
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Riccardo Zennaro:: RF group :: Paul Scherrer Institut

BOC production at PSI

CERN 24.11.2021

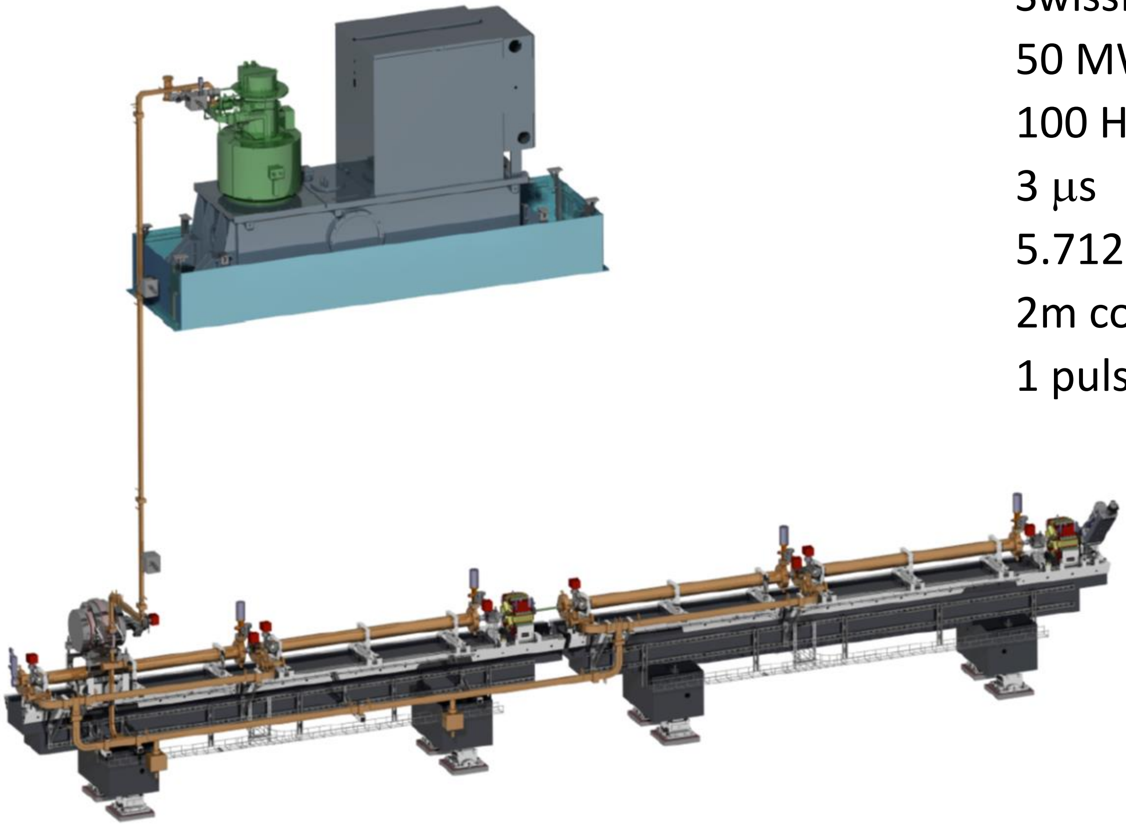
Starting point

Why BOC?

Probably because I had the opportunity to work with Igor during my time at CERN and I was impressed by his competences, ideas and much more.

He also strongly supported me with comments/suggestions during the initial design phase at PSI

Motivation: SwissFEL



SwissFEL module

50 MW

100 Hz

3 μs

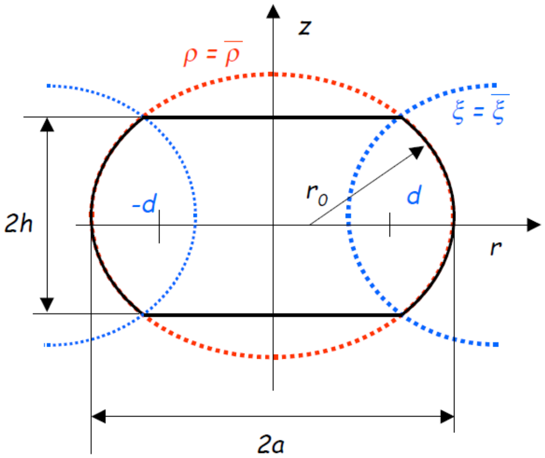
5.712 GHz

2m constant gradient ACs x4

1 pulse compressor

BOC: simple analytical description

BOC is a single resonator coupled to an external circular waveguide thanks to multiple coupling holes placed at λ/4 distance



$$z = \sqrt{a r_0 \left\{1 - \left(\frac{r}{a}\right)^2\right\}}$$

Eigenfrequency

$$ka = \nu_{mn} + \frac{(q - 1/2)\alpha}{\sin\theta}$$

where:

ν^{o}_{mn} *Root of Bessel function*

$$\sin\alpha = \sqrt{\frac{a}{r_0}}\sin\theta \qquad \cos\theta = \frac{m}{\nu_{mn}}$$

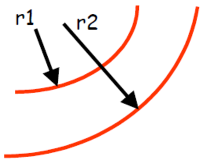
Q factor

$$Q_E = \frac{a}{\sigma_s}$$

First order design:

The full geometry can be analytically defined

External waveguide dimension

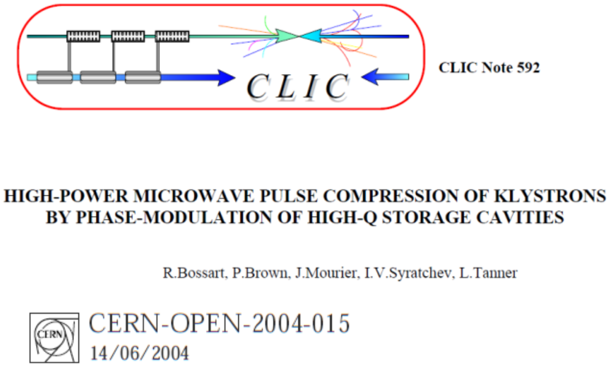


$$\frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda}{2(r_2 - r_1)}\right)^2}} - \frac{2\pi(r_2 + r_1)}{2m} = 0$$

All these formulas and pictures from a Igor's presentation in 2001

BOC: S11 minimization

This is probably the most delicate part of the design, very useful and exhaustive considerations from Igor here:



CLIC Note 592

HIGH-POWER MICROWAVE PULSE COMPRESSION OF KLYSTRONS BY PHASE-MODULATION OF HIGH-Q STORAGE CAVITIES

R.Bossart, P.Brown, J.Mourier, I.V.Syratchev, L.Tanner

CERN-OPEN-2004-015
14/06/2004

Description of the BOC as two orthogonal degenerated resonance modes at the same frequency in the ideal case. This condition is broken by the waveguide coupler that introduce an asymmetry.

Basic recommendations:

- $TM_{n,1,1}$ mode with *n* as large as possible (space and technological limits)
- Even number of coupling irises
- Fake coupling holes to partial compensate asymmetries
- Even number of fake coupling holes

Initial considerations at PSI

1) After a quick estimation (first order design) of the working mode ($TM_{18,1,1}$), RF parameters, overall size, etc. we discussed on the best technological solution for the BOC production.

Two possible solutions were taken into consideration:

- Welded design
- Fully brazed design

At PSI both solution were possible:

- EBW machine
- Large brazing oven for accelerating structure production

We selected the second solution because of better geometrical accuracy and reproducibility

Initial considerations at PSI

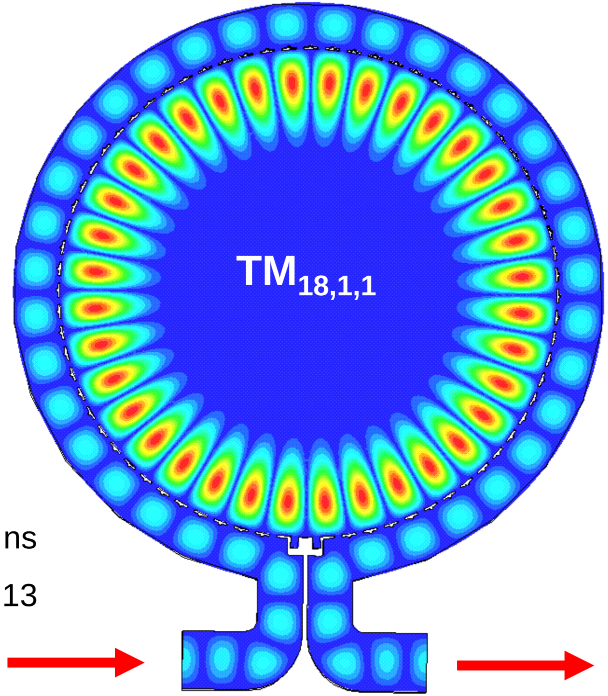
2) Once the size and shape (first approximation) were defined and the brazing technology selected we took the following decisions:

