Operational experience and performance of the Silicon Vertex Detector after the first long shutdown of Belle II

Kieran Amos - INFN Trieste
on behalf of the Belle II SVD group

14th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors

Academia Sinica, Taipei

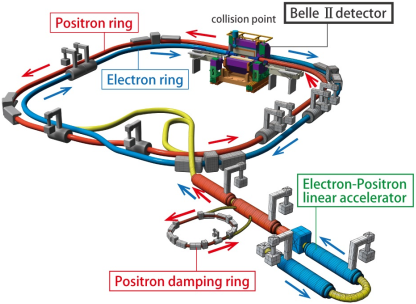
Nov 17, 2025

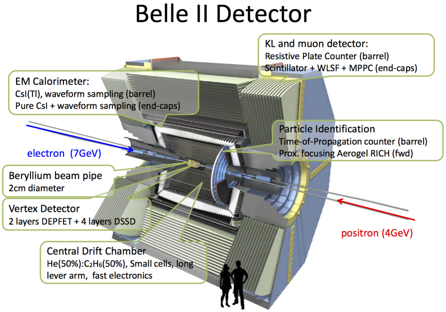
Belle II

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TRIESTE

HSTD 14
Nov. 16, 2025
Academia Sinica

SuperKEKB & Belle II



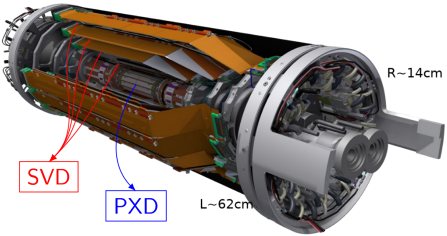


- e^+e^- collider with asymmetric beam energies
- $E_{\rm cm} \sim 10.58$ GeV = B factory
- Regular data-taking since April 2019
- Restart data-taking in Nov 2025
- Long shutdowns in 2023 and planned for 2032

Performance

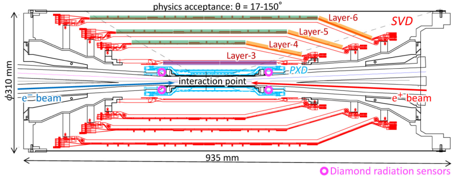
- Current integrated luminosity: **575 fb^{-1}** ($\sim$1/2 Belle)
- Peak luminosity recorded: **5.1 × 10^{34} cm^{-2}s^{-1}**
- Design integrated luminosity: **50 ab^{-1}**
- Target peak $\mathcal{L}$: **6 × 10^{35} cm^{-2}s^{-1}**

The Belle II VerteX Detector (VXD)



Two Sub-detectors:

- **PXD:** 2 layer of depleted field effect transistor (DEPFET) pixel silicon sensors
- **SVD:** 4 layered arrangement of strips of double sided silicon strip sensor This talk!
- Inner (outer) radii 14 (135) mm



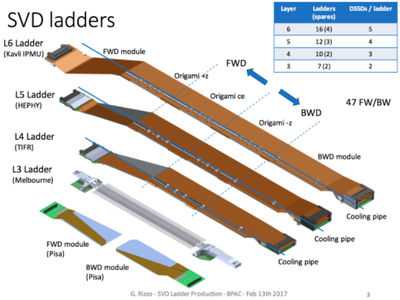
Role of SVD:

- Standalone low-momentum tracks
- Precise vertexing for long-lived particles
- Track extrapolation to PXD
- Charged particle id using dE/dx at < 1 GeV
- Low material budget $\approx 0.7\% X_0$/layer, hit time resolution ≈ 3 ns

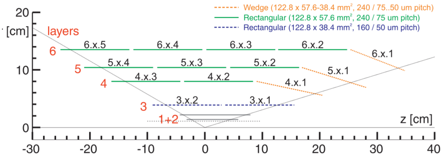
The Silicon Vertex Detector (SVD) 2022 JINST 17 P11042

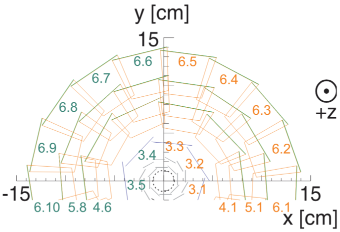
Double sided silicon strip sensors (DSSD) modules arranged in independent units called ladders

