Pre-alignment measurement uncertainty evaluation and thermal influences

OUTLINE

- ✓ Accelerator Pre-alignment background
- ✓ Uncertainty and GUM supplement 1
- ✓ PACMAN pre-alignment budgeting
- ✓ CMM uncertainty modeling
- ✓ Thermal uncertainty compensation and modeling
- ✓ First stochastic modeling results
- ✓ Interim conclusions and future work

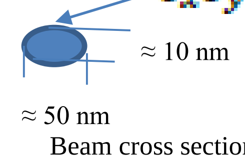
by

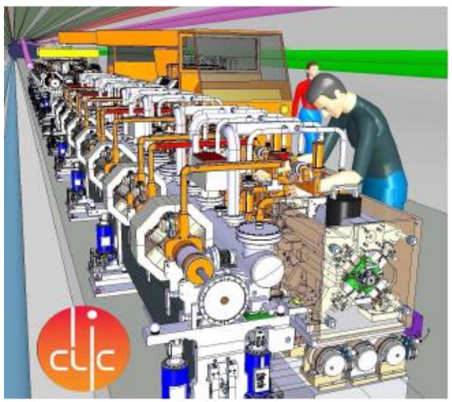
Iordan Doytchinov

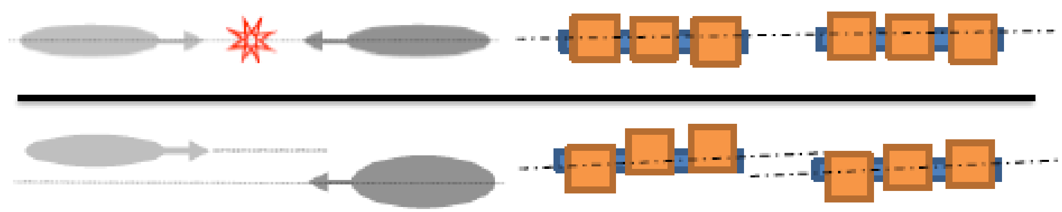
Background – accelerator alignment

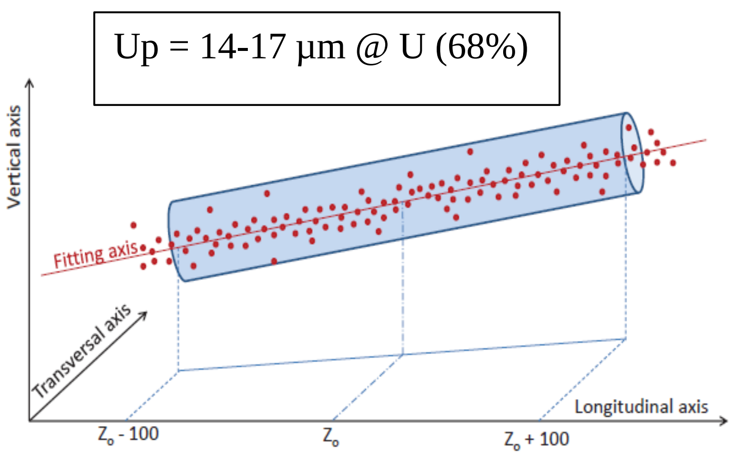
$$N_{colision\ event} \propto L\ (Luminosity)$$

$$L\ (Luminosity) \propto \frac{f_{rep} N_e^2}{\sigma_x \sigma_y}$$







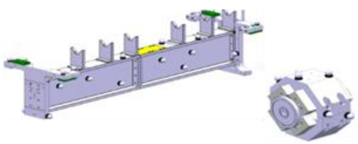


"Micron level stability/alignment of the two-meter repetitive modules constituting the two main linacs is one of the most important requirements to achieve the luminosity goal for the CLIC collider" [F. Rossi, K Osterberg, I . Kossyvakis, D. Gudkov et all, IPAC 2013]

Pre-alignment, error budgeting state of art

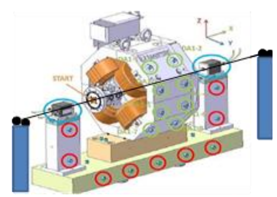
…In general, the uncertainties reported here have to be interpreted in a loose sense as the best-scenario standard deviation over repeated measurements of the same object. A rigorous assessment of the absolute accuracy, involving systematic comparisons with a reference instrument, has not been carried out in most of the published cases …

L. Bottura, M. Buzio, SPauletta, N Smirnov: Measurement of magnetic axis in accelerator magnets: comparison of methods and instruments. CERN, TE Department 2006

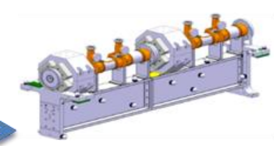


MPEE as error index

Repeatability as one of the index of error



Repeatability or MPEE



$U_{pre-alignment}$ State of art

$U_{pre-alignment}$ ≈ 20µm (not full error budgets following GUM Supplement 1)

Pre-alignment, error budgeting state of art

Accelerator			Magnet									Instrumentation		Uncertainty			
Institute	Machine	L [m]	Type	Technology	Lm [m]	Aperture [mm]	I [A]	dB/dr [T/m]	B_{max} [T]	T [K]	Moves	Magnetic	Survey	Axis to sensor [µm]	Sensor to ref. [µm]	Total [µm]	Ref.
BNL	**RHIC**	3862	quad	superconducting	1.13	80	5000	71.00	5.7	4.5	no	Colloidal Cell	Theodolite	40	25	47	[2]
BNL	**RHIC**	3862	quad	superconducting	1.13	80	10	0.14	0.01	300	no	Harmonic Coil	Theodolite	25	25	35	[2]
BNL	**SASE**	-	undulator	permanent	4.00	6	-	-	0.8	300	no	Pulsed Wire	Interferometer	10	8	13	[3]
KEK	**B-factory**	3016	quad	resistive	0.40	110	500	10.20	1.12	300	yes	Harmonic Coil	Laser Tracker	15	5	16	[4]
SLAC	**LCLS**	3000	quad	resistive	0.05	12	n.a.	15.00	0.18	300	no	Hall Sensor	CMM	8	1	8	[5]
SLAC	**LCLS**	3000	undulator	permanent	3.40	12	-	-	1.3	300	no	Hall Sensor	CMM	8	15	17	[6]
SLAC	**LCLS**	3000	quad	resistive	0.15	12	n.a.	12.00	0.14	300	yes	Vibrating Wire	CMM	18	10	21	[7]
JASRI	**SPring-8**	1436	quad	resistive	0.64	85	n.a.	17.40	1.48	300	yes	Harmonic Coil	Laser + CCD	2	10	10	[8]
SLAC	**FFTB**	3200	quad	resistive	0.46	23	220	83.00	1.91	300	no	Vibrating Wire	CMM + Micrometer	4	15	15	[9]
MIT-Bates	**SHR**	190	quad	resistive	0.28	35		0.50	0.02	300	no	Harmonic Coil	Theodolite	*26*	*43*	51	[10]
FNAL	**LHC**	26660	quad	superconducting	8.00	63	11850	215.00	13.55	4.5	no	Stretched Wire	Laser Tracker	33	50	60	[11]
FNAL	**LHC**	26660	quad	superconducting	8.00	63	2	0.04	0.00	300	no	Stretched Wire	Laser Tracker	33	50	60	[11]
CERN	**LHC**	26660	quad	superconducting	8.00	40	11850	223.00	8.92	1.9	no	SSW	Laser Tracker	5	80	80	[12]
CERN	**LHC**	26660	quad	superconducting	8.00	50	2	0.04	0.00	300	no	SSW	Laser Tracker	20	80	82	[13]
CERN	**LHC**	26660	quad	superconducting	8.00	50	0.5	0.01	0.00	300	no	AC Harmonic Coil	Laser Tracker	51	80	95	[14]
Cornell	**CESR**	768	quad	superconducting	7.50	67	n.a.	13.00	0.87	n.a.	no	Vibrating Wire	Laser Tracker	10	51	52	[15]
Cornell	**CESR**	768	solenoid	superconducting	0.30	200	n.a.	-	0.008	300	no	Vibrating Wire	Laser Tracker	10	25	27	[16]
CNRS/CEA	**SOLEIL**	354	quad	resistive	0.46	66	n.a.	23.00	1.52	300	yes	Harmonic Coil	(mech. tol.)	*5*	*30*	30	[17]
ELETTRA	**SR**	259	quad	resistive	0.49	75	n.a.	20.60	1.55	300	yes	Harmonic Coil	Telescope	*5*	*25*	25	[18]
CERN	**LEP**	26660	quad	resistive	1.55	59	n.a.	9.70	0.57	300	yes	Harmonic Coil	Laser + PSD	20	50	54	[19]

L. Bottura, M. Buzio, SPauletta, N Smirnov: Measurement of magnetic axis in accelerator magnets: comparison of methods and instruments. CERN, TE Department 2006

Importance of the right decision

“There was no way, without full understanding, that one could have confidence that conditions the next time might not produce erosion three times more severe than the time before..... .“

