Early results for phase 1 of the BEAST-II experiment at SuperKEKB

2017 Congress of the Canadian Association of Physicists
Kingston (Ontario), Canada, May 29th – June 2nd, 2017

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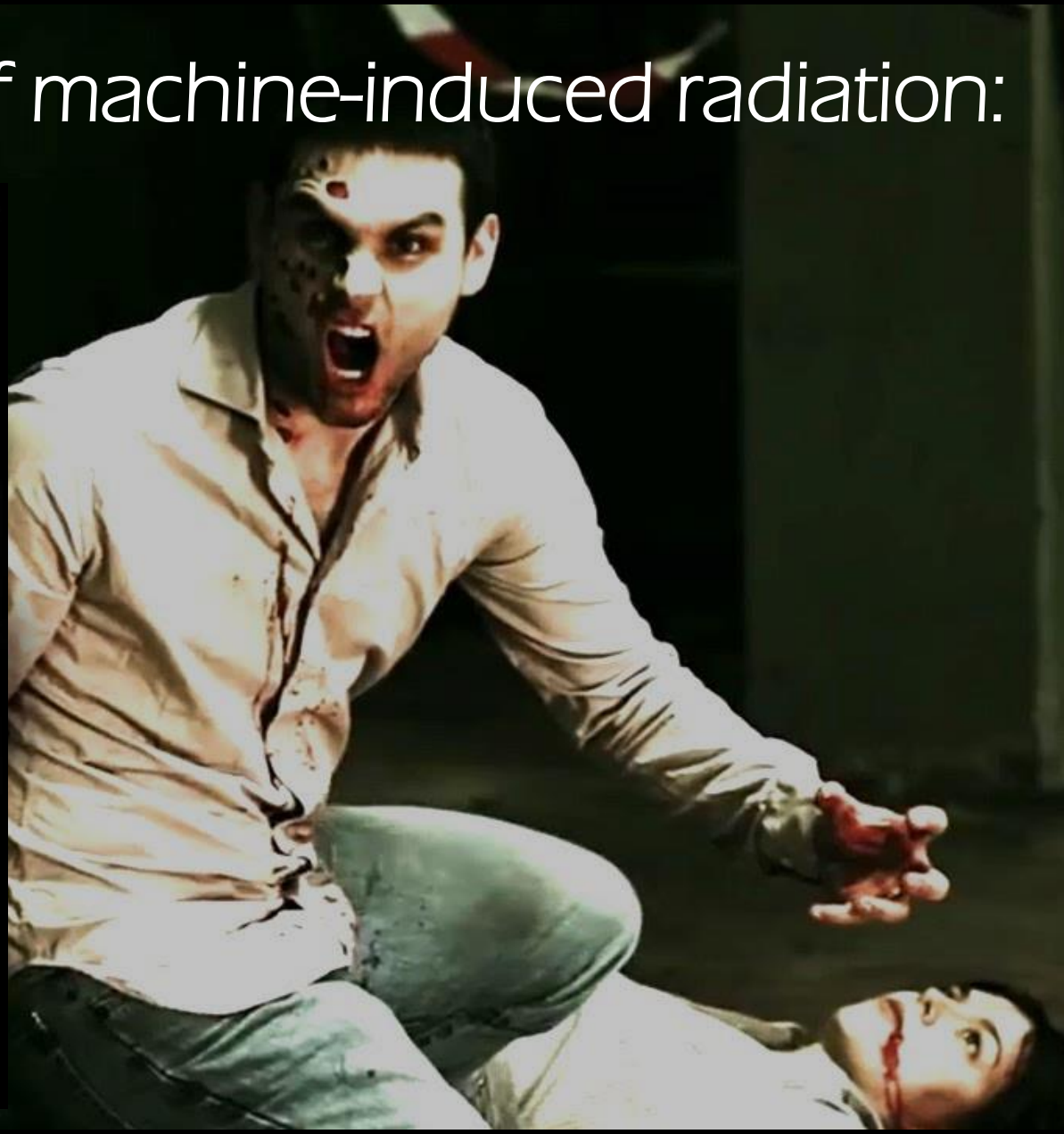
University of Victoria

Belle II

SuperKEKB Commissioning Detector
BEAST II
Belle II Collaboration

The side-effects of machine-induced radiation:



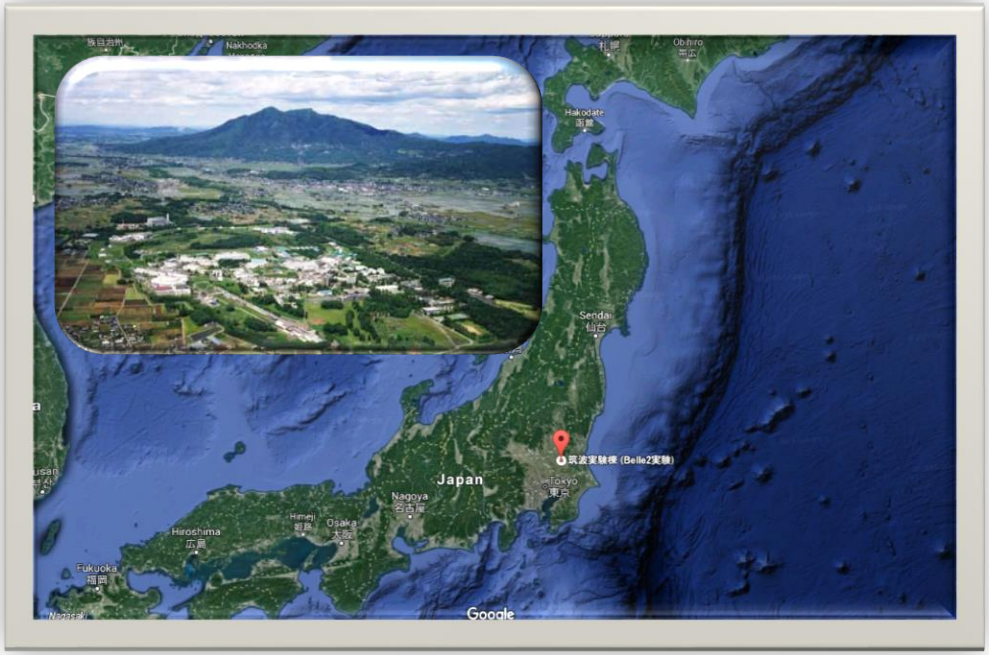
Decay. Dir. Luke Thompson. Self-distributed, 2012. Film.

The side-effects of machine-induced radiation:

It ain't always pretty!

Decay. Dir. Luke Thompson. Self-distributed, 2012. Film.

The Belle-II experiment at SuperKEKB



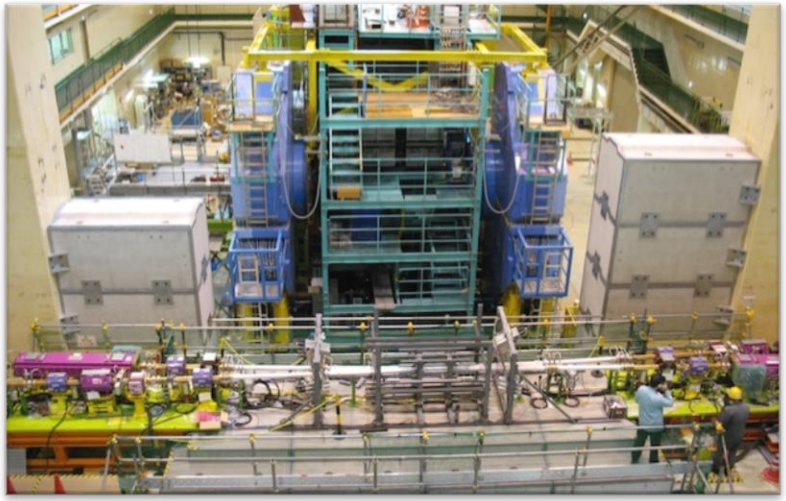
Key Scientific Goals

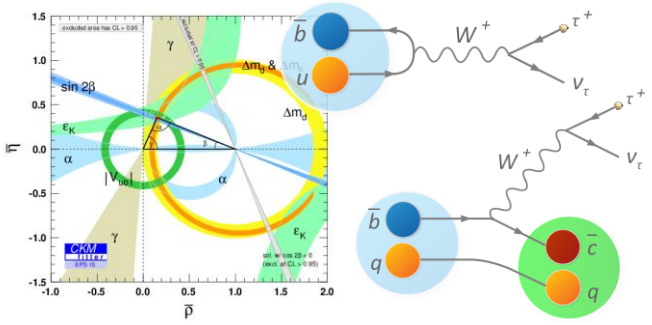
Address fundamental questions about the Universe with measurement at the Precision Frontier in collisions of electrons and positrons

- Matter / anti-matter asymmetry
- New fundamental forces in nature?
- What is the nature quarks and leptons?
- What is the nature of dark matter?

Conduct high-luminosity / high-precision measurements

- Direct searches for new processes
- Precision measurements of standard model parameters





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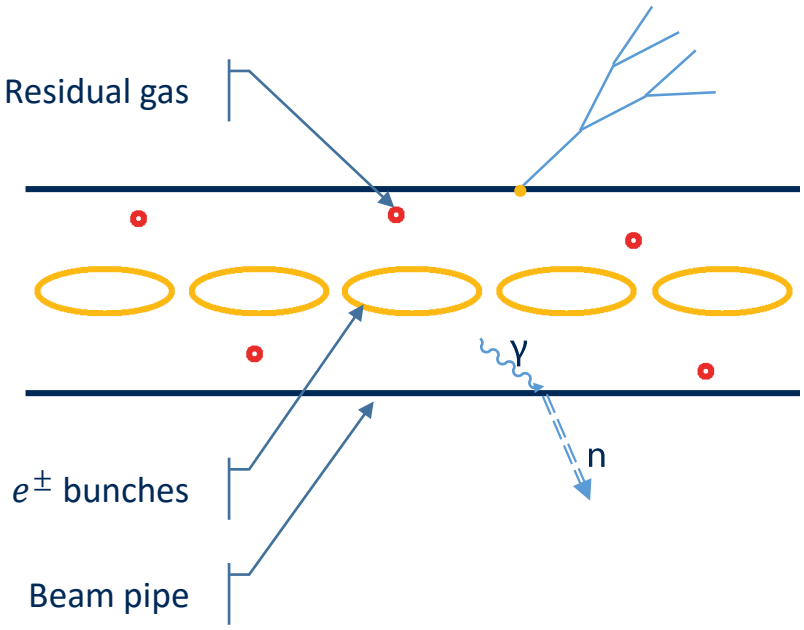
Some background on backgrounds

What we mean by machine-induced (or “beam”) backgrounds?

- Particle colliders (e.g. SuperKEKB) circulate ‘bunches’ of charged particles
- Finite beam lifetime: losses arising from a number of physical processes
- Lost particles hit the walls of the vacuum chamber; generate EM showers, neutrons
- Secondary particles reach the detector, irradiate sensors and “pollute” physics signals



Many physical processes involved

- Synchrotron radiation
- Giant dipole resonance
- Beam-gas interactions
- Intra-bunch effects
- Beam-beam interactions
- Photon-stimulated desorption
- Electron cloud effect
- Injection background

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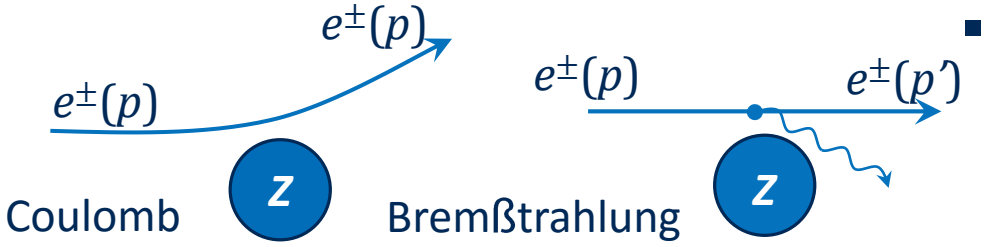
Expected background sources during phase 1

Only contributions independent of luminosity are expected

$$\frac{dN}{dt} = \underbrace{A \cdot IPZ_e^2}_{\text{Beam-gas}} + \underbrace{B \cdot \frac{I^2}{\sigma_y}}_{\text{Touschek}} + \underbrace{\cdots}_{\text{Other effects}}$$

Beam-gas interactions

- Beam particles scattering off residual gas atom nuclei (charge Z)
- Coulomb and Bremßtrahlung
- Predicted $\boxed{\text{Rate}_{\text{beam-gas}} \propto I_{\text{tot}} P Z_e^2}$
- Should decrease as a power-law w.r.t. integrated beam dose



Touschek effect

- Intra-bunch scattering $(p_{\parallel} \leftrightarrow p_{\perp})$
- Beam particle kicked out of acceptance
- Predicted $\boxed{\text{Rate}_{\text{Touschek}} \propto \frac{I^2}{\sigma_y}}$

