深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Cycle of Seminars by Carlo Pagani

Seminar # 7

The 3.9 GHz 3rd Harmonic System of the European XFEL

Shenzhen, 23 December 2022 / INFN LASA, 15 January 2025

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INFN LASA

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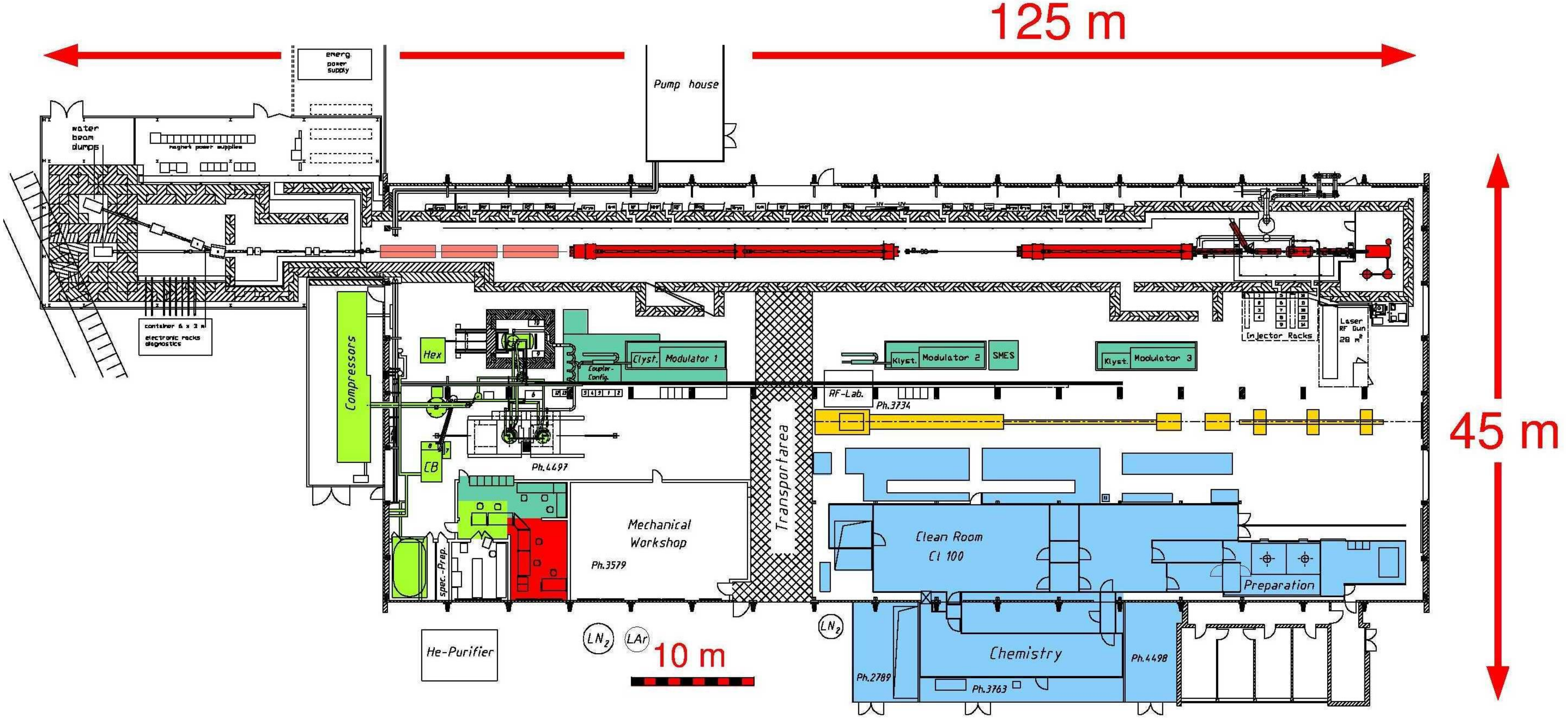
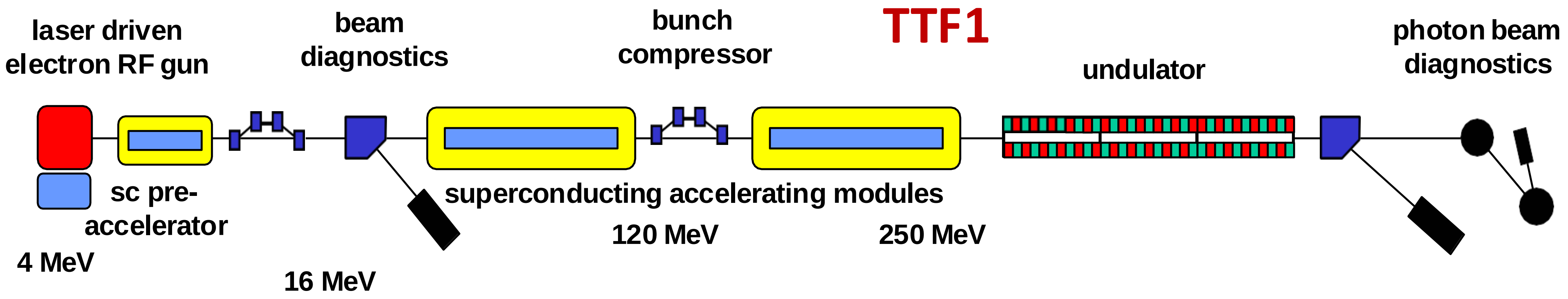
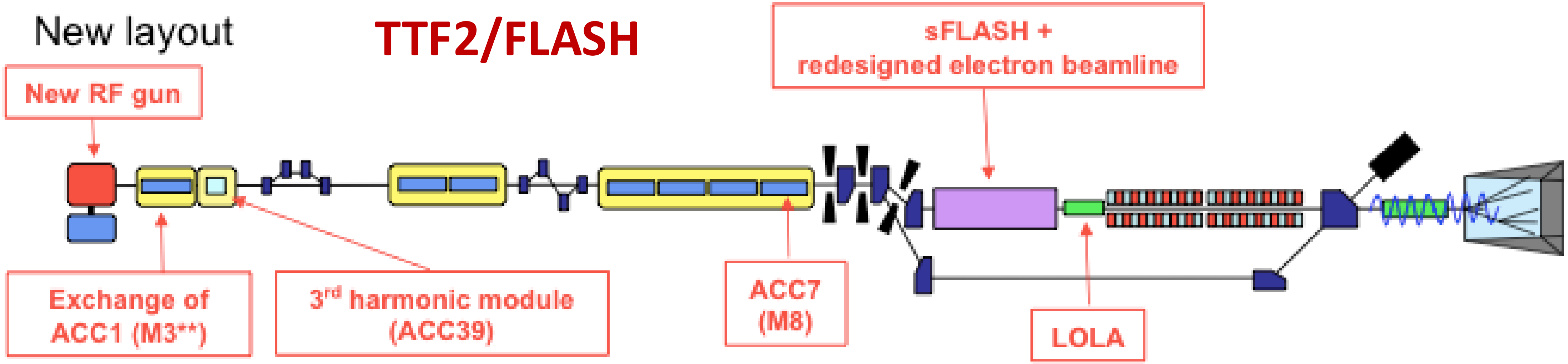
2. ACC39 made by Fermilab for FLASH
3. AH1 made by INFN-LASA for European XFEL

TESLA Test Facility for e^+e^- Linear Collider



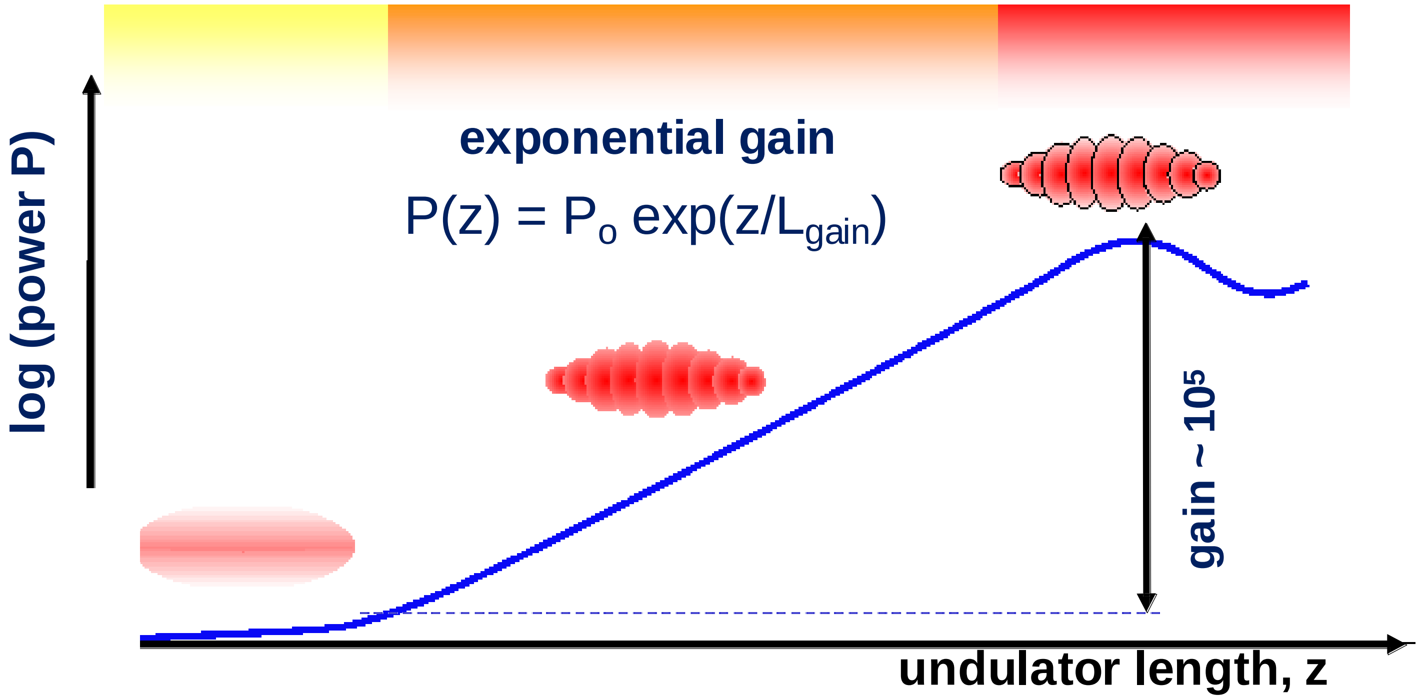
From TTF1 to TTF2/FLASH

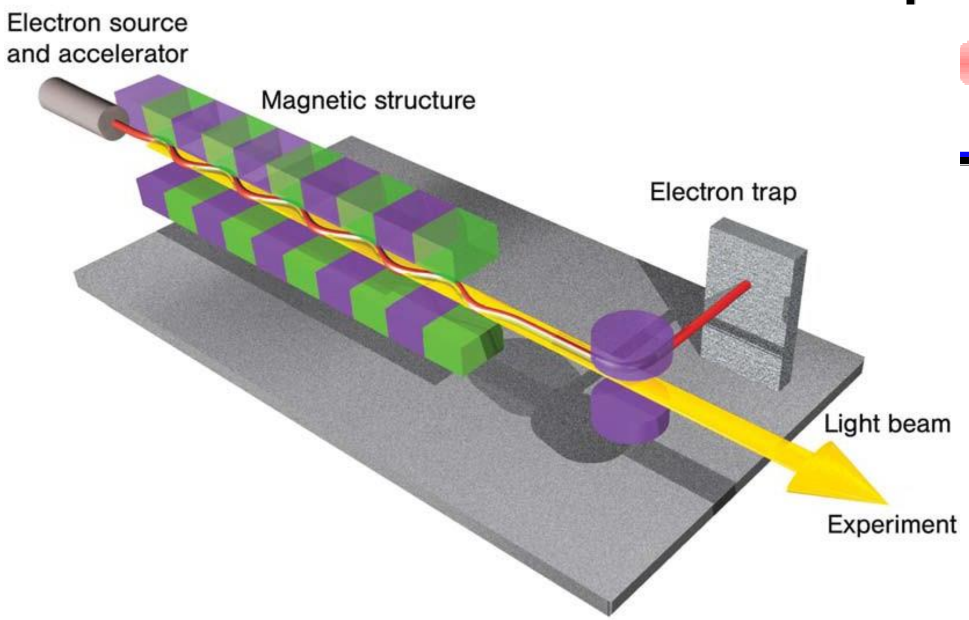




SASE: Self Amplifiesd Spontaneous Emission

- bunch interacts with undulator field
- micro bunches develop
- micro bunches emit coherently ~ N^2 ($N \approx 10^6$)

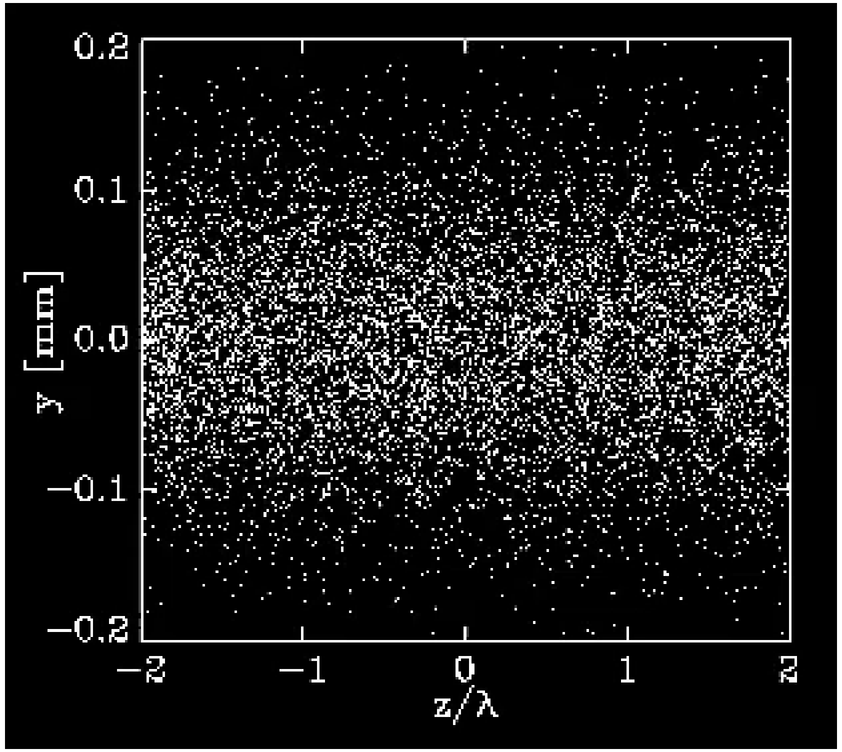




Key requirement:

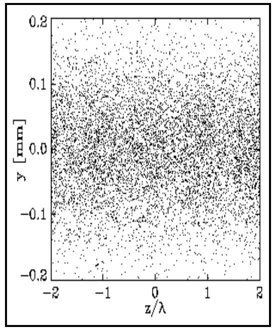
- **high peak currents** of > 1 kA
- **low emittance** < λ/4pi ~ 1-2 μm
- **low energy spread** $\Delta E/E < 10^{-3}$

Modulation of the electron bunches

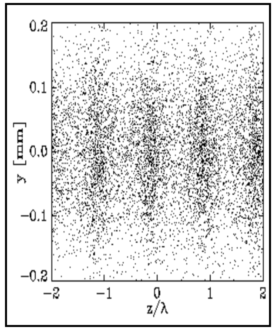


GENESIS **simulation of the TTF parameters**
Sven Reiche (UCLA)

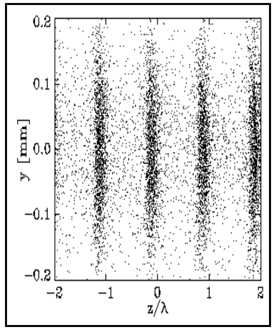
undulator entrance



half-way saturation

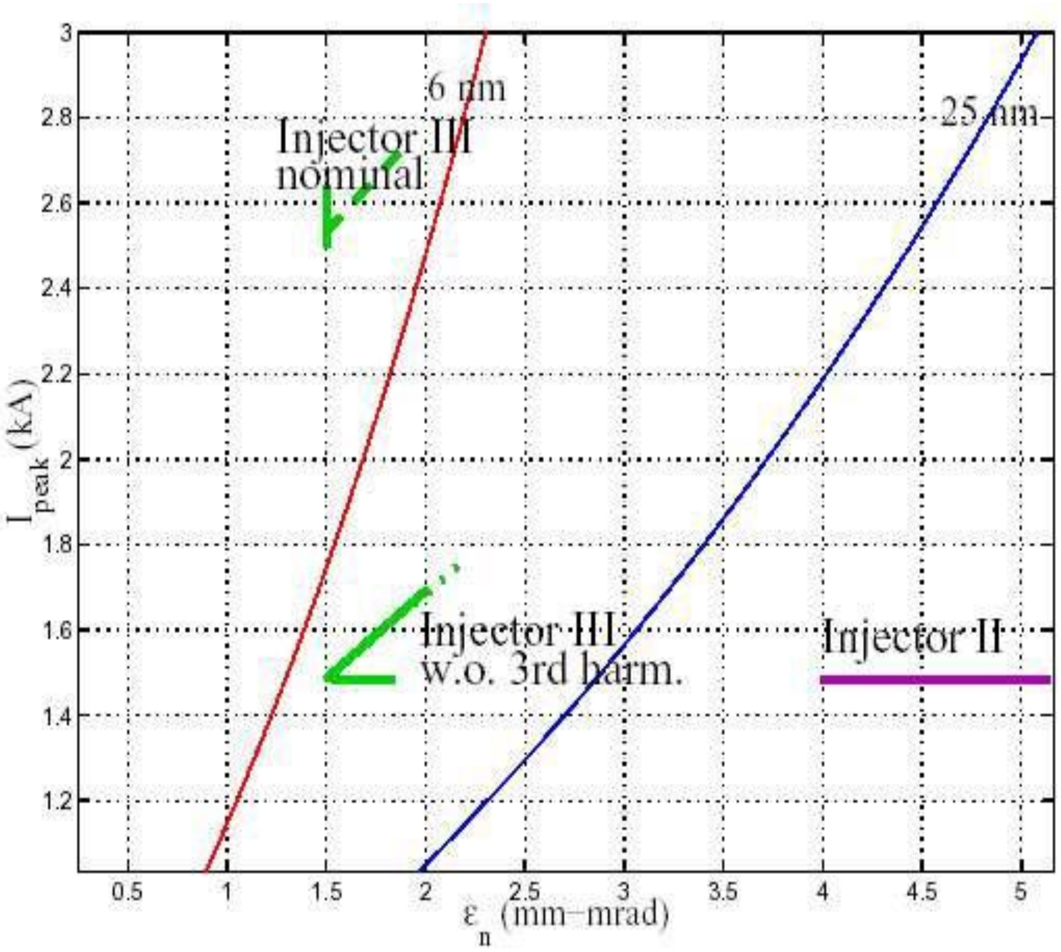


full saturation



VUVFEL requirements at TTF

from Proc. of EPAC 2002, 1798 (2002)



VUVFEL beam requirements for lasing at 25 and 6 nm

- 1st lasing of VUV-FEL at long wave length λ (32 nm acheived) does not require the 3.9 GHz module
- Trying to lase at shorter λ requires higher peak current I ≈ 2.5 kA
- 3.9 Ghz module required for
  - driving the FEL instability
  - getting radiation pulse with significant energy

3rd Harmonic Module mini-Review. P. Piot. 11.08.2005

3rd Harmonic System for TTF

TESLA-FEL **01-03** (2001)

Conceptual Design of the XFEL Photoinjector

M. Ferrario (INFN-LNF), K. Flöttmann (DESY),
B. Grigoryan (YerPhI), T. Limberg (DESY),
Ph. Piot (DESY)

February 20, 2001

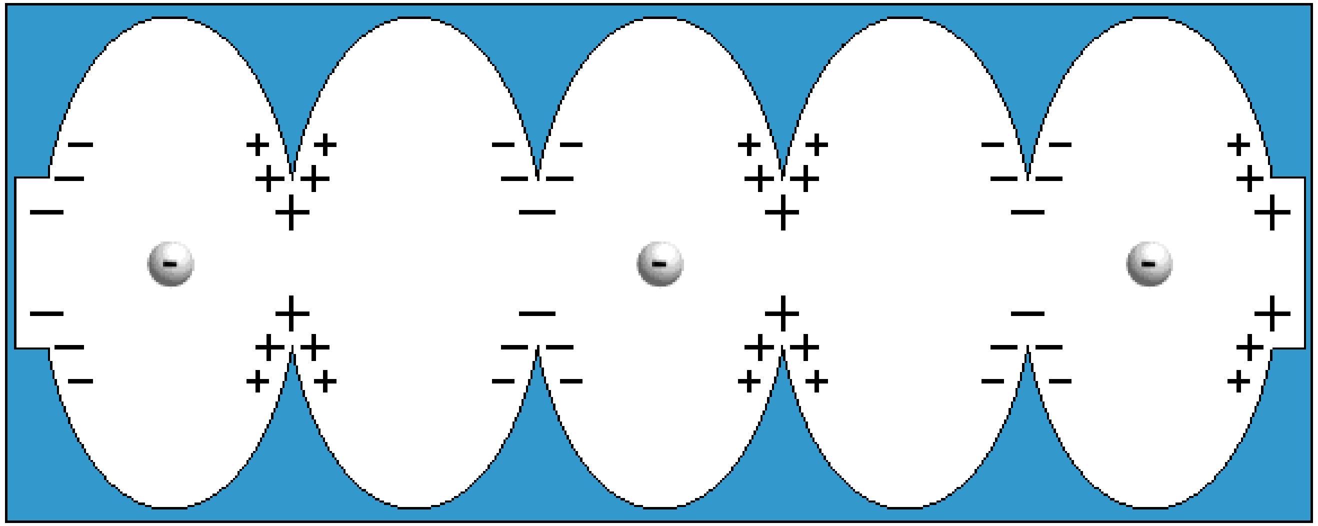
[14] Smith T. I., "Intense low emittance linac beams for free-electron lasers", *proc linear acc. conf.'84* SLAC report **303**, pp. 421-425 (1986);

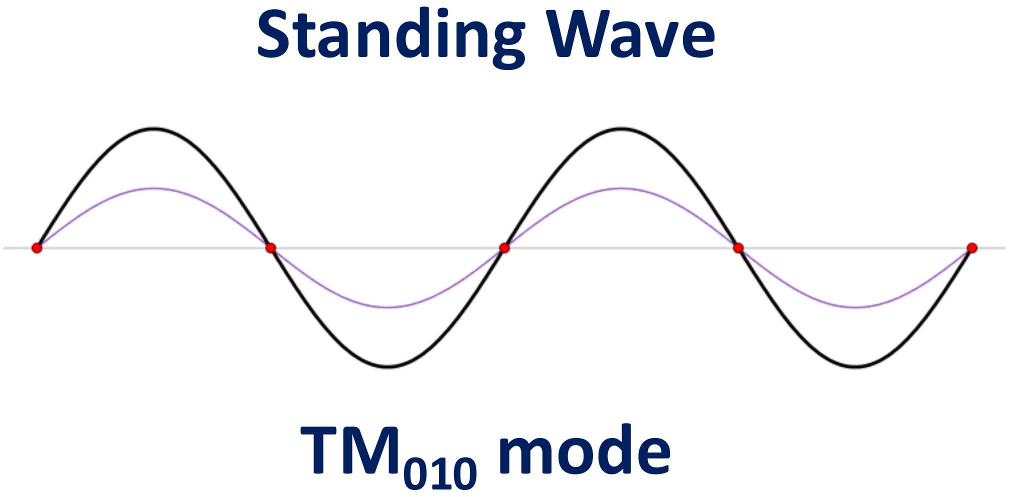
Dowell D., et. al, "The BOEING photocathode accelerator magnetic compression and energy recovery experiment", *Nucl. Instr. Meth.* **A375**, pp. 108-111 (1996);

Piot Ph., Flöttmann K. Limberg T., TESLA-FEL **01-06** (2001)

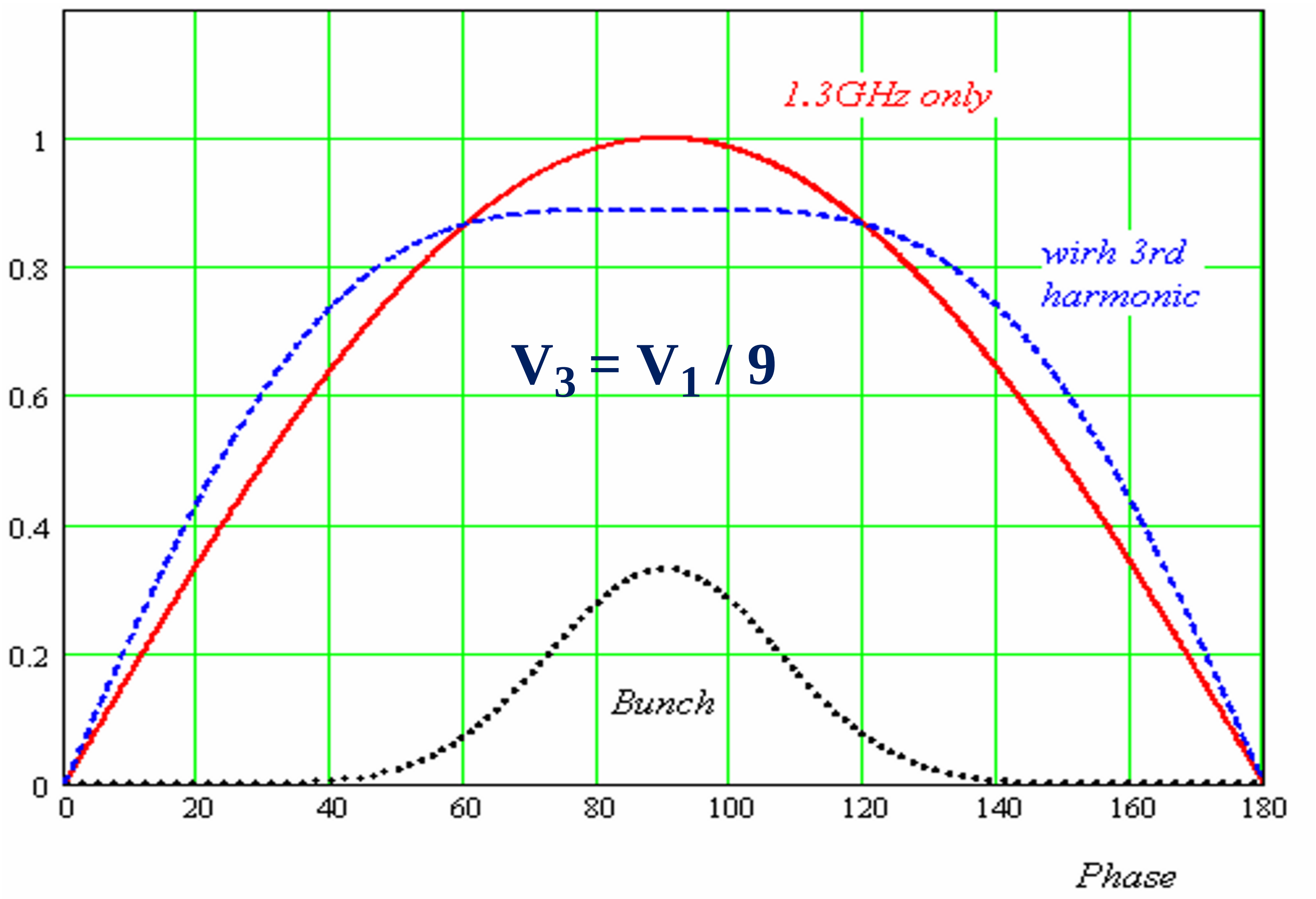
Origin of the non linear Energy Distribution