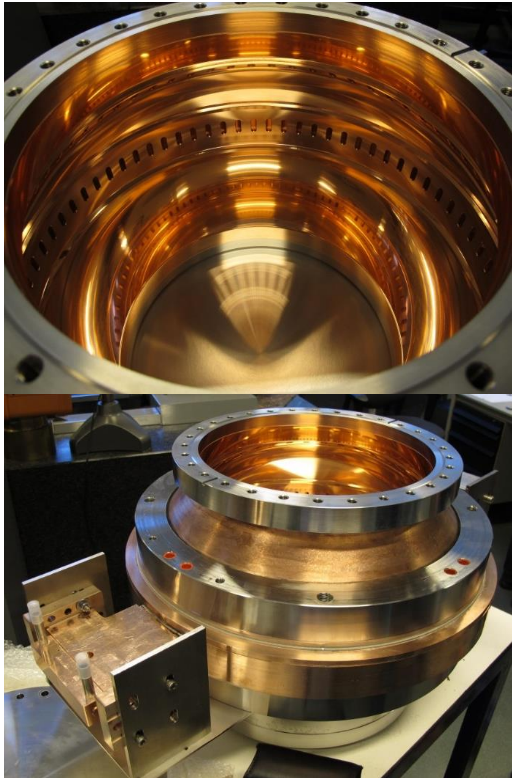
- Tuning based design with two tuning rings that can be machined after RF measurements
- Resonator defined by a single body, better control of the inner volume and surface quality, no discontinuities, probably better high power performances
- No RF probes, no strong need, design simplicity, cost
- no UP machining needed (thanks to tuning)
- No extreme low roughness requirement (100 nm)
- Use of a 5 axis machine for the production
- Investment of PSI workshop on a Hermle 5 axis machine for the SwissFEL, 26 C-band BOCs required at the time (only Aramis beamline)

C-band BOC for SwissFEL

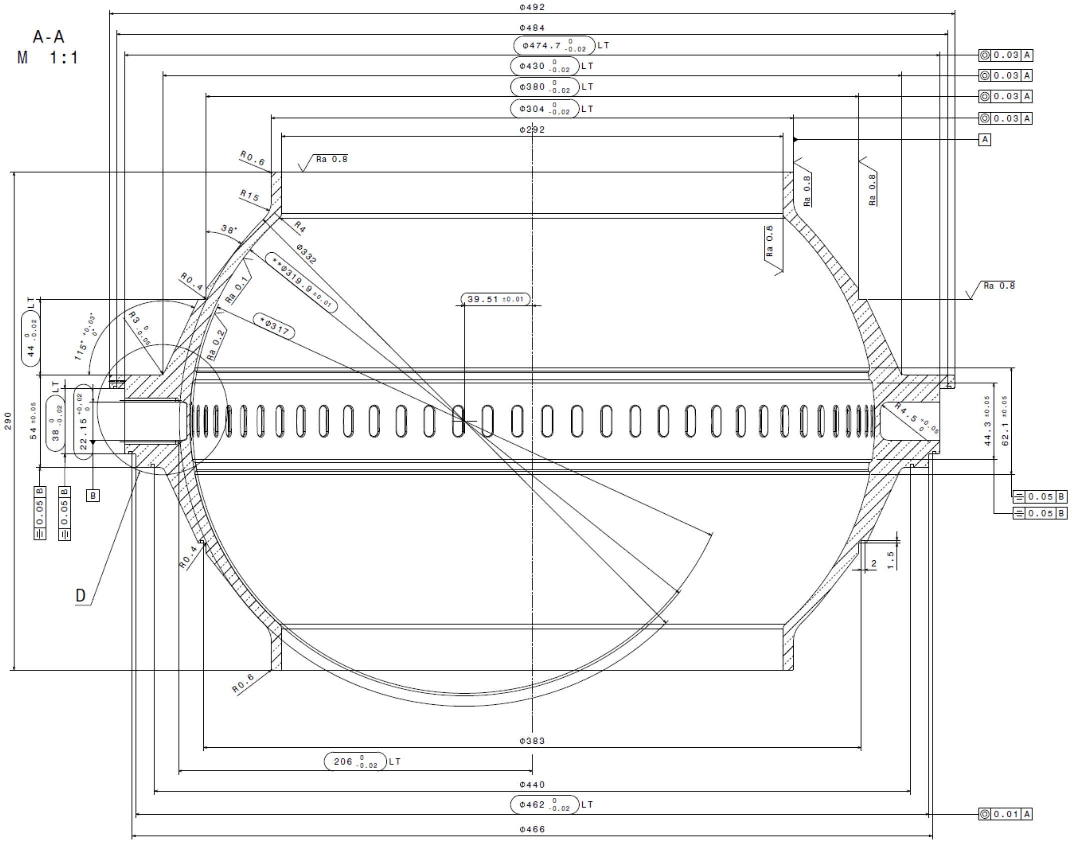
Pulse compressor Design parameter

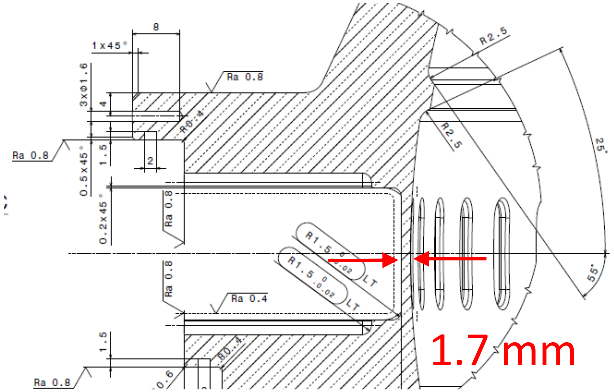
- Type Barrel Open cavity
- Frequency 5.712 GHz
- Resonant mode TM18,1,1
- Diameter 492 mm
- Number of coupling slots 70
- Q 222000
- Coupling factor (β) 10
- Max. input power 50 MW
- RF input pulse length 3 μs
- RF compressed pulse length 330 ns
- Energy multiplication factor (M) 2.13
- Repetition rate 100 Hz





First problem: the wall thickness





1.7 mm

Very thin wall, high criticality for the robustness of the body

Action: evaluation of the problem

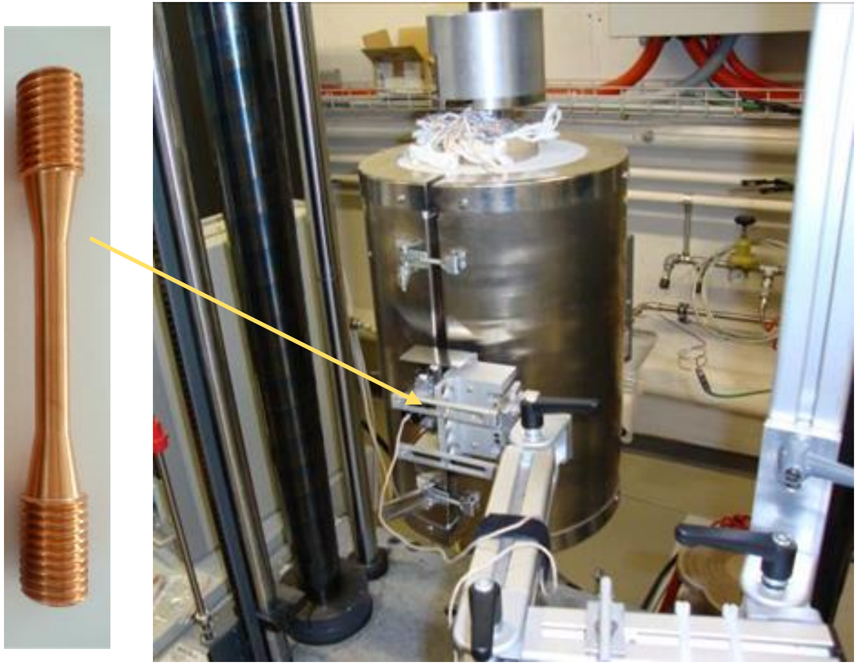
OFE Cu mechanical properties

Difficulties to find information in literature on annealed copper or test at large temperature.

