Recent developments towards CW operation of the superconducting XFEL accelerator

Elmar Vogel for all colleagues working on a future CW operation mode of the European XFEL
@ CHILFEL Seminar, May 6th 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

MATTER AND TECHNOLOGIES

DESY.

This talk and transparencies contain contributions

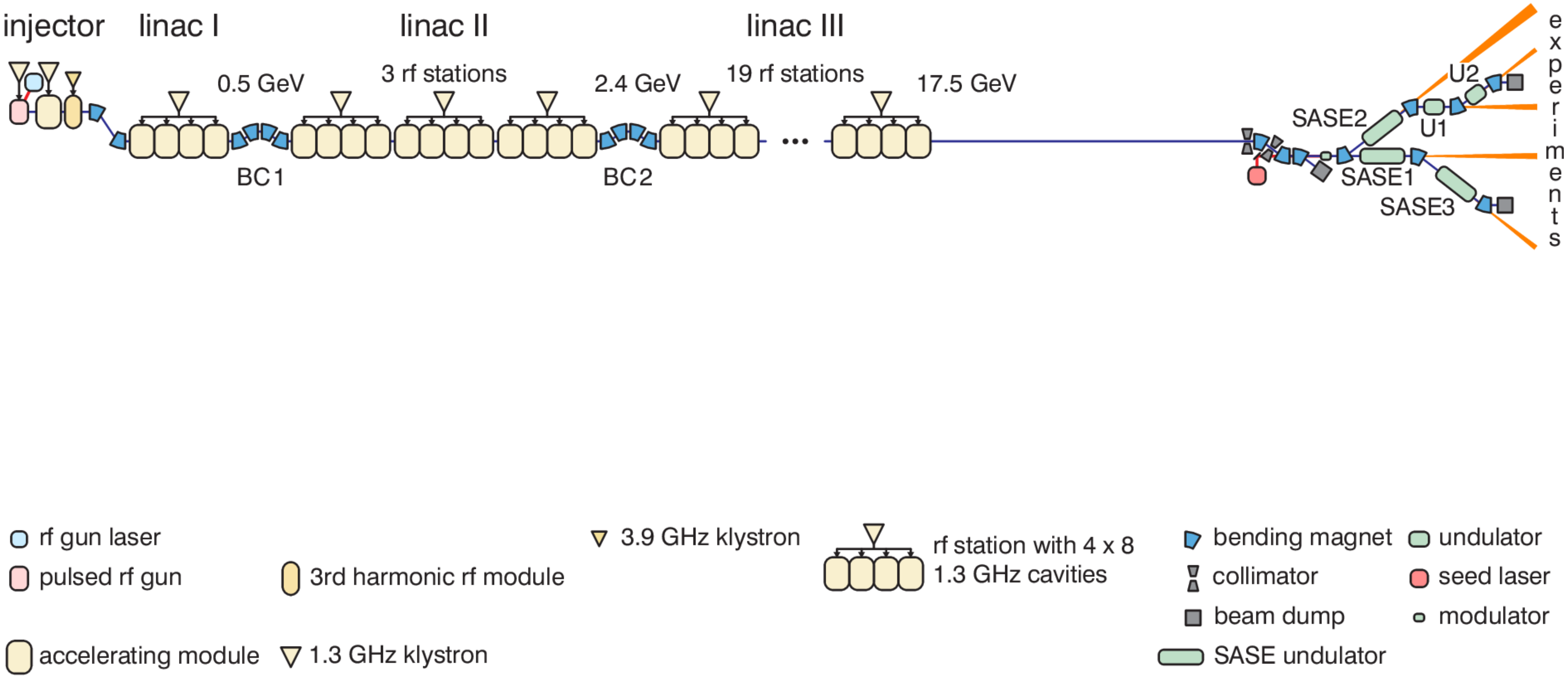
from colleagues in form of transparencies, photographs, information, etc., in particular

Dmitry Bazyl	Joachim Kahl
Andrea Bellandi	Denis Kostin
Julien Branlard	Ruediger Onken
Ye Lining Chen	Houjun Qian
Stefan Choroba	Detlef Reschke
Guilherme Dalla Lana Semione	Tobias Schnautz
Arti Dangwal Pandey	Jacek Sekutowicz
Martin Dohlus	Lea Steder
Jens Iversen	Hans Weise

Many more colleagues are working on a future CW operation mode of the European XFEL. Many thanks to them! The list above contains only the names of the colleagues who provided in any form concrete contents for this talk.

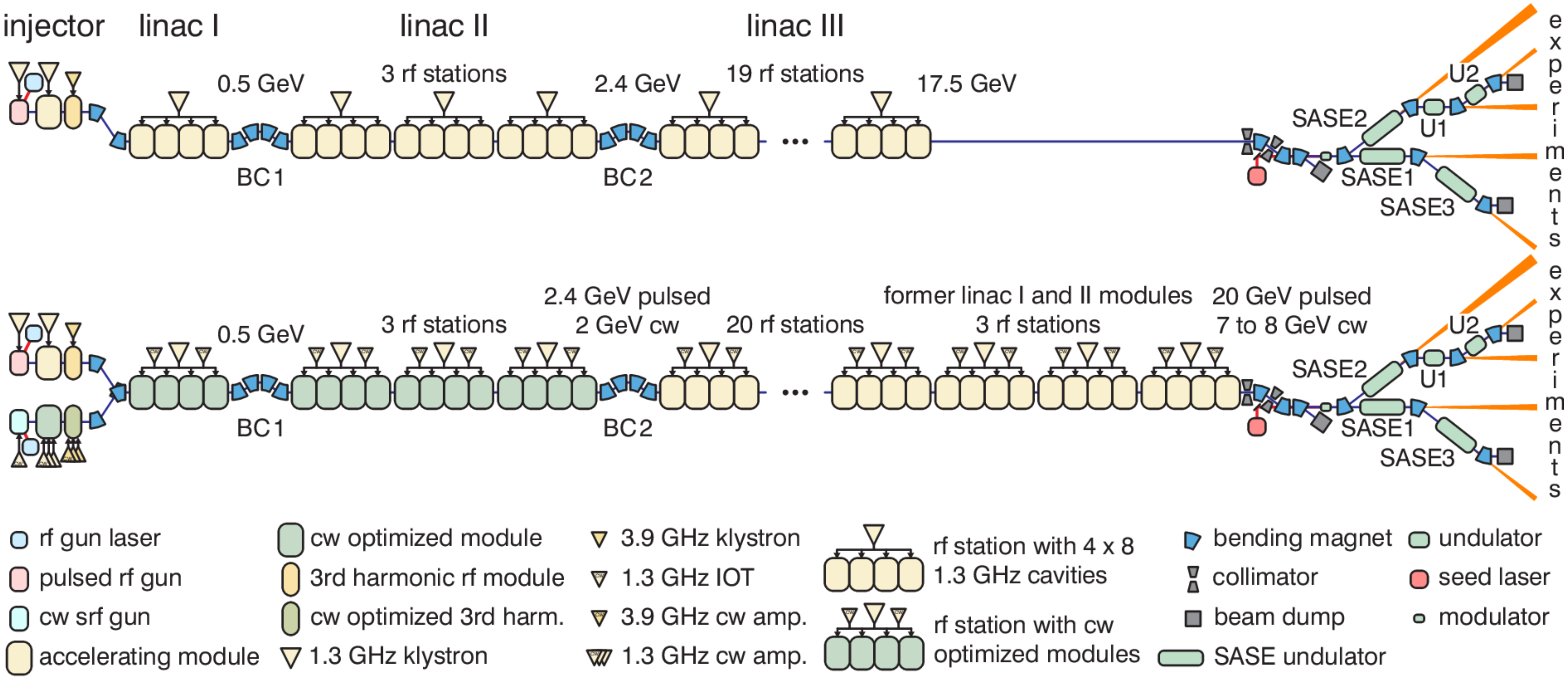
European XFEL

At present: operation with pulsed rf for high energy but with restrictions w.r.t. the time structure



European XFEL

CW upgrade: operation with pulsed rf or with cw rf at lower energy but with flexible time structure



Main Linac / Linac III

- RF power source
- RF power switches
- RF control
- performance of present modules and cavities
- concerning cryogenics

RF power source

Inductive output tube (IOT)

Motivation

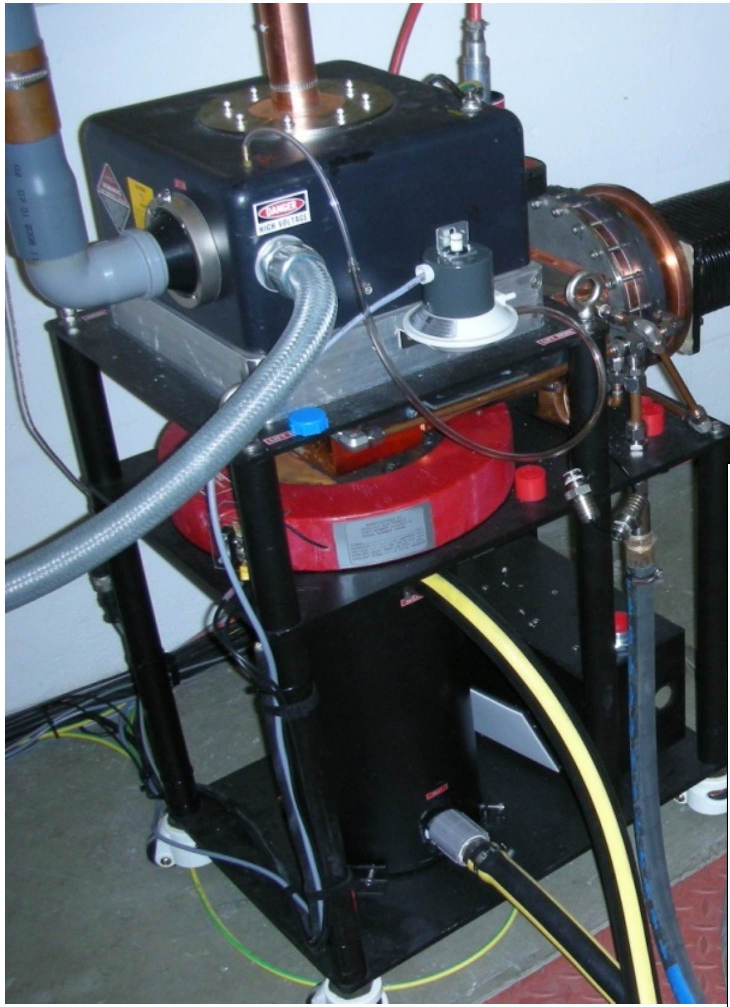
- XFEL klystrons not designed for CW operation
- additional CW RF system (2x) adjacent to klystrons

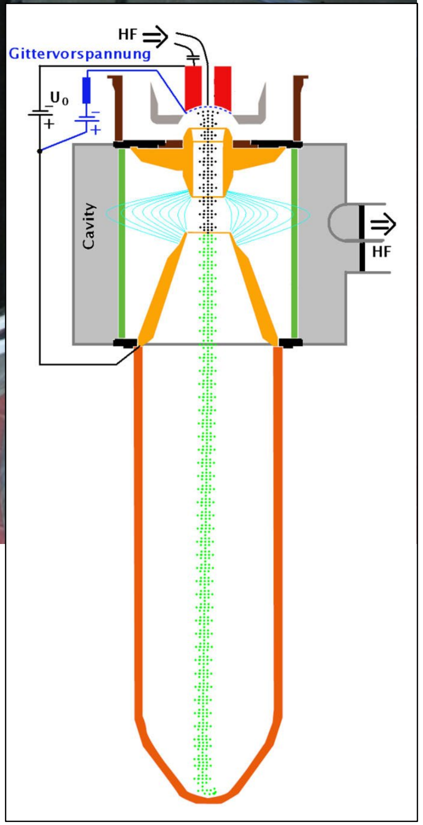
Requirements

- RF output power: 120 kW at 1,3 GHz

Status

- IOT prototype in test operation at DESY since 2010
- 120 kW initially achieved
- after some years a disruptive discharge appeared
- hence, design requires further improvements
- provides still sufficient RF power for CW module tests





An IOT operates similar to a klystron but uses current modulation like an ordinary triode rather than a buncher cavity.

