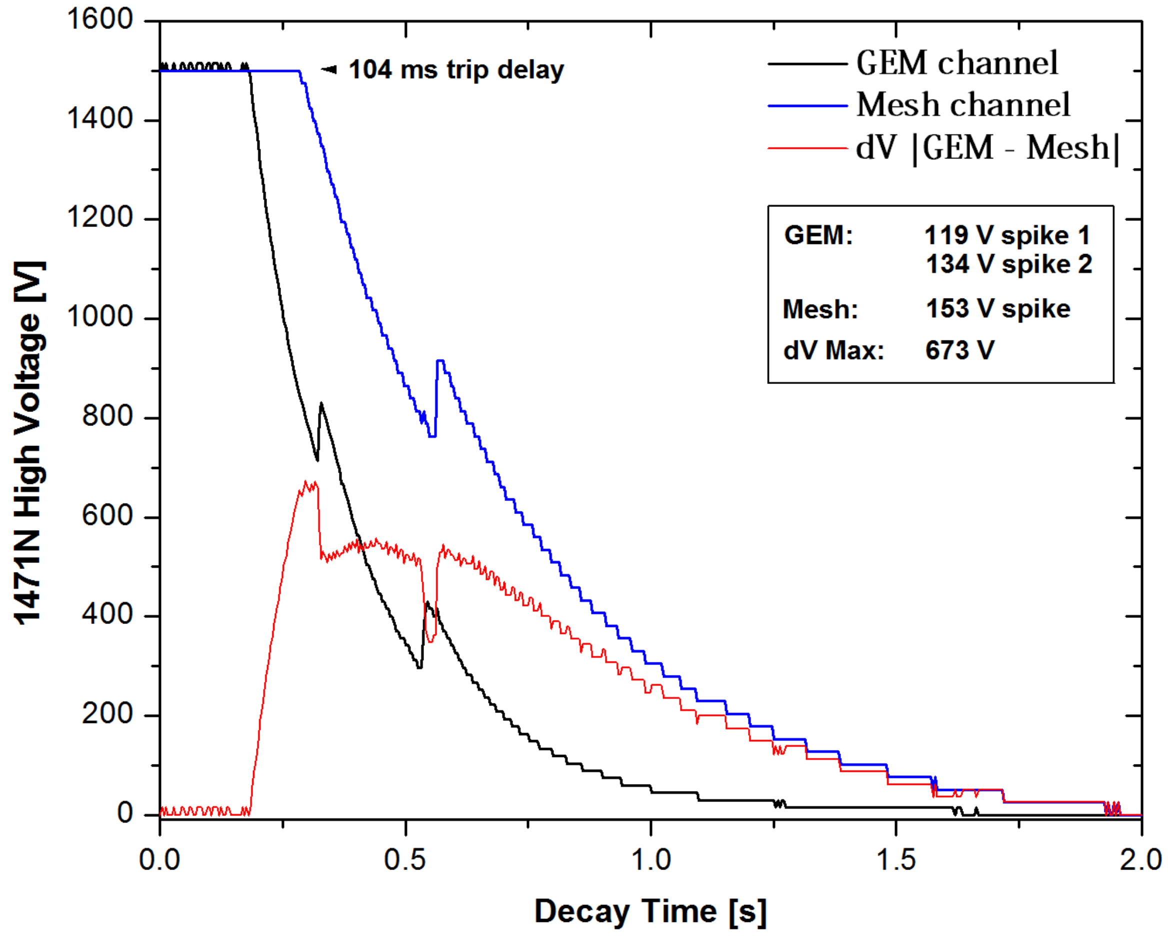
TRIP DETECTION AND PROTECTION

The Zener diodes of the divider ensures that both GEM and Mesh channels trip together, once the Zener breakdown potential is surpassed.

- There is an evident **time delay** between the trips of GEM and Mesh channel (~ 80 – 200 ms), before enough current is drawn trough Zener to surpass trip threshold of Mesh PS and bring it down.

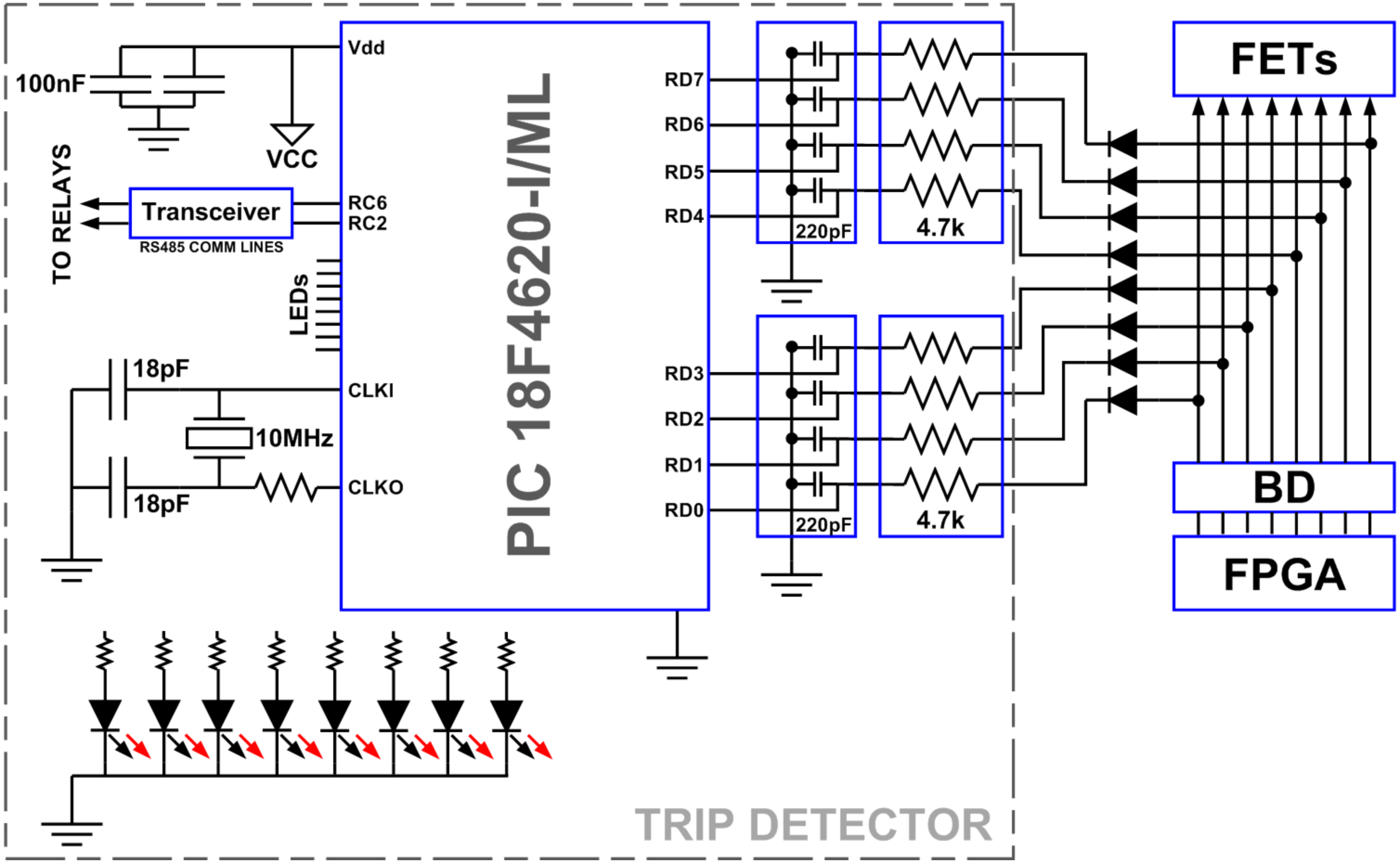
→ Result: Mesh-to-Top-GEM sparking

Trip Decays have to be synchronized with additional protection boards.



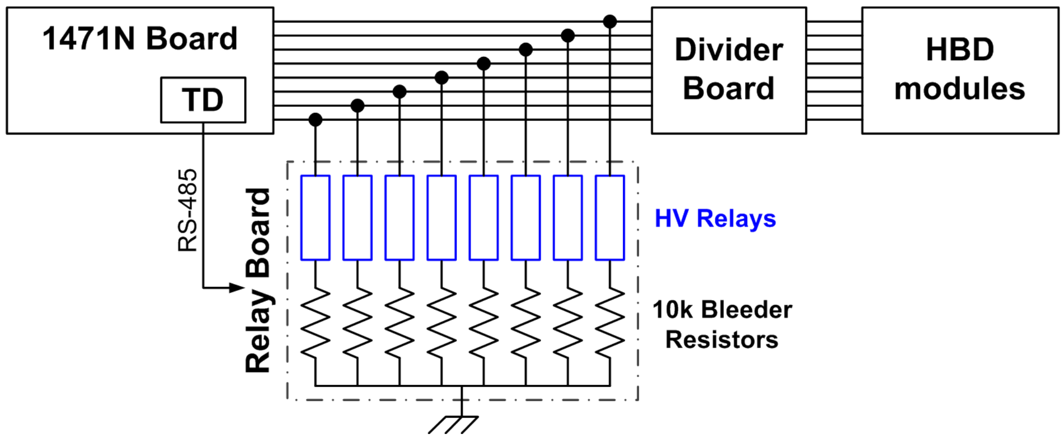
TRIP DETECTION AND PROTECTION

- A **Trip Detector board measures the FET phases** for HV generation from the FPGA and senses the phase loss for a particular channel and triggers external Relay board.

