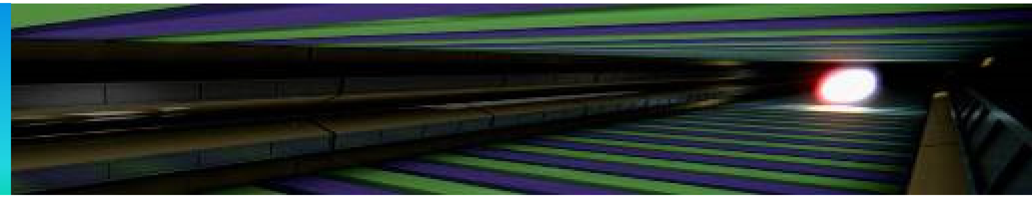


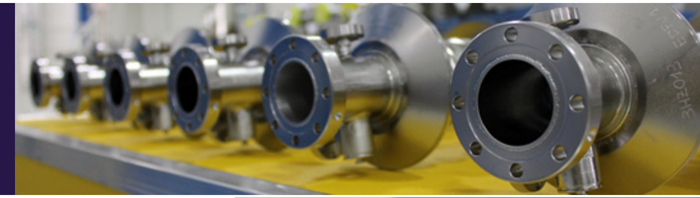
Operating the Third Harmonic SRF System in the E-XFEL Injector

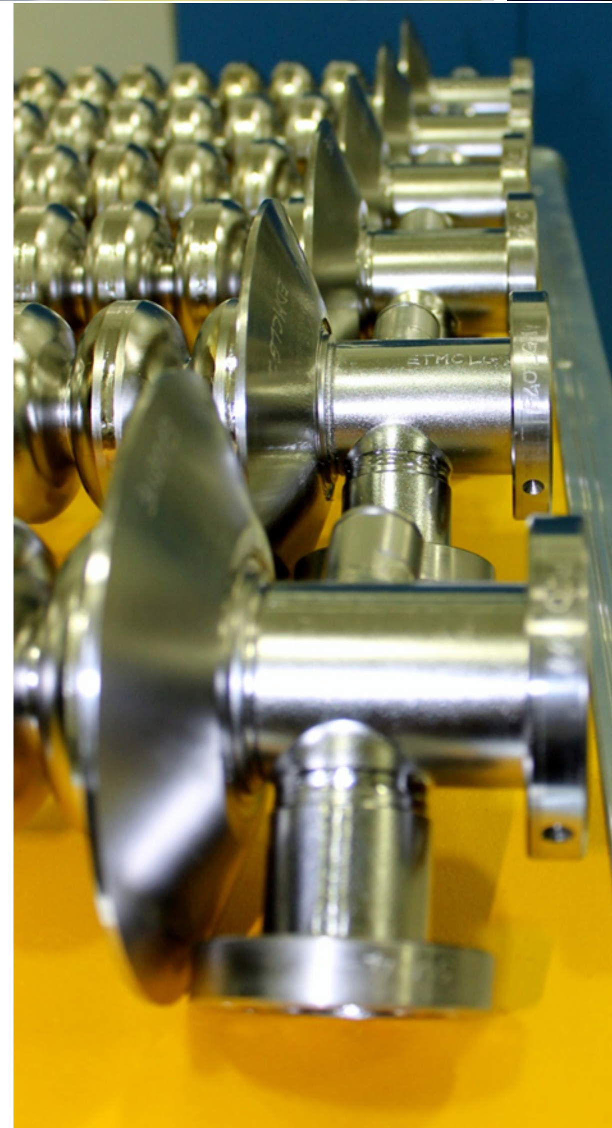
Paolo Pierini*, INFN-LASA & DESY

For the **INFN/DESY XFEL-WP46** team

(* from July 2017 at ESS ERIC)

Outline

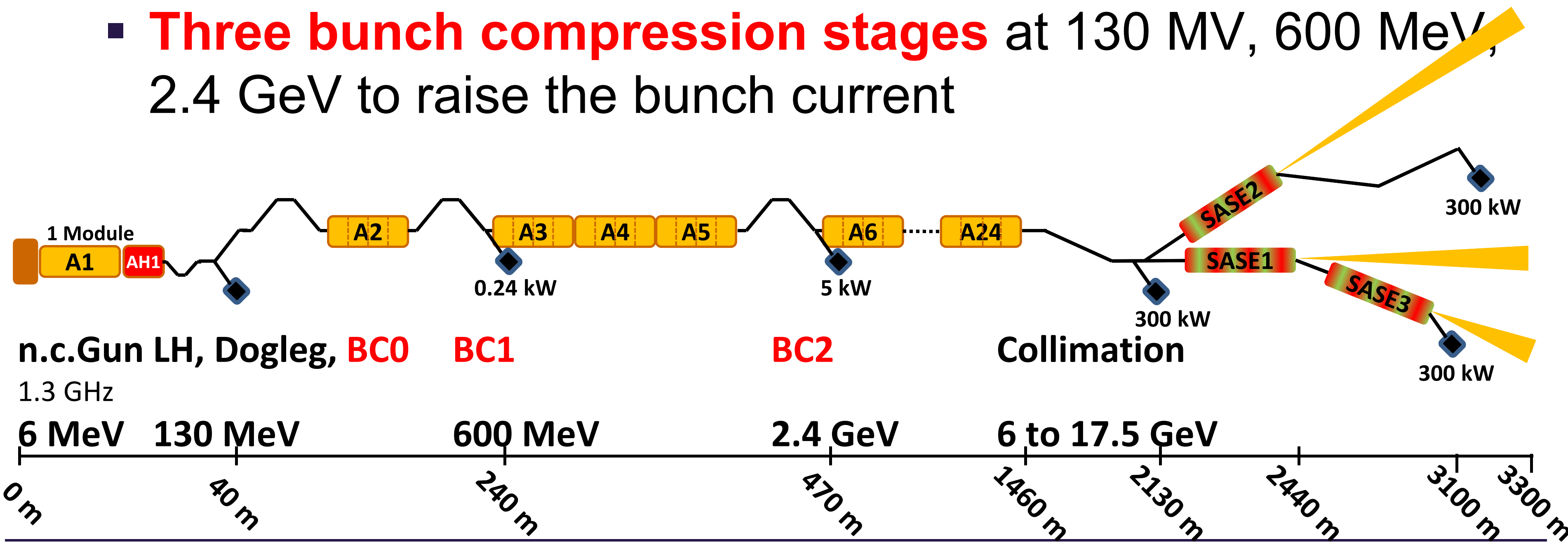




- XFEL in a nutshell
- Why a third harmonic system?
- What is in there?
- Cavities VT Qualification
- Cavity package Qualification
- Assembly & Tunnel Installation
- Technical Commissioning
- Performances of AH1
  - Injector Run (130 MeV): Dec 15-Jul 16
  - XFEL Commissioning: Jan 17-Jun 17

XFEL in a nutshell

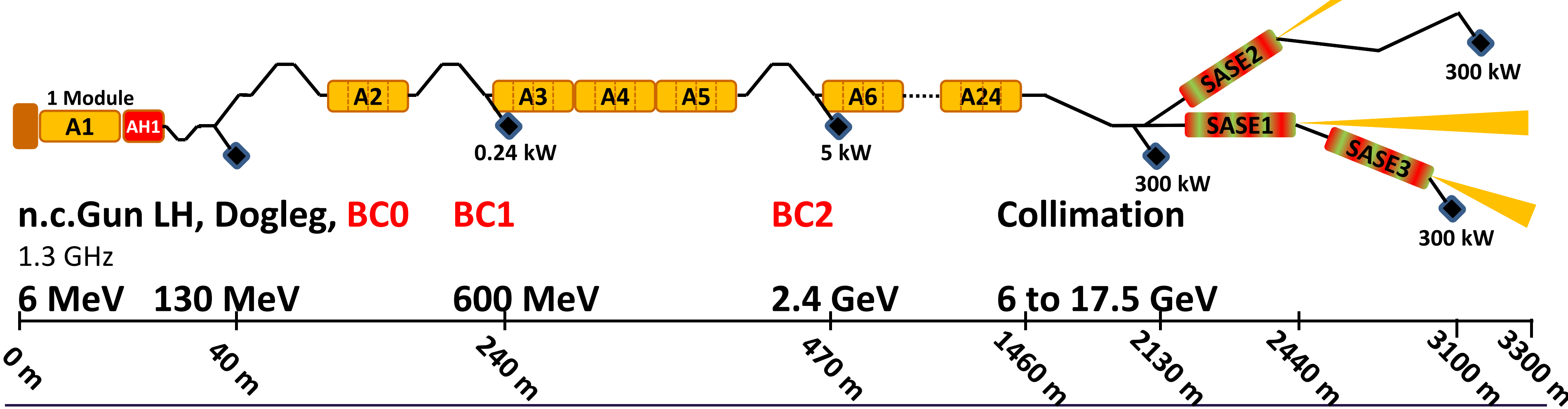
- 1.3 GHz SRF linac with 17.5 GeV, 5 kA bunches for an FEL operating in the 1-0.5 Å regime
  - 27000 e- bunches/s (0.6 ms flattop @ 10Hz, 2700 b/pulse)
  - 1 klystron driving 4 8-cavity modules in **vector sum mode**
- Beam quality (emittance at high currents) is the key
  - **Three bunch compression stages** at 130 MV, 600 MeV, 2.4 GeV to raise the bunch current



XFEL in a nutshell

- 1.3 GHz SRF linac with 17.5 GeV, 5 kA bunches for an FEL operati[redacted]
  - 27000[redacted]00 b/pulse)
  - 1 klys[redacted]um mode
- Beam quality (emittance at high currents) is the key
  - **Three bunch compression stages** at 130 MV, 600 MeV, 2.4 GeV to raise the bunch current

