Goniometer and controls

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in collaboration with EN-STI

8th HL-LHC Collaboration Meeting, CERN, 15-18 October 2018

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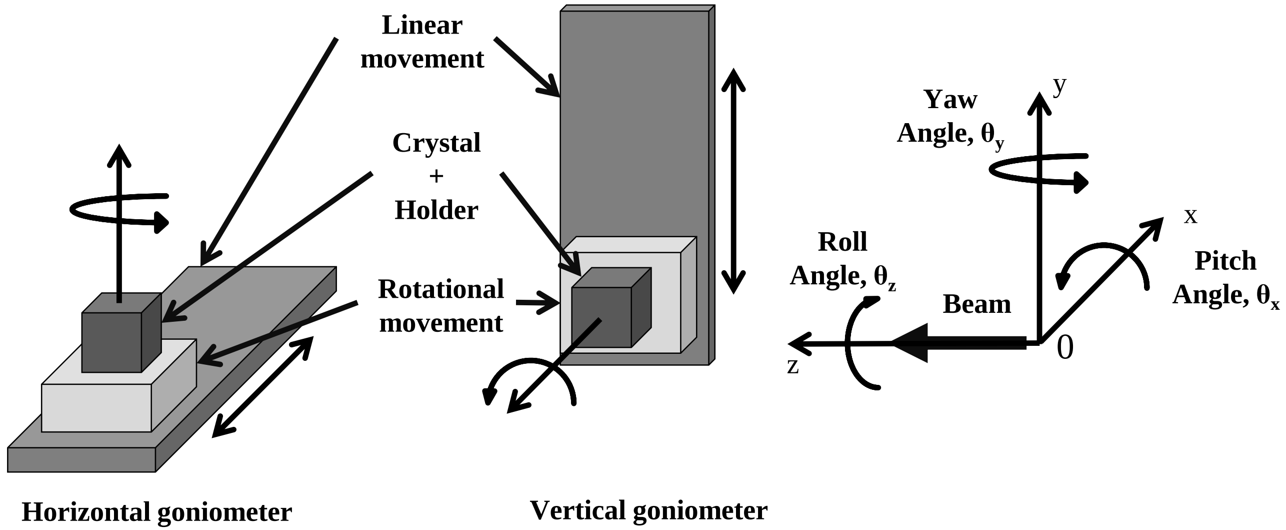
Coordinate reference system



Orientation independent angle nomenclature	Angle w.r.t. beam	
	Horizontal goniometer	Vertical goniometer
Rotation	Yaw	Pitch
Tilt	Pitch	Yaw
Roll	Roll	Roll

Goniometers for Crystal Collimation – Specifications

Property	Specification
Linear stroke	> 50mm
Linear resolution	5 um
Linear accuracy	+/- 20 um
Total angular range	+/- 10 mrad
Yaw angular resolution	0.1 urad
Yaw angular accuracy over the entire linear range	+/- 1 urad
Yaw angular overshoot	10%
Yaw angular settling time	20 ms
Yaw angle max speed in scan mode	50 urad/s
Pitch angular accuracy over last 10 mm travel	Few urad
Roll angular accuracy over last 10 mm travel	Few tens of urad

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Goniometers for Crystal Collimation – A technological challenge

- LHC UHV Compatibility
- Radiation resistant to 10MGy mixed field irradiation
- Bake-Out at ≥ 220 ºC
- Low impedance

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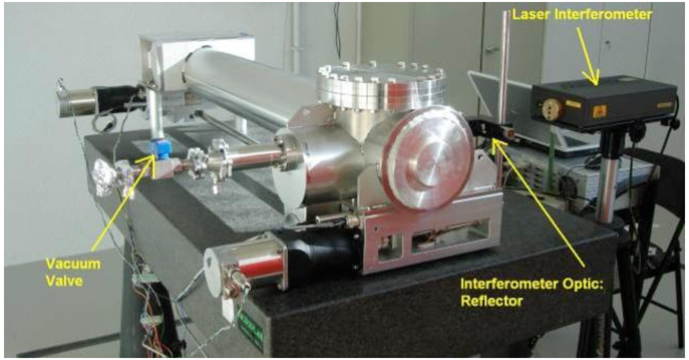
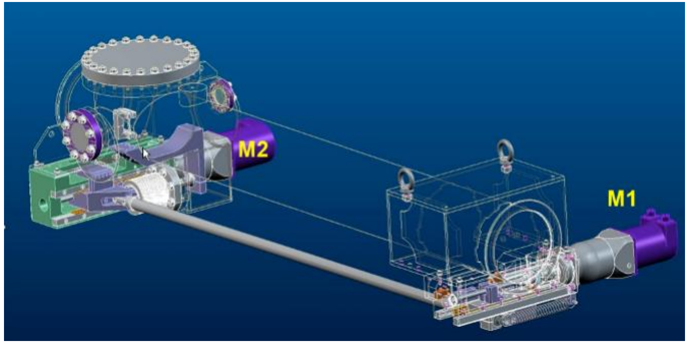
The design evolution: dual axes – lever arm





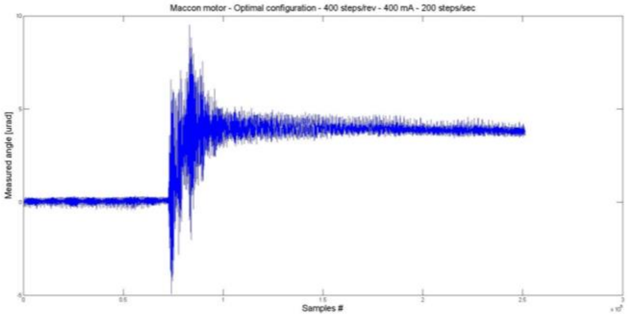
- Linear movement: 2 linear motorised axes moving simultaneously
- Rotational movement: 1 linear motorised axis moving