We needed to evaluate the copper properties for:

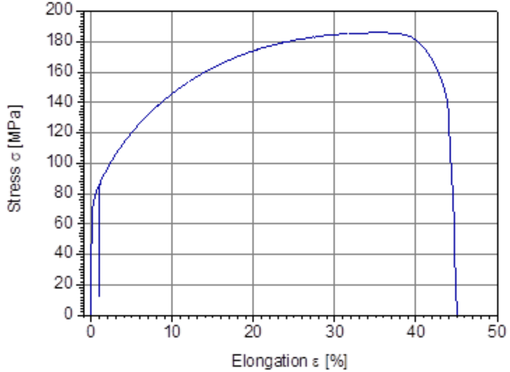
- annealed Cu at room temperature (operation condition)
- annealed Cu at brazing temperature (830 °C) (brazing condition)

To evaluate the material properties we had few tensile tests at PSI up to 830 °C



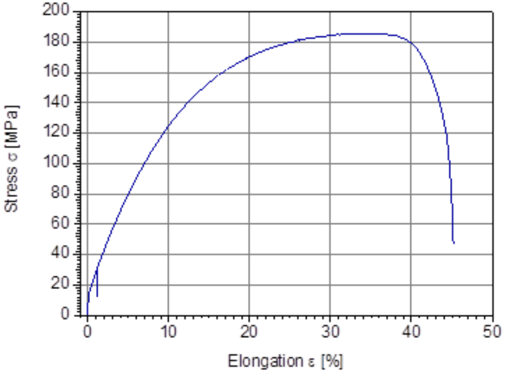
Tensile testing examples

Cu-OFE: Preliminary test 1, test T = 40 °C



Hard Cu @ 40 °C

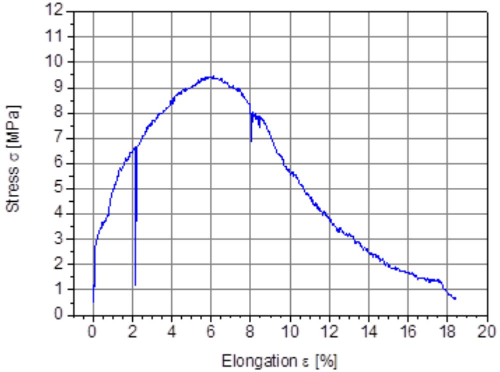
Cu-OFE: Specimen 5, annealed T = 800 °C, test T = 40 °C



Annealed Cu (800 °C) @ 40 °C

Operational condition

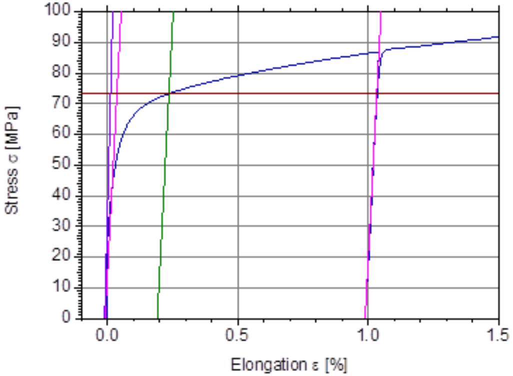
Cu-OFE: Specimen 13, annealing T = 850 °C, test T = 830 °C



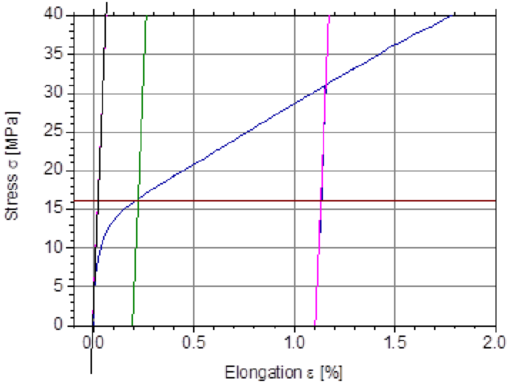
Annealed Cu (850 °C) @ 830 °C

Condition in oven during 2nd brazing

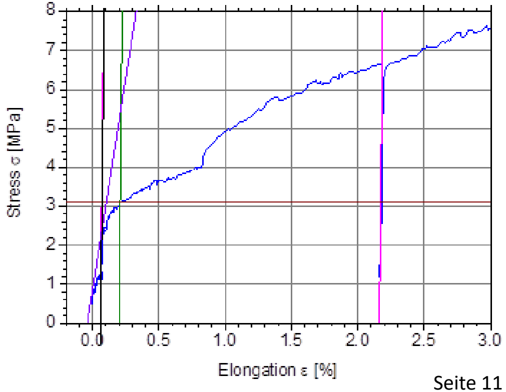
Cu-OFE: Preliminary test 1, test T = 40 °C



Cu-OFE: Specimen 5, annealed T = 800 °C, test T = 40 °C



Cu-OFE: Specimen 13, annealing T = 850 °C, test T = 830 °C



Results

testXpert Dateiname	BTS testXpert Prüfungs-Nr	Swiss FEL Proben-Nr.	Glüh-T [°C]	Prüf-T [°C]	E [GPa]	E aus Diagramm [GPa]	E Hyst [GPa]	**E Hyst** aus Diagramm **[GPa]**	$R_{p0,2}$ [MPa]	**$R_{p0,2}$** korrigiert **[MPa]**	**R_m [MPa]**	**R_m** korrigiert **[MPa]**	F_m [N]	F_m korrigiert [N]	**A_g [%]**	A [%]	**A** aus Diagramm **[%]**	**Z [%]**
CU-FEL.ZSE	1	1	keine	40	229	323	207	164	89	73	227	186	17824	14616	34.5	k.W.	45	70.8
	2	2	keine	40	137	n.b.	126	97	79	66	225	185	17632	14458	35	k.W.	46.3	77.4
	3	3	keine	40	97	111	136	111	79	65	225	185	17675	14494	36	49.8	49.8	77.2
	4	3	500	40	5	72	k.W.	72	46	25	208	171	16315	13378	27	k.W.	42	90.9
	5	4	500	40	5	98	130	98	k.W.	27	225	185	17655	14477	35	45.3	45.3	89.1
	6	5	800	40	22	60	82	60	20	16	227	186	17796	14593	34	45.1	45.1	80.3
	7	6	800	40	8	18	124	121	15	18	223	183	17520	14366	34.5	43.6	43.6	85.8
	8	7	500	550	24	24	k.W.	71	26	20	63	52	4968	4074	8.5	k.W.	27	85.9
	9	8	500	550	-41	<0	k.W.	<0	29	24	66	54	5179	4247	8.5	k.W.	26.5	91
	10	10	keine	40	211	111	138	111	126	103	238	195	18699	15333	33	45.6	45.6	78.4
CU-FEL1.ZSE	1	11	850	830	1	2	k.W.	k.W.	4	2	13	11	1013	831	3	15.3	15.3	45.5
	2	12	850	830	9	7	k.W.	19	5	4	13	11	1056	866	6	18.4	18.4	31.1
	3	13	850	830	6	2	k.W.	32	4	3	12	10	910	746	6	18.4	18.4	21.7
	4	14	850	40	23	17	73	63	18	14	228	187	17933	14705	33.5	43.3	43.3	85.5
	5	15	850	40	23	18	89	70	20	17	233	191	18268	14980	32.5	44.0	44.0	89.6
	6	16	850	40	11	11	k.W.		23	19								
	10	16	850	40	54		87	84	64		191	191	15005		32	43.7	43.7	88.1
	7	17	850	40	102	102	k.W.		23	23								
	8	17	850	40	227		89	92	60		189	189	14863		31	k.W.	40.0	86.5
	9	18	850	40	-7	n.b.	84	86	16	16	187	187	14702		33	k.W.	42.0	85.2

k.W.	kein Wert vorhanden	d = 10 mm	L_0 = 50 mm
n.b.	nicht bestimmbar	S_0 = 78.54 mm²	

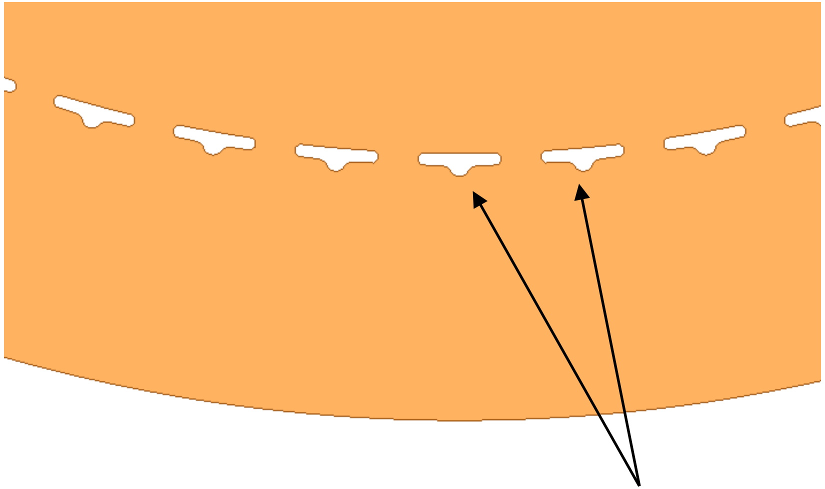
To be compared to values from ANSYS computation: ~ 20 MPa (operation, weight + vacuum pressure) Critical!