Presented by Detlef Reschke, Monday session



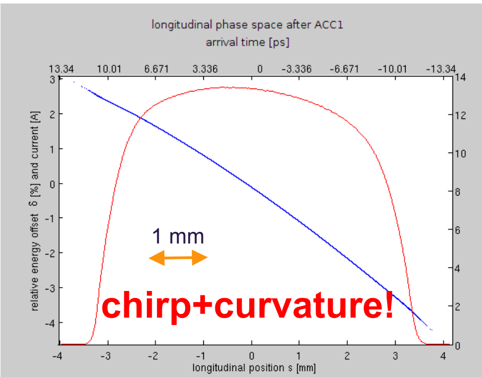
Why a third harmonic system

- EXFEL needs **longitudinal phase space manipulation** before the bunch compression stages
  - A **proper** current profile along the bunch for lasing is thus obtained by **control of energy chirp, curvature, skewness in the longitudinal phase space**
    - → Removing the RF curvature from the 1.3 GHz module caused by the long bunch length at the injector
    - → Compensating wake fields in the main linac, BC non linear optics, space charge effects…
- How? Add a (third) harmonic voltage and properly set its **amplitude** and **phase** relative to the main accelerating voltage

M. Dohlus, T. Limberg, "Bunch compression stability dependence on RF parameters", 27th FEL Conference (2005) p. 253

Phase space manipulation in a glance

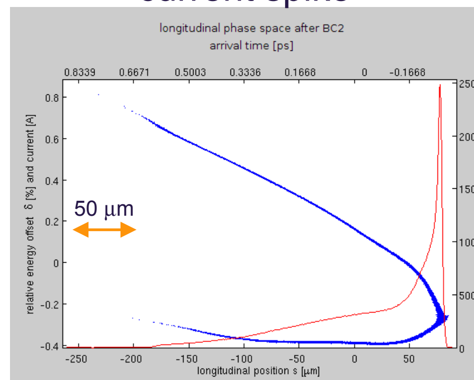
Using only A1 to chirp the beam (no AH1)



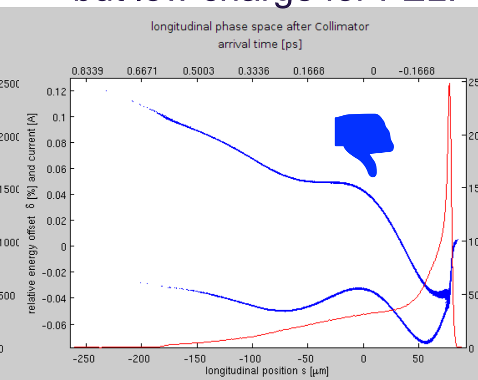
Longitudinal phase space

Current along bunch

At final compression stage current spike

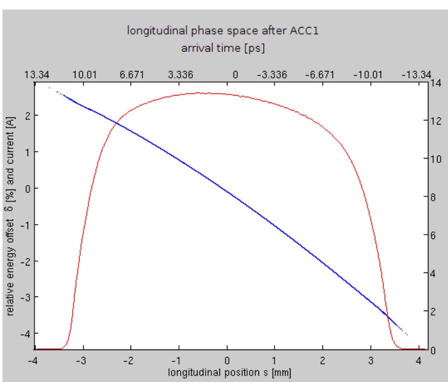


Large current spike but low charge for FEL!



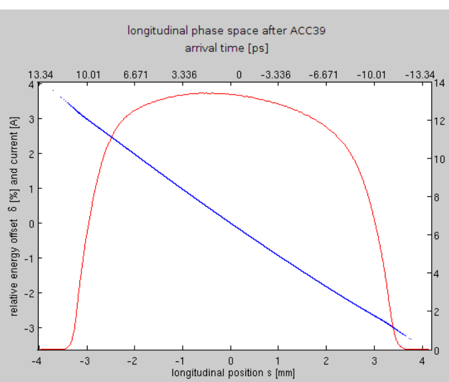
With third harmonic manipulation

After A1 (150 MeV)



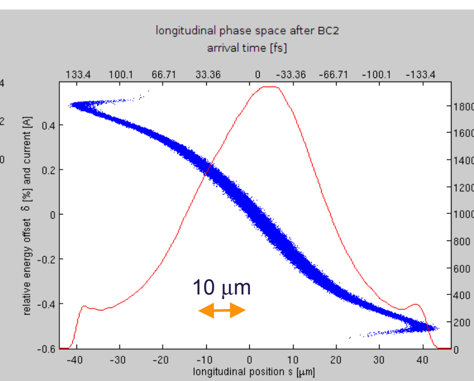
Off crest operation creates chirp+curvature

After AH1 (130 MeV)



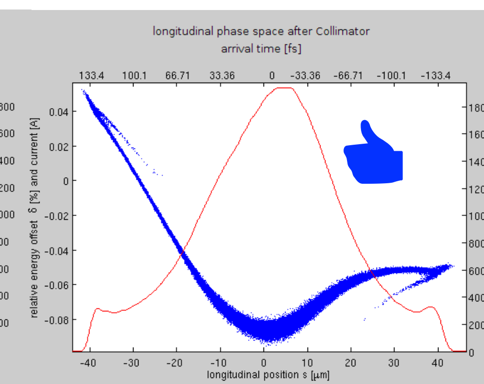
AH1 removes curvature and prepares for BC

After BC2 (2.4 GeV)



At final compression stage good current profile

After L3+CL (17.5 GeV)



Beam flattened for good FEL emission

What is in the AH1 module?

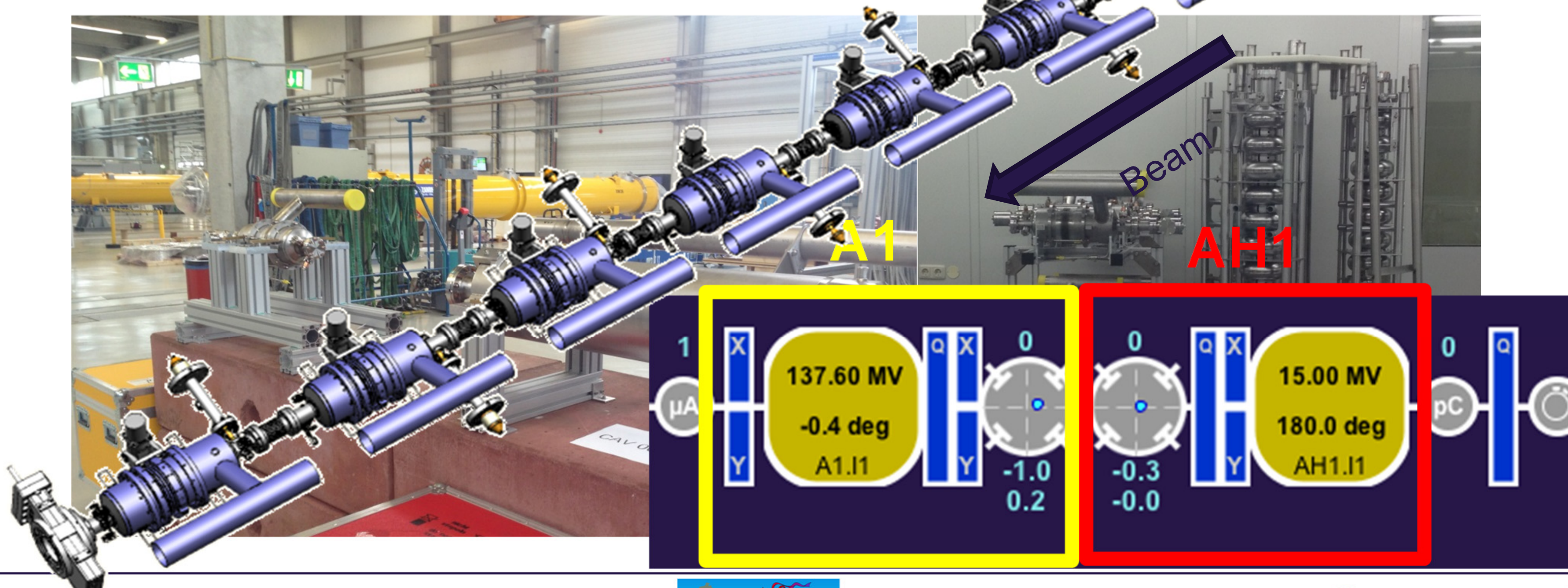
- The third harmonic system (AH1) is functionally **like a standard main XFEL module**, but contains 8 cavities at 3.9 GHz (3 times the frequency, therefore 1/3 of the size)
- IN-KIND Contribution to XFEL by INFN (50%: Cavities and module) and DESY (50%: Couplers, RF and infrastructure)
  - Joint: installation, technical commissioning and initial operation

What is in the AH1 module?

- The third harmonic system (AH1) is functionally **like a standard main XFEL module**, but contains 8 cavities at 3.9 GHz (3 times the frequency, therefore 1/3 of the size)
- IN-KIND Contribution to XFEL by INFN (50%: Cavities and mo… and DESY (50%: Couplers, RF and infrastructure)
  - Joint: installation, technical commissioning and in… operation

What is in the AH1 module?

