LCLS-II

Beam Line HOM Absorber Design

design, tests, concerns

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LCLS-II CM Interconnect FDR,

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Outline

- Motivation
- HOM power
- Beam Line Absorber design
- Tests at FLASH Sept.2008 and 2009
- Thermal simulations and Thermal Connection to 40 K Tube
- Final Remarks

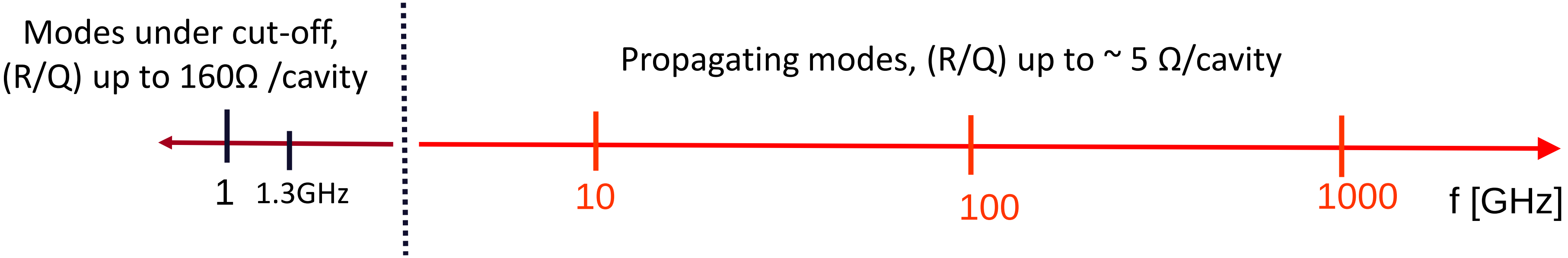
LCLS-II (SCRF) Baseline Parameters

Parameter	symbol	nominal	range	units
Electron Energy	E_f	**4.0**	2.0 - 4.14	GeV
Bunch Charge	Q_b	**100**	10 - 300	pC
Bunch Repetition Rate in Linac	f_b	**0.62**	0 - 0.93	MHz
Average e^- current in linac	I_{avg}	**0.062**	0.0 - 0.3	mA
Avg. e^- beam power at linac end	P_{av}	**0.25**	0 - 1.2	MW
Norm. rms slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-}s}$	**0.45**	0.2 - 0.7	μm
Final peak current (at undulator)	I_{pk}	**1000**	500 - 1500	A
Final slice E-spread (rms, w/heater)	σ_{Es}	**500**	125 - 1500	keV
RF frequency	f_{RF}	**1.3**	-	GHz
Avg. CW RF gradient (powered cavities)	E_{acc}	**16**	-	MV/m
Avg. Cavity Q0	$Q0$	**2.7e10**	1.5 - 5e10	-
Photon energy range of SXR (**SCRF**)	E_{phot}	-	**0.2 - 1.3**	keV
Photon energy range of HXR (**SCRF**)	E_{phot}	-	**1 - 5**	keV
Photon energy range of HXR (**Cu-RF**)	E_{phot}	-	**1 - 25**	keV

240kW 0-1.2MW

Motivation

HOMs of the LCLS-II and XFEL cavity:



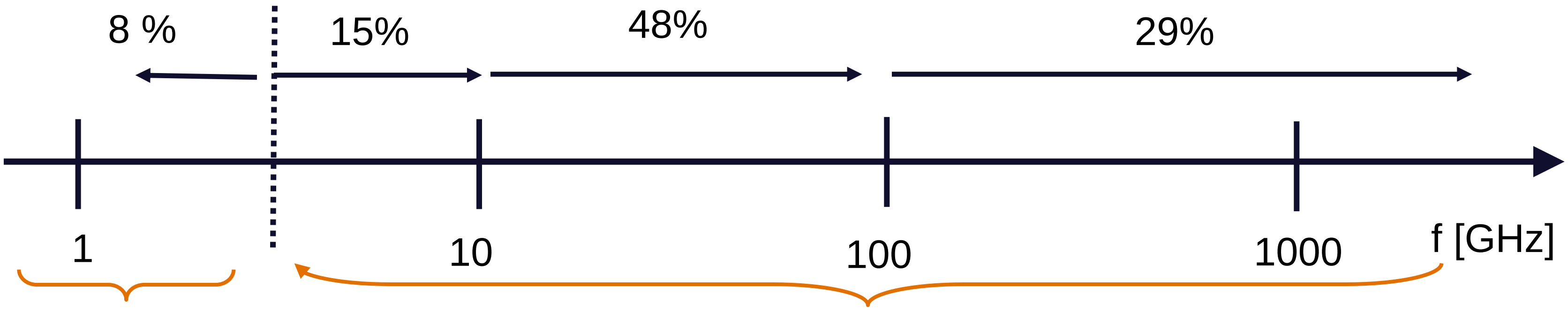
Modes under cut-off,
(R/Q) up to 160Ω /cavity

Propagating modes, (R/Q) up to ~ 5 Ω/cavity

CW mode: XFEL beam (200 pC @ 0.1 MHz @ σ_z = 25 µm): **0.6 W/CM**

LCLS-II beam (300 pC @ 1 MHz @ σ_z = 25 µm): 13.8 W/CM

(similar power for XFEL2000 parameters)

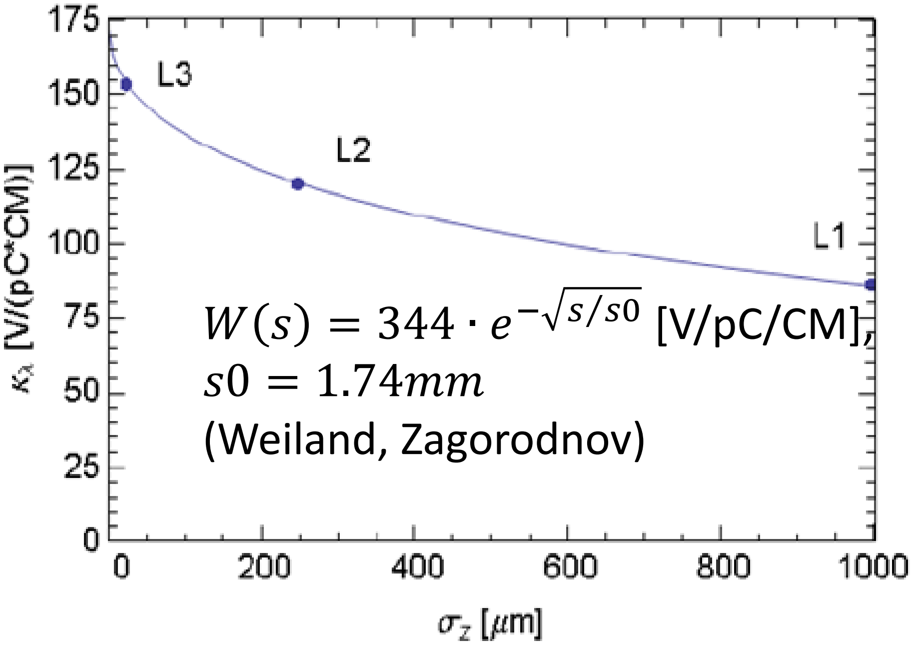


HOM couplers

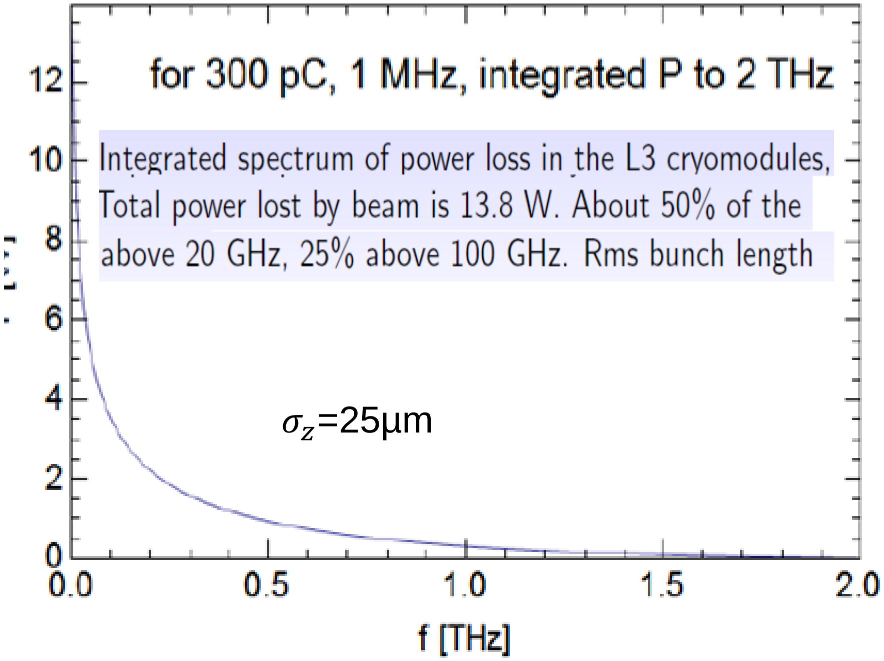
Beam Line Absorber

HOMs and Wakes in LCLS-II SC Linac: Steady-state losses

- In LCLS-II, HOM's generated by the beam will add to the power load, especially in the last linac (L3), where the peak current is highest.
- Ceramic absorber (between CMs , tied to 50K) → to absorb propagating HOM power >85%
- The HOM power generated by the beam is $P \sim Q^2 \cdot f_{rep}$. The nominal charge Q = 100 pC; however, the combination Q = 300 pC, f_{rep} = 1 MHz, will generate the highest HOM power
- The beam (Q = 300 pC, f_{rep} = 1 MHz) loses **7.7, 10.7, 13.8 W/CM in L1, L2, L3** (except for first two CMs)



$$W(s) = 344 \cdot e^{-\sqrt{s/s0}}\ \text{[V/pC/CM]},$$
$$s0 = 1.74mm$$
(Weiland, Zagorodnov)



for 300 pC, 1 MHz, integrated P to 2 THz

Integrated spectrum of power loss in the L3 cryomodules, Total power lost by beam is 13.8 W. About 50% of the above 20 GHz, 25% above 100 GHz. Rms bunch length