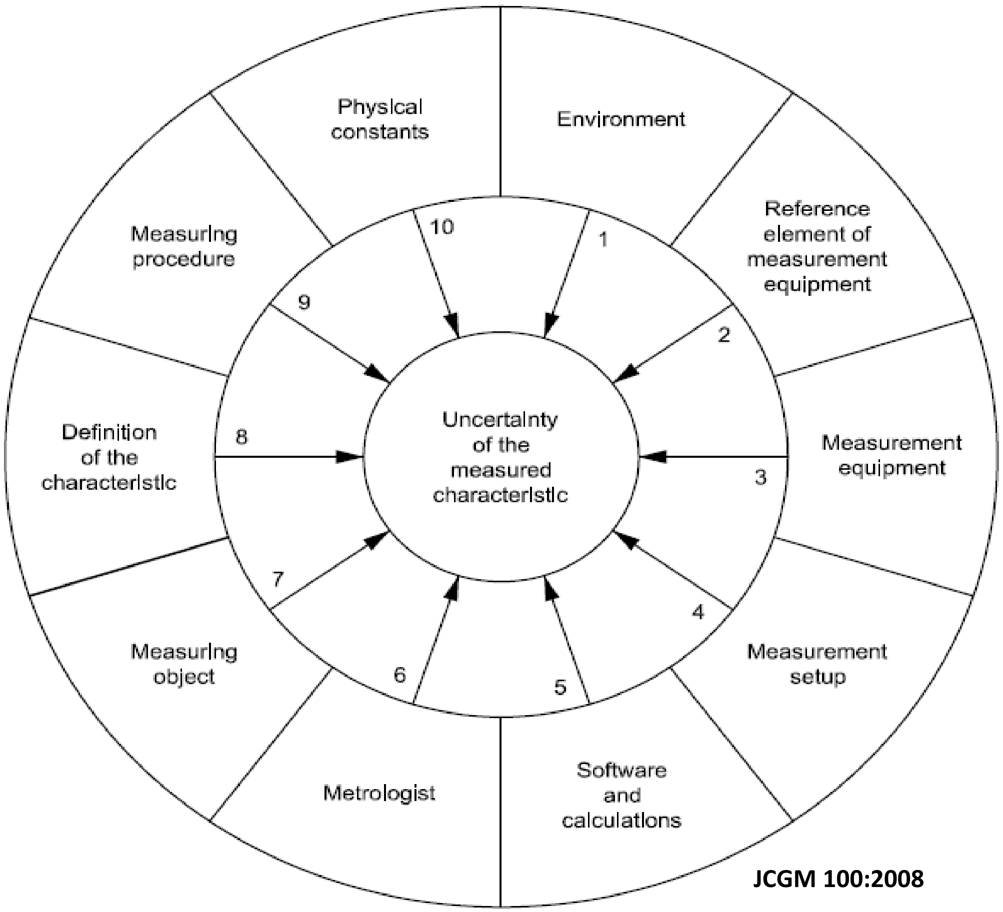
"For a successful technology," Feynman concluded, "reality must take precedence over public relations, for nature cannot be fooled.“

Feynman, Richard P. (1986) Appendix F - Personal Observations on Reliability of Shuttle

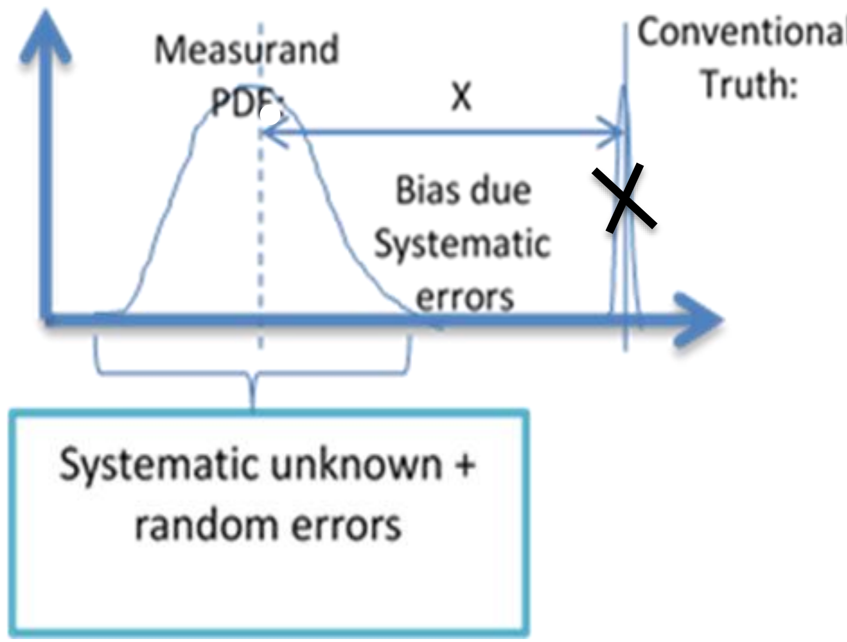
The Uncertainty in Simple Words

Uncertainty (as a quantitative measure such as standard deviation, always positive):

An estimate characterizing the range of values within which the true value of a measurand lies (VIM 1st ed., 1984, entry 3.09).



JCGM 100:2008

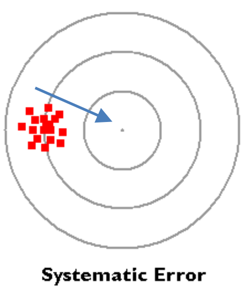


The GUM Supplement 1 Method

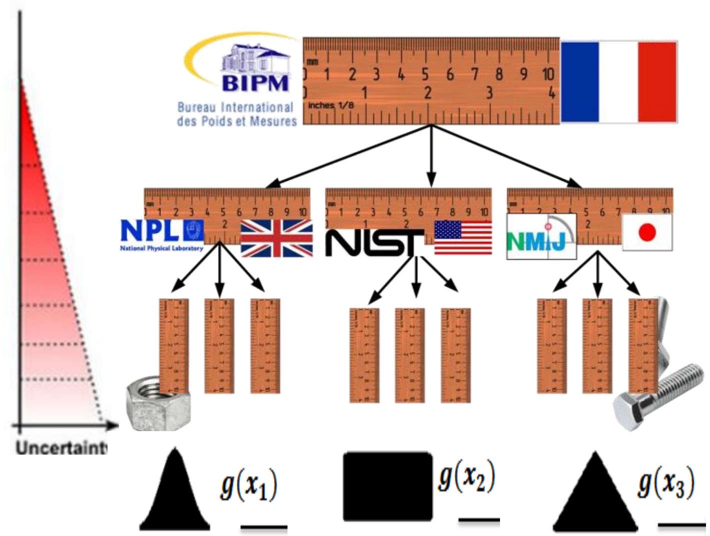
1) Quantify all systematic errors and compensate for them

2) Quantify all uncertainty sources with Probability Density functions

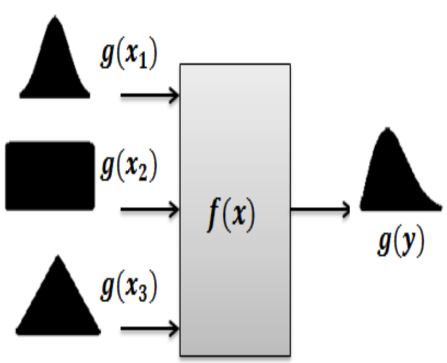
3) Propagate all PDF's trough a virtual model of the pre-alignment with Monte carol like methods to provide Probability density function of the pre-alignment Uncertainty



1)

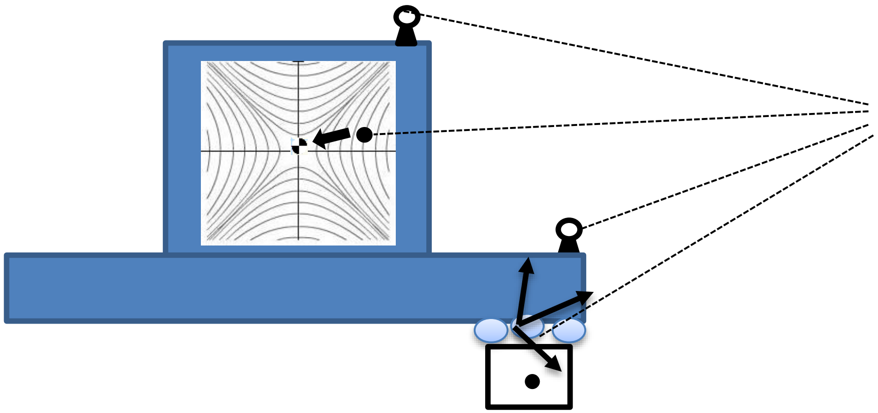


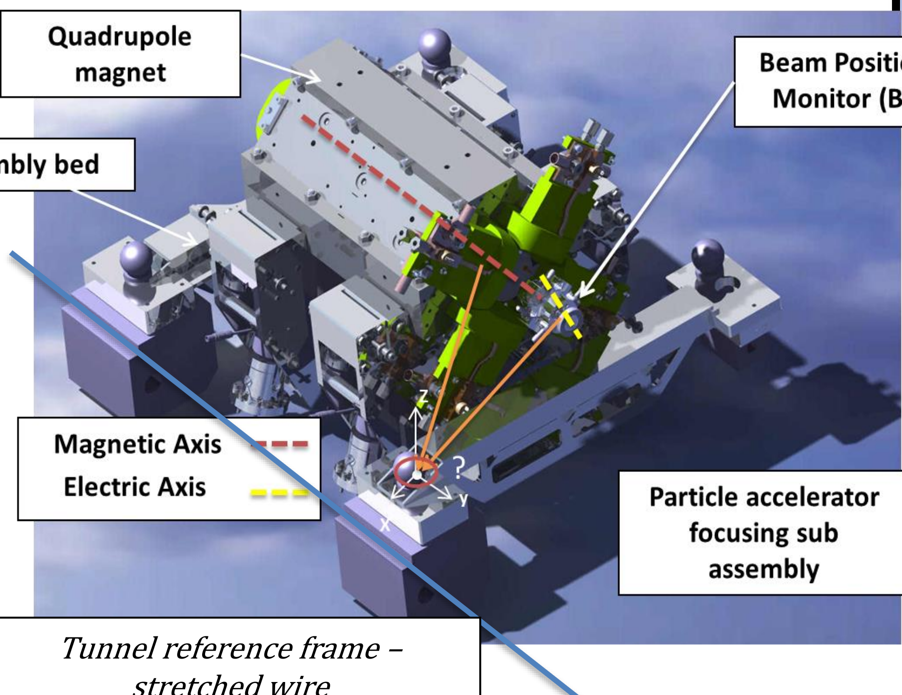
2)