RF power switches

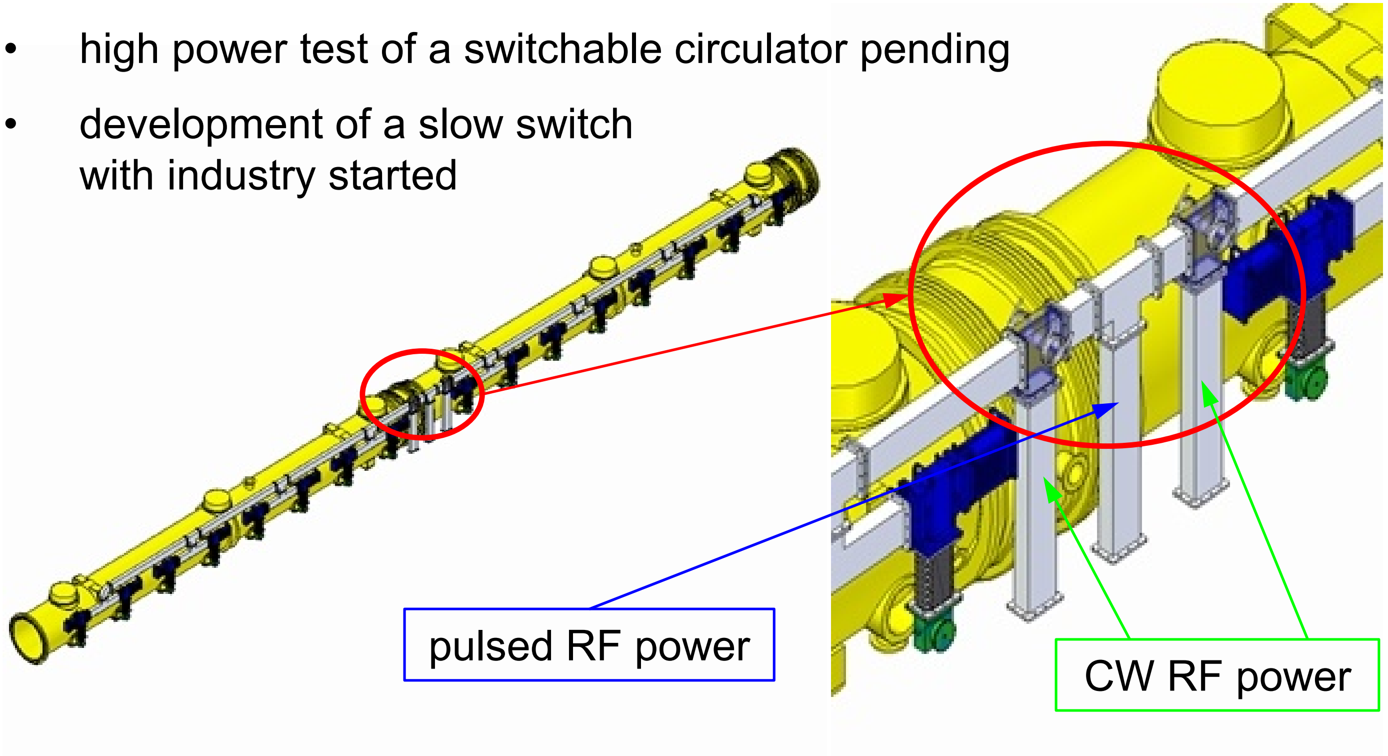
alternating operation of the XFEL in pulsed and CW mode

Goal

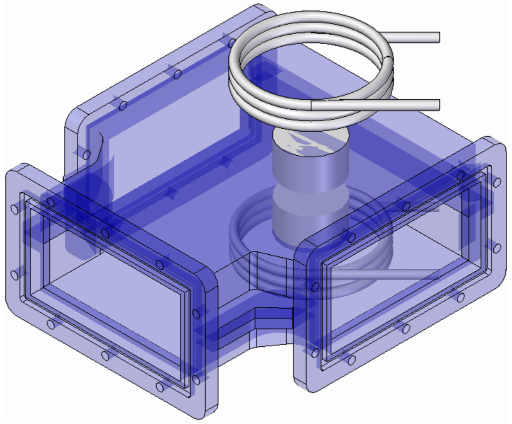
- We need a device switching the RF power distribution between the pulsed and CW RF power source.

Status

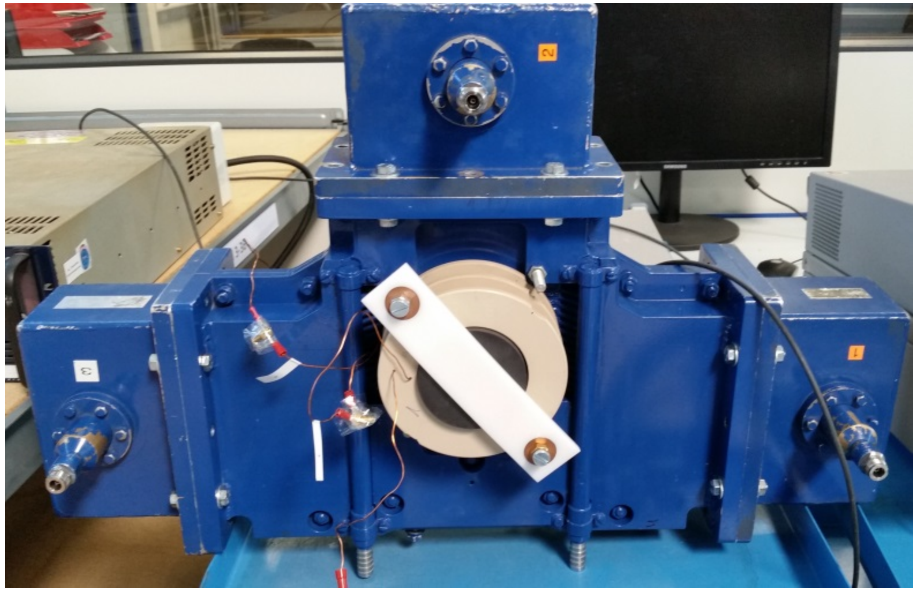
- low power test of a (in ~2 ms) switchable circulator successful
- high power test of a switchable circulator pending
- development of a slow switch with industry started



sketch drawing of a switchable circulator



first prototype of a switchable circulator

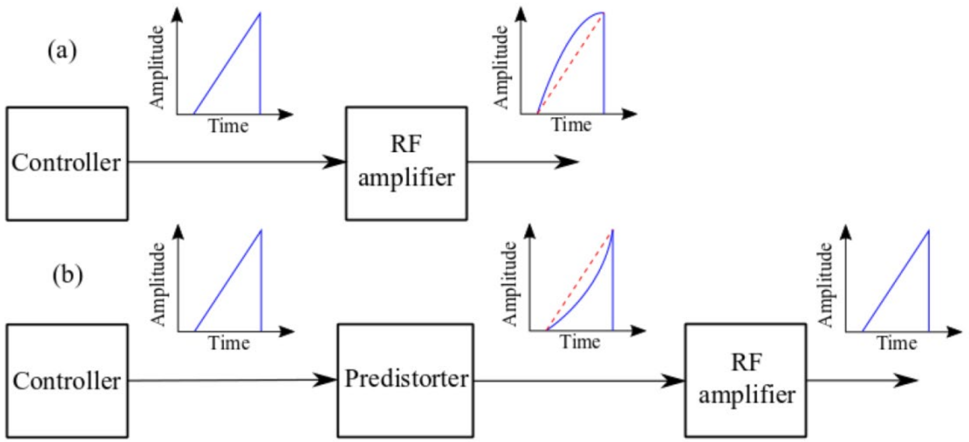


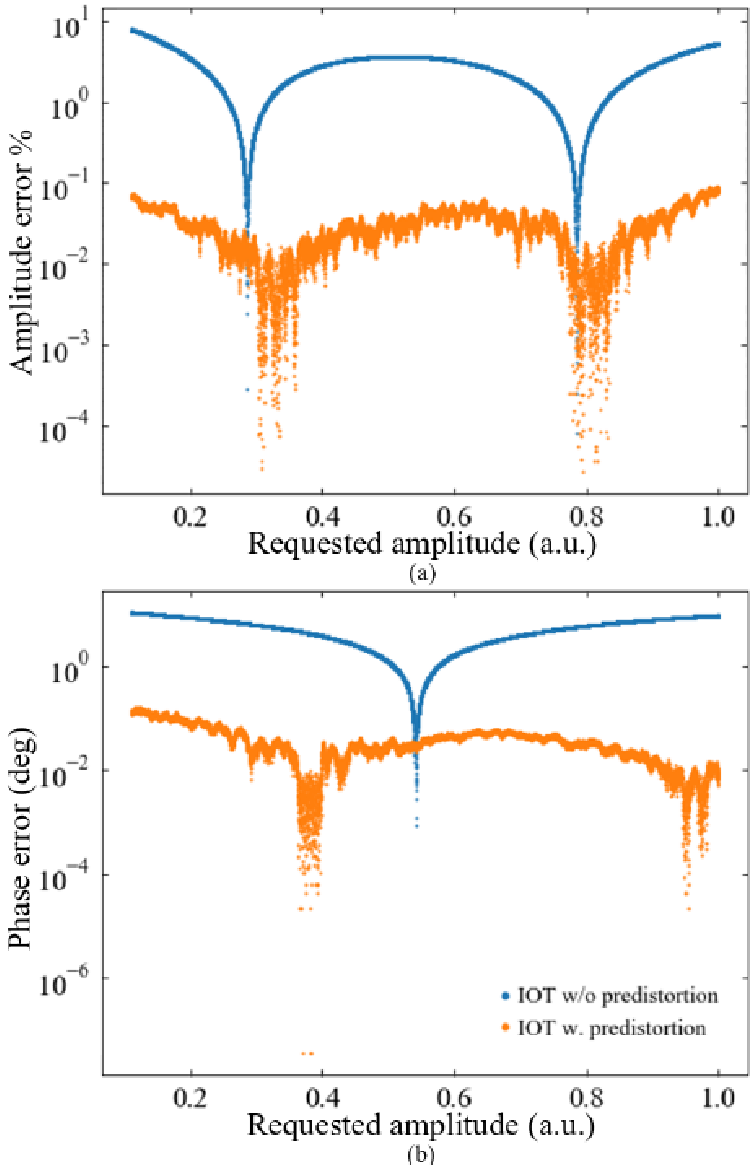
RF control for CW operation

RF power source linearization

Development of a pre-distorter in the LLRF drive firmware

- tested with IOT and klystron
- provides 2 orders of magnitude improvement in linearization





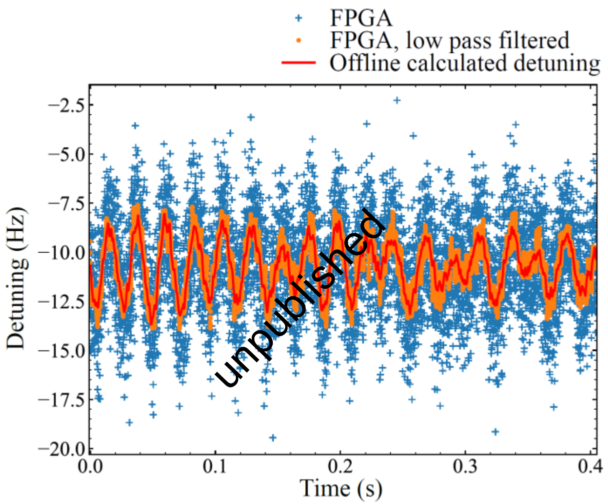
Reference: "Results on FPGA-based High Power Tube Amplifier Linearization at DESY",
Bellandi et al., IEEE Transactions on Nuclear Science (Volume: 67, Issue: 5, May 2020)

RF control for CW operation

Detuning and bandwidth computation in CW

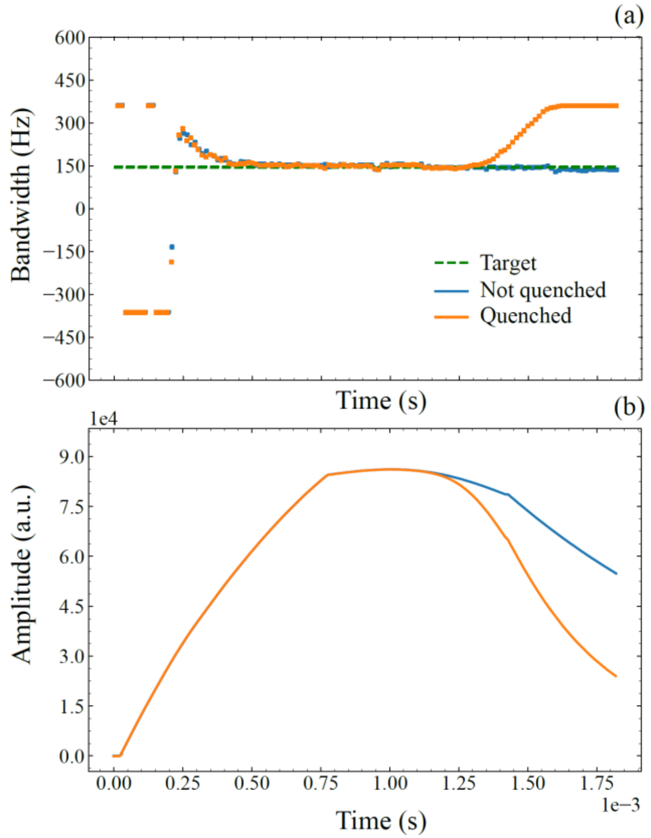
Development of a detuning / bandwidth estimator component in FPGA

- component is implemented and validated with RF in pulsed and CW mode
- predicts very accurately (< 1Hz resolution) cavity detuning / bandwidth within a few 10s usec of data acquisition



Reference: "Online Detuning Computation and Quench Detection for Superconducting Resonators", A. Bellandi et al. publication pending

