The alignment of the LHC

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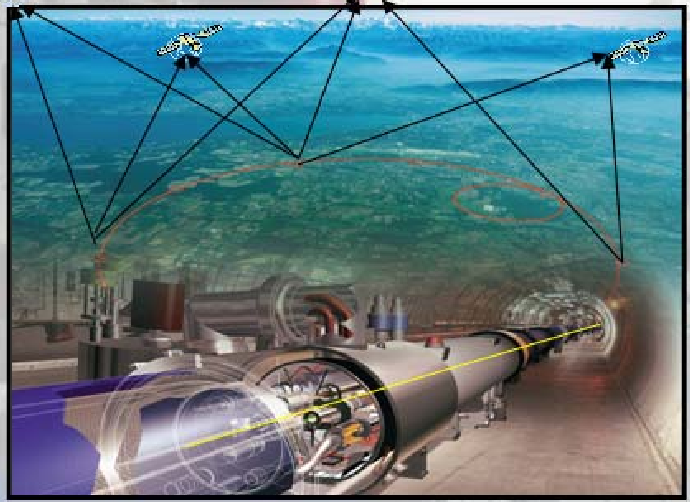
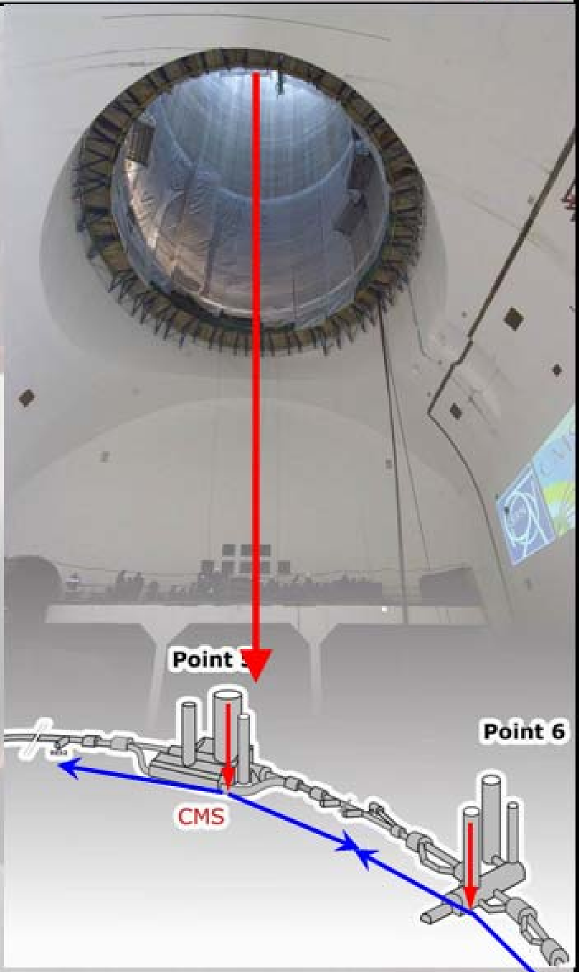
Outline

- The geodetic network
- The first alignment
- The smoothing
- Beam-based alignment estimates
- Conclusion

The geodetic Network (1)

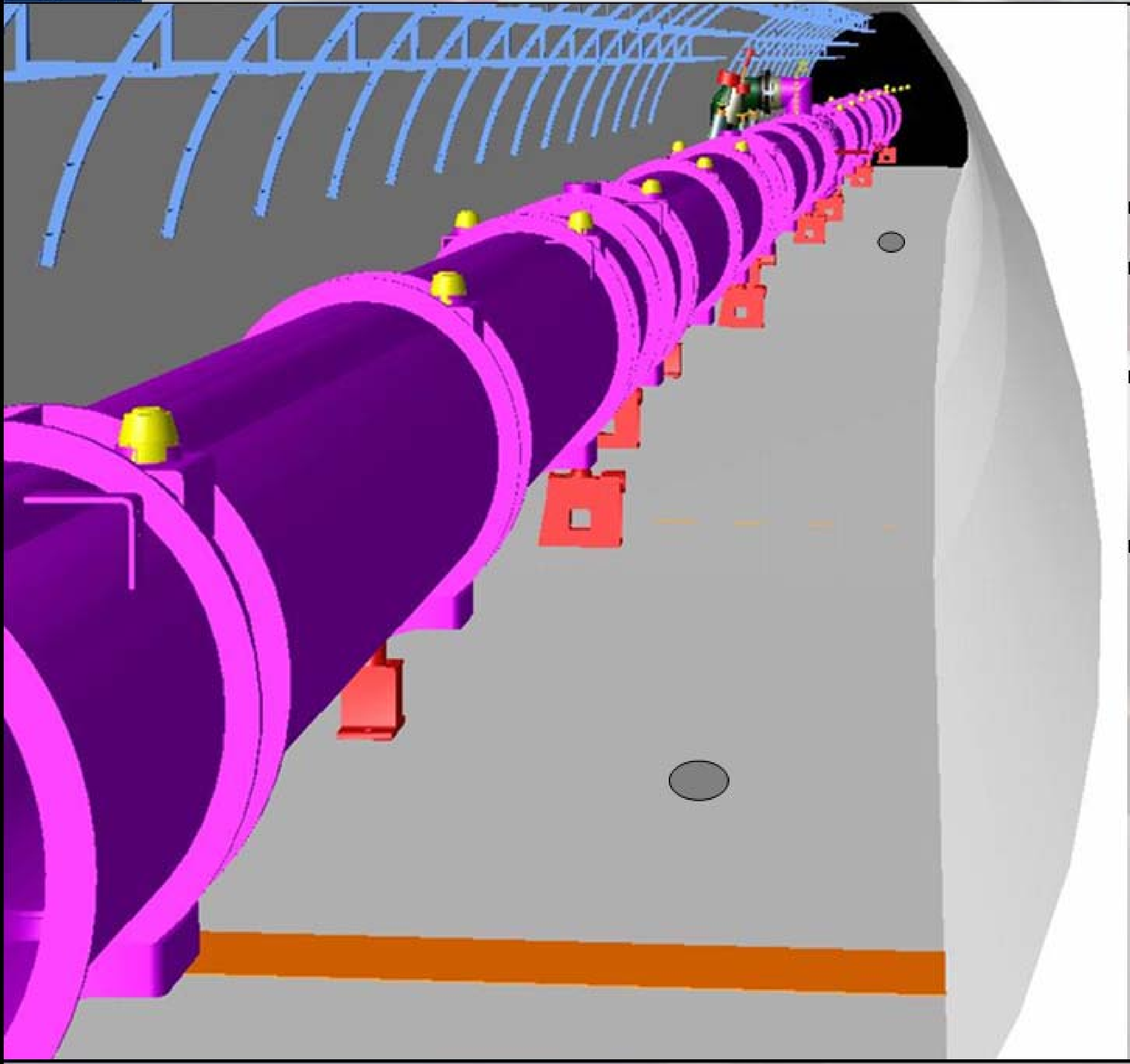


- A surface network was determined with GPS measurements
- A geodetic network was transferred to reference tripods and used to align LEP MQs
- MQs smoothed over the years to obtain the best achievable accuracy



- LHC network measured from LEP MQs : absolute accuracy of ± 2mm close to shafts ± 4.5mm in the middle of the Arc

The first alignment



- **In Vertical**
- **From the geodetic network**
- **How**
  - Using optical level NA2
- **Accuracy**
  - In order to obtain the best absolute position
  - A relative position of 0.25 mm at 1 σ

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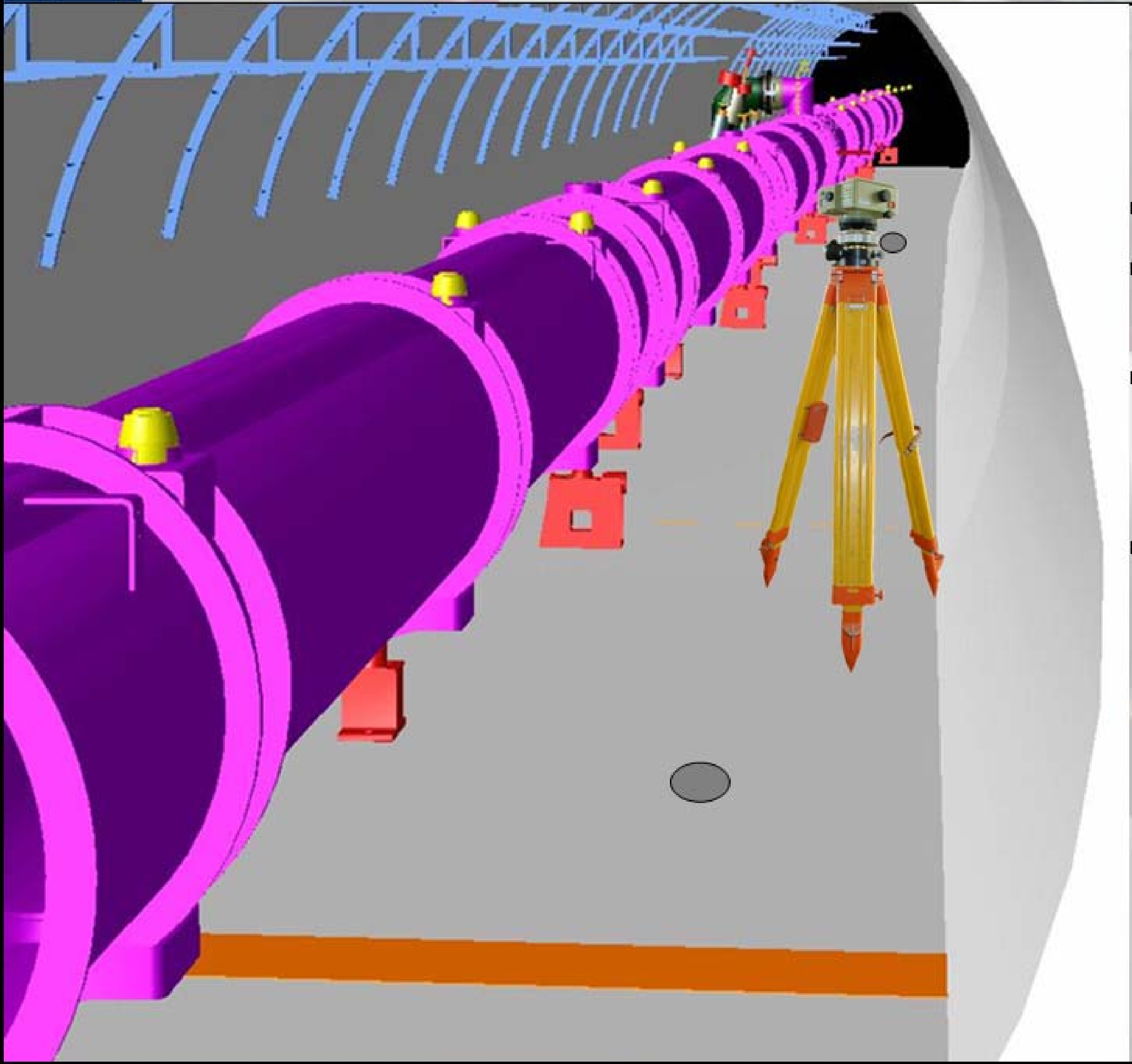