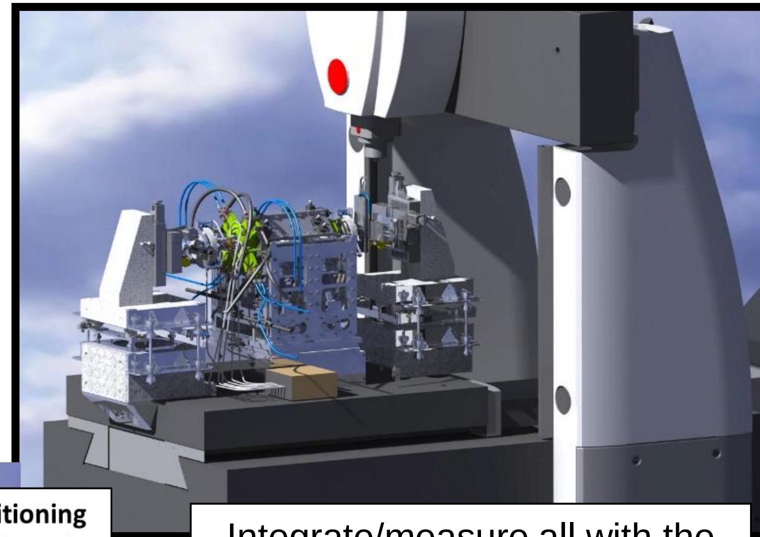


3)

PACMAN pre-alignment





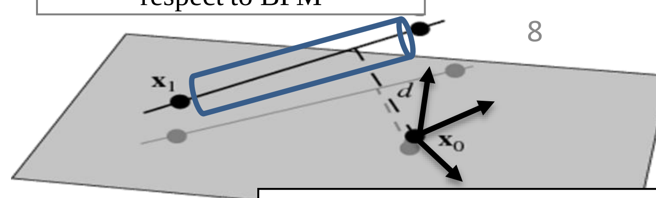


Integrate/measure all with the CMM

Upm= 12 µm @ U (68%) with respect to magnetic axis

Upb = 7 µm @ U (68%) with respect to BPM

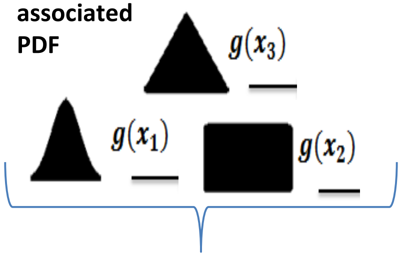
8



x0 - Assembly reference coordinate frame

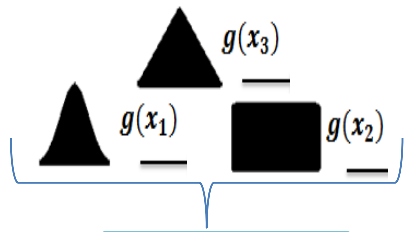
PACMAN uncertainty budgeting

Input parameters and their associated PDF



CMM + tactile probe uncertainties
Virtual CMM model

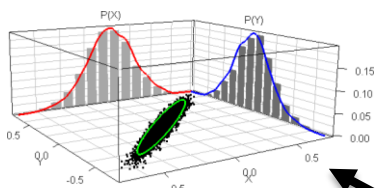
≈ micron range (below 10, 5 microns for MPEE



Magnetic measurement uncertainties

≈ micron range (below 5 microns)

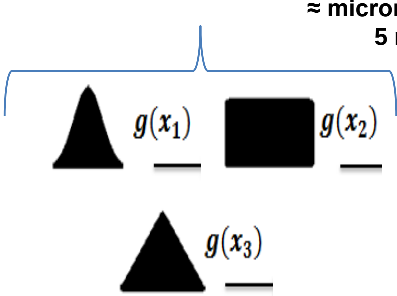
Um



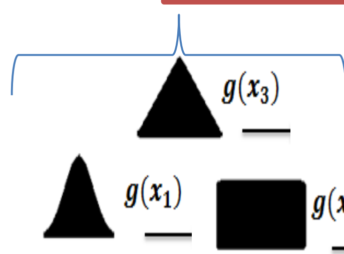
Final pre-alignment uncertainty

Non-contact head measurement uncertainties

≈ micron range (below 5 microns)



Magnetic axis and fiducials environmental drift uncertainties

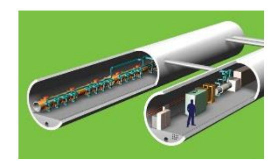


Create virtual pre-alignment model that can estimate "Measurement Specific" uncertainty

Being able to provide Up statement for each specific measurement sequence, conditions, assembly design measured.

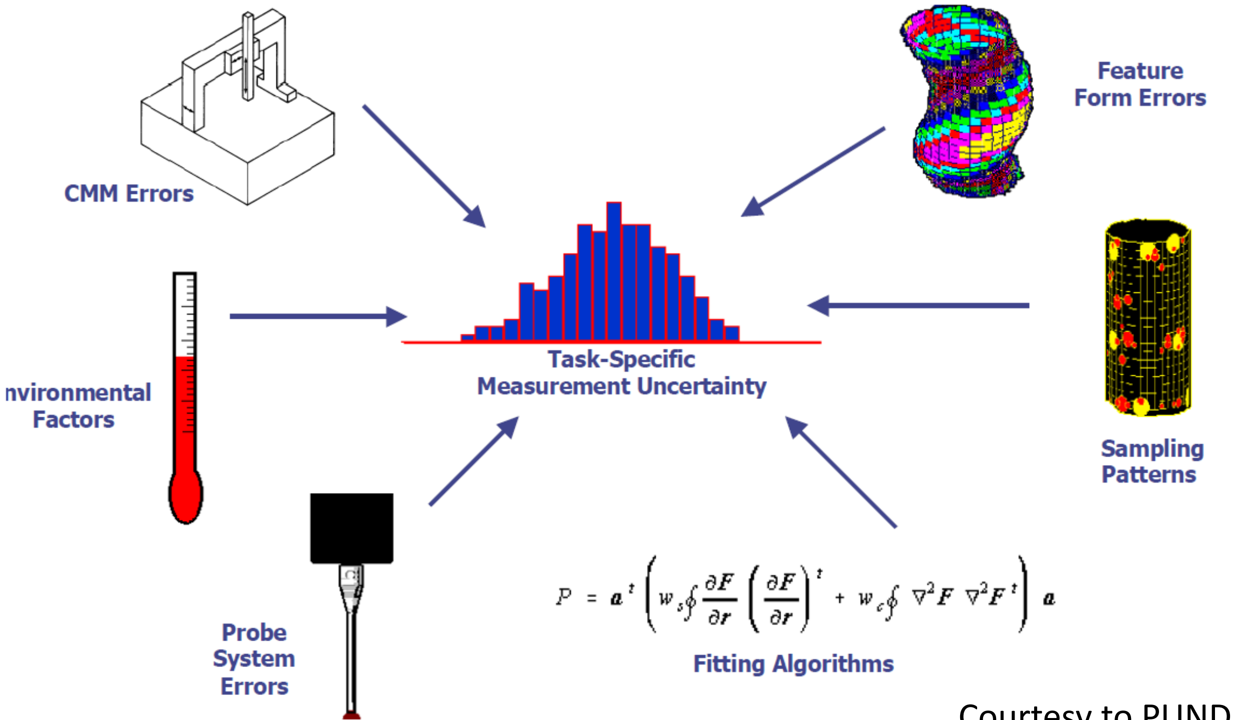
Thermal issues = biggest error contributor and uncertainty source! – up to 200 microns of thermal deformation of assembly for gradients of 25 C between metrology and tunnel conditions

CMM = 20 +- 0.1



Tunnel 40 C Air; 45 C Magnet

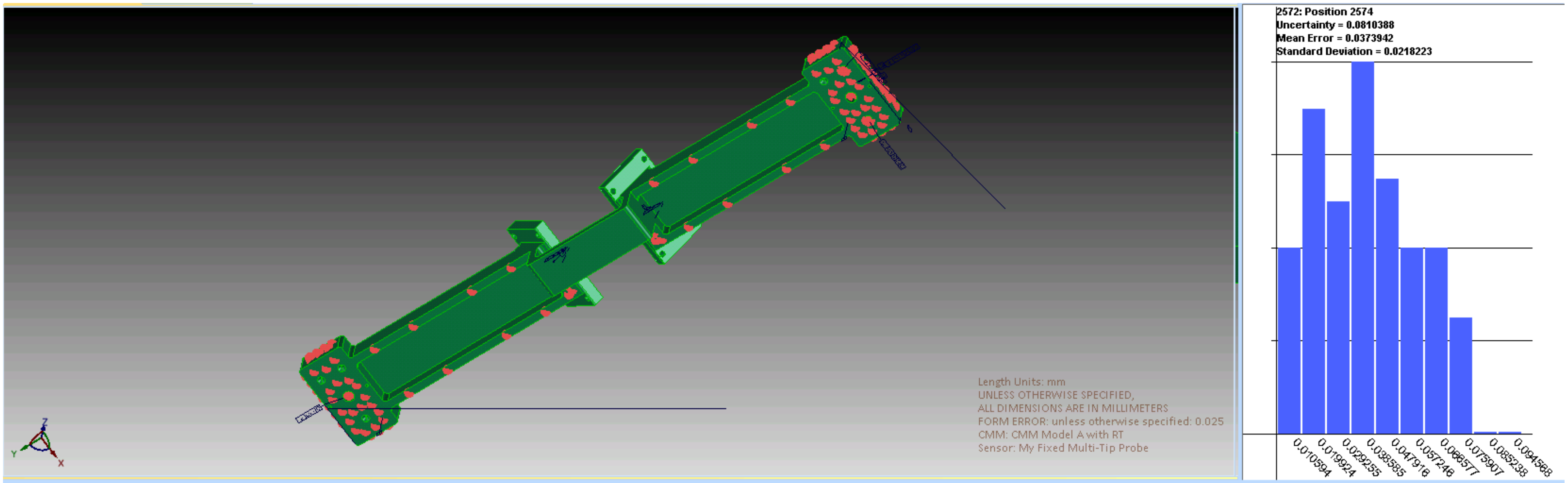
Task specific uncertainty modelling of CMM