σ_z=25µm

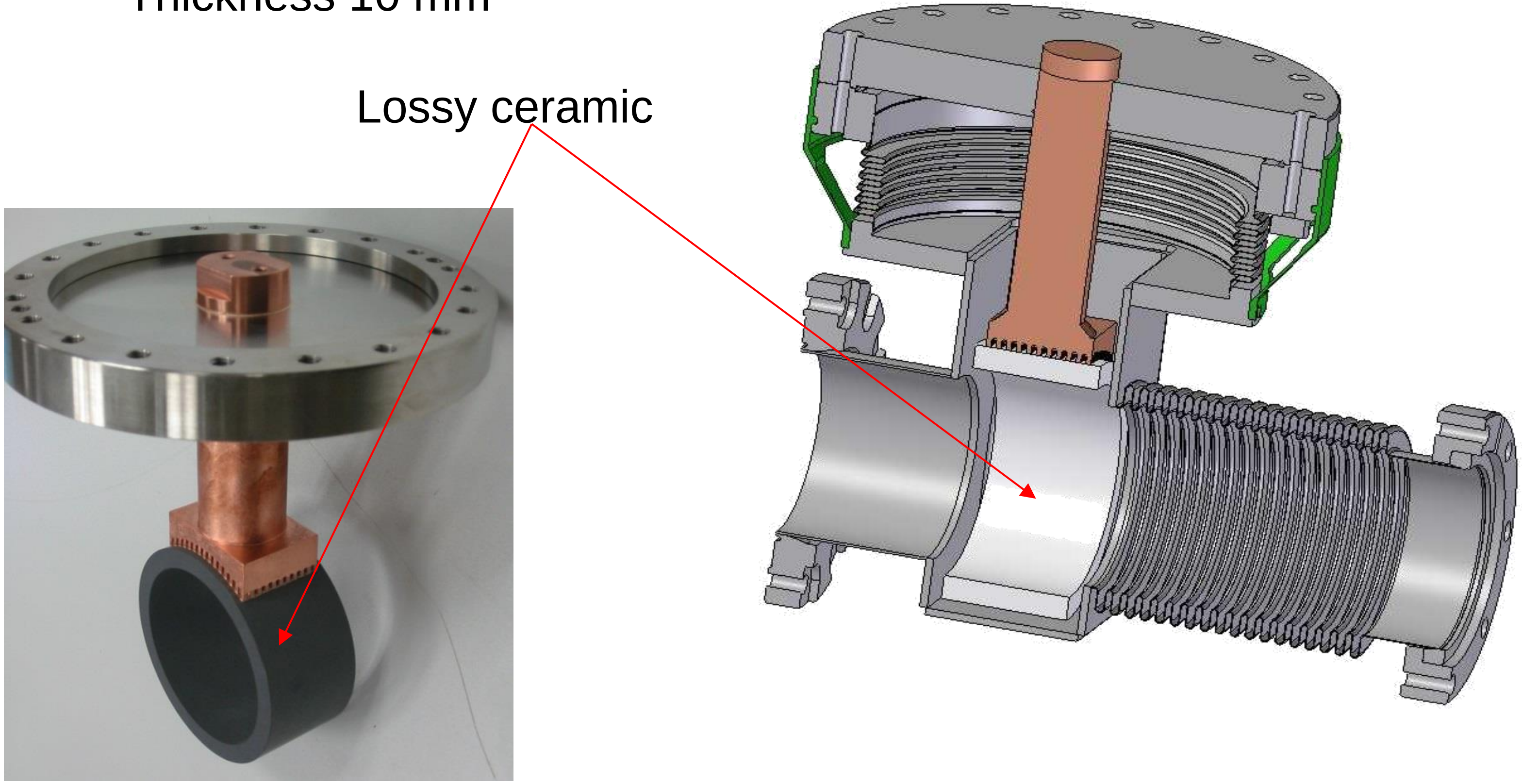
Transient Wakes

- For a short bunch passing through a periodic structure, it takes on the order of the catch-up distance, z_{cu}=$a^2/2\sigma_z$, to reach the steady-state wake. For L3 taking *a = 3.5 cm &* σ_z= 25 µm, **z_{cu} = 25m**
- When the beam enters the first CM of L3, the first cells loss factor is higher (see LCLS-II TN-13-04). In the first four CMs of L3 losses are: **29.5, 14.5,** 13.8, 13.8 W
- Direct calculation of the transient wake is difficult to do because of the huge number of mesh points involved. However, G. Stupakov /SLAC has obtained the transient wake with Echo using scaling law.

Beam Line Absorber

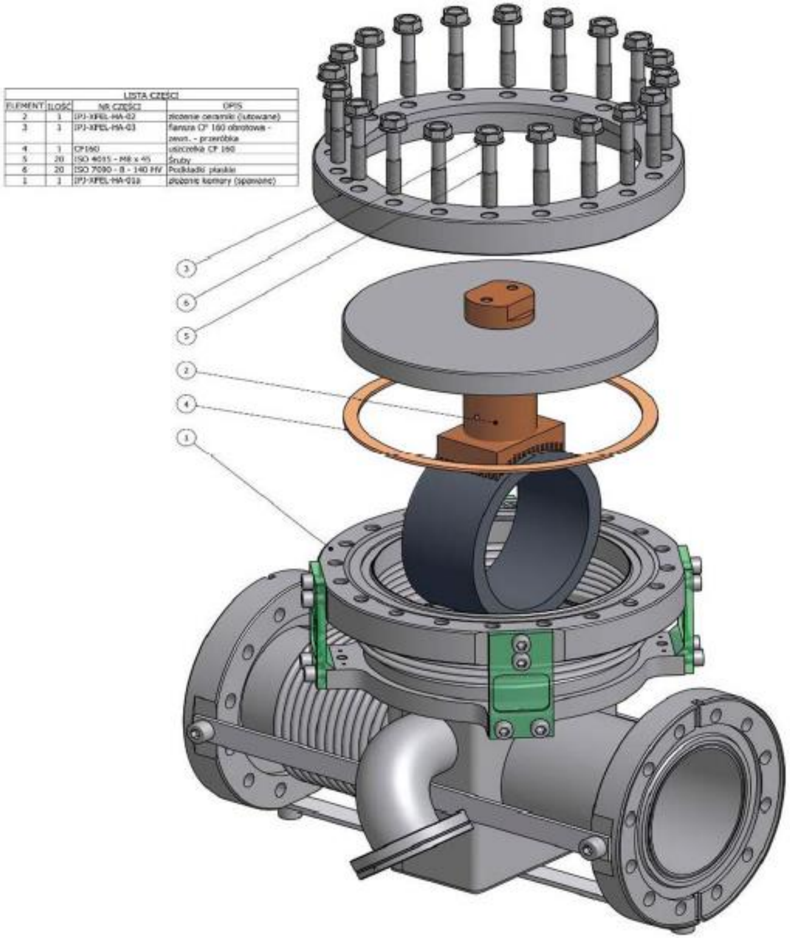
Mechanical design

Ceramic Ring: Ø 90mm
Length 50 mm
Thickness 10 mm

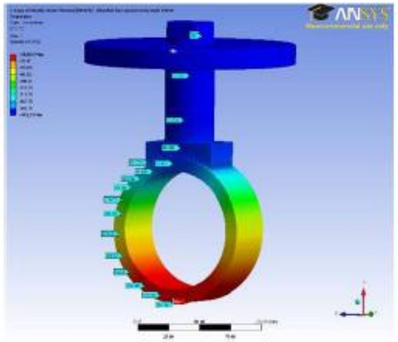

Lossy ceramic

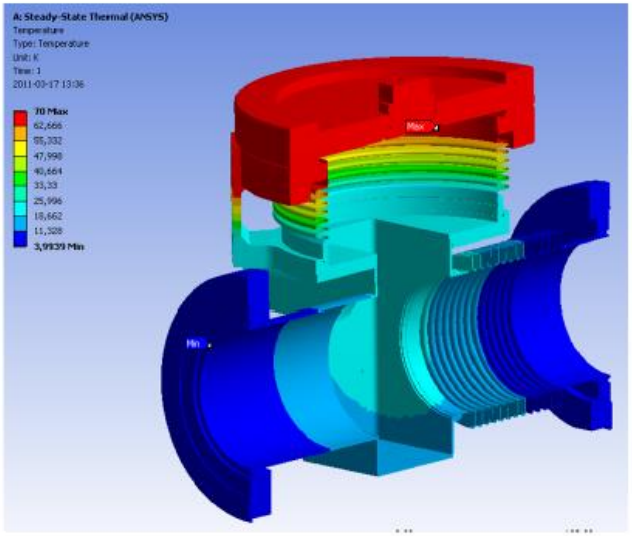
Estimated absorption efficiency for the periodic structure: one BLA/cryomodule is 83% (M. Dohlus)

HOM BLA Design

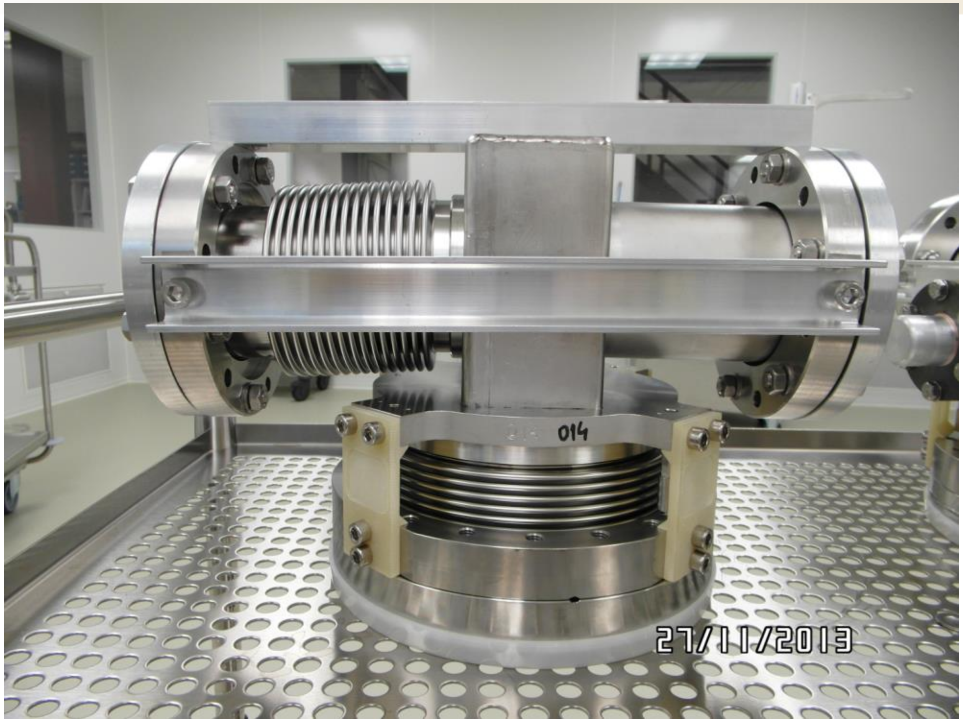


LISTA CZĘŚCI			
ELEMENT	ILOŚĆ	NR CZĘŚCI	OPIS
2	1	IPJ-XFEL-HA-02	złożenie ceramiki (lutowane)
3	1	IPJ-XFEL-HA-03	flansza CF 160 obrotowa - zewn. - przeróbka
4	1	CF160	uszczelka CF 160
5	20	ISO 4015 - M8 x 45	Śruby
6	20	ISO 7090 - 8 - 140 HV	Podkładki płaskie
1	1	IPJ-XFEL-HA-01a	złożenie komory (spawane)

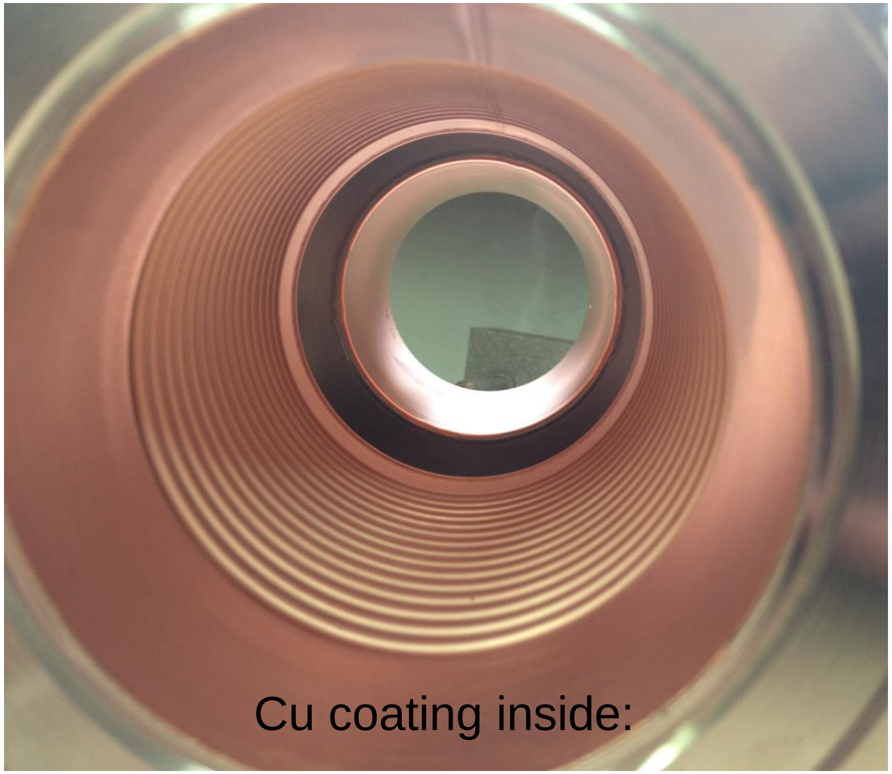



A: Steady-State Thermal (ANSYS)
Temperature
Type: Temperature
Unit: K
Time: 1
2011-03-17 13:36

Production



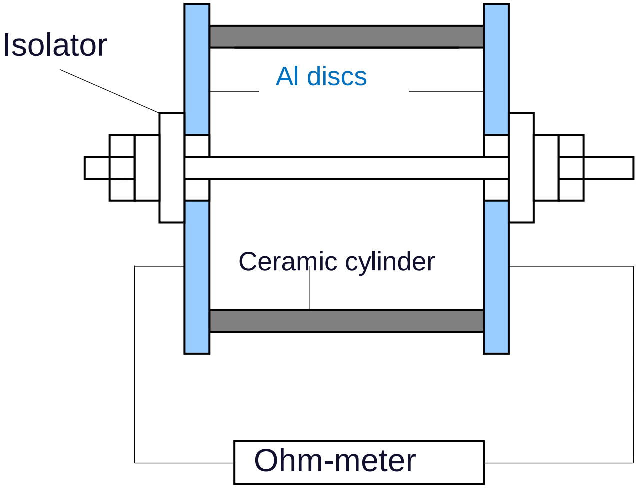
BLA with protecting Al-bars after shipment to DESY.