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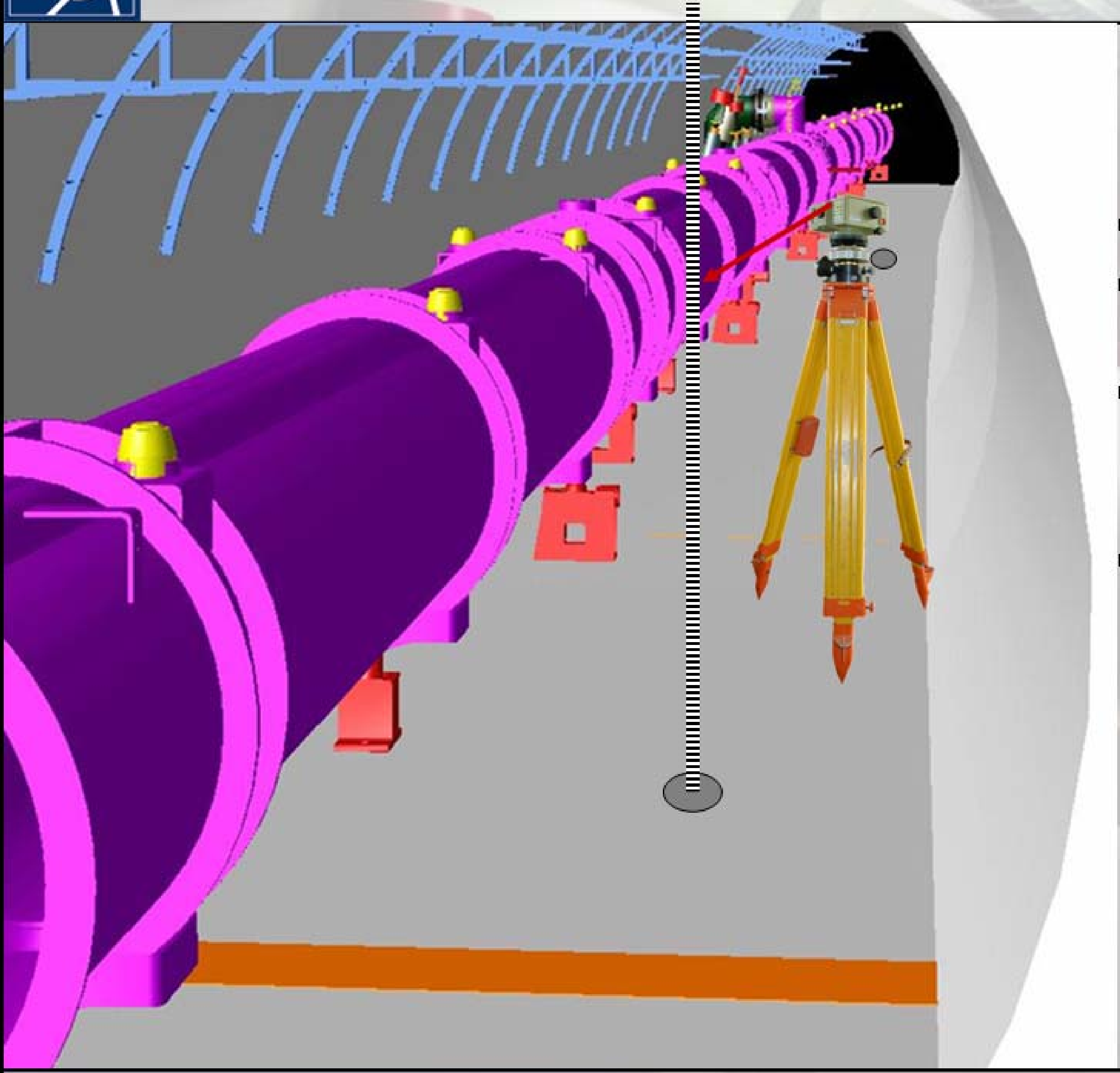

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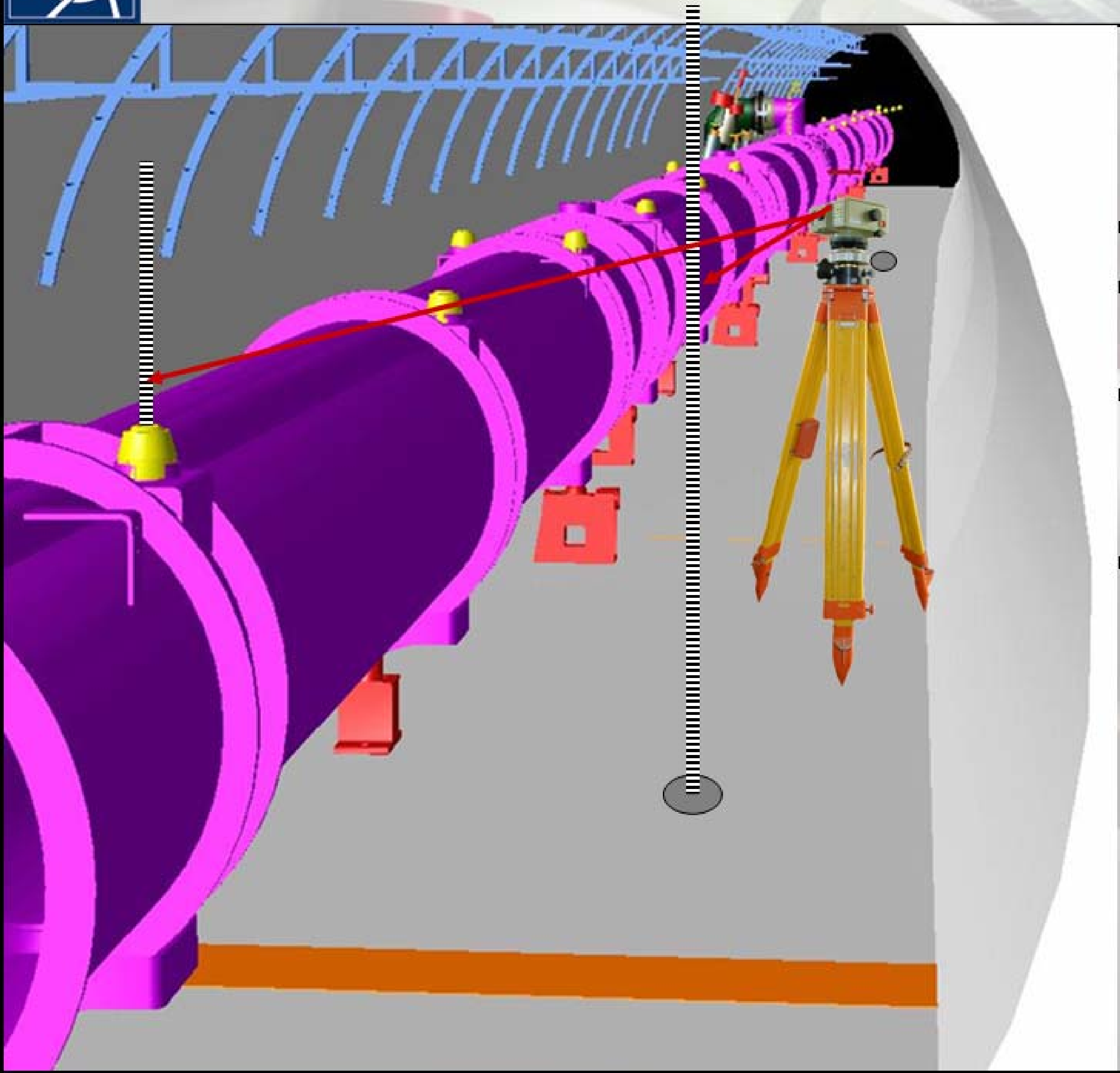

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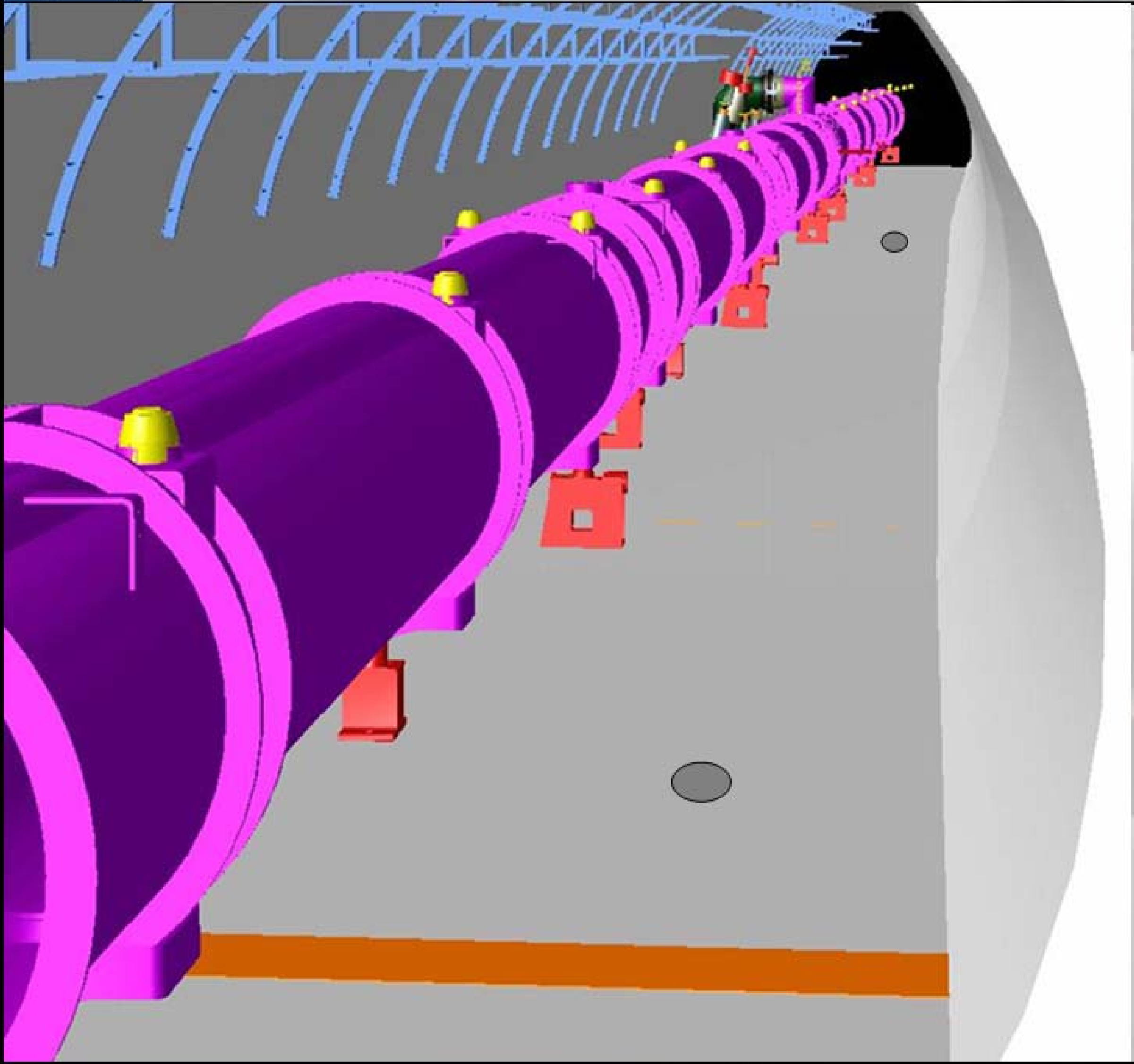

