LHCb upgrade: VELO aperture

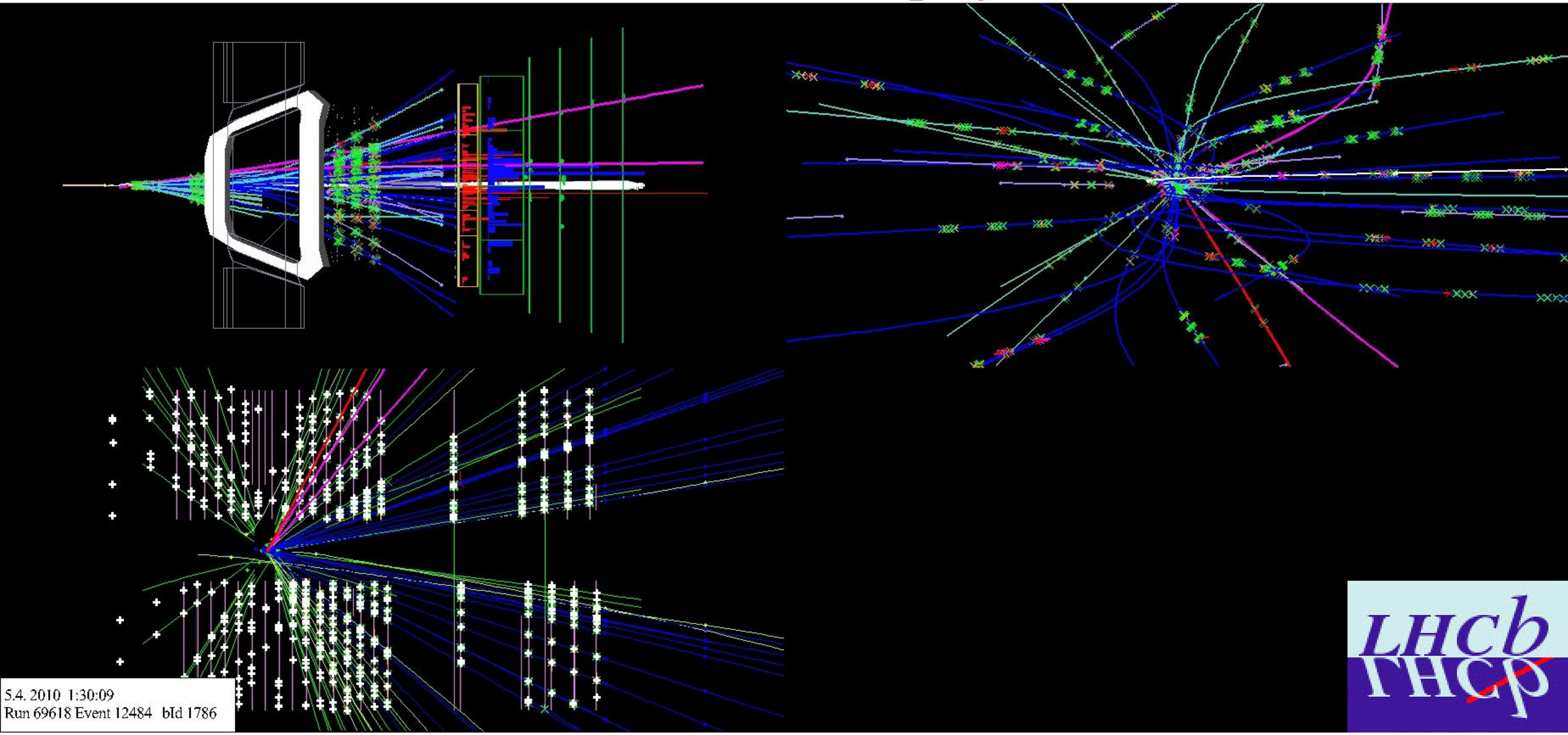
- Motivation, very briefly
- Minimum required aperture vs operational parameters
- A guestimate of some contributions
- What is needed to move forward

$B^+ \to J/\psi\ K^+$

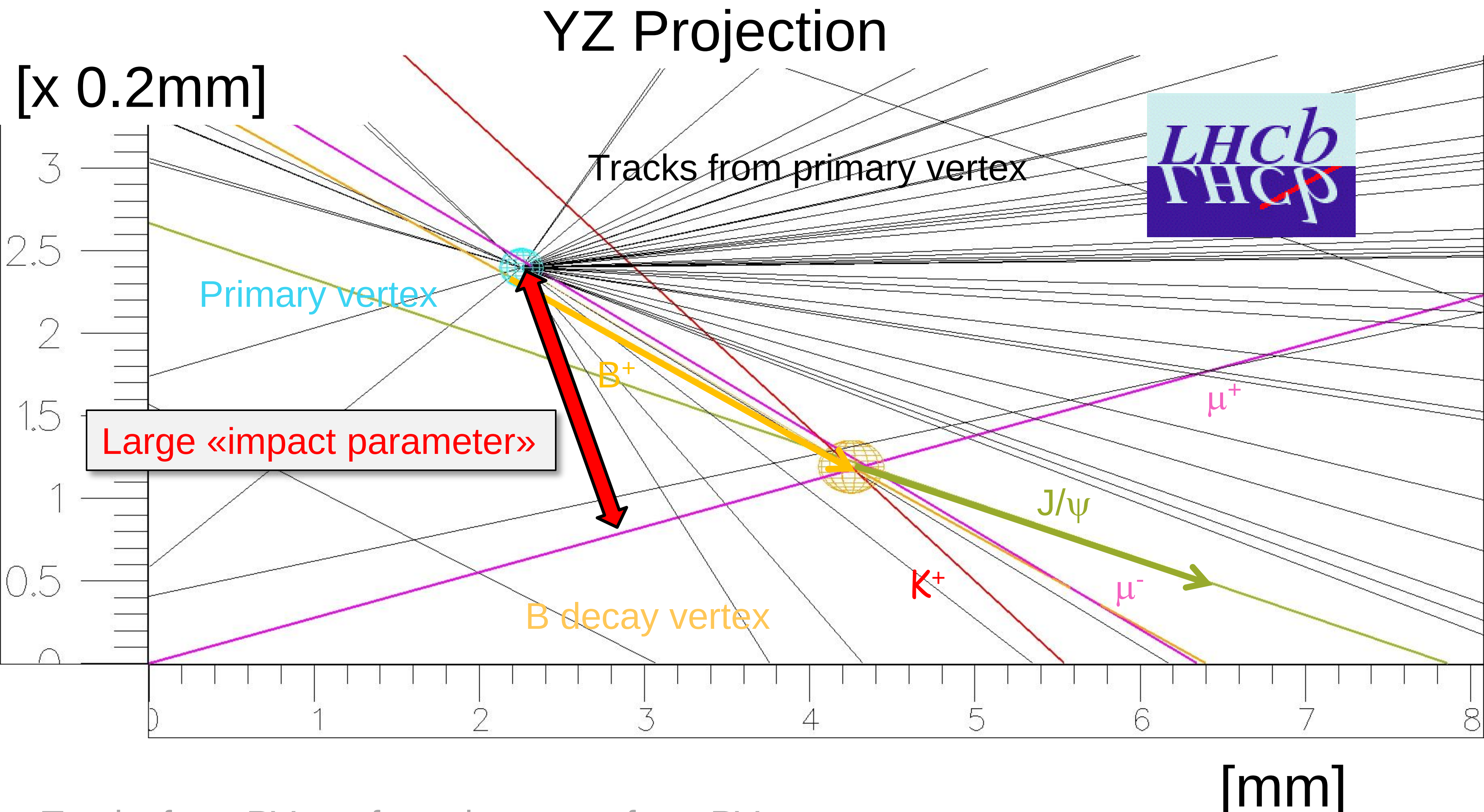
Mass = (5326.7±10.9) MeV/c^2
Momentum: p = 62.7 GeV/c, p_T = 10.48 GeV/c
Cos(α) = 0.9999, dist = 2.03mm