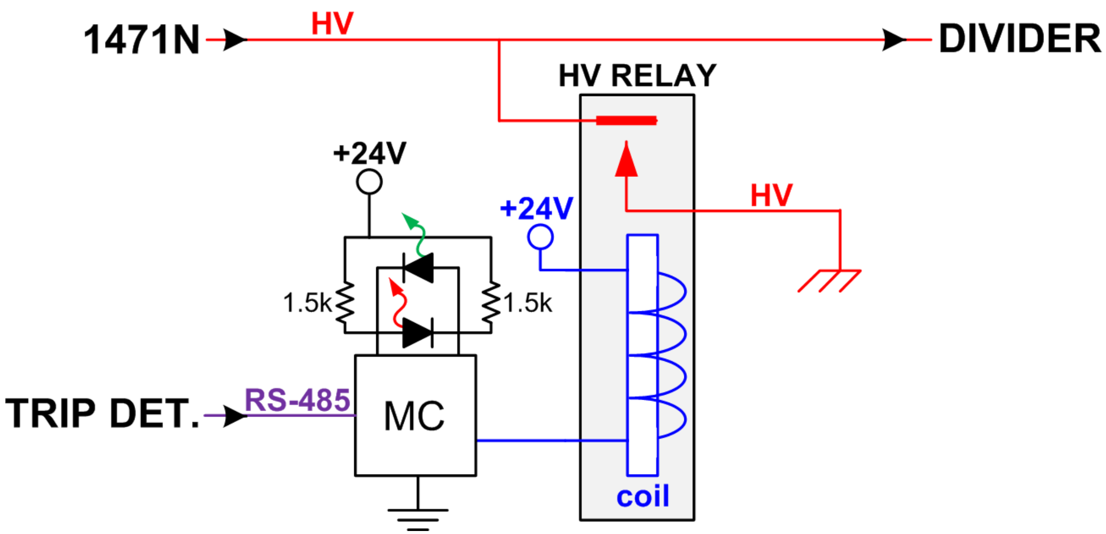


TRIP DETECTION AND PROTECTION

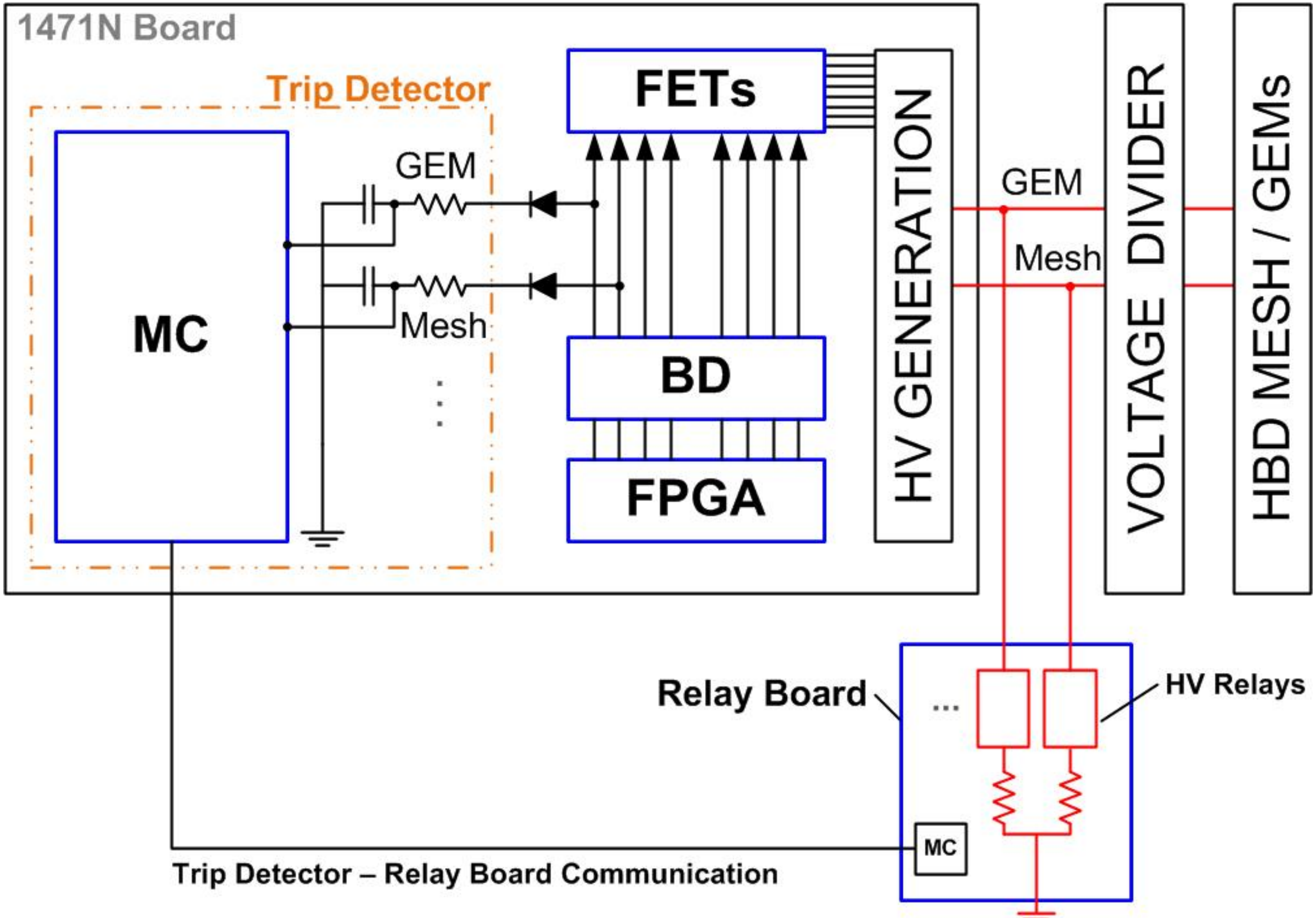
- The Trip Detector triggers via RS-485 an external Relay Board to **discharge stored energy** in HBD module and 1471N output caps of the particular channel.



- The gate to chassis ground is closed by using a coil's field, which is activated through a microcontroller instructed by the Trip Detector.

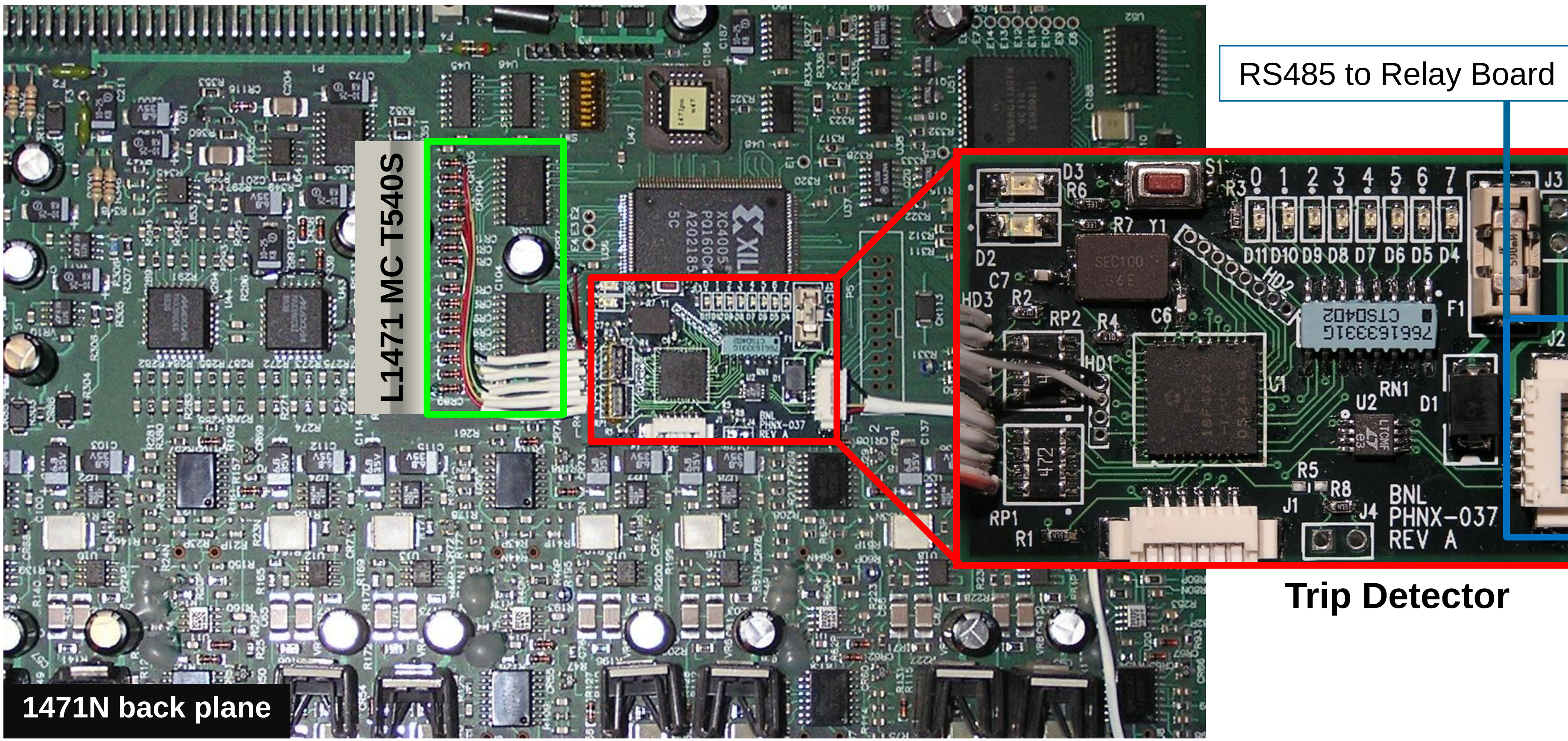


TRIP DETECTION AND PROTECTION



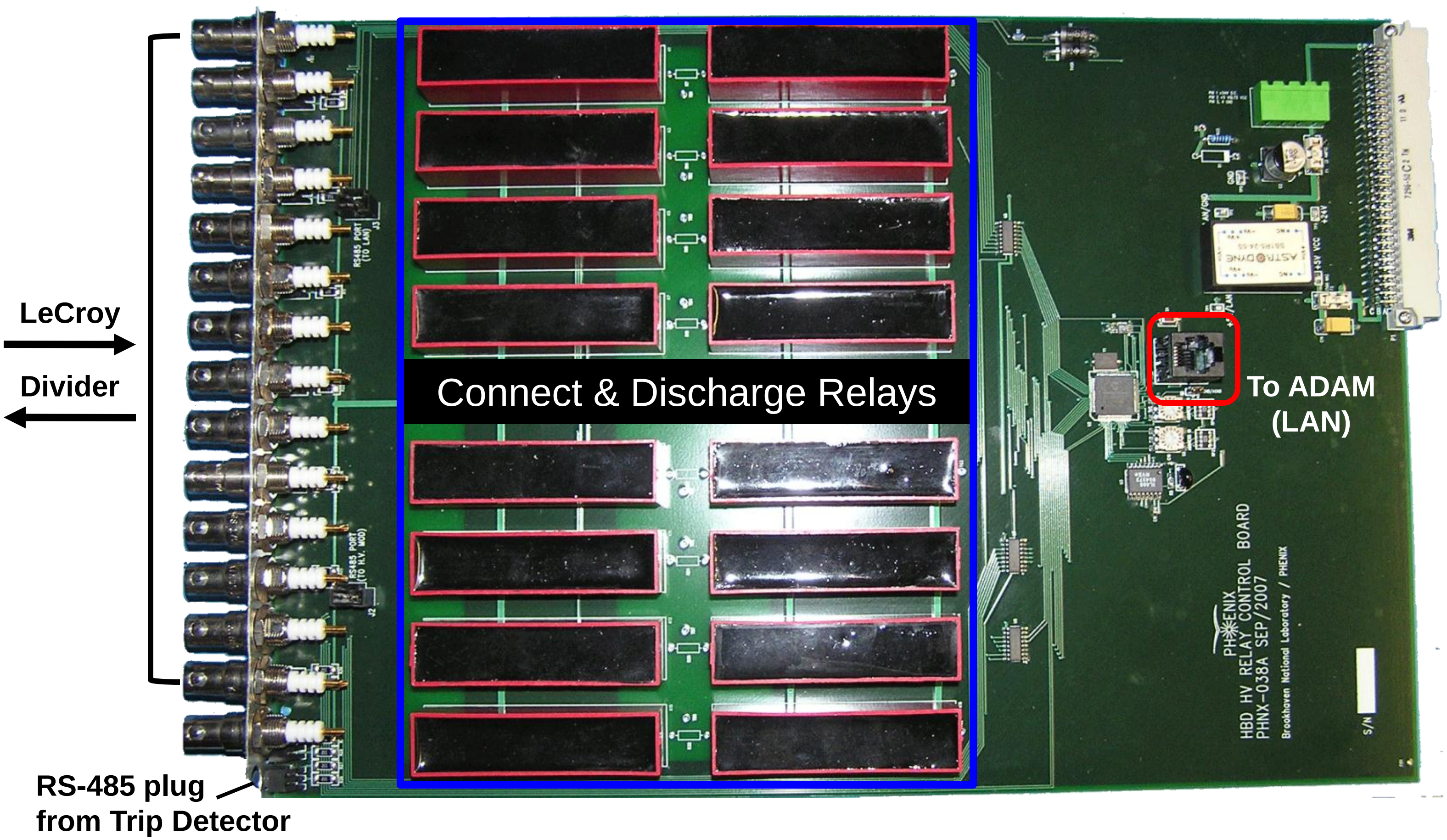
TRIP DETECTION AND PROTECTION

- The **Trip Detector board was glued on top of the FPGA chip** and connected to the output of the buffer/line driver via on-board soldered diodes
- DC supply and grounding is realized through the support lines on the 1471N board



