Paul Scherrer Institut

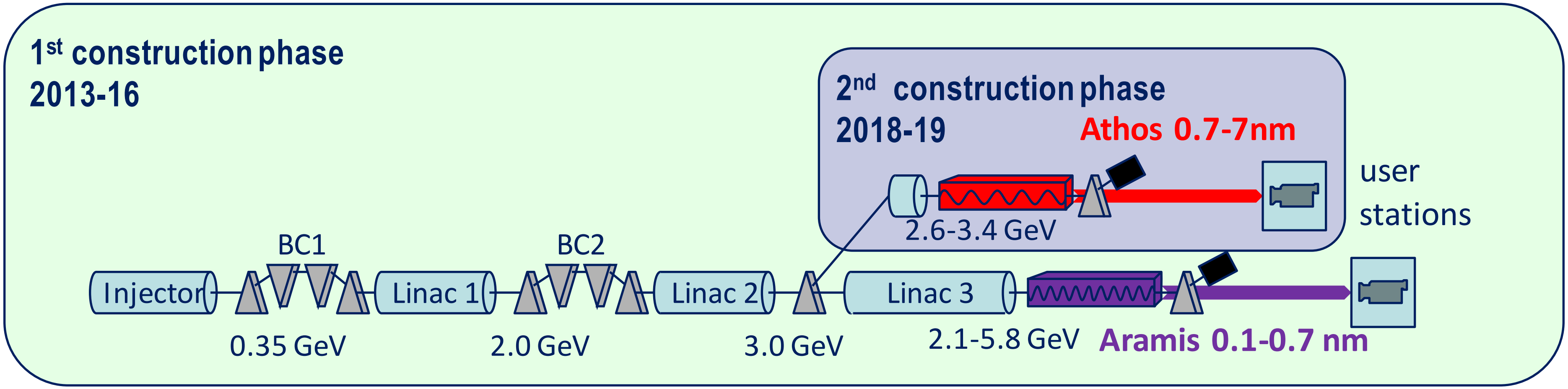
C-Band Testing for SwissFEL

04.06.2013

P. Craievich on behalf of RF group

International Workshop on Breakdown Science and High Gradient Technology (HG2013)

SwissFEL Project

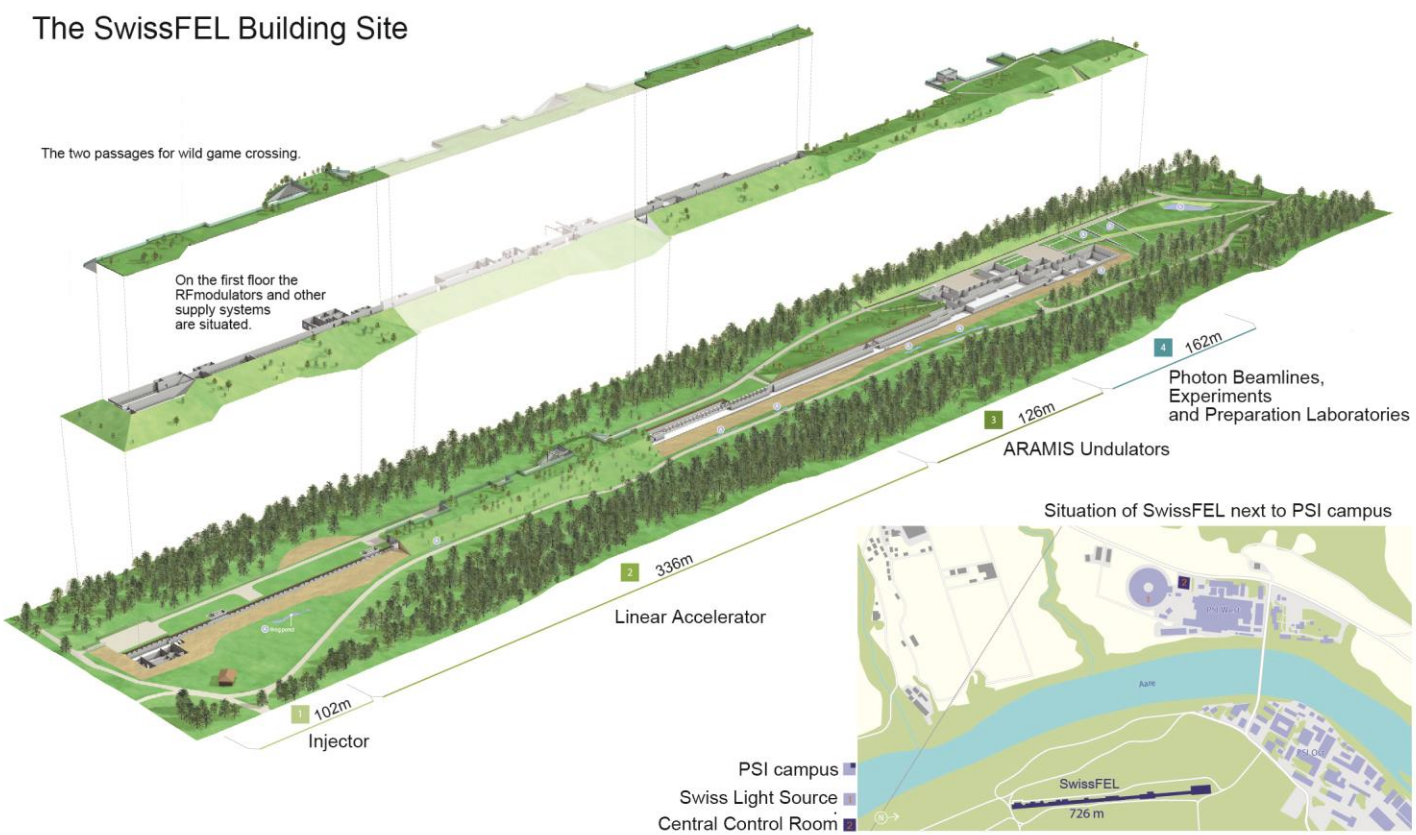


Overall Length: 726 m

Parameter	Long pulses	Short pulses	Unit
Maximum beam energy	5.8	5.8	GeV
Charge per bunch	200	10	pC
Core slice emittance	0.43	0.18	mm.mrad
Projected emittance	0.65	0.25	mm.mrad
Slice energy spread (rms)	350	250	keV
Relative energy spread	0.006	0.004	%
Peak current	2.7	0.7	kA
Repetition rate	100	100	Hz
Bunch length (rms)	25	6	fs
Bunch compression factor	125	240	
Aramis line			
Beam energy	2.1 – 5.8		GeV
Wavelength range (SASE)	1 – 7		Å
Undulator type	In-vacuum (λ_U = 15 mm)		
Polarization	linear		
Athos line			
Beam energy for Athos	2.5 – 3.4	-	GeV
Wavelength range (seeded and SASE)	7 – 70	-	Å
Undulator type	Apple II (λ_U = 40 mm)	-	
Polarization	Fully variable	-	

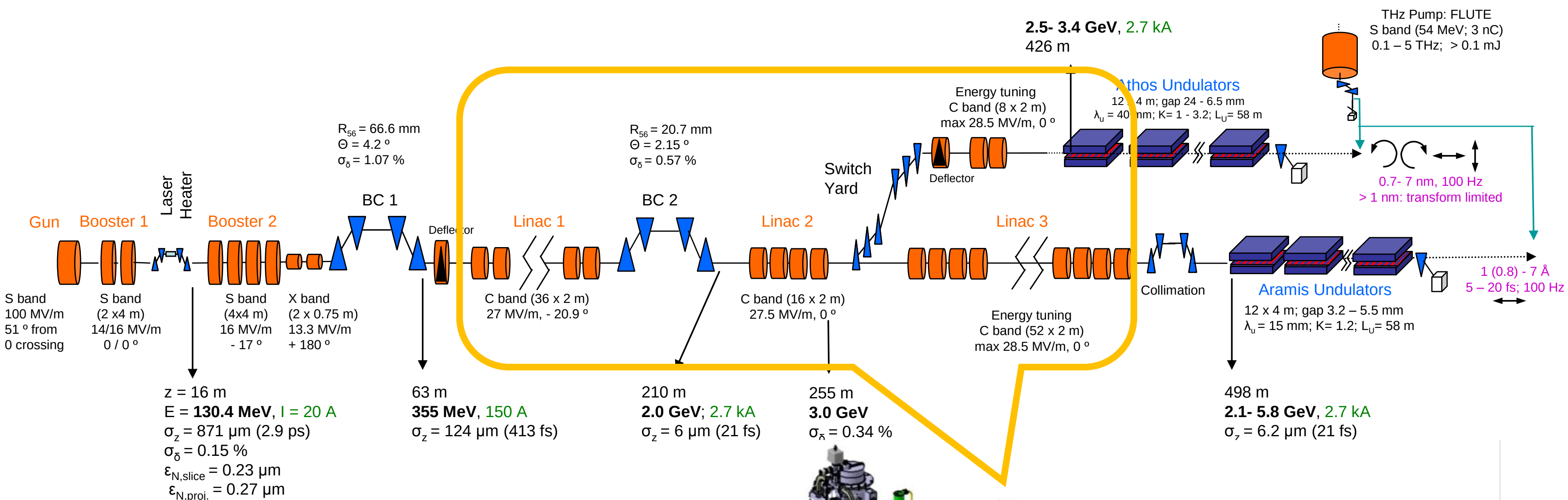
2 bunches for RF pulse @28ns
(Fast Kicker + septum)

