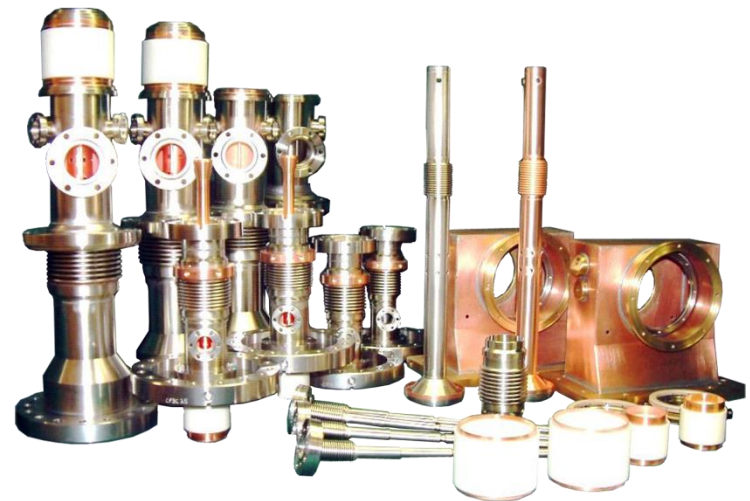


RECENT CPI EXPERIENCE FABRICATING FUNDAMENTAL POWER COUPLERS FOR SRF ACCELERATORS



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COMMUNICATIONS & POWER INDUSTRIES LLC
DECEMBER 2, 2015**

- ◆ Review of CPI Power Coupler Manufacturing Experience
- ◆ Summary of Critical Power Coupler Manufacturing Elements
- ◆ Lessons Learned from XFEL Program
- ◆ Comments on LCLS-II and IFMIF Programs