- Electrons are gaining energy integrating the electric field while crossing the RF accelerating cavity
- In each point of the cavity the field vary sinusoidally vs time
- Because of the the non negligible bunch length the energy gain along the bunch is not constant and not linearly distributed
- Bunch compression needed for high peak current is strongly affected

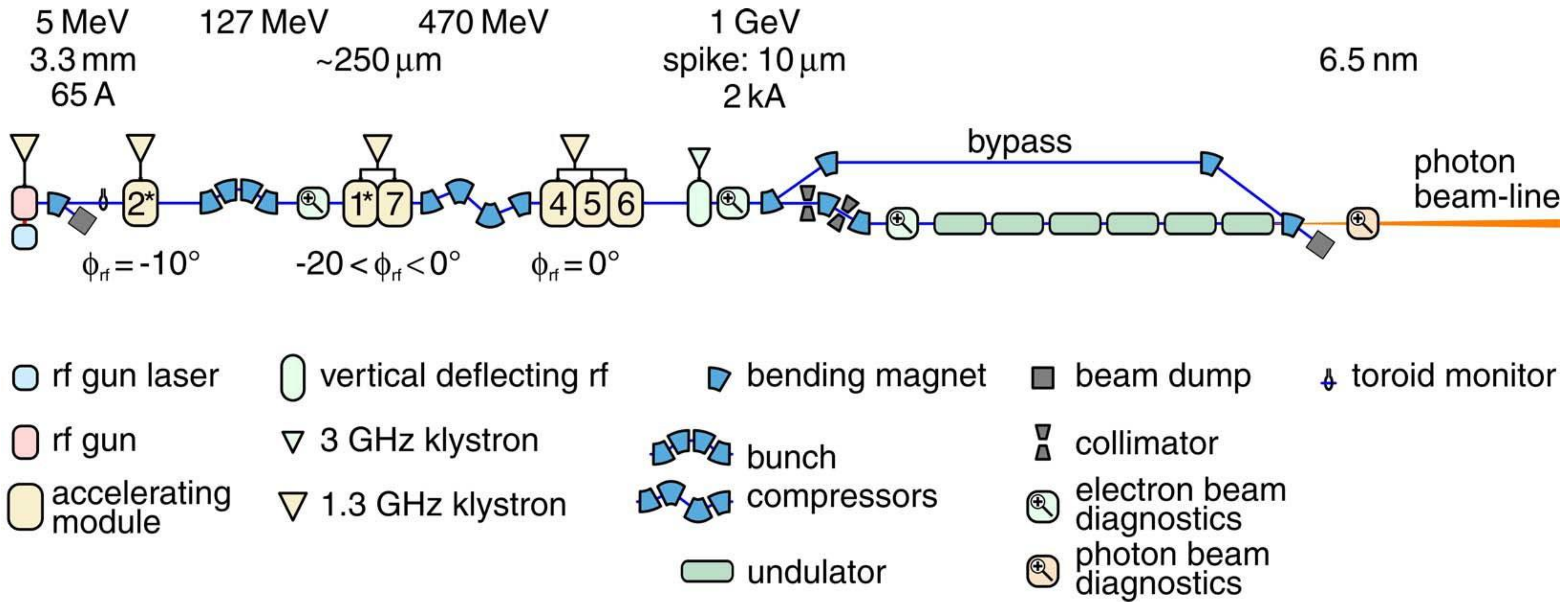




Energy Distribution along the Bumch

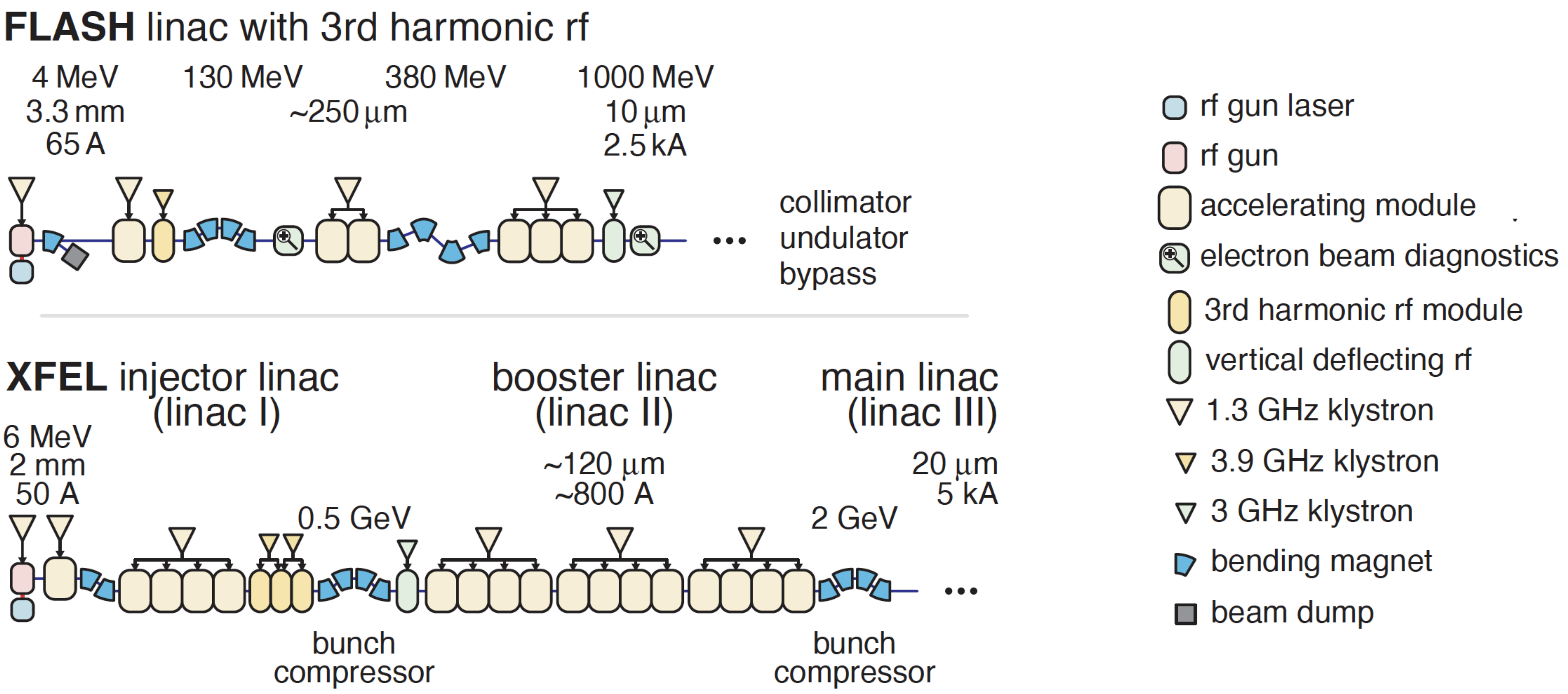


TTF/FLASH as in 2007



- **initial bunch length restricted** by collective effects
- **two stage bunch compression**
- **off crest acceleration** in ACC1 and ACC2/3
- requires good rf **field stability**

FLASH and XFEL with 3rd Harmonic



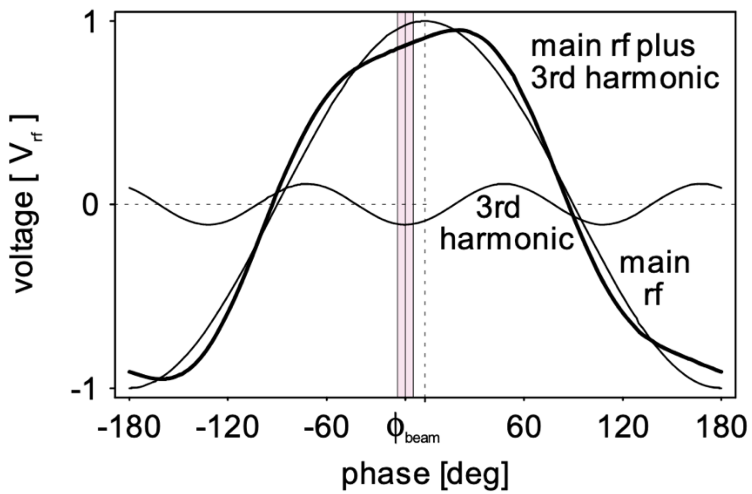
3^{rd} Harmonic for high peak curreny

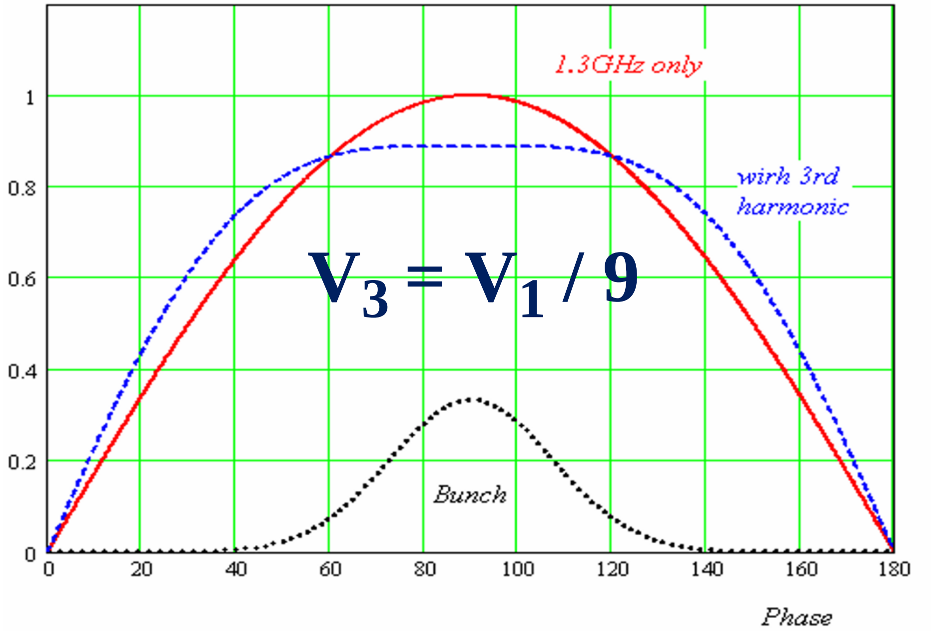
The 3^{rd} harmonic module operating in decelerating phase in conjunction with the ACC1 module provides linearization of the rf acceleration field with time during the duration of the beam bunch.

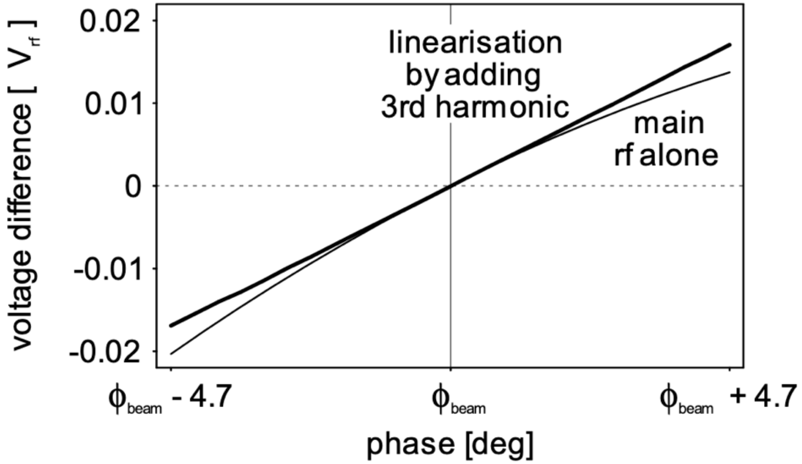
Near crest at bunch center s = 0

$$\frac{A_{3.9}}{A_{1.3}} = -\frac{\omega_{1.3}^2}{\omega_{3.9}^2}\left(\frac{\cos\phi_{1.3}}{\cos\phi_{3.9}}\right) \approx \frac{1}{9}$$

$\phi_{3.9}$ is ~180 deg (decelerating mode) and s = - ct. The head of the bunch is at positive s and $\phi_{1.3}$ must be positive too







Shifting $\phi_{3.9}$ by 12°, a linear chirp is obtailed for a more efficient compression

The 3rd Harmonic Module from Fermilab

Proceedings of the 2003 Particle Accelerator Conference

DEVELOPMENT OF THE THIRD HARMONIC SC CAVITY AT FERMILAB

N. Solyak, I.Gonin, H. Edwards, M.Foley, T.Khabiboulline, D.Mitchell, J.Reid, L.Simmons,
Fermilab, P.O.Box500, Batavia, IL 60510, USA.

Proceedings of PAC09, Vancouver, BC, Canada TU5PFP058

CONSTRUCTION OF A 3.9 GHZ SUPERCONDUCTING RF CAVITY MODULE AT FERMILAB*

H.Edwards, T.Arkan, M. Ge, E. Harms, A. Hocker, T. Khabiboulline, M. McGee, D. Mitchell, D. Olis, N. Solyak, M. Foley, A. Rowe, Fermilab, Batavia, Illinois, 60510, U.S.A.

Contents

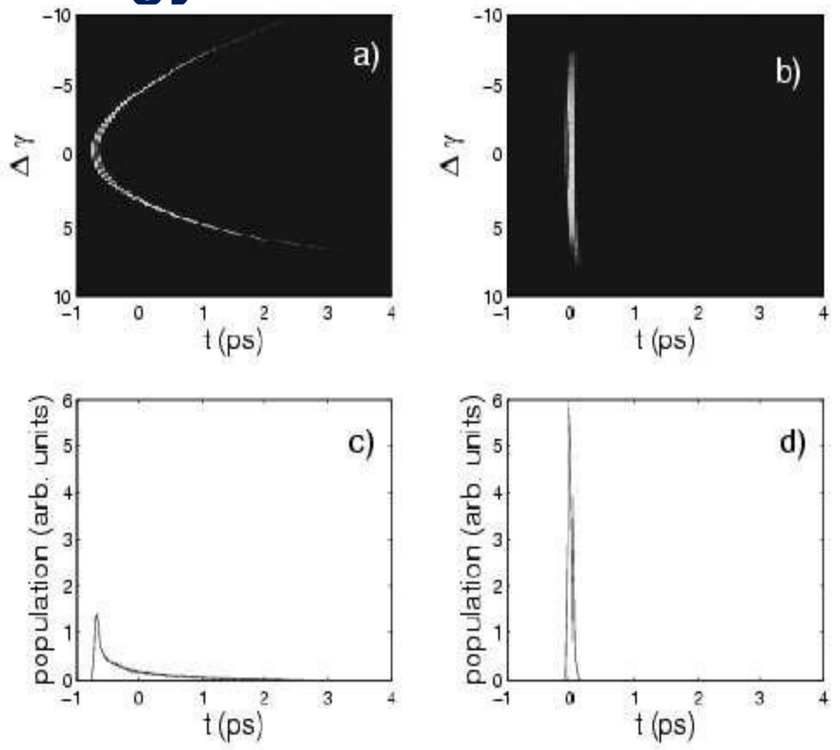
Beam dynamics aspects

- Motivation:
  - single-pass **FELs demand high brightness e- beam**
  - **small emittance and high peak currents** are needed: $L_G \propto I^{-1/2}\, \varepsilon^{5/6}$
  - user also want radiation pulse with **significant energy**

- Design criteria for the x-ray FEL (VUV-FEL):

1. **generate a long e- bunch**
   - ➢ charge-density reduced
   - ➢ space charge effect mitigated
2. **accelerate to high enough energy**

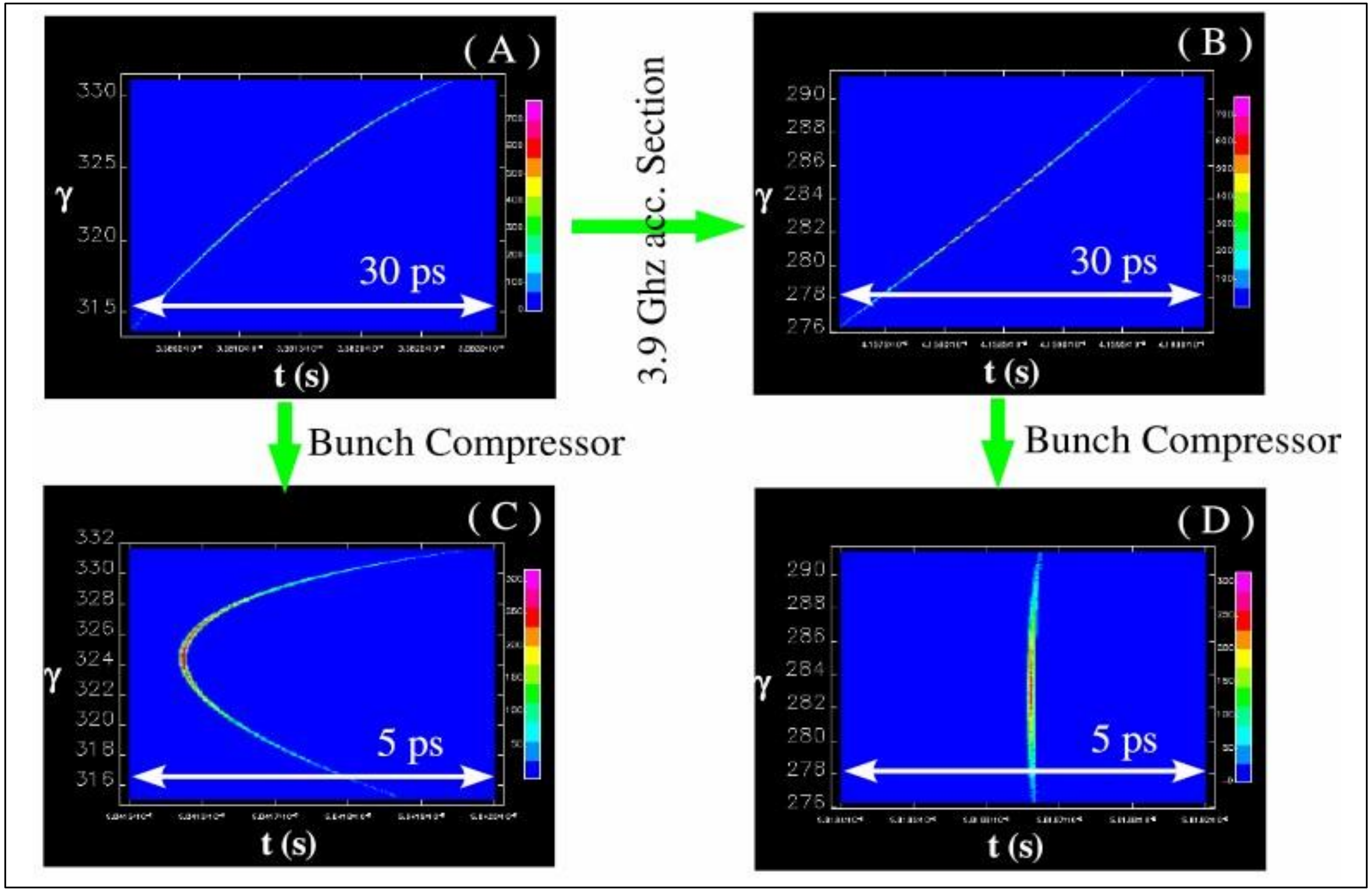
   (SC force $\propto 1/\gamma^2$)
3. **take care of the bunch compression**



3rd Harmonic Module mini-Review. P. Piot. 11.08.2005

1 & 2 induce a non-linear distortion of the longitudinal phase space $\Longrightarrow$ impact on the bunch compression

3rd Harm. to Improve Beam Characteristics

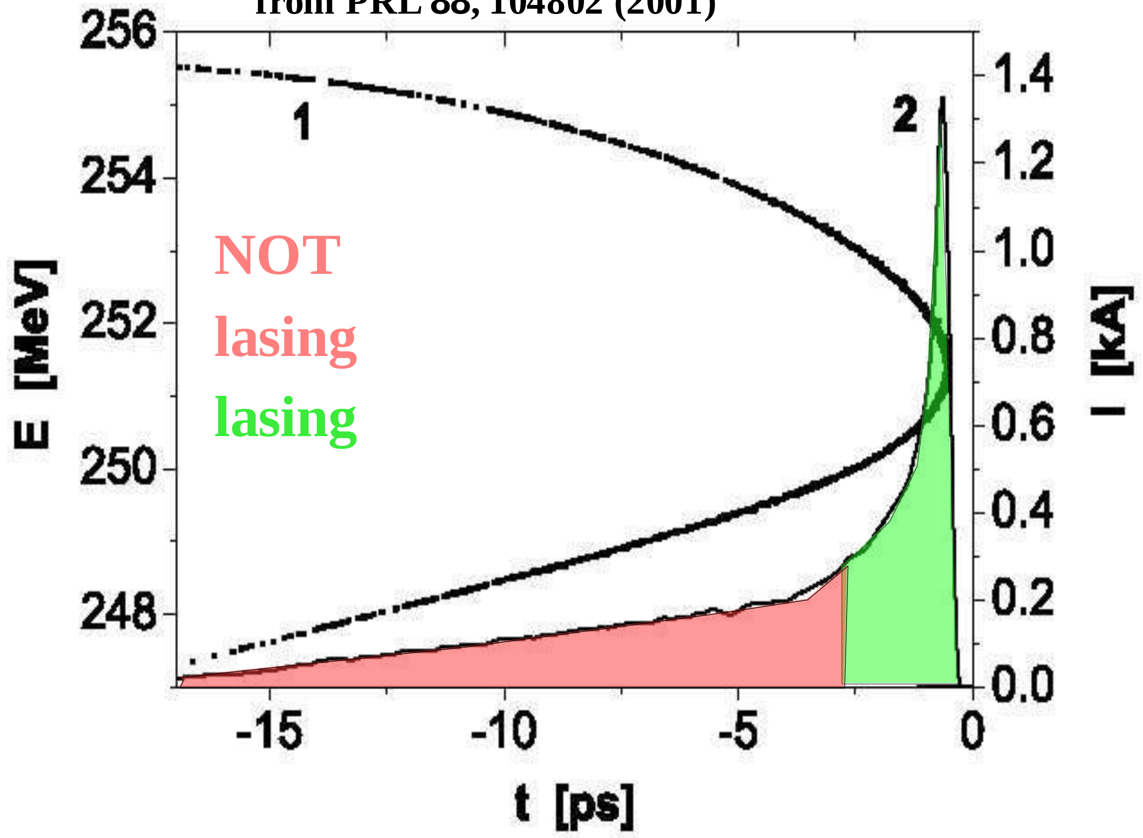


Energy distribution in the bunch before and after bunch compressor **without (left)** and **with (right)** the **3rd harmonic cavity**, calculated for TTF photoinjector.