- 172 sensors, 1.2 m^2 sensor area, 224k readout strips
- Forward sensors slanted to maximise acceptance with smaller incidence angle
- 28 diamond sensors for radiation monitoring and beam abort



Layer	Ladders (spares)	DSSDs / ladder
6	16 (4)	5
5	12 (3)	4
4	10 (2)	3
3	7 (2)	2

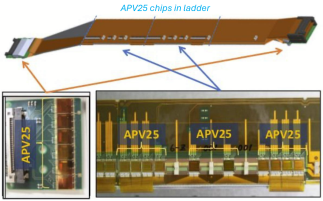




"Windmill" geometry

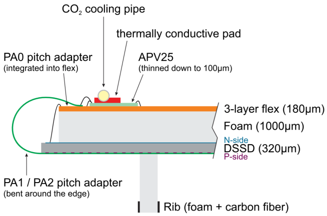
Sensor, Readout and Module Design

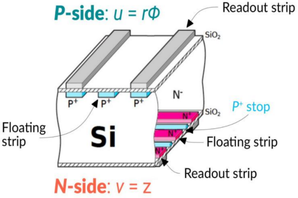
- Perpendicular strips to provide 2D spatial info
- Bias voltage: 100 V, Depletion voltage: 20 — 60 V
- Sensor thickness: 300 - 320 µm
- Strip pitch: 50/75 µm ($r - \varphi$) and 160/240 µm (z)
- Readout: 1748 APV25 chips
- Cooling via two-phase CO_2 system at -25°C



Front-end ASIC: APV25 — 2001 NIMA 466 P359

- Features short signal shaping time (50 ns) and good radiation hardiness (> 100 Mrad)
- Originally designed for use at LHC ⇒ Ideal for high backgrounds at Belle II
- 128 readout channels, clock frequency 40 MHz, power consumption 0.4 W



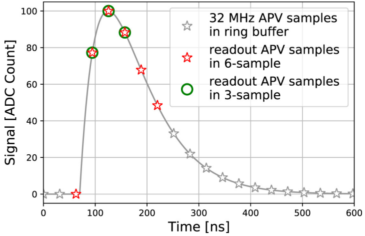


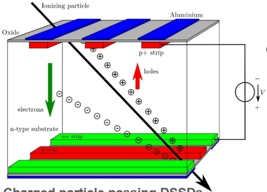
Chip-on-sensor concept (Origami)

- Chips on each sensor to minimize the signal path length
- Chips on the same side of the sensor using wrapped flex to readout sides
- Cooling only on one sensor side

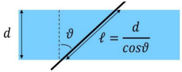
Data Reconstruction

- APV25 operated in multi-peak mode at 32 MHz (collision frequency is 254 MHz)
- ⇒ More than 1 sample needed to get the pulse shape and estimate the peak position
- 6 samples recorded, 3/6 samples method ready for deployment in future to reduce dead time (lower data size transfer from chip to peripheral electronics) at high luminosity





Charged particle passing DSSDs



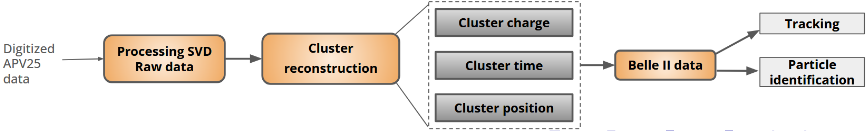
d ≡ 300 - 320 μm

Cluster

Collection of strips with signal-to-noise ratio (SNR) above certain threshold

Measurement of:

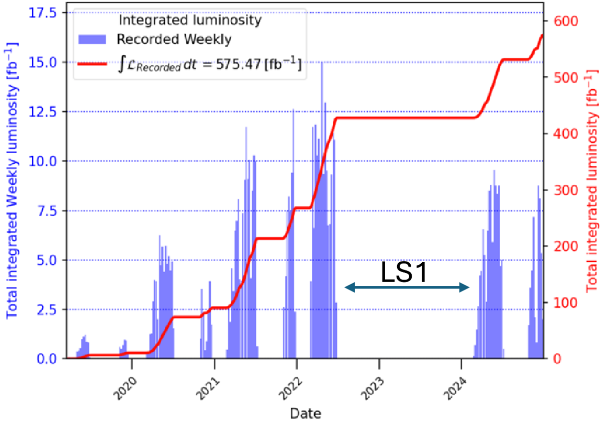
- **Charge:** Sum of the charges of each strip belonging to the cluster; depends on incident angle of the particle
- **Time** of the hit with respect to the trigger signal
- **Position** of the cluster
- **Noise:** Quadrature sum of noise of each strips