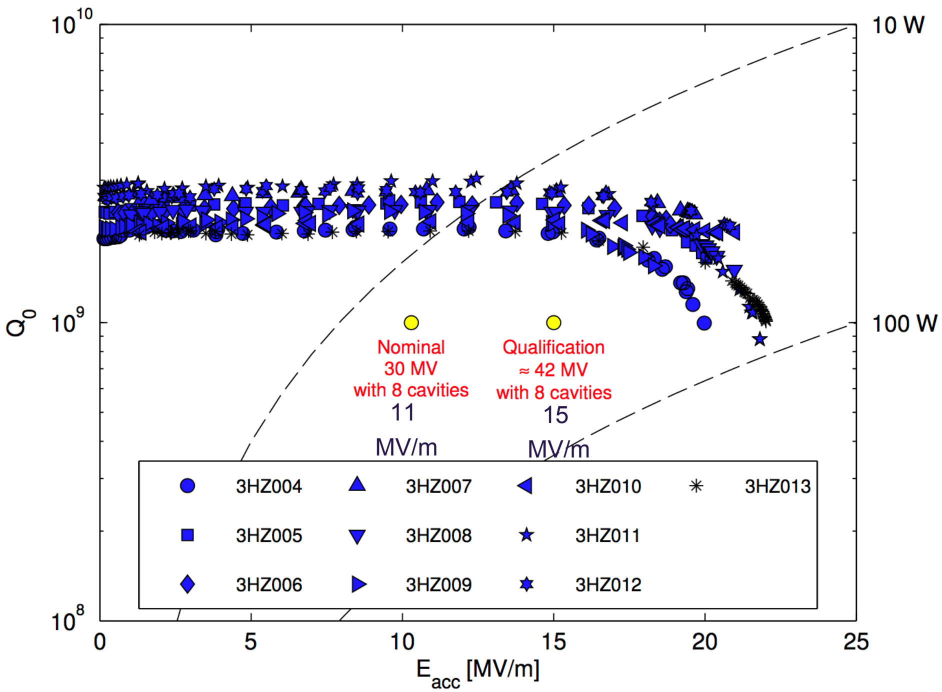
- The third harmonic system (AH1) is functionally **like a standard main XFEL module**, but contains 8 cavities at 3.9 GHz (3 times the frequency, therefore 1/3 of the size)
- IN-KIND Contribution to XFEL by INFN (50%: Cavities and mo[…] and DESY (50%: Couplers, RF and infrastructure)
  - Joint: installation, technical commissioning and in[…] operation



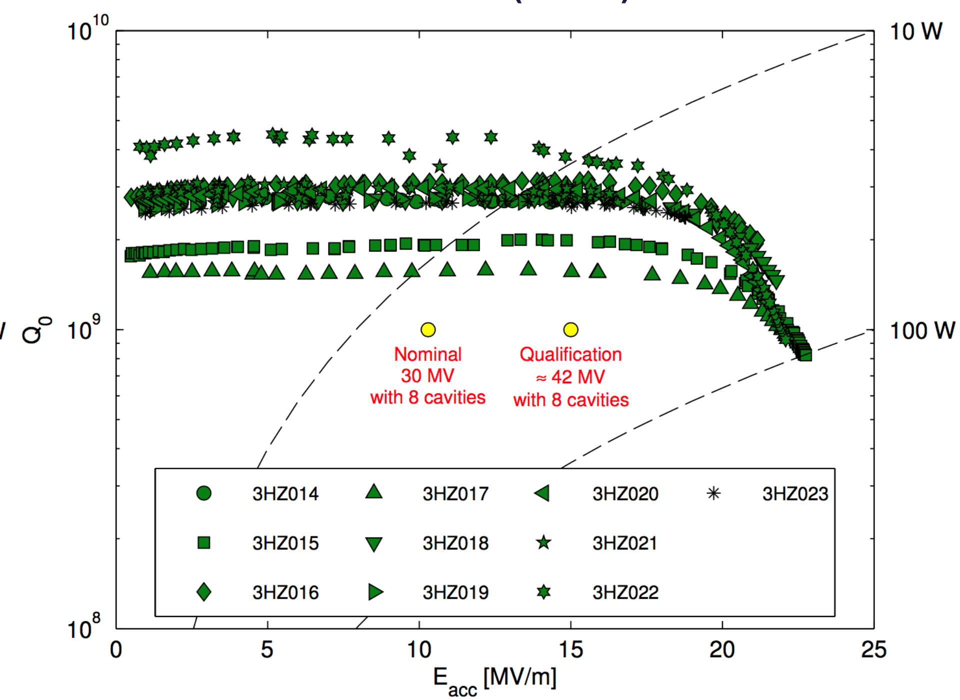
Cavity production and testing

- 3 prototypes and 2 batches of 10 cavities procured by INFN
  - Mechanical production & BCP treatment at Vendor
  - Preparation to test and VT at INFN-LASA

1st batch (X3M1)



2nd batch (X3M2)

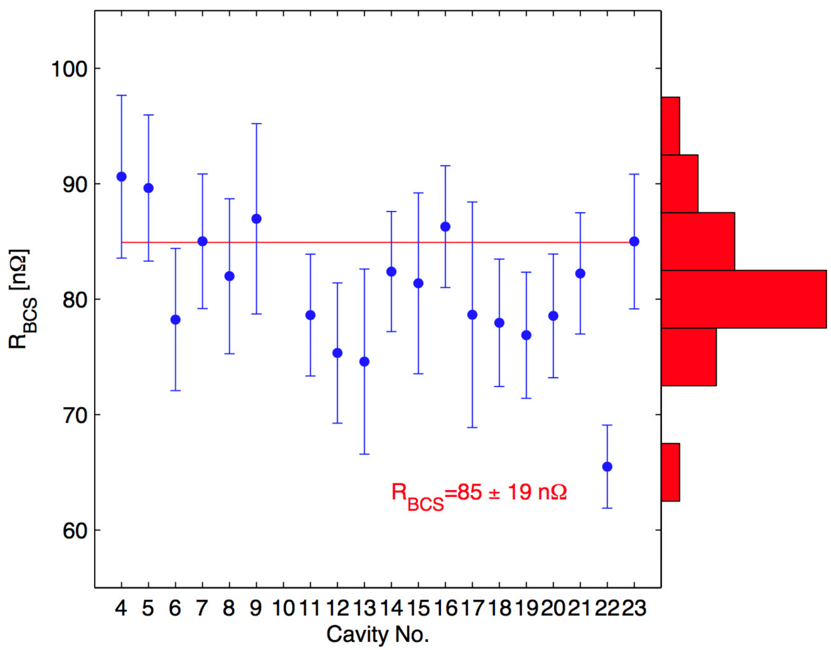


PP et al, "Fabrication and vertical test experience of the European X-ray Free Electron Laser 3.9 GHz superconducting cavities", PRAB, 20, 042006 (2017)

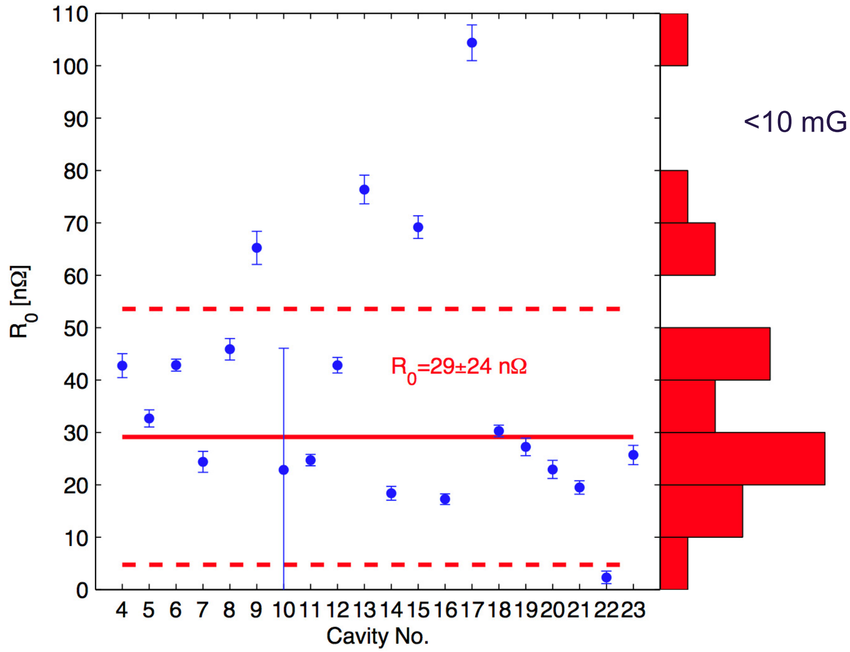
VT Qualification summary

	E_{acc} [MV/m]	Q_0 [10^9]
First Batch	20.4±1.1	2.39±0.29
Second Batch	19.9±2.4	2.77±0.65
	20.1±1.9	**2.58±0.45**

R_{BCS}: as expected from the f^2 scaling



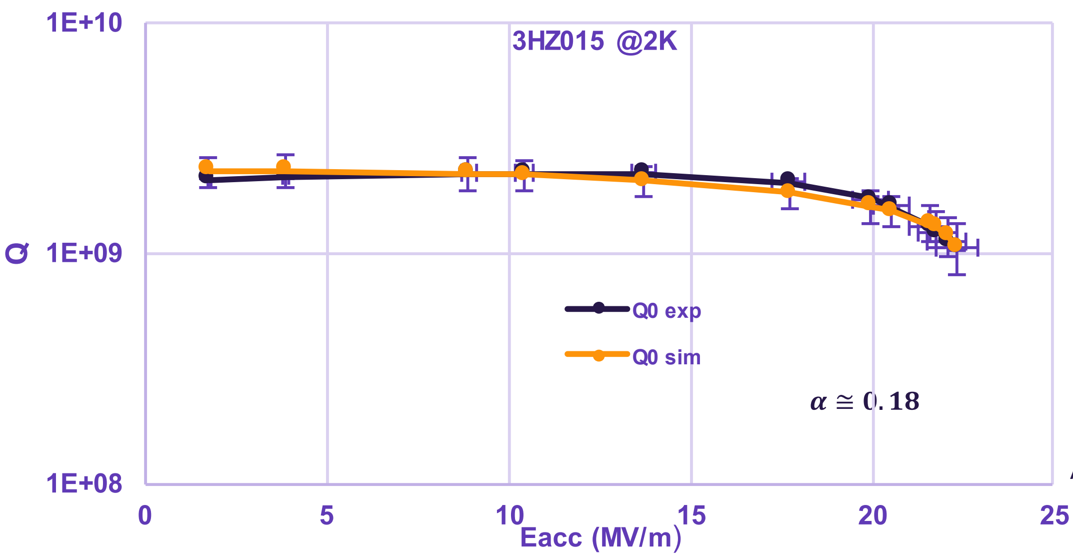
R_0: Follows JLAB scaling R_0=5.3+1.89 (f[GHz]) [nΩ]



PP et al, "Fabrication and vertical test experience of the European X-ray Free Electron Laser 3.9 GHz superconducting cavities", PRAB, 20, 042006 (2017)
G. Ciovati et al, "Residual resistance data from cavity production projects at Jefferson lab", IEEE Trans. Appl. Supercond. 21, 1914 (2011)

Behavior at high field

- All cavities quench at around 20-22 MV/m
  - Dissipated power on the cavity in the 20-100 W range
  - Thermal equilibrium model with field dependent BCS reproduces the slope of Q_0 vs E_{acc} curves at different T
  - **Thermal breakdown** around 20 MV/m seems the limiting mechanism of 3.9 GHz structures with BCP



