BOND

Mock-up design of sliding solution for the reaction tooling

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01/04/2025

Outline

- Introduction and aim
- Selected solutions and basic mock-ups
- Racetrack coil mock-up
- Flared-end coil mock-up
- Conclusion

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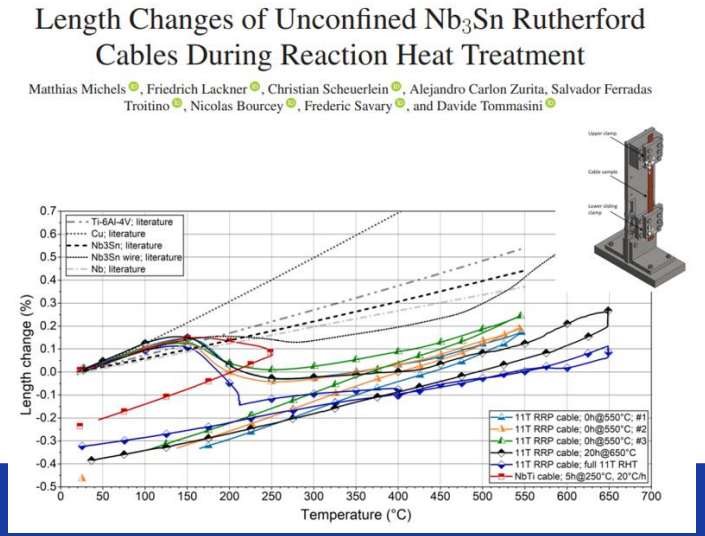
Introduction and aim

- During the reaction cycle, relative movements will happen due to
  - Different thermal coefficient expansion of the materials involved coil, mold components (stainless steel, titanium)
  - The change in dimension of the Nb_3Sn cable
- Due to the geometry of the coil (flared-ends), the winding table is sectorized to enable the heads to move freely w.r.t the straight part
  - Prior to winding, gaps are set in between the winding table and the winding poles (avoid tensioning of the Nb_3Sn at any moment of the coil fabrication)
- The goal of the present study is to explore the best sliding solution to be applied to the reaction mold to allow the longitudinal movement of the coil ends w.r.t the straight part
  - Keeping the alignment of the sectorized mold
  - Low friction

Courtesy of N. Peray



Introduction and aim

- Discussions ongoing with EN-MME for measurement campaign on displacements during RHT
  - Take advantage of an oven in building 112 to perform DIC measurements
  - Based on the results the measured displacements, target the right measurement device to be further implemented in the reaction mold

The idea would be to remove one of the fans on top, to open a window.
Discussions ongoing regarding the feasibility for oven intervention.

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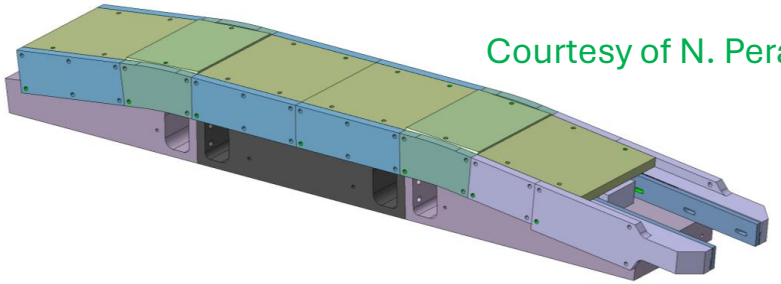
Selected solutions and mock-ups

- As previously mentioned, the sliding system will be independently implemented to the reaction mold based on the mock-up results
- Selected products based on mock-up purposes (size, load, etc…)

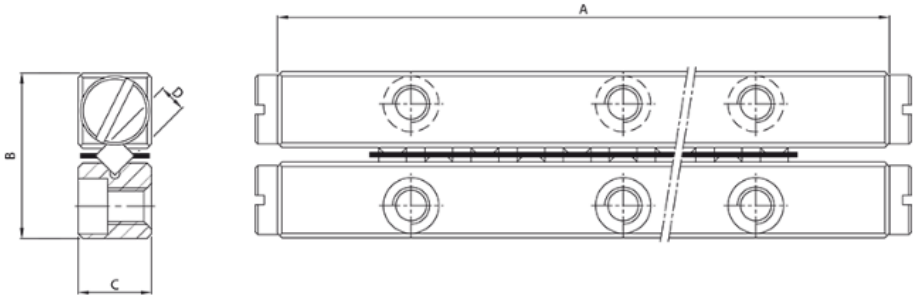


Courtesy of N. Peray

Linear Ceramic Bearings

- 1 set CRZ-3075x10AA-SI:
  - 4 pcs ZrO_2 rails (Si_3N_4 rails available upon request and for a MOQ)
  - 2 pcs stainless steel roller cage and Si_3N_4 rollers

Weight (Kg)	Load (N)	Stroke (mm)	A (mm)	B (mm)	C (mm)	D (mm)
0.135	1360	48	75	18	8	3



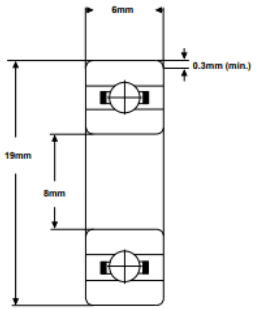
Circular Ceramic Bearings

smb bearings

- Full Si_3N_4 bearings without cage CCSI-698

SMB Bearings

Part Number: CCSI-698



Radial Ball Bearing

(for illustration only)

Material (rings & balls)	Silicon Nitride (Si3N4)
Material (cage)	Full complement, PEEK or PTFE
Closures	None
Load rating (stat)	60 Kgf
Load rating (dyn)	142 Kgf
Speed Limit *	11,000 rpm
Standard Lubrication **	None

* with adequate lubrication
** may vary

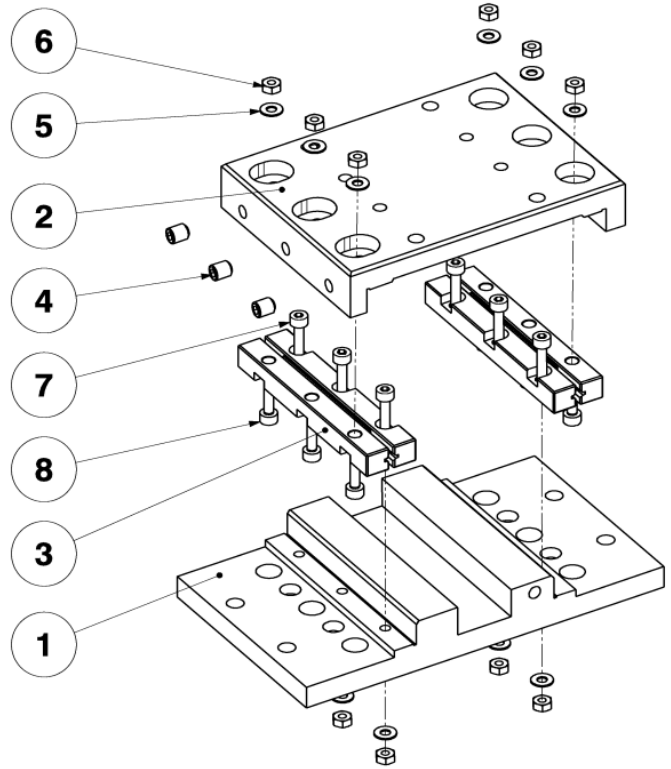
These bearings comply with EU ROHS and REACH regulations.

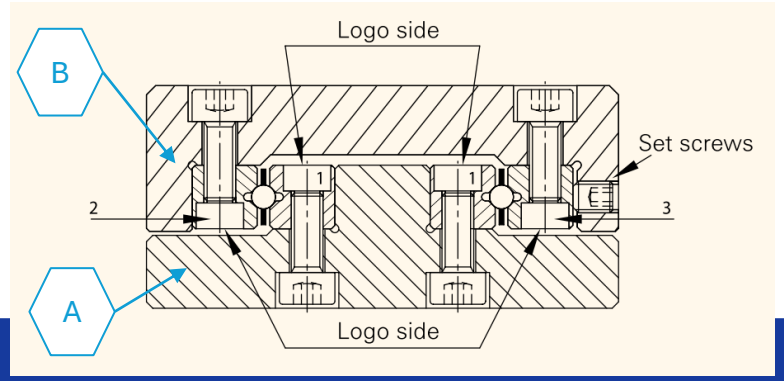
RADIAL PLAY	C2	CN	C3	C4
(microns)	0 - 7	2 - 13	8 - 23	14 - 29

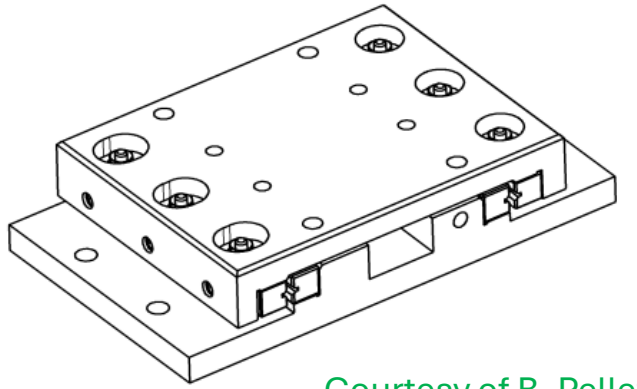
TOLERANCE	P0
Bore Deviation	+0 / -0.008mm
OD Deviation	+0 / -0.008mm
Width Deviation	+0 / -0.120mm

Linear Ceramic Bearings

- The system is composed by 3 different materials
  - Rails made by ZrO_2 (Supplier CTE 10.3 x 10^{-6}/°C)
  - Rollers made by Si_3N_4 (CTE 3 x 10^{-6}/°C)
  - Roller cage made by 304 stainless steel
- The implementation and assembly of such system requires to follow the supplier's guidelines
  - To ensure a proper installation, the system needs to be preloaded via the set screws (recommended torque)
  - In our mock-up the parts #A and #B are made of titanium to be as close as possible to the rail material in terms of CTE
  - 1 system per side is enough for the longitudinal alignment/guiding







Courtesy of B. Pellet

Linear Ceramic Bearings

- Expected lifetime
  - Compliant with DIN ISO standard 14728-1:2017
  - Fatigue
    - Load applied onto the rails
    - Amount of acceleration and speed
    - Quality and age of the lubricant

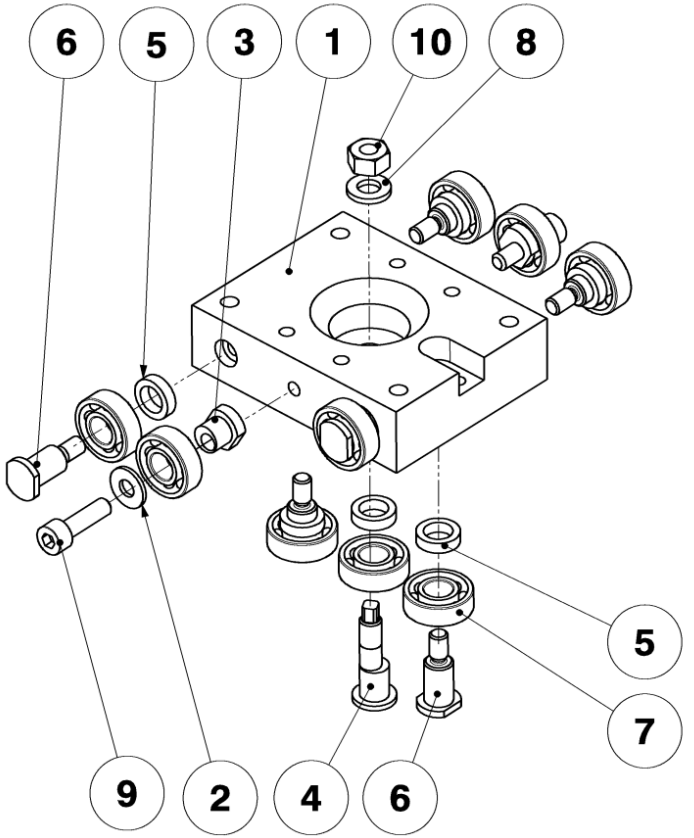
    Neglected in our case
  - Short stroke
    - When the rolling element fail to roll completely, and the stroke is lower w.r.t. the diameter of the roller/ball
- Nominal operational calculation life (L_{10})
  - Assuming the supplier's guidelines are respected
  - The expected lifetime is expressed in meters
  - Considering the same type of rails but made of stainless steel (conservative assumption)
    - **L_{10} = 603 m** (90% reliability)
    - **L_1 = 126 m** (99% reliability)
  - **Tests should be carried out to assess the real lifetime**

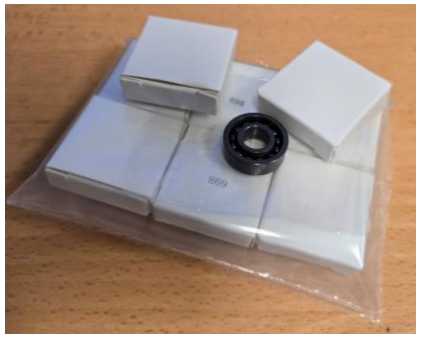
$$L_{10} = a_1 \cdot (C_{dyn}/P)^E \cdot 1.15 \cdot F_T \cdot F_H \cdot 10^5 \text{ meters}$$