3rd Harmonic Module mini-Review. P. Piot. 11.08.2005

Case of TTF1: nonlinear compression

from PRL 88, 104802 (2001)



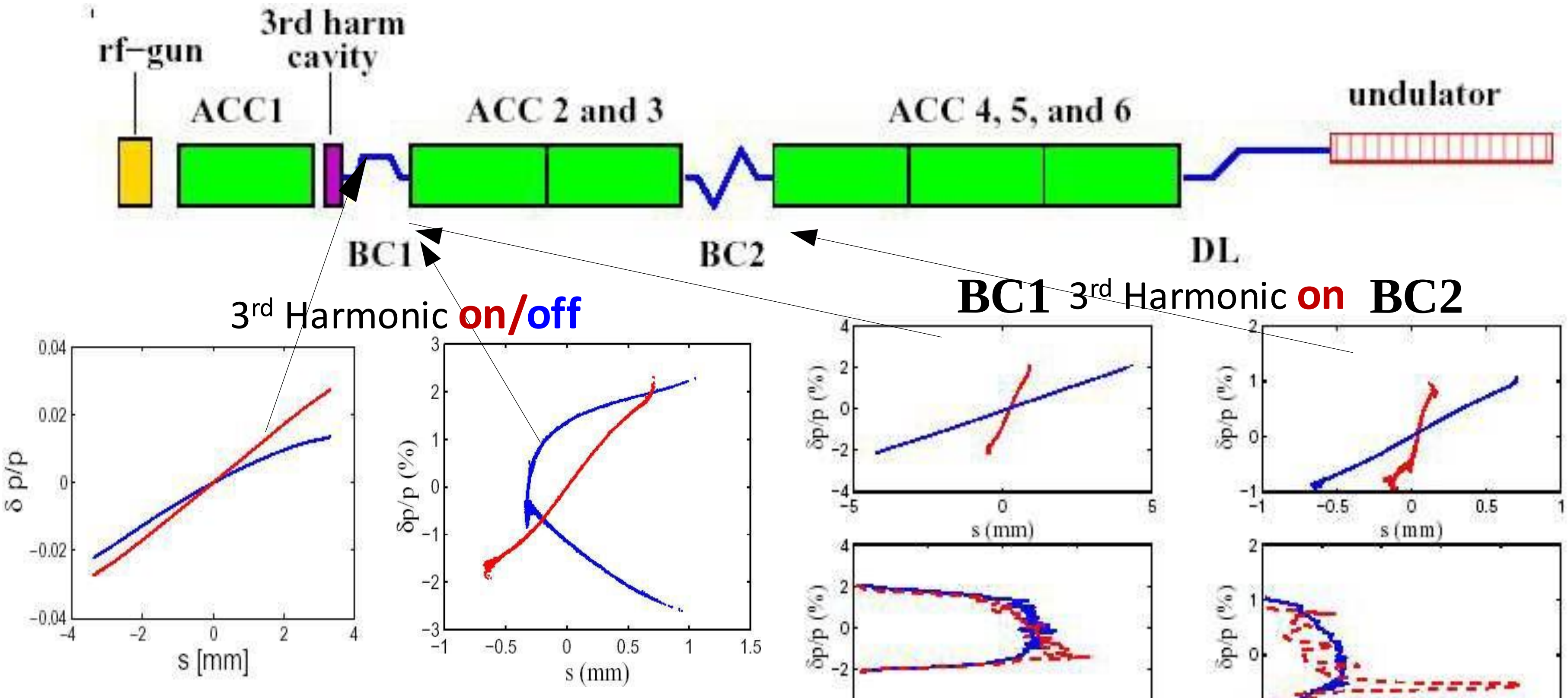
1: longitudinal phase space

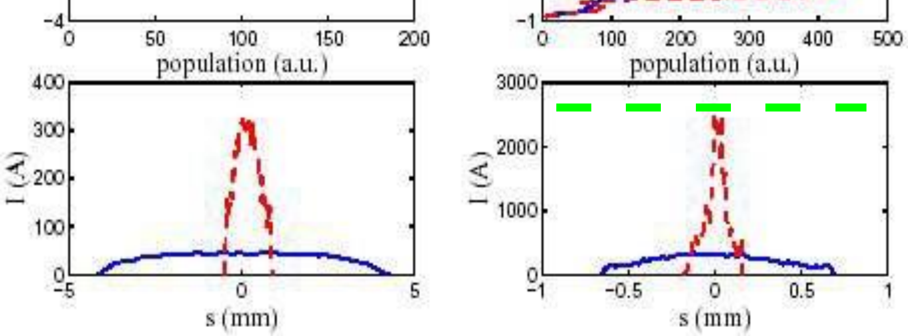
2: charge temporal distribution

- **Pros:**
  - **sub-ps** radiation pulses
  - **stable** compression
  - natural at TTF-1
- **Cons:**
  - throw away a lot of **charges**
  - radiation pulse **energy reduced**
  - **beam dynamics** associated to head and tail very different
  - **hard to tune** and diagnose the e- beam

3rd Harmonic Module mini-Review. P. Piot. 11.08.2005

Beam dynamics aspects





phase spaces

and

beam profiles

before BCs

and

after BCs

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3.9 GHz System main requirements

$E_{3.9} \approx 1/9\, E_{BC1}$ i.e. $E_{3.9} \leq 20$ MeV

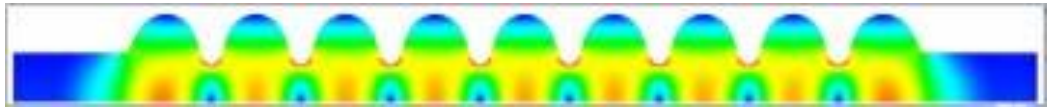
3rd Harmonic System decelerates the beam

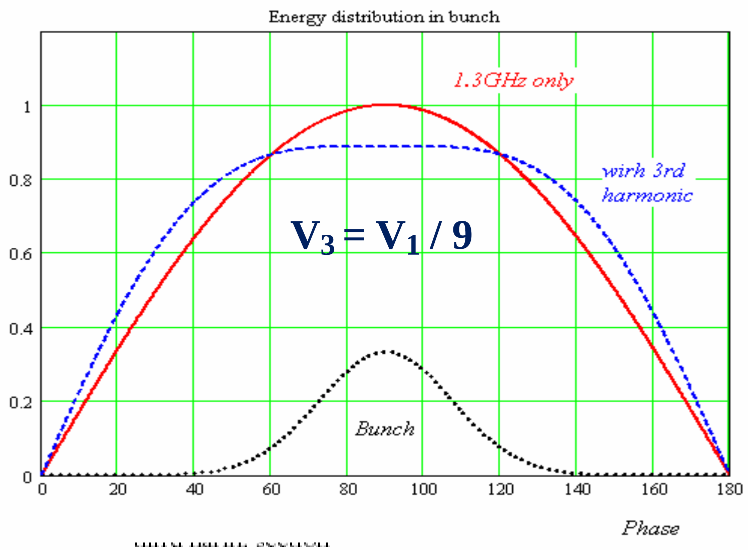
3.9 GHz Cavity General Parameters

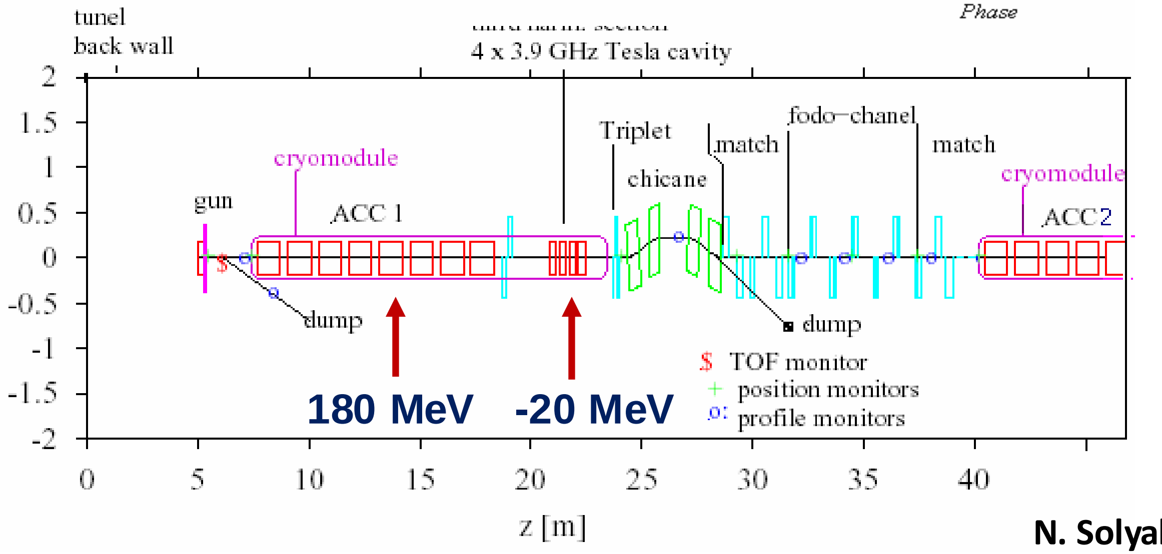
Third harmonic cavity (3.9GHz) was proposed to compensate nonlinear distortion of the longitudinal phase space due to cosine-like voltage curvature of 1.3 GHz cavities.

3.9 GHz Cavity: Parameter List

Number of cavities	4
Active Length	0.346 m
Gradient	14 MV/m
Phase	-179 deg
R/Q	750 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc}=14 MV/m)	68 mT
Q_ext	9.5 e+5
BBU limit for HOM, Q	<1.e+5
Total energy	20 MeV
Beam current	9 mA
Forward Power	11.5 kW
Coupler power	45 kW







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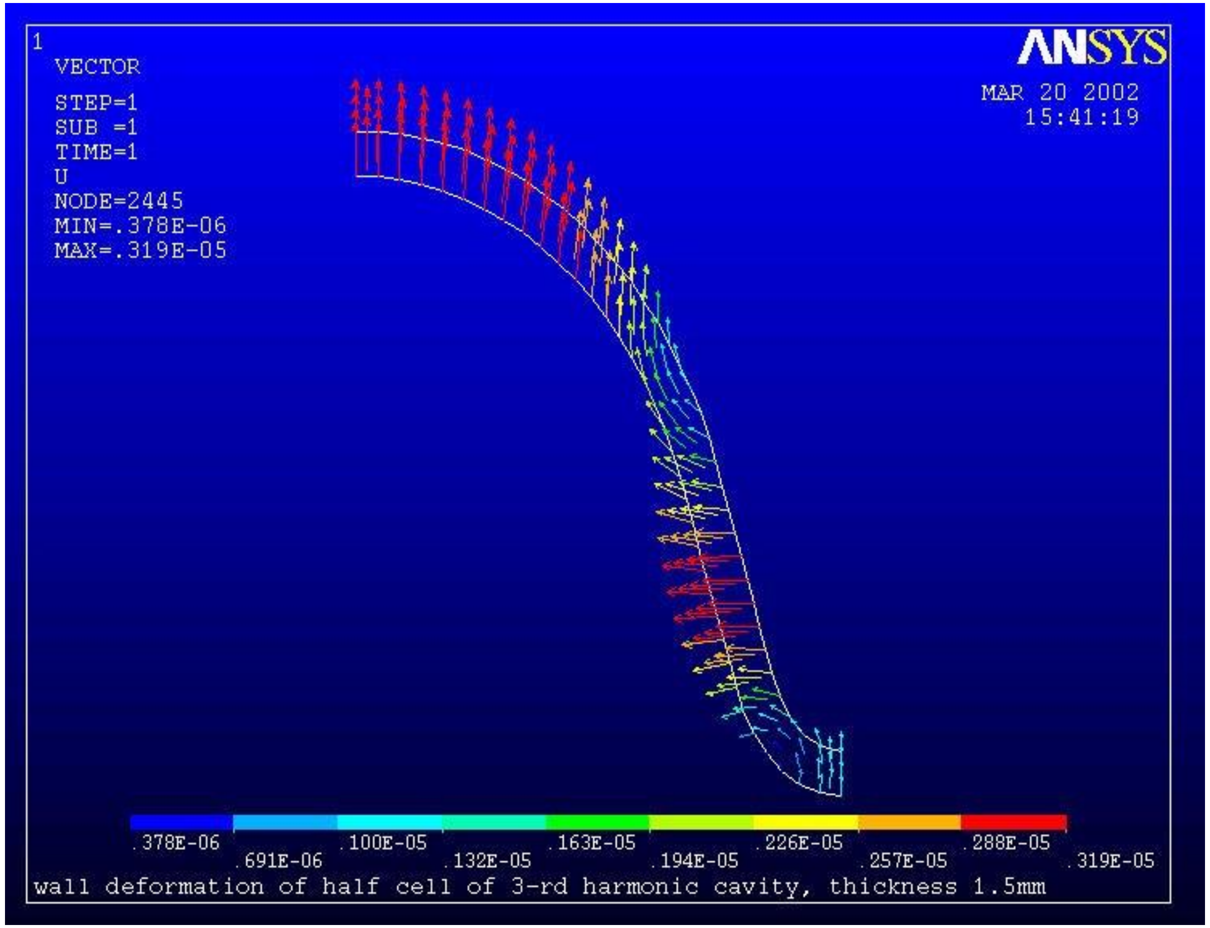
Frequency shift due to Lorentz forces



Displacement of the cell wall due to Lorentz force.
(wall thickness = 1.5 mm)

- HFSS simulation of half cell
  - $P = (\mu_0 H^2 - \varepsilon_0 E^2)/4$
  - data exchange (HFSS-ANSYS)
- ANSYS simulation of stresses in half cell
  - different wall thickness
  - Yung modulus, Poisson's ratio
- Frequency shift due to Lorentz force (Slater's Theorem)

$$\Delta F = F/(4W)\int_{\Delta V}(\varepsilon_0 |E^2 - \mu_0 H^2)dV$$

$E_{acc} = 15MV/m$

Wall Thikness	ΔF
1.5 mm	200 Hz
2.8 mm	90 Hz

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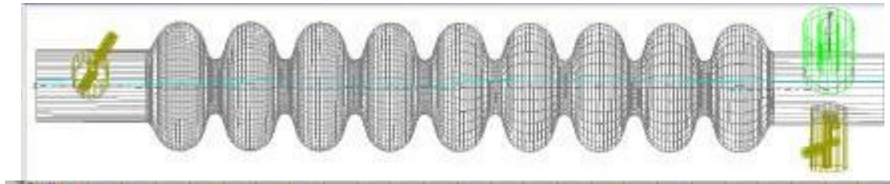
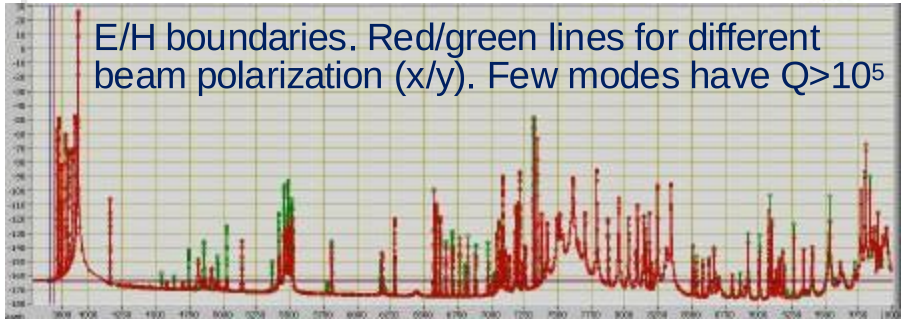
Cavity bandwidth ⁇ 4kHz → No Stiffening ring

Extensive HFSS Calculation @ Fermilab

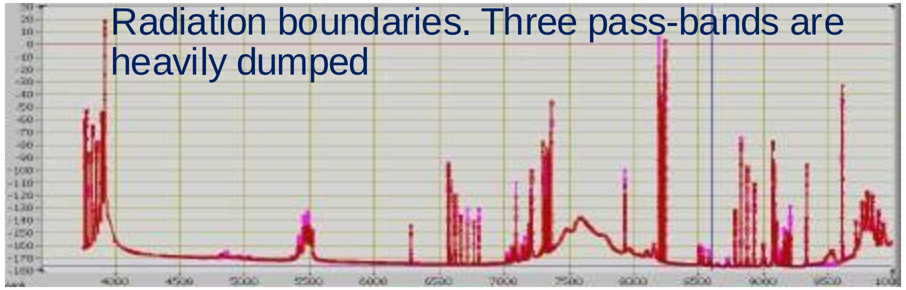
HFSS 3D 9 cells cavity model with:
- 2 High Order Mode (**HOM**) **couplers**,
- matched **Main coupler** port,
- different type of beam pipe terminations,
- distributed and phased current sources.

Calculations in driven mode.

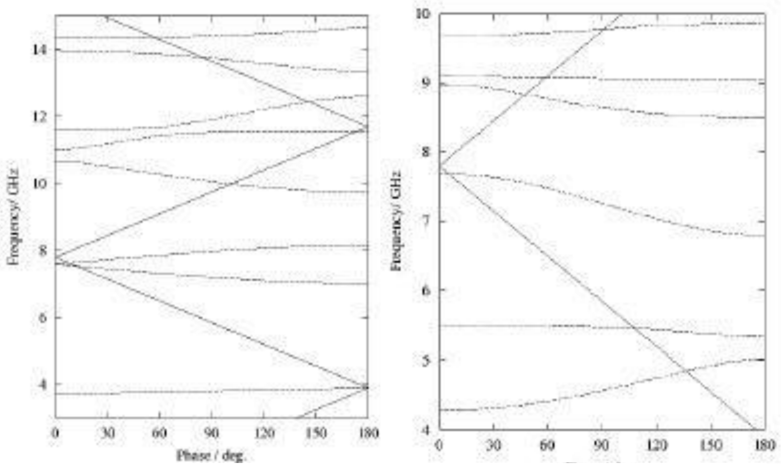




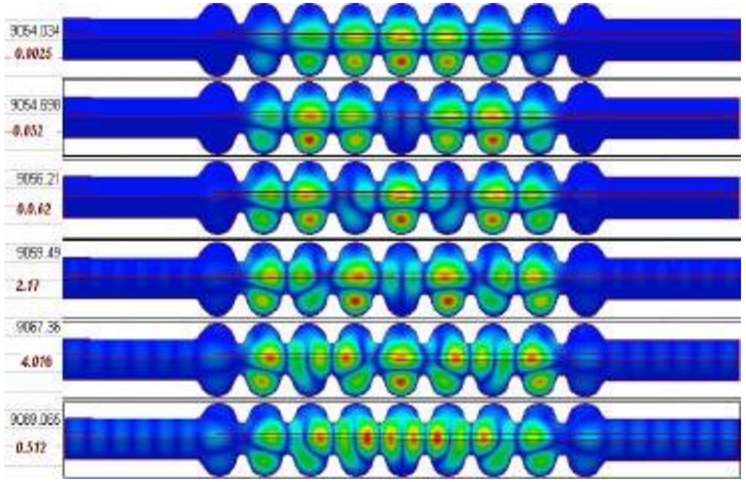
E/H boundaries. Red/green lines for different beam polarization (x/y). Few modes have Q>10^5



Radiation boundaries. Three pass-bands are heavily dumped



Monopole(left) and Dipole (right) passbands for mid-cell of the 3rd harmonic cavity



Trapped modes in 5th dipole passband

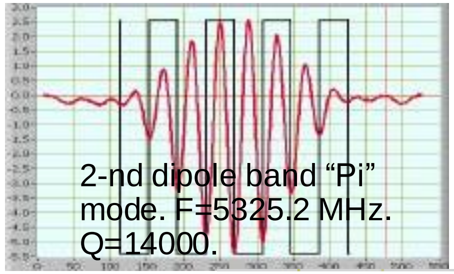
3rd Harmonic Module mini-Review. T. Khabiboulline. 11.08.2005

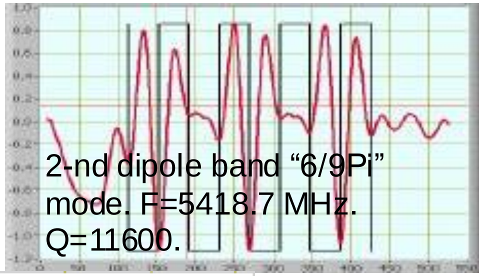
Qualification tests on Cu Cavity Prototypes

9 cells Cu cavity measurements with:

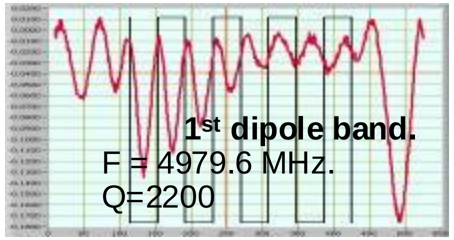
- 2 High Order Mode (**HOM) couplers**,
- **Main coupler port** with matched termination,
- Beam pipes with metal plates,
- Excitation and pick-up from different ports. **Bead-pull and S-parameter** measurements for **single cavity and double cavity** system.

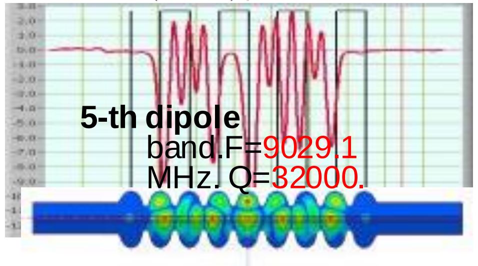
Dipole modes with high Qext (single cavity)





$$W_{\perp}(\tau = \frac{s}{c}) = c \cdot \sum_{n} \left(\frac{R}{Q}\right)_{n} \cdot \sin(\omega_{n}\tau) \cdot \exp\left(-\frac{\omega_{n}\tau}{2Q_{n}}\right)$$



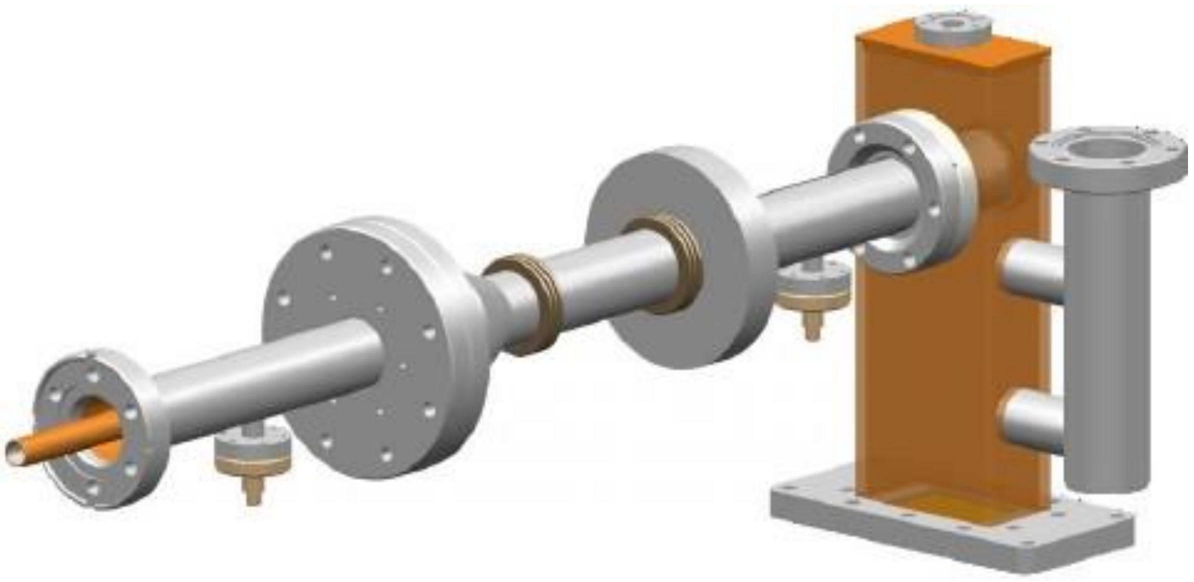


3rd Harmonic Module mini-Review. T. Khabiboulline. 11.08.2005

3.9 GHz RF Coupler Design: Parameters

3.9 GHz RF Coupler Main features

- ∅30mm/ ∅13mm coaxial line
- Standard copper waveguide
- Fix coupling
- No DC biasing
- Cold window: DESY TTF3 cylindrical ceramic
- Warm window: CPI 3.9 GHz WG window
- Two sets of bellows (flexibility)
- All internal parts are copper plated (30 µm inner and 10 µm outer part of coax)
- All part are brazed
- Pick-ups and glass window for diagnostics
- Good pumping performances



In Collaboration with CPI

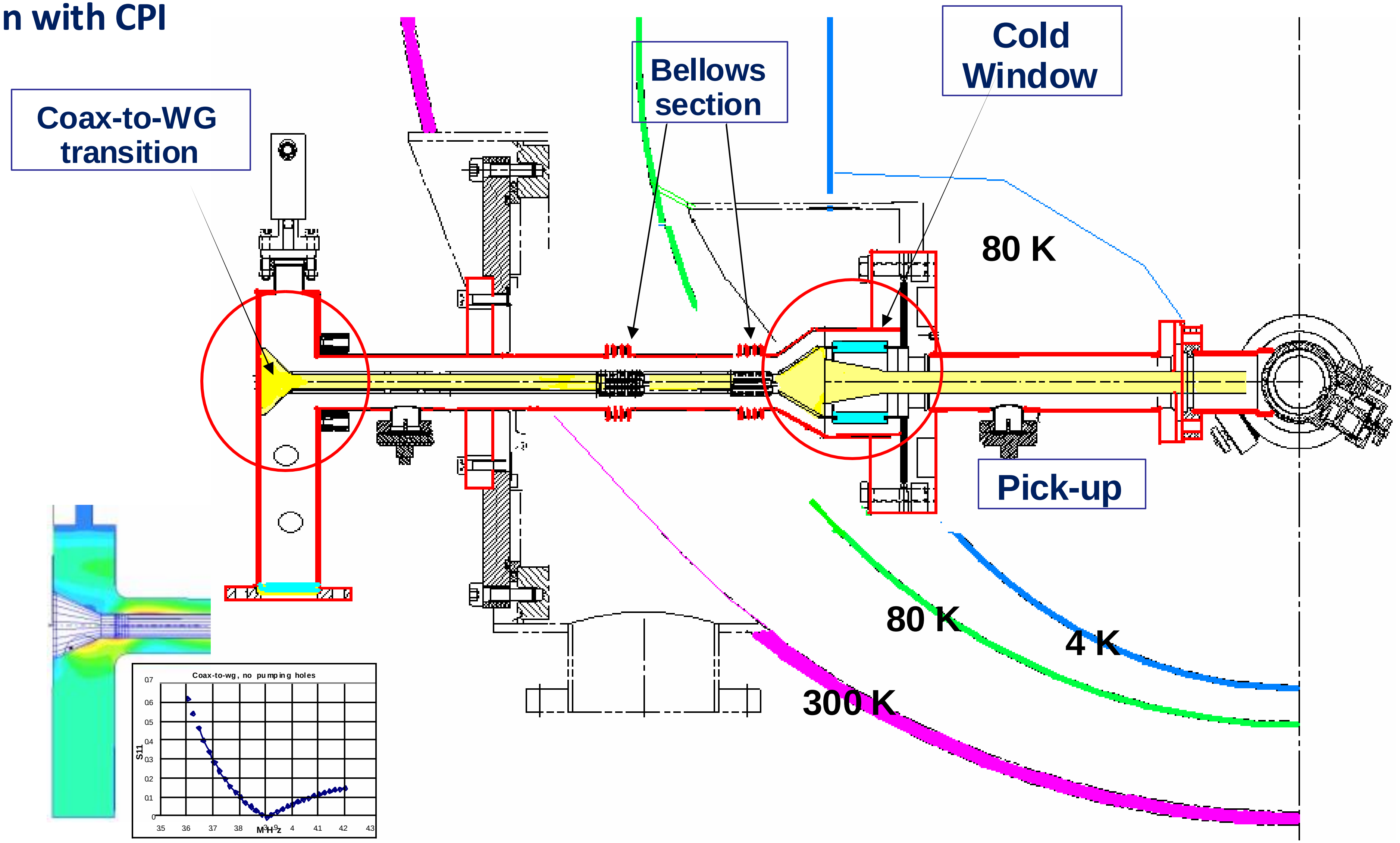
P_{peak} = 45 kW (I_b=9mA) (processsing at 80kW) Pulse =1.3 ms