Heat transfer can be linearized assuming weak quasi-particle overheating ($T_{qp} - T_0 \ll T_0$)

$$T_{qp} - T_{bath} = \frac{\alpha T_{bath}}{R_{s,0}} \left(\frac{H}{2H_c}\right)^2 R_s(H, T_{qp})$$

Overheating parameter $$\alpha = \frac{R_{s,0} B_c^2}{2\mu_0^2 T_{bath}} \left(\frac{1}{Y} + \frac{d}{k} + \frac{1}{h_k}\right)$$

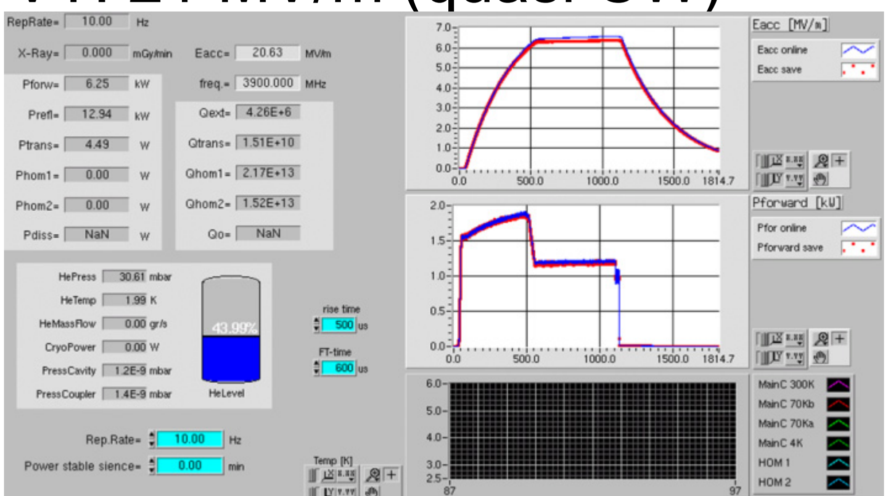
A. Gurevich, "Reduction of Dissipative Nonlinear…", arXiv:1408.4467 (2014)

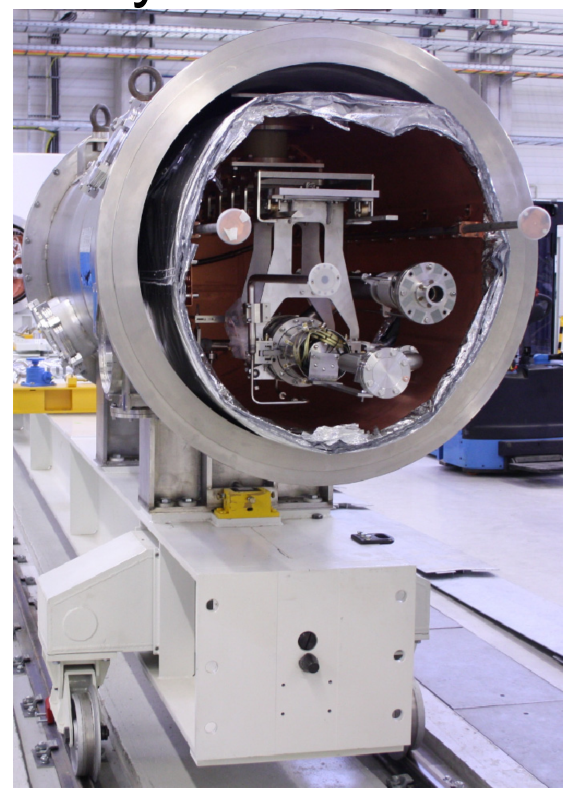
J.T. Maniscalco et al., "The importance…", JAP 121, 043910 (2017)

M. Bertucci et al., to be published

Validation test in AMTF (March 2015)

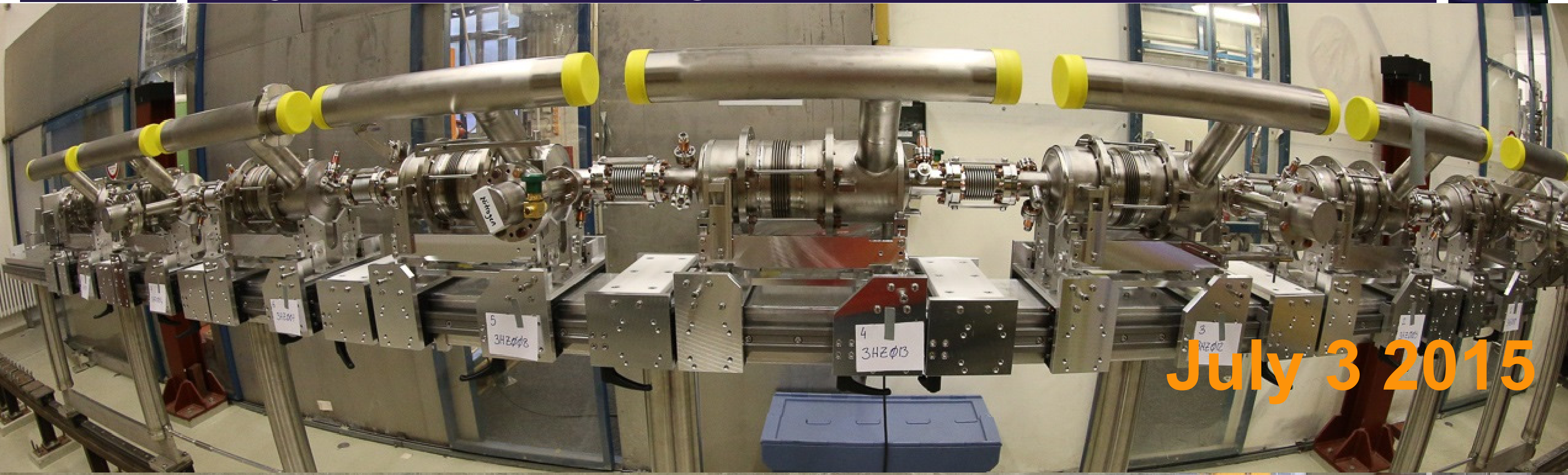
- No module test prior to installation!
- Horizontal test for the **cavity package qualification**
  - Cold Tuning System & Coupler assembly
- Open loop operation at 20 MV/m
  - Quench at 24 MV/m,10 Hz, 1.3 ms
  - VT: 21 MV/m (quasi CW)





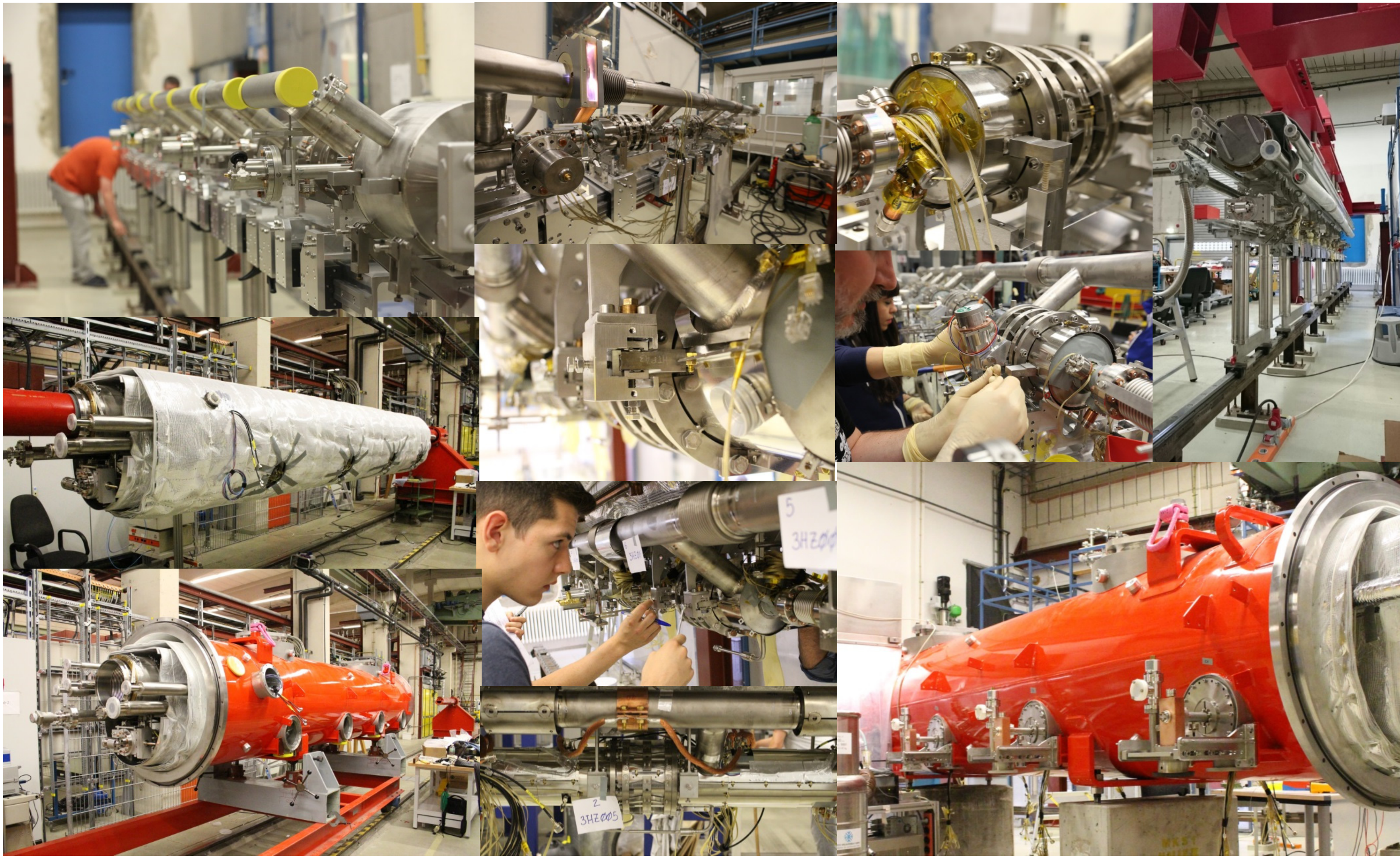
CG Maiano et al, “Validation of the superconducting 3.9 GHz cavity package for the European X-ray Free Electron Laser”, PRAB, 20, 042005 (2017)

