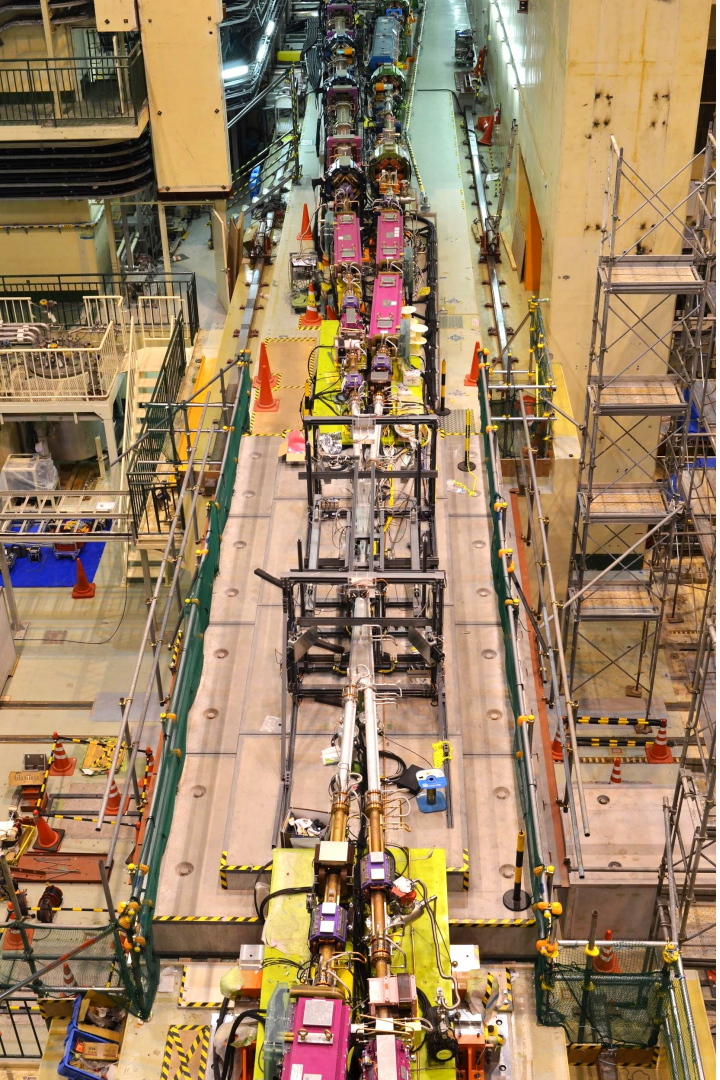


BEAST II

The commissioning detector for Belle II and SuperKEKB, **part I**

Peter M. Lewis
UH Manoa
PNNL Belle II summer school 8.18.16

The metatalk

First session (this talk)

- I will assume you know “everything” about Belle II and “nothing” about SuperKEKB or BEAST
- A general **introduction to SuperKEKB** and **beam backgrounds**
- A general **introduction to BEAST**
- A possibly insulting **introduction to basic particle detection techniques** and technologies, illustrated with BEAST detectors

Second session

- **SuperKEKB commissioning** experience
- **BEAST phase I results** with dirty technical details

First: what is BEAST?

BEAST is many things:

- The overall effort to **understand "beam backgrounds"** around Belle II
- A ragtag **team of Belle II members** who have given themselves a cool logo
- The **detectors and related systems** charged with the task

But first let's step back and talk about **SuperKEKB**

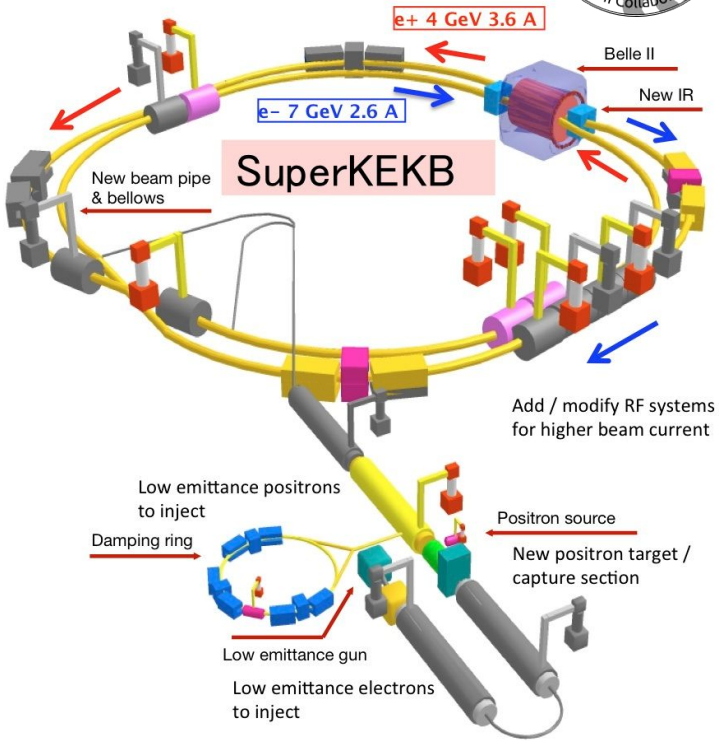
SuperKEKB Commissioning Detector
BEAST II
獣
Belle II Collaboration

SuperKEKB

SuperKEKB basics

Basic overview of the accelerator

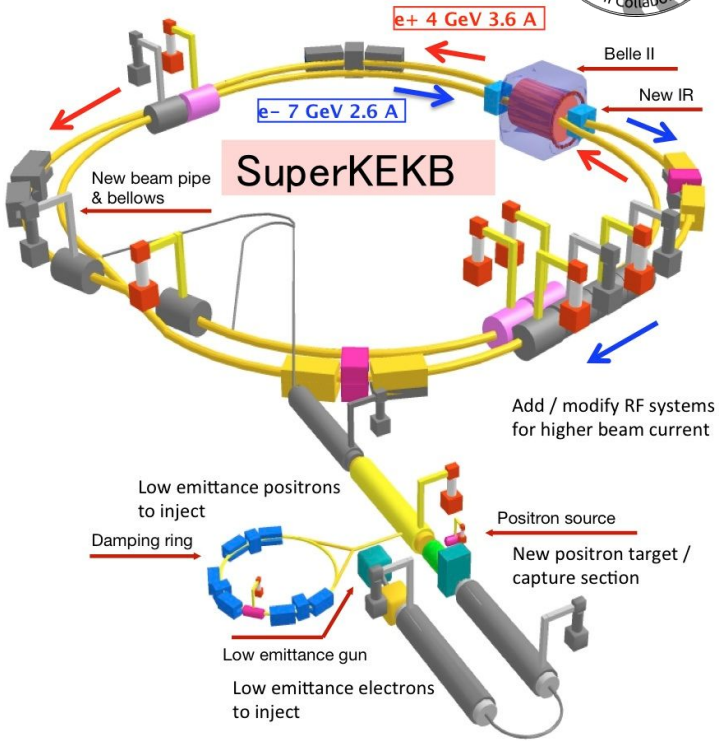
- Located in Tsukuba, Ibaraki, Japan at KEK
- Facility covers **a few square km** (ring circumference is 3km)
- Purpose: make lots of *B* mesons for Belle II (**~55 billion pairs!**)
- Method: slam electrons into positrons at Υ(4S) energy: ~10GeV in center of mass
    - Electron beam: 7GeV
    - Positron beam: 4GeV



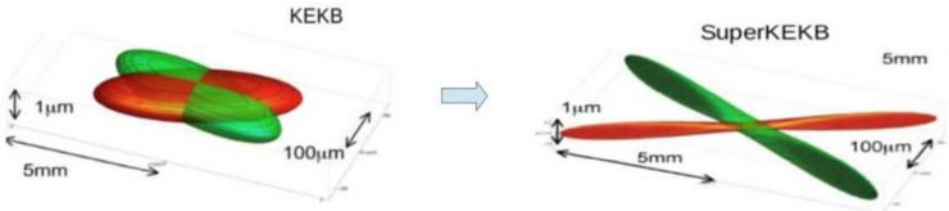
SuperKEKB basics

How does it work?

- (magic!)
- Electrons/positrons **accelerated** with radio-frequency *E*-fields
- Electrons/positrons ***injected*** into a pair of ring-shaped beam pipes in ***bunches*** in opposite directions
- Bunches are **steered** around a ring with *B*-fields
- Counter-circulating electron/positron bunches are **focused** and steered into each other inside the Belle II detector (the "**interaction point**" or IP)



SuperKEKB basics



Main upgrade from KEKB

- "Nanobeam" scheme for very high luminosity (**40x KEKB**)
  - Innovative new collision strategy for maximizing luminosity
  - Tiny beam cross-sections at IP: 10 μm x **50nm** (horizontal x vertical), 1/20 size of KEKB
  - Also a doubling of KEKB beam current: 6.2A
  - **SuperKEKB will generate a huge amount of unwanted "beam background" near the IP**

~x2 in beam current

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8\times10^{35}\,cm^2 s^{-1}$$

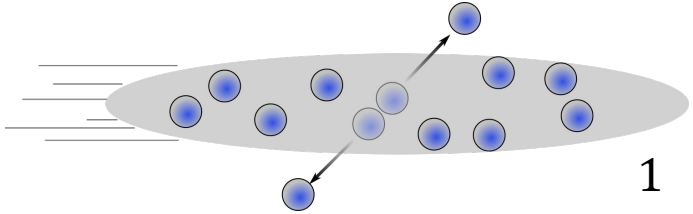
Vertical beta function reduction (5.9→0.3 mm) gives x20

Beam Energies 8.0/3.5→7.0/4.0

So what are these "beam backgrounds"?

Beam backgrounds

Beam backgrounds



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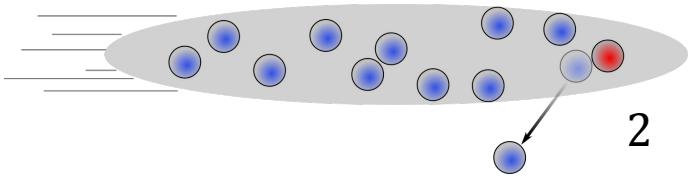
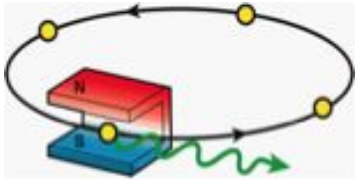
All the stuff we don't want



2

- From the beams:
  - **Touschek scattering (1)**: Coulomb scattering between two particle in the same beam bunch
  - **Beam-gas (2)**: scattering off residual gas atoms in the beam pipe
  - **Synchrotron radiation (3)**: photons emitted when electrons are bent by magnetic fields
  - (more)
- From collisions:
  - **Radiative Bhabha (4)**:
  - (more)



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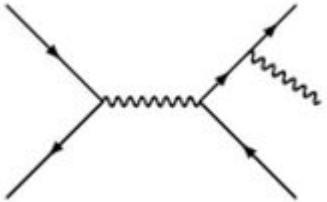

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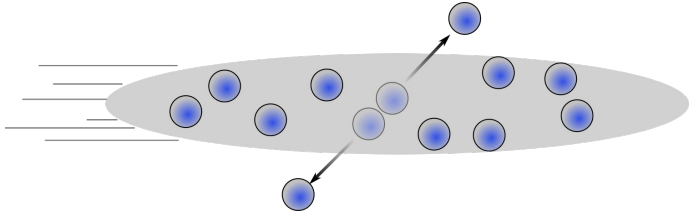
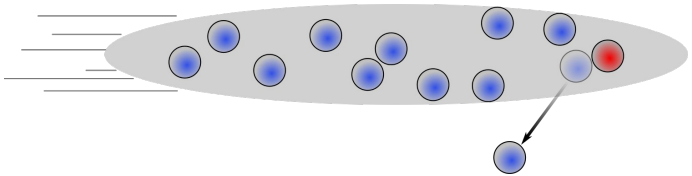
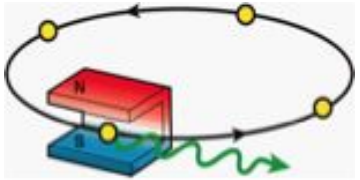
Beam backgrounds

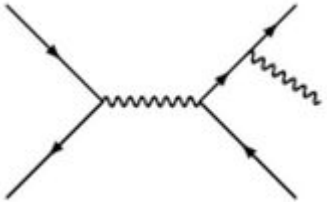


Why is it bad?