Other operational losses

- Do not fit the simplest picture.
- Harder to simulate. *e.g.*
  - Injection-related noise

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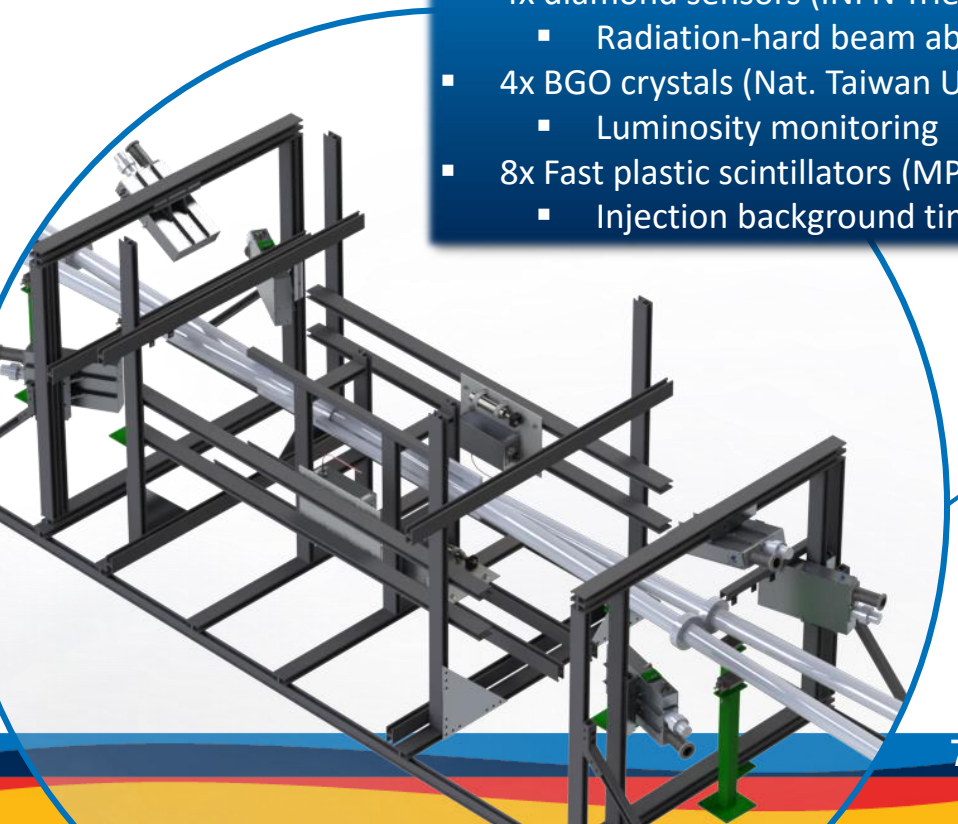
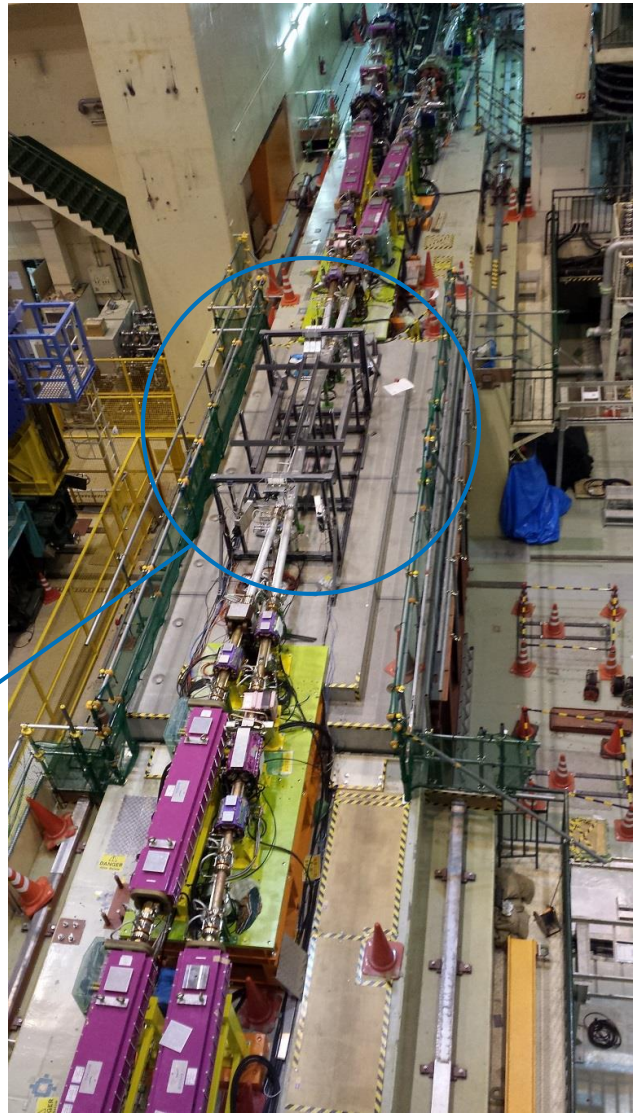
Meet the BEAST: Beam Exorcism for a Stable Experiment

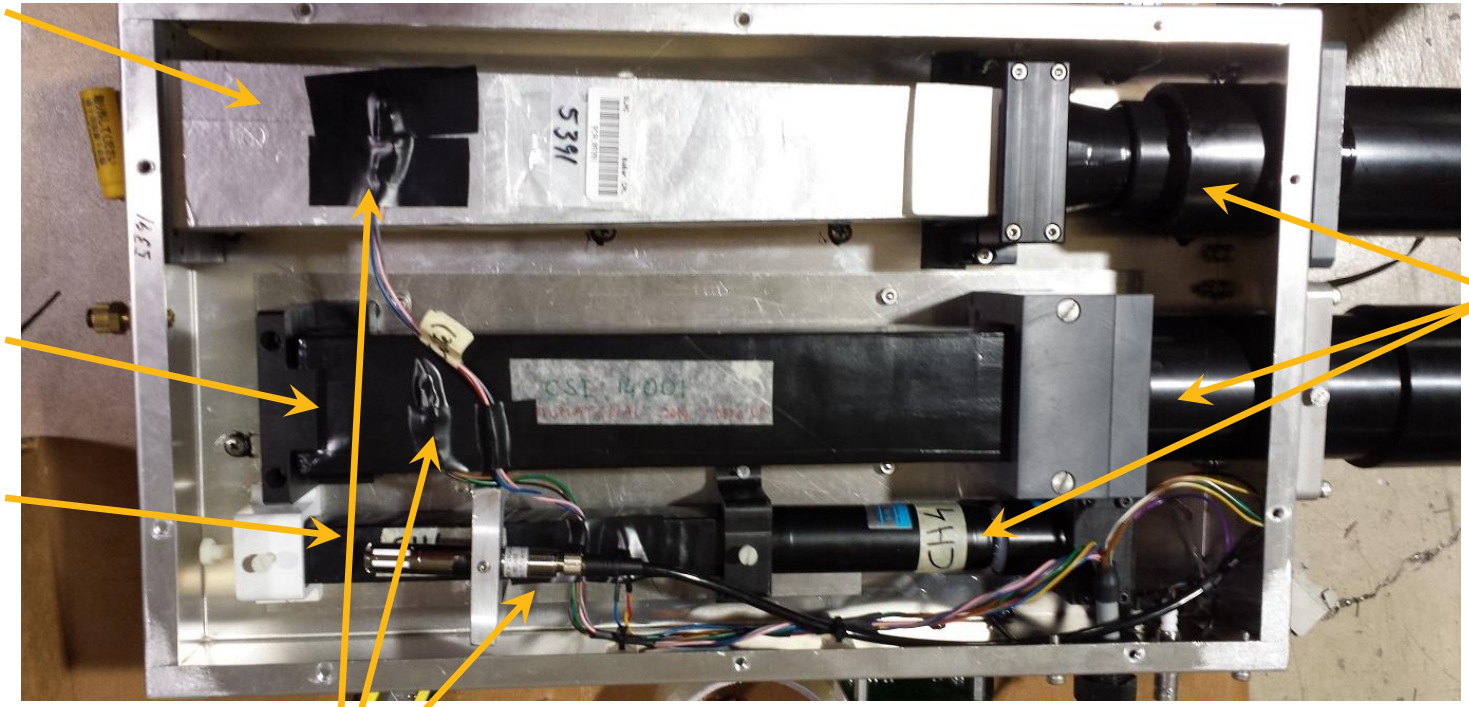
- 4x He3 tubes (UVic)
  - Thermal neutron detectors
- 6x Crystal calorimeter units (UVic)
  - EM radiation measurement
- 4x µTPCs (University of Hawaii)
  - Directional fast neutron detection
- 64x PIN diodes (Wayne State, UH, KEK)
  - x-ray dose along z-axis
- 4x diamond sensors (INFN Trieste)
  - Radiation-hard beam abort sensors
- 4x BGO crystals (Nat. Taiwan University)
  - Luminosity monitoring
- 8x Fast plastic scintillators (MPI Munich)
  - Injection background time-structure





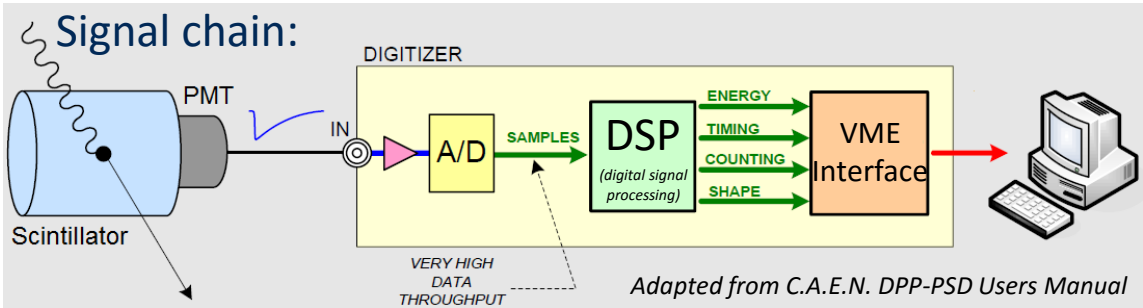
Inside one crystal calorimeter unit: three crystals and readout

Photograph of the BEAST Crystal setup at KEK before installation



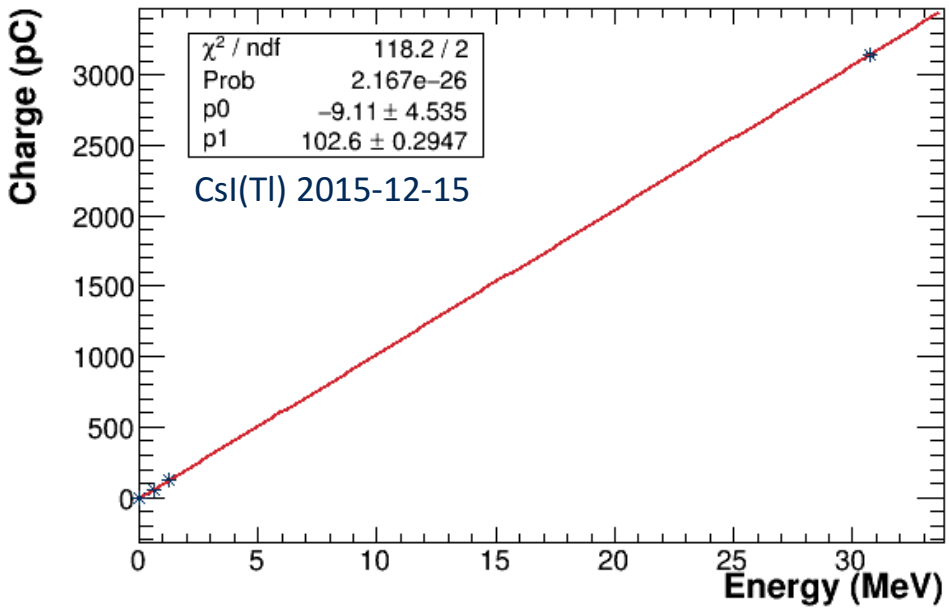
Environment monitors

- 3 × temperature
- 1 × relative humidity

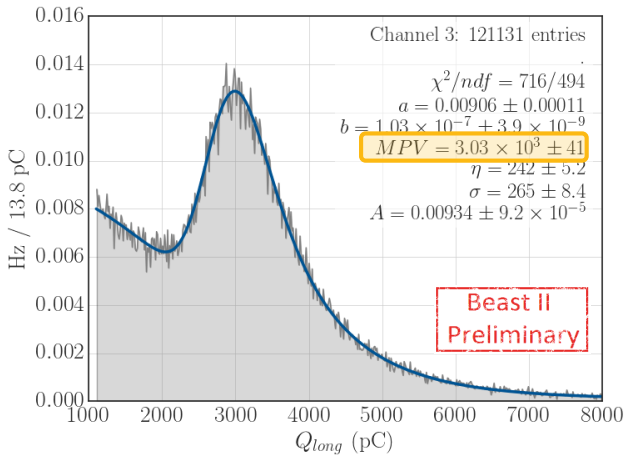


Calibration and dose-dependence of system gain

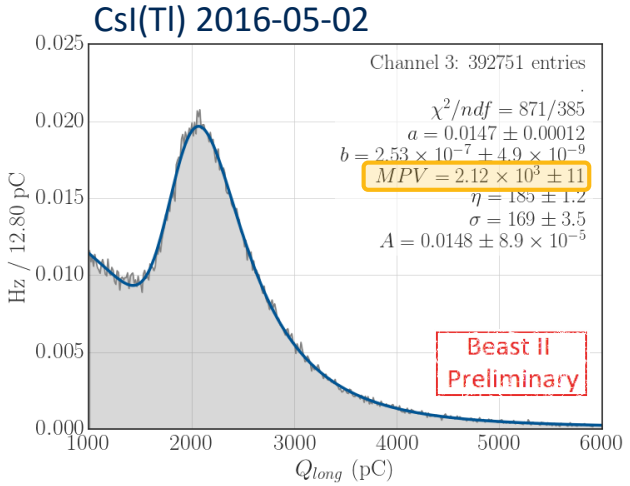
- 3-point energy calibration using pedestal run, ^{60}Co source and cosmic ray muons
- Notable calibration changes during data-taking period
- Absorbed dose: 10-100 Gy (depending on channel)
- CsI(Tl) radiation hardness study by Longo (2016)
  - 10Gy →reduction in gain between 5% and 45%
  - Possible PMT damage on top