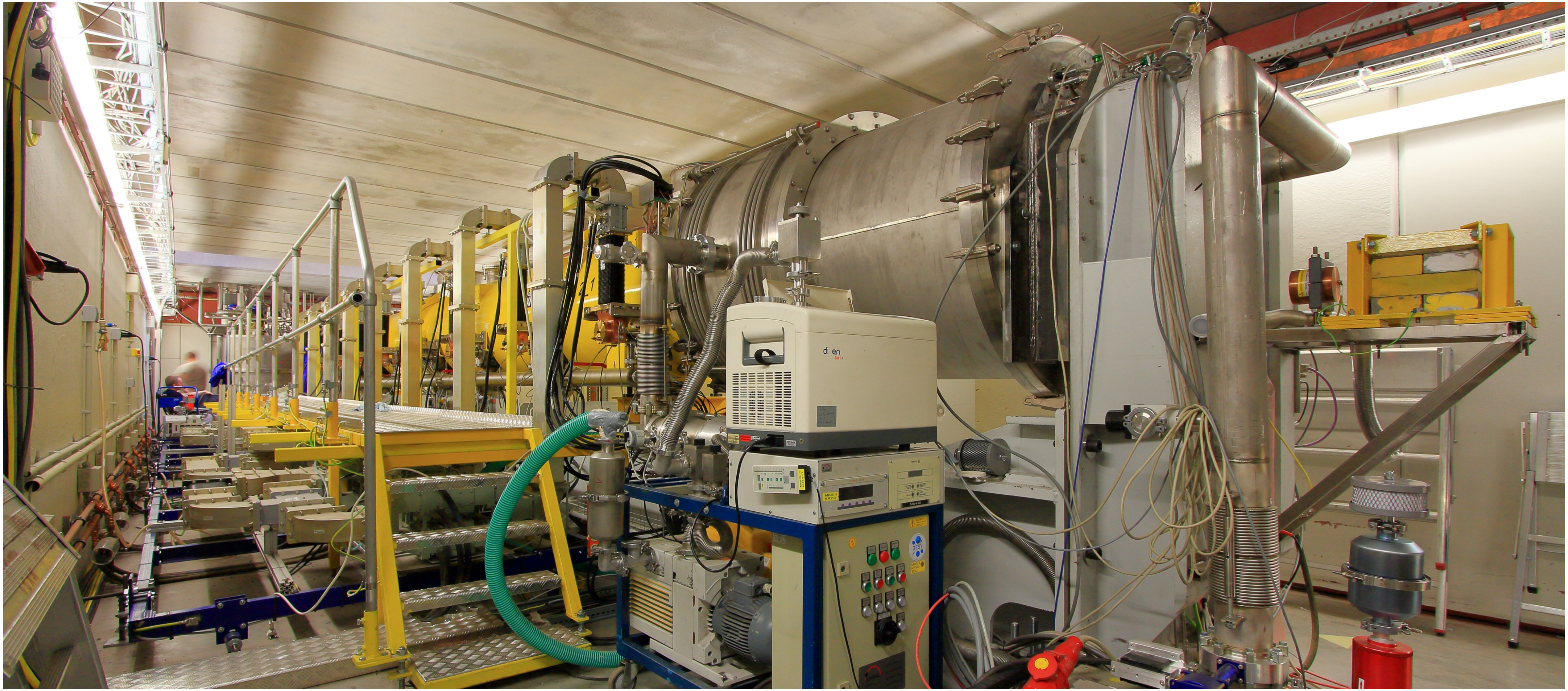
- Bandwidth can be used to detect quenches in pulsed and CW operation



- Detuning can be used for fast piezo feedback to cancel wide-band microphonics-induced detuning

Performance of present XFEL modules and cavities

powered with CW RF at the Cryomodule Test Bench (CMTB)



Performance of present XFEL modules and cavities

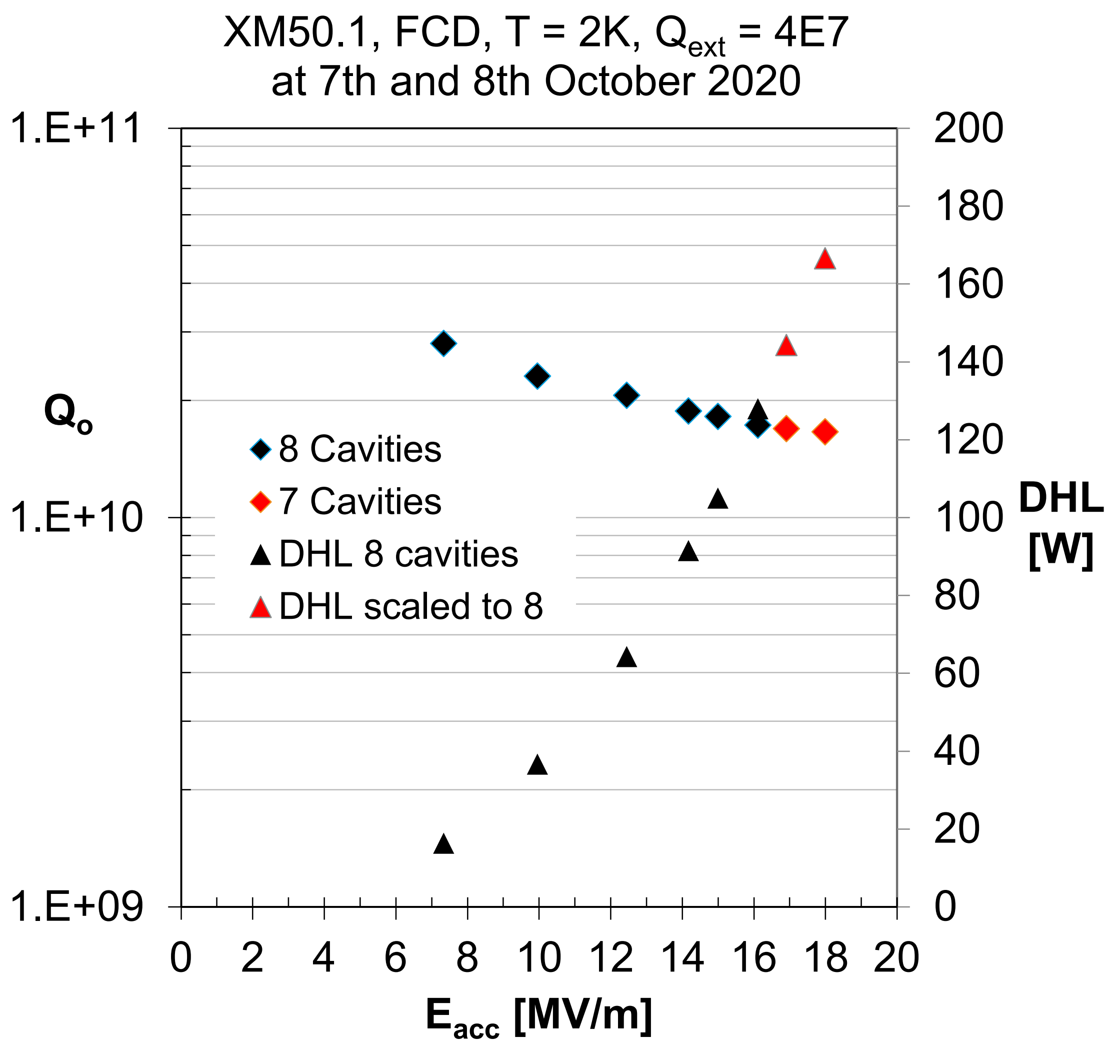
powered with CW RF at the Cryomodule Test Bench (CMTB)

XFEL series modules tested with CW RF

- XM4 reached 15 MV/m per cavity in 2015
- XM50.1 reached 16 MV/m per cavity in October 2020, operating 7 out of 8 cavities 18 MV/m where reached

XFEL pre-series module with 7 large grain cavities

- XM-3 reached 17 MV/m per cavity in April 2017



Conclusion

- reasonable gradients are achieved operating XFEL type modules in CW
- **But:** the high gradients operating CW come on the expense of a strong increase of the dynamic heat load (DHL) which needs to be cooled away by the cryogenic system

Concerning cryogenics

conclusions from the XM50.1 dynamic heat load measurements

Present cooling capacity at 2 K

- The heat load limit is 20 W at 2 K per cryomodule when operated in the 12-cryomodule long cryogenic string.
- Currently, the total XFEL cryogenics system capacity is 1,9 KW at 2 K, defined by the cold compressors.
- The AMTF series tests of XFEL modules reveal a static heat load of 6 W at 2 K per cryomodule.

Conclusions from the XM50.1 results

- A dynamic heat load of 14 W at 2 K per cryomodule is reached at an average gradient of 7 MV/m providing an energy gain of 5.36 GeV in 23 x 4 x 8 = 736 cavities in the linac III. This is in line with the 20 W limit above.
- For 6 GeV energy gain in linac III one needs to operate an average gradient of 7.84 MV/m creating a dynamic heat load of 20.4 W at 2 K per cryomodule and 2,43 kW at 2 K in total for linac III.

Future cooling capacity at 2 K

- For the CW operation mode the cooling capacity at 2 K needs to be doubled.

Installing CW RF optimized modules and cavities at the beginning of the accelerator (injector, linac I and linac II) preserves 0.5 GeV at BC1 and 2 GeV at BC2 and consequently for the most part the bunch compression scheme.

Linac I and Linac II

- CW optimized modules and cavities
- Nitrogen doping and infusion
- large grain cavities
- power couplers

CW optimized modules and cavities

bringing the cryogenic load and the capacity of the cryogenics systems in line with each other

Goal

- reaching the "LCLS-II acceptance limits" operating CW
  - minimum voltage per module: 128 MV
  - heat load operating 128 MV: total at 2 K ≤ 93 W
- preserving the pulsed RF properties of the linac II
  - minimum voltage per module: 240 MV (L2 spec.)
  - meeting the XFEL acceptance criteria from 2014

Comments

- The LCLS-II modules do not meet the XFEL linac II criteria for the pulsed RF!
- Studies will tell, if this criteria require modification.

Under study

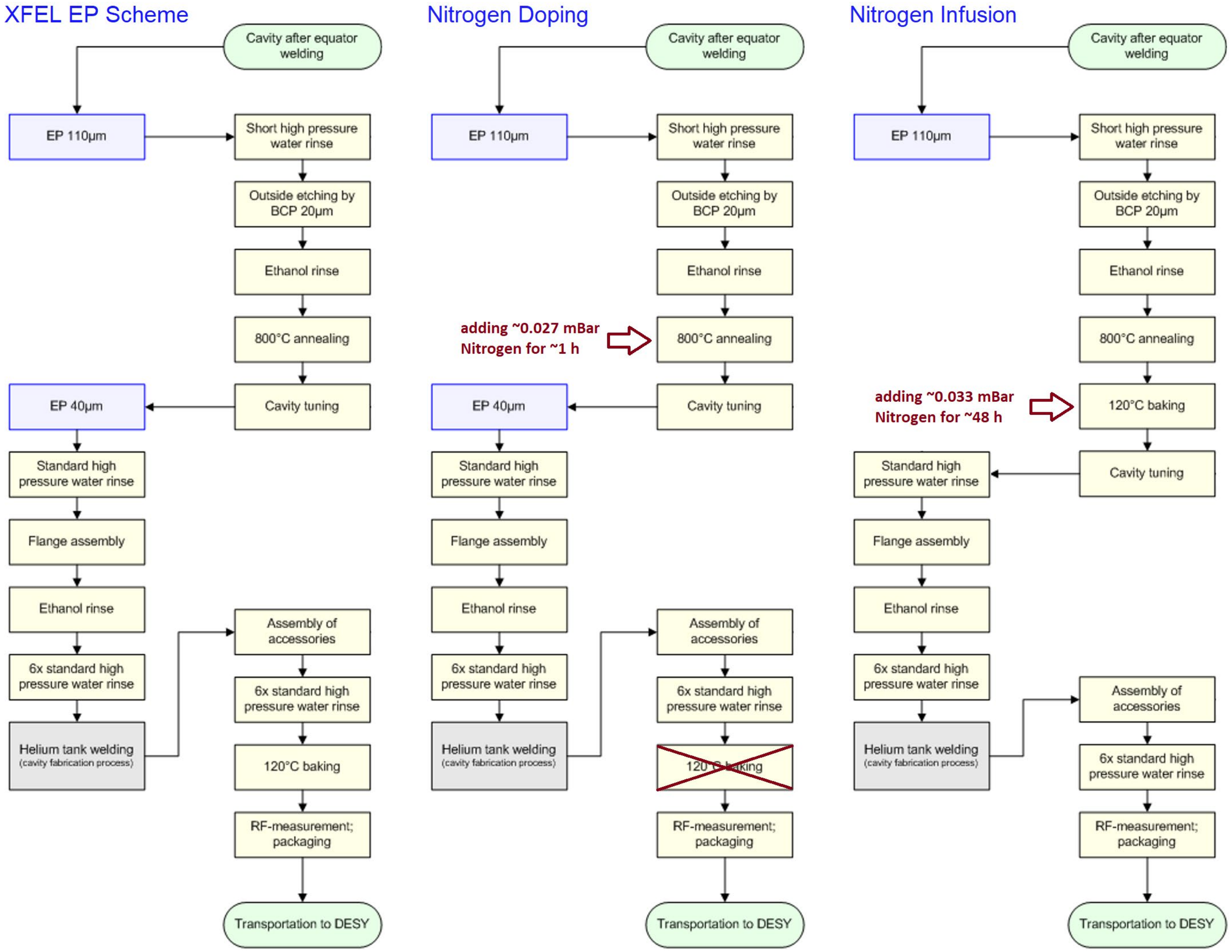
- cavities with higher Q_0 values cause less heat load
  - Nitrogen doping (limited at medium gradients!)
  - Nitrogen infusion
  - large grain cavities
- optimized power couplers