~ 0.5 MPa (2^{nd} brazing, weight only)

Proposed solutions

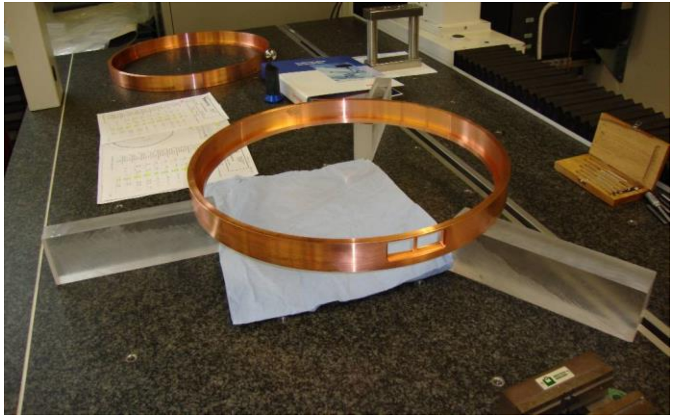
To reinforce the wall the geometry has been modified in between the slots.

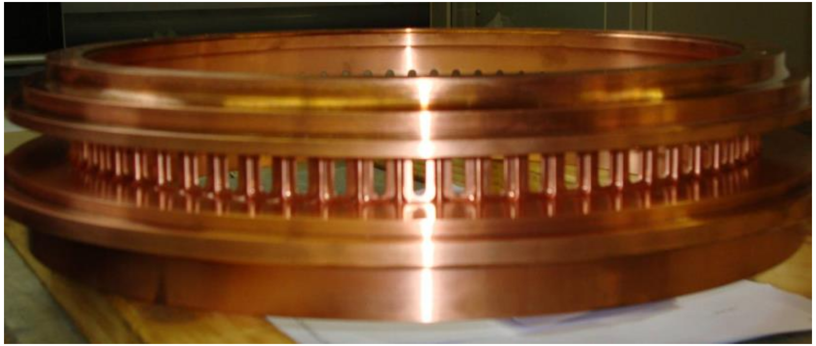
The external waveguide has been re-matched to provide the correct phase advance



reinforcements

Pre-prototype

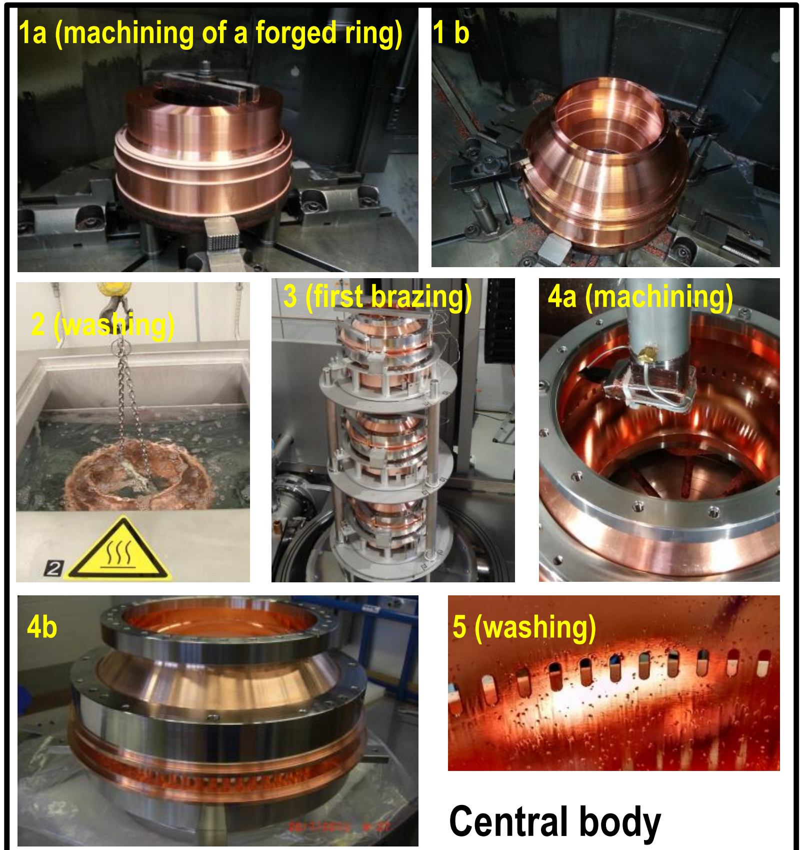




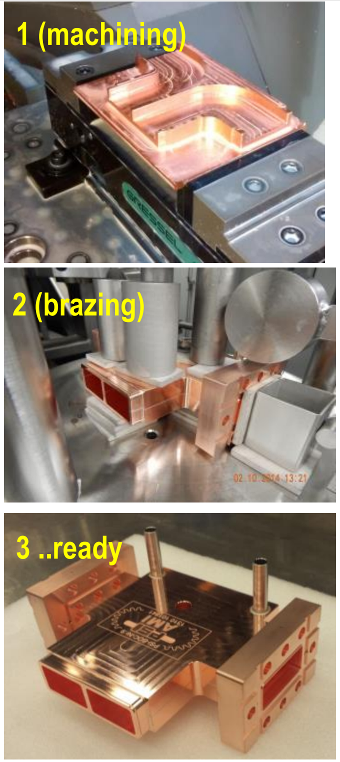
To validate the design a pre-prototype was produced in order to verify:

- Machine programming
- Deformation during production
- Brazing
- Deformation due to atmospheric pressure

BOC production steps



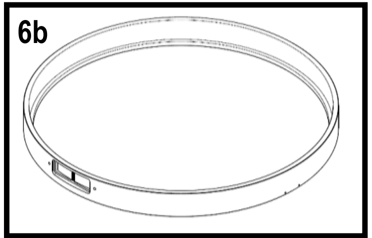
Central body



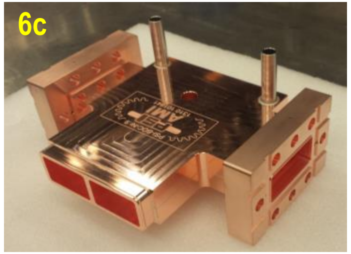
Coupler

BOC production steps

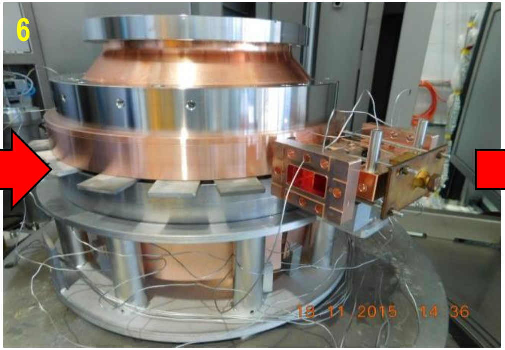
Central body +



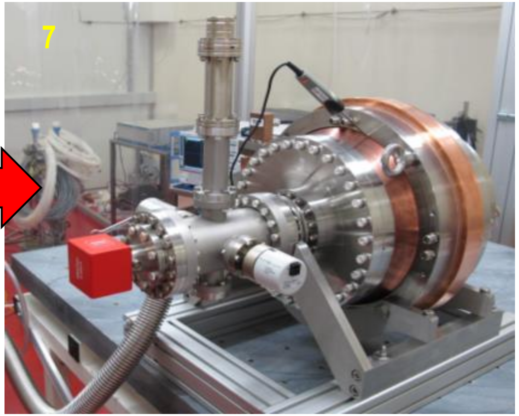
External ring +



Coupler

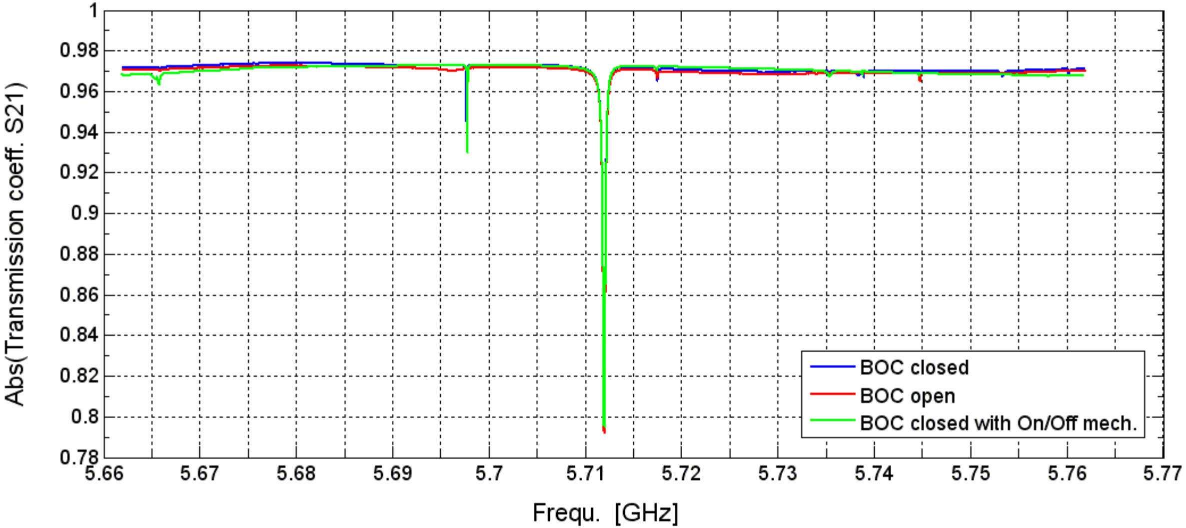


Second brazing



Final vacuum and RF tests

On-off mechanism: just one unit for the prototype



On-off mechanism with SiC absorbing material to dump neighbor modes.

