Design and Control of Fast Actuators for Beam Wire Scanners at CERN

Jonathan Emery (CERN)

Acknowledgements to all my BI colleagues working on the Wire Scanner systems
Mechanics, Electronics, Software and Physics teams

25.04.2023

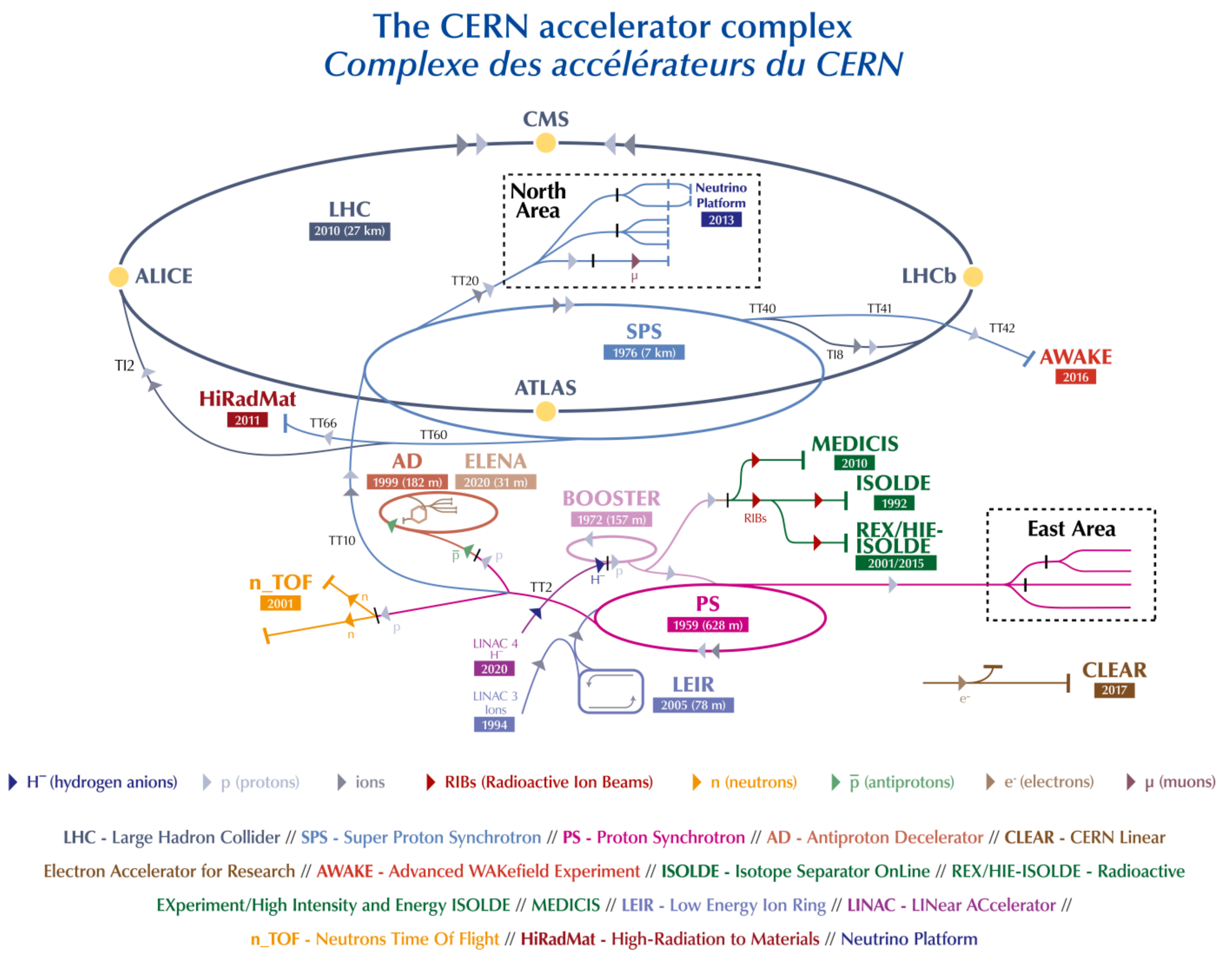
abstract

- **Developing fast actuators that can operate in the vacuum vessels of accelerators presents challenging engineering problems in various domains. In addition to vacuum constraints, which in some cases include compatibility with bake-out after installation, these systems must also deal with radiation effects on electronics and thermomechanical responses to direct particle energy deposition and/or electromagnetic beam coupling.**

- **This presentation will focus on how fast actuators are designed and controlled for fast beam wire scanners at CERN, which are dedicated to beam size measurements in the LHC and its injectors. Emphasis will be given to the recent design and production of the new generation for the injectors, which can reach speeds of 20m/s, have already demonstrated a position determination precision better than 5um, and have shown high reliability. Finally, a dedicated section will discuss the ongoing work for the LHC scanner consolidation.**

Design and Control of Fast Actuators for Beam Wire Scanners (BWS) at CERN

- **Actuator and Beam Wire-Scanner**
- **R&D Engineering challenges**
  Environmental constraints, specification, lifecycle
- **LHC Injectors Upgrade BWS**
  Legacy systems analysis
  Design detailed description
  (Mechanics / Electronics / Control / Firmware)
- **Calibration & commissioning**
- **BWS LHC consolidation project**



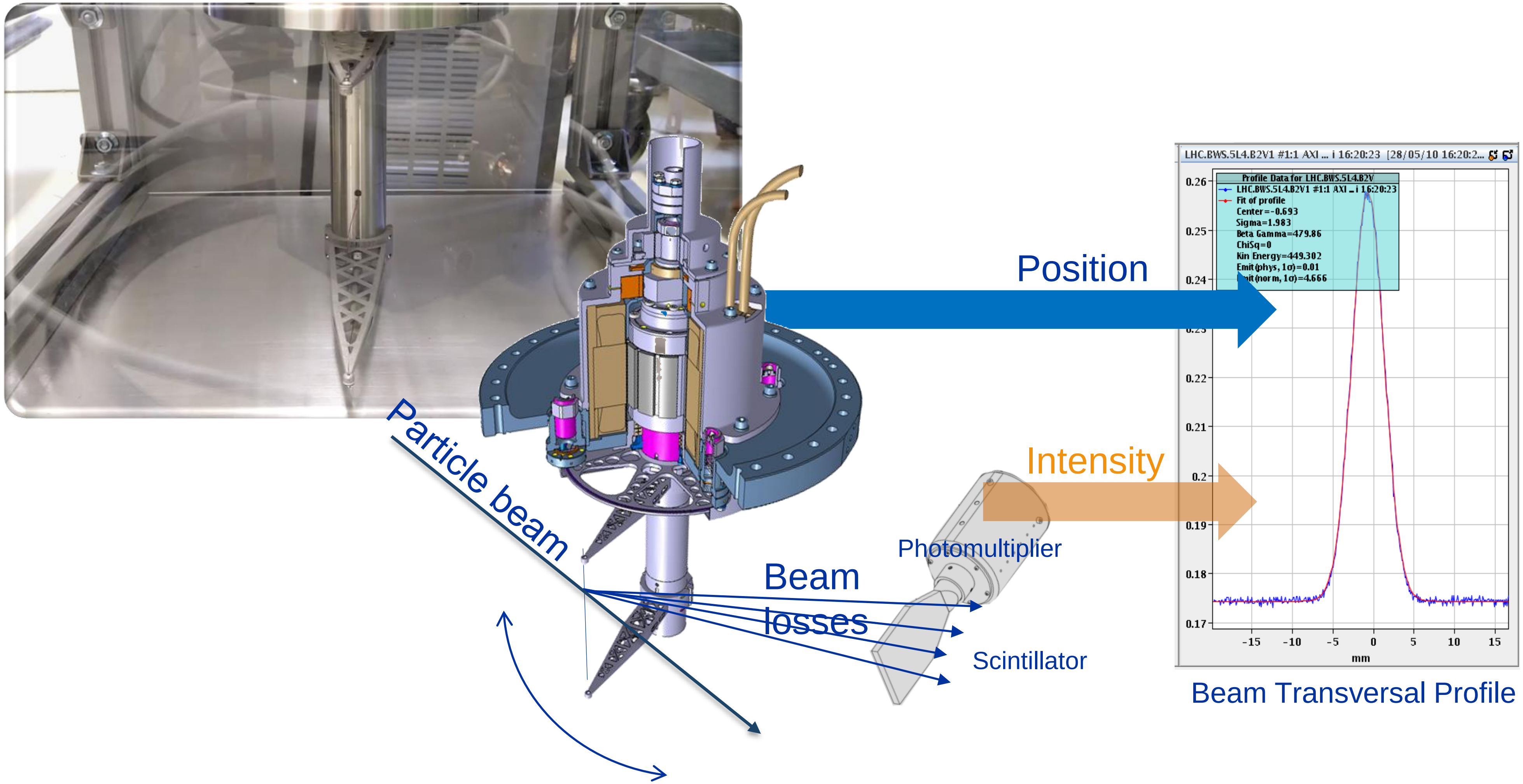
Fast actuator for Beam Wire scanner at CERN

- **An actuator for instrumentation is build with:**

  - Mechanism to move an object into the beam
  - Motorization to provide torque/force
  - Sensors to evaluate physical quantities (angle, position, light, current, voltages, etc.)
  - Cables between mechanism and controller
  - Controller to provide energy, regulation, measurements

- **Fast actuators are required in circular accelerators when**
  - Energy/Intensity above the damage threshold of the intercepting material at low spd
  - In case high beam losses due to the interaction potentially damaging other equipment (e.g. supraconducting magnet in LHC)

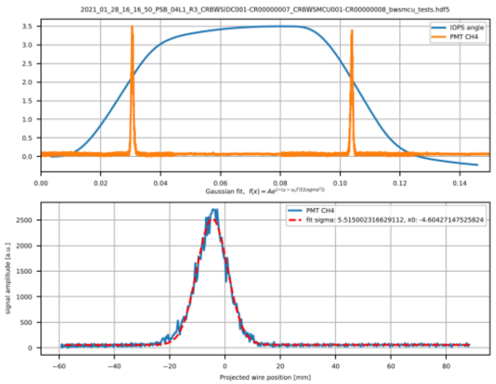
LIU Beam wire scanner instrument



Reference instrument for **transverse beam size** measurement

Critical for **machine optimisation**

And for **calibrating** other BI instruments



The 30 μm wire moves at 20m/s through the particle beam
A control problem can break the wire leading to months of unavailability

R&D Engineering challenges Environmental constraints (1/2)

- **Radiation damages to material and electronics**
  => activation of bulk material making handling delicate
  => accelerated aging of isolation material (i.e., cables)
  => destruction of semiconductors junction, making radiation hard electronics expensive and time consuming to develop

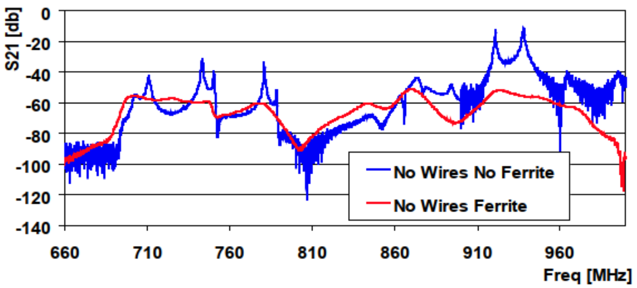
- **Vacuum and Ultra High Vacuum (UHV) requires the exclusion of outgassing materials**
  => leaving almost only metals & ~ceramics
  => no lubricant (e.g., in guides and ball bearings)
  => no glue or composite material
  => insulation material for cables limited (~kapton)

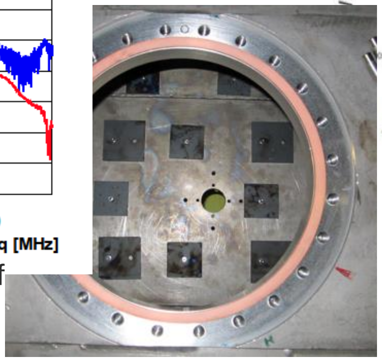
- **Temperature of the bakeout procedure for UHV (in the LHC for instance) 50h at**
  min 100 C, for water evaporation then
  about 300 C, when possible, for Non-Evaporable Getters (NEG) activation

R&D Engineering challenges
Environmental constraints (2/2)

- **Electromagnetic beam coupling**
  => beams are generating electro-magnetic waves when traveling in vacuum chambers, inducing perturbation on sensitive system.
  => shapes of the vacuum vessels can create impedance mismatch and resonances.
  => Sensitive to beam parameters (BP), requires carful design and mitigation when BP are changing!

2003 first series of broken wires
Installation of ferrites on the tank walls

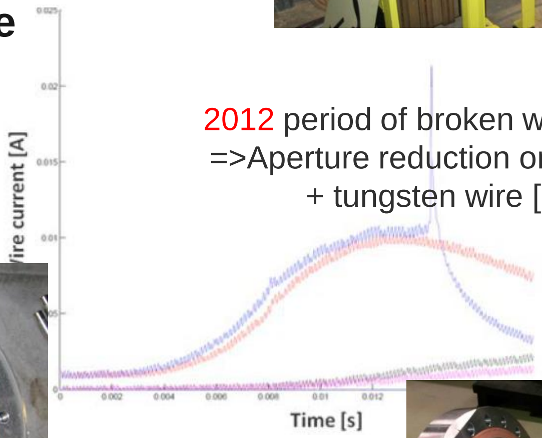


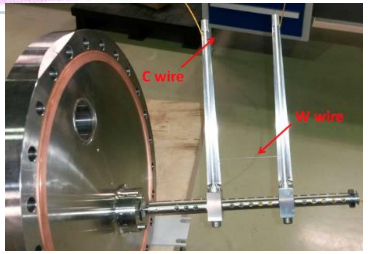


Electro-magnetic spectrum of S21 in db of signal transiting through the tank using antenna probes method. F. Roncarolo [2003-RON]

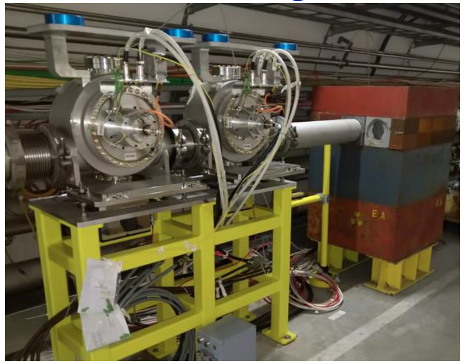
Legacy design

2012 period of broken wires during scans
=>Aperture reduction on some scanners
+ tungsten wire [2014-PIS]

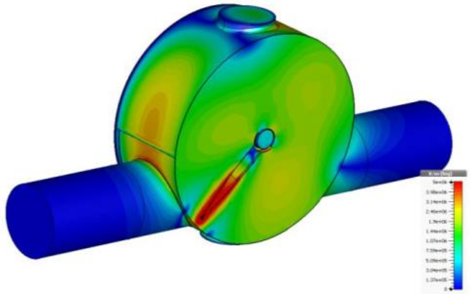




LIU design



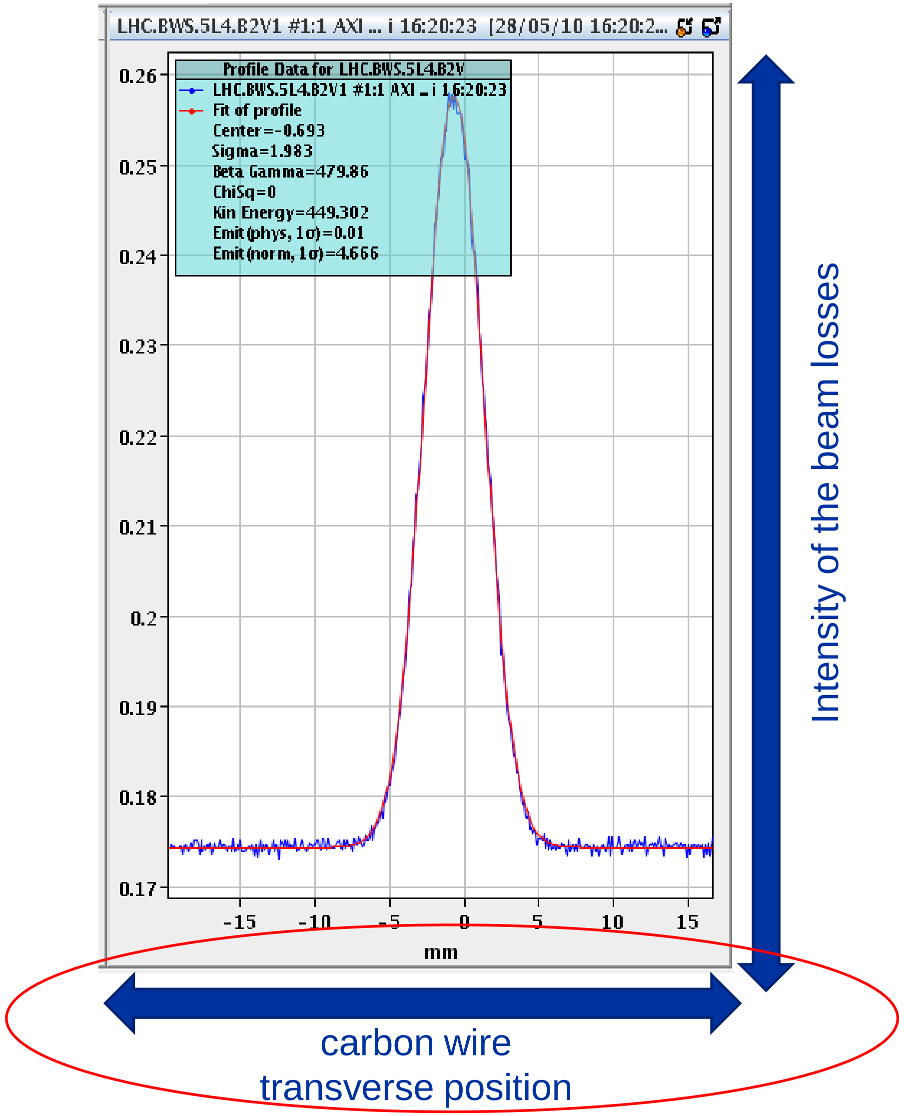
2017 Qualification



Electro-magnetic Field configuration forks at 135 deg PS-SPS BWS (LIU) 882 MHz C. Vollinger [2017-VEN]

2023
C-Wire breakage issue with LIU Tank, new Beam parameters brake wires at parking position! (on-going issue)

R&D Engineering challenges: Specification



- **Understand the stakeholders needs:**

  => Machines Operation teams & Beam physics studies:

  For LIU we started using future beam size spec:
  Beam size of 150um sigma in LHC post LIU upgrade,
  3 points per sigma (~1% error),
  5um wire position determination

- **Integrate the legacy experience:**
  Speed of the actuator (target speed of 20 m/s)
  half rotation only (minimise beam losses, 2 measures per cycle)

  For actuators:
  => Precision sensitive to mechanism design (play, backlash, frictions)
  => Repeatability play a role in the carbon wire position incertitude
  => Calibration of the instrument with a bench to improve the accuracy

R&D Engineering challenges: LifeCycle

OpenSE LifeCycle

2007 – 2021 => 14 years for the LIU BWS

‘Classical’ problem for large system engineering,
but probably not so common for beam instrumentation.

- **Under estimation of project complexity**
  => long delays for deliverables
  => Over budget
  => Temporary workforce turnover
  (students, fellows, etc …)
  => change in management

More conservative approach
- e.g. incremental innovation vs new approach
leave room & budget for redesigns
give weight to documentation

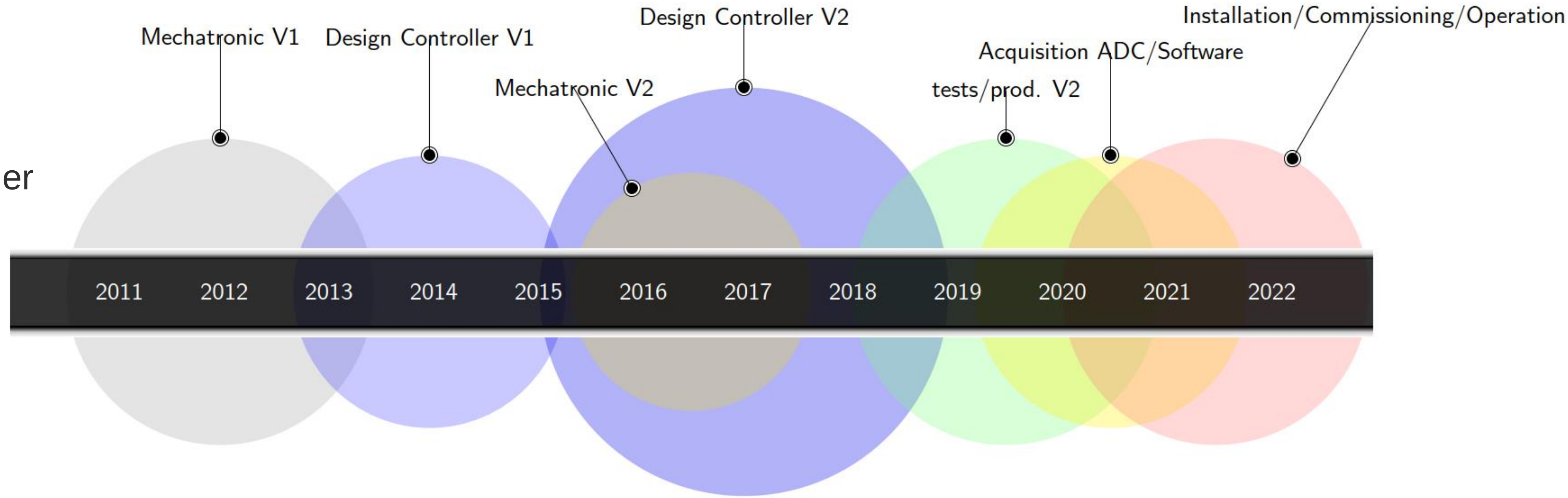
- **“Very” Long Lifecycle for instruments (20 and more years)**
  => end of life of components
  => maintenance becomes difficult
  => Knowhow lost when designers leaves the projects

Look into space & military approach
clear maintenance policy
redesign of modules at define time

R&D Engineering challenges: LifeCycle

OpenSE
LifeCycle

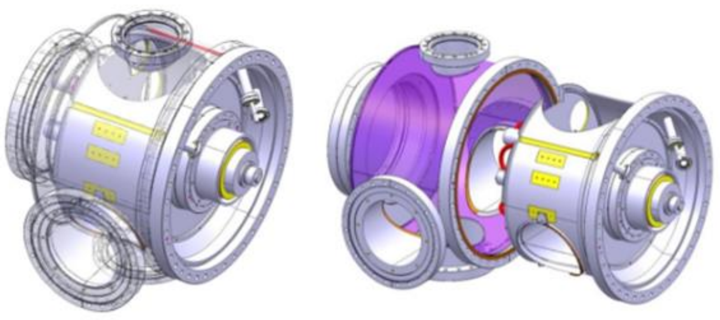
Beam wire scanner
LIU stages



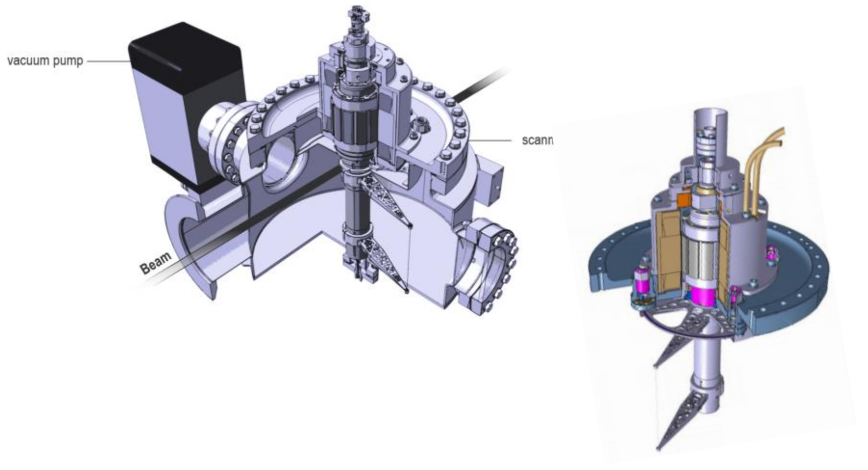
LHC Injectors Upgrade Beam Wire Scanner

- **2007: First brainstorming for a new design with the objective of improving reliability and precision/accuracy of existing systems**
- **funded by LHC injectors Upgrade**
- **Prototypes in the machines:**
  2015: v1 in the Super Proton Synchrotron (26 GeV-450GeV)
  2017: v2 in the Proton Synchrotron Booster (160 MeV-2GeV)
  2018: v2 in the Proton Synchrotron (2GeV-26GeV)
- **2019-2020 : Installation of the 17 scanners across the LHC injectors facility**
- **2021: Delivery of 6 scanners & 8 controller to the *European Spallation Source (ESS)***
- **2021-2022 runs with a total of 125 kscans**

2015: SPS Scanner



2017: PSB Scanner



Legacy generation system analysis (1/3)

Multiple tools available for this analysis:

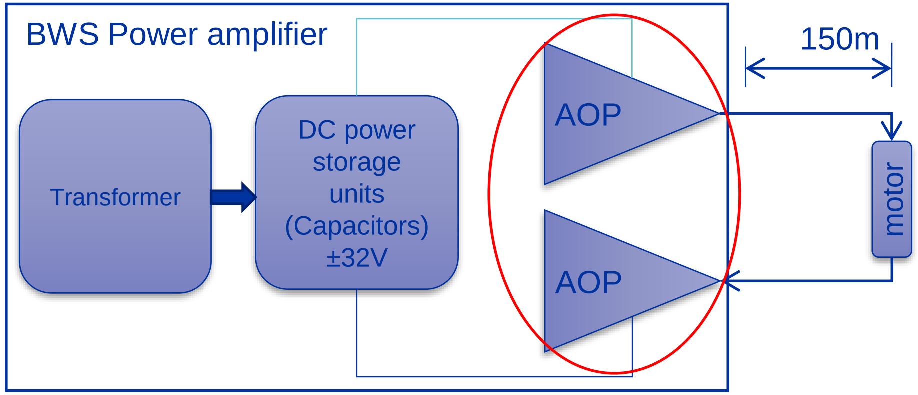
- **Performance review**
  - Beam measurements
  - laboratory measures (calibration bench)
- **Operational failure modes and occurrences**
- **Documentation and reverse engineering**

Machine	Scanner type	installed	Secondary particles detector (Scintillator Filters Photomultiplier)	Fast acquisition (bunch profiling)	Scanner per tank	Maximum speed (m/s)	Wire size	Aperture (mm)	Accuracy/ *beam size repeatability [μm]	2012 run, Number of cycles per scanner
PSB	Rotating fast	8	1 for 2 scanners	x	2	20	12x7μm (C)	112	≈100	3k – 11k
PS	Rotating fast	5	2 per scanner	x	1	15-20	12x7μm (C)	112	≈100	2k – 11k
SPS	Rotating (short and Long)	6	1 for 2 scanners	Yes	2	6	30μm (C)	170	40*	4.5k - 9.5k
SPS	Linear	4	1 for 2 scanners	yes	2	1	30μm (C)	56	15*	0.2k
LHC	Linear	8	1 for 4 scanners	yes	4	1	30μm (C)	60	15*	4k

Legacy system performance review table [2013-EME]

system Component	machine	Occurrences	Failure source	Mitigation	System under design
Linear Power Amplifier	All & lab	16 (2 in 2012)	Electrical glitch to unprotected outputs, Use of componant (PA50) on the limit of its specification	Replacement of supplies	Use of switch mode power supplies and filters
Multiplexers	LHC, PS	3	Mechanical relay failure in the tunnel	Replacement of relays	Use dedicated cables and control electronics
Step motor controler	PSB, LHC	2	Electronic board aging	End of life electronics to be upgraded	Avoid filter wheel by the use of high dynamic detector
Motion control	PS	1	VME bus access switch off VME	Replacement of the card	Motion control in the power supply disconected from the VME
CPU RIO 3	SPS	1	Unexpected reboot	Replacement of the card	

Failure mode and occurrence analysis (electronics) [2013-EME]



Legacy generation system analysis (2/3)

Component	machine	Occurrences	Failure source	Mitigation	System under design
Wire	SPS	4 (2012)	Beam induced RF heating	Modification of the tank, use of ferrites to limit RF mode (already successfully used in the past)	~~Beam pipe inside the tank, thin gap for the wire to pass~~
Wire	SPS	2 (2012)	Wire fixation non-conformity	More intensive functional verification before vacuum closure	Avoid need of performing wire exchange in the tunnel by exchange of complete scanner
Wire	LHC	2 (2012)	Electronics/Software failures left the wires in 'IN' position	Investigation during LS1	Trigger function moved from the software to the Hardware/Firmware
Wire	SPS	2 (2011)	VME bus transaction errors Caused position control failure leading to a mechanical stress.	Hardware adapter to new CPU.	Decoupling of the actuator control and the VME bus.
Wire (damage)	LHC, SPS?	1 confirmed	Interaction with too intense beams	Study of the aging process, review of scanning beam intensity limits.	Increase of the nominal speed with better accuracy than the linear scanner
Bellows	PS	2	Vacuum leak after 5k cycles	Design change in 2011 to 100k cycles	Avoid bellows by use magnetic force through vacuum barel at the motor gap
Bellows	LHC	1	Vacuum leak after 10k cycles	Design change forseen in 2013 to 50k	

Failure mode and occurrence analysis (mechanism) [2013-EME]

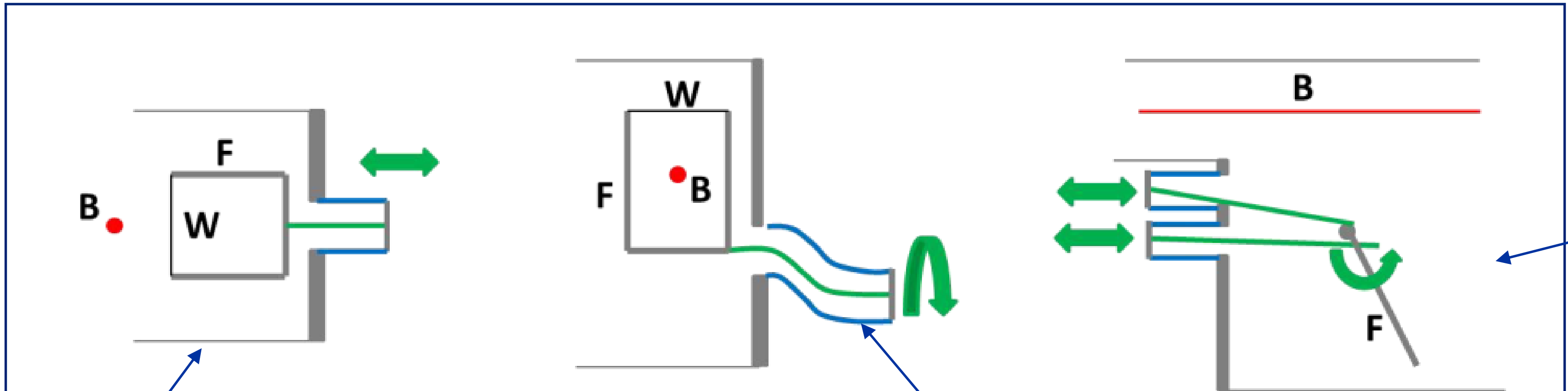
Proposal discarded by simulation after 2013

Motion drive independent from high level software layer

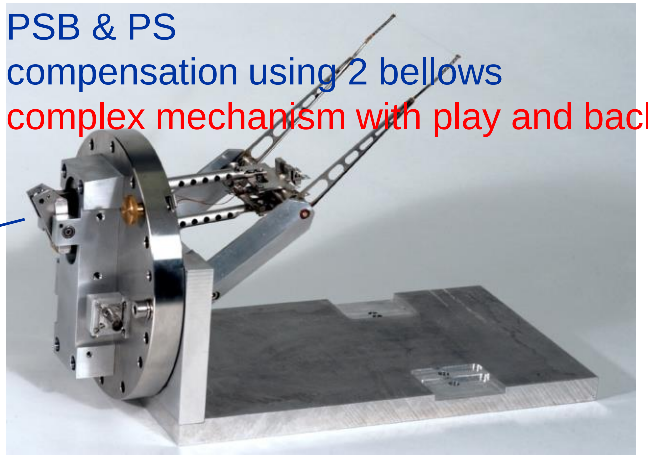
Wire speed above 20 m/s
Difficult to achieve with linear system

No bellows for high reliability

Legacy generation system analysis (3/3)
Vacuum force on actuators with bellows

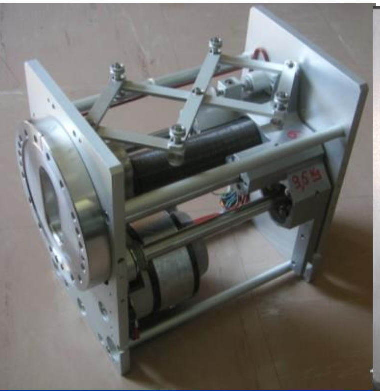


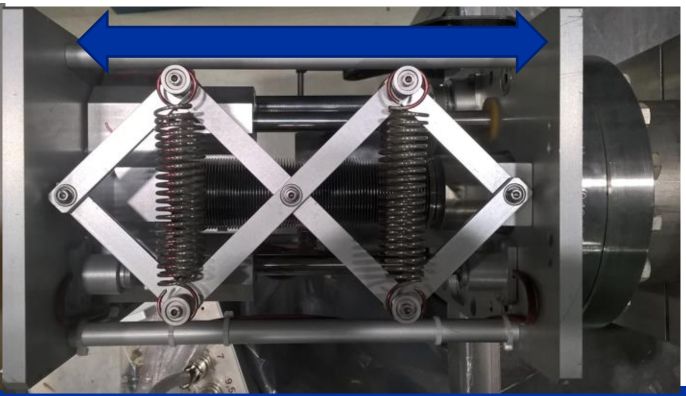
J. Herranz Alvarez "Minimisation of the wire position uncertainties of the new CERN vacuum wire scanner," Presented 29 Feb 2016, Ph.D. dissertation, Jan. 2016. [2016-HER].



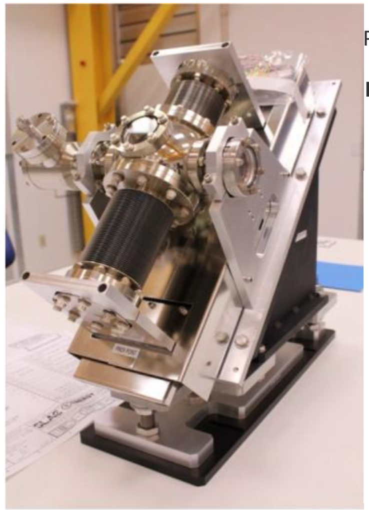
PSB & PS
compensation using 2 bellows
complex mechanism with play and backla

SPS & LHC linear
compensation with springs (not linear)
compensation with magnetic system possible
on-going -> using frictions (requires more force)

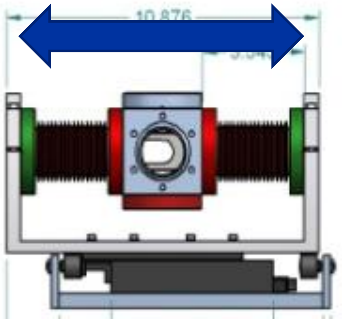




SPS rotary
no compensation
complex mechanism with play
requires bearings on both sides



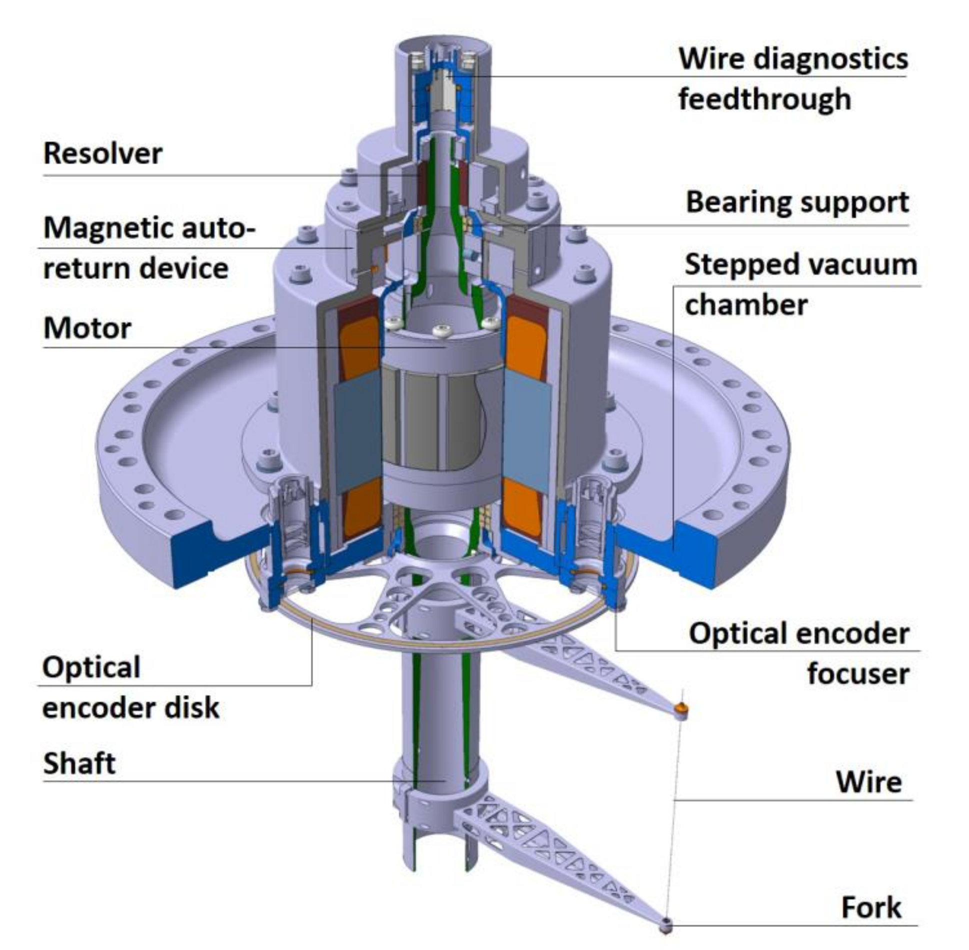
PERFORMANCE OF THE NEW FAST WIRE SCANNER AT THE LCLS
P. Krejcik#, M. Campell, M. D'Ewart, H. Loos, K. Luchini, IBIC 2015
SLAC, Menlo Park, CA 94306, USA



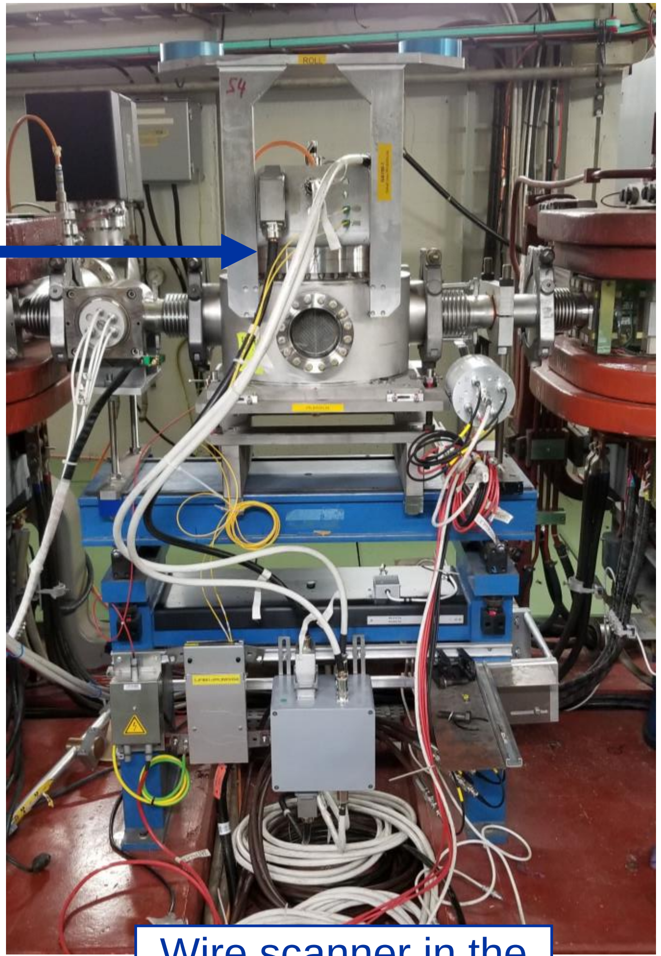
! Weight of the system in action for large aperture !

Solution for the Wire scanner rotational type “LIU”

- **All moving parts in vacuum**
- **All stators outside the vacuum**
- **Thin membrane none-magnetic stainless-Steel**
- **No electronics for the sensors next to the scanner**
- **Inertia optimized for high acceleration**



Wire scanner rotational type “LIU” (2020)



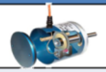
Wire scanner in the CERN PS accelerator

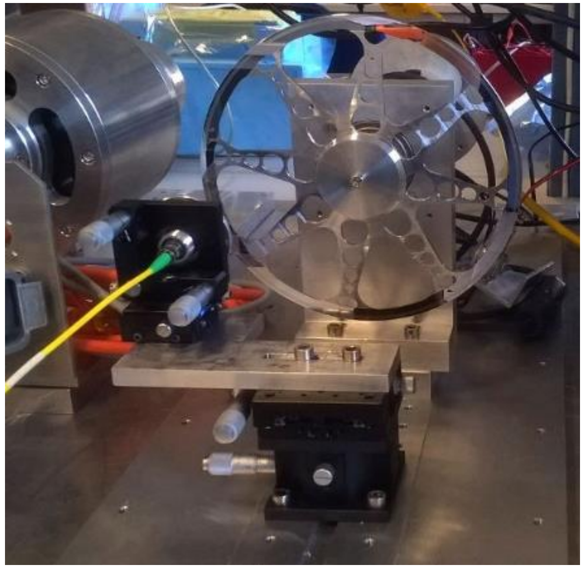
LIU angular sensors

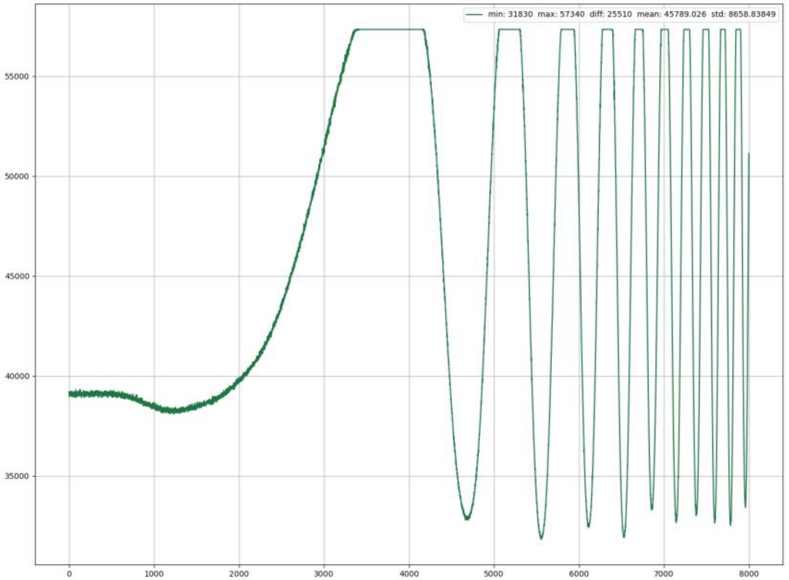
- No angular sensor found to comply with specification (accuracy, precision, radiation, temperature, reliability) => use of 2 different sensors

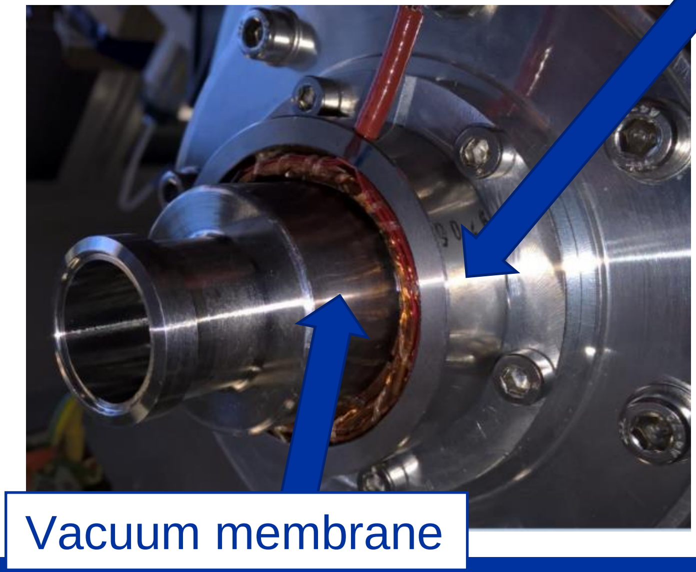
1) Commercial encoder for the control feedback [2013-Kou]

2) Optical encoder based on fiber optics with optoelectronics at the surface (In-house R&D) [2012-SIR]

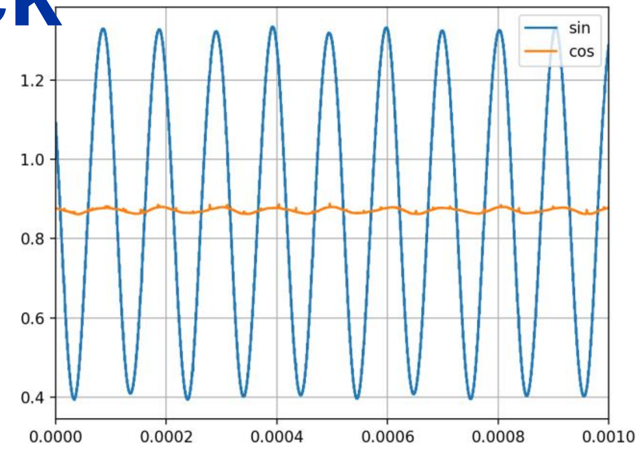
	Electrosyn	Camille Bauer	Netzer	Micronor	Admotec
					
Technology	Capacitive	Capacitive	Capacitive	Optic	Inductive
Accuracy/ Repeatability expected	7 arc sec	288 arc sec standard product, possibility to be increased with R&D	~ 5 arc sec With calibration and selected range of 30°	~ 5 arc sec High frequency ADC and pos. extraction in off line	~ 60 arc sec With calibration
Vacuum	+ +	+	+	+ +	+ +
Temperature	+	+	+	+	+ +
Radiation	+	- +	- +	+ +	++
Advantage	• Good experience of our environment • Absolute position		• Only the rotor in the vacuum • Absolute position • Low error due to eccentricity	• EMI/ RFI immunity • No delay • No electronics in the tunnel • No losses of signal	• Absolute position • Standard product • High factor transformation
Inconvenient	• Accuracy is decreasing with acceleration •Electronic in the tunnel • Analog signal transmission (EMI/RFI, Losses in the cables)	• Electronics in the tunnel • Accuracy • Analog signal transmission (EMI/RFI, Losses in the cables)	• Electronics in the tunnel • Analog signal transmission (EMI/RFI, Losses in the cables)	• Incremental position	• Electronics in the tunnel • Accuracy • Losses in the cables



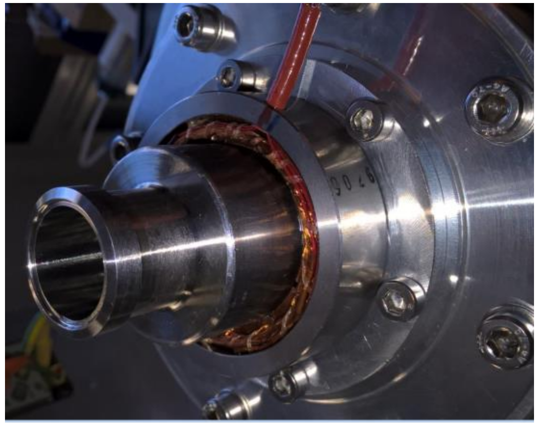


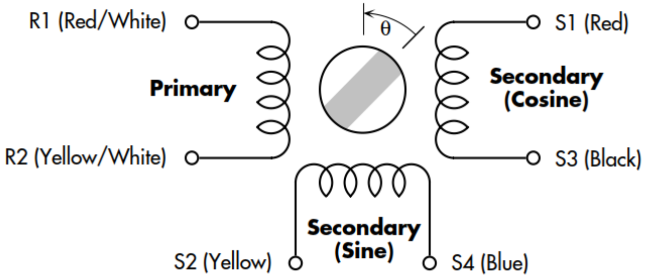


Angular sensor for the control feedback

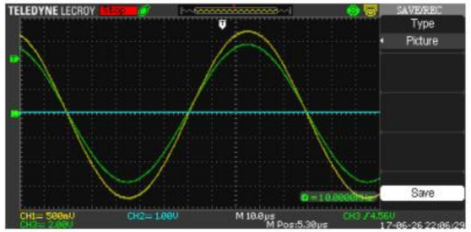


- Resolver based measure ~ like a variable transformer
- Modulation carrier at 10kHz
- Analog transmission over twisted pairs with NES18 (individually shielded pairs up to 220 m)
- Resolver to digital uses tracking loop => very good noise immunity
  + Custom FPGA based carrier frequency shifter to compensate vacuum membrane & long cables



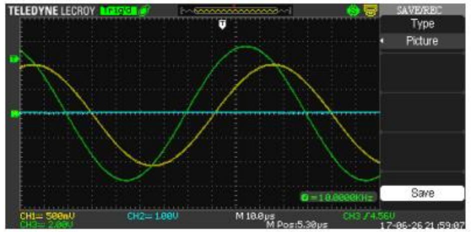


Stator s/n 9028



CH1 (courbe jaune): Sinus U2s; Uamp = 1.72V @10kHz

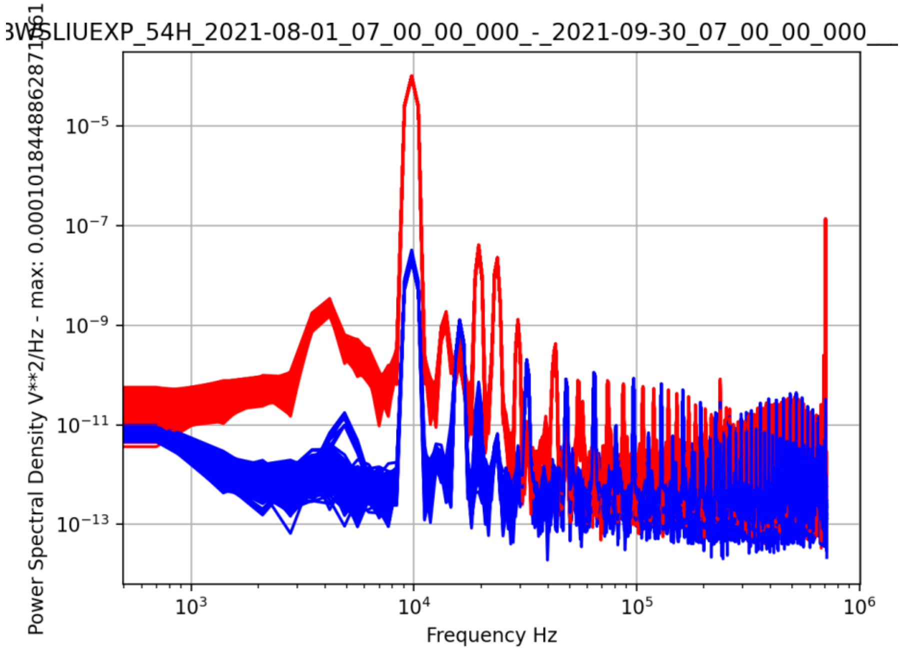
CH3 (courbe verte): Reference U1; Uamp = 5.76V @10kHz → TR = 0.299



CH1 (courbe jaune): Sinus U2s; Uamp = 1.04V @10kHz

CH3 (courbe verte): Reference U1; Uamp = 5.6V @10kHz → TR = 0.186

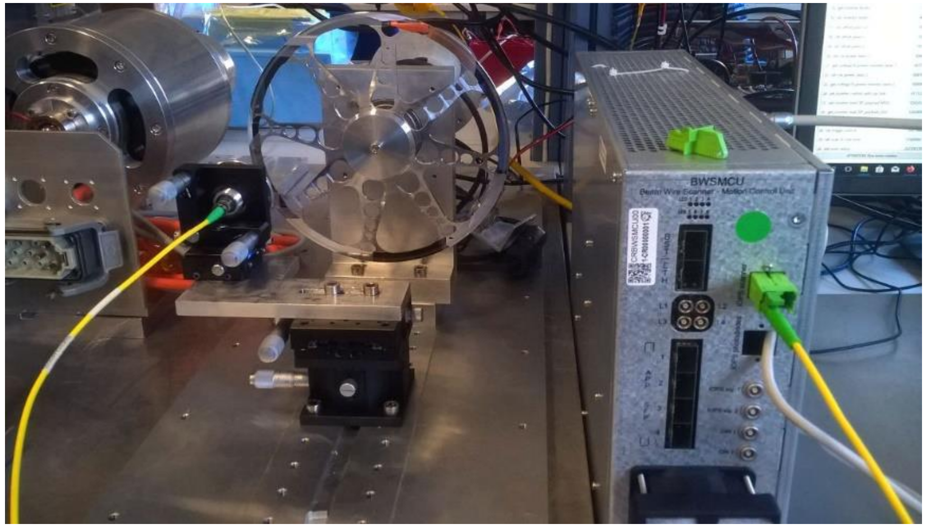
La membrane réduit le signal U2 d'environ 38% est comporte un déphasage de 42°. Avec le stator s/n 9026 on a obtenu les mêmes résultats.