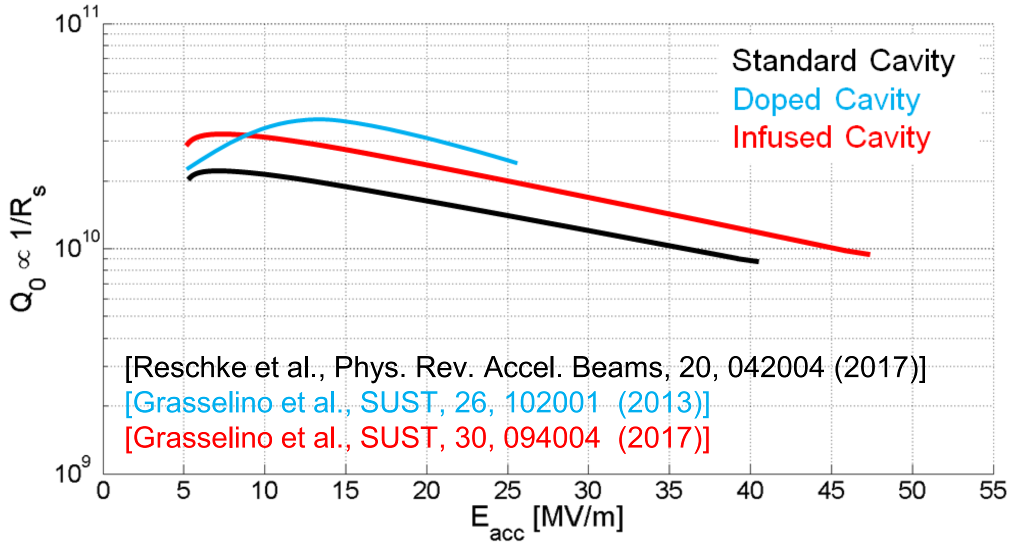
To be done for a first prototype module

- larger diameters of Helium supply and return lines

Nitrogen doping and infusion

modifications of the XFEL surface preparation process





Status

- Nitrogen doping has been developed at FNAL and industrialized for the LCLS-II cavity production resulting in high Q values but limited maximum gradients. Consequently, this process is no solution for a XFEL CW upgrade!
- Nitrogen infusion has been performed at FNAL, resulting in high Q values and high gradients
- SRF laboratories world wide try to reproduce the Nitrogen infusion process

Nitrogen infusion studies

search for stable recipe producing high performance cavities

Two R&D approaches at DESY

- in-situ infusion of samples followed by surface characterization techniques

  ⇨ decoding the surface physics

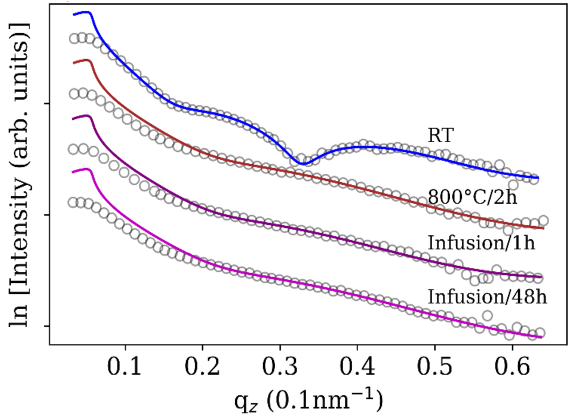
- heat treatment of cavities and samples
  - vertical tests of cavities
  - surface analysis of samples

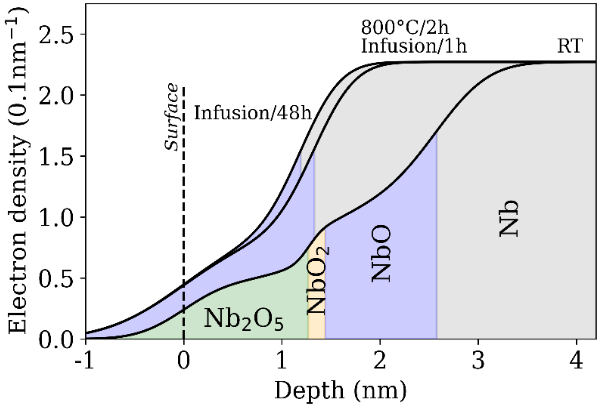
  ⇨ correlation of surface and RF properties

Nitrogen infusion studies at FS-NL

in-situ XRR: Low temperature N2 treatment of Nb SRF cavities

SC Nb(100) → 800 °C/2 h, $\sim 10^{-7}$ mbar → 120 °C / 48 hours, N_2 (3.3×10^{-2} mbar)



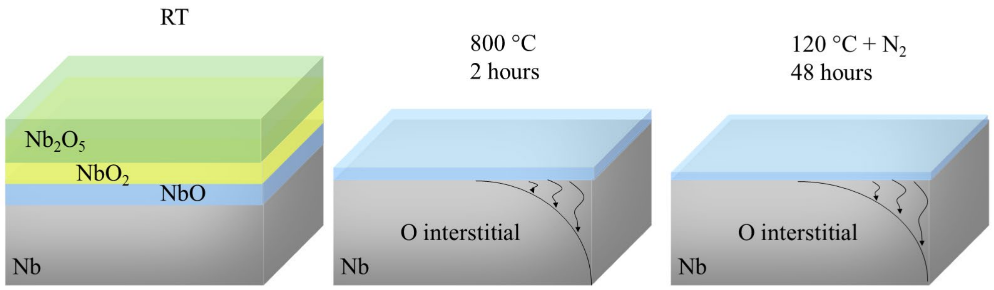


Role of nitrogen in the infusion process

- sample treatment in UHV chamber on high-purity, UHV-annealed single crystal Nb (100) – as a model system
- surface analysis wrt. oxides, nitrides, hydrides and interstitials
- in-situ XRR and GIXRD experiments, XPS, SEM, AFMtext

Results of in-situ XRR & XPS

- NbO remains during treatment
- but no nitride phase identified after nitrogen infusion process
- no other unexpected layers
- natural oxides re-grow after venting



[G. D. L. Semione, A. Dangwal Pandey, S. Tober *et al.* in: Phys. Rev. Accel. Beams 22, 103102 (2019)]

Nitrogen infusion in UHV at very low pressure

Large grain Nb (100) sample: in-situ XPS experiment, Nb-N observed

decoding the role of the nitrogen in the infusion process

- sample treatment in UHV chamber on UHV-annealed single crystal Nb (100) – as a model system

800 °C + 120 °C/12 h in UHV

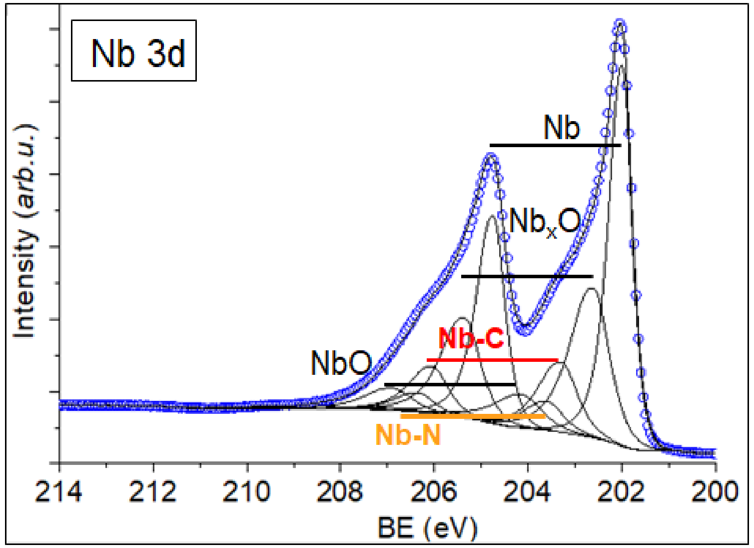
- NbO, NbC present on surface
- no Nb-N observed

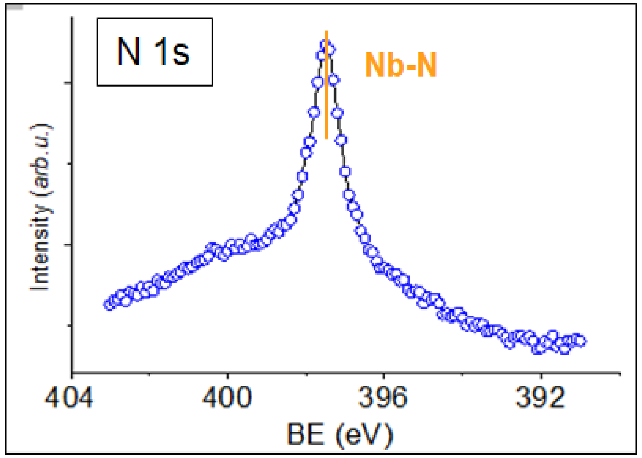
+ 120 °C in N2 (0.004 mTorr)/13 h

- NbO grows further
- NbC still visible
- Nb-N observed on surface

results of in-situ XPS

- NbO phase present after 800°C annealing
- Nb-N bond formation observed after nitrogen-infusion process
- On-going study: changes in surface layer after oxidation (venting)?

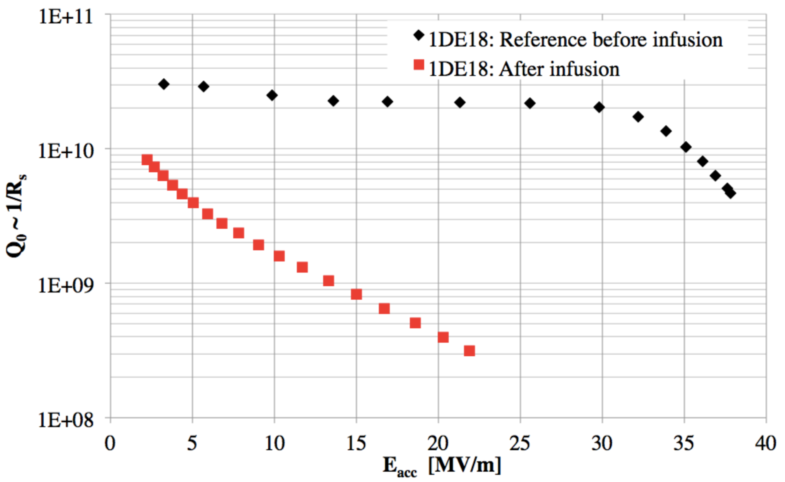


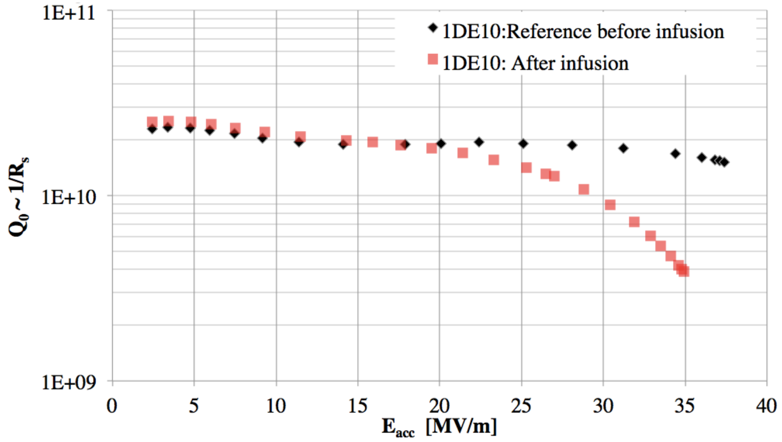


[A. Dangwal Pandey et al. , SRF 2019]

Evolution of the infusion process at DESY

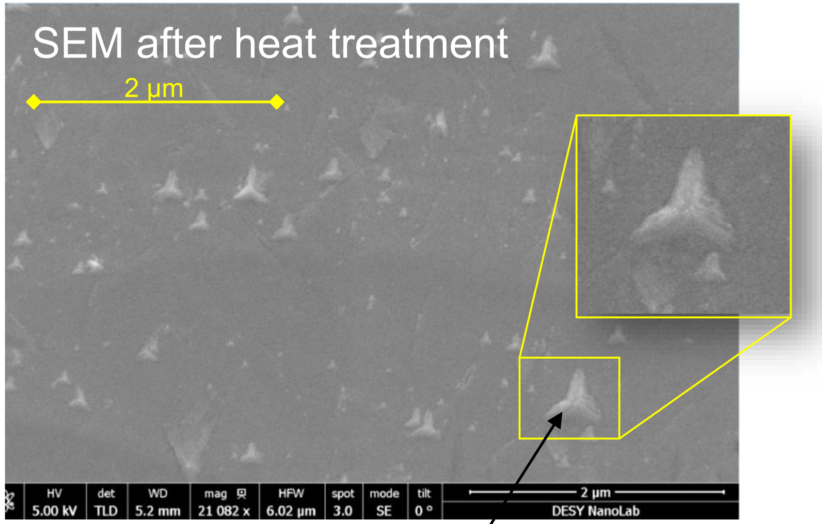
the furnace vacuum does not meet requirements