This device was produced for the prototype but we decided not to install in SwissFEL, the measurement do not show the need of damping material and machine operation does not really require the possibility to operate without compression

BOC tuning

New design: the number of tuning steps has been gradually reduced from 4 to 0.

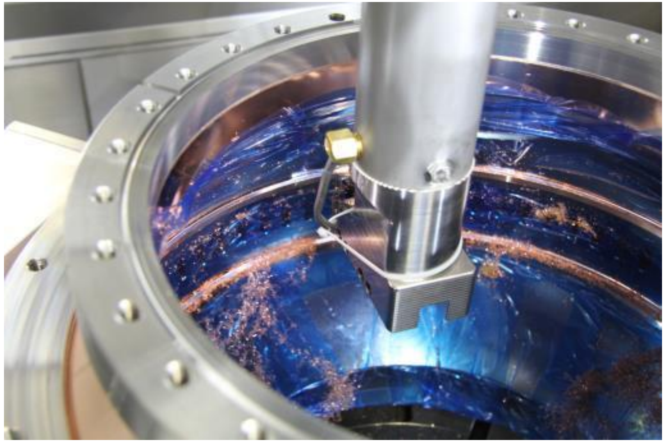
Starting from BOC 4 the two tuning ring have completely removed requiring a small adjustment of the RF design.

Advantages:

1) By removing completely the tuning rings we do not need anymore the machining of the rings, the final washing of the BOC and a baking cycle in the vacuum oven. Around 1 week /BOC time saving.
2) Better high power performance (cleaner surface) and reduction of the field enhancement (no rings and much better control of the surface quality)

Disadvantages:

1) Risk to have unusable BOCs (wrong frequency) but at the end all the BOCs were on frequency (failing rate = 0)



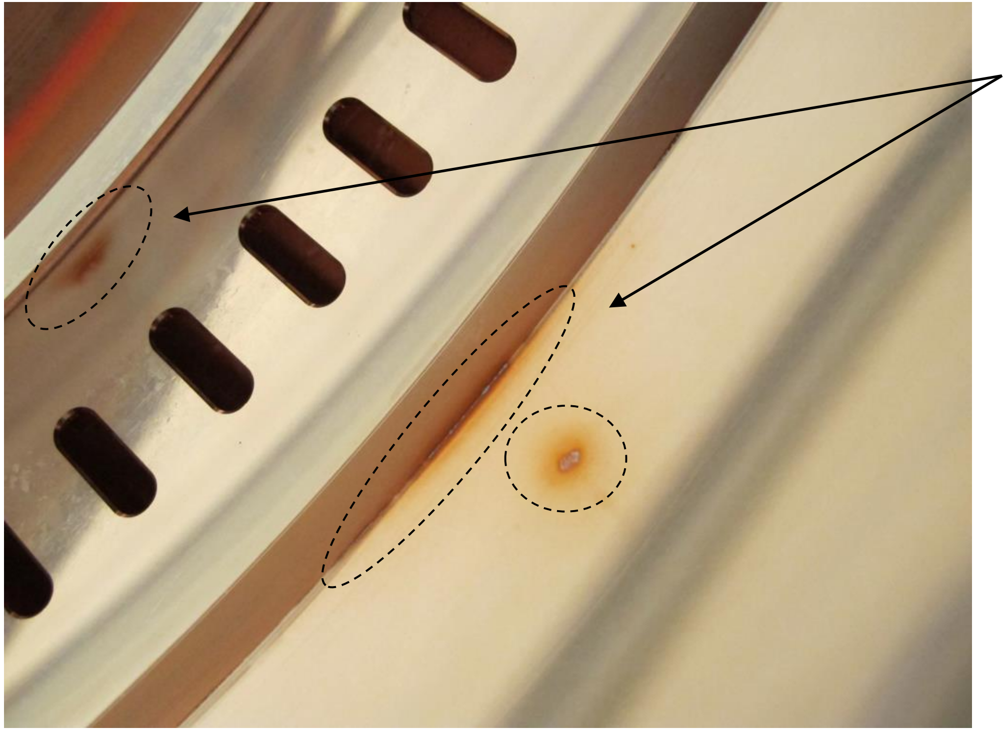
- Machining of the tuning rings in the old design
- The inner surface was protected by plastic foils
- After each tuning step the BOC was removed from the machine, cleaned and measured
- After the last step a baking cycle in vacuum oven was performed

Tuning and RF tests

#	Maker	Tuning steps	f (MHz)	Q_0	Power test	Breakdown rate
0	VDL	4	5711.952	219000	✓	$3 \cdot 10^{-8}$ (35 MW; phase jump) (1) $2*10^{-8}$ (40 MW phase modulation) (1)
1	PSI	4	5712.061	226000	✓	$3*10^{-8}$ (40 MW phase jump) (2)
2	PSI	3	5711.944	225000	-	-
3	PSI	2	5712.159	218000	-	-
4	PSI	0	5711.979	217000	-	
5-33	PSI	0	Series production			

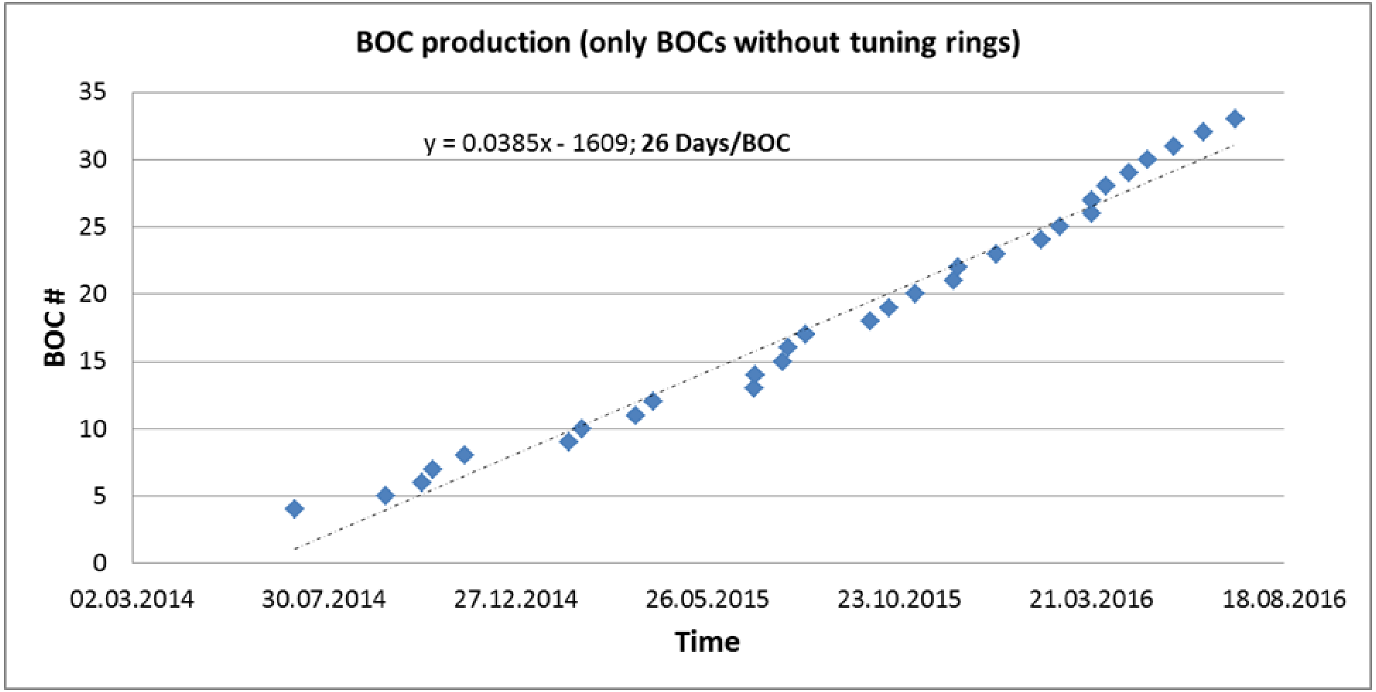
1) Very likely the BDR was limited by a waveguide bend placed at the BOC output. Post test inspection shows no clear BD indication on the BOC surface, instead we had a large amount of BD spots on the bend surface. Poor statistic, requires very long test time.
2) PSI BOC 1 required a much faster conditioning .This BDR result has been obtained only after removal of the waveguide bend which was limiting the performance.

