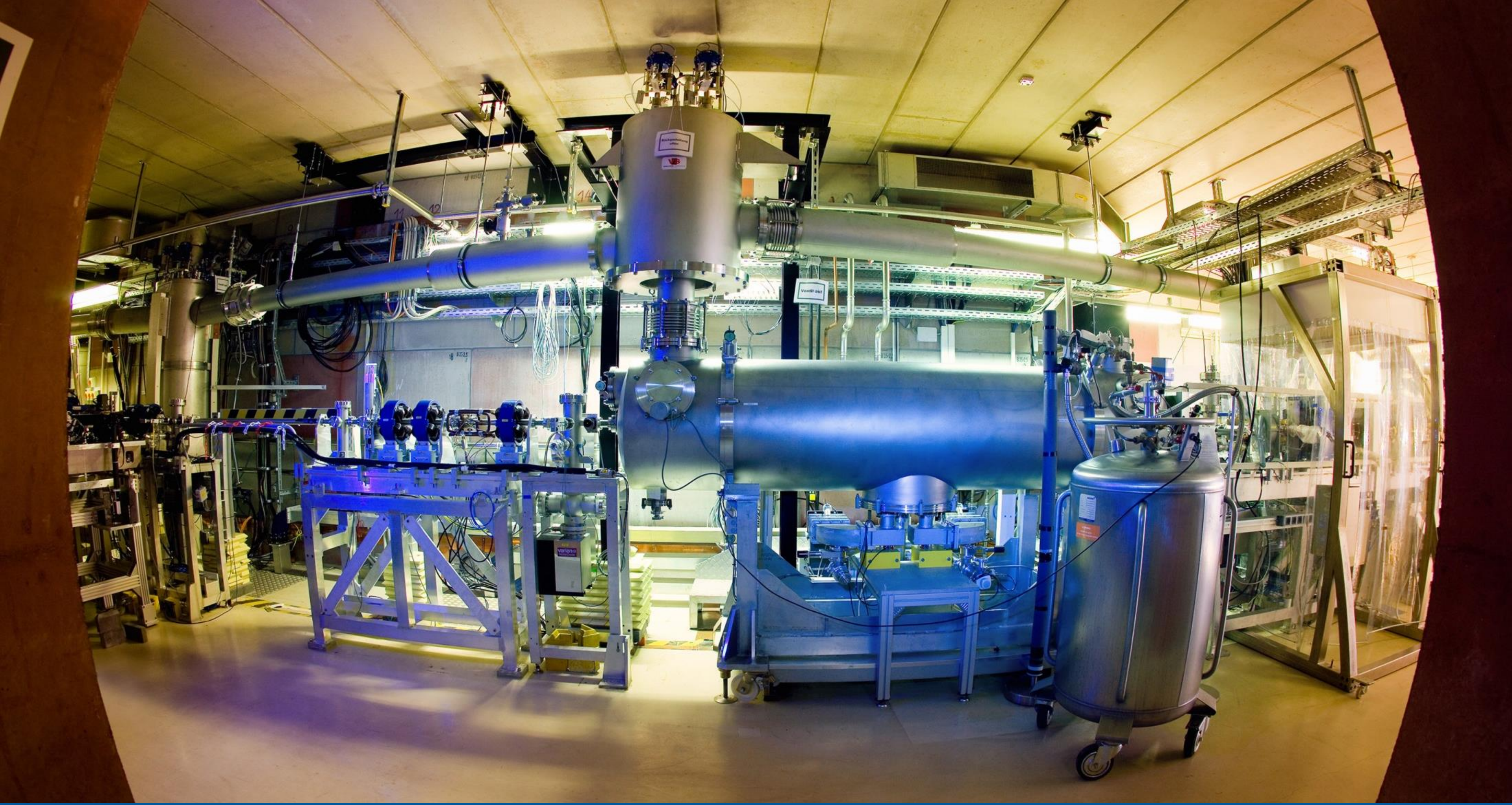


Two decades of CW SRF operation at ELBE