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  - Local horizontal smoothing
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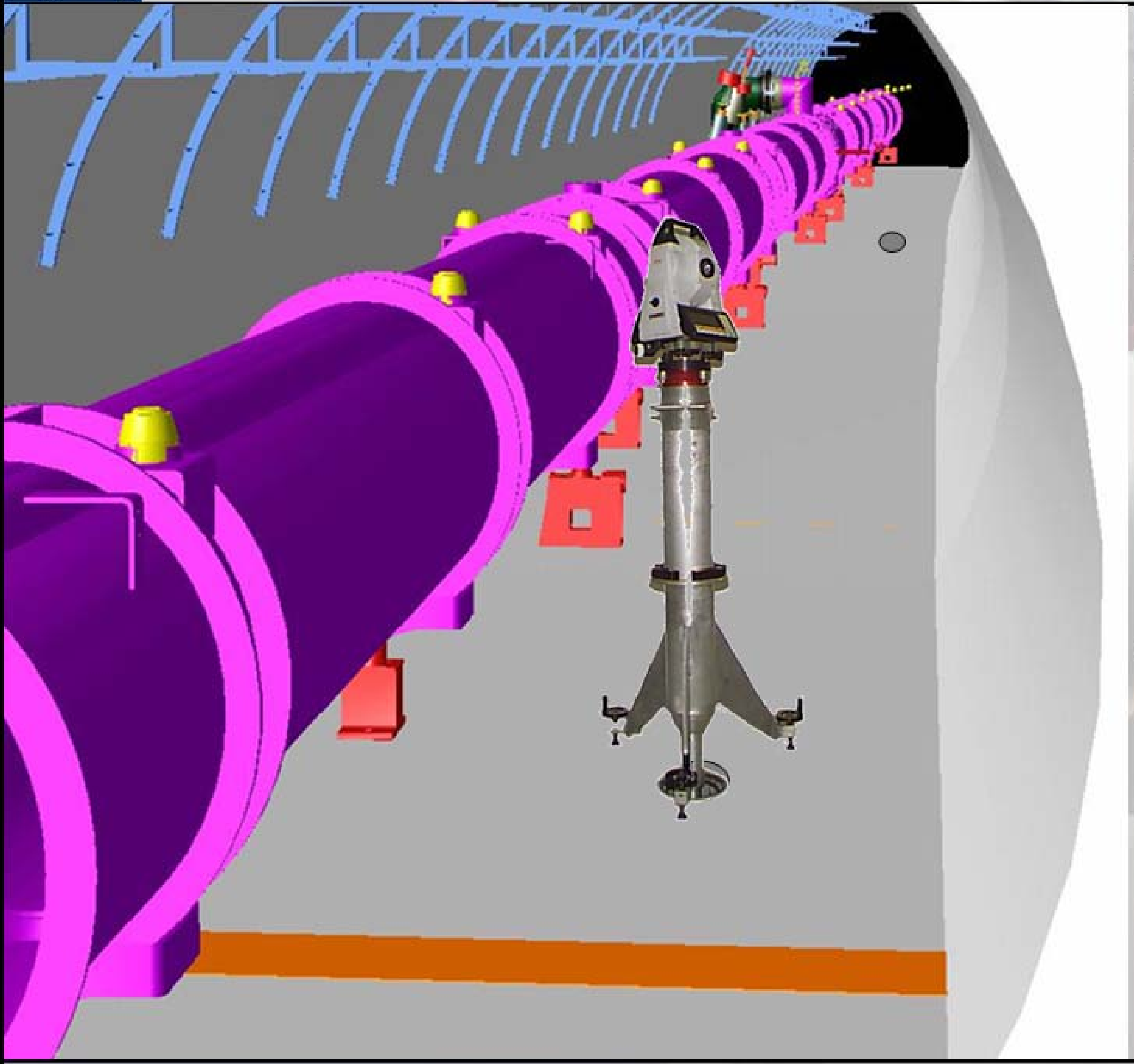

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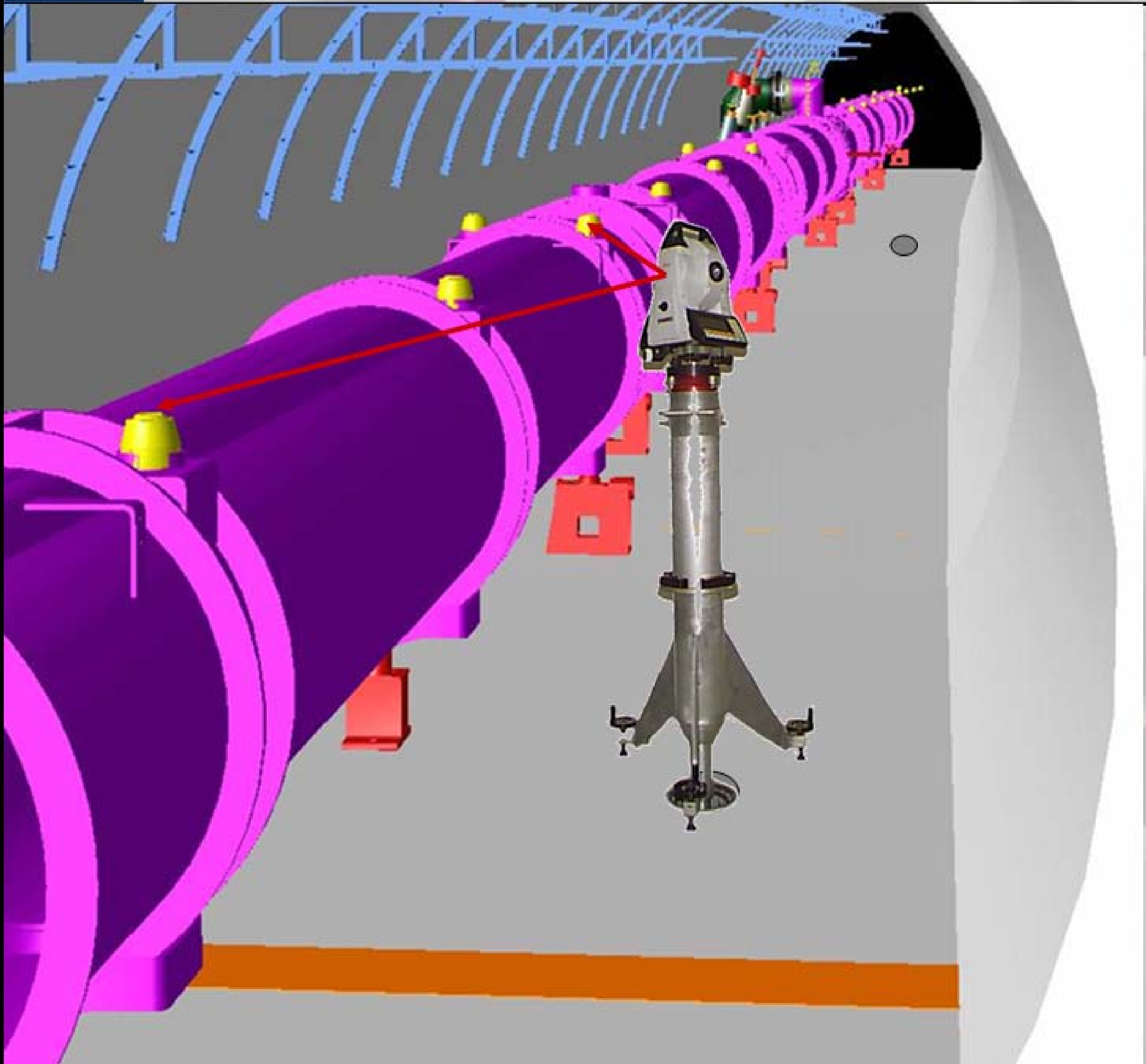

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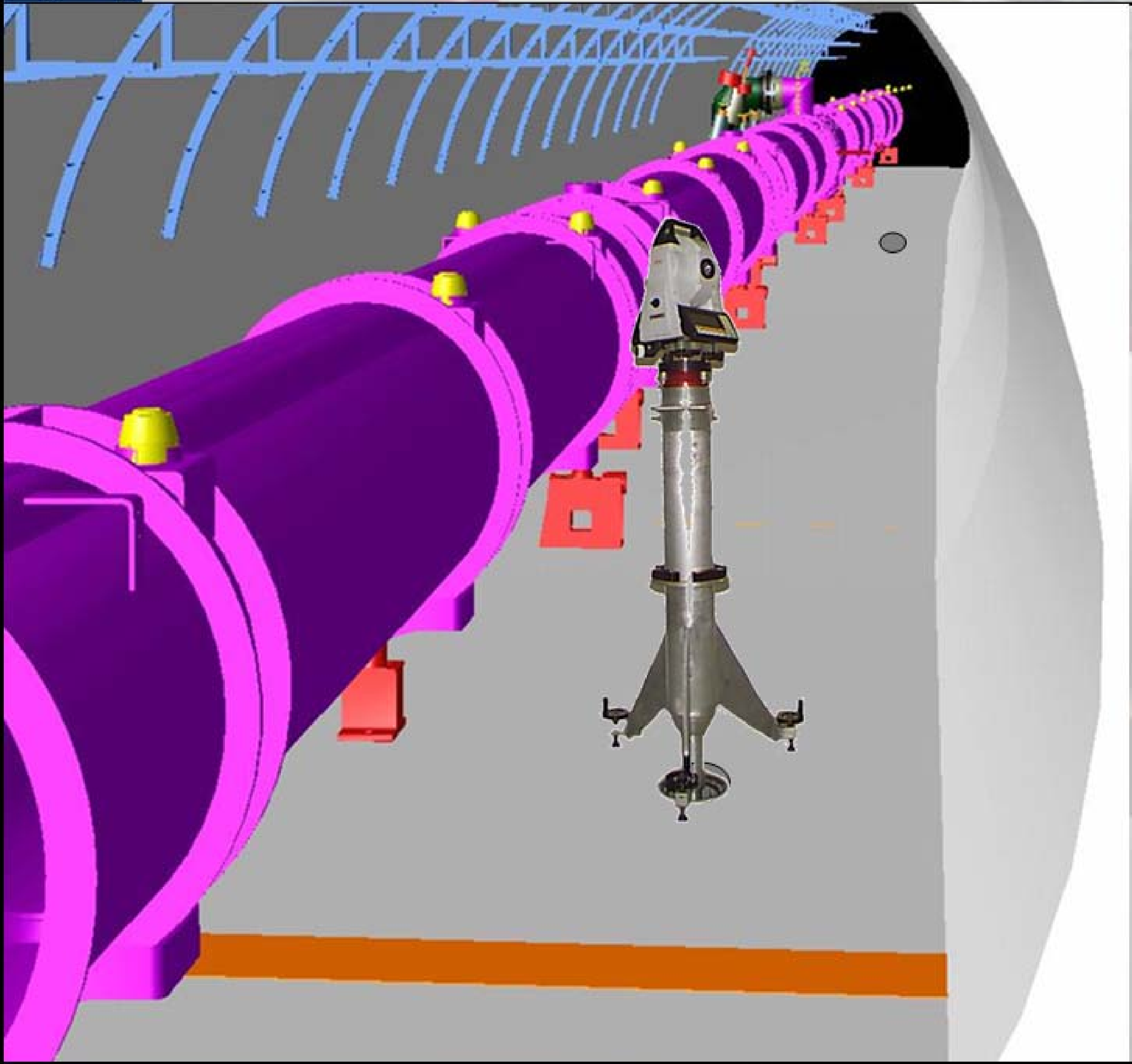