Major AH1 Assembly Milestones

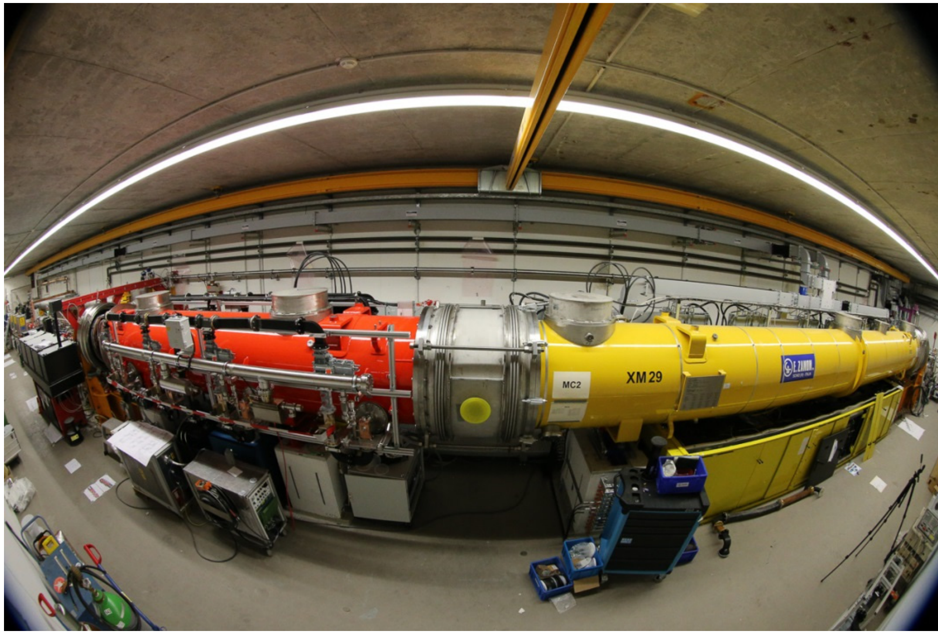


European XFEL

The assembly in Halle III (14 weeks)



Final Preparation stages in tunnel

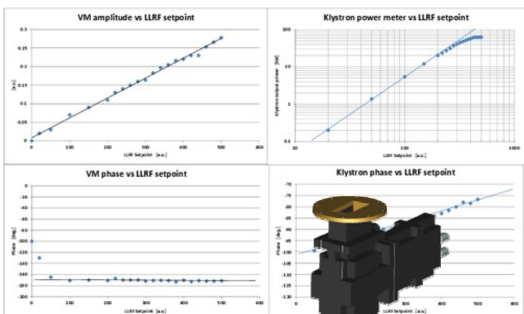


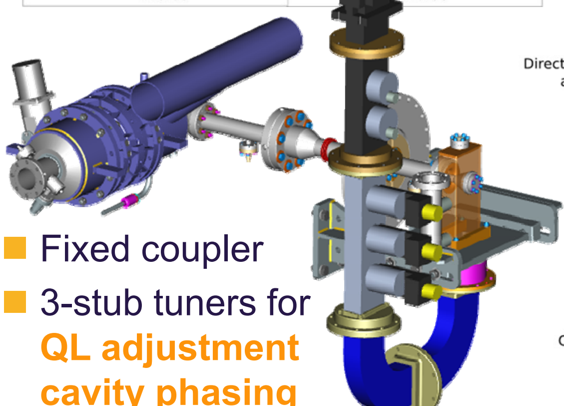
- Assembly WG distribution
- Injector String Integration
- Dec 10: **Start cooldown**
- Dec 15, Cryo OK- cavity pre-tuning
- Dec 16, calibration: **AH1 Ready**

RF Distribution layout

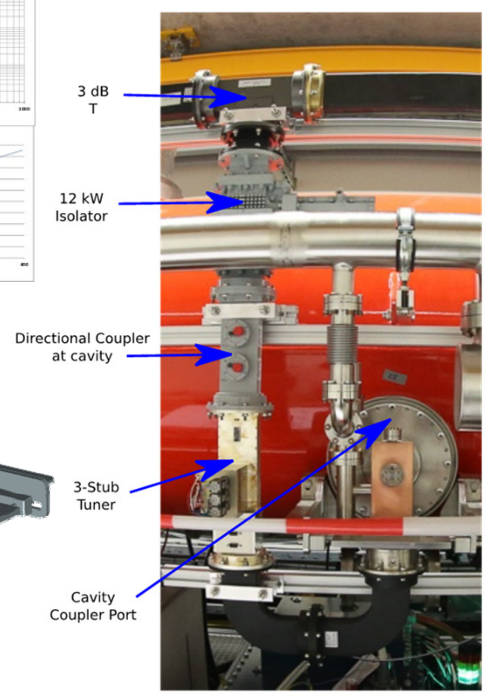
- Vector Sum
  - 8 cavities
- 1 Pulsed Klystron (Max. 80 kW)

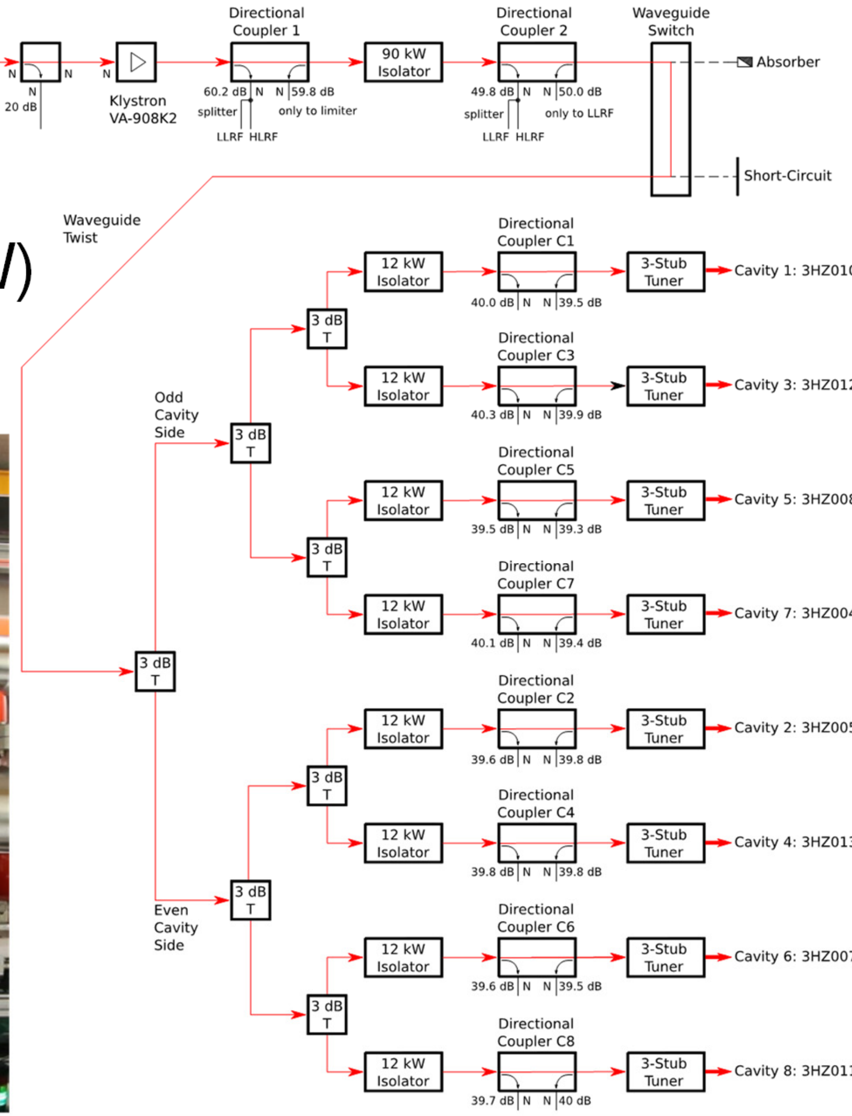
Klystron up to 60 kW





- Fixed coupler
- 3-stub tuners for **QL adjustment** **cavity phasing**





Main commissioning checklist

- Similar to the Linac modules (few specific to 3.9 GHz)
  - Coupler conditioning (hardly needed at all)
  - Frequency tuning from parking
  - RF based rough gradient calibration
  - Closed-loop operation
  - Cryogenic performance assessment
  - Cavity performances, up to quench limit
  - Phase alignment (with beam) and QL tuning
  - Beam-based gradient calibrations
  - HOM thermal stability studies
  - + LLRF hardware checklist and advanced calibrations
- Preserving (and improving) beam quality