Rep. rate = 5Hz

N. Solyak

3.9 GHz RF Coupler Design: cut view

In Collaboration with CPI



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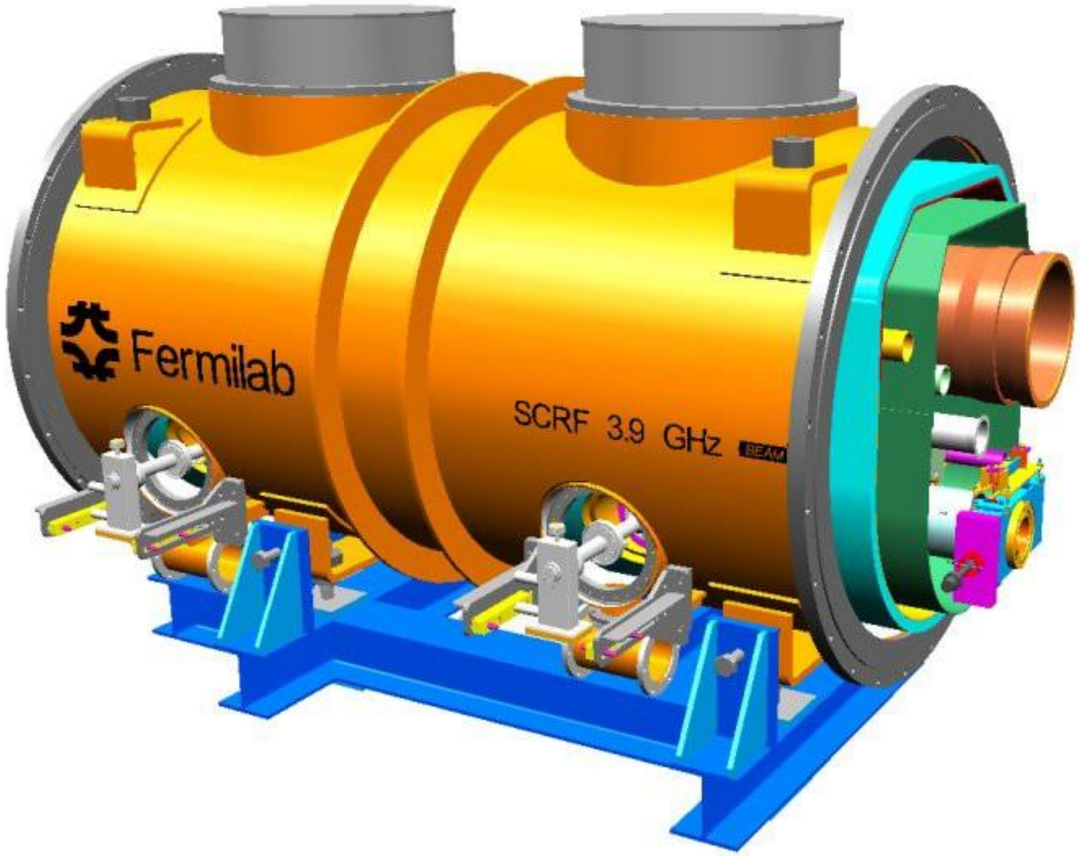
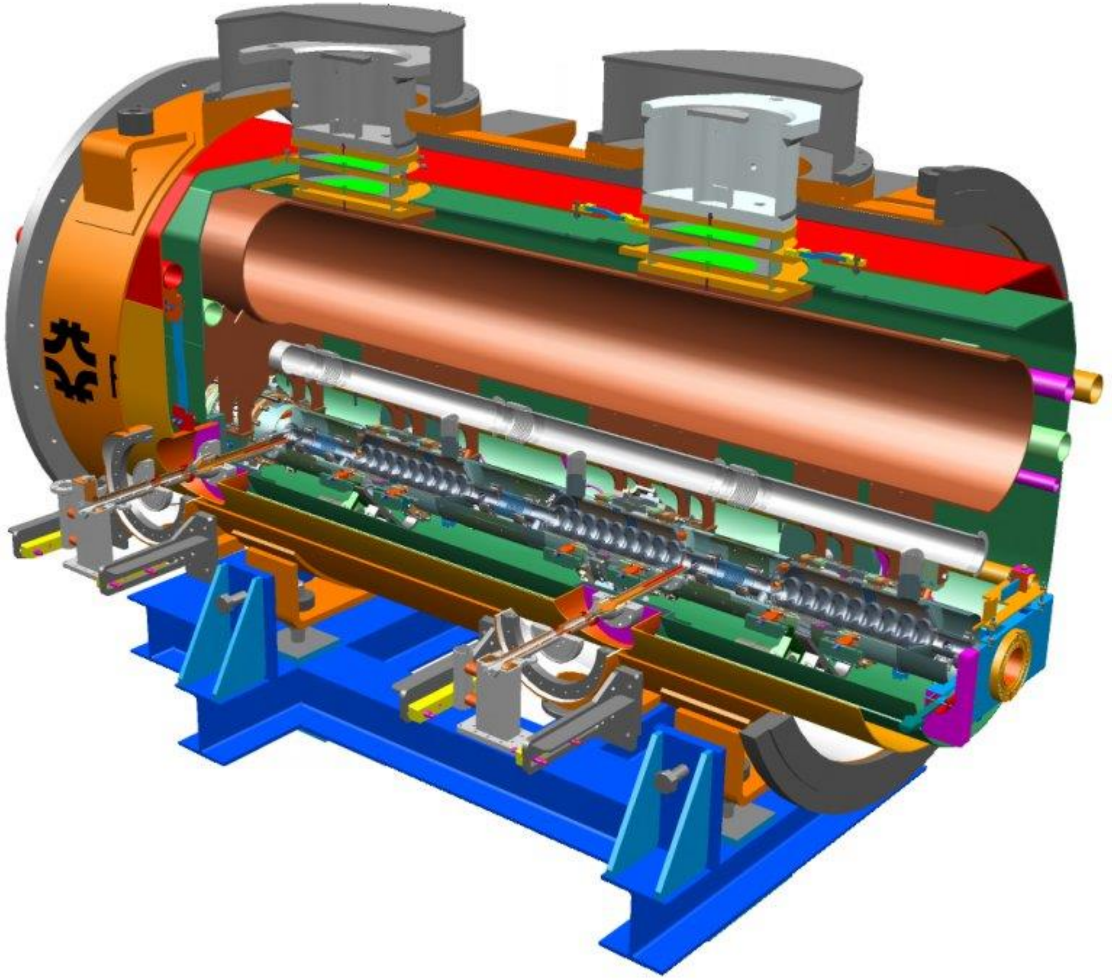
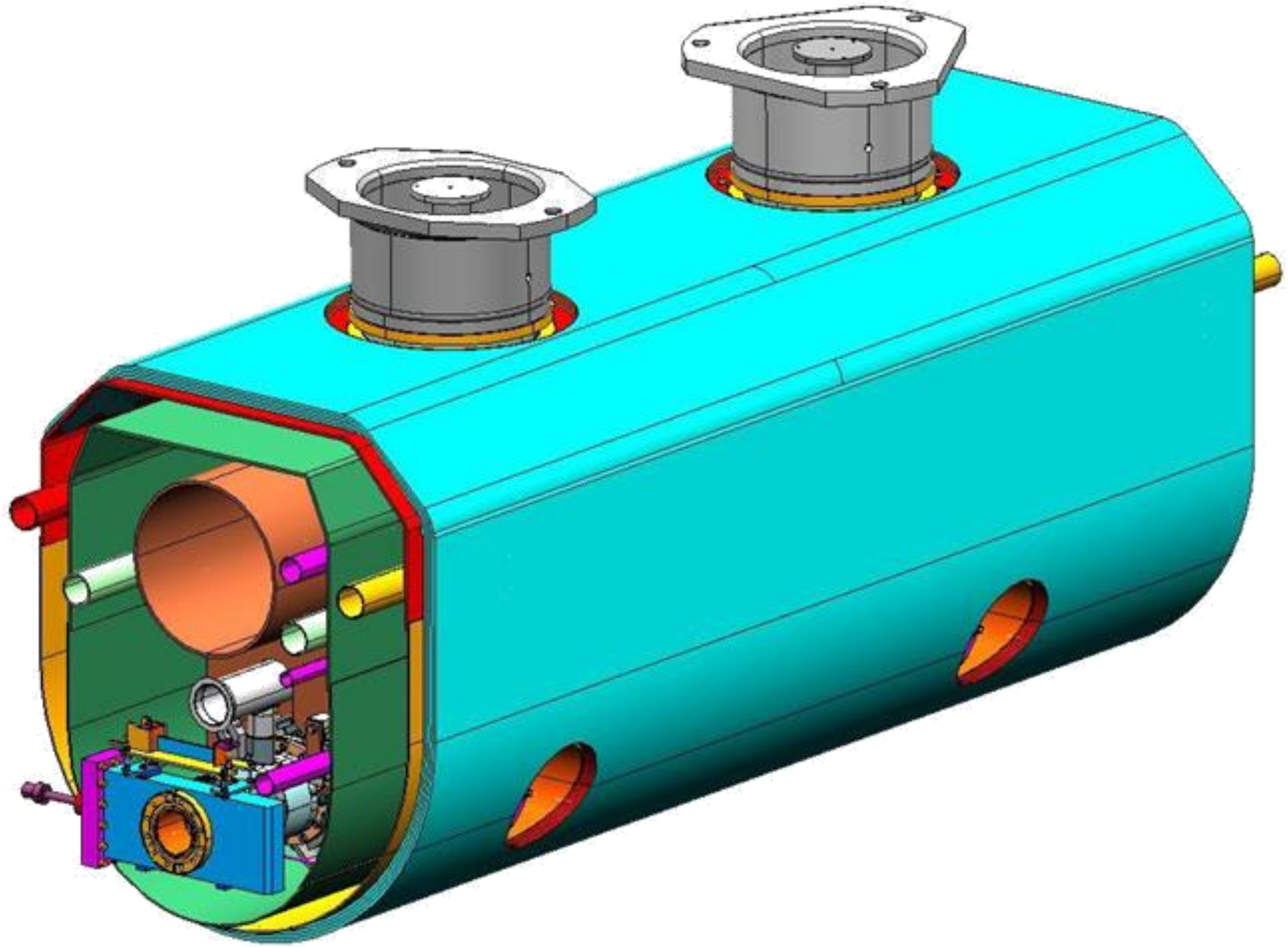
3rd Harmonic Cryomodule for TTF2