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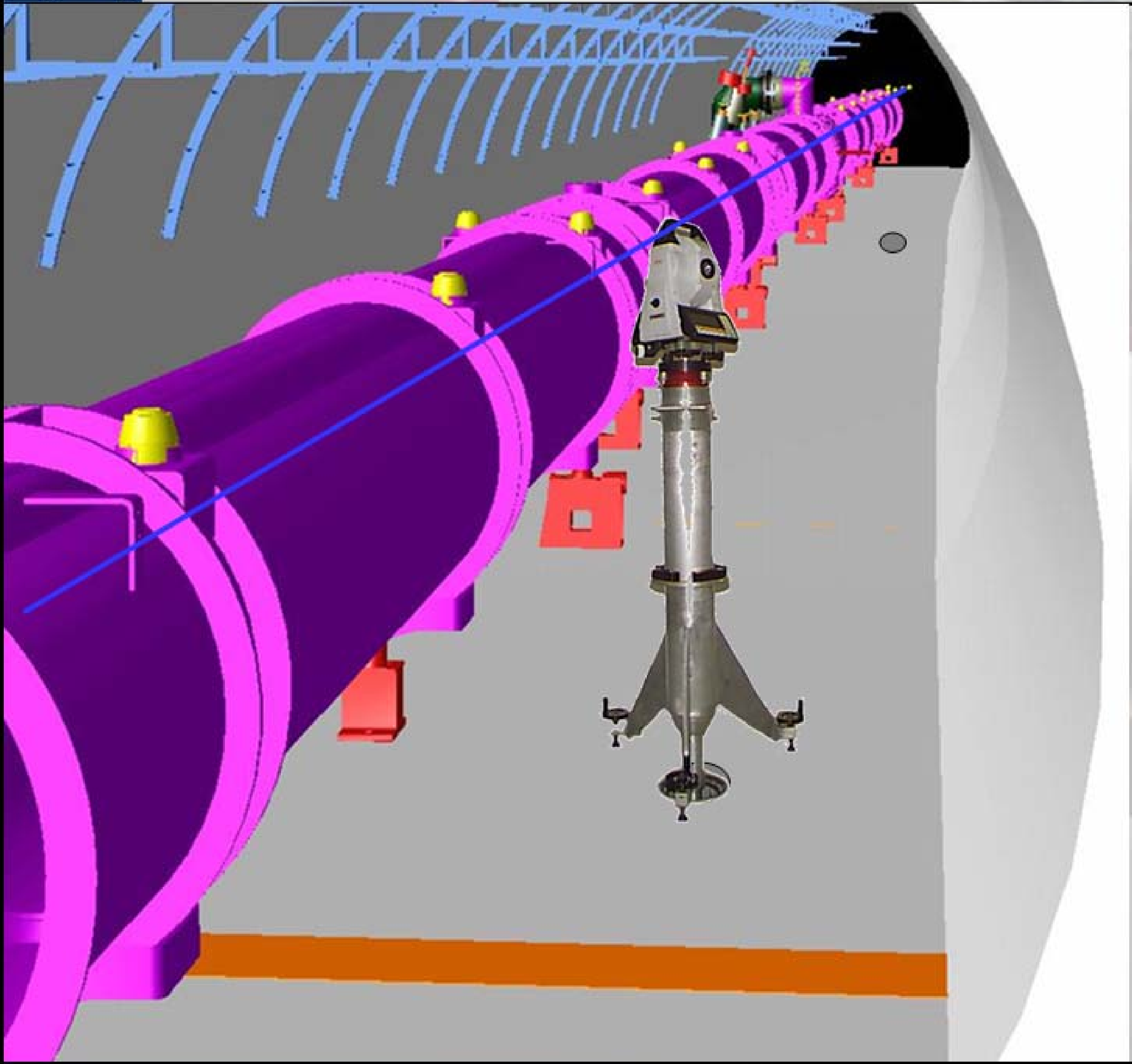

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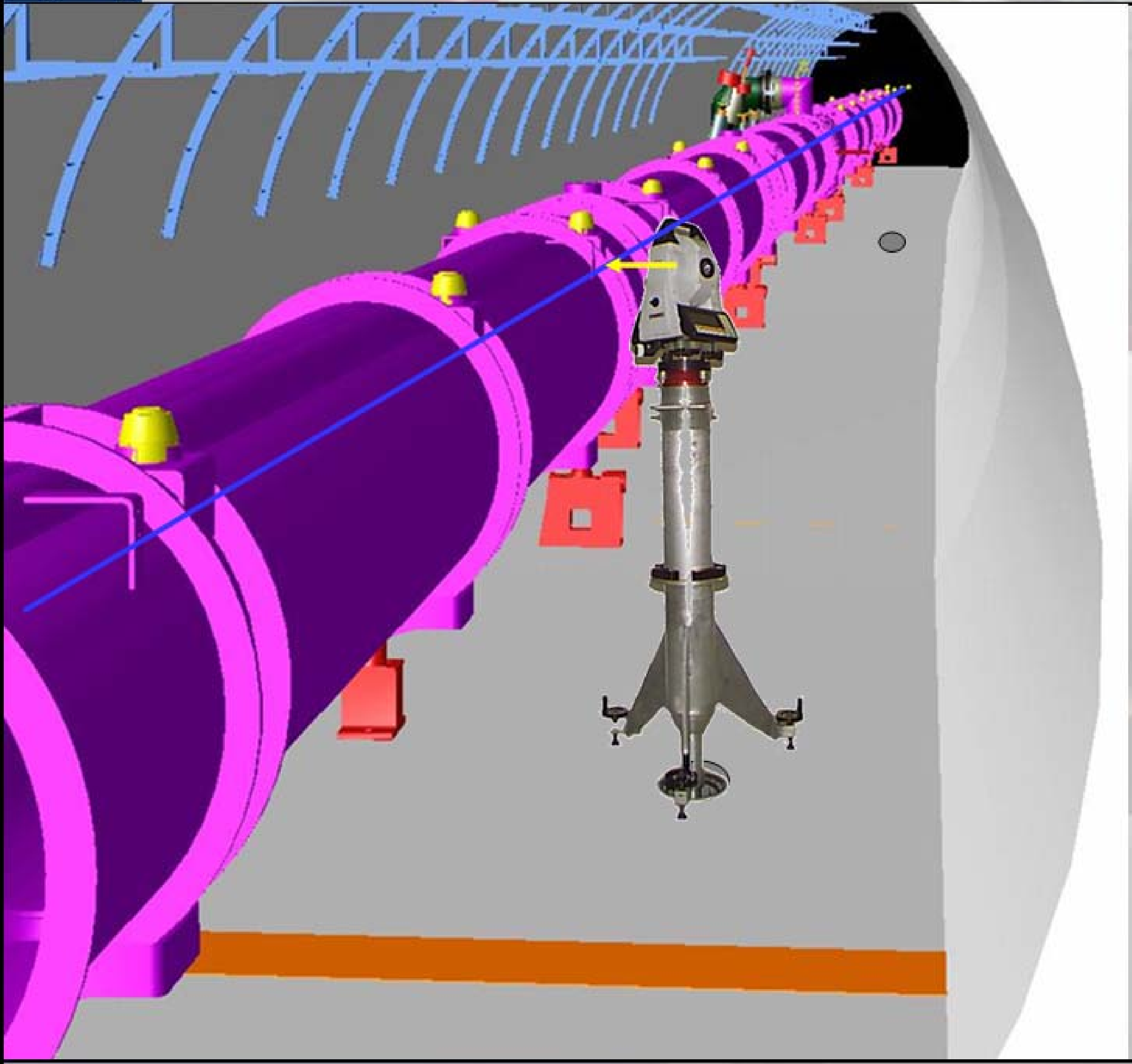

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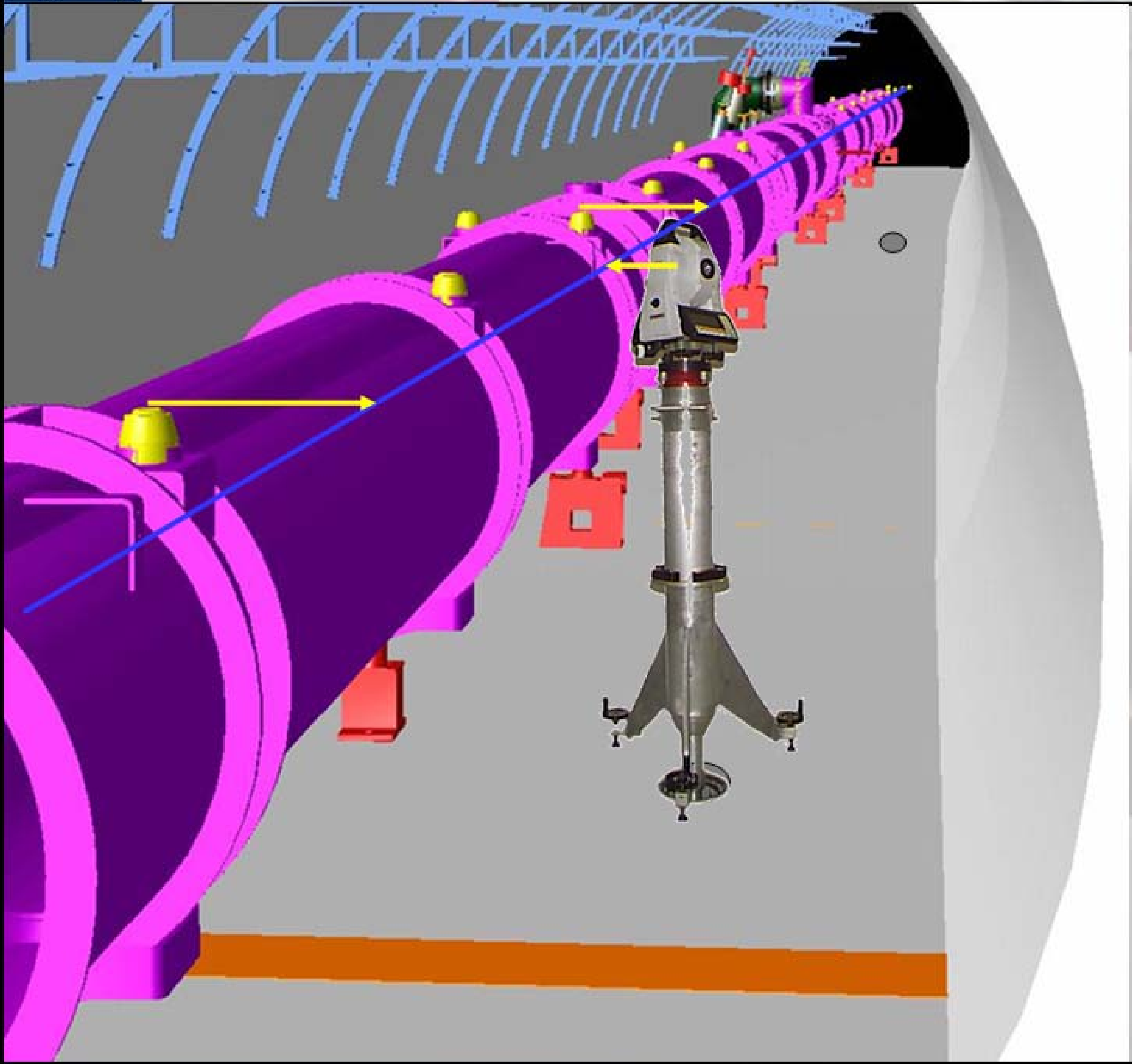