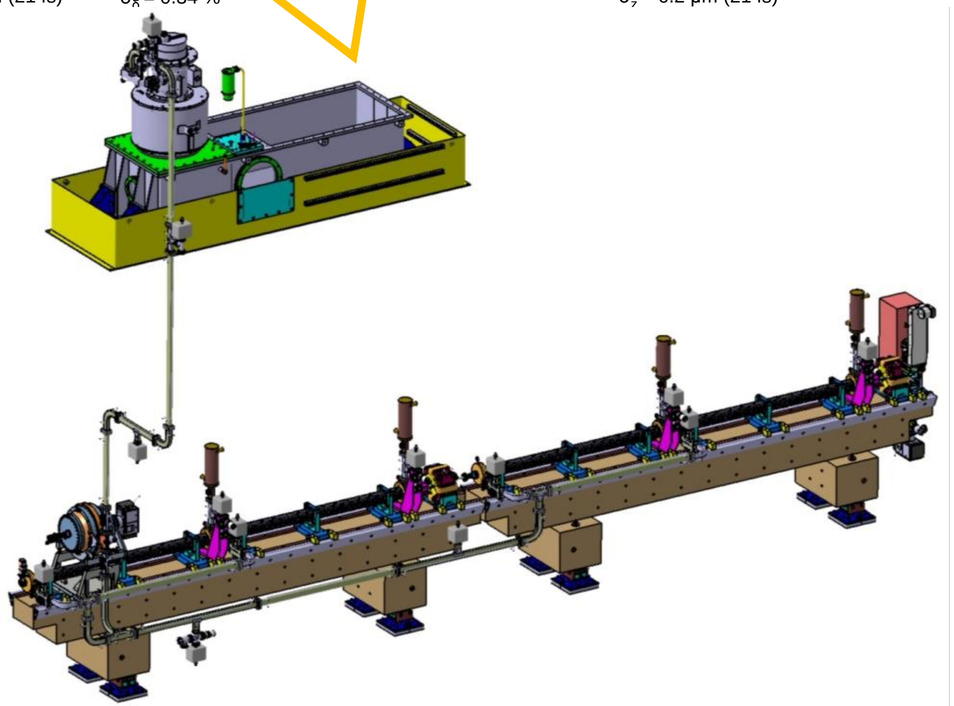
SwissFEL Building Site



- Ground breaking April 2013
- Preparatory work already ongoing
- July 3rd, 2013: laying of the foundation stone

C-band (5712 MHz) Linac Module





Main hardware components in C-band:

- ❑ 26 + 2 Linac module (total 112 structures)
- ❑ 26 + 2 pulse compressors
- ❑ 26 + 2 klystron
- ❑ ~560 m waveguide

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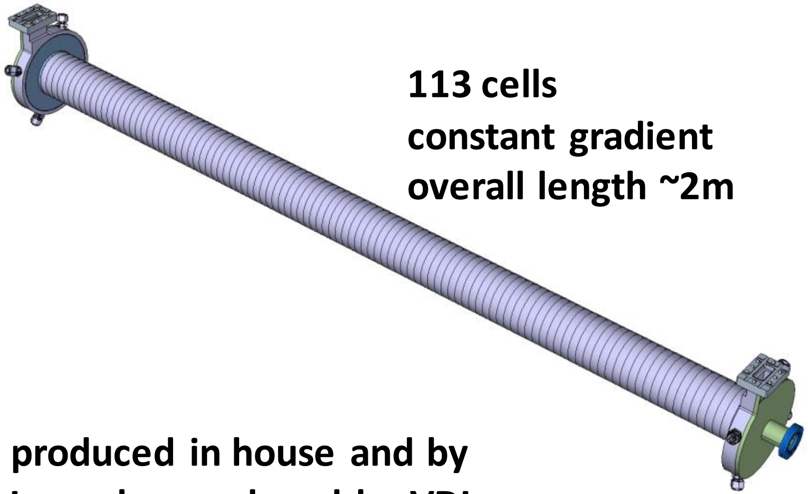
C-band Linac Module: accelerating structures

- In house development of ultra-precise machined accelerating structure **without tuning** (short structure program and 2m nominal structure)
- In house development of the brazing technique for the 2m structure

Specifications

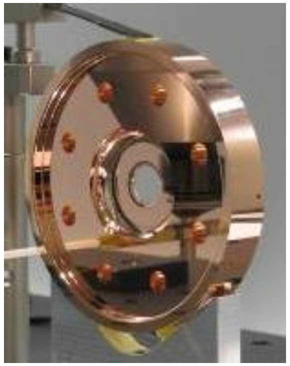
Operating frequency	5712.0	MHz
Phase advance for cell	$2\pi/3$	
Accelerating gradient	28	MV/m
Max. repetition rate	100	Hz
Operating temp.	30	°C
Filling time	329	ns
vg/c	3.1-1.2	%
R/Q	7.24-8.68	kΩ
Q (30°C)	10870-10790	
Iris radius (20°C)	7.238-5.447	mm

Ref. J. –Y. Raguin and M. Bopps, Proceedings of LINAC2012



113 cells
constant gradient
overall length ~2m

Cups produced in house and by VDL, J-coupler produced by VDL



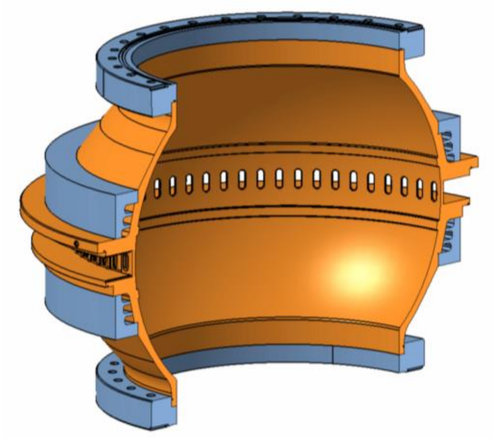
VDL

Double rounded cups

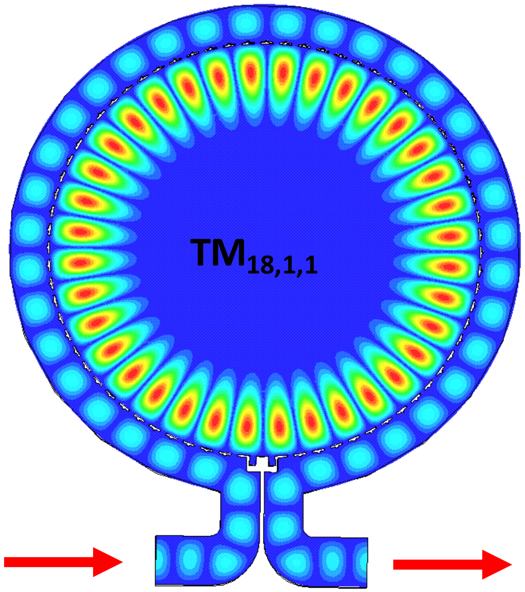
C-band Linac Module: pulse compressor

Specifications

Operating frequency	5712	MHz
Resonant mode	$TM_{18,1,1}$	
Diameter	492	mm
Number of coupling slot	70	
Q	216000	
Coupling factor	10	
Max input power	50	MW
RF input pulse length	3	µs
RF compressed pulse length	0.33	µs
Energy multiplication factor (M)	2.13	
Repetition rate	100	Hz
Operating temp.	30	°C



Barrel Open Cavity (BOC)



- **Whispering gallery mode:** intrinsic high Q-factor
- **Open:** it resonates without blind flanges without power radiation
- **HOM damping:** no field on axis, easy location for HOM absorber
- **Mode selection:** the multi-hole (70) design provides a good selection of the fundamental mode
- **Single cavity:** conventional pulse compressor are composed by two resonating cavities and an hybrid

Ref. R. Zennaro et al., Proceedings of IPAC2013

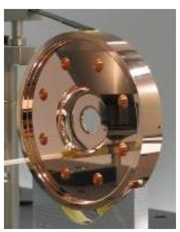
C-band technology @PSI

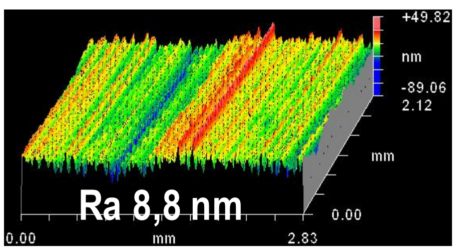
Ultra Precise turning machine

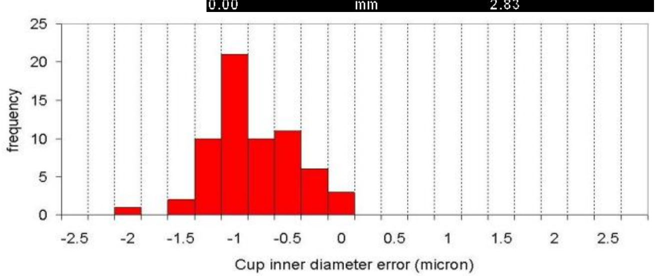
Brazing stacking provided by a robot

Vacuum brazing furnace installed and operative

Surface quality and tolerances well below the specs. (Specs.: R_a 25 nm and inner diameter $\pm$ 4μm)







5 axes machine for BOC production (installed and operational)

Test stand for RF at C-band (TRFCB)

ScandiNova Modulator

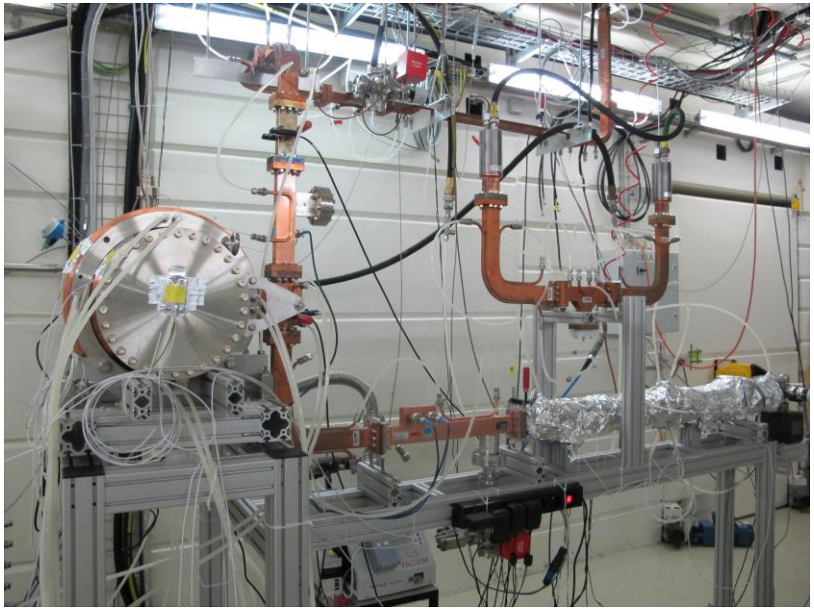
- K2 Modulator in regular use at OBLA 24/7 100 Hz operation for structure conditioning
- New C-Band Prototype Modulator ordered: to be delivered in March 2014; development under PSI quality control and intermediate reviews

C- band Klystrons: Toshiba development for PSI

- Toshiba E37202 60 Hz 2.5 μs, delivered in May 2011
- From 60 Hz 2.5 μs to 100 Hz 3 μs, delivered in December 2011
- Klystron with heat recovering system (HRS). The klystron collector cooling water is at 60 °C (separate circuit) the body at 30 °C. The 80° C water is used to heat PSI buildings. Site Acceptance Test this week.