Muons are magenta, kaon is red

LHCb Event Display

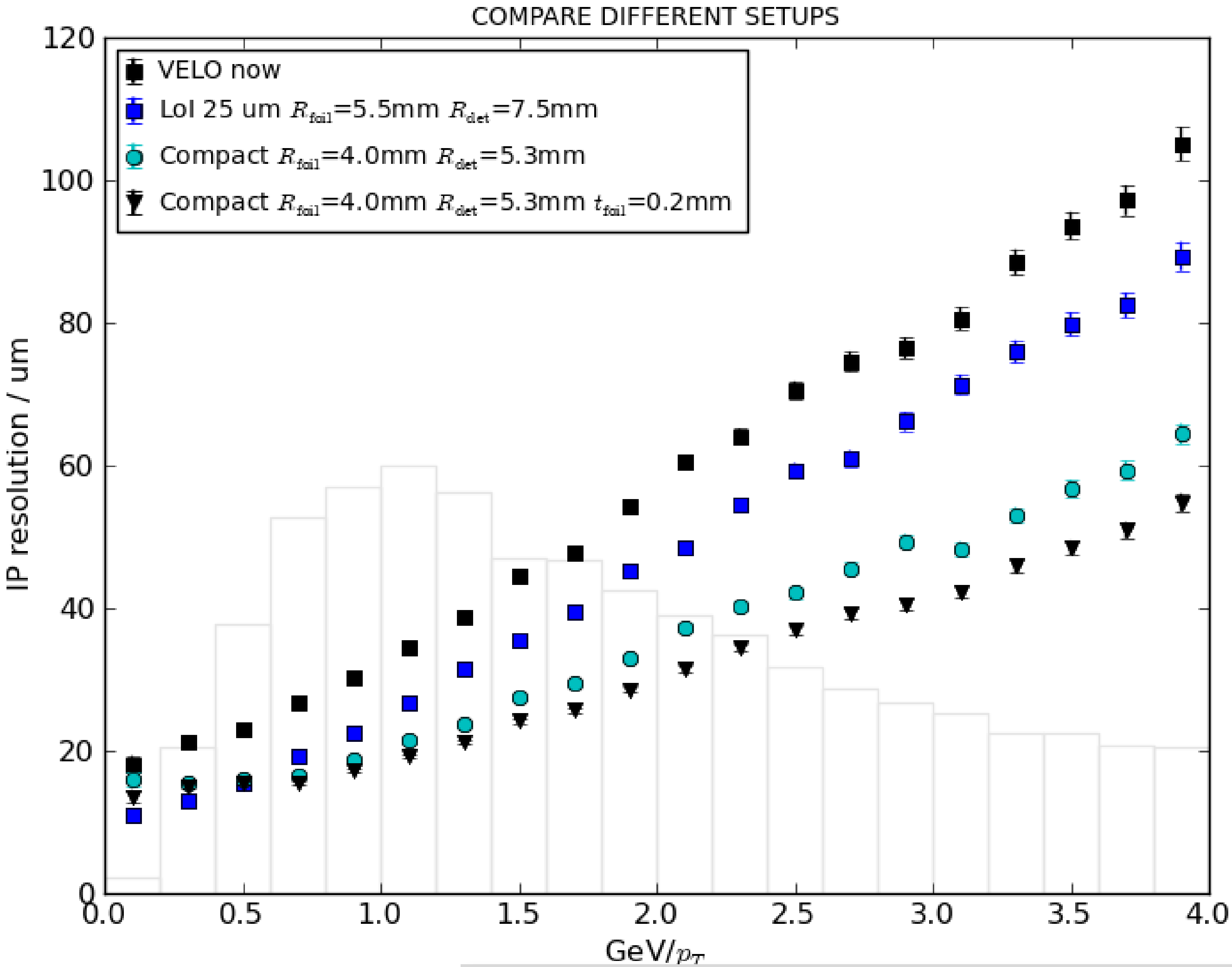


$B^+ \to J/\psi K^+$



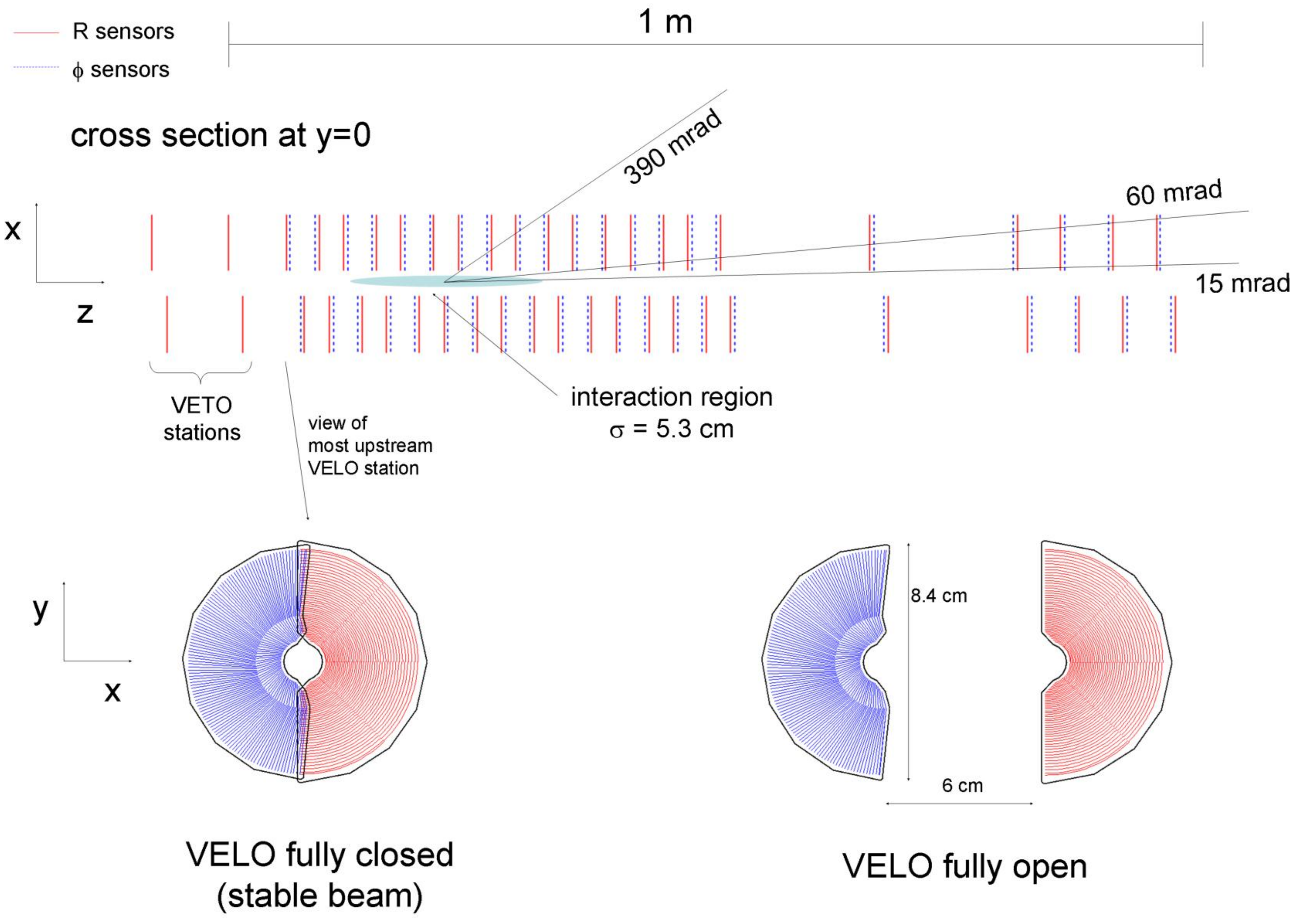
Tracks from PV are forced to come from PV