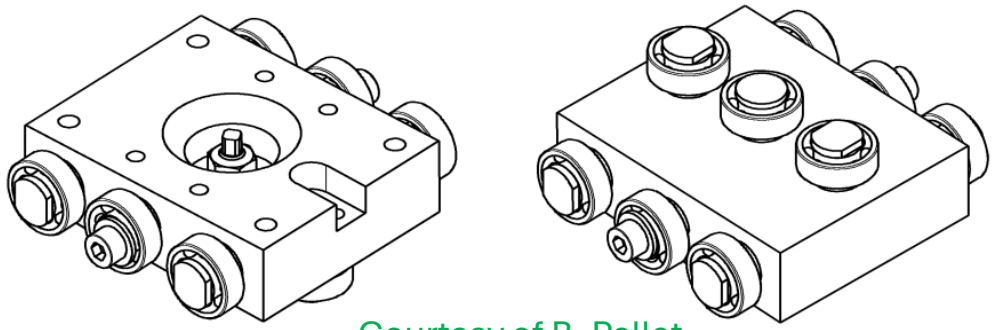
L	= Expected life in meters
a_1	= Reliability factor
C_{dyn}	= Effective dynamic load rating in N
P	= Equivalent load in N
E	= 10/3 for cylinder and needle rollers, or 3 for balls
1.15	= An empirical factor applicable to the materials employed
F_T	= Correction factor for temperature effects
F_H	= Correction factor for rail hardness grades (below 58 HRC)

Circular Ceramic Bearings

- Full Si_3N_4 ball bearings without cage
  - Can be used up to 1200°C at low speed and low axial loads
  - In principle for temperatures between 500-900°C a GH4099 nickel-based alloy cage could be used (not stored at the time of the PO)
- The implementation and assembly of such system could be more challenging w.r.t. another system
  - Fitting shaft/bearing must be careful check both at ambient and high temperatures to
    - Ensure the alignment of the mold parts during the whole reaction cycle
    - Make sure that interference fits due to differential thermal expansions do not reduce the radial play of the bearing to an unacceptable level (or shaft and housing fits should always accommodate for differences in expansion coefficients)
  - 3 bearings per raw where the central one is installed in an eccentric axis for alignment







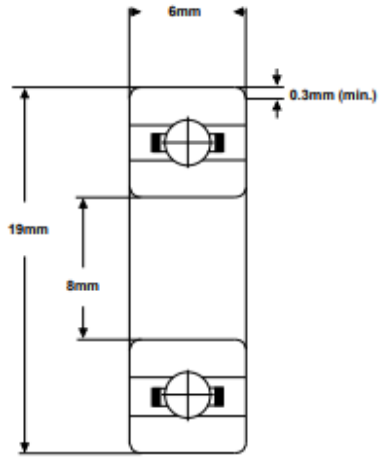
Courtesy of B. Pellet

Circular Ceramic Bearings

- Based on supplier's exchanges, the theoretical lifetime (in hours) with
  - 60kgf radial load
  - 1kgf axial load
  - 100rpm speed
    - $L_{90\% \text{ reliability}} = 455h$
    - $L_{95\% \text{ reliability}} = 291h$
    - $L_{99.5\% \text{ reliability}} = 35h$
- The actual theoretical life is longer if we consider negligible speed
  - At 10rpm speed → $L_{99.5\% \text{ reliability}} = 350h$
- In our case the bearings will not even complete 1 turn:
  - About 18° rotation (≈ 3mm) for basic mock-ups
  - About 30° rotation (≈ 5mm) for racetrack coil mock-up
  - At 1rpm speed → **$L_{99.5\% \text{ reliability}} = 3500h$**
  - **Tests should be carried out to assess the real lifetime**

SMB Bearings

Part Number: CCSI-698



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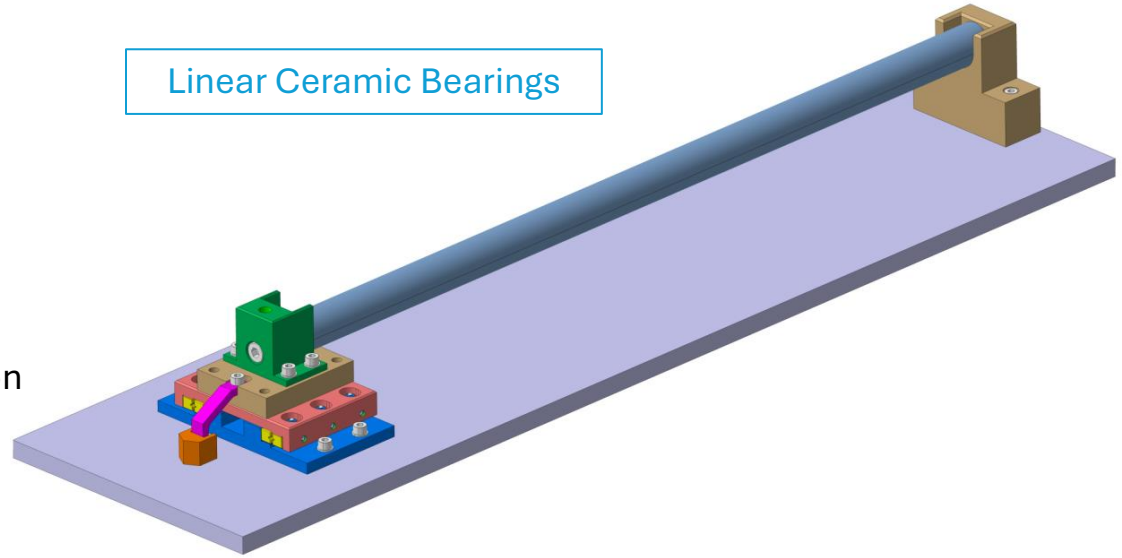
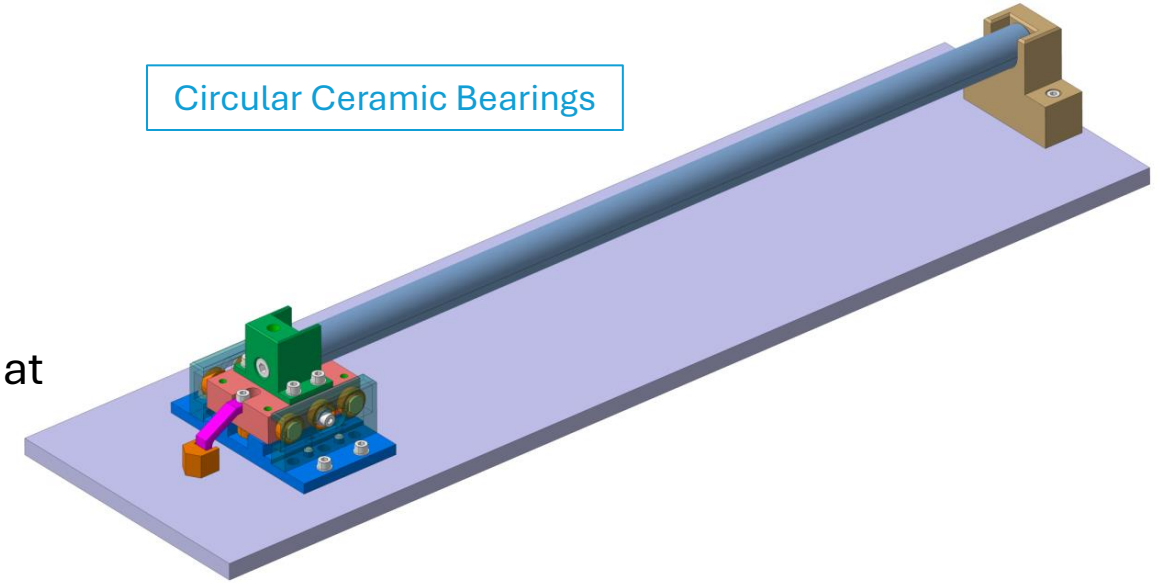
Mock-ups

- Mock-ups are built to
  - Assess the behavior of the sliding systems during a RHT cycle
  - Check the assembly of the sliding systems (weaknesses if any)
  - Determine the most suitable solution to be implemented to the reaction mold
  - All the drawings are signed, and the manufacturing is almost finished
- The basic mock-ups feature
  - A 600mm long 304 stainless steel bar
  - The sliding system (either linear or circular ceramic bearings)
  - All the rest of the components made by titanium
  - Possibility to install weight on top of the floating mass
- The differential expansion between 304SS and titanium at 650°C, considering a length of 600mm, is about 2.8mm