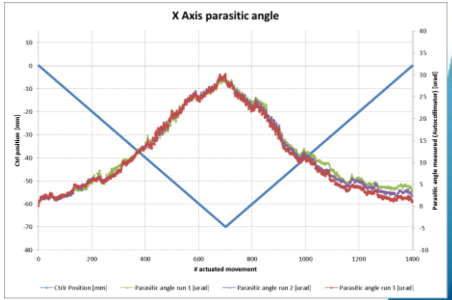
Advantages:

- ✓ Open loop control → Robustness
- ✓ No active elements inside vacuum

Drawbacks:

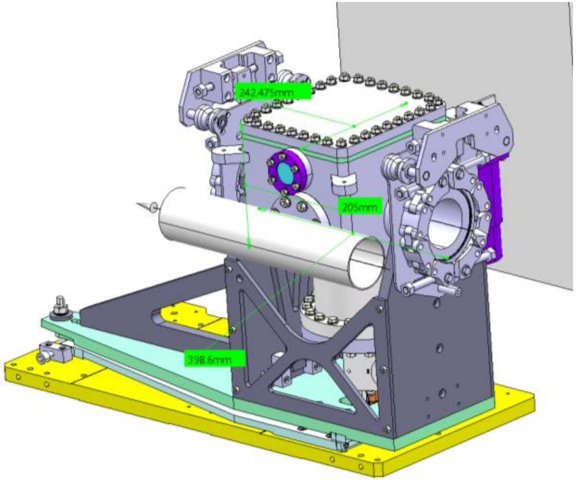
- Resolution requirements require long lever arm to avoid high ratio gearbox with backlash/friction/speed limitation/wear issues
- Long lever arm increases system inertia and flexibility
  - ➔Low system resonances
  - ➔High overshoot and sensitivity to tunnel disturbances
  - ✕ Strong coupling between linear and angular movement both static and dynamic
  - ✕ Unacceptable dynamic behaviour (90% overshoot)

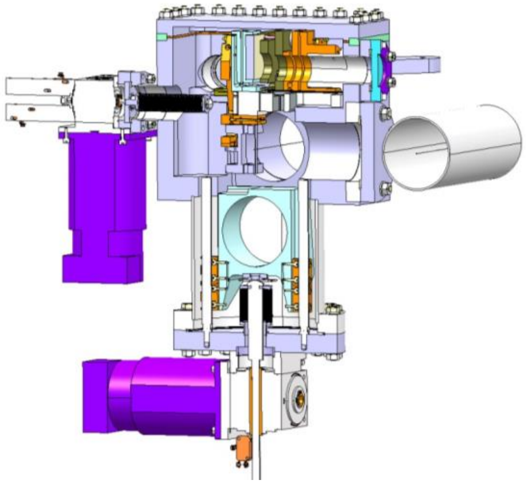




Piezo goniometer design concept

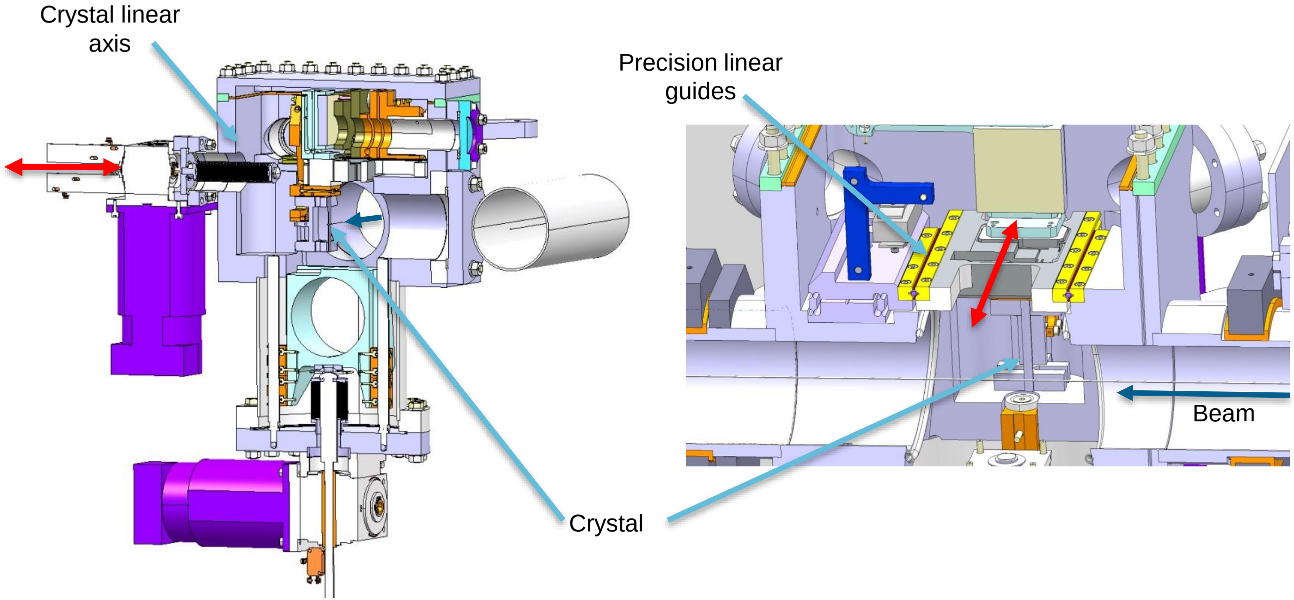
- Linear movement: Stepper motor actuated lead screw drive axis
- Rotational movement: Piezo actuated rotational stage
- Beam pipe segment inserted when goniometer not in operation to make device ‘transparent’ to the circulating beam