Test of C-band components

- Short and 2-m structures
- Waveguide components (commercial: RF loads, DC etc..)
- RF load to 300 MW pk, 12kW average
- Pulse compressor (BOC)
- Full C-band module test

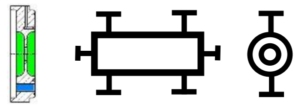
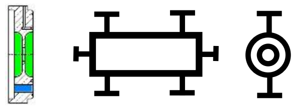
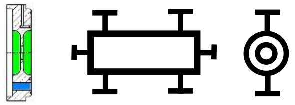
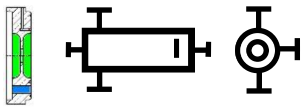


C-Band test program for short structures

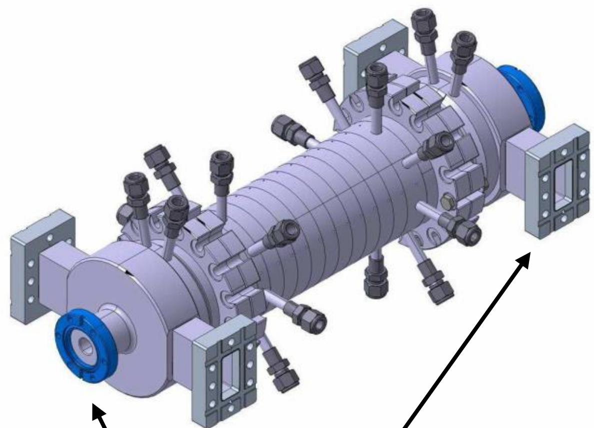
November 2011

No large brazing oven

November 2012

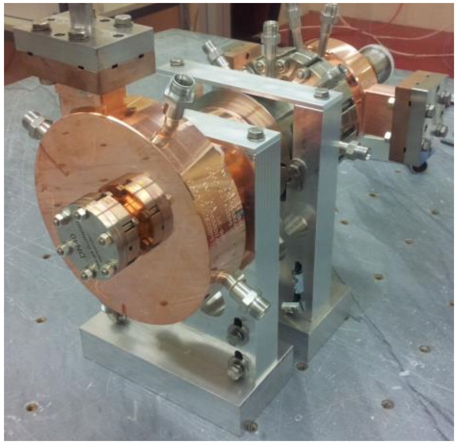
C-band test structures		Status
	**1st Short** Structure, **double** rounded, **bigger radius**	**Fully tested (10 Hz)**
	**2nd Short** structure, **double** rounded, **bigger radius**	**Fully tested (100 Hz)**
	**3rd Short** structure, **double** rounded, **smaller iris**	**Fully tested (100 Hz)**
	**4th Short** structure, **Double rounded, smaller iris, Output J-Coupler**	**Fully tested (100 Hz)**

Test Structure	Structure 1,2	Structure 3, 4
Type	Constant impedance	Constant impedance
Number of regular cells	11	11
Frequency	5.712 GHz	5.712 GHz
Phase advance/cell	$2\pi/3$	$2\pi/3$
Iris aperture radius /thickness	7.267/2.5 mm	5.478/2.5 mm
Group velocity	3.1 % c	1.4 % c
Q	10400	10350
R/Q	7214 Ohm	8522 Ohm
Nominal gradient (MV/m)	28 MV/m at 28 MW	28 MV/m at 10.84 MW



Mode launcher (structures 1,2,3)

J-coupler (structure 4)

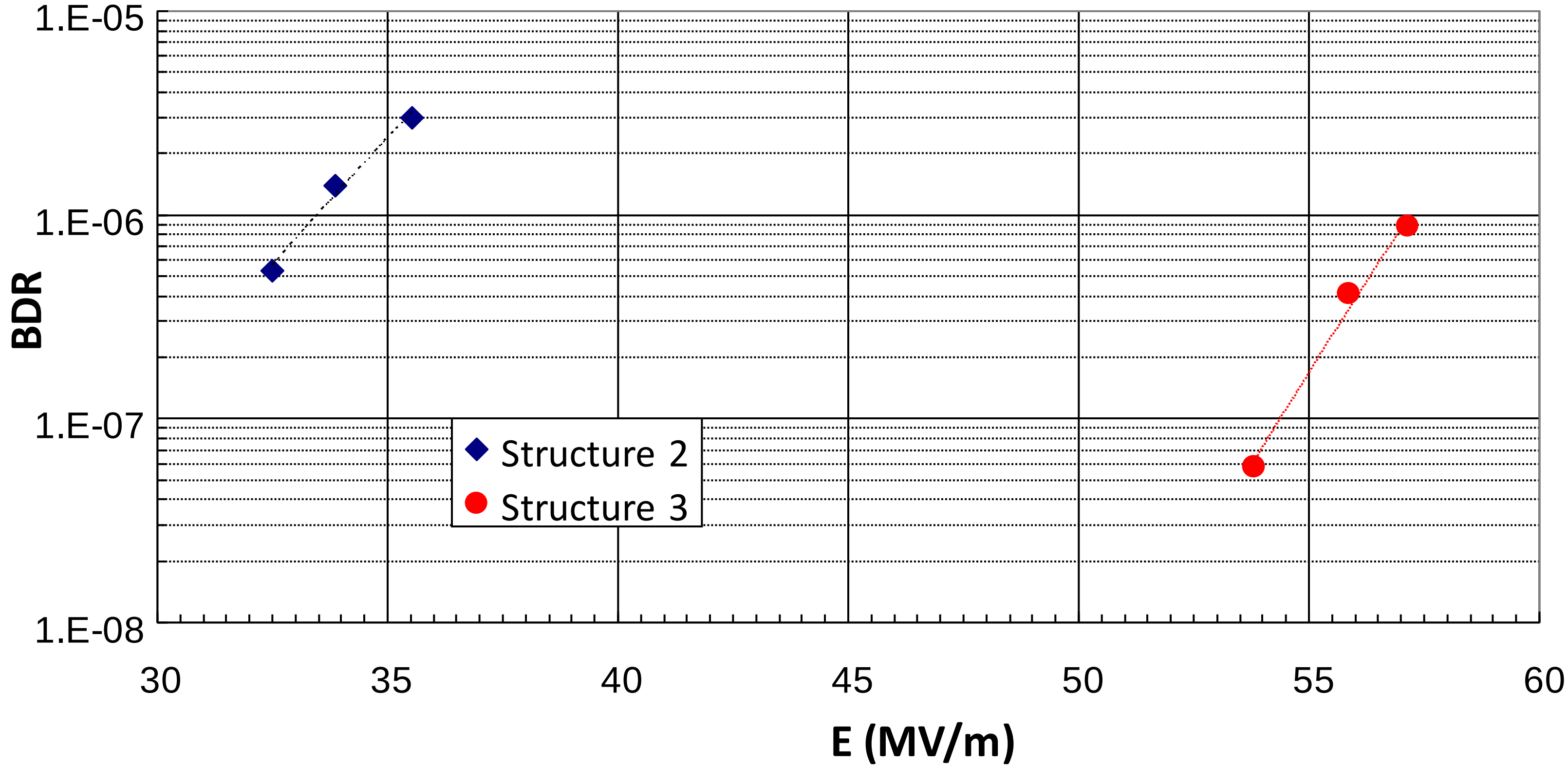


Ref. R. Zennaro, A. Citterio et al., LINAC2012 and IPAC2012

Short Structure Results: High Power Test

Geometry equivalent to nominal input structure

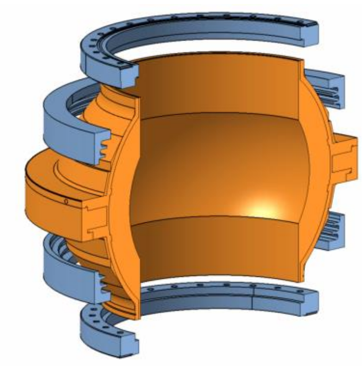
Geometry equivalent to nominal output structure



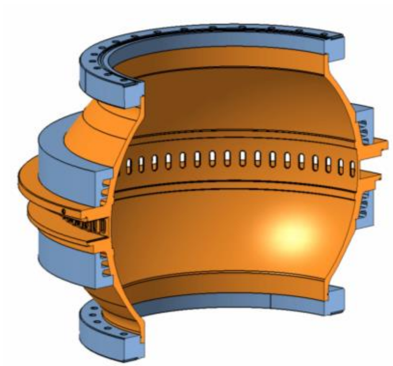
- Maximum available power 50 MW
- Test at 1 μs that is about 3 times the nominal filling time
- We do not need extremely large gradient in SwissFEL but we need to test the AS at higher gradient to get ~10^{-6} or 10^$^{-7}$ BDR. With the pulse compressor we intend to reach even larger gradients

BOC production steps

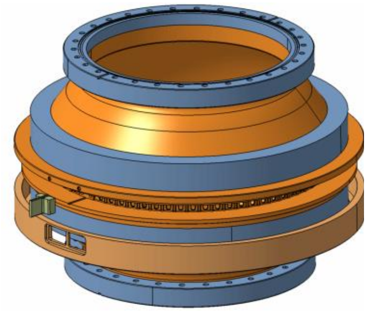
1: brazing of the flanges and cooling channels