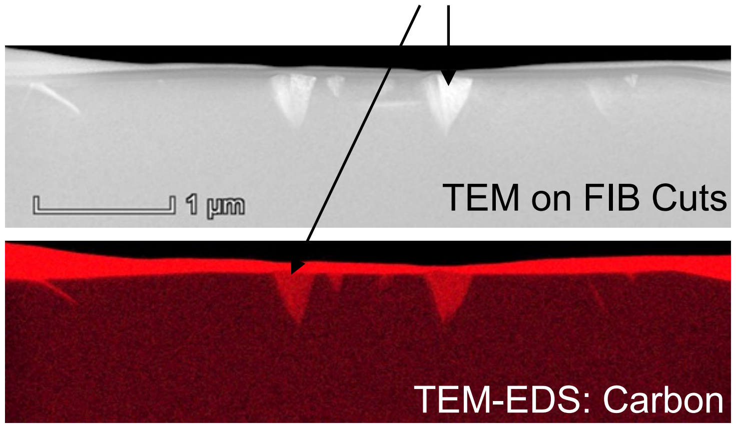


Conclusions and plans

- the DESY furnace is not able to achieve a successful Nitrogen infusion process
- star-like structures found on samples
  ⇨ hint of potential hydro-carbon contamination
- furnace upgrade required and in progress
- **improved furnace infrastructure available mid 2021**



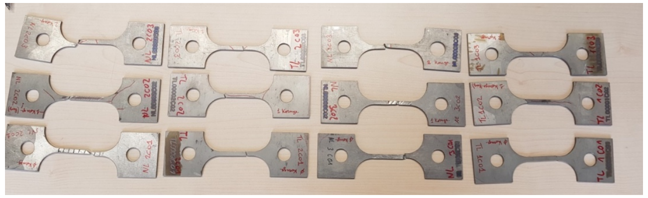
'star-like' precipitates identified as carbon using advanced surface analysis techniques



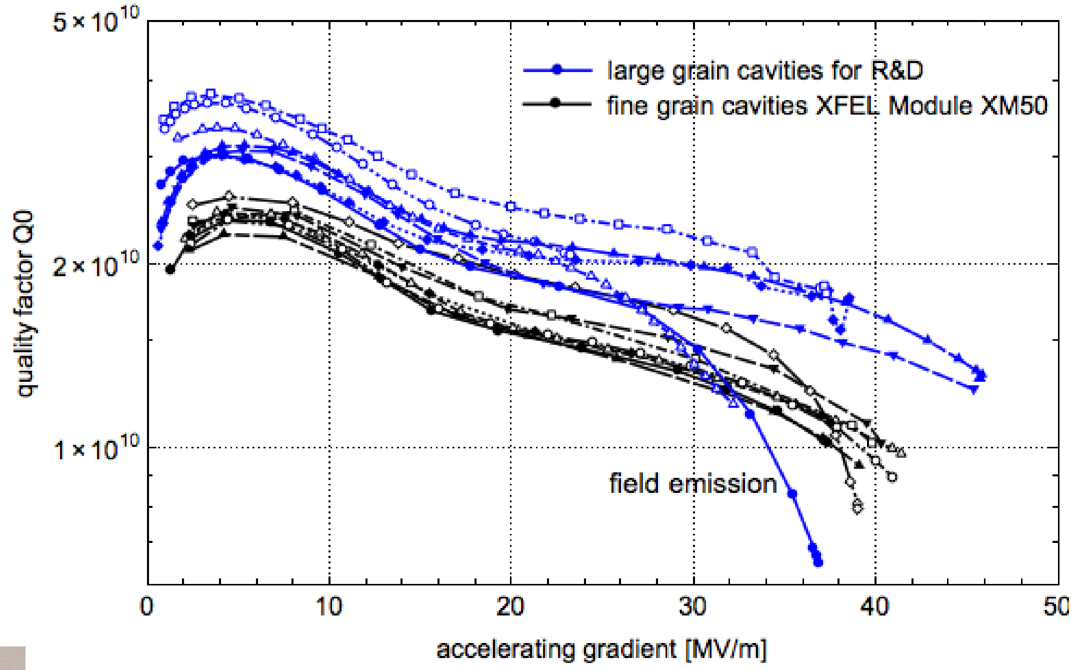
Large grain cavities

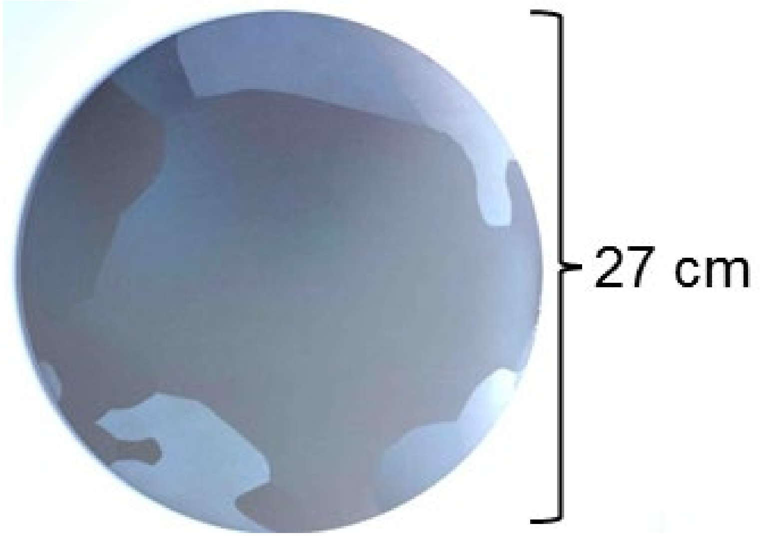
provide higher Q-value with same surface treatment

- significant **better Q_0** with same reach for E_{acc}
- disks cut from ingot: typical **grain size of few cm**
  - profound **experience at DESY**
- Goal: pressure equipment directive (PED) compatibility
  - cutting, forming, welding processes under investigation
- material characterization
  - warm and cold traction tests
  - hardness tests
  - RRR measurements



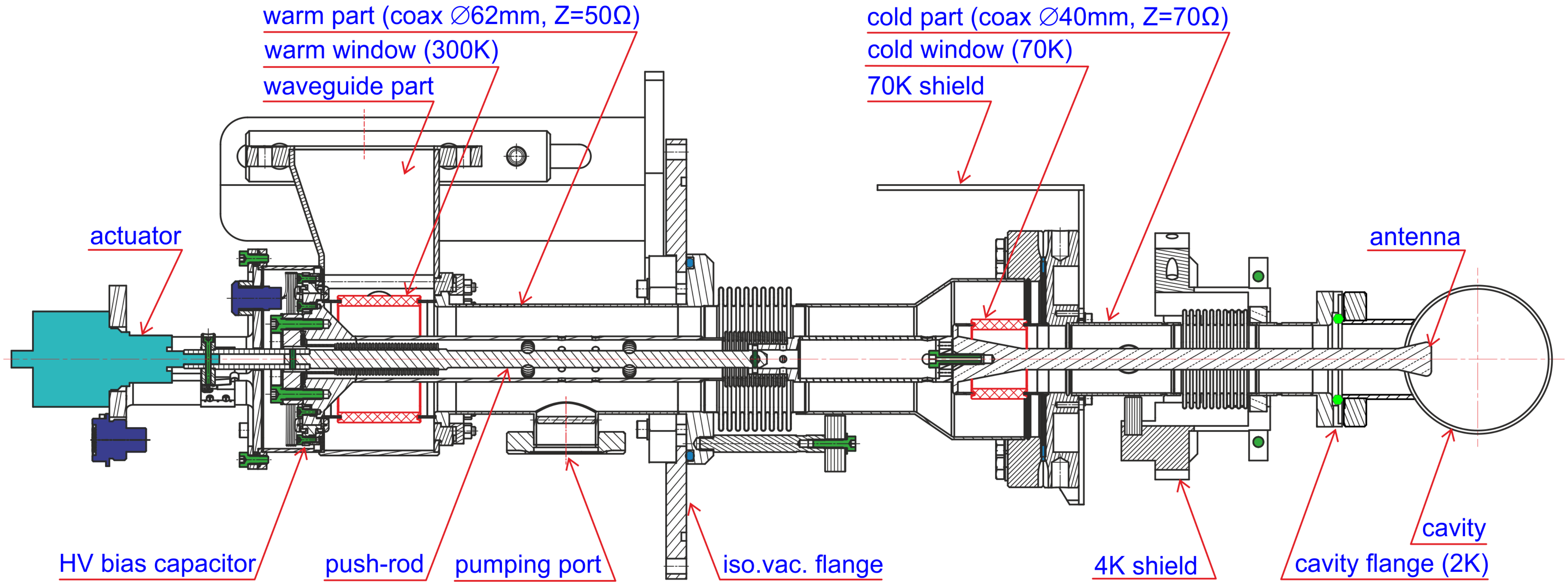
- surface-sensitive characterization & analysis of cavity test data
  - investigation of grain boundaries (less than in FG) - responsible for RF losses?
  - systematic studies of correlations: cavity treatment vs. performance
- fabrication supervision of four LG 9-cell cavities for SHINE





Power couplers

are occasionally largely underestimented componets transfereing the RF power into the cavities



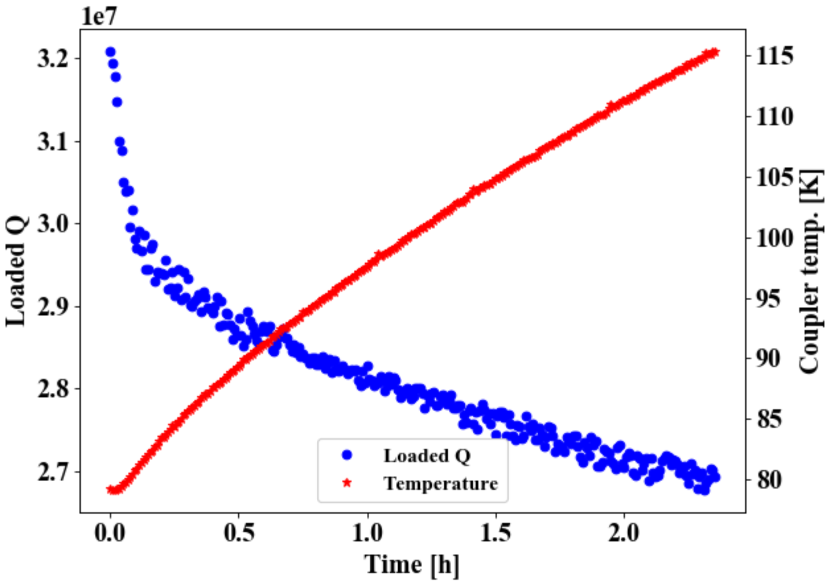
The coaxial Fundamental Power Coupler (FPC) consists of warm, cold and waveguide main parts. It is made of copper and copper plated (10/30 µm) stainless steel with alumina TiN coated ceramic windows. The motorized antenna tuning (±10 mm) permits Q_{ext} adjustment (10^6..10^7).

Power couplers

transferring CW RF rather than pulsed RF

Limiting factors

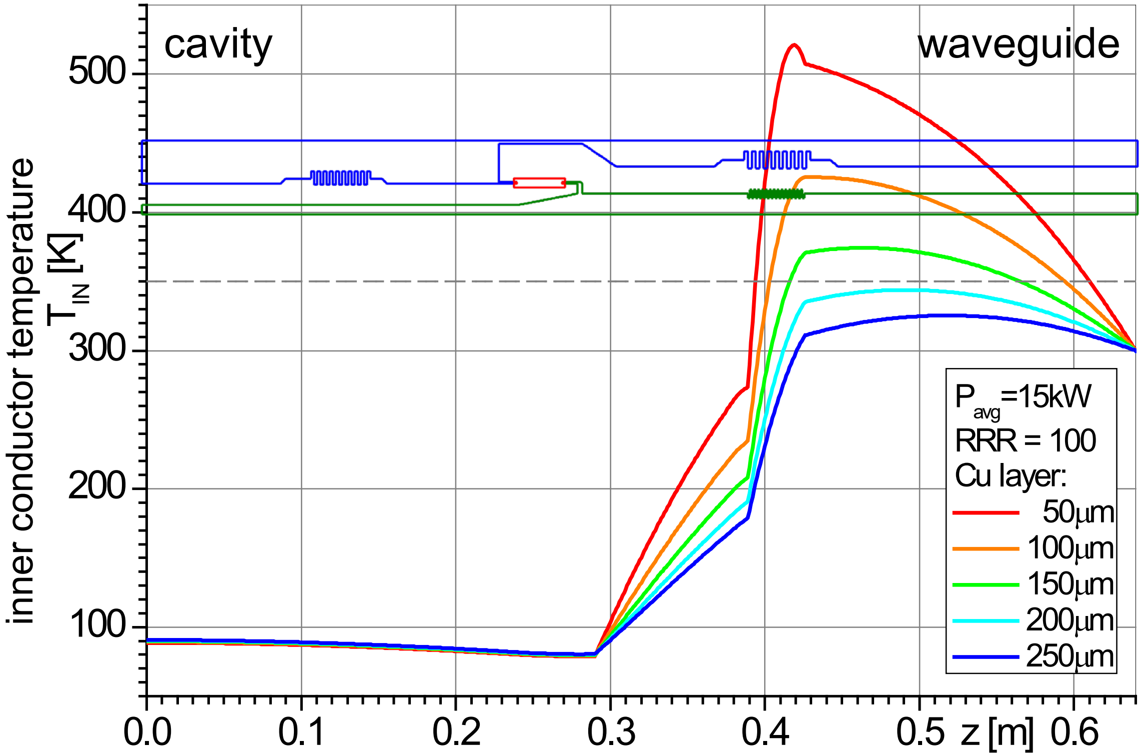
- cryogenics
- field emission and gamma-radiation
- overheating
- Q_{load} limit



Change of Q_{ext} and the coupler temperature sending 4 kW CW RF to XM50.1 cavity #5. The other couplers behave similar.