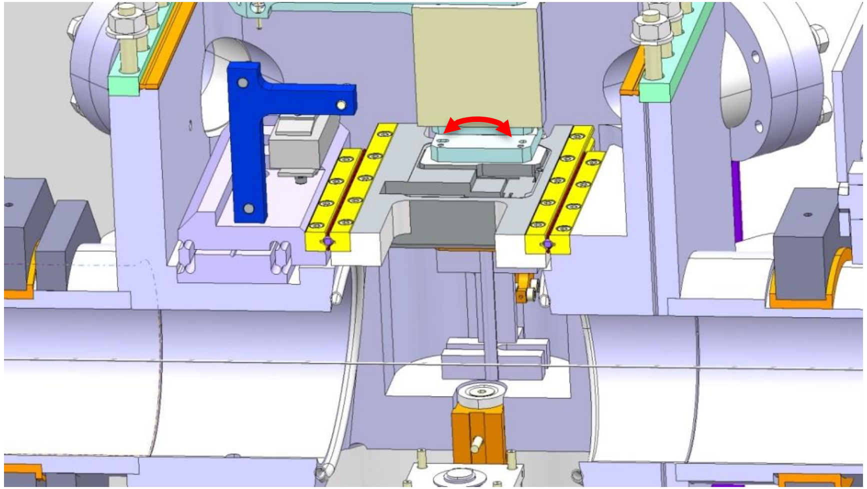
Linear movement

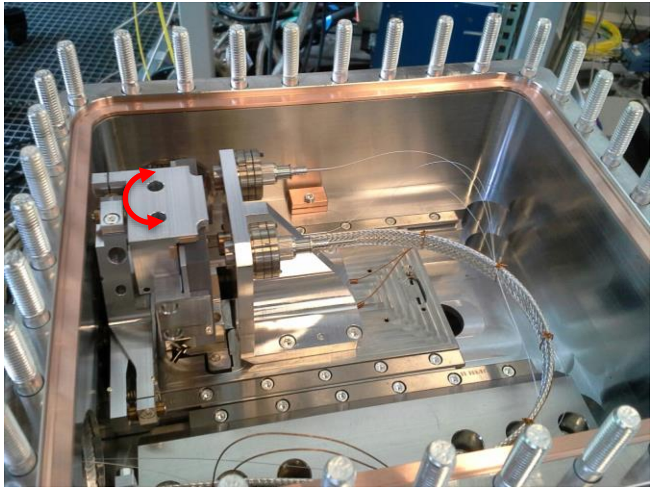
- Stepper motor actuated linear axis
- Resolution: 2.5µm (even lower in micro-stepping mode)
- Precise linear roller ceramic bearings with cage in stainless Steel AISI 316 L to minimize the crystal parasitic angles during the linear movement
- The termal expansion during the Bake Out process (180-220C) is allowed thanks to the fact that one of the four guide systems is mounted on an elastic support.



Rotational movement

- Piezo actuated rotational stage mounted on linear axis





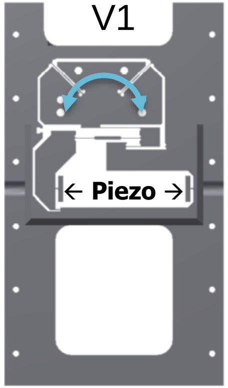
Rotational stage

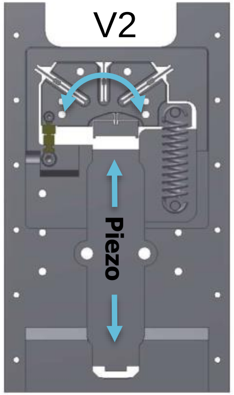
- Flexural-hinge based rotational stage
  - Piezo linear movement ➔ Crystal rotation
  - No backlash

- Piezo actuated
  - ✓ Infinite theoretical resolution
  - ✓ High force to size ratio
  - ✓ Immune to magnetic fields
  - ✗ Hysteresis and creep ➔ Closed-loop position control required

- Theoretical resolution (Piezo + Electronics): **25 nrad**
- 2 generations of rotational stage developed, V1 and V2:

Version	Stiffness	1st resonance	Piezo bakeout temperature	Installed in LHC goniometers
V1	‘Low’	≥ 35Hz	110ºC	B1-H and B1-V
V2	‘High’	≥ 130Hz	220ºC	B2-H and B2-V





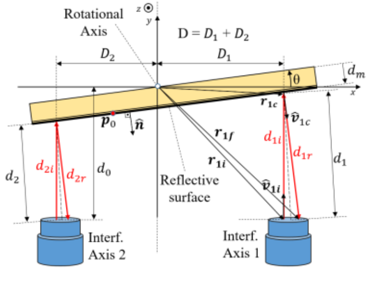
Dual-Interferometer Based Angular Measurement System

- 2 linear interferometric axes (Attocube Interferometer) mounted on the rotational stage. Beams reflected in gold coated mirror mounted on rotational head:
  - Resolution: 1 pm
  - Repeatability: 2 nm
  - Accuracy: 0.14 ppm

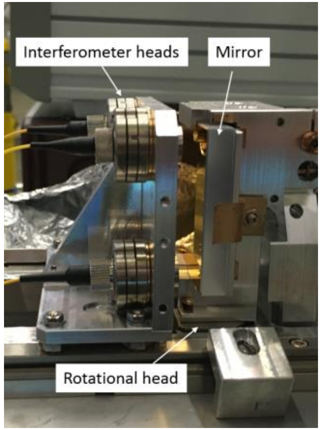
- Angular estimation:

$$\theta = \tan^{-1}\left(\frac{d_1 - d_2}{D}\right)$$

  - Angular reading resolution: **0.022 nrad**
  - Angular accuracy (evaluated with uncertainty propagation law): **± 5 nrad (with D=45mm)**
  - Angular reading rate: **240 kHz**

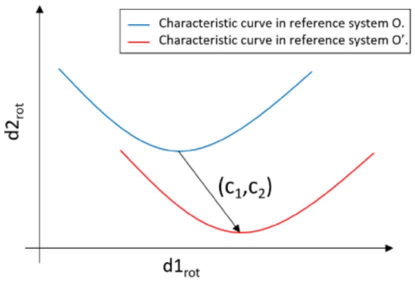


Dual-interferometer based angular measurement diagram.