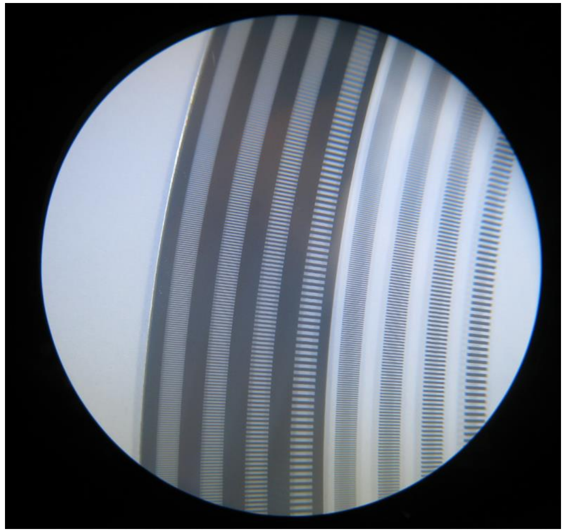


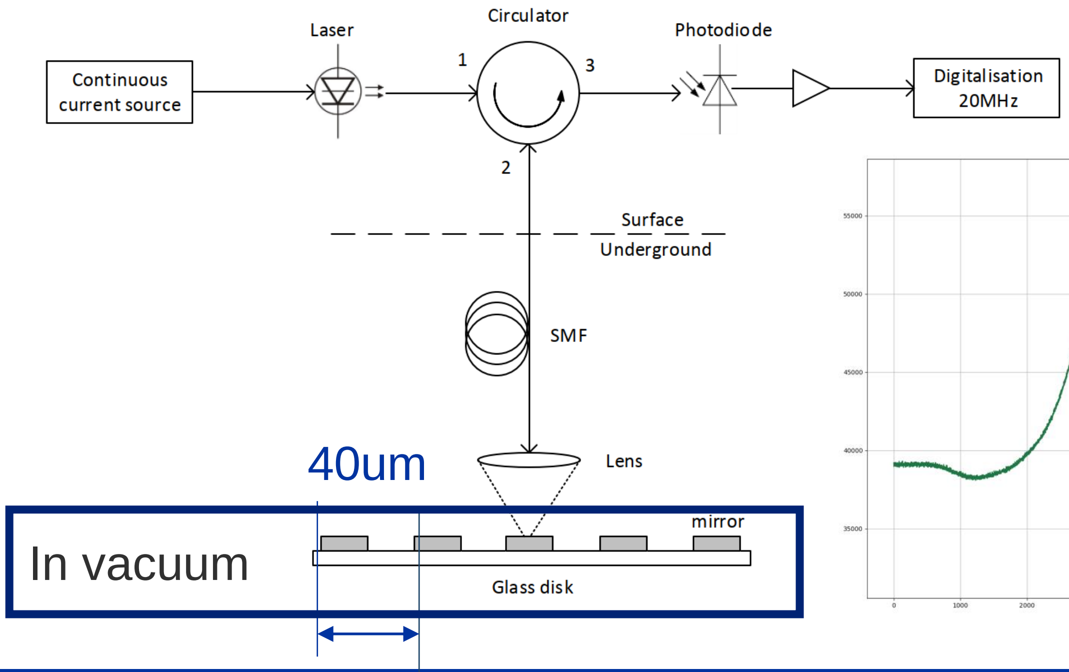
PS54H – 465 scans – signal at angle 0[rad]

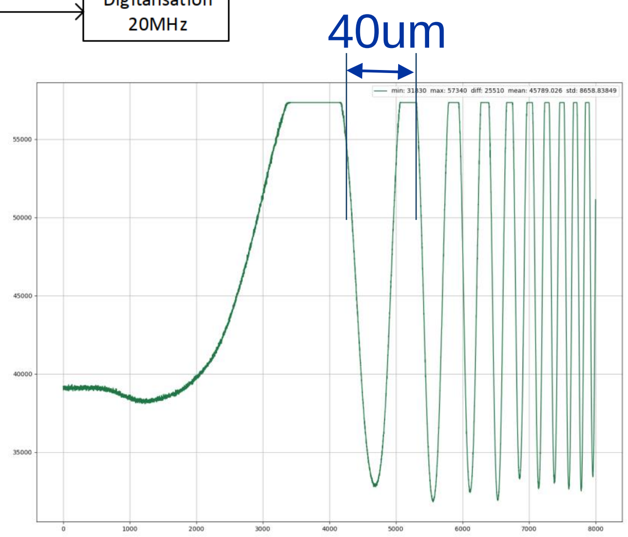
Angular sensor for the high precision angle

- Incremental optical sensor with absolute references marks
- In-house design (disk/electronics/processing)
- disk in vacuum
- Immune to EMI all the way
- Based on optical fibers and reflective
- Digitalized on the drive to detect each slit can be integrated in the control

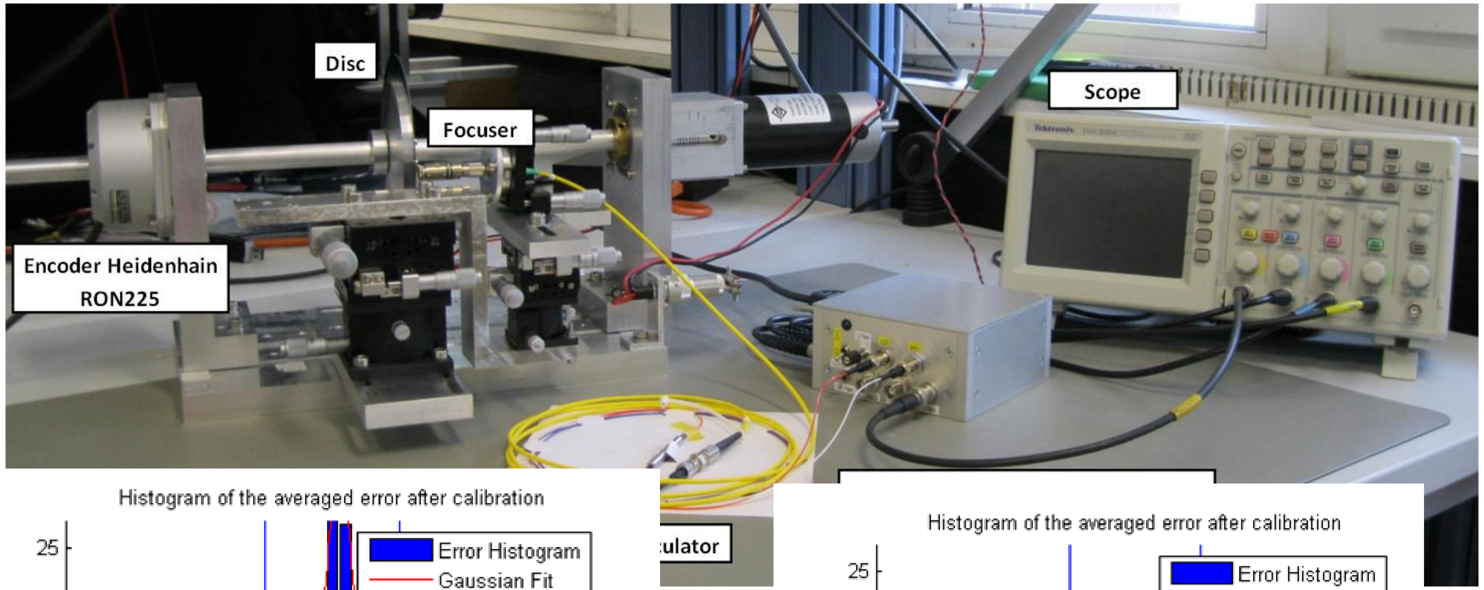


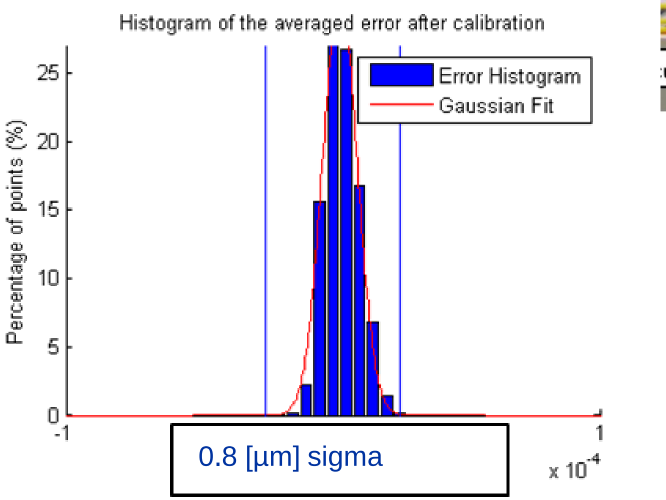




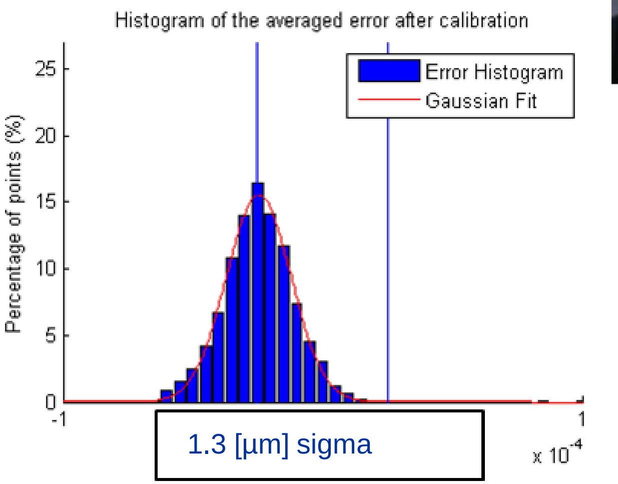


LIU angular sensors: Optical encoder test bench

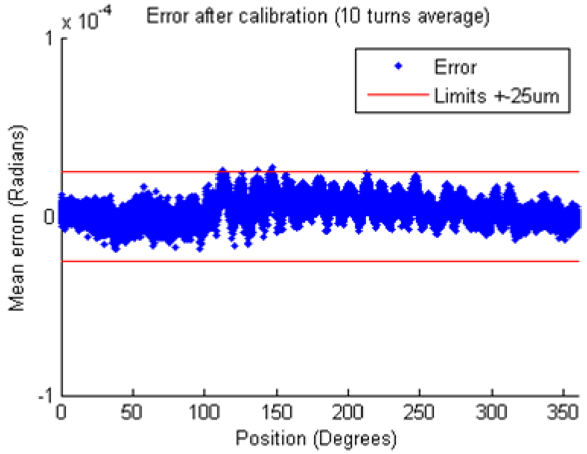




Présentation des erreurs résiduelles sous forme d'histogramme
Calibration avec Heidenhain RO225



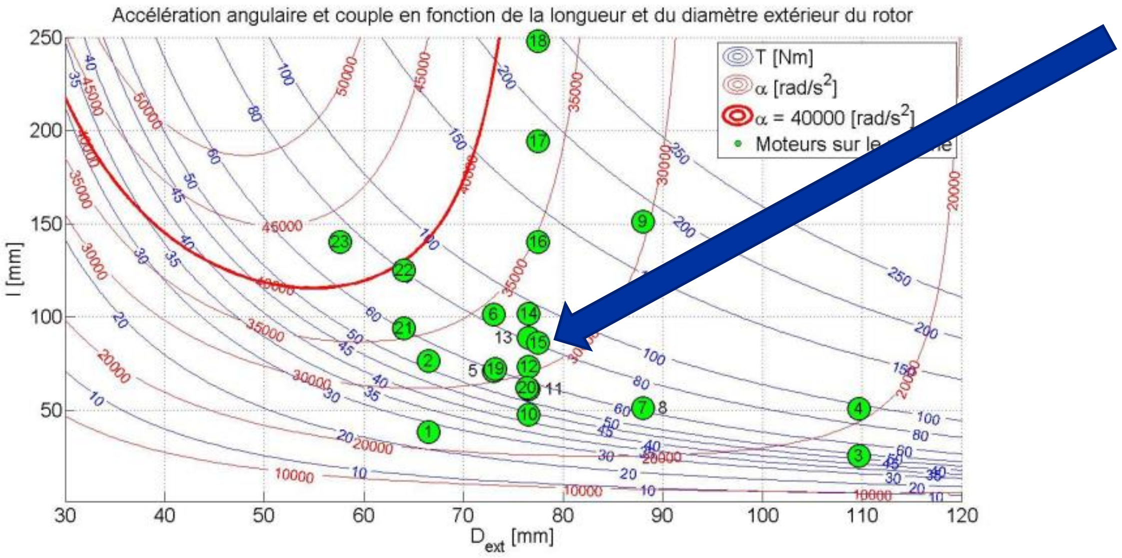
Présentation des erreurs résiduelles sous forme d'histogramme. Calibration avec 2 encodeurs (un de chaque côté du disque)



Moyenne des erreurs résiduel de 10 tours

Motorization

- Standard DC motor not suitable for UHV (brushes and coils glue/isolation)
- Step motor poor for torque/volume ratio and prone to vibration (step by step operation)
- Selection of Permanent Magnet Synchronous Motor (PMSM)
- Motor design optimization for LHC (Bsc. Project) with the HEIG-VD was carried out and an detailed survey was produced [2014-GRO]
- Model No 15 was selected and modified for vacuum (magnet type and fixture)



State of the art in PMSM motorization
Sorted by rotor length and diameter [2014-Gro]

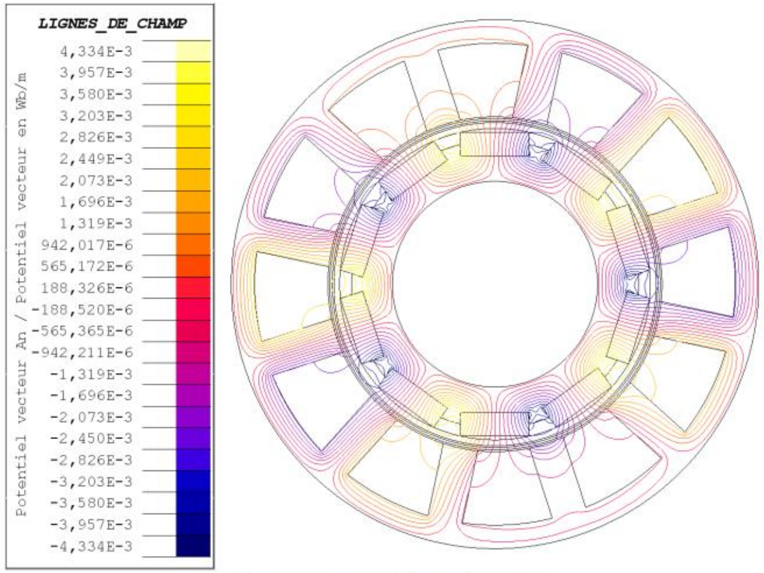
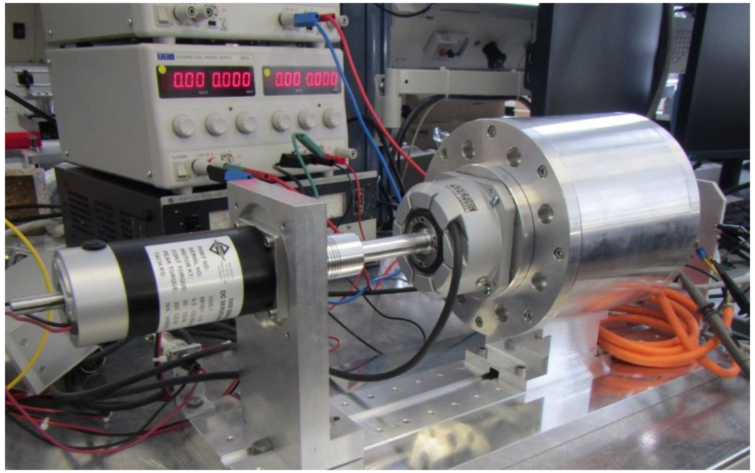


figure 6.31 : ARE : Lignes de champ

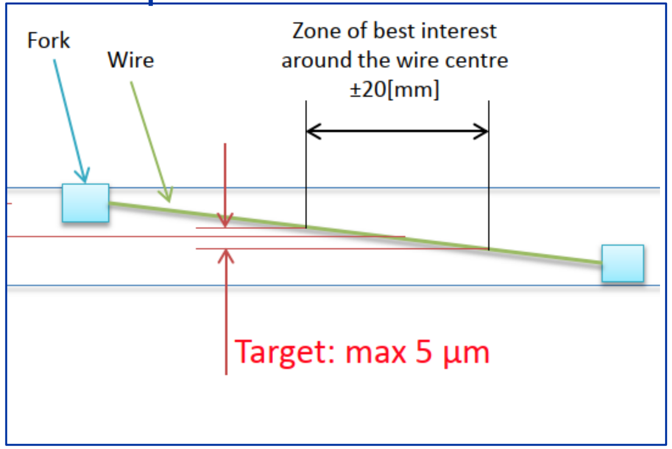
Field lines of a custom PMSM study for the LHC [2014-GRO]


Lab setup for motor qualification

Mechanics optimization examples

- **Mechanical optimization by numerical simulation [2013-SAM]**
- **Vacuum membrane between rotor and stator optimization (to 0.3-0.4mm)**
- **Shaft diameter and thickness for a target inertia and maximal twist (35mm with 5mm wall)**

Basic specification of shaft twist



Vacuum membrane wall thickness optimization

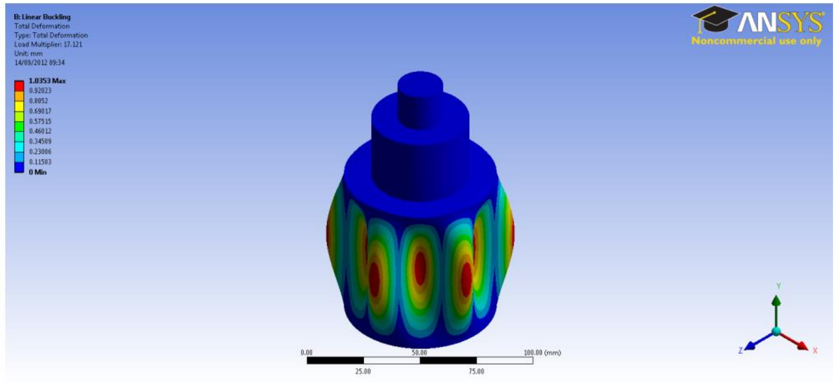
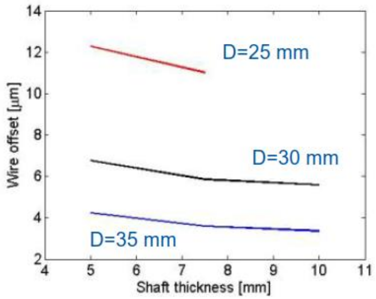
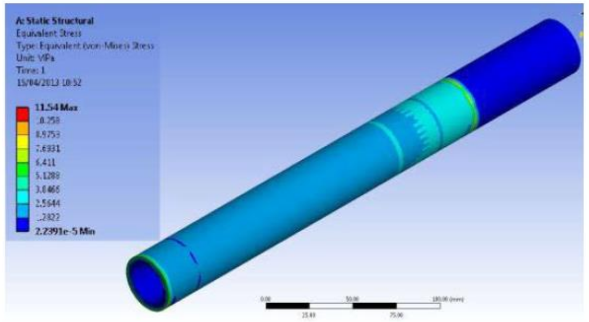


Figure 4.1.1: First buckling mode shape for the motor housing.

Shaft twist for different dimensions



Shaft stress



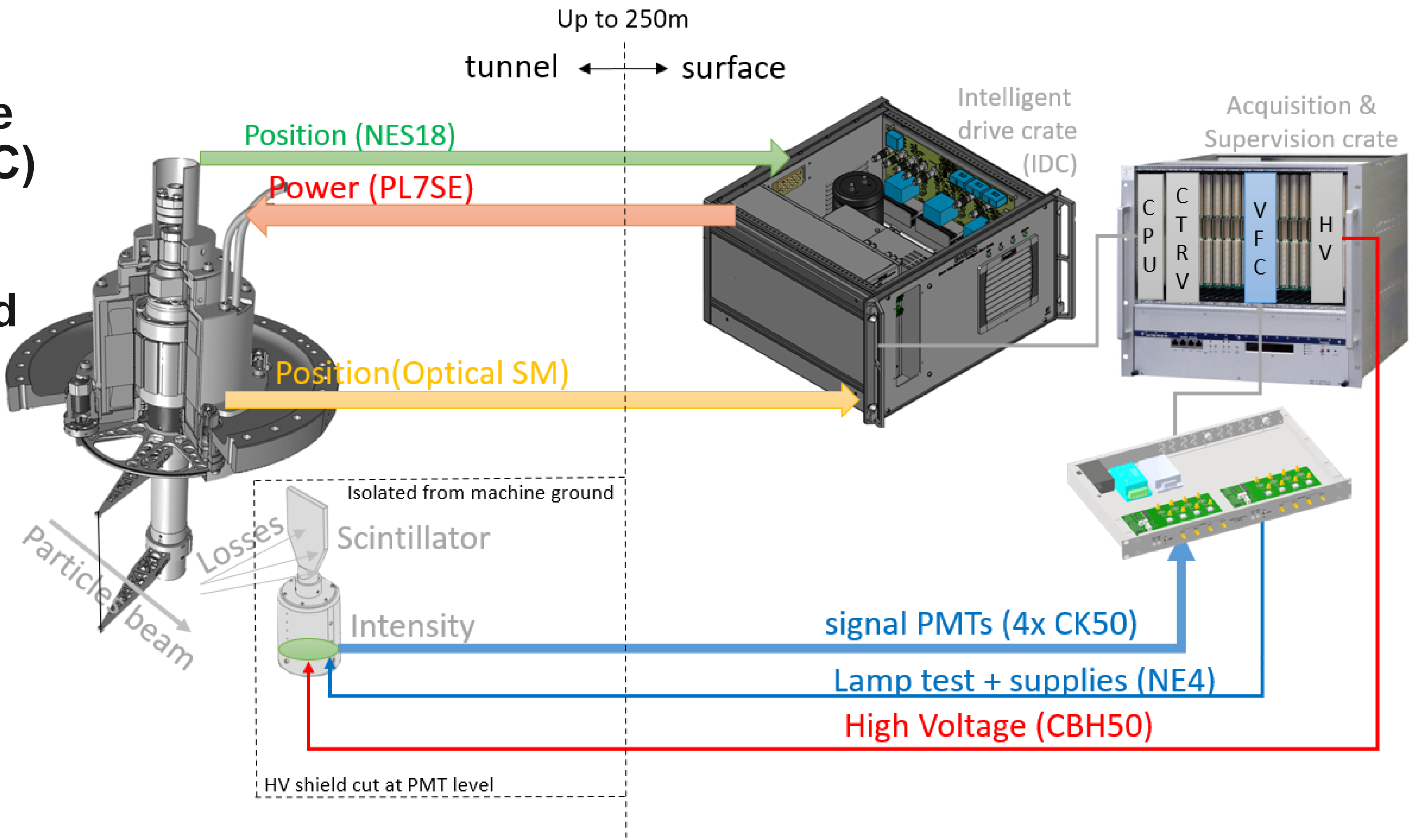
Use 35 mm shaft with 5 mm wall thickness