2D toy model for IP resolution in VELO

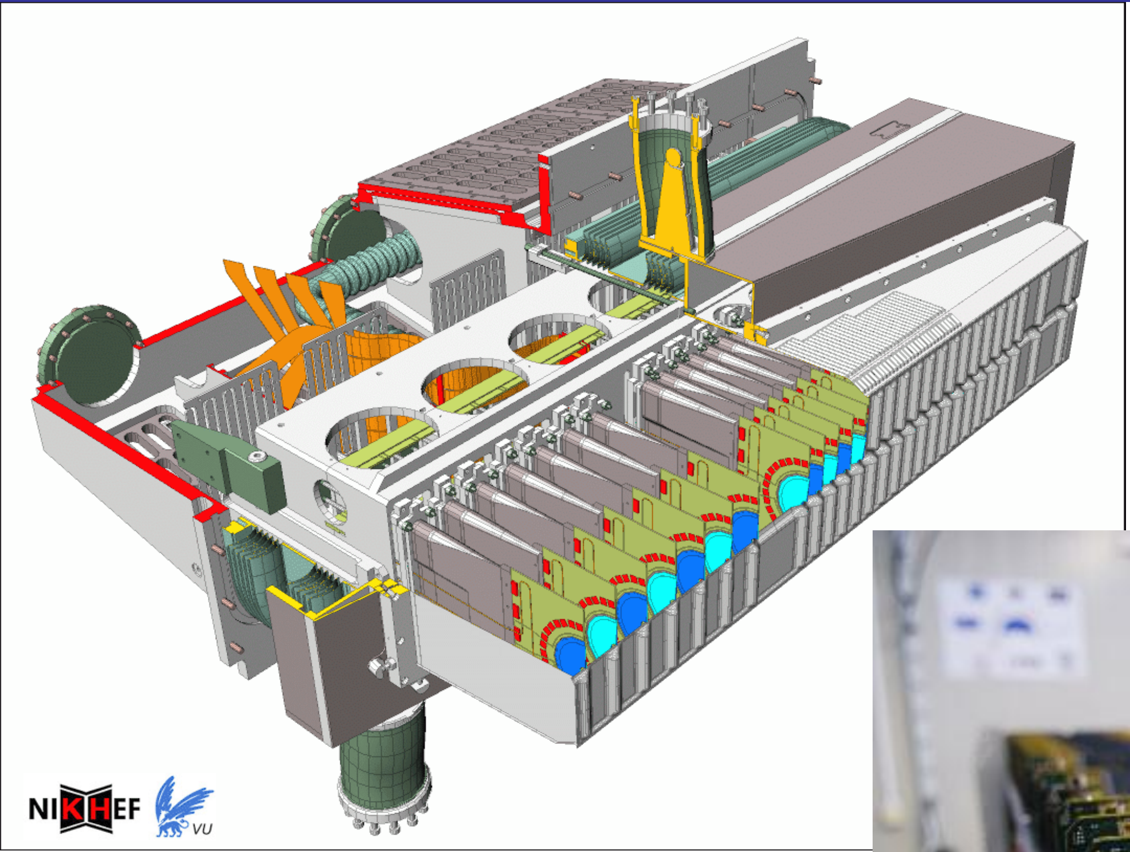


To be verified/confimed with full LHCb simulation

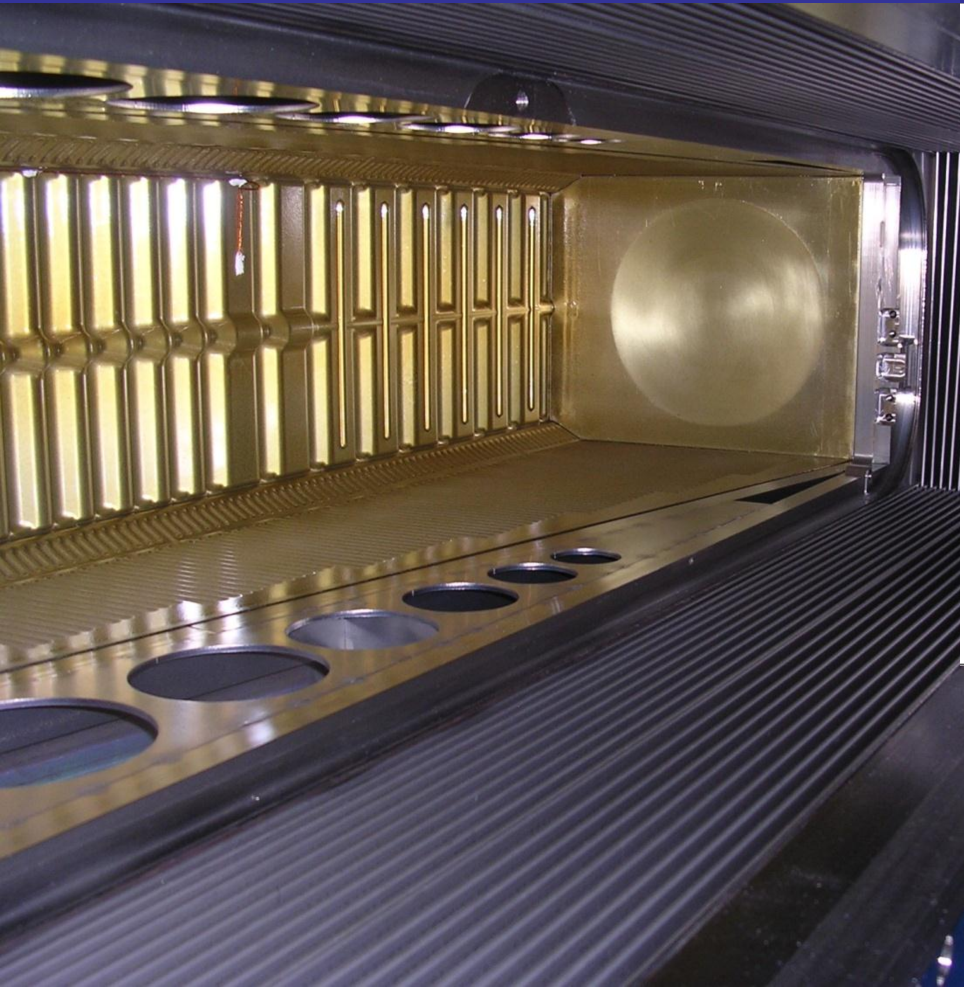
Current VELO layout

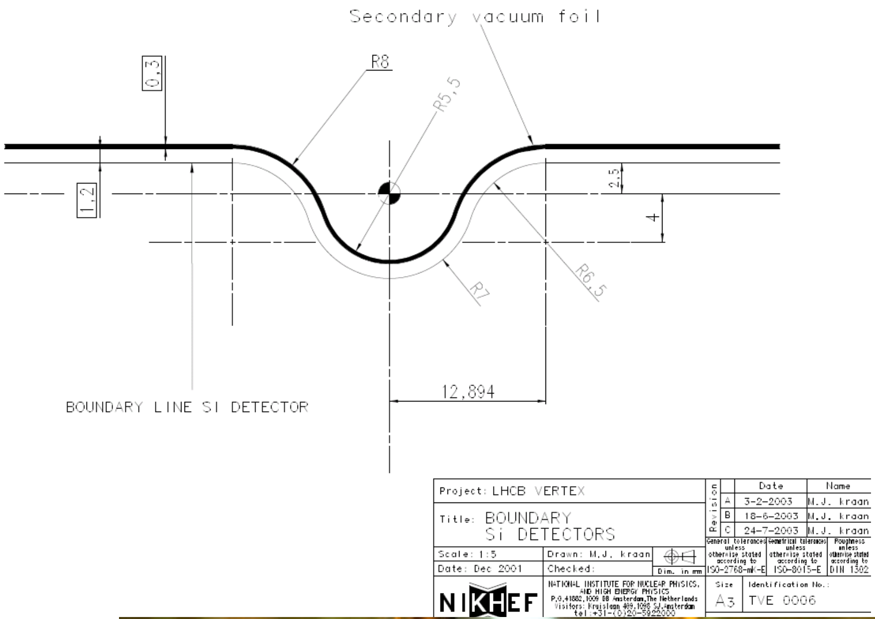


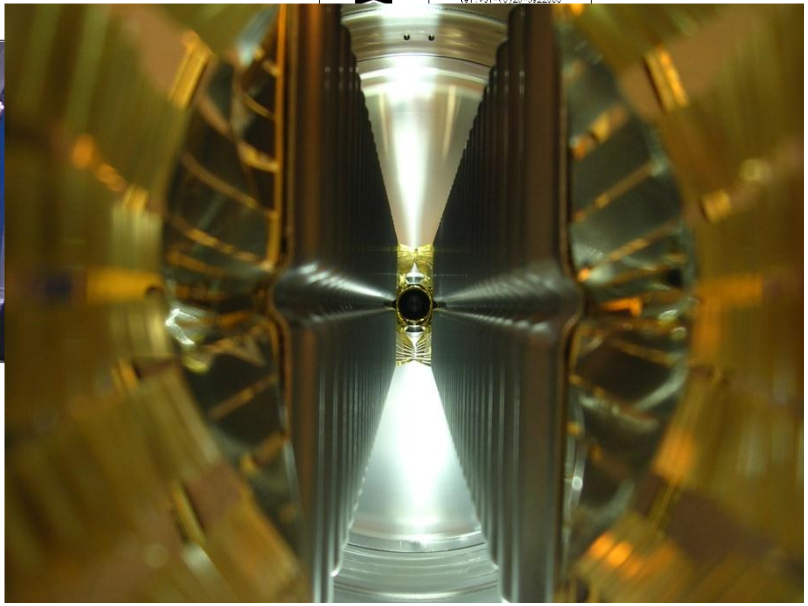
Current VELO half with silicon detectors



The foil now




Secondary vacuum foil
R8
0,3
R5,5
1,2
2,5
4
R7
R6,5
12,894
BOUNDARY LINE SI DETECTOR
Project: LHCB VERTEX
Title: BOUNDARY Si DETECTORS
Scale: 1:5
Drawn: M.J. kraan
Date: Dec 2001
Checked:
Dim. in mm
Revision
Date
Name
A 3-2-2003 M.J. kraan
B 18-6-2003 M.J. kraan
C 24-7-2003 M.J. kraan
General tolerances unless otherwise stated according to ISO-2768-mK-E
Geometrical tolerances unless otherwise stated according to ISO-8015-E
Roughness unless otherwise stated according to DIN 1302
NIKHEF
NATIONAL INSTITUTE FOR NUCLEAR PHYSICS, AND HIGH ENERGY PHYSICS
P.O.41882,1009 DB Amsterdam,The Netherlands
Visitors: Kruislaan 409,1098 SJ,Amsterdam
tel:+31-(0)20-5922000
Size A3
Identification No.: TVE 0006



Reminder

- VELO is in garage position (each half retracted by 30 mm) if the LHC not in STABLE BEAMS (or UNSTABLE BEAMS, never used...)
  - If it moves away from garage => hardwired beam dump
- In STABLE BEAMS, VELO is closed and carefully centered around the luminous region (within μm) based on imaging
  - Vertical adjustment range is +/-5mm (both halves in common)
  - Horizontal adjustment is -30mm/+5mm from nominal beam line, each half independently

=> VELO closed aperture only in STABLE BEAMS

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

Reminder: how was the current minimum radius defined

- Original definition of minimum radius for the RF foil (1998!!)
- Decided to use RF foil inner radius of 5.5 mm

Reconsider based on experience!

jbj / SL-AP 12.06.98

APERTURE AT THE IP OF LHCB
- FOR DISCUSSION -

In collision, the inner radius of the vertex detector shall be large enough to leave space for n transverse beam units including tolerances, i.e.

$$r_{min} = \Delta_{co} + \Delta_{tol} + n\sigma \quad (1)$$

with $\sigma = (\varepsilon\beta^*)^{1/2}$, $\varepsilon = 5.0310^{-4}$ at 7 TeV. For the other parameters, I tentatively define

$$\Delta_{co} = 1 \text{ mm} \qquad \Delta_{tol} = 2 \text{ mm} \quad (2)$$

$$n = 15 \quad (3)$$

$$\beta^* = 36 \text{ m} \quad \Leftrightarrow \quad \sigma = 0.14\text{mm} \quad (4)$$

This supposes (Δ_{tol}) a vertex detector which is adjustable in both the horizontal and the vertical direction. Needless to say, the detector must in addition be opened at injection, otherwise σ must be computed at injection ($\sim$ 4 times larger). The value of β^* is the maximum value which is affordable with the crossing angle needed, adding 20% for beta-beating.