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The final alignment

- **Smoothing**
  - Improves the relative accuracy of the components by suppressing the steps which pertubates the particle beams
  - takes place when the magnets are « cold », i.e. all the mechanical constraints have occured
- **What magnets**
  - All cryo-magnets not only the MQs
  - To prevent the shearing of the tubes in the interconnect
- **Accuracy**
  - 1 σ deviation to a smooth curve not exceeding 0.15mm
- **Steps**
  - Roll angle, Vertical and horizontal measurements
  - Calculation of the smooth curve with « PLANE »
  - Displacement of the magnets out of tolerance

Roll angle measurements

- **With a special instrumentation installed on two fiducials**

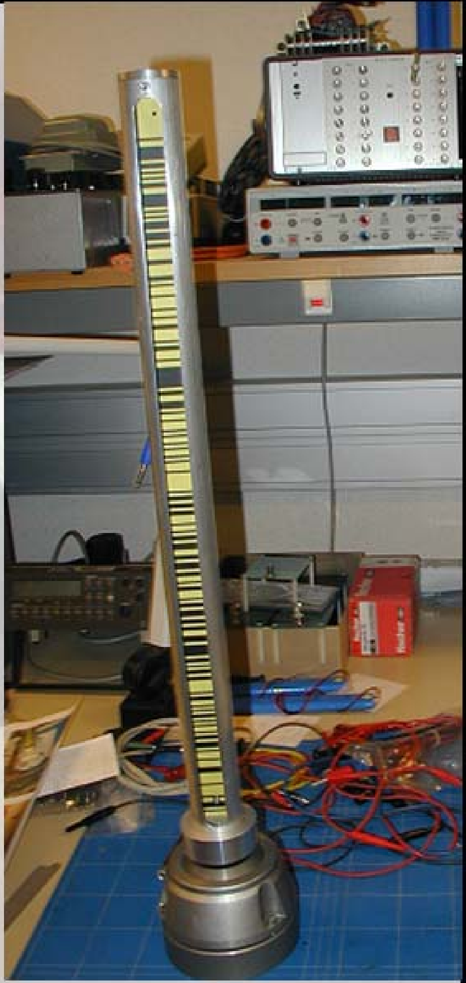
Roll angle measurements

- **With a special instrumentation installed on two fiducials**
- **No important movements**
- **Slight degradation**

Sector	Initial alignment		before smoothing	
	Avg (mrad)	Stdev (mrad)	Avg (mrad)	Stdev (mrad)
1-2	0.00	0.04	-0.01	0.07
2-3	-0.01	0.04	0.00	0.06
3-4	0.00	0.06	-0.02	0.09
4-5	-0.01	0.04	0.03	0.09
5-6	0.00	0.04	0.01	0.08
6-7	0.00	0.04	-0.01	0.10
7-8	0.00	0.05	-0.04	0.08
8-1	0.01	0.05	0.05	0.11

Vertical smoothing

- **Done in 2007-2008**
- **Instruments**
  - Digital level DNA03
  - CERN made staff



Vertical smoothing

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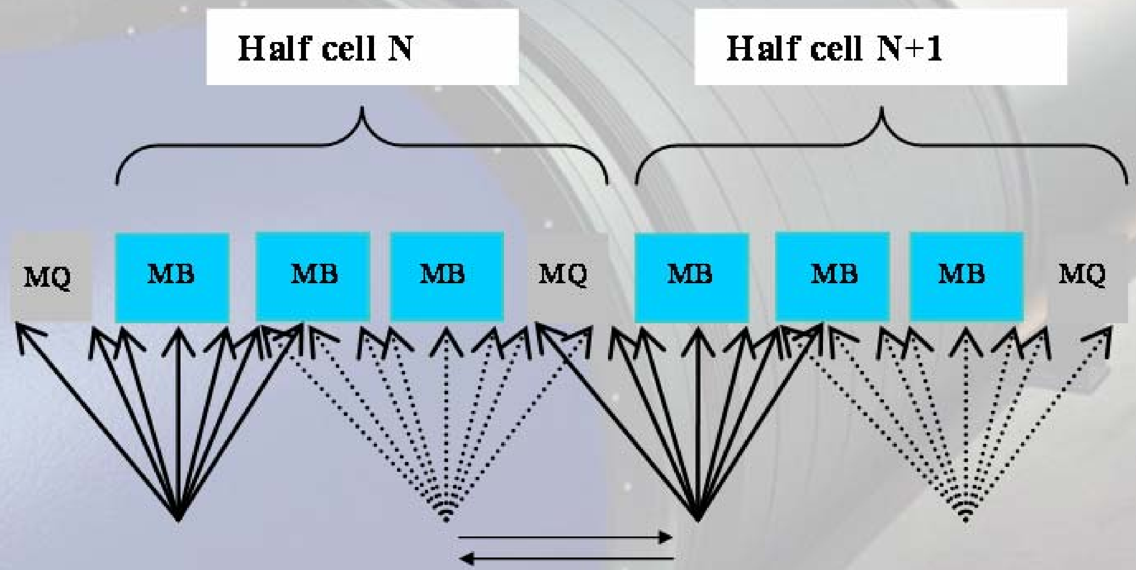
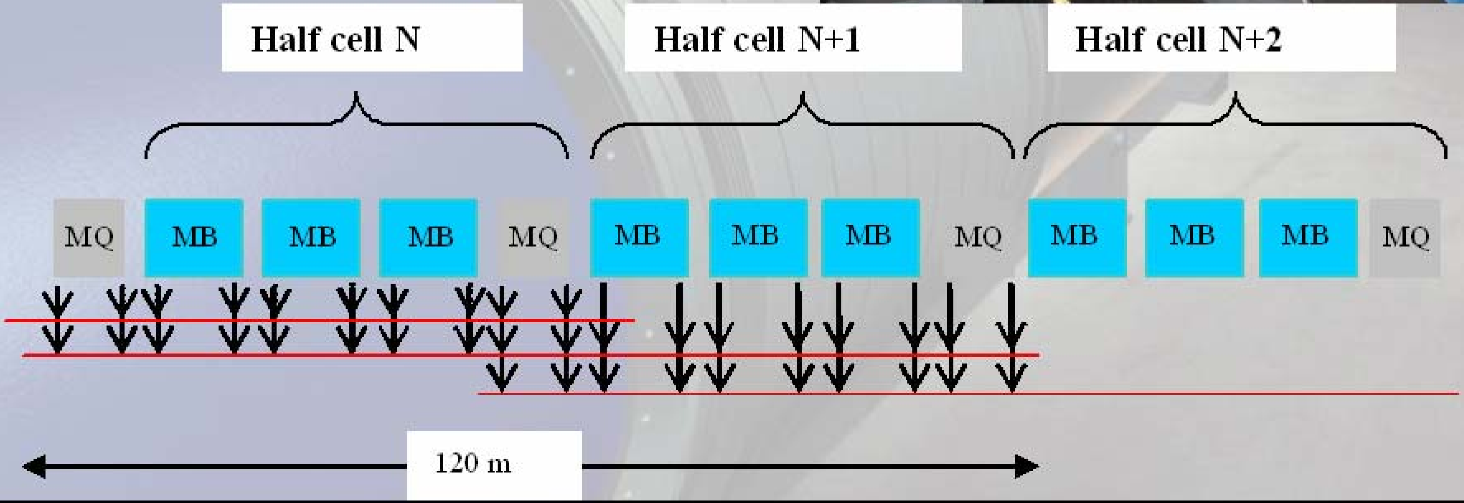
- **Measurement sequences**



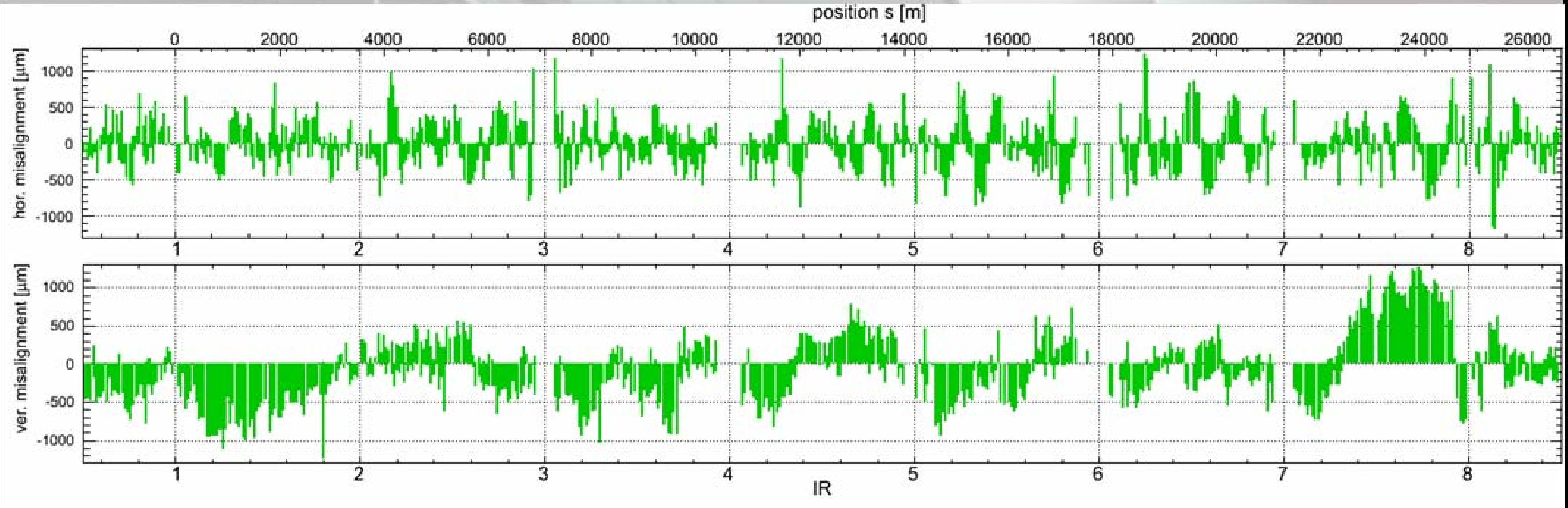
Horizontal smoothing

- **Done in 2007-2008**
- **Instruments**
  - Ecartometer and stretched wire (very good for relative positionning)
  - Protected inside a duct
- **Measurement sequences**
  - Redundancy of 3 for MQs and 2 for MBs