CsI(Tl) 2016-01-29

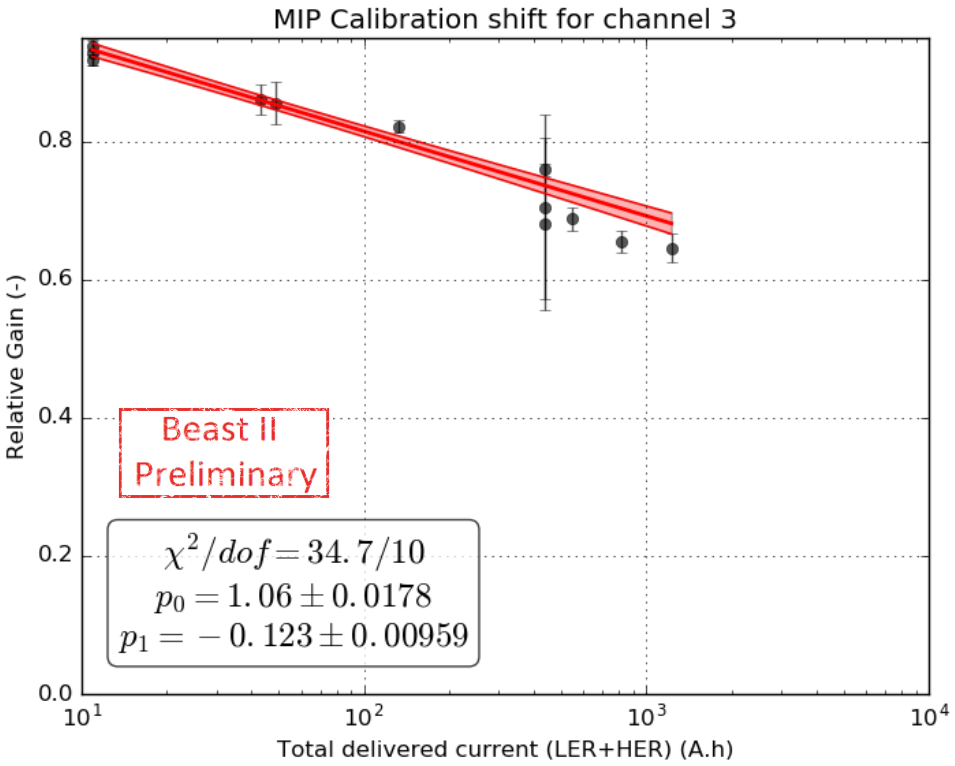


CsI(Tl) 2016-05-02

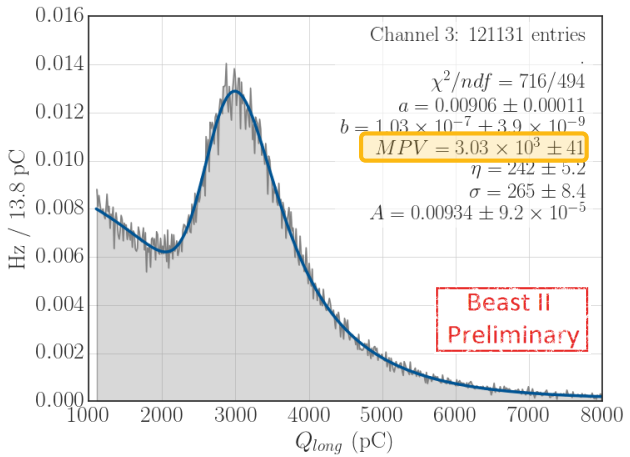


Calibration and dose-dependence of system gain

- Notable calibration changes during data-taking period
- Need to track ‘daily’ changes in gain. Use cosmic muons
- Correct energy measurements relative to beam dose:



CsI(Tl) 2016-01-29



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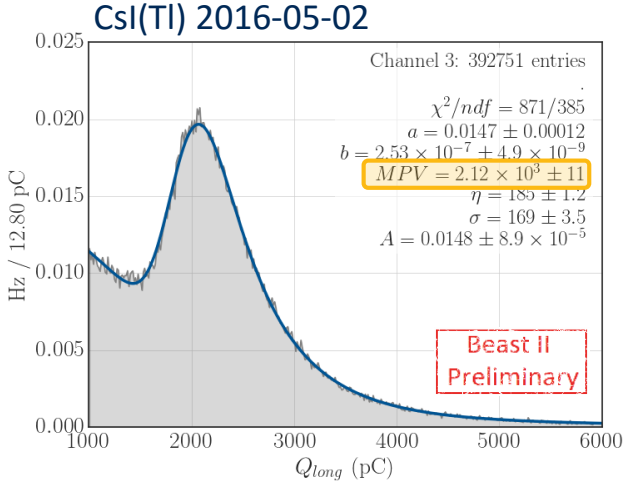
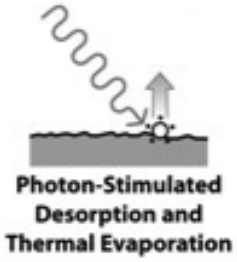


Data taking February – June 2016

Lessons from beam-gas interactions: vacuum scrubbing

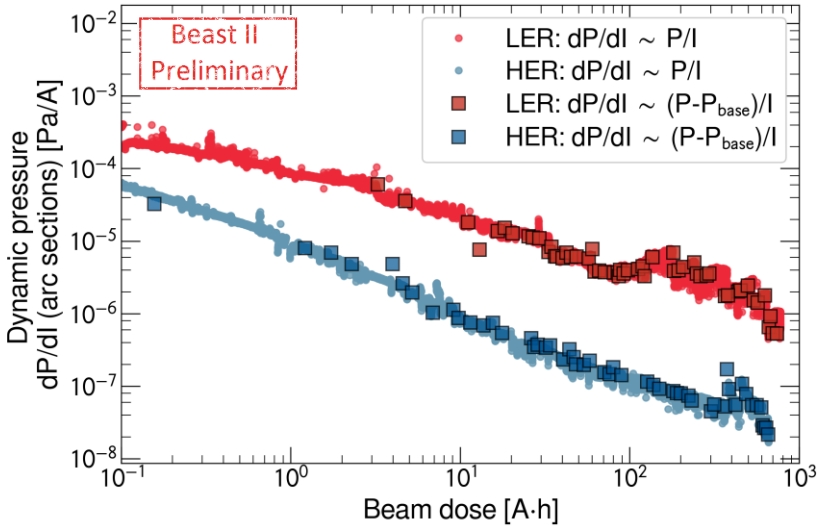


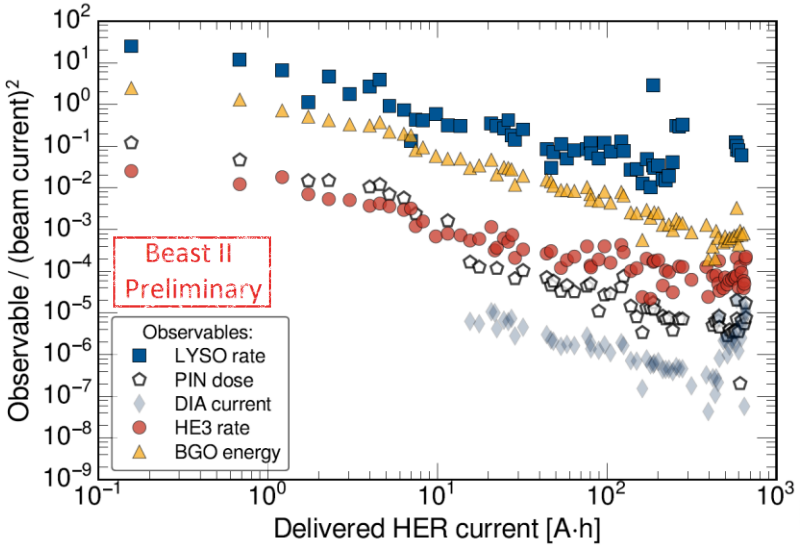
- During operation: photons and electrons hit the vacuum chamber walls, and eject molecules adsorbed on the surface
- Pressure is indeed 'dynamic':

$$P \sim P_{\mathrm{base}} + I \cdot dP/dI$$

  - dP/dI is linked to the probability of desorption of a gas molecule
  - P_{base} is the dynamic equilibrium pressure (2×10^{-8} Pa HER ; 5×10^{-8} Pa LER)
- This probability decreases as a power-law w.r.t. delivered beam current, so should beam-gas background rates.

✓ Indeed, this is observed in the time (or dose) dependence of backgrounds:



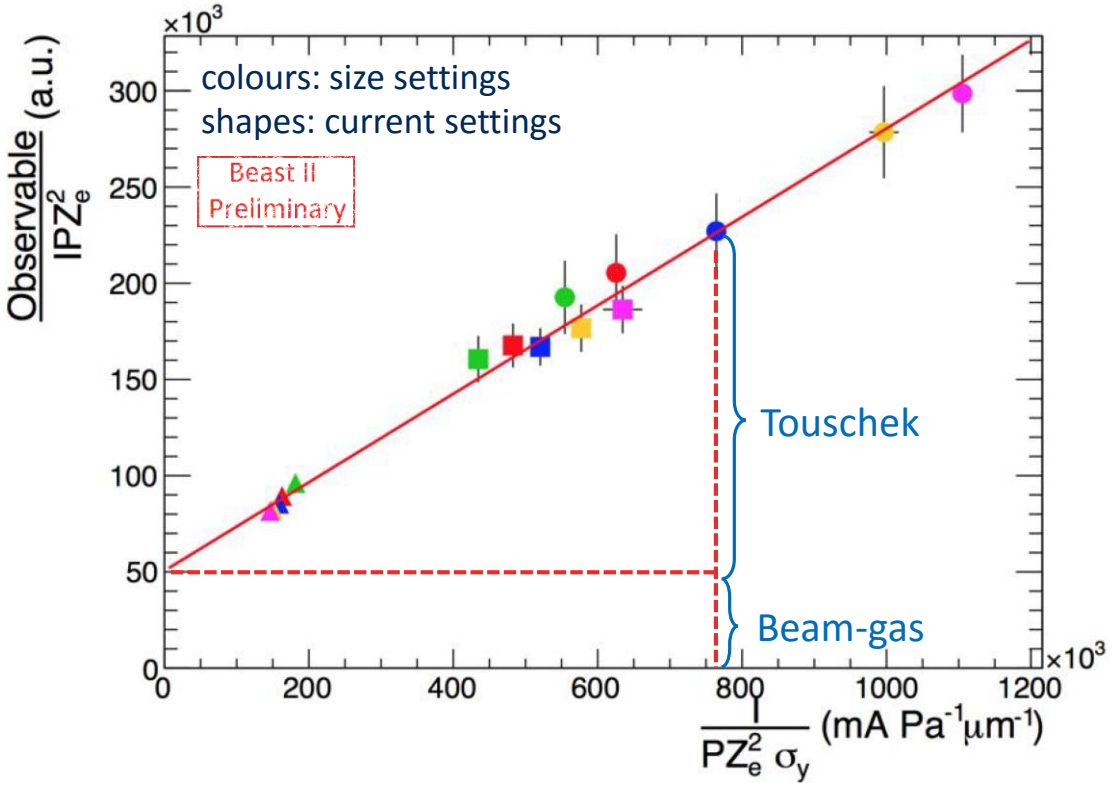


Beam loss model: a ‘heuristic’ model for analysis

- Study runs: artificially enhance one contribution by systematically scanning parameters

$$\frac{dN}{dt} = A \cdot IPZ_e^2 + B \cdot \frac{I^2}{\sigma_y}$$

- Dividing by IPZ_e^2, we can fit line to disentangle Touschek and beam-gas effects
- Example: Dose rate seen by BGO during LER size (σ_y) and current (I) sweeps