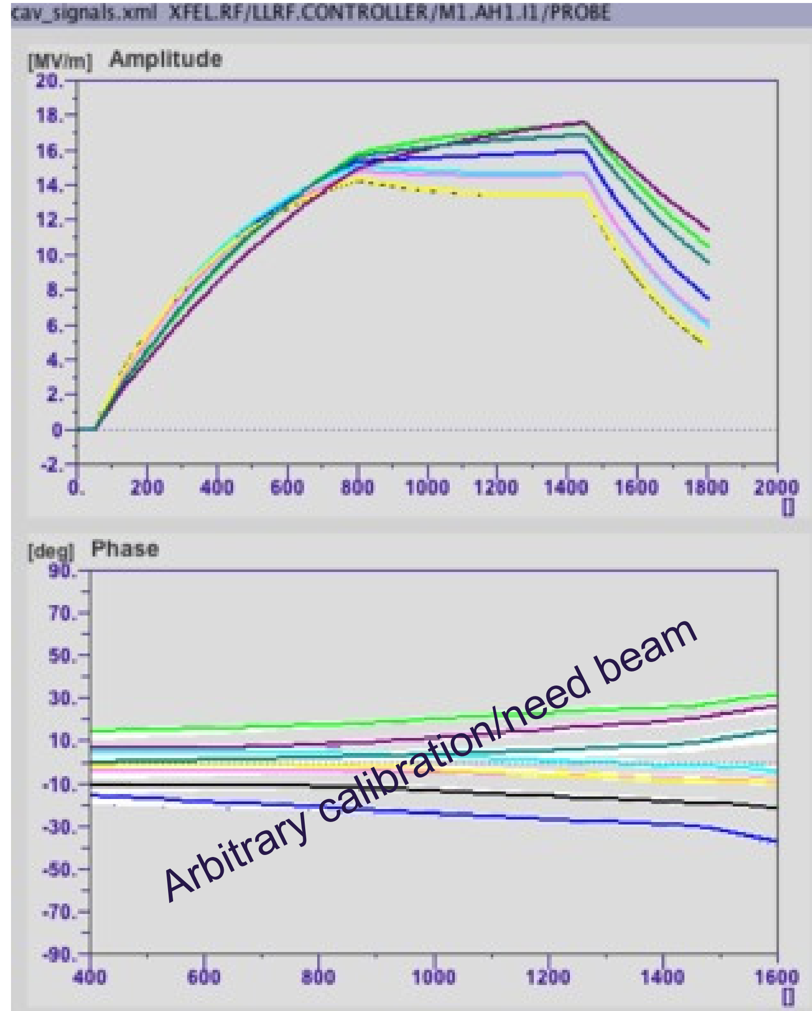
Main commissioning checklist

- Similar to the Linac modules (few specific to 3.9 GHz)
  - Coupler conditioning (hardly needed at all)
  - Frequency tuning from parking
  - RF based rough gradient calibration
  - Closed-loop operation
  - Cryogenic perf
  - Cavity performa
  - Phase alignme
  - Beam-based gradient calibrations
  - HOM thermal stability studies
  - + LLRF hardware checklist and advanced calibrations
- Preserving (and improving) beam quality

See also talk by Mathieu Omet, Friday morning

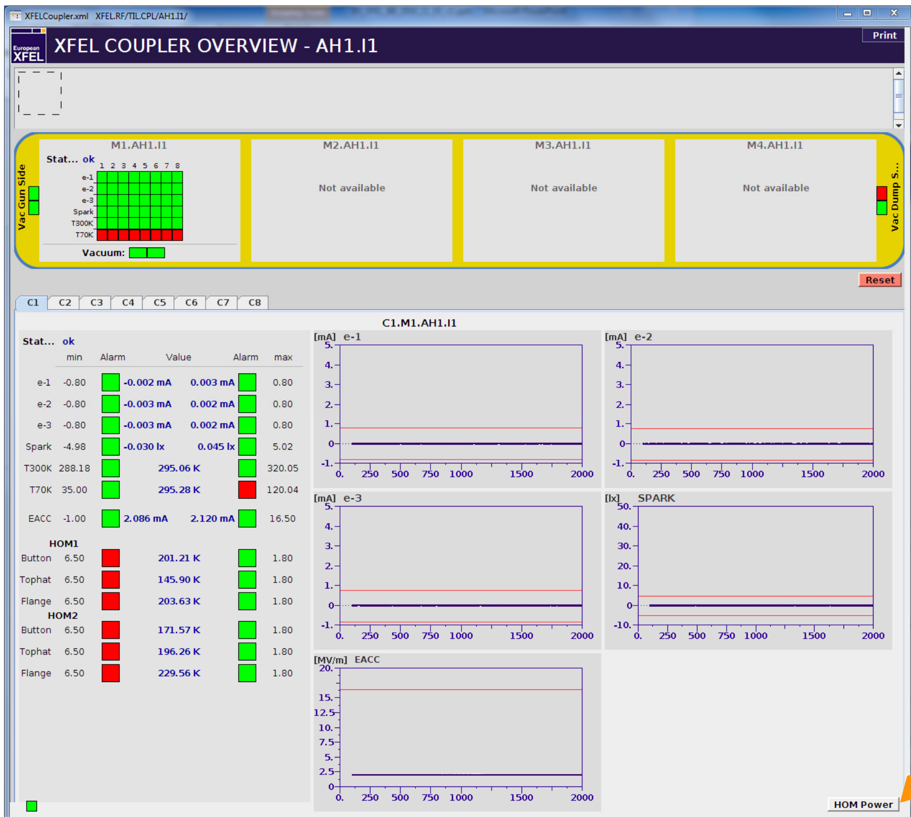
First operation at nominal gradient on Day 1

- **18 December 2015**
  - **Operation with no beam**
  - First *rough* calibration (LLRF)
    - → Assume $P_{cav}=P_{kly}/10$
  - Nominal pulse structure
    - → Fill: 750 us/FlatTop: 650 us
  - Gradient well above nominal
    - → 40 MV of VS voltage
    - → First quench > 45 MV
  - ***Cavity phasing missing and QL values not yet tuned***
  - **LLRF in FB mode**



Technical interlocks

- Several interlocks guarantee the cavities and couplers integrity, some are the same of those in the ML modules, some are particular to AH1



Coupler (same as 1.3 GHz)

- e-pickups (3x)
- Spark detector
- Window temperatures (70K/300K)

Cavity (additional)

- 3 T sensors on each HOM coupler
- Gradient interlock RF diode

+Cryo OK signal

Also, HOM power diagnostics

Initial QL values (nominal 3.2E6)

- Cumulative effect of antenna / cavity tolerances & FF
  - Spread in the QL values (all stubs out), factor of 2

/svn/XFEL/LLRF/SC_modules/Injector/XLLRF_inj_diag_cav.xml XFEL.RF/LLRF.DIAGNOSTICS/AH1.I1/

Diagnostic server readouts for: MAIN.M12.AH1.I1

	C1	C2	C3	C4	C5	C6	C7	C8	
dA/A pulse2p	0.0029	0.0044	0.0035	0.0030	0.0029	0.0029	0.0031	0.0096	%
dP pulse2p	0.0578	0.2234	0.1489	0.1761	0.1058	0.1940	0.3331	0.5576	deg
loaded Q	4.07E6	8.35E6	5.59E6	4.61E6	4.96E6	4.09E6	6.16E6	7.31E6	
Detuning	138	165	212	145	-17	-7	-147	268	Hz

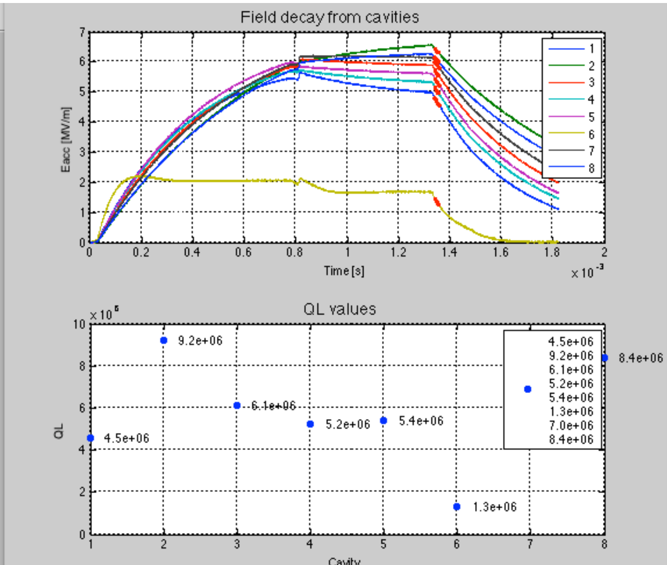
TUNING

/svn/XFEL/LLRF/SC_modules/Injector/XLLRF_inj_diag_cav.xml XFEL.RF/LLRF.DIAGNOSTICS/AH1.I1/

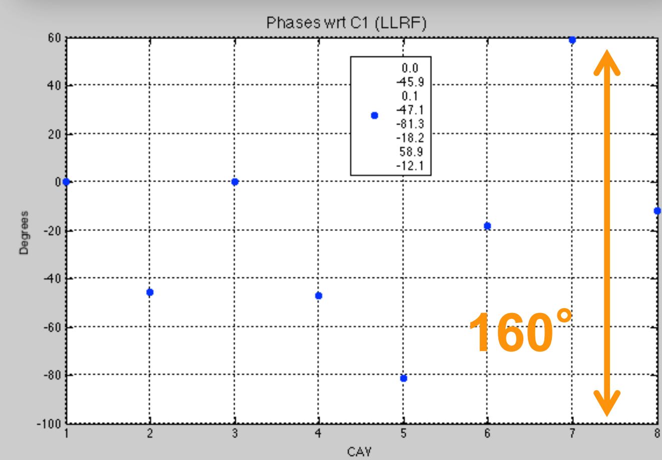
Diagnostic server readouts for: MAIN.M12.AH1.I1

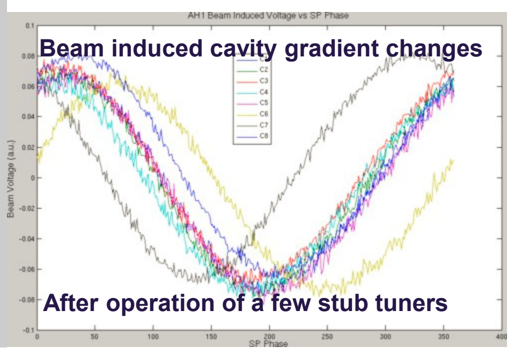
	C1	C2	C3	C4	C5	C6	C7	C8	
dA/A pulse2p	0.0005	0.0005	0.0015	0.0013	0.0012	0.0011	0.0013	0.0027	%
dP pulse2p	0.0840	0.0945	0.1256	0.1174	0.0921	0.2335	0.2452	0.5983	deg
loaded Q	3.28E6	3.34E6	3.33E6	3.20E6	3.20E6	3.25E6	3.20E6	3.27E6	
Detuning	-36	2	72	29	-24	53	51	59	Hz