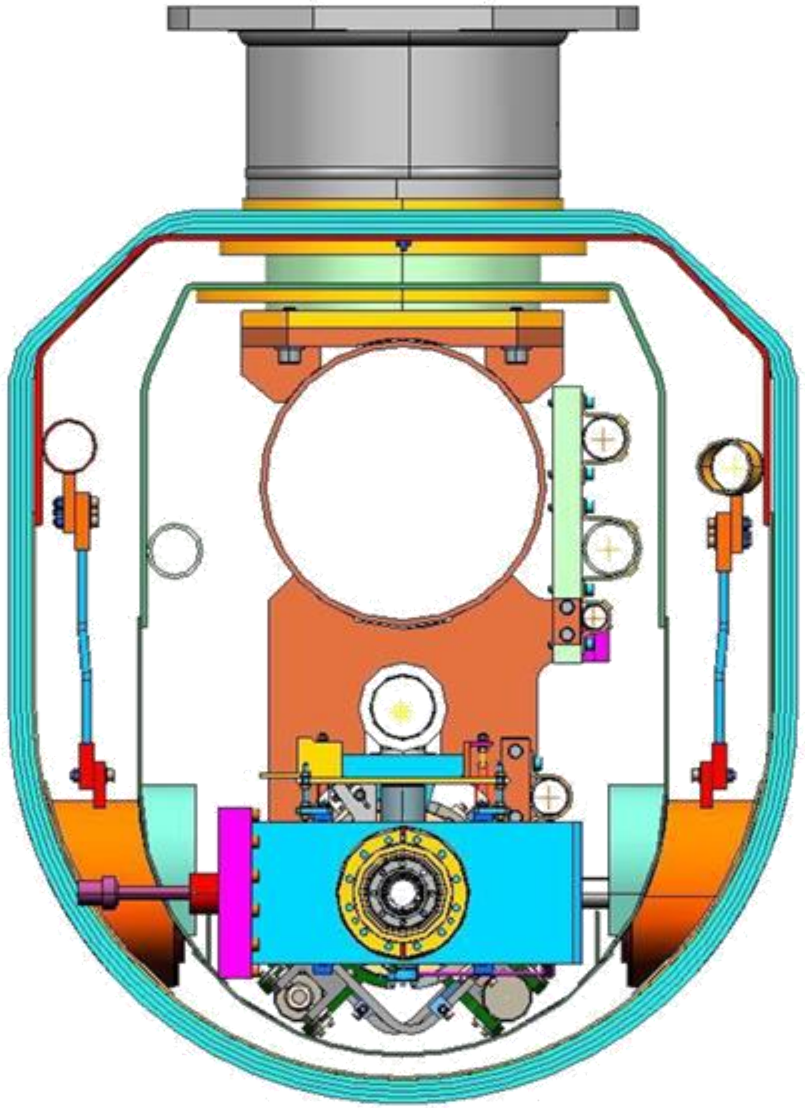




Don Mitchell

ACC39 Cryomodule designed at Fermilab

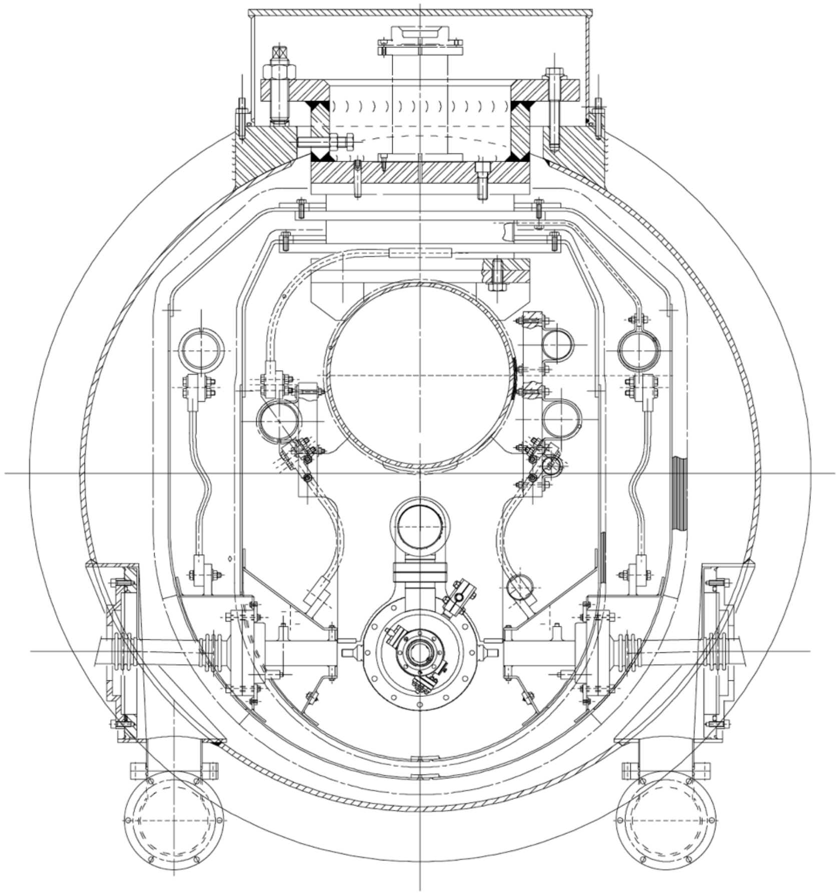




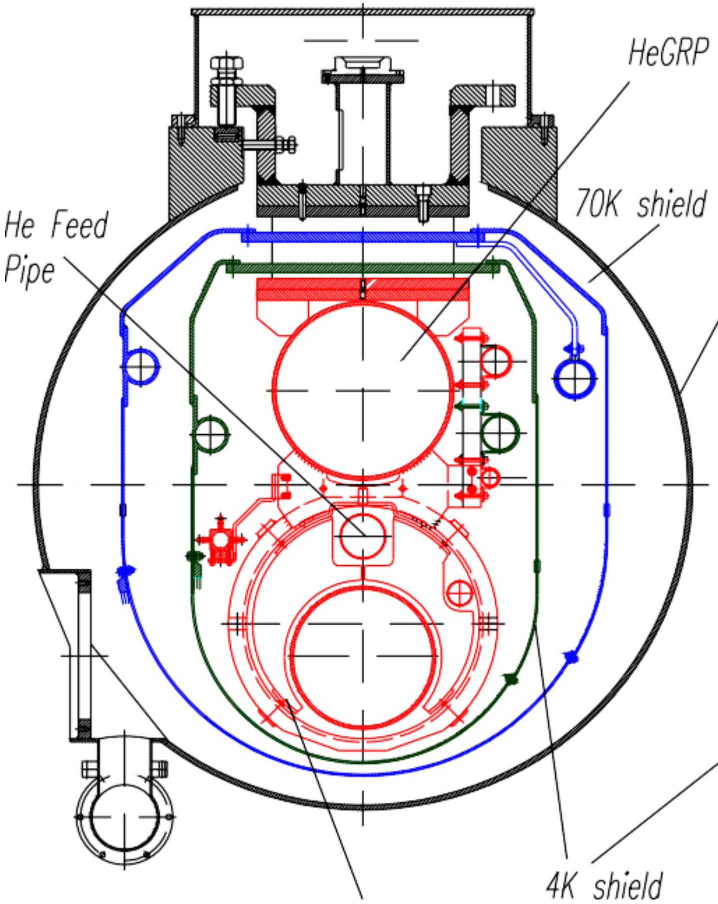
Don Mitchell

ACC39 Design derived from INFN Cry 2/3

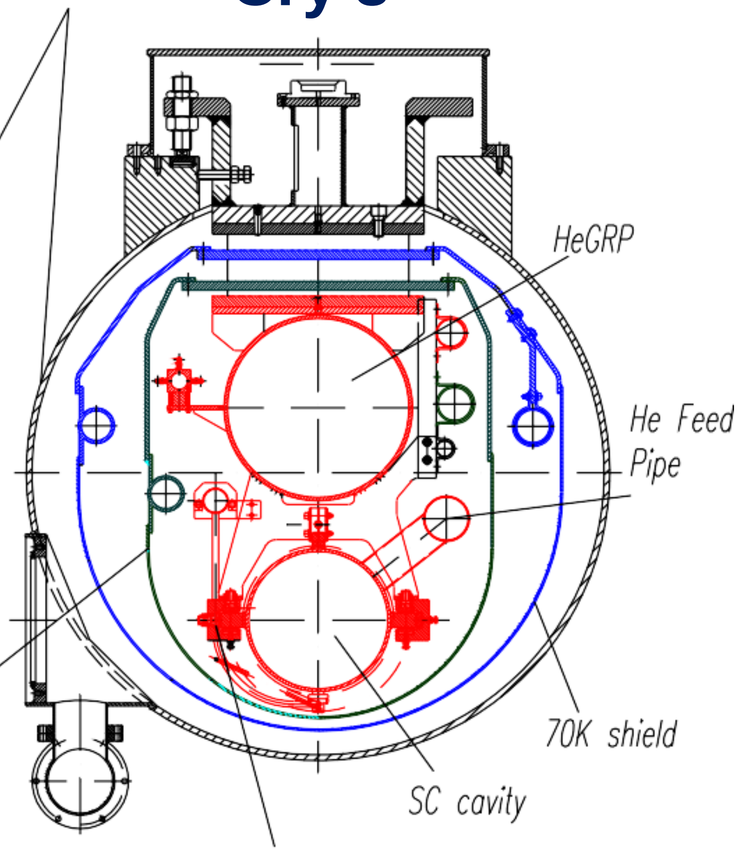
ACC39



Cry 2

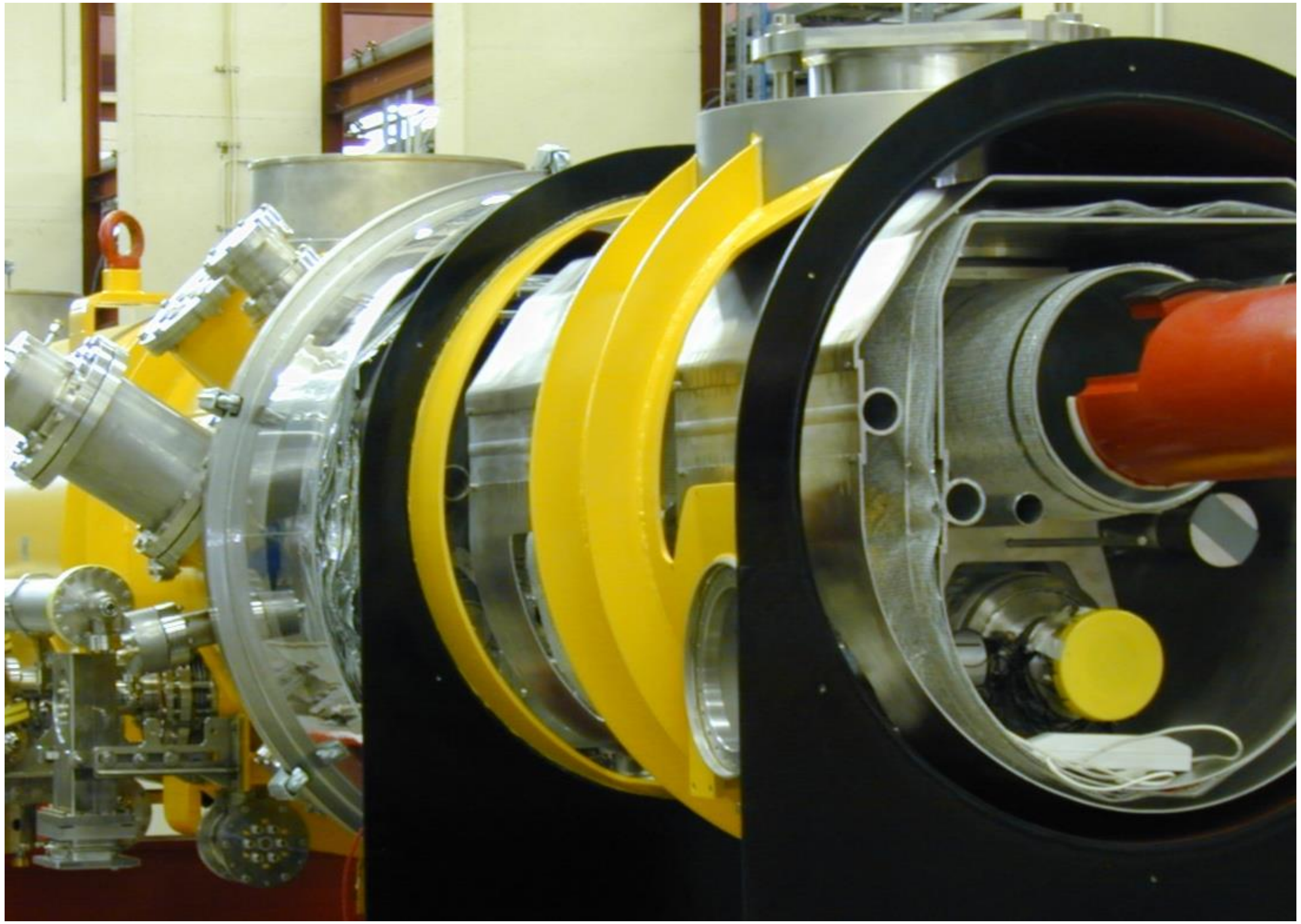


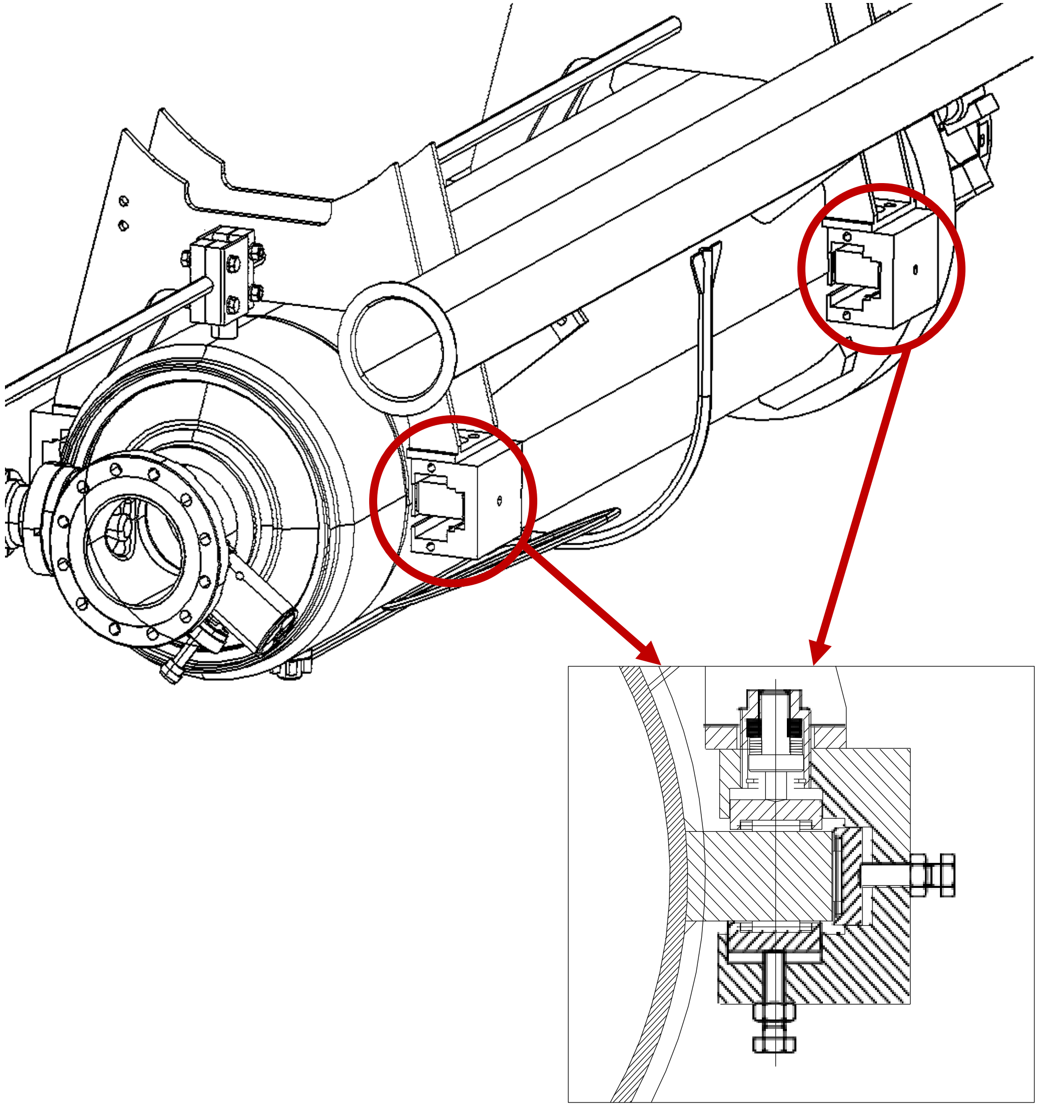
Cry 3



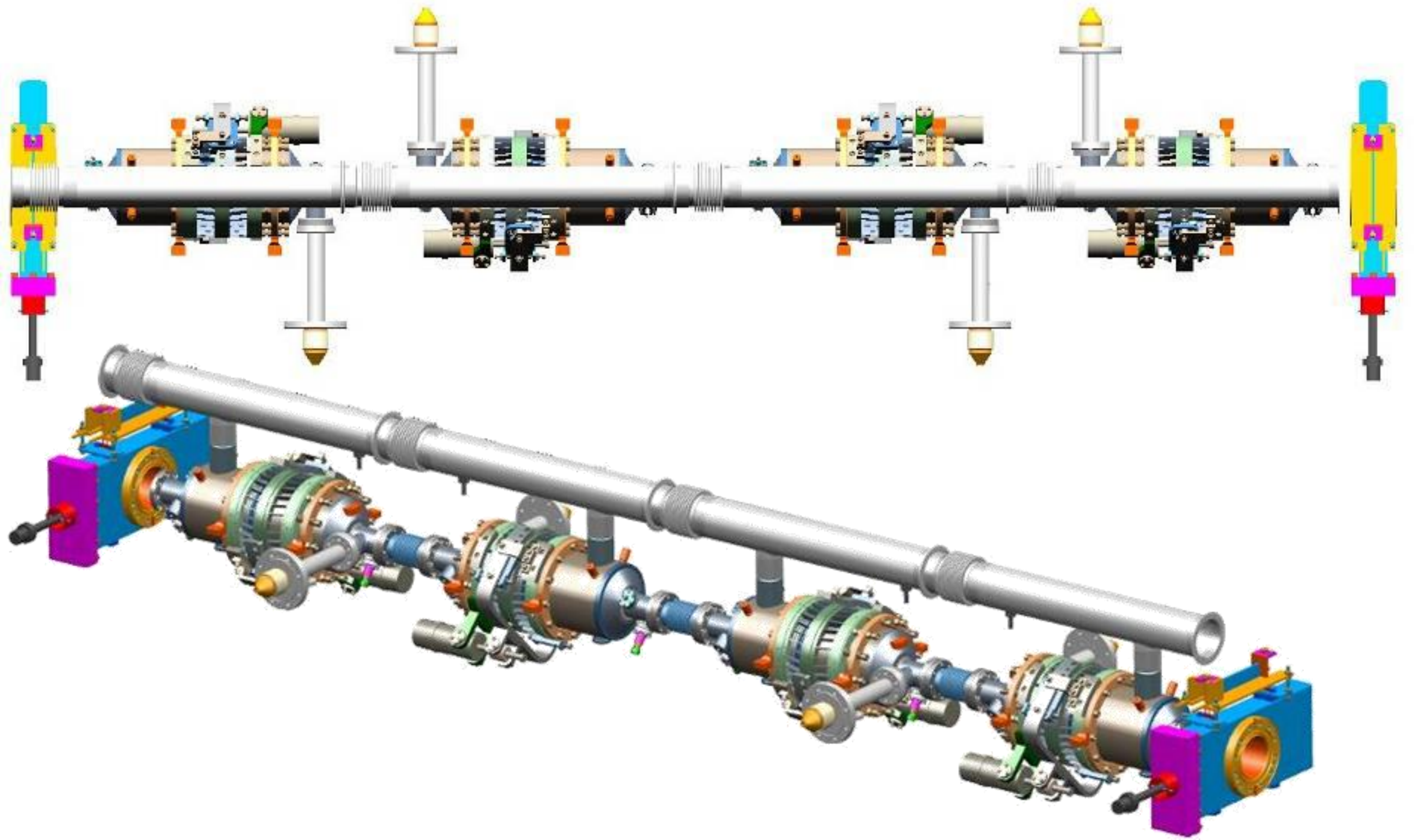
Module 1, 2 & 3 in TTF I

Cry2 to Cry3: Diameter Comparison



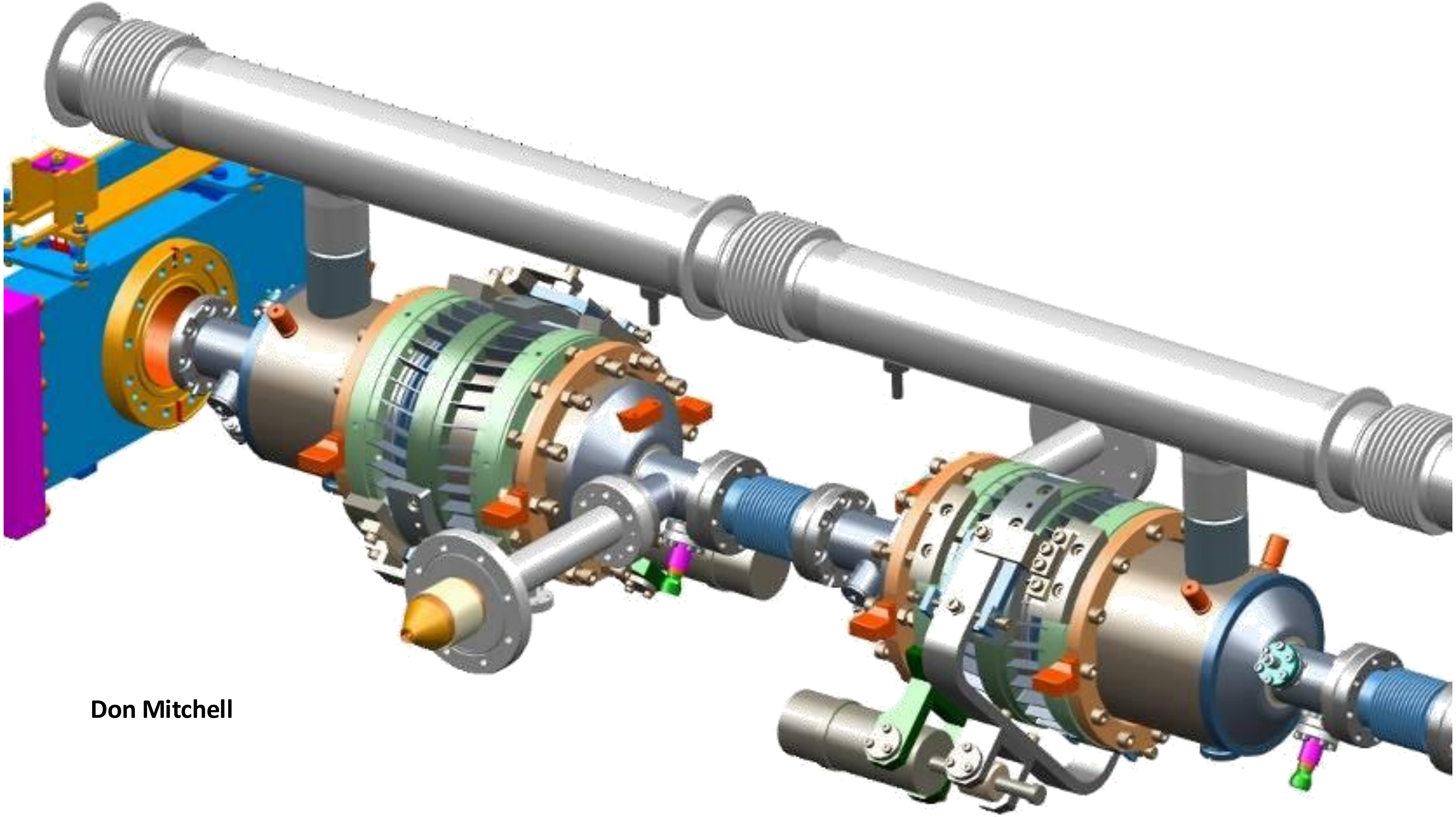


3rd Harmonic Cavity String



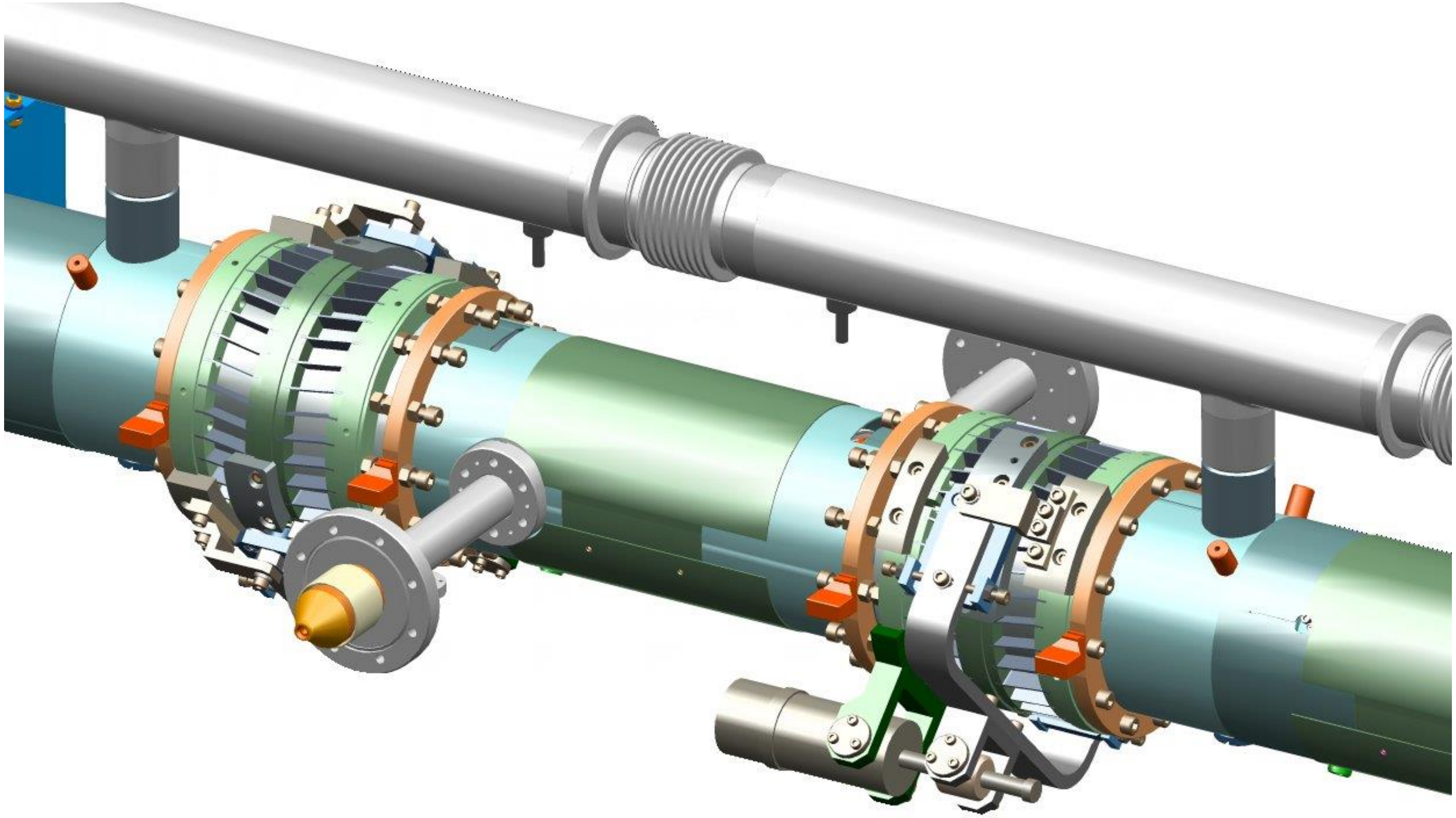
Don Mitchell

Cavity String closeup

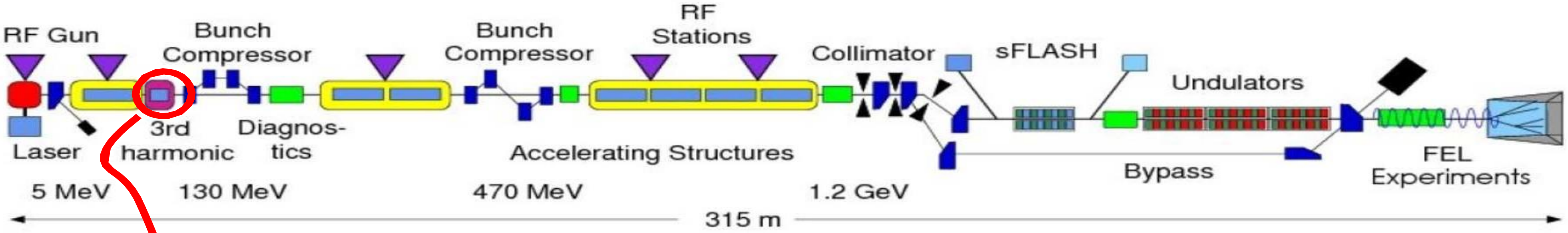


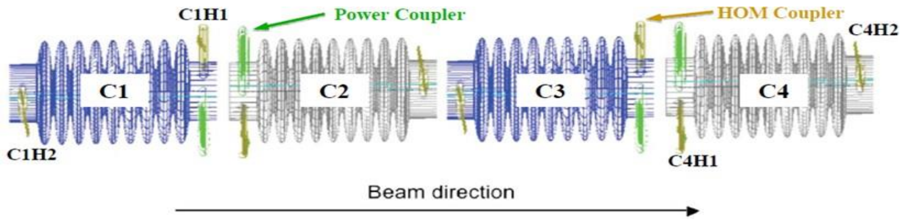
Don Mitchell

Magnetic Shield closeup



ACC39 @ FLASH

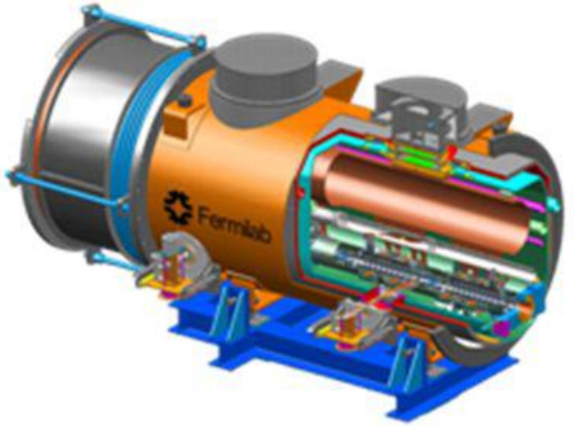




Number of cavities	4
Cavity length	0.346 m
Design gradient	14 MV/m
Phase	-179°
Cavity frequency ($\omega/2\pi$)	3.9 GHz
R/Q ($V^2/(2\omega U)$) [5]	373 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc}=14MV/m)	68 mT
Loaded Q_L	1.3×10^6
Max dipole R/Q at $\omega/2\pi$	50.20 Ω/cm², 4.831 GHz

Pei Zhang

ACC39 Module from Fermilab to FLASH

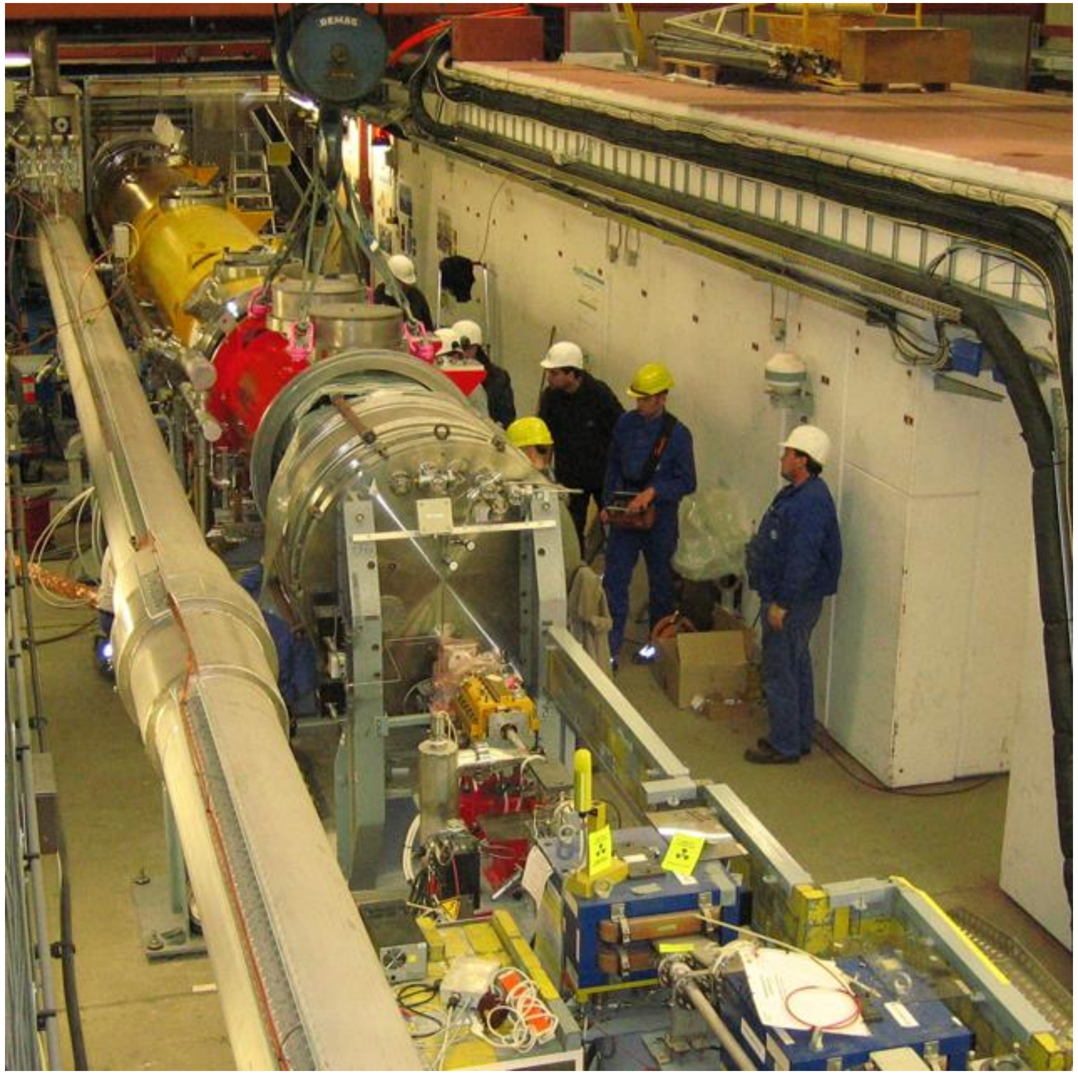


Designed at FNAL

Assembled at CAF

Tested at CMTB/DESY

Fully Operational at FLASH/DESY



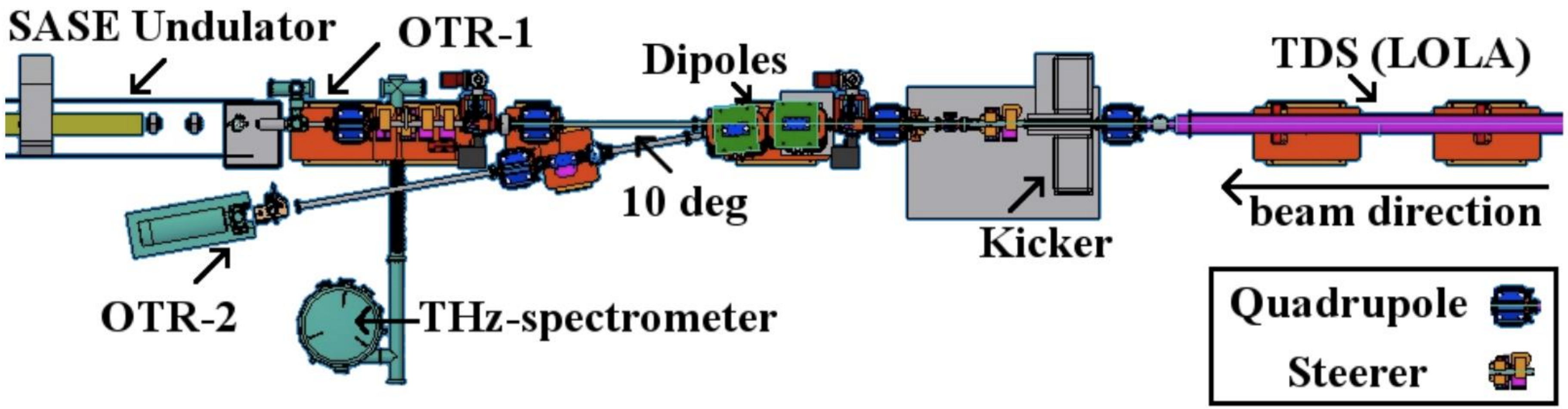
Commissioning of Fermilab Contribution

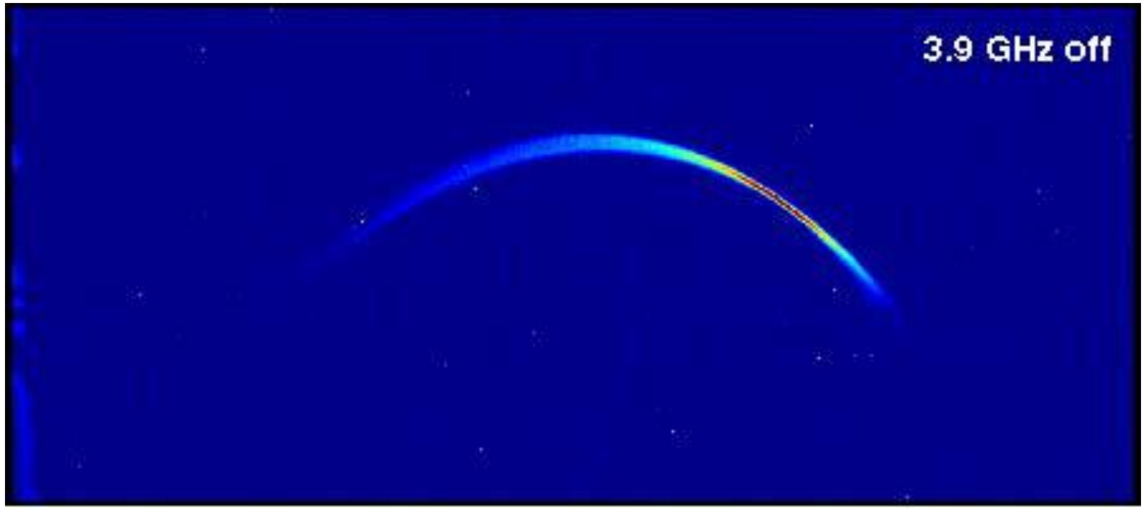
Proceedings of IPAC'10, Kyoto, Japan THPD003

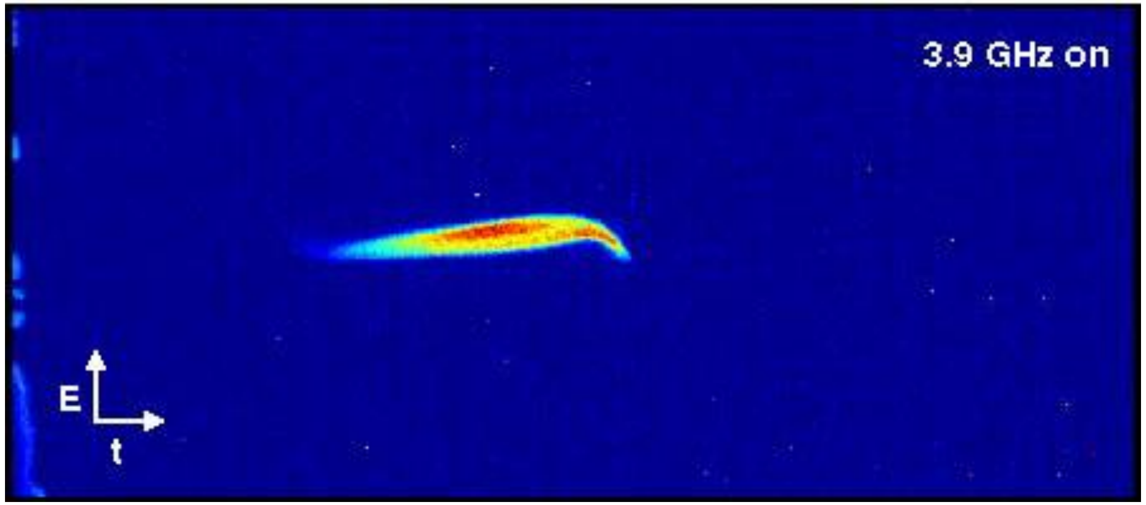
TEST AND COMMISSIONING OF THE THIRD HARMONIC RF SYSTEM FOR FLASH

E. Vogel, C. Albrecht, N. Baboi, C. Behrens, T. Delfs, J. Eschke, C. Gerth, M.G. Hoffmann, M. Hoffmann, M. Hüning, R. Jonas, J. Kahl, D. Kostin, G. Kreps, F. Ludwig, W. Maschmann, C. Müller, P. Nommensen, J. Rothenburg, H. Schlarb, C. Schmidt, J. Sekutowicz,
Deutsches Elektronen Synchrotron (DESY), Hamburg, Germany
H. Edwards, E.R. Harms, A. Hocker, T.N. Khabiboulline, Fermilab, Batavia, Illinois, USA
M. Kuhn, Hamburg University, Germany

Phase Space Linearization Acheived







Contents

1. Longitudinal Phase Space Linearization

2. ACC39 made by Fermilab for FLASH

3. **AH1 made by INFN-LASA for European XFEL**

INFN In-Kind Contribution to the E-XFEL

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 042006 (2017)

Fabrication and vertical test experience of the European X-ray Free Electron Laser 3.9 GHz superconducting cavities

P. Pierini,[*] M. Bertucci, A. Bosotti, J. F. Chen, C. G. Maiano,[†] P. Michelato, L. Monaco, M. Moretti,[‡] C. Pagani,[§] R. Paparella, and D. Sertore

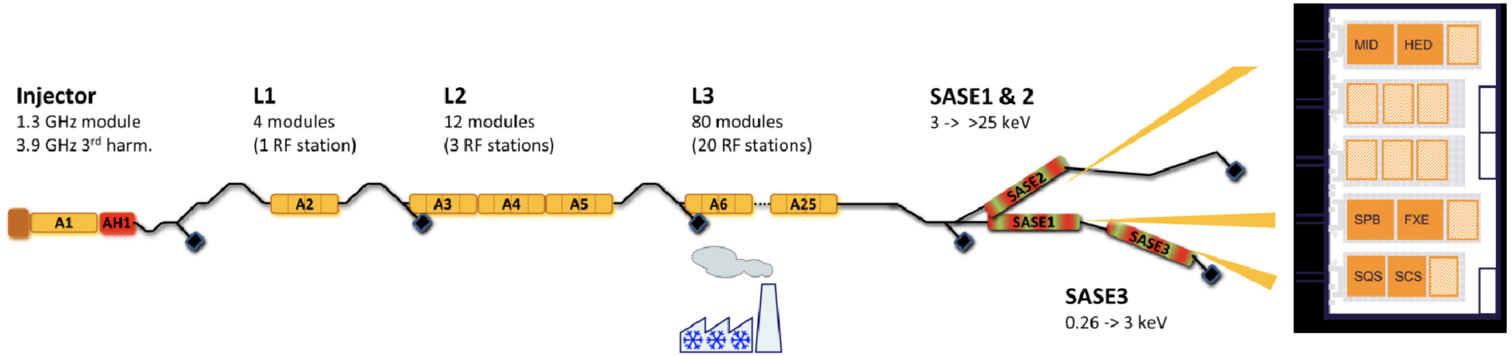
INFN Sezione di Milano–Laboratorio LASA, Via Fratelli Cervi 201, 20090 Segrate (Mi), Italy

E. Vogel

Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany

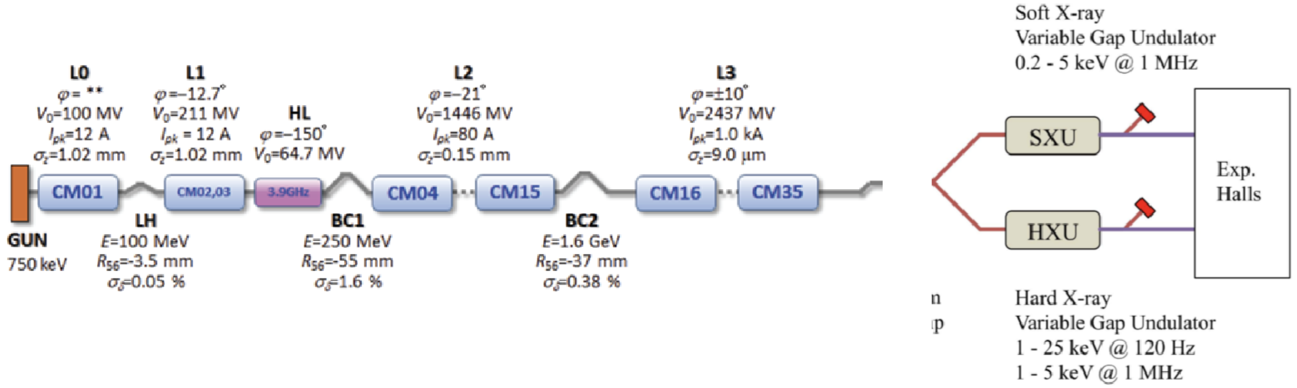
(Received 21 December 2016; published 27 April 2017)

Same Scheme in the 3 major XFELs



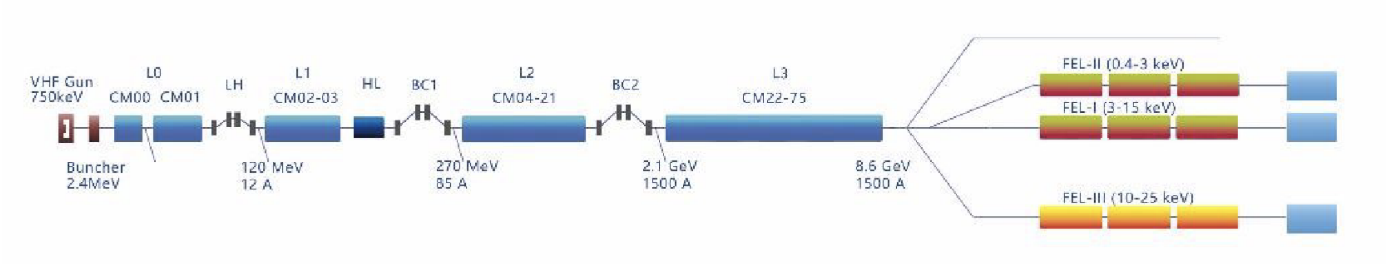
European XFEL

construction during 2009 – 2016
in operation since 2017
cw upgrade after 2025 (?, tbc)