Solution

- increasing the inner conductor copper plating from 30 µm to 150 µm

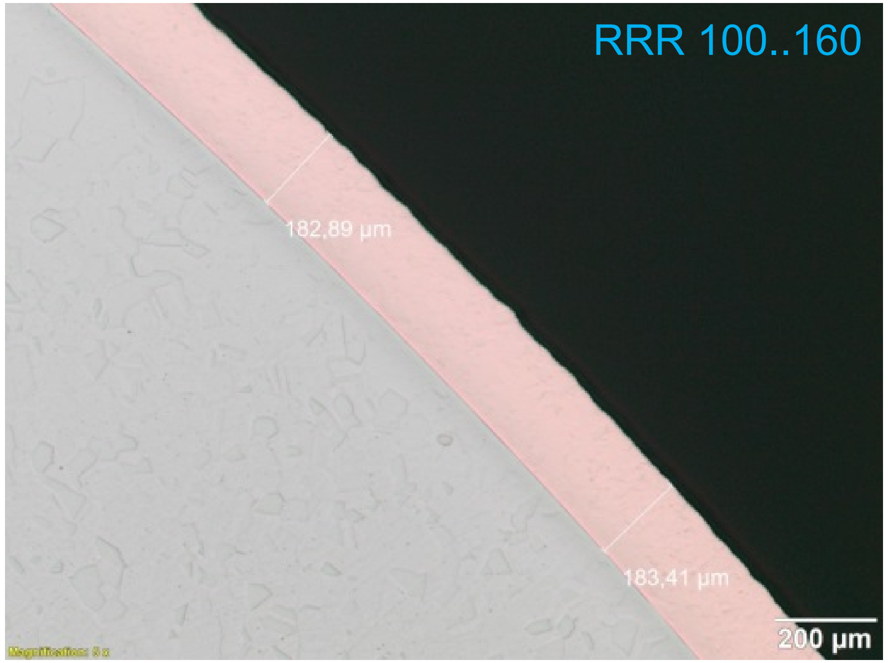


Power couplers

optimized for CW operation

With 150 µm re-plated power couplers in XM46.1

- 9 couplers have been re-plated by industry



- assembled into XM46.1
- successfully tested with pulsed RF at AMTF
- test with CW RF at CMTB foreseen for Q1 2021

New coupler conditioning and test stand

- former test stand in Halle 3 has been dissassebeld
- during XFEL construction LAL provided conditioned and tested couplers to CEA and the XFEL project
- setup of a new test stand at XATB3 in AMTF ongoing

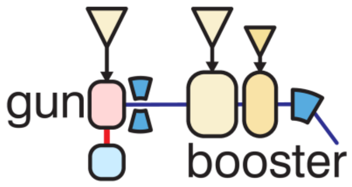
Injector

- concepts of high brightness injectors
- SRF photoinjector
- NC gun study
- 3rd harmonic RF

Concepts of high brightness injectors for XFELs

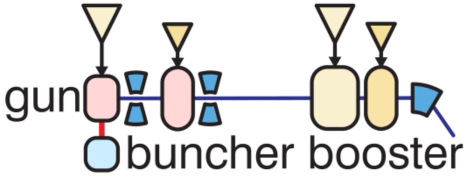
'pancake' versus 'cigar' photo emission

High gradient gun based injector



- 'pancake' emission
  - short laser pulse, high emission current
  - high gradient requires high frequency
- high gradient pulsed nc guns, L-band & S-band
  - $E_{emission}$ = 40 to 60 MV/m, 50 to 70 % of $E_{cathode}$
- **cw srf guns have the potential to reach similar fields**
  - L-band: HZDR, HZB, DESY, KEK, PKU

Medium low gradient gun based injector



- 'cigar' emission
  - long laser pulse, low emission current
  - long bunch requires low frequency
- DC gun based ERL injector
  - $E_{cathode}$ < 5 MV/m, V_{gun} < 500 kV
- VHF-band nc cw gun (LBNL)
  - $E_{emission}$ ~ 20 MV/m, V_{gun} ~ 750 kV

- VHF-band quarter wave resonator (QWR) srf gun: BNL, Wisconsin/SLAC/ANL

All superconducting gun

for optimal integration of cathodes in an ultra-clean SC cavity

existing cathode insertion systems still face challenges

- w.r.t. multipacting, field emission, cathode heating, cathode lifetime, etc.
- R&D still required and ongoing
- e.g. performed at HZDR, HZB and KEK

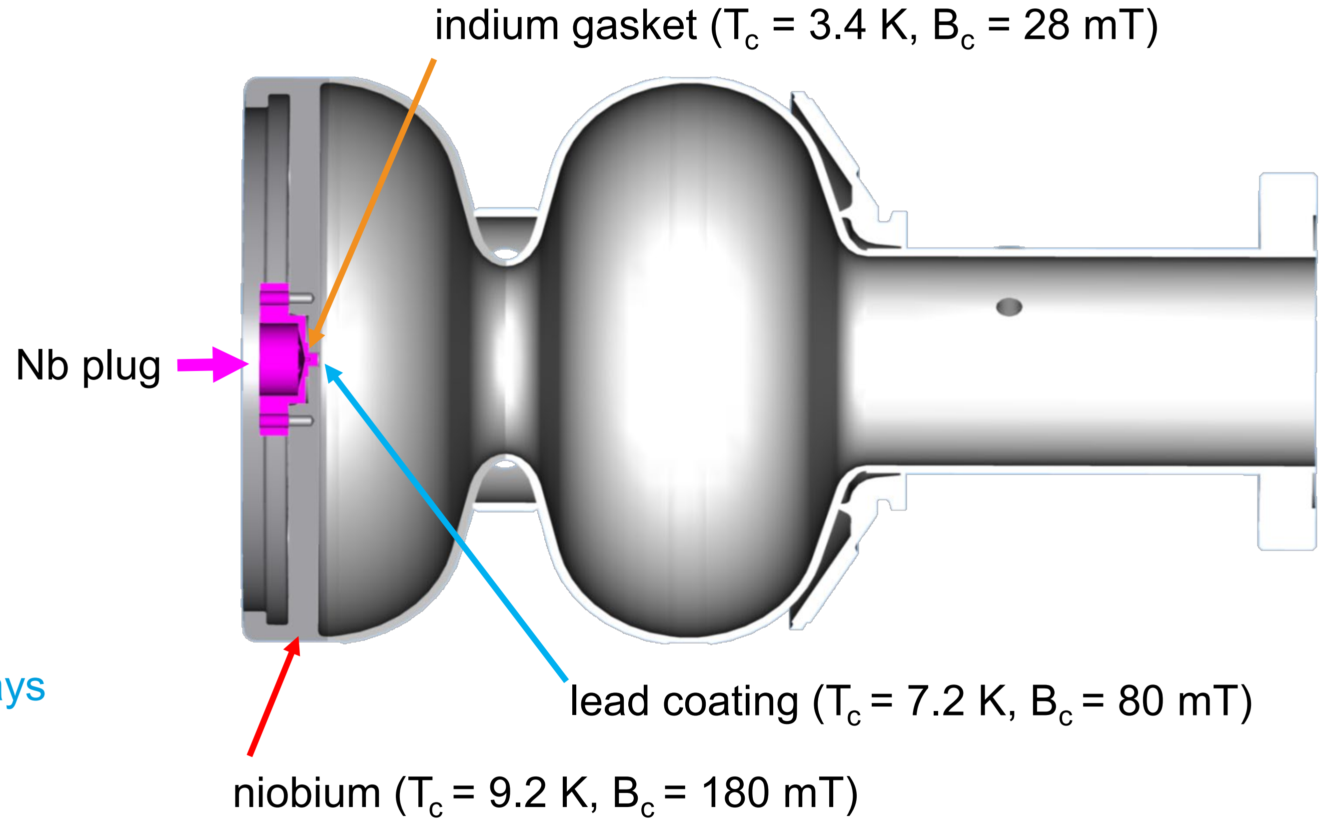
DESY approach: superconducting (sc) cathode attached to the cavity backside

☺ cleaning after cathode insertion in a clean room

☺ cathode particles (lead) should not heat and quench the cavity

😐 exchanging the cathode

⇨ only reasonable with cathode lifetimes above 100 days



All superconducting gun

present status and activities

Achievements

- back-wall is mechanical stable
- mechanical fabrication results in correct frequency
- the substantial effort invested into the surface treatment bears first fruits
    - BCP (buffered chemical polishing) at Zanon
      ⇨ $E_{peak\ on\ axis}$ up to 48 MV/m measured at 16G5
    - EP (electro polishing) at KEK
      ⇨ $E_{peak\ on\ axis}$ up to 54 MV/m measured at 16G4

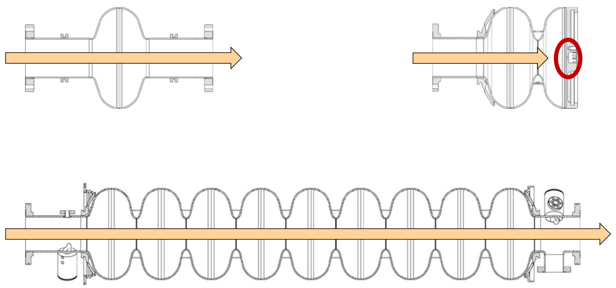
Next main activities

- integrating all lessons learned into two new SRF gun cavities 16G09 and 16G10 which may first be used in a horizontal test setup

[for the complete subject, see also the transparencies of my one hour talk: "SRF Photo Injector Development at DESY", I gave at the DESY Technical Seminar M, November 6th 2020]

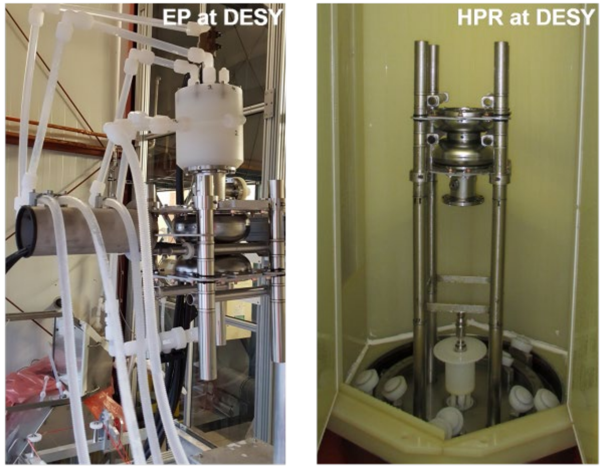
Surface treatment of gun cavities

The special cavity geometry require new approaches as compared to accelerating cavities!



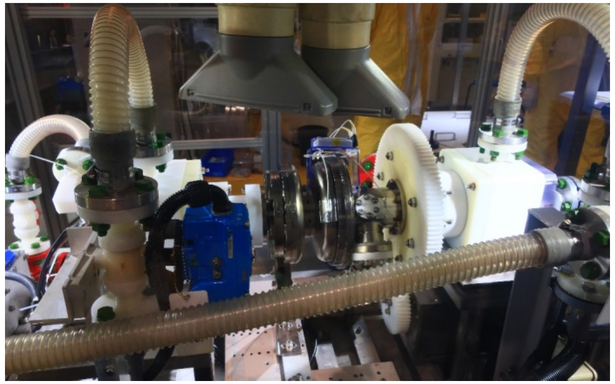
Four Generations 1.6 Cell Cavities

Surface Treatment by EP & HPR



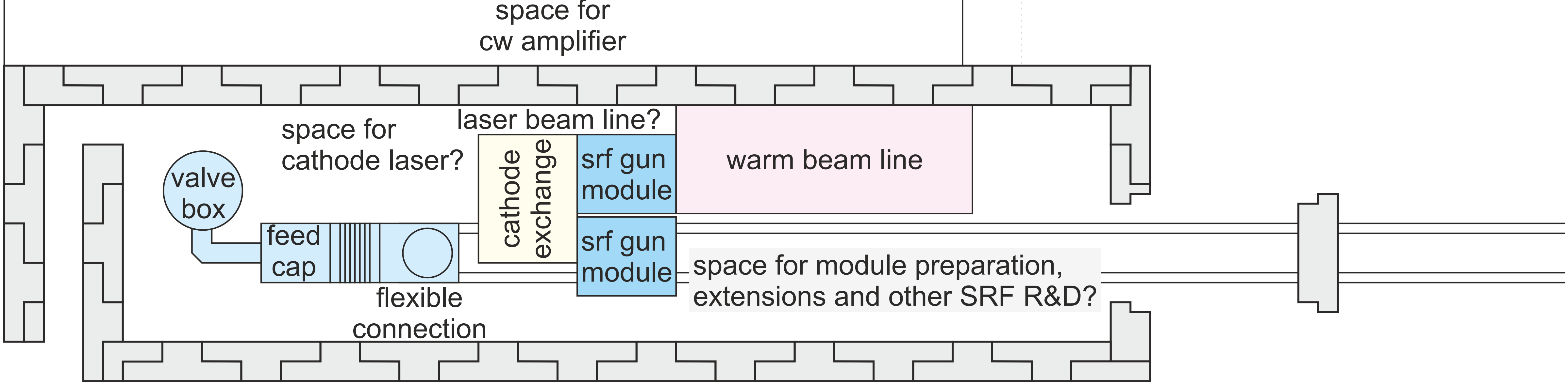
EP treatment of 16G4 at KEK

Successful collaboration with KEK: applying horizontal EP to 16G4 and VT at KEK.



