Simulations, Design and prototyping of the BPM buttons for SOLEIL II

Nicolas HUBERT 11/12-12-2024

Button BPMs Workshop, ALBA Synchrotron

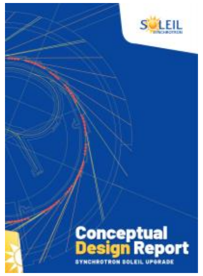
SOLEIL SYNCHROTRON

SOLEIL II
La science éclaire l'avenir
Science lights up the future

SOLEIL II Project and Timeline

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035

CDR



TDR

- **Definition of deliverables**
- **Budget profile**
- **Machine specifications**
- Specs for Call For Tenders
- **Consolidated plan for infrastructure**
- **Experimental floor**
- Plan for beamline moves and restart
- **Project Management Organisation**

Shutdown

Stage 1: Construction

- Decommissioning of the current machine
- A new machine in operation
- Restart of all beamlines
  7-10 upgraded + 19 adapted BLs
- Upgrade of support laboratories
- R&D on enabling technologies

Stage 2: Towards full performances

- Full upgrade of the remaining 19 beamlines
- Upgraded support laboratories – Completion
- R&D programme on enabling technologies – Cont.

- Shutdown + commissioning: 24 months (restart of user program)
- Stage 1: 6 years
- SOLEIL II budget: ~ 309 M€ (inc. 15% contingency)
  → 252 M€ (Ministry-LPR) + (57M€ from savings and members)
  - Stage 1 (6 years): ~ 186 M€ (42 M€)
  - Stage 2 (5 years): ~ 123 M€ (15 M€)

2025-2026: 50 M€ in line with the spending profile

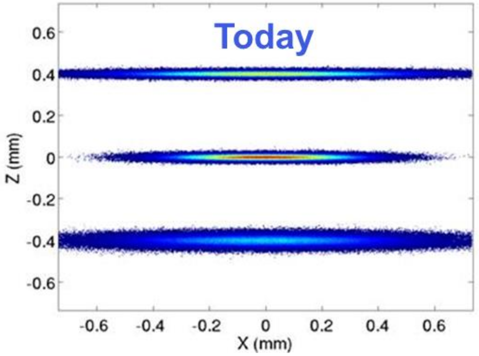
SOLEIL II La science éclaire l'avenir Science lights up the future

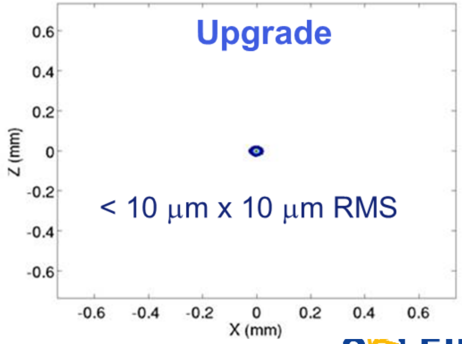
SOLEIL II Storage Ring Key Features

1. **Non-standard MBA lattice: 12 x 7BA + 8 x 4BA / 2.75 GeV / 354 m / 500 mA**
2. **~83 pm.rad (~53 pm.rad round beam as ultimate goal).**
3. **22 straight sections (7 different lengths).**
4. **Large photon spectrum (far IR to hard X-rays).**
5. **NEG coated very small vacuum chamber diameter (12 mm)**
6. **Extensive use of permanent magnets (all dipoles, RB and main quadrupoles).**
7. **Miniaturization.**
8. **Off-axis injection.**
9. **High performance Multipole Injection Kicker (MIK).**
10. **Energy savings and reduced energy footprint.**

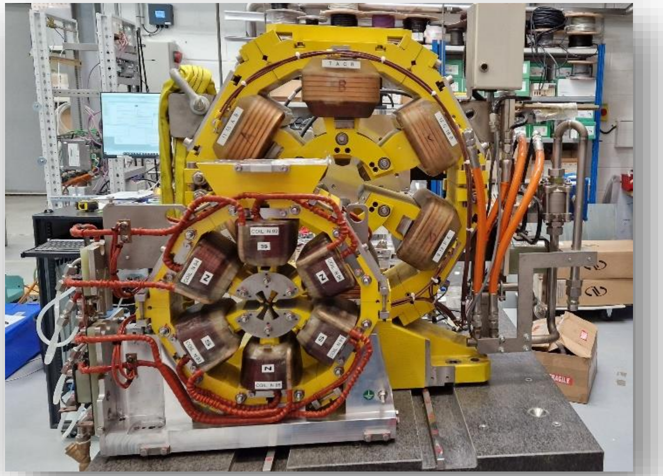
\+

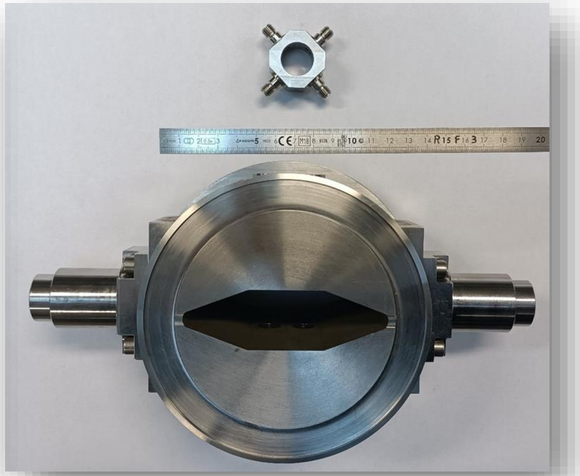
LINAC upgrade
New low-emittance Booster
Innovative Insertion Devices






Quadrupole SOLEIL/SOLEIL II


Sextupole SOLEIL/SOLEIL II

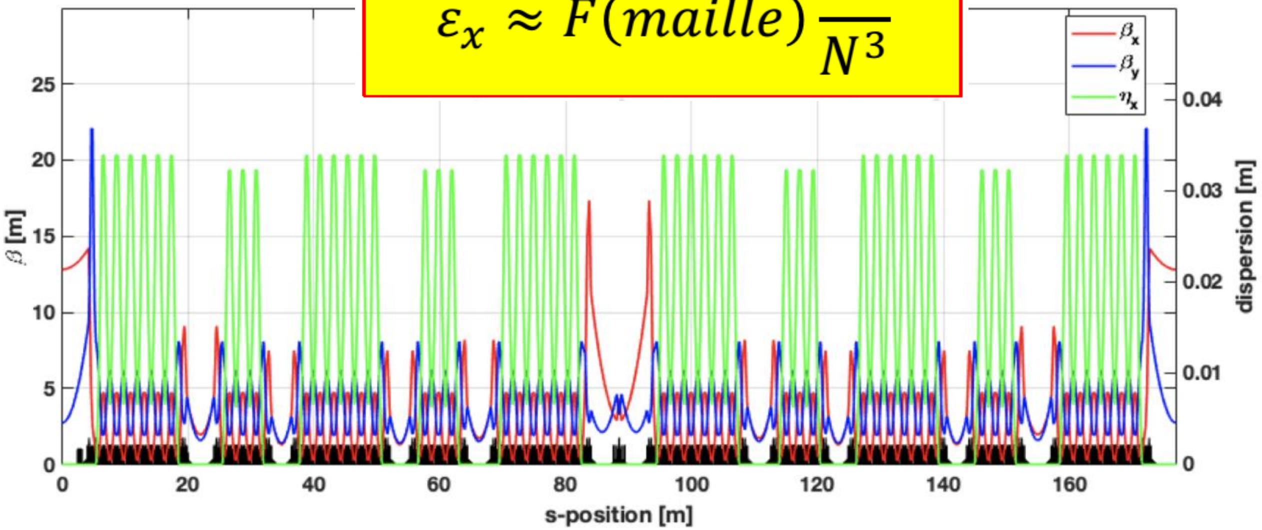

BPM vacuum chamber SOLEIL/SOLEIL II

SOLEIL II Storage Ring Key Parameters

Upgrade Project of the SOLEIL Accelerator Complex, SRN, 2023
https://doi.org/10.1080/08940886.2023.2186661
A brief introduction to the Synchrotron SOLEIL and its upgrade programme. *Eur. Phys. J. Plus* **139**, 80 (2024).
https://doi.org/10.1140/epjp/s13360-024-04872-2

29 beamlines **1 CRYO-EM microscope**

$$\varepsilon_x \approx F(maille)\frac{E^2}{N^3}$$



Twiss functions (horizontal and vertical beta function in red and blue. horizontal dispersion in green) along half of the SOLEIL II storage ring circumference.