Smoothing results

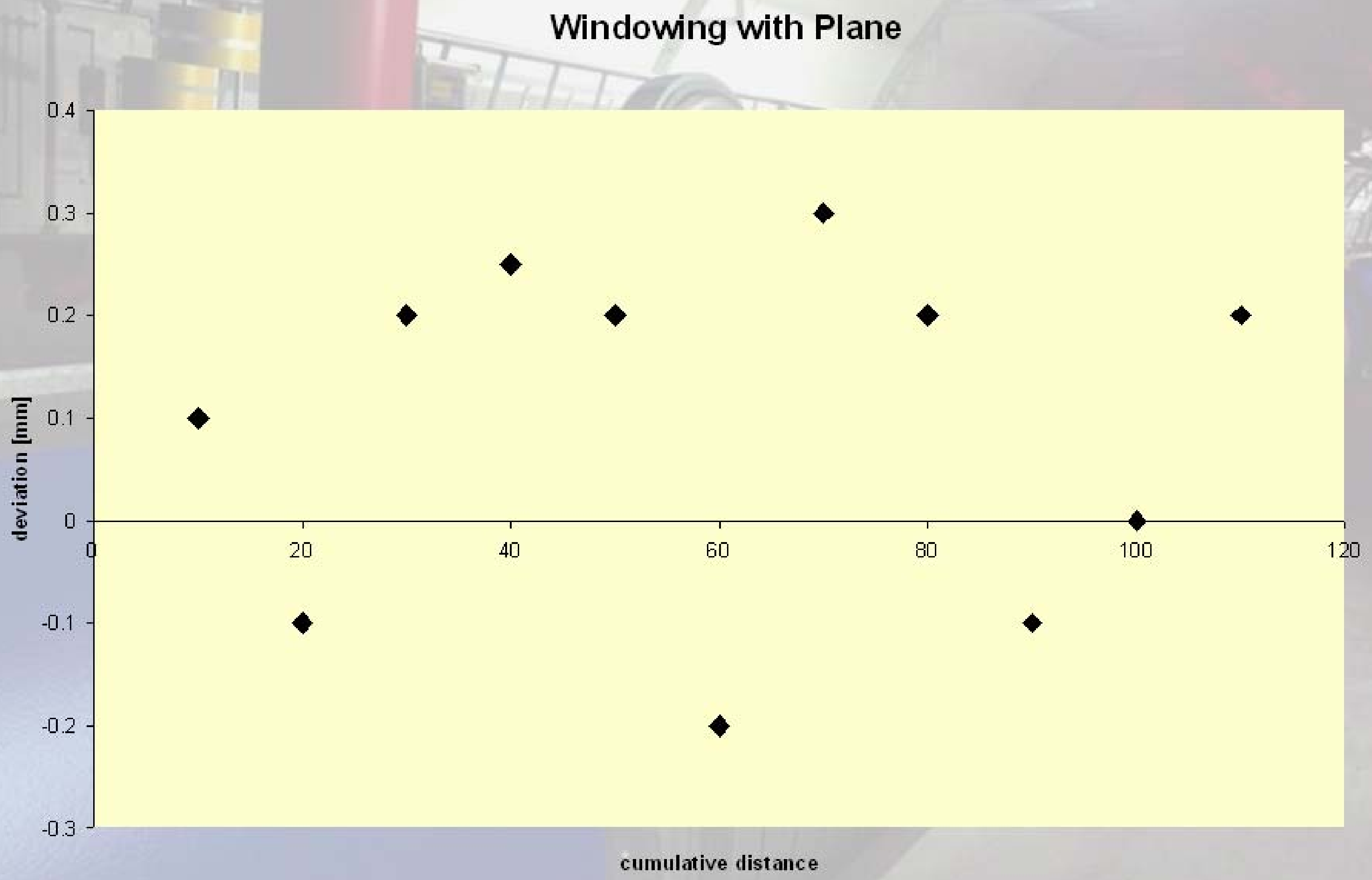
- **Calculations done sector by sector**
  - A fixed point at each extremity of the sector
  - Radial constraint of 2mm in H
  - Residuals of measurements at 1 σ 0.04 mm
- **H : average very close to 0 for all sectors**
- **V : average between -0.4 mm and +0.4 mm**



Smoothing with 'PLANE'

- **What is PLANE ?**
  - Software to calculate a smooth curve and the points to be realigned
  - Principles : windows and polynomials
  - Parameters : size of the window and Tol above which the points are rejected
  - Works in vertical and horizontal plane

Smoothing with PLANE (2)



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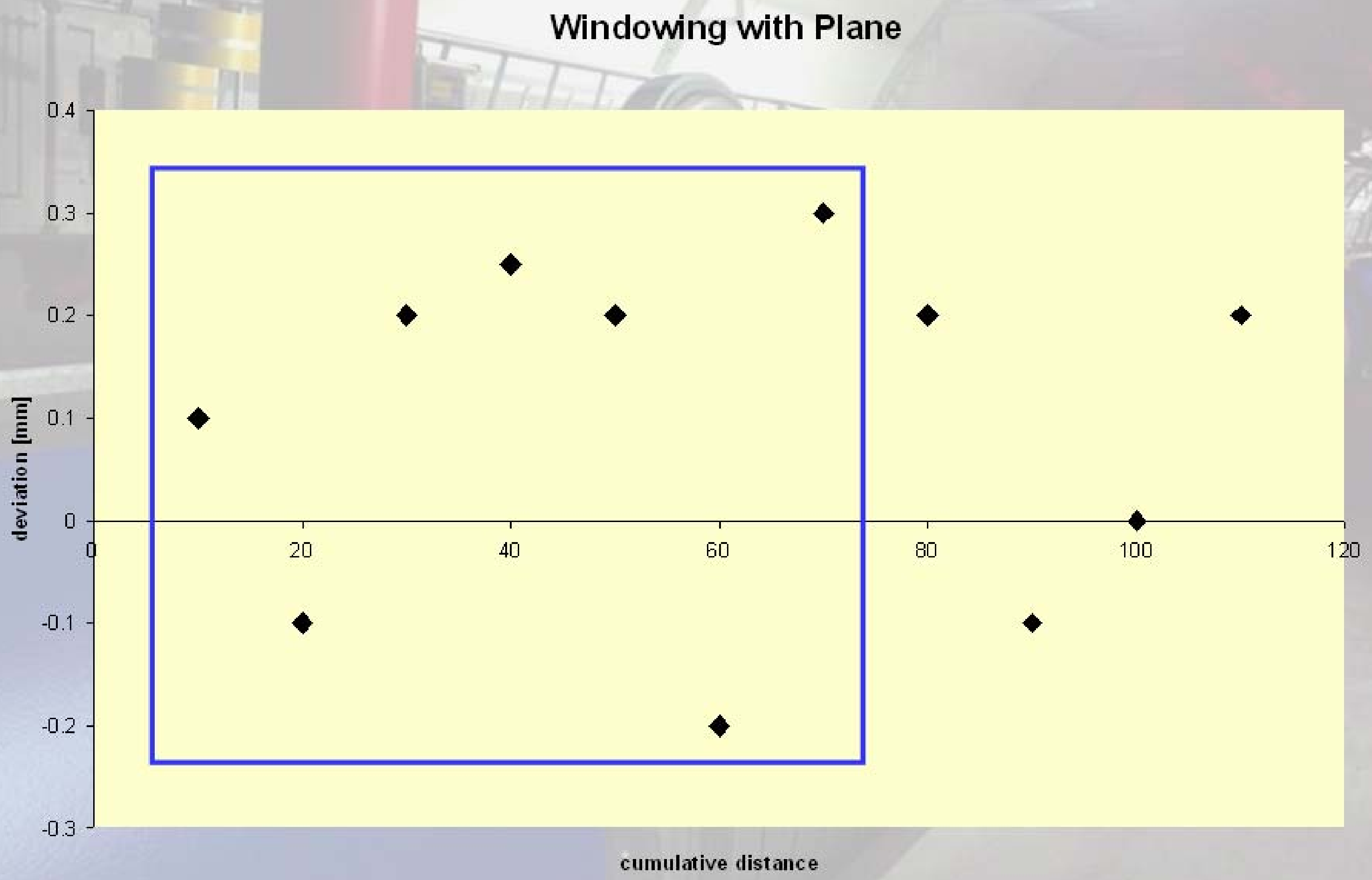

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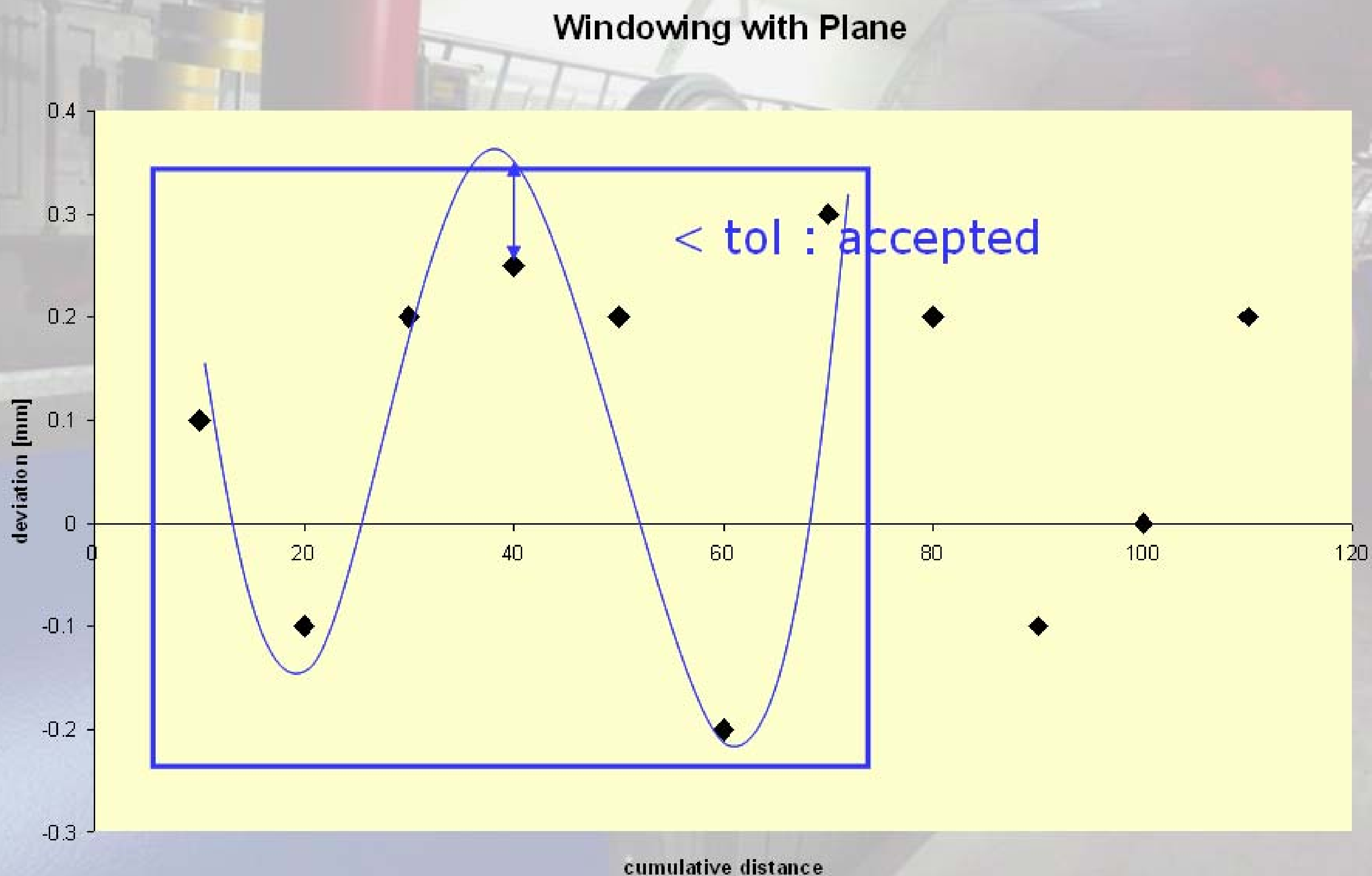