The end result would then be

$$r_{min} = 1 + 2 + 2.1 = 5.1\text{mm} \quad (5)$$

Table 1: Considerations of J.-B. Jeanneret on the minimum possible distance of the Vertex Detector from the beam.

See

- wwwslap.cern.ch/collective/impedance.wkg/12-06-98/notes.ps

Reminder

- LHCb upgrade takes place in LS2
- After LS2:

  Target LHCb luminosity $L_{\mathrm{LHCb}} = 2{\cdot}10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

  perhaps starting with $L_{\mathrm{LHCb}} = 1\cdot10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

assume need a factor 4 for leveling to desired luminosity through a fill

- 25 ns is crucial
- Example numbers: (7TeV, γ = 7460)

  β^* = 3 m

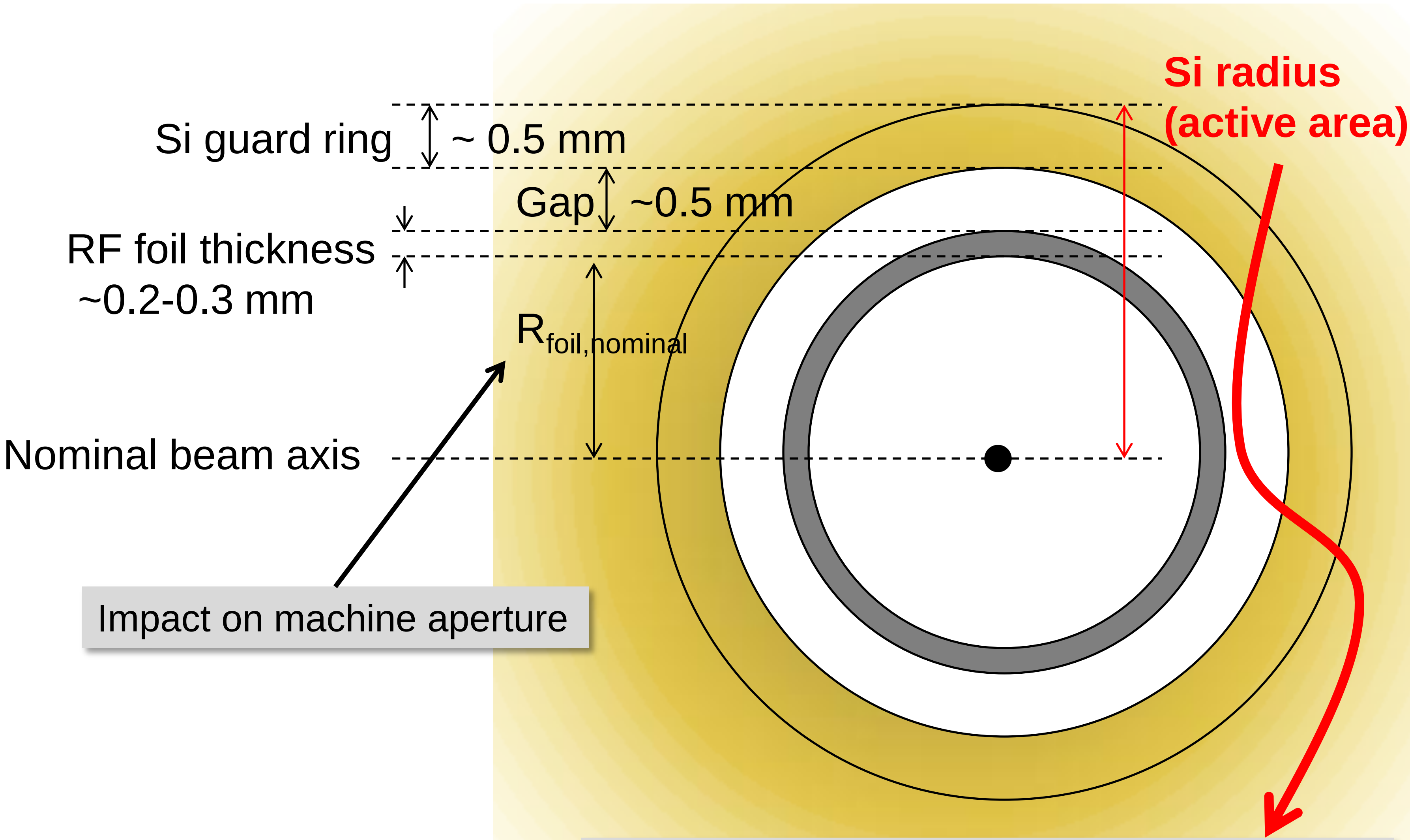
  ε = 2.2 um/7460

  N = $1.8 \cdot 10^{11}$

  } L = $8 \cdot 10^{33}$ $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

- However, N and ε can only be guessed, and β^* will be chosen accordingly.... Fortunately, as we will see, it is the luminosity that needs to be known precisely to determine the aperture limit to first order.

The various bits we would like to minimize



Our aim: Si radius (active area) ~ **5.1 mm**
Need foil at less than ~3.8 mm

Why 5.1 mm ?

- Pitch = 25 um
- Chip quantizes in 128 channels/chip

$$\pi R_{sensitive} = 128 \text{ channels/chip} * 25 \text{ um/channel} * n_{chips}$$

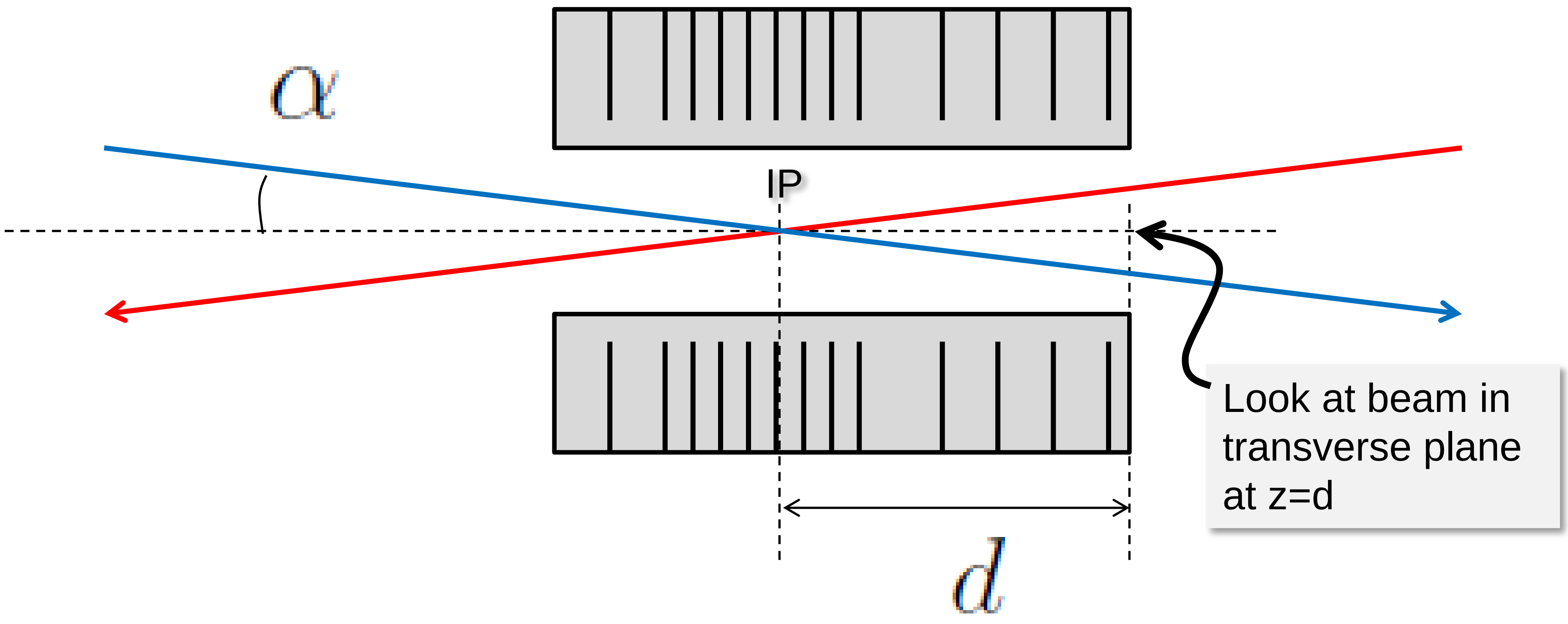
$$R_{sensitive} = 1.0186 \text{ mm} * n_{chips}$$