LIU Wire-scanner electronic system architecture

- **Early in the project, it was decided to develop in-house the 'critical' driving part (IDC)**

- **The acquisition of the photomultipliers was started later in synergy with other equipment (FPGA based digitalizes)**

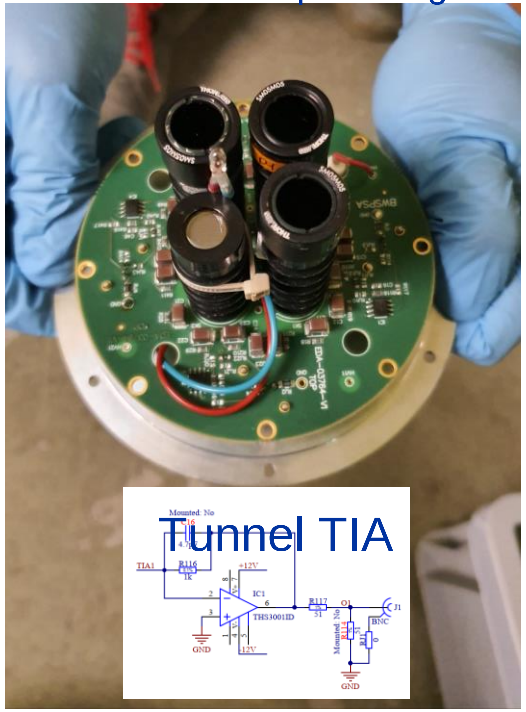
- **2 iterations were necessary to build the final system (as for the kinematic unit)**



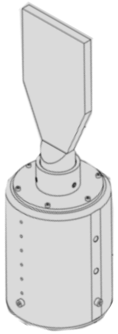
Acquisition chain of the secondary shower signal

- Photomultipliers equipped with different filters to cover large dynamic range
- Variable supply voltage to change the PMT gain and maximize signal to noise ratio
- Analog transmission from tunnel to surface robust and simple but susceptible to interferences
- Acquisition chain isolated from machine ground to limit noise

PMT with custom powering base



Tunnel TIA



50-220m with CK50

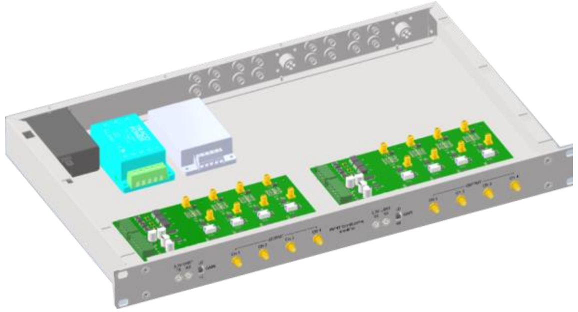
No filter

1 %

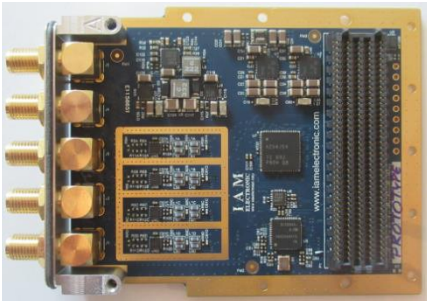
0.1 %

0.01 %

Surface conditioner/amplifier

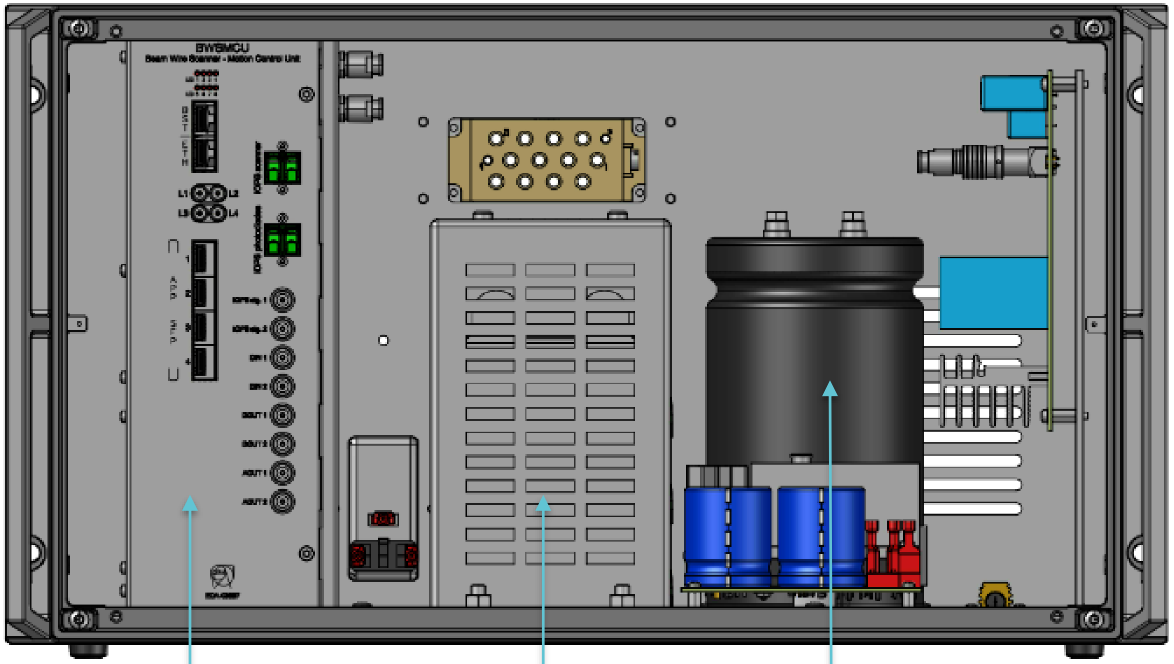


DC-coupled 500MHz / 14 bits ADC



Intelligent Drive Crate (IDC)

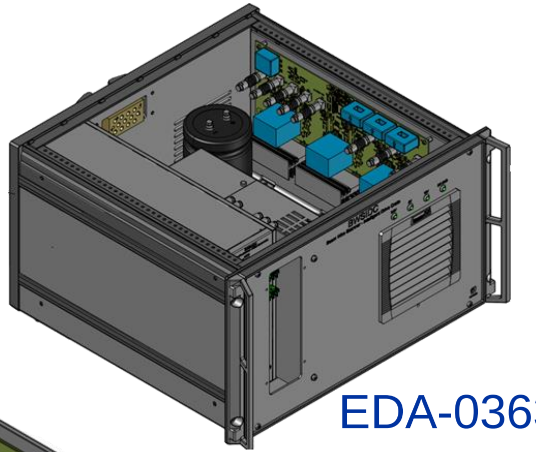
6U, ≈ 22Kg



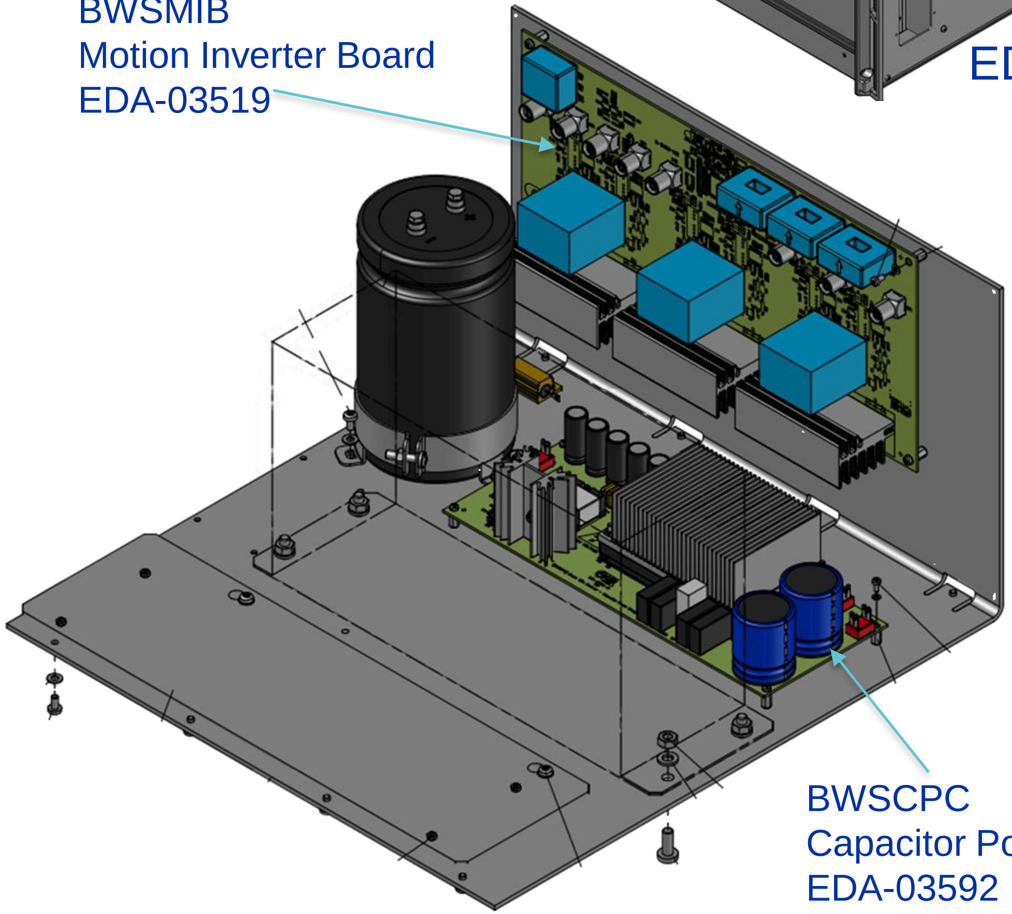
BWSMCU
Motion Control Unit

Output filter “sinus”

DC-BUS Capacitor



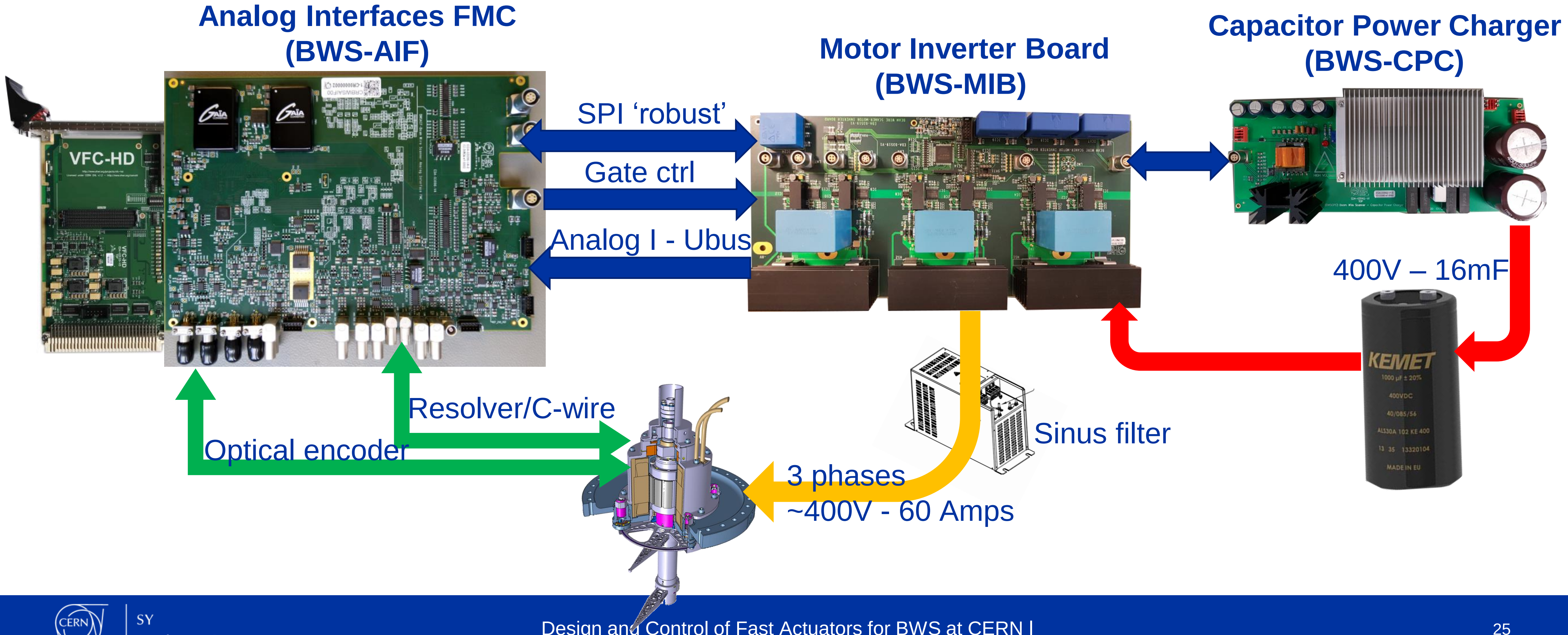
EDA-03634



BWSMIB
Motion Inverter Board
EDA-03519

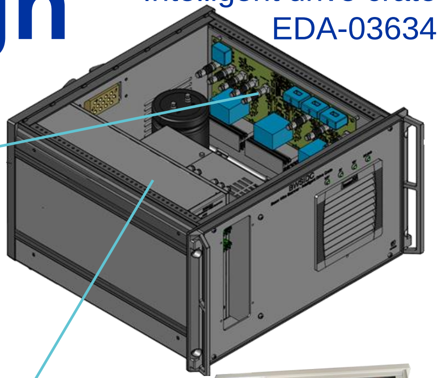
BWSCPC
Capacitor Power Charger
EDA-03592

Electronics of the Intelligent Drive Crate (IDC)



Minimization of motor drive EMI during design

Intelligent drive crate
EDA-03634

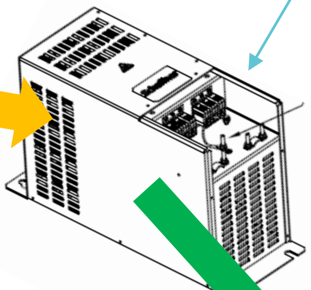


- PMT signals (1mA - 1V on CK50)
  Motor powering (400V, ~60A)
- Signal and power cables routed together
- Motor drive technology:
  linear drive (legacy scanners – still in LHC and PSB)
  Switch mode power stage for the LIU scanners
- LIU power cable exclusively driven during on-demand scans lasting about 2x50ms with Pulse Width Modulation at 16kHz.
- “EMC study for the control of Wire Scanner”, EDMS-1416465
  Collaboration with Swiss University to validate this technology in the context of BWS (2013)

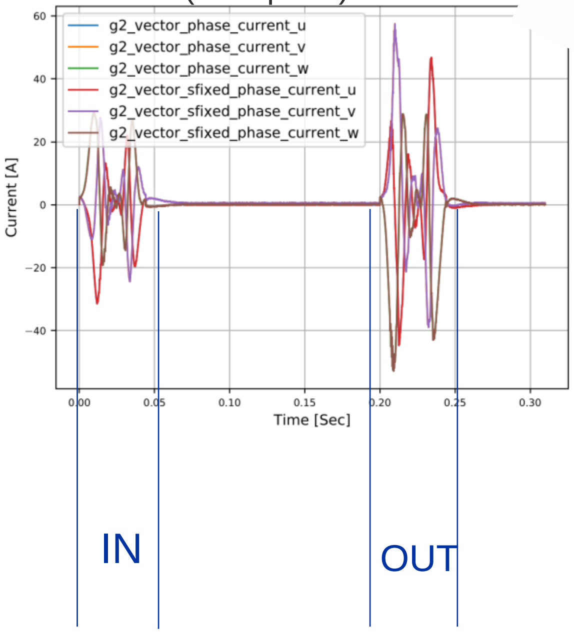
  ---Introduction of a large EMC filter at the output stage
  ---Recommendation to design a custom drive to integrate large EMC filter while ensuring high performance using “vector control technics”
  ---Validate our selection of the shielded power cable (CERN type “PL7SE”)

Cross-section
“PL7SE”
7 conductors of 6mm^2
with outer shielding.
EMC connector
mounting procedure
EDMS-2172897

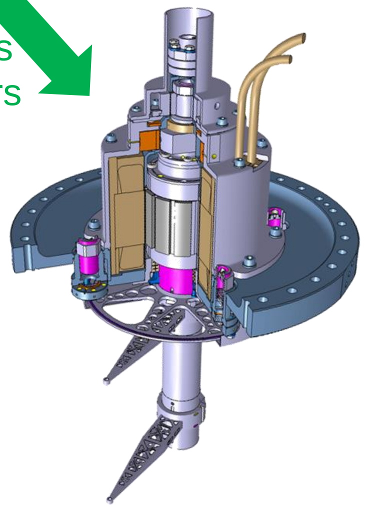
“Motion Inverter Board” EDA-03519



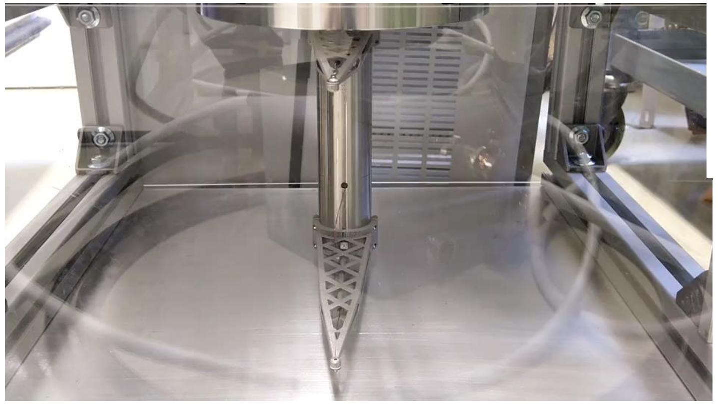
Example of output currents
(low speed)

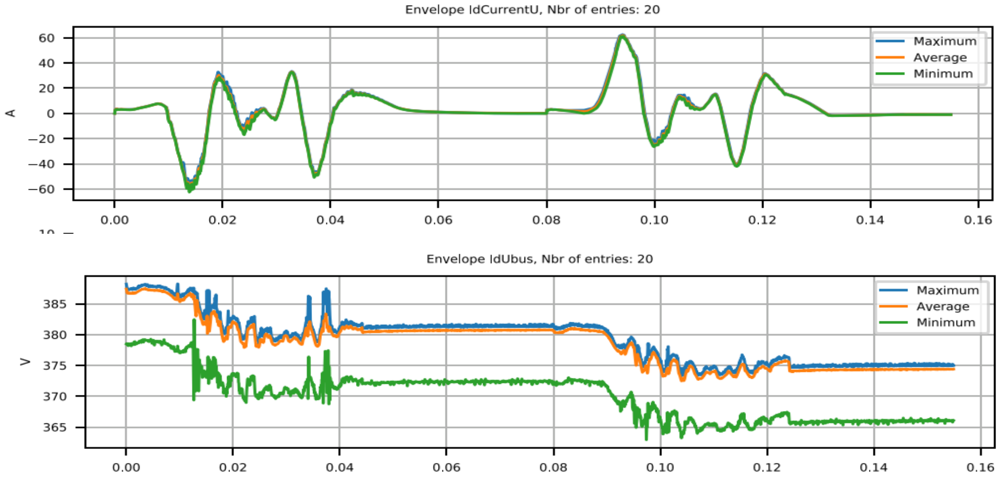


3 phases
~400V - 60 Amps
Up to ~230meters



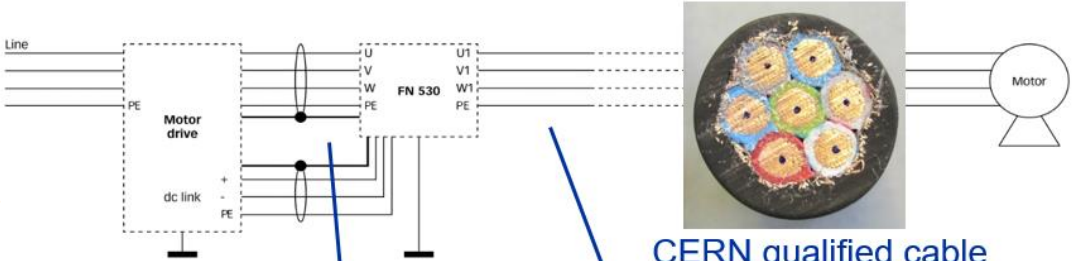
PWM Motor driving technology and EMI



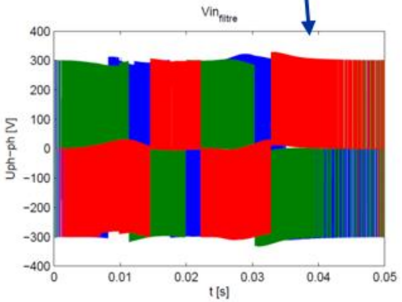


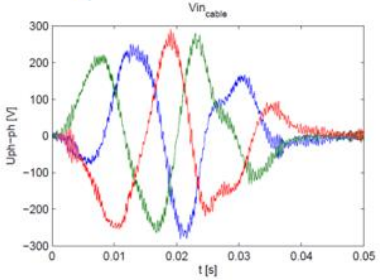
IGBT based Three phase full bridge inverter

Output filter with post filter current sensing

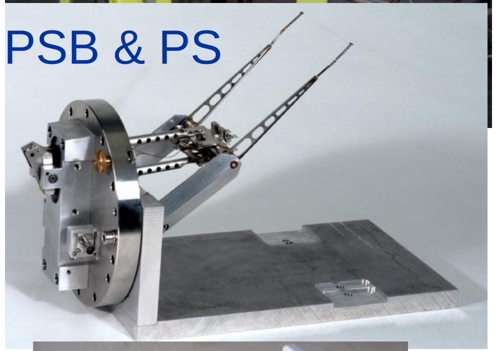


CERN qualified cable

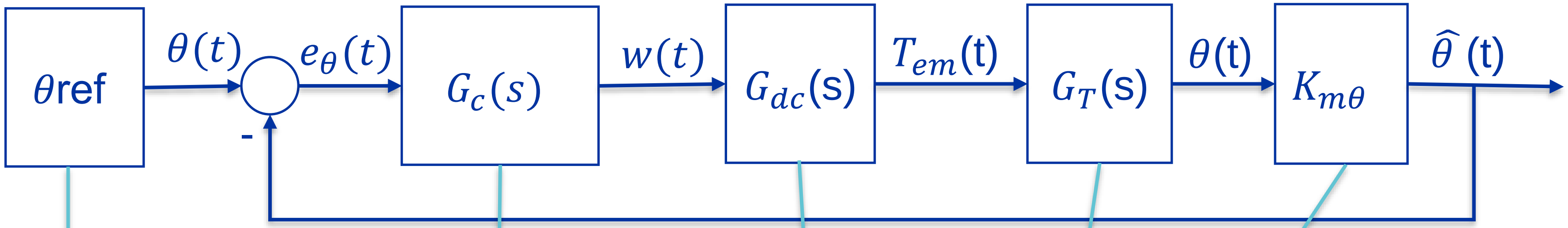


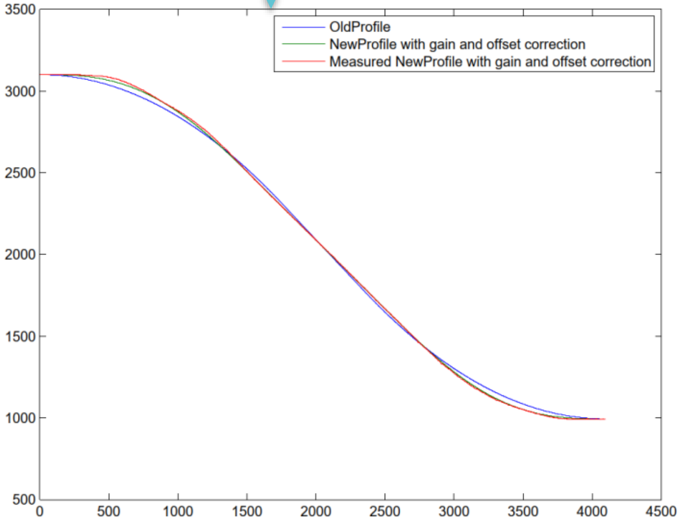


Wire scanner Legacy systems control ~1980~2024 for all BWS mechanisms



Controller | *Plant*



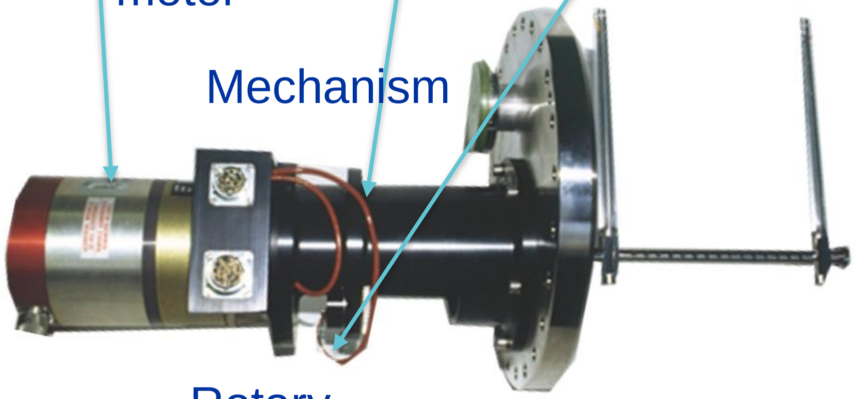


$$Gc(s) = Kc$$

[2019-EME]