1-fold symmetry when introducing a chicane for 2 canted long ID beamlines

Parameters	SOLEIL	SOLEIL II
Energy [GeV]	2.75	2.75
Circumference [m]	354.10	353.97
Maximum Beam Current [mA]	500	500
Lattice Type	DBA	**7BA-4BA**
Cell Number	24	20
Natural Emittance [pm.rad] Round beam (100% coupling)	**3 900** **-**	**83** **53**
Energy Spread	1.02 E-3	0.91 E-3
Natural RMS Bunch Length [ps]	16.1	8.6
Transverse Damping Times, $\tau_x/\tau_y/\tau_s$ [ms]	6.9 / 6.9 / 3.5	7.8 / 14.3/ 12.4
Momentum Compaction Factor	4.2 E-4	1.06 E-4
Energy Loss per Turn [keV]	917	453
Overall RF Voltage [MV]	2.6	1.8
RF Frequency [MHz]	352.20	352.33
RF Power into the Beam [kW]	575	245
Synchrotron Frequency [kHz]	4.2	1.8

Parameters without insertion devices nor harmonic cavity

La science éclaire l'avenir
Science lights up the future

SOLEIL II BPM specifications

- Guidelines:
  - Resolution at nominal current for user operation
  - Signal level at low current for optimum resolution during first turns
  - Extreme Stability

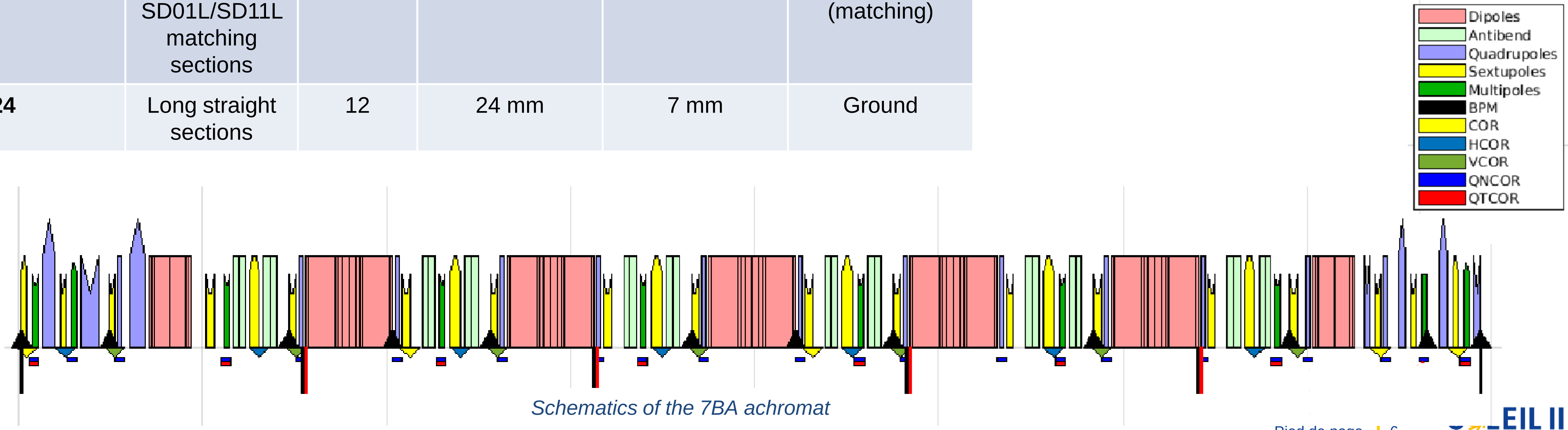
Type	Data	Spec.	Conditions
Resolution	Fast acquisition (~100 kHz, DC-2kHz bandwidth)	100 nm rms	Nominal current / Nominal filling pattern (500 mA / 416 bunches)
	Turn by Turn	1 µm rms	
		100 µm rms	0.1-1 mA in 1 quarter (commissioning)
	Slow Acquisition (~10 Hz)	1 µm rms	
Beam Current Dependence	-	10 µm	From 0.1 mA – to nominal current
Absolute accuracy	-	< 500 µm	Before BBA
		< 5 µm	After BBA
Long term Stability	-	500 nm	Day drift
		1 µm	Week drift

SOLEIL II BPM Types

- A large number of BPM types:

SOLEIL II BPMs	Location	Nb. of units	Chamber inner diameter	Button diameter	Fixation
BPM16	Arcs	128	16 mm	6 mm	Girder
	Arcs, behind BM source points	16			Welded on dipole vacuum chamber
BPM20	Standard straight and SD01L/SD11L matching sections	40	20 mm	7 mm	Ground (SS) or girder (matching)
BPM24	Long straight sections	12	24 mm	7 mm	Ground

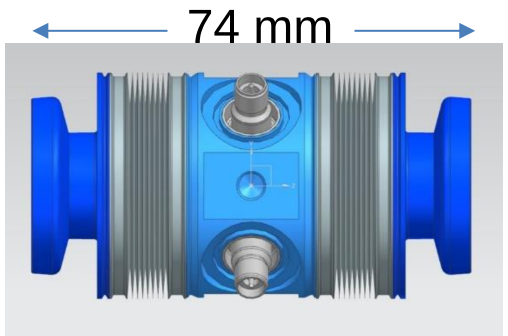
Guidelines for highest stability:
- All BPMs in the shadow of SR: **enlarged tapered sections**
- **BPM is a fixed point:**
  - Dedicated rigid support
  - Bellows to minimize constraints form VC.

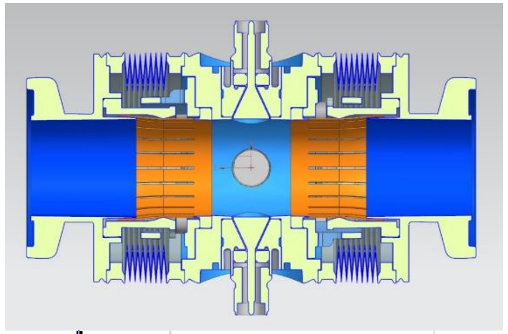


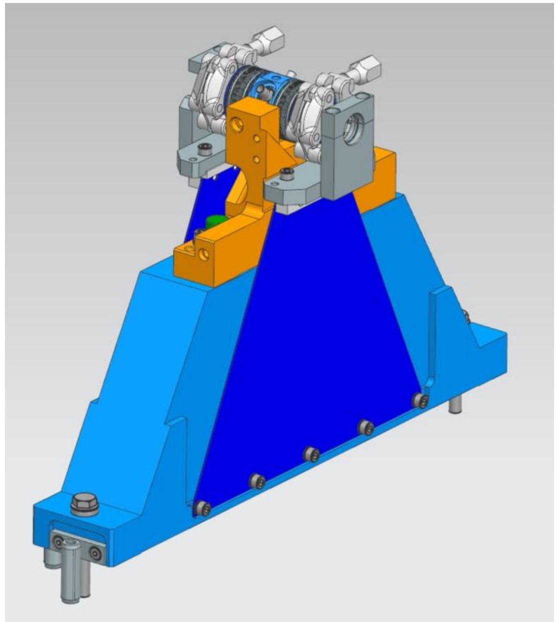
Schematics of the 7BA achromat

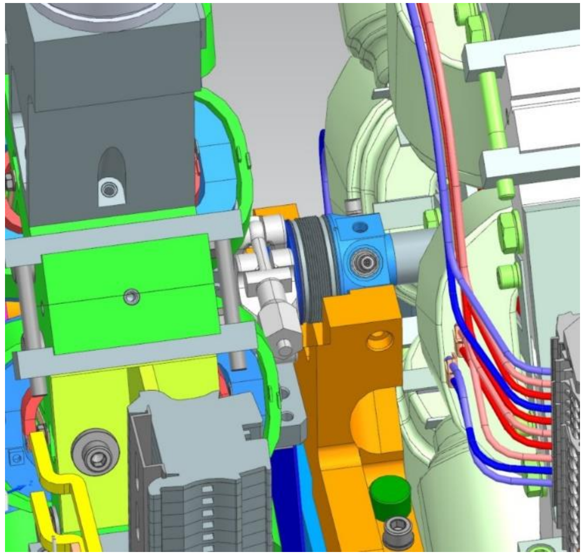
SOLEIL II BPM Types

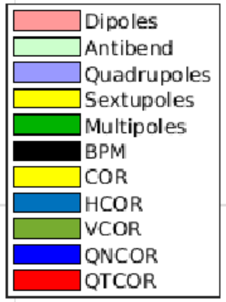
- A large number of BPM types:
  - Standard arc BPM16 (x128): **ultracompact** with two bellows