Courtesy to PUNDITCMM ™

ISO 10360 or ASME B89.4.1 Performance tests done with tracable measurement artefacts

Task specific uncertainty modelling of CMM



Simulation

Simulation | Information

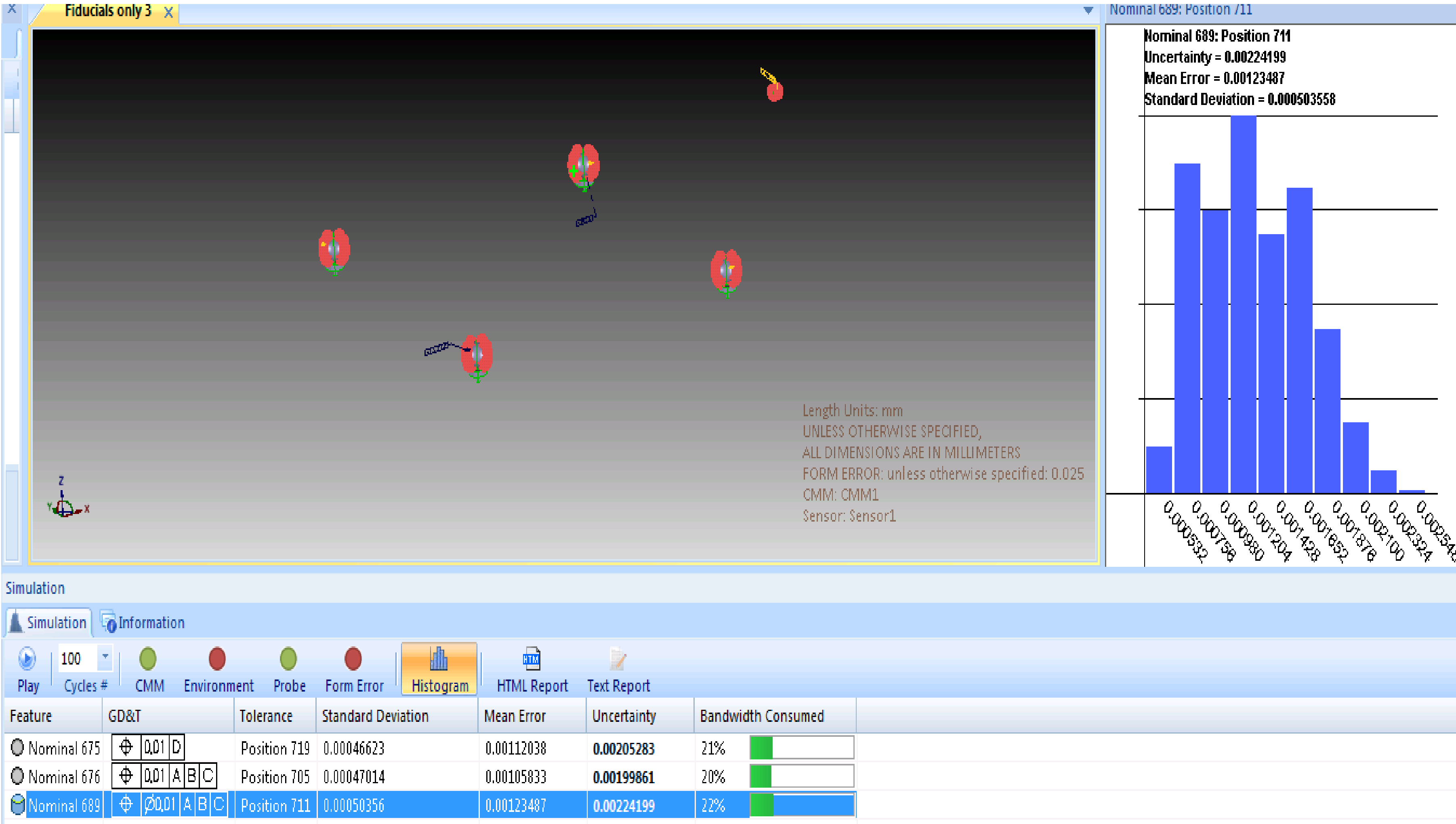
Play | 100 Cycles # | CMM | Environment | Probe | Form Error | Histogram | HTML Report | Text Report

Feature	GD&T	Tolerance	Standard Deviation	Mean Error	Uncertainty	Bandwidth Consumed
Nominal 2510	⏥ 0.1	Flatness 2567	0.0442137	0.104402	**0.192829**	193%
Nominal 2517	⏥ 0.005	Flatness 2565	0.00157183	0.00205043	**0.00519409**	104%
2568	⌓ 0.1 C D E	Profile of a Surface 2571	0.00235133	0.00280073	**0.00750339**	8%
2572	⌖ 0.1 C D E	Position 2574	0.0218223	0.0373942	**0.0810388**	81%
2586	⌖ Ø0.1 A B C	Position 2589				
2606	⌖ Ø0.1 G	Position 2608	0.0284095	0.0660363	**0.122855**	123%

Uncertainty for specific measurement tasks can vary from Below the MPEE to far above it !!!

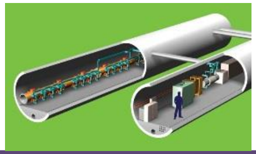
Task specific uncertainty modelling of CMM

Curtesy for providing the modelling software (PUNDITCMM™) to METROSAGE



The Thermal problem, compensation of effects

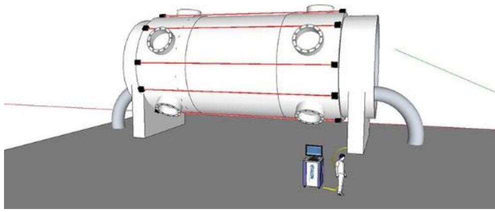
A) Pre align at the operational conditions? Be able to perform 7-10 micro meter traceable to the meter standard pre-alignment at 45 C.



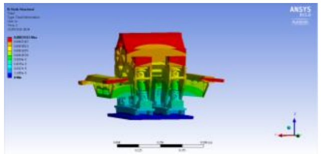
Tunnel 40 C Air; 45 C Magnet

B) Re-design the metrology frame so thermal effects are significantly reduced or made highly deterministic?

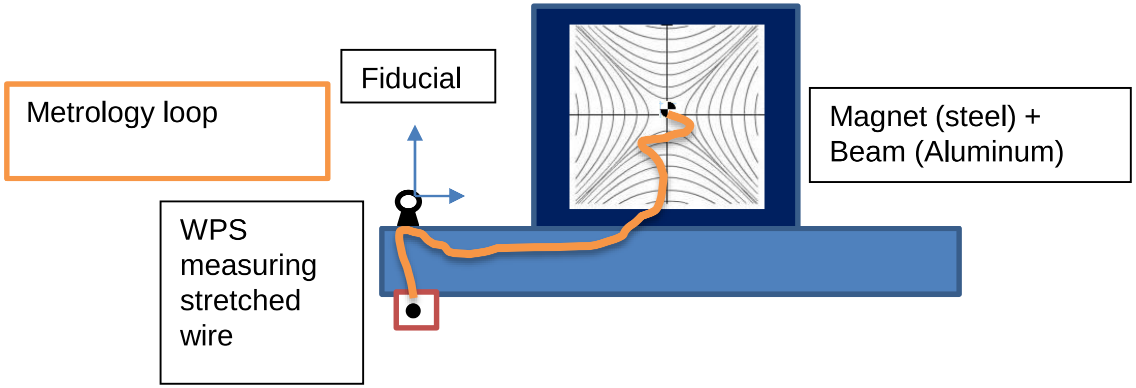
C) Introduce “real-time” metrology over the metrology frame to compensate for the thermal effects



D) Use modelling to predict the mechanical behaviour having as input the temperature influences?



Metrology frame and thermal effects



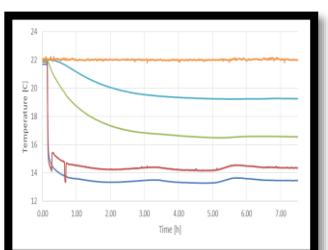
Drift of:

A) Magnetic axis

B) WPS and reference fiducial marks

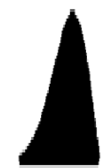
How to compensate thermal errors and evaluate the uncertainty of the compensation?