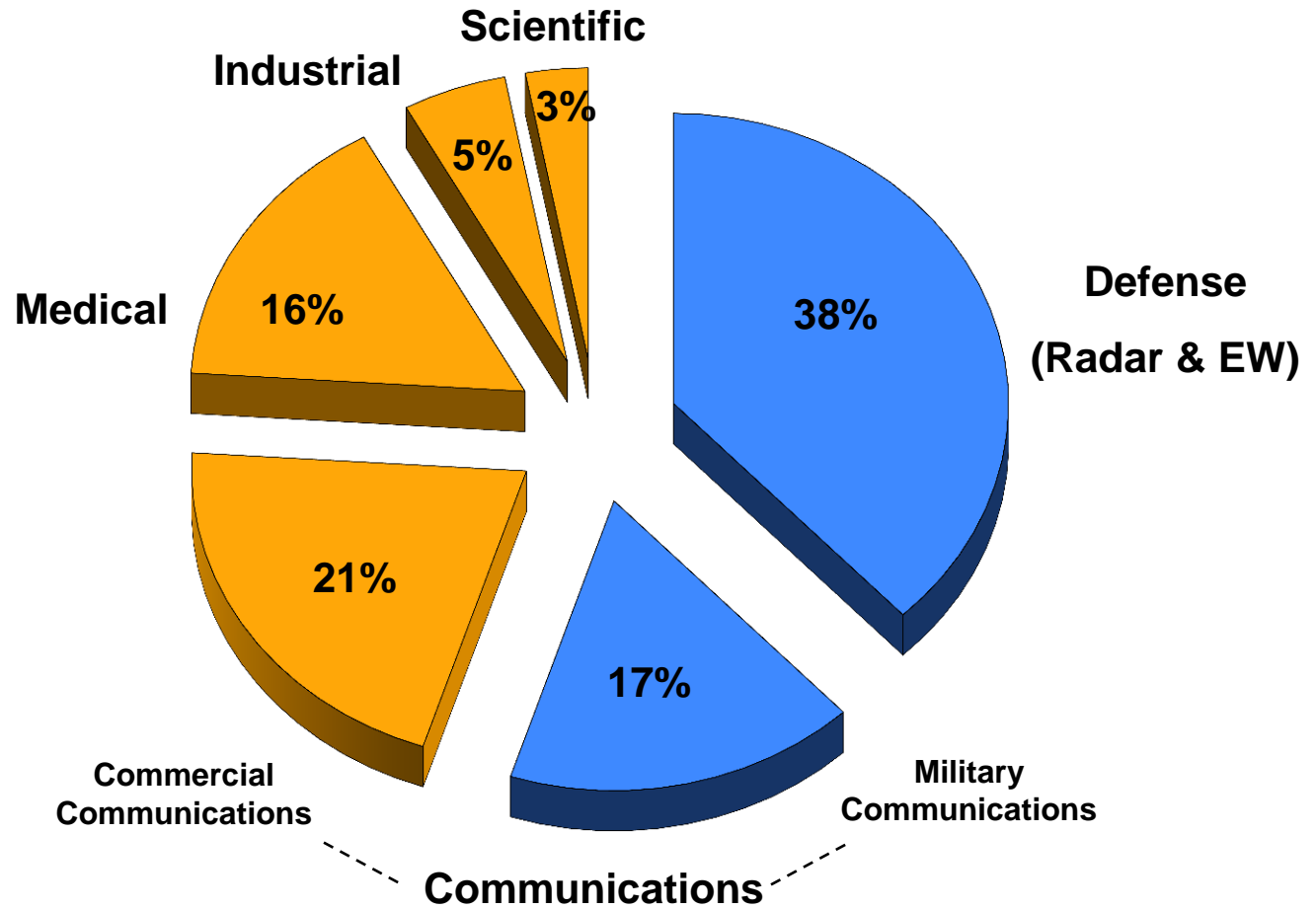


- ◆ Communications & Power Industries LLC (CPI)
 - Leading provider of components & subsystems used in generation, amplification, transmission & reception of microwave signals
 - Founded in 1948, original business of Varian Associates
 - Spun out of Varian Associates in 1995
 - Acquired by Veritas Capital in February 2011
 - FY 2014 sales: \$475M
 - 1,800 employees worldwide
 - Worldwide sales and service organization
- ◆ Long heritage of:
 - Technology leadership
 - Innovation
 - Product & service excellence
 - Leading market share
 - Microwave tube design and manufacturing expertise