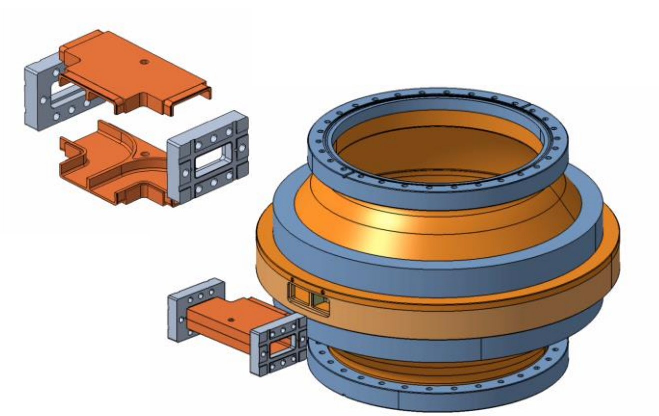
2: machining (turning) of the central body



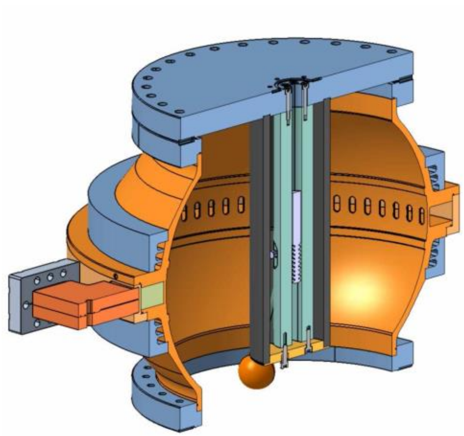
3: brazing of the “power divider” and the external ring



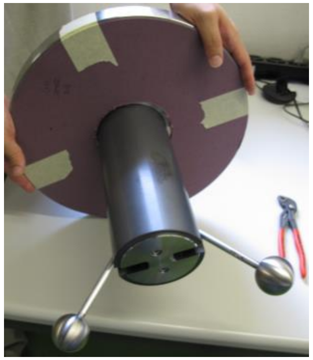
4: brazing of input/output waveguide to the body



5: insertion of the on/off mechanism and damping material



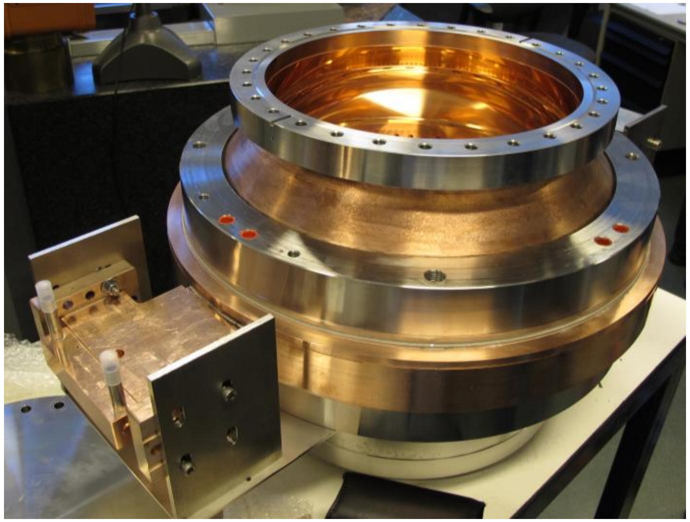
ON/OFF mechanism and HOM absorber

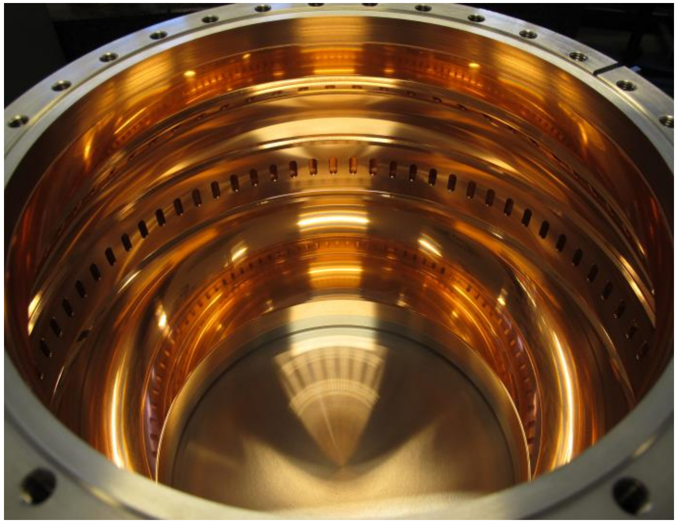


The on/off mechanism allows to detune the BOC and to operate with uncompressed pulse; a silicon carbide HOM absorber is also mounted on the same flange

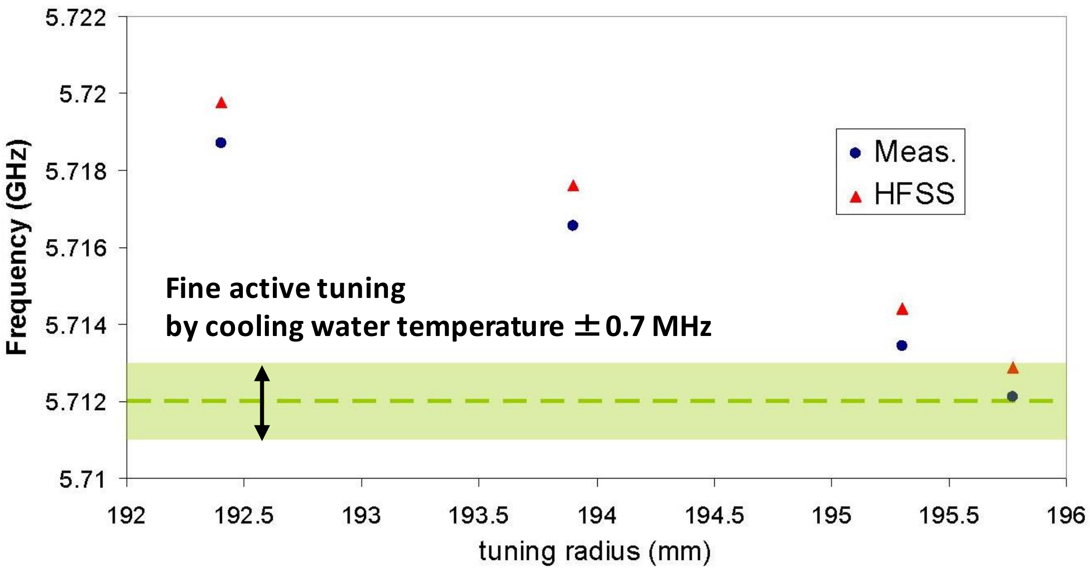
Courtesy of T. Stapf

BOC: prototype by VDL

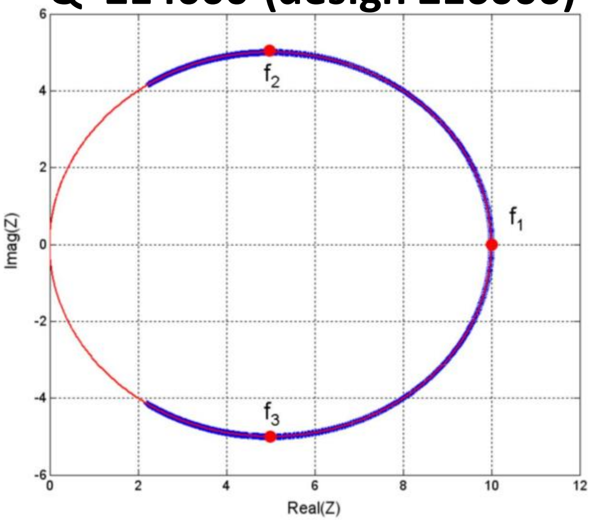




4 steps tuning procedure (tuning range ± 8MHz)



β=10 (design 10)
Q=214000 (design 216000)



Ref. R. Zennaro et al., Proceedings of IPAC2013

BOC: RF cold measurements

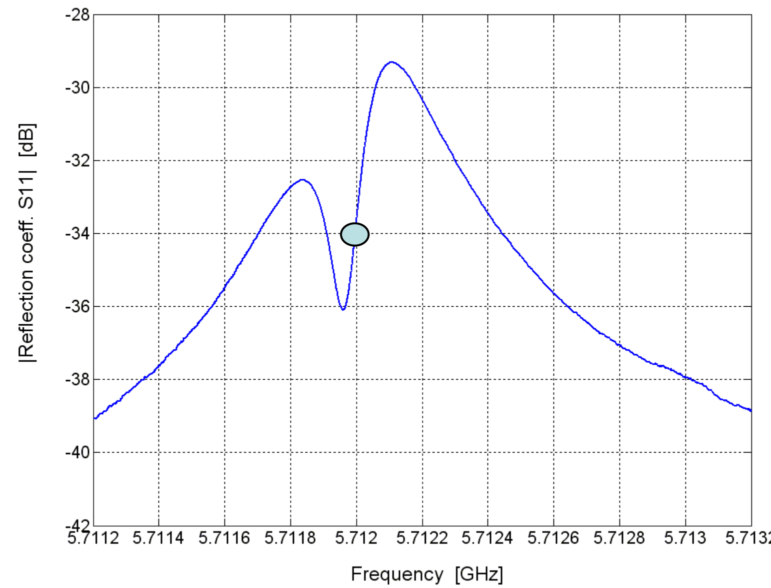
- Reflected power (S11) limited to -34 dB at the resonant frequency and always below -28 dB in a 20 MHz range.

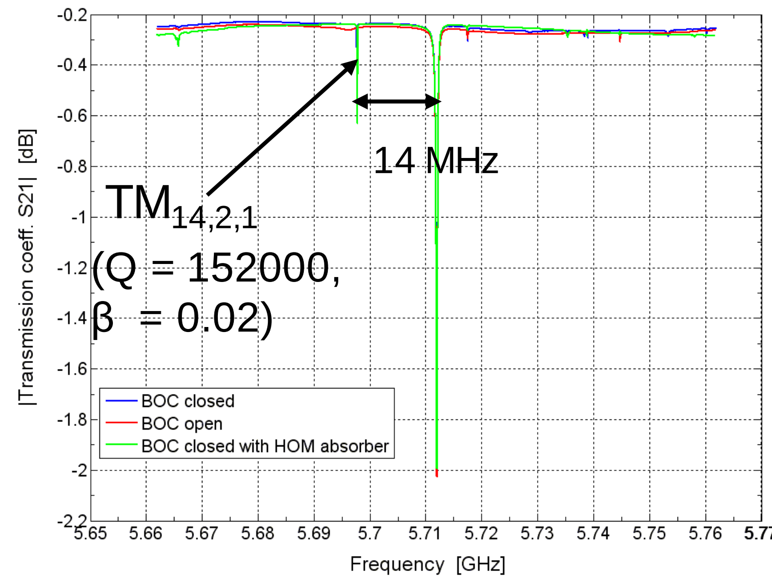
- RF measurements performed in a large frequency range (100 MHz) in three configurations:
  - → BOC open (no resonance),
  - → BOC closed without HOM absorber
  - → BOC closed with HOM absorber.