LCLS-II

under construction since 2014
first lasing expected in 2021
HE 8 GeV upgrade until 2026

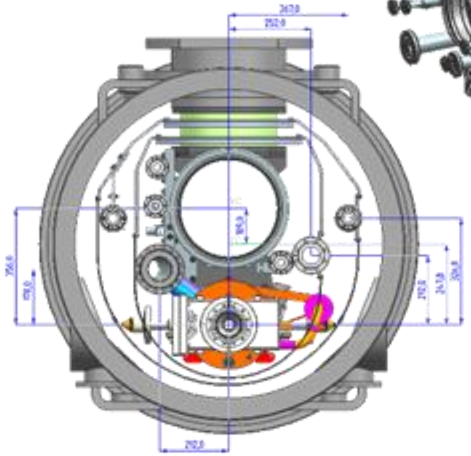


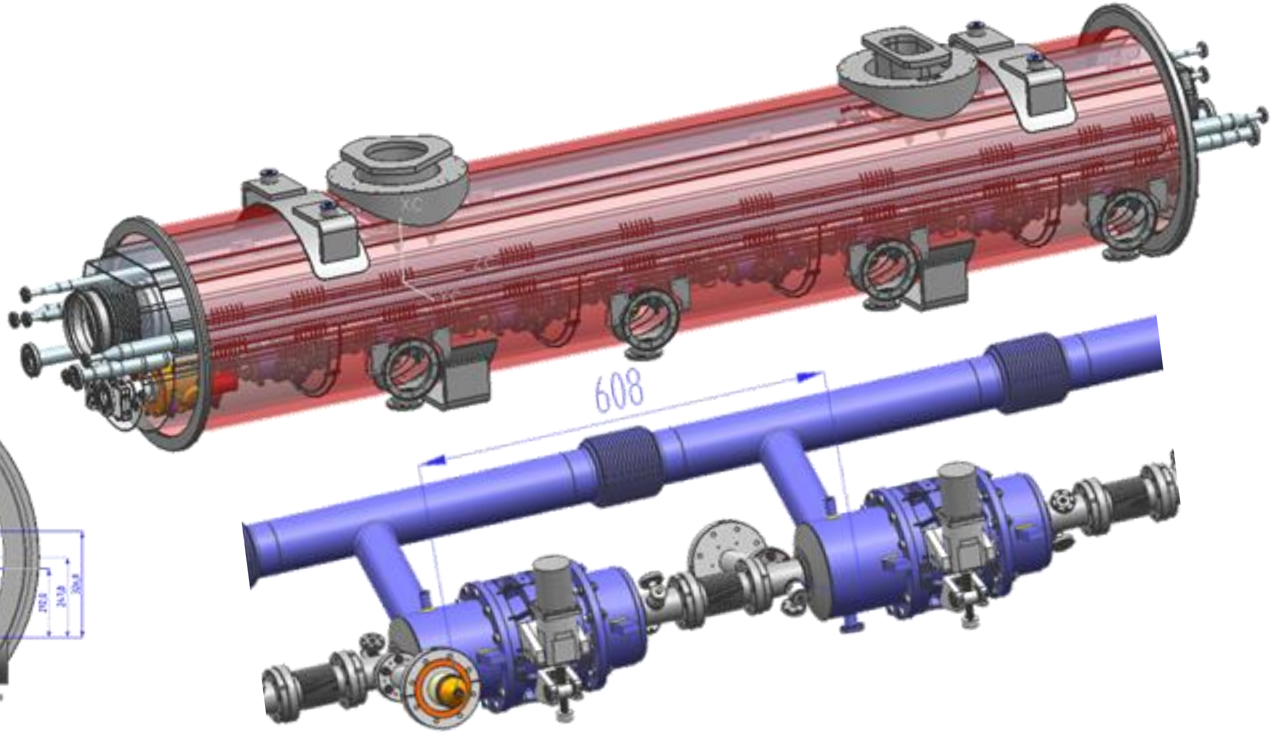
SHINE SARI

under construction since 2018
to be commissioned in 2025
goal: cw and 8 GeV

Hans Weise @ FEL2021

E-XFEL WP46 - 3rd Harmonic Module





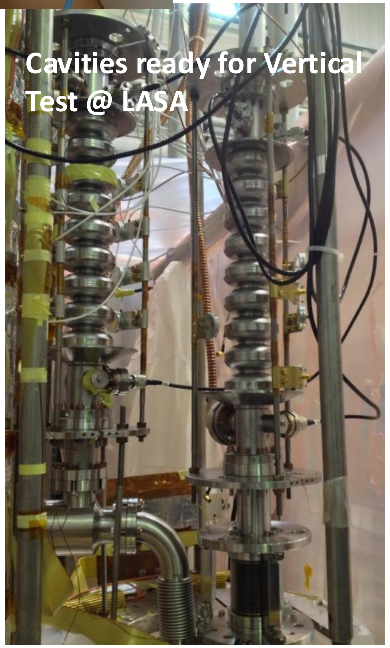
Due to alternating couplers requirement, for coupler kick compensation, and to the position of the 2-phase pipe there are two dressed cavity configurations (left and right)

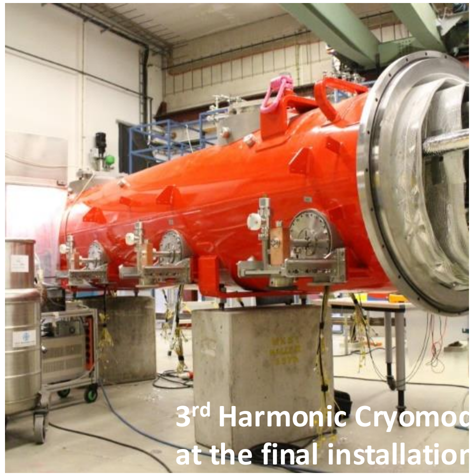
Blade tuner updated to the **“slim” type**, concept derived from ILC tuner work by INFN. Lighter, cheaper, motor to the side.

Design of the Module is **“Plug compatible”** with XFEL modules

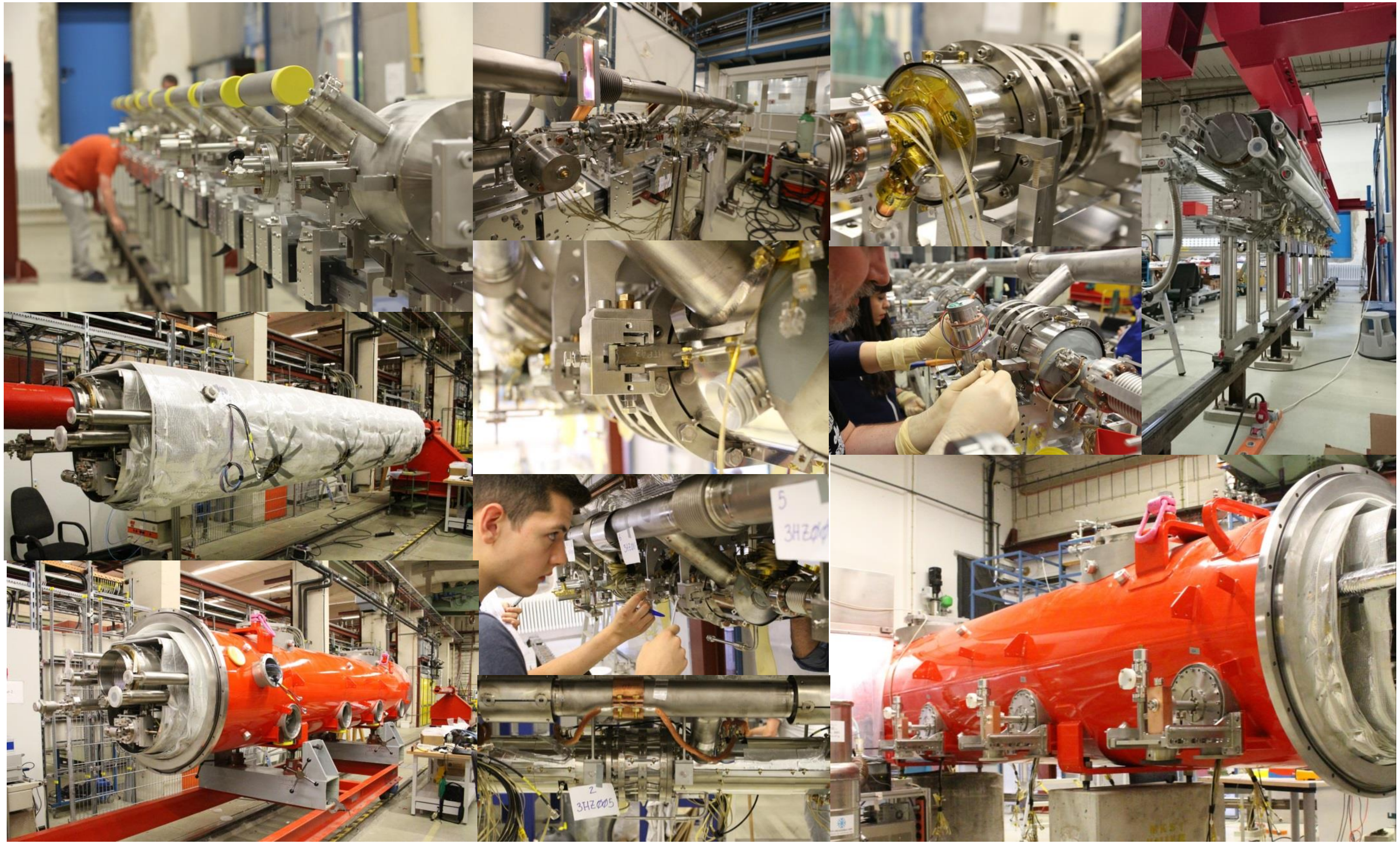
E-XFEL 3rd Harmonic Module

- 10 3.9 GHz cavities produced and treated by the industry
- **Naked cavities Vertical tested at LASA**
- Integrated at the industry
- Equipped with Power Coupler and assembled in the string at DESY
- String moved into the cryomodule for final installation
- **Module in E-XFEL tunnel by end of September ‘15.**
- First beam in E-XFEL Injector by the **end of ‘15**,

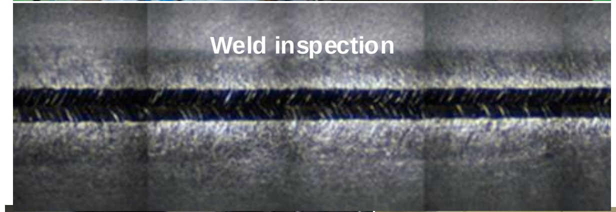


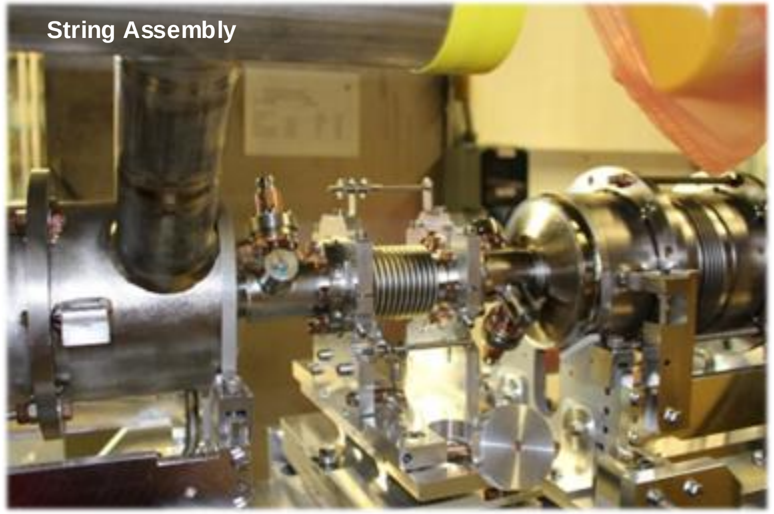


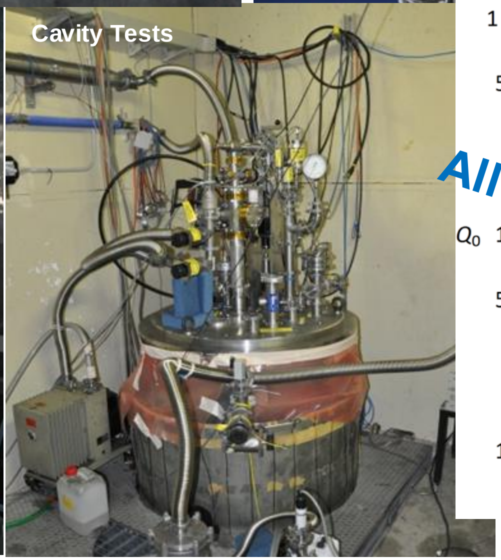
Module Assembly by INFN at DESY

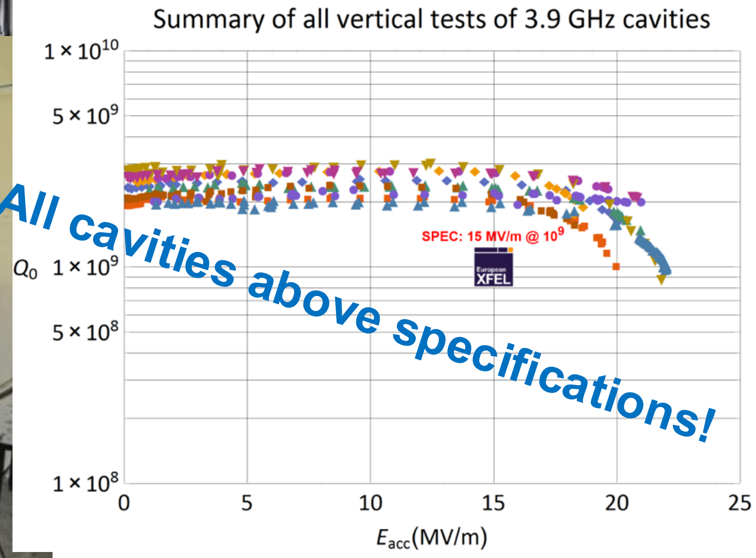


WP46 - Cavity Fabrication and Test

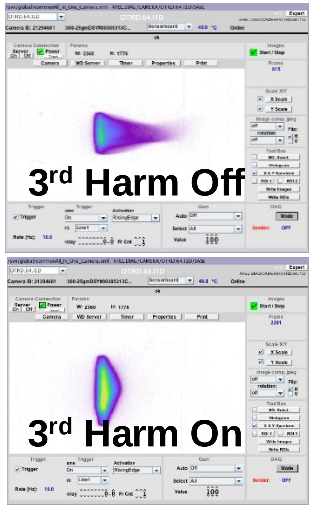








XFEL Injector' Beam



XFEL 3rd harmonic: cavites and Cryomodule

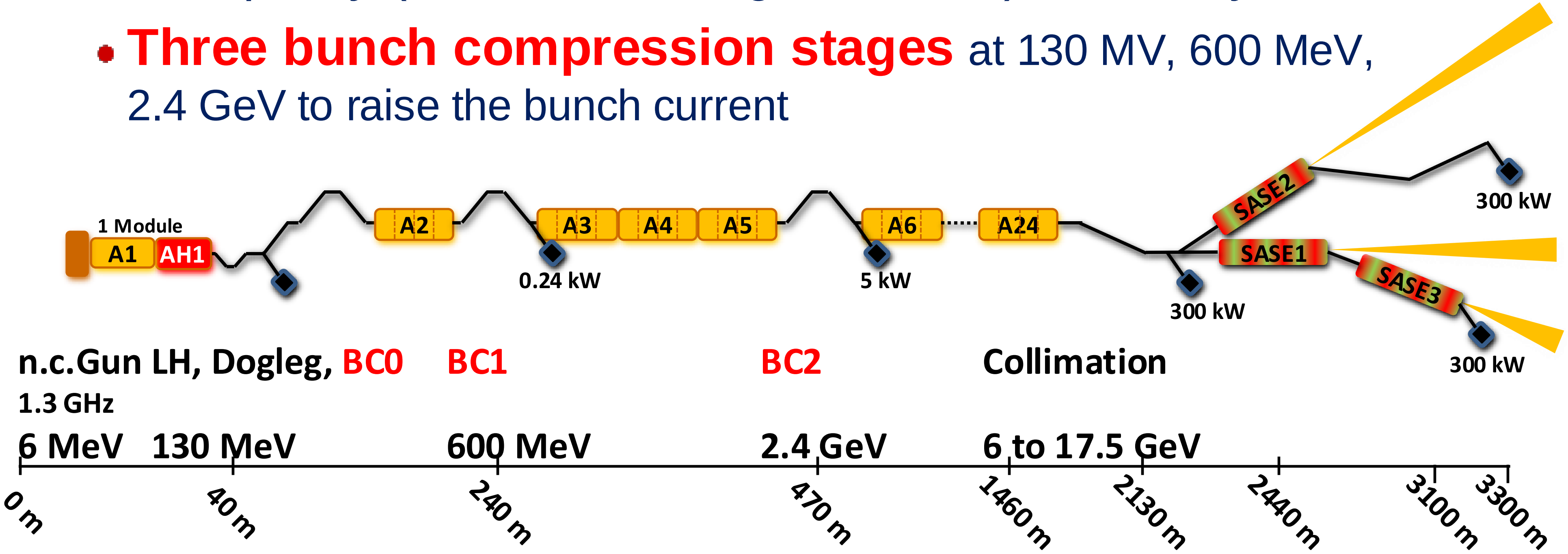
E-XFEL in a nutshell

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



P. Pierini, SRF2017, Lanzhou

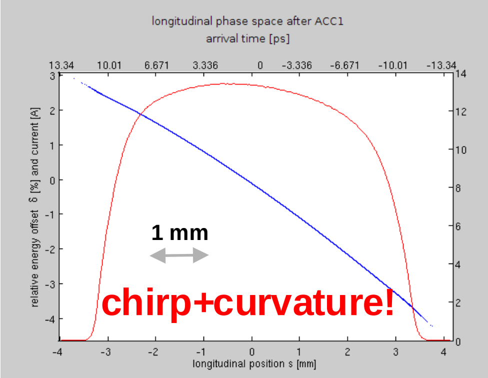
3rd Harmonic for Longitudinal Phase Space

- 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

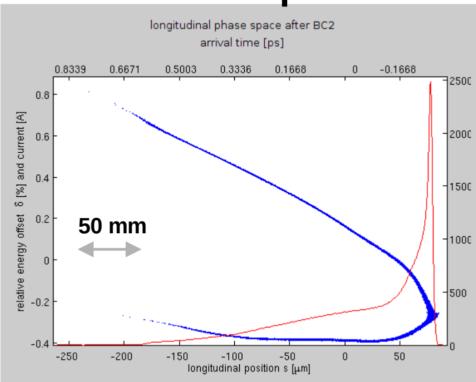
Phase space manipulation in a glance

Using only A1 to chirp the beam (no AH1)

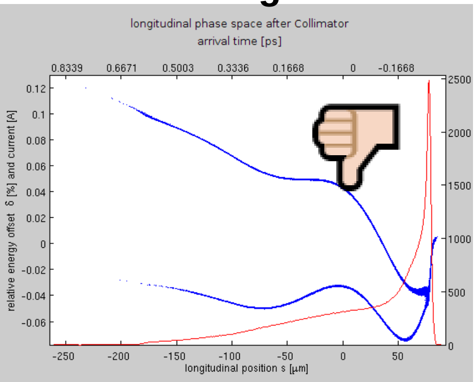


Longitudinal phase space
Current along bunch

At final compression stage current spike

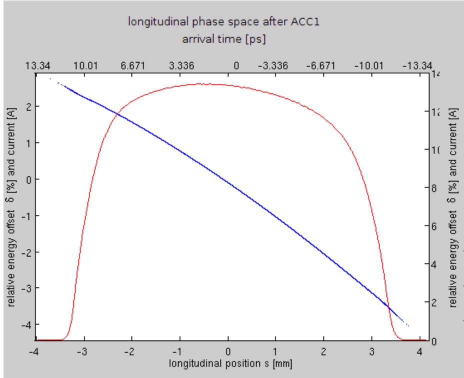


Large current spike but low charge for FEL!



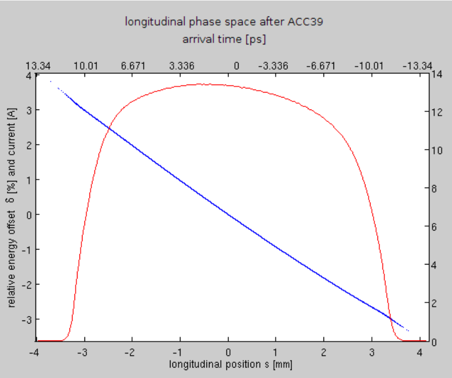
With third harmonic manipulation

After A1 (150 MeV)



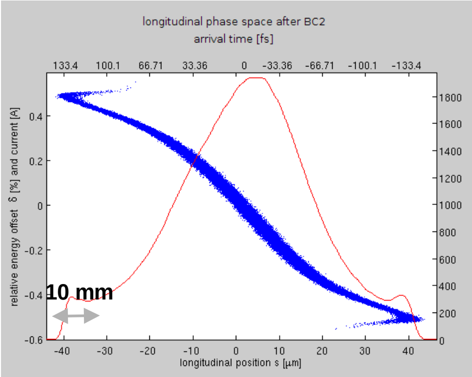
Off crest operation creates chirp+curvature

After AH1 (130 MeV)



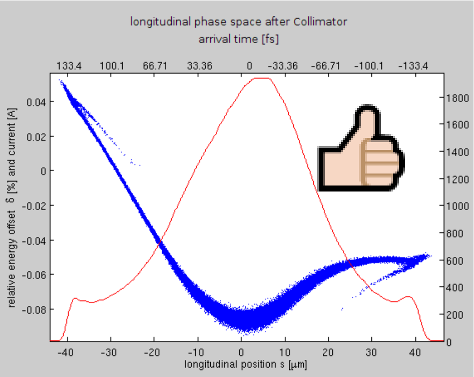
AH1 removes curvature and prepares for BC

After BC2 (2.4 GeV)



At final compression stage good current profile

After L3+CL (17.5 GeV)



Beam flattened for good FEL emission

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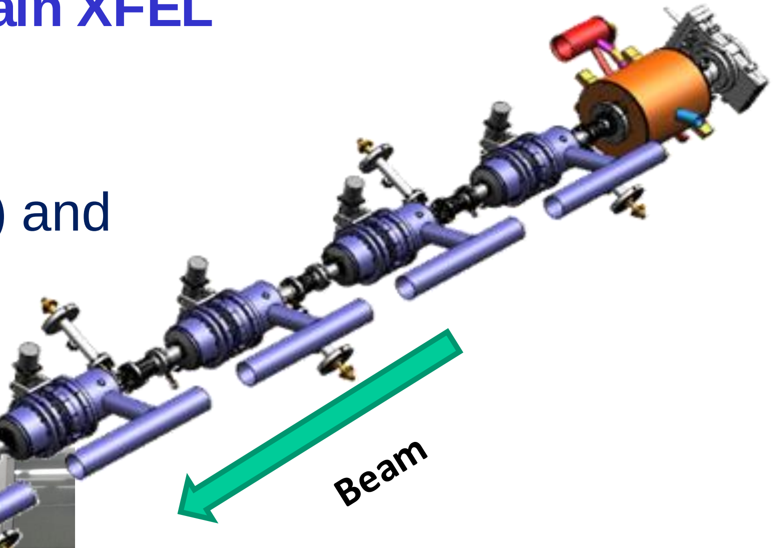
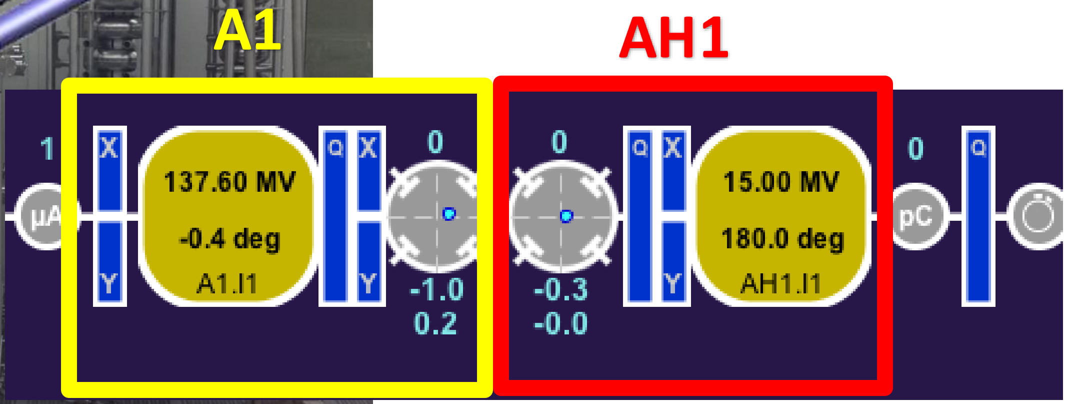
What is in the AH1 module?