- Effect on detectors
  - Can cause permanent damage
    - In Belle/KEKB, unexpected backgrounds **burnt a hole in the beam pipe** and damaged inner detectors
    - **Especially dangerous at SuperKEKB**
  - Temporary damage or faults to electronics
- Obscures physics processes
  - Fakes interesting physics signals
  - Rejecting fake signals also lowers efficiency
- **This is where BEAST II comes in...**

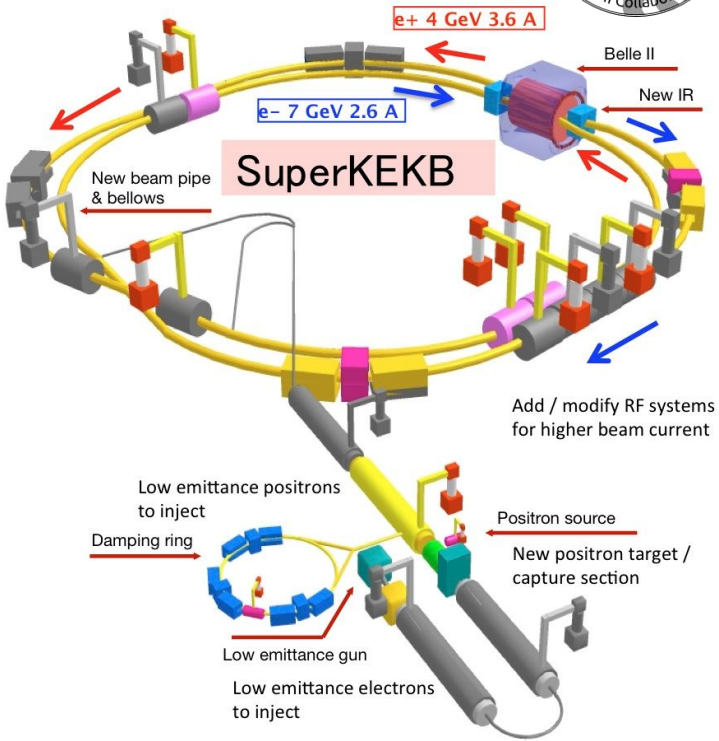




Beam backgrounds

Some jargon

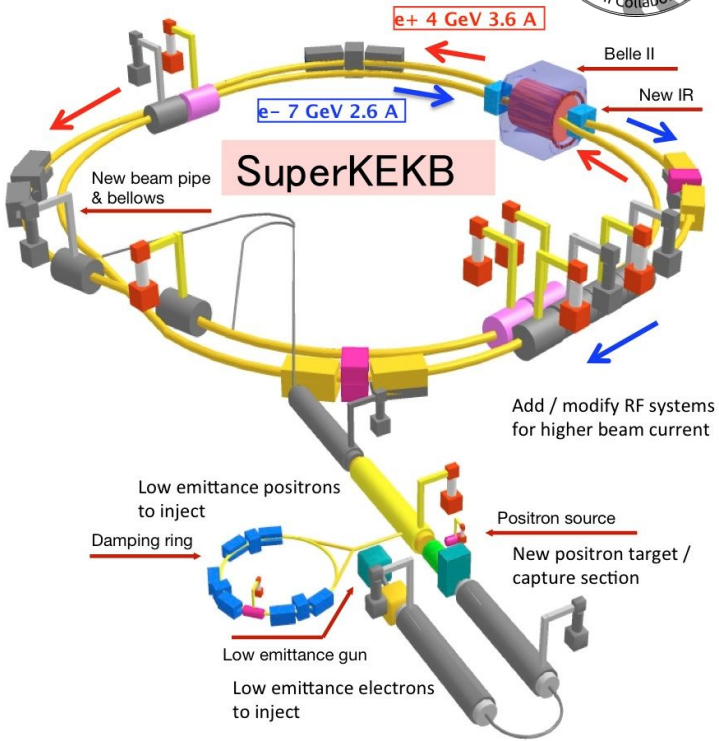
- **Beam loss**
  - All beam backgrounds come from electrons/positrons leaving the beam. This is seen as a **decrease in current**
- **Loss position**
  - **Location of the beam loss** along beam pipe
  - Important so we can shield appropriately
- **Lifetime**
  - The **1/e time** for current decay in a stored beam
  - Partial lifetimes from each beam loss type



Beam backgrounds

Some jargon

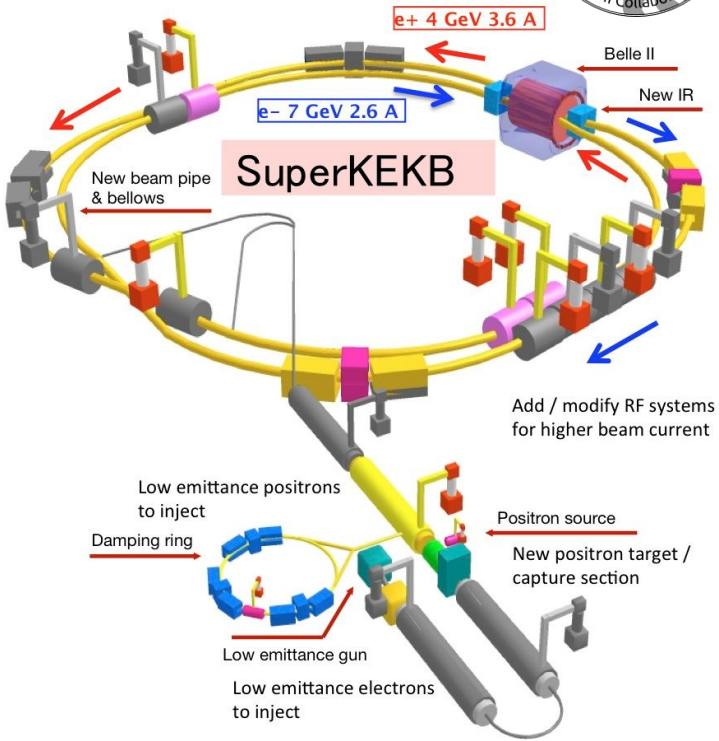
- **Beam scrubbing**
  - Crank up current to **stimulate desorption of impurities from beam pipe walls**, which are then pumped out
  - Essential for **getting rid of beam-gas** that could harm Belle
- **Optics**
  - An analogy with light and high-index materials: a system of **magnets that steer and focus the beams**



Beam backgrounds

Some jargon

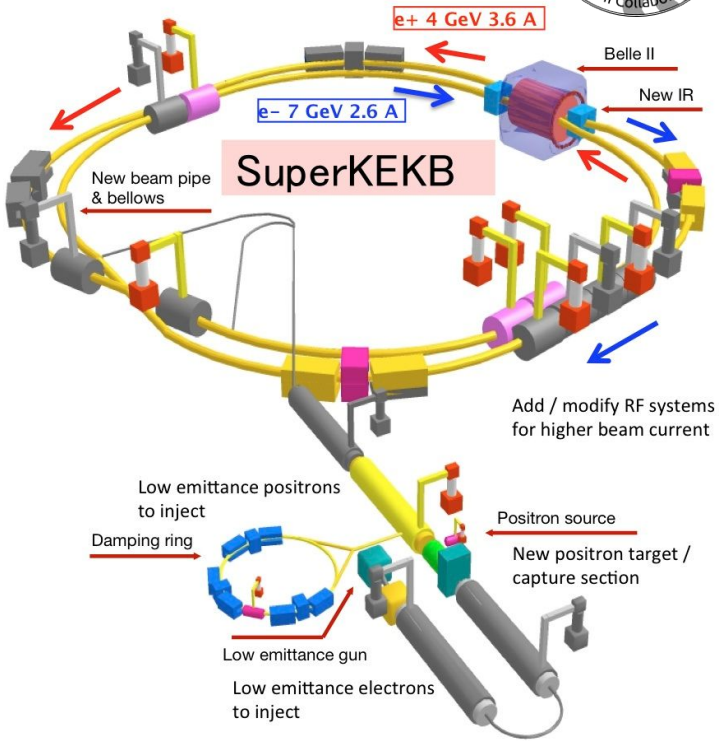
- **Injection**
  - System for transporting electrons/positrons **from linear accelerator to storage ring**
  - Background associated with **injecting charge into a bunch**
  - Could be **several orders of magnitude** above stored beam backgrounds for a short time
  - **Repetition rate**: frequency of injection
  - **Injection charge** (self-explanatory)
  - **Tuning the injection** to minimize messiness of bunches and damp oscillations is an **art**, and is critical for Belle II performance



Some perspective

SuperKEKB does this:

- **Steers multiple amps of charge in 3km-long counter-circulating relativistic chains of organized bunches**
- **Squeezes these bunches down to tens of nanometers and collides them head-on**
- **Never creates black holes or mutant monsters**
- (...all so you can have small statistical error bars in your analysis)
- **These people are heroes**



Commissioning

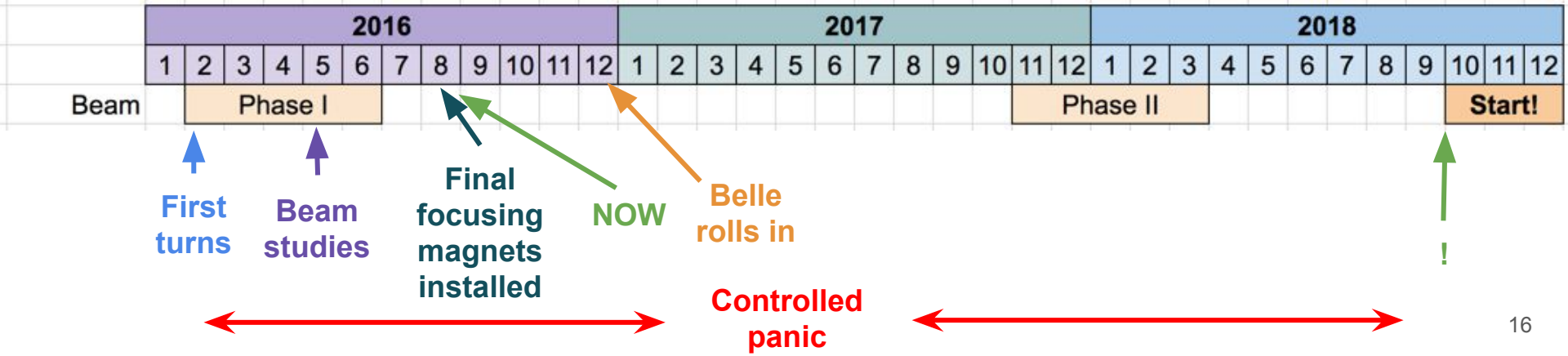
Schedule: commissioning SuperKEKB

Phase I (completed)

- Circulate both beams; **no collisions**
- Tune accelerator optics, etc.
- Beam scrub
- **Beam studies**

Phase II (2017-18)

- First collisions
- Develop beam abort
- Tune accelerator optics, etc. (nano-beam)
- **I won't discuss today**



Commissioning requirements

SuperKEKB

- Real-time **monitoring** of beam conditions
- **Quantify** effects of tuning on beam loss
- Isolate the **type and source** of beam loss
- Inform beam loss **simulations** to optimize performance

Belle II

- Guarantee a **safe**-enough radiation environment for Belle II
- **Mitigate** beam backgrounds
- Inform beam background **simulations** so they are properly accounted for in physics analysis

We need a "commissioning detector": a stand-in for Belle II to provide diverse real-time measurements of beam conditions...

Enter the BEAST

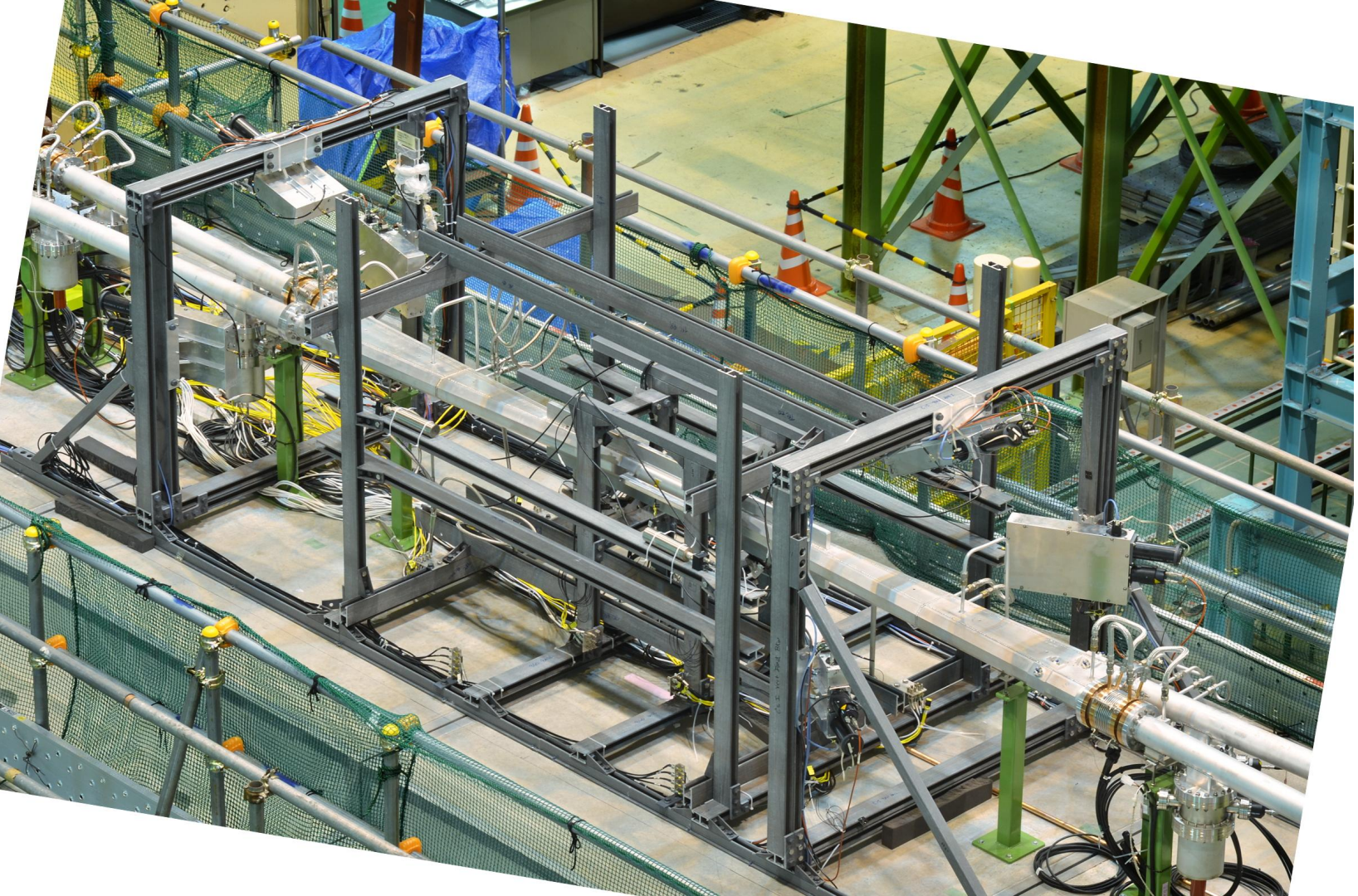
Primary detectors in BEAST II* for phase I:

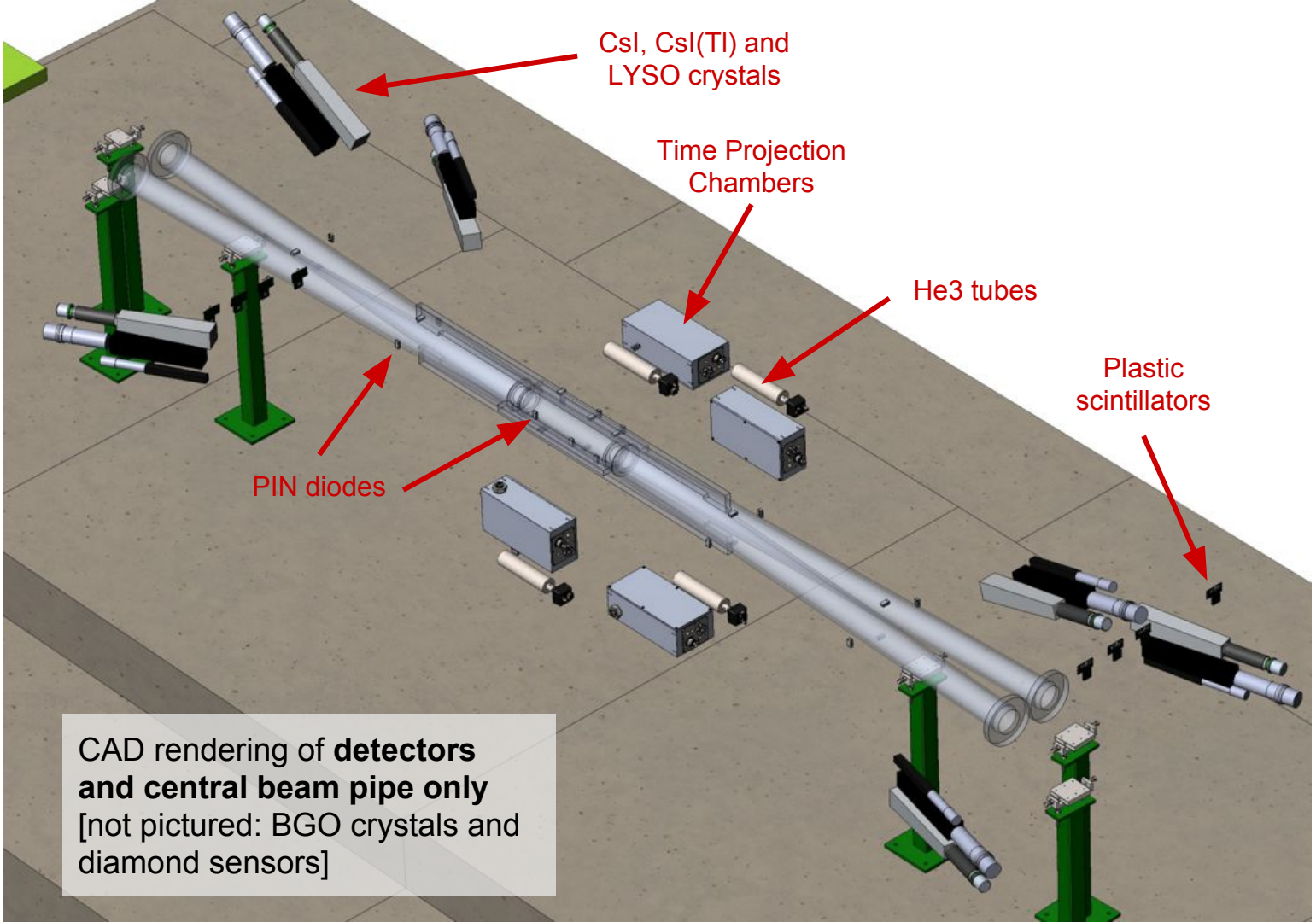
System	Institution	#	Unique measurement
PIN diodes	Wayne St.	64	Neutral vs. charged dose rate
Time Projection Chambers	U. Hawaii	4	Fast neutron flux and tracking
Diamonds	INFN Trieste	4	Beam abort
He3 tubes	U. Victoria	4	Thermal neutron rate
CsI(Tl) crystals	U. Victoria	6	EM energy spectrum, injection backgrounds
CsI+LYSO crystals	INFN Frascati	6+6	
BGO crystals	National Taiwan U.	8	Luminosity and EM rate
CLAWS plastic scintillators	MPI Munich	8	Fast injection backgrounds

*Belle had its own BEAST

Belle and the BEAST

Belle II will eventually roll in on a pair of railroad tracks





CAD rendering of **detectors and central beam pipe only** [not pictured: BGO crystals and diamond sensors]

BEAST detectors

PIN diodes

Role in BEAST II

- General-purpose ionizing radiation detector
  - Instantaneous ionization current at 32 positions at ~1-1000Hz
  - Integrated dose
- Wayne State U. and U. Hawaii

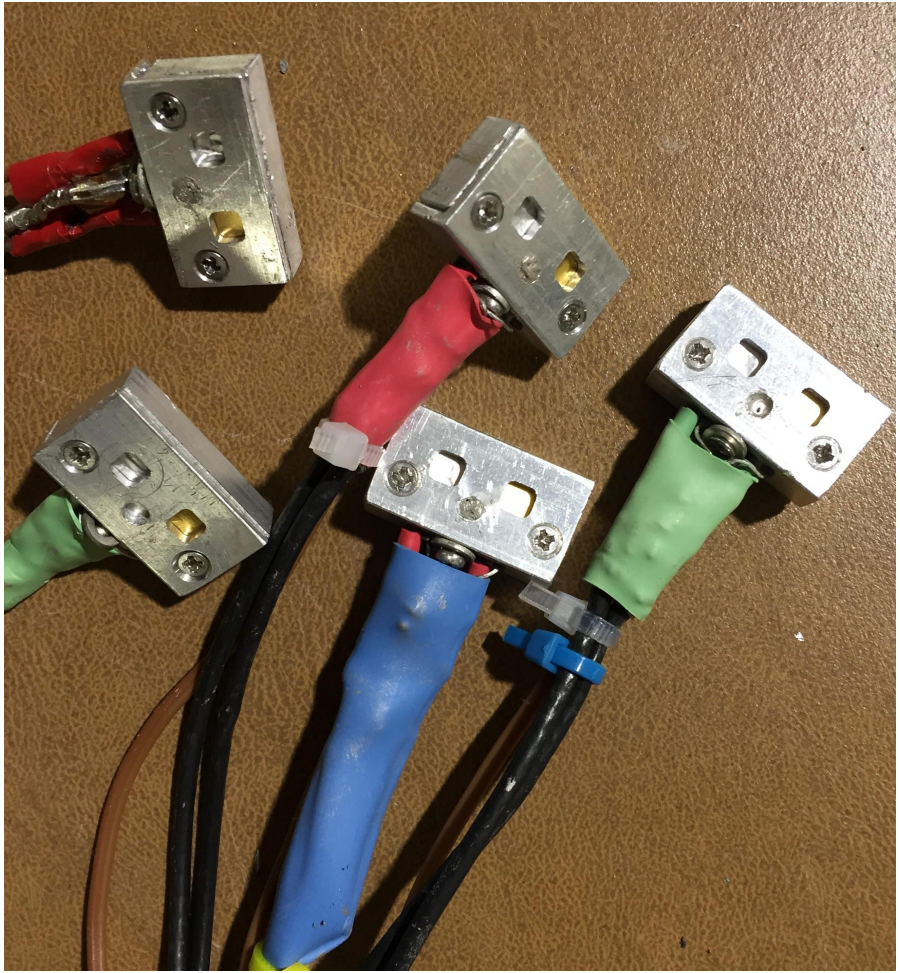
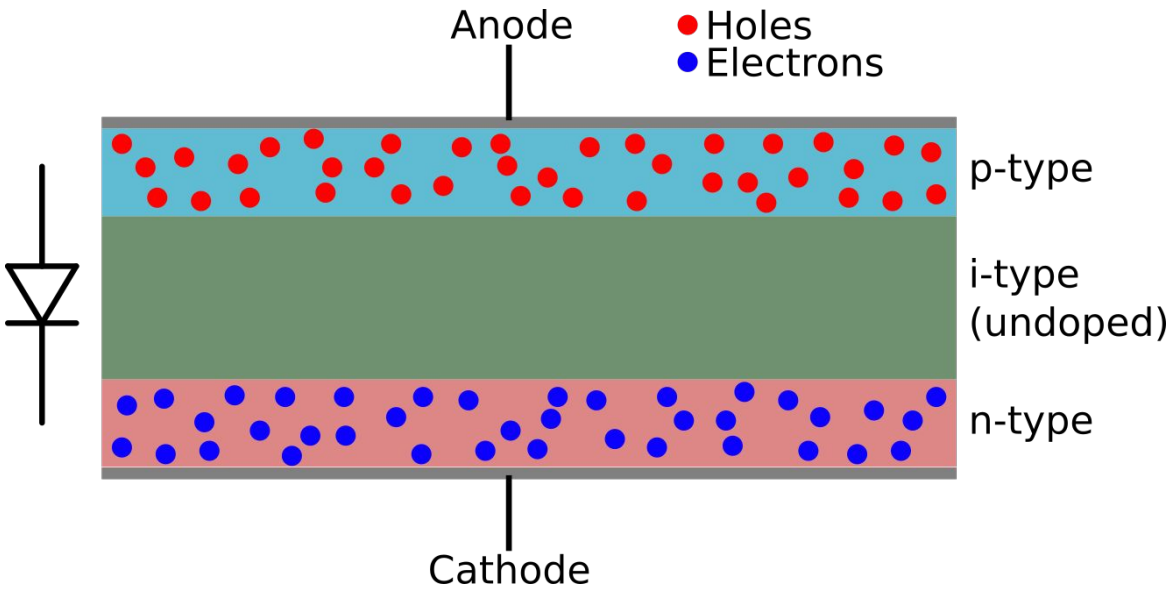


Photo by M. Nayak

PIN diodes

Principle (simplified)

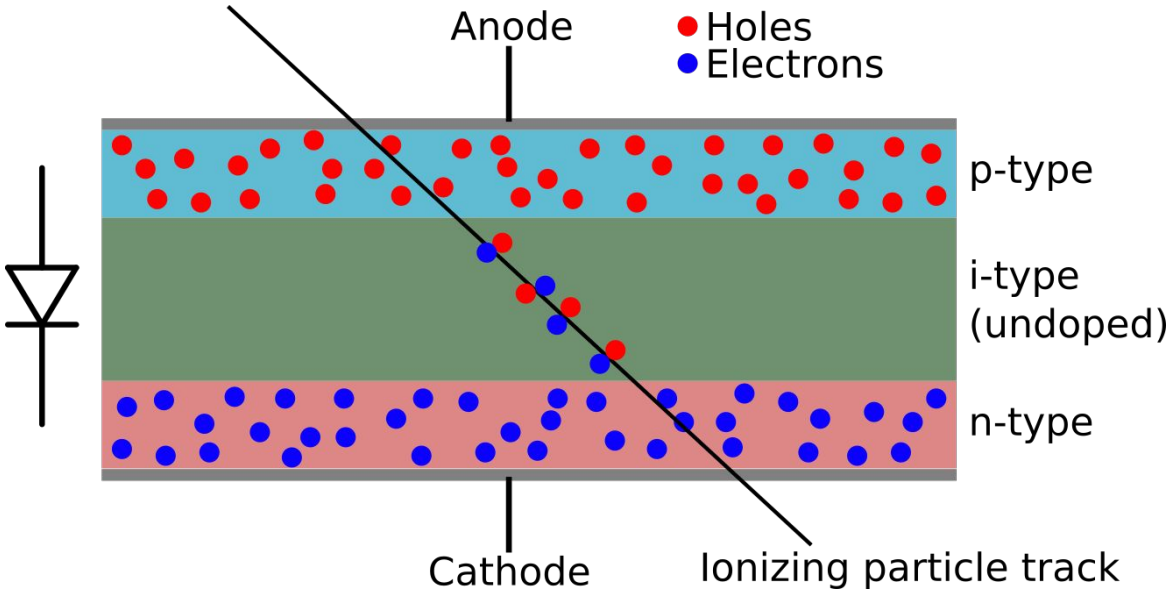
- Silicon diode with large undoped region between p- and n-type semiconductors
- Unbiased: electric field in undoped region generated by intrinsic arrangement of electrons and holes
- Steady state: no current (in ideal case)



PIN diodes

Principle (simplified)