DC motor

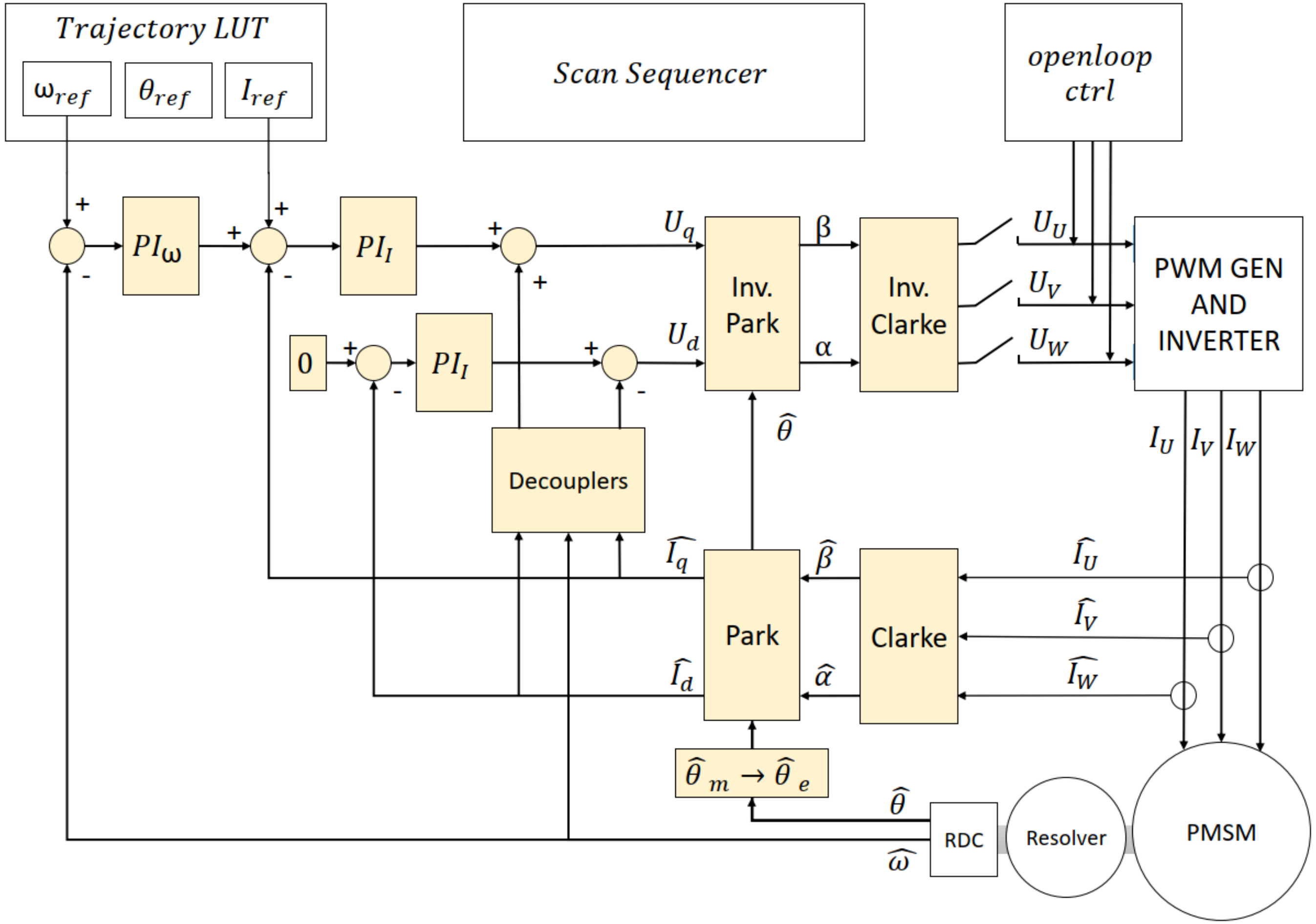
Mechanism



Rotary Potentiometer

FPGA motion control with Field Oriented Control

- **Classic Field Oriented Control with PI controllers for the current and speed. (Clarke-Park transform) [2015-MAC] [2017-EME]**
- **Controllers are operating in the motor rotor frame**
- **Open loop capability [2023-DI] (for positioning and commissioning)**
- **Trajectory on LUT**
- **Scan sequencer for low level ctrl**

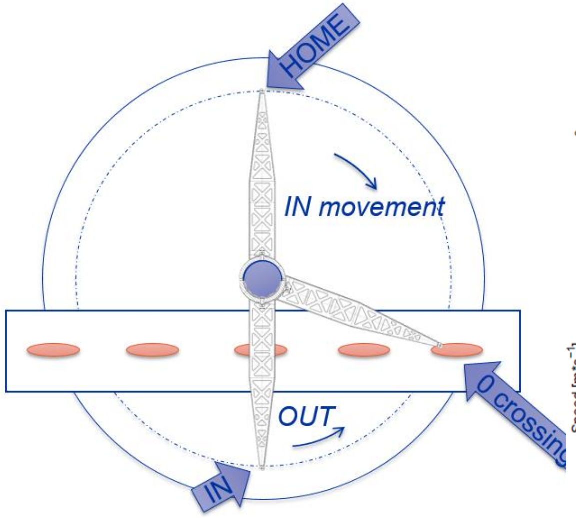


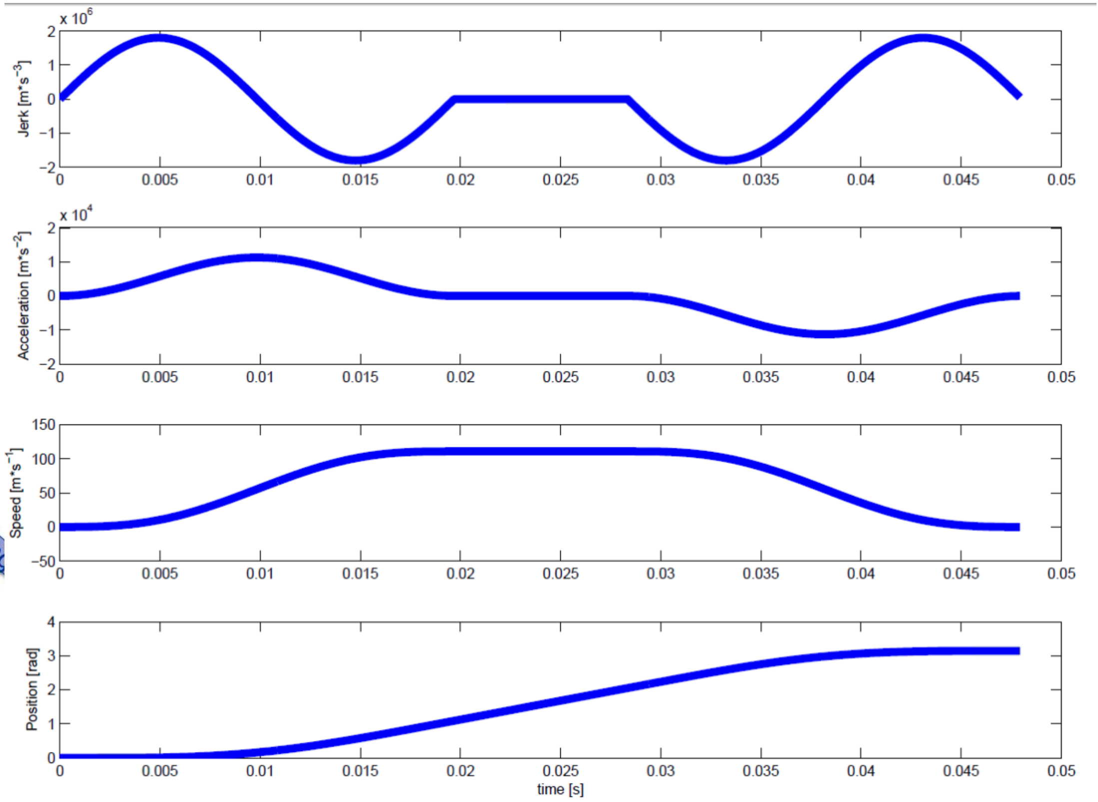
[5] J. Emery, A. Barjau, B. Dehning, J. H. Alvarez, P. J. Lapray, and M. Macchini. Design and validation methodology of the control system for a particle beam size measurement instrument at the cern laboratory. In *2017 American Control Conference (ACC)*, pages 4221–4228, May 2017.

[6] M. Macchini, S. Saponara, L. Fanucci, and J. Emery. Motion control design of a PMSM and FPGA implementation for the Beam Wire Scanner at CERN, Apr 2015. Presented 30 Apr 2015.

Trajectory lookup tables

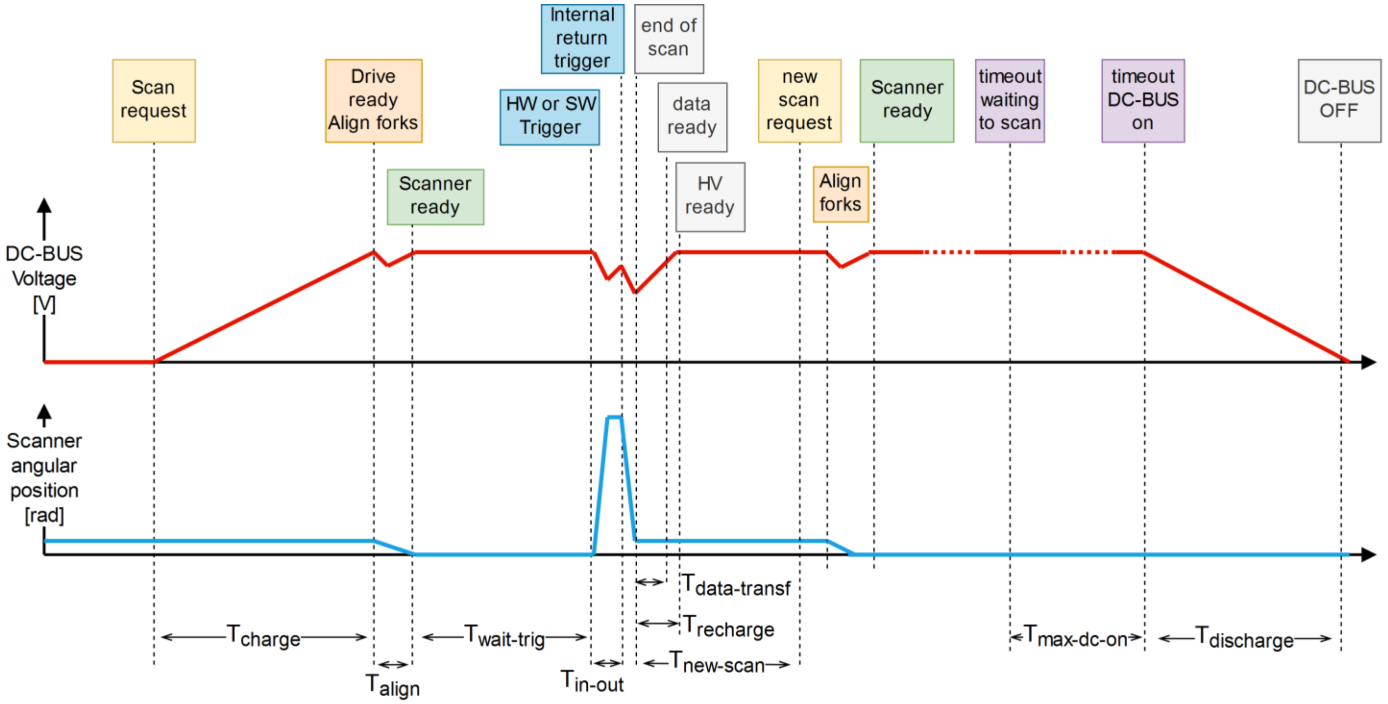
- **Tables pre-calculated offline (MatLab/Python) and then embedded into FPGA ~optimization algorithm to find desired angle and top speed.**
- **4 table sets (position/speed/current)**
- **Part of the plant model is embedded into it Acceleration -> current**





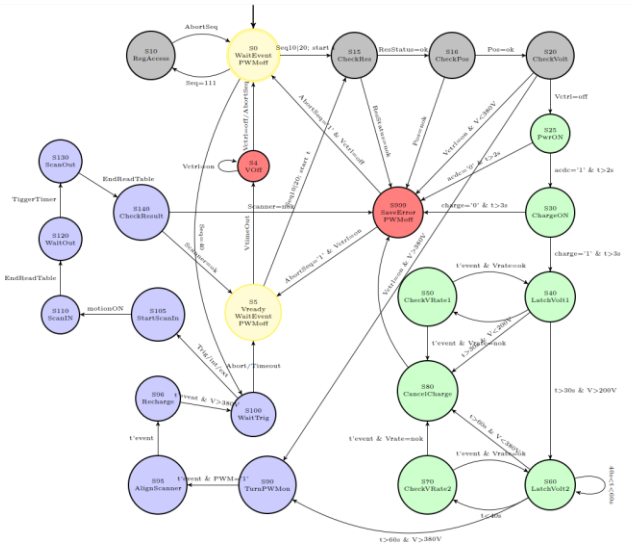
Scan sequencer

- **Critical sequencing of action to perform a scan is integrated into low level FPGA control**
- **Implementation as state machine with error codes read by RT software**
- **Decoupling of critical and none critical operation on this sensitive actuator**



Name	min.	max.	unit	description
T_{charge}	60	70	s	Charging time of the DC-BUS
T_{Align}	tbd	tbd	s	Align forks and recharge DC-BUS
$T_{wait-trig}$	-	60	s	Timeout waiting for trigger
T_{in-out}	0.1	1	s	Between IN trig to OUT trigger
$T_{data-transf}$	tbd	tbd	s	Move IOPS data to BWSASC
$T_{recharge}$	1	5	s	Recharge DC-BUS to 100%[1]
$T_{new-scan}$	$T_{data-transf}$	$T_{max-dc-on}$	s	Between end of scan and new request[1]
$T_{max-dc-on}$	-	5	minutes	wait for scan request, DC-BUS at 100%
$T_{discharge}$	-	<10	minutes	Time to discharge the DC-BUS[1]

[1] Scan request can be initiated during DC-BUS charge or discharge.



Production, Installation and tests

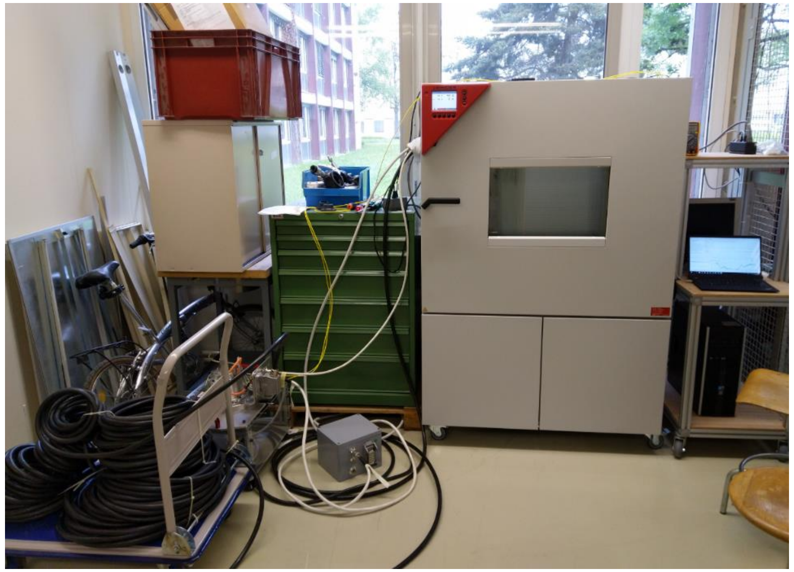
Electronics

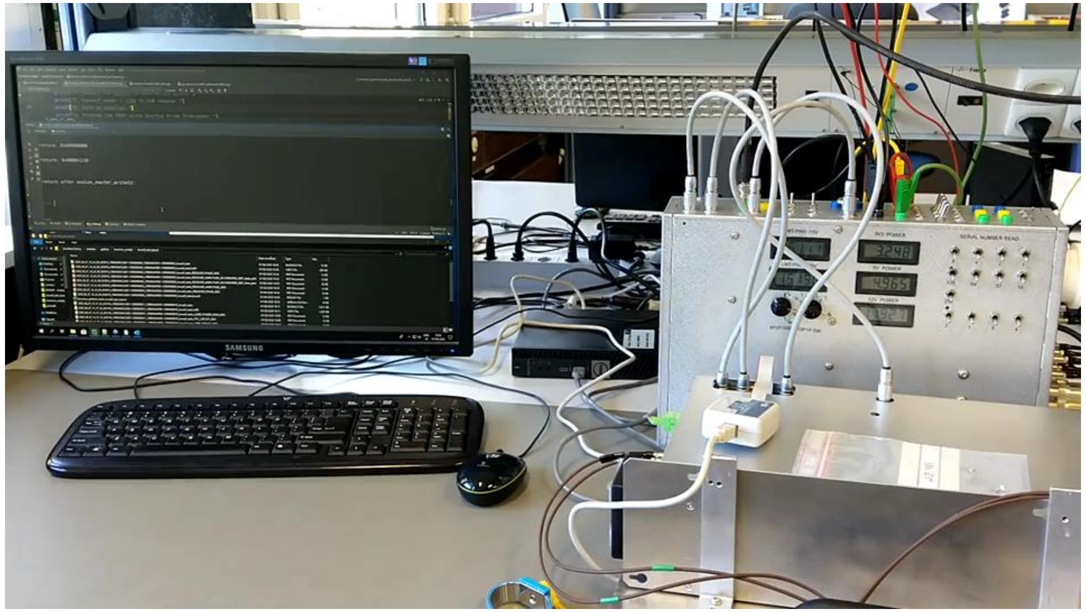
- PCB board production and assembly subcontracted through CERN service
- Final assembly, cablings and tests at CERN
- Test bench for all boards, automated for the most complex using Labview & python
- Same scripts family used for testing parts of the drive and IST in the machines!

Mechanics

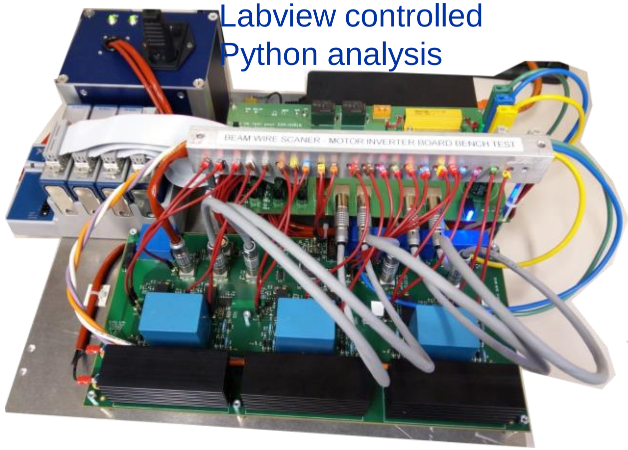
- Mechanical parts subcontracted
- Conformity checked at CERN
- Complete assembly done at CERN
- Final step is to install the carbon wire
- Check of the scanner performance using laser based calibration bench

Electronics production and test tools





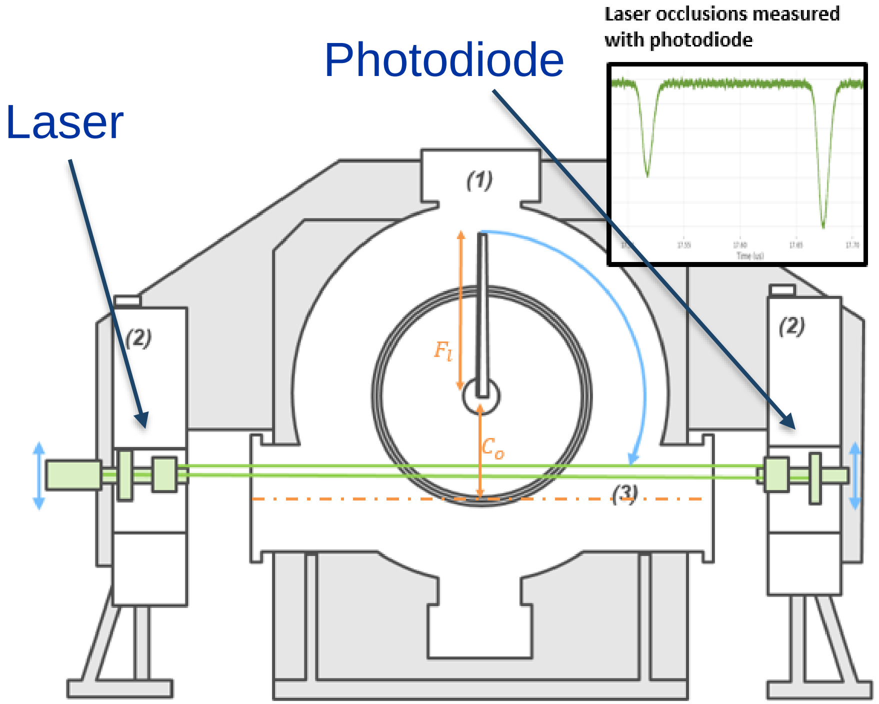
BWSMIB bench
Labview controlled
Python analysis

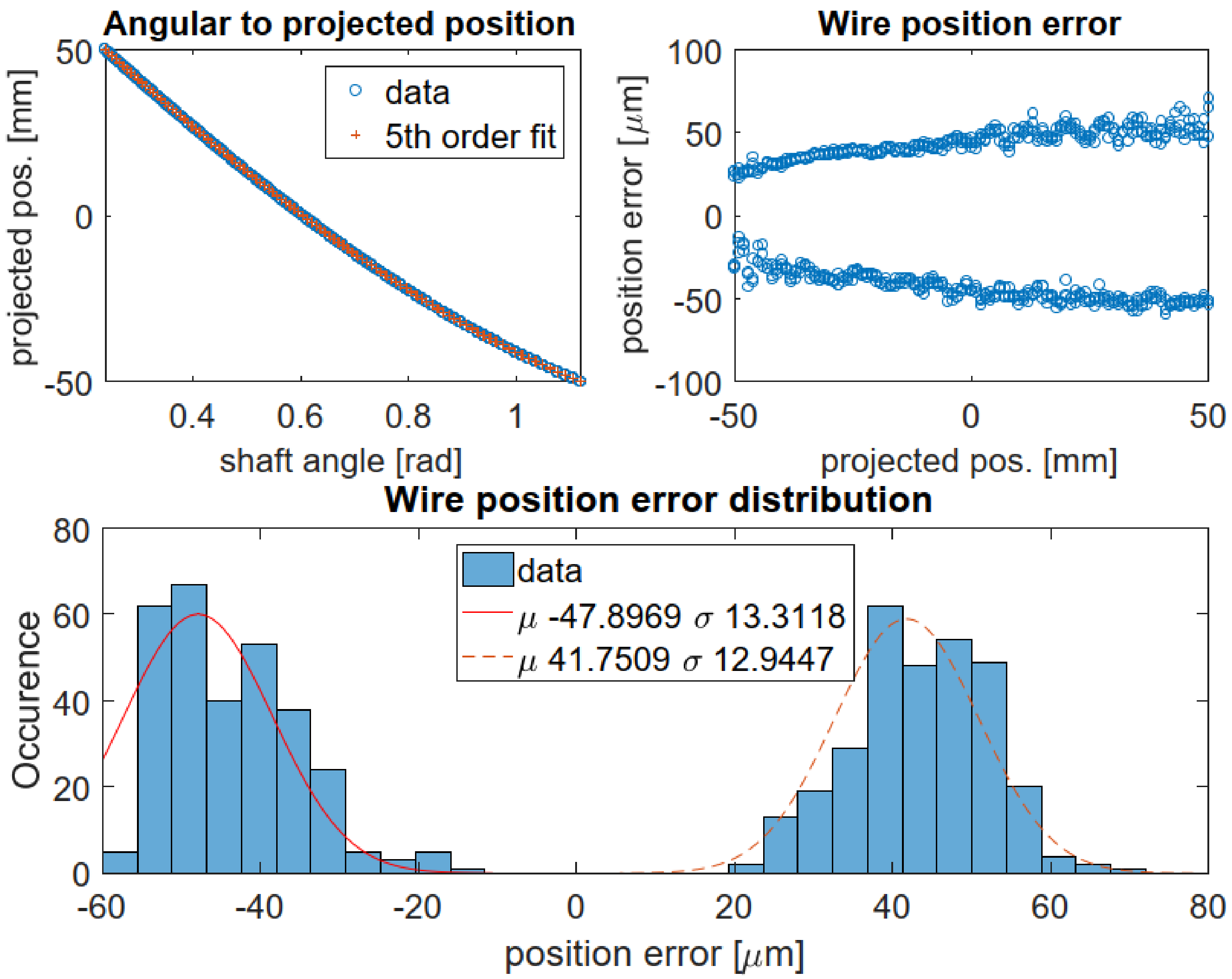


BWSIDC automated functional bench with scanner
Python based script using JTAG & Ethernet

BWSAIF (Motor inverter) bench
Python based script using JTAG (soon to be migrated to Ethernet)