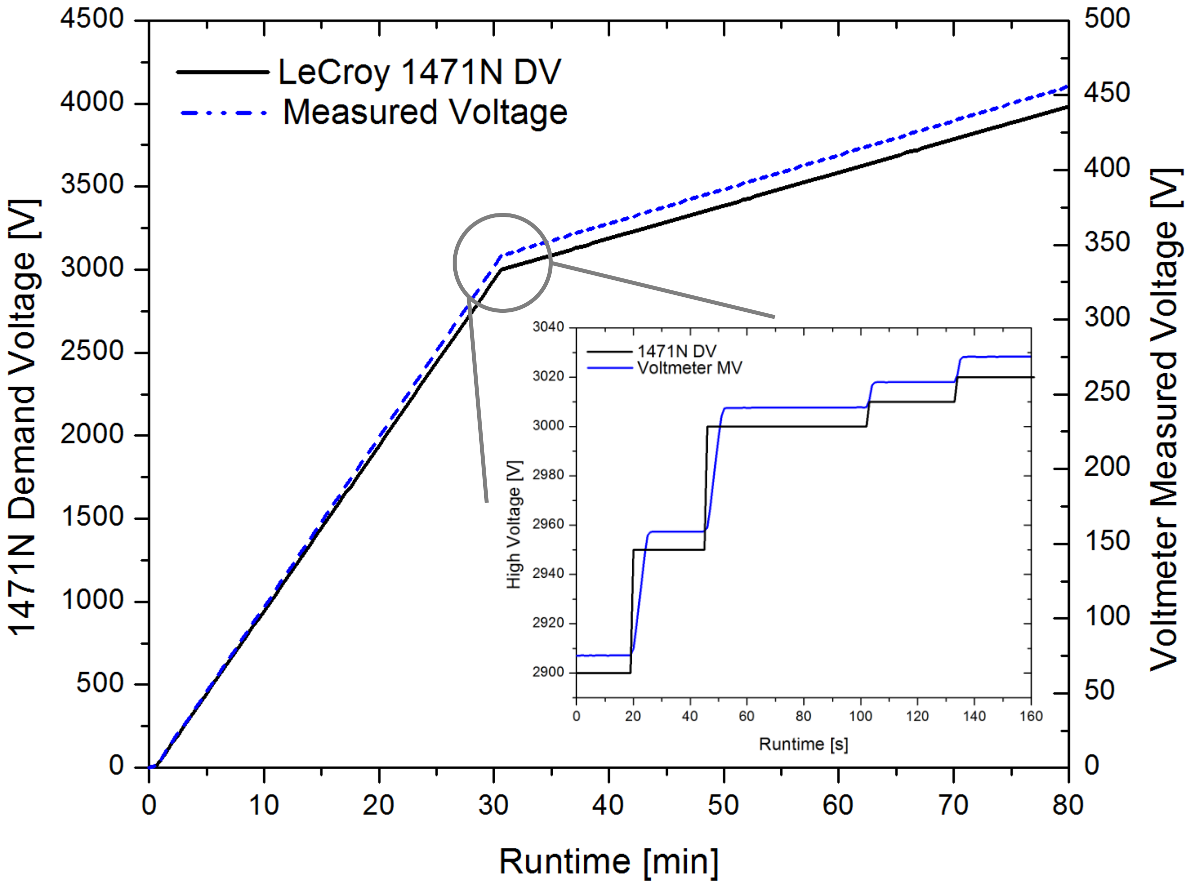
TRIP DETECTION AND PROTECTION

- The Relay Boards are powered independently through a 5V and 24V DC supply
- Connect relays have not been used for Run-9 and Run-10; not necessary.



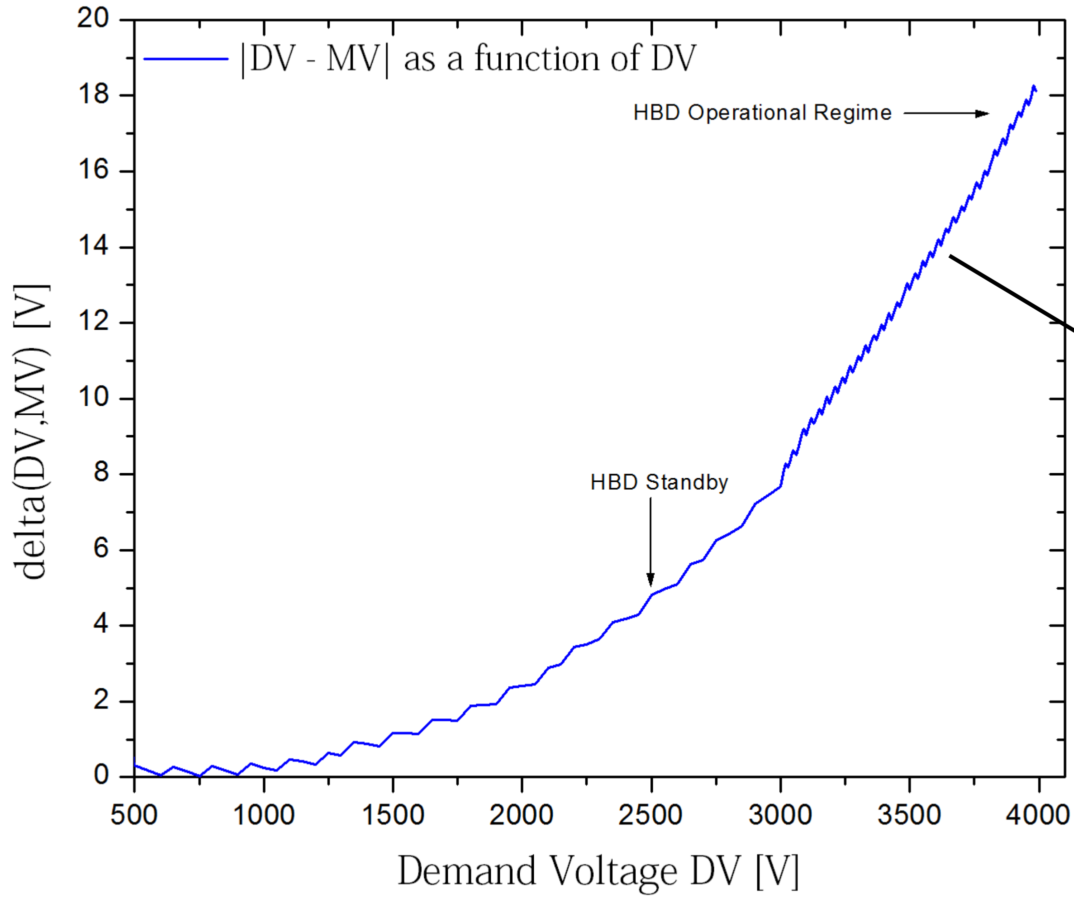
OFFLINE HV CALIBRATION

- The **calibration of the true 1471N output voltage** was performed by utilizing the original Run-9/10 divider board with precisely measured resistors installed.
- HVC client performed the calibration automatically and ramped each channel up to 4kV.



OFFLINE HV CALIBRATION

- When the manufacturer of the 1471N board did not load the correct calibration coefficients for the 3rd order polynomial for its HV output, one can see an increasing delta between demand voltage DV and measured voltage MV



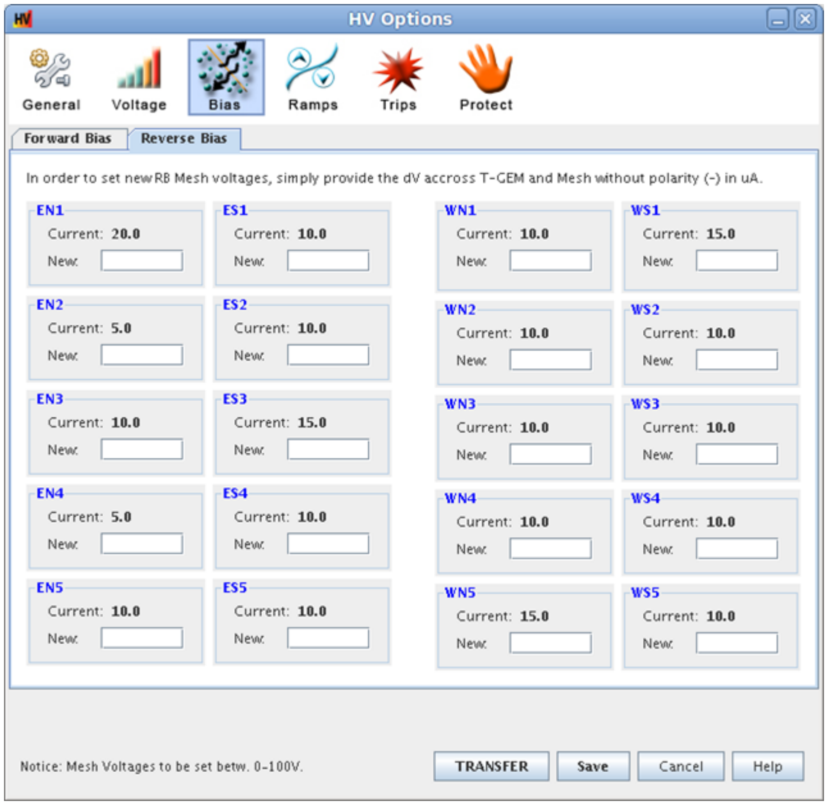
Most of the Run-9 1471N module had this issue. Therefore, HVC uses calibration functions to compensate for these offsets

LINEAR
(good for HBD at operational voltages)

HVC SOFTWARE SUITE

Full control over all system parameters is given by a **large software suite** written in Java and C++ with over 500k lines of code. An extensive set of GUIs are provided:

Main Control Panel



Options Panel for Expert configurations.

HVC SOFTWARE SUITE

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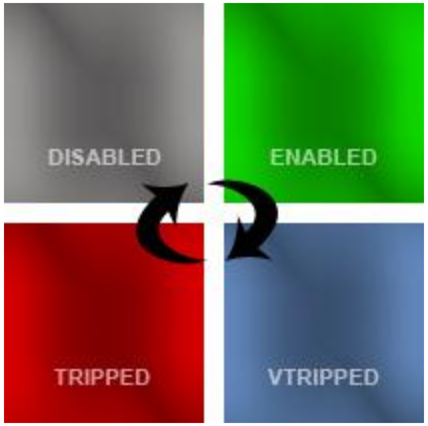


Module Status Deviation for Shift Crews.

HBD Module Control for PHENIX Shift Crews.

HVC SOFTWARE SUITE

Full control over all system parameters is given by a **large software suite** written in Java and C++ with over 500k lines of code. An extensive set of GUIs are provided:

HBD HV Surveillance Panel

HBD | HV Channel Listing

Chn	DV	MV	MC	MPC	MC:EC	TP	DZ_l	DZ_h	RUP	RDN	TC	TPC	M:DV	M:MV	M:MC	dV	STATUS	TRIP
EN1	-2500.0	-2500.4	-89.605	-89.635	99.969	20.0	-71.706	-107.559	25	25	-109.619	-200.0	-2421.0	-2422.2	-0.054	20.0 RB	enabled	OK
EN2	-2500.0	-2500.4	-90.468	-90.464	101.319	20.0	-71.432	-107.149	25	25	-109.276	-200.0	-2436.3	-2436.8	0.0040	5.0 RB	enabled	OK
EN3	-2500.0	-2499.8	-89.082	-87.221	99.919	20.0	-71.324	-106.985	25	25	-109.162	-200.0	-2430.4	-2431.0	-0.013	10.0 RB	enabled	OK
EN4	-2500.0	-2500.1	-88.856	-88.858	99.067	20.0	-71.754	-107.631	25	25	-109.689	-200.0	-2435.0	-2436.5	-0.052	5.0 RB	enabled	OK
EN5	-2500.0	-2500.0	-89.528	-89.517	99.874	1.5	-88.296	-90.986	25	25	-109.641	-200.0	-2430.3	-2431.1	0.011	10.0 RB	enabled	OK
ES1	0.0	0.2	-0.015	-0.369	-210....	-5.75	0.0060	0.0070	25	25	-109.012	-200.0	0.0	0.8	-0.0020	0.0 Z	disabled	OK
ES2	-2500.0	-2499.8	-89.111	-89.215	99.934	1.57	-87.77	-90.57	25	25	-109.177	-200.0	-2430.5	-2430.7	0.029	10.0 RB	enabled	OK
ES3	-2500.0	-2499.8	-89.695	-89.745	99.928	1.4	-88.503	-91.016	25	25	-109.767	-200.0	-2425.2	-2426.2	0.048	15.0 RB	enabled	OK
ES4	-2500.0	-2500.7	-89.522	-89.531	99.893	1.5	-88.274	-90.962	25	25	-109.593	-200.0	-2430.9	-2433.5	-0.027	10.0 RB	enabled	OK
ES5	-2500.0	-2500.9	-89.326	-89.301	99.827	1.47	-88.165	-90.796	25	25	-109.449	-200.0	-2430.7	-2431.3	0.0070	10.0 RB	enabled	OK
WN1	-2500.0	-2500.2	-89.623	-89.594	99.94	1.49	-88.341	-91.013	25	25	-109.67	-200.0	-2430.9	-2430.7	-0.265	10.0 RB	enabled	OK
WN2	-2500.0	-2499.8	-89.551	-89.551	99.954	1.49	-88.257	-90.927	25	25	-109.599	-200.0	-2430.7	-2430.8	-0.283	10.0 RB	enabled	OK
WN3	-2500.0	-2500.3	-89.615	-89.65	99.805	1.51	-88.434	-91.146	25	25	-109.78	-200.0	-2430.4	-2430.2	-0.296	10.0 RB	enabled	OK
WN4	-2500.0	-2500.3	-89.436	-89.459	99.824	1.5	-88.25	-90.938	25	25	-109.583	-200.0	-2430.5	-2430.1	-0.219	10.0 RB	enabled	OK
WN5	-2500.0	-2500.4	-89.615	-89.651	99.88	1.45	-88.422	-91.024	25	25	-109.709	-200.0	-2425.0	-2425.8	0.049	15.0 RB	enabled	OK
WS1	-2500.0	-2498.9	-89.525	-89.523	100.058	1.61	-88.033	-90.914	25	25	-109.513	-200.0	-2425.9	-2425.1	0.094	15.0 RB	enabled	OK
WS2	-2500.0	-2499.5	-89.713	-89.691	100.039	1.6	-88.243	-91.113	25	25	-109.696	-200.0	-2431.0	-2431.0	0.024	10.0 RB	enabled	OK
WS3	-2500.0	-2501.7	-89.696	-89.716	99.724	1.4	-88.685	-91.203	25	25	-109.883	-200.0	-2430.1	-2429.7	0.051	10.0 RB	enabled	OK
WS4	-2500.0	-2501.9	-89.816	-89.778	99.835	1.4	-88.705	-91.224	25	25	-109.896	-200.0	-2430.3	-2431.0	0.151	10.0 RB	enabled	OK
WS5	-2500.0	-2500.6	-89.535	-89.551	99.868	1.47	-88.335	-90.971	25	25	-109.631	-200.0	-2430.3	-2431.2	-0.0040	10.0 RB	enabled	OK

HVC SOFTWARE SUITE

A number of important features were included in the software suite, such as:

- HVC is able to run an **automated *in situ* online calibration procedure** with the actual divider chain of each GEM in place. Calibration functions are generated for the system's Control Monitor. As a result, **HV precision better than ~ 0.02% at 4 kV**.

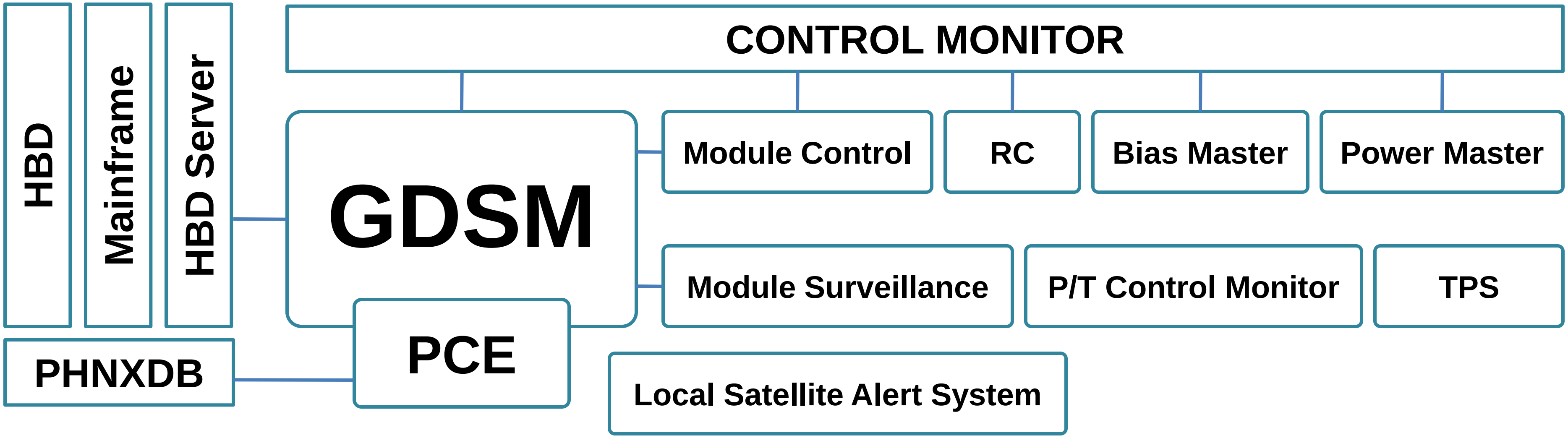
- This precision enables HVC's **Trip Protection System** to detect any **additional current draw** above the nominally expected at the level of **~ 100 nA**, which would be an indication of a partial or complete short in one of the GEMs and cause the system to initiate a "**virtual trip**" by safely lowering the applied GEM/Mesh HV and inform the operator that intervention was required.

- The **virtual trip thresholds** were set in the order of **~ 1.5%** of expected standing current (~2 μA) while the hardware trip thresholds were set to 20 μA (GEM), 5 μA (Mesh), which means that **hardware trips** were only fired for **short-time peaking current** (e.g. sparks).

- The **P/T** is permanently measured and **divided into 5 distinct bins** (~ 1%). The number of bins results from typical P/T fluctuations during RHIC runtimes and the **intended gain variation of +/- 10%**. Once a certain bin boundary is passed, a **custom set of voltages** is applied to **compensate** for the expected resulting **gain variation**.

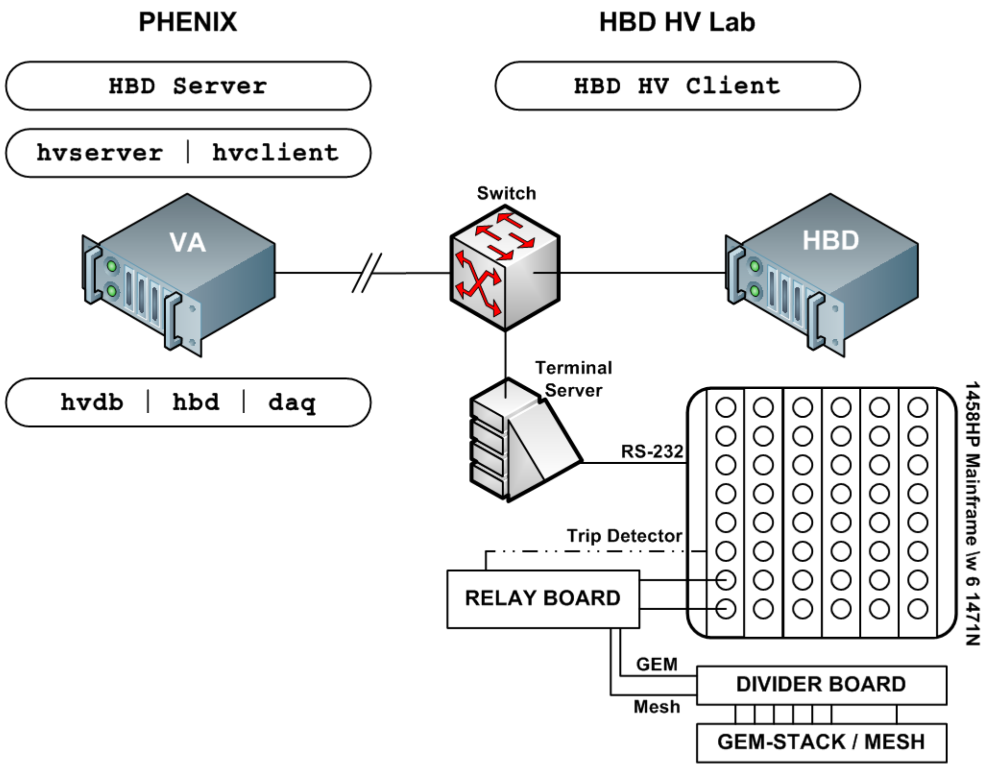
HVC Software Suite: Subsystems

- HVC introduces 12 concurrently operating control subsystems, which respond to measurements fed back from the mainframe within τ_S and are triggered by the Control Monitor based on control policies and online references
- The Global Detector Status Module (**GDSM**) is responsible for receiving and distributing data from the HV mainframe within the HVC client. Access to the PHENIX database servers with previously collected data is controlled by the ParaConfig Exchange Module **(PCE**). Module Control allows to enable, disable and recover GEM modules from a trip. Ramp Control (**RC**) represents the only subsystem with the ability to modify voltage settings of the detector. The **Bias and Power Master** provide access to RB/FB settings and Mainframe Power, respectively. The subsystems, Module Surveillance, P/T Control Monitor and Trip Protect System (**TPS**) are served with data updates from GDSM. The **Alert System** permits the communication to external devices to send HVC alerts.



TESTING AND PHENIX INSTALLATION

- The development, testing and study of the HVC system was possible through the **HBD Simulation Project**, which simulated the HBD with actual PHENIX control environment



TESTING AND PHENIX INSTALLATION

- In 2008, the **HVC completed an intense 6-months crash testing period**, where all <u>mathematically possible scenarios</u> were simulated and the system's response analyzed.

- ✓ IBM Blue Gene
- ✓ 103.22 Teraflops
- ✓ 18-rack config
- ✓ 18432 nodes

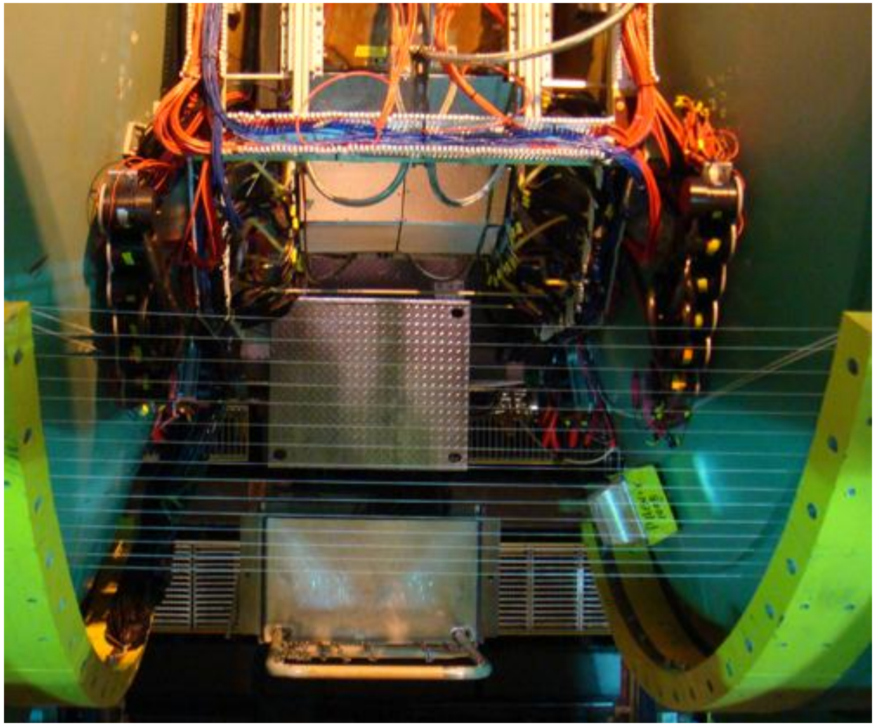
TESTING AND PHENIX INSTALLATION

INSTALLATION OF HVC IN PHENIX

- ALL 40 channels (GEMs & Mesh chn.) have been ramped up and measured via Fluke by controlling them one by one through the **HV Control System**, which was run on a laptop connected to the PHENIX wireless.
  - ✓ Installation chn. check procedure automatically ramped & disabled chn. by chn. after measurement.
  - ✓ The channel check has been completely successful!