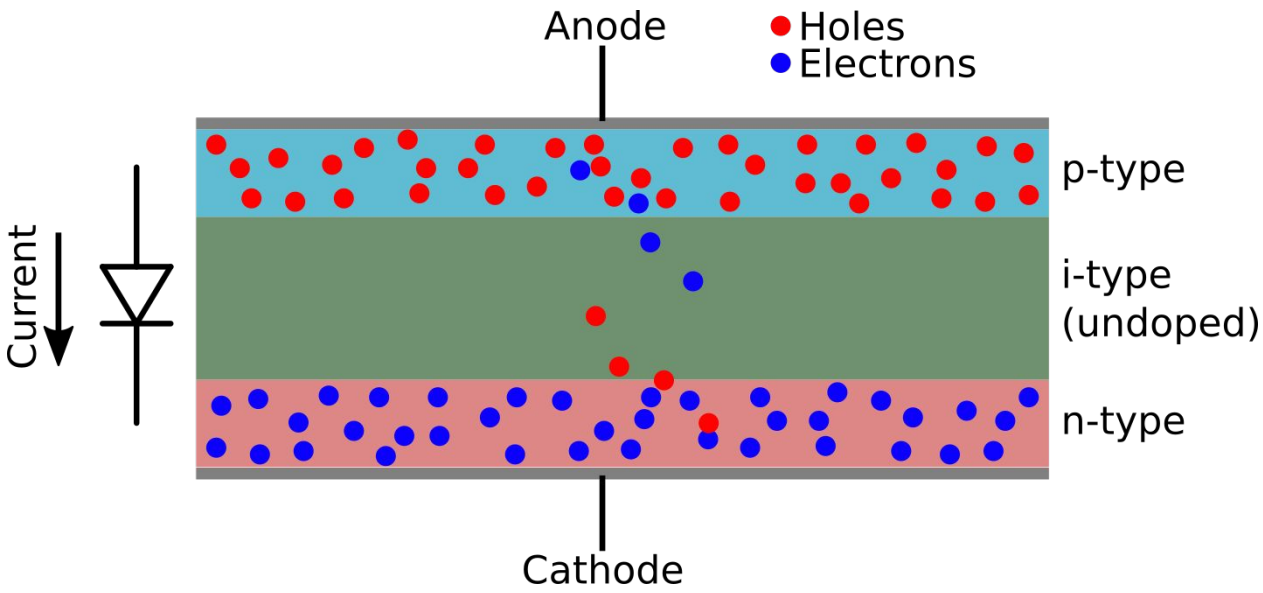
- Ionizing radiation liberates electrons and holes
- Charges drift to p and n regions



PIN diodes

Principle (simplified)

- Ionizing radiation liberates electrons and holes
- Charges drift to p and n regions
- **Current generated, equal to ionization charge**
- (heat and light also generate current)

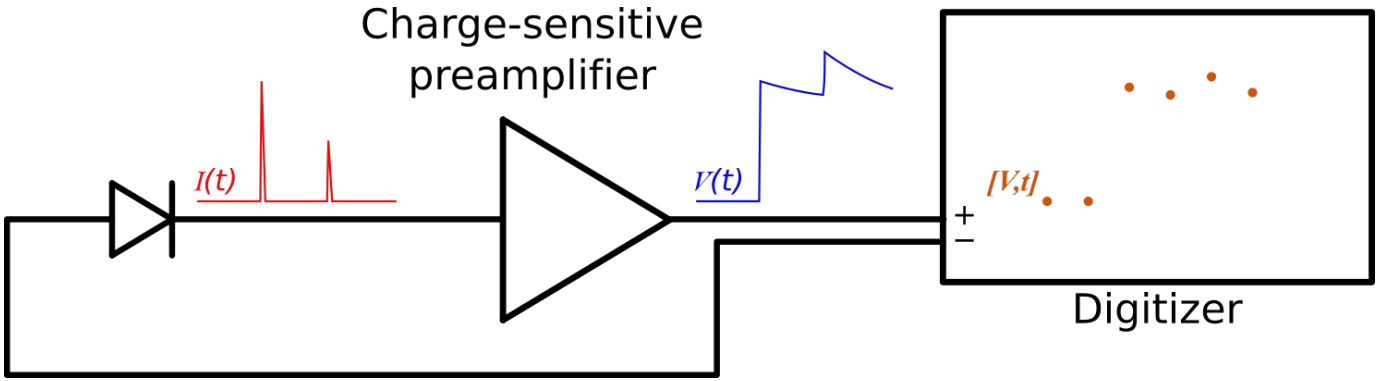


PIN diodes

Readout

- Ionizing radiation is a **very small current delta function**
- Charge-sensitive preamplifier converts current to long-fall-time (~140μs) voltage pulse

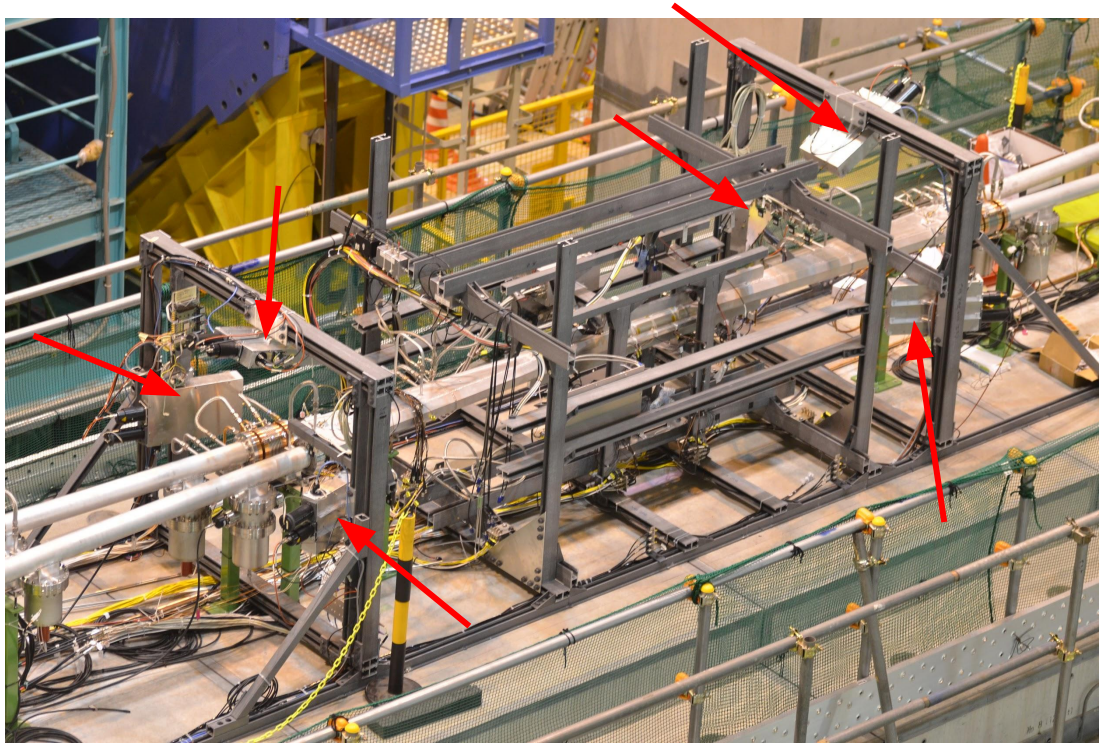
- High-rate hits pile up to a measurable DC voltage
- Voltage is digitized at 1Hz-100kHz
- Remaining **signal is converted t**o ionization rate



Calorimeter crystals

Role in BEAST

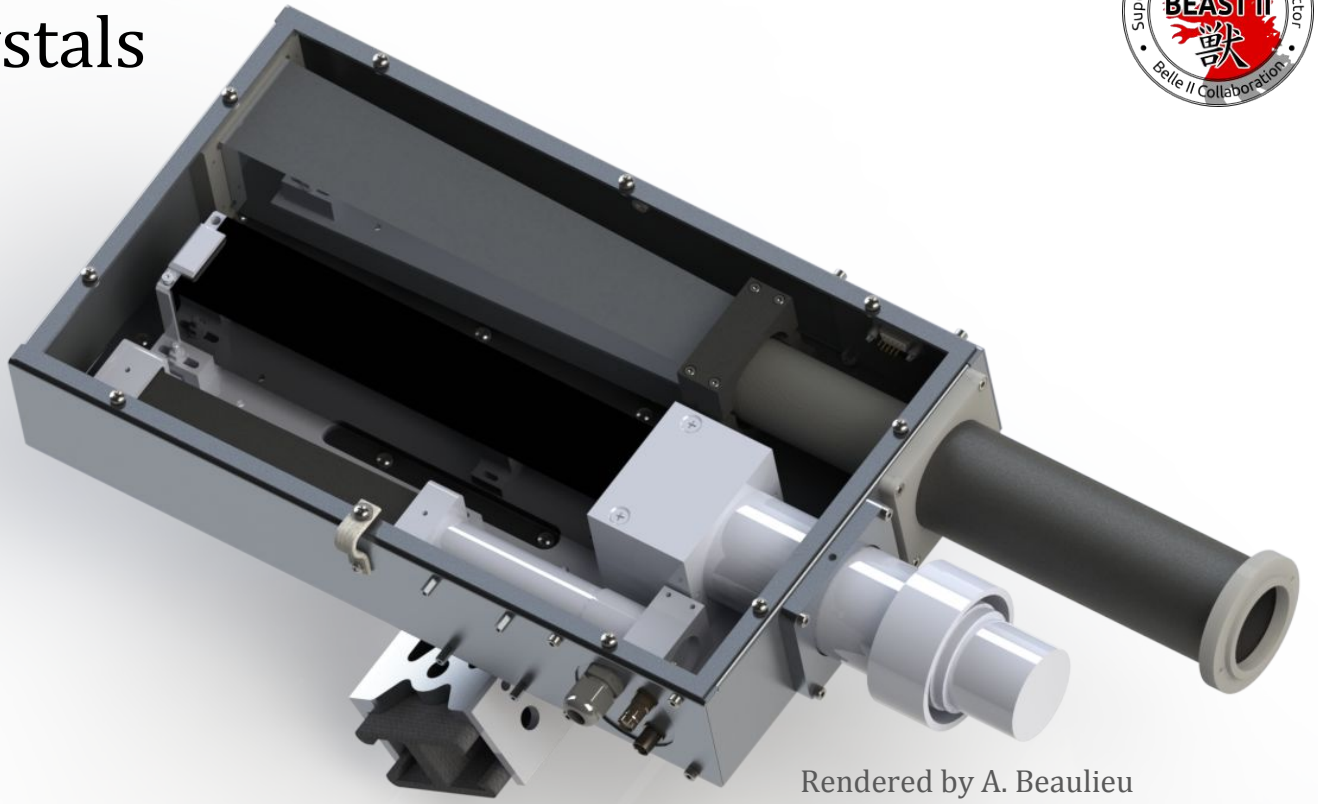
- Principally used to count and measure the energy of gamma rays
- U. Victoria and INFN Frascati



Calorimeter crystals

General design

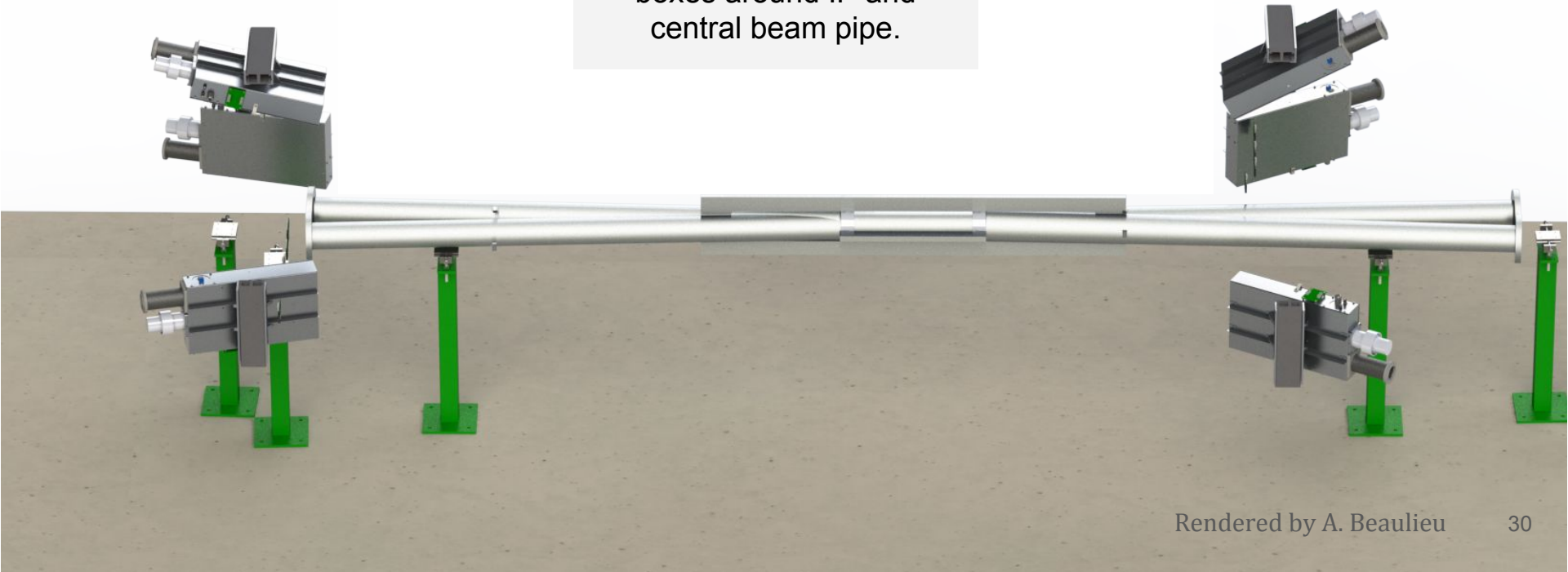
- Six boxes with three different crystals each (CsI, CsI(Tl) and LySO)
- Crystals point toward IP



Rendered by A. Beaulieu

Calorimeter crystals

Arrangement of 6 crystal boxes around IP and central beam pipe.