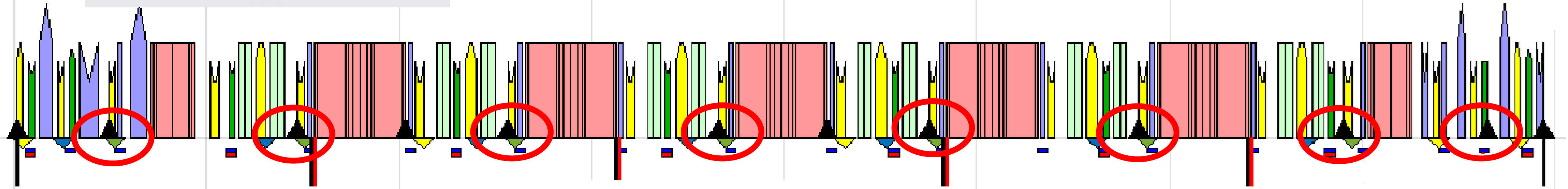








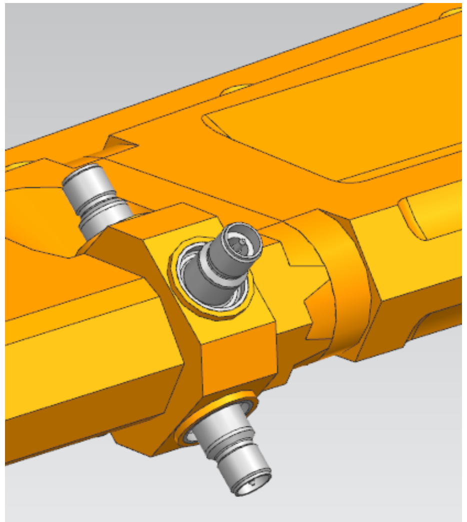


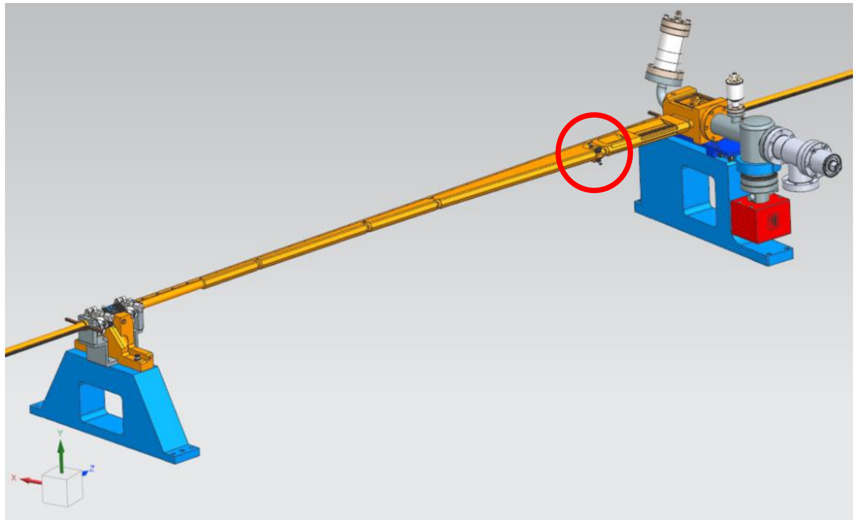


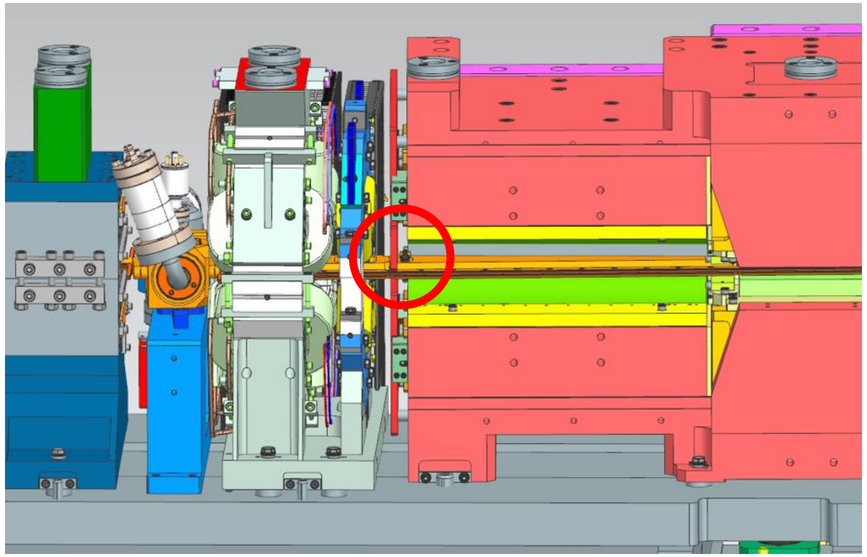
Schematics of the 7BA achromat

SOLEIL II BPM Types

- A large number of BPM types:
  - Additional arc BPM16 (x16): **Welded** on the dipole vacuum chamber



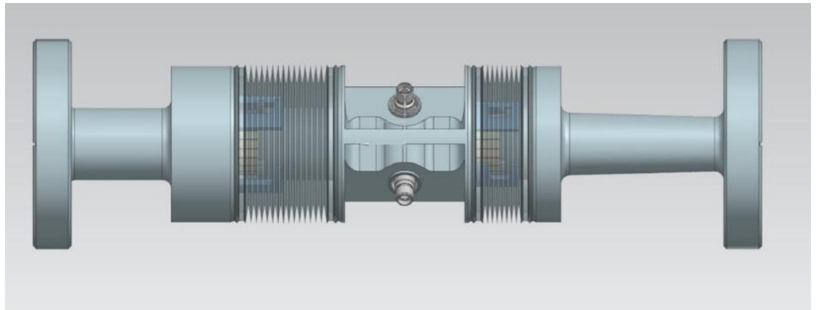


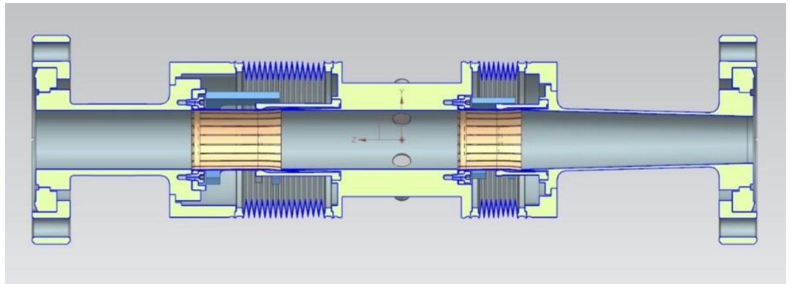


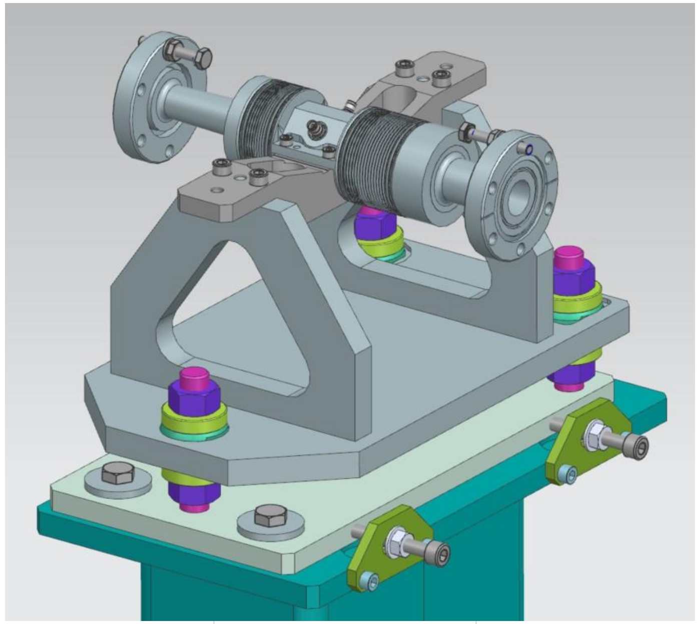
Schematics of the 7BA achromat

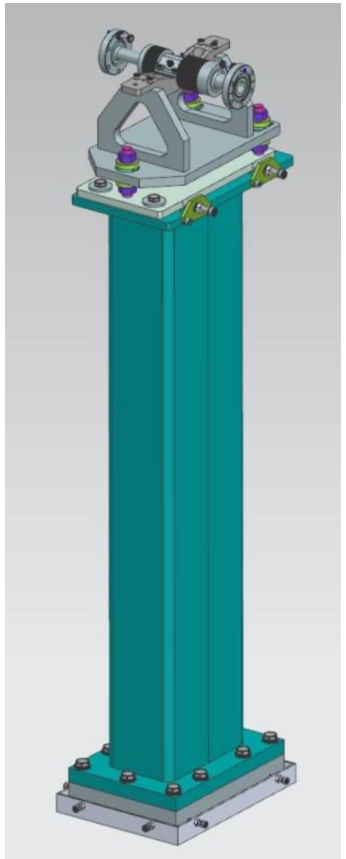
SOLEIL II BPM Types

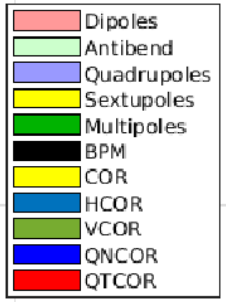
- A large number of BPM types:
  - Standard straight section BPM20 (x40): Invar Stand