Cu coating inside:

Production: Spec for the ceramics:

- Heat conductivity at 40K > 50 W/(m*K)
- DC resistivity(across the cylinder) < 200MΩ at 70K



Measured absorption properties:

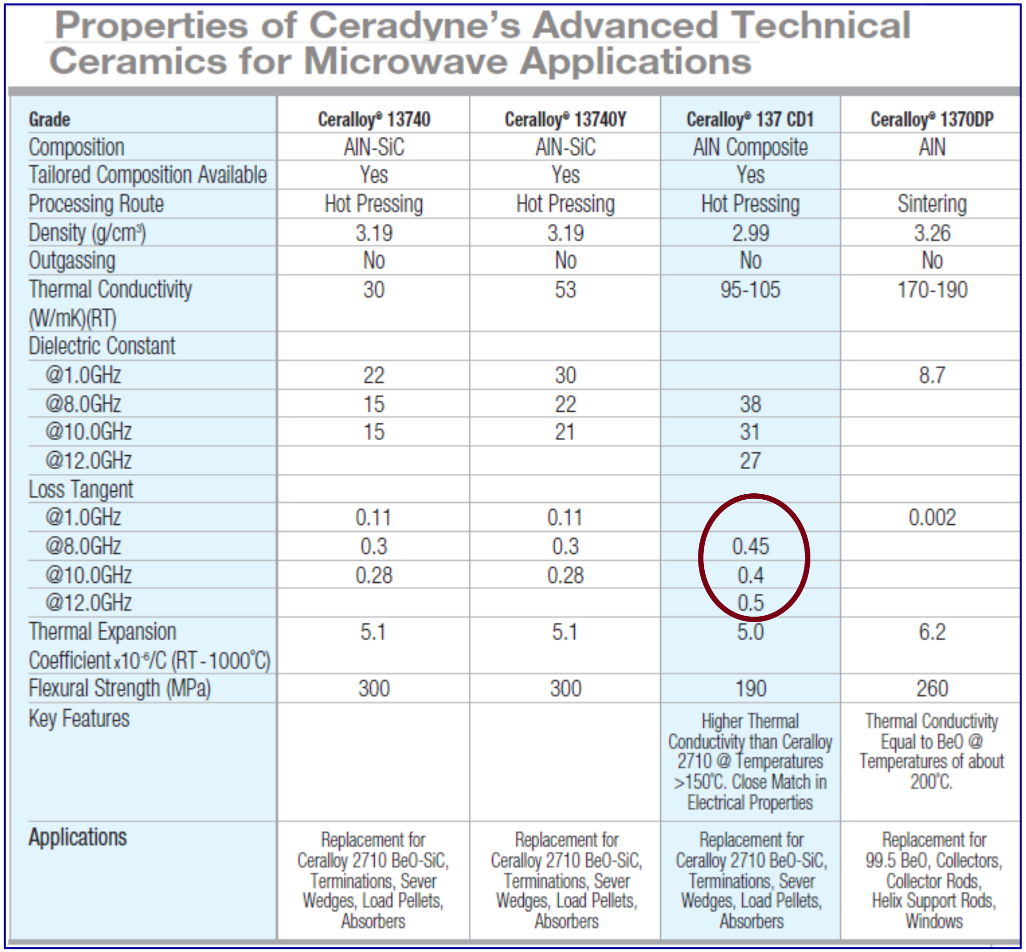
Ceradyne CA137

ε<30 @ tgδ> 0.1 for 5 GHz < f < 40 GHz

Sienna Technologies AlN STL-150D

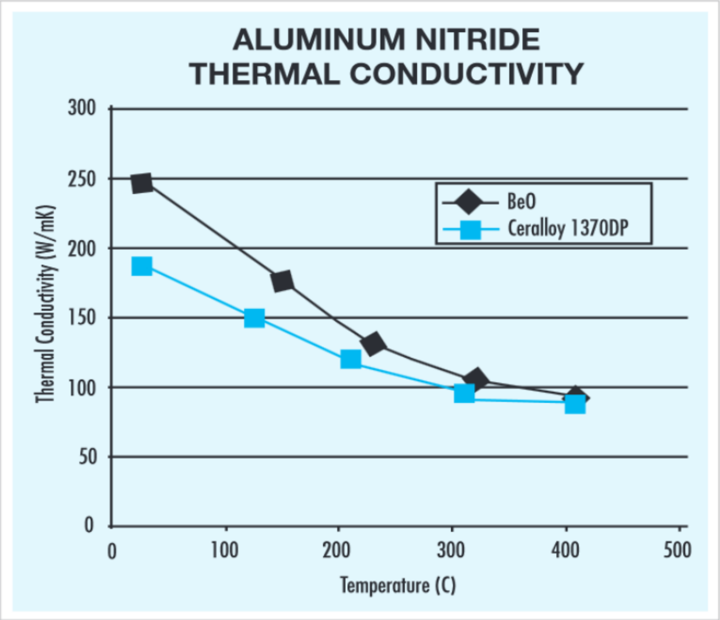
ε<30 @ tgδ> 0.4 for 5 GHz < f < 12 GHz

Lossy Ceramics: Ceradyne Inc.



Properties of Ceradyne's Advanced Technical Ceramics for Microwave Applications

Grade	**Ceralloy® 13740**	**Ceralloy® 13740Y**	**Ceralloy® 137 CD1**	**Ceralloy® 1370DP**
Composition	AlN-SiC	AlN-SiC	AlN Composite	AlN
Tailored Composition Available	Yes	Yes	Yes	
Processing Route	Hot Pressing	Hot Pressing	Hot Pressing	Sintering
Density (g/cm³)	3.19	3.19	2.99	3.26
Outgassing	No	No	No	No
Thermal Conductivity (W/mK)(RT)	30	53	95-105	170-190
Dielectric Constant				
@1.0GHz	22	30		8.7
@8.0GHz	15	22	38	
@10.0GHz	15	21	31	
@12.0GHz			27	
Loss Tangent				
@1.0GHz	0.11	0.11		0.002
@8.0GHz	0.3	0.3	0.45	
@10.0GHz	0.28	0.28	0.4	
@12.0GHz			0.5	
Thermal Expansion Coefficient x10^{-6}/C (RT-1000°C)	5.1	5.1	5.0	6.2
Flexural Strength (MPa)	300	300	190	260
Key Features			Higher Thermal Conductivity than Ceralloy 2710 @ Temperatures >150°C. Close Match in Electrical Properties	Thermal Conductivity Equal to BeO @ Temperatures of about 200°C.
Applications	Replacement for Ceralloy 2710 BeO-SiC, Terminations, Sever Wedges, Load Pellets, Absorbers	Replacement for Ceralloy 2710 BeO-SiC, Terminations, Sever Wedges, Load Pellets, Absorbers	Replacement for Ceralloy 2710 BeO-SiC, Terminations, Sever Wedges, Load Pellets, Absorbers	Replacement for 99.5 BeO, Collectors, Collector Rods, Helix Support Rods, Windows

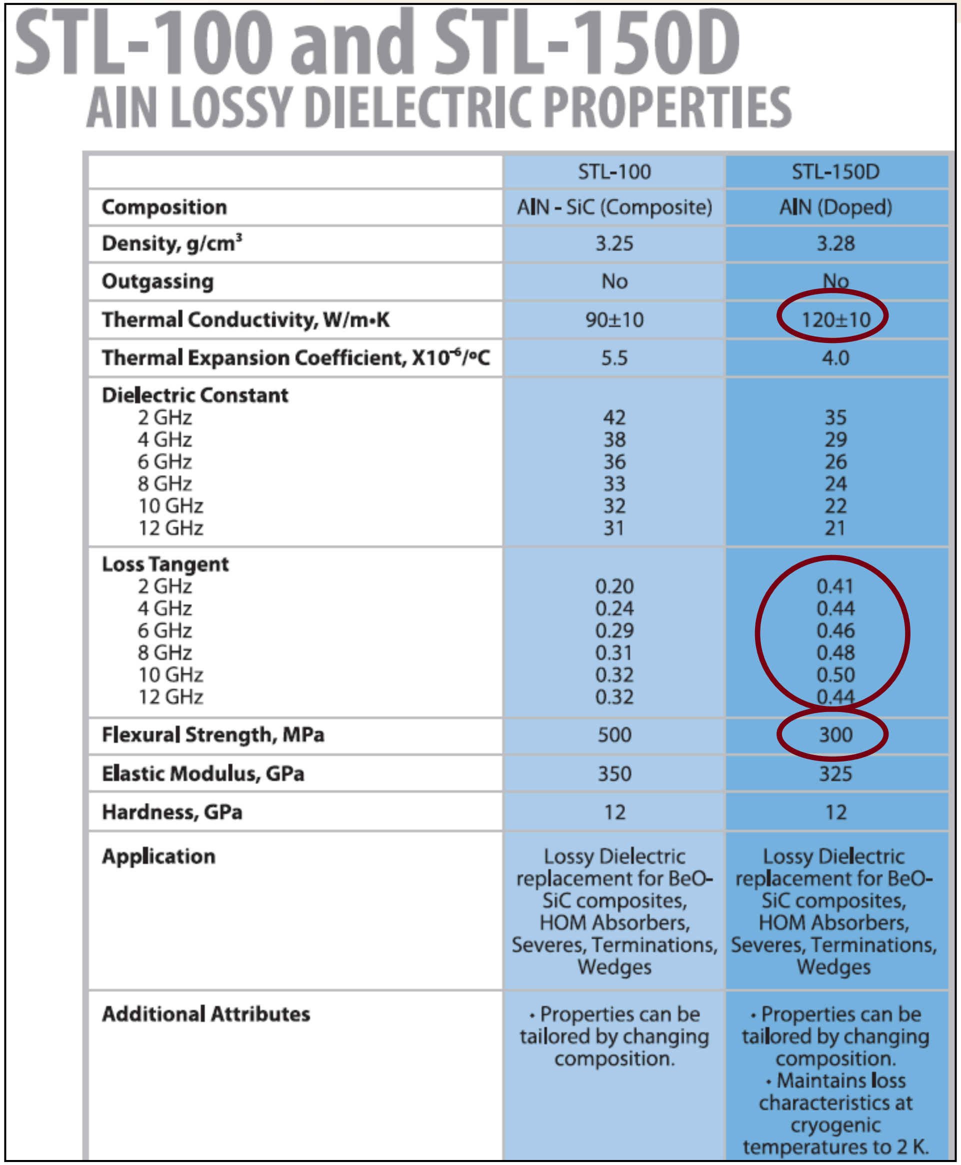


Ceradyne CA137

We used λ=70W/m·K in our modeling,
Will be redone with actual T dependence

CERADYNE does not produced the rings anymore (Jacek)

Lossy Ceramics:



STL-100 and STL-150D

AIN LOSSY DIELECTRIC PROPERTIES

	STL-100	STL-150D
Composition	AlN - SiC (Composite)	AlN (Doped)
Density, g/cm^3	3.25	3.28
Outgassing	No	No
Thermal Conductivity, W/m•K	90±10	120±10
Thermal Expansion Coefficient, X10^{-6}/°C	5.5	4.0
Dielectric Constant 2 GHz 4 GHz 6 GHz 8 GHz 10 GHz 12 GHz	 42 38 36 33 32 31	 35 29 26 24 22 21
Loss Tangent 2 GHz 4 GHz 6 GHz 8 GHz 10 GHz 12 GHz	 0.20 0.24 0.29 0.31 0.32 0.32	 0.41 0.44 0.46 0.48 0.50 0.44
Flexural Strength, MPa	500	300
Elastic Modulus, GPa	350	325
Hardness, GPa	12	12
Application	Lossy Dielectric replacement for BeO-SiC composites, HOM Absorbers, Severes, Terminations, Wedges	Lossy Dielectric replacement for BeO-SiC composites, HOM Absorbers, Severes, Terminations, Wedges
Additional Attributes	• Properties can be tailored by changing composition.	• Properties can be tailored by changing composition. • Maintains loss characteristics at cryogenic temperatures to 2 K.

STL-100 and STL-150D

ALUMINUM NITRIDE LOSSY DIELECTRICS

Aluminum nitride (AlN) based lossy dielectrics are drop-in replacements for beryllia-silicon carbide (BeO-SiC) composite lossy dielectrics at a more economical cost and without the potential toxicity concerns.