- In the last two cases a resonance appears 14MHz below the working mode and it is not damped by the silicon carbide absorber

  → $TM_{14,2,1}$ from HFSS

- Basically this resonance does not represent a problem for the operation since it is very low coupled and outside of the klystron bandwidth



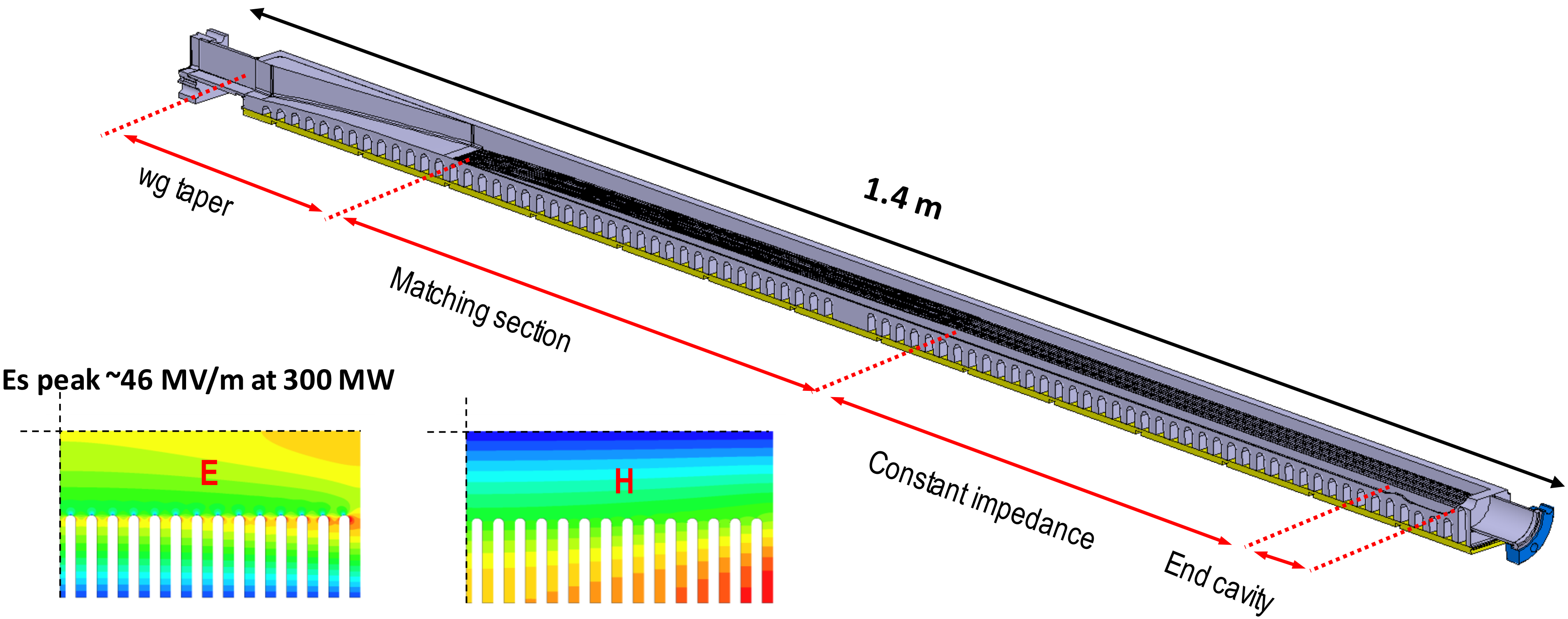


RF Load for BOC power test 1/2

The compressed pulse from BOC has a peak power up to 300MW peak and 12kW average power:

- NIHON KOSHUA load is limited to 50 MW and dry loads to 25 MW → we need a different solution
- Concept based on magnetic stainless steal (SS430) X-band loads developed at CERN (I. Syratchev);
- Different design to improve compactness (losses a f^1.5; 0.9m load at 11.424 GHz is equivalent to 2.55 m at 5.712 GHz)
- C-band load: RF design in house and manufacturing by CINEL (Italy)

STRUMENTI SCIENTIFICI CINEL s.r.l.



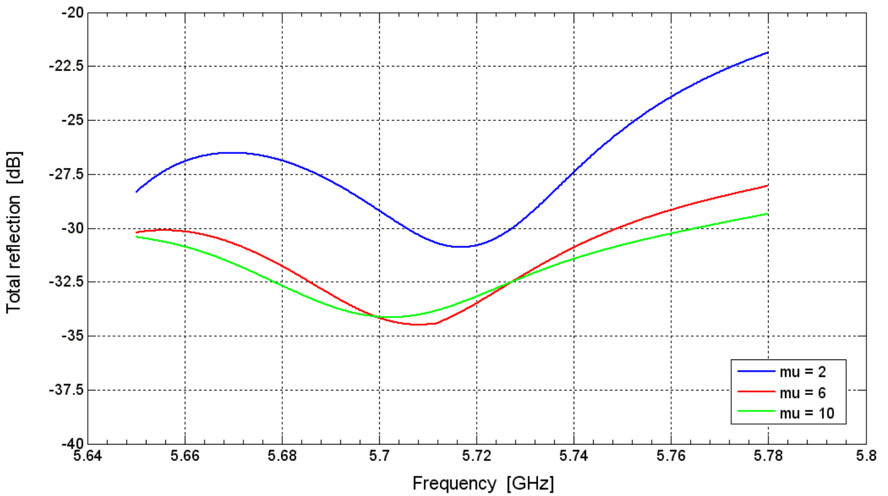
RF Load for BOC power test 2/2

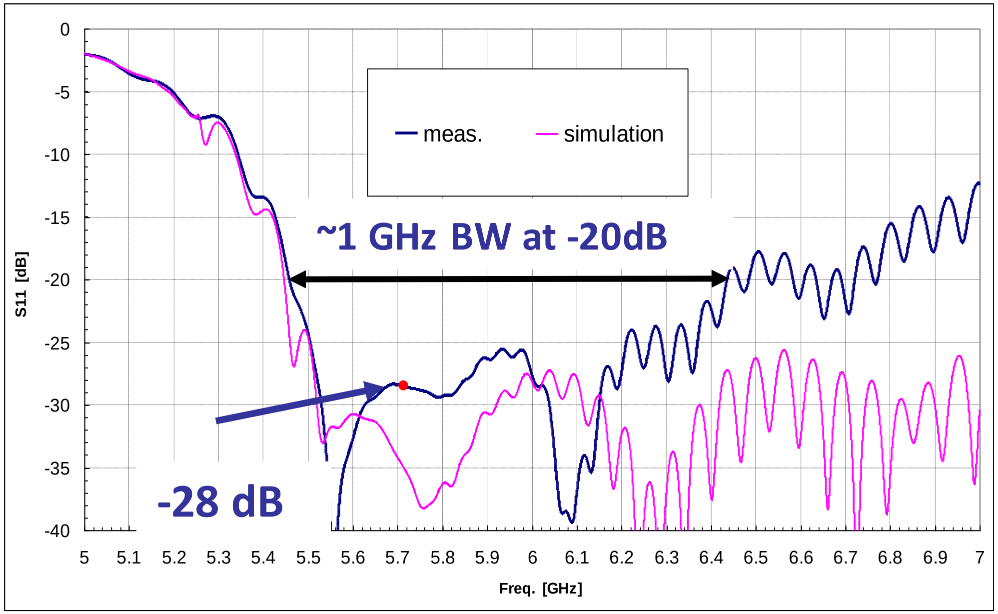
Material study for the load:

- no information on literature about the μ of SS430 at C-band*
- cavity test of 3 dissipative materials: SS430 (X6Cr17), X17CrNi16-2 (AISI431) and X20Cr13
- lower Q with material SS430 but difficult to find on the market
- chosen material: **AISI431**