CPI's Diverse End Markets

Commercial

Government & Defense



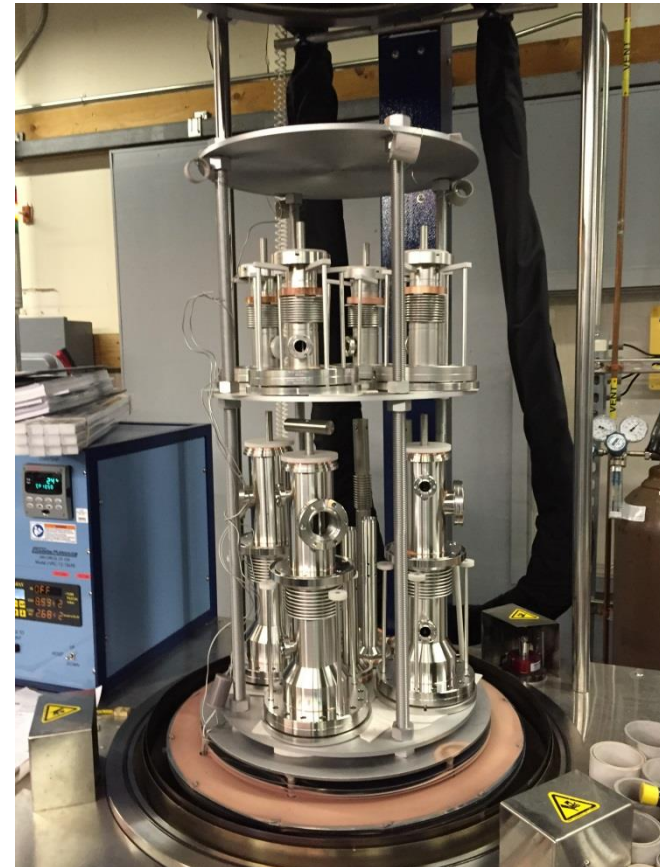
FY 2014 Sales: \$475M

- ◆ Business Volume: \$70M
- ◆ Number of Employees: 300
- ◆ 160,000 sq. ft. Manufacturing Space
- ◆ Products Manufactured:
 - Microwave Devices
 - Integrated Assemblies
 - Control Components
 - Receiver Protectors
 - Microwave Transmitters & Subsystems
 - GaN Solid State Power Amplifiers
 - VED Transmitters
 - Vacuum Electron Devices and Power Couplers
 - Magnetrons
 - Crossed Field Amplifiers
 - Ring Loop TWTs
 - Fundamental Power Couplers

Key Process Technologies Developed for Power Couplers

- ◆ Key process technologies qualified by DESY, CNRS-Orsay, SLAC, XFEL, and Cornell
- ◆ TIG welding of stainless steel components
- ◆ Vacuum brazing
 - Metal to metal seals
 - Stainless steel to stainless steel
 - Copper to stainless steel
 - Ceramic to metal joints
 - Alumina to copper
- ◆ E-beam welding of copper cylinders
 - 100% penetration depth required
 - Complex fixtures required to protect ceramic surfaces from spattered material
- ◆ High RRR-copper plating of stainless steel
 - Thickness and RRR carefully controlled
 - Plating thickness from 30 μm – 150 μm
- ◆ Multiple post-plate processes developed and tested
 - Technical details are CPI proprietary
- ◆ TiN coating of alumina windows for multipactor suppression
 - Thickness and composition carefully controlled
 - Secondary yield less than unity
- ◆ Automated inspection with Coordinate Measurement Machine (CMM)
- ◆ Full visual inspection with borescope
- ◆ ISO 4 / ISO 6 clean room for particle-free cleaning and assembly
- ◆ 150°C bake-out after clean room assembly

- ◆ In-house machine shop
- ◆ In-house chemical processing and electroplating facility
- ◆ Clean assembly area