$$= \ldots\ 4.074 \text{ mm},\ 5.092 \text{ mm},\ 6.111 \text{ mm},\ \ldots$$

$$(\ n_{chips} = \ \ldots\ 4\ ,\ 5\ ,\ 6\ \ldots\ )$$

VELO view crossing plane

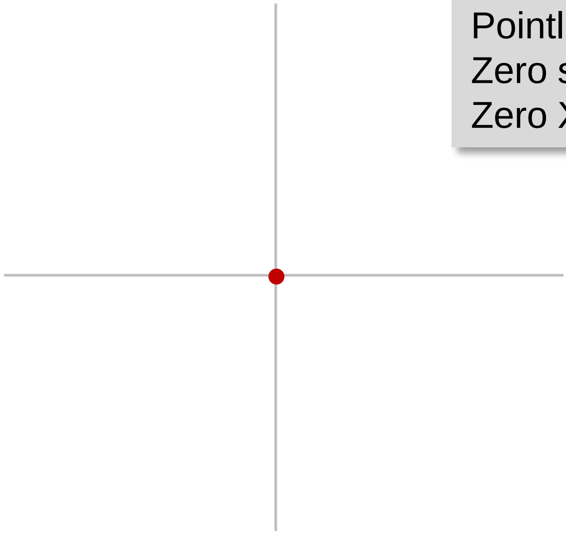
VELO closed, axial symmetric



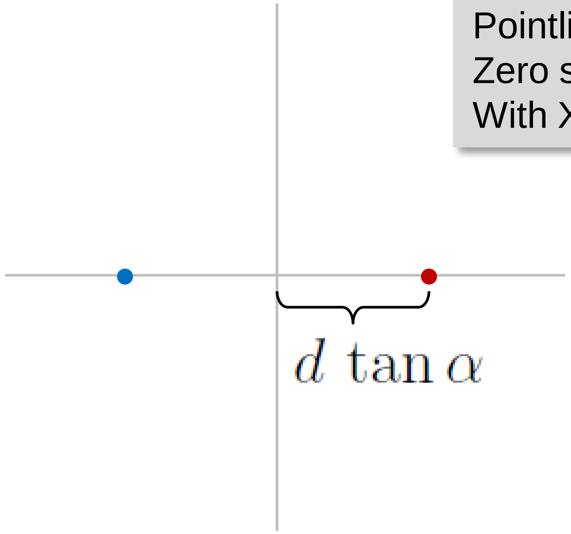
Orthogonal plane: separation

Beam position at z=d

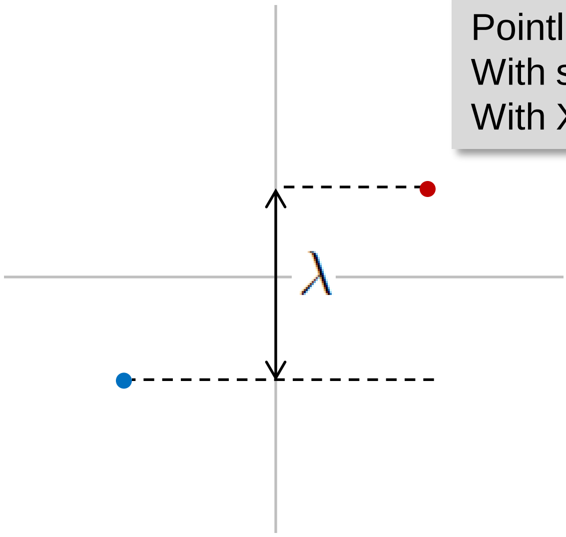
Pointlike beams
Zero separation
Zero Xing angle



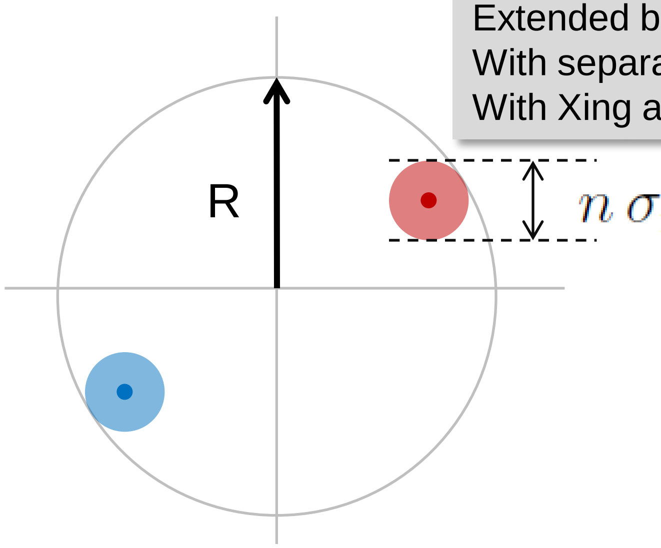
Pointlike beams
Zero separation
With Xing angle



Pointlike beams
With separation
With Xing angle

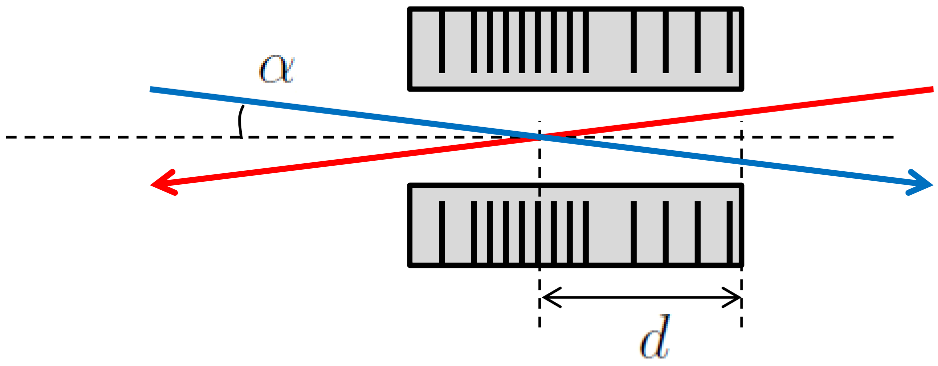


Extended beams
With separation
With Xing angle



Minimum required radius for RF foil: main players

Sum up contributions:



$$R_{\min} = \sqrt{(d \tan \alpha_{\max})^2 + \left(\frac{\lambda_{\max}}{2}\right)^2} + n\,\sigma_{\max} + \Delta_{\mathrm{tol}}$$ + other terms

$d \leq 800$ mm

n =15 ?

mechanical tolerance of the RF foil

How much is

$\lambda_{\max}$?
$\sigma_{\max}$?
} Discussed next slides

$\alpha_{\max}$? → From beta* (optics) solution

Δ_{tol} ? → From measurement on new boxes

What are the “other terms” ?

- VELO closing precision: better than ±20 um
  - See end of talk

Negligible

- VELO foil distortions due to temperature changes: to be evaluated but expected to be negligible

?? measure

- Uncorrected drifts of the boxes or beams relative to each other during a fill: from experience, smaller than 100 um (see last LEB)

Negligible or add 100 um

- Hourglass effect (larger beam size away from IP):

$$\sigma(d) \; / \; \sigma(0) \; = [\, 1 + (d/\beta^*)^2 \,]^{1/2} \quad < \; 1.077$$

if $d < 0.8$ m and $\beta^* \geq 2$ m.

$< \; 1.28$

if $d < 0.8$ m and $\beta^* \geq 1$ m.

ion runs ? (no leveling)

Scale σ_{max} by largest hourglass factor assuming $d < d_{upgrade\text{-}velo}$ and $\beta^* \geq \beta^*_{min}$

Luminosity, definitions

- The two beams are assumed round and identical $\sigma = \sqrt{\epsilon\,\beta^*}$
- Initial values (t=0) are denoted with a subscript 0
- Initial head-on luminosity is $$L_0 = \frac{k\,N_0^2\,f}{4\pi\,\sigma_0^2}$$
- Evolution of luminosity (including a changing separation λ) is

$$L(t) = \frac{k\,N^2(t)\,f}{4\pi\,\sigma^2(t)} \cdot e^{-\frac{\lambda^2(t)}{4\sigma^2(t)}}$$