Beam Based calibration: Cavity Phases



Cavity transient, QL determination and phase calibration



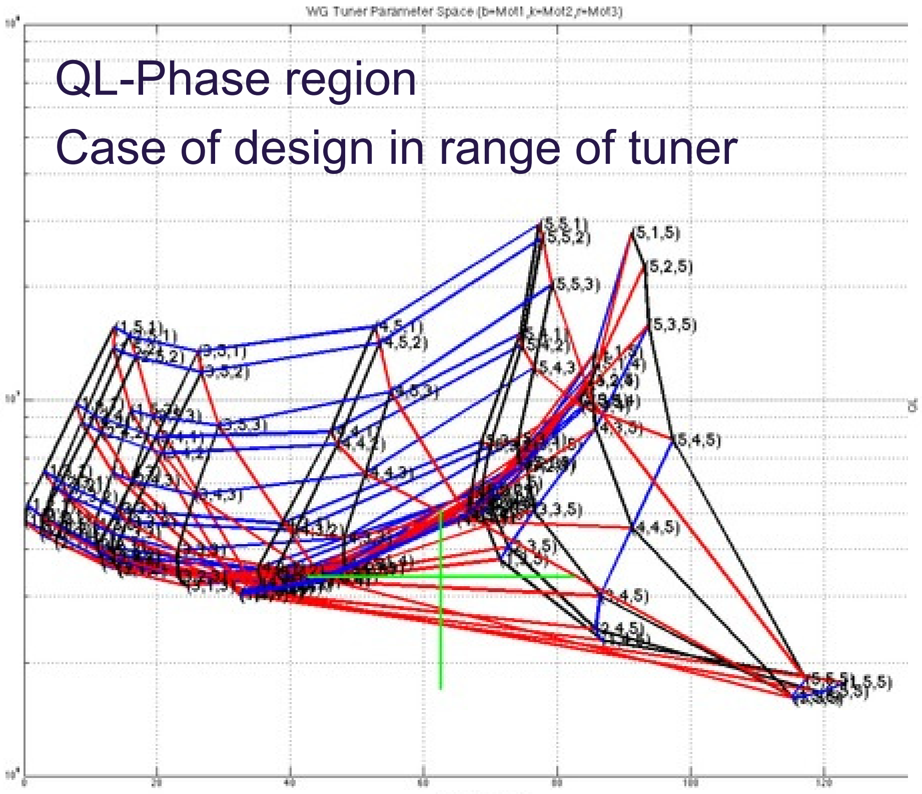


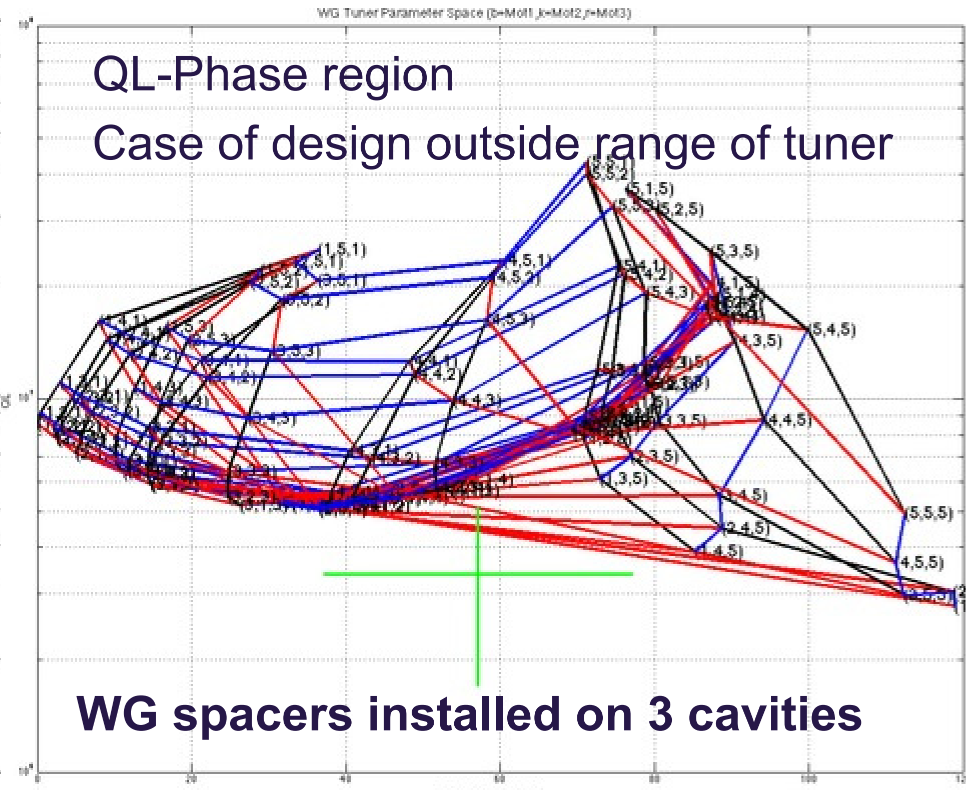
- **January 2016, on beam**
  - Beam transients
  - Phase Calibrations
- Preliminary to :
  - **Phase Tuning**
  - **QL tuning**
- Large initial cavity phase spread
  - *WG assembled in tunnel, no cal.*

Tune with
- 3-stub tuners
- WG Spacers

QL tuning & Phase alignment

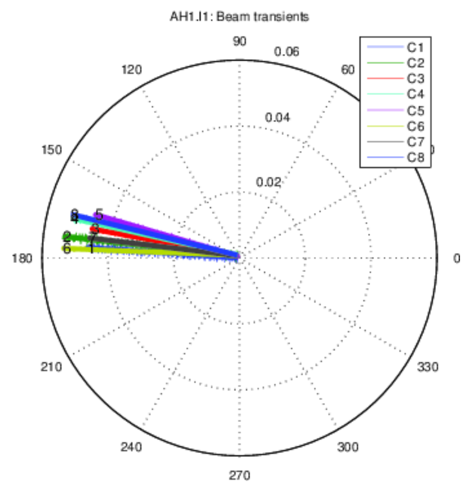
- **1 February 2016**, AH1 moved 1 ms after the beam
  - Allow injector commissioning while aligning cavity phases
- Individual maps of all 3-stub tuner positions

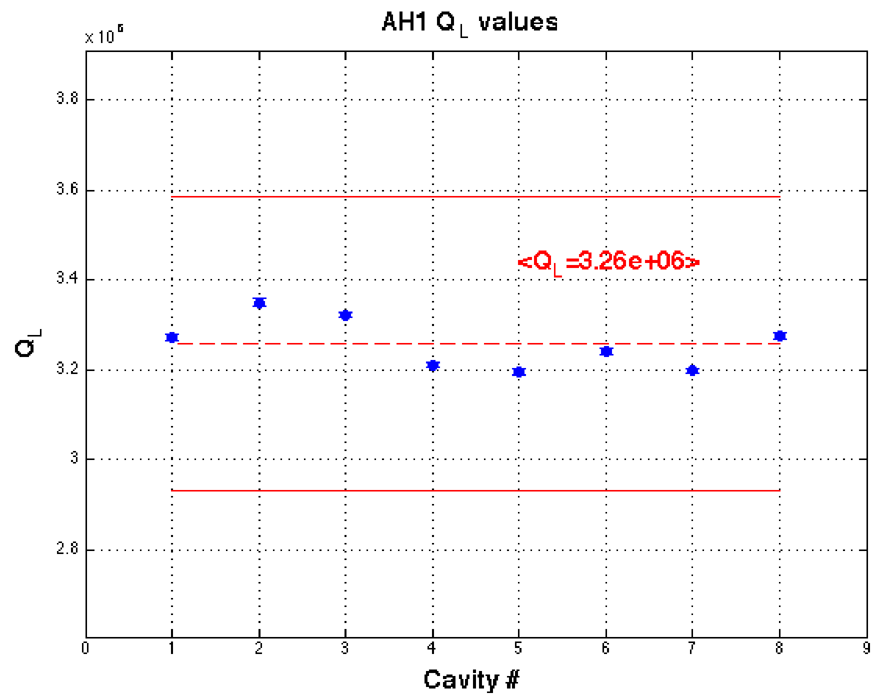




Started regular operation in injector

- **10 February 2016**
  - QL aligned well within the 10% requirement
  - Phases within 15°

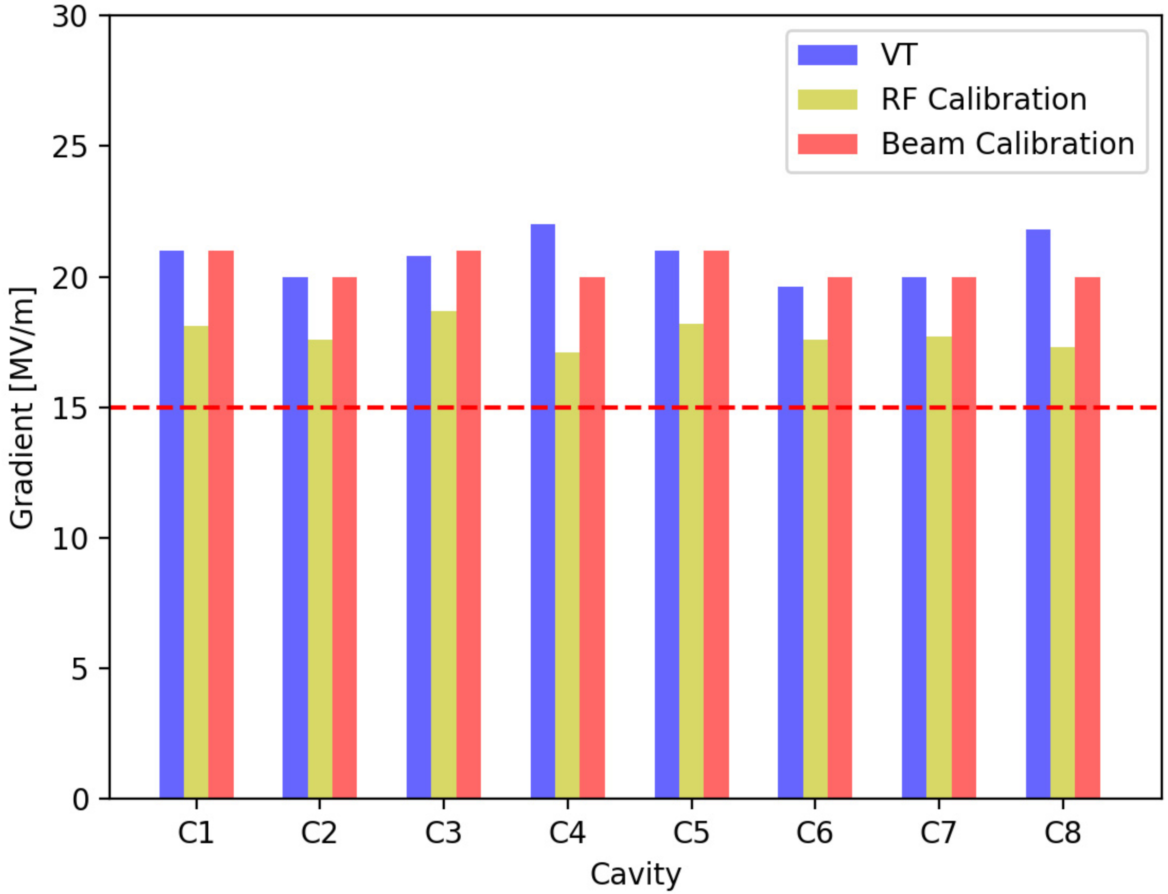




- **16 February 2016**
  - Back on beam
  - Moved to -180° (wrt on-crest), calibration with beam energy