 - Manufacturing cells set up for power coupler and power tube assembly
- ◆ Manufacturing equipment
 - Mixed gas and vacuum braze furnaces
 - TiN coating system
 - TiG and laser welders
 - Optical inspection station
 - Coordinate Measurement Machine (CMM) for automated inspection





- ◆ Class 1000 and class 10 clean room for power couplers
 - Sized for cleaning and assembly of 8 couplers per week in a single shift
 - Gowning area
 - Air shower
 - Ultrasonic cleaner
 - Ultra-pure water system
 - Rinse station
 - Nitrogen drying cabinet
 - Particle counters
 - Multiple oil-free turbo-molecular vacuum pumps
 - Residual Gas Analyzers
 - 150°C bake-out station adjacent to clean room



Model	Accelerator Application	Freq. (MHz)	Peak and Avg. Power (kW)	Status
VWP-3097	IFMIF Prototype (CEA Saclay)	175	200 and 200	Delivered 2 Delivering 8
VWP-3098	FRIB Prototype (MSU)	322	14 and 14	Delivered 2
VWP-3124	RFQ (ORNL)	402	14 and 14	Delivered 3
VWP-3107	NSLSII Upgrade (AES, BNL)	500	500 and 500	Delivered 1
VWP-3070	Free Electron Laser Injector (AES, BNL)	748	1000 and 1000	Delivered 2
VWP-1185, 1186	Free Electron Laser Injector (AES, JLAB)	748	350 and 350	Delivered 4
VWP-1133, 1162	SNS (JLAB) and RIA (MSU)	805	1000 and 60	Delivered 8
VWP-3049 (TTF3)	Tesla Test Facility (CNRS Orsay, DESY), ILC (Fermi, SLAC), and Triumf	1300	1110 and 7.2	Delivered 114
VWP-3126 (XFEL)	XFEL (EuXFEL)	1300	1110 and 7.2	Delivering 150
VWP-3130, 3135	LCLS-II (SLAC)	1300	7 and 7	Delivering 140
VWP-3032, 3069	ERL Injector (Cornell, Triumf, Daresbury)	1300	75 and 75	Delivered 18
VWP-3113	SRF Accelerator (Univ. Beijing)	1300	75 and 75	Delivered 2
VWP-3108	Energy Recovery Linac (Cornell)	1300	10 and 10	Delivered 10
VWP-3088	Third Harmonic Accelerating Cavity (Fermi, DESY, XFEL)	3900	12.5 and 12.5	Delivered 31