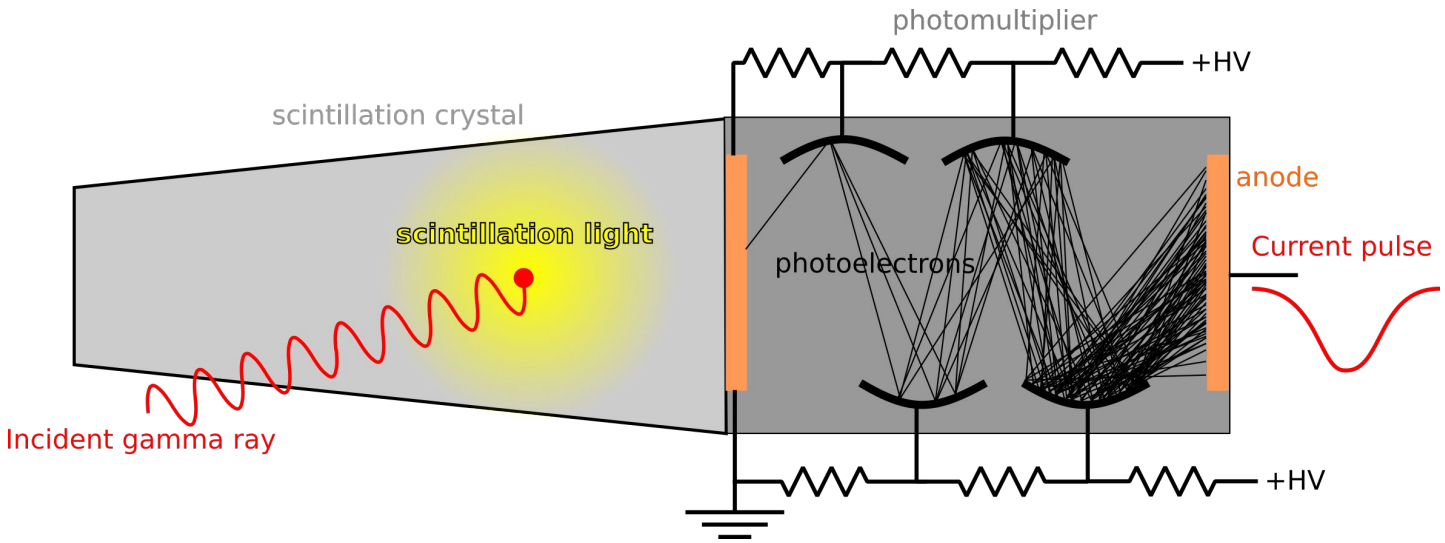


Rendered by A. Beaulieu

Calorimeter crystals

Principle

- Gamma ray (or charged particle) stimulates light emission in scintillating crystal
- Light incident on a metal cathode ejects photoelectrons
- Photoelectrons are amplified through multiple stages using high voltage
- Current is collected at anode as a current proportional to collected light



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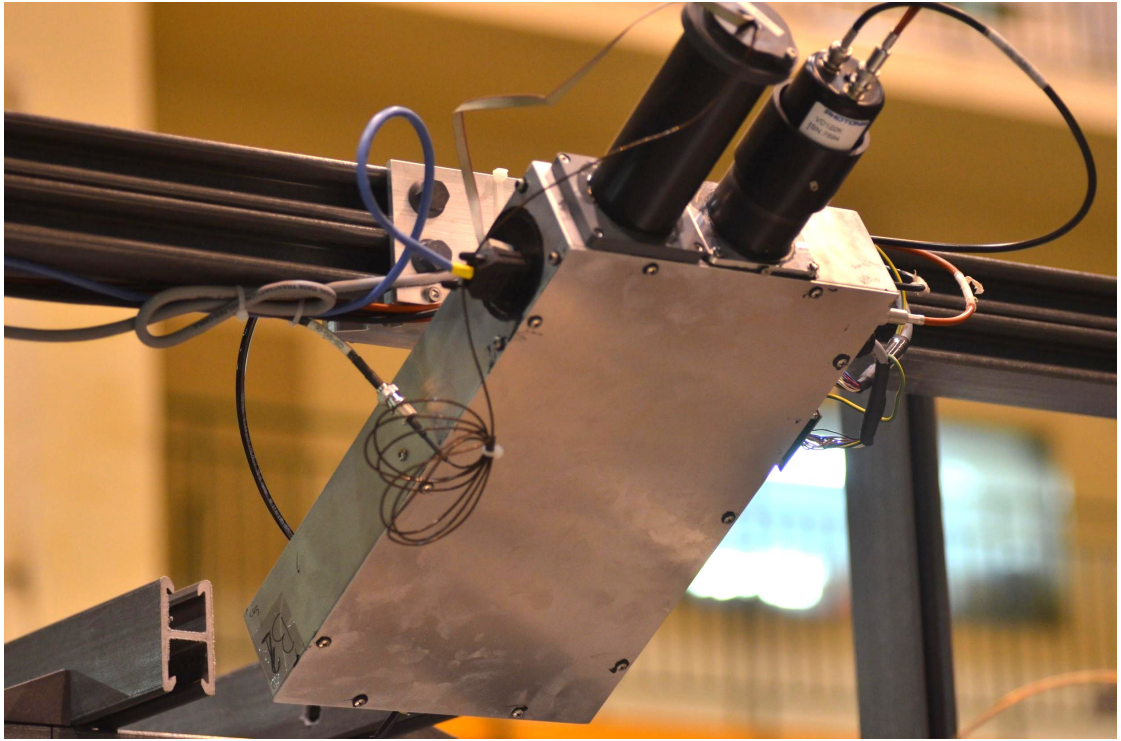
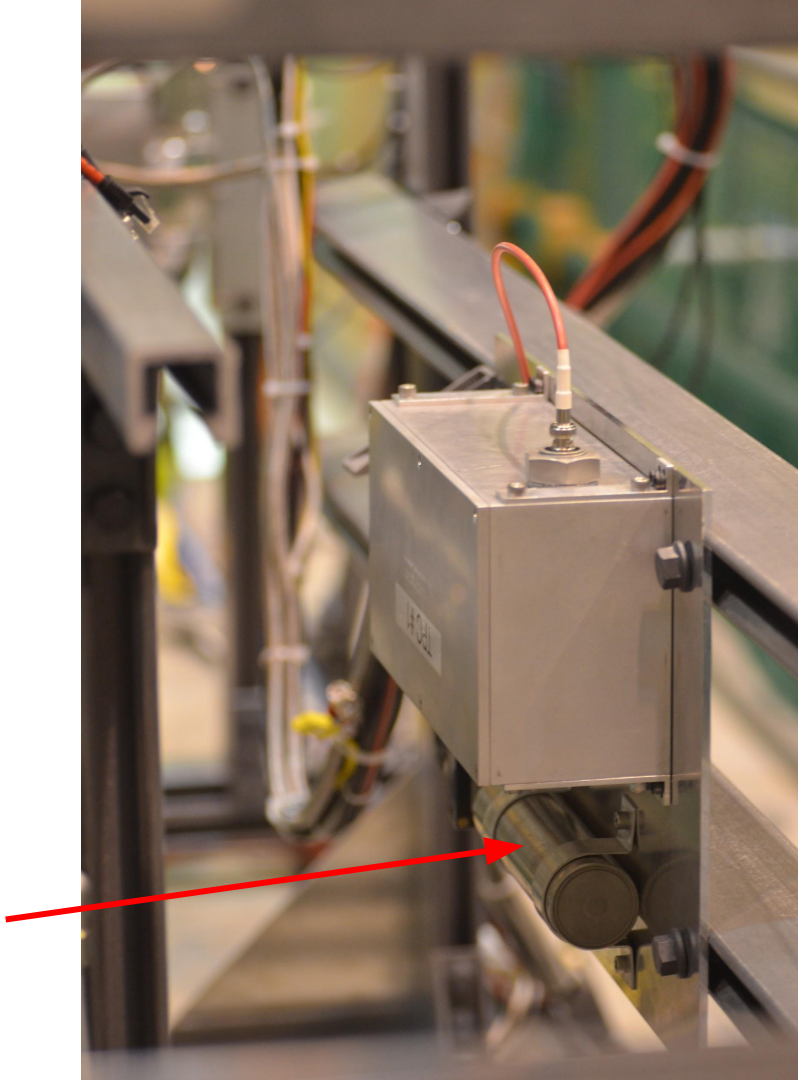


He3 tubes

Principle

- U. Victoria
- Super-simple thermal neutron counter



He3 tubes

Principle

- U. Victoria
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- Gas tube filled with Helium 3 at ~4atm
- Tube grounded, single ~1.4kV wire runs down the middle
- Slow neutrons get captured by He-3 nucleus

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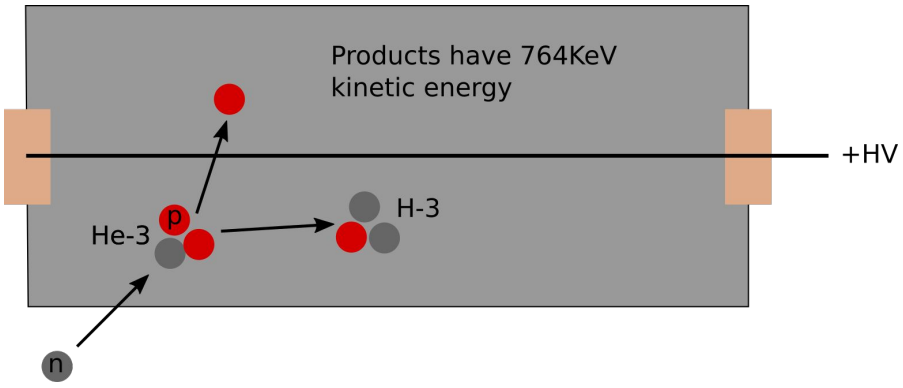
- Nucleus splits, releasing energy:

$$^{3}He + n \rightarrow {}^{3}H + p + 764KeV$$



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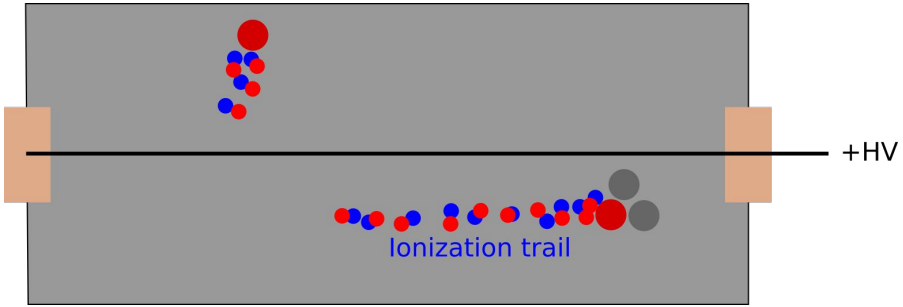
- Proton and tritium come to rest in gas, leaving ion trail in wake



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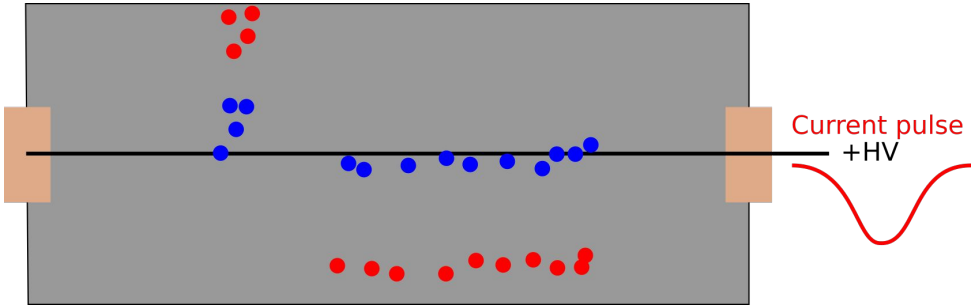


- Free electrons drift to anode in electric field and produce current pulse
- Digitization is similar to CsI case; all current pulses are identical