Linear Ceramic Bearings



Circular Ceramic Bearings



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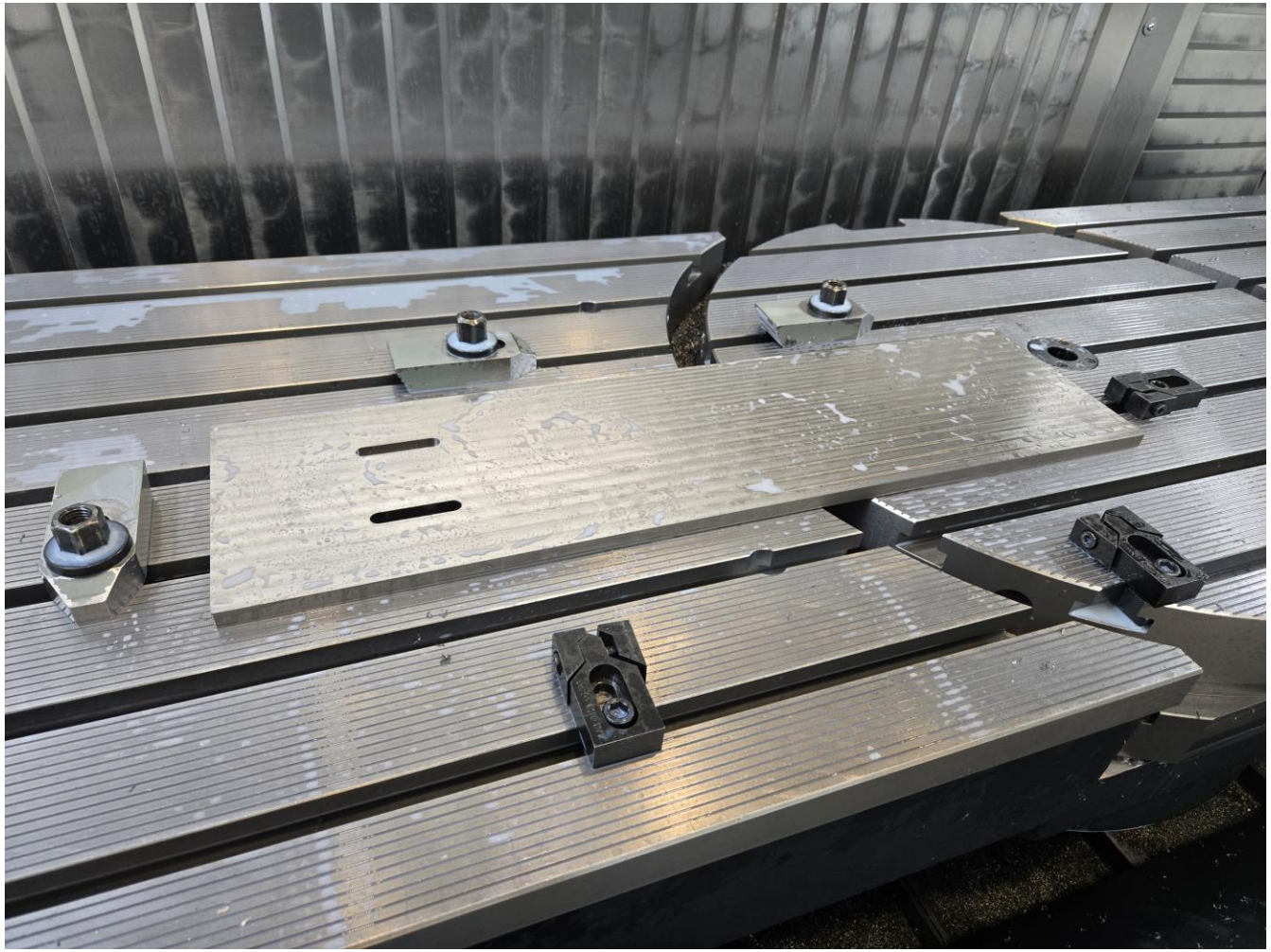
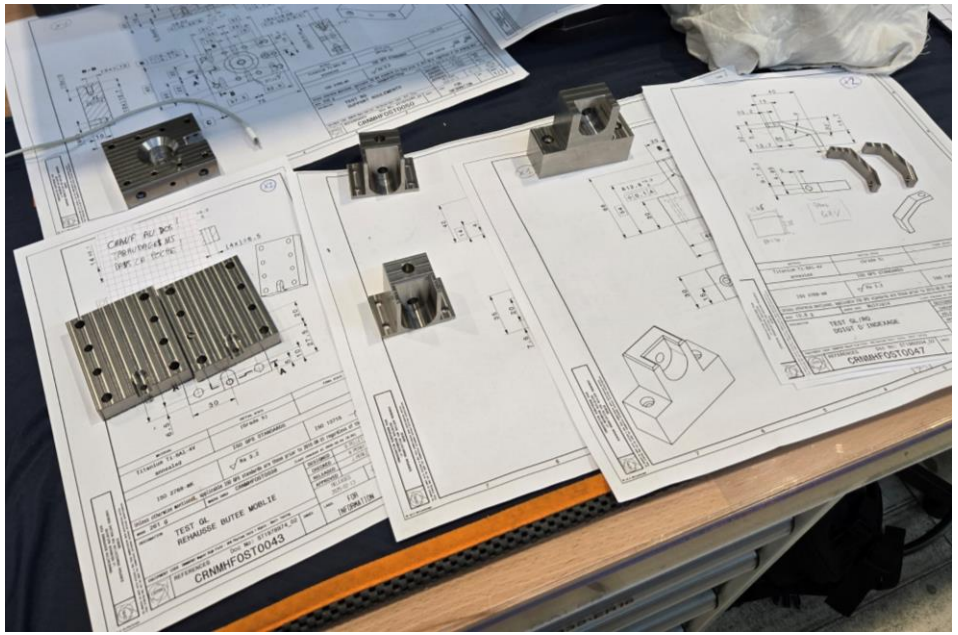
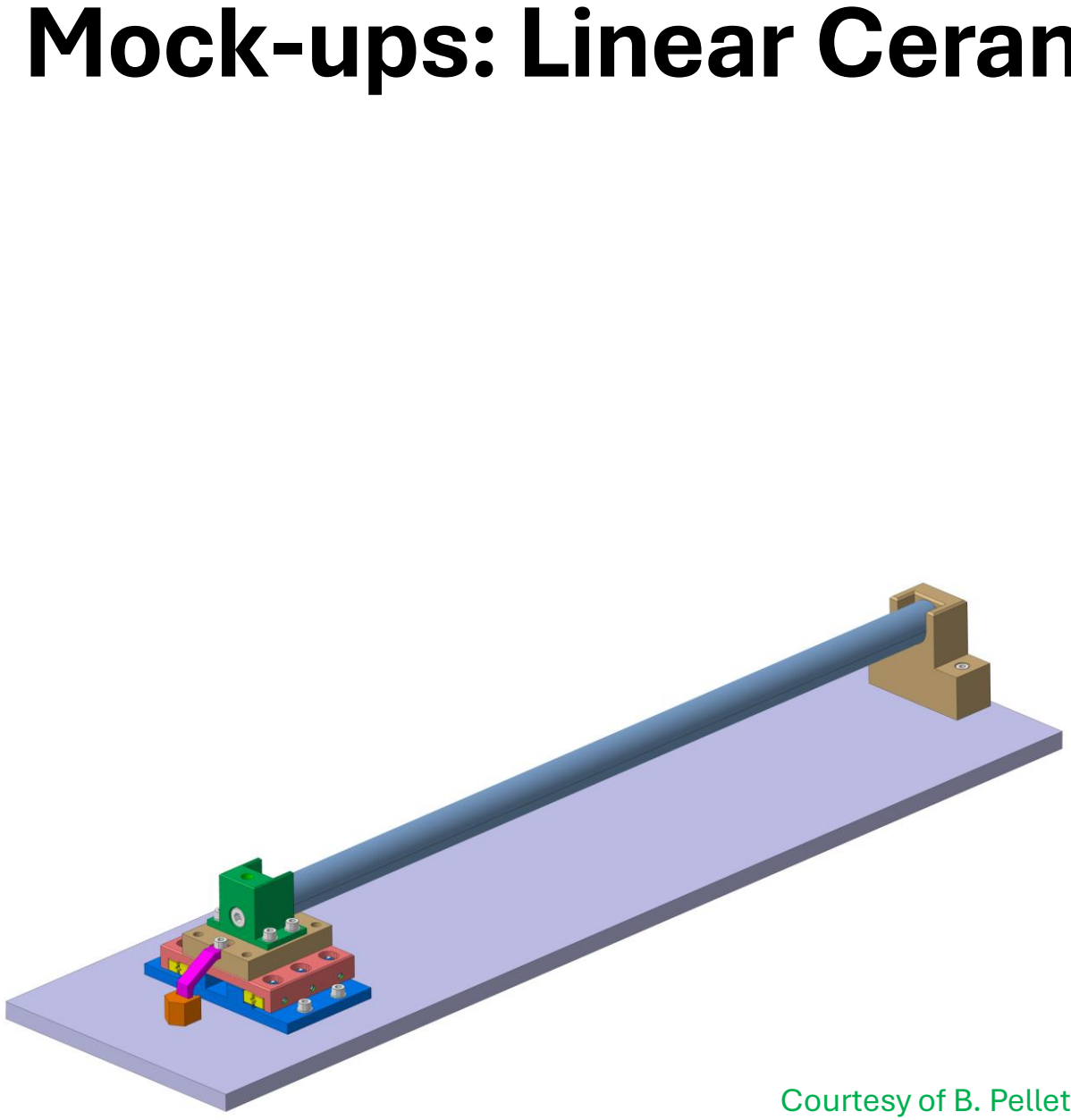
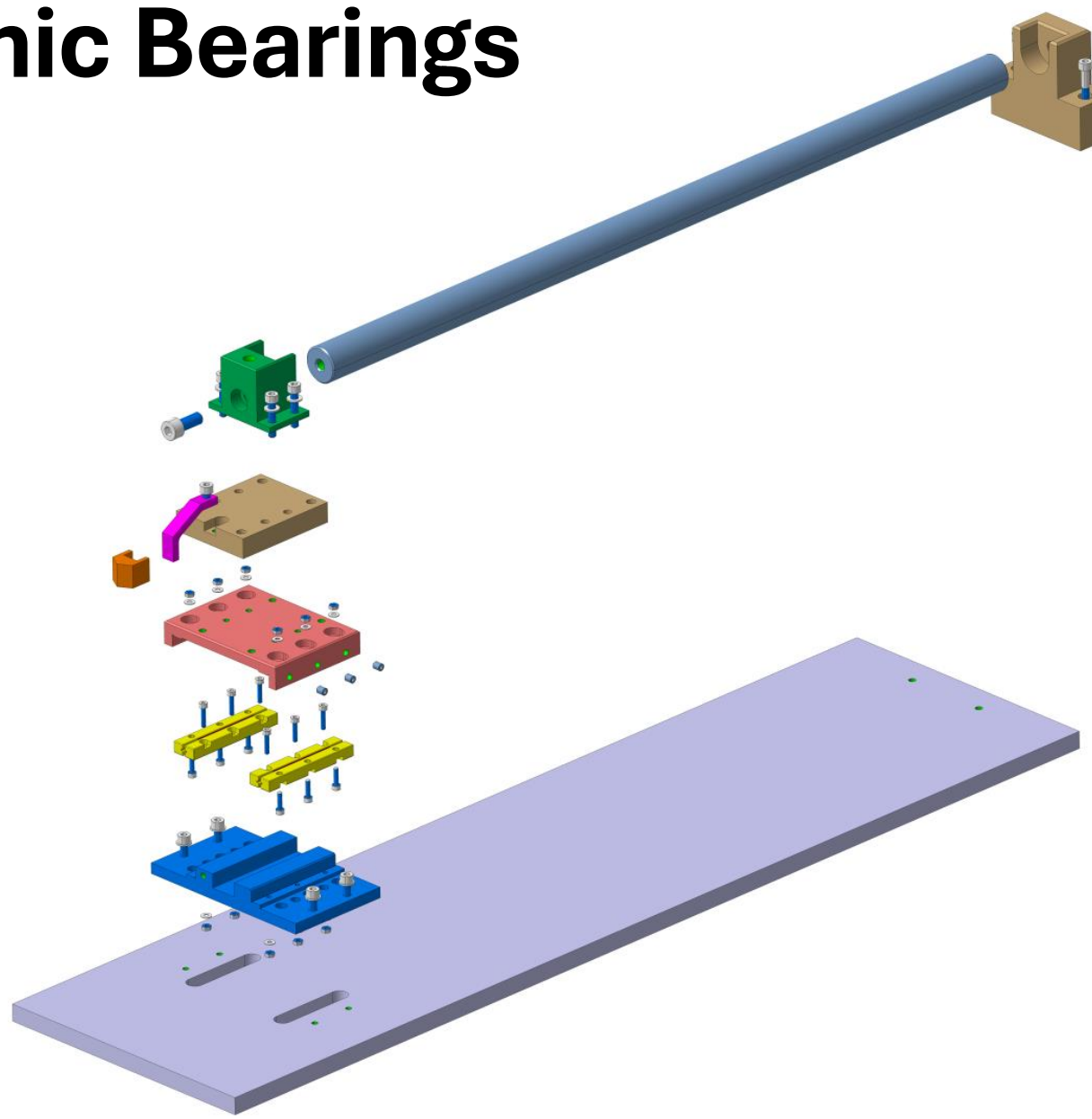
Mock-ups





Mock-ups: Linear Ceramic Bearings





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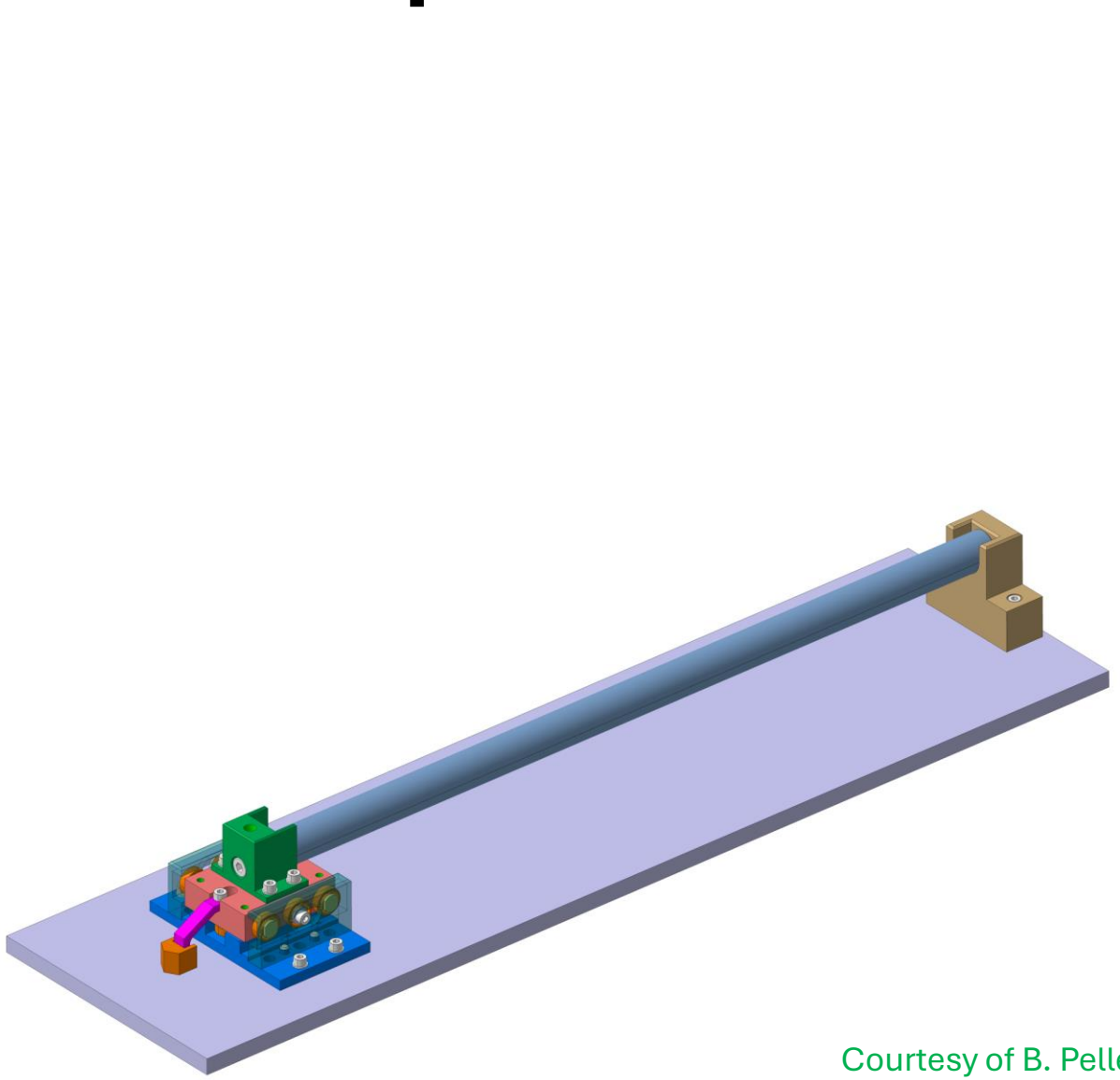
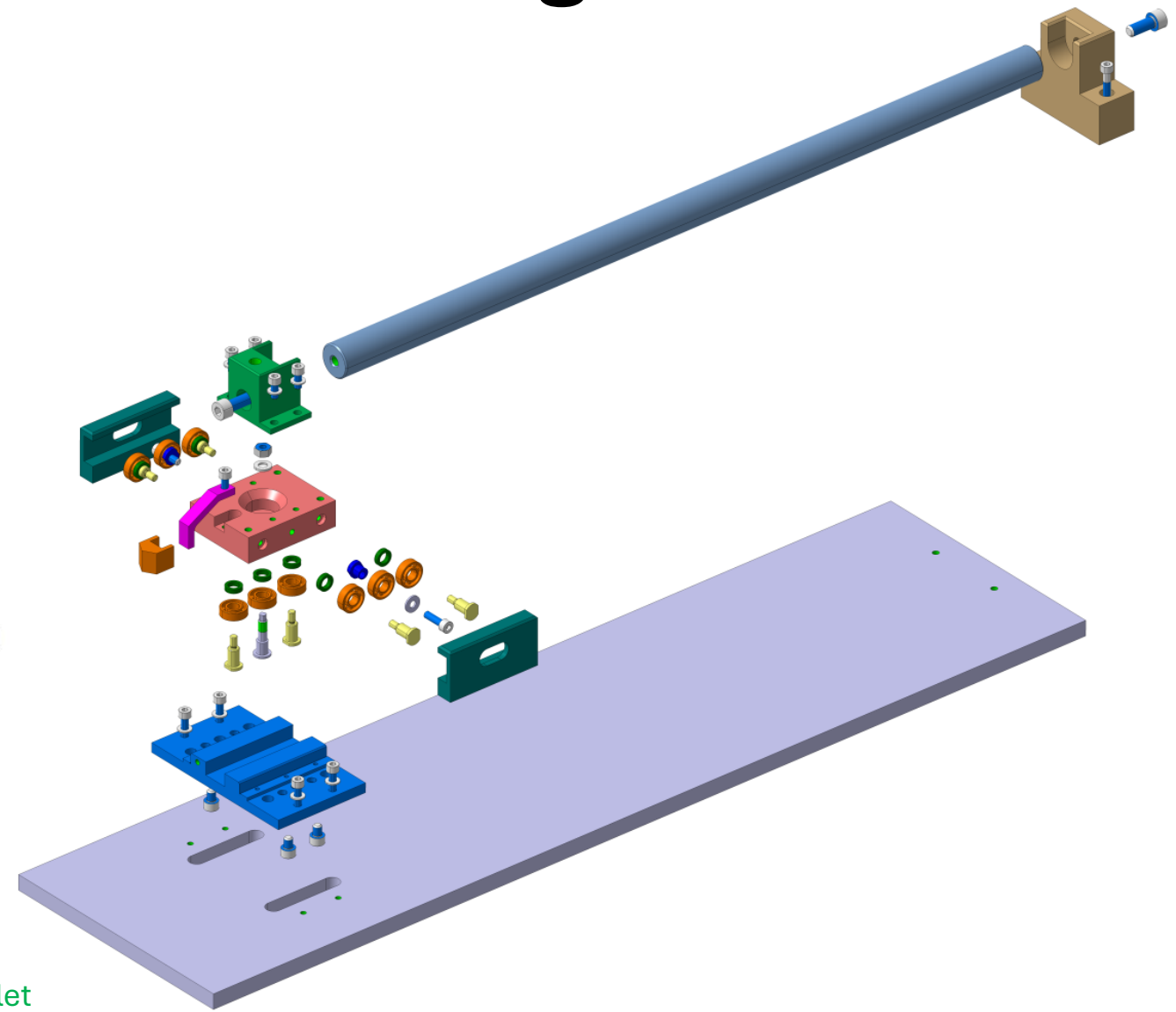
Mock-ups: Circular Ceramic Bearings