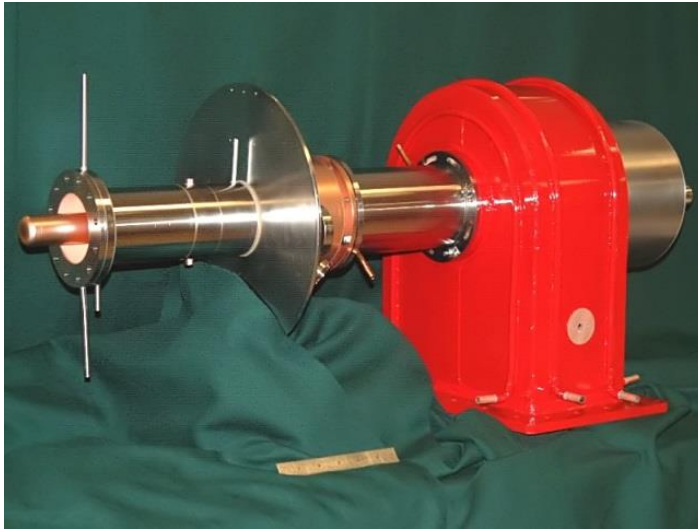
VWP-3049 TTF3



VWP-3032 Cornell 75 kW CW



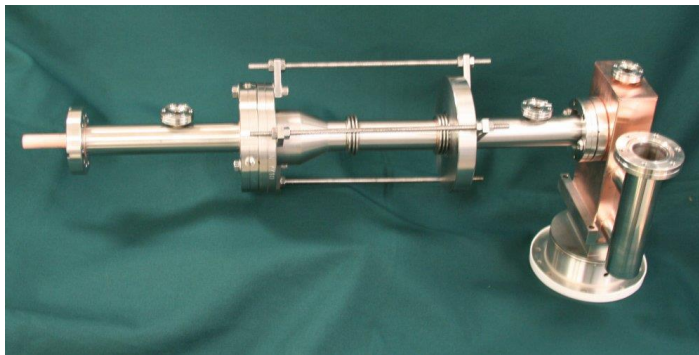
VWP-3126 XFEL
VWP-3130 LCLS-II



VWP-3070 AES 500 kW CW



VWP-1133 SNS



VWP-3088 3.9 GHz XFEL

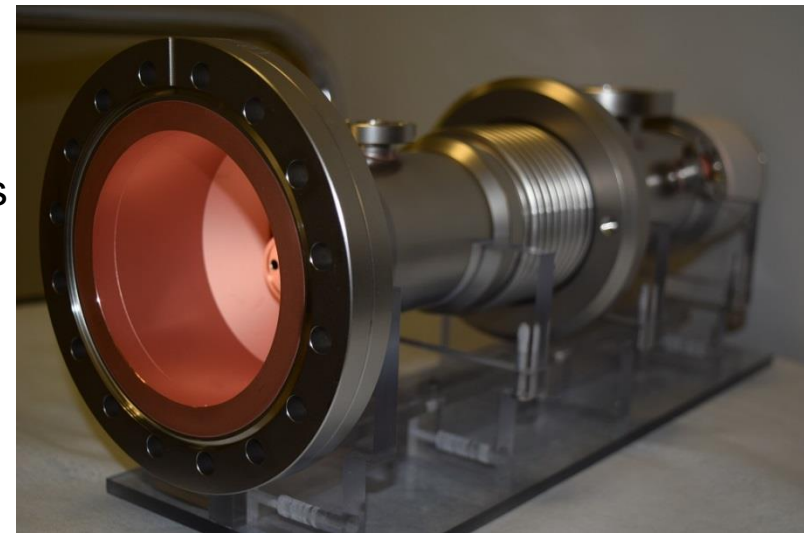
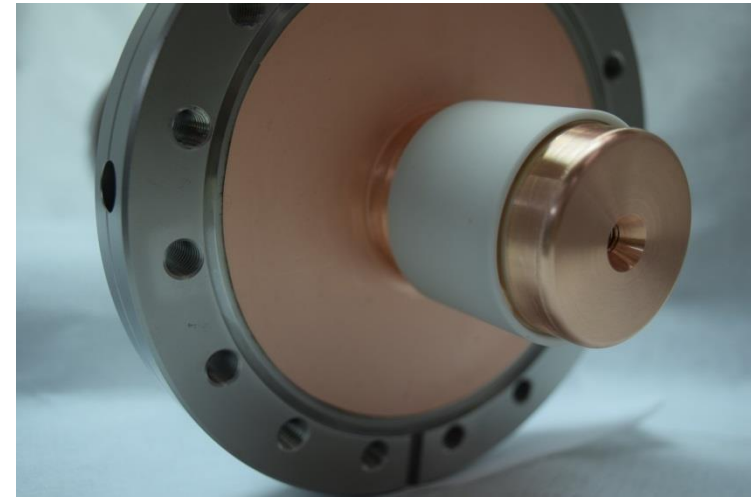


VWP-3097 IFMIF

- ◆ CPI is providing 150 XFEL power couplers and 24 test stands for the XFEL
- ◆ The contract includes:
 - preparation and qualification of process samples
 - fabrication of XFEL couplers
 - cleaning and assembly in an ISO4 / ISO6 clean room
 - required CPI to build and qualify a new clean room modeled after SLAC's and LAL's power coupler clean rooms
 - significant assistance provided by SLAC, JLAB, DESY, XFEL personnel
 - delivery of 8 prototypes and 142 production couplers
 - clean room assembly and conditioning of the first 8 couplers at SLAC
 - work performed at SLAC while CPI clean room was being completed
 - work performed under a DOE Work for Others agreement
 - monthly inspection visits from representatives of XFEL team
 - XFEL representatives can inspect anything on the production floor
 - final inspection by CPI quality assurance inspector
 - bake-out and conditioning and final acceptance of 142 production couplers at LAL