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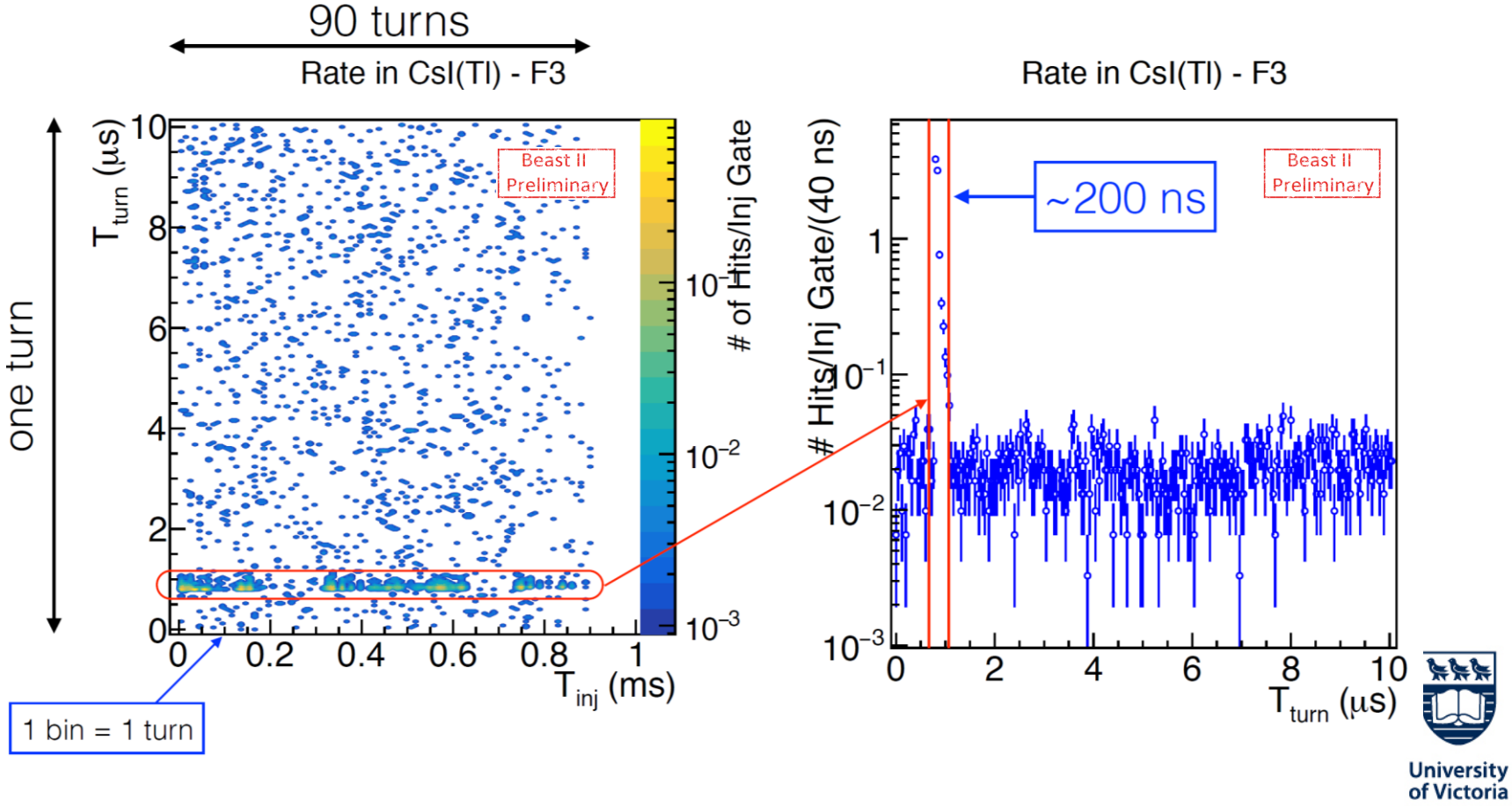
Lessons from injection background: first measurement

- Injection: filling of the bunches with the lowest charge
- "Noisy" process ($\epsilon < 1$), achieved while experiment is running
- No current simulation is able to predict effects of continuous-injection scheme
- Prime interest for machine settings and vetoing pixel detector DAQ



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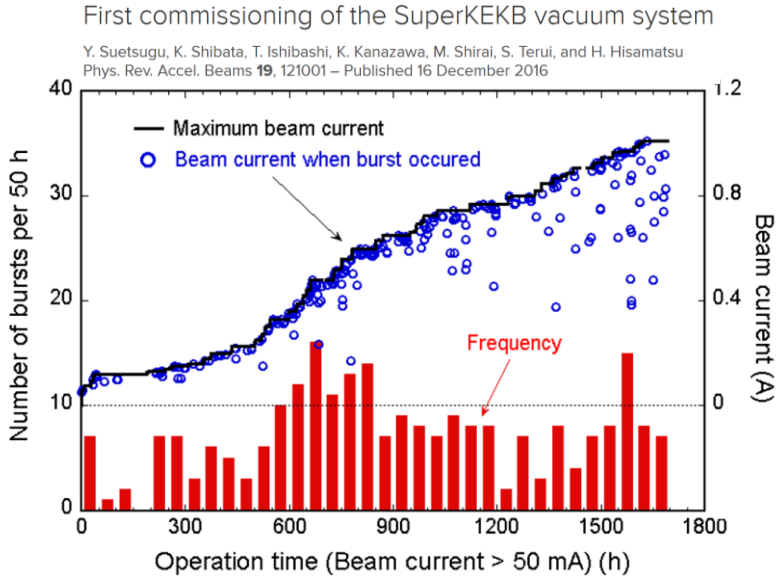
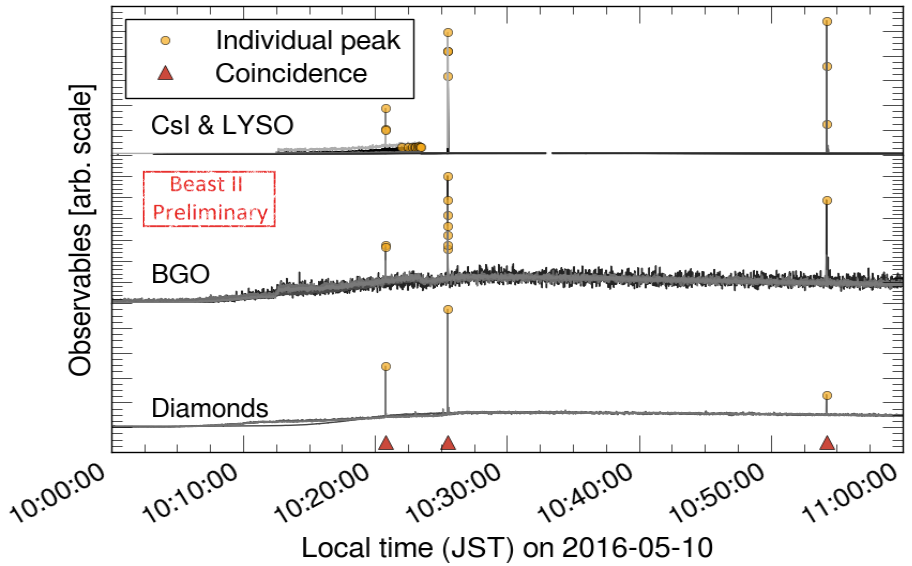
Transients (aka beam-dust, UFOs)

- Sharp pressure “bursts” measured by accelerator group leading to beam aborts
  - Can BEAST measure corresponding increase in background?
  - Do these events correlate with operating conditions and history?
  - How the resulting dose compare to normal operating conditions?
  - Are these peaks a hazard for the Belle II detector?
- Methodology:
  - Peak is sample at least 6 std. dev. above signal mean (60s time window)
  - Require at least 2 different channels from 2 different subdetectors
- Results: Not public yet, so stay tuned!





Conclusions

- The BEAST experiment provides **critical data to test and improve our models** of machine induce background
- **Successful data-taking** period for phase I between February and June, 2016
- The BEAST detectors were able to observe a **great range of phenomenon**
- Most goals for phase 1 have **been met**
- Current challenges:
  - Absolute dose calculations
  - Data/simulation comparisons
- Final report (Belle 2 note) in process, to be submitted as a NIM A paper

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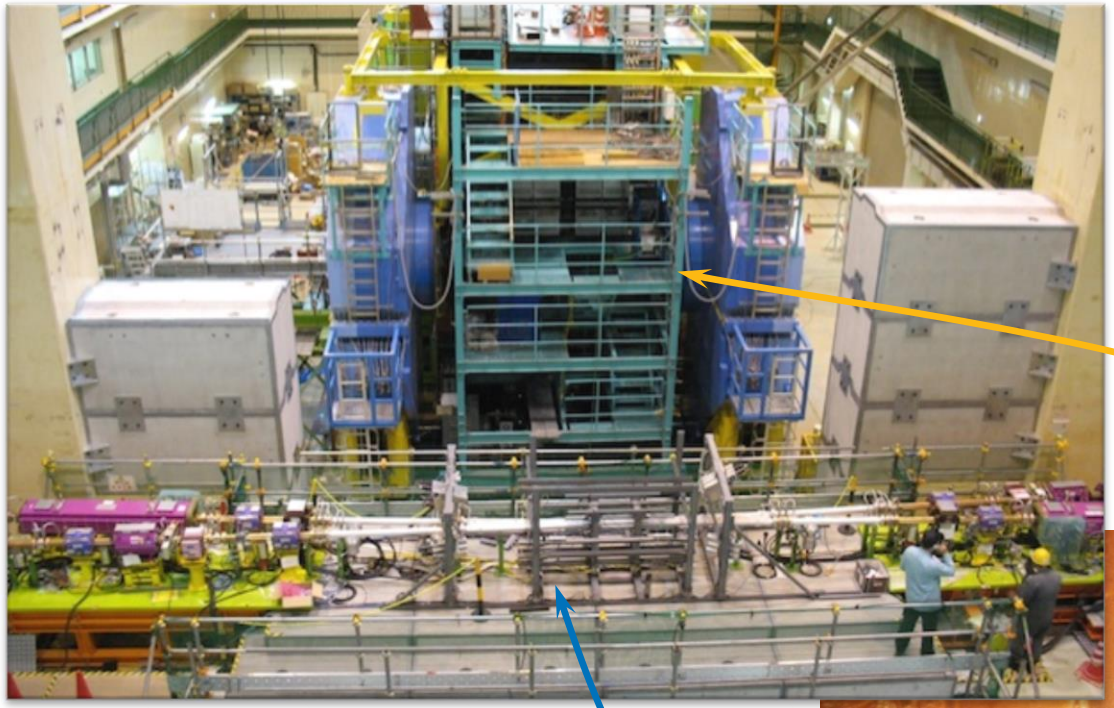
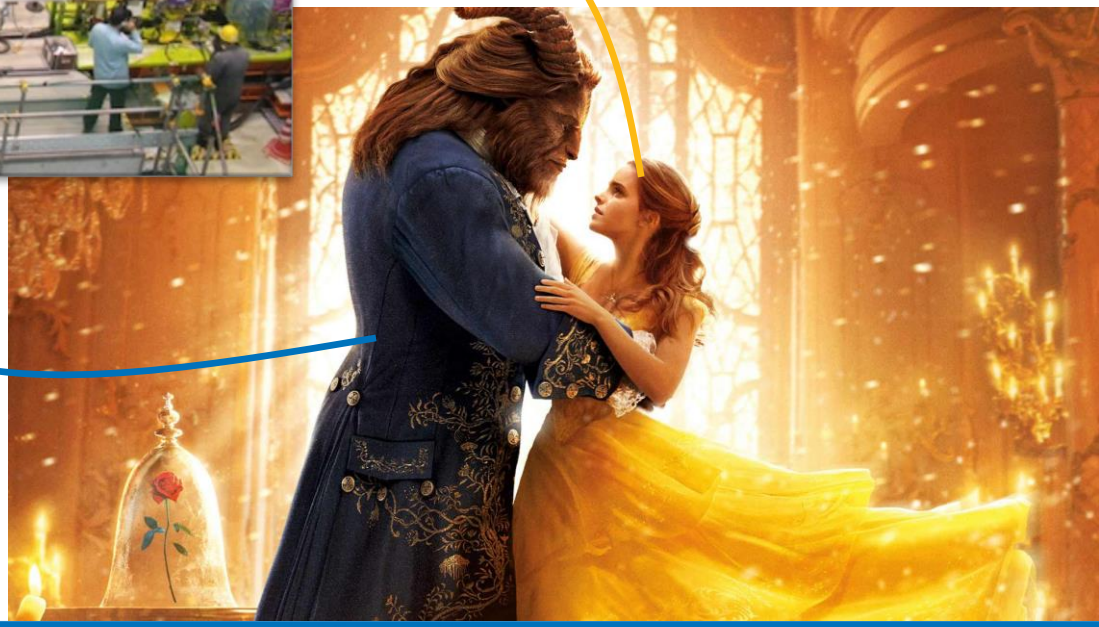
With BEAST: Beam Exorcism for a Stable Experiment