Calibration of every scanner before installation

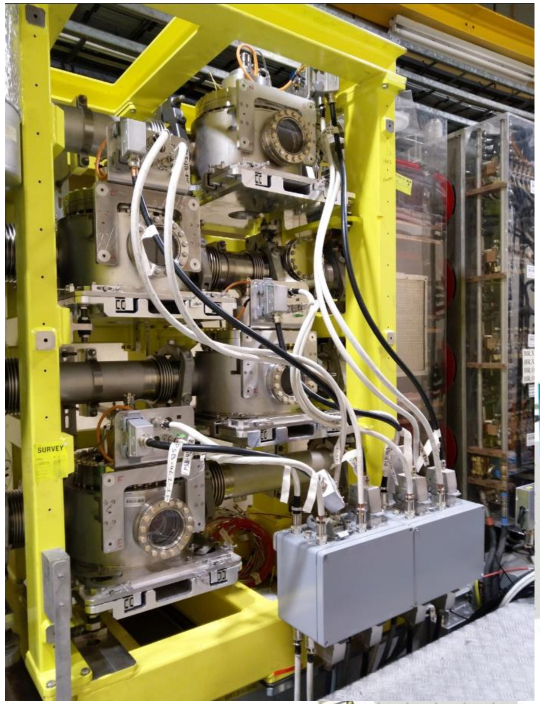




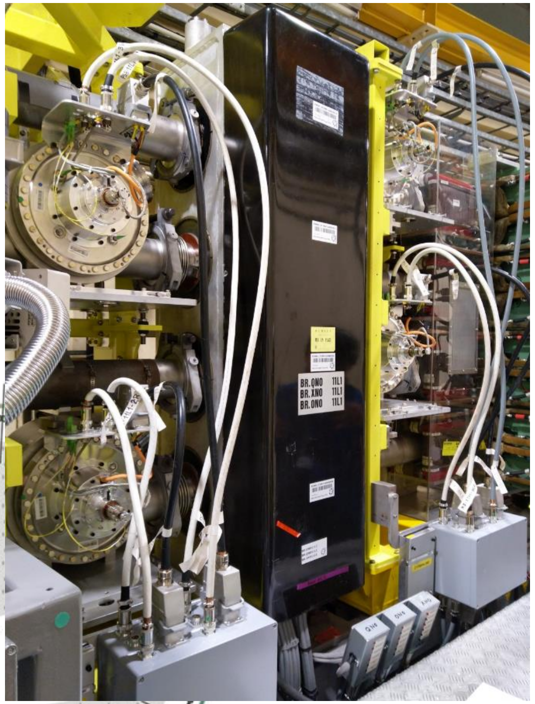
	Residuals RMS [μm]			INOUT Slack [μm]		
V [rad/s]	55	110	133	55	110	133
Device #						
CR03	2.04	3.27	5	32	92	115
CR04	1.38	1.55	3.84	28	76	100
CR05	1.45	2.30	4.05	30	87	110
CR06	4.29	2.56	4.76	31	87	113
CR07	3.15	3.50	4.80	29	80	106
CR08	2.35	2.28	5.89	31	88	110
CR09	0.72	1.95	2.56	42	120	150
CR10	1.99	2.69	3.94	32	88	110
AVG	2.2	2.5	4.4	31.9	89.8	114.3
STD	1.0	0.6	0.9	4.0	12.4	14.2

2019 Calibration results

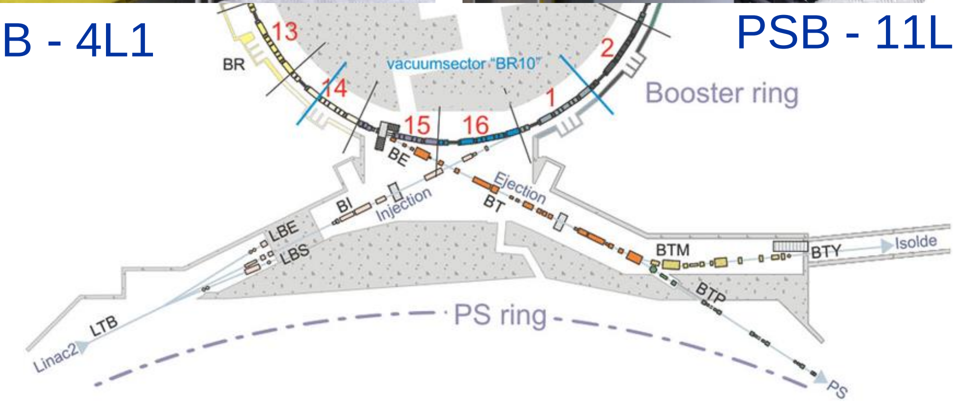
Accelerator tunnel installation of the LIU BWS 2021

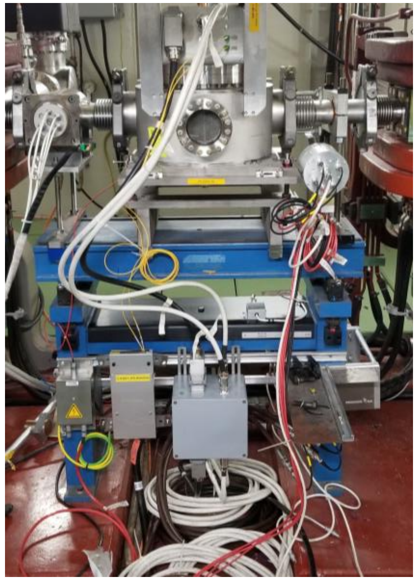


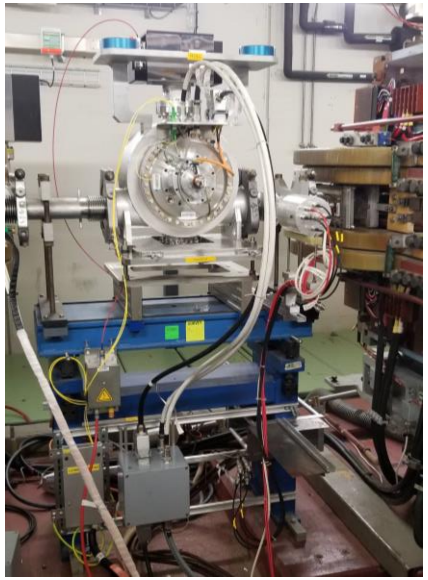
PSB - 4L1

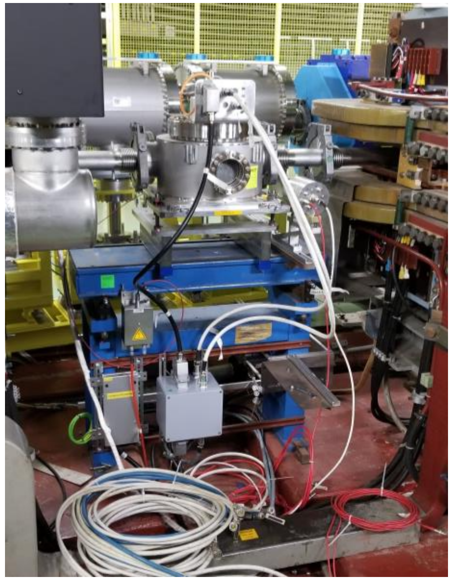


PSB - 11L1

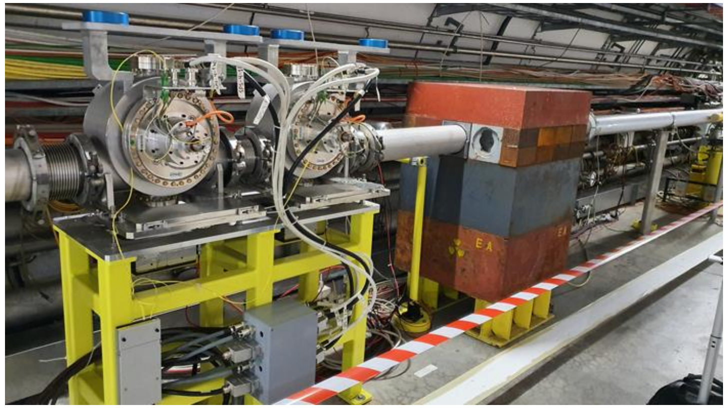








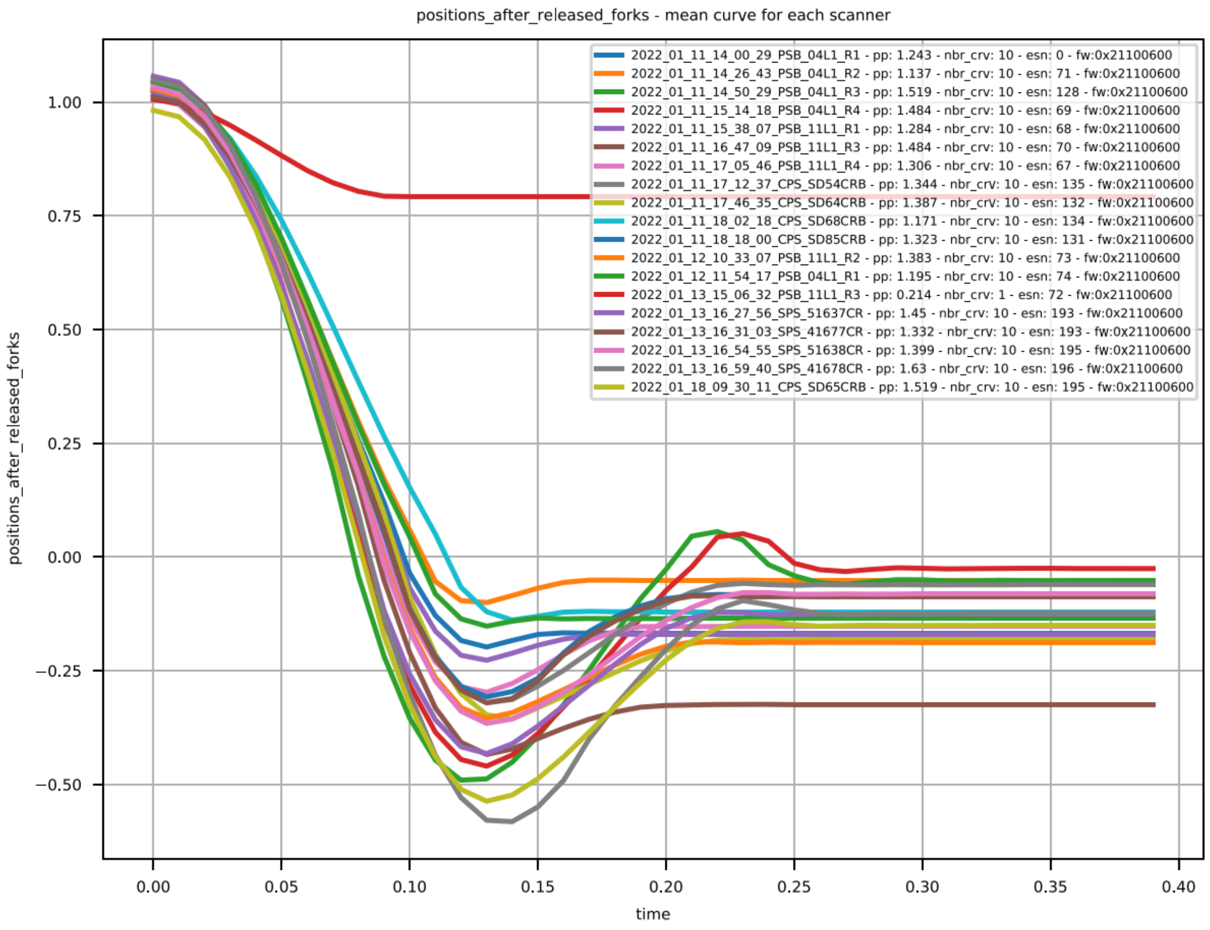
PS – 54 – 64 – 65 – 68 - 85



SPS - LSS4 - LSS5

Individual system test (IST): Friction tests

- **Evaluation of the friction before installation and before beam.**
- **“step by step” control of the brushless motor to move the shaft at 1 rad and release it.**
- **The magnetic break move back the shaft and the position over time is recorded.**
- **Final position and undershoot are evaluated**

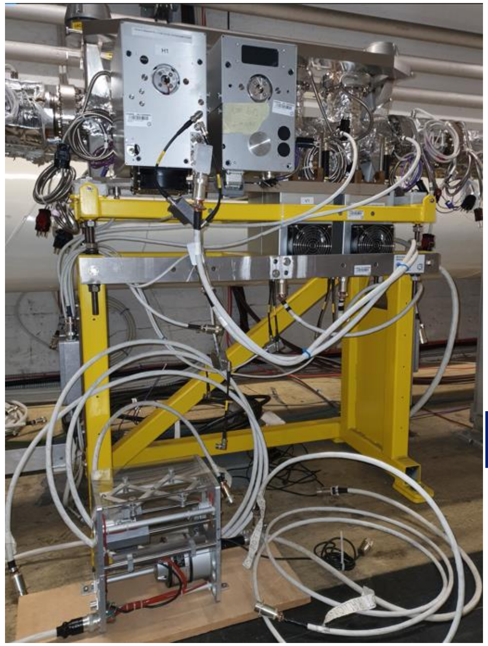


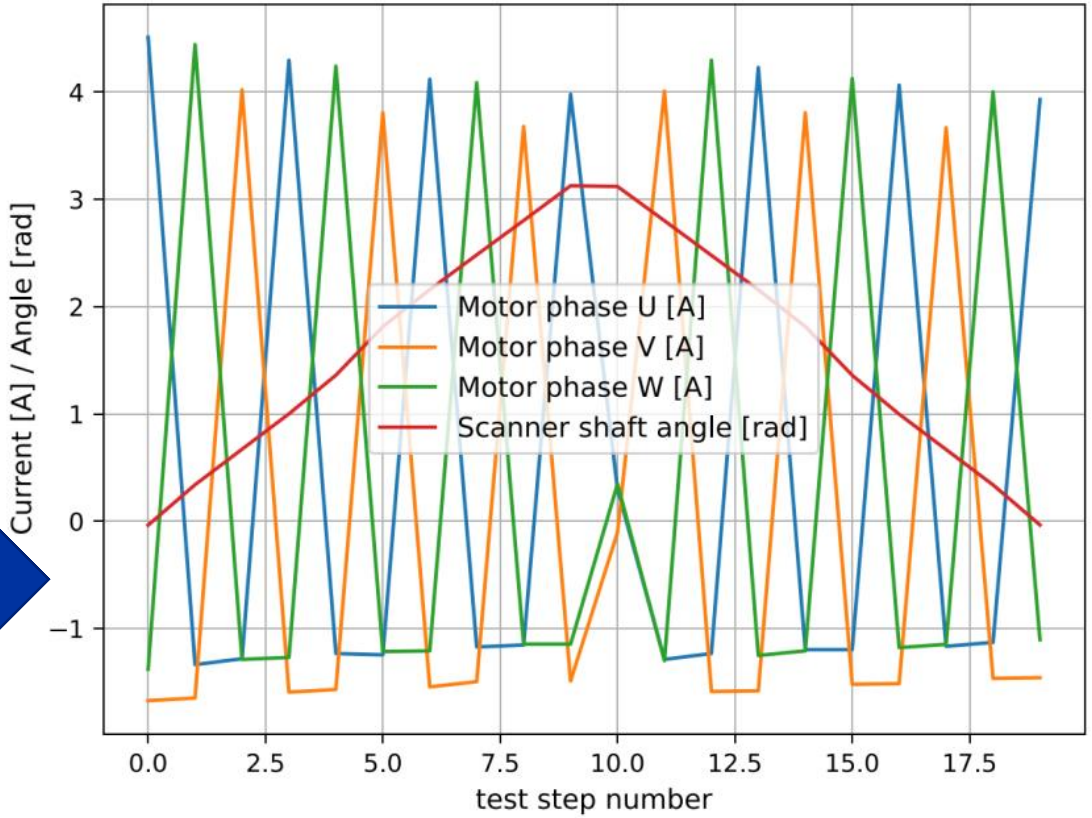
Friction evaluation procedure put in place for the IST 2022 before the run

Individual system test (IST): Open loop Test

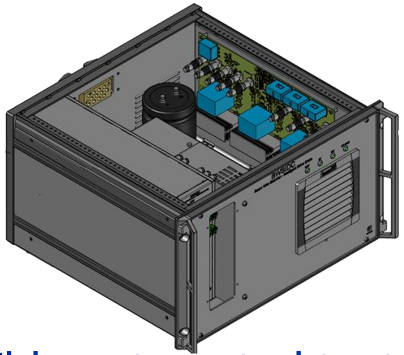
The LIU brushless motor is controlled in step-by-step instead of vector control

Legacy Individual System test in the LHC (2008 generation)



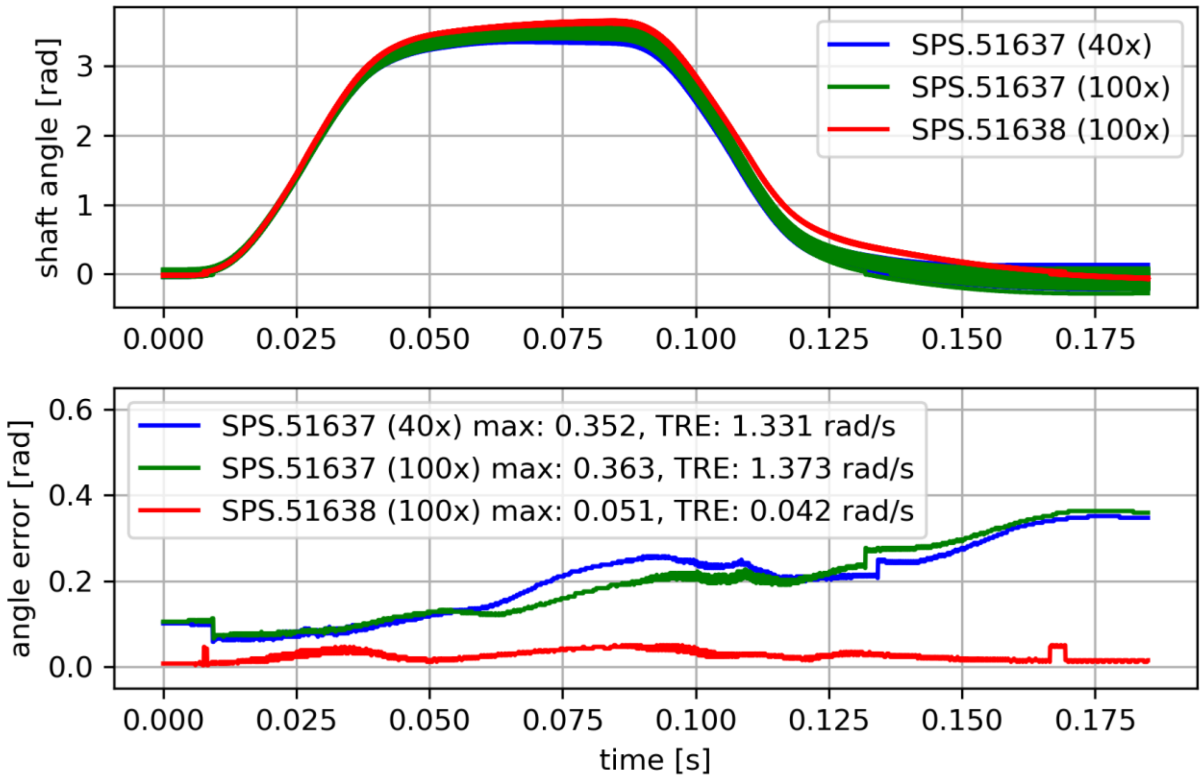


Automated System test called Open Loop Test (OLT)



This automated test (python) can detect:
- Mechanism frictions
- Resolver issue
- Motor phase issue
- Drive power stage issue

IST procedure for preventive maintenance
Trajectory reproducibility Error (TRE)



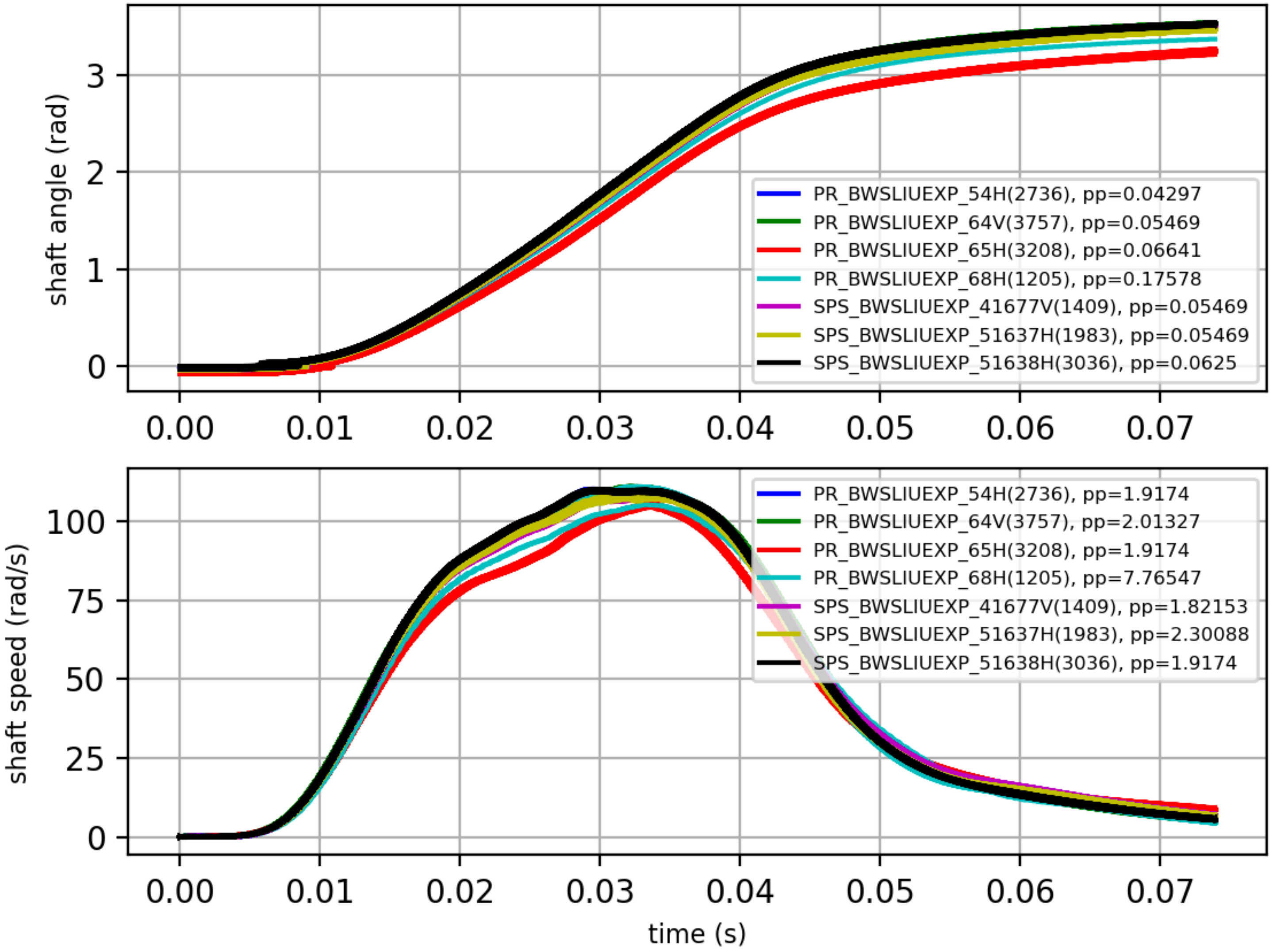
Motion pattern reproducibility for two SPS scanners, as they move through the beam axis and back. One of the two is less reproducible

N	A	L $[m]$	TRE1 $[mrad/s]$	TRE2 $[mrad/s]$	N1 $[bin]$	N2 $[V^2/Hz]$	N3 $[V^2/Hz]$
R1H	PSB	60	21	-444	171	0.02	0.041
R2H		60	21	-174	158	0.00	0.004
R3H		60	697	-127	88	0.00	0.014
R4H		60	21	0	133	0.00	0.003
R1V		55	232	-253	144	0.01	0.015
R2V		55	85	-301	145	0.00	0.002
R3V		55	63	-48	95	0.00	0.003
R4V		55	845	-127	126	0.01	0.007
54H	PS	185	63	-48	1706	44.1	0.013
64V		230	63	-79	901	8.04	0.940
65H		232	106	63	492	1.04	0.024
68H		215	21	0	522	2.15	0.014
85V		216	85	-32	1634	19.2	2.036
41677V	SPS	170	169	-111	487	0.36	0.439
41678V		170	63	95	155	0.12	0.121
51637H		150	1373	63	378	0.63	0.045
51638H		150	42	-16	2526	0.88	0.238

Table 2: Scanner name (N), accelerator (A), cabling length (L), trajectory reproducibility error (TRE1) in 2020 and 2022 (TRE2), PMT noise (N1), noise @16 kHz in May 2021 (N2) and noise @16 kHz in July 2022 after installation of noise limiter on the PS scanners (N3).