Channel Check on Bridge

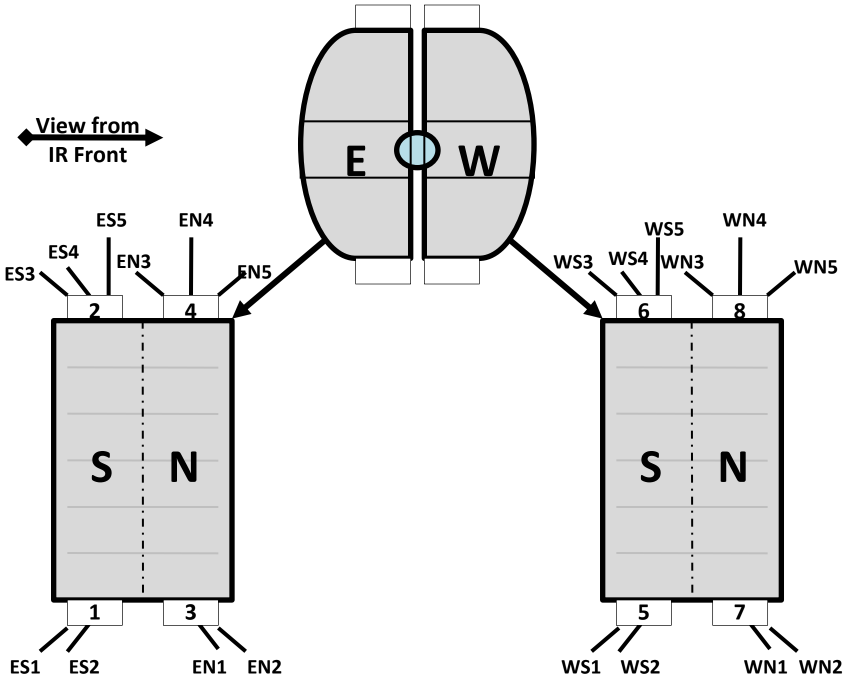
View of HBD from Bridge

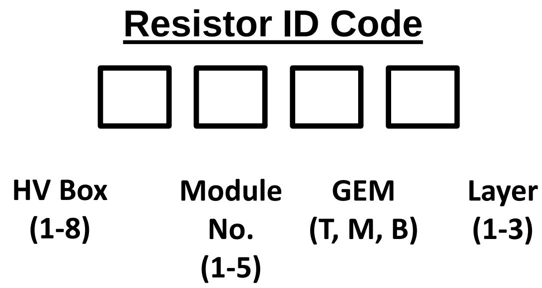


TESTING AND PHENIX INSTALLATION

INSTALLATION OF HVC IN PHENIX

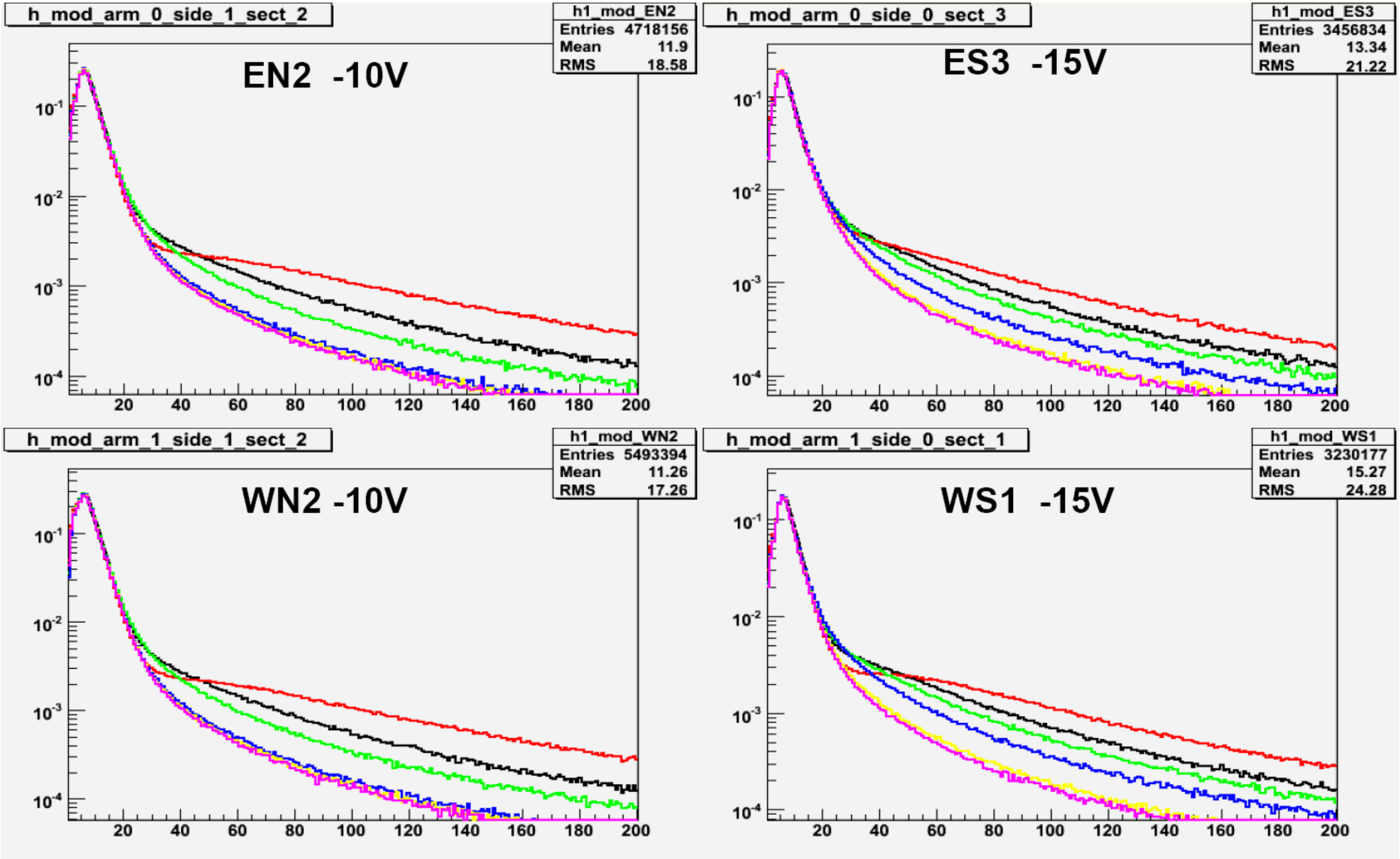
- All resistors installed in the 8 divider boards have been precisely measured and entered into the hvdb database on the PHENIX database server
- Each resistor was labeled with a unique index (allows tracking of changes)
- HVC Server and Client installed in PHENIX Control room by removing the tunnel used by the HBD Simulation Project; the switch from laboratory to PHENIX completed in ms.





COMMISSIONING: dV SCANS

dV Scan results: +30V 0V -5V -10V -15V -20V



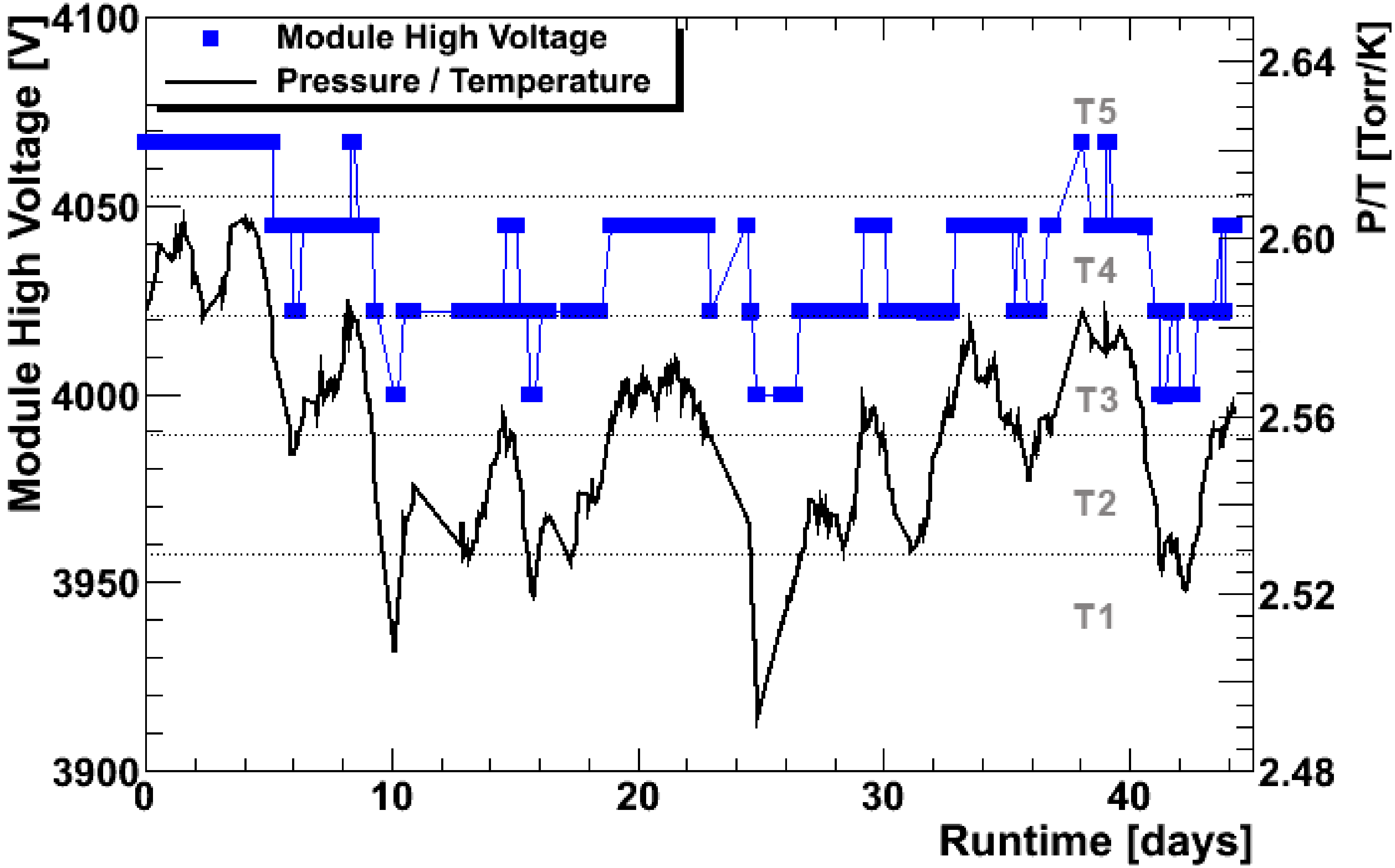
PRODUCTION PERFORMANCE

The **HVC has been successfully governing the HBD** throughout the **p+p Run-9** and **Au+Au Run-10** at RHIC and has achieved all performance goals beyond the expected:

- ✓ System shown to be **very robust**, as during the entire runtime, neither HBD server nor HVC clients did crash once.
- ✓ **HVC adapted dynamically** to all GEM modules and applied custom control functions based on their individual condition (e.g. partial shorts).
- ✓ **Trip decays** of 1471N GEM/Mesh trips were **synchronized** by Trip Protection boards. However, mostly Virtual Trips were initiated by the system after detection of partial or complete shorts.
- ✓ **Online backup of parameter data** provided crucial resource for HBD experts to **analyze and diagnose the condition** of GEMs offline, especially after a Virtual Trip.
- ✓ Run-10: only **2** modules showed two **complete shorts**, **2** showed **partial shorts**, all of which were compensated for by simply changing one external resistor.
- ✓ **P/T fluctuations between ~ 2.49 – 2.60 Torr/K** during Run-10. Due to the exponential correlation with HBD gain, dramatic gain instabilities **would** have been the consequence..

