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# Adaptation of XFEL/ILC-type Cryo-module for CW Operation at LCLS-II: Issues, Solutions and Results

Vyacheslav Yakovlev Upgrading Existing High Power Proton Linacs Workshop 9 November, 2016

## Outline

- Why XFEL/ILC technology for LCLS II?
- LCLS II requirements versus XFEL/ILC :
  - CW operation;
  - low beam current.
- Issues and necessary CM design changes:
  - Cryo-load;
  - HOMs and wakes;
  - Couplers (HP and HOM);
  - Tuners
- Test results
- Conclusion



### **LCLS II Linac**



- Thirty-five 1.3 GHz 8-cavity cryomodules
- Two 3.9 GHz 8-cavity cryomodules
- Four cold segments (L0, L1, L2 and L3) which are separated by warm beamline sections.

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## Why XFEL/ILC technology for LCLS II?

- XFEL/ILC technology is very well-matured, there is a great experience accumulated by DESY in R&D, design and mass production: >100 CMs successfully manufactured and installed in XFEL tunnel;
- XFEL technological culture developed by DESY provides very good performance of the CMs gradient, cryo-losses, small field emission, high production yield;
- XFEL technology has been successfully transferred to US; US National Laboratory, FNAL, has a good experience in ILC CM production: CM2 was the first CM demonstrated the gain 250 MeV/CM;

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• XFEL CMs have the same application as LCLS II – acceleration of short electron bunches for the light source.



XFEL cryomodules (DESY):

- eight SC cavities/CM
- one CS quad/CM
- 1.3 GHz, 9-cell elliptical cavity



### CM2 (Fermilab) 250 MeV/CM



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## LCLS II requirements versus XFEL/ILC :

	XFEL	LCLS II	Issue
Operation	pulsed	CW	
Duty factor, %	0.65	100	
Beam current, mA	5	0.1 (0.3)	
Gradient, MeV/m	23.6	16	
Total cryo-load@2K, W/CM	14	80*	(1)Q0
			(2)He vessel
			(3)HOM coupler
Bandwidth, Hz	280	30	(4)Tuner
Average input RF power/cavity, kW	2.5	6	(5)HP coupler

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\*Use of one 4 kW cryo-plant

### Requirements for $Q_0$ :

Dynamic losses:

- HOM excitation
- Transient radiation
- Couplers
- HOM damners

Static losses:

- Couplers •
- Magnet leads •

### $Q_0 \approx 2.7e10 @ 2K, 16 MeV/m$ in order to get the load ~80 W/CM

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Active CM 2K Sum [W]	7	71.5 80.7 79.8 80.7					8	1.0			
Static, dynamic sum	7.46	64.08	7.46	73.23	7.46	72.37	7.46	73.23	7.46	73.52	
HOM absorber (conduction to 2 K)		-		-		-		-		-	
Dynamic losses, other beamline components		1.32		1.32		1.32		1.32		1.32	
Electric heater		0.50		0.50		0.50		0.50		0.50	
Magnet current leads	0.56	0.03	0.56	0.03	-	-	0.56	0.03	0.56	0.32	
Input coupler	0.48	0.40	0.48	0.40	0.48	0.40	0.48	0.40	0.48	0.40	
RF dynamic load		61.83		70.98		70.15		70.98		70.98	
Temperature Level	2	K	2К 2К 2К		2K 2K		2	K			
	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	
Remaining portion of transient wake power to 40K	0,80		0.80		0.80		0.80		0.80		
Portion transient wake power to 2K	0.20			0.20	0.20		0.20		0.20		
Transient wake power [W]	4.8			4.8	4.8		4.8		4.8		
HOMs with new current for analysis [W]	2.7			2.7	5.0		3.3		10.0		
HOMs with baseline 0.3 mA current [W]	8			8	15		10		30		
Dynamic RF load per cavity (W)	7.73		1	8.87	8.77		8.87		8.87		
New beam current for analysis [mA]	0.10		(	0.10	0.10		0.10		0.10		
Baseline beam current [mA]	0.30		(	0.30	0.30		0.30		0.30		
R/Q [ohms]	1012		1	1012 750		750	1012		1012		
Cavity length [m]	1.038		1.038		0	0.346		1.038		1.038	
Baseline fraction of cavities powered	0.88		0.94		0.94		0.94		0.94		
Baseline powered cavities total	7.0		15.0		15.0		90.0		7.5		
Number of cavities total	8		16		16		96		8		
Number of cavities per CM	8		8		8		8		8		
Number of cryomodules	1		2		2		12		1		
	2 7E+10		2.7E+10		2.5E+09		2.7E+10		2.7E+10		
Baseline E with fraction of cavities powered (MV/m)	16.00		16.00		12.50		16.00		16.00		
E for all cavitles powered [MV/m]	14.00		15.00		11 72		15.00		15.00		
Cryomodule	1	0		11		HL		12	130	:M16	