Real time Thermal measurements



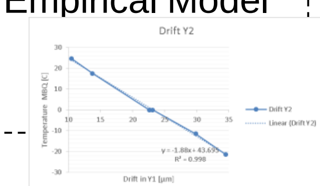
Thermal drift modules

X, Y, Z +



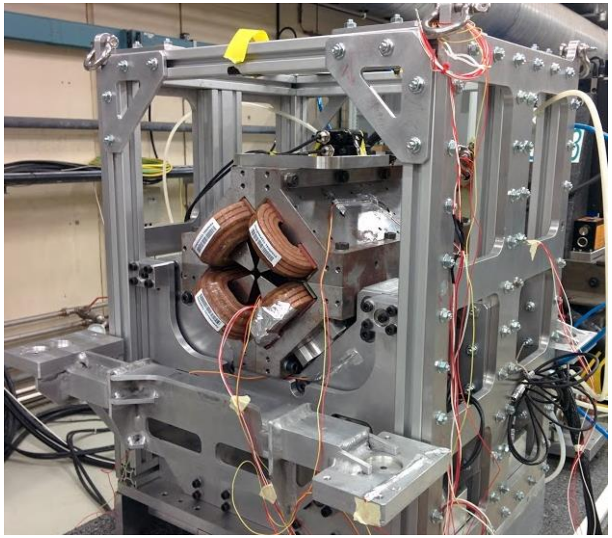
Fiducials and magnetic axis drift in X, Y, Z + Uncertainty of modeling