TPCs

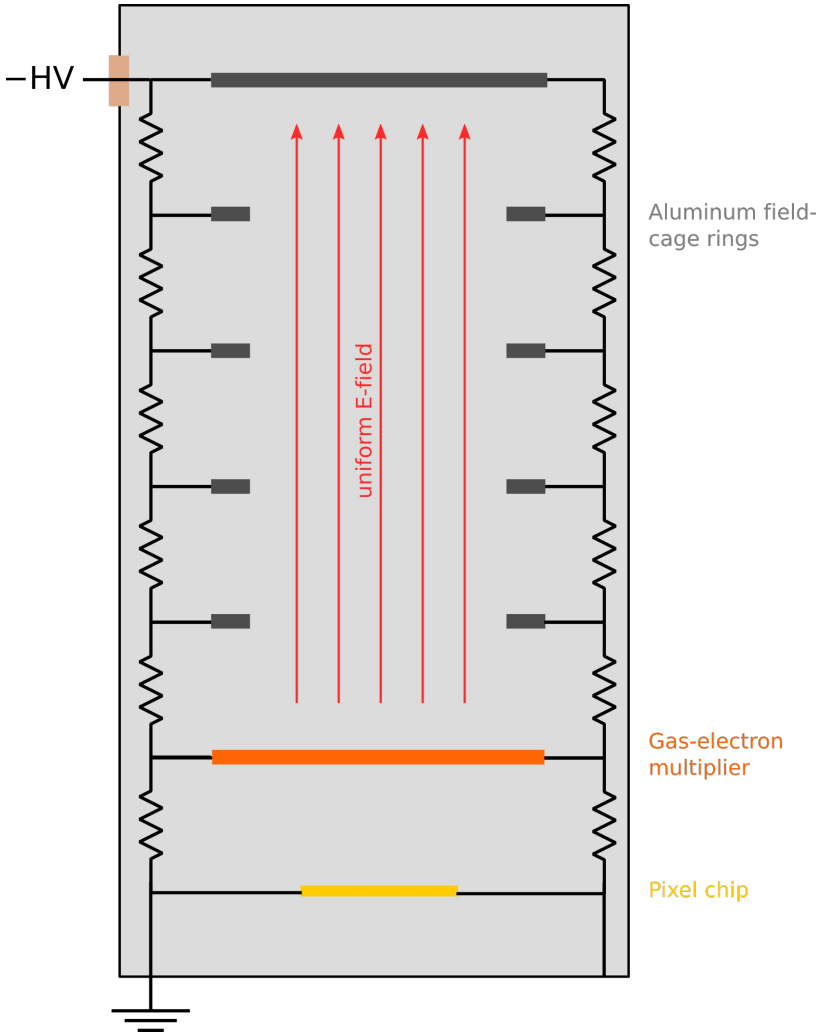
Use in BEAST

- Time projection chambers
- Designed and built at UH
- By far the most technically complex detector in BEAST phase I
- Primarily for **directional detection of fast neutrons**
    - These caused chaos in both Belle and BaBar commissioning
- Four TPCs are installed for phase I, eight will be in phase II

TPCs

Principle

- Volume of gas (70:30 Helium:CO_2)
- Ladder of aluminum rings with linearly increasing potential to set uniform E-field



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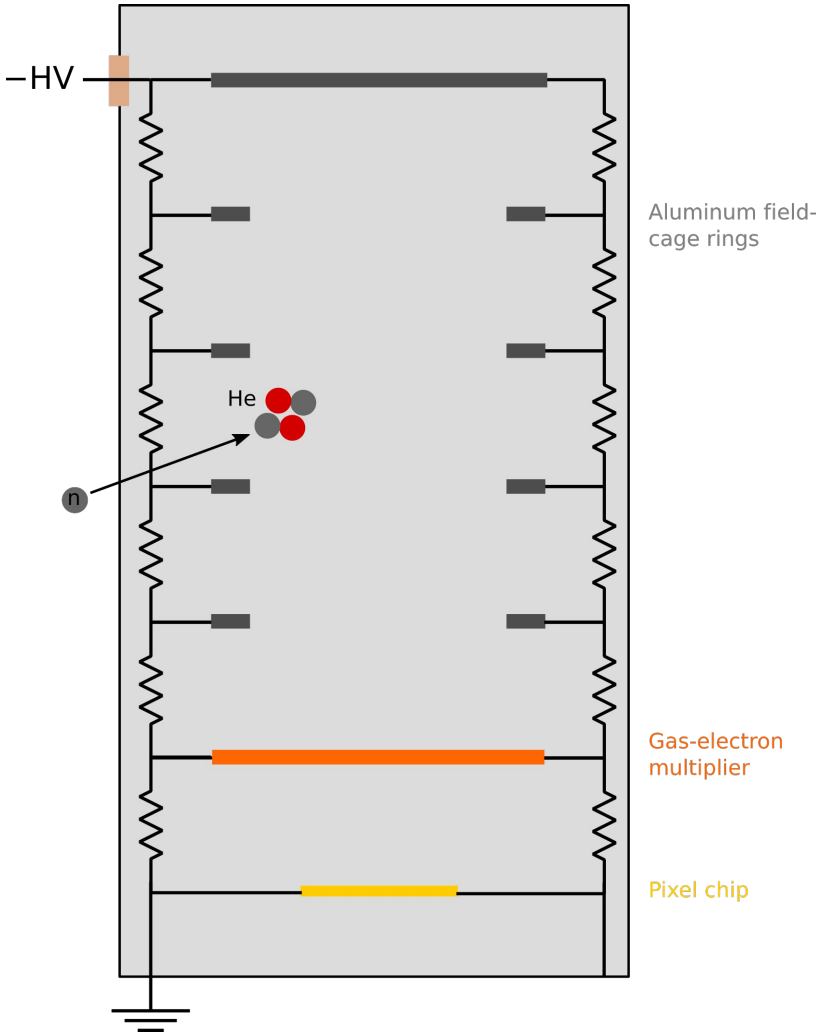

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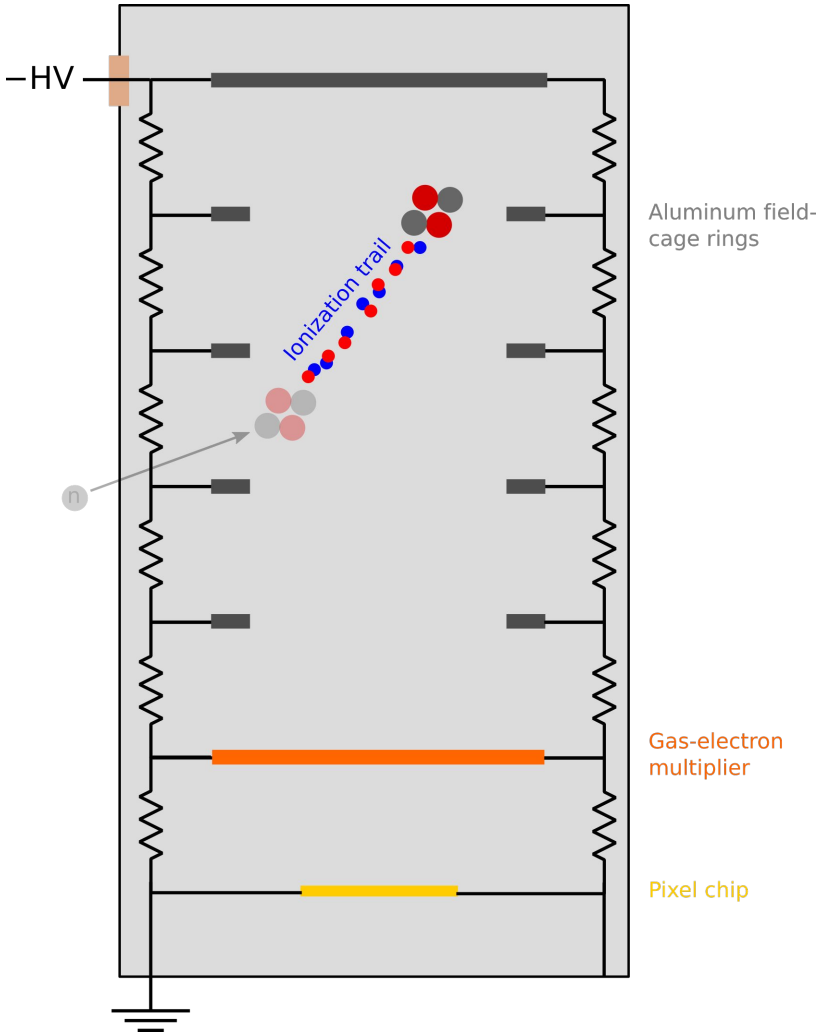

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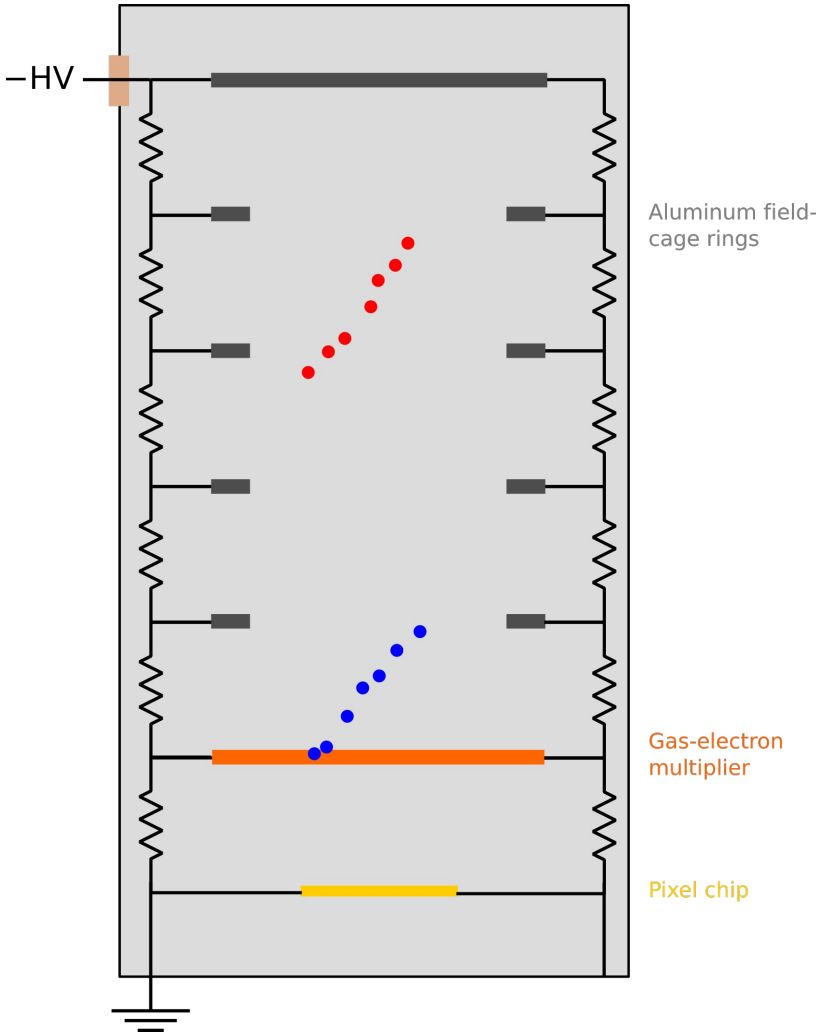
- Electrons in ion cloud drift in E-field toward gas-electron multipliers (GEMs)



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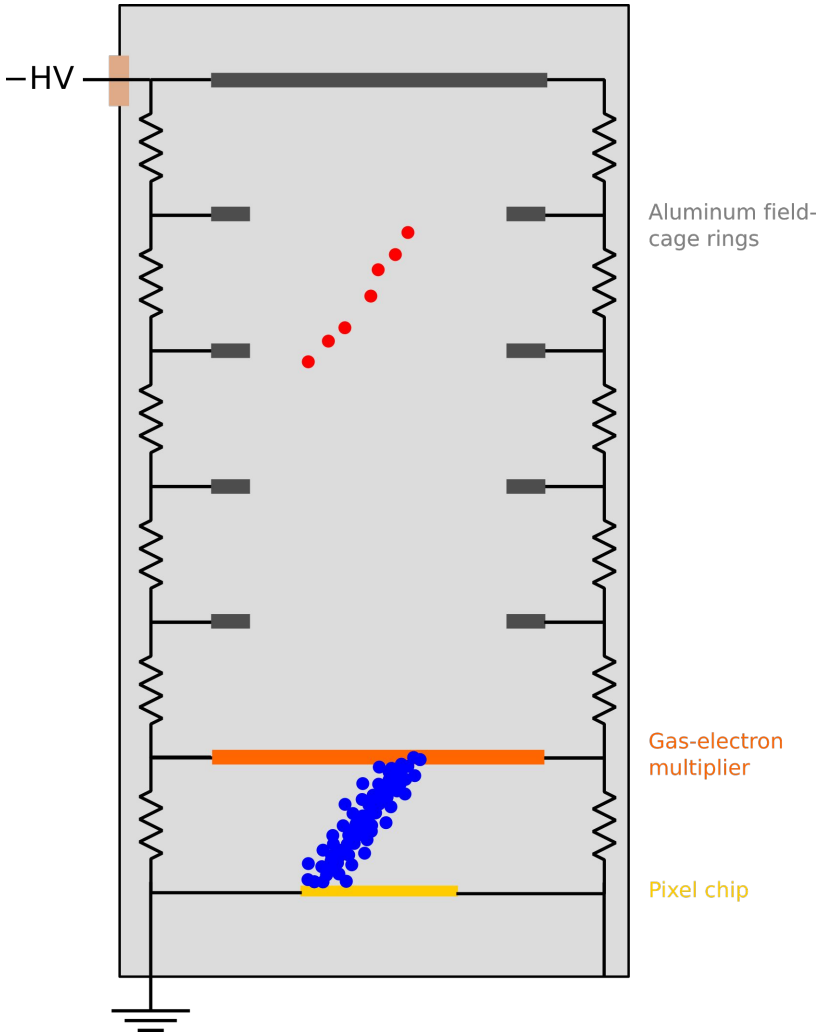
- Nucleus “recoils” through the gas, leaving an ionization trail behind
- Electrons in ion cloud drift in E-field toward gas-electron multipliers GEMs
- GEMs multiply the electrons by a factor of many thousands
- Pixel chip records charge with high spatial and time resolution