# **N-doping:**

- "Standard" XFEL technology provides ~1.4e10@2K, 20-23 MeV/m (CM);
- N-doping: discovered in the frame of R&D on the Project-X SC CW linac (A. Grassellino).

Cavity Treatment:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP





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A. Grassellino, N-doping: progress in development and understanding, SRF15

### N-doping:

- Provides Q<sub>0</sub> 2.5-3 times higher than "standard" processing.
- Trade-off:
- Lower acceleration gradient, 20-22 MeV/m not an issue for LCLS II;
- Higher sensitivity to the residual magnetic field.
- Remedy:

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- Magnetic hygiene and shielding improvement
- Fast cooldown



# VTS test results of dressed prototype cavities

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A. Grassellino, N-doping: progress in development and understanding, SRF15

### Fast cooldown

•  $Q_0 = G/R_s$ ;  $R_s = 10$  nOhm for  $Q_0 = 2.7e10$ 

 $R_s = R_0 + R_{BCS} + R_{TF},$ 

 $R_{TF}=s^*\eta^*B_{res}$ , s is sensitivity to residual magnetic field  $B_{res}$ ,  $\eta$  is flux expulsion efficiency.  $\eta$  is material-dependent!

• For pCM Nb (Wah Chang):

 $R_{BCS}$ =4.5 nOhm,  $R_0$ =1-2 nOhm,  $R_{TF}$ ≈1 Ohm for 5mG  $\rightarrow Q_0$ =3.5e10

• For production material:

Change heat treatment temperature from 800 C to 900 C+ deeper EP (S. Posen):  $R_{BCS}$ =4.5 nOhm,  $R_0 \approx 2$  nOhm,  $R_{TF} \approx 2$  Ohm for  $B_{res} \approx 5$ mG  $\rightarrow Q_0 > 3$ e10



"Fast": 2 – 3 K/minute ,"slow": < 0.5 K/minute

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### A. Grassellino, N-doping: progress in development and understanding, SRF15

### Impact of Modified LCLS-II Recipe on Q<sub>0</sub>



#### Studies leading to modified recipe:

S. Posen, M. Checchin, A. C. Crawford, A. Grassellino, M. Martinello, O. S. Melnychuk, A. Romanenko, D. A. Sergatskov and Y. Trenikhina, *Efficient expulsion of magnetic flux in superconducting radiofrequency cavities for high Q<sub>0</sub> applications, J. Appl. Phys. 119, 213903 (2016), <u>dx.doi.org/10.1063/1.4953087</u>. A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov and O. Melnychuk, <i>Ultra-high quality factors in superconducting niobium cavities in ambient magnetic fields up to 190 mG*, Appl. Phys. Lett. **105**, 234103 (2014); <u>http://dx.doi.org/10.1063/1.4903808</u>.

A. Grassellino, A. Romanenko, S Posen, Y. Trenikhina, O. Melnychuk, D.A. Sergatskov, M. Merio, N-doping: progress in development and understanding, Proceedings of SRF15, <a href="http://srf2015proc.triumf.ca/prepress/papers/moba06.pdf">http://srf2015proc.triumf.ca/prepress/papers/moba06.pdf</a> .