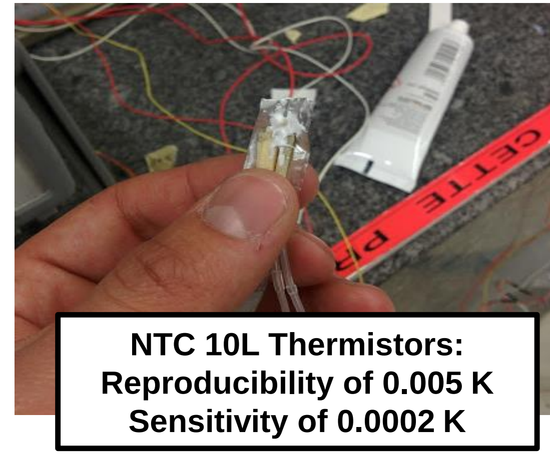
Empirical Model

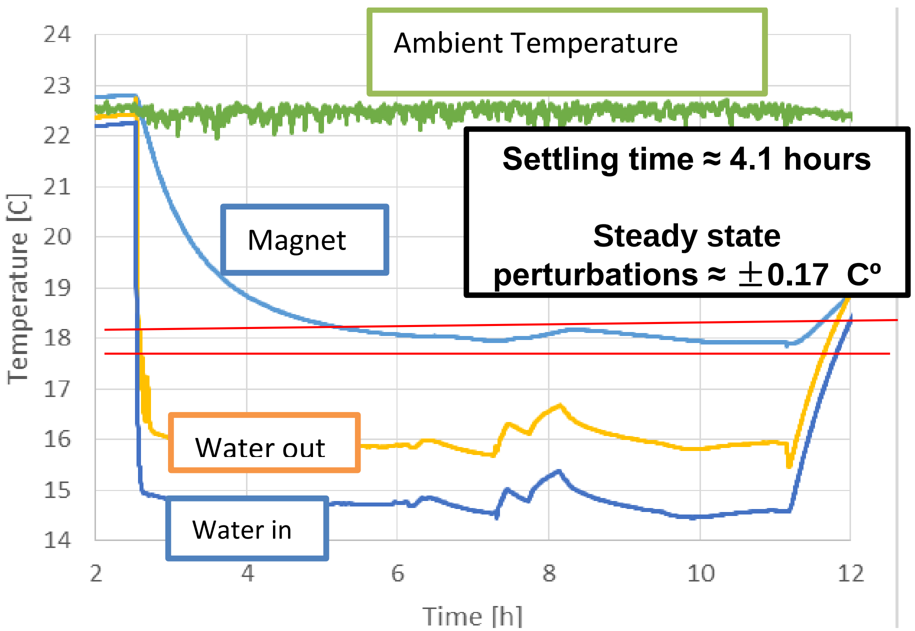


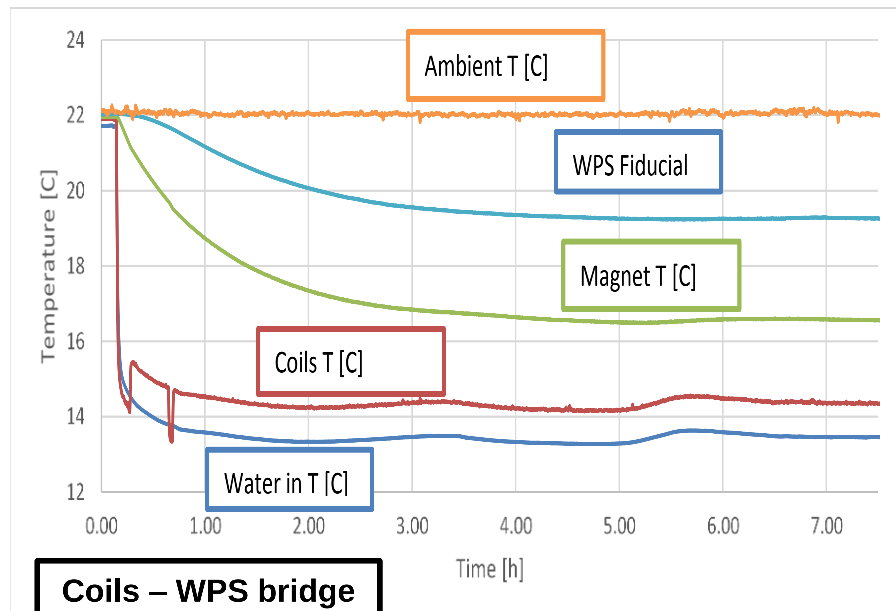
Numerical Model

First thermal characterizations



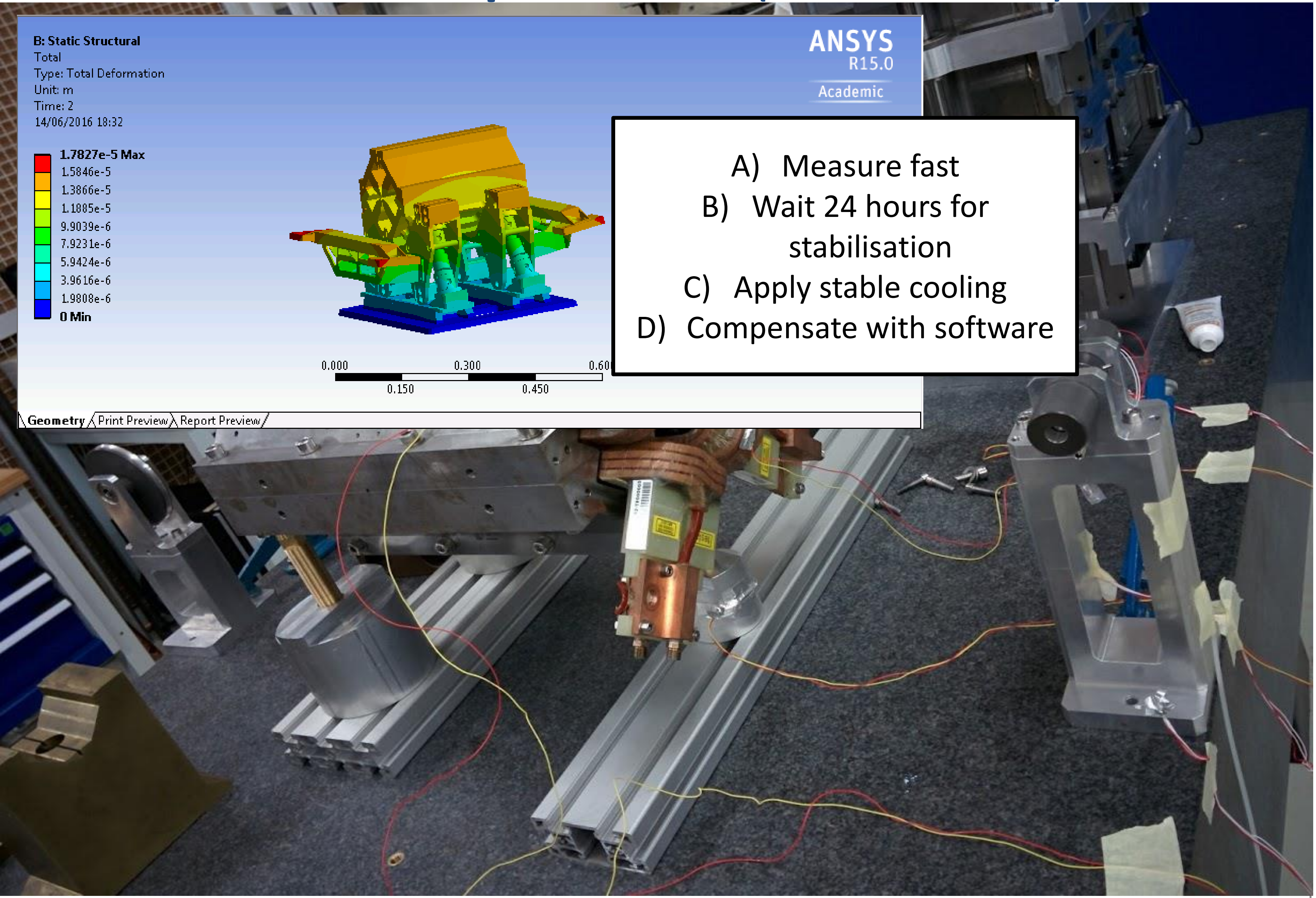






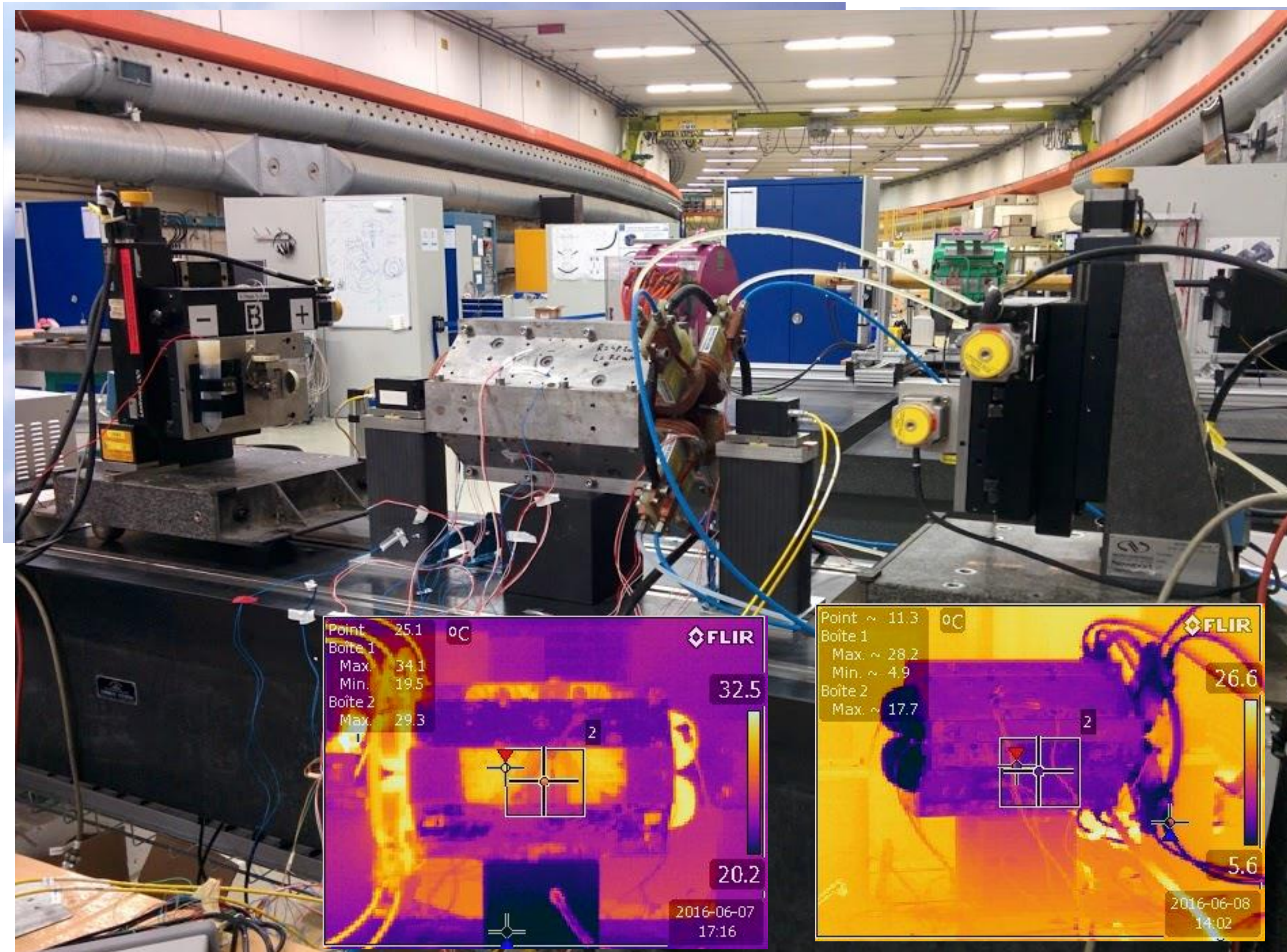
Coils – WPS bridge gradient ≈ 5 C°

Thermal Experiments (4A vs 125 A)

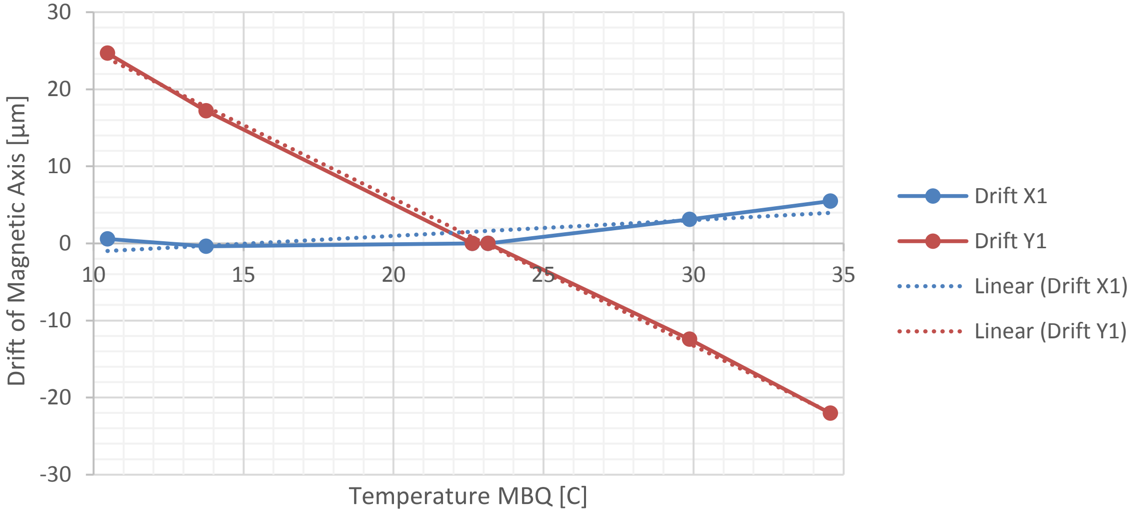


A) Measure fast
B) Wait 24 hours for stabilisation
C) Apply stable cooling
D) Compensate with software

Experimental design



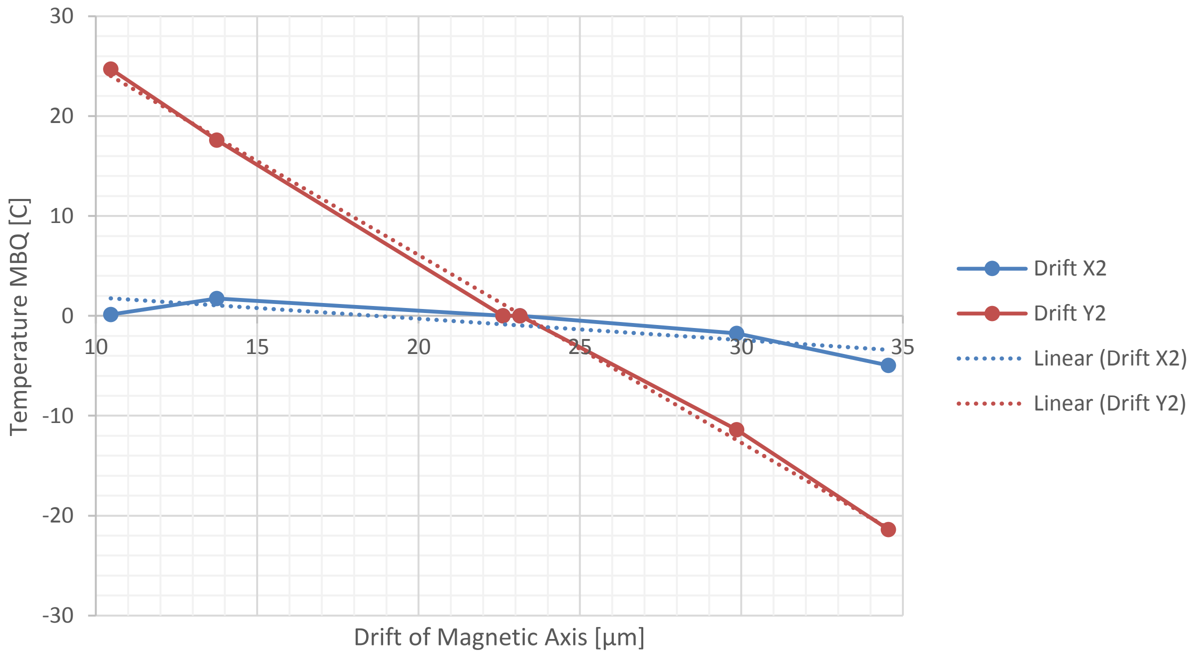
First experimental results



Magnetic axis drift ≈ 1.9 microns/ 1 Celsius

Heating of magnet creates negative horizontal drift

Uncertainty of model = function of thermal and drift measurement stability/uncertainty



Stochastic Finite Element Modelling

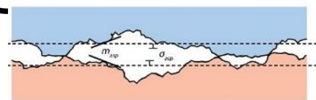
(Input Output parameters)

Geometry parameters from (CAD), Form/real VS CAD dimensions

Material parameters: CTE

Boundary condition parameters: (body temperatures, or heat transfer parameters, assembly contact definitions)

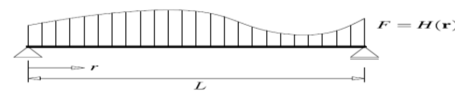
Assembly interface parameters: Thermal resistance/conductance coefficients of interfaces



FEM solvers + random fields

FEM (ANSYS) Thermal

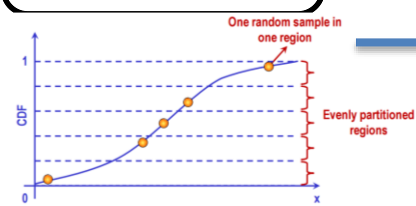
FEM (ANSYS) Mechanical



-General Randomisation or random fields?
- Mesh design parameters (1,2,3,4)