Courtesy of B. Pellet

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- Introduction and aim
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- **Racetrack coil mock-up**
- Flared-end coil mock-up
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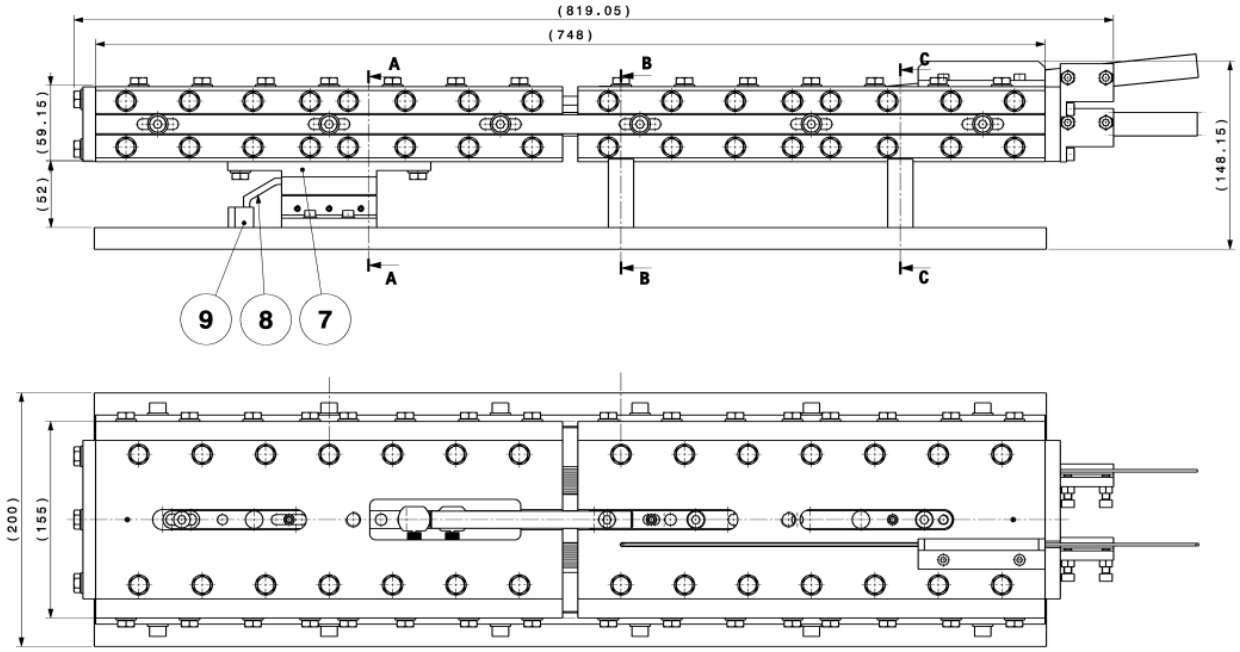
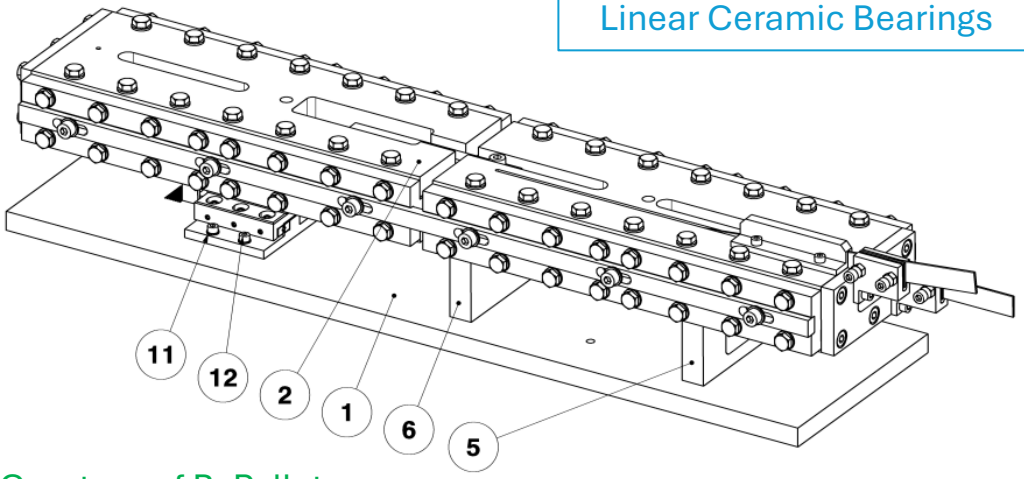
Racetrack coil mock-up

- Build a racetrack coil using a sectorized mold in order to
  - Test the sliding solution with a Nb_3Sn cable
  - Implement and test a gap measurement system
  - Have valuable inputs of the sliding phenomena for the design of BOND reaction mold
- This mock-up features
  - 2 modified MQXFB outer layer poles (gap between poles)
  - MQXFB insulated cable winding leftovers or flat MQXFB insulted cable: 10 turns (about 15m of cable)
  - Cable expansion assumption for the reaction mold cavity: 4.5% azimuthal and 1.2% radial (same as for MQXFB coils)
  - Sectorized mold (gap between the winding table/reaction plates) as for BOND
  - Implementation of a mechanical system to measure the longitudinal displacement of the floating pole and/or DIC measurements
- All the drawings are signed and the manufacturing started (parts foreseen for 05/25)

Racetrack coil mock-up



Linear Ceramic Bearings



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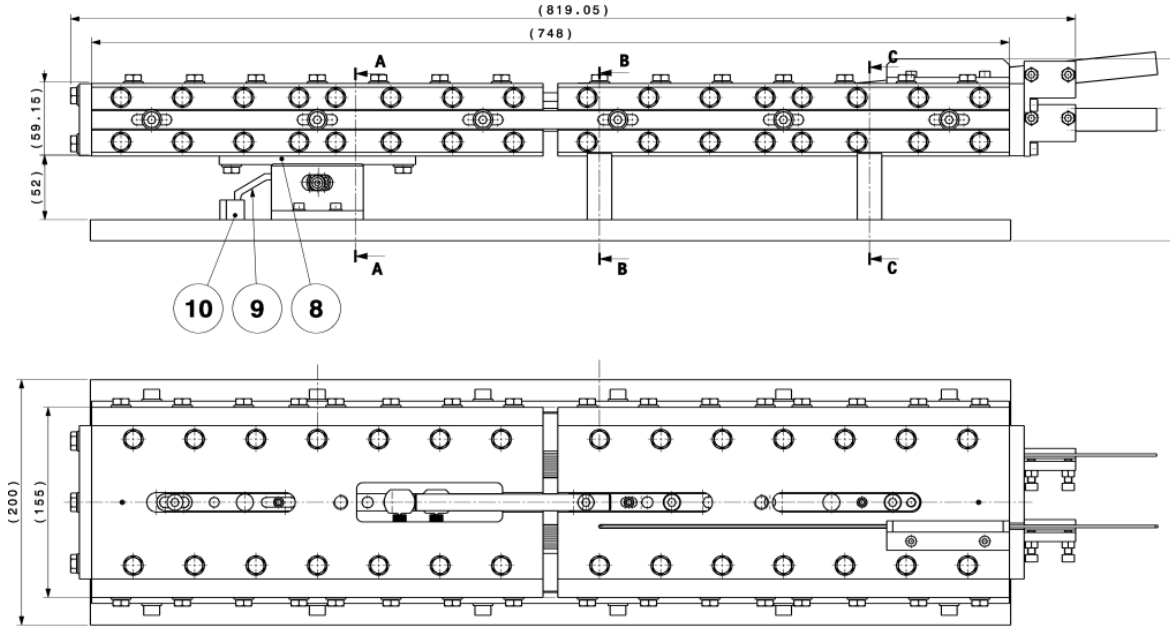
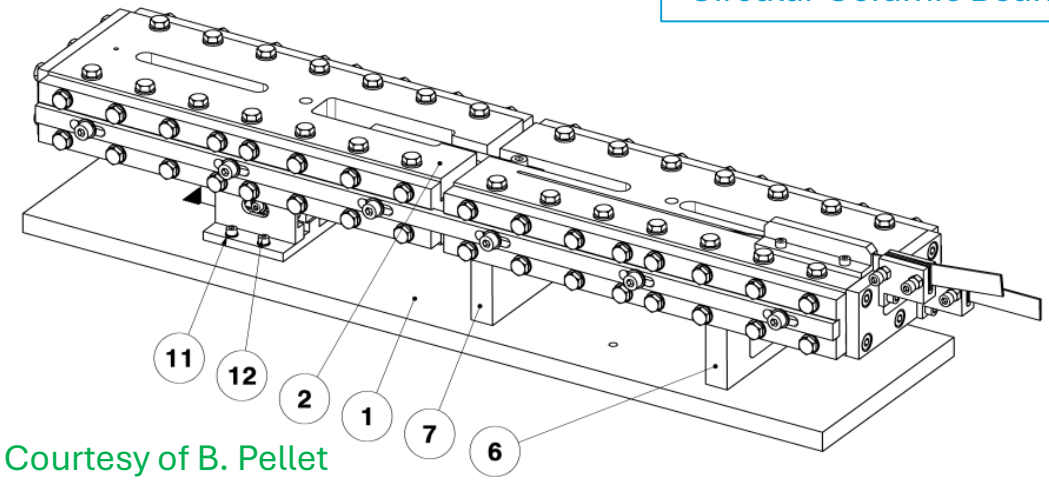