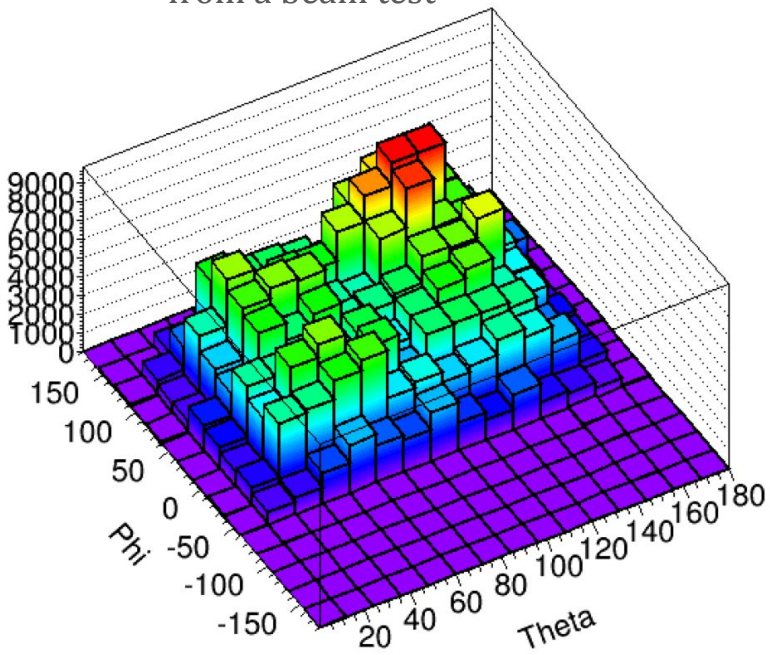


TPCs

Properties

- Background-free operation:
  - Adjustable threshold well above pixel noise
  - Readout triggered only by pixels crossing above threshold
  - With multiple GEMs, single-electron efficiency is possible
- Directional detection
  - Single-track precision ~1 degree
  - Pointing back to a fast neutron source (right) demonstrated

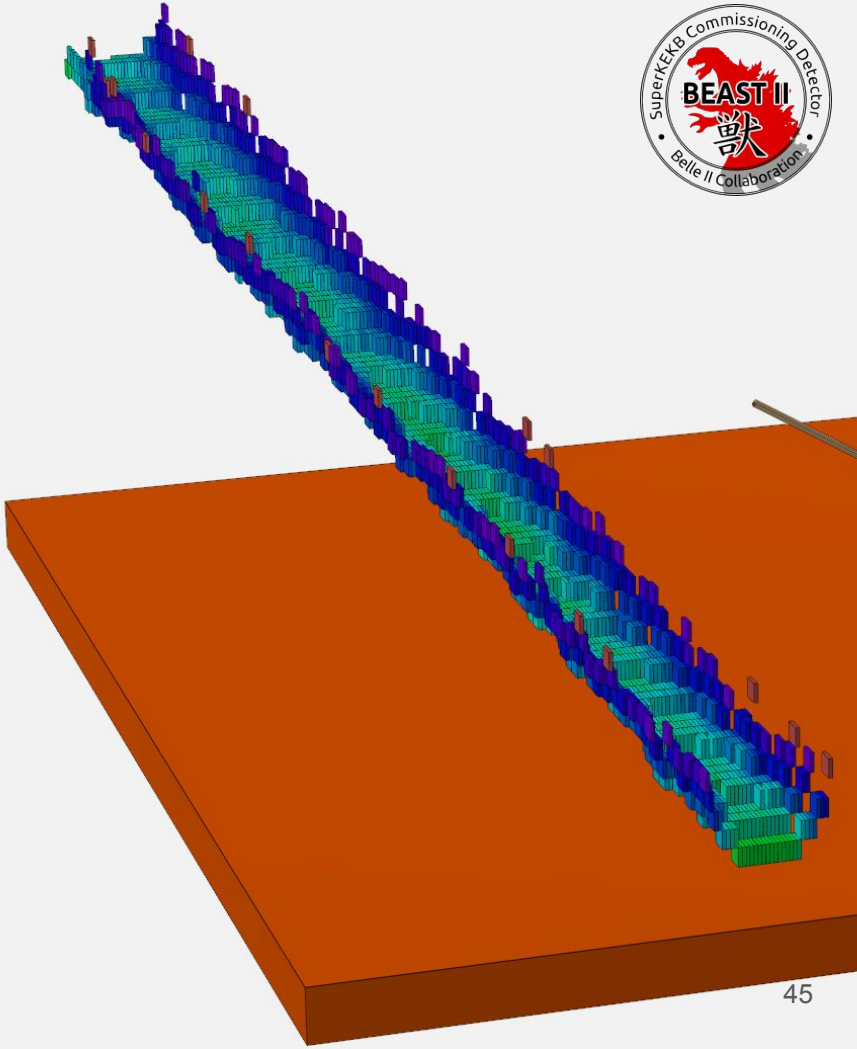
Angular distribution of neutron recoils from a beam test



TPCs

Data

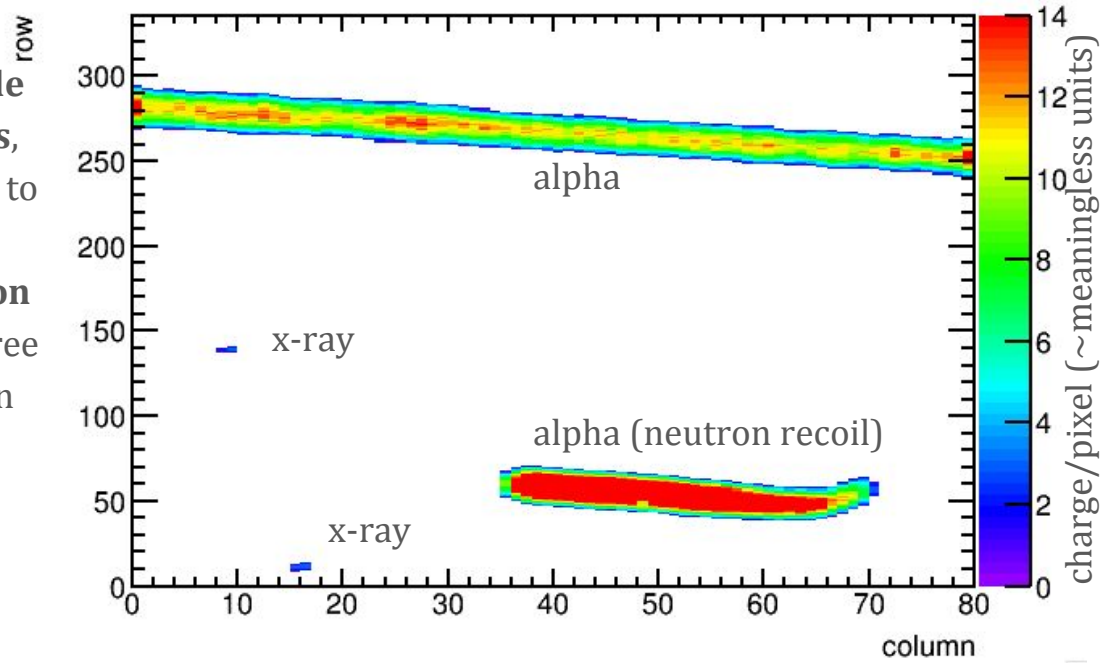
- Pixel chip data is like **taking multiple pictures of charge cloud as it drifts**, with each “exposure” corresponding to a new slice of the cloud
- Right: **4D reconstruction of ionization cloud from an alpha particle** (color encodes total ionization collected per pixel)



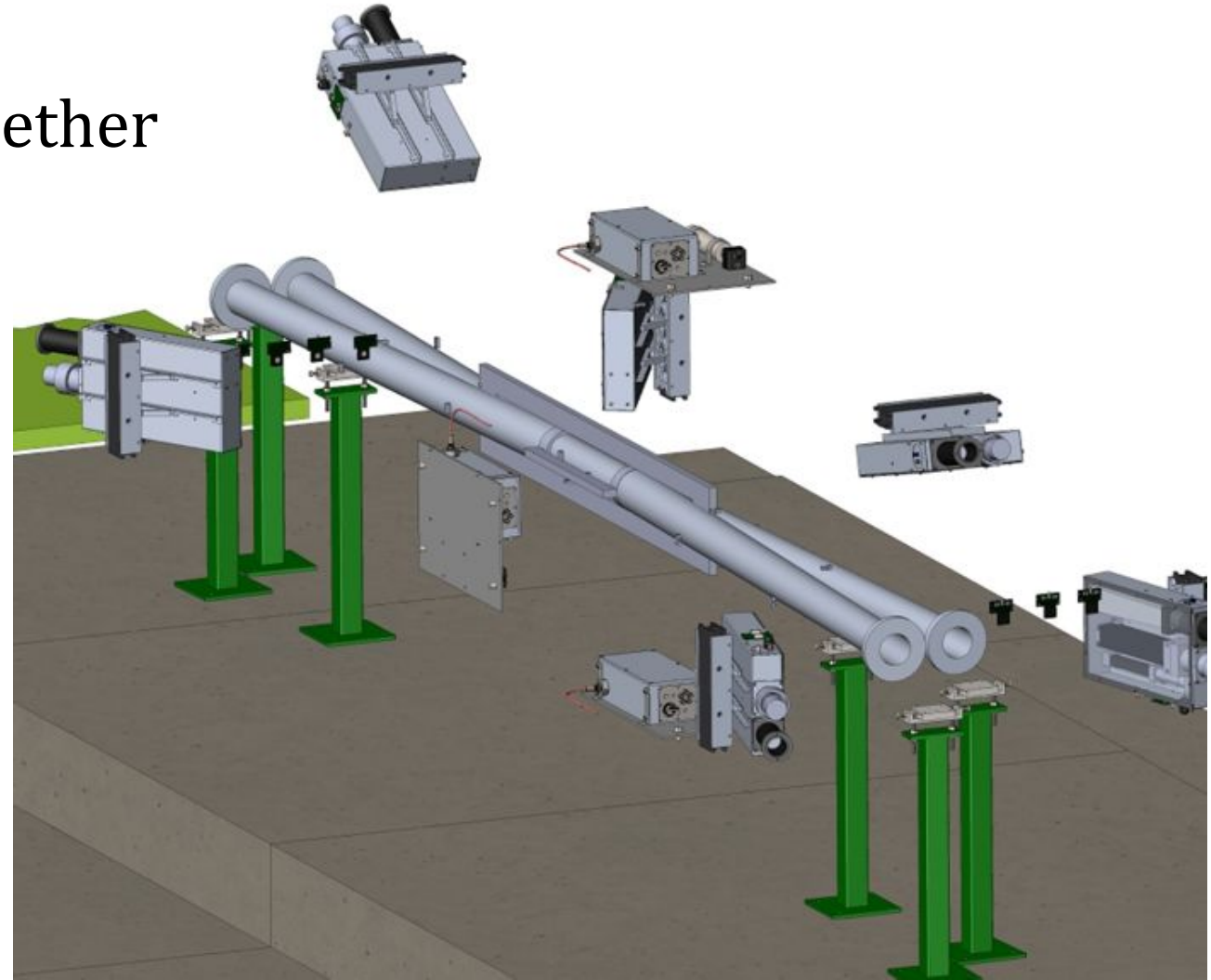
TPCs

Data

- Pixel chip data is like **taking multiple pictures of charge cloud as it drifts**, with each "exposure" corresponding to a new slice of the cloud
- Right: **3D plot (2D spatial projection plus charge density in color)** of three different characteristic event types in TPC:
  - Alpha
  - x-ray
  - Neutron recoil



All together



Rendered by A. Beaulieu

SuperKEKB Commissioning Detector
BEAST II
獣
Belle II Collaboration

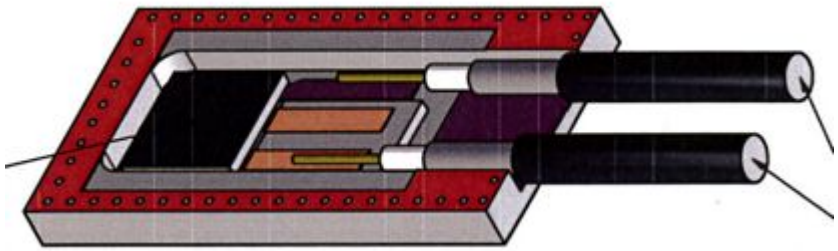
End of part I

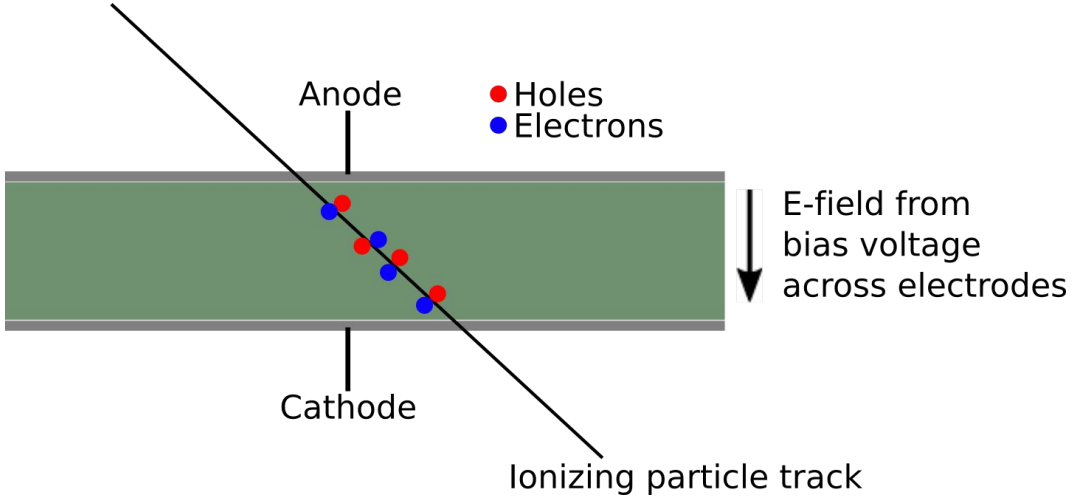
Additional slides (neglected detector details)