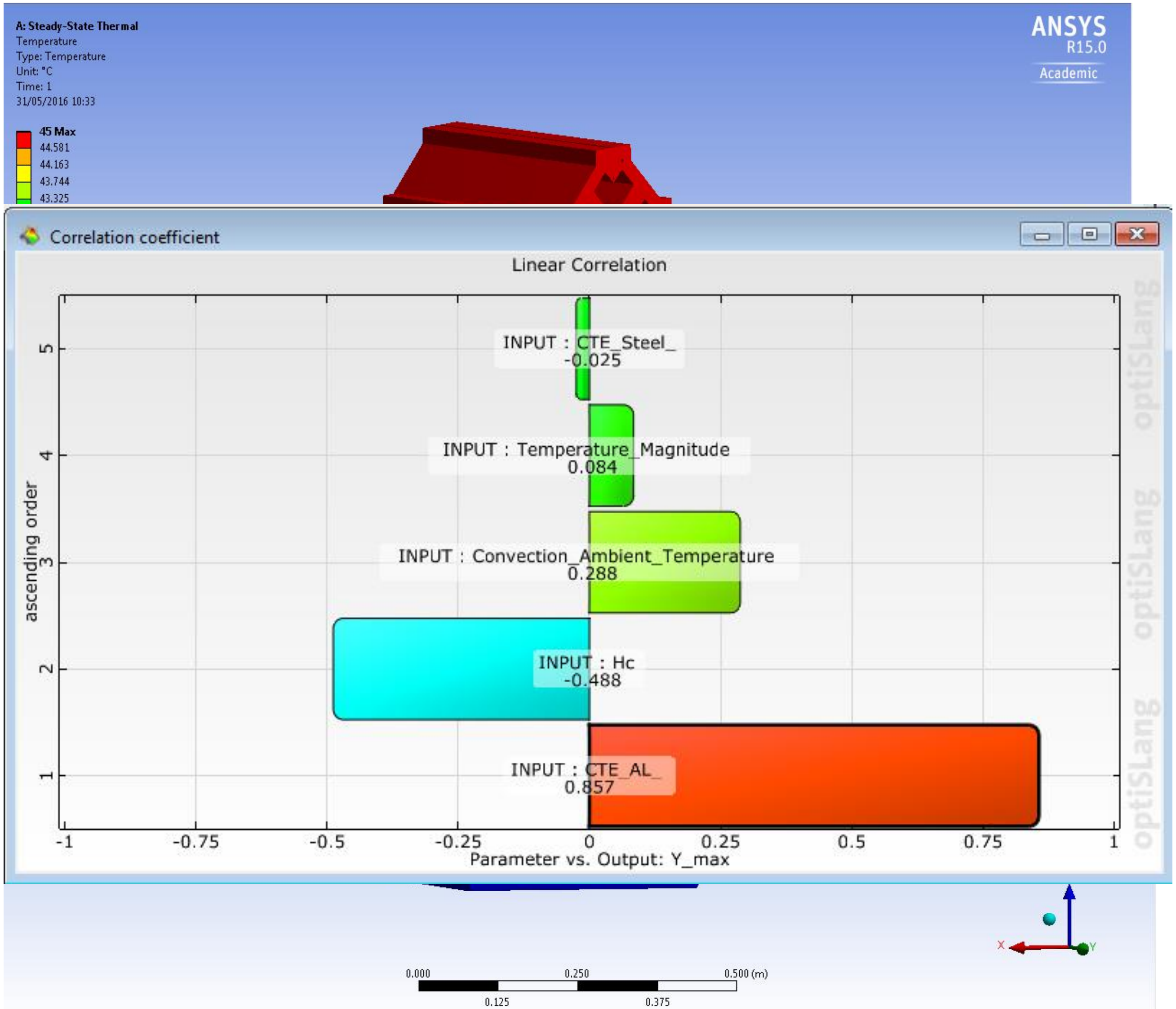
Result + Uncertainty

Smart sampling algorithm such as Latin Hyper cube

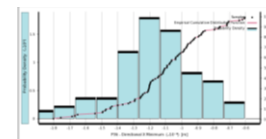


ANSYS DoE, 6 sigma analysis, interfaced with: Dynardo (Opti_Slang),
In fiture with Dynardo SoS packages)

MBQ module predicted thermal influences (CMM to tunnel environment)



Up to 190µm deformation (excluding macro alignment bases of assembly!) Uncertainty STD: 15.6 µm – 1 µm depending on Uncertainty of control parameters



Critical uncertainty input parameters

1) **CTE**
2) **Hc**
3) **T (accuracy thermal measurements)**

Non Critical

1) **Hw – Not important …**
2) **Geometrical tolerance not important..**

Current and upcoming work

→ Finishing of experimental bench, experimental evaluation of MBQ and WPS metrology frame drift. Creation of empirical model and it's uncertainty propagation with MC method.

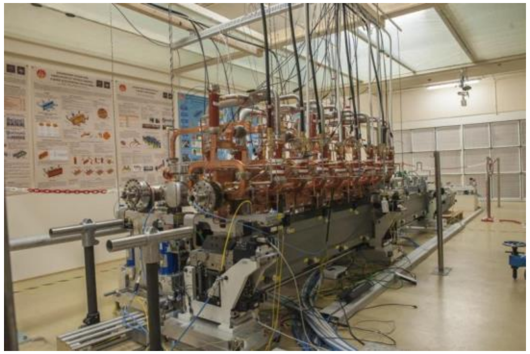
→ Focus on calibration of the stochastic Finite Element Methods for comparison against experimental evaluations.

- Experimental and modeling evaluation of all critical parameters

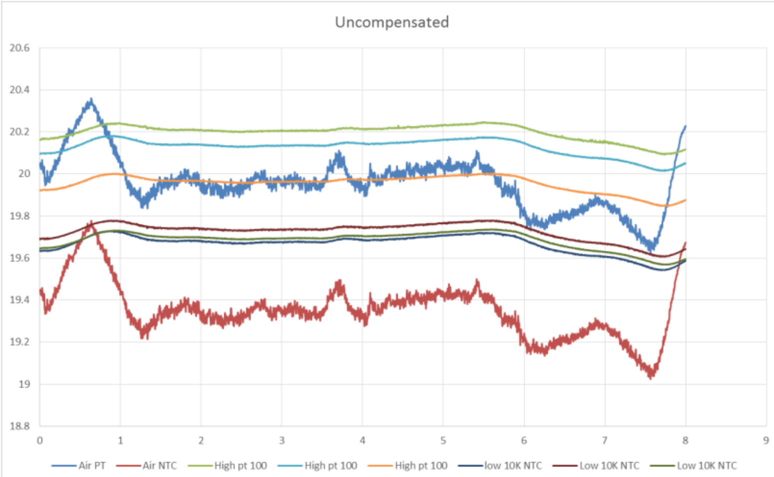
→ Crosscheck of Stochastic Finite Element Method against:

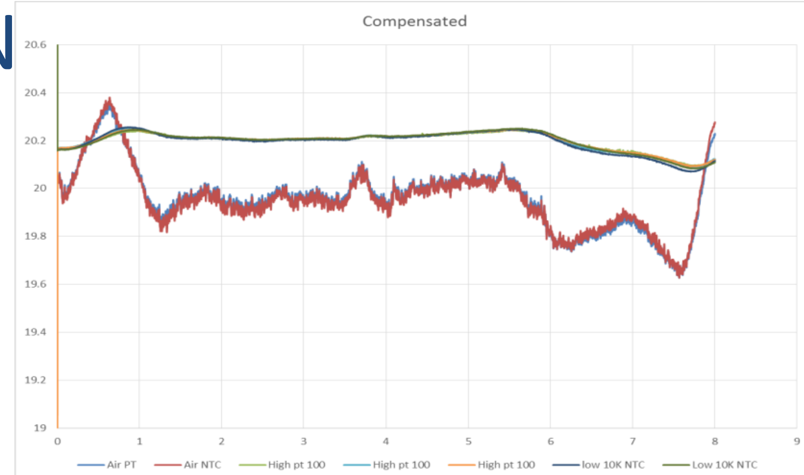
A) CMM thermal drift measurements

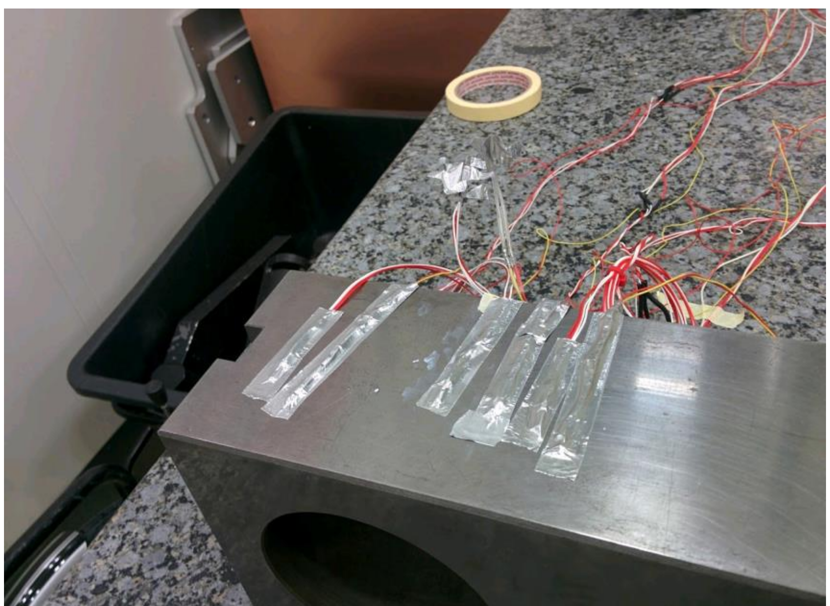
B) CLIC 2 beam module



BACKUP Thermal Experiments (self-calibration d N







→ **Performed self calibration at metrology laboratory of existing setup:** STD of Correction coefficient = 0.013 K max to min 0.00092K (3 days of testing)

→ **Putted together a new setup and send it to NPL for calibration and absolute uncertainty analysis against ITS-90:** 23 Sensors (10 NT 5k and 13 PT 100) together with Agilent DAQ (to be returned by Friday 29th of April)