Sienna STL-100 and STL-150D AlN lossy dielectrics offer:

- Custom tailorable dielectric properties to meet application specific requirements
- Temperature independent loss characteristics (STL-150D)
- Thermal conductivity that is comparable to BeO-SiC composites
- No out-gassing in vacuum
- High mechanical strength

These attributes make Sienna STL-100 and STL-150D AlN lossy dielectrics the best choice as high performance microwave absorber applications including:

- HOM Absorbers in Accelerators
- Absorbers, Severes, Terminations, and Wedges in Vacuum Electron Devices (microwave tubes)
- Loss Loads

Sienna's technical team is ready to help you implement Aluminum Nitride in your next generation of products.

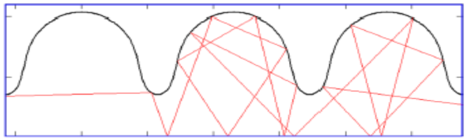
Contact us for applications assistance and fast prototyping.

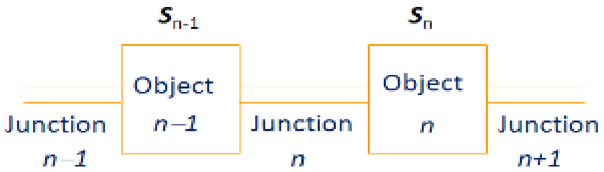
Wakefield power losses in CM models

- *Ray Tracing (diffusion) model - M. Dohlus*
- *Scattering matrix approach - K. Bane/ G.Stupakov*
- *Simple Analytical Estimation using diffusion approach.(V.Yakovlev / A.Saini)*

$$I_i^{abs} \sim n_i S_i \int P_0(\omega)\,\mathrm{Re}(Z_i\,(\omega)d\omega$$

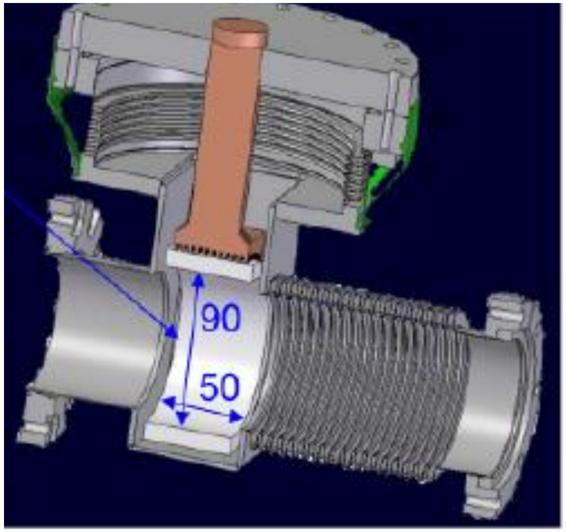
coarse models: photon tracking





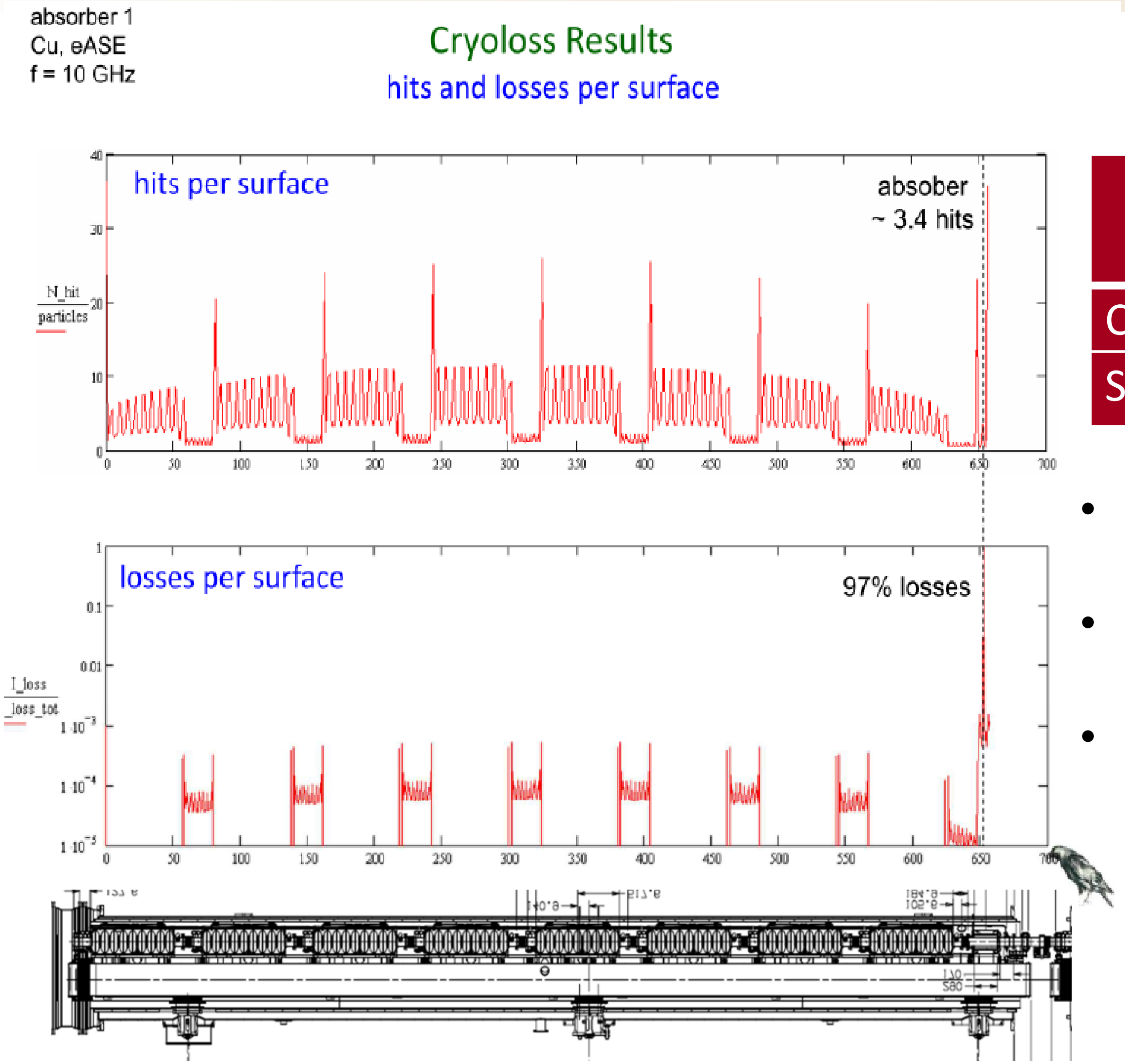
S_{n-1} S_n

Junction $n-1$ | Object $n-1$ | Junction n | Object n | Junction $n+1$



material probe 4: $\mathrm{Re}(\varepsilon) \approx 40\ \varepsilon_0$
$\tan(\delta) \approx 0.70$

Distribution of power losses in CM (diffusion model)



Distribution of power losses in CM

	P_{cav} (W)	P_{bellow} (W)	P_{absorb} (W)
Cu bellow	0.07	0.76	13.0
SS bellow	0.03	7.6	6.2

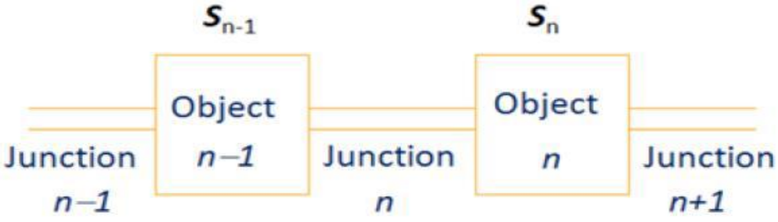
A.Saini

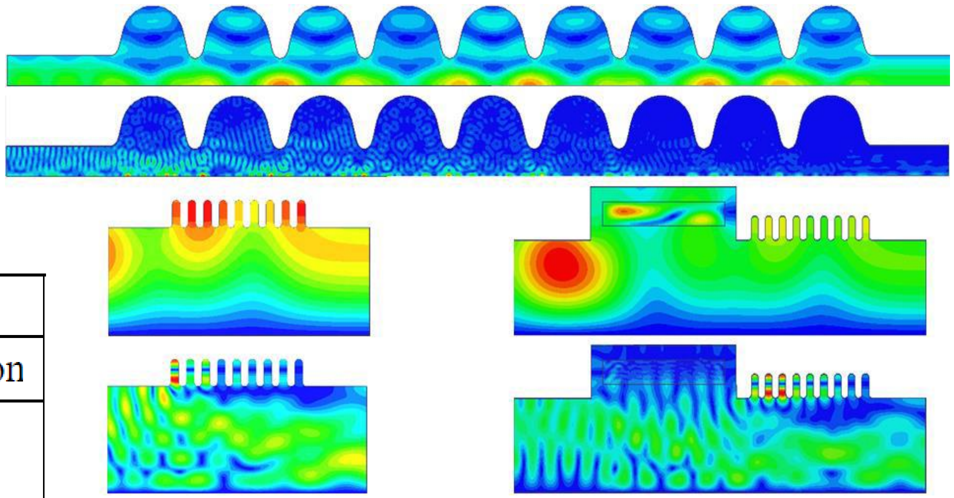
- Power dissipation at 2K (inside the cavity) is negligible.
- Most of HOM power is deposited to absorber in case of copper bellow.
- For SS below ~50% of HOM power is absorbed in bellows.

Q: How HOM power generated in transition CM are distributed along the string of CMs?➔ averaged over string.

S-matrix model (K.Bane, SLAC)

At a number of discrete frequencies, 4, 8, 12, 16, 20 and 40 GHz, we used the field solver to calculate the scattering matrix for each element type (cavity, bellows, drifts and absorber) for all TM0n monopole modes propagating in the beam pipe at each respective frequency





Radial geometries of the cavity, bellows and absorber with field plots (|E| for cavities; |H| for others) from HFSS simulations at 4 GHz and 20 GHz, with TM01 input from the left.

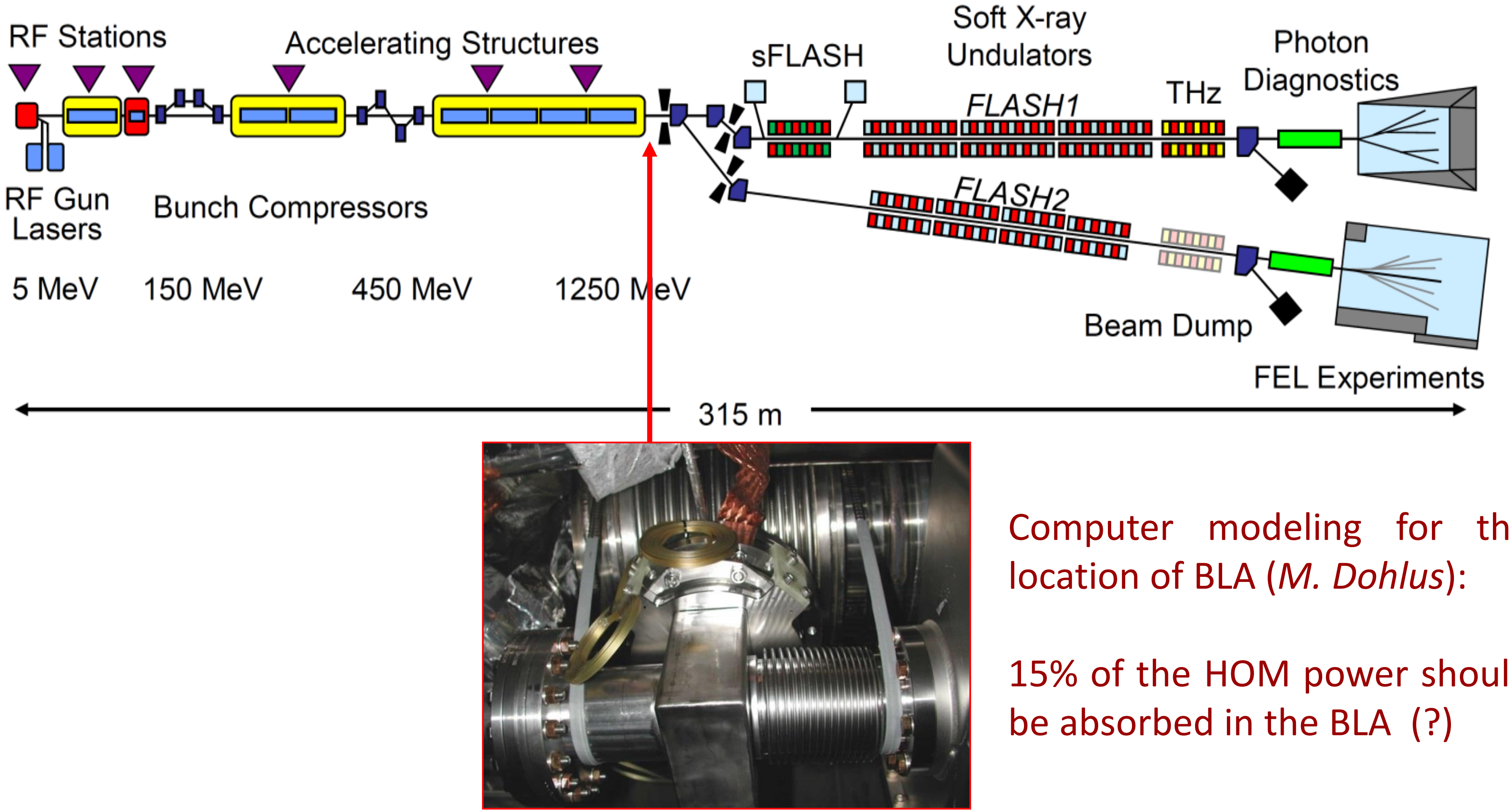
Table 1. Percent of Untrapped HOM Power to 2 K.

f (GHz)	Copper		Stainless Steel	
	S-matrix	diffusion	S-matrix	diffusion
4	0.75	0.35	19	13
8	3.5	0.55	49	18
12	0.5	0.70	23	21
16	0.55	0.85	10	24
20	1.1	1.0	47	26
40	1.1	1.6	35	33
Total		2.7		39

Conclusion: Two complementary approaches provide confidence in the effectiveness of the beamline HOM absorbers. Only a few percent HOM power will be lost at 2K.