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





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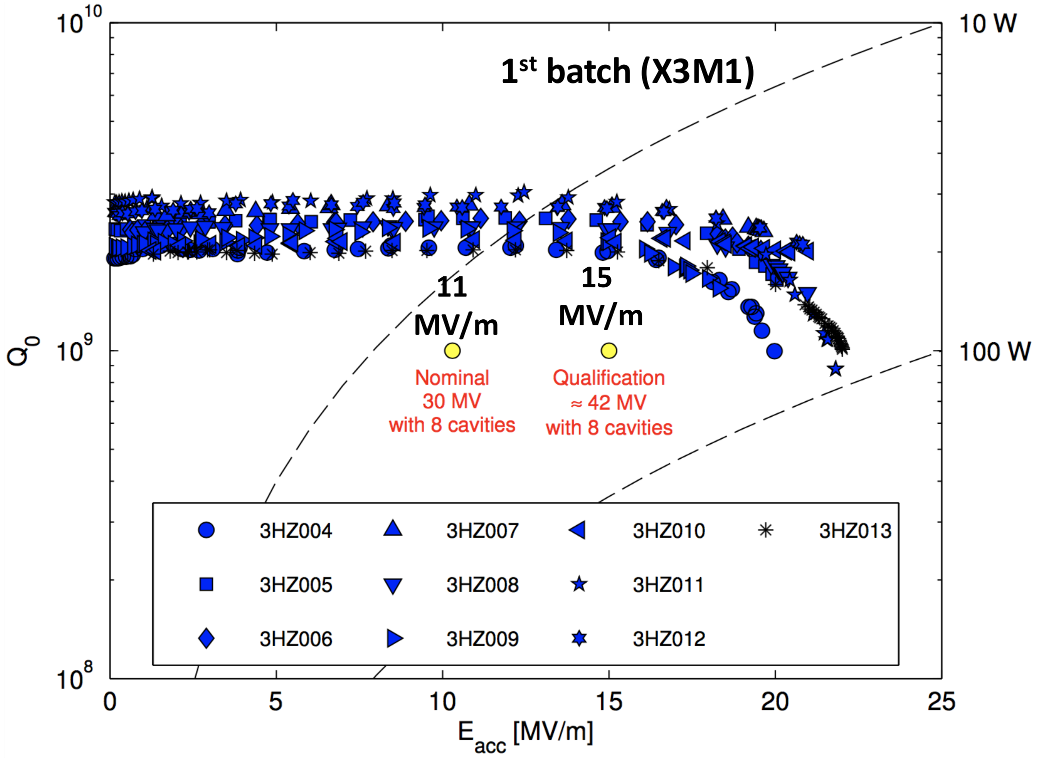
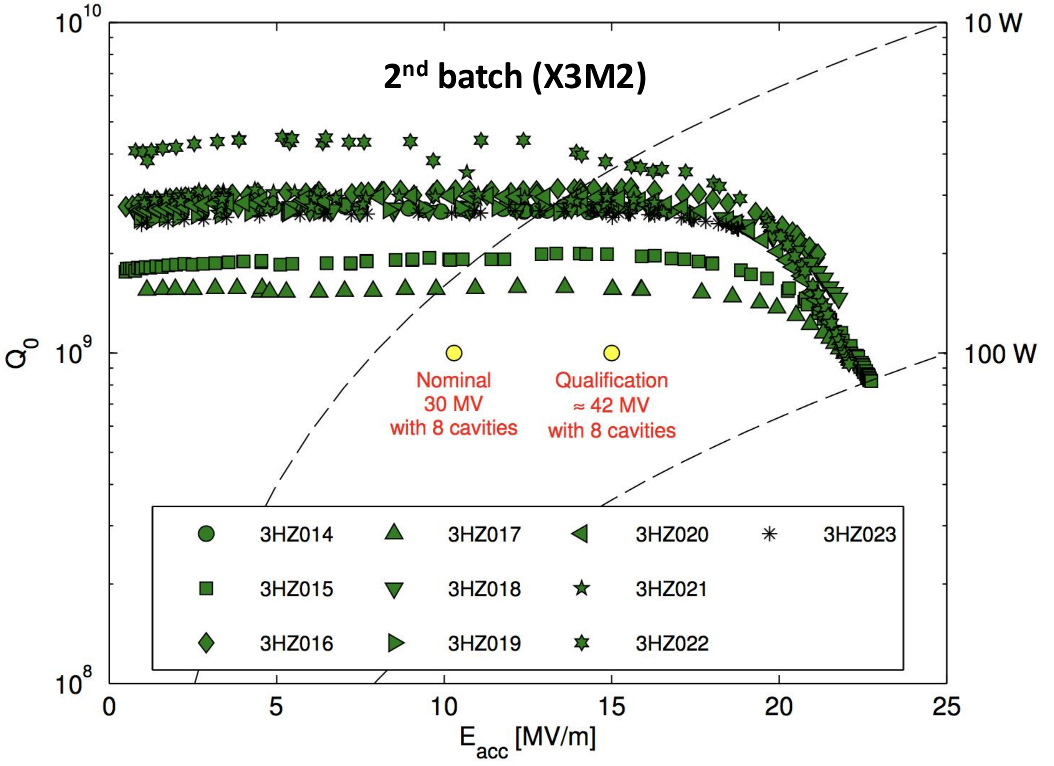
Cavity production and testing

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





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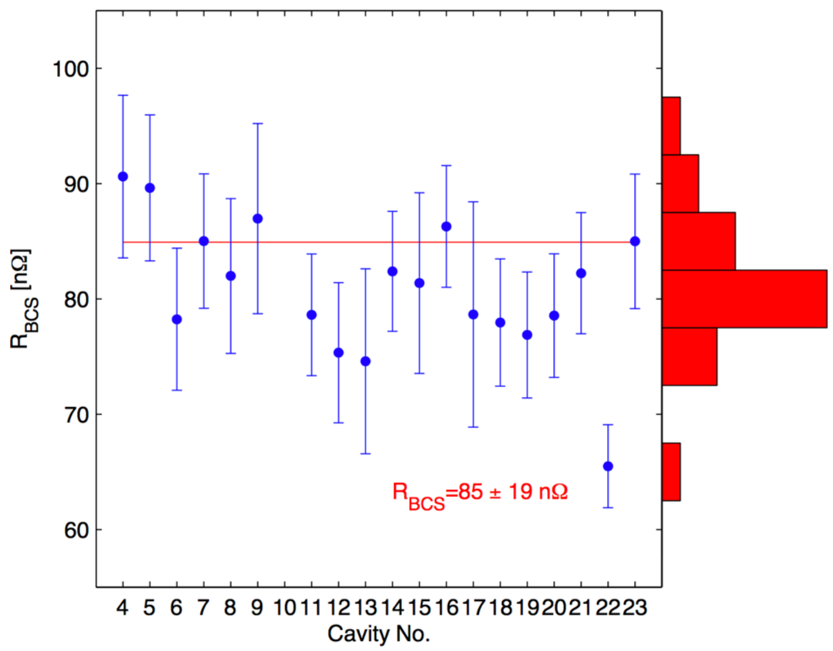
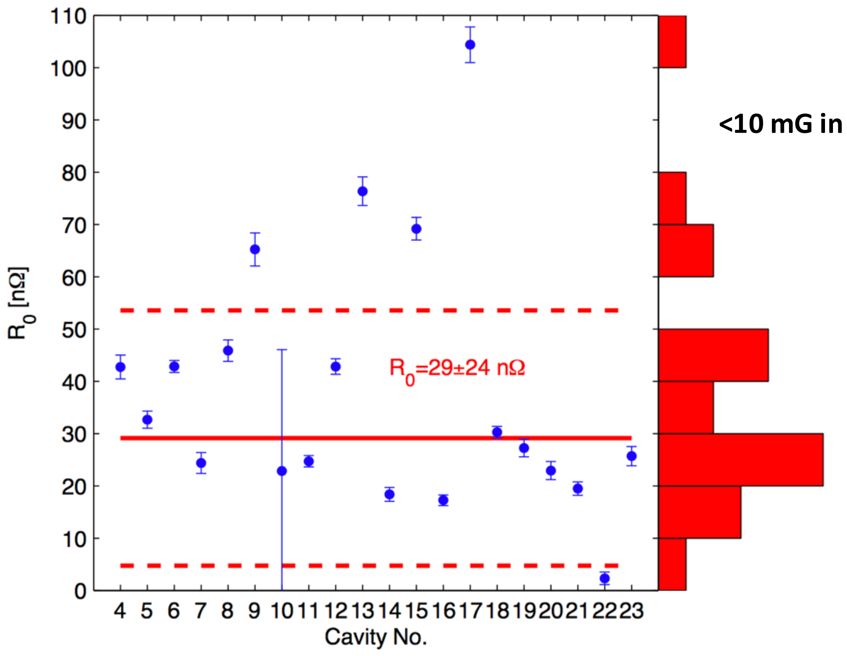
VT Qualification summary

	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]



<10 mG in VT

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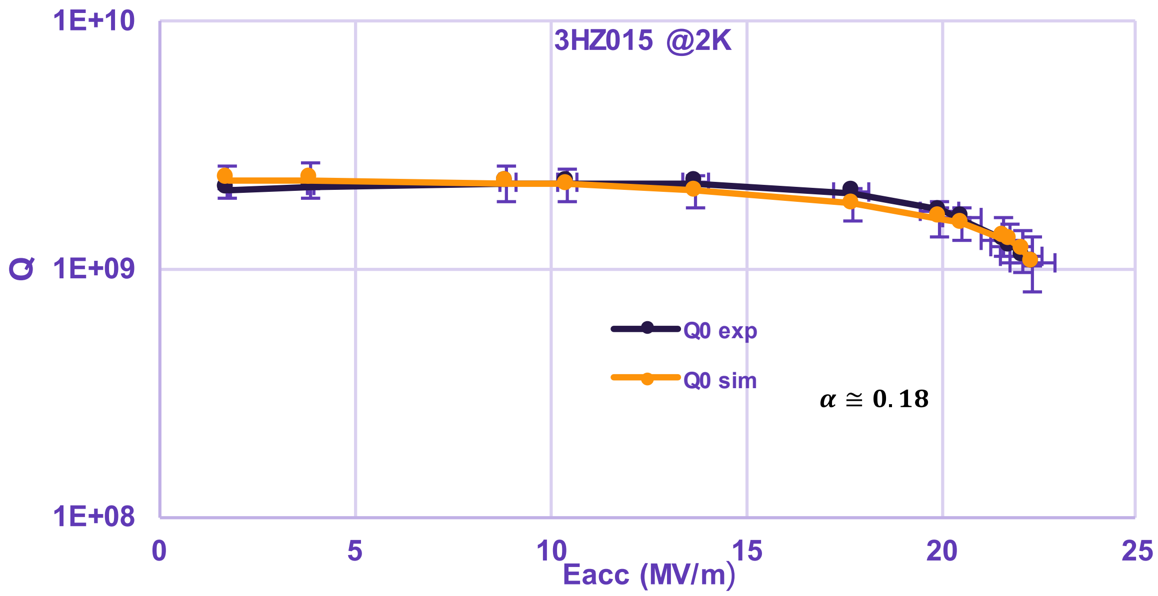
Behavior at high field

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

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

P. Pierini, SRF2017, Lanzhou

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

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

Validation test in AMTF (March 2015)

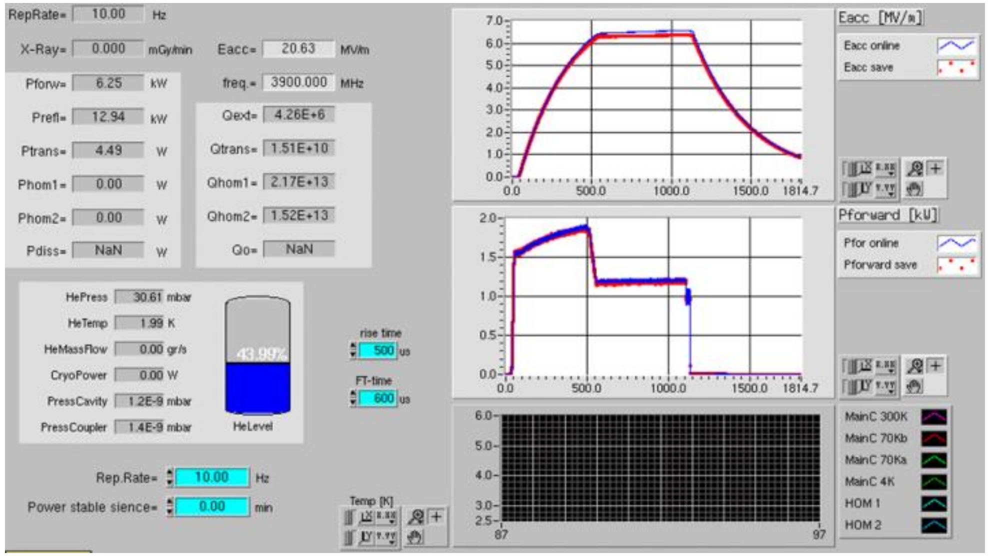
No module test prior to installation!

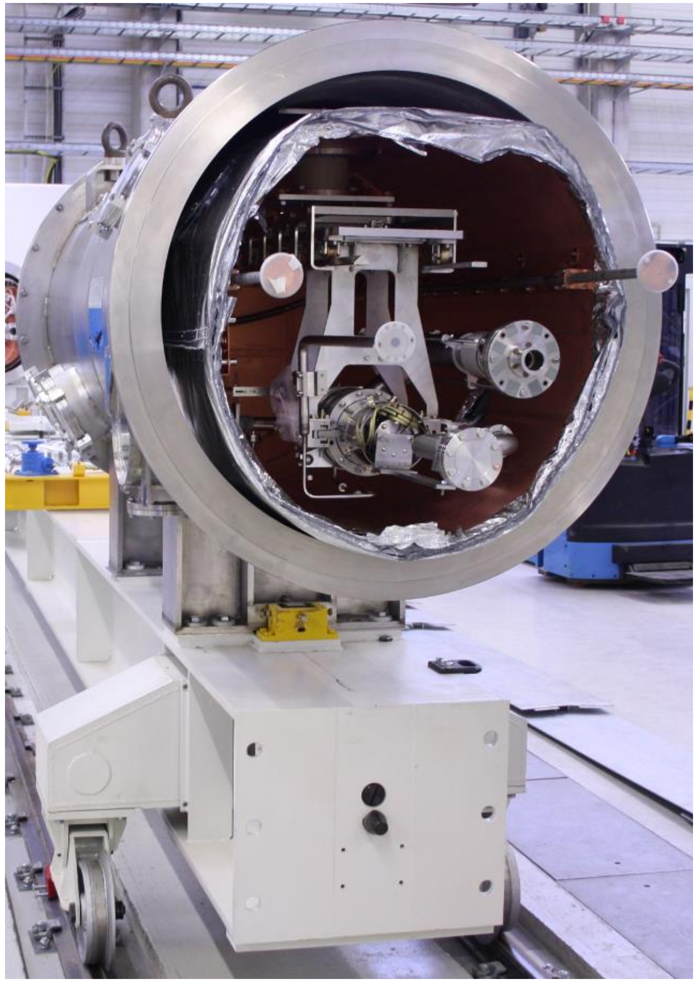
Horizontal test for the **cavity package qualification**

- 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)





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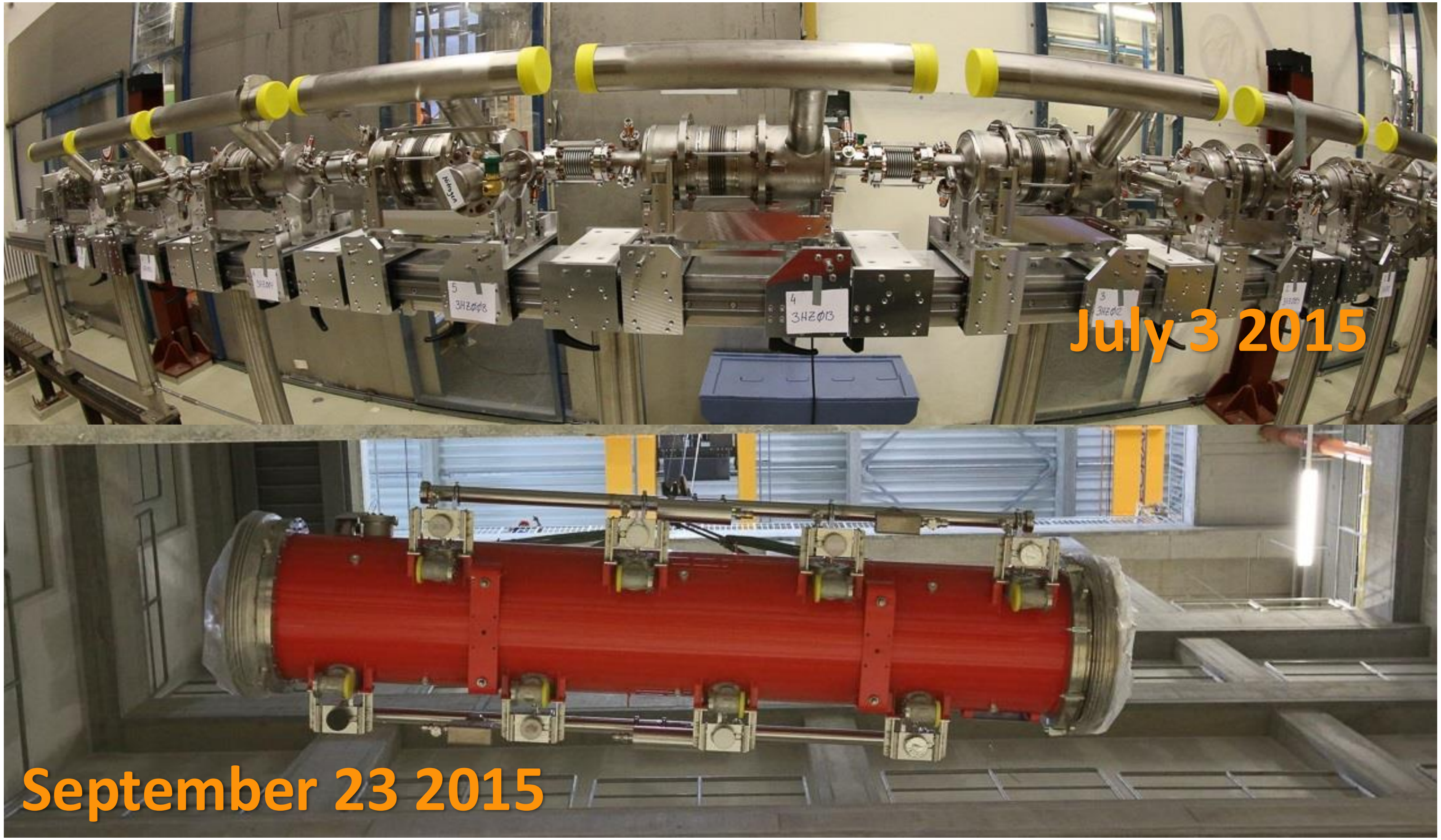
Major AH1 Assembly Milestones



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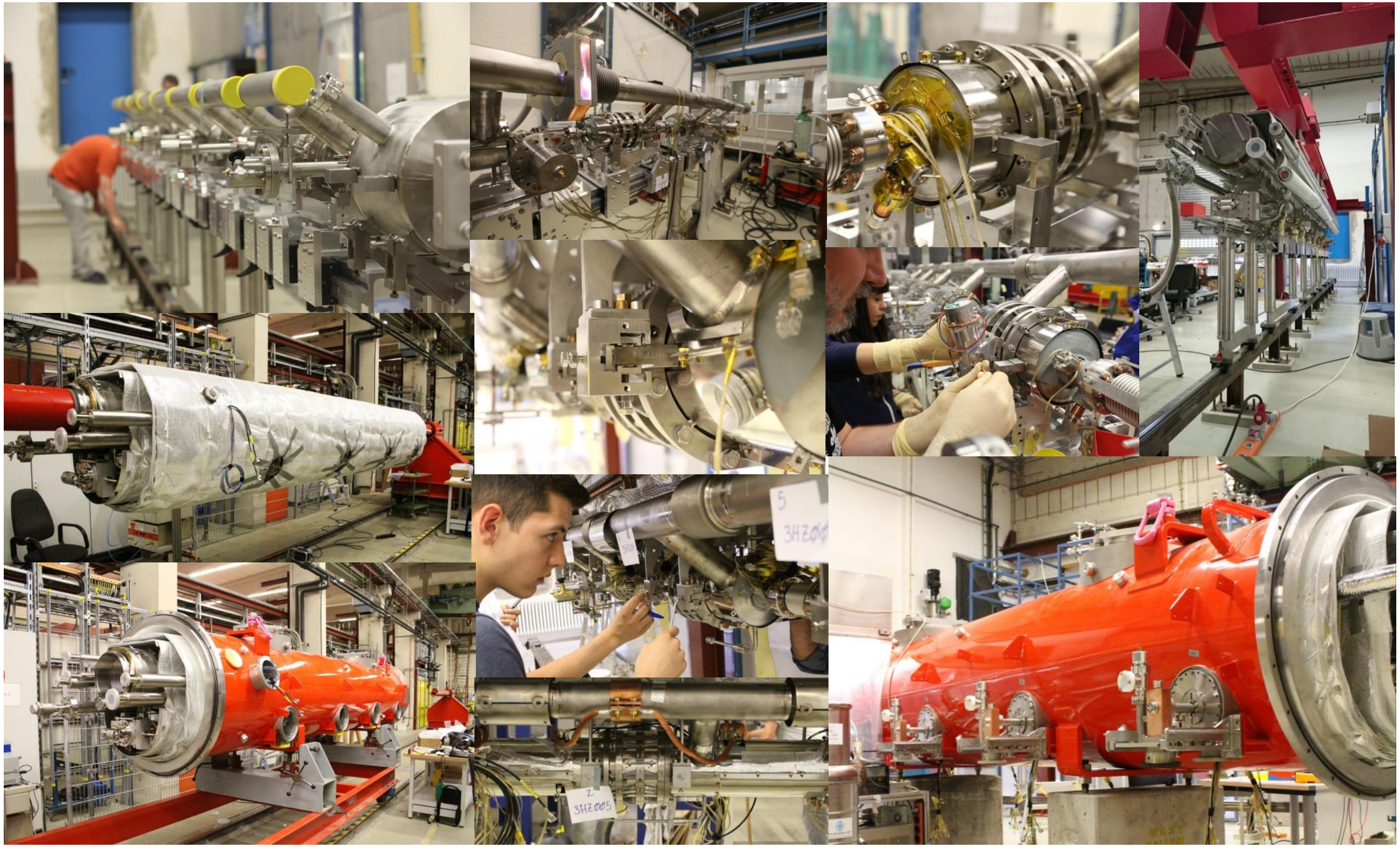
The assembly in Halle III (14 weeks)



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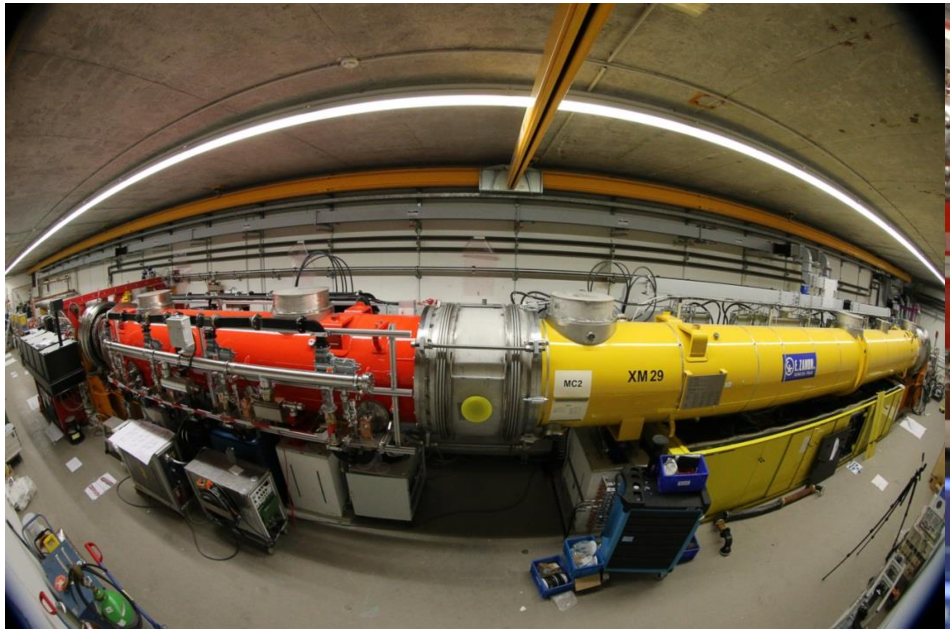
Final Preparation stages in tunnel