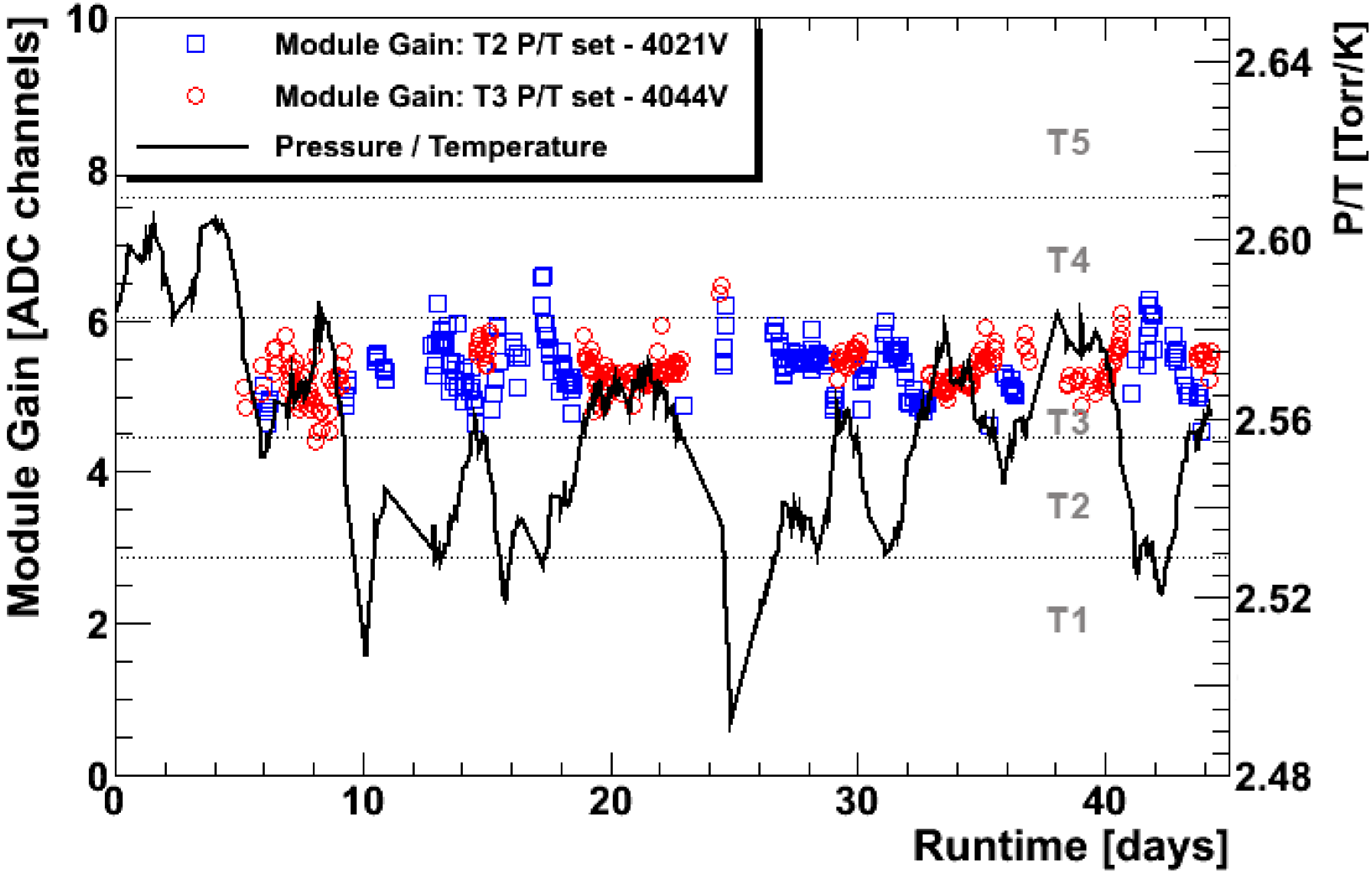
PRODUCTION PERFORMANCE

✓ **HVC applied a custom set for each P/T bin (T1 – T5).**



PRODUCTION PERFORMANCE

✓ **HVC was able to stabilize the gain within the indented operating range of +/- 10%.**

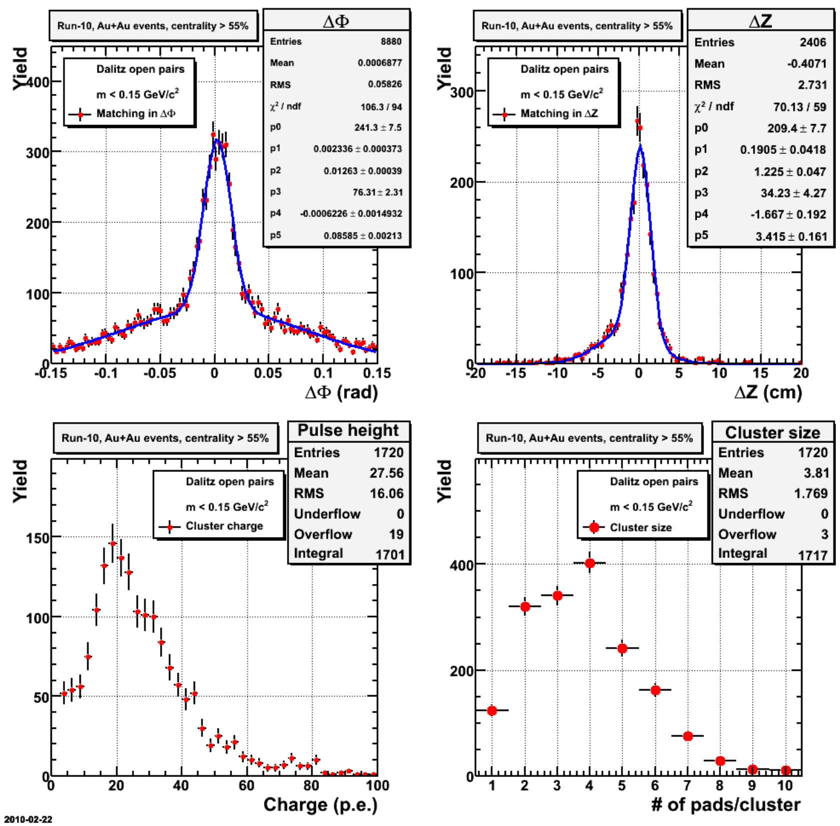


PRODUCTION PERFORMANCE

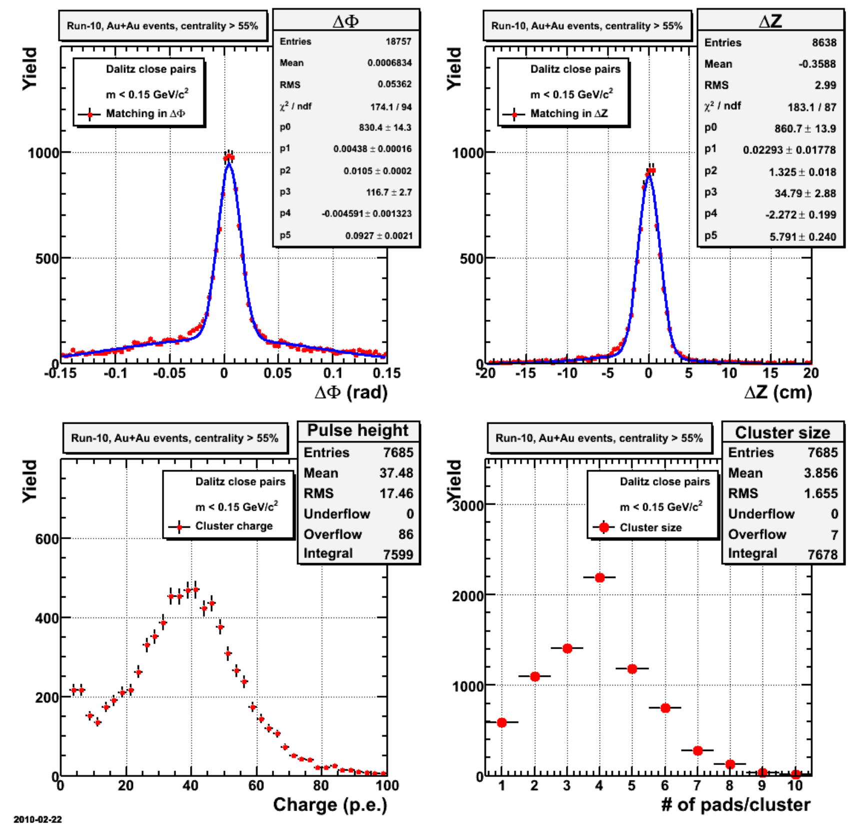
The HVC allowed the HBD in Run-9 and Run-10 to achieve its performance goals.

- HBD has shown to be capable of separating single (20 pe) from double hits (40 pe)

Single Electron Response



Double Hit Response



SUMMARY

The HVC system allowed **optimal control over the HBD** and has proven to optimize the detector's performance, while providing protection against damage from possible discharges.

- ✓ Online calibration method allowed HV output precision of less than **~ 0.02% at 4 kV** and provided the flexibility to **set any drift field**, enabling the **detection of single electrons** but the **rejection of MIPs** with an efficiency **≥ 90%**.
- ✓ Implementation of add. hardware trip protection, such as Zener diodes, 1471N phase detection and discharge relay boards, **synchronized trip decay** of Mesh/GEM channels and **prevented any discharge damages on GEM foils** at trip conditions.
- ✓ Software Suite has proven its **robustness, flexibility and efficiency** utilizing grid- and multi-core resources with convenient local/remote client access.
- ✓ HVC represents **first intelligent detector control system** with a **real-time TDC** successfully implemented and the capability to learn from dynamic control subjects.
- ✓ HPC-driven design of **HVC allows to extend its application** to any other detector system requiring dynamics, high-precision and stability.

The dataset provided by the HBD allows PHENIX now to efficiently study the LOW-MASS DILEPTON CONTINUUM. As we know from Run-7, this was in part due to the direct IMPACT of the implementation of ADAPTIVE HV CONTROL.

THE END.

THANK YOU.

BACKUP SECTION

BACKUP

THE DILEPTON CHALLENGE AT RHIC

WHY IS IT SO HARD??