SVD Operation Status and Performance

Epochs:

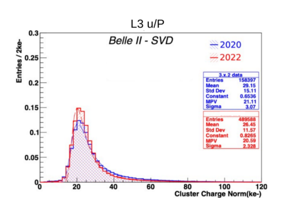
- **Run1 :** March 2019 - June 2022
- **Long shut down 1 :** July 2022 - Dec 2023
- **Run2:** Jan 2024 - Ongoing



Performance Highlights Run1

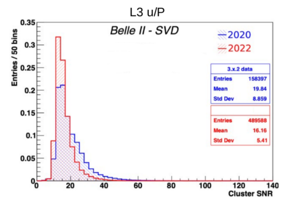
Cluster charge

- Stable throughout and matching the expectation: 24ke$^-$ for a minimum ionising particle passing through a $\approx$ 320 μm thick silicon sensor



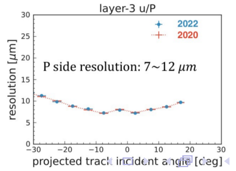
Cluster SNR

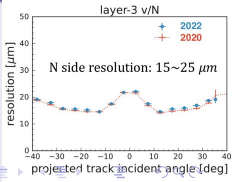
- Very good cluster SNR in all 172 sensors
- Small reduction for 2022 due to radiation damage



Position resolution

- Stable position resolution within 7–25μm observed, as expected from strip pitches





Operational Experience Run1

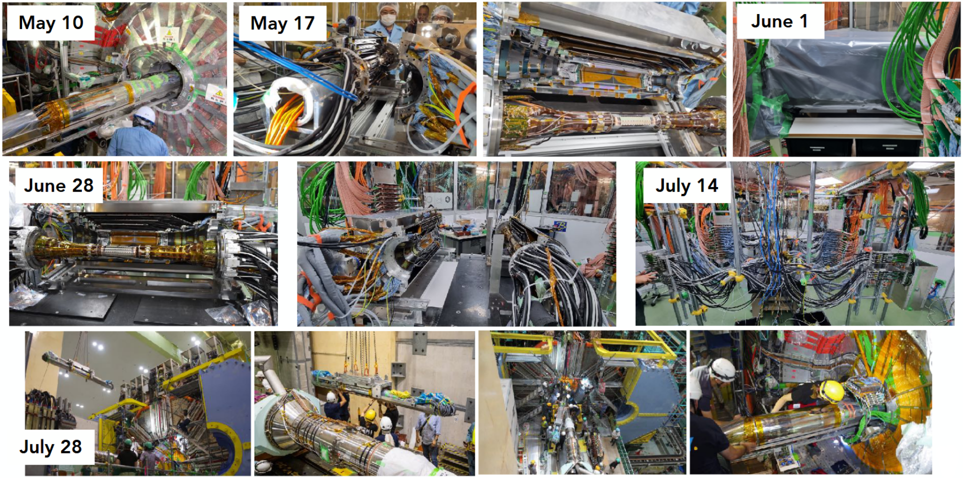
- Smooth and stable operation without major issues
- Stable environment and calibration constants evolution consistent with expectation
- Excellent detector performance:
  - Good signal-to-noise ratio (SNR)
  - precise position and time resolution and large hit efficiency ($> 99\%$), stable over the data taking period)
  - Masked strips are less than 1% (mainly due to initial defects during sensor production or ladder assembly)
- Background effects are well under control

Long Shut Down 1: July 2022 - Jan 2024

Several improvements in the accelerator and detectors

- VXD upgraded with complete PXD (in Run1 only layer 1 + partial layer 2) keeping the same SVD
- Intense hardware activities on SVD for the VXD de-installation/re-installation
  $\Rightarrow$ More than 5 months with many delicate steps
- Several SVD test campaigns performed after each step during LS1
- Optimized the cooling conditions with complete PXD
- VXD alignment and performance validated using cosmic rays after reinstallation