### Ambient Magnetic Field Management Methods

- 2-layer passive magnetic shielding
  - Manufactured from Cryoperm 10
- Strict magnetic hygiene program
  - Material choices
  - Inspection & demagnetization of components near cavities
  - Demagnetization of vacuum vessel
  - Demagnetization of assembled cryomodule / vessel
- Active longitudinal magnetic field cancellation
- Magnetic field diagnostics:
- 4 cavities instrumented with fluxgates inside helium vessel (2 fluxgates/cavity)
- 5 fluxgates outside the cavities mounted between the two layers of magnetic shields



### **Ambient Magnetic Field Management Methods**



### Helmholtz coils wound onto vessel directly



2-layer magnetic shields manufactured from Cryoperm 10

S. Chandrasekaran, Linac 2016, TUPLR027



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### ILC / XFEL CM Modifications for LCLS-II

- Component design based on TESLA / ILC / XFEL designs
  - Cavities XFEL identical mechanically, processed to high Q0
  - Helium vessel XFEL-like (modified ILC with bellows at end for end lever tuner)
  - HOM coupler XFEL-like
  - Magnetic shielding increased from XFEL to maintain high Q0
  - Tuner XFEL-like end-lever style
  - Magnet Fermilab/KEK design split quadrupole
  - BPM DESY button-style with modified feedthrough
  - Coupler XFEL-like (TTF3) modified for higher QL and 6 kW
    CW
- Concerns based on global experience
  - Tuner motor and piezo lifetime: included access ports
  - Maintain high Q0 by minimizing flux trapping: new requirement
    constraints on cool-down rate through transition temperature

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T. Peterson, LCLII 1.3 GHz Cryomodule, LCLS II meeting, 12 May 2015.

### **Cavity modifications**



### Cryomodule Thermal and Hydraulic Design

- LCLS-II CM is a modified TESLA/XFEL CM for CW mode operation
  - Thermal shields, intercept flow, and cryogenic supply and return flow in series through a string of cryomodules
- Heat load range (design within the cryomodule includes generous margins)
  - 80 to 150 W per cryomodule at 2 K depending on local HOM deposition and cavity Q0
  - A cavity may see as much as 25 W
- Cost savings: Omit 5 K thermal shield
  - Simplification since large dynamic heat at 2 K makes such a thermal shield of marginal value
  - Retain 5 K intercepts on input coupler
- Two-phase pipe is 100 mm diameter and closed at each end
  - 0.5% slope or 6 cm elevation difference over 12 m
  - 100 mm diameter two-phase pipe is nearly full at one end, nearly empty at the opposite end
- Cryomodule (CM) thermal and hydraulic design is well advanced
  - Steady-state flows and upset conditions with venting analyses
  - Liquid supply valve for 2-phase liquid level, cool-down valve for "fast" cooldown

T. Peterson, LCLII 1.3 GHz Cryomodule, LCLS II meeting, 12 May 2015.

### Cryomodule Thermal and Hydraulic Design

Liquid Helium Levels in the 2-phase pipe with LCLS-II Tunnel Slope ~0.5%



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### Main couplers

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- TTF-III couplers: input power = 300kW pulse, 2.5 kW average. Loaded Q is 4.5e6 (XFEL);
- LCLS-II input power = 6 kW/cavity CW including overhead.
  Loaded Q is 4e7 (XFEL).
- Necessary modifications:
- Shorten antenna 8.5mm to provide  $Q_{ext} = 4.10^7$  with range (1-5).10<sup>7</sup>
- $\circ$  150-200  $\mu$ m Cu plating of "warm" inner conductor  $\rightarrow$  reduce Temp
- Improved thermal connection in CM at 5K and 50K
- New design-Aluminum Waveguide box, copper flex ring
- Prototypes (ILC/TTF3 modified couplers) tested at HTS and installed/ tested at pCM



N. Solyak, I. Gonin, A. Grassellino, C. Grimm, T. Khabiboulline, J. Ozelis, K. Premo, O. Prokofiev, D. Sergatskov, G.Wu, STUDY OF LCLS-II FUNDAMENTAL POWER COUPLER HEATING IN HTS INTEGRATED CAVITY TESTS, IPAC 2016

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### HOM feed-through

- ILC type feedthrough limits cw gradient < 10 MV/m. With antenna shape modification only it is possible to increase limit up to 40 MV/m, but Q<sub>HOM</sub> will be higher.
- XFEL design is good for >20 MV/m at cw, tested at HTS and pCM.
- Further improvement is proposed (F-parts and antenna modification)