✓ **Weak source of e^-e^+-pairs to detect:**

Hadron decays
[m>200 MeV/c² pT> 200 MeV/c]
~ 4 x 10^{-6} / π^0

✓ **Presence of many charged particles:**

Central Au-Au Collisions
$dN_{ch}/dy \approx 700$

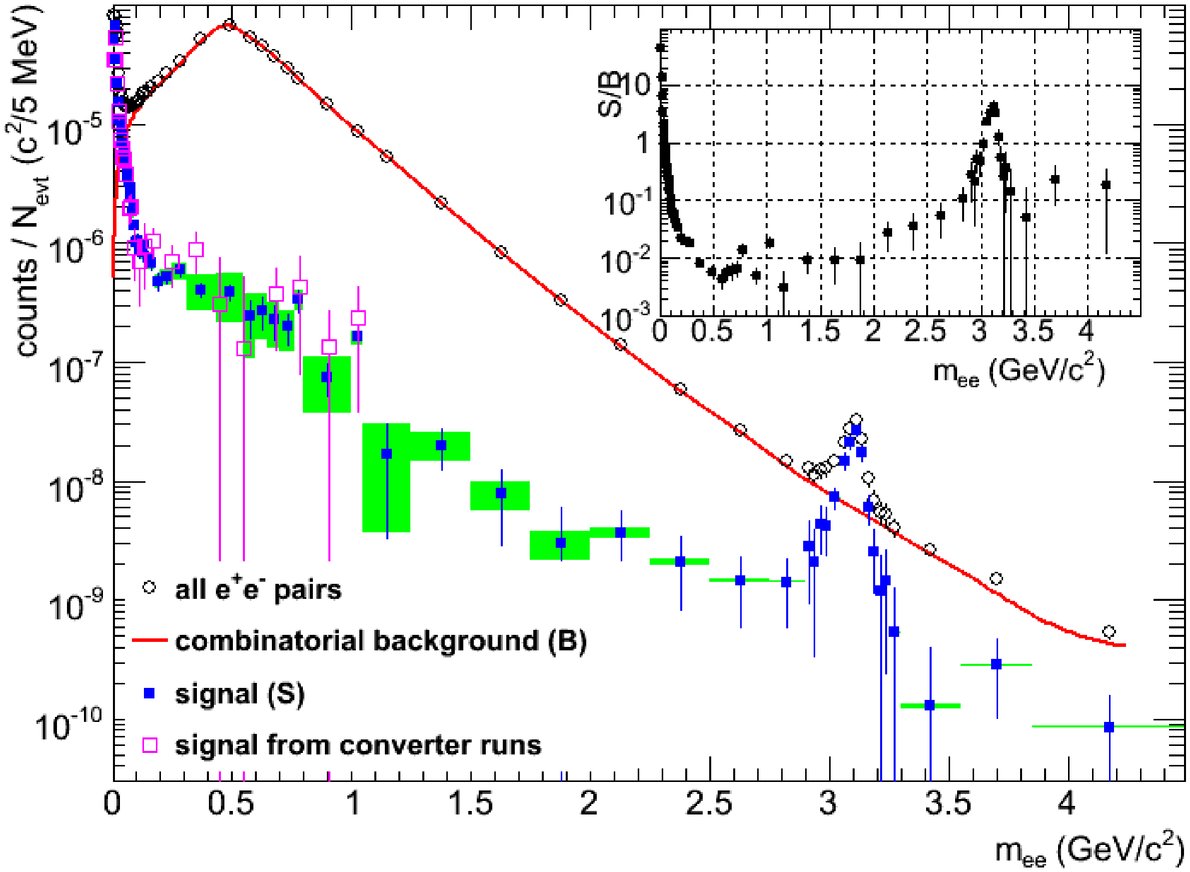
✓ **Presence of several pairs from…**

π^0 Dalitz decays
~ 10^{-2} / π^0
γ conversions
~ 10^{-2} / π^0

→ **Enormous combinatorial background ∝ $(dN_{ch}/dy)^2$**

UNCORRECTED MASS SPECTRA

Mass distribution of e^+e^--pairs, normalized mixed event background (B), signal yield (S) [subtracting mixed event BG, cross and conversion pairs]



Check of BG subtraction:

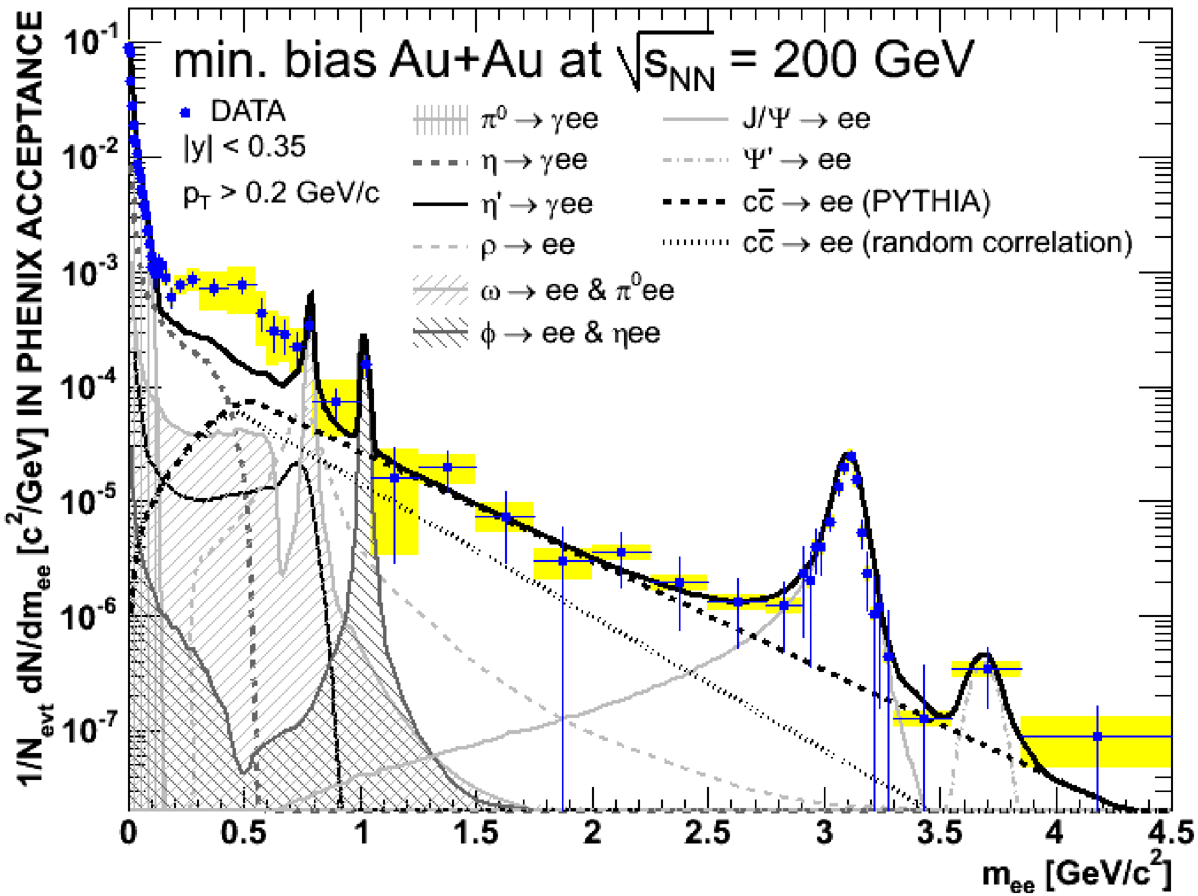
- ✓ Increase number of photon conversions (Phys. Rev. Lett. 98, 172301 ‘07) by wrapping add. Material around beam pipe (5 x 107 events)
- ✓ Comb. BG & cross pair contribution larger by factor of ~ 2.5
- ✓ Good agreement with stat. error

Background subtraction
$\sigma_S/S = \sigma_{BG}/BG \times BG/S$

Cross pair subtraction
9% S < 600 MeV/c^2

COCKTAIL COMPARISON

Comparison of invariant e^+e^--pair yield to expected yield from meson decays and correlated decays of charmed mesons.

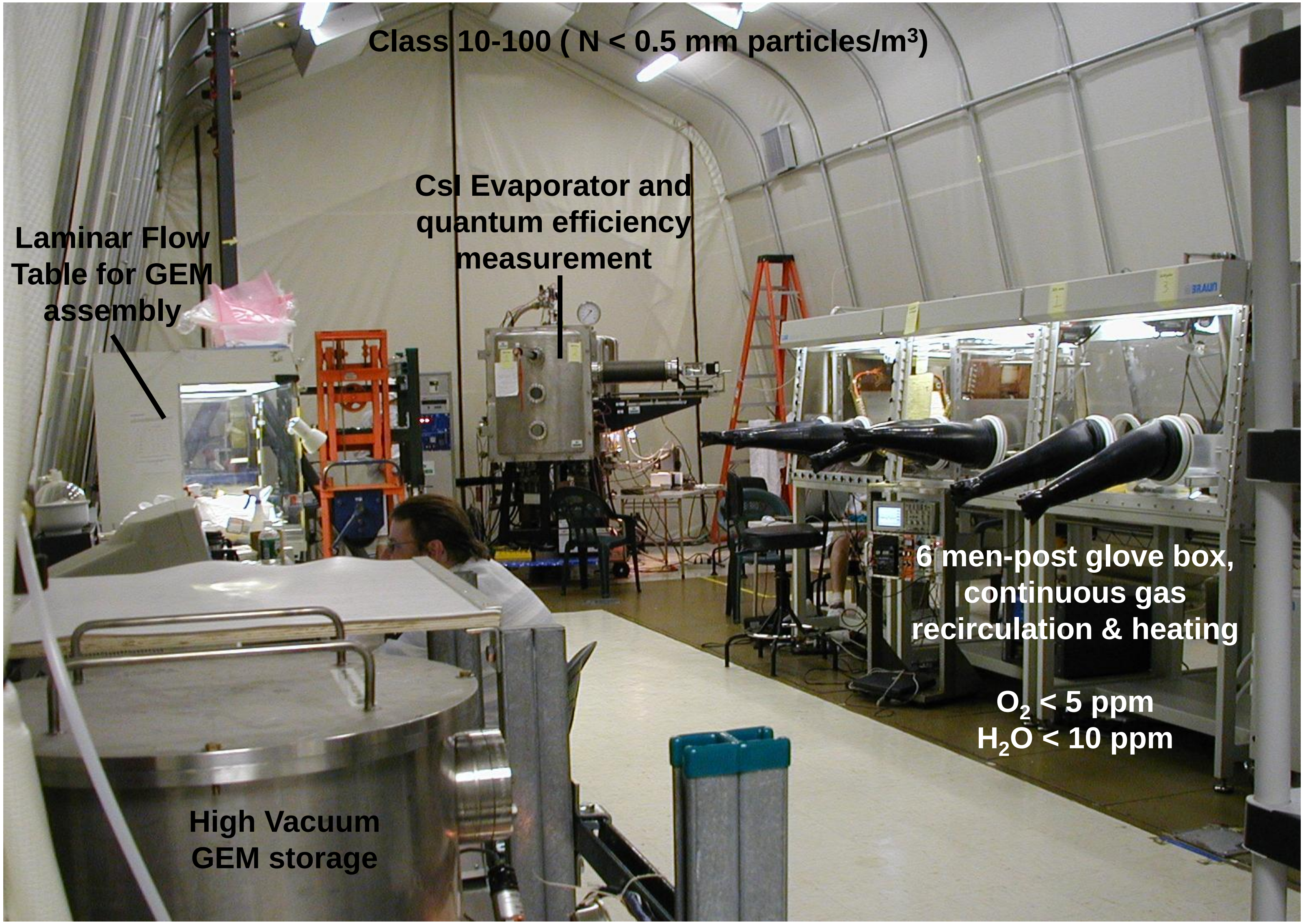


Focus on low-mass continuum:

- Enhancement 150 – 750 MeV/c^2 by factor of 3.4 ± 0.2 (stat.) ± 1.3 (syst.) ± 0.7 (model)

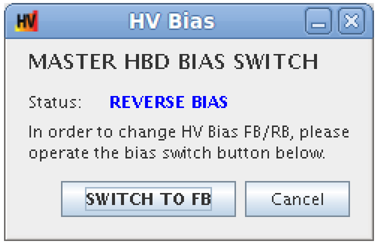
- Cocktail from hadronic sources
- Charm from...
  - ✓ PYTHIA
  - ✓ Single electron non photonic spectrum w/o angular correlations