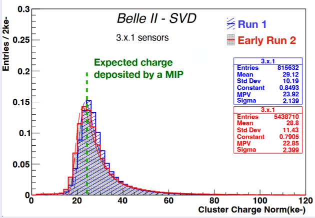
IVXD Removal and Reinstallation: Summer 2023

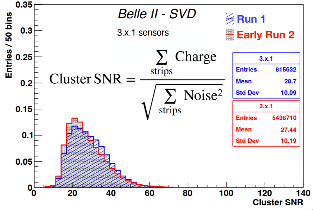


Performance Highlights Run2

Cluster charge and SNR

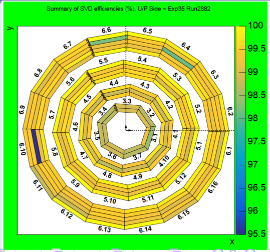
- No significant changes observed compared to Run1





Sensor Efficiency

- $> 99\%$ for most of the sensors
- $> 98.5\%$ for the inner layer
- Stable throughout all of 2024



Effects of Beam Backgrounds

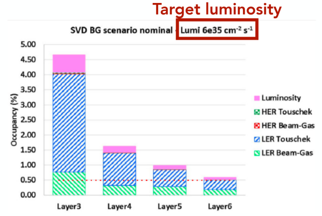
Beam background (BG) effects are significant in high luminosity scenario

- **Instantaneous effects:** high occupancy or sudden bust of radiation due to beam loss
  $\Rightarrow$ With SVD occupancy $> 6\%$ degradation of tracking performance expected
  $\Rightarrow$ Possibility of permanent damage from radiation spikes, like pinhole creation, but no new pinholes observed after 2019, despite multiple severe beam loss events in Run2
- **Integrated effects:** integrated dose exceeding the SVD radiation budget and leading to permanent performance deterioration:
  $\Rightarrow$ Can increase leakage current and strip noise, and lower charge collection efficiency

Occupancy

- Current SVD hit occupancy is $< 1\%$
- Increase observed in Run 2 due to machine conditions
- Nominal occupancy extrapolation to target luminosity is 4.7% for inner strip layer, but large uncertainties due to changes in machine conditions and possible interaction region re-design to reach target luminosity.

$\Rightarrow$ Current level of occupancies well below the nominal range to affect tracking performance



Conservative estimate of projected occupancy is 8.7% !

Upgrade of the VXD, with new VTX fully pixelated, now being proposed to cope with high BG occupancy and the new interaction region changes (see talk by Shijie WANG tomorrow)

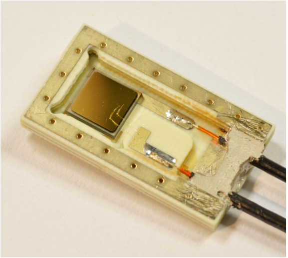
Effects of Radiation

Radiation effects from non-ionising energy loss (NIEL) can cause bulk (in n substrate) or surface damage (in SiO2 layer)

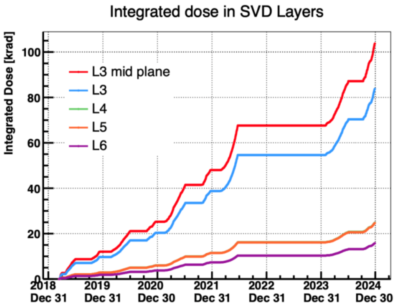
- Robustness of SVD and its performance crucial for maintaining the integrity of Belle II
- Dose and sensor parameters are constantly monitored over experiment lifetime

Radiation dose measurements:

- Dose is constantly monitored using 28 diamond sensors
- Measurements are done online and stored for later analysis
- Total SVD integrated dose on middle of inner layer is ≈ 100 krad
- Corresponds to 1 MeV equivalent neutron fluence of $\approx 2.5 \times 10^{11} n_{eq}/cm^2$, evaluated using the ratio dose/equivalent neutron fluence extracted from BG simulation