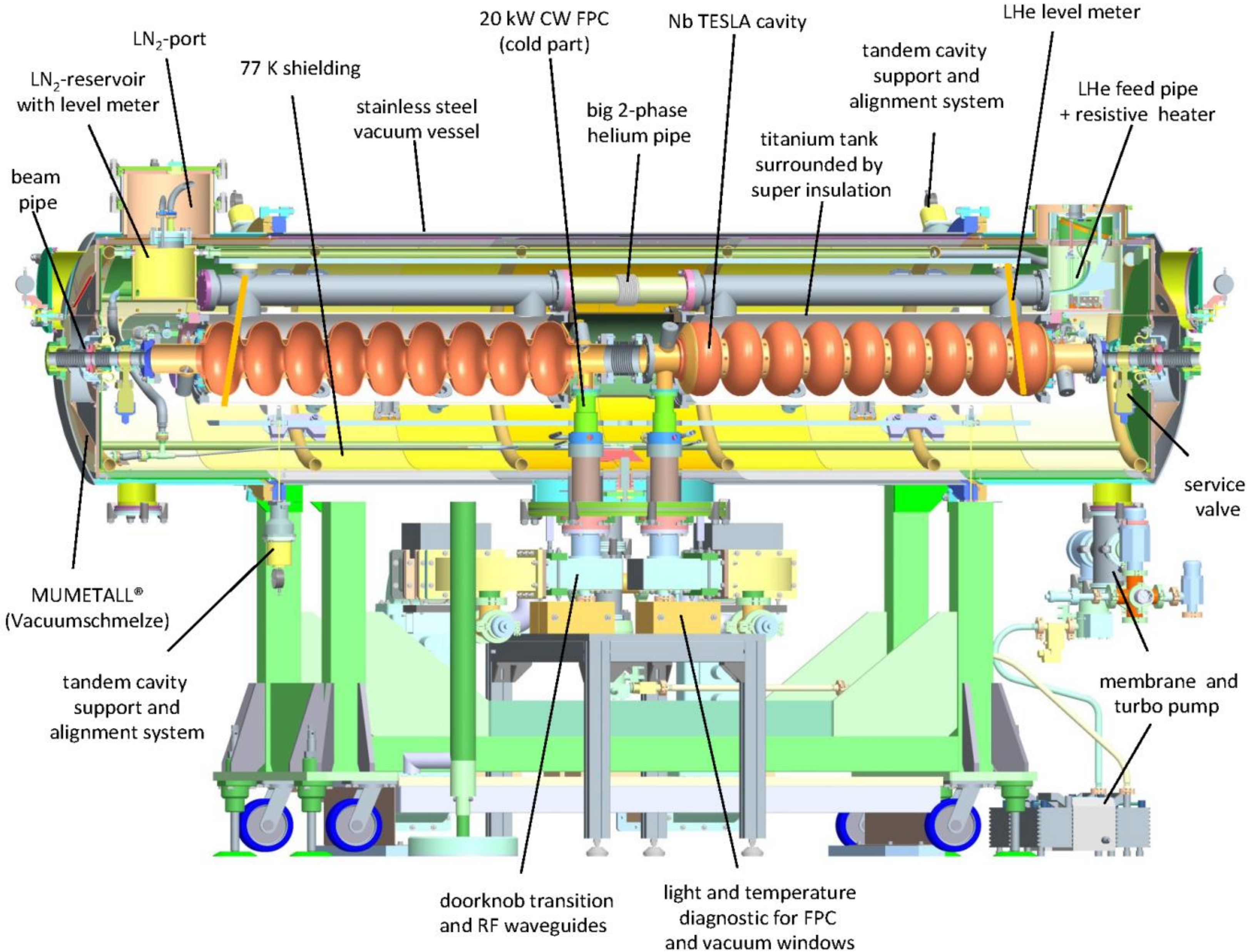
André Arnold on behalf of the whole ELBE team