Beast phase I detector
on beam line

Belle II detector
(rolled out)



Supplemental Material

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The Belle-II experiment at SuperKEKB

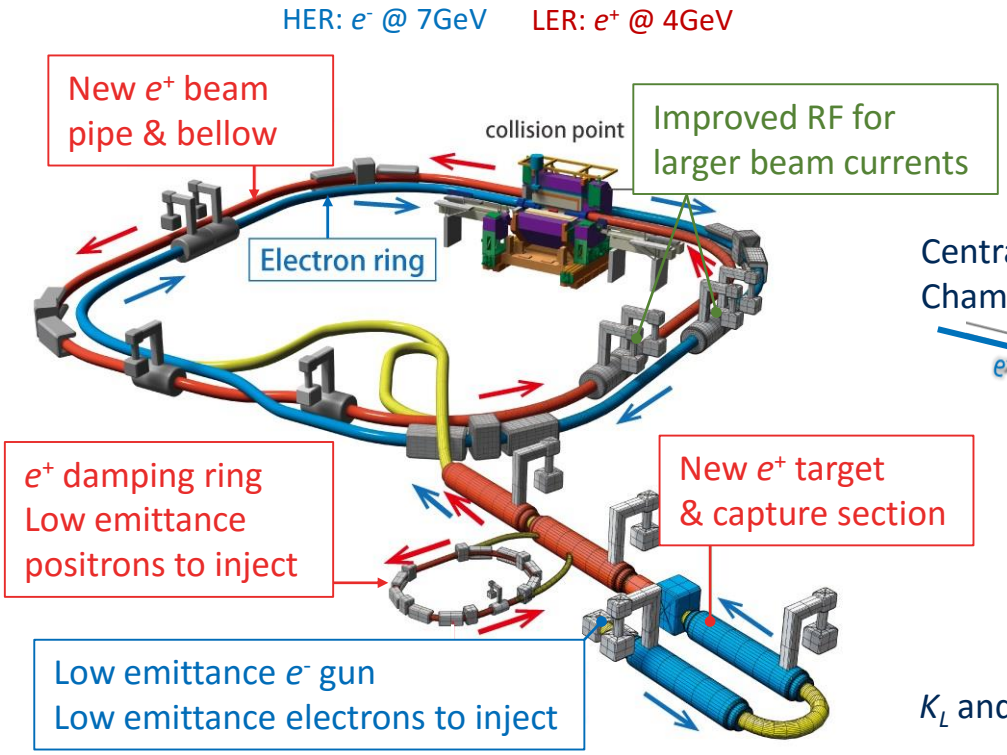
Overview of the experimental hardware

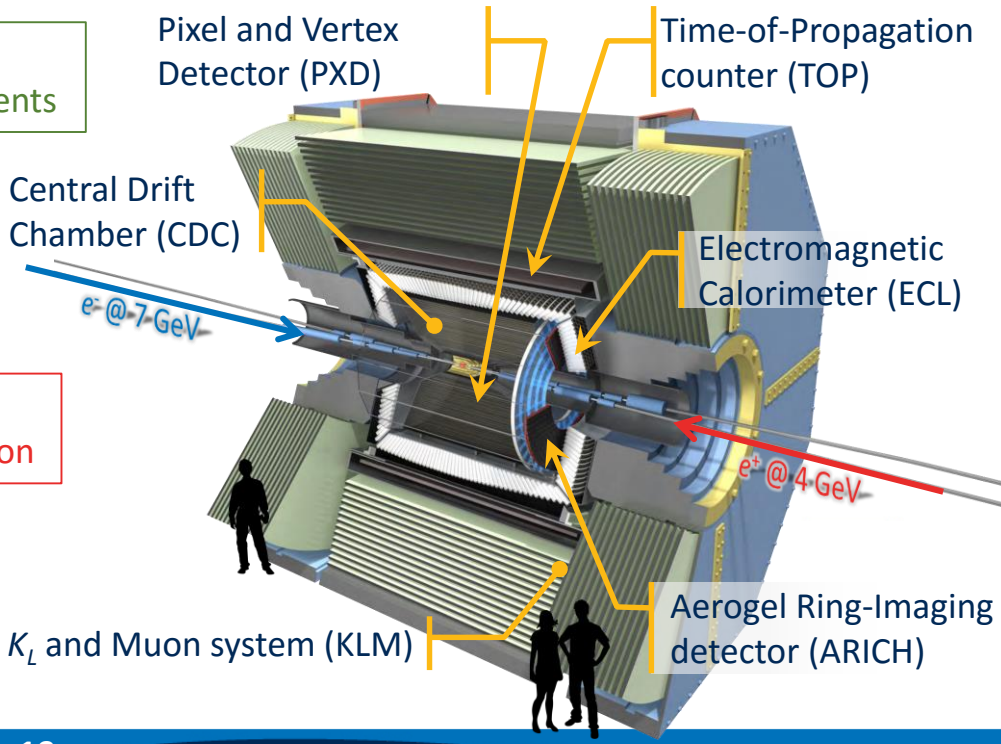
40-fold increase in luminosity

- 2x higher current 20x smaller beams

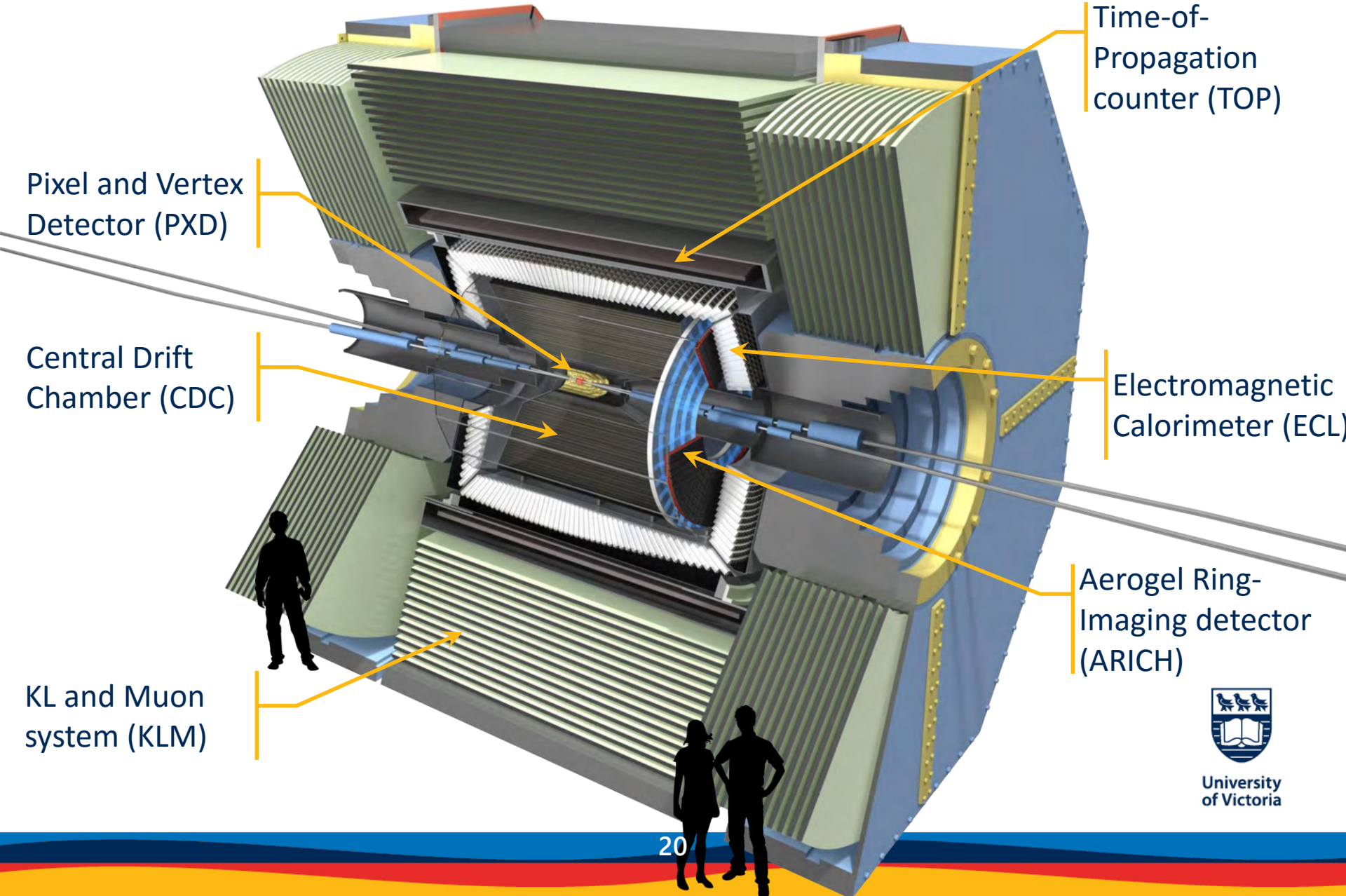
New detector in existing structure

- Upgraded components to handle higher rates, improve resolution and identification





The Belle-II detector at a glance



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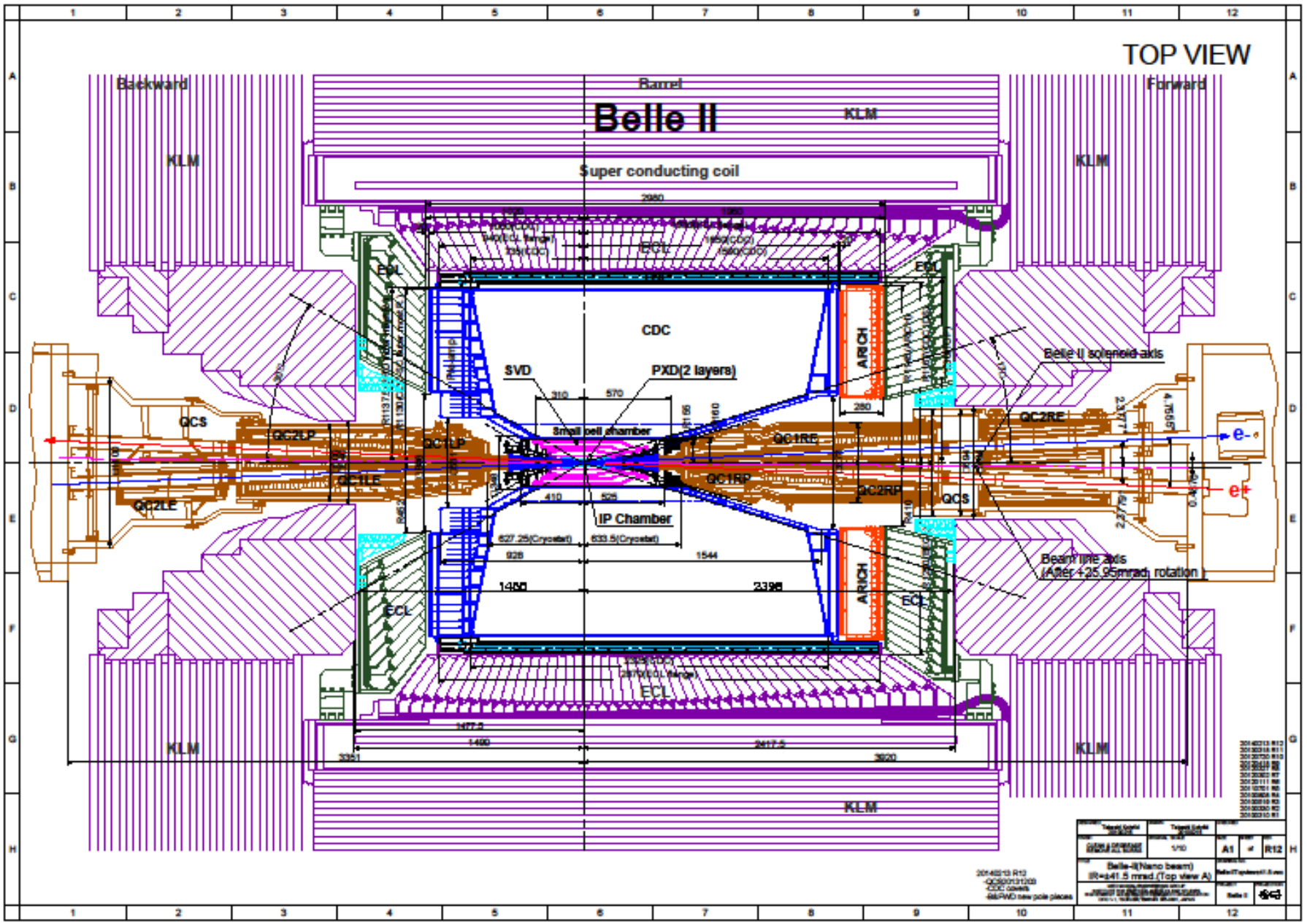
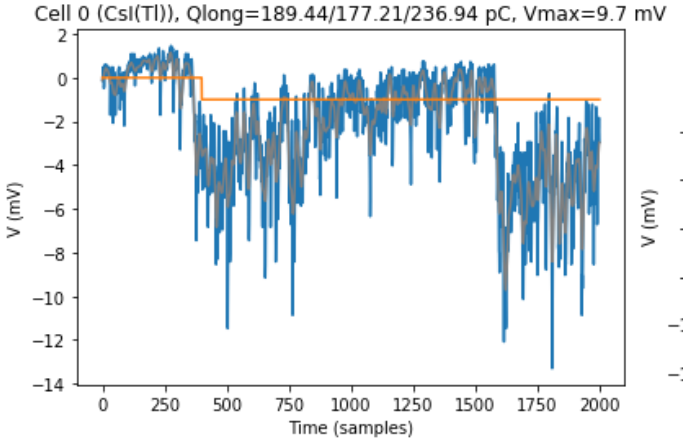
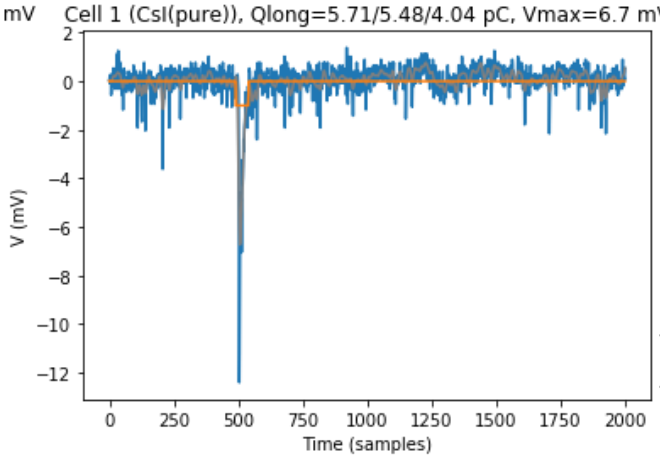
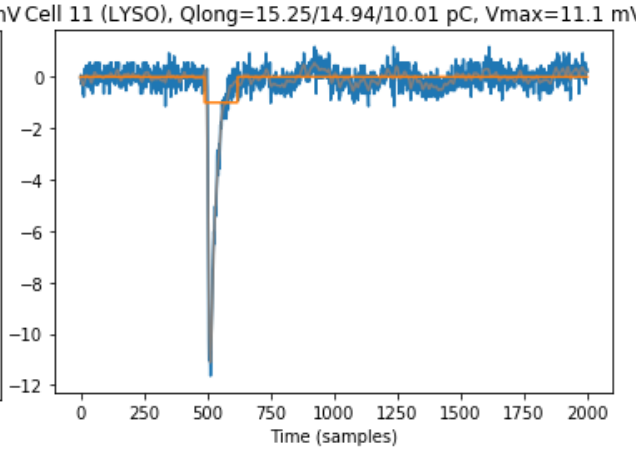