Circular Ceramic Bearings



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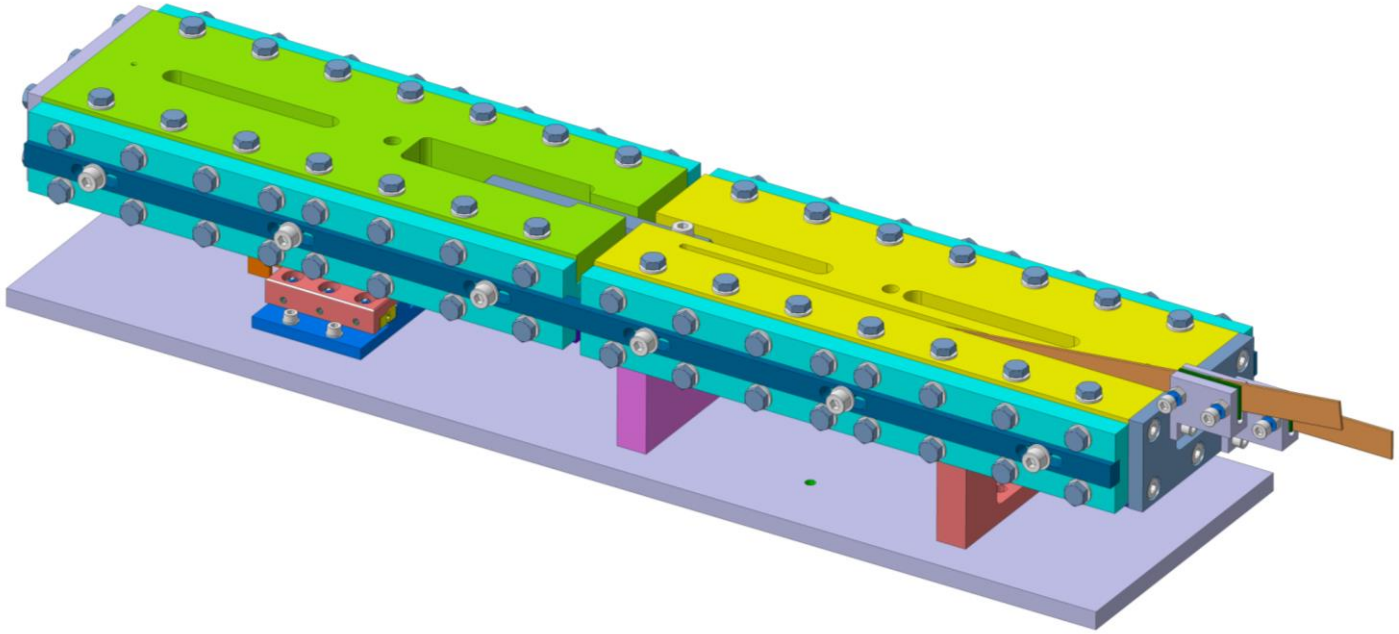
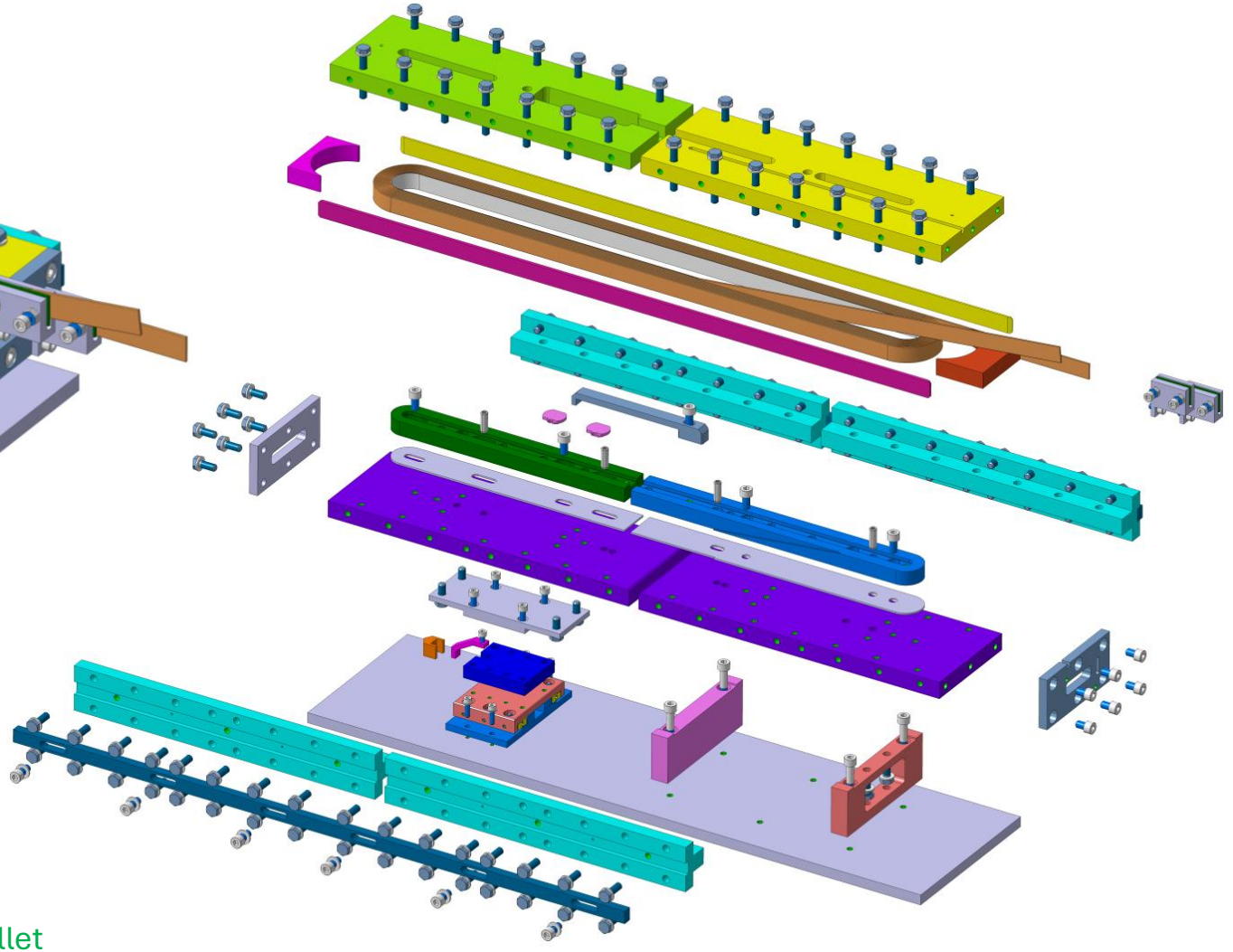
Racetrack coil mock-up

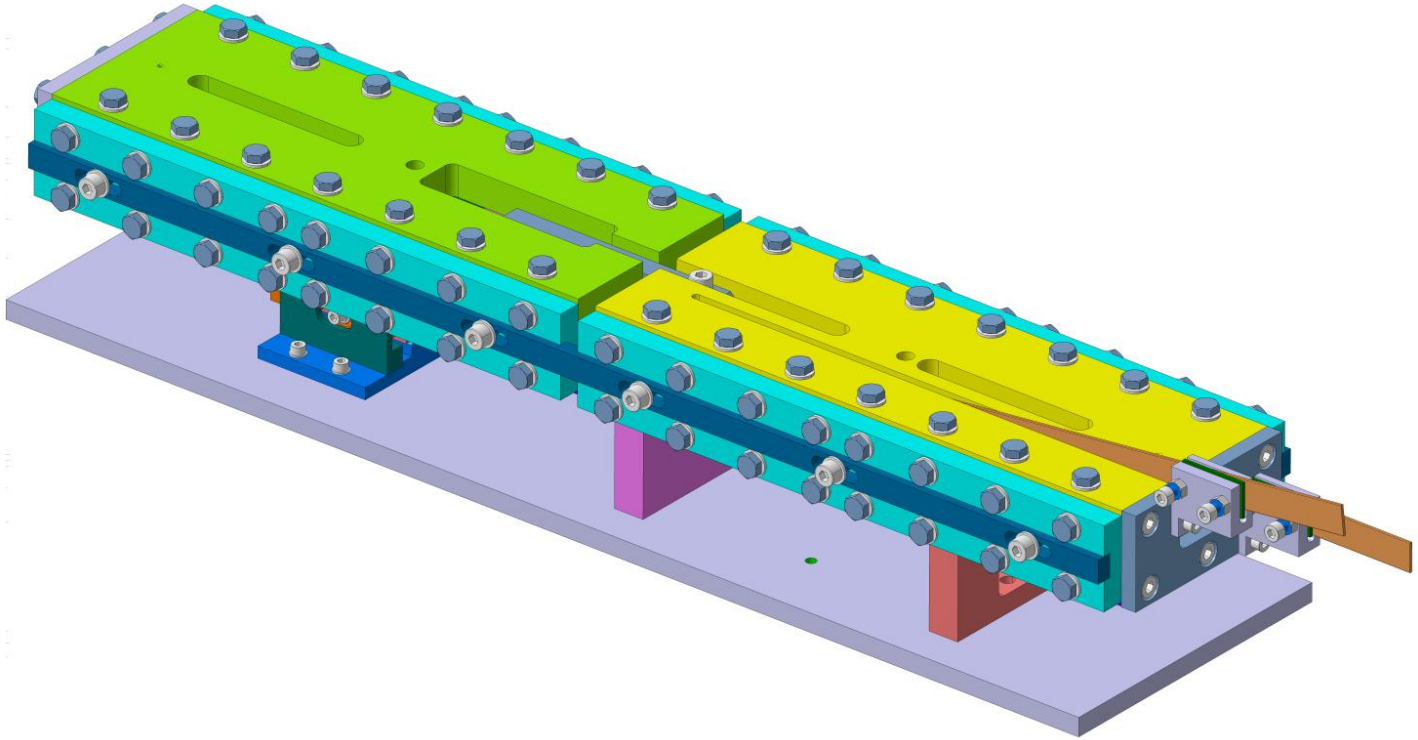


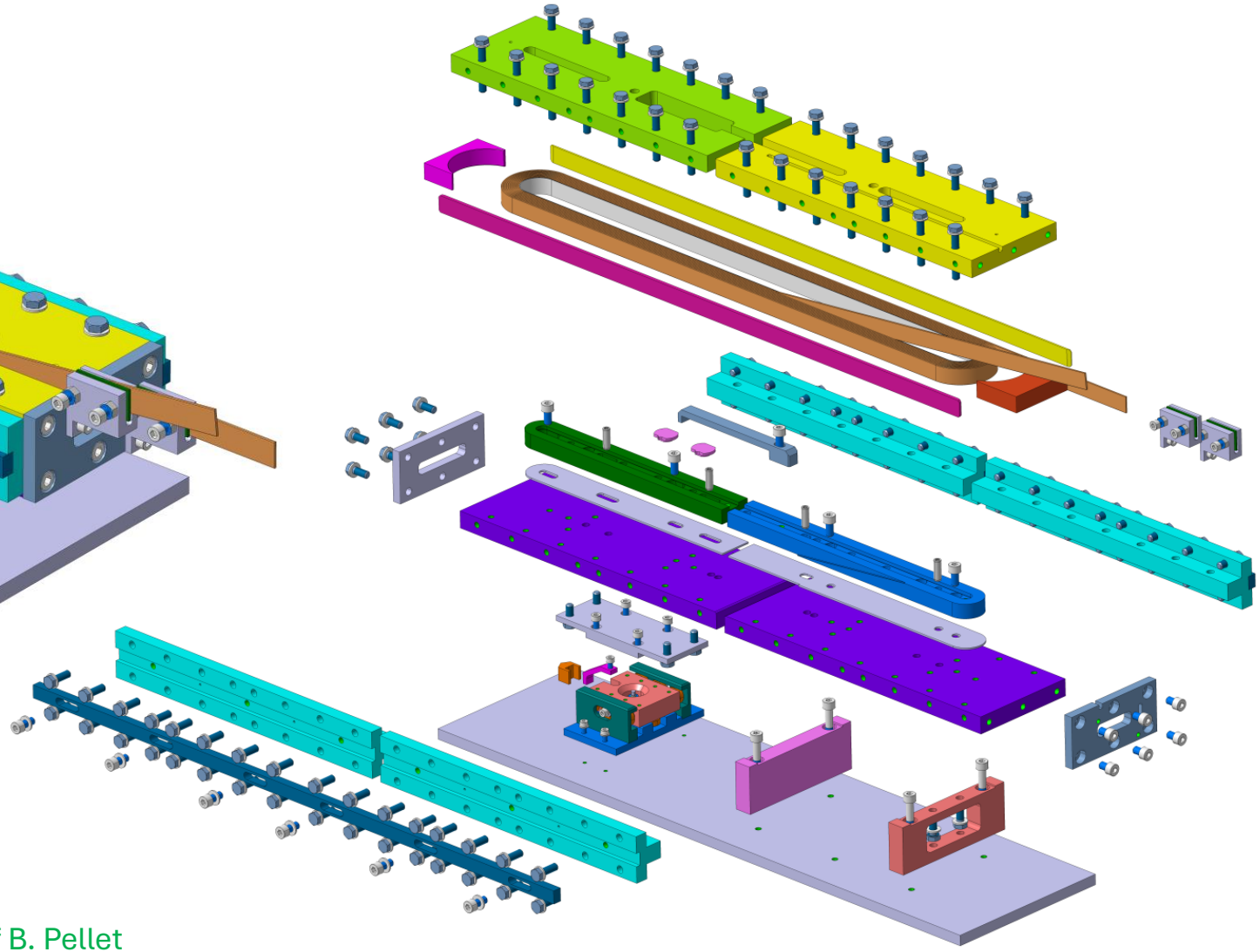


- Set-up suitable for both sliding systems (linear and circular ceramic bearings)