First sketch of SRF photo injector test stand at DESY

located in the AMTF bunker XATB3



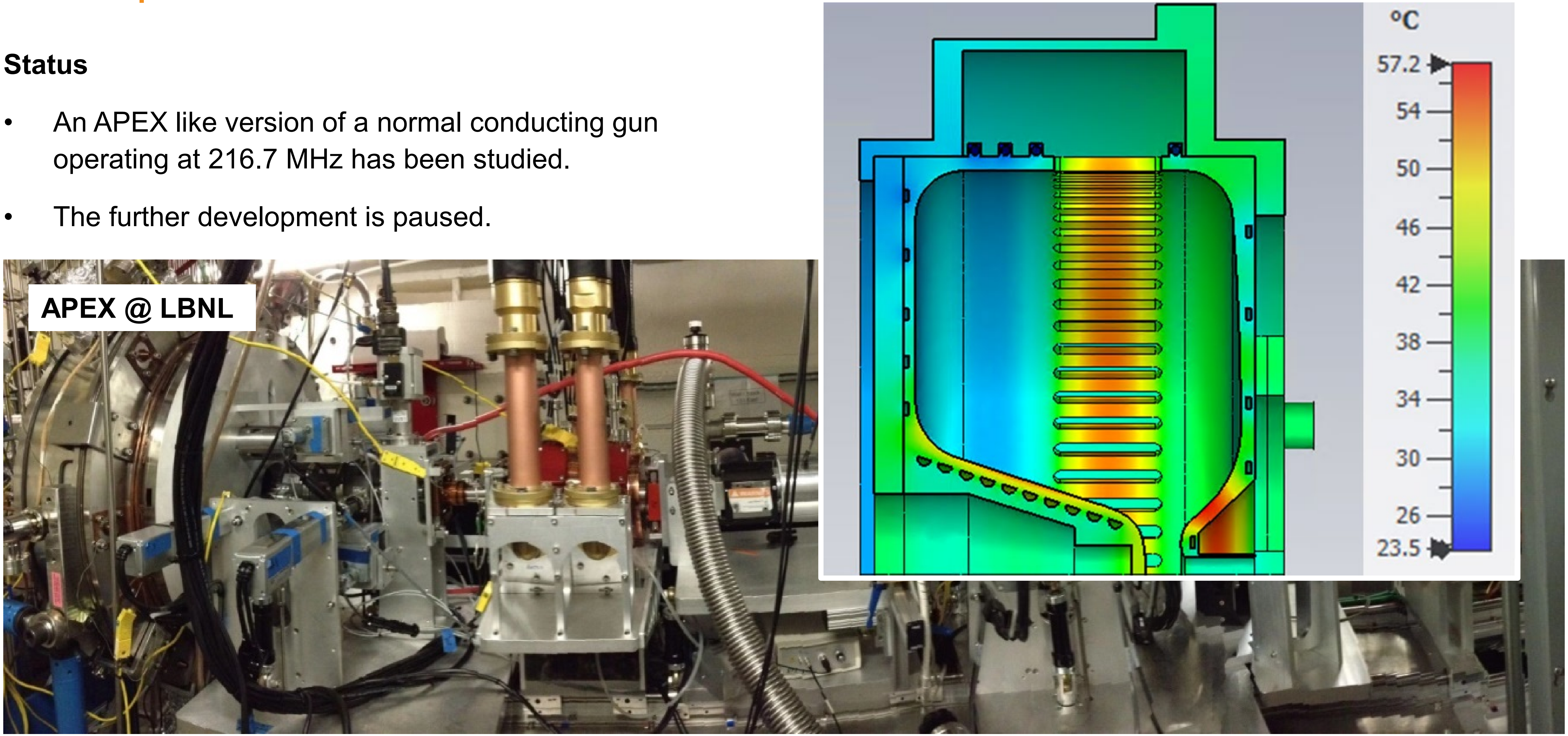
NC gun study

as backup solution

Status

- An APEX like version of a normal conducting gun operating at 216.7 MHz has been studied.
- The further development is paused.

DESY version of an APEX like NC gun

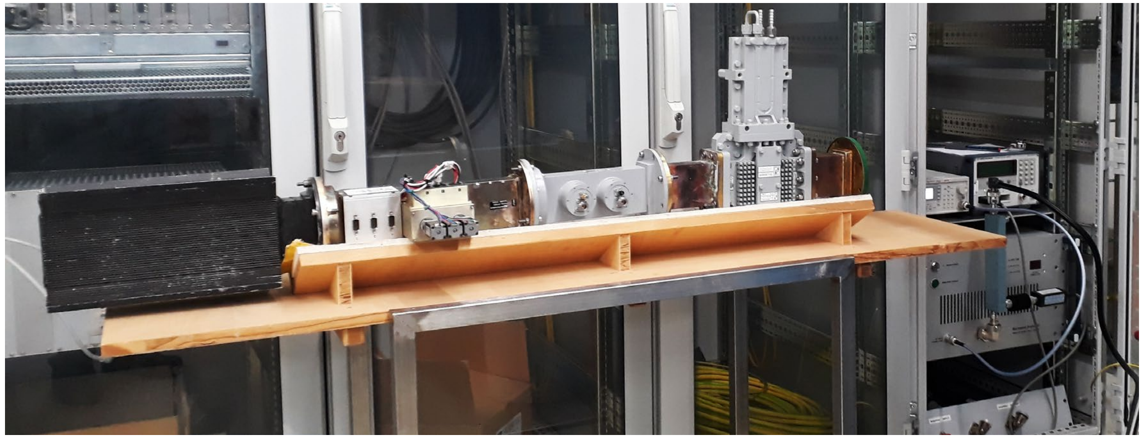


The 3rd harmonic RF

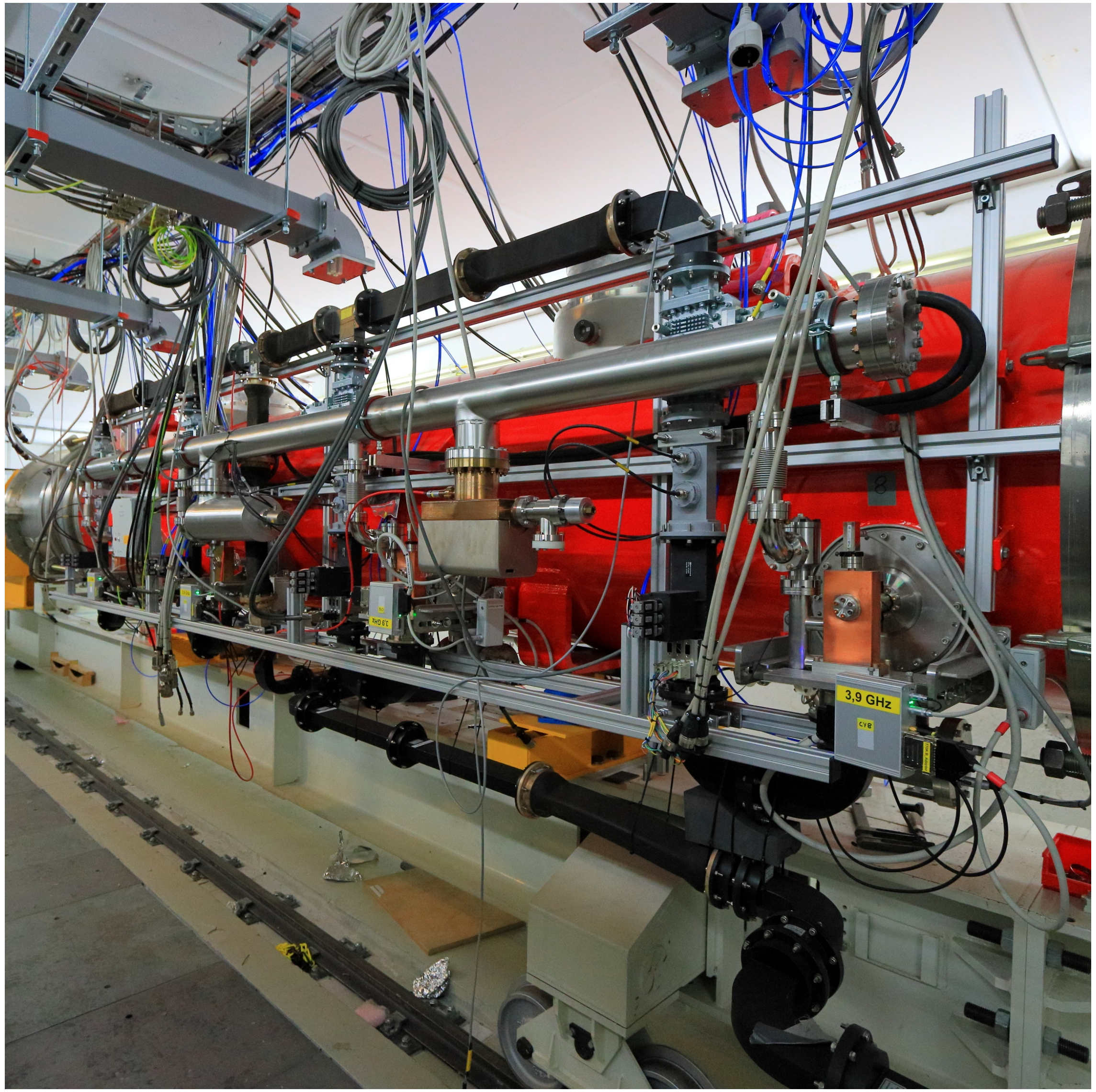
in a CW injector requires CW operation, too

Status and activities

- the XFEL 3.9 GHz spare module is installed in the AMTF module test stand XATB1
- we purchased a solid state amplifier providing 1 kW 3.9 GHz CW RF
- test of the 3.9 GHz waveguide parts with 3.9 GHz CW RF is presently in preparation



- a test of a 3.9 GHz cavity in the XFEL 3.9 GHz spare module will follow



Putting it all together

- CW injector beam dyamics
- CW start to the end (s2e) beam dyamnics

In general: A lower beam emittance from the injector and/or higher final beam energy result in shorter wave length provided to users.

CW injector beam dynamics

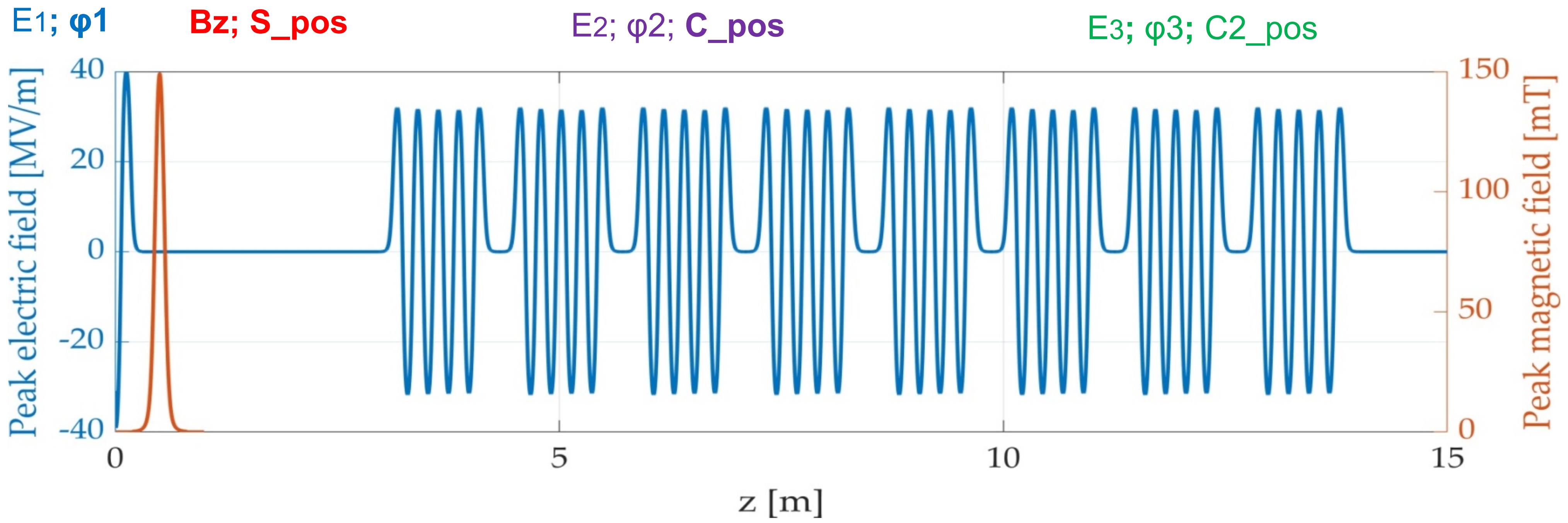
parameters used and studied for the optimization