First power test with VDL cavity



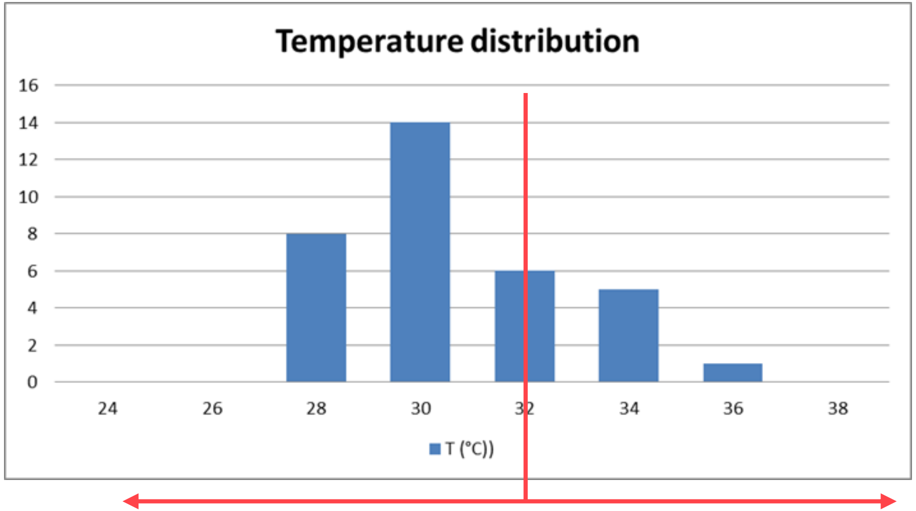
- Several dark spots near the tuning rings but not in the edge with lager field enhancement.
- The spots were on opposite side near the two rings (for one ring between the ring itself and the middle plane, for the other ring on the external part)
- We assumed it was due to residual cleaning material.
- Action: vacuum baking after last tuning step

Serial production



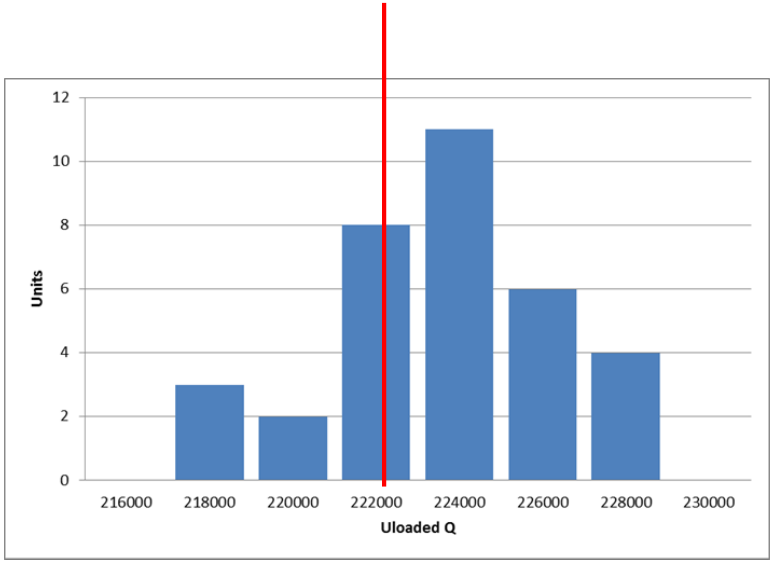
We have completed the production of 33 BOC in August 2016; the HERMLE 5 axis machine was not fully dedicate to the BOC production, low priority of the brazing oven)

Production statistics



Specified tuning range 32±7 °C

Computed Q (HFSS)

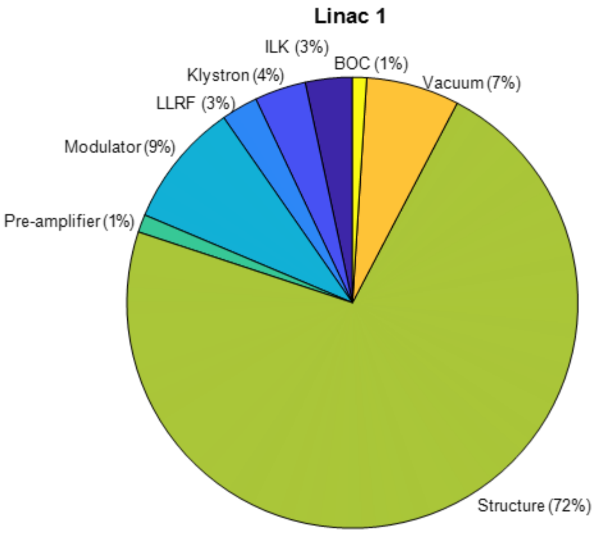


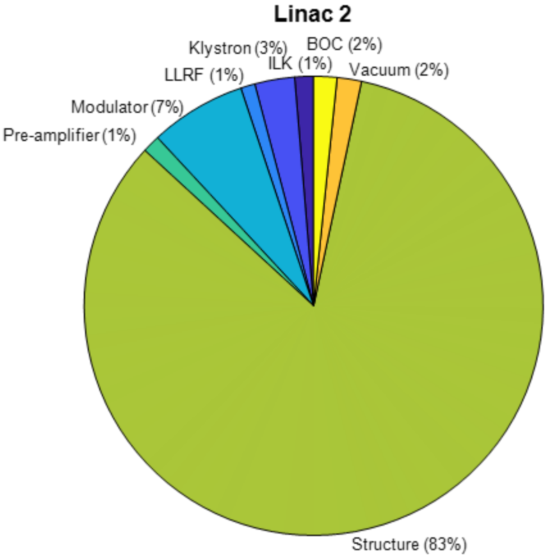
BOC in operation

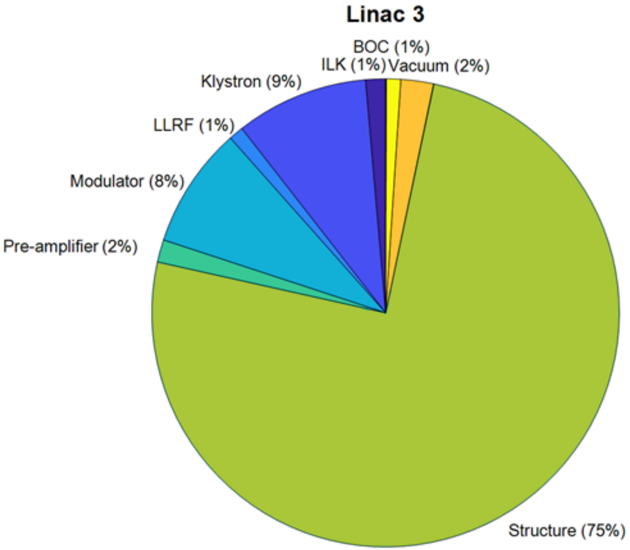
Preliminary study on fault statistics in SwissFEL

Linac 1	9 C-band stations	BOC BDR=$8*10^{-10}$
Linac 1	4 C-band stations	BOC BDR=$8*10^{-10}$
Linac 1	13 C-band stations	BOC BDR=$3*10^{-9}$

NB: BDR taking into accounts all the reflected power interlock generated in between klystron output and structure inputs, i.e. BOC & full waveguide network

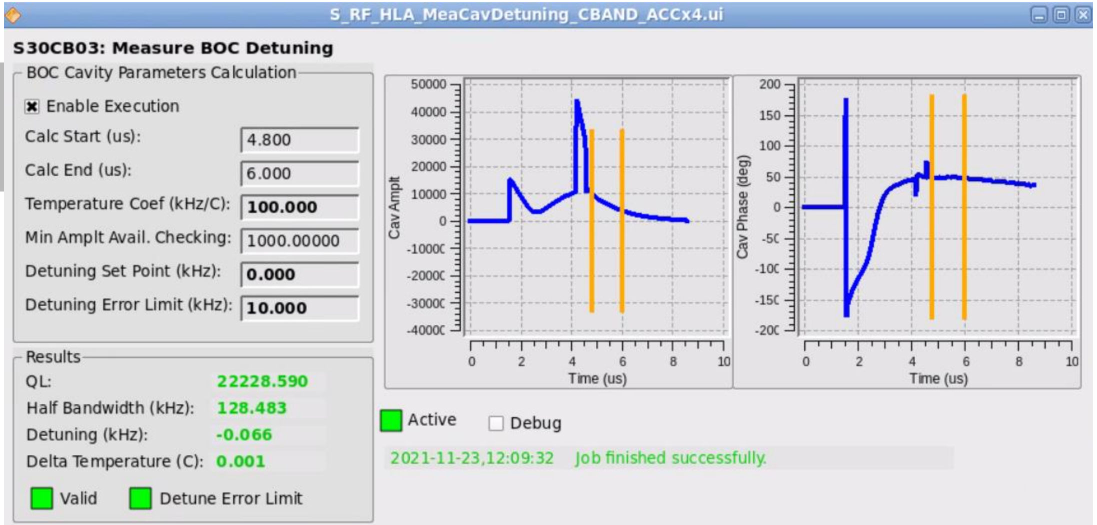






Courtesy of T. L. Geoffrey

BOC cooling and stability



S_RF_HLA_MeaCavDetuning_CBAND_ACCx4.ui

S30CB03: Measure BOC Detuning

BOC Cavity Parameters Calculation

☒ Enable Execution

Calc Start (us):	4.800
Calc End (us):	6.000
Temperature Coef (kHz/C):	100.000
Min Amplt Avail. Checking:	1000.00000
Detuning Set Point (kHz):	0.000
Detuning Error Limit (kHz):	10.000