Courtesy of B. Pellet

Racetrack coil mock-up





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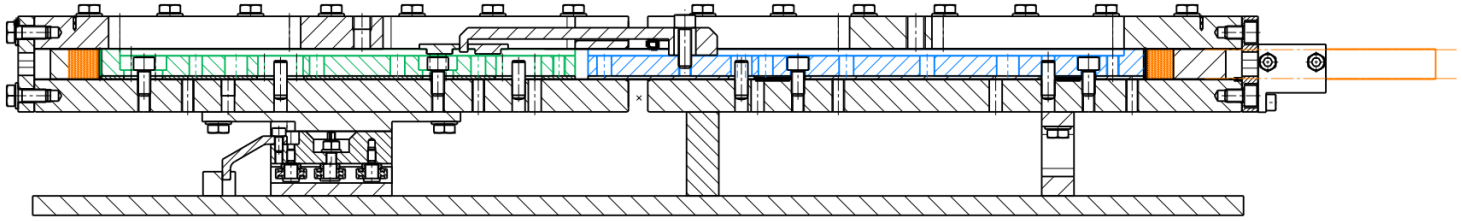
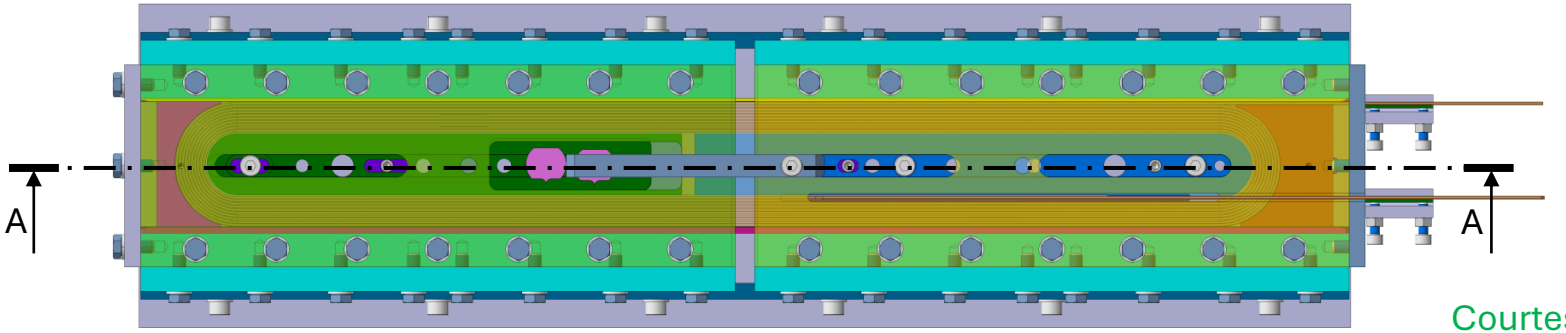
Courtesy of B. Pellet

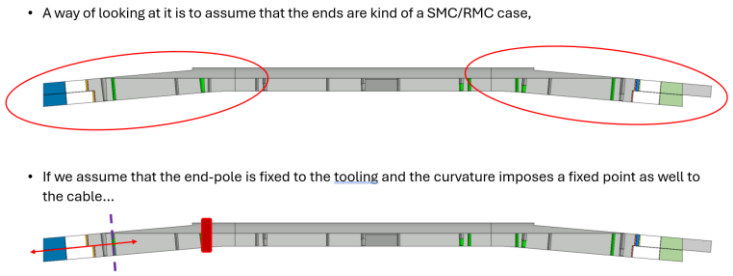
Racetrack coil mock-up

- Tests can be done to validate/explore different scenarios
  - 1 pole fixed and 1 pole completely free (just pinned to the base plate to ensure alignment) with gap between poles and 2-parts mold
    - Assuming no friction between the coil and the mold, the sliding system should not move or end the cycle in the same depart position
  - Both poles fixed to the base plates (and pinned for alignment) with gap between poles and 2-parts mold
    - Simulation of a fix point, the sliding system should move accordingly to the cable expansion/contraction

A-A







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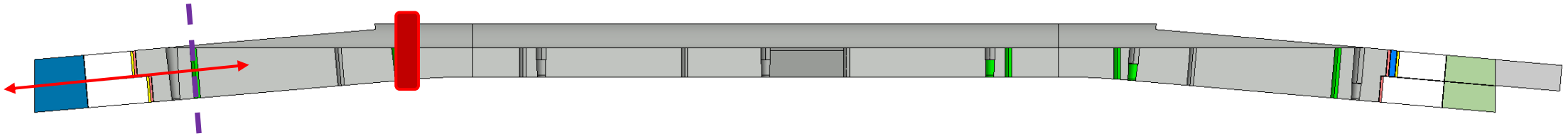
Flared-end coil mock-up

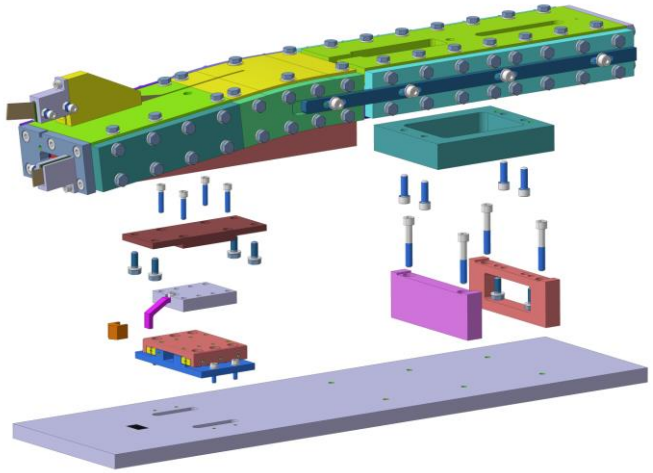
- The last stage of the mock-up program
  - The flared-ends represent a natural fixed point which cannot be simulated by the racetrack coil mock-up
    - How would the coil move during RHT?
    - Would we need to sectorize the end poles (magenta dashed line) to make the ends free to move?

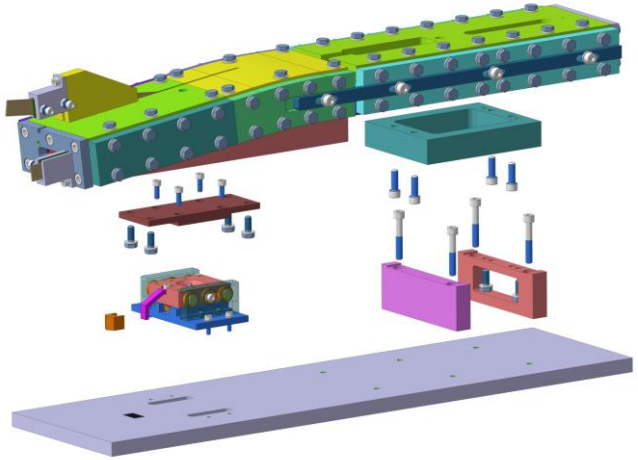


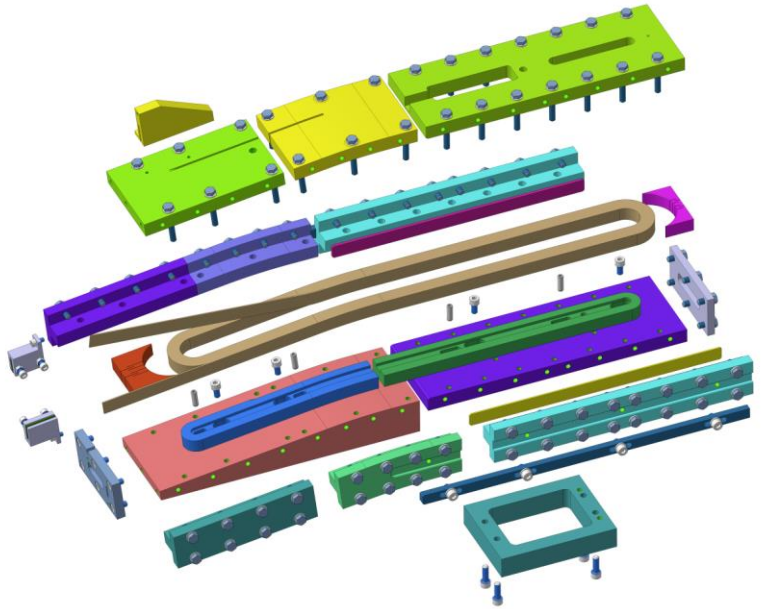
- This mock-up is an evolution of the racetrack coil mock-up
  - Take advantage as much as possible of the components manufactured for the racetrack coil mock-up
  - Manufacturing of 2 versions of the inclined pole
    - Monolithic pole
    - 2-parts pole
- 3D model almost finished

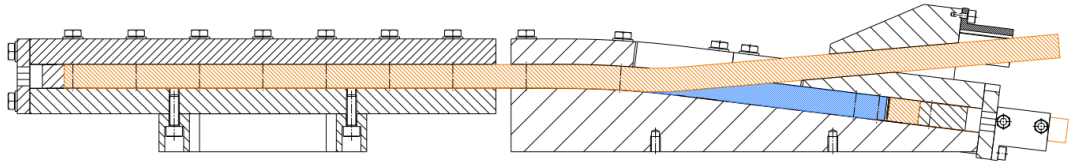
Flared-end coil mock-up

- Monolithic pole

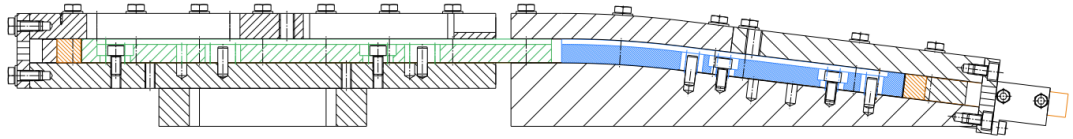








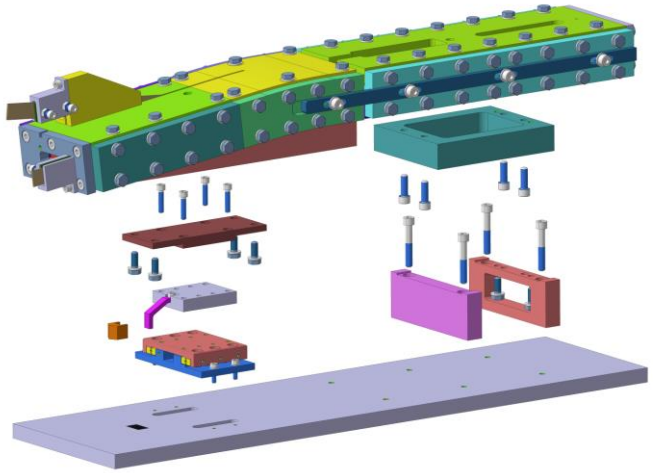
Coupe saut de couche, pole cc une partie

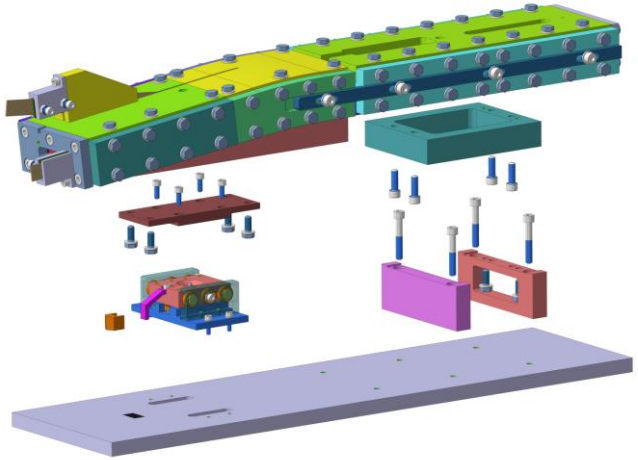


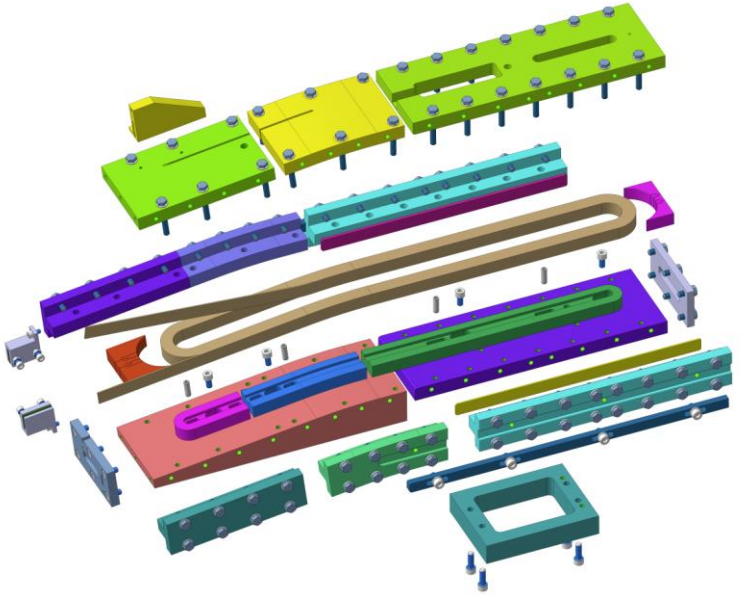
Coupe milieu, pole CC en une partie

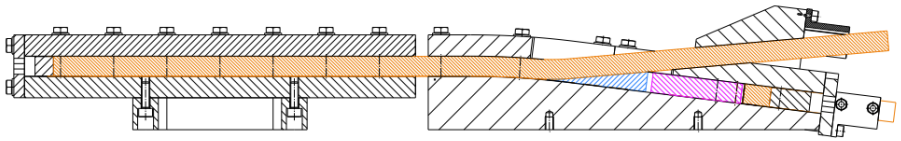
Flared-end coil mock-up

- 2-parts pole

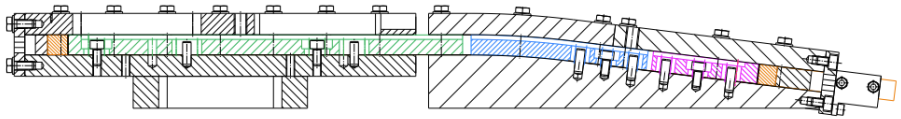








Coupe saut de couche, pole cc en deux parties



Coupe milieu, pole cc en deux parties

Outline

- Introduction and aim
- Selected solutions and basic mock-ups
- Racetrack coil mock-up
- Flared-end coil mock-up
- **Conclusion**