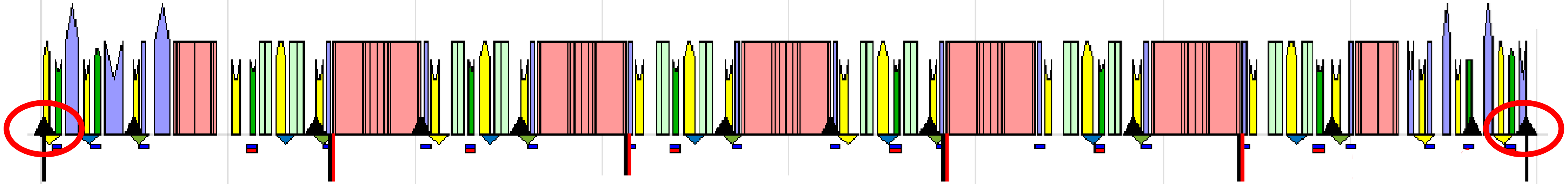






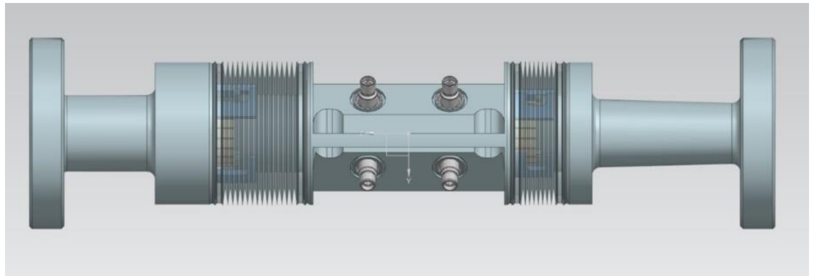


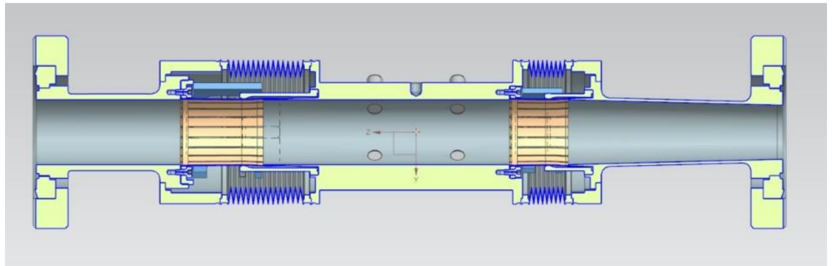


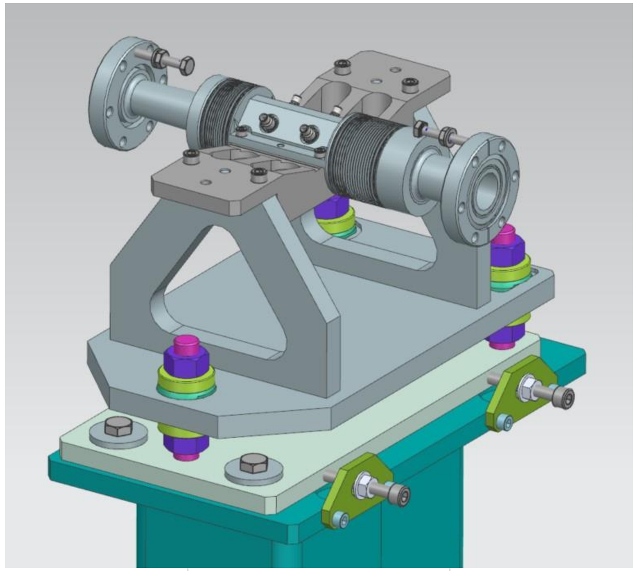


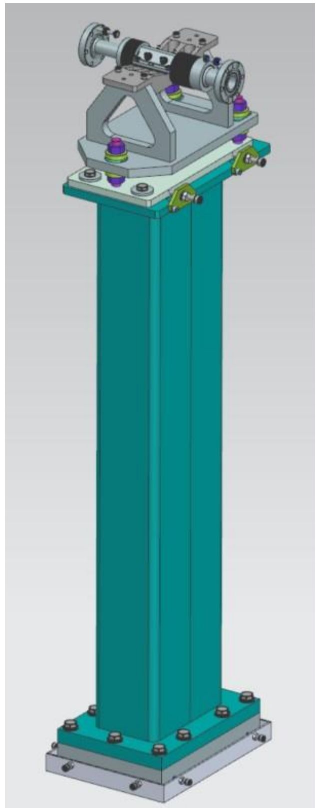
Schematics of the 7BA achromat

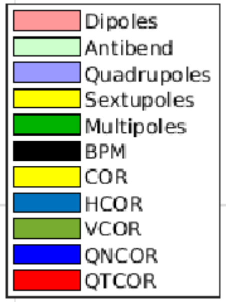
- A large number of BPM types:
  - Long straight section BPM24 (x12): Invar Stand

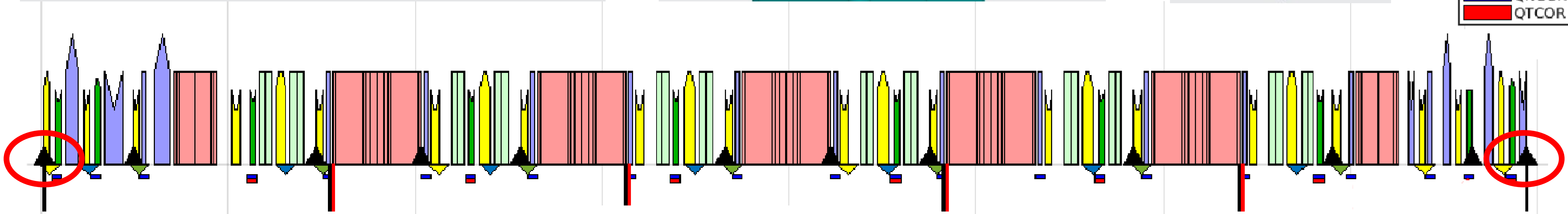








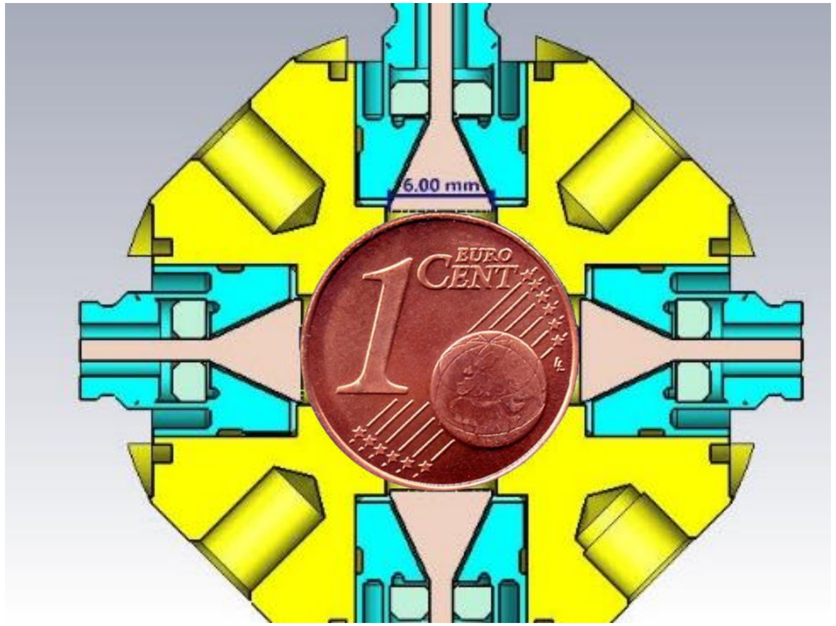




Schematics of the 7BA achromat

Button Design

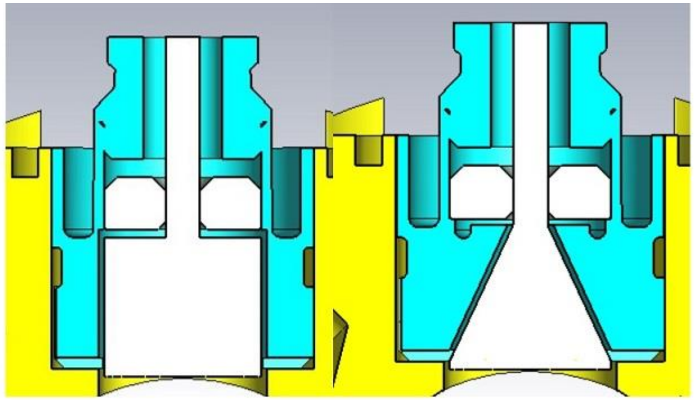
- Button diameter:
  - Compromise between:
    - Collected signal
    - Impedance
    - **Mechanical integration**

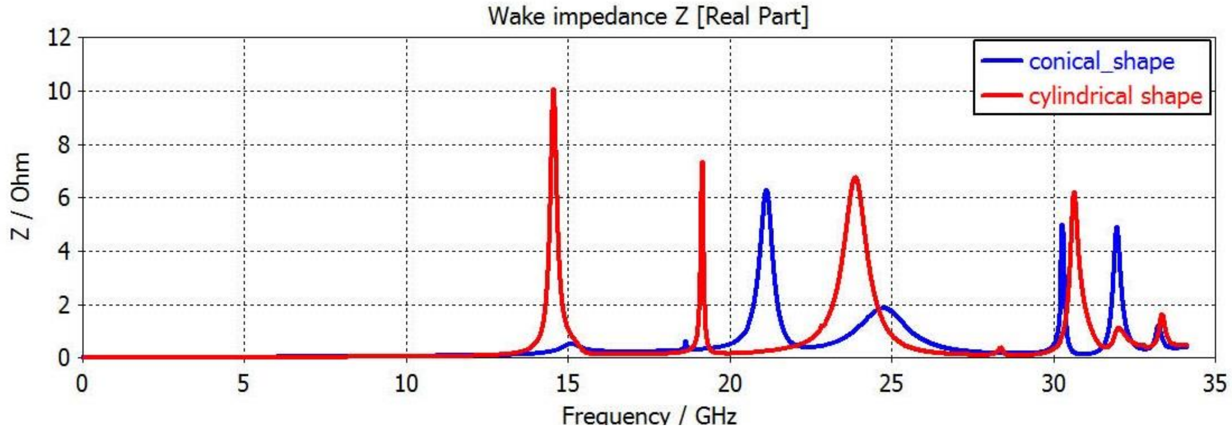


	SOLEIL	SOLEIL II BPM16	SOLEIL II BPM20	SOLEIL II BPM24
Beam-Button Distance [mm]	14.9	**8.1**	**10.1**	**12.1**
Electrode Diameter [mm]	10	**6**	**7**	**7**
Output Power at 500 mA 416 bunches	-0.7 dBm	**-2.6 dBm**	**-1.5 dBm**	**-3.1 dBm**

Button Design

- Button shape:
  - Conical shape to shift resonances frequencies:

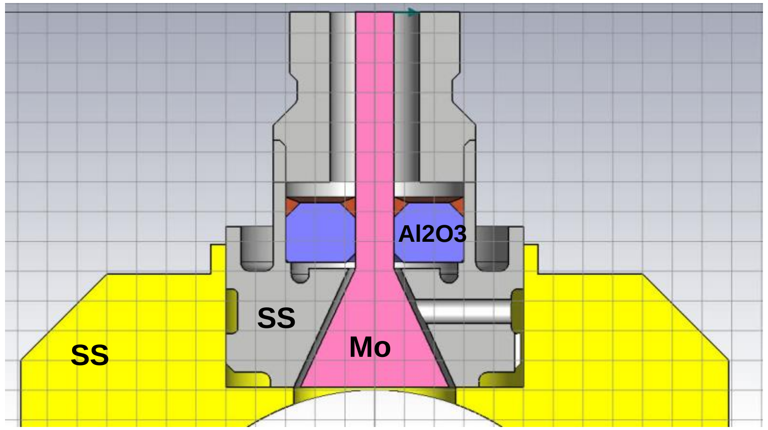




Comparison of the long. Impedance (real part) for a straight (red) and conical (blue) shape of the button.