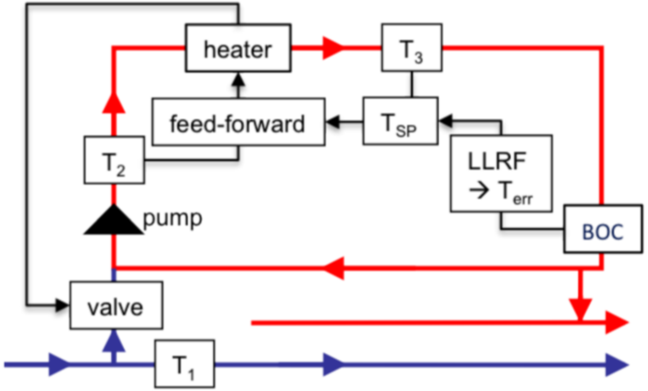
Results

QL:	22228.590
Half Bandwidth (kHz):	128.483
Detuning (kHz):	-0.066
Delta Temperature (C):	0.001

🟩 Valid 🟩 Detune Error Limit

🟩 Active ☐ Debug

2021-11-23,12:09:32 Job finished successfully.



heater

T_3

feed-forward

T_{SP}

LLRF

→ T_{err}

T_2

pump

BOC

valve

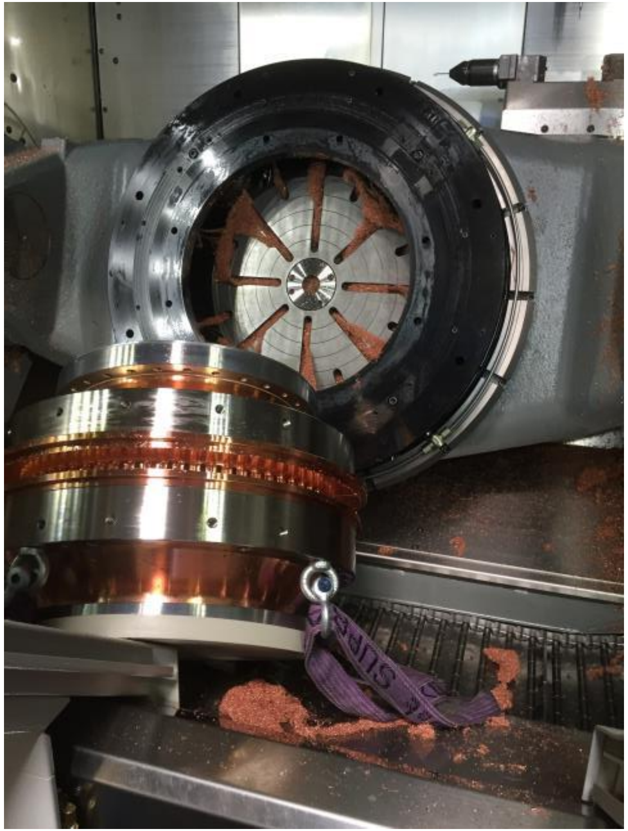
T_1

The mixing ratio between the cold water from the supply line and the water circulating in the local circuit can be adjusted with an adjustable valve. A heater with a total power of 2.4 kW is installed within the local circuit and it is used to precisely control the water temperature at the inlet of the pulse compressor. In order to optimize the speed of the regulation a feed-forward algorithm is used to drive the heater.

Stability reached~3.5 mK (rms)

max. time response around 5 min (RF power on-off)

Problem 1: production accident

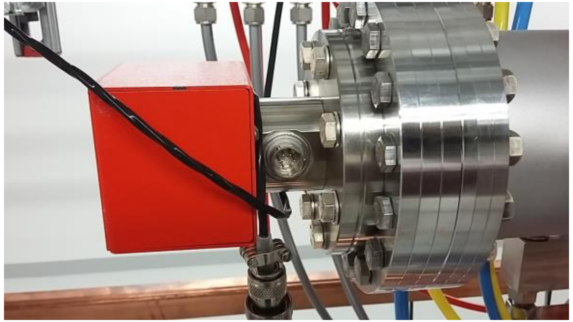


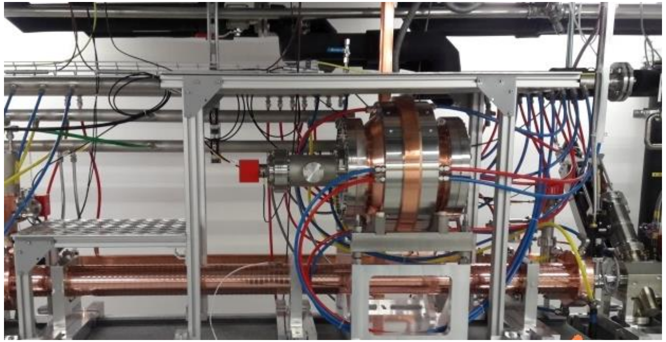
Things not always go as they should…

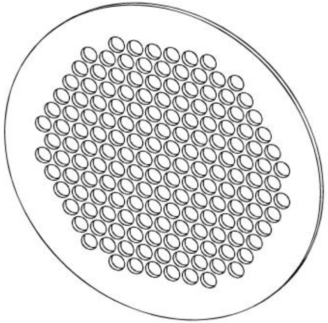
This BOC was brazed anyway and it was on frequency !

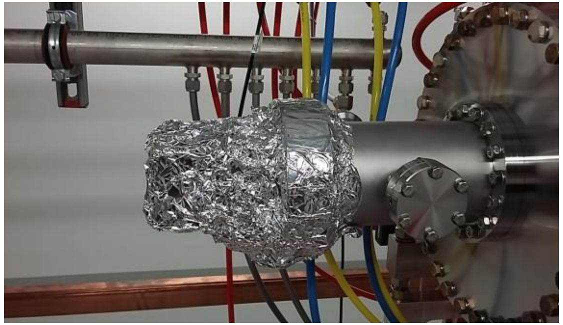
***Comment**: human factor and know-how are fundamental; we have one BOC with a virtual leak, it’s the only one which was not brazed by the usual technician. This BOC was brazed a second time and installed in the machine*

Problem 2: RF leak





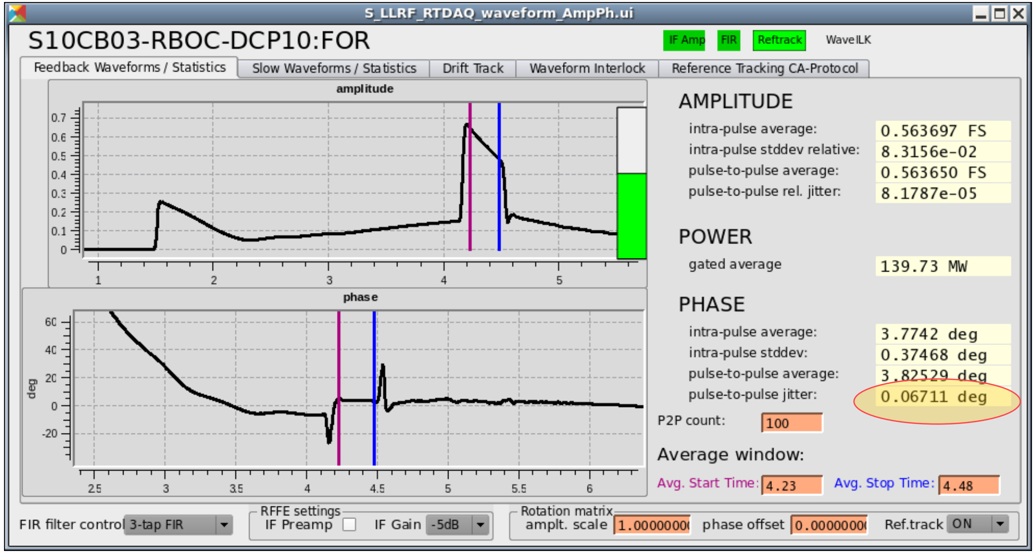




By using an antenna in the SwissFEL tunnel we realized that we had an RF leak at 5.712 GHz. By moving the antenna around the waveguide system we could localize the leak. It was at the vacuum pump of the BOC (neg + ion pump). The cable for heating the neg was a sort of antenna emitting the signal into the bunker