Clean HBD Tent in Stony Brook



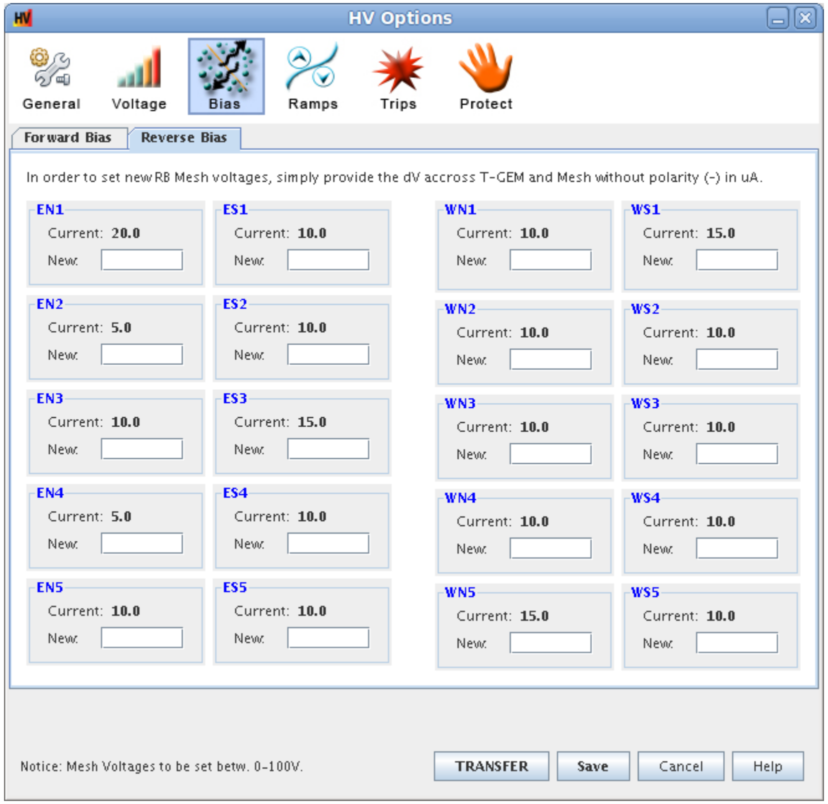
dV Scans and Module Bias

- In order to find the optimal drift field to achieve a maximal suppression of the MIP signals, one can use HVC to perform a so-called dV Scan.



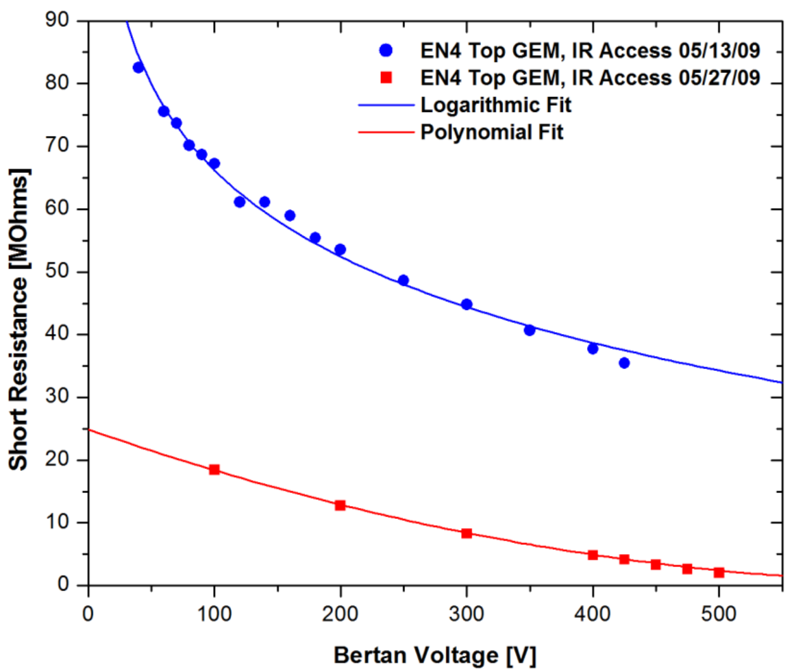
dV Scan procedure:

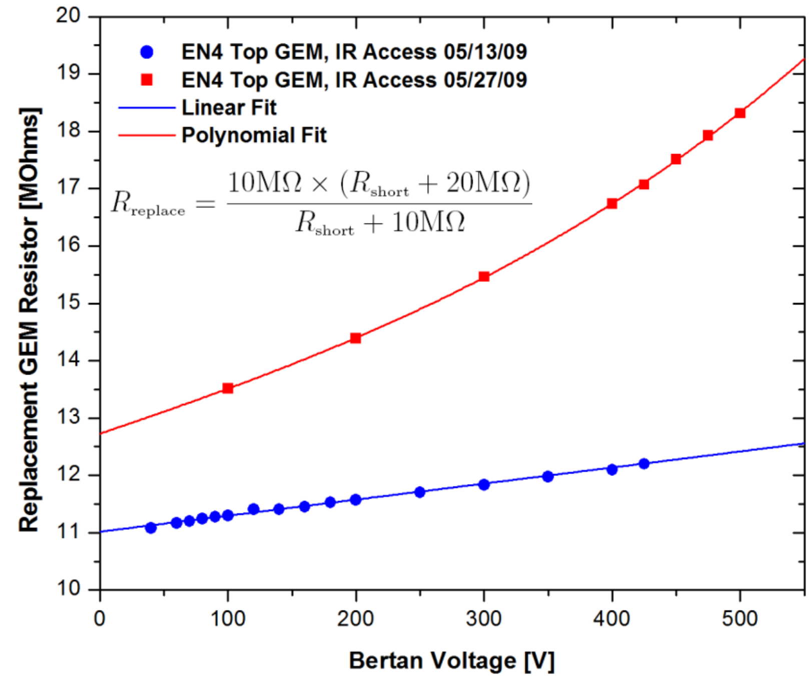
1. Set detector to Reverse Bias mode using the *Bias Master* panel
2. Use Options Tool to set RB values for all modules to e.g 0V
3. Activate Ramp Control to upload the bias voltages to the mainframe
4. Take a run with the PHENIX DAQ system and collect data for e.g. 5M events
5. After repeating steps 1 – 4 for multiple bias voltages, typically from 0V to 25V in 5V steps, analyze collected data and produce pulse height spectra to find maximal MIP suppression



RESISTOR EXCHANGE AND BERTAN TEST

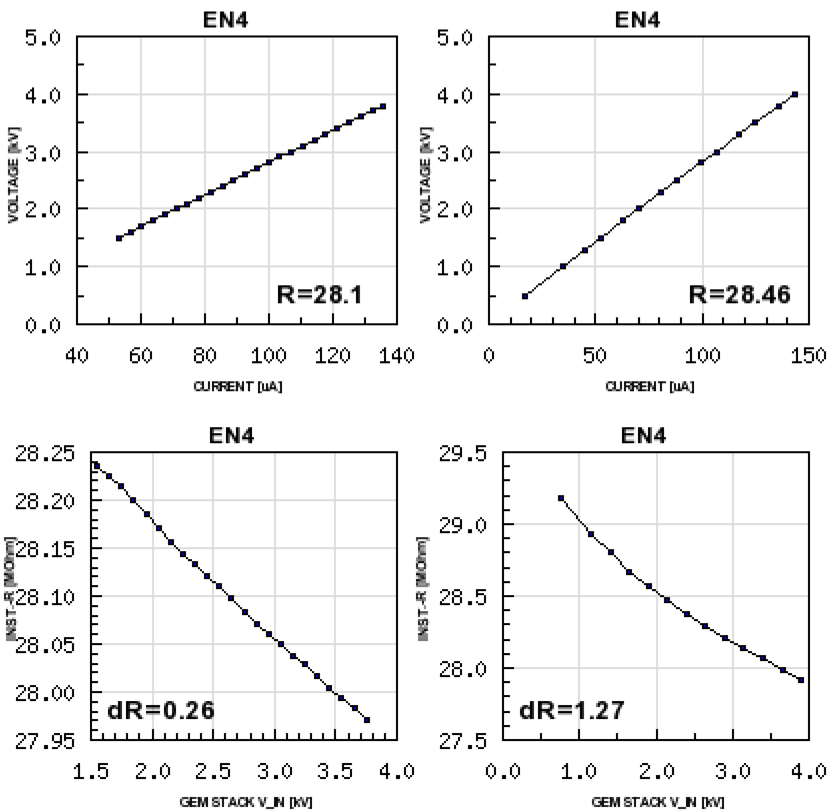
- When the Trip Protect System reports a new partial or dead short of a particular module, its gain will significantly drop and an IR becomes necessary to modify the GEM resistor
- Therefore, one uses a Bertan power supply and applies voltage to each GEM of the particular stack up to 500V and notes the measured current
- One can then use these measurements to find the optimal replacement resistor for the 10M GEM resistor:

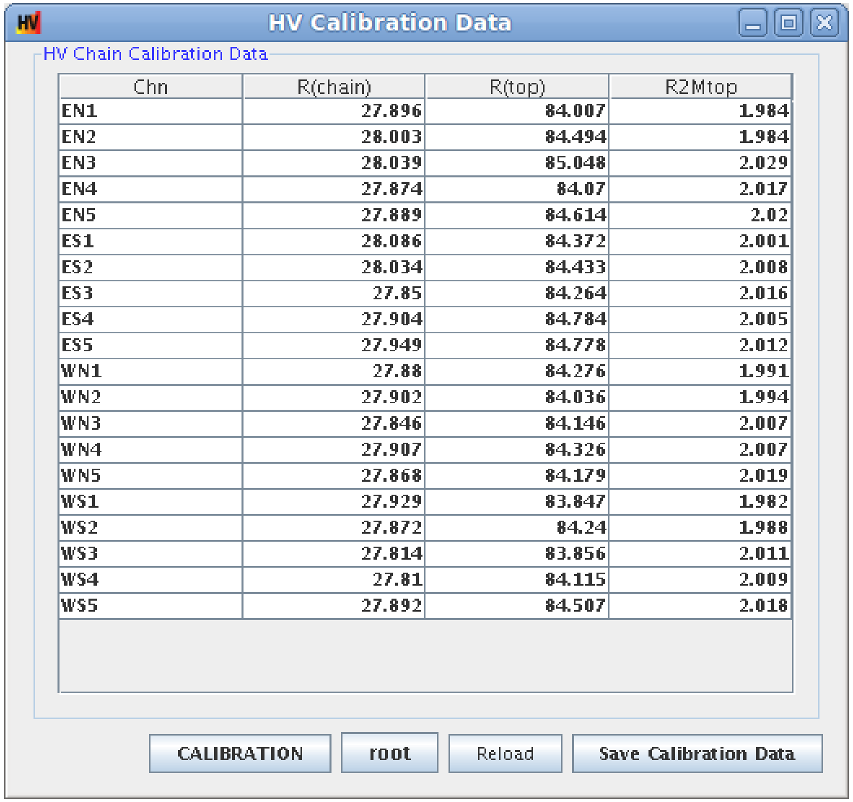




HV ONLINE MODULE CALIBRATION

- After resistor modifications or changes to the 1471N modules, one can use HVC to run a calibration for the Trip Protect System
- The system ramps the detector along a configured path up to 4kV, collects the data and generates calibration coefficients for the expected current at any given voltage





Chn	R(chain)	R(top)	R2Mtop
EN1	27.896	84.007	1.984
EN2	28.003	84.494	1.984
EN3	28.039	85.048	2.029
EN4	27.874	84.07	2.017
EN5	27.889	84.614	2.02
ES1	28.086	84.372	2.001
ES2	28.034	84.433	2.008
ES3	27.85	84.264	2.016
ES4	27.904	84.784	2.005
ES5	27.949	84.778	2.012
WN1	27.88	84.276	1.991
WN2	27.902	84.036	1.994
WN3	27.846	84.146	2.007
WN4	27.907	84.326	2.007
WN5	27.868	84.179	2.019
WS1	27.929	83.847	1.982
WS2	27.872	84.24	1.988
WS3	27.814	83.856	2.011
WS4	27.81	84.115	2.009
WS5	27.892	84.507	2.018