Quench Gradients (VT vs Module)

- RF based calibration in tunnel initially did not correlate too well with VT quench gradients



Due to large uncertainties in WG distribution details

Good agreement after beam based calibrations

HOM performance

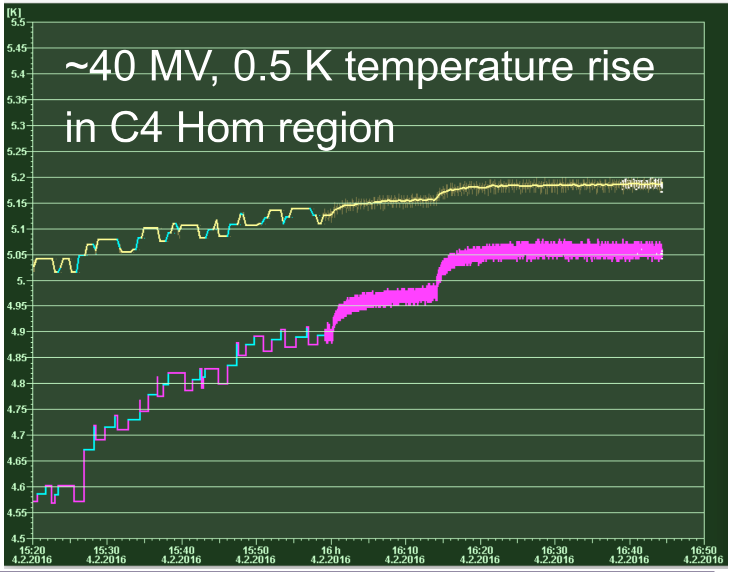
- Cavity Q0 is 2E9 (VT measure)
- Qt is 1E10 (VT calib)

Cav	QH1	QH2
C1	7.29E+09	5.64E+11
C2	1.14E+12	5.72E+10
C3	8.70E+10	1.33E+11
C4	1.91E+09	6.29E+11
C5	3.18E+11	2.68E+11
C6	8.32E+11	5.05E+11
C7	1.36E+11	6.28E+10
C8	4.50E+11	N/A

C1 HOM1 suboptimal tuning

C4 HOM1 detuned (cavity Q0)

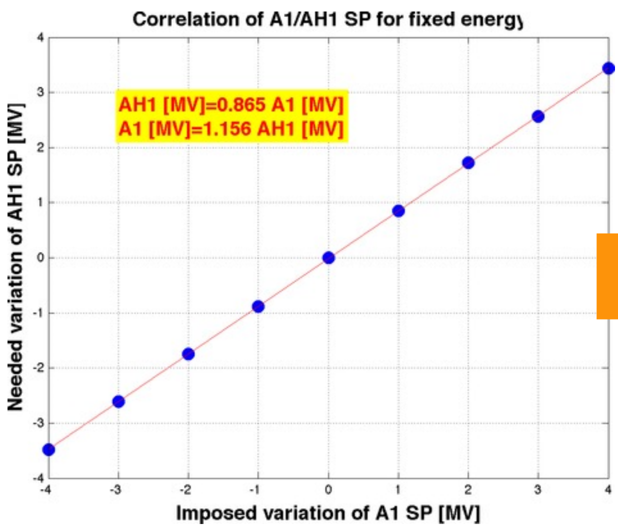
However, stable thermal behavior at 1.3 ms, 10 Hz operation up to SP in excess of 40 MV

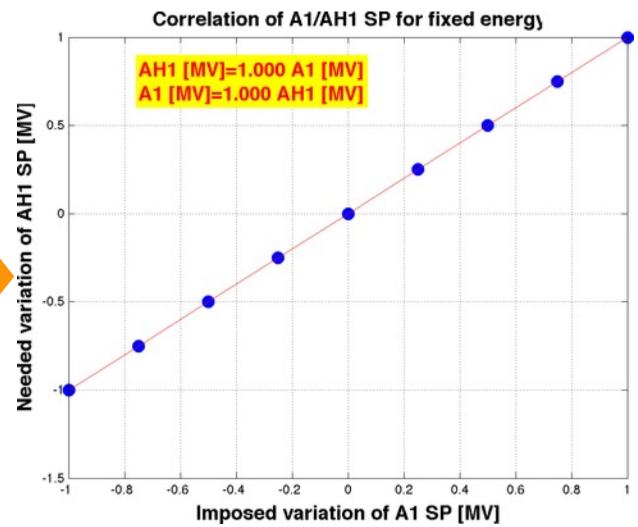


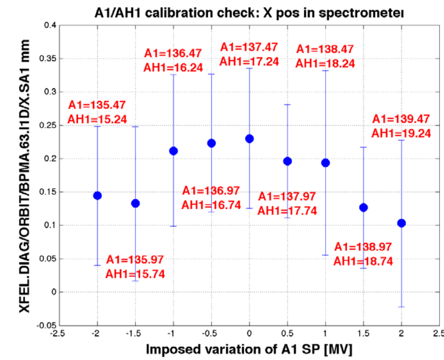
Thermal sinking is sufficient for stability (at 1% d.f.)

Beam Based Calibration of Module voltage

- RF calibration did not give sufficient consistency in A1/AH1 correlation. BB calibration using dispersive section.

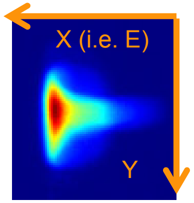






- A1/AH1 need to be in good relative calibration (phase and amplitude) to **control the beam** with Sum Voltage Controls
  - Improved consistency in VT/XTIN **quench fields**
  - **Important to check after rf calibrations are done**

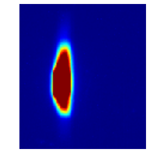
RF Curvature linearization by AH1

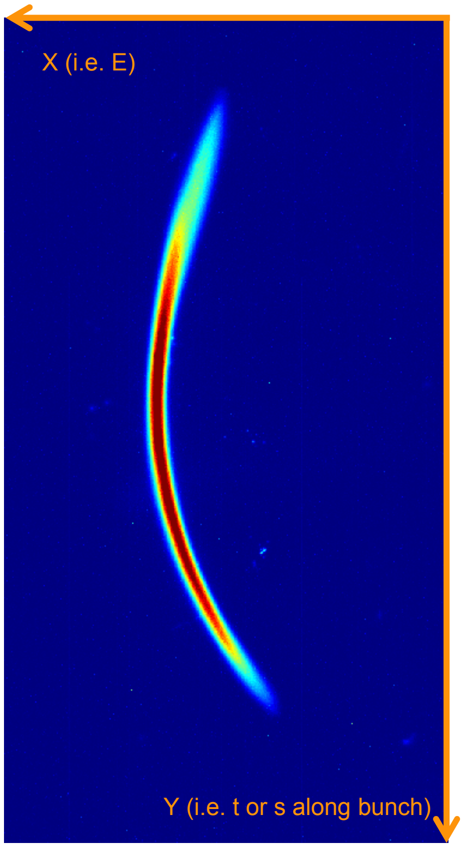


Beam image on screen in the spectrometer beamline

← AH1 off

AH1 on →

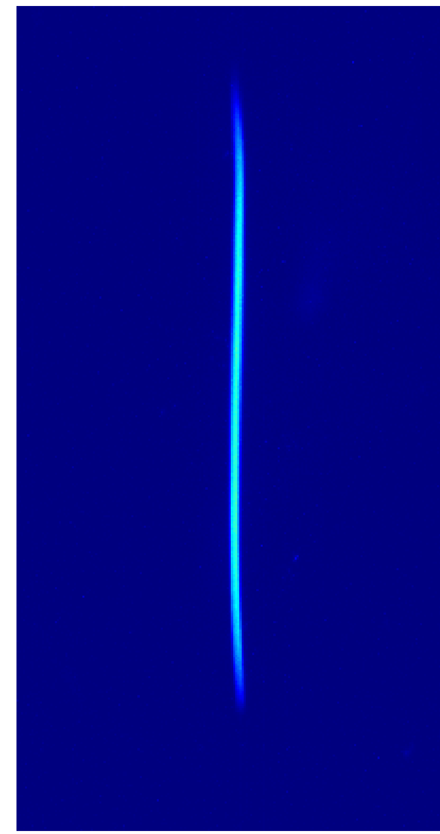




Beam image on screen in the spectrometer beamline, switching on the Transverse Deflecting Structure (TDS)

← AH1 off

AH1 on →



Vector Sum Control of the sum RF field of the two modules allows to set the beam shape parameters (e.g. chirp, curvature, skewness) for proper matching to the downstream compression stages

Summary

- **RF commissioning and operation of the 3.9 GHz module in the tunnel was a success**
  - Achieved performances above nominal during the early injector commissioning stages in December 2015, with the AH1 pulse shifted in time from the beam
- **Module in regular operation with beam since January 2016 in the Injector run and ready for operation at the start of the XFEL commissioning phase in January 2017**
- **First XFEL lasing at 9 Å on May 4th 2017 (then 2 and 1.5 Å reached in summer): final confirmation of proper third harmonic system performance**
  - (and of course of many other important systems…)

Thanks for your attention

- **Acknowledgements:**
  - The team at INFN LASA
  - The M-groups at DESY (MIN, MSK, MKS, MSL, MXL…)
  - The great XFEL BKR team
  - Elvin Harms and the ACC39 at FNAL