Laser profile

- longitudinal laser shape: Gaussian
- transverse laser shape: radial uniform
- transverse size: sig_x/sig_y
- pulse duration: sig_z

Cathode

- Lead
- initial thermal kinetic energy: 0.22 eV
- charge: 100 pC



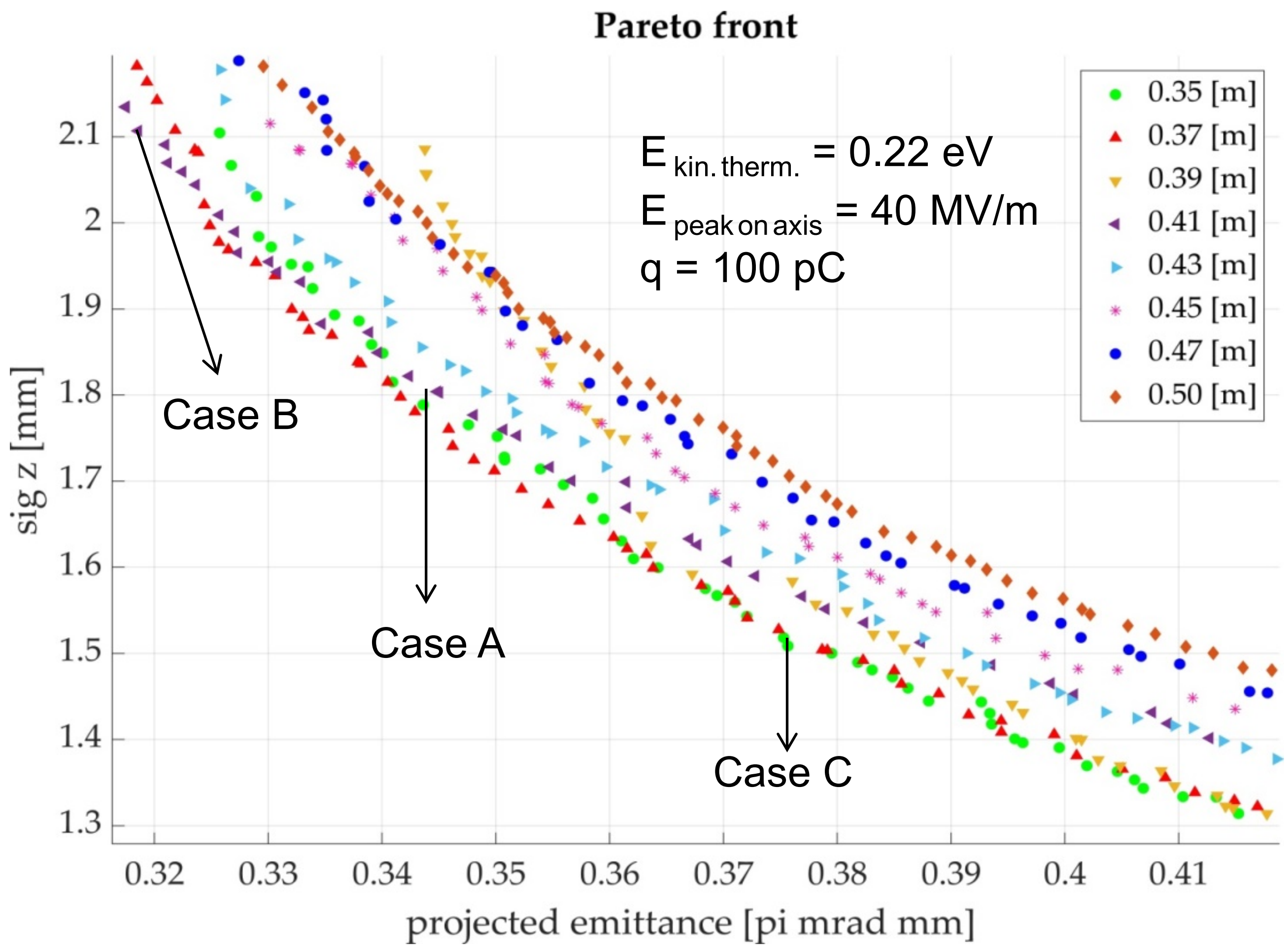
Injector optimization

the effect of the solenoid position

Constraints, assumptions and tools used

- the position of the focusing solenoid has geometric constrains in the cryostat
- initial laser profile: Gaussian (longitudinal) and radial uniform (transverse)
- ASTRA is used for the beam dynamics simulations
- a multi-objective optimization code (written at LBNL) is used for the optimization
- objective functions: rms bunch length *sig z* and *projected transverse emittance*
- three cases have been chosen for further s2e particle tracking to evaluate trade-off between slice emittance and the peak current
- $E_{\text{peak on axis}}$ = 50 MV/m under study, too

the rms bunch length and the emittance at 15 m



Injector-to-undulator (s2e) beam dynamics studies started

towards a CW operation of the European XFEL[1,2]

Proposed energy gain budget

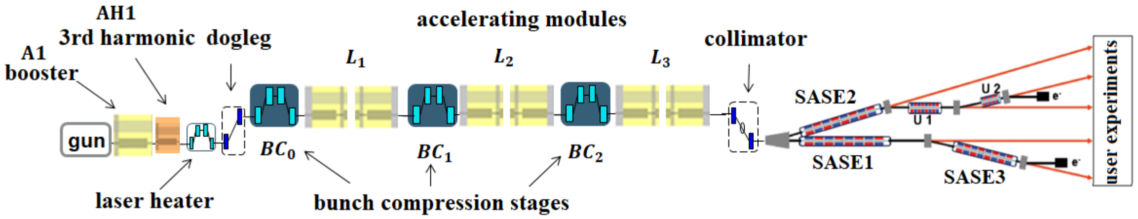
- **16 MV/cavity** for 1.3 GHz
- **4 MV/cavity** for 3.9 GHz
  - → 110 MeV @ BC0
  - → 500 MeV @ BC1
  - →2000 MeV @ BC2
  - →**8000 MeV** final beam energy

Machine layout stays similar for simulation studies

- **varied** injector layout e.g. in positioning of solenoid, booster, etc.
- **kept** 3rd harmonics, 3 bunch compression stages & design optics for CSR reduction

Start-to-End simulation capabilities

- Injector → **ASTRA or KRACK3**[3]
- Injector to Undulaltor → **OCELOT**[4] **or IMPACT-Z**
- SASE → **GENESIS**



Collective effects through the whole beamline

- 3D **SPACE CHARGE** / 3D **WAKE** / 1D **CSR** (arb. trajectories)
- Semi-automatic **optimization algorithms for RF** & **longitudinal beam dynamics parameters** in presence of collective effects

References:

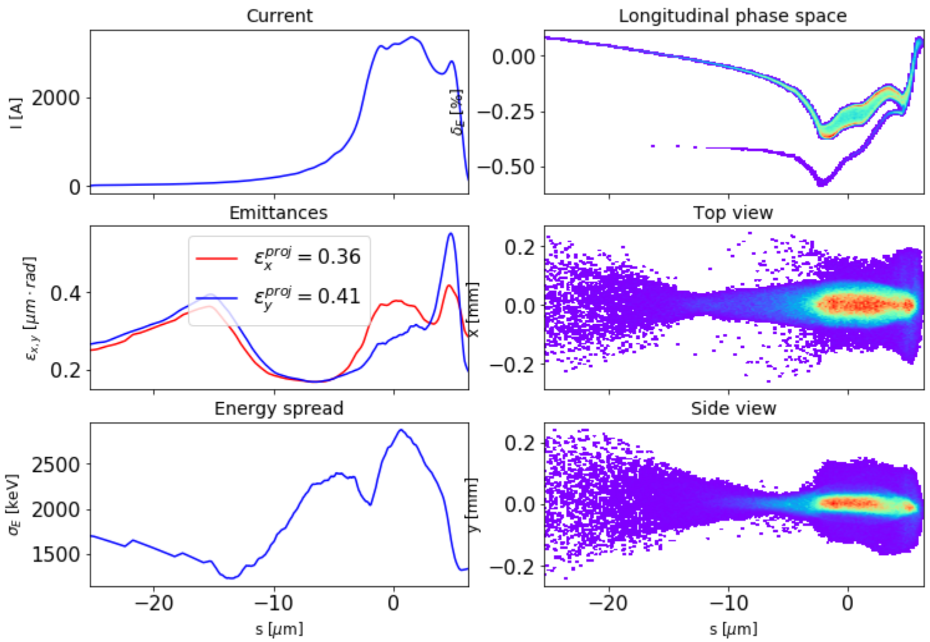
1. W. Decking et al, Nat. Photonics14, 391 (2020)
2. R. Brinkmann, E.A. Schneidmiller, J. Sekutowicz, M.V.Yurkov, NIM A 768 20-25 (2014)
3. Y. Chen, I. Zagorodnov, M. Dohlus, Phys. Rev. Accel. Beams 23, 044201 (2020)
4. I. Zagorodnov, M. Dohlus, S. Tomin, Phys. Rev. Accel. Beams 22 024401 (2019)

Studies of e-bunch qualities before SASE1

exemplary case studies with OCELOT & IMPACT-Z

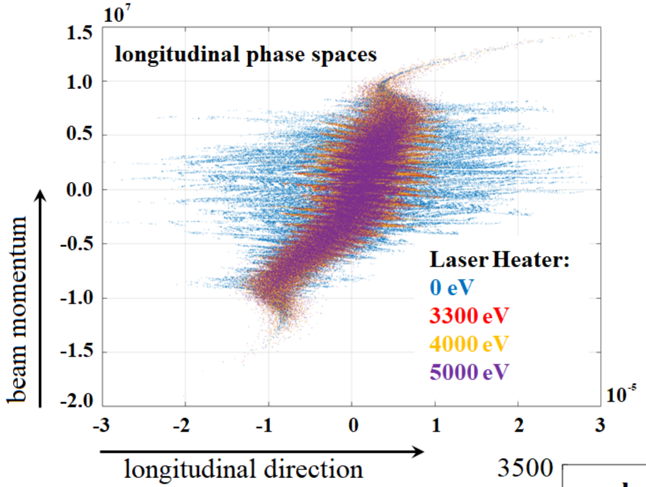
FAST Start-to-End Optimization in OCELOT

- peak current ~3.5 kA for 100 pC bunch of 8 GeV
- no significant emittance growth to injector (~0.38 μm)
- laser heater result in controllable slice energy spread (~2.5 MeV)
- looks promising & needs to be further studied



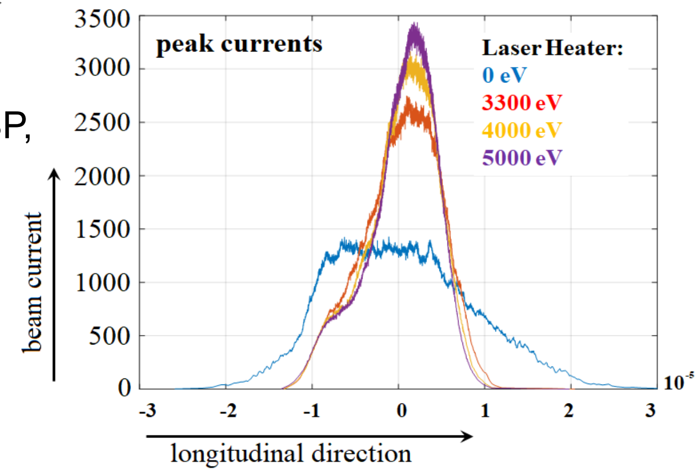
Investigations of micro Bunching with IMPACT-Z

(w.r.t. laser heater; 62 millions simulation particles used)



- Simulated longitudinal phase spaces (LPS) with high resolution to resolve micro bunching effect
- Set-point (SP) increase of laser heater (LH) improved LPS

- As increasing the LH SP,
  - tighter LPS resulted
  - I_{peak} increased
  - slice energy spread δE reduced (not shown here)



Summary and Outlook

Summary and Outlook

towards CW operation of the superconducting XFEL accelerator

CW upgrade of the European XFEL

- operation with pulsed rf or with cw rf at lower energy but with flexible time structure

Main Linac / Linac III

- moving present linac I and linac II modules to the end
- the RF for four modules is provided by one klystron in pulsed operation and two IOTs in CW operation
- RF control is under development, MIMO comes next
- resent CW module test: beam energy after linac III depends on cooling capability

Linac I and Linac II

- require CW optimized modules, couplers and cavities, combining high Q (for CW RF) and high gradients (for pulsed RF)
- Cavities treated by Nitrogen Infusion and Large Grain Cavities are being studied

Injector

- CW L-band SRF photo injector is the first choice, looks promising but requires still some development
- CW operation study of 3rd harmonic system started

Putting it all together – beam dynamics

- injector beam dynamics optimization studies just started, more to come
- injector-to-undulator (s2e) beam dynamics studies just started, first promising results, more to come

Thank you for your attention