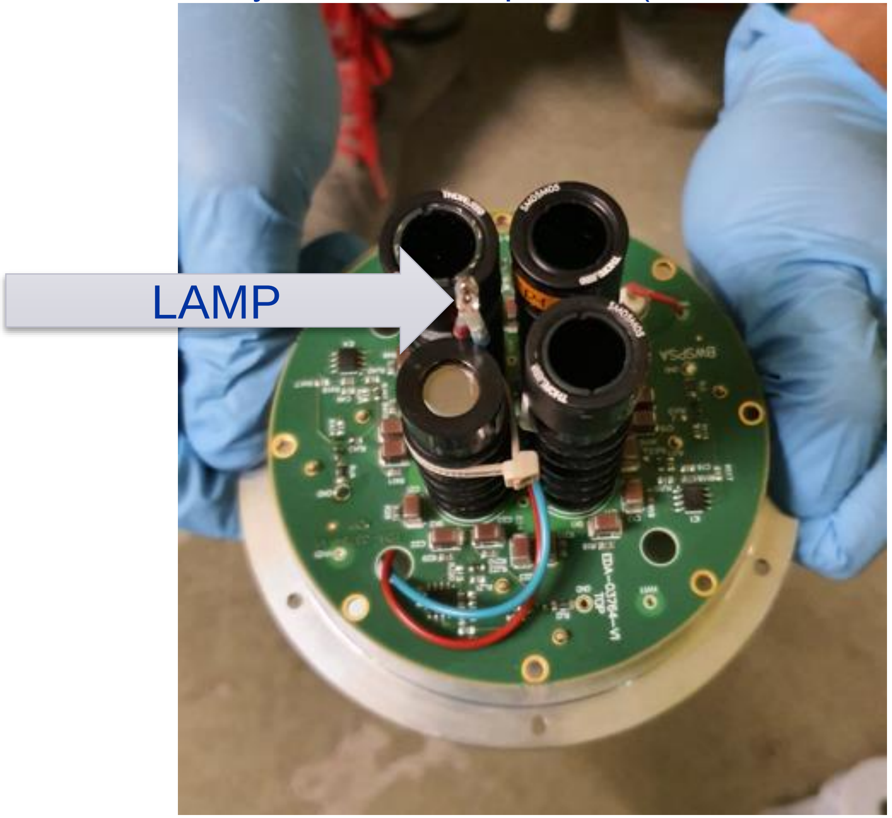
Motion reproducibility check after run2022

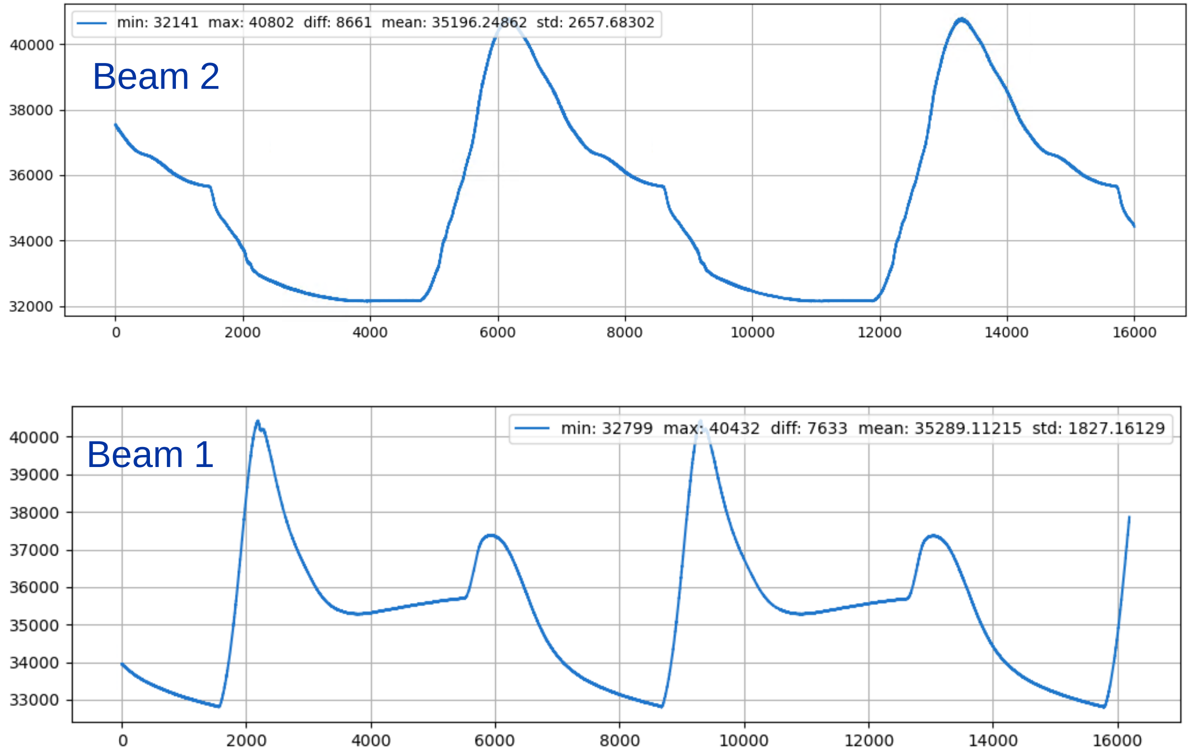
- **Motion instability check, run 2022, few scanners in the PS and SPS. Few thousand scans on top of each others, the system is highly reproducible.**



IST procedure: PMT assembly check using a lamp

MPMT incandescent lamp pulsing at 20Hz
seen by the “slow” acquisition (inside the drive)





Two example of one photomultiplier response to the lamp stimulation

Some beam measurements

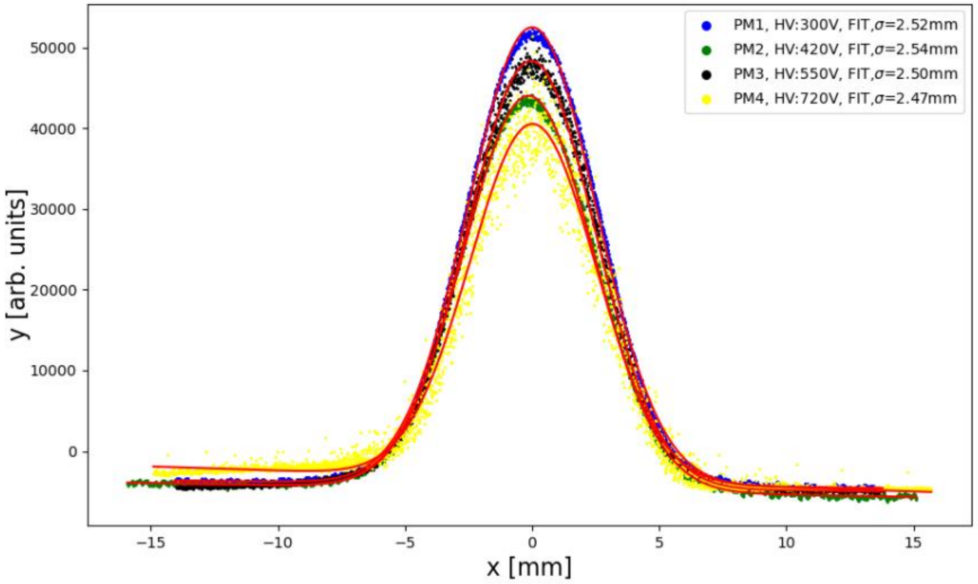


Figure 14: PSB horizontal profile of a LHC25 beam as measured by one of the LIU BWS.

IBIC 2022 – ASSESSING THE PERFORMANCE OF THE NEW BEAM WIRE SCANNERS FOR THE CERN LHC INJECTORSS. Di Carlo and al.

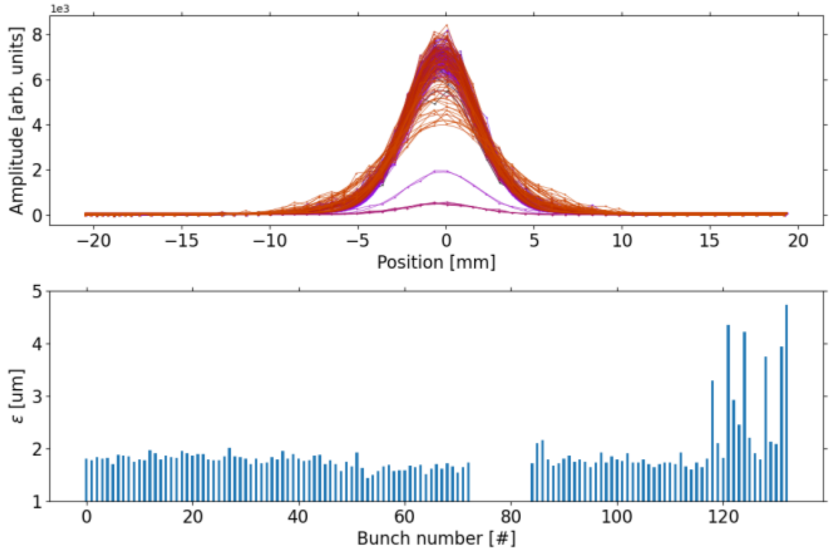
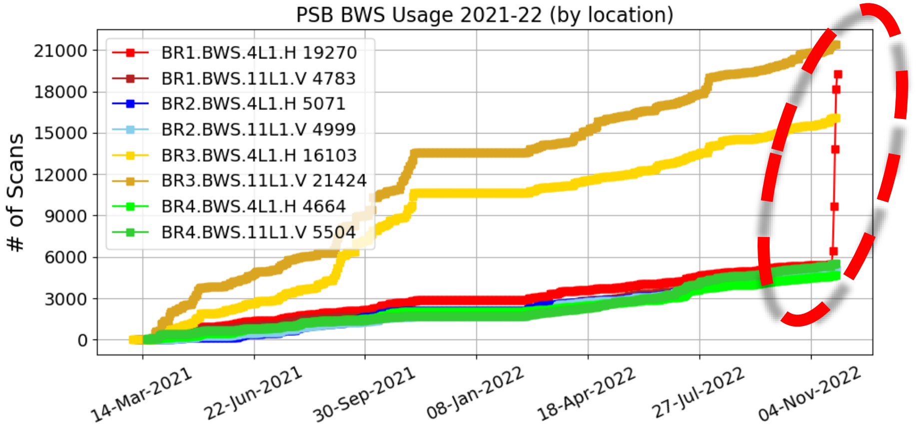
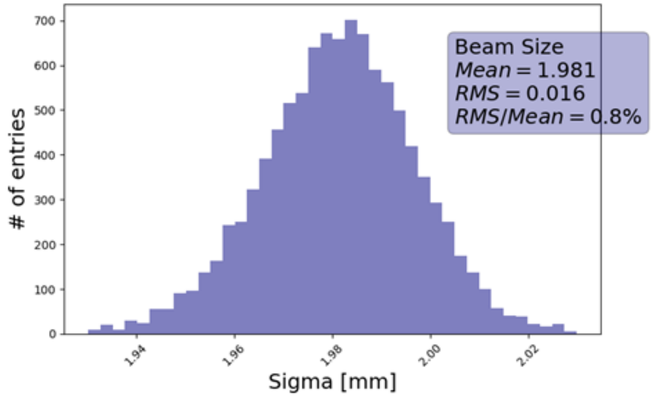


Figure 5: Top: SPS profiles of bunches separated by 25ns. Bottom: corresponding bunch-by-bunch emittances.

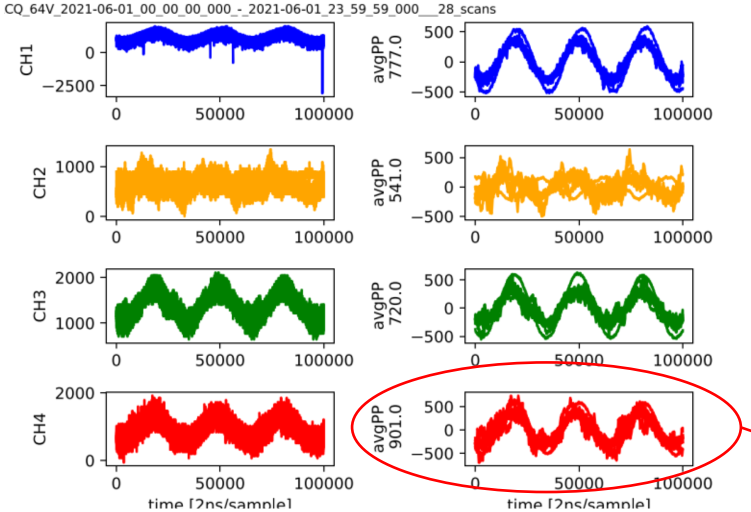


- End of the run 2022: 14k scans in 3 days on R1 Horizontal
- Proved **system reliability** and **beam reproducibility**



Average distribution of 10K out scans

Run 2021 Noise analysis



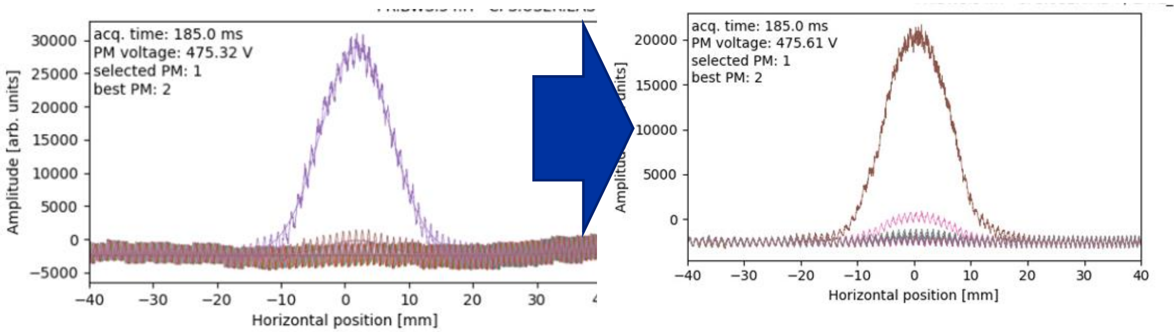
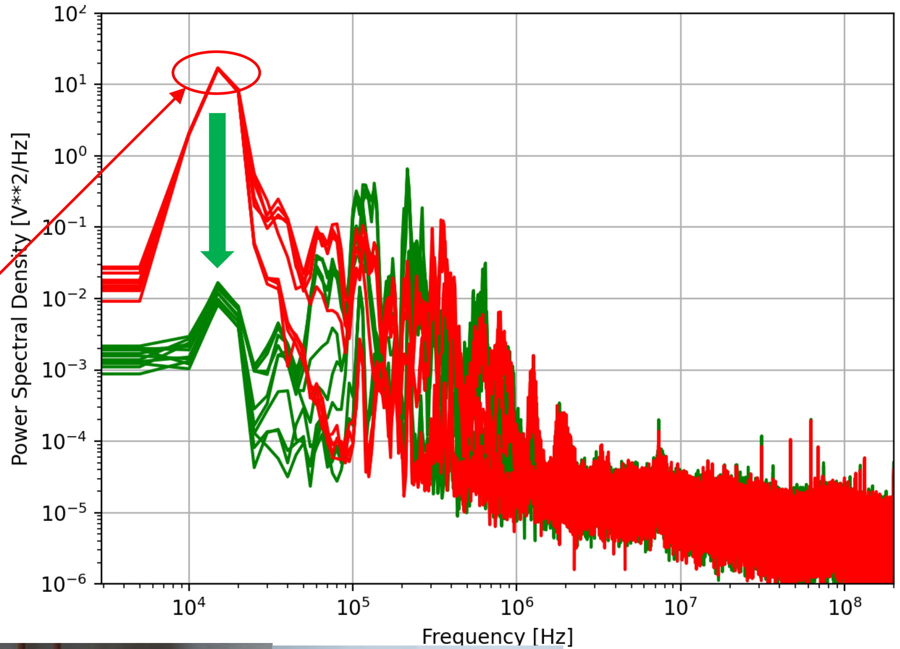
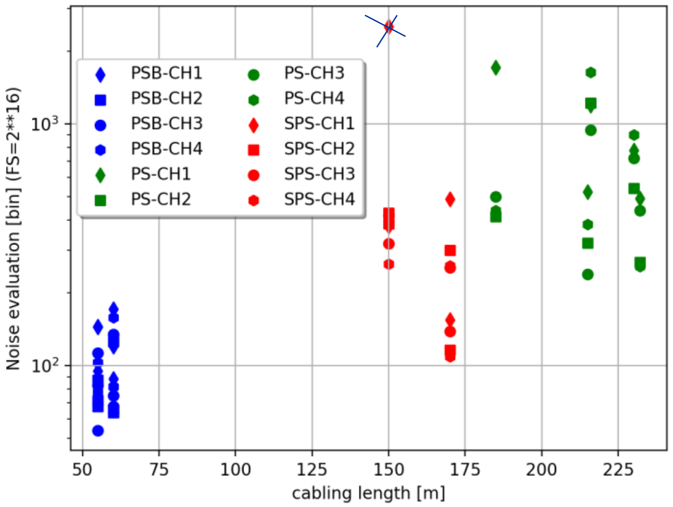


Table 1: LIU BWS name (N), accelerator (A), cabling le [m] (L), trajectory reproducibility error [mrad/s] (TRE), PMT noise [bin] (N1) noise @16 kHz [V^2/Hz] (N2).

N	A	L	TRE	N1	N2	scan*
R1H	PSB	60	21	171	0.02	2047
R2H	PSB	60	21	158	0.00	1361
R3H	PSB	60	697	88	0.00	4528
R4H	PSB	60	21	133	0.00	1572
R1V	PSB	55	232	144	0.01	1681
R2V	PSB	55	85	145	0.00	1261
R3V	PSB	55	63	95	0.00	6499
R4V	PSB	55	845	126	0.01	1431
54H	PS	185	63	1706	44.1	2866
64V	PS	230	63	901	8.04	2797
65H	PS	232	106	492	1.04	1028
68H	PS	215	21	522	2.15	331
85V	PS	216	85	1634	19.2	497
41677V	SPS	170	169	487	0.36	4517
41678V	SPS	170	63	155	0.12	325
51637H	SPS	150	1373	378	0.63	2040
51638H	SPS	150	42	2526	0.88	1095

*Total of 35'876 scans (up to 01.09.2021)

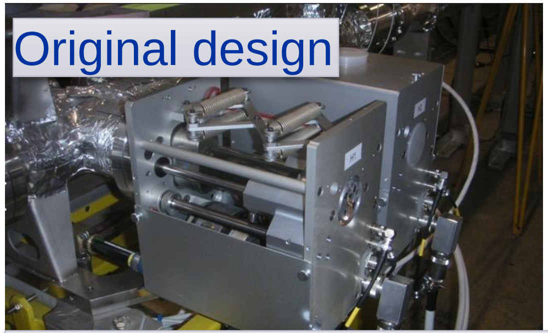




Promising test with Nanocrystalline toroidal ferrites from VAC (Thanks to R. Ruffieux)

LHC development

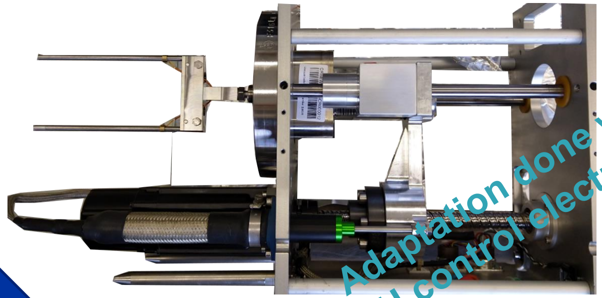
LHC BWS mechanism adaptation for the electronics



- DC motor (60V, 0.31Nm)
- Belt transmission
- Friction based translation
- Springs compensate forces against vacuum

LS2

'Hybrid' system
Linear prototype compatible with existing vacuum part

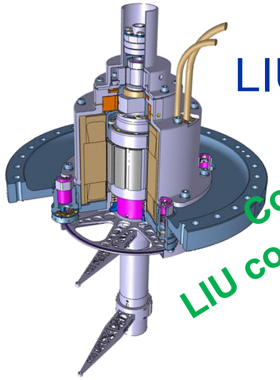


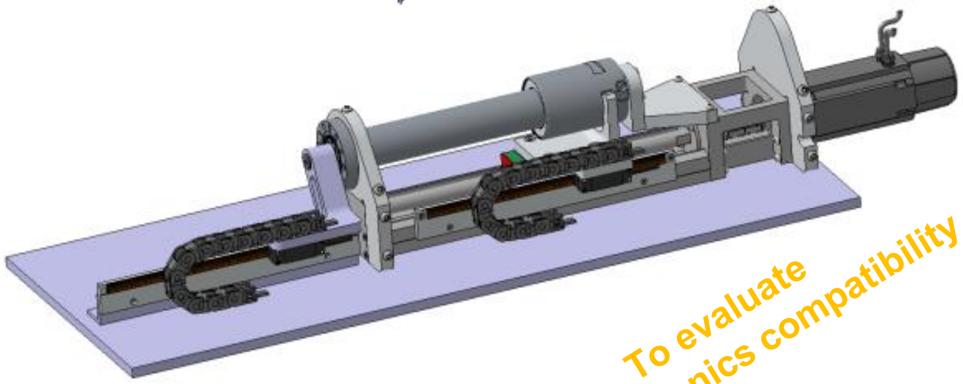
Changes for LIU compatibility
- Brushless motor (320V, 3 Nm)
- Resolver
- Lead screw translation
- LIU connectors

Input from ML (D. Gudkov)
- Direct drive
- locking safety brake
- Lead screw spec and position
- Mobile part design
- Springs replaced by frictions

LS3

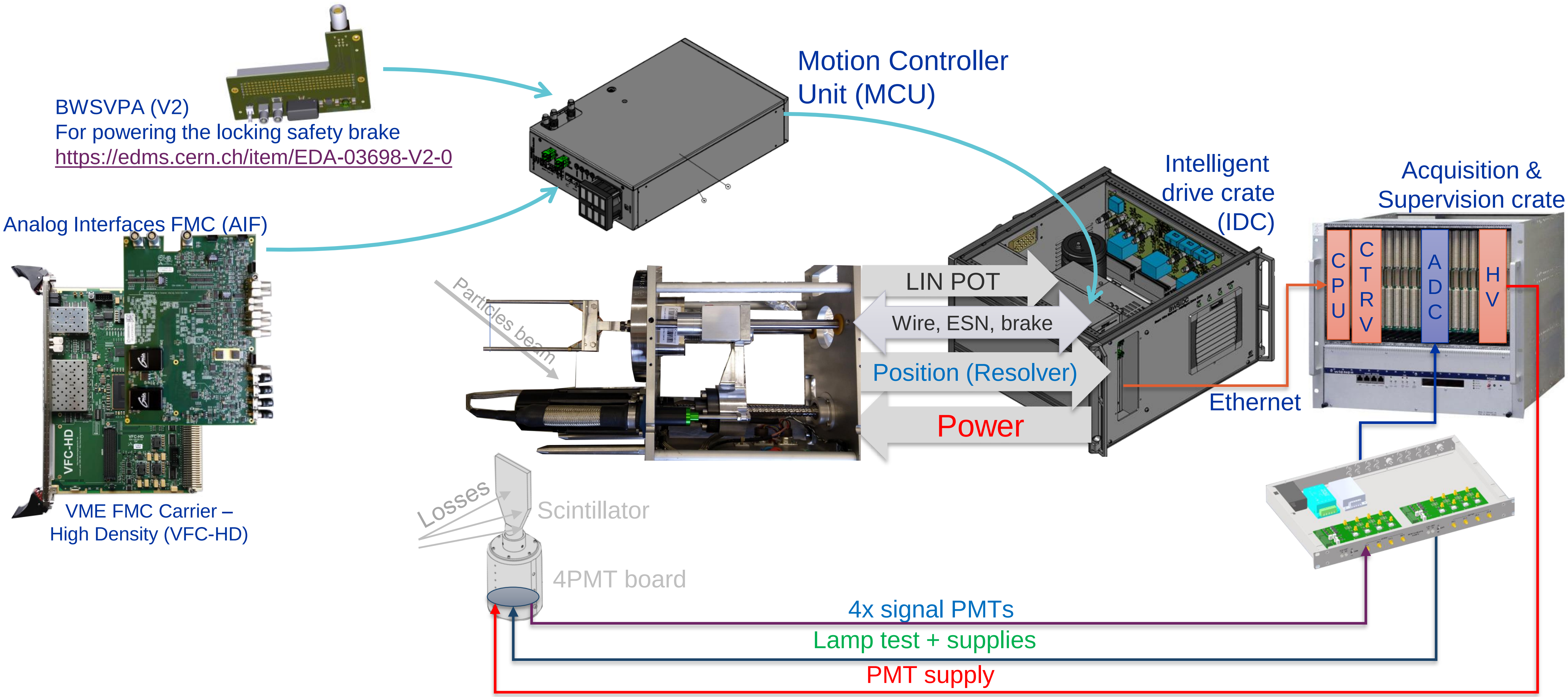
Options for the electro-mechanical consolidation





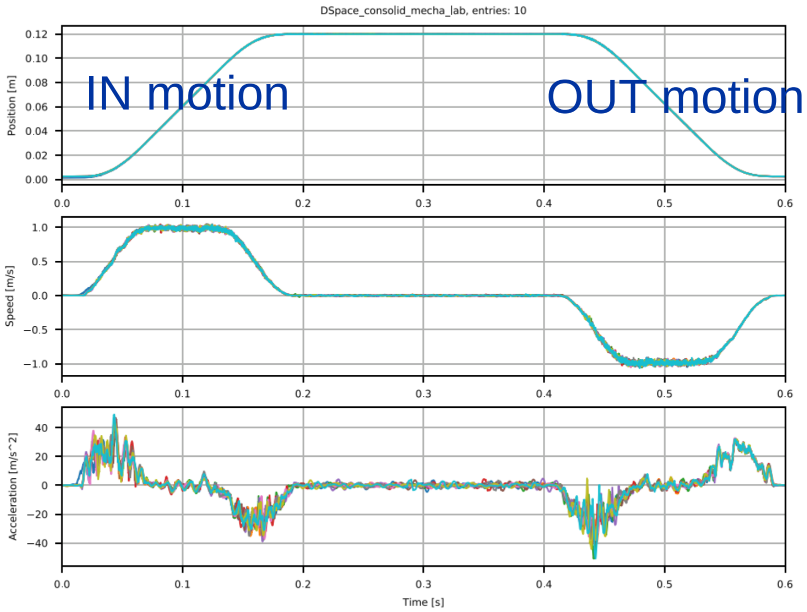
Bellow less new design

LHC hybrid prototype with LIU electronics

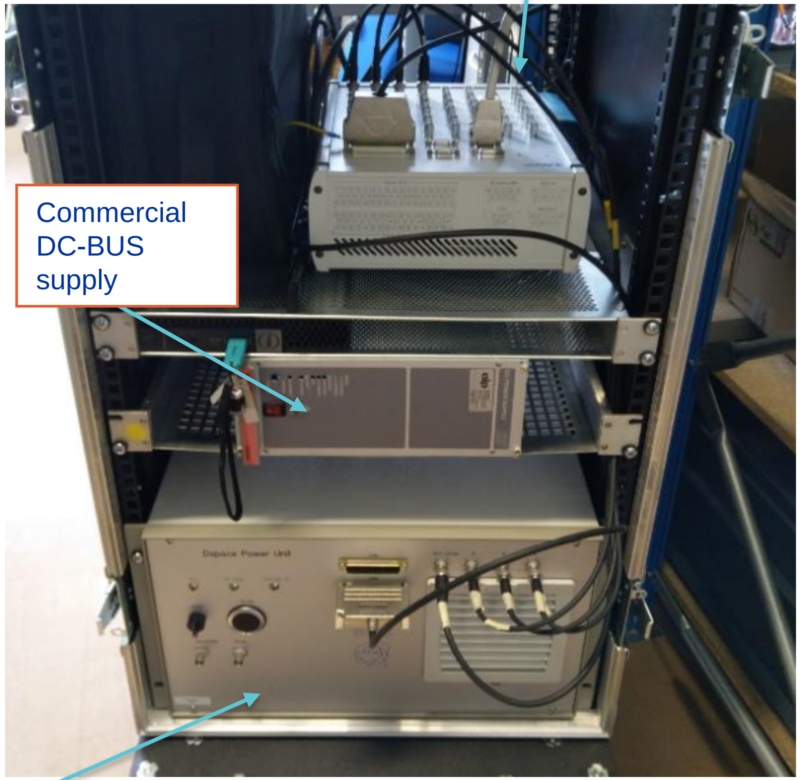


LHC consolidation prototype ‘hybrid’