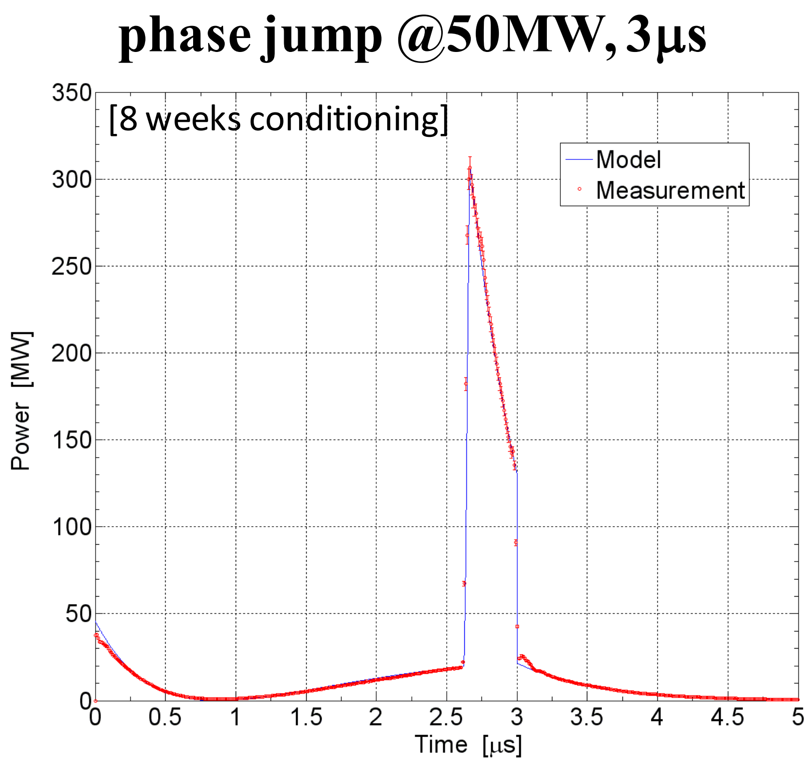
Reflection coefficient

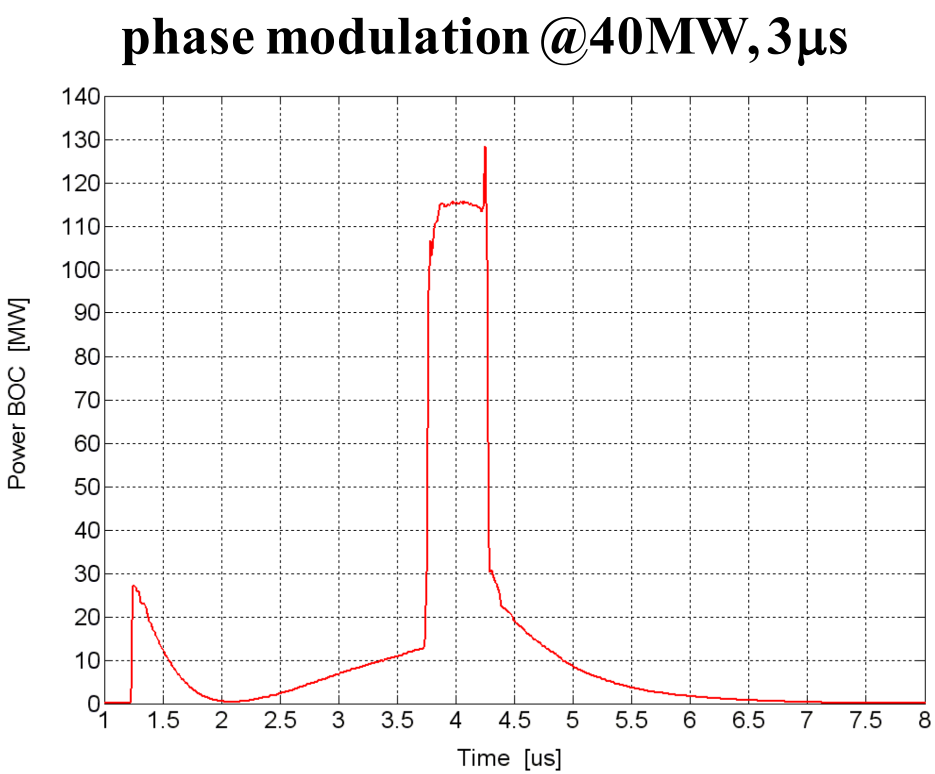
***RF design optimized for a large range of μ**





BOC power tests and BDRs





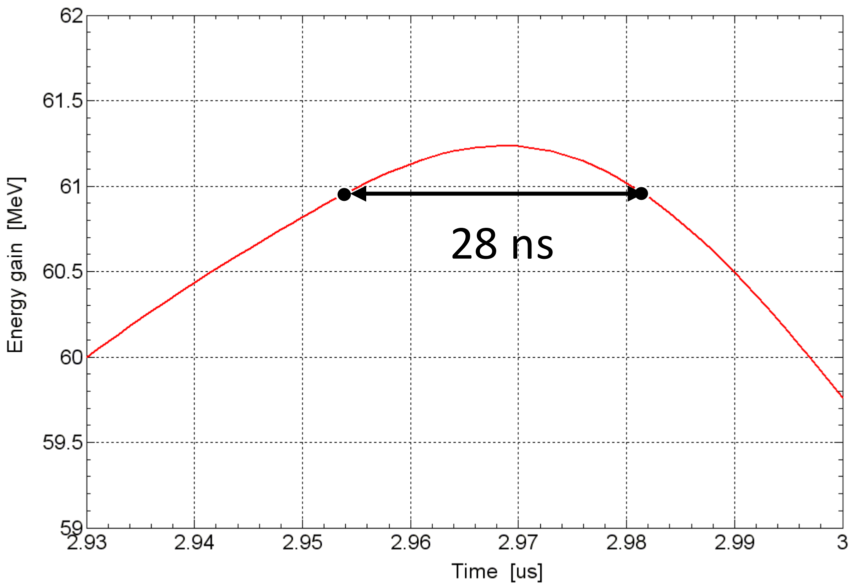
- 40 MW, phase jump: 26 BDs in 144 hours (6 days) equivalent to BDR=$5*10^{-7}$
- 35 MW phase jump: 1 BD in 115 hours (4.8 days) equivalent to BDR=$3*10^{-8}$
- 40 MW phase modulation: 1 BD in 181 hours (7.5 days) equivalent to BDR=$2*10^{-8}$

Not significant for statistic

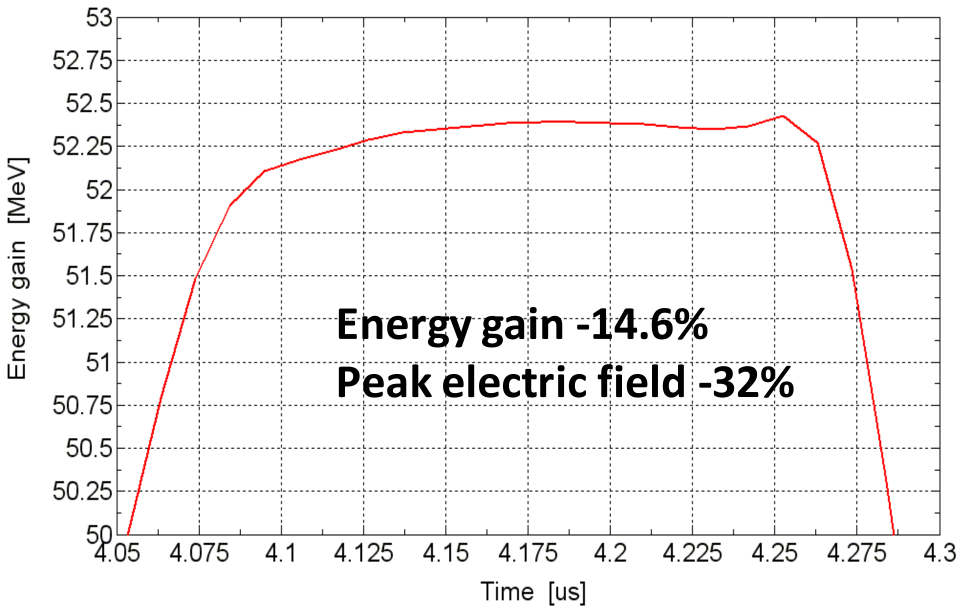
Courtesy of. R. Zennaro and A. Citterio

BOC: beam energy gain

Phase jump @40MW



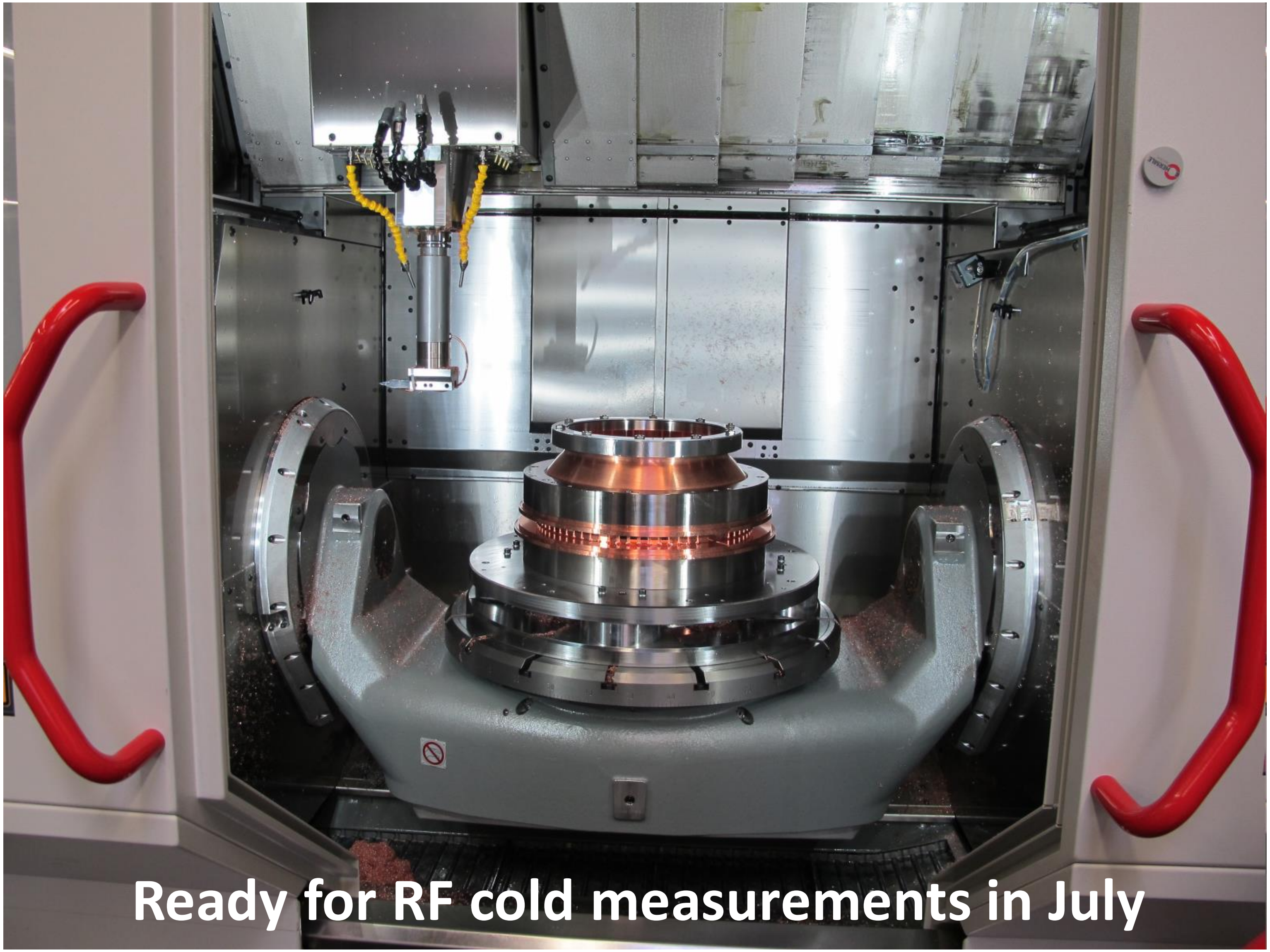
Phase modulation @40MW



SwissFEL energy gain scheme based on BOC performances:

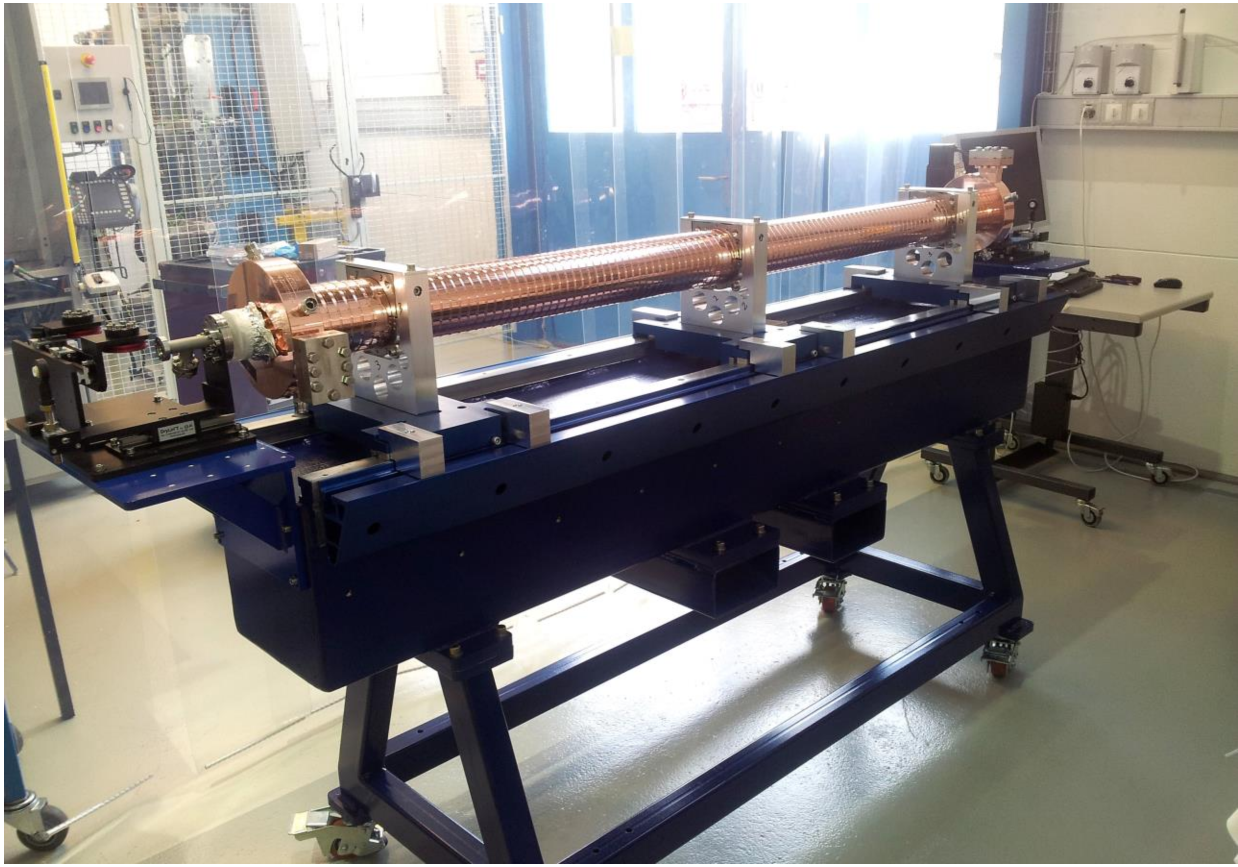
- **Linac 1 with phase modulation operation**: on-crest energy gain of 52 MeV/structure (26.3 MV/m) @40 MW from klystron.
- **Linac 2 and 3 with phase jump operation**: on-crest energy gain of 58.3 MeV/structure (29.5 MV/m) @36 MW from klystron.

2nd BOC under production in PSI



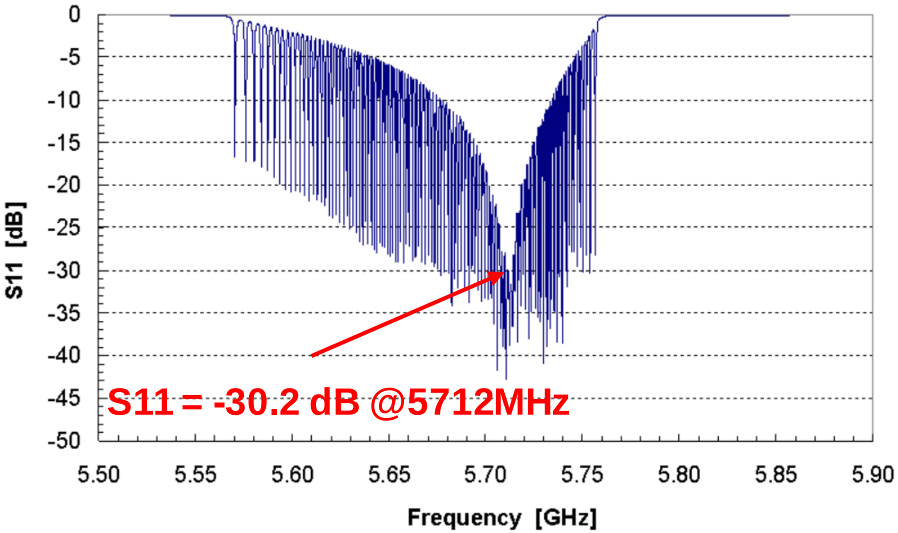
Ready for RF cold measurements in July

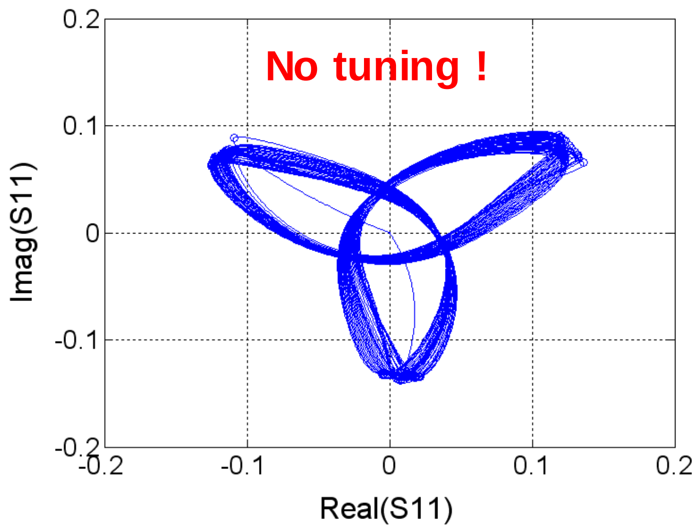
First C-band Accelerating Structure

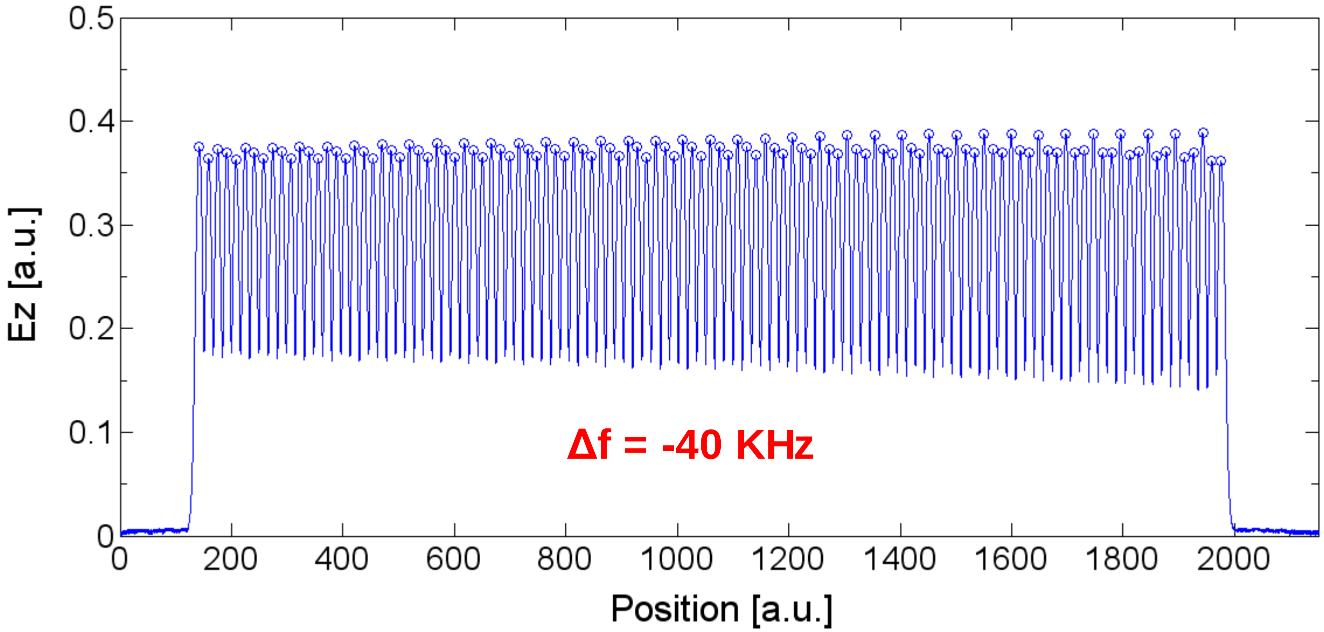


- ❑ **Pre-machining of the cups at PSI and final cut at VDL**
- ❑ **RF cold measurements**
- ❑ **Starting power test in June/July**