Button Design

- Materials:
  - Button/pin: Mo
  - Ceramic: Alumina
  - Button housing: stainless steel 316 L
  - BPM block:
    - Stainless steel 316 L
    - Copper coating: 10 µm
- Trapped mode around buttons:
  - heat dissipation distribution depends on materials conductivity

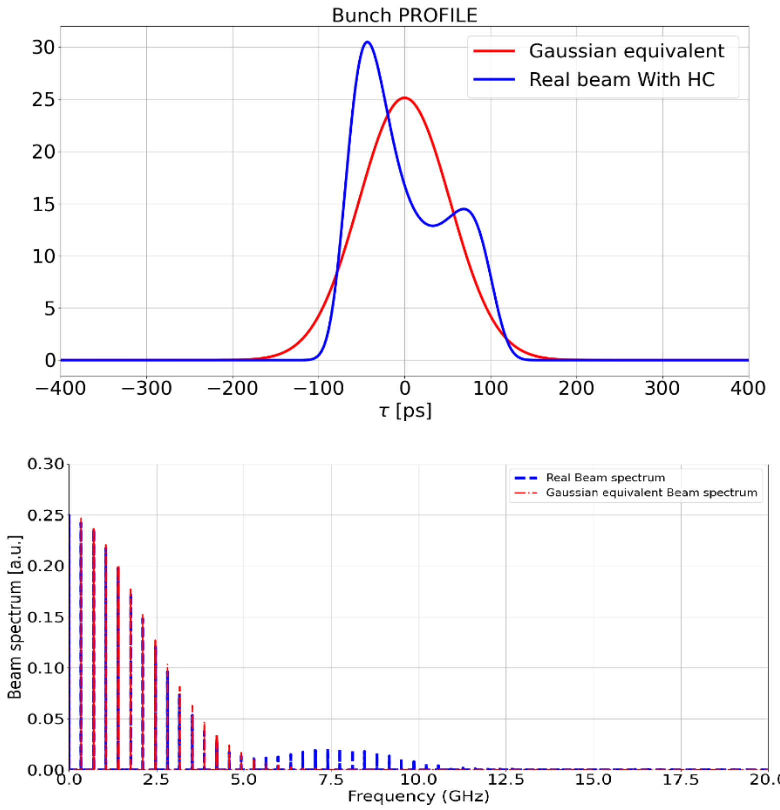


Heat dissipation in the button/housing gap with respect to material. I. Pinayev et al: 'Evaluation of Heat Dissipation in the BPM Buttons', Proceedings of PAC09, Vancouver.

Button Body	Mo	Cu	316L
Mo	50/50	46% on the button	74 % on the button
Cu	64% on the button	50/50	85 % on the button
316L	26% on the button	15% on the button	50/50

Simulations

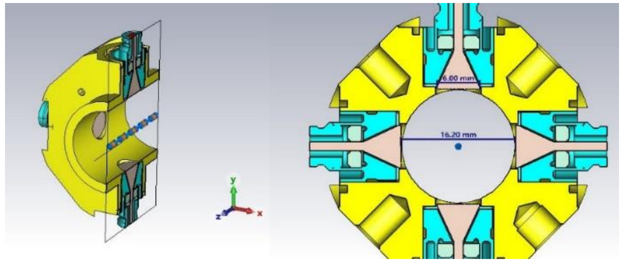
- Simulation of the different BPM types:
  - Filling patterns for SOLEIL II:
    - **500 mA in 416 bunches**
    - 200 mA in 32 bunches (to be confirmed)
  - 2 scenario for the simulations:
    - **Nominal** with Harmonic Cavity:
      - 50 ps rms but non-Gaussian profile
    - **Worst case** without Harmonic Cavity:
      - 15 ps rms gaussian
      - Beam current limited to 300 mA
  - Tools:
    - **CST** and **mbtrack II** Python script for EM simulations
      - Considering a block in copper
    - ANSYS and CST for thermal simulations:
      - Considering a block in stainless steel

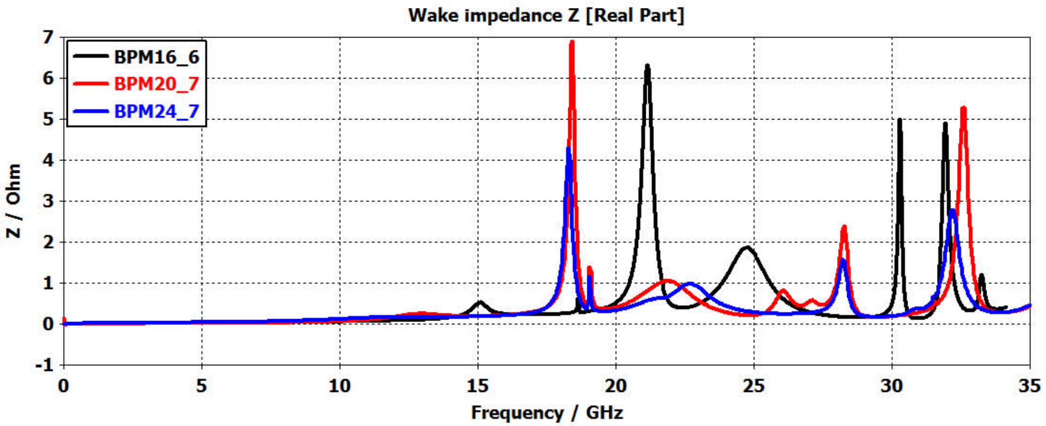


Gaussian (red) and real (blue) bunch profile and beam spectrum with HC..

Electromagnetic Simulations

- BPM section only:



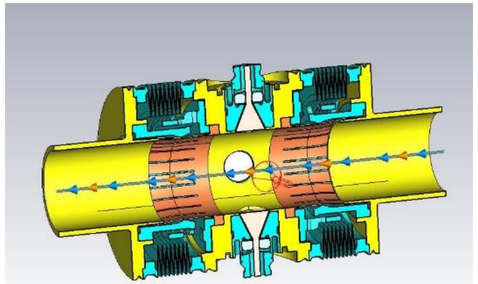


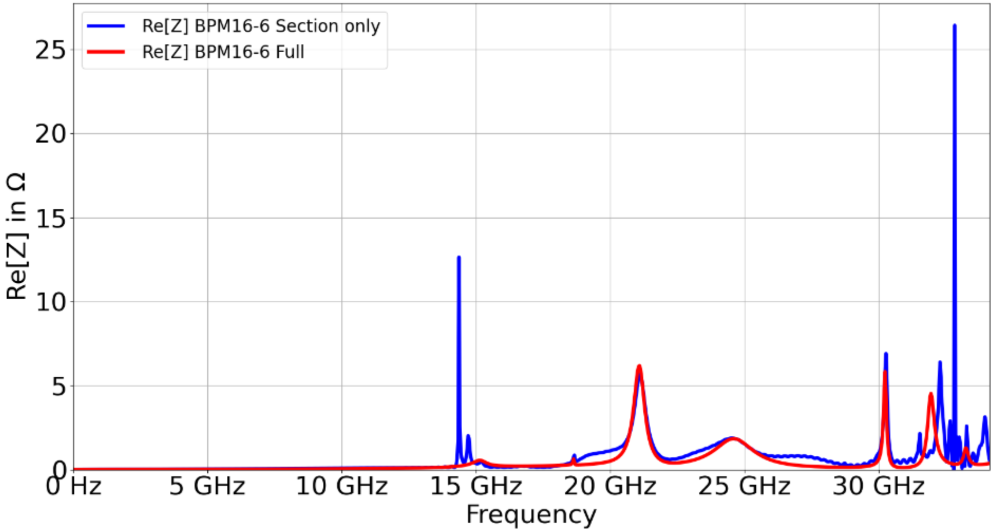
Long. impedance (real part) for the 3 BPM sections

Power Loss for the different BPM sections

Power loss (W)	BPM16	BPM20	BPM24
Nominal w. HC	0.1	0.15	0.12
Worst case w/o. HC	0.3	0.51	0.40

- Including bellows:
  - New resonance at 15 GHz
    - Not visible simulating the bellow alone
    - Investigating on its origin (small beam pipe diameter reduction?)





Long. Impedance (real part) for the BPM16 section (blue) and with bellows (red).

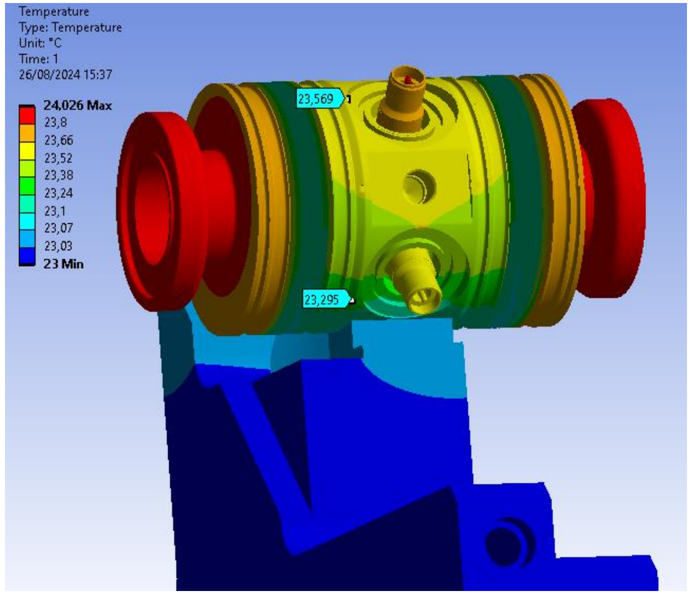
Power Loss for the different BPMs

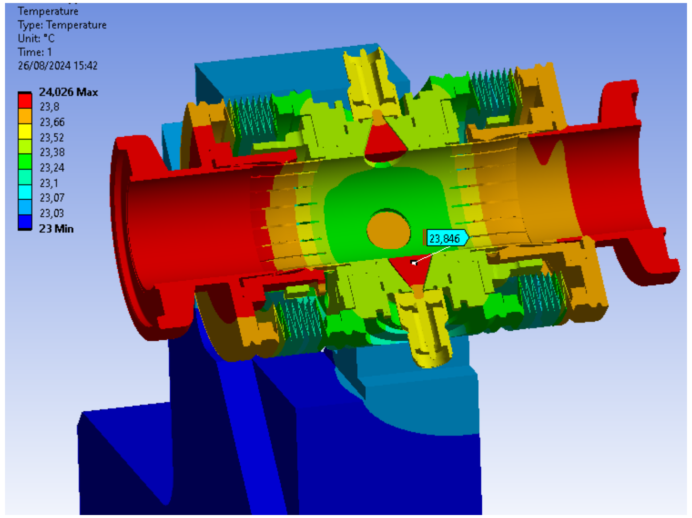
Power loss (W)	BPM16	BPM20	BPM24
Nominal w. HC	0.14	0.21	----
Worst case w/o. HC	0.44	0.7	----

Thermal simulation

- BPM16 full block:
  - ~Homogeneous heat deposition along the BPM pipe
  - Calory evacuation by air and BPM stand
  - **Temperature raise limited to +1 °C** in the worst-case scenario.