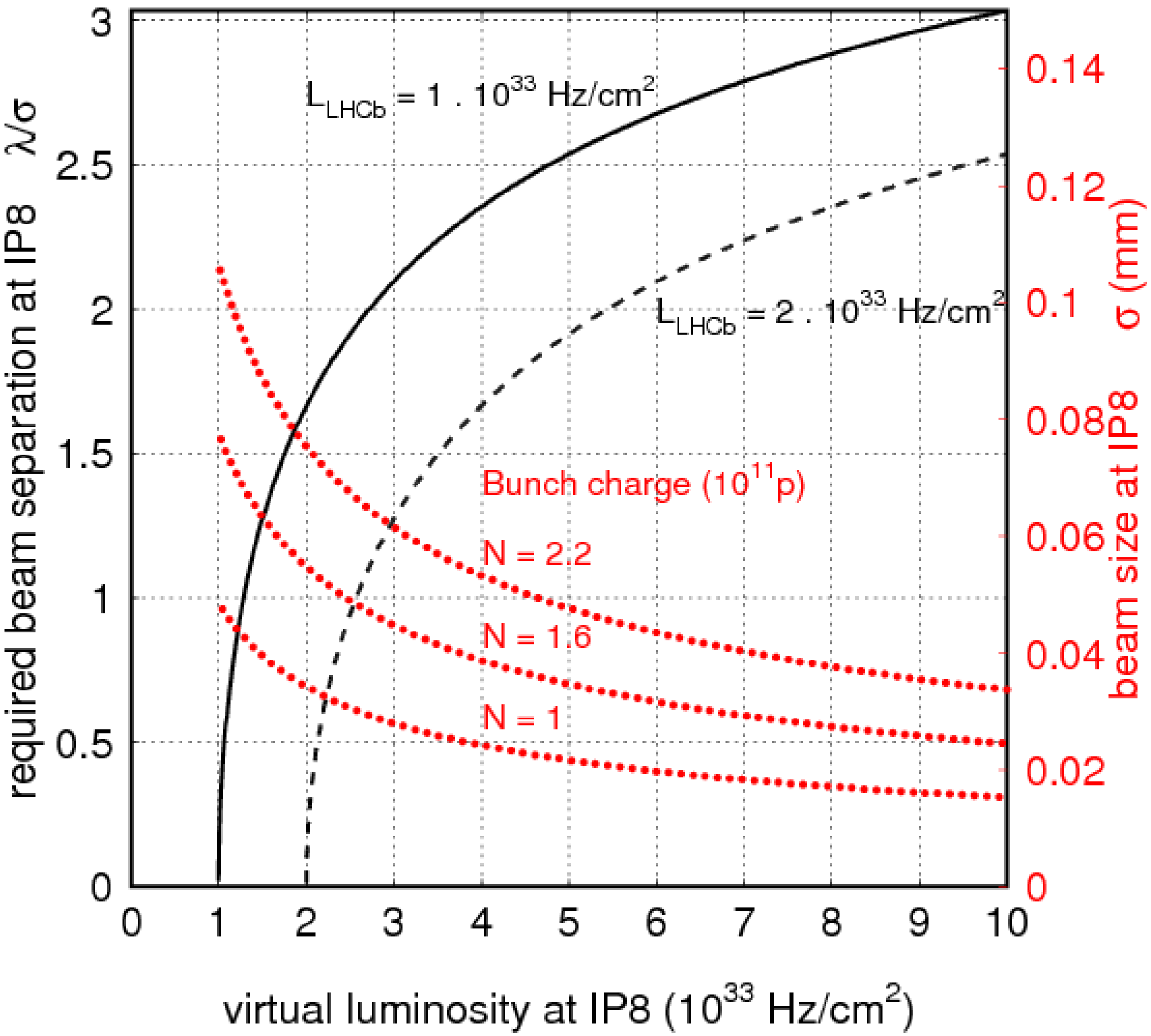
- Consider two cases for LHCb:

  a) Separation leveling

  b) Squeeze leveling

Typical IP8 separations and beam sizes after LS2

- Virtual luminosity is luminosity without separation



$$L_{\mathrm{LHCb}} = \frac{k\,N^2(t)\,f}{4\pi\,\sigma^2(t)} \cdot e^{-\frac{\lambda^2(t)}{4\sigma^2(t)}}$$

$$L_{\mathrm{virtual}} = \frac{k\,N^2(t)\,f}{4\pi\,\sigma^2(t)}$$

$$\lambda(t) = 2\sigma(t)\sqrt{\ell n\left(\frac{L_{\mathrm{virtual}}(t)}{L_{\mathrm{LHCb}}}\right)}$$

a) Separation leveling: how it works

- Initial bunch charge N_0 and initial transverse emittance ε_0 are such that one can choose a fixed β* which fulfills

$$L_0 = \frac{k\, N_0^2 f}{4\pi\, \sigma_0^2} = 4\, L_{\mathrm{LHCb}}$$

- Maximum (initial) separation λ_0 is given by assumption of decay factor (=4):

$$\lambda_0 = 2\sigma_0 \sqrt{\ell n(4)} \approx 2.35\, \sigma_0$$

- If the beam size increases or bunch charge decreases during the fill, then the separation needs to be reduced such that

$$\frac{k\, N^2(t) f}{4\pi\, \sigma^2(t)}\, e^{-\frac{\lambda^2(t)}{4\sigma^2(t)}} = L_{\mathrm{LHCb}}$$

a) Separation leveling: limit case

- Separation is largest at the start of fill and depends on the reserve factor (4) and on the operational LHCb luminosity:

$$\sigma_0 = N_0 \sqrt{\frac{k\,f}{16\pi\, L_{\mathrm{LHCb}}}} \approx \begin{cases} 17\ \mu\mathrm{m} \cdot \dfrac{N_0}{10^{11}\ p} & \text{for } L_{\mathrm{LHCb}} = 2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \\ 24\ \mu\mathrm{m} \cdot \dfrac{N_0}{10^{11}\ p} & \text{for } L_{\mathrm{LHCb}} = 1 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \end{cases}$$

$$\lambda_0 = 2\sigma_0 \sqrt{\ell n(4)} \approx \begin{cases} 40\ \mu\mathrm{m} \cdot \dfrac{N_0}{10^{11}\ p} & \text{for } L_{\mathrm{LHCb}} = 2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \\ 56\ \mu\mathrm{m} \cdot \dfrac{N_0}{10^{11}\ p} & \text{for } L_{\mathrm{LHCb}} = 1 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \end{cases}$$

- The most conservative limit comes from the lower operational luminosity

b) Squeeze leveling (beams head-on, no separation)

- N_0 and ε_0 are such that one can choose a range of β* which fulfills throughout a fill:

$$\frac{k\, N^2(t)\, f}{4\pi\, \beta^*(t)\, \epsilon(t)} = L_{\mathrm{LHCb}}$$

- The squeeze function will change such that

$$\beta^*(t) = \frac{k\, N^2(t)\, f}{4\pi\, L_{\mathrm{LHCb}}\, \epsilon(t)}$$

- Hence, the beam size will obey

$$\sigma(t) = \sqrt{\beta^*(t)\, \epsilon(t)} = \sqrt{\frac{k\, N^2(t)\, f}{4\pi\, L_{\mathrm{LHCb}}}}$$

- N(t) can only decrease, i.e. one has a maximum (initial) beam size

$$\sigma_0 = N_0 \sqrt{\frac{k\, f}{4\pi\, L_{\mathrm{LHCb}}}} \approx \begin{cases} 34\ \mu\mathrm{m} \cdot \dfrac{N_0}{10^{11}\ p} & \text{for } L_{\mathrm{LHCb}} = 2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \\ 48\ \mu\mathrm{m} \cdot \dfrac{N_0}{10^{11}\ p} & \text{for } L_{\mathrm{LHCb}} = 1 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \end{cases}$$

The derived limits

- We assume here that $N_0 \leq 2.2 \cdot 10^{11}$, then it follows that

$$\lambda(t) \leq \lambda_0 \leq 125\mu\text{m}$$

$$\sigma(t) \leq 106\ \mu\text{m}$$

- Taking these two limits for λ and σ is a conservative approach, since when λ is large σ is small, and vice versa. The two values will not reach the limit simultaneously
  - But we will also see that the λ limit is much less important than the limit imposed by σ and by the crossing angle

- Important: using these limits means that any special physics request which needs larger beams or larger separation will have to be evaluated separately before it is tried out.

Putting it together

$$R_{\min} = \sqrt{(d \tan \alpha_{\max})^2 + \left(\frac{\lambda_{\max}}{2}\right)^2} + n\,\sigma_{\max} + \Delta_{\mathrm{tol}} \quad \text{+ other terms}$$

- The constraint due to $\lambda_{\max}$ and $\sigma_{\max}$ is directly depending on:
  - LHCb operational luminosity and the reserve factor ($L_{virtual}/L_{LHCb}$)
    - larger luminosity => smaller beam sizes and/or smaller beam separation
  - Bunch charge
    - larger bunch charge => larger beam size and/or more beam separation

- But (interestingly) it is **not** directly depending on:
  - Beam energy
  - Beam emittance and/or beta star

  Although these affect the choice of crossing angle!

Numerical example (or a guess)

α_{max} = 500urad

λ_{max} = 125um

σ_{max} = 106um

$$R_{min} = \sqrt{(d \tan \alpha_{max})^2 + \left(\frac{\lambda_{max}}{2}\right)^2} + n\,\sigma_{max} + \Delta_{tol}$$ + other terms

[(0.8m * 5e-4)^2 + (125um/2)^2]$^{1/2}$ + 15*106 um = 2 mm

0.4 mm (2) | 0.063 mm (3) | 1.59 mm (1)

It seems that 3.5 mm is a reasonable starting point (upper limit) for these contributions

Summary and conclusions

- Defining the LHCb operational luminosity, the maximum bunch charge and maximum crossing angle allows one to make a 1st order estimation of the minimum upgrade VELO aperture in STABLE BEAMS
- LHCb needs a go-ahead (before mid November) for assuming that R_{min} will be at most 3.5 mm (now was 5.1 mm), which allows to safely plan a minimum radius of 4.6 mm for the silicon sensors inner edge (inactive area).
  - exact R_{min} value can turn out to be smaller later, which only impacts on the final choice of the RF foil inner radius
  - Allows us to decouple silicon sensor R&D from RF foil R&D
- Points to be settled: (consequences to be understood!)
  - Largest IP8 net crossing angle after LS2
  - Smallest and largest β* at IP8 after LS2

Time line

- This argumentation was presented to the Lhc-Experiment Beampipe (LEB) working group
  - 21st LEB meeting, 19 July 2012
  - https://indico.cern.ch/conferenceDisplay.py?confId=198975
  - 22nd LEB meeting, 10 September 2012
  - https://indico.cern.ch/conferenceDisplay.py?confId=204787
- Today presented also to the “Parameter and Layout Committee” (HL-LHC)
- Will finalize on next LEB, 8 October 2012
- Get LHC approval for assuming $R_{min} \leq 3.5$ mm (LMC or HL-LHC ?) before mid November
- VELO upgrade mini workshop in Santiago 19-20 Nov 2012
  - Decide on geometry of VELO sensors
  - https://indico.cern.ch/conferenceDisplay.py?confId=206515

