Super VELO studies: Status and plans

Elba Workshop: Beyond the LHCb Phase-1 Upgrade
30 May 2016 Mark Williams
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- High track-finding efficiency
- Low ghost/clone rate
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Beyond the Phase-1 Upgrade: VELO Summary 30 May 2017 Mark Williams
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Silicon pixels

High read-out rate

High performance, low material cooling
Sound familiar?

Phase-I upgrade VELO must fulfil same basic requirements

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**Additional challenges:**

- 10x higher particle multiplicity
- 10x denser vertex environment
- 10x higher radiation damage
Phase-I VELO

Very high performance at Run 3-4 luminosity

Tracking efficiency > 99.5% for long tracks

Impact parameter resolution ~20 (60) μm at high (low) $p_T$.

Ghost rate < 3%
Phase-II Challenge A: 10x particle multiplicity

Phase-I VELO performance breaks down at Phase-II luminosity (L=2x10^{34})

Tracking efficiency reduced to 96% (not so bad)
+ less flat
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Ghost rate explodes ($\sim2\% \rightarrow 40\%$)
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Phase-I VELO performance breaks down at Phase-II luminosity \( (L=2 \times 10^{34}) \)

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+ less flat

Ghost rate explodes (~2% → 40%)

Spatial resolution degrades due to reduced track-finding performance
Phase-II Challenge A: 10x particle multiplicity

Can recover most performance with modest improvements:

- Smaller pixels (55μm → 27.5μm)
- Thinner silicon (200μm → 100μm)
- Re-optimised pattern recognition

![Graphs showing performance improvements](image_url)

-Manuel Jahn

LHCb simulation

Manuel Jahn
Phase-II Challenge B: 10x vertex multiplicity

At Phase-II luminosity, ~50 visible interactions / crossing

PV separation ~3mm on average, but peaks at very small values (<500μm)

With phase-I detector, PVs start to merge

PV reconstruction recovered with smaller pixels

BUT we start to suffer from PV-track mis-association…
Phase-II Challenge B: 10x vertex multiplicity

Assigning incorrect PV to track → poorly measured lifetime

Becomes a dominant systematic for time-dependent analyses

Can be recovered by adding timing information to tracks

PV resolution: 6.5 ps

$\sigma_t = 200 \text{ps}$

Preliminary study with time information added to all VELO hits

e.g. 200ps per-hit resolution → 6.5ps PV resolution (8.5ps for 2-body SV)
Phase-II Challenge B: 10x vertex multiplicity

Assigning incorrect PV to track $\rightarrow$ poorly measured lifetime

Becomes a dominant systematic for time-dependent analyses

**Can be recovered by adding timing information to tracks**

With no timing information, **14%** mis-association rate

With 200ps resolution (per-hit), PV mis-association rate reduces **below 1%** (Phase-I upgrade expectation).
See dedicated talk (next) by Margherita Obertino

How precise?

- PV distribution has RMS ~150ps
- For 4D pattern recognition, need **single hit resolution** sufficient to separate hits from ~50 different interactions: O(10-30ps).
  - Simulation shows we can achieve decent tracking performance with spatial hit information alone (but need small pixels)
  - 4D tracking would give larger gains – worth investigating
- For PV association, **track resolution** must be O(10ps) – can combine information from multiple hits, and don’t need time information from all hits
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Some general comments:

• Difficult to achieve precise timing information with small pixels
• Fast timing detectors more susceptible to radiation damage
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Suggests separate technologies for spatial and time information

Dedicated timing planes and/or timing sensors at larger radius
Pixels with timing

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**Timepix4** aiming for 200ps timing information – could potentially get time/space information simultaneously

Still challenges to extend this functionality to potential ‘SuperVeloPix’ chip:

• Need to qualify **radiation hardness**
• Need to push **hit rate** (e.g. Velopix has 10x output rate of timepix3, but sacrifices information to achieve this)
• Will **Pixel size** be small enough? (we need <30μm, larger if we have 4D)
SuperVeloPix?

- 55μm pixels
- 130 nm technology
- 1 ns timing precision

- Reduced pixel size
- 65 nm technology
- ~200 ps timing precision
- 4-sided buttable design

- Even better timing precision?

Timepix3

+ Radiation hard
+ 800 Mhit/s readout
(10x Timepix3)

VeloPix
Under validation – all looks good!

Timepix4
Now in design phase

SuperVeloPix?
Small pixels, timing, high rate, radiation hard, …
Phase-II Challenge C: 10x radiation damage

Highly non-linear radiation dose

Phase-I upgrade: Maximum dose of $8 \times 10^{15}$ 1 MeV $n_{eq}$ cm$^{-2}$ after 50 fb$^{-1}$
(closest active area 5.1 mm from beam).