What has worked well

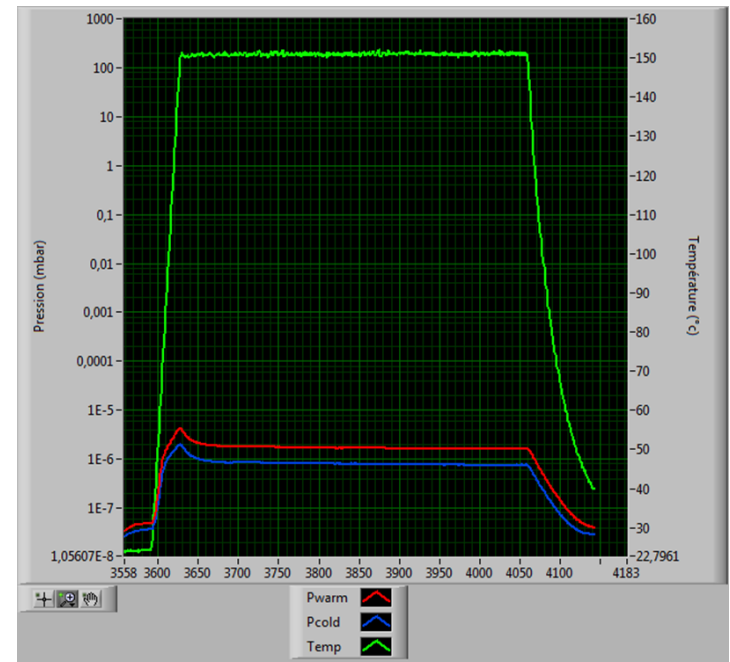
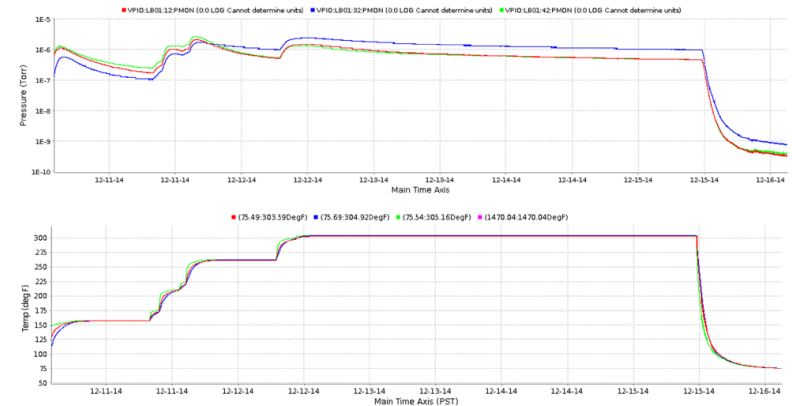
- ◆ Significant assistance provided by XFEL team
- ◆ Detailed design reviews on site at CPI
- ◆ Hands-on training at SLAC on clean room activities
- ◆ Vacuum and clean room experts helped qualify CPI's new clean room
- ◆ Monthly inspection visits helped us further refine the manufacturing processes and inspection criteria
- ◆ CPI plating process has been predictable and reproducible at high production rate
 - High quality
 - Improved fixtures
 - Manageable yield issues
 - Note that visual inspection criteria is still much too subjective
- ◆ Note that not everything worked flawlessly at the start of production
 - Quality iteratively improved



- ◆ First 8 couplers cleaned, assembled, baked out, RGA tested, conditioned at SLAC
- ◆ All 8 couplers conditioned successfully within 20 – 30 hours at SLAC
- ◆ All 8 couplers were accepted
 - Couplers are installed in cryomodule and are now in tunnel
- ◆ First sets of production couplers delivered to LAL were not accepted
 - Conditioning took longer than the norm and gray staining of some ceramics was noted
 - CPI slowed production while investigating the differences between prototypes and production couplers
 - We systematically reviewed all production steps, materials, and processes
 - A few “production ramp-up” issues were found that were attributable to new people, new procedures, and new equipment
 - None of these issues were conclusively determined to be the culprit
 - We reviewed all aspects of the new CPI clean room since this was the first time it was used
 - DESY and SLAC experts audited the process – no findings
 - We sampled the ultra-pure water and nitrogen – not the cause
 - We investigated differences between the SLAC cleaning, bake-out and conditioning process, and the CPI cleaning with LAL bake-out and conditioning process
 - Some differences found – importance debatable
 - We iteratively improved several CPI-proprietary processes based on test data from LAL, and inputs from our customer, and conditioning time improved
 - The improvements also resulted in cleaner ceramics
 - Unfortunately it took months before we could ramp production back up