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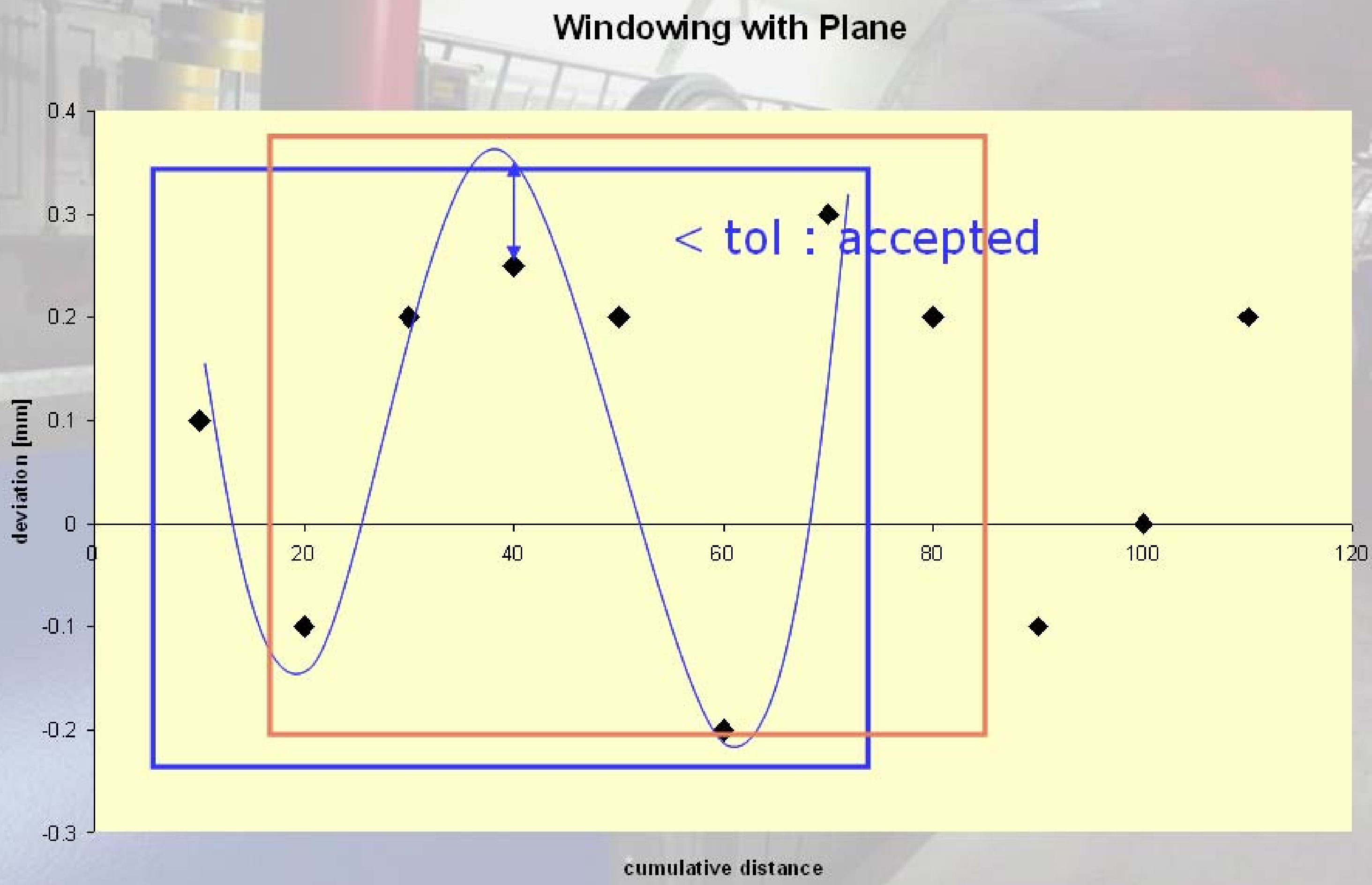

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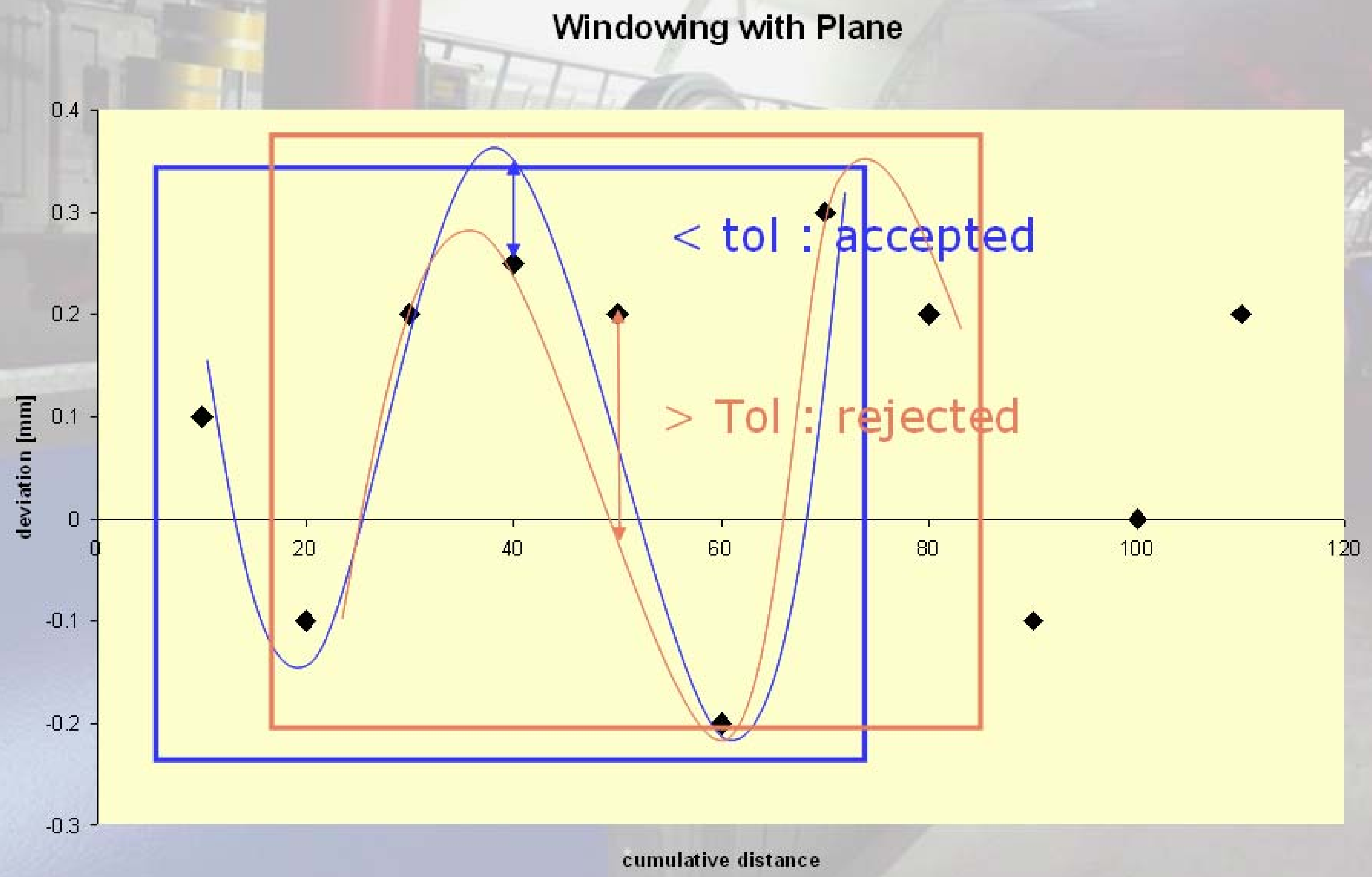