Phase-II will see $5-8 \times 10^{16}$ 1 MeV $n_{eq}$ cm$^{-2}$ over course of lifetime

This is beyond the limits of current silicon technology – very important to find a solution
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Planar silicon retains acceptable charge collection efficiency up to $10^{16}$ 1 MeV n_{eq} cm^{-2} (plot from 2013, 300μm Si)

45μm LGAD detectors lose gain beyond a few $10^{14}$ 1 MeV n_{eq} cm^{-2}

3D pixels efficient to $\sim 10^{16}$ 1 MeV n_{eq} cm^{-2}
Options to survive Phase-II dose:

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   - **Pro:** Can use existing technology
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     Not very ambitious
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2. **Develop sensors that can tolerate full dose of** $8 \times 10^{16} \text{ 1 MeV } \text{n}_{\text{eq}} \text{ cm}^{-2}$
   - **Pro:** Can use traditional construction/operation methods
     Retain high performance
   - **Con:** Requires significant progress in rad hardness, with no commercial pressure,
     and no obvious roadmap
     Even more challenging for fast timing detectors
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3. **Replace modules as required over lifetime of detector**
   - **Pro:** Doesn’t rely on developing rad hard sensors
     - Retain high performance
   - **Con:** Mechanically challenging (depending on strategy)
     - May increase cost (depending on £/module)
Phase-II Challenge C: 10x radiation damage

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2. Develop sensors that can tolerate full dose of $8 \times 10^{16} \text{ 1 MeV } n_{eq} \text{ cm}^{-2}$
3. Replace modules as required over lifetime of detector

Most likely some combination of these two approaches

Dream scenario:
• Develop sensors that can survive for a full ~4 year run ($\sim 4 \times 10^{16} \text{ 1 MeV } n_{eq} \text{ cm}^{-2}$)
• Replace hottest modules during long shutdown

More likely:
• Develop sensors which can survive for ~2 years
• Replace in situ when required (automated cassette loading?)
Reaching Further: Removing RF Foil

Radius of 1\textsuperscript{st} hit

Material before 2\textsuperscript{nd} hit

Hit resolutions

\[
\sigma_{IP}^2 = \frac{r_1^2}{p_T^2} \left( 0.0136 \ \text{GeV/c} \sqrt{\frac{x}{X_0}} \left( 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right) \right)^2 + \frac{\Delta_{02}^2 \sigma_{i2}^2 + \Delta_{01}^2 \sigma_{i1}^2}{\Delta_{12}^2} + \sigma_{\text{extrap}}^2.
\]

- Multiple scattering dominates IP resolution at low \( p_T \)
- Proportional to material traversed before 2\textsuperscript{nd} hit
- RF foil is by far the largest material contributor

![LHCb simulation chart]
Reaching Further: Removing RF Foil

Significant and immediate physics gain from removing the RF foil
Also consider alternative designs with less material. Smaller gains but fewer obstacles

**Factor 2 gain in IP resolution at low $p_T$**

35% improved PV resolution → Factor 2 reduction in uncertainties for SL channels (see talk by Patrick O.)
Can we do this?

Two main questions (need YES to both):

- **Q:** Can we ensure a leak-tight VELO and qualify to a level which meets the **machine vacuum** criteria?
  
  **A:** Depends on machine requirements. Significant expertise from Phase-I VELO R&D.
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- **Q:** Can we guide the wake fields with an alternative method, without harming VELO operations (e.g. wires)?
  
  **A:** For machine considerations, see talk by Nicolo Biancacci. For VELO operation, open question: need to test.
A Possible Phase-II VELO

Main modules have two technologies:

- **Small-r:** small pixels, radiation hard, timing information optional
- **Large-r:** larger pixels, fast timing, reduced rad hardness

Minimal RF protection between beam and sensors

Retractable modules as in current/phase-I VELO

Automated ‘cassette replacement’ (?)

Cooling from evaporative CO₂ in microchannels? (benefit from phase-I experience)

At large-z, a few dedicated single-tech modules ensure all particles in acceptance have spatial & timing into
Summary: next steps

Four main streams:

Develop silicon detectors with **small pixel size** (~30μm), high data rates, and as radiation hard as possible (aim for >$4 \times 10^{16}$ 1 MeV n$_{eq}$ cm$^{-2}$).

Possible technologies: hybrid detectors (e.g. SuperVeloPix), 3D sensors, HV-CMOS? (see talk from *Themis*)
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