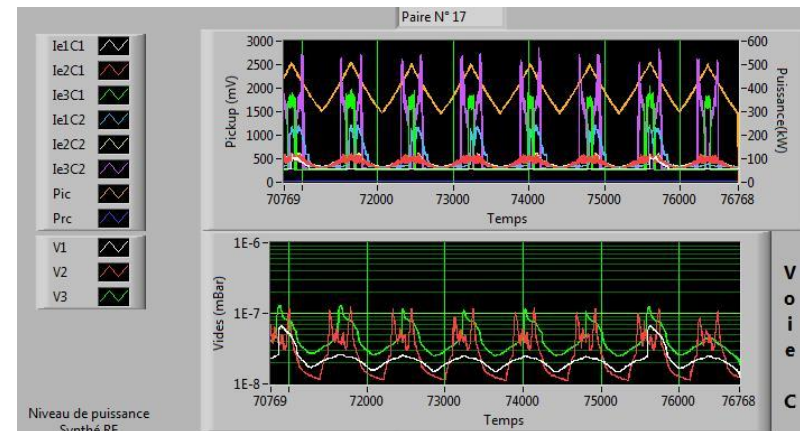
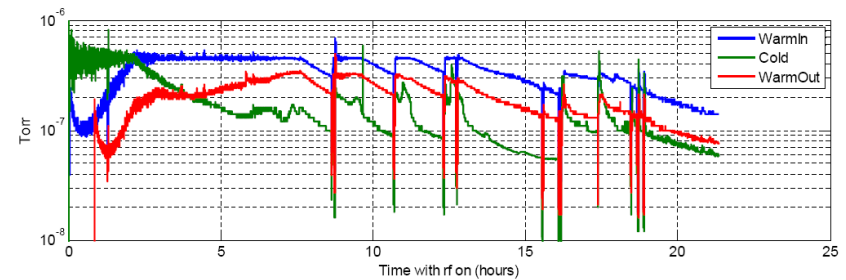
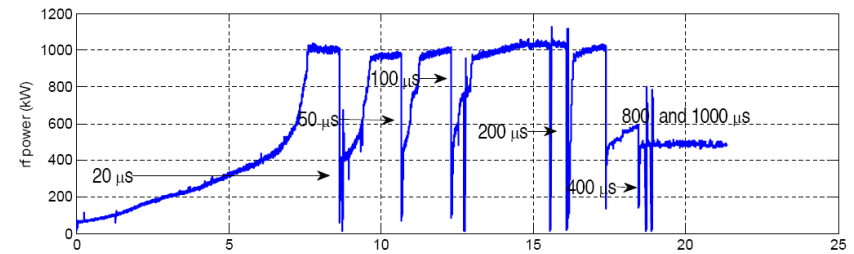
Bake-out

- ◆ SLAC bake-out (top)
 - 150°C for 72 hours with ramp up to full temperature over >48 hours
 - Typical vacuum pressure at temperature at end of bake-out 5E-7 Torr
 - Typical vacuum pressure at room temperature at end of bake-out < 5E-9 Torr
- ◆ LAL bake-out (bottom)
 - 150°C for 48 hours with ramp up to full temperature over a short time
 - Typical vacuum pressure at temperature at end of bake-out 7E-7 Torr
 - Typical vacuum pressure at room temperature at end of bakeout < 3E-8 Torr
- ◆ Primary difference in bake-out is ramp up time and duration
- ◆ Early in the production cycle, several coupler pairs were baked-out twice at LAL with improved conditioning results but not completely effective