Diamond sensors

Principle and role in BEAST

- University of Trieste
- Similar to PIN diodes, except:
  - Chemical vapor deposited diamond replaces silicon semiconductor
  - Bias voltage across electrodes for drifting charge rather than semiconductor junctions
  - Very high radiation tolerance
  - Low noise, high speed

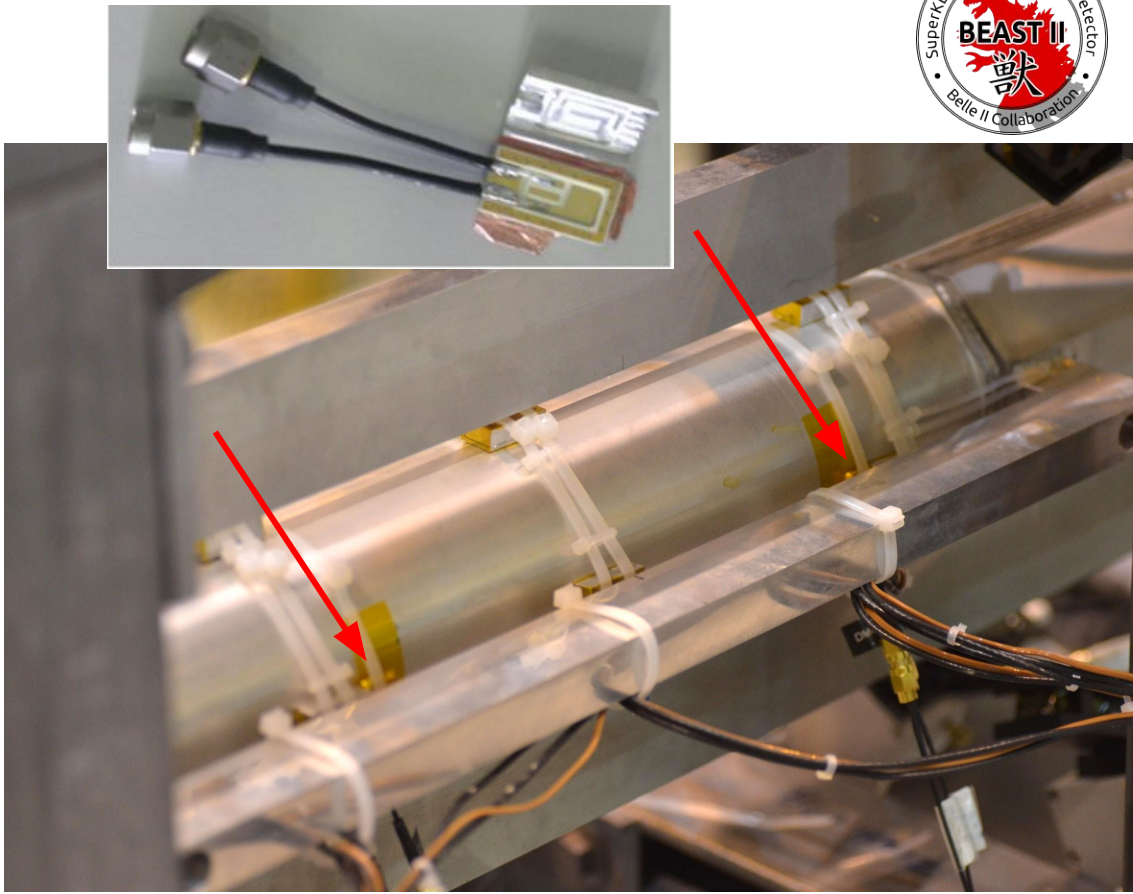




Diamond sensors

Location and use

- For generating “beam abort signal”
  - Look for rapid and dangerous increase in radiation levels
  - Generate abort signal to SuperKEKB to shut down beam to protect detectors
  - In phase I, it is a test of this system
- Four sensors around IP with adjacent PIN packages

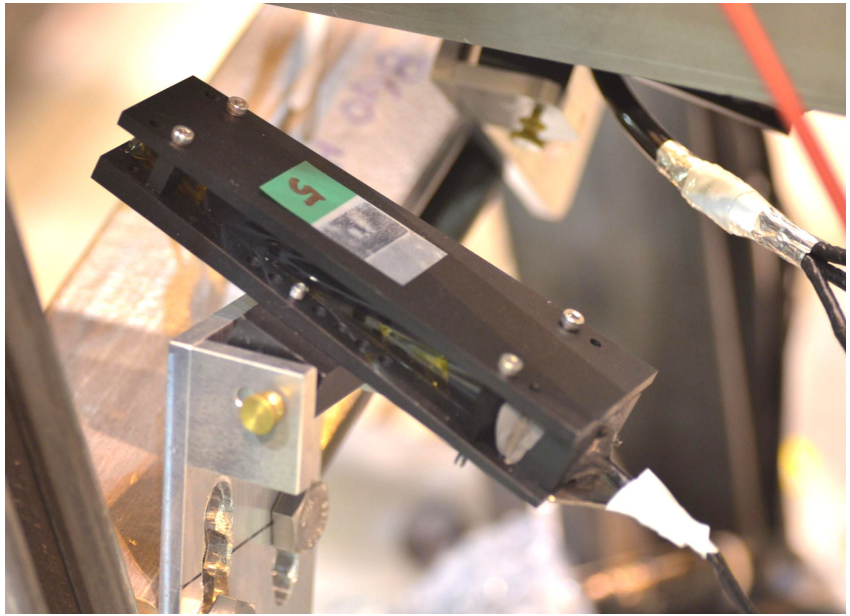


BGO crystals

Principle and use in BEAST

- National Taiwan University contribution
- Bismuth germanium oxide: BGO
- 8 scintillating crystals (slightly different characteristics compared with CsI)
- Fibers carry light 37m to PMTs
- Custom readout board
- As a luminosity monitor:
  - Looks for back-to-back electron/positron pairs in the collision center-of-mass frame
  - From Bhabha scattering (scales predictably with luminosity):

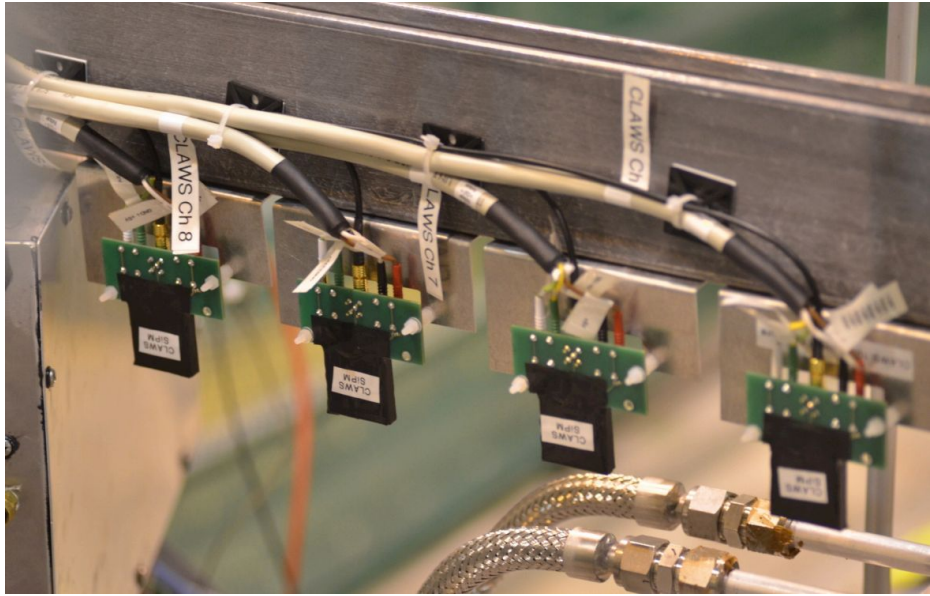
$$e^+e^- \rightarrow e^+e^-$$



CLAWS

Principle and use in BEAST

- MPI Munich
- 8 rectangular *plastic* scintillators in horizontal plane (very fast: needs <1ns time resolution)
- Looking for “injection background”
  - Every 20ms, accelerator “tops off” bunches circulating in rings
  - Recently topped-off bunches are messy and eject a lot of background as they pass the IP
  - Watch bunches “cool down” after injection; give feedback to Belle II detectors



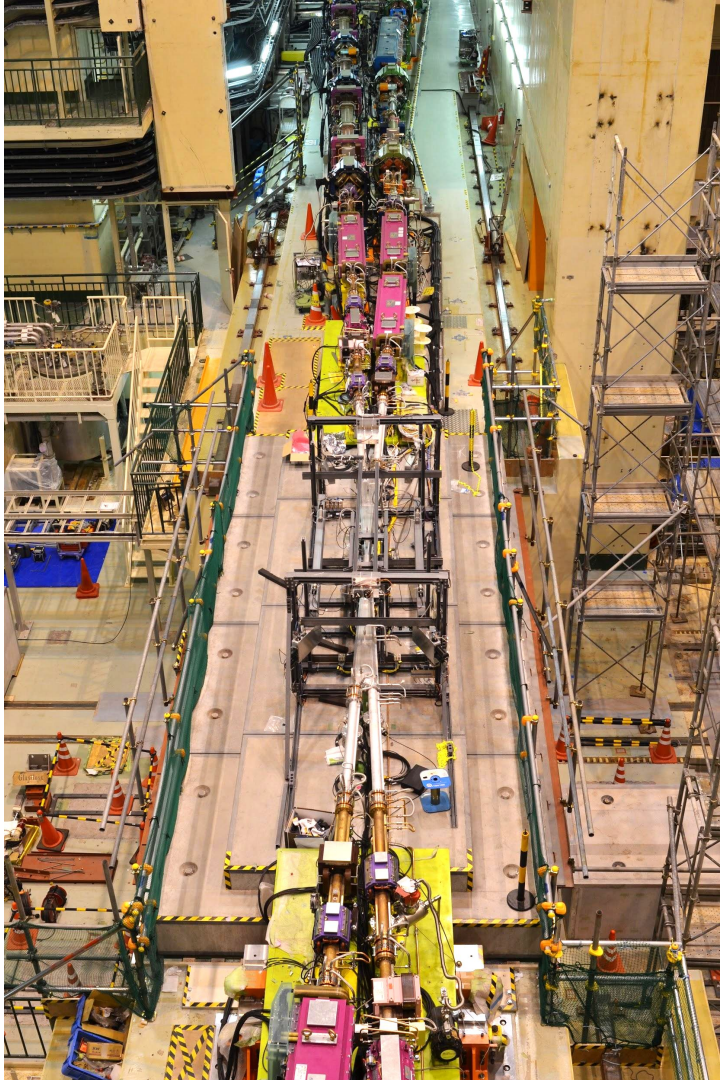
BEAST II: from the top

Location

- Crossing point of **electron beam** and **positron beam** (**interaction point, or "IP"**)
- Belle II will roll into the same location in phases II+III

Structure

- Detectors mounted on non-magnetic fiberglass structure
- Aluminum central beam pipe



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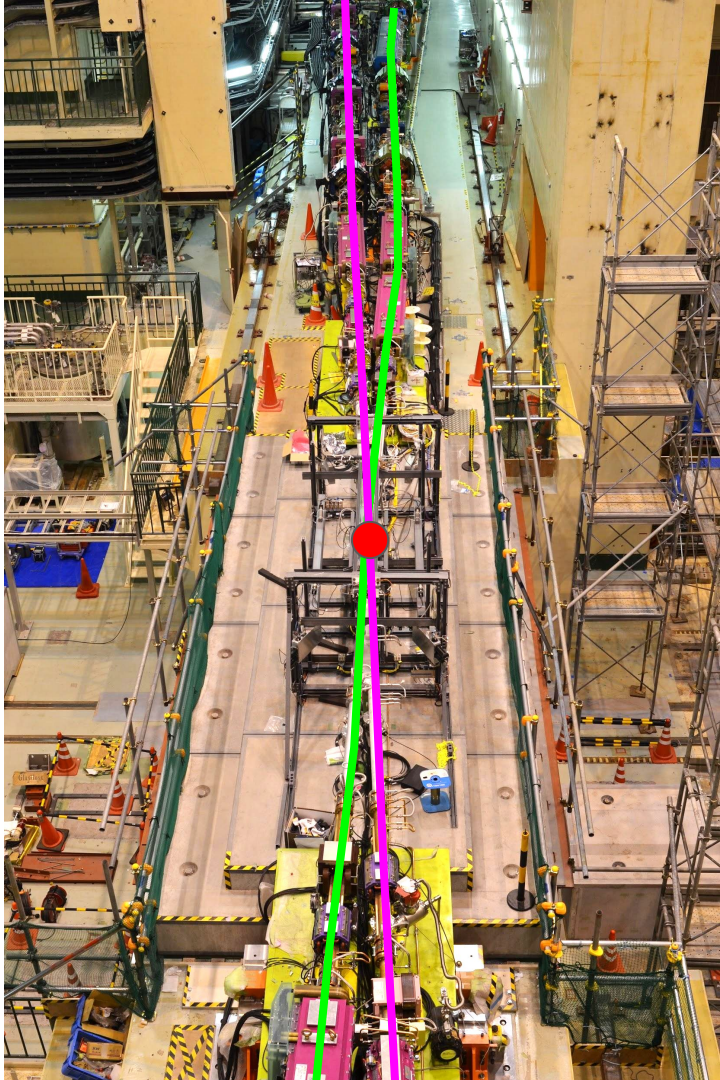
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