Test Setup at FLASH

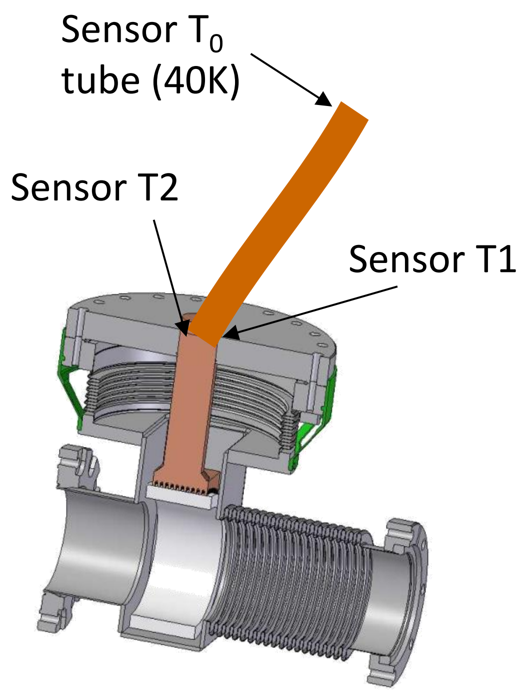
2 Beam Tests in September 2008 and 2009

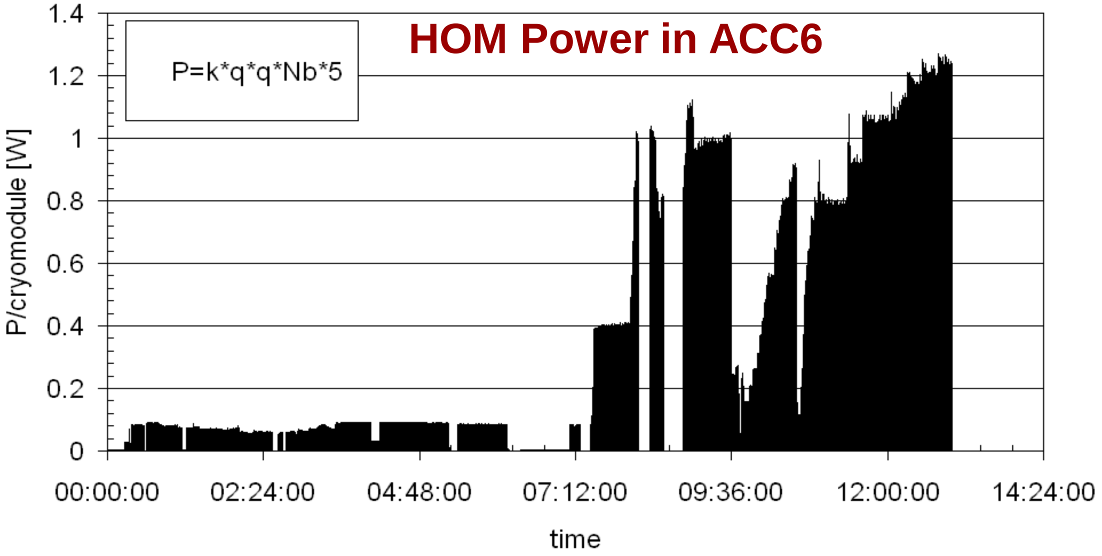


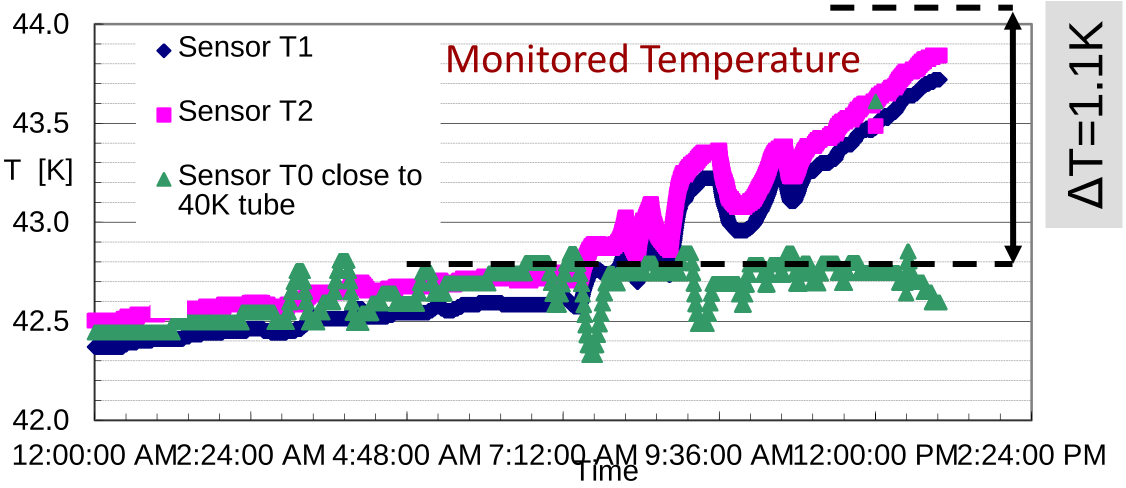
Computer modeling for the location of BLA (*M. Dohlus*):

15% of the HOM power should be absorbed in the BLA (?)

High current run at TTF-II in 2008







Braid cross-section (Cu OFH)= 74mm^2

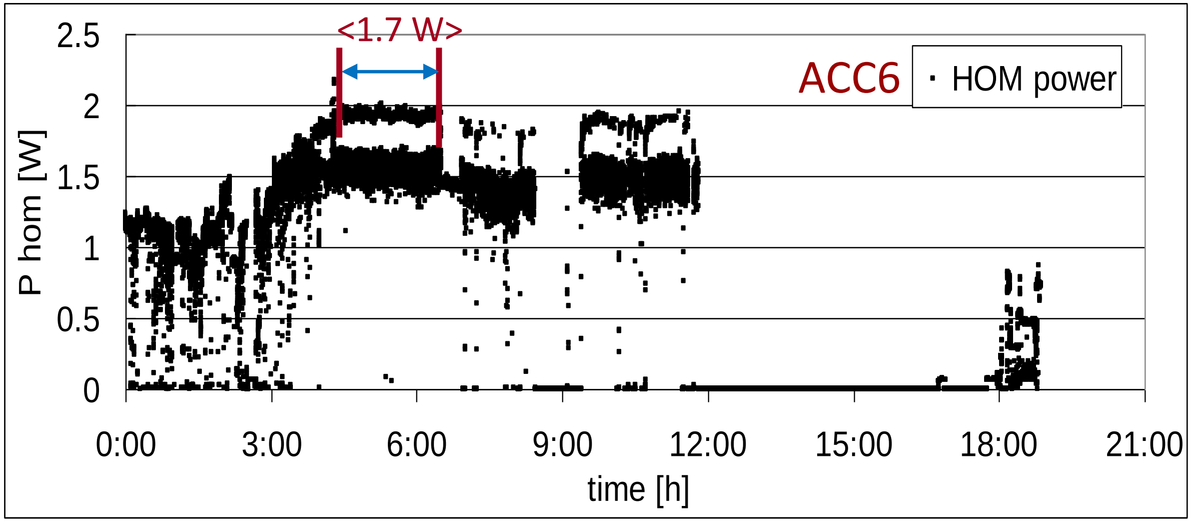
Heat conductance of the braid :

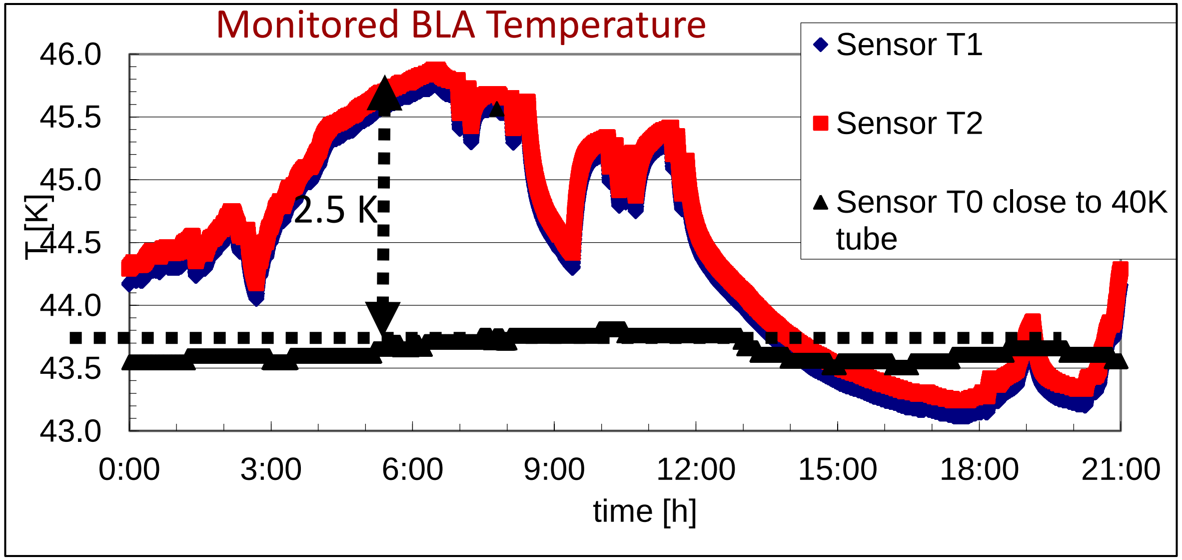
$$\kappa = 1250 \frac{W}{m \cdot K} \cdot \frac{74.4 \cdot 10^{-6} m^2}{0.7m} = 0.13 \frac{W}{K}$$

9 mA run in 2009

Measured and calculated absorbed power in two tests

	Sept.08	Sept.09
Computed Absorbed Power [W]	0.180	0.255
Measured Absorbed Power [W]	0.143 (-20%)	0.325 (+27%)





Accuracy of measurements?
Accuracy of simulation?

Thermal connection Beam Absorber design (XFEL)

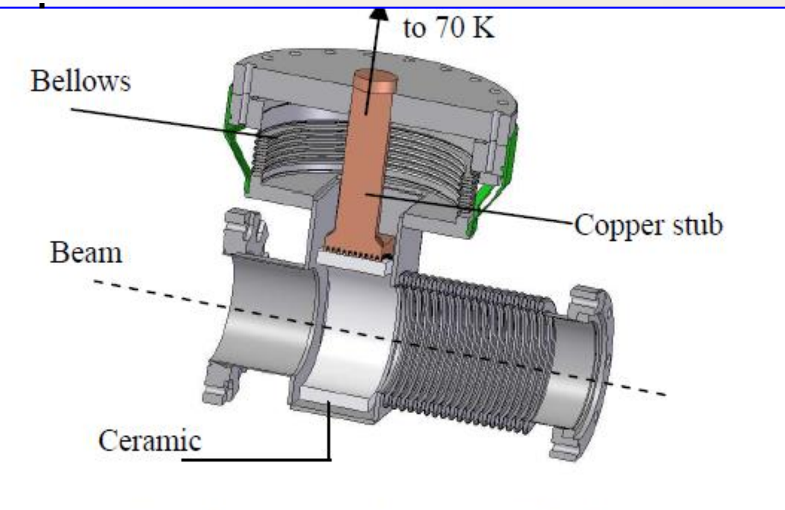


Figure 2: Layout of the beam line absorber.