Extra slides

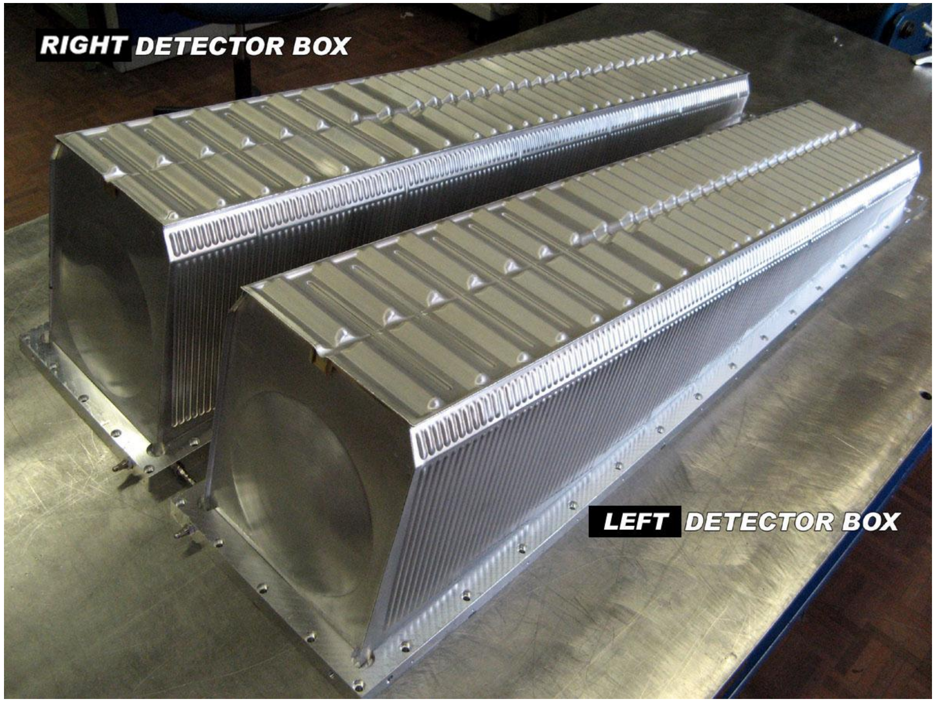
RF foil (box): current boxes installed

Keywords: low mass, leak tight, RF shield, low impedance, stiff and precise

Production method: (NIKHEF/VU)

- High pressure & temperature deformation
- Weld five foils together
- Coat interior with Torlon

- Difficult
- Time-consuming (much trial & error)
- Non perfect results (small cracks in the welds)
- But the boxes work !! (zero problems encountered so far)



RF foil (box): new production R&D

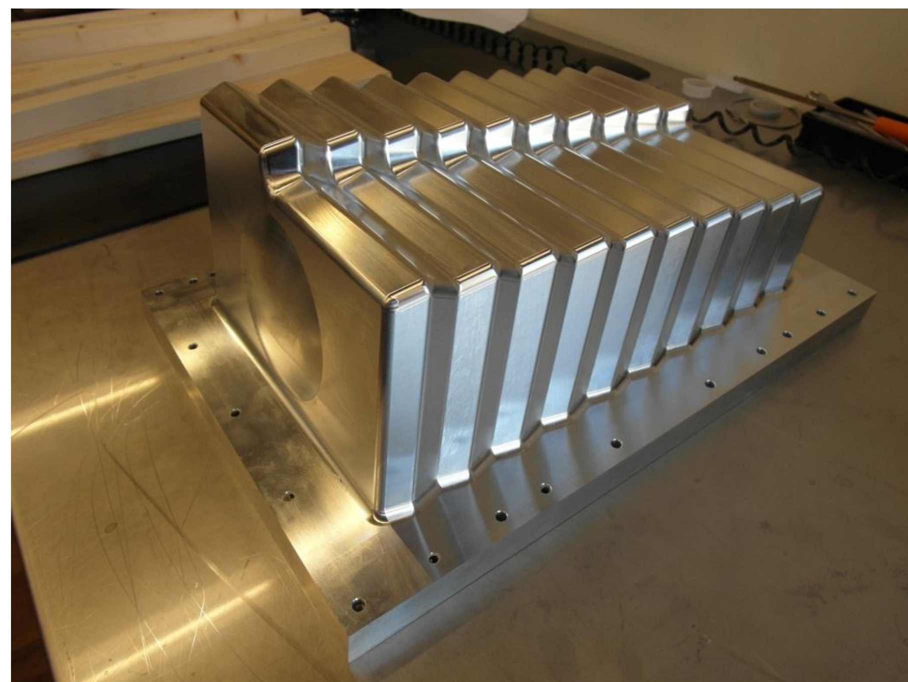
Keywords: low mass, leak tight, RF shield, low impedance, stiff and precise

New production method is being studied: (NIKHEF/VU)

- Mill the shape out of a block (5-axis precision milling machine)
- More flexibility to change the shape
- Especially important for the pixel option (L-shape box)

Prototype shown here (one of two)

- Wall thickness 0.3 mm (hope to reach 0.2 mm)
- Leak tightness: good for one box, small leak in other (repair to be investigated)
- Mechanical tolerances: to be assessed



RF foil tolerances

Measurement on the current VELO RF boxes

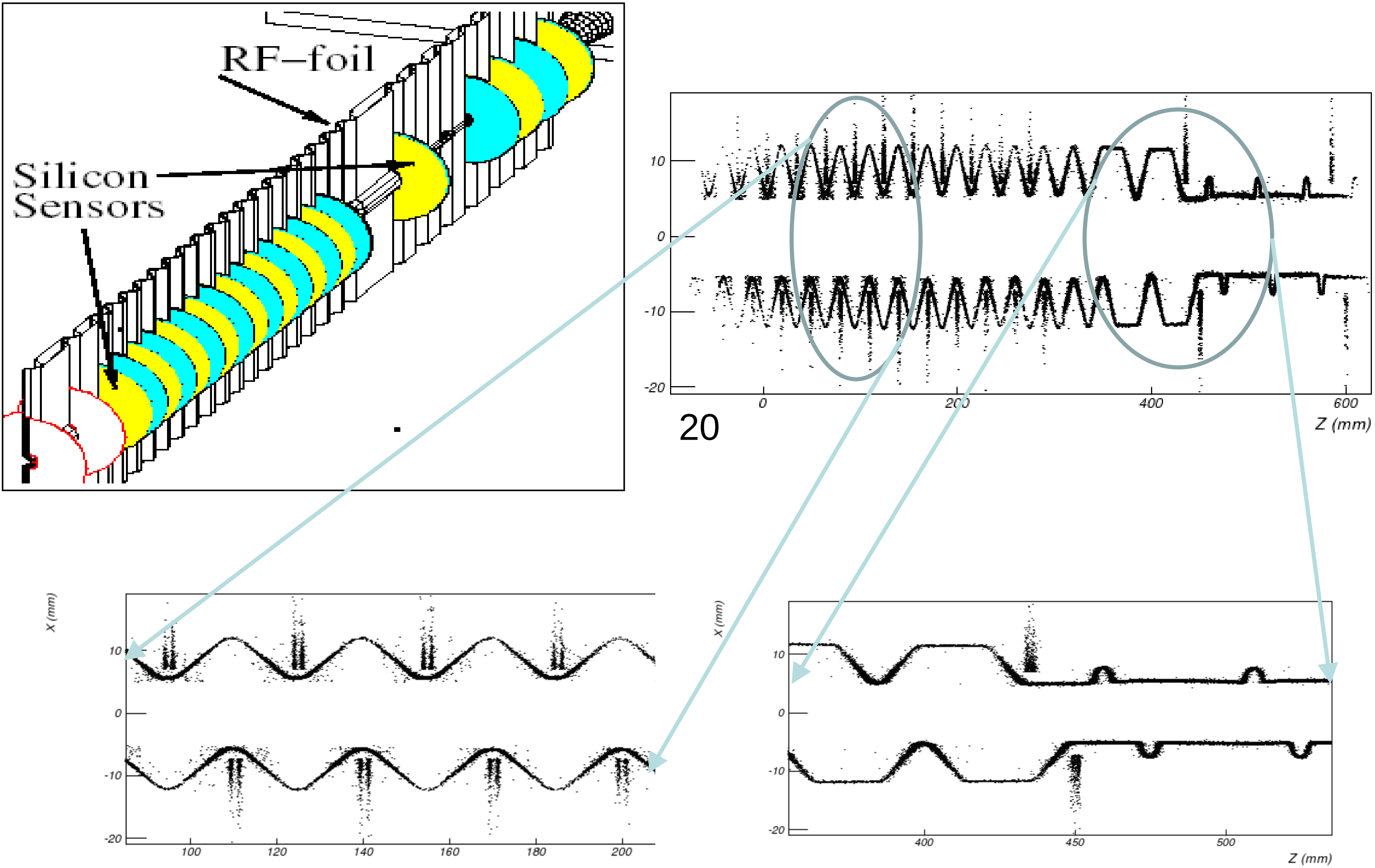
- performed before installation can be found here
  - http://www.nikhef.nl/pub/departments/mt/projects/lhcb-vertex/test/secondary_foil/deflection/Metrology_0612updated.pdf
  - Typically, the foils are within 0.5 mm of their nominal position over the whole surface.