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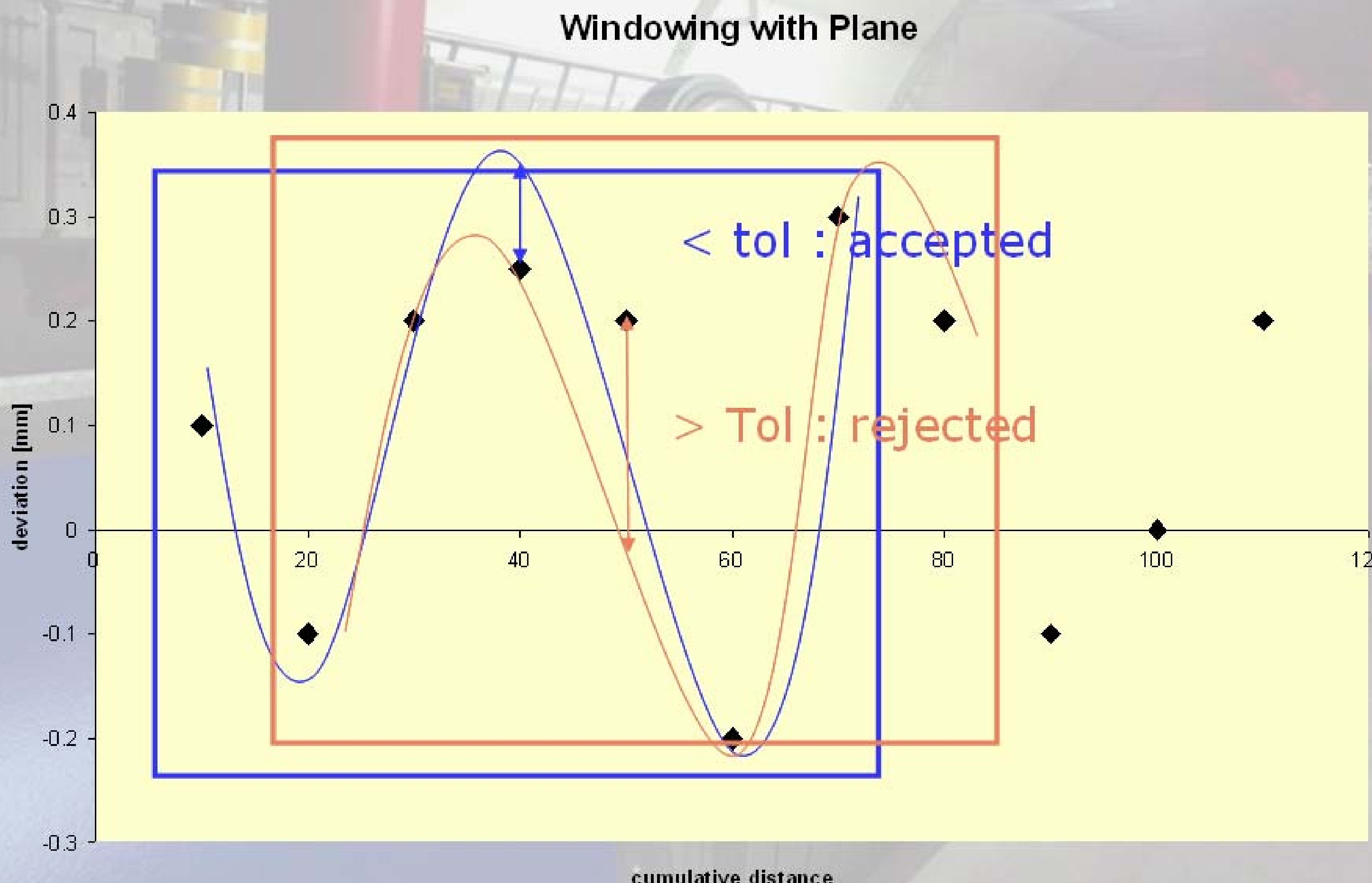
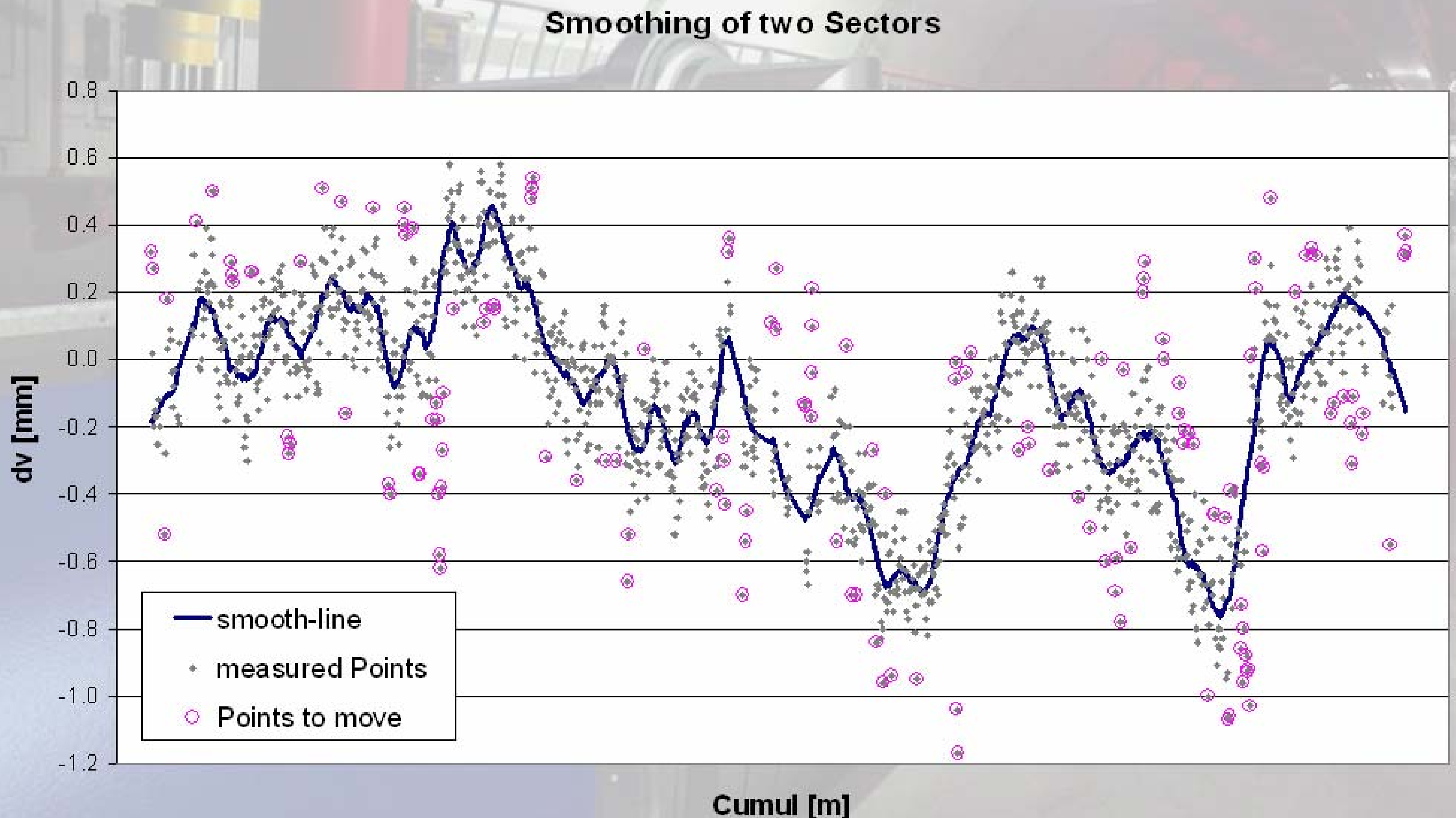


- **Window size : 63**
- **Tol : 0.3 mm**

Minimise the number of magnets to move

Smoothing with PLANE (3)



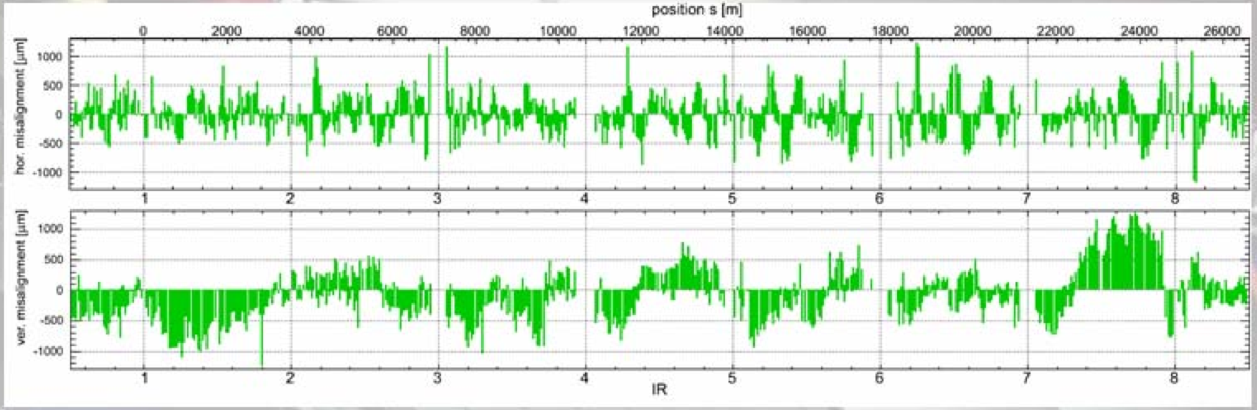
Smoothing with PLANE : results

Sector	Vertical			Horizontal		
	Pre displ. (mm)	Post displ. (mm)	Points to move	Pre displ. (mm)	Post displ. (mm)	Points to move
1-2	0.16	0.10	41	0.19	0.11	56
2-3	0.16	0.12	63	0.20	0.11	90
3-4	0.18	0.11	84	0.21	0.11	72
4-5	0.15	0.13	45	0.19	0.11	65
5-6	0.15	0.10	49	0.22	0.11	52
6-7	0.13	0.10	20	0.20	0.11	65
7-8	0.15	0.11	46	0.17	0.10	40
8-1	0.16	0.11	65	0.30	0.10	96

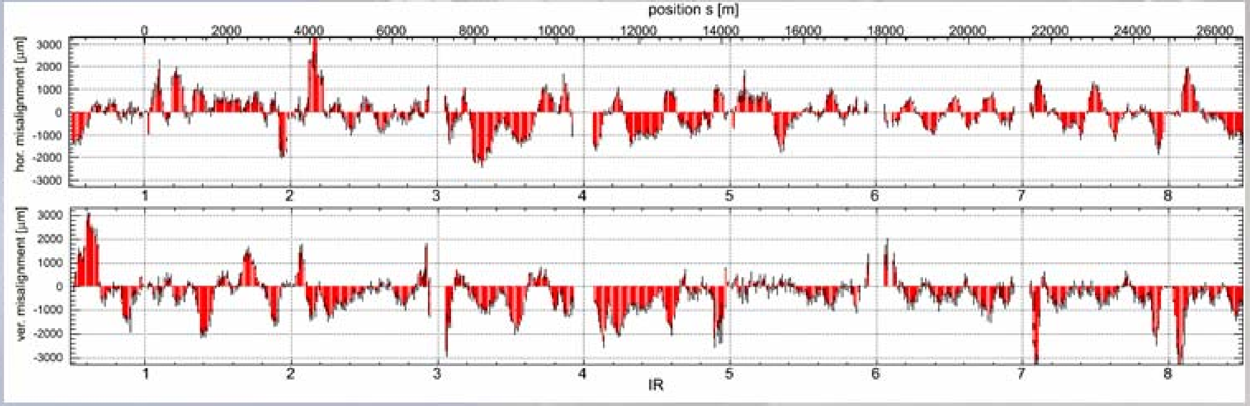
- Good improvement of the deviation after smoothing
  - deviations under 0.15 mm rms as specified
  - ~53 Magnets moved/sector in V and 67 in H
- Same accuracy in V and H

Beam-based alignment estimates (1)

- Geodetic measurements



- Beam-based alignment estimates



- Cell to cell misalignment 0.1 mm rms. Global is 0.7(H), 1.2(V)@90%
- While there are difference, both measurements are in good agreement !!

Beam-based alignment estimates (2)

- Why are there differences ?
- They have different reference systems
  - Geodetic measurements are local
    - They are fixed at the 8 IR points and the combination with the smoothing make that errors are distributed all along sector and error max in the center of arc
  - Beam based alignment estimates are global
    - Beam estimate based on short- and long-range feed-down effects of lattice quadrupoles
    - Any local quadrupole shift is seen by all BPMs

- Because of good alignment, very few correctors were activated and less than a dozen iterations were needed to establish circulating beams

Conclusion

- The alignment is done in several steps
  - First alignment with respect to the geodetic network (1 σ relative deviation of 0.25 mm) derived from LEP
  - Final alignment (smoothing) at cold temp.
    - to detect errors or movements
    - to improve the relative position of magnets
    - In both planes no important relative deviations
    - Limited number of magnets was moved
    - 1 σ deviation under 0.15 mm rms reached
- Instruments used are not from the shelf or in house improved
- Beam based alignment estimates shows good correlation with alignment
- Because of good alignment, it was easy to make beams circulating on September2008, 10th