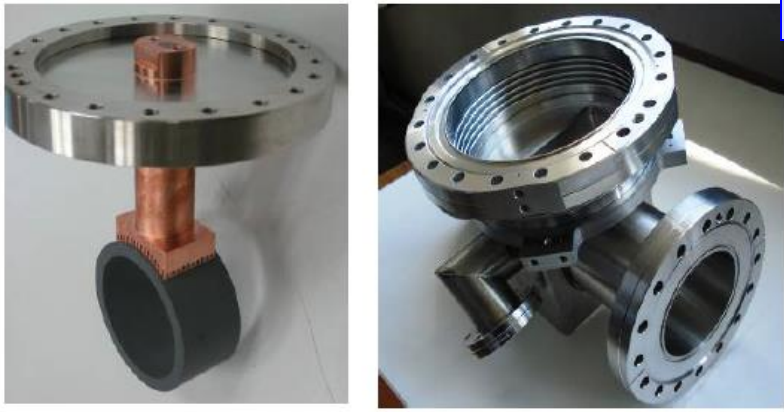
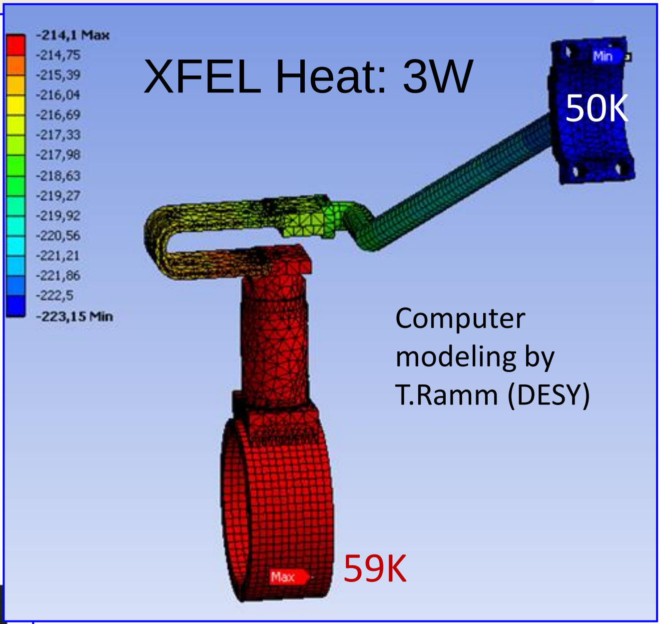


Figure 3: parts of the BLA prototype: (left) damping ceramic ring welded to the copper stub and (right) housing made of stainless-steel. *(Courtesy of J.Sekutowicz)*



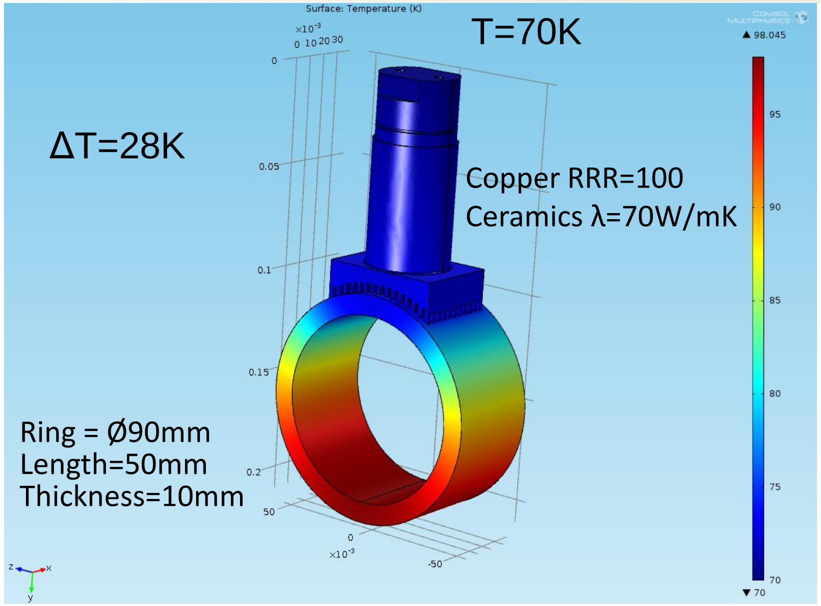
XFEL Heat: 3W

Computer modeling by T.Ramm (DESY)

Thermal connection made of a copper stub, terminated on each end with short braid, eliminating mechanical forces during the cool down and warm up cycles.

- With XFEL proposed thermal connection (S ~ 3 cm^2) for 3W T_c=59 K when the He tube is at 50 K.
- For 30 W (max in 1st CM in L3) dissipated HOM power the highest temperature of the ceramic ring = 230 K ➔ will be improve for LCLS-II CM.
- Remaining design issues:
  - *Larger cross-section of stub? => 4-5 cm^2*
  - *Weight = 21 kg. Need support?*

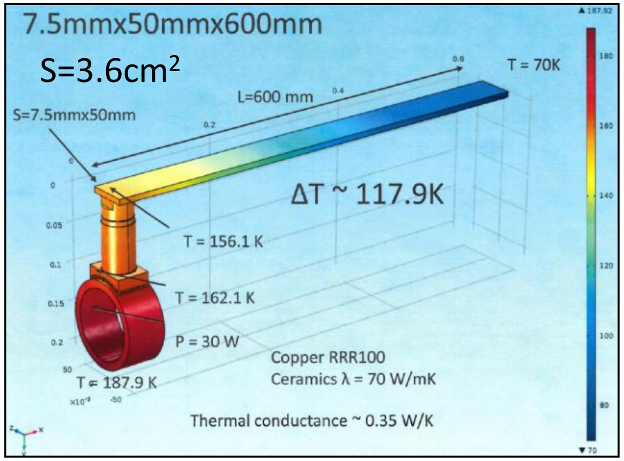
Thermal simulations

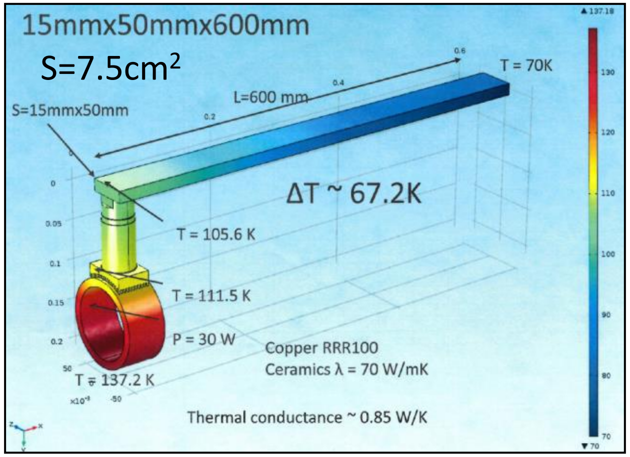


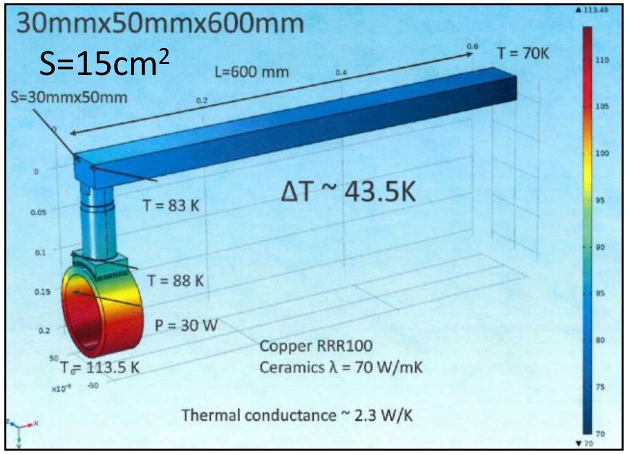
- Maximum power dissipation ~30W (1st CM in L3) ➔ Should be ~15 W/CM average ?

- Proposed copper stub cross-section ~4-5cm^2 will provide T ceramics < 150 K

- Thermal stresses analysis (I.Gonin):
  - Max stresses at Cu-Ceramic brazing joint, acceptable for P<30W