C-band Structure: RF cold measurements 1/2

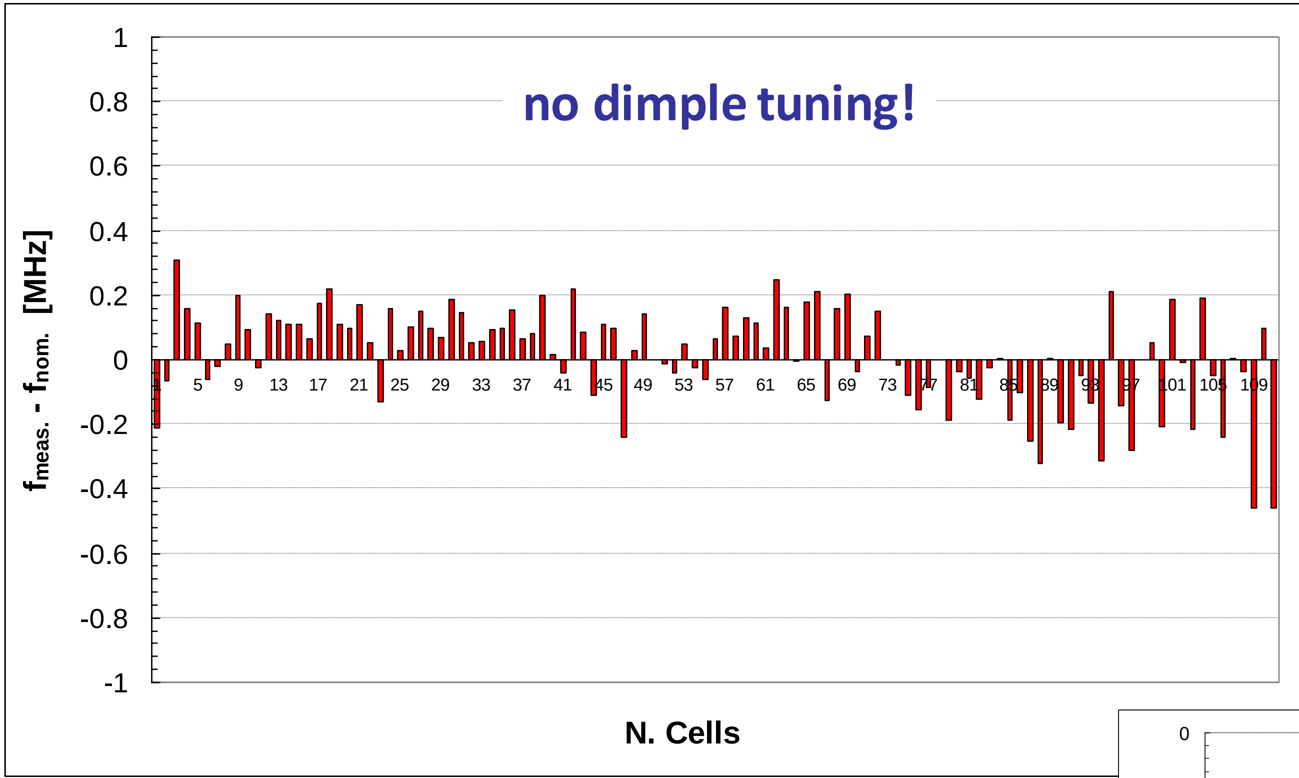


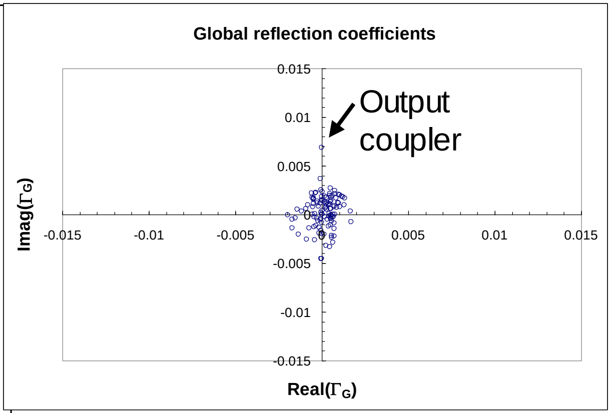




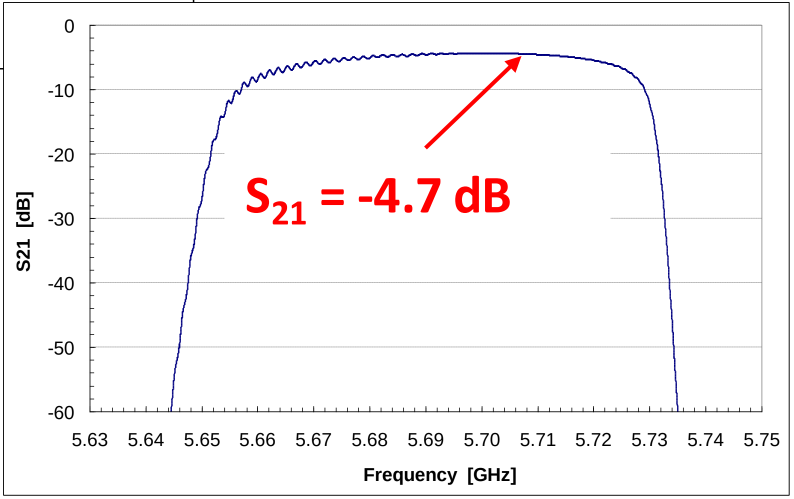
Ref. A. Citterio

C-band Structure: RF cold measurements 2/2





transmitted power



$Q_{est} = Q_{sim} \pm 1\%$

Ref. A. Citterio

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Summary

Proof of the reliability of the C-band technology at 100 Hz:

- **High power tests on short structures:** high gradients with low BDRs, 57 MV/m (small irises) and 35 MV/m (large irises) @ 1 μs RF pulse width and 50 MW klystron power.

- **C-band load:** successful RF design and production of a C-band load able to work with 300 MW peak power and to absorb 12 kW average power during BOC operation in phase jump mode.

- **Impressive achievements for first pulse compressor (BOC):**

  → β, Q, and S_{11} according to the RF design,

  → compressed RF pulse with phase jump (50 MW klystron, 3 μs) and phase modulation (40 MW klystron, 3 μs),

  → energy gain for SwissFEL inside expectations.

- **Accelerating structures:**

  → proof of ultra-precise machining of the cups and brazing procedure,

  → no dimple tuning feature needed,

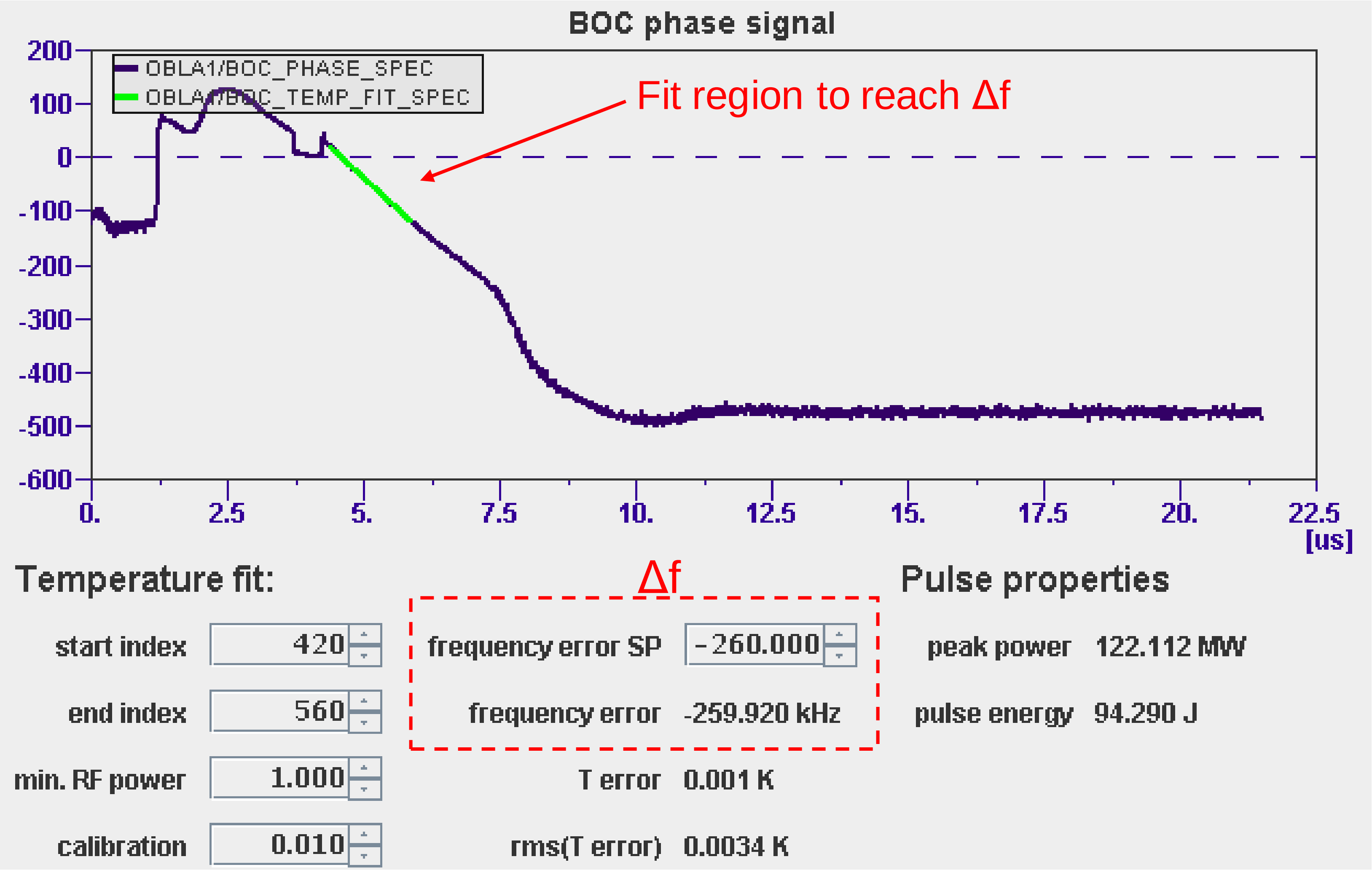
  → TRFCB now dedicated to the high power test for the first 2-m structure.

Special thanks to Riccardo Zennaro and Alessandro Citterio

Thanks for your attention

BOC: temperature regulation system

The phase slope of the BOC is used to stabilize the working temperature:



4 mK rms stability temperature