Assembly WG distribution

Injector String Integration

Dec 10: **Start cooldown**

Dec 15, Cryo OK- cavity pre-tuning

Dec 16, calibration: **AH1 Ready**

P. Pierini, SRF2017, Lanzhou

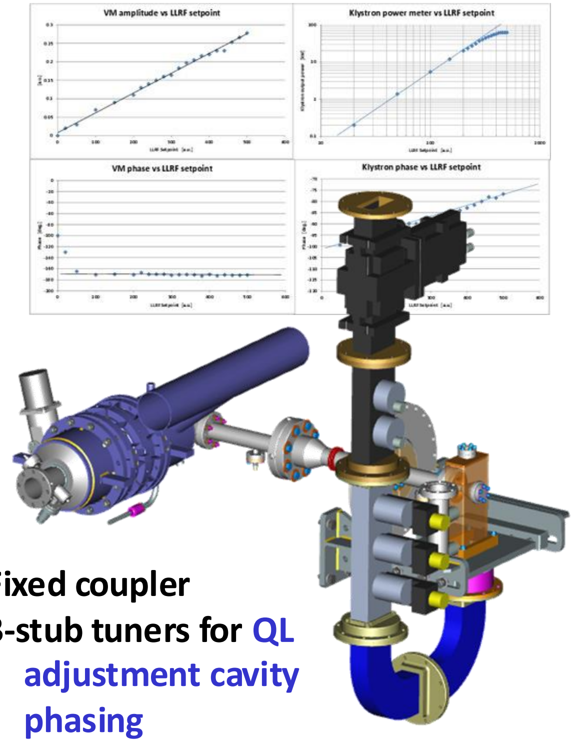
RF Distribution layout

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

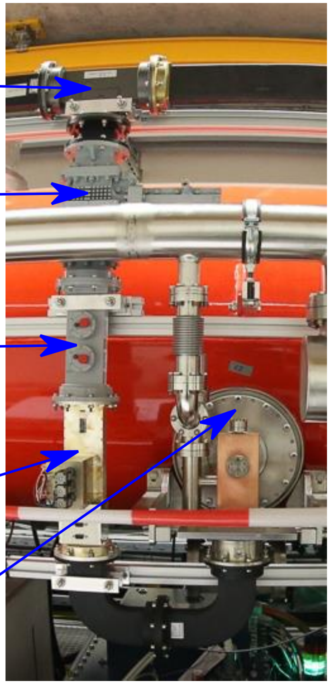
3 dB T

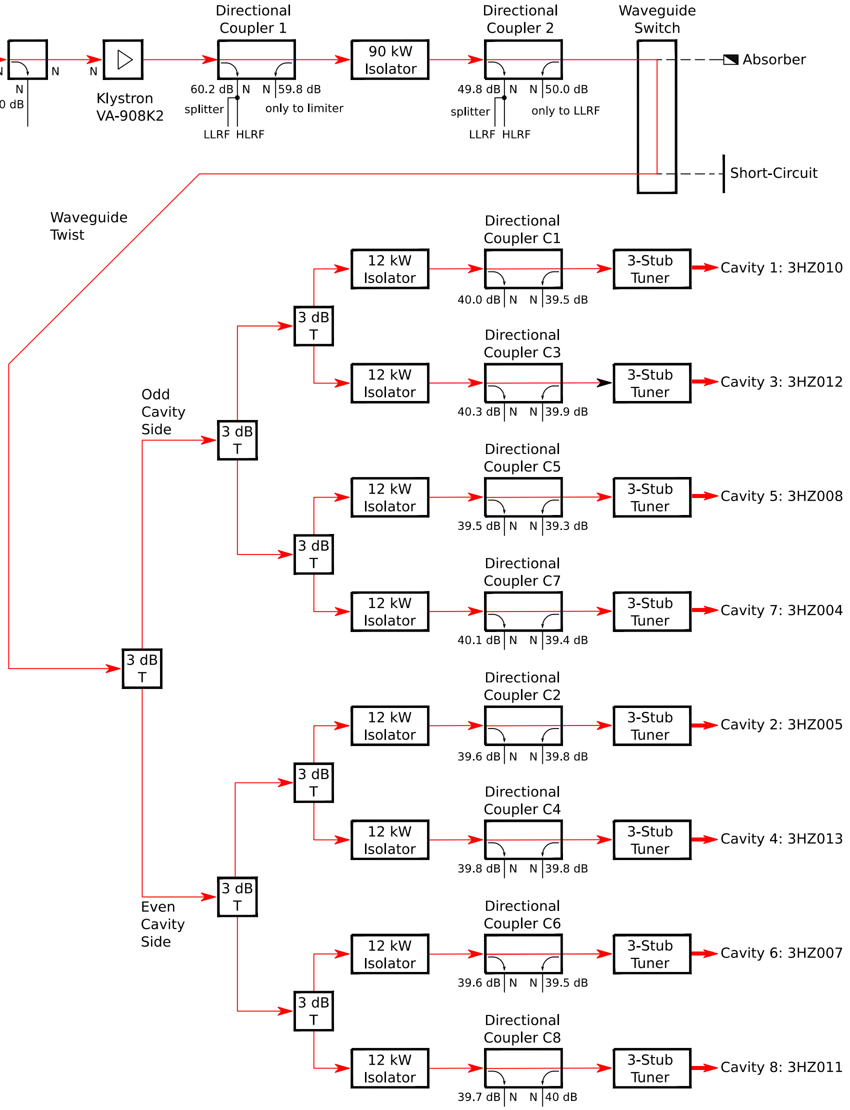
12 kW Isolator

Directional Coupler at cavity

3-Stub Tuner

Cavity Coupler Port





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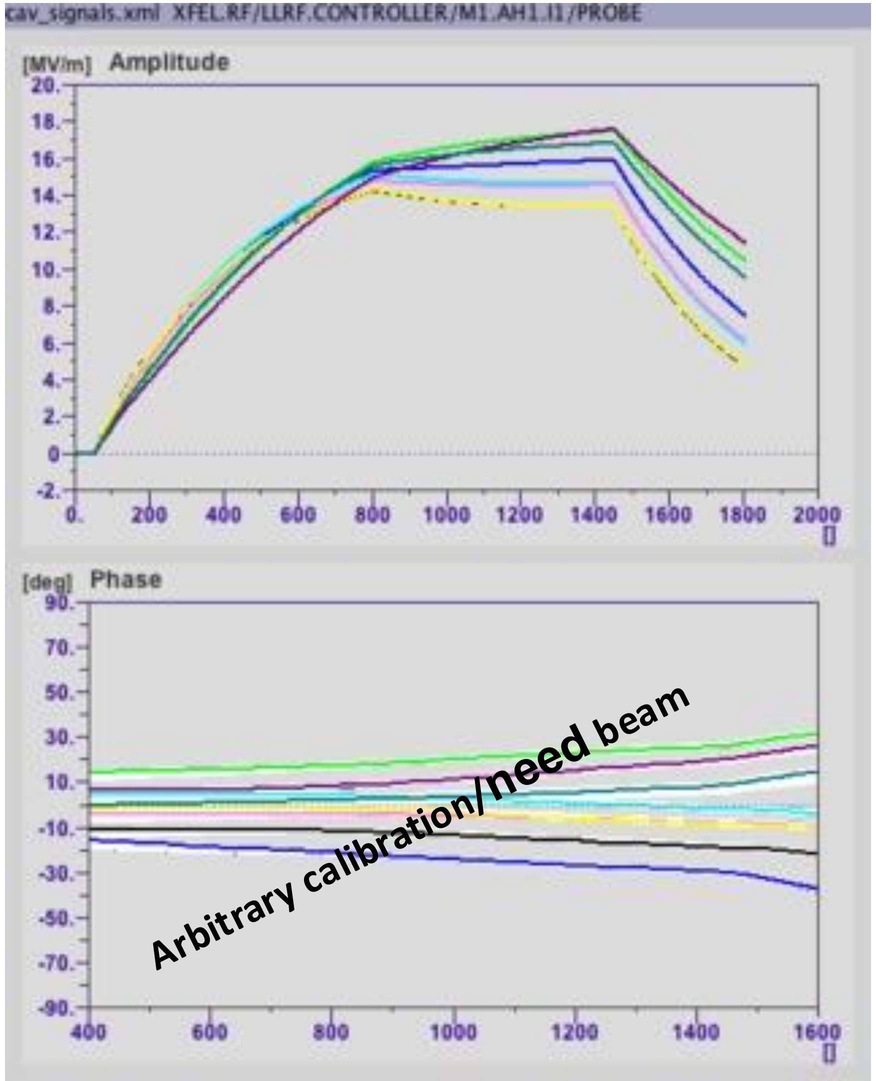
First operation at nominal gradient on Day 1

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 Q_L values not yet tuned***
- **LLRF in FB mode**



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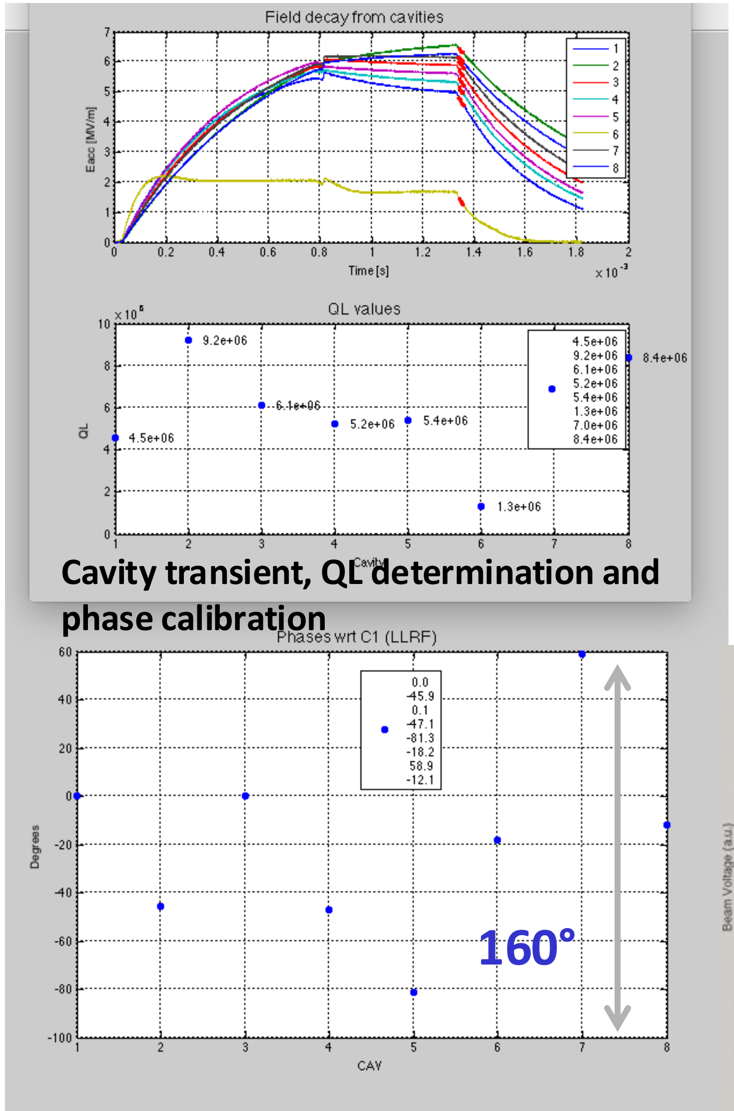
Beam Based calibration: Cavity Phases



January 2016, on beam

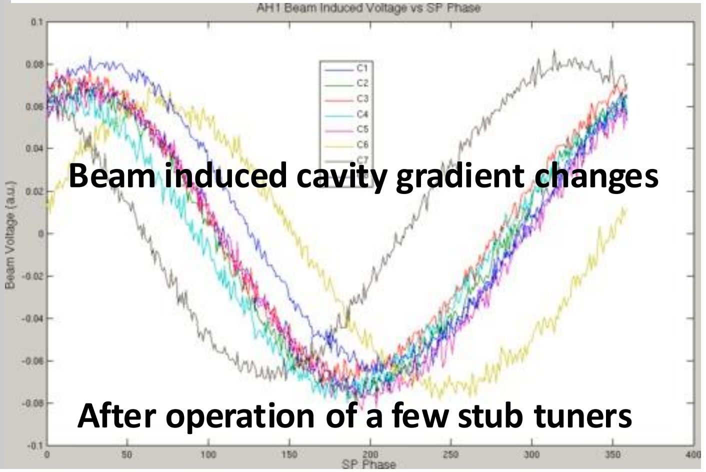
- Beam transients
- Phase Calibrations

Preliminary to :

- **Phase Tuning**
- **Q_L tuning**

Large initial cavity phase spread

- *WG assembled in tunnel, no cal.*



Tune with
- 3-stub tuners
- WG Spacers

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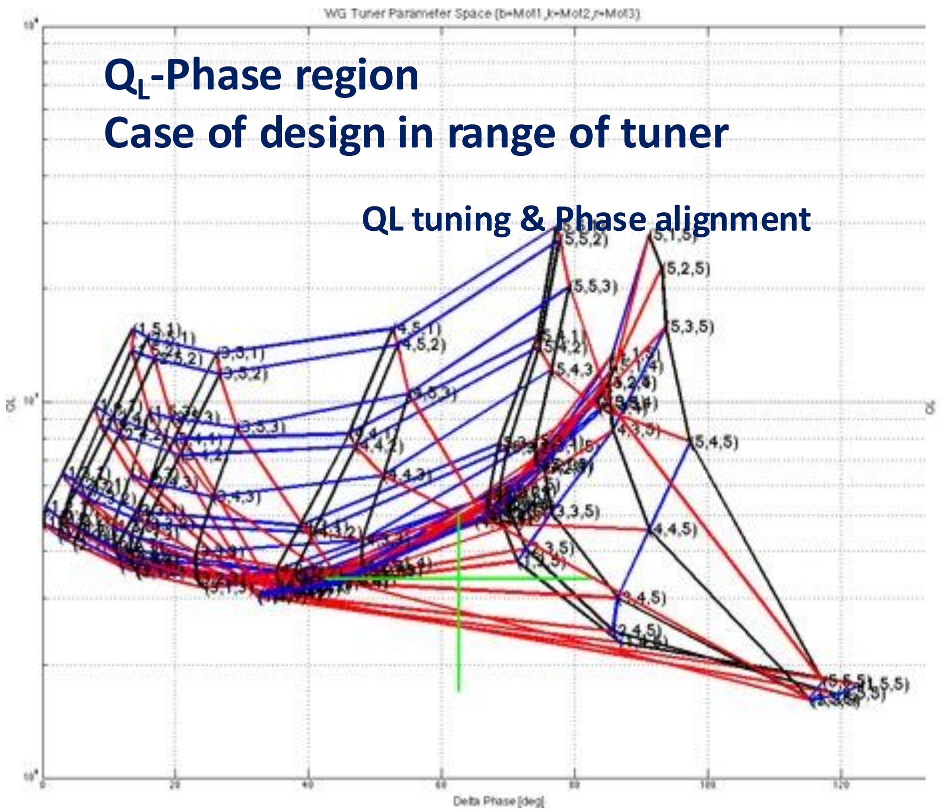
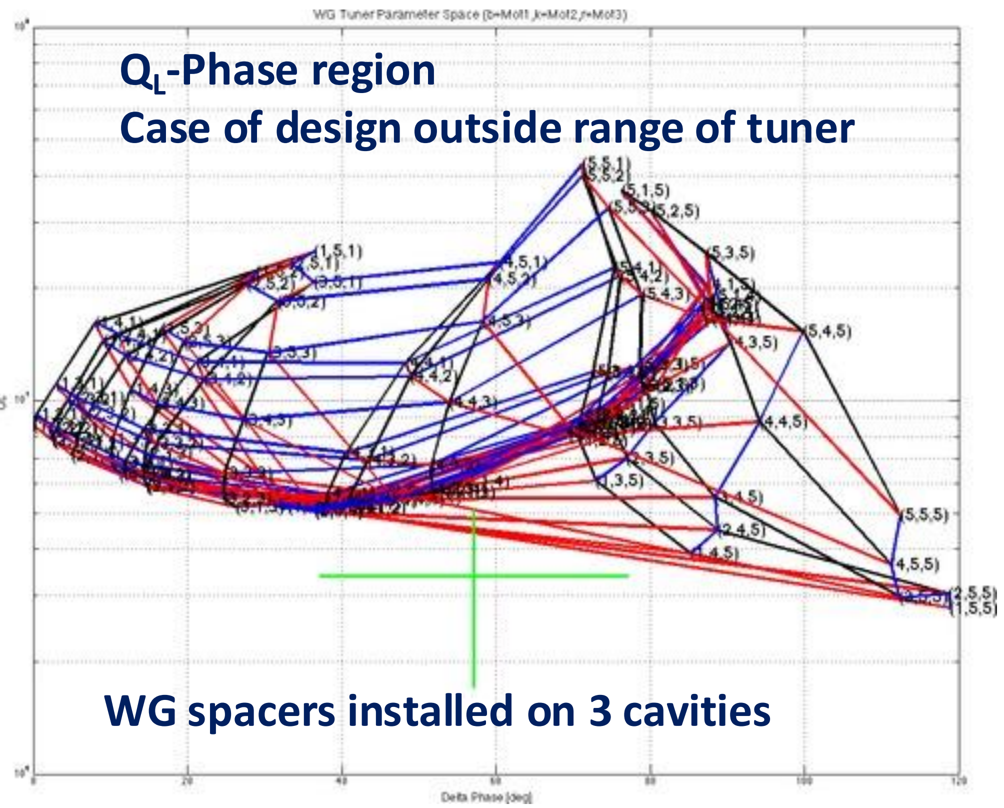
Q_L tuning & Phase alignment

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





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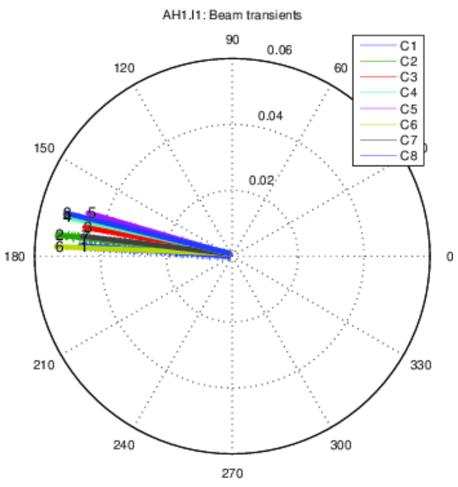
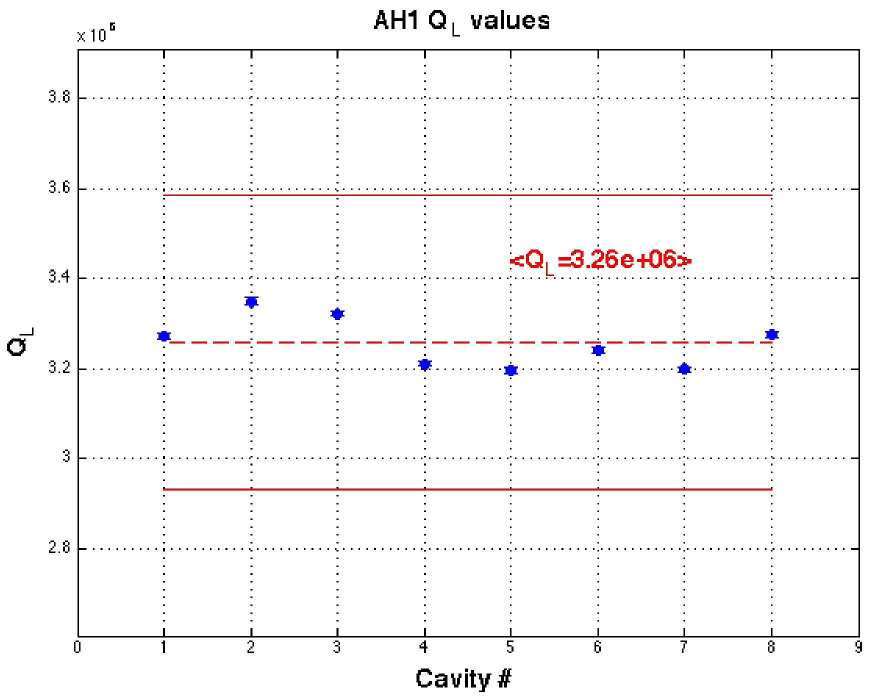
Started regular operation in injector

10 February 2016

- Q_L aligned well within the 10% requirement
- Phases within 15°





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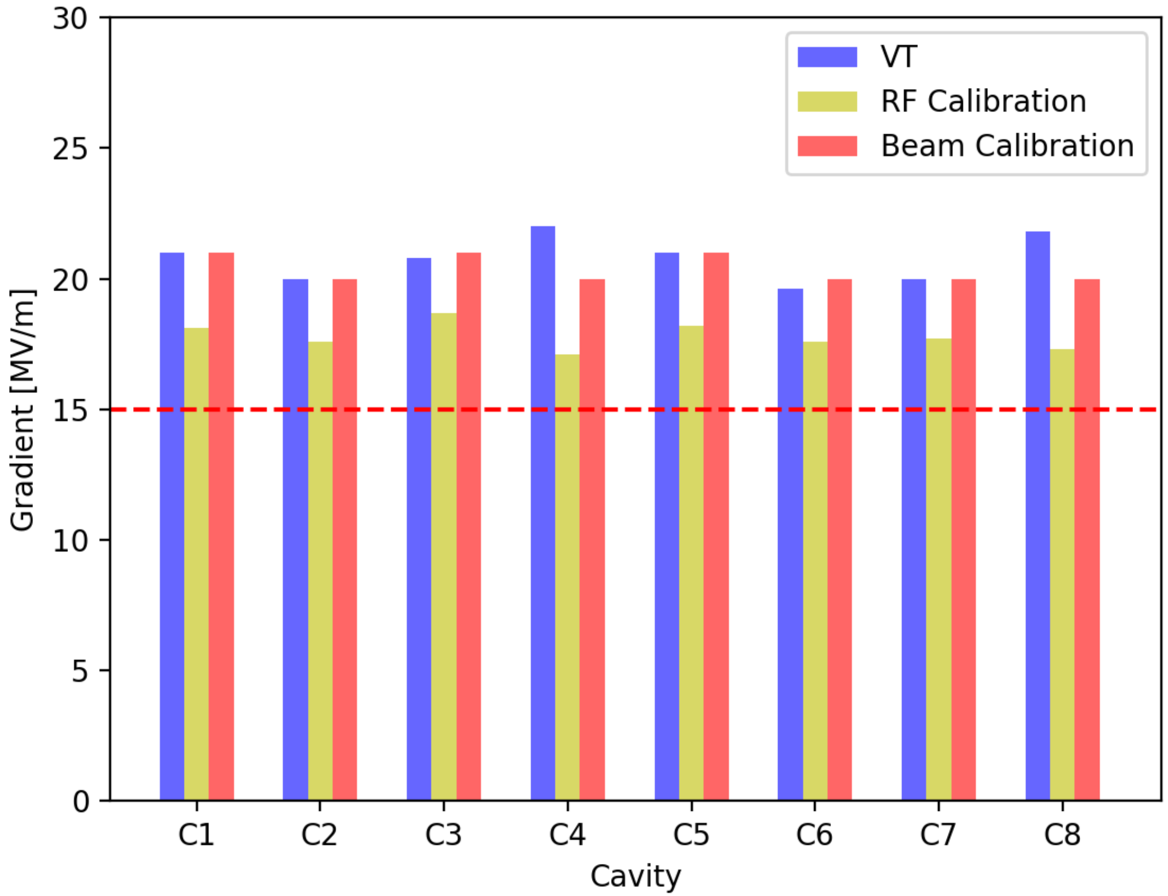
16 February 2016

- 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

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HOM performance

Cavity Q0 is 2E9 (VT measure)

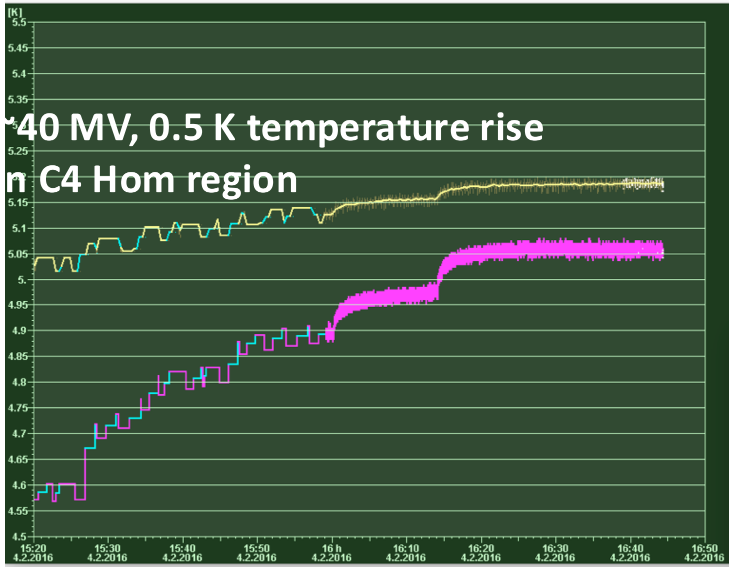
Qt is 1E10 (VT calib)

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.)

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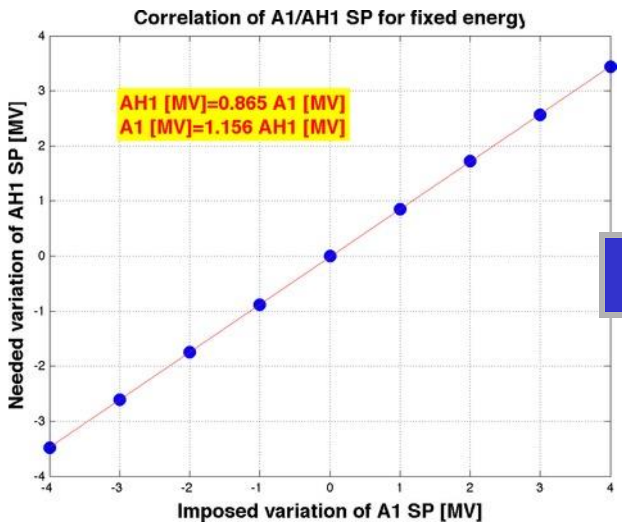
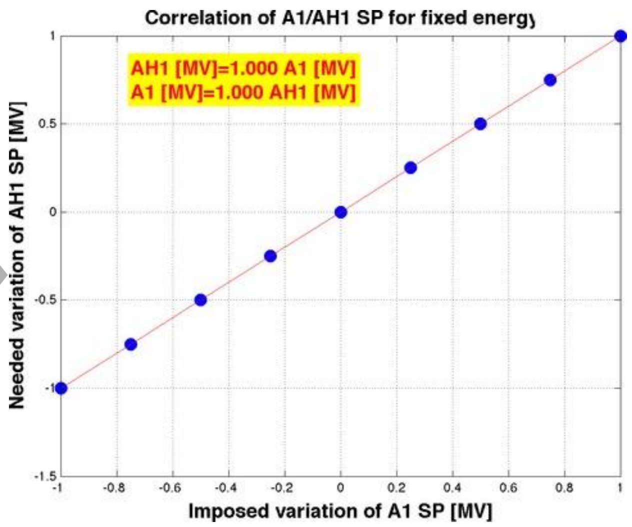
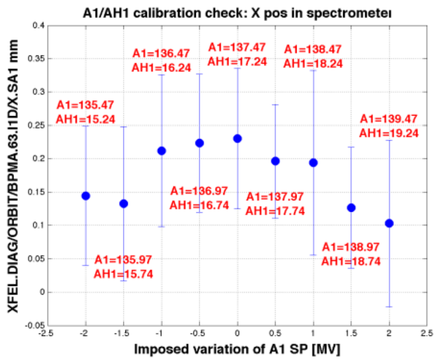
Beam Based Calibration of Module voltage

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







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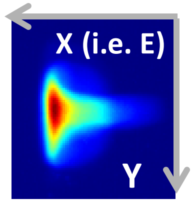
A1/AH1 need to be in good relative calibration (phase and amplitude) to **control the beam** with Sum Voltage Controls

- Improved consistency in VT/XTIN **quench fields**
- **Important to check after RF calibrations are done**

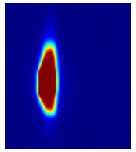
RF Curvature linearization by AH1

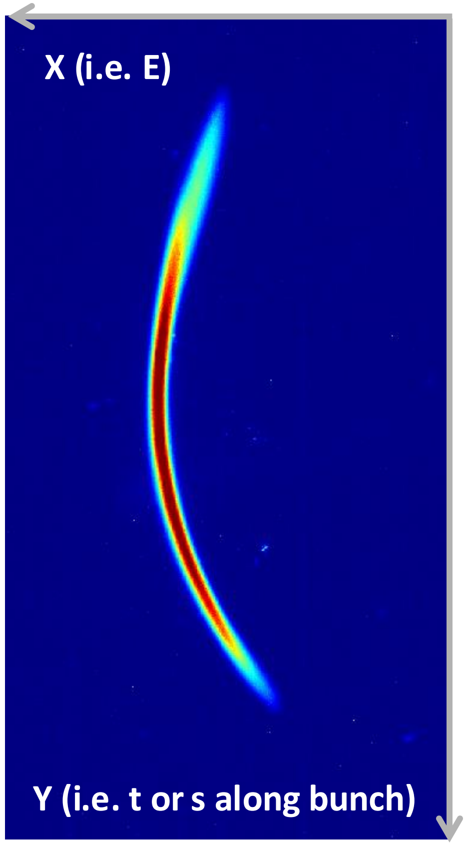
Beam image on screen in the spectrometer beamline



← AH1 off

AH1 on →



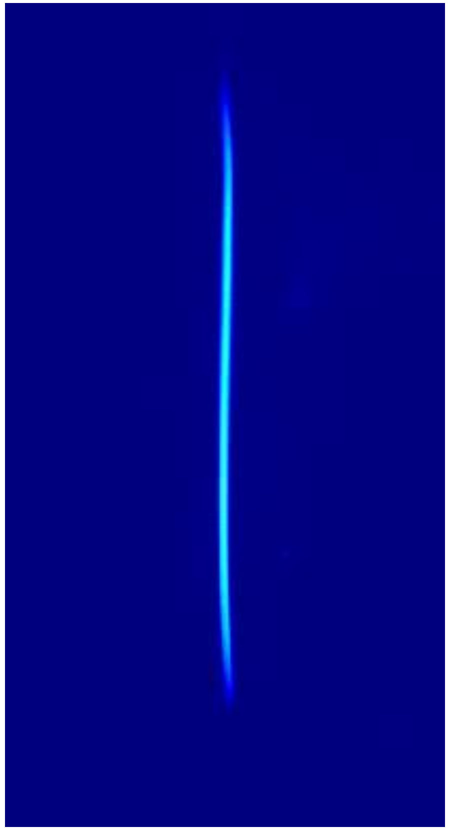


Beam image on screen in the spectrometer beamline, switching on the Transverse Deflecting Structure

← 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



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Summary of 3.9 GHz Module Experience

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…)

Since then, AH1 is a crucial part of the European XFEL user facility reliably operating in Hamburg

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Thank you for your attention