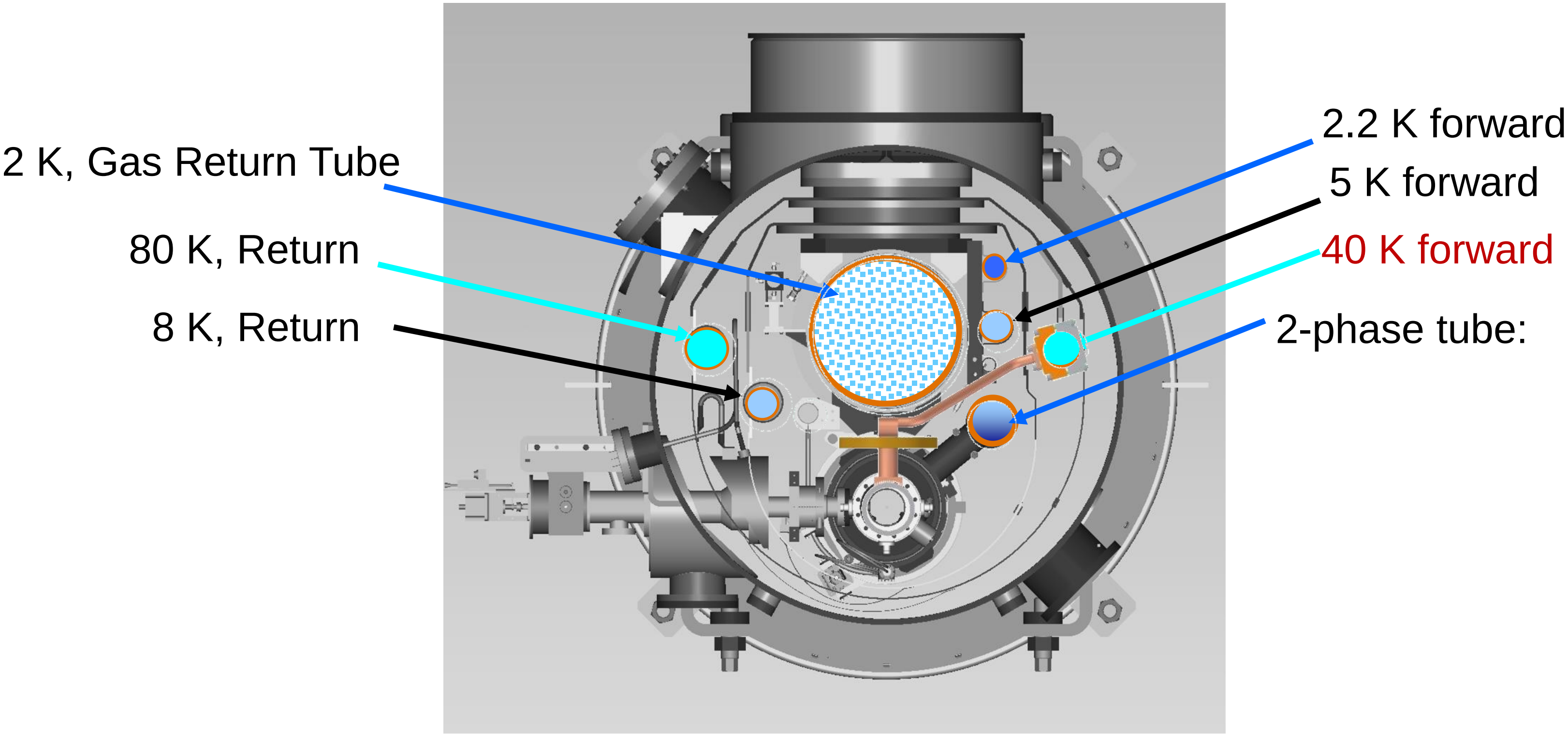






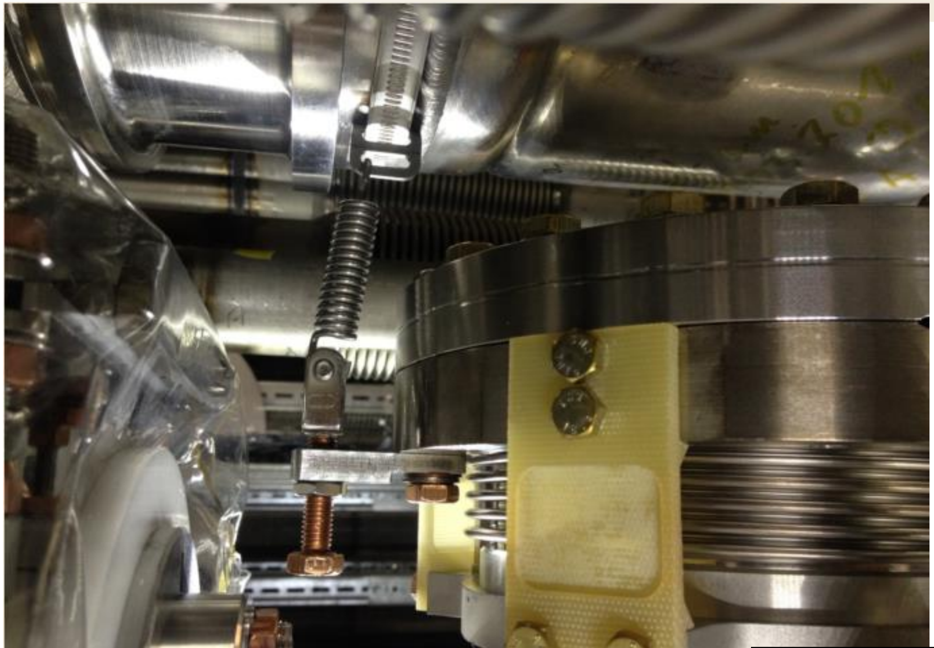
Thermal Connection to 40K Tube

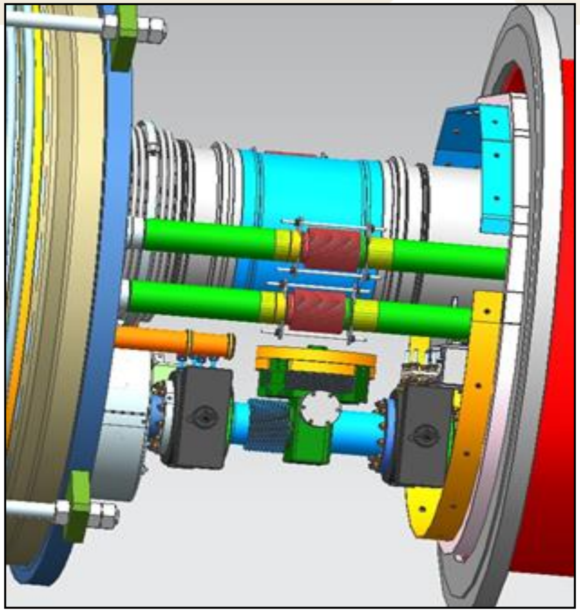
Modeling by T. Ramm showed that thermal connection is not a trivial part of the BLA.

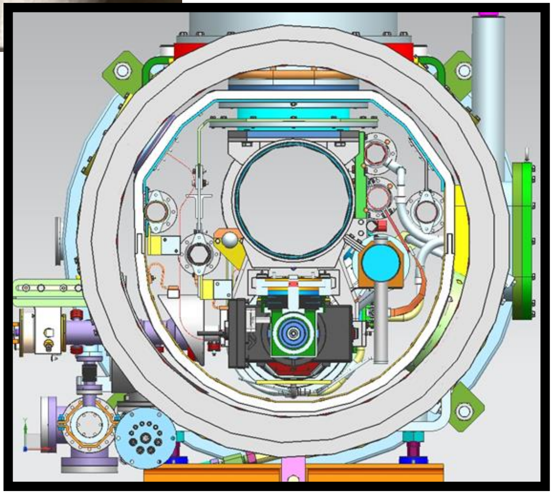


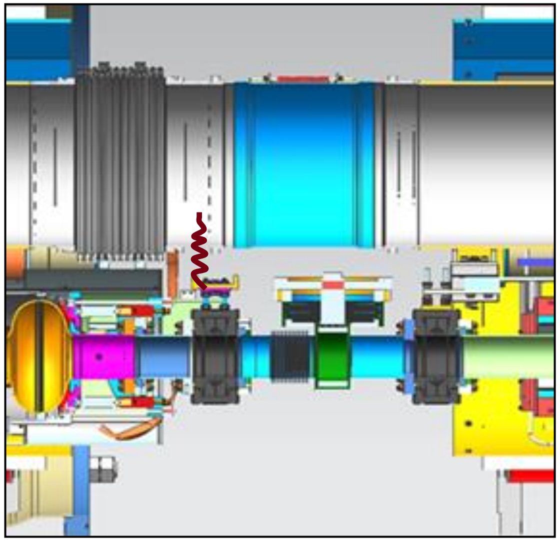
It is rather complicated due to very limited space between cryomodules.

Supporting HOM Absorber









XFEL proposal for support

Status of the HOM beamline Absorber

LCLS-II adopted Eu-XFEL HOM Absorber design:

- Capable to absorb up to 100W of HOM power with spectrum > 1THz
- High Absorbing efficiency > 85%.
- R&D program and several design iteration since TESLA era.
- Industrial studies for XFEL, improvements on absorbing materials, brazing, cleaning.
- Tested with beam at FLASH (2008/2009); good agreement with simulation
  - Minor issues (cleaning, support in CM, thermal straps) will be finalized. Work in collaboration with XFEL team.

Procurement (JLAB):

Permission from DESY to use HOM absorber design received

Technical information and quotation from vendor (INS-Swierk in Poland)

- Drawings, specs, cleaning and QA/QC docs.
- Quotation for 1 and 35 units.

Ready to start procurement for series production (35 units)

Remarks

- HOM Beamline Absorber design for LCLS-II project is based on tested design, developed for a decades and modified for XFEL. Parameters meet LCLS-II requirements.

- LCLS-II CW operation produces high cryogenic losses. It requires good thermo-connections to remove heat and keep temperature under control. Thermal simulations in progress to define losses and finalize configuration of the thermal braids and connections.

- Design Concerns:
  - Ceramics loss tangent was measured up to 40 GHz. No data for higher frequencies, where major HOM power is expected.
  - Diameter of ceramic ring is parameter for optimization of efficiency
  - Braid cross-section is defined by L3 HOM power level. Can be reduced in L1 and L2, where power level is smaller.

- Design Concerns (based on production experience, see Jacek slides in appendix):
  - Permeability (μr<1.16)
  - Copper plating and adhesion
  - Cleaning issues

Acknowledges

Thanks

Jacek Sekutowicz and Martin Dohlus for provided materials

Fermilab, JLAB and SLAC team

Ivan Gonin, Timergali Khabiboulline, Andrei Lunin, Slava Yakovlev, Arun Saini, Tug Arkan, Yuri Orlov for help with simulations, design and discussiom

Back-up slides

Slides fro Jacek Sekutowicz presentation at SLAC

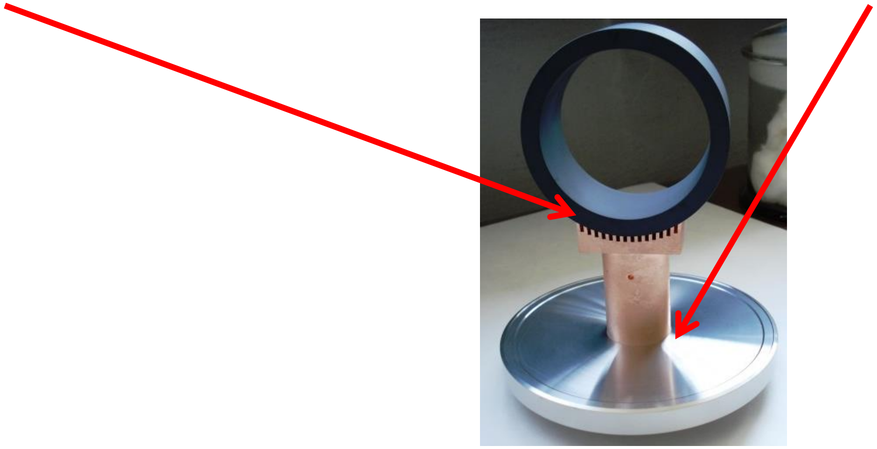
Production

DESY Experience and concerns

Vacuum

All BLAs undergo leak test, performed by the vendor. 84 of 85 produced BLAs have passed this acceptance test.

One would expect that the vacuum oven brazing of ceramic ring to Cu-stub at 950 C and Cu-stub to Stainless Steel at 1050 C

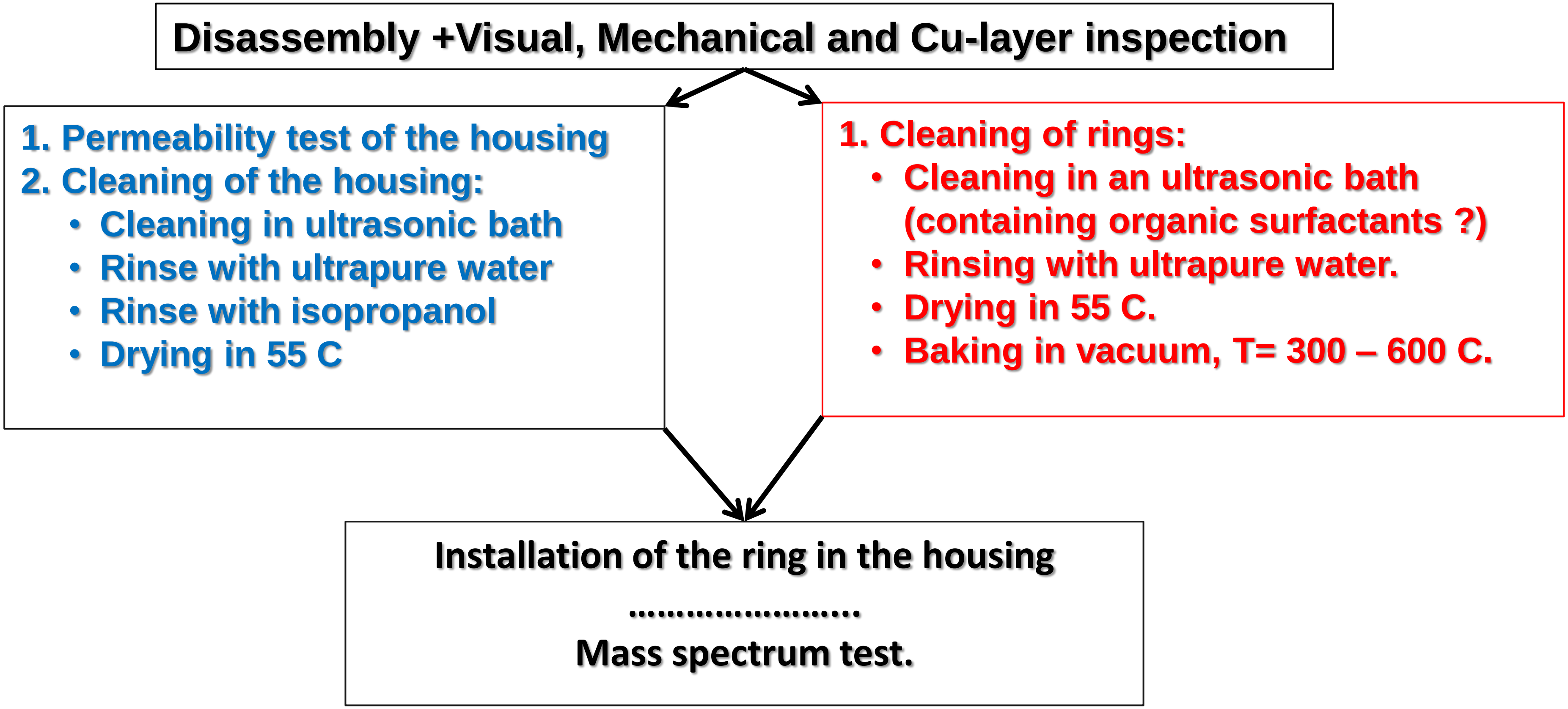


and the Cu-coated housing heat treatment in 450C (1h) should make BLAs very clean. **This is not the case** and an additional cleaning is performed at DESY. It is very time consuming and not always successful. There is mainly a problem with masses 40-100. The partial pressures are rather factor of 100 than factor of 1000 smaller than the total pressure.

Production

Experience and concerns

Vacuum, cont.



Disassembly +Visual, Mechanical and Cu-layer inspection

1. Permeability test of the housing
2. Cleaning of the housing:
- **Cleaning in ultrasonic bath**
- **Rinse with ultrapure water**
- **Rinse with isopropanol**
- **Drying in 55 C**

1. Cleaning of rings:
- **Cleaning in an ultrasonic bath (containing organic surfactants ?)**
- **Rinsing with ultrapure water.**
- **Drying in 55 C.**
- **Baking in vacuum, T= 300 – 600 C.**

Installation of the ring in the housing

……………………..