Sensor dimensions: $4.5 \times 4.5 \times 0.5\,mm^3$

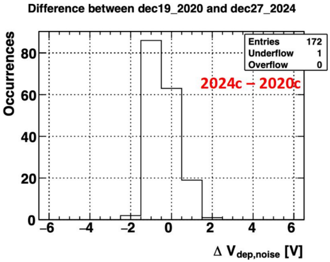


Study of Radiation Damages

Change in depletion voltage

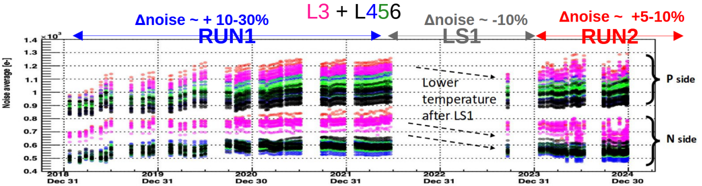
Change in doping concentration due to bulk damage can change depletion voltage

- Determined by measuring the noise as a function of the applied reverse bias voltage
- No significant change in full depletion voltage observed in all sensors



Sensor Noise levels

- 10 — 35% increase in noise by end of Run1
  ⇒ Due to radiation damage, o degradation in performance
- Reduction in noise by 10% after LS1
  ⇒ reduction of operating temperature of CO_2 cooling and possible annealing effects
- Noise changes in Run2
  ⇒ Lower operating temperature and PXD ON/OFF in different moments during local runs (PXD off from May 2024)



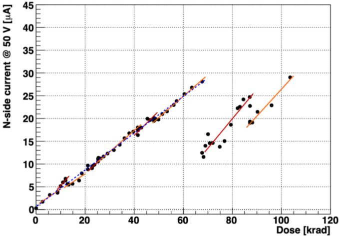
Leakage current vs. dose
Evolution of leakage current is proportional to n_{eq} , hence no change in proportional behaviour expected with similar background composition

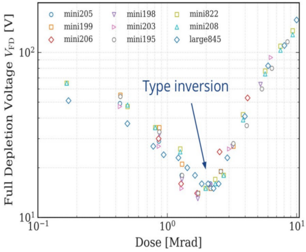
- Linear correlation between dose and leakage current as expected from NIEL model conditions

Irradiation campaign Carried out with 90 MeV electron beam at ELPH Tohoku University (equiv. neutron fluence: $3 \times 10^{13}\ n_{\text{eq}}/\text{cm}^2$)

- Type inversion confirmed at ≈ 2 Mrad (equiv. neutron fluence $\approx 6 \times 10^{12}\ n_{\text{eq}}/\text{cm}^2$)
- Type inverted sensor confirmed to collect charge well after 10 Mrad of irradiation

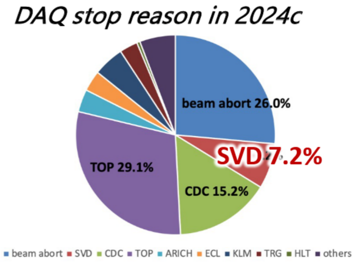
https://arxiv.org/abs/2509.17373
No new pinhole defects so far in Run2 despite multiple severe beam loss events





Mitigation of SEU Errors

- Frequent front-end ASIC (APV25) errors due to single event upset (SEU) observed in 2024c
  - Caused by worse injection background conditions compared to previous periods
  - Mostly on ladders in the innermost layer (layer-3)
  - No serious SEU protection (like majority voting) in APV25
- More frequent SEU is expected under future machine conditions



Mitigation:

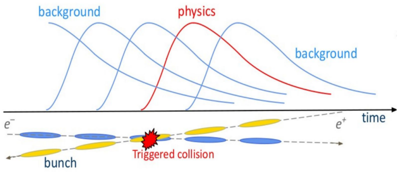
- Firmware-based automatic SEU recovery was implemented during the 2025 shutdown.
- Recovery complete in $\approx 20\,\text{ms}$ while keeping DAQ running with a very short busy.
- The new feature has been tested successfully

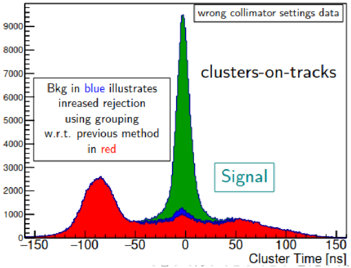
$\Rightarrow$ Implemented for 2025 data-taking

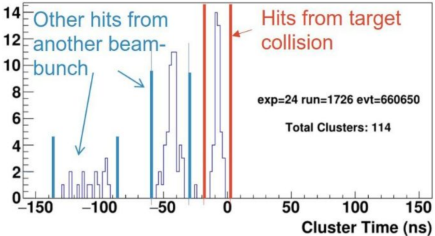
Future Improvements to Background Rejection