- Limitation: Relative measurement of the distances implies RELATIVE ANGLE.

- Proposed solution: Absolute Angle Recovery Method
  - Algorithm based on the Characteristic Curve (d_2 vs d_1) of the rotational stage over the full angular range
  - Use of this setup-specific curve as reference system
  - Angle successfully recovered during the different MDs and commissioning stages in the range ±100 urad (high variation between goniometers)



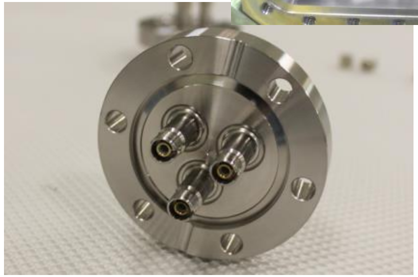
AARM working principle

P. Serrano Gálvez, M. Butcher and A. Masi, "A Dual-Interferometer-Based Angular Measurement System With Absolute Angle Recovery Method," in *IEEE Transactions on Instrumentation and Measureme* 10.1109/TIM.2018.2857598

Technological solutions developed

- Piezoactuators:
  - Bakeout Temperature
    - Typically limited well below the Curie Temperature (e.g. V1 T_curie=150ºC)
    - High temperature piezos developed with industrial partner (Noliac): Curie temperature (250 ºC) and bus wire soldering melting point 300ºC
  - Radiation resistance
    - With radiation:
      - electrical insulation can fail
      - stroke reduction
    - Gamma radiation tests performed (stroke reduction ≤20% at 10MGy). Particle irradiation tests imminent
    - Insulation free piezo stacks developed and range oversized
- Optical fibres
  - Typically not UHV compatible
  - Flourine-free patchcords were selected
- Interferometer optics
  - Typically not bakeable, UHV compatible nor radhard
  - Compatible optics developed with industrial partner (Attocube)

  Markus Brugger, Mario Di Castro, Alessandro Masi, Roberto Losito, Christoph Bödefeld, ‘Laser Interferometry in Radiation Harsh Environments’, 2014
- Optic fibre feedthroughs
  - Typically not bakeable at >200ºC
  - High temperature feedthroughs (>250 ºC) and glue-free developed with industrial partner (Vacom)



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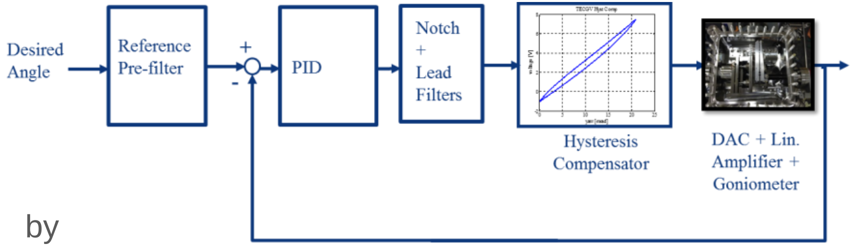
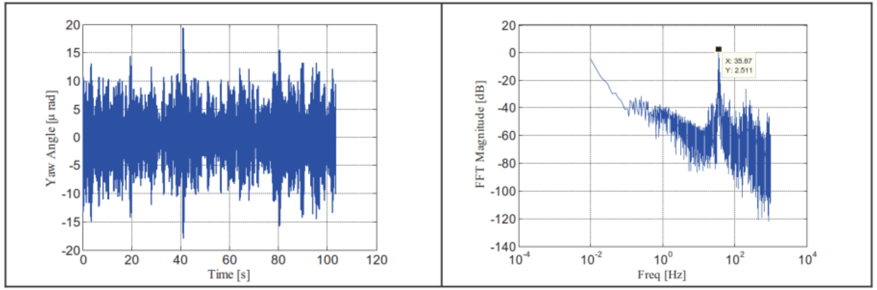
Control algorithm to achieve the angular position accuracy of 1 urad

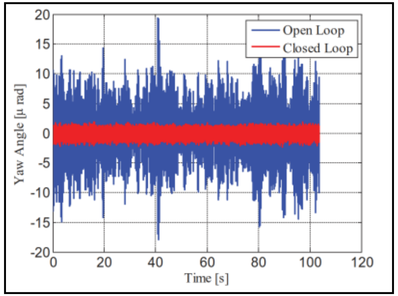


V1 rotational stage:

- 1st resonance at ≥ 35Hz
- Environmental disturbances in LHC are amplified by resonance
- CD-inspired feedback position control algorithm used to attenuate resonance