TOP VIEW
Backward
Barrel
Forward
Belle II
KLM
Super conducting coil
ECL
EID
CDC
ARICH
SVD
PXD(2 layers)
Belle II solenoid axis
Small bell chamber
IP Chamber
QCS
QC2LP
QC1LP
QC1LE
QC2LE
QC1RE
QC1RP
QC2RP
QC2RE
e-
e+
Beam line axis
(After +25.95mrad. rotation)
Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)

Waveform examples







1 time sample is 2 ns

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Calibration

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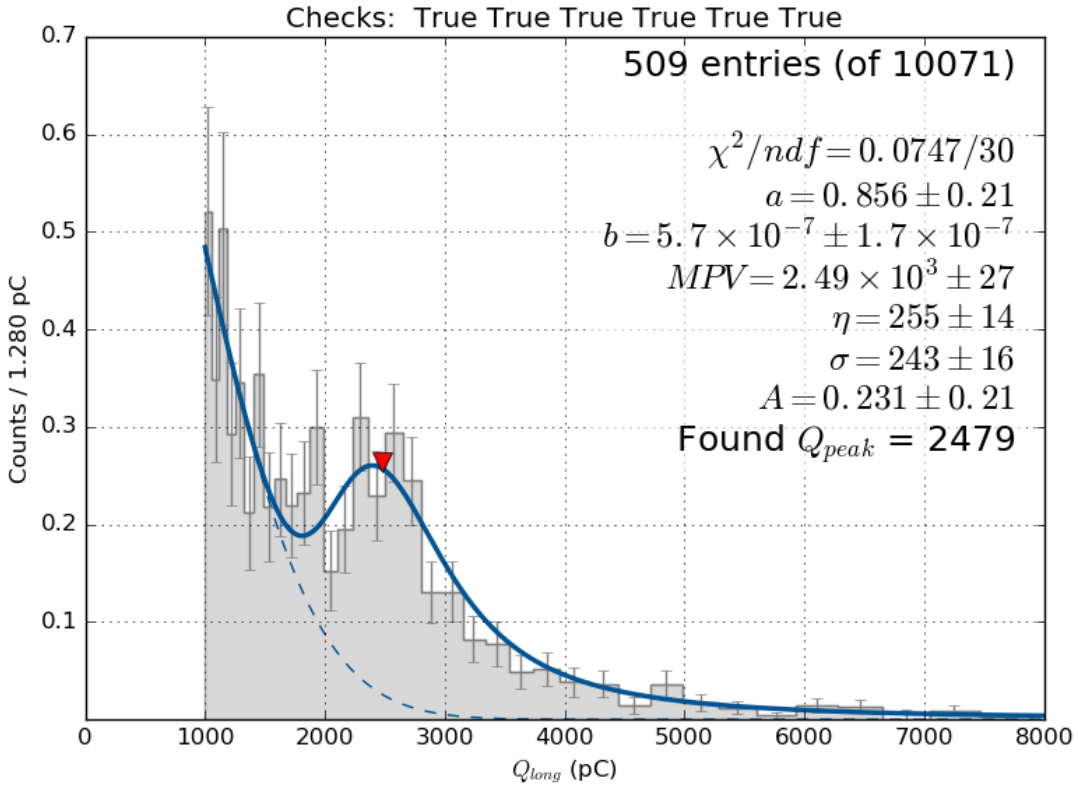
Example of low statistics “good” fit



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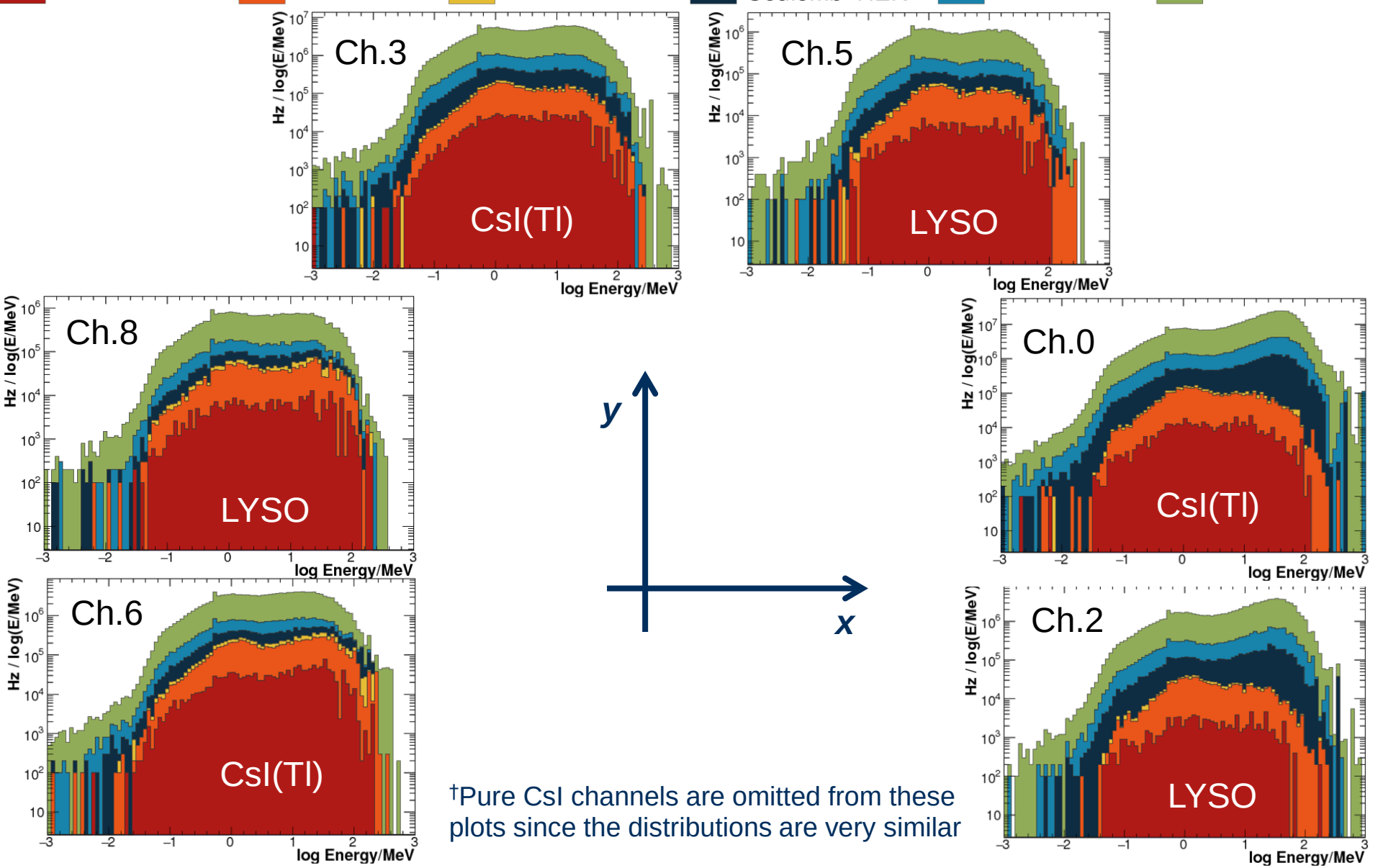
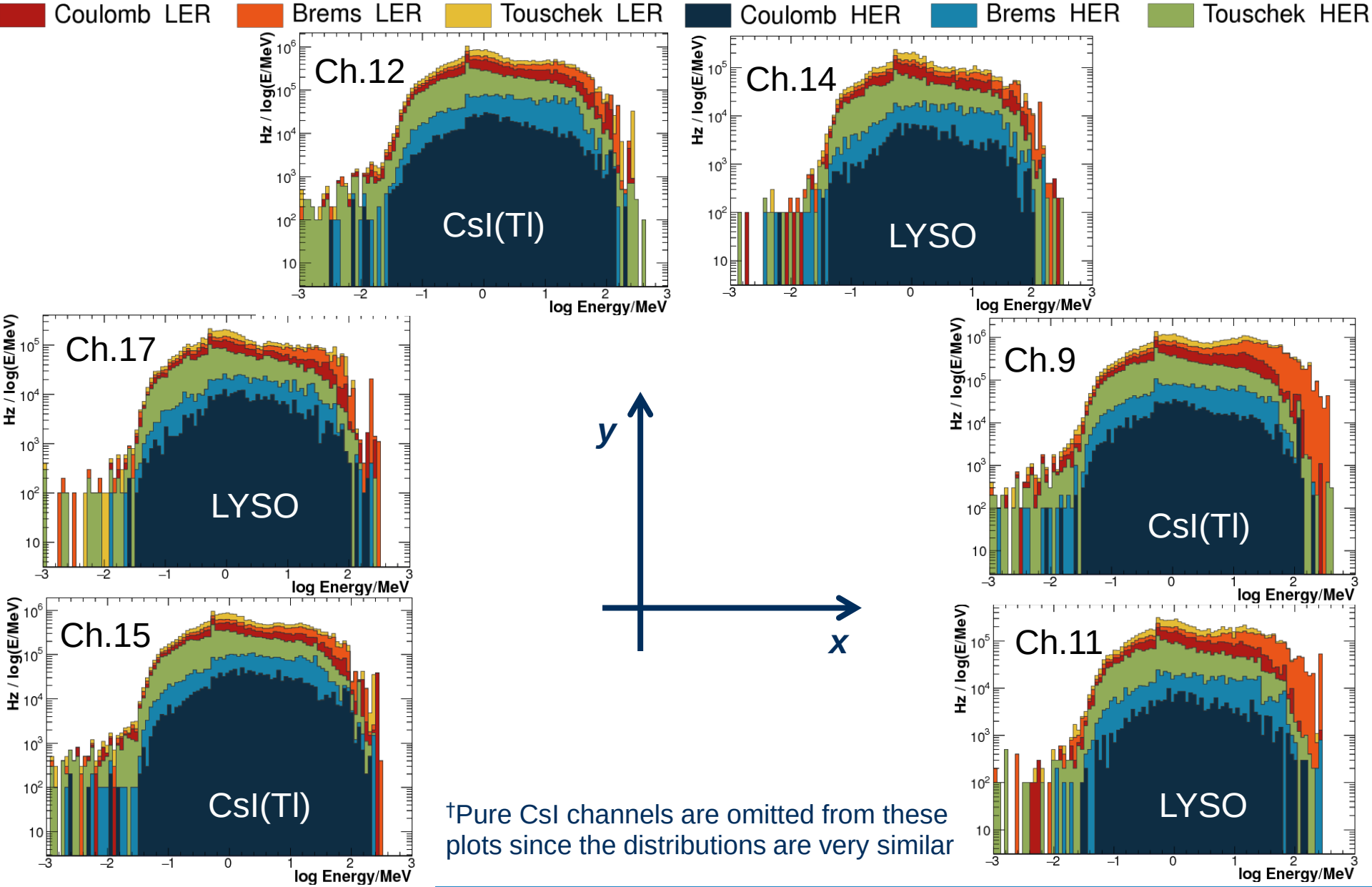
CsI(Tl) and LYSO – Forward channels†