Partner von DRESDEN concept exzellenz-dresden.de

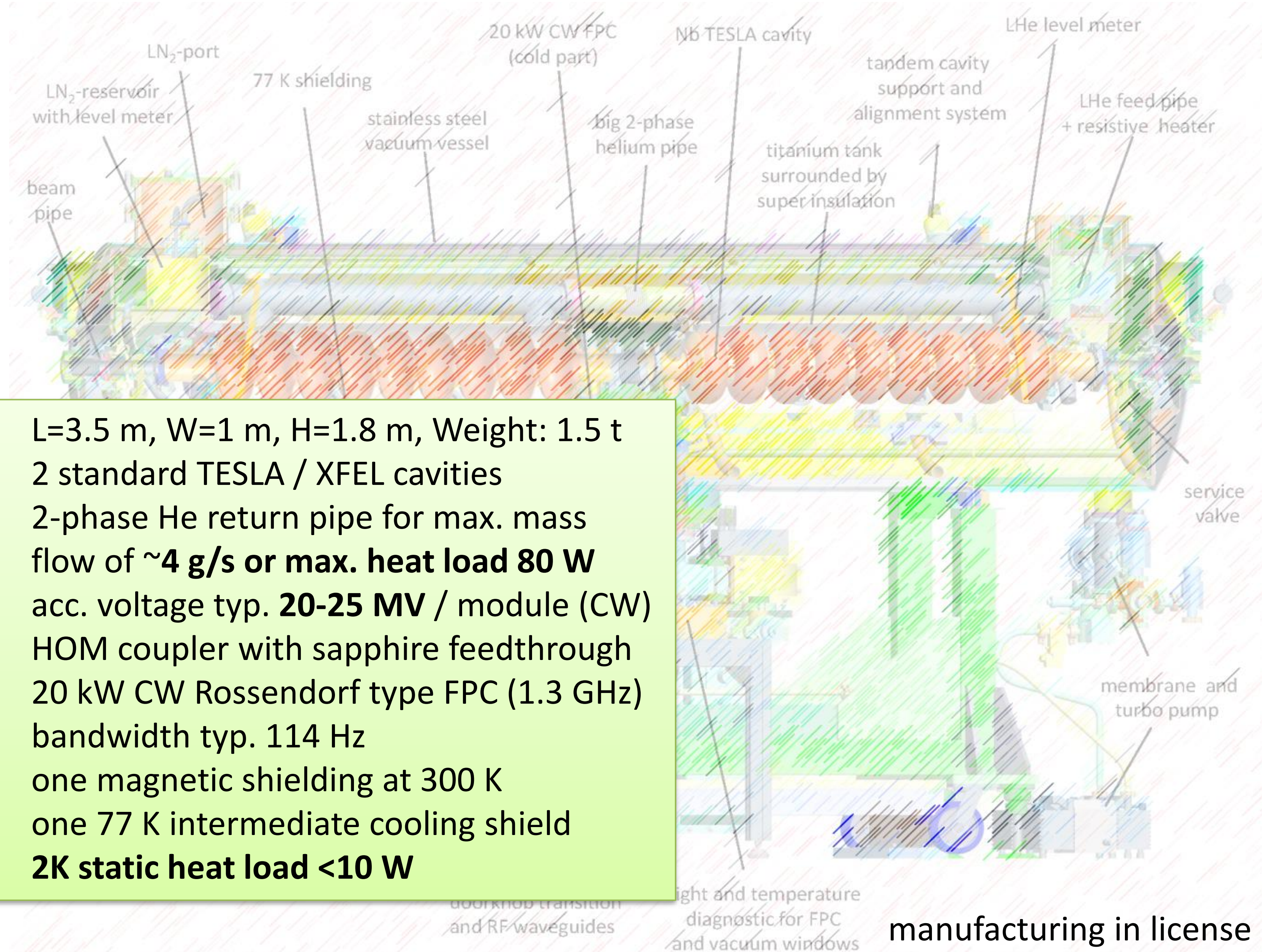
HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

The compact ELBE cryomodule



The compact ELBE cryomodule



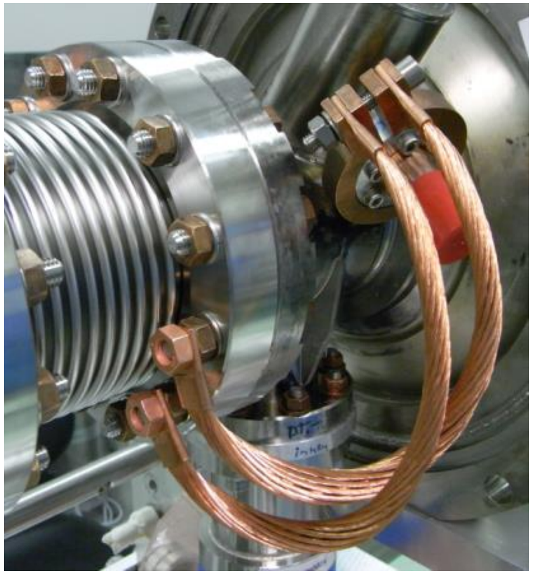
- L=3.5 m, W=1 m, H=1.8 m, Weight: 1.5 t
- 2 standard TESLA / XFEL cavities
- 2-phase He return pipe for max. mass flow of ~**4 g/s or max. heat load 80 W**
- acc. voltage typ. **20-25 MV** / module (CW)
- HOM coupler with sapphire feedthrough
- 20 kW CW Rossendorf type FPC (1.3 GHz) bandwidth typ. 114 Hz
- one magnetic shielding at 300 K
- one 77 K intermediate cooling shield
- **2K static heat load <10 W**

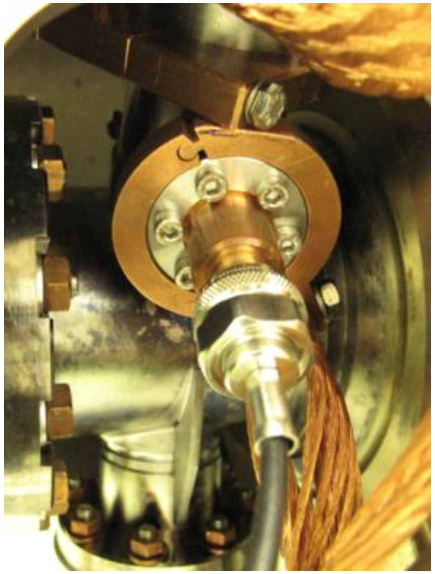
manufacturing in license by RI

Measures for a better CW capability

- sapphire HOM feedthroughs and thermal anchors to improve CW capability by **better therm. stability**
- proper selection of non-ferromagnetic materials and demagnetization of all parts to ensure m**agnetic hygiene → meas. magn. flux inside module: 1-3 µT**