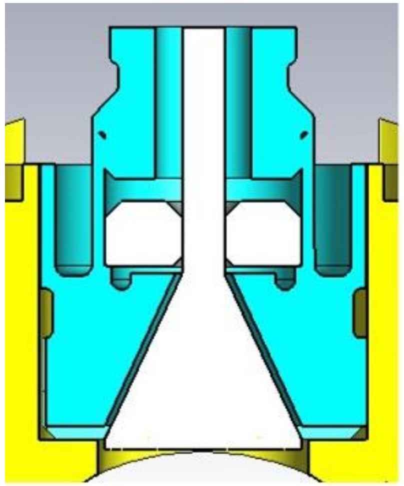
- To be checked on other BPM types, but no issue expected.

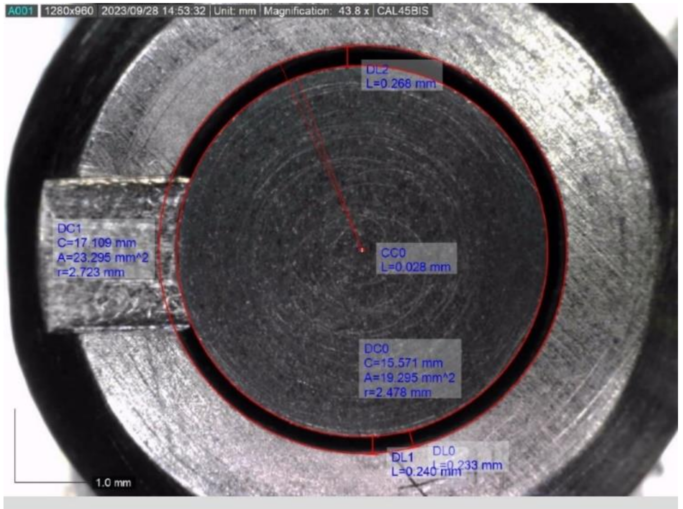




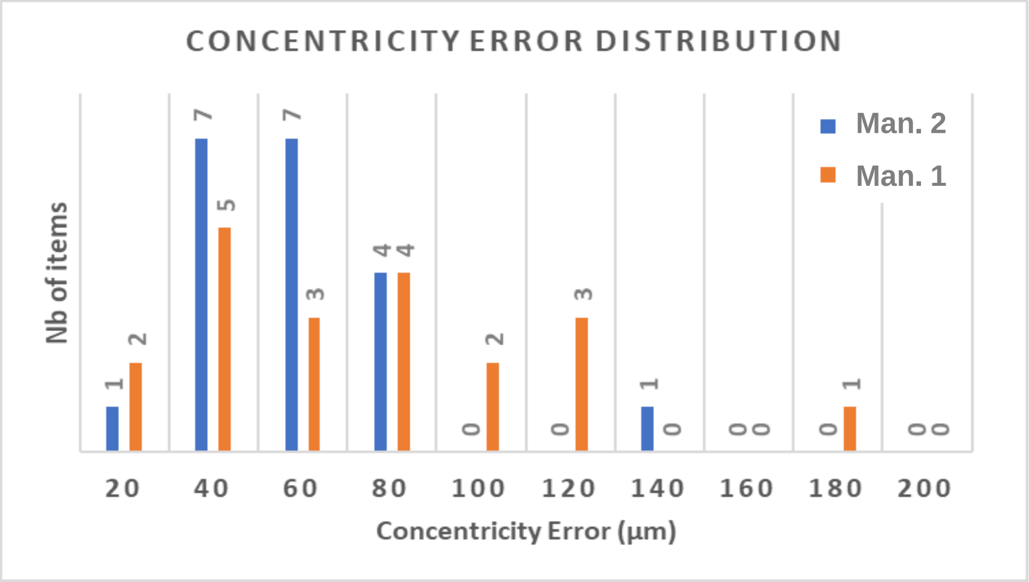
ANSYS Thermal simulations for BPM16

- Two batches of 20 feedthroughs produced:
  - Mechanical realization:
    - Optical check: microscope and interferometry
    - Concentricity: 100 µm on the 200 µm gap:
      - 20% out of specs for manufacturer 1
      - 5% out of specs for manufacturer 2



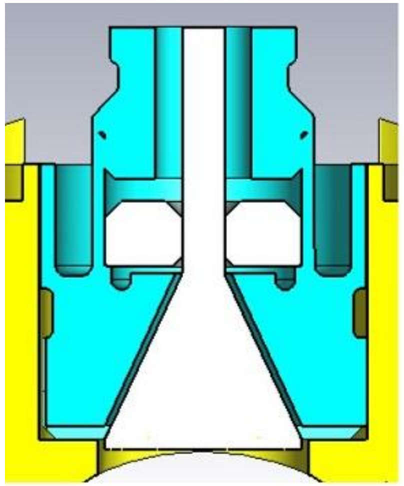


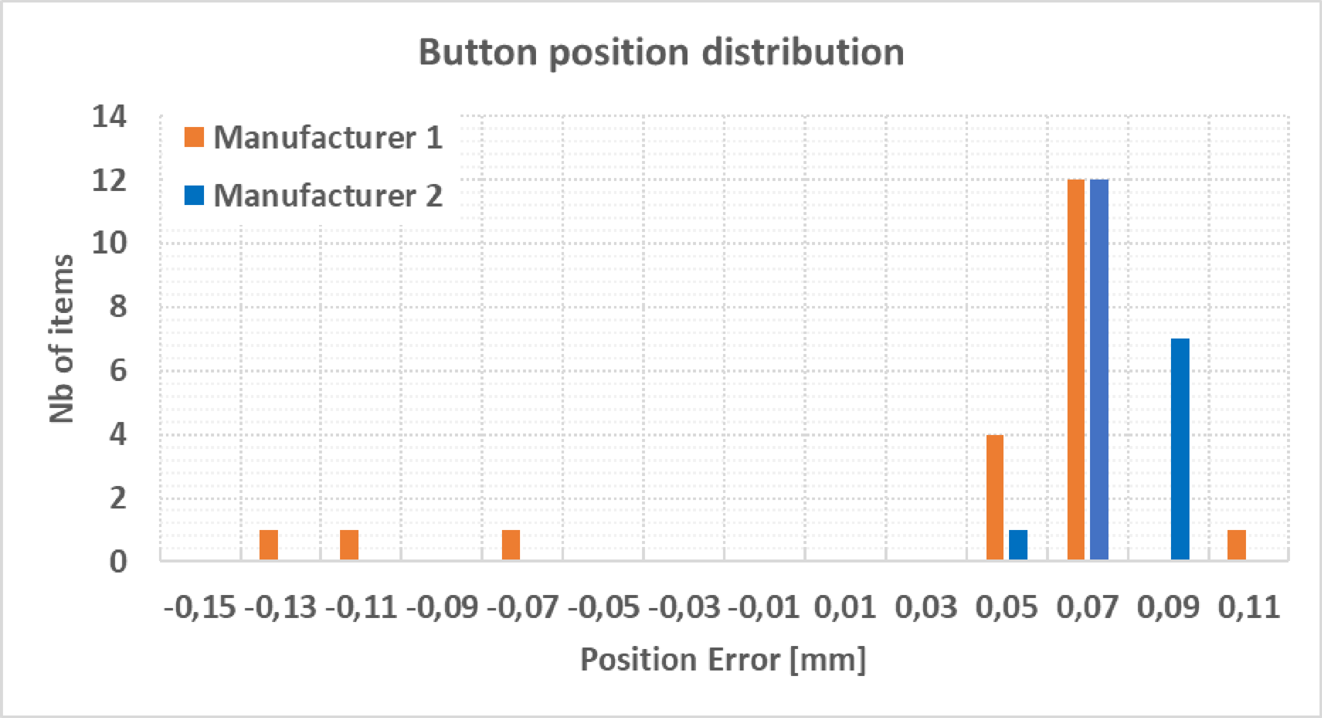
Microscope imaging for concentricity measurement