Mass spectrum test.

Production

Spec for Stainless Steel

- For flanges 316LN SS ESR (1.4429)
- Housing and bellows 316LN (1.4435)

Vacuum spec:

- No outgassing from ceramics (accordingly to the material properties description by vendors)
- The integral leak rate has to be ≤ $1 \cdot 10^{-10}$ mbar·l·sec^{-1}

To ensure that BLA is hydrocarbons free, two conditions have to be fulfilled for the outgassing:

- For a total pressure of 10^{-7} mbar
- The sum of all partial pressures of masses from 45 to 100 must be less than 10^{-3} of the total pressure.

Permeability spec:

$\mu_r \leq 1.05$ later less conservative 1.16

Production

Experience and concerns, cont.

Permeability

Good adhesion of the Cu-coating requires an interlayer of Nickel.

1. The 1st delivery had this layer of the order of 3+µm, adhesion was very good but the thick Ni layer made permeability, μ_r , significantly ≥ 1.05. All with $\mu_r > 1.16$ have been sent back for re-coating.

2. DESY requested to keep $\mu_r \leq 1.16$ (much less conservative value).
   The thickness of Ni layer was reduced to ca. 1µm.
   These BLAs had still good adhesion and $\mu_r \leq 1.12$.

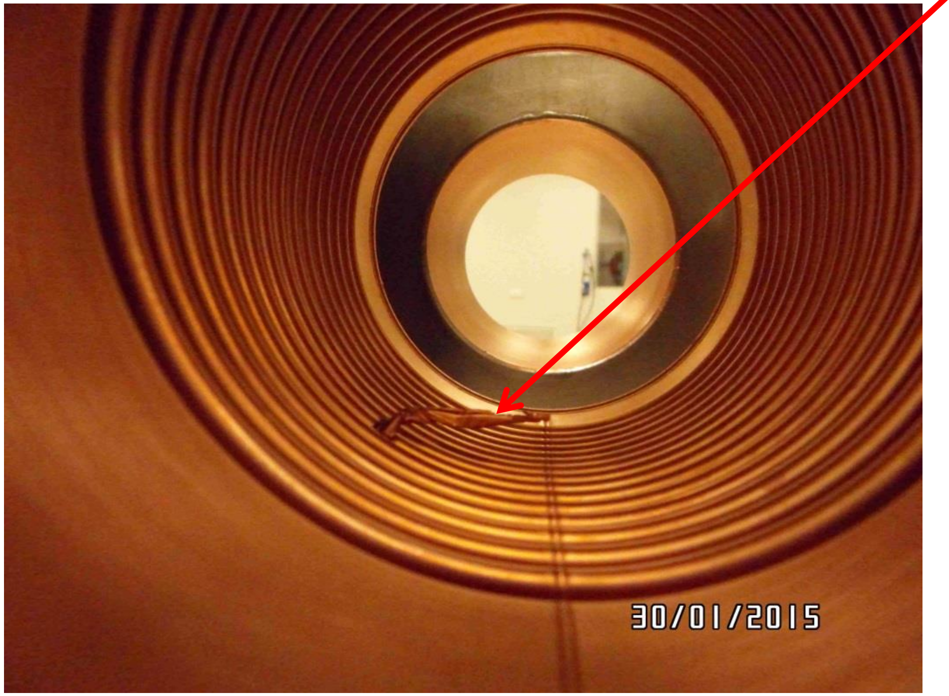
3. Then the thickness of Ni layer has been reduced second time to 0.3-0.7µm(??). μ_r dropped below 1.04, but adhesion was poor in convolutions of bellows, peeling off was observed in many BLAs.

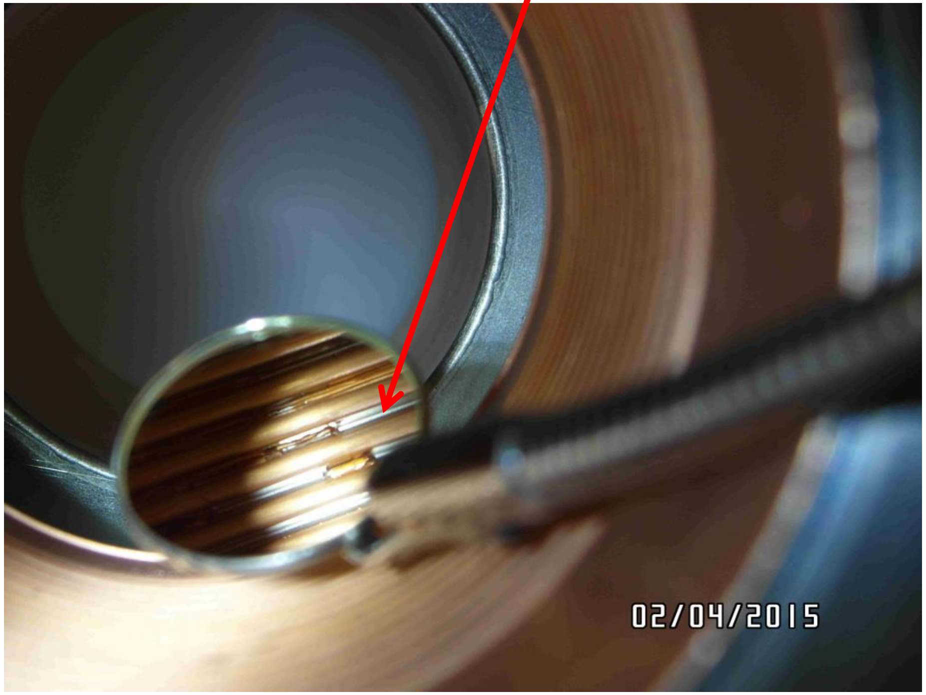
Production

Experience and concerns

Permeability, cont.

Poor adhesion observed at DESY, on January 30th and on April 2nd, 2015





All these BLAs have been sent back to vendor for re-coating.
These which were sent back to DESY have good adhesion and low μr.

Final Remarks

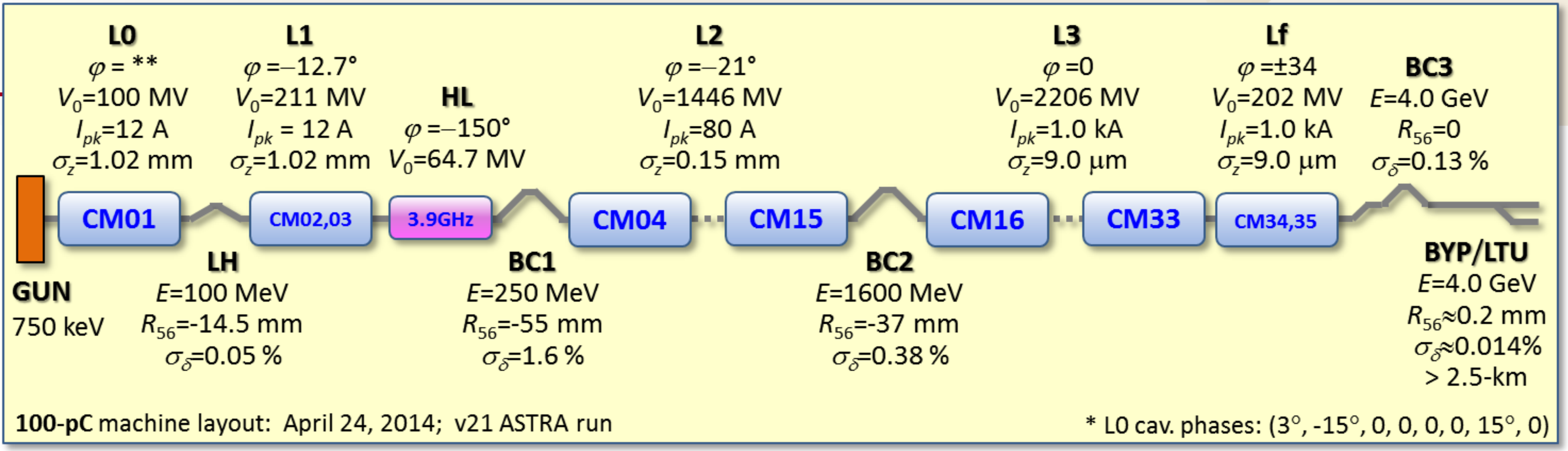
- ✓ In two tests we observed absorption of the high frequency HOMs
- ✓ The amount of HOM power was close to the calculated power

- ✓ Cleaning is still time consuming

- ✓ Issue with adhesion and μr seems to be solved

See PRD:
LCLSII-2.4-PR-0041

Linac RF and Compression



L0
φ = **
V_0=100 MV
I_{pk}=12 A
σ_z=1.02 mm

L1
φ =–12.7°
V_0=211 MV
I_{pk} = 12 A
σ_z=1.02 mm

HL
φ =–150°
V_0=64.7 MV

L2
φ =–21°
V_0=1446 MV
I_{pk}=80 A
σ_z=0.15 mm

L3
φ =0
V_0=2206 MV
I_{pk}=1.0 kA
σ_z=9.0 μm

Lf
φ =±34
V_0=202 MV
I_{pk}=1.0 kA
σ_z=9.0 μm

BC3
E=4.0 GeV
R_{56}=0
σ_δ=0.13 %

CM01 CM02,03 3.9GHz CM04 CM15 CM16 CM33 CM34,35

GUN
750 keV

LH
E=100 MeV
R_{56}=-14.5 mm
σ_δ=0.05 %

BC1
E=250 MeV
R_{56}=-55 mm
σ_δ=1.6 %

BC2
E=1600 MeV
R_{56}=-37 mm
σ_δ=0.38 %

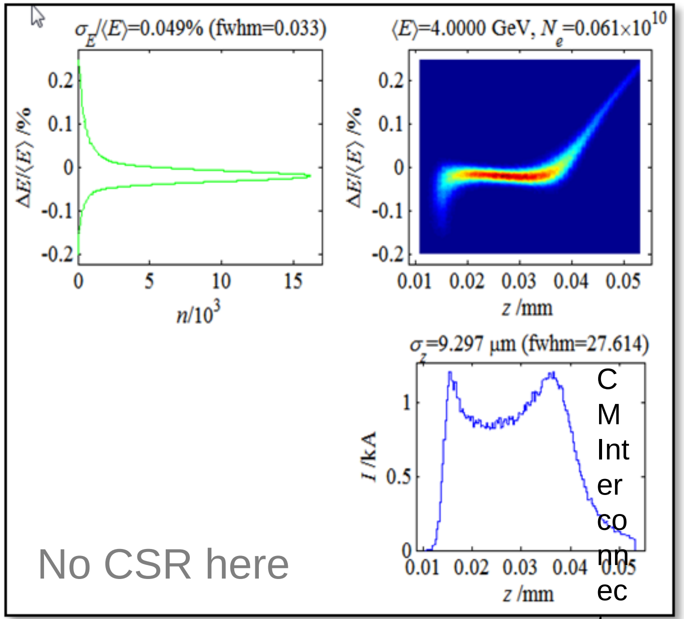
BYP/LTU
E=4.0 GeV
R_{56}≈0.2 mm
σ_δ≈0.014%
> 2.5-km

100-pC machine layout: April 24, 2014; v21 ASTRA run

* L0 cav. phases: (3°, -15°, 0, 0, 0, 0, 15°, 0)

Linac Sec.	V_0 (MV)	φ (deg)	Acc. Grad.* (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cav's per Amp.
L0	**100**	**	**16.3**	**1**	**8**	**1**	**1**
L1	**211**	**-12.7**	**13.6**	**2**	**16**	**1**	**1**
HL	**-64.7**	**-150**	**12.5**	**2**	**16**	**1**	**1**
L2	**1446**	**-21.0**	**15.5**	**12**	**96**	**6**	48
L3	**2206**	**0**	**15.7**	**18**	**144**	**9**	48
Lf	**202**	**±34**	**15.7**	**2**	**16**	**1**	**1**

Includes 2.5-km RW-wakes



No CSR here

CM Interconnect Revie

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* Nom. crest grads. averaged over powered cavities (worst phasing requires 16 MV/m)

** L0 cav. phases: ~(3°, –15°, 0, 0, 0, 0, 15°, 0), with cav1 at 70% & cav2 at 21% of cav-3-7 grads.

April 24, 2014 – P. Emma (100 MeV injector, 150-μm bunch length after BC1, -37-mm BC2 R_{56})