†Pure CsI channels are omitted from these plots since the distributions are very similar

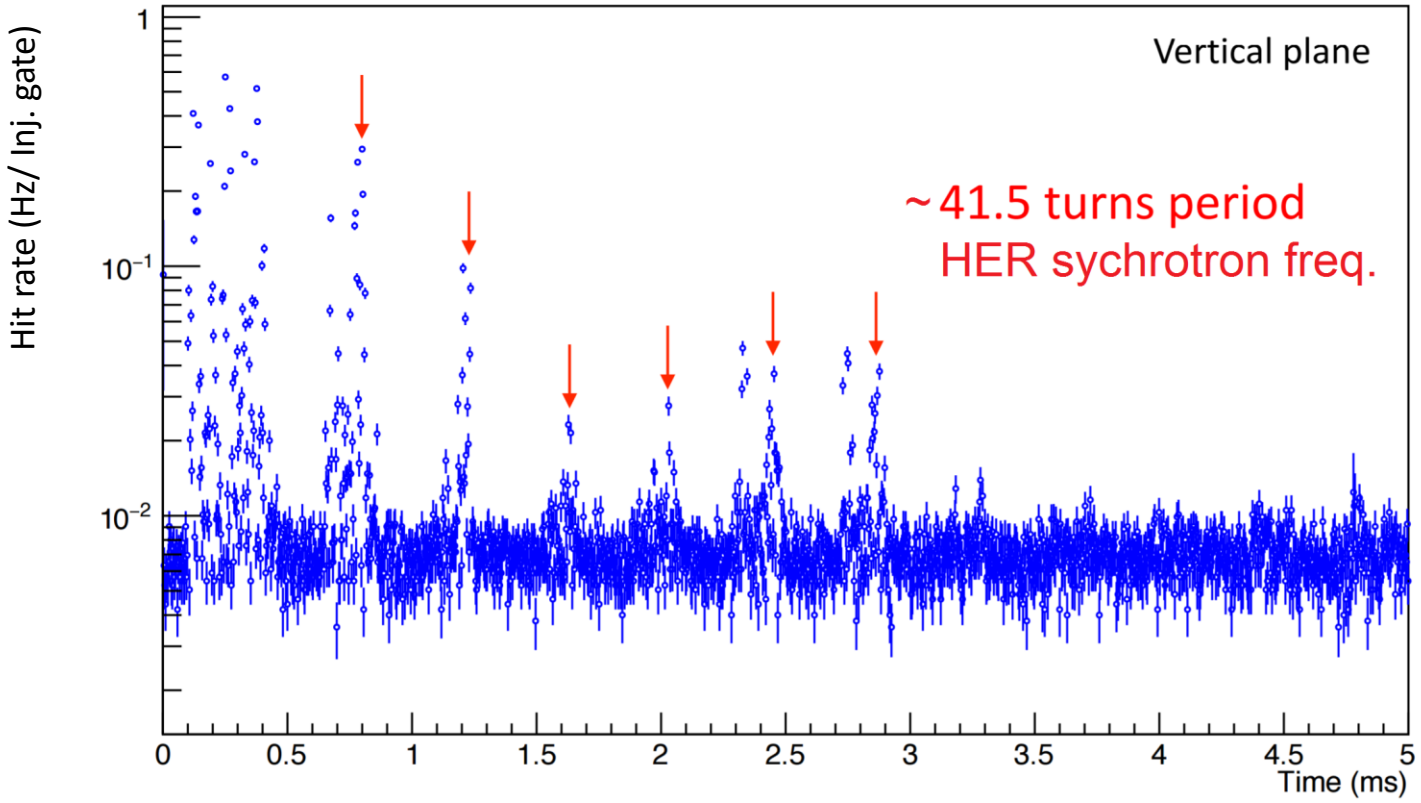
CsI(Tl) and LYSO – Backward channels†



†Pure CsI channels are omitted from these plots since the distributions are very similar

Lessons from injection background: influence of settings

- Example of degraded efficiency due to wrong injection phase
- Much longer background time structure from visible synchrotron oscillations



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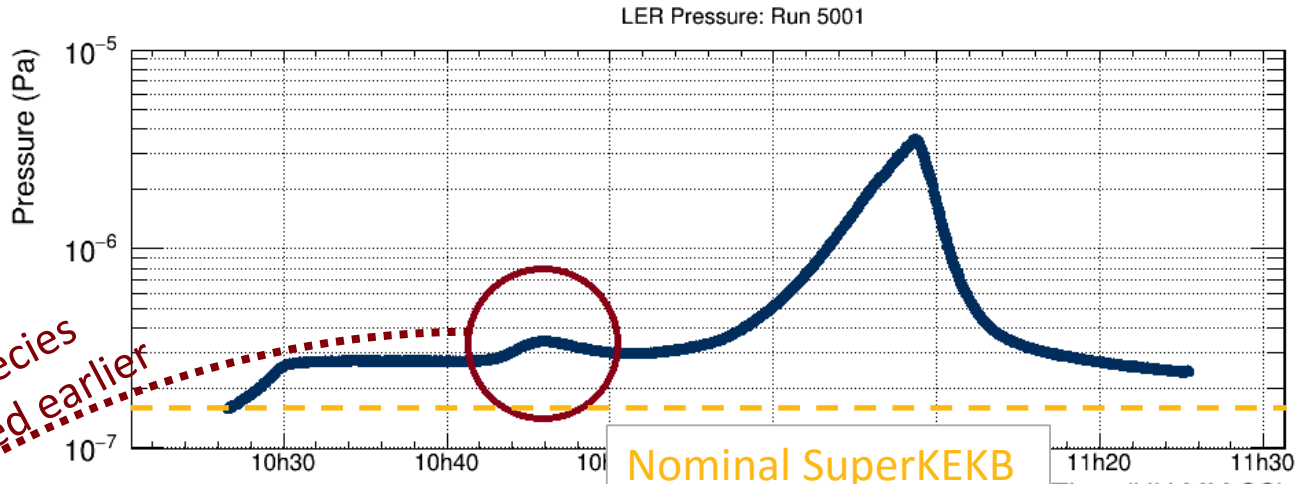
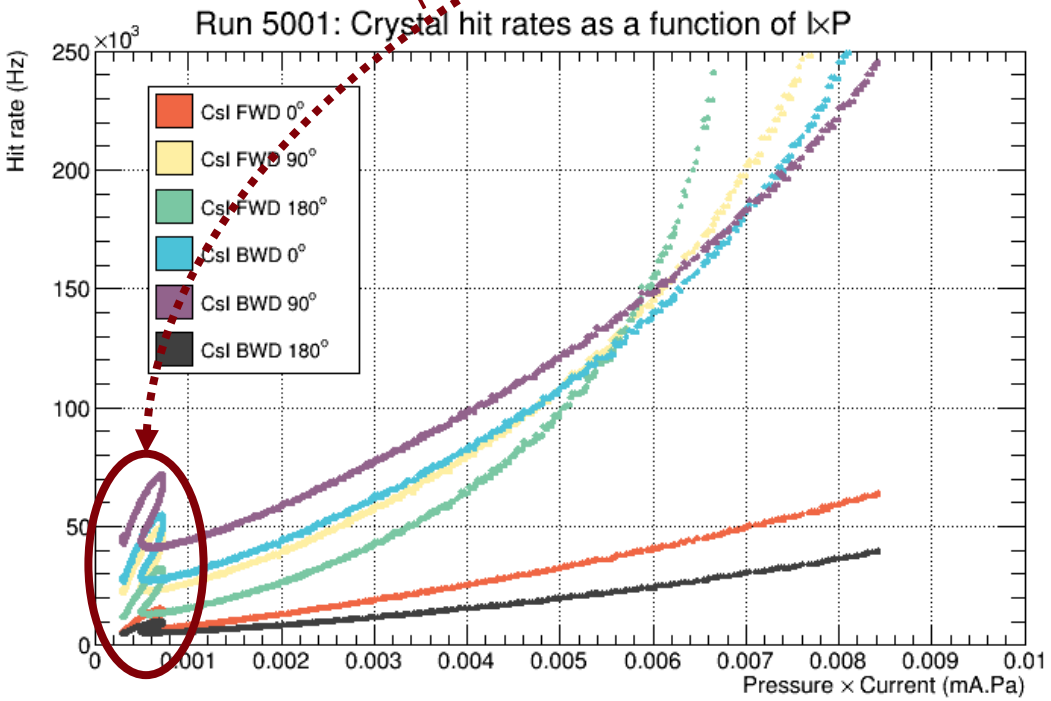
Beam-gas interactions: effect of pressure



Light species released earlier

Nominal SuperKEKB operating pressure 1.3×10^{-7} Pa



Elements to study:

- Gas-species dependence
- Location of the pressure bump

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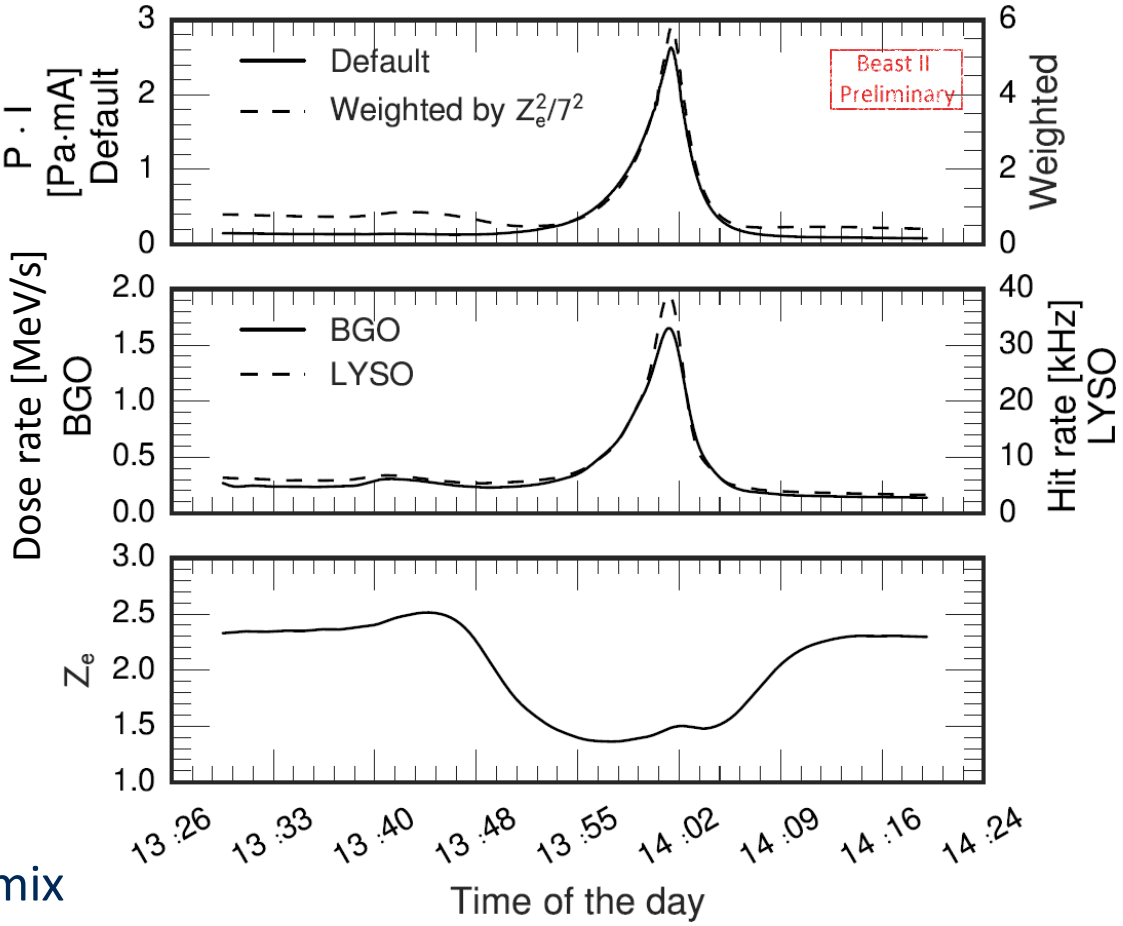
Lessons from beam-gas interactions: gas contents matters!