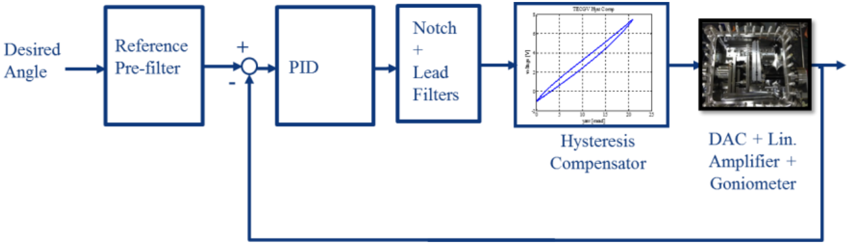


Open-loop noise



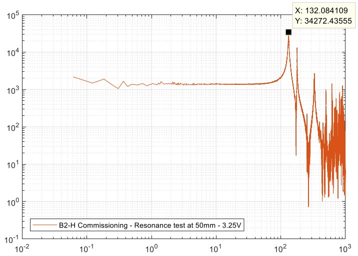
Closed-loop noise

Control algorithm to achieve the angular position accuracy of 1 urad

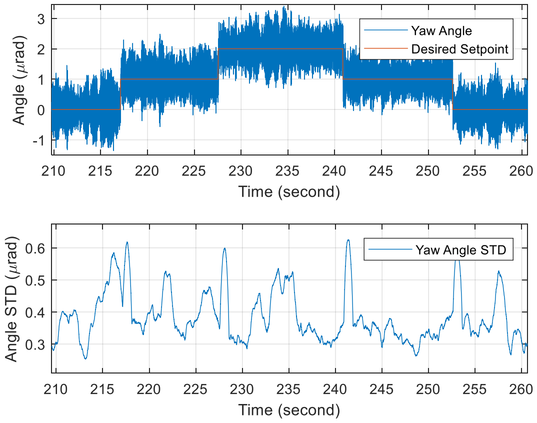


V2 rotational stage:

- 1st resonance at ≥ 130Hz
- Significantly less sensitive to environmental disturbances
- Closed-loop still necessary for creep and hysteresis compensation and quick response.



System identification (B2-H)

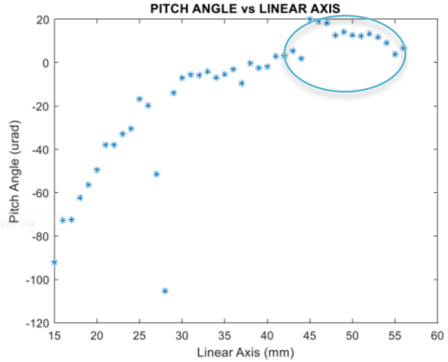


Closed-loop performance (B2-H)

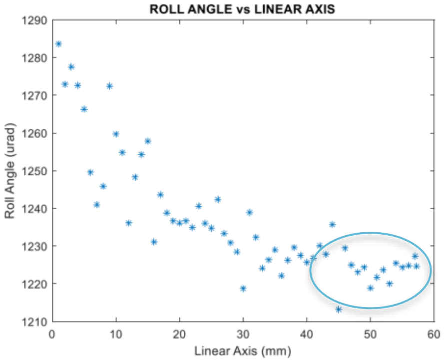
Parasitic angles

- Precise linear guidance used with manual adjustment to achieve small parasitic angles in beam region (last 10mm of stroke):

Goniometer	Max. rotation variation (urad)	Max. Pitch variation (urad)	Max. roll variation (urad)
B1-H	16	20	18
B1-V	30	10	10
B2-H	20	20	10
B2-V	18	10	25



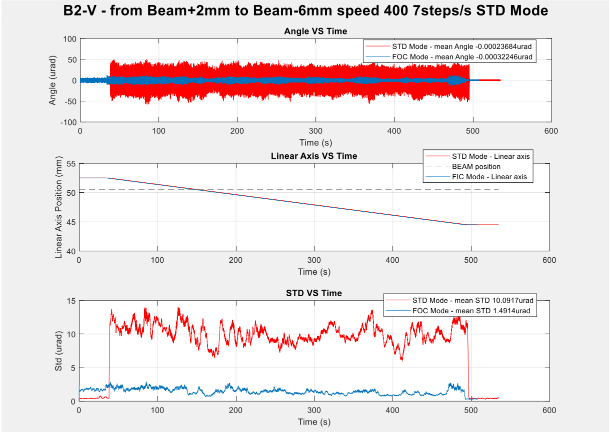
Goniometer B2-H



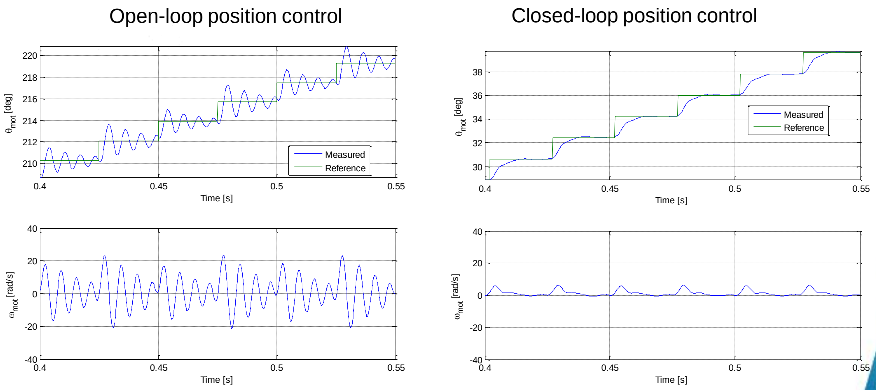
Brushless Driver with Field Oriented Control Mode (FOC)

What is the impact of the linear axis profile on the yaw angle ?

- FOC – Position and current controlled in Closed Loop:
  - Optimal torque generation.
  - Indirect torque diagnosis.
  - Disturbance rejection.
  - Possibility to damp dynamics.



- Transition between modes FOC and STD (Standard mode) without loss of steps.
- Vibrations highly reduced during linear axis profiles (Angular STD reduced by factor 5).