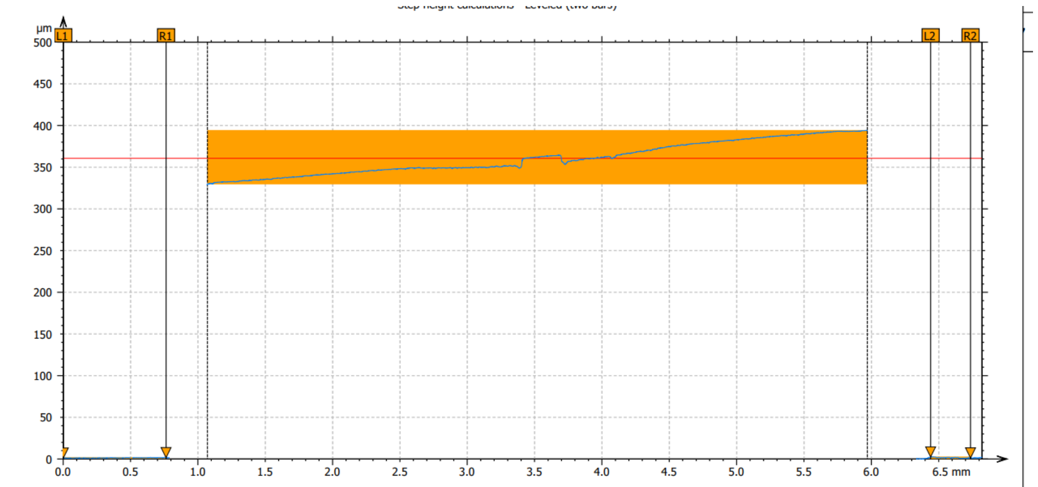


Prototyping

- Two batches of 20 feedthroughs produced:
  - Mechanical realization:
    - Optical check: microscope and interferometry
    - Button position with respect to housing not well controlled:
      - Systematic error for manufacturer 2: +~70 µm
      - Much higher dispersion for manufacturer 1: -150 to +110 µm





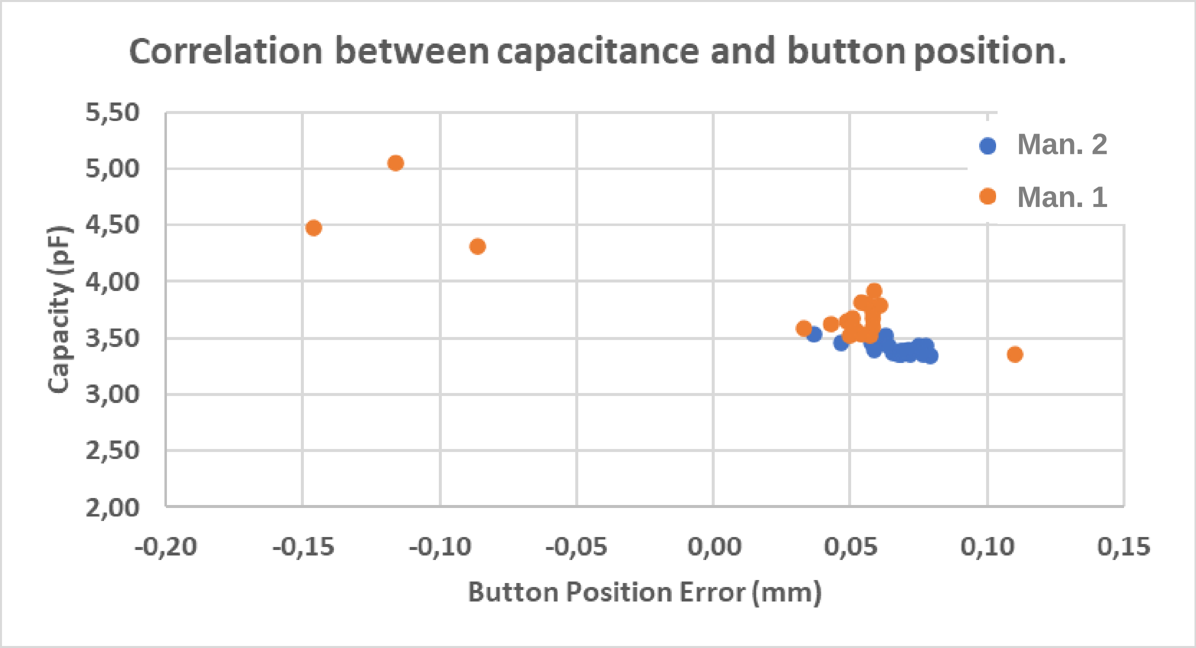


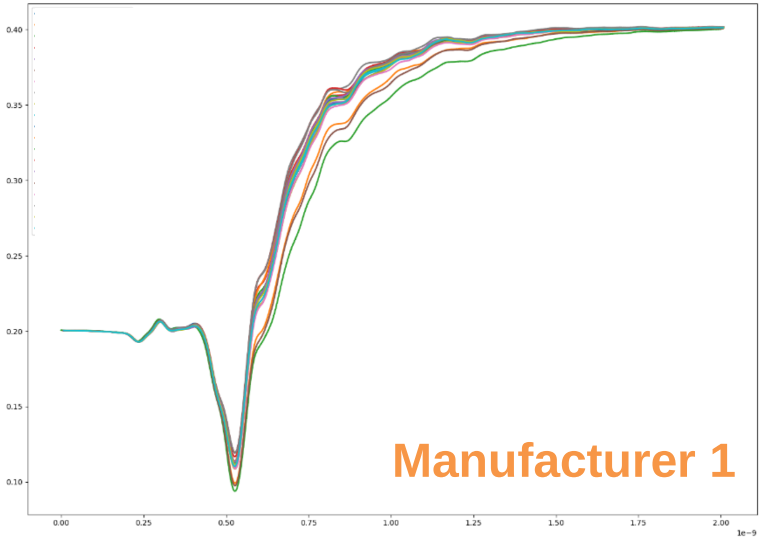
Parameters	Unit	Mean	Min	Max	Step 1	Step 2
Width	mm	0.531	0.298	0.764	0.764	0.298
Maximum height	µm	359.933	359.687	360.179	359.687	360.179
Minimum height	µm	358.470	358.142	358.798	358.798	358.142
Mean height	µm	359.249	359.175	359.323	359.323	359.175
Horizontal distance between centers	mm	6.206	6.206	6.206	*****	6.206
Pos (L)	mm	3.219	0.000	6.439	0.000	6.439
Pos (R)	mm	3.749	0.763	6.736	0.763	6.736
Height (L)	µm	-358.924	-359.601	-358.247	-359.601	-358.247
Height (R)	µm	-359.305	-359.482	-359.128	-359.128	-359.482

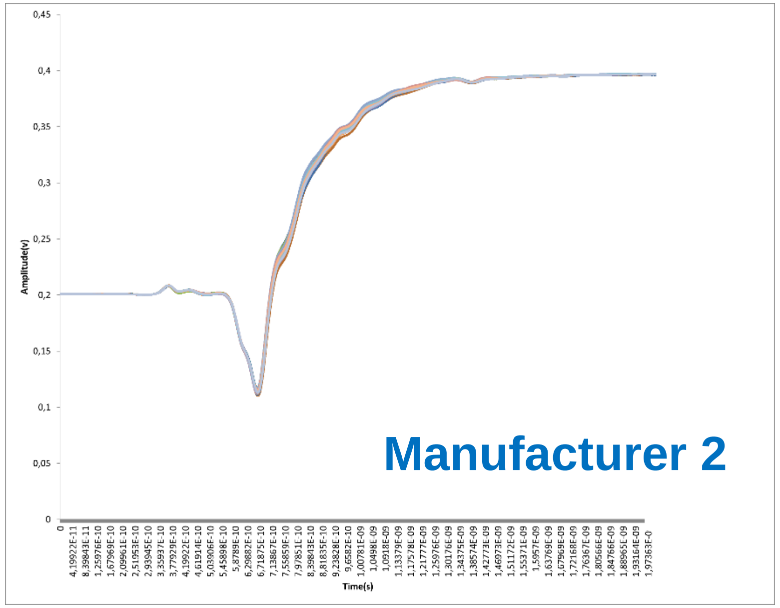
Button profile survey by interferometry

Prototyping

- Two batches of 20 feedthroughs produced:
  - Electrical measurements
    - Isolation -> OK
    - Capacity: TDR measurement
      - In correlation with mechanical errors
      - Very small dispersion for manufacturer 2

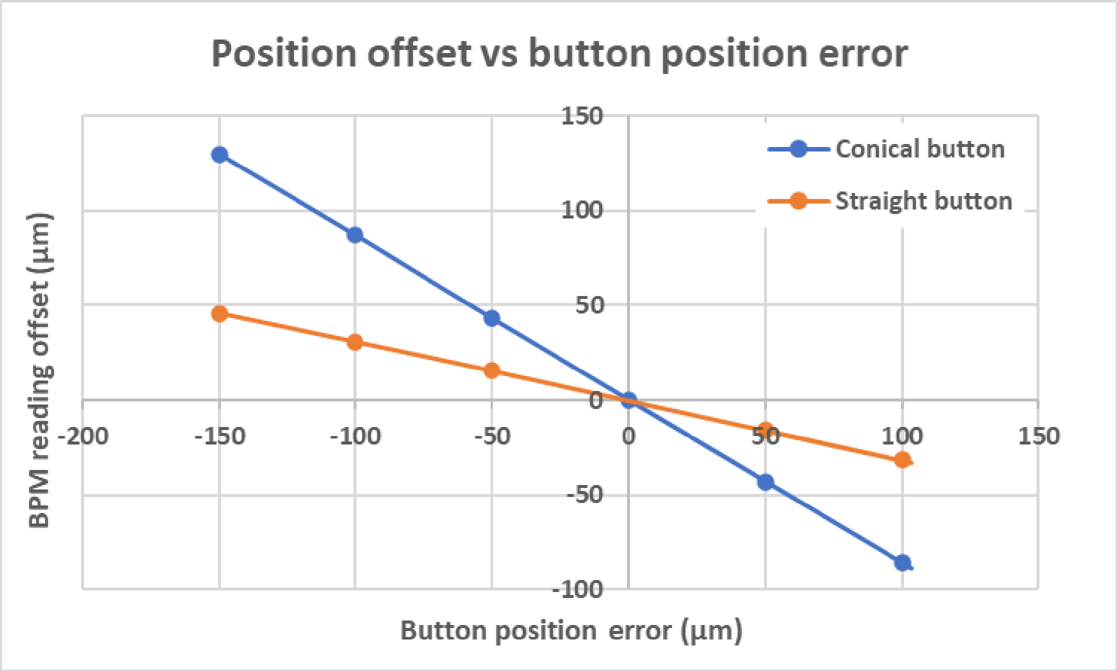




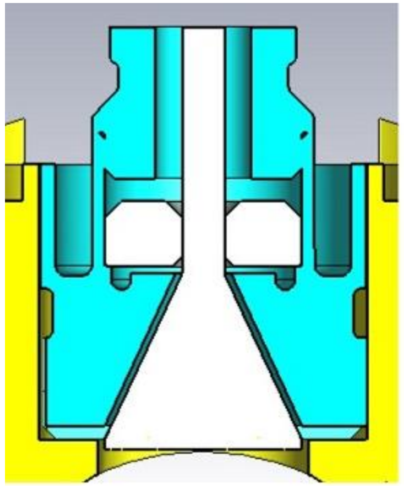


TDR measurement

- Effect of button position errors on the BPM offset:
  - Offset is enhanced by the conical shape of the button (capacity modification)



BPM reading offset for one mispositioned button.