XFEL feedthroughs (sapphire; Mo pin, copper sleeve to thermal strap 2K)



N.Solyak, et al., "Higher Order Mode Coupler Heating in Continuous Wave Operation", ELSEVIER, Physics Procedia, Volume 79, 2015,



### **Tuner modification**







### **DESIGN OPTIMIZATION**

- Mechanical size limitations must fit on the "short-short" cavity (DESY tuner can fit only on "short-long").
- Location of the piezo. Piezo stroke translate directly to the cavity (At DESY design only ½ of piezo stroke going to cavity). Piezo preloaded inside encapsulation.
- Robust/Low cost tuner frame design.
- Features that must prevent loosening of the tuner part during 20 years operation (20 thermo-cycles).
- Design elements that allow to replace active elements of tuner without dis-assembly tuner.
- Access ports in CM.
- NEW ACTIVE COMPONENTS:
  - Electromechanical actuator (stepper/gear/spindle) designed by Phytron per FNAL specs (LVA 52-LCLS II-UHVC-X1)
  - Piezo tuner- encapsulated piezo-stack designed by PI per FNAL specs (PI-885.51)

Y. Pischalnikov et al., "Design and Test of Compact Tuner for Narrow Bandwidth SRF Cavities." In Proc. IPAC2015, Richmond, VA, USA. Y. Pischalnikov et al., "LCLS II Tuner Assembly for the Prototype Cryomodule at FNAL." In Proc. NAPAC2016, Chicago, IL, USA.



### Prototype Cryomodule Latest Preliminary Results

- Cryomodule remnant field ≈ 1 mG
- Fast cool down in a cryomodule demonstrated
- Q0  $\approx$  2.7e10 in a CW cryomodule

	τV	S				
Cavity	Max Gradient [MV/m]	Q0 @16MV/m	Max Gradient*** [MV/m]	Usable Gradient* [MV/m]	FE onset [MV/m]	Q0 @16MV/m 2K** extrapolated
TB9AES021	23	3.1E+10	19.6	18.2	14.6	2.6E+10
TB9AES019	19.5	2.8E+10	19	18.8	15.6	2.6E+10
TB9AES026	21.4	2.6E+10	17.3	17.2	17.4	2.7E+10
TB9AES024	22.4	3.0E+10	21	20.5	21	2.5E+10
TB9AES028	28.4	2.8E+10	14.9	14.2	13.9	2.4E+10
TB9AES016	18	2.8E+10	17.1	16.9	14.5	2.9E+10
TB9AES022	21.2	2.8E+10	20	19.4	12.7	3.2E+10
TB9AES027	22.5	2.8E+10	20	17.5	20	2.5E+10
Average	22.1	2.8E+10	18.6	17.8	16.2	2.7E+10
Total Voltage	183.1 MV		154.6	148.1		

\*Usable Gradient: demonstrated to stably run CW, FE < 50 mR/h, no dark current

\*\*Fast cooldown from 45K, >40 g/sec, extrapolated from 2.11K

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G. Wu, FNAL SRF Department meeting, 24 October 2016, https://indico.fnal.gov/conferenceDisplay.py?confld=13185

### **Acceptance Criteria**

- Cryomodule total voltage exceeds specification
  - Average usable gradient exceeds 17 MV/m
  - Average gradient with field emission onset exceeds 16 MV/m
- Cryomodule heatload meets specification
  - Average Q0 ~ 2.7e10 at 16 MV/m
- HOM coupler meets specification
- Tuner exceeds specification
  - Cavity tuned to 1.300000 GHz +/- 20 kHz
- Coupler meets specification
  - 4e7 Nominal
  - Range 1e7 6e7
  - Stable temperature
- ✓ BPM meets specification
- Quadruple magnet exceeds specification
  - No quench up to 20 A current







What we cannot test until linac operation

- Beam dynamics effects
  - HOM absorber loads
  - HOM coupler performance
  - BPM functioning
  - Magnet package except for electrical checks
- Cryogenic operation of a long (up to 12 CM) string with fullsized cryogenic plant
  - System with integrated heating, full flow rates, and pressure drops
  - Long string on 0.5% slope (although CM's will be tested on slope at Fermilab)
  - Full cryomodule-to-cryomodule interconnect