Linear Driver Mode	Angle Std during LHC linear profiles [urad]
Standard Stepping mode	10.1
FOC	1.49

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Piezo Goniometer – Performance reached

Property	Specification	Achieved
Linear stroke	> 50mm	55 mm
Linear resolution	5 um	2.5 um
Linear accuracy	+/- 20 um	+/- 20 um
Total angular range	+/- 10 mrad	+/- 10 mrad (at installation)
Yaw angular resolution	0.1 urad	25 nrad
Yaw angular accuracy over the entire linear range	+/- 1 urad	+/- 1 urad (V.2)
Yaw angular overshoot	10%	5.8% 100 urad step/ 10.8% with 1000 urad/s
Yaw angular settling time	20 ms	50 ms (<20 ms with controller opt.)
Yaw angle max speed in scan mode	50 urad/s	100 urad/s (up to 1000 urad/s)
Pitch angular accuracy over last 10 mm travel	Few urad	2 urad/mm
Roll angular accuracy over last 10 mm travel	Few tens of urad	2 urad/mm

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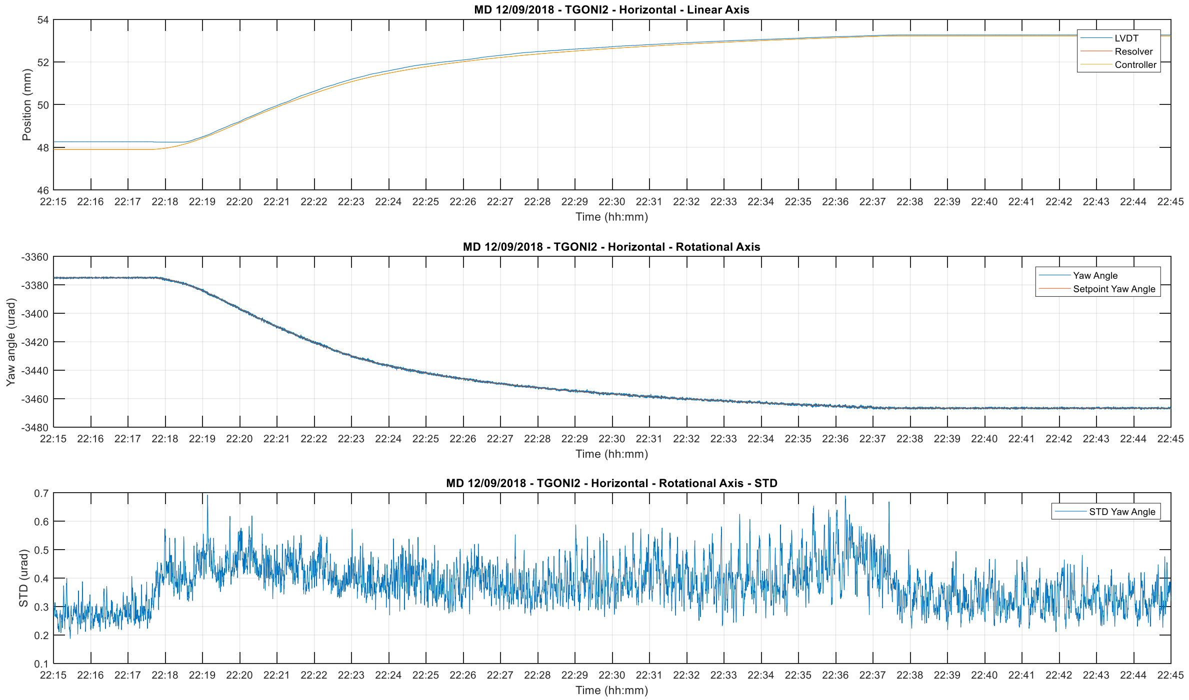
Feedback from 2017-2018 Operation

- Successful operation for more than 10 MDs (2015-2018)
  - Channelling angle always found in all goniometers (one skew plane issue).
  - Channeling angle in the same position between MDs (variations known in advance due to Angle Recovery uncertainty).
  - Combined movement for CH during Ramp-up with angular std < 6 urad (in later goniometer versions <1 urad).
- Successful long-run operations during High-Beta Tests in LHC (11-14 September 2018)

Example of profile performance - MD 12-09-2018

Synchronised Ramp-Up in all piezo goniometers of LHC



B2-H gonio achieved performance in operation

Yaw angle vaues acquired at 2 KHz – STD evaluated with sliding windows on 2000 samples

Operational Issues by component

Control Software	1. Software stuck – Reboot needed
Interferometric system	2. Interferometer reading error during operation
Interferometric system	3. Angular range reduction due to interferometer reading error
LVDT	4. Non-linearity of the LVDT

SCENARIO 2

SCENARIO 1

Gonio REWORK EXTERNALLY + SW Improvements and upgrades

REWORK INTERNALLY
Implies opening the tank

SCENARIO 3

Installation of the new generation goniometer

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Operational Issues - PXI and Software

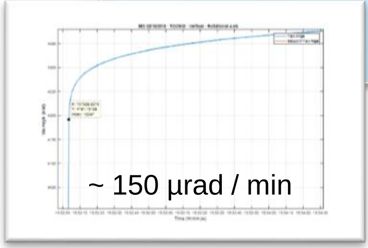
ISSUE	IMPACT	PROBABILITY	Cause	Solution / Mitigation
1. Controls Stuck	VERY HIGH The PXI is not able to communicate. It is not possible to perform any movement	LOW It happened 3 times since YETs 2018	▪ 1 during manual retrieving of data (happened during MD 12/09/2018) ▪ 1 Unknown (High CPU? Memory leakage?) ▪ 1 PXI rebooted manually due to high CPU (to avoid risks during operation)	Improve software robustness ▪ **ALL SCENARIOS**

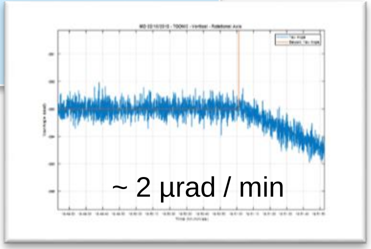
Operational Issues - Interferometric system

ISSUE	IMPACT	PROBABILITY	Cause	Solution / Mitigation
2. Interferometer reading error during operation	VERY HIGH - Angular reading and reference is lost. - Angular controller passes to OPEN LOOP keeping the same voltage:	LOW It never happened, but due to the degradation of signals the probability is increasing.		

CRYSTAL ANGLE DRIFTs.