- First temporary solution, aluminum paper to shield
- Advanced solution: new gaskets
- Final solution (pragmatic): remove the cable from the neg

Problem 3: possible phase jitter



AMPLITUDE

intra-pulse average: 0.563697 FS
intra-pulse stddev relative: 8.3156e-02
pulse-to-pulse average: 0.563650 FS
pulse-to-pulse rel. jitter: 8.1787e-05

POWER

gated average 139.73 MW

PHASE

intra-pulse average: 3.7742 deg
intra-pulse stddev: 0.37468 deg
pulse-to-pulse average: 3.82529 deg
pulse-to-pulse jitter: 0.06711 deg

P2P count: 100

Average window:

Avg. Start Time: 4.23 Avg. Stop Time: 4.48

FIR filter control 3-tap FIR

RFFE settings
IF Preamp ☐ IF Gain -5dB

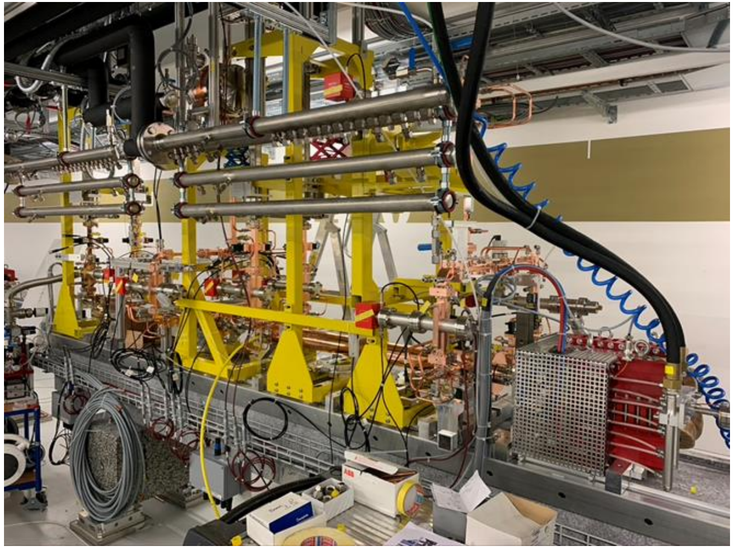
Rotation matrix
amplt. scale 1.0000000 phase offset 0.0000000 Ref.track ON

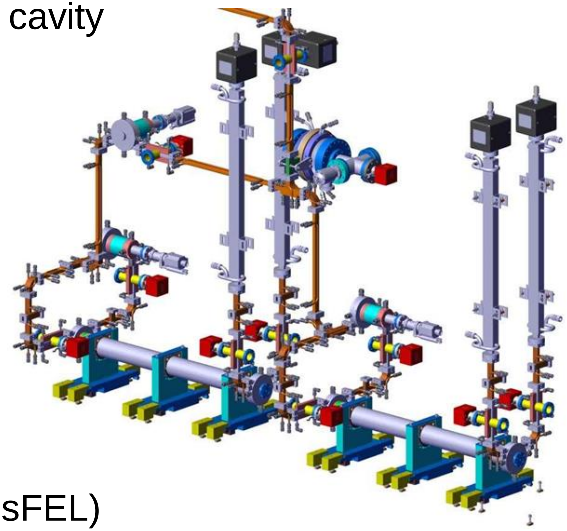
Few BOCs introduce jitter to the RF phase up to ~0.07° rms.

It seems to be a multipacting problem increasing the power level above 40 MW the problem disappears

XBOC: pulse compressor for the Polarix project

CERN-PSI-DESY Collaboration for the design, production and beam measurements of variable polarization X-band deflecting cavity

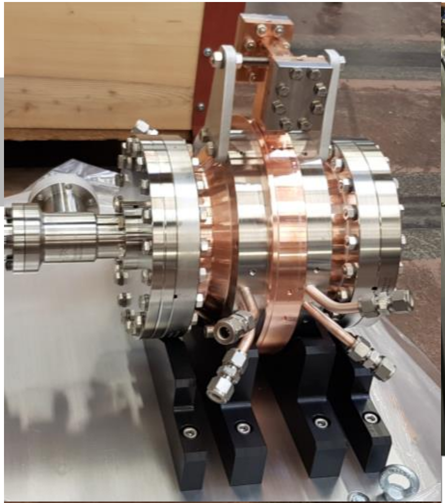


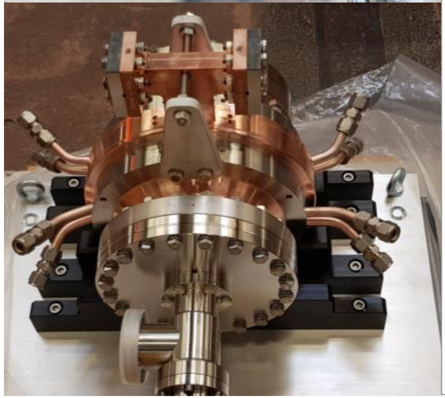


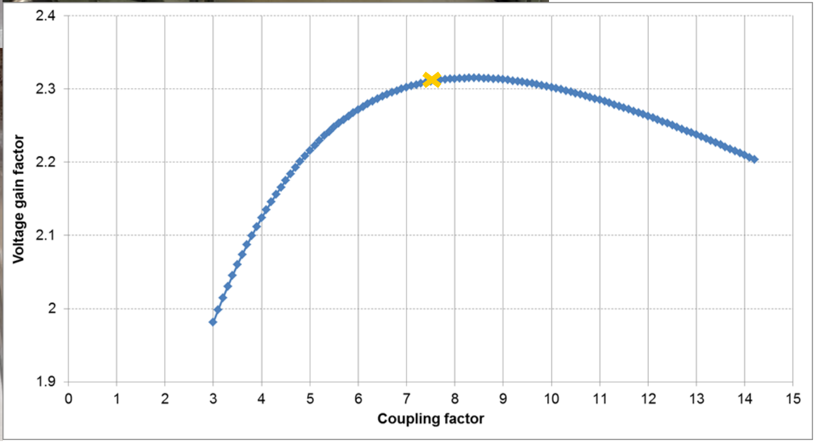
Post-undulator PolariX TDS for ATHOS beamline (SwissFEL)

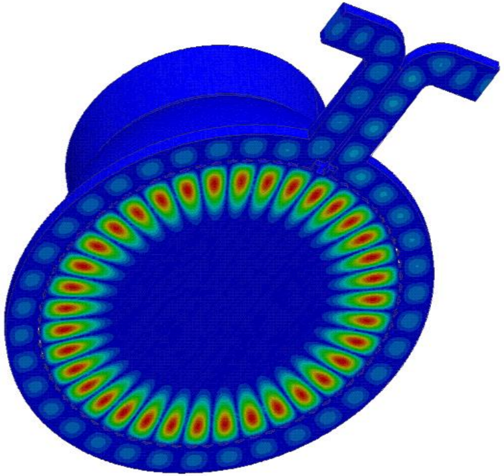
The Polarix collaboration has been the motivation to design and produce an X-band BOC (XBOC) at PSI.

XBOC









XBOC is in first approximation a scaled version of the C-band BOC, same working Mode $TM_{18,1,1}$,similar mechanical design and same production scheme

XBOC production

XBOC #	**Destination**	**Production date**	**Temperature (°C) for vacuum operation at 11995.2 MHz**	**Q_0**	**β**	**Max S11 (dB) in ±25 MHz range**
HFSS design			40	150000	7.5	-33
0	PSI ATHOS	05/09/2018	41.2	157800	7.9	-31
1	DESY FLASH II	08/10/2020	38.7	150000	7.3	-26.7
2	DESY SINBAD	15/10/2020	40.9	160000	7.8	-28.1
3	DESY SINBAD	08/07/2021	36.7	178500	9.2	-29

Summary

- 34 C-band BOC and 4 XBOC produced entirely at PSI, design, machining and brazing
- Simple and tuning-free mechanical design based on a single piece central body
- No HOMs problems, no need of RF damping
- Two machining steps, two brazing steps
- First brazing step (body+ cooling rings+ circular flanges) to define a solid piece that can be easily handled and fixed to the machine for the finishing
- Second brazing step to close the external waveguide and add the coupler
- Good high power performance
- So far we did not have any operational serious problem
- Strongly recommended pulse compressor topology especially for high frequencies

Conclusion

Thanks for your attention and stay safe