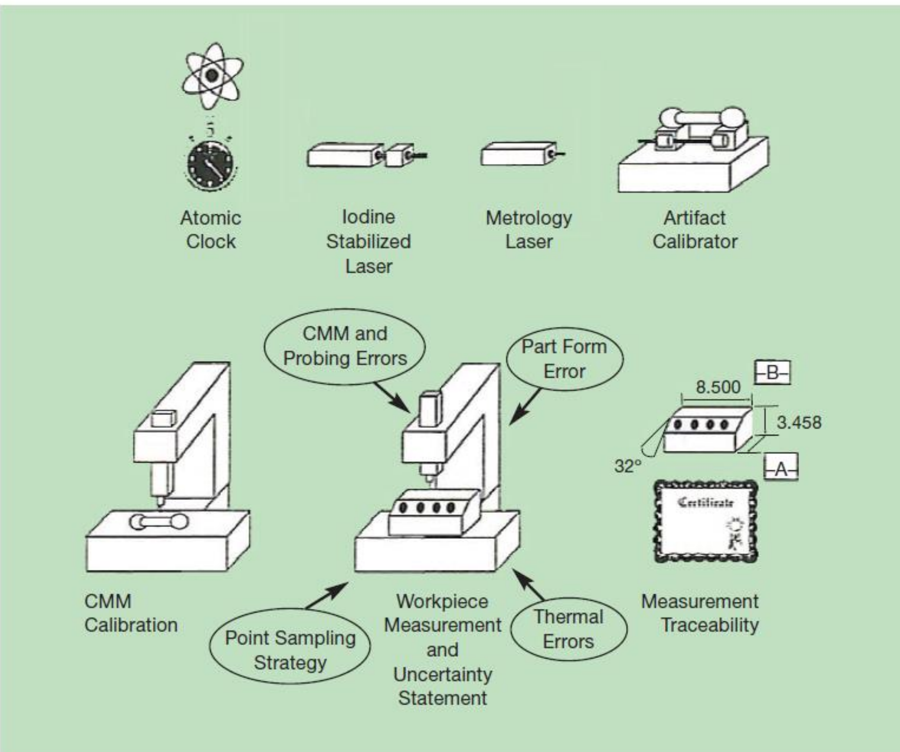
U of total thermal measurment = +/- 0.03 °C [Square shape]

Table Uncertainties stated In state of art

Accelerator			Magnet									Instrumentation		Uncertainty			
Institute	Machine	L [m]	Type	Technology	Lm [m]	Aperture [mm]	I [A]	dB/dr [T/m]	B_{max} [T]	T [K]	Moves	Magnetic	Survey	Axis to sensor [μm]	Sensor to ref. [μm]	Total [μm]	Ref.
BNL	**RHIC**	3862	quad	superconducting	1.13	80	5000	71.00	5.7	4.5	no	Colloidal Cell	Theodolite	40	25	47	[2]
BNL	**RHIC**	3862	quad	superconducting	1.13	80	10	0.14	0.01	300	no	Harmonic Coil	Theodolite	25	25	35	[2]
BNL	**SASE**	-	undulator	permanent	4.00	6	-	-	0.8	300	no	Pulsed Wire	Interferometer	10	8	13	[3]
KEK	**B-factory**	3016	quad	resistive	0.40	110	500	10.20	1.12	300	yes	Harmonic Coil	Laser Tracker	15	5	16	[4]
SLAC	**LCLS**	3000	quad	resistive	0.05	12	n.a.	15.00	0.18	300	no	Hall Sensor	CMM	8	1	8	[5]
SLAC	**LCLS**	3000	undulator	permanent	3.40	12	-	-	1.3	300	no	Hall Sensor	CMM	8	15	17	[6]
SLAC	**LCLS**	3000	quad	resistive	0.15	12	n.a.	12.00	0.14	300	yes	Vibrating Wire	CMM	18	10	21	[7]
JASRI	**SPring-8**	1436	quad	resistive	0.64	85	n.a.	17.40	1.48	300	yes	Harmonic Coil	Laser + CCD	2	10	10	[8]
SLAC	**FFTB**	3200	quad	resistive	0.46	23	220	83.00	1.91	300	no	Vibrating Wire	CMM + Micrometer	4	15	15	[9]
MIT-Bates	**SHR**	190	quad	resistive	0.28	35		0.50	0.02	300	no	Harmonic Coil	Theodolite	*26*	*43*	51	[10]
FNAL	**LHC**	26660	quad	superconducting	8.00	63	11850	215.00	13.55	4.5	no	Stretched Wire	Laser Tracker	33	50	60	[11]
FNAL	**LHC**	26660	quad	superconducting	8.00	63	2	0.04	0.00	300	no	Stretched Wire	Laser Tracker	33	50	60	[11]
CERN	**LHC**	26660	quad	superconducting	8.00	40	11850	223.00	8.92	1.9	no	SSW	Laser Tracker	5	80	80	[12]
CERN	**LHC**	26660	quad	superconducting	8.00	50	2	0.04	0.00	300	no	SSW	Laser Tracker	20	80	82	[13]
CERN	**LHC**	26660	quad	superconducting	8.00	50	0.5	0.01	0.00	300	no	AC Harmonic Coil	Laser Tracker	51	80	95	[14]
Cornell	**CESR**	768	quad	superconducting	7.50	67	n.a.	13.00	0.87	n.a.	no	Vibrating Wire	Laser Tracker	10	51	52	[15]
Cornell	**CESR**	768	solenoid	superconducting	0.30	200	n.a.	-	0.008	300	no	Vibrating Wire	Laser Tracker	10	25	27	[16]
CNRS/CEA	**SOLEIL**	354	quad	resistive	0.46	66	n.a.	23.00	1.52	300	yes	Harmonic Coil	(mech. tol.)	*5*	*30*	30	[17]
ELETTRA	**SR**	259	quad	resistive	0.49	75	n.a.	20.60	1.55	300	yes	Harmonic Coil	Telescope	*5*	*25*	25	[18]
CERN	**LEP**	26660	quad	resistive	1.55	59	n.a.	9.70	0.57	300	yes	Harmonic Coil	Laser + PSD	20	50	54	[19]

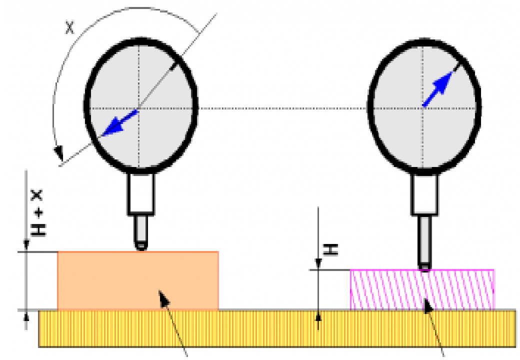
The Right decision = f(Measurement value + Uncertainty certificate)

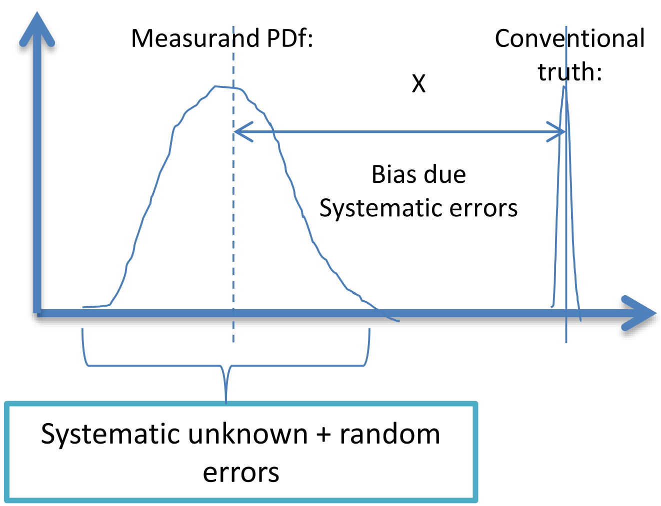
Traceability allows to ensure that the measurement uncertainty is within the limits of required for a certain task.



Application of Simulation Software to Coordinate Measurement Uncertainty Evaluations Jon M. Baldwin et all

Principle applied to achieve traceability in CMM : the comparator principle





Establish this tractability link to the national standards!?

PACMAN Thermal error compensation and uncertainty estimation

PARAMETER	Min	Max	Mean value	STD	CoV
Hc	2.871954766	7.128045234	5	0.995831099	0.19916622
CTE_AL_	1.81E-05	2.79E-05	2.30E-05	2.29E-06	0.09958311
CTE_Steel_	9.45E-06	1.46E-05	1.20E-05	1.19E-06	0.09958311
Temperature_Magnitude	44.78719548	45.21280452	45	0.09958311	0.002212958
Convection_Ambient_Temperature	39.78719548	40.21280452	40	0.09958311	0.002489578
Y_max	9.70E-05	0.000147282	0.000122964	1.26E-05	0.102465159
Z_max	6.01E-05	9.84E-05	8.11E-05	9.41E-06	0.116078923
Y_min	-0.000137259	-9.02E-05	-0.000114545	1.18E-05	-0.102714291
Z_min	-4.59E-07	2.96E-05	1.81E-05	7.27E-06	0.401840307
Total_Max	0.000171743	0.000230495	0.00019609	1.56E-05	0.079632237
Ynos_Maximum	8.16E-06	1.31E-05	1.07E-05	1.15E-06	0.107543103
Ynos_Minimum	-1.32E-05	-8.13E-06	-1.08E-05	1.17E-06	-0.109242892
Z_nos_Minimum	0.000128909	0.000182301	0.00015371	1.35E-05	0.087911705
Z_nos_Maximum	0.000136117	0.000188317	0.000159563	1.35E-05	0.084672691
Y_max_cv	9.65E-05	0.000147167	0.000122957	1.26E-05	0.102415704
Z_max_cv	5.99E-05	9.83E-05	8.11E-05	9.41E-06	0.115995879
Y_min_cv	-0.000137187	-8.98E-05	-0.00011454	1.18E-05	-0.102670001
Z_min_cv	-6.37E-07	2.91E-05	1.81E-05	7.27E-06	0.402155492
Total_Max_cv	0.000170523	0.000230463	0.000196078	1.58E-05	0.080656935
Ynos_Maximum_cv	8.26E-06	1.32E-05	1.07E-05	1.15E-06	0.107230442
Ynos_Minimum_cv	-1.33E-05	-8.26E-06	-1.08E-05	1.17E-06	-0.108823732
Z_nos_Minimum_cv	0.000127297	0.000184004	0.000153694	1.34E-05	0.087356282
Z_nos_Maximum_cv	0.00013565	0.00019009	0.000159563	1.34E-05	0.084272797

Input parameters sensitivity:

1) **CTE - Important, can be controlled to…**
2) **Hc – Important, can be controlled to**
3) **T – Important, can be controlled to**
4) **Hw – Not important …**
5) **Tolerancing not important..**