OPEN LOOP during profile	OPEN LOOP during static position
FAST drift	SLOW drift



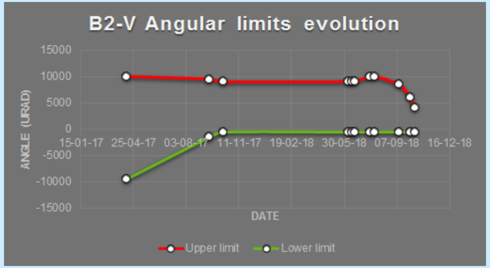


Operational Issues - Interferometric system

ISSUE	IMPACT	PROBABILITY
3. Interferometer error during operation	VERY HIGH - Angular reading and reference is lost. - Angular controller passes to OPEN LOOP keeping the same voltage:	LOW It never happened, but due to the degradation of signals the probability is increasing.
4. Range reduction due to interferometer reading error	HIGH - Angle range is reduced and eventually can exclude the CH.	MEDIUM The range is being reduced due to the increase number of errors in the interf. axes.

DEVICE	INTERFEROMETER N. of errors (Since beginning 2017)	Number of MDs	Installed
B1-H	3	13	Mar-15
B1-V	2	13	Mar-15
B2-H	0	5	Feb-18
B2-V	6	9	Apr-17

EXAMPLE OF RANGE REDUCTION



Operational Issues - Interferometric system

ISSUE	IMPACT	PROBABILITY	Cause	Mitigation	Solution
3. Interferometer error during operation	VERY HIGH - Angular reading and reference is lost. - Angular controller passes to OPEN LOOP keeping the same voltage:	LOW It never happened, but due to the degradation of signals the probability is increasing.	The interferometer signals are degrading slowly, most probable due to radiation effect on the fibers.	**SCENARIO 2** **SCENARIO 1** - Replacement of external fibres. - Replacement of internal fibres and head adjustment. (implies opening the tank)	
4. Range reduction due to interferometer reading error	HIGH - Angle range is reduced and eventually can exclude the CH.	MEDIUM The range is being reduced due to the increase number of errors in the interf. axes.	The interferometric signals are reaching the interferometer error threshold and therefore the errors are more frequent.		**SCENARIO 3** Installation of new generation goniometer

Operational Issues - LVDT

ISSUE	IMPACT	PROBABILITY	Cause	Solution / Mitigation
4. Non-linearity of the LVDT	LOW - The LVDT reading is not as accurate as intended and can interfere with the operation of the profile limits	LOW Only B2-V is affected	Mechanical issue in the connection of the LVDT core or lead screw.	**SCENARIO 2** **SCENARIO 1** - Adjustment of LVDT shaft. - Replacement of LVDT mechanical connection and lead –screw mechanism (implies opening the tank) **SCENARIO 3** - Installation of new goniometer

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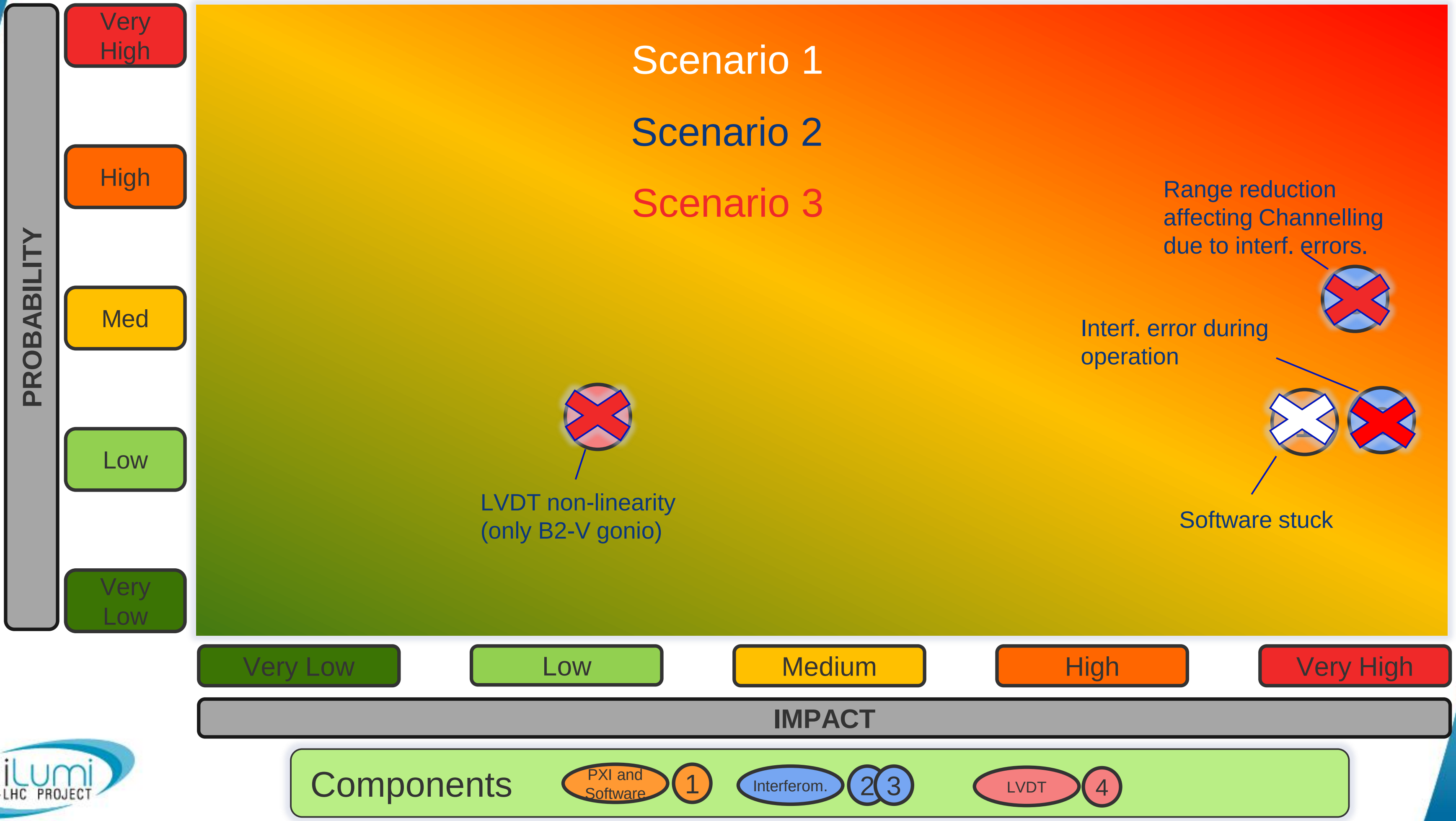
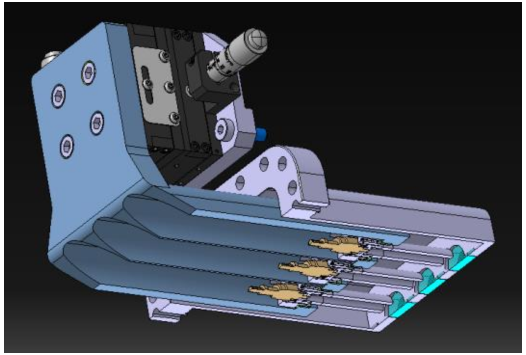
Operational Issues – Current Design