Mechanical errors are acceptable if their dispersion among produced buttons is small. Button sorting would be mandatory with production from manufacturer 1.

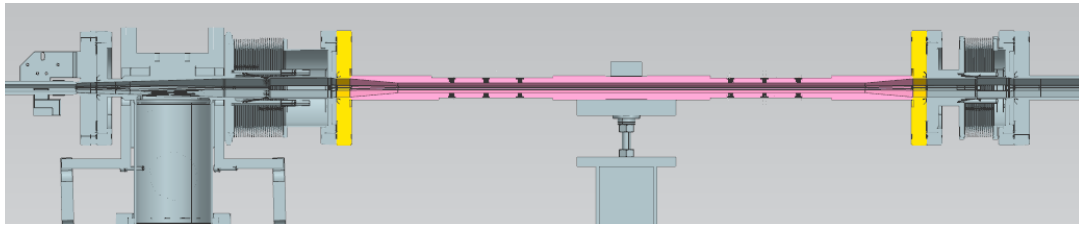
Prototyping

- Two batches of 20 feedthroughs produced:
  - Vacuum:
    - He leak test passed successfully before installation.

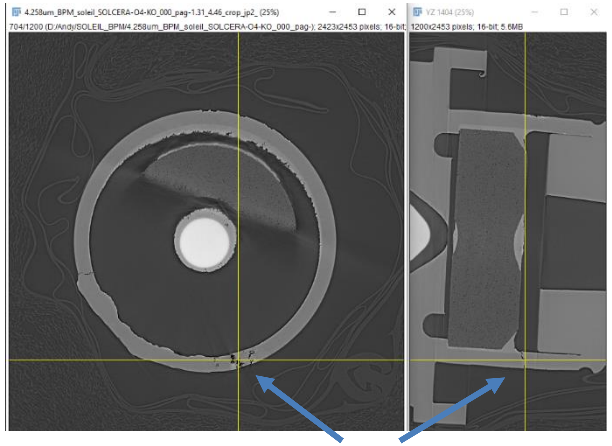
Helium leak test

Beam Tests on SOLEIL

- Dedicated vacuum chamber:
  - Possibility to install 12 feedthroughs for each manufacturer.
  - Welding:
    - Feedthrough are too small for TIG welding!
      - Large heat deposition in the vicinity of ceramic and brazing
      - Numerous vacuum leaks
        - 25 % failures with manufacturer 1
        - 92% failures with manufacturer 2
    - Better choose laser welding:
      - Heat much more localized
      - Can be pulsed to reduce even more heating.
      -> Tight vacuum chamber

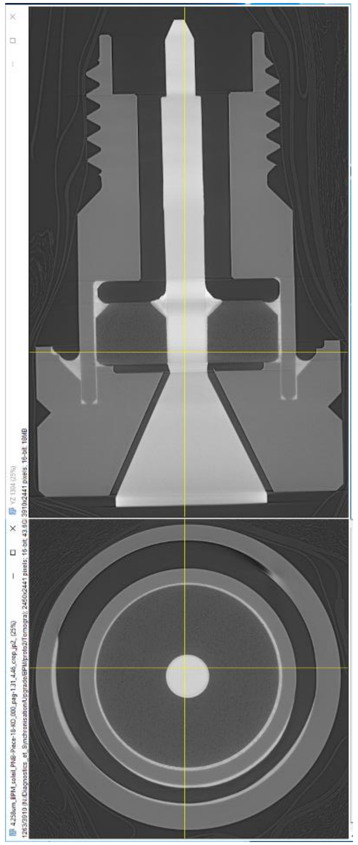


Vacuum chamber for testing SOLEIL II BPM feedthroughs

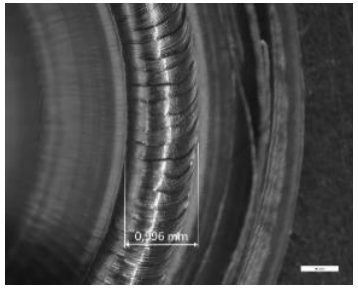


CT scan by ESRF BM18. Crack is visible on the upper part (in-air) of Manufacturer 1.

However CT-scans showed no evidence of the leak cause…



Manufacturer 2 CT scan. No visible damage.

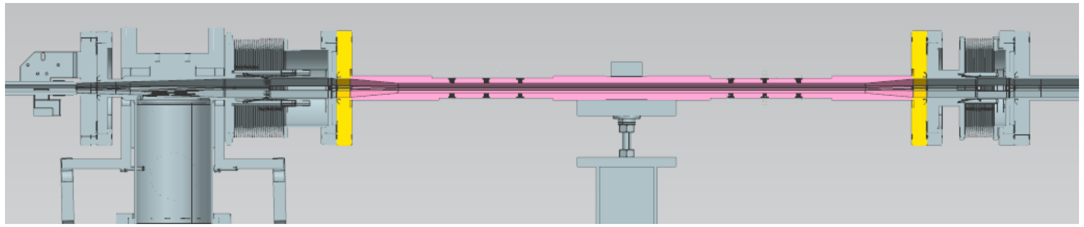


Pulsed-laser welding.

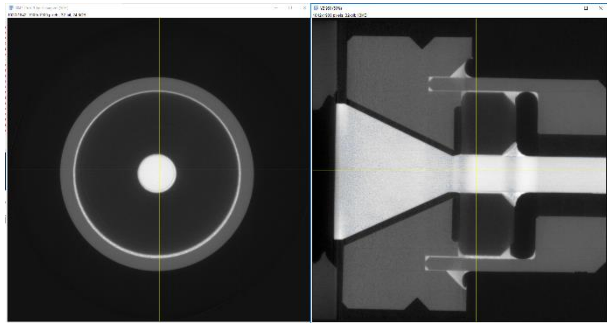
Beam Tests on SOLEIL

- Dedicated vacuum chamber:
  - Possibility to install 12 feedthroughs for each manufacturer.
  - Bake-out (200 °C):
    - Numerous vacuum leaks
      - 8 % man. 1 (1 feedthrough probably weakened by TIG welding)
      - **83% man. 2: -> Design/realization issue**
    - Failure causes under investigation:
      - Too high mechanical constraints during bake-out for this small design
      - Bad realization (lack of brazing fillers?)
    - Design evolution is foreseen…
      - New pre-series production with extensive bake-out tests.

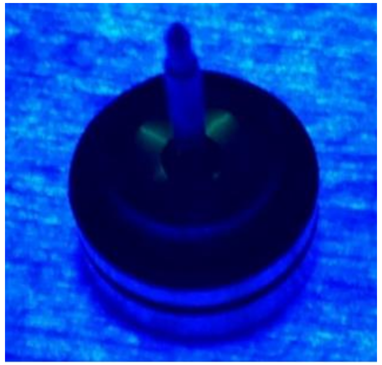
Vacuum chamber will be installed in January 2025 with 11 remaining feedthroughs from manufacturer 1.

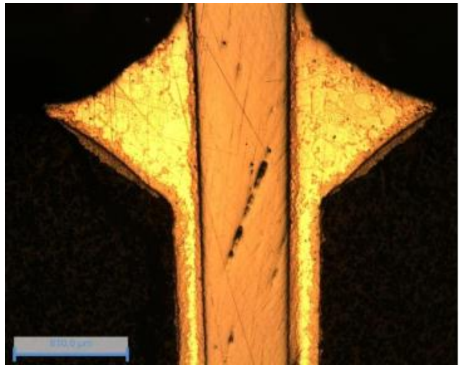


Vacuum chamber for testing SOLEIL II BPM feedthroughs

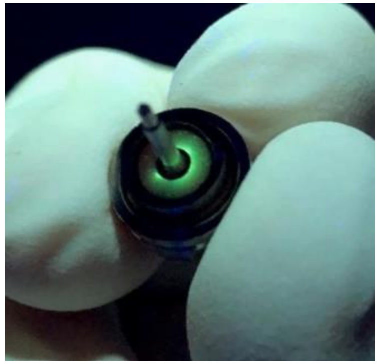


CT Scan by SOLEIL PSICHE Beamline





Microscopic inspection after metallographic cut.



Fluorescent oil shows transversal (top) or radial (bottom) cracks

Conclusion

- Reduction of the vacuum chamber inner diameter has many consequences for the BPM design:
  - Number of BPM types (4)
  - Multiplication of tapers to keep BPMs in the shadow of SR
  - Mechanical integration of the buttons, welding process
  - New techniques for the button metrology
- Qualification of 2 different manufacturers:
  - Manufacturer 1: Bake-out proof but worse mechanical realization
  - Manufacturer 2: Good mechanical realization but not bakeable
- Next steps for SOLEIL II button BPMs
  - Beam test of the remaining buttons for conical shape validation.
  - Modify the design for better robustness to mechanical constraints.
  - Production of 2 pre-series for bake-out extensive tests.
  - Production of the series:
    - ~650 buttons with 6 mm diameter
    - ~300 buttons with 7 mm diameter