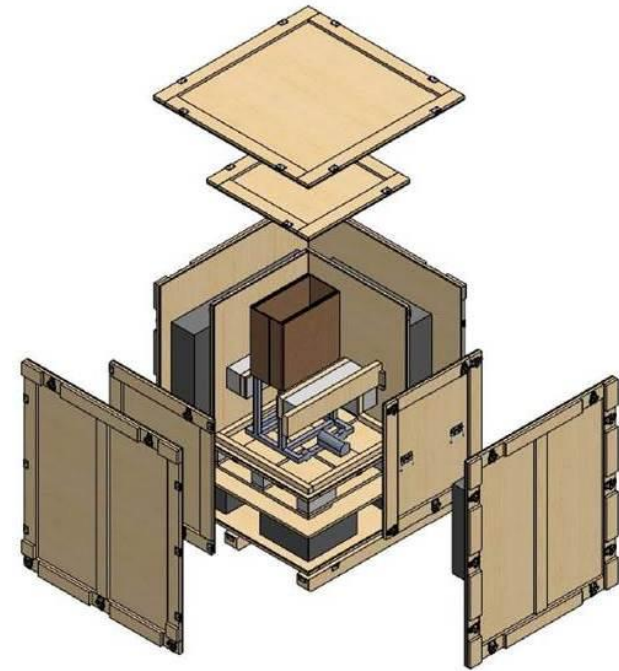
Conditioning

- ◆ SLAC conditioned the 8 prototype couplers and 2 production couplers in 20 - 30 hours
 - example at top shows power and pressure as a function of time
- ◆ SLAC interlock setting at step 1 (initial ramp up to 1 MW) set at 1E-6 Torr, which is higher than at LAL
- ◆ After CPI improved processes, conditioning time for couplers at LAL is comparable to SLAC
 - example at bottom during power sweep shows power and electron activity and pressure as a function of time for accepted coupler



Shipping

- ◆ Shipping from CPI in Beverly, MA to LAL in Orsay, France takes longer (and costs more) than planned but it is trouble free
 - We have shipped 60+ couplers without damage to any couplers
- ◆ Couplers are shipped in re-usable crates
 - Shipping crates qualified via drop test by vendor
 - Shock monitors (trip indicators) always used
 - Shock recorders used to evaluate process
- ◆ We ship the couplers via air freight from Boston to Germany
- ◆ Customs clearance must take place in Germany so the XFEL doesn't pay import fees
- ◆ The couplers are trucked from Germany to LAL in Orsay, France
- ◆ The average shipping time from BMD to LAL is 15 calendar days
 - varies from 7 – 21 days
 - standard deviation 4.5 days
- ◆ Shipping crates and test stands are shipped back directly from LAL to CPI and take about a week



Summary

- ◆ Qualifying the couplers at SLAC under slightly different conditions than at LAL made it more difficult to identify the root cause and corrective action of the longer conditioning time at LAL
- ◆ Resolution of the problem was delayed by the long shipping time between CPI and LAL and by LAL's production commitments
 - Fitting CPI couplers, which required some troubleshooting, into the ongoing production process at LAL proved to be difficult
 - A prototype phase with LAL was planned but wasn't possible
- ◆ Over twenty couplers queued up at LAL while we troubleshooted the problem
- ◆ Production was delayed by 4-5 months as a result
- ◆ Ideally we would have qualified the couplers under identical conditions as in production
 - While qualification at LAL would have been ideal, it was not feasible from a contractual standpoint
- ◆ Ideally it would have been beneficial to have a shorter feedback time between fabrication and conditioning / acceptance
- ◆ This is a critically important element for any large production program that is starting up

Summary

- ◆ 8 TTF-3 style prototypes being built with a few changes
 - thicker plating on the warm inner conductor assembly for CW operation
 - SLAC qualified CPI's thicker plating process last year (C. Adolphsen 2014 TTC talk)
 - minimal post-processing of the copper plated surfaces
 - variants being tested under XFEL contract
 - shorter cold antenna
 - SLAC drawings with updated dimensions and tolerances
 - 150°C bake-out by CPI after clean room operations
 - full temperature RGA test required
 - bake-out station qualified
- ◆ 132 XFEL-style production couplers will also be delivered next year



Summary

- ◆ CPI built 2 prototype couplers for the IFMIF program several years ago
 - Couplers are low frequency (175 MHz), and physically large
 - Operate at high average power (200 kW CW)
- ◆ We currently are building 8 production couplers
- ◆ The initial prototype program was comprehensive and very well documented (largely due to the customer requirements) so the current program is going reasonably well, albeit slowly



- ◆ CPI has built over 300 power couplers over the last 12 years
- ◆ With help from DESY, CNRS-Orsay, SLAC, JLAB, Fermi, XFEL, and Cornell, CPI has qualified its key processes for the fabrication of power couplers
- ◆ CPI is currently manufacturing 300 power couplers for the XFEL, LCLS-II, and IFMIF
- ◆ Even with our processes in near continuous use for the last 12 years, some improvements needed to be instituted as we transitioned from, prototypes and low rate initial production, to full-scale production
- ◆ While these lessons-learned have been painful, they haven't been insurmountable