Conclusion

- The mock-up program development is a parallel activity whose goal is to provide the best sliding solution to implement to the reaction mold of BOND coils
- The studied sliding solutions are based on ceramic bearings
  - Linear ceramic bearings
  - Circular ceramic bearings
- The mock-up development is going through 3 consecutive steps:
  1. Basic mock-ups (with stainless steel bar)
     - Short cut to validate the assembly/behavior of the sliding solutions
     - Start testing displacement measurement systems
     - Parts under manufacturing (foreseen by the end of the week)
  2. Racetrack coil mock-up (made by 10 turns of Nb_3Sn insulated cable to make a flat coil, 1 layer)
     - Assess the behavior of the preferred sliding solution with a Nb_3Sn cable which expand/contract during the RHT cycle
     - Sectorized mold and poles (BOND concept) to compare gaps before/after the RHT cycle
     - Implement displacement measurement systems
     - Parts under manufacturing (foreseen by mid of May)
  3. Flared-end coil mock-up (made by 10 turns of Nb_3Sn insulated cable to make a coil with a flared-end, 1 layer)
     - Assess the impact of the flared-end on the gap evolution and on the coil behavior during RHT cycle
     - 3D design almost finished

Thank you

Spare slides

ZrO_2 properties (supplier datasheet)

MATERIAL PROPERTIES STANDARD 2000

	Properties *		Units	Test	Porcelain	Mullite	ALUMINA AD-85	ALUMINA AD-90	ALUMINA AD-94	ALUMINA AD-96	ALUMINA FG-995	ALUMINA AD-995	ALUMINA AD-998	ZIRCONIA AZ-25	ZIRCONIA ZTA	ZIRCONIA TTZ	ZIRCONIA YTZP	CARBIDE SCNB	CARBIDE SCRB	CARBIDE SC-30	CARBIDE WC
						$3Al_2O_3 * 2SiO_2$	Nom. 85% Al_2O_3	Nom. 90% Al_2O_3	Nom. 94% Al_2O_3	Nom. 96% Al_2O_3	Nom. 98.5% Al_2O_3	Nom. 99.5% Al_2O_3	Nom. 99.8% Al_2O_3	Alumina-Zirconia Composite	Zirconia-Toughened Alumina	MgO Partially Stabilized Zirconia	Y_2O_3 Partially Stabilized Zirconia	Nitride Bonded Silicon Carbide	Reaction Bonded Silicon Carbide	Direct Sintered Silicon Carbide	Tungsten Carbide
MECHANICAL	Density		gms/cc	ASTM-C20	2,40	2,80	3,42	3,60	3,70	3,72	3,80	3,90	3,92	3,82	4,05	5,72	6,02	2,60	3,10	3,15	14,90
	Crystal Size	Average	MICRONS	THIN-SECTION	-	10	6	4	12	6	6	6	6	5	2	35	1	-	12	5	2
	Water Absorption		%	ASTM-373	0	0	0	0	0	0	0	0	0	1	0	0	0	8	0	0	0
	Gas Permeability		-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	-	0	0	0
	Color		-	-	WHITE	TAN	WHITE	WHITE	WHITE	WHITE	WHITE	IVORY	IVORY	WHITE	WHITE	IVORY	IVORY	GRAY	BLACK	BLACK	GRAY
	Flexural Strength (MOR)	20° C	MPa (psi X 10^3)	ASTM-F417	130 (19)	170 (25)	296 (43)	338 (49)	352 (51)	358 (52)	375 (54)	379 (55)	375 (54)	172 (25)	450 (65)	620 (90)	900 (130)	48 (7)	462 (67)	480 (70)	1930 (280)
	Elastic Modulus	20° C	GPa (psi X 10^6)	ASTM-C848	104 (15)	150 (22)	221 (32)	276 (40)	303 (44)	303 (44)	350 (51)	370 (54)	370 (54)	-	360 (52)	200 (29)	210 (30)	152 (22)	393 (57)	410 (59)	627 (91)
	Poisson's Ratio	20° C	-	ASTM-C848	-	-	0,22	0,22	0,21	0,21	0,22	0,22	0,22	-	0,23	0,30	0,23	-	0,19	0,21	-
	Compressive Strength	20° C	MPa (psi X 103)	ASTM-C773	590 (86)	550 (80)	1930 (280)	2482 (360)	2103 (305)	2068 (300)	2500 (363)	2600 (377)	2500 (363)	2310 (335)	2900 (421)	1750 (254	2500 (363)	140 (20)	2500 (363)	3500 (507)	5000 (725)
	Hardness		GPa (kg/mm^2)	KNOOP 1000gm ROCKWELL 45 N	5.9 (600) 60	7.4 (750) 70	9.4 (960) 73	10.4 (1058) 75	11.5 (1175) 78	11.5 (1175) 78	13.7 (1400) 82	14.1 (1440) 83	14.1 (1440) 83	10.4 (1058) 75	14.4 (1475) 85	11.8 (1200 77	12.7 (1300) 81	-	24.5 (2500) -	27.5 (2800) -	-
	Tensile Strength	25° C	MPa (psi X 103)	ACMA TEST # 4	-	-	155 (22)	221 (32)	193 (28)	221 (32)	248 (36)	262 (38)	248 (36)	-	290 (42)	352 (51)	-	-	307 (44.5)	-	-
	Fracture toughness		Mpa m 1/2	NOTCHED BEAM	2	2	3-4	3-4	4-5	4-5	4-5	4-5	4-5	5-6	5-6	11	13	-	4-5	4-5	-
THERMAL	Thermal Conductivity	20° C	W/m K	ASTM-C408	5,0	3,5	16,0	16,7	22,4	24,7	27,5	30,0	30,0	13,0	27,0	2,2	2,2	80,0	125,0	150,0	100,0
	Coefficient of Thermal Expansion	25-1000° C	1X 10^{-6}/°C	ASTM-C372	9,5	5,3	7,2	8,1	8,2	8,2	8,2	8,2	8,2	8,5	8,3	10,1	10,3	3,9	4,3	4,4	5,1
	Specific Heat	100° C	J/kg°K	ASTM-E1269	-	950	920	920	880	880	880	880	880	-	885	400	400	-	700	-	-
	Thermal Shock Resistance	ΔTc	°C	NOTE 3	-	300	300	250	250	250	200	200	200	500	300	350	350	400	400	300	-
	Maximum Use Temperature		°C	NO-LOAD COND.	1400	1700	1400	1500	1700	1700	1700	1750	1750	1400	1500	500	1500	1600	1400	1750	1000
ELECTRICAL	Dielectric Strength		ac-kV/mm (ac V/mil)	ASTM-D116	-	9.8 (248)	9.4 (240)	8.3 (210)	8.3 (210)	8.3 (210)	8.7 (220)	8.7 (220)	8.7 (220)	-	9.0 (228)	9.4 (240)	9.0 (228)	-	-	-	-
	Dielectric Constant	1 MHz	25° C	ASTM-D150	5,9	6,0	8,2	8,8	9,1	9,0	9,6	9,7	9,8	9,8	10,6	29,0	29,0	-	-	-	-
	Dielectric Loss (tan delta)	1 MHz	25° C	ASTM-D2520	0,0024	0,0020	0,0009	0,0004	0,0004	0,0002	0,0001	0,0001	0,0001	0,0010	0,0005	0,0010	0,0010	-	-	-	-
	Volume Resistivity	25° C	ohm-cm	ASTM-D1829	-	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{13}$	$>10^{14}$	$>10^{13}$	$>10^{13}$	-	$<10^3$	$>10^5$	$<10^3$
		500° C	ohm-cm	ASTM-D1829	-	$5X10^{12}$	$4X10^8$	$4X10^8$	$4X10^9$	$4X10^9$	$2X10^{10}$	$2X10^{10}$	$2X10^{10}$	$5X10^7$	$2X10^9$	$2X10^4$	$2X10^4$	-	$<10^3$	$<10^3$	$<10^3$
		1000° C	ohm-cm	ASTM-D1829	-	$3X10^5$	-	$5X10^5$	$5X10^5$	$5X10^5$	$2X10^6$	$2X10^6$	$2X10^7$	$<10^3$	$3X10^6$	$<10^3$	$<10^3$	-	$<10^3$	$<10^3$	$<10^3$
WEAR	Impingement		-	NOTE 4	-	-	1,00	0,45	0,52	0,50	0,48	0,47	0,47	-	0,41	0,63	0,20	-	0,14	-	0,04
	Rubbing		-	NOTE 4	-	-	1,00	0,04	-	0,60	-	-	-	-	0,49	0,57	0,20	-	0,20	-	0,16

This chart is intended to illustrate typical properties of advanced ceramic materials available from Coors Ceramics Company. The designer should recognize that exact properties may vary according to product configuration and can sometimes be tailored to meet specific requirements.

Contact Coors Ceramics Company for cost-effective design, development and manufacturing assistance. The information set forth herein is offered for comparison only, and is not to be construed as absolute engineering data or constituting a warranty or representation for which we assume legal responsibility.

Notes:

1. DATA MEASUREMENTS -
   All data measurements are typical and made at room temperature unless otherwise noted.

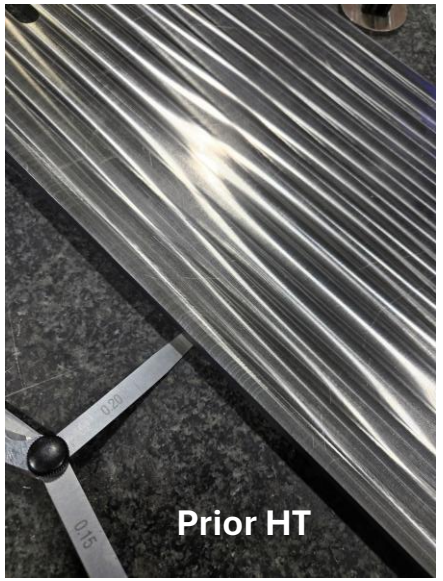
2. COMPOSITION CONTROL -
   All Coors ceramic compositions are controlled using modern chemical, spectographic, and X-ray fluorescent methods.

3. THERMAL SHOCK RESISTANCE -
   Tests are run by quenching samples into water from various elevated temperatures. The change in temperature where a sharp decrease in flexural strength is observed is listed as Tc.

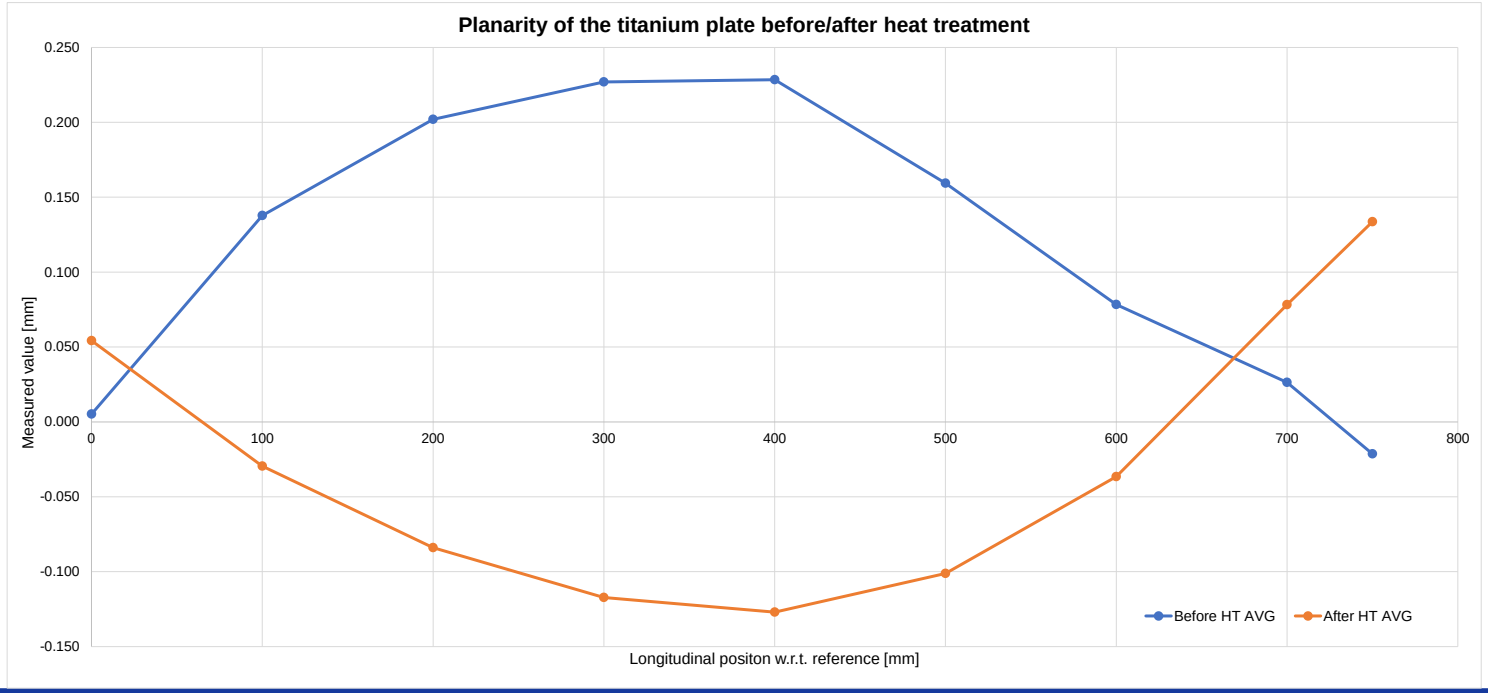
4. WEAR RESISTANCE -
   Impingment tests are run using a dry fused alumina abrasive. Rubbing tests are run using a dry 240 grit fused alumina abrasive. The indices in the chart are calculated by dividing the material volume loss by the volume loss of a AD-85 alumina control. The lower in the index, the better the wear resistance.