Data from the motor resolver



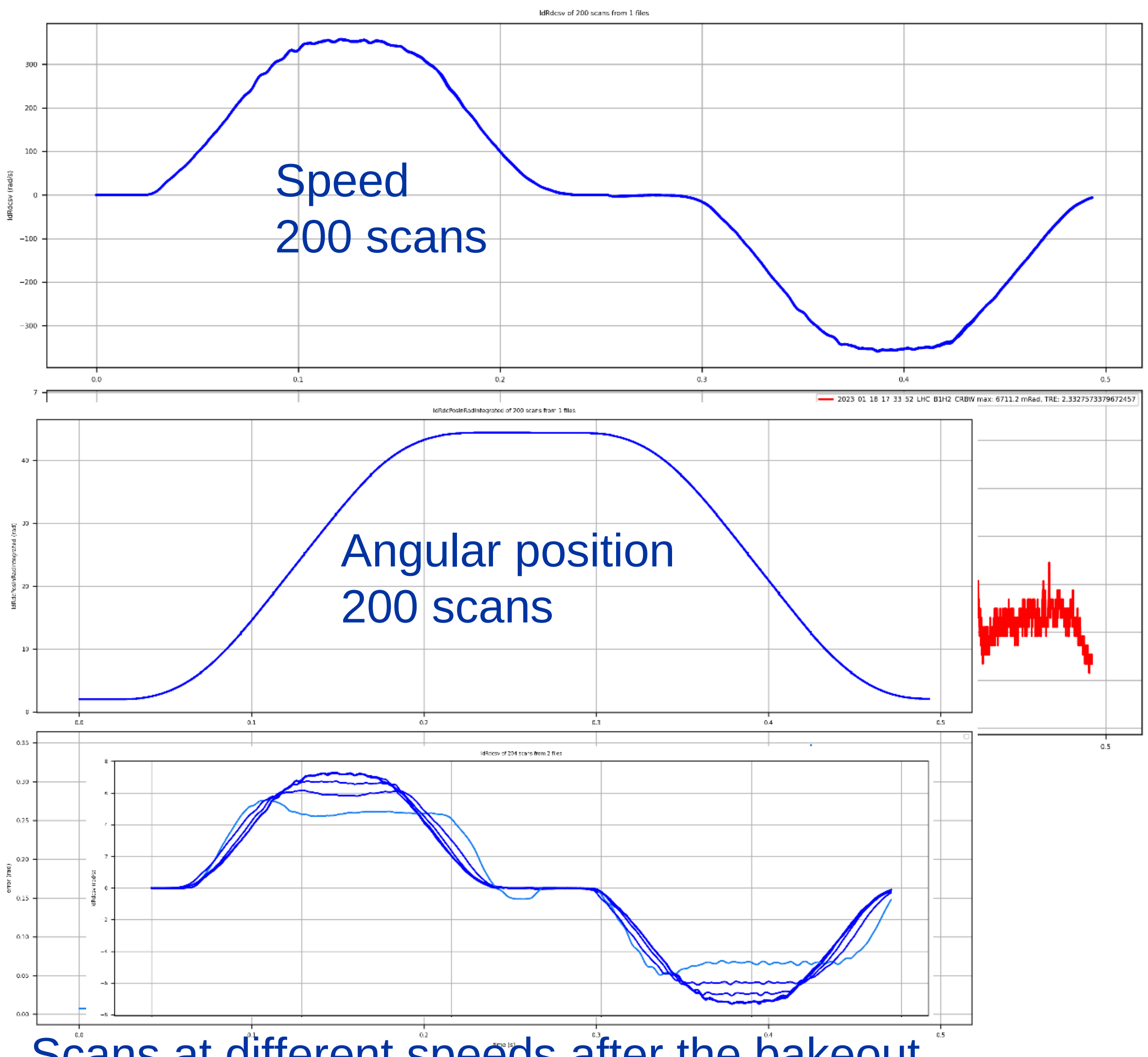
1. Dspace control system (running Simulink models)



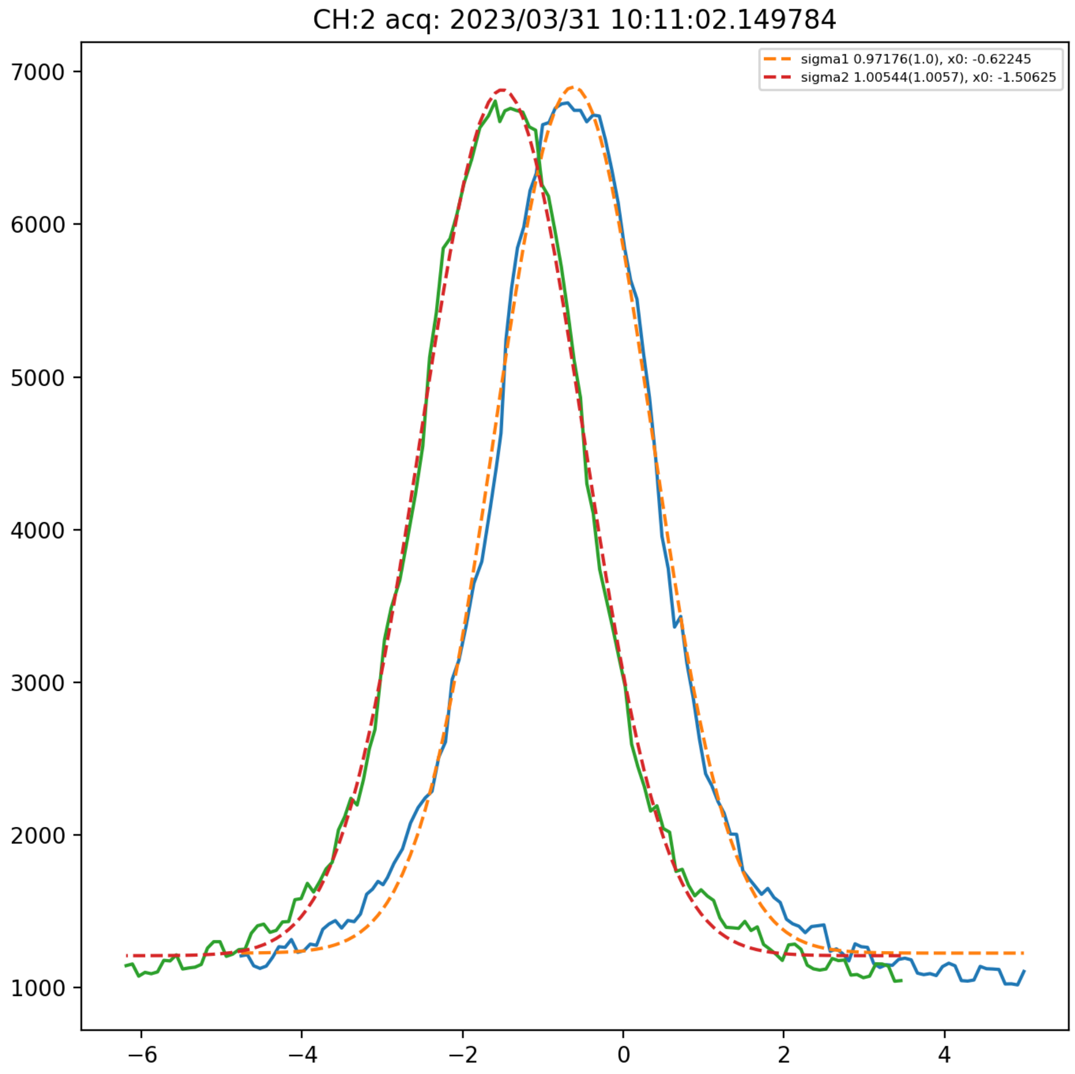
Commercial DC-BUS supply

LIU BWS Inverter

BEAM 1 – Prototype B1H2 – preliminary results

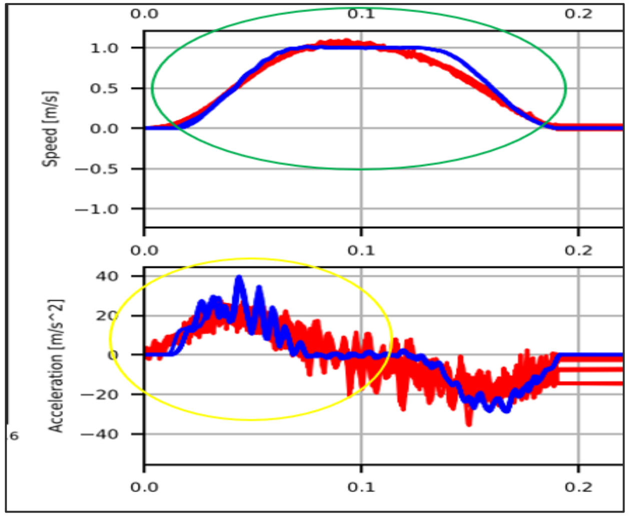


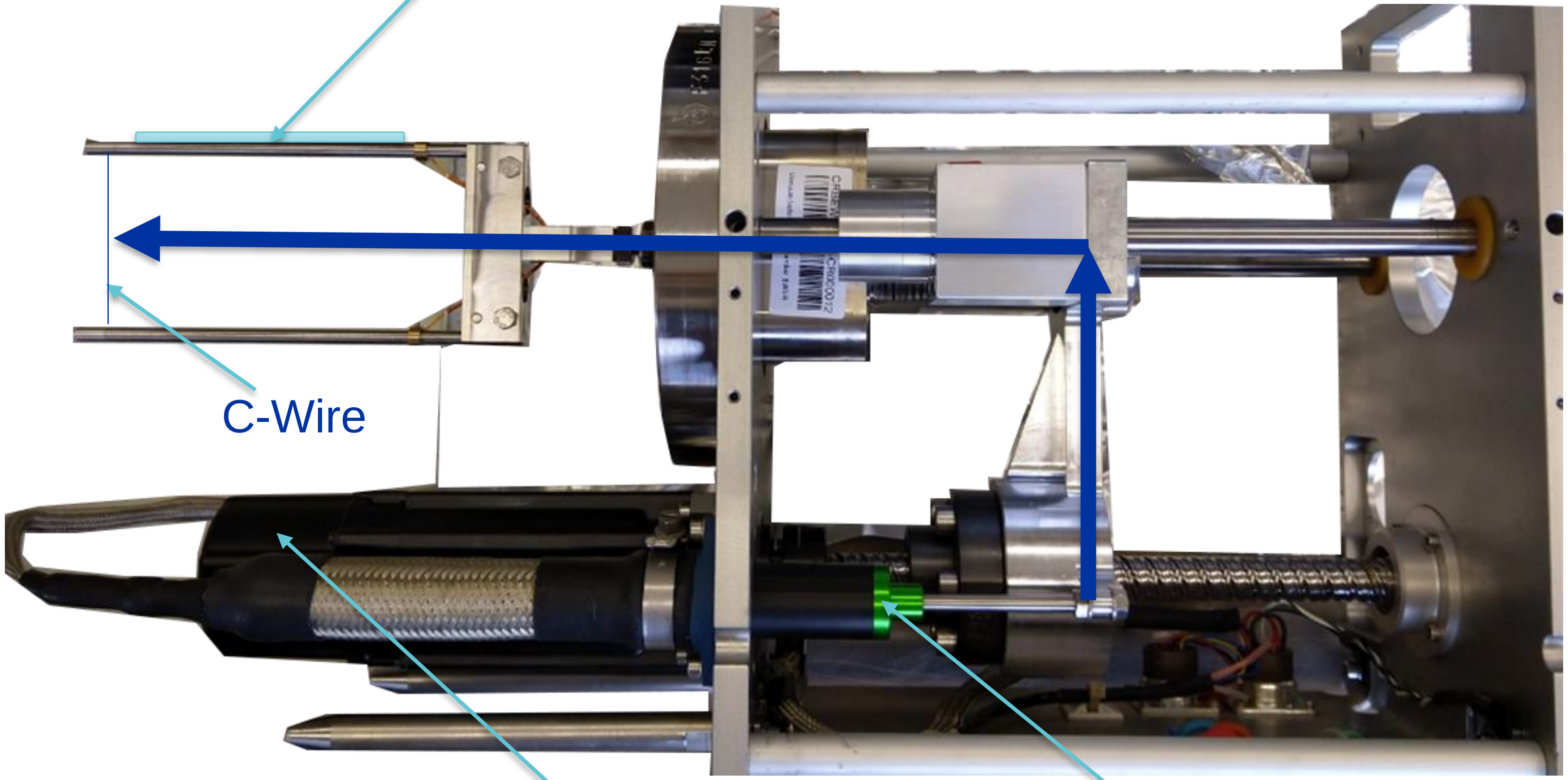
Scans at different speeds after the bakeout



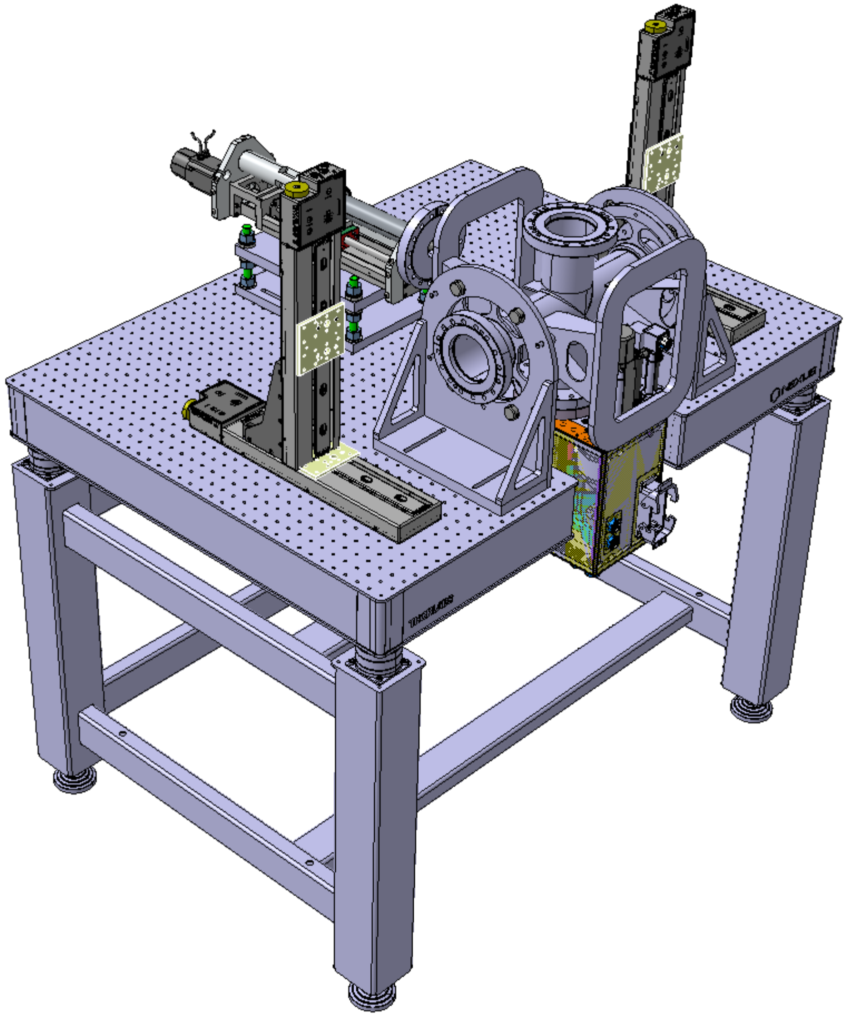
Laboratory performance assessment platform

- C-Wire position is <u>indirectly</u> measured by the potentiometer/resolver
- Effect of driving forces to the wire dynamics unknown
- A laser can be used to detect the C-Wire position during displacement
- The future lased based test bench will assess the C-Wire position at a <u>determined (pot/Res) position</u> and with a <u>predefined motion dynamics</u>

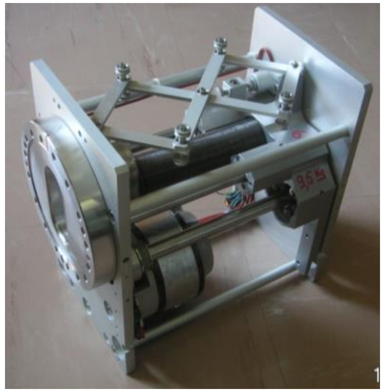




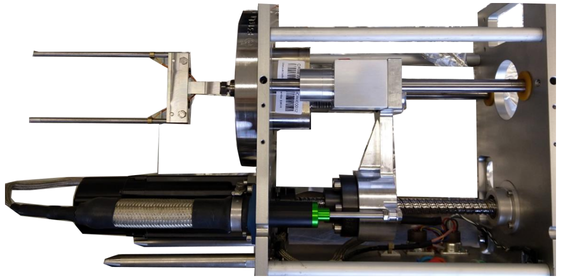
Linear calibration bench starting in 2023



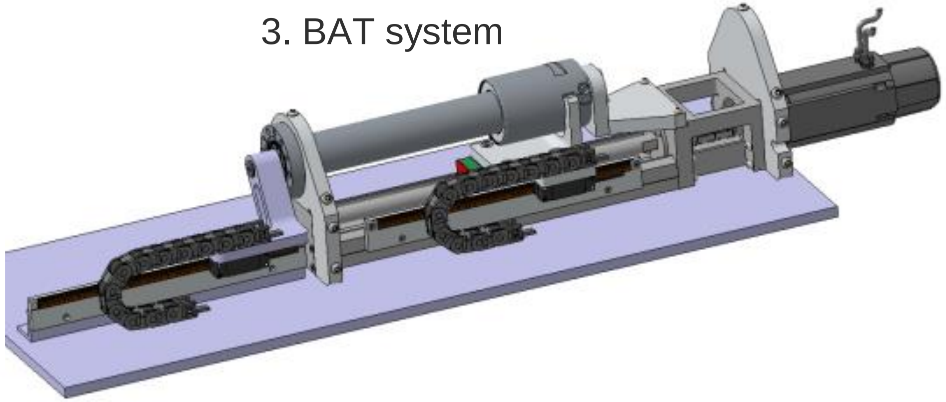
1. LHC linear 2008 type



2. Hybrid system - PROTO#3



3. BAT system



4. Linear motor-based actuator (2024?)

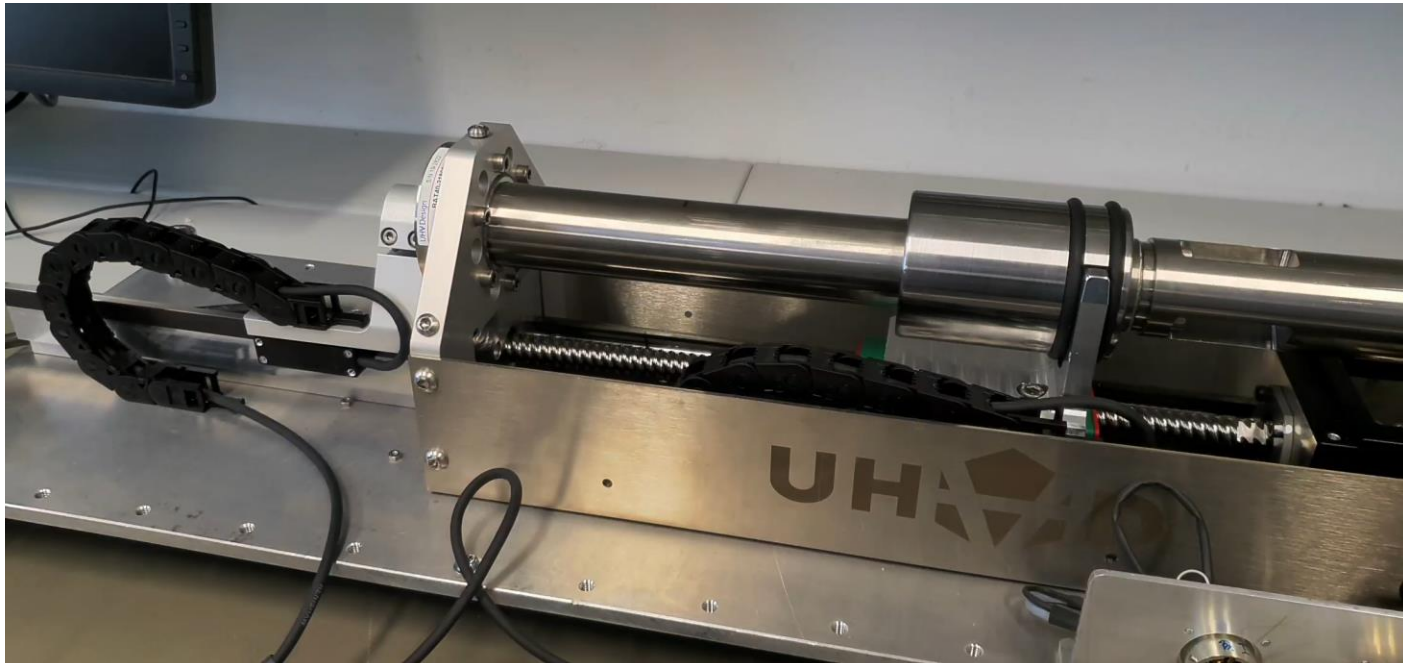
Bellow free – motion tests March 2023

- Bellow free coupling from the industry using ‘passive’ link with permanent magnets, recommended for 0.5m/s but could achieve 1m/s

- Tests on-going in the lab to model this coupling and minimize motion vibrations

- Relatively heavy and not build for high speed

- Project planned end of 2023 for custom design, optimization of the system weight and magnetic fields for high speed



Summary

- Design and control of fast actuators at CERN for use on wire-scanner systems

- It involves multidisciplinary teams working together (physics, mechanics, electronics, control & software teams)

- The new generation of scanner was a large effort which was started in 2007 and in 2020, we installed 17 systems and still working on them (impedance in SPS)

- We achieve a maximum speed ~24 m/s (tangential) with wire precision determination in the order of 5um.

- Operation/beam study teams feedback is very positive.

- We took the option of building many parts of the system to tailor them for our particular use and for high performance.

- This in-depth knowledge is now being applied for the LHC design which will most probably be a linear mechanism to deal with machine impedance challenges

Thank you for your attention

References

[2003-RON] F. Roncarolo and al., “Cavity mode related wire breaking of the SPS Wire Scanners and loss measurements of wire materials”, Proceedings of PAC 2003.

[2012-SIR] J.L. Sirvent Blasco, “Design of an optical fibre based angular position sensor for wire scanners complying with ultra-high vacuum, high temperature and radiation conditions of the CERN´s accelerators”, Master thesis, 2012. https://cds.cern.ch/record/1491608

[2013-KOU] M. Koujili, “Design and construction of a new actuator for the LHC wire scanner”, Ph.D. dissertation, Feb. 2013. https://cds.cern.ch/record/2235683

[2013-EME] J. Emery, “BWS-Review-2013-Emery-Overview of current scanners and technical choices for a new wire scanner”, Review of the New CERN Fast Wirescanner, Apr. 2013. https://indico.cern.ch/event/229959

[2013-SAM] S. Samuelsson, “Mechanical optimisation of a high-precision fast wire scanner at CERN”, Master Thesis, 2013. https://cds.cern.ch/record/1595524

[2014-PIS] E. Piselli and al., “CERN-SPS Wire Scanner Impedance And Wire Heating Studies”, Proceedings of IBIC 2014.

[2014-GRO] C. Grosjean, “Motor and Break Design for the Wire Scanner”, Bachelor thesis, 2014. https://cds.cern.ch/record/2791364

[2015-MAC] M. Macchini, “Motion control design of a PMSM and FPGA implementation for the Beam Wire Scanner at CERN” , Master Thesis, Apr. 2015. https://cds.cern.ch/record/2021089

[2016-HER] J. Herranz Alvarez “Minimisation of the wire position uncertainties of the new CERN vacuum wire scanner,” Presented 29 Feb 2016, Ph.D. dissertation, Jan. 2016. https://cds.cern.ch/record/2156989

[2017-EME] J. Emery and al., “Design and validation methodology of the control system for a particle beam size measurement instrument at the cern laboratory”, American Control Conference (ACC), 2017, IEEE, 2017, pp. 4221–4228. doi: /10.23919/ACC.2017.7963604

[2017-VEN] R. Veness, “Status and Summary of the Impedance Results for the LIU Wire Scanner”, LIU BWS Mechanics Production Readiness Review, Mar. 2017. https://indico.cern.ch/event/618262

[2019-EME] J. Emery and al., “A low fluctuation control strategy for pmsm direct drive system targeting particle beam instrumentation application,” in 2019 IEEE Conference on Control Technology and Applications (CCTA), IEEE, 2019, pp. 437–443. doi: 10.1109/CCTA.2019.8920688.

[2023-DI] S. Di Carlo and al.,“Commissioning of the LHC Injectors Upgrade fast wire scanners and first experimental results”, NIMA, Volume 1053, August 2023, 168328 https://authors.elsevier.com/c/1h2hXcPqbosek

home.cern