Current occupancy at 1% but expected to rise.
⇒ SuperKEKB goal luminosity:
$6 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$
Crucial to reduce occupancy and keep high tracking performance in high background conditions

- Excellent hit time performance (resolution < 3ns) can be exploited to remove off-time tracks
- **Cluster grouping** on event by event basis using the cluster times
  - Further reduces the fake rate by 15% on high-background data







These measures expected to handle occupancy up to 5 to 6%
⇒ Not yet implemented, but ready to deploy if occupancy reaches 2 to 3%

Summary

Since Run1:

- Stable cluster charge, position resolution of 7–25μm
- Excellent hit time resolution and hit efficiency $> 99\%$
- No deterioration in performance from radiation damage after $\approx 100\,\mathrm{krad}$

Long shut-down 1:

- Upgraded VXD with installation of complete PXD
- Confirmed performance during commissioning

Run2:

- Ongoing since Jan 2024
- Performances consistent with Run1 despite changes in beam conditions
- In 2025, first collisions due to be recorded this week
- New algorithms developed to mitigate expected higher BG at future luminosity
  $\Rightarrow$ Expected to handle occupancy of up to 6%

Future:

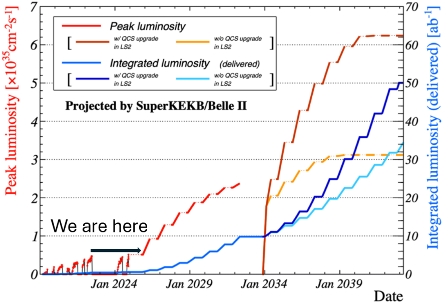
- Upgrade of the VXD, with new VTX fully pixelated, now being proposed to cope with high BG occupancy and the new Interaction Region changes needed to reach the target luminosity (Talk by Shijie Wang tomorrow!)

Backup

Upgrade Proposal VXD $\Rightarrow$ VTX

To achieve the target $\mathcal{L} = 6 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$ and $\int \mathcal{L}dt = 50\ \text{ab}^{-1}$ a major re-design of the I.R. (i.e. QCS upgrade) is needed.

- The VXD provides excellent performance at occupancy $< 1\%$.
- Performance degradation expected in high BKG scenario at target luminosity, where (with large uncertainties in the extrapolation):
  - PXD layer 1: $32\ \text{Mhz/cm}^2 \rightarrow 2\%$ occupancy
  - SVD layer 3: $9\ \text{Mhz/cm}^2 \rightarrow 9\%$



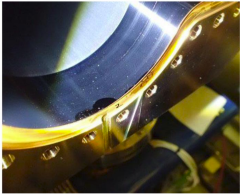
A new fully pixelated CMOS detector proposed to replace the VXD. Requirements:

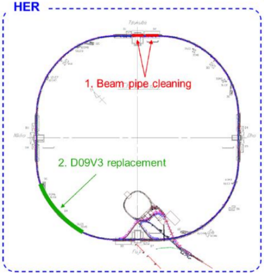
- Improved tracking resolution and space-time granularity to cope with increased backgrounds at target luminosity:
  - Hit rate up to $120\ \text{Mhz/cm}^2$, resolution $< 15\ \mu\text{m}$, Integration time $50 - 100$ ns
- Improved radiation tolerance to ensure long-term detector performance:
  - TID: 100 Mrad
  - NIEL: $5 \times 10^{14} n_{eq}/\text{cm}^2$
- Reduced material budget about $3.0\% X_0$ (sum of all layers)
- Adapt to the new interaction region re-design
- VTX Installation planned during the long shutdown 2, starting in 2032, TDR preparation in 2027.

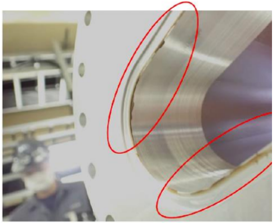
Vacseal Cleaning

Beam pipe cleaning

- During D9V3 collimator replacement work black stains found on HELICOFLEX flange connections
- Analysis of stains consistent with vacseal used on flange connections
- After removal, decrease in SBL originating from cleaned area
- During 2025 many additional areas cleaned of vacseal stains







Asymmetric Collisions