- Vacuum bump: increase pressure to study beam-gas losses
- Simulations assume $Z=7$, however:
  - Proportions of gas blend is not constant during the experiment
  - Residual gas analyzers were installed in the positron ring… we should use them



$$\langle Z_e^2 \rangle = \frac{\sum_j b_j Z_j^2}{\sum_j b_j}$$

b_j : the proportion b_j of each *element* Z_j in the mix

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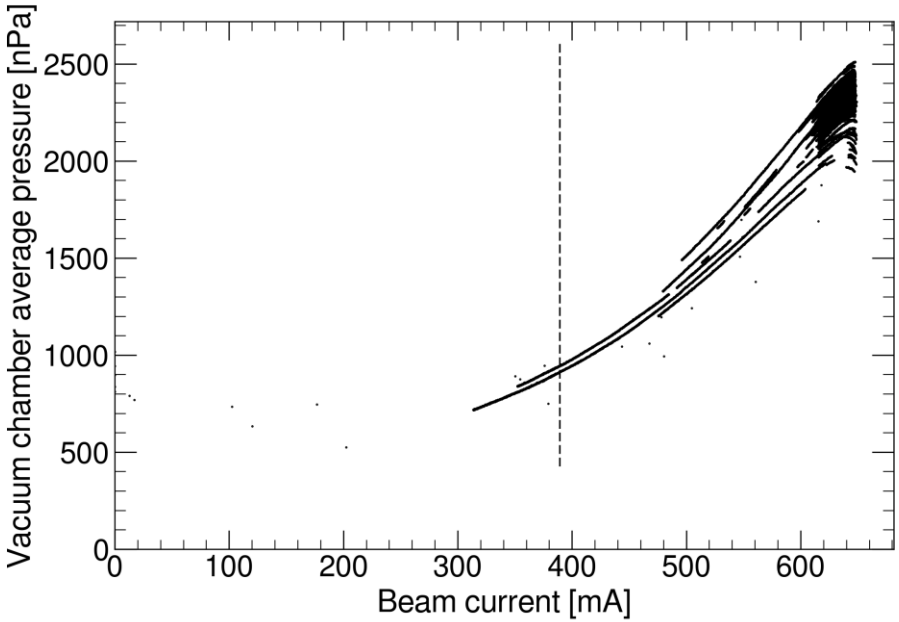
Lessons from beam-gas interactions: dynamic pressure

- ‘Marco’ analysis possible using the ‘dynamic pressure’:

$$P \sim P_{\mathrm{base}} + I \cdot dP/dI$$

  - dP/dI is linked to the probability of desorption of a gas molecule
  - P_{base} is the dynamic equilibrium pressure (2×10^{-8} Pa HER ; 5×10^{-8} Pa LER)
- However useful, this representation isn’t accurate to look at the detail of the beam-gas probabilities…
- Pressure not a quite linear function of current:



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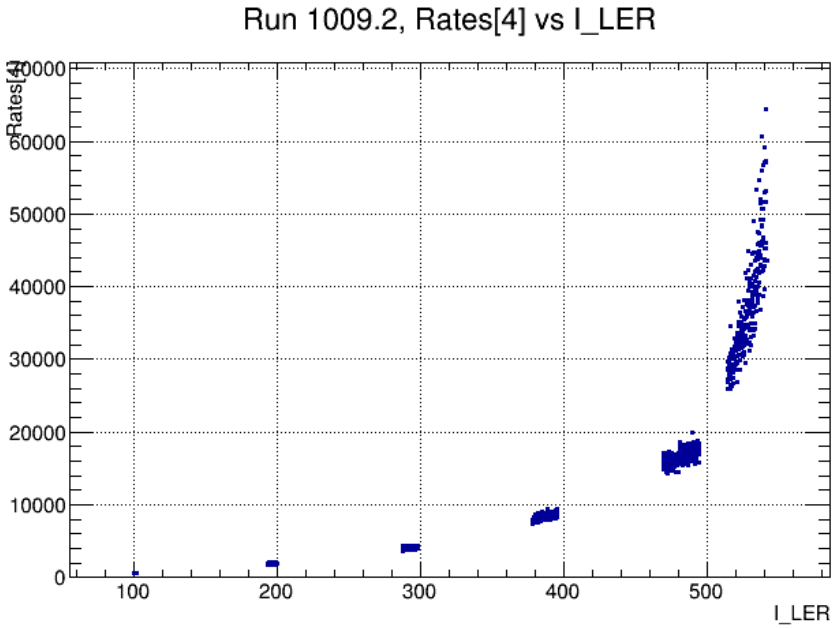
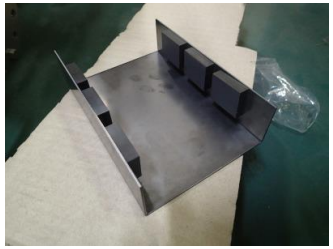
Observation of the electron-cloud effect

Beam blow-up at high currents. Typical of *e*+ machines.

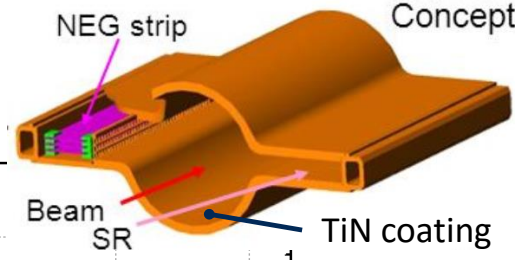
The BEAST crystal system noted very rapid increase of rates for $I_{LER} > 450$ mA

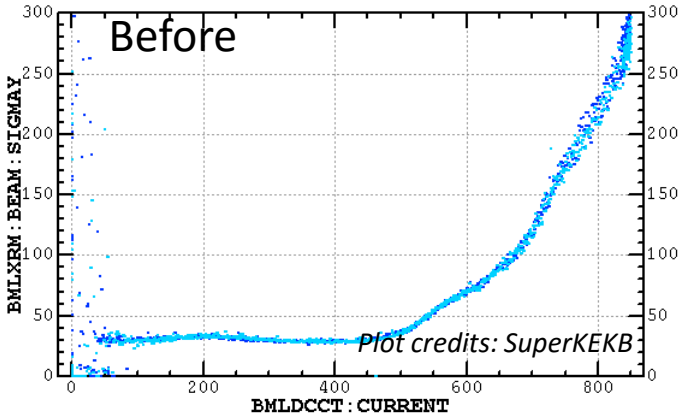


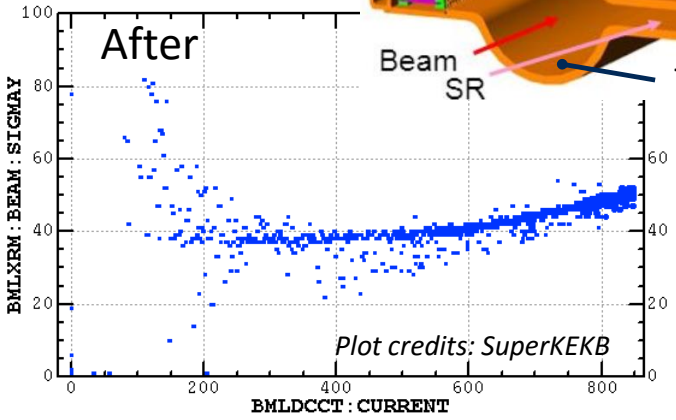
Corrections June 2-5: coils and permanent magnet solenoids



Beam-pipe geometry:







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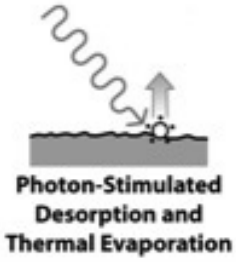
Lessons from beam-gas interactions: vacuum scrubbing

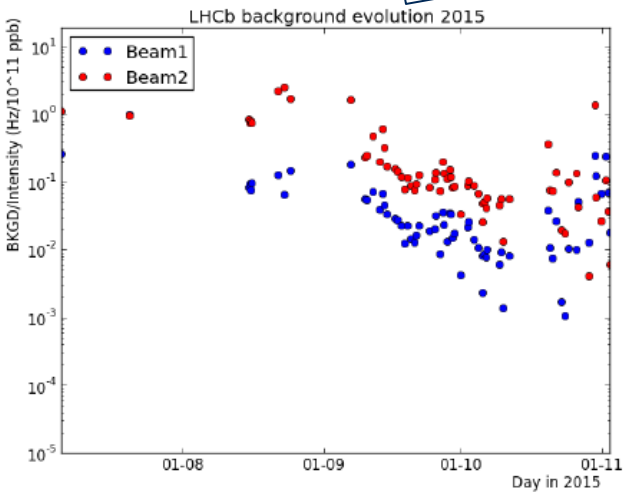


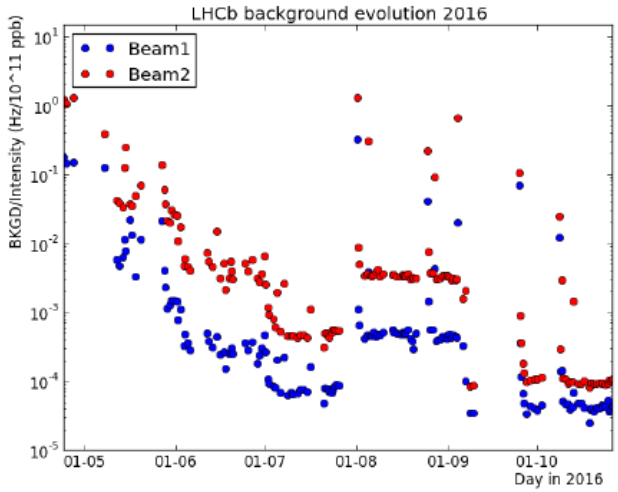
- During operation: photons and electrons hit the vacuum chamber walls, and eject molecules adsorbed on the surface
- Pressure is indeed 'dynamic':

$$P \sim P_{\text{base}} + I \cdot dP/dI$$

  - dP/dI is linked to the probability of desorption of a gas molecule
  - P_{base} is the dynamic equilibrium pressure (2×10^{-8} Pa HER ; 5×10^{-8} Pa LER)
- This probability decreases as a power-law w.r.t. delivered beam current, so should beam-gas background rates.
- ✓ Indeed, this is observed in the time structure of backgrounds:

This is also studied at the LCH





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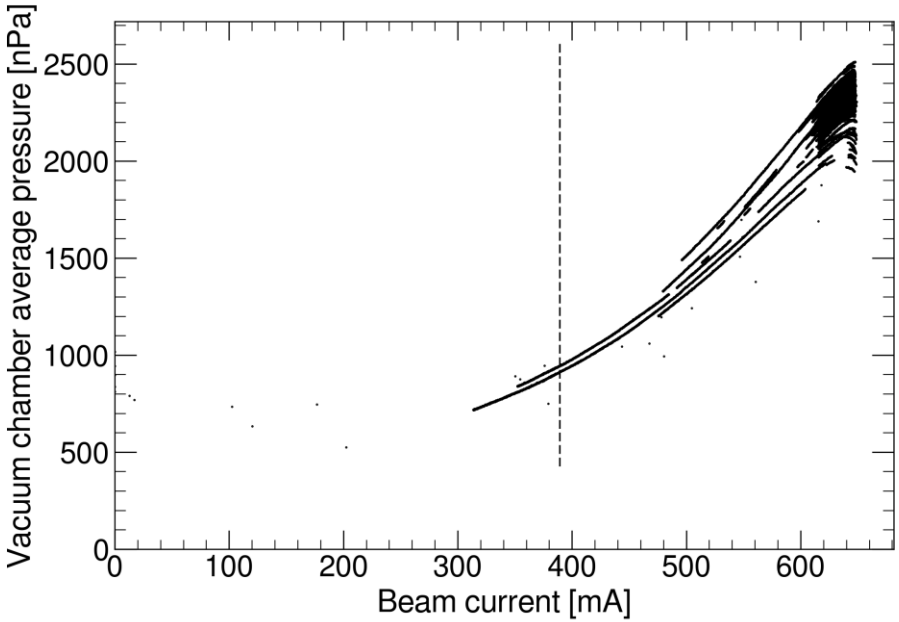
Lessons from beam-gas interactions: dynamic pressure

- 'Marco' analysis possible using the 'dynamic pressure':

$$P \sim P_{\mathrm{base}} + I \cdot dP/dI$$

  - dP/dI is linked to the probability of desorption of a gas molecule
  - P_{base} is the dynamic equilibrium pressure (2×10^{-8} Pa HER ; 5×10^{-8} Pa LER)
- However useful, this representation isn't accurate to look at the detail of the beam-gas probabilities…
- Pressure not a quite linear function of current:



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