- from particle interactions (tomography) are being worked on

Measurements on the new (upgrade) RF boxes using the milling method are yet to be done, but expect to have better tolerances than the current foils (less stress in foils)

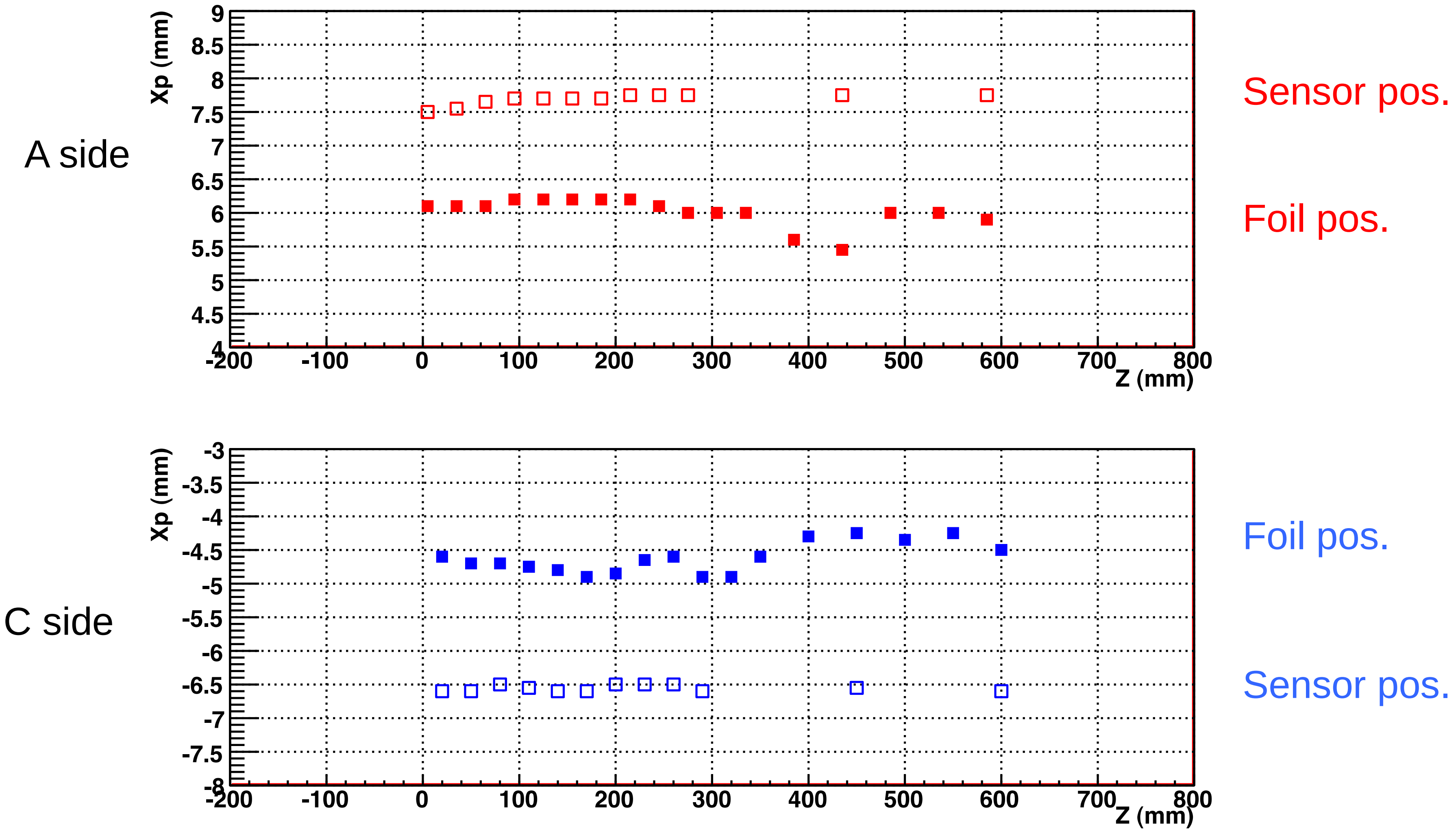
Tomography of the VELO

Victor Coco, Veerle Heijne, Tjeerd Ketel



Hole size (PRELIMINARY!!)

Hole radius is small, $(X^A - X^C)/2$ = 4.9 mm, at z ≈ 440 mm (nominal 5.5mm)
and quite nominal, $(X^A - X^C)/2$ = 5.6 mm, at z ≈ 160 mm



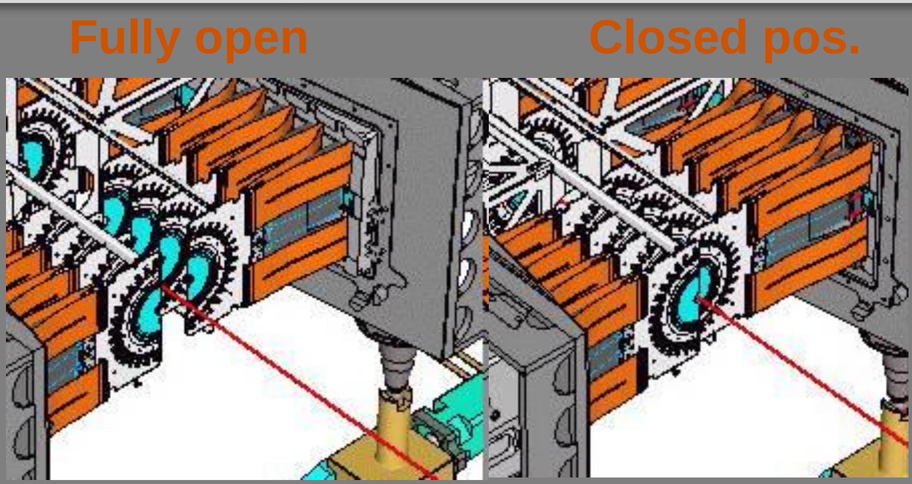
Stability plot (2010 data, but similar for 2011-2012)

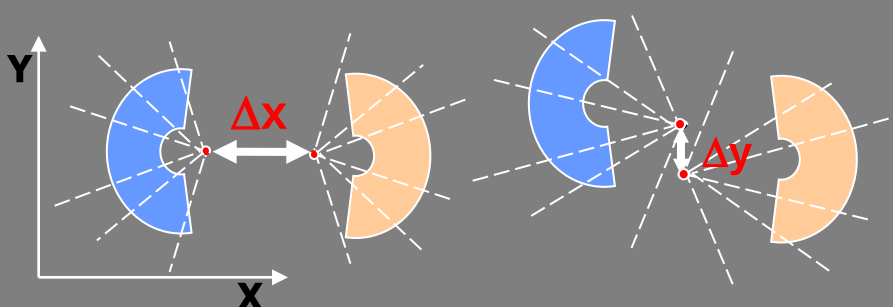
(slightly modified) Slide from S. Borghi, Vertex2011, Rust, Austria

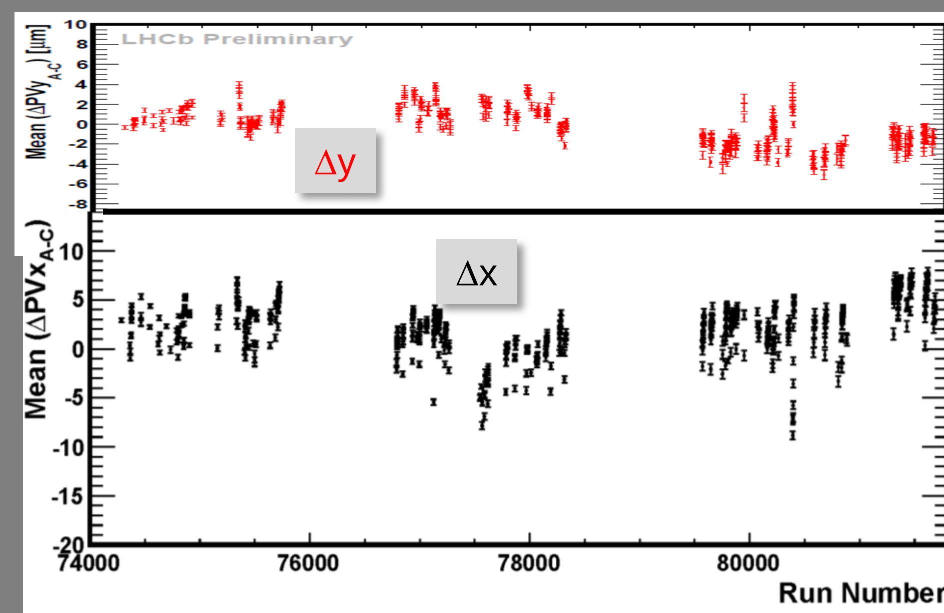
- VELO centred around the beam for each fill when the beam declared stable

- PV method:
  - Reconstruct PV using tracks in left or in the right side
  - Evaluation of misalignment by the distance between the 2 vertices

- Stability of 2 half alignment by PV method:
  - within ± 5 μm for Tx
  - within ± 2 μm for Ty







Position of luminous region vs VELO halves