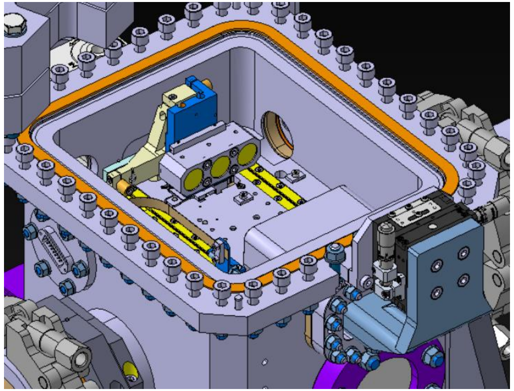
New generation goniometer

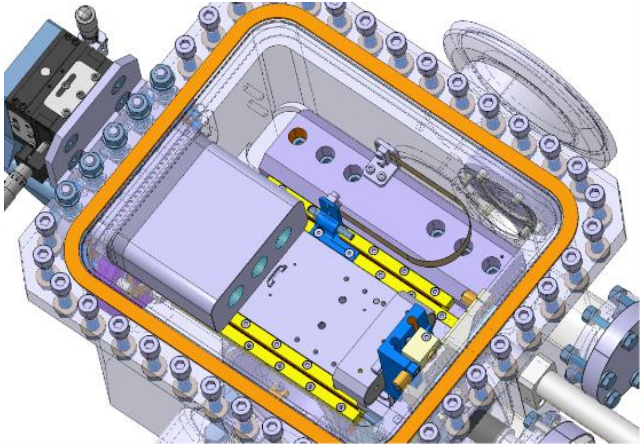
Fixed interferometer head improvement (outside the tank)

- ✓ Reading through viewport: No need for fragile UHV Fibers and Feedthrough
- ✓ Re-alignable in the tunnel if needed without opening the tank
- ✓ Redundant measurement of Yaw Angle approved by Machine Protection
- ✓ Linear Axis position measured with interferometer system
- ✓ Parasitic Yaw angle compensation
- ✓ Fully compliant with TE-VSC specifications
- ✓ Increased Reliability, Availability, Maintainability & Safety (RAMS)



See details in Marco`s talk





Proposals for an operational system

Scenario	Details	Impact on Run 3
1	- SW improvements & upgrades - Replacement of the external fibers cables NO DISMANTLING OF THE CURRENT GONIOMETERS	Not same reliability as nominal collimation system, operational scenarios to be defined → High probability that system becomes unavailable during the run
2	In addition to scenario 1: - Re-alignment of the gonio internal optics - Replacement of the internal optical fibers OPENING OF THE GONIOMETER TANK (*)	All the goniometers status will be restored as at the installation The operational reliability could be slightly improved wrt run 2 even if it is not still comparable to the nominal collimation system
3	INSTALLATION OF THE NEW GENERATION GONIOMETER	System fully operational

(*) : To be checked feasibility with RP see Marco`s Talk

The current control system will be updated during LS2 to be compatible with any of the above scenario

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Plan for New Goniometer Version

- Viewport and retroreflectors – RADIATION TEST → To be started Asap
- Fixed head solution – ALREADY VALIDATED
- Production of a new generation goniometer prototype to be used as future spare → Next year at the latest
- Installation strategy for new generation goniometer → See Marco`s talk

Conclusions

- As result of a long conceptual design validation process the piezo and interferometry goniometer technology has shown to be mature and appropriate to fulfill the tight LHC crystal collimation requirements
- The new generation goniometer will ensure an operational device for run 3 characterized by a proper RAMS for LHC operation
- Without any intrusive interventions during LS2 (i.e. scenario 1) on the current installed LHC goniometers the probability of the issues experienced during run3 could increase (except for software problems)
- An intrusive campaign during LS2 on all the existing goniometers of optics realignment and optical fibers replacement could guarantee operational conditions even slightly improved wrt run 2

Acknowledgement

Roberto Losito
Simone Gilardoni
Walter Scandale
Paolo Chiggiato
Marco Calviani
Oliver Aberle
Inigo Lamas Garcia
Stefano Redaelli
Simone Montesano
Andrea Stevanato (CINEL)
Clement Derrez
Alessandro Danisi
Ricardo Picatoste
Raffaelo Esposito
Alessandro Giustiniani
Sergio Calatroni
Giuseppe Bregliozzi
Vittorio Vaccaro
Benoit Salvant

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Thank you!