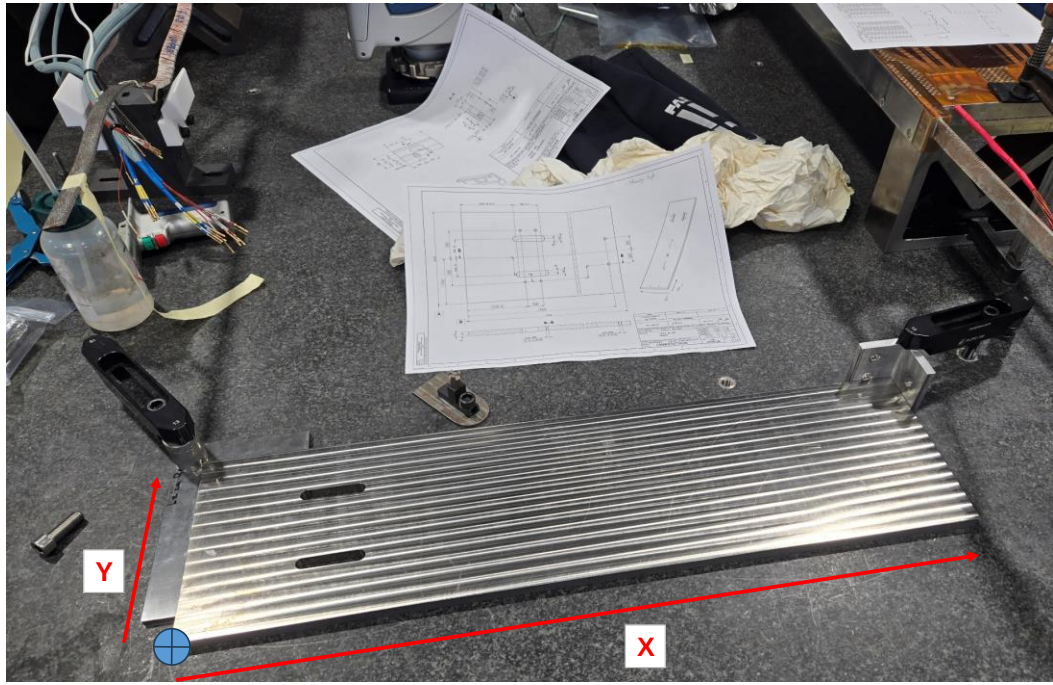
Metrology of the plate before/after HT

- The plate is checked with dial gauge
  - <u>Prior HT</u>
    - The plate has a belly shape with a maximum of about 0.280 mm towards the middle
    - It is not something local, but the deformation is general
  - <u>After HT</u>
    - The plate deformed in the opposite direction due to release of internal tensions
    - The HT cycle was effective and needed prior to perform the finishing



Courtesy of A. Vieitez Suarez





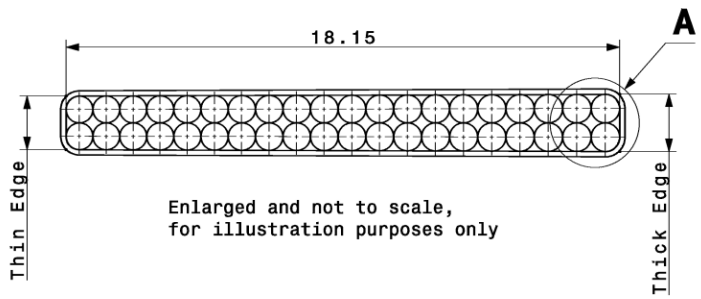
Racetrack coil mock-up

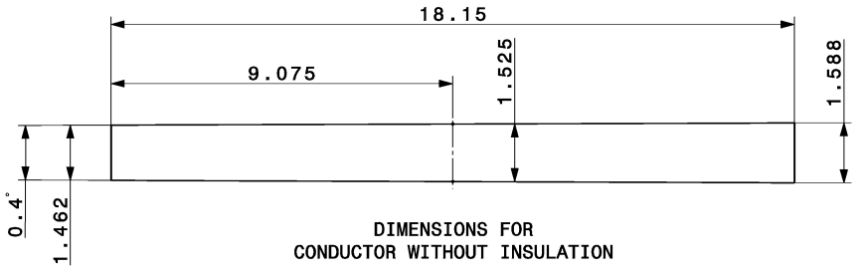
- Insulated cable reference parameters in the table below from drawing LHCMQXFBC0057
- Based on expansion coefficient assumptions:
  - 4.5% azimuthal
  - 1.2% radial

UNREACTED CABLE DIMENSIONS	
Strand Type	Nb3Sn
Strand Diameter	0.85mm
Number of strands	40
Width	18.15mm
Mid-thickness	1.525mm
Keystone Angle	0.4º
(Thin Edge Height)	(1.462mm)
(Thick Edge Height)	(1.588mm)
Inner Core	12mm x 25μ
INSULATION THICKNESS	
S-2 Glass Braided Sleeve	0.145mm ±0.005 (Thickness is measured in compressed state under 5MPa)

18.36mm (reacted bare cable) → 18.65mm (insulated reacted cable)

1.594mm (reacted bare cable) → 1.884mm (insulated reacted cable)





Some comments on gaps

- For the first-order assessment of the required gaps, we follow a similar logic than for TFD (see J.L. Rudeiros presentation).

Main parameters

$C_{c,wt}$ Contraction due to the relaxation of winding tension (about 0.05% - 0.1% ?)
$C_{c,r}$ Contraction due to reaction (about 0.35% - see next slide)
$C_{e,cable}$ Expansion of the cable at 650 °C (about 0.2 % - see next slide)

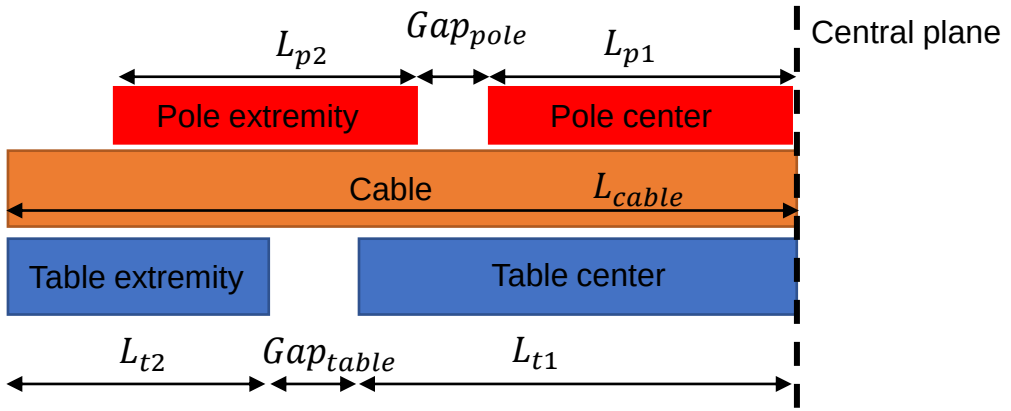
Pole

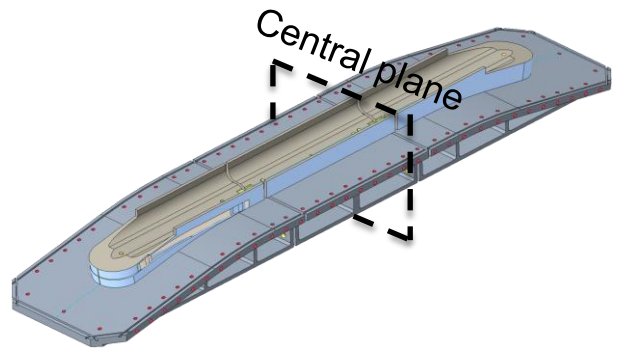
$$\begin{cases} Gap_{pole,0} \geq L_{cable}\left(C_{c,r} + C_{c,wt}\right) \sim 3.4\ mm \\ Gap_{pole,r} \geq \alpha_{Ti}\left(L_{p1} + L_{p2}\right)\Delta T\ - L_{cable}C_{e,cable} < 3.4\ mm \end{cases}$$

Table

$$\begin{cases} Gap_{table,0} \geq L_{table}\left(C_{c,r} + C_{c,wt}\right) \sim 3.4\ mm \\ Gap_{table,r} \geq \alpha_{ss}\left(L_{p1} + L_{p2}\right)\Delta T\ - L_{cable}C_{e,cable} \sim 7\ mm \end{cases}$$

Assuming SS 316

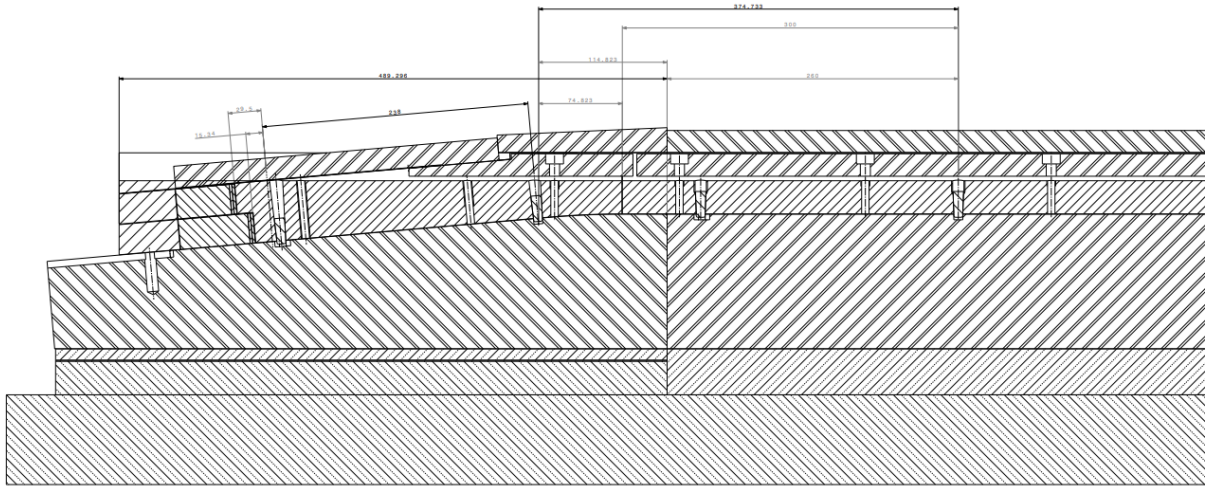


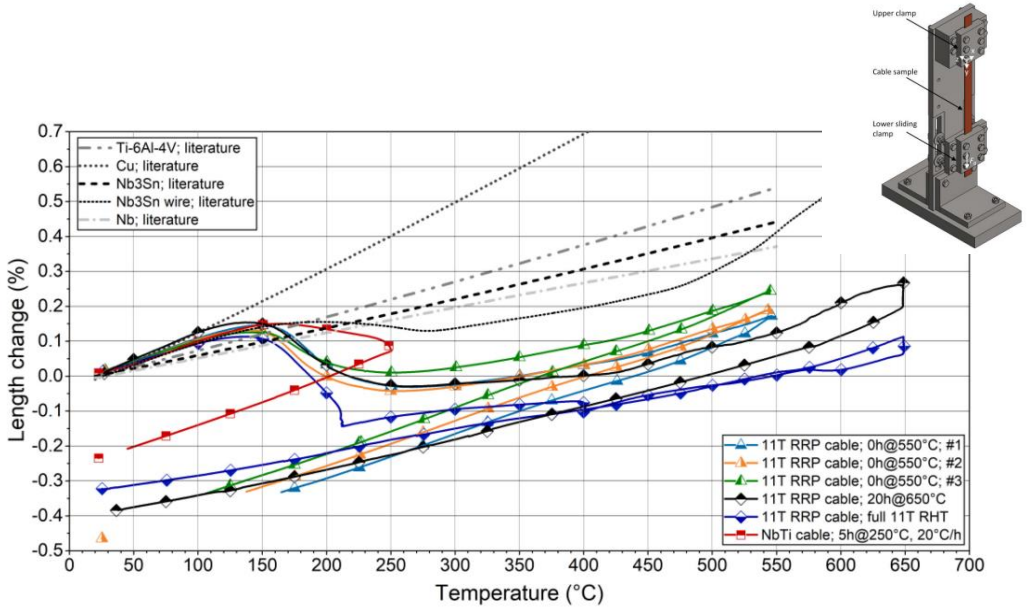


** Without considering the change in coil length after releasing winding tension

* Courtesy of Jose Luis Rudeiros

Some comments on gaps



Length Changes of Unconfined Nb_3Sn Rutherford Cables During Reaction Heat Treatment

Matthias Michels, Friedrich Lackner, Christian Scheuerlein, Alejandro Carlon Zurita, Salvador Ferradas Troitino, Nicolas Bourcey, Frederic Savary, and Davide Tommasini