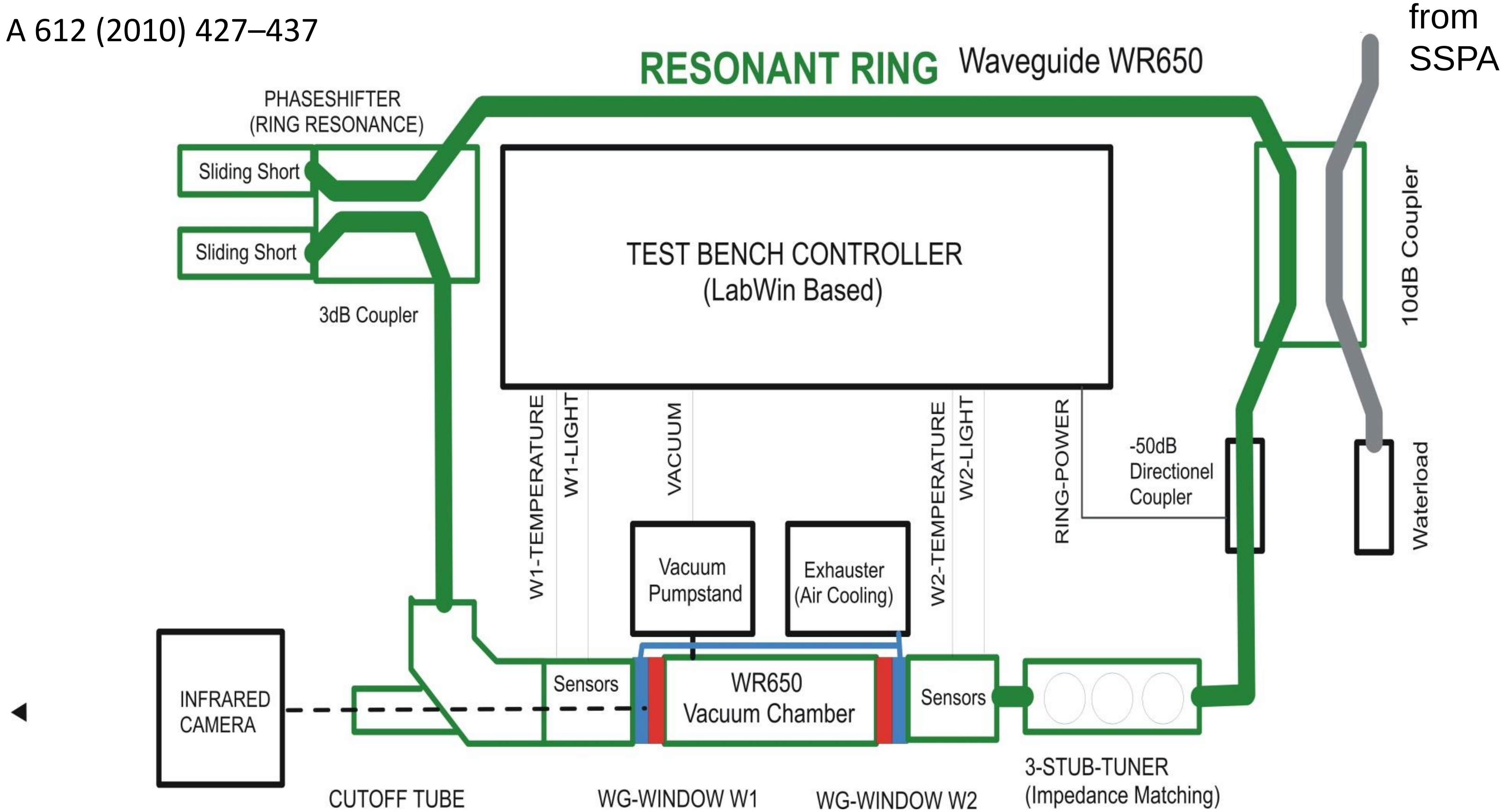
Fe-Rh Thermometer	HOM (coupler)	HOM (tuner)	Pickup (tuner)
C1 @ 10.5 MV/m	3.9 K	4.2 K	8.0 K
C2 @ 7.5MV/m	3.1 K	4.0 K	7.2 K
C3 @ 8 MV/m	86.6 K	71.1 K	16.1 K
C4@ 8 MV/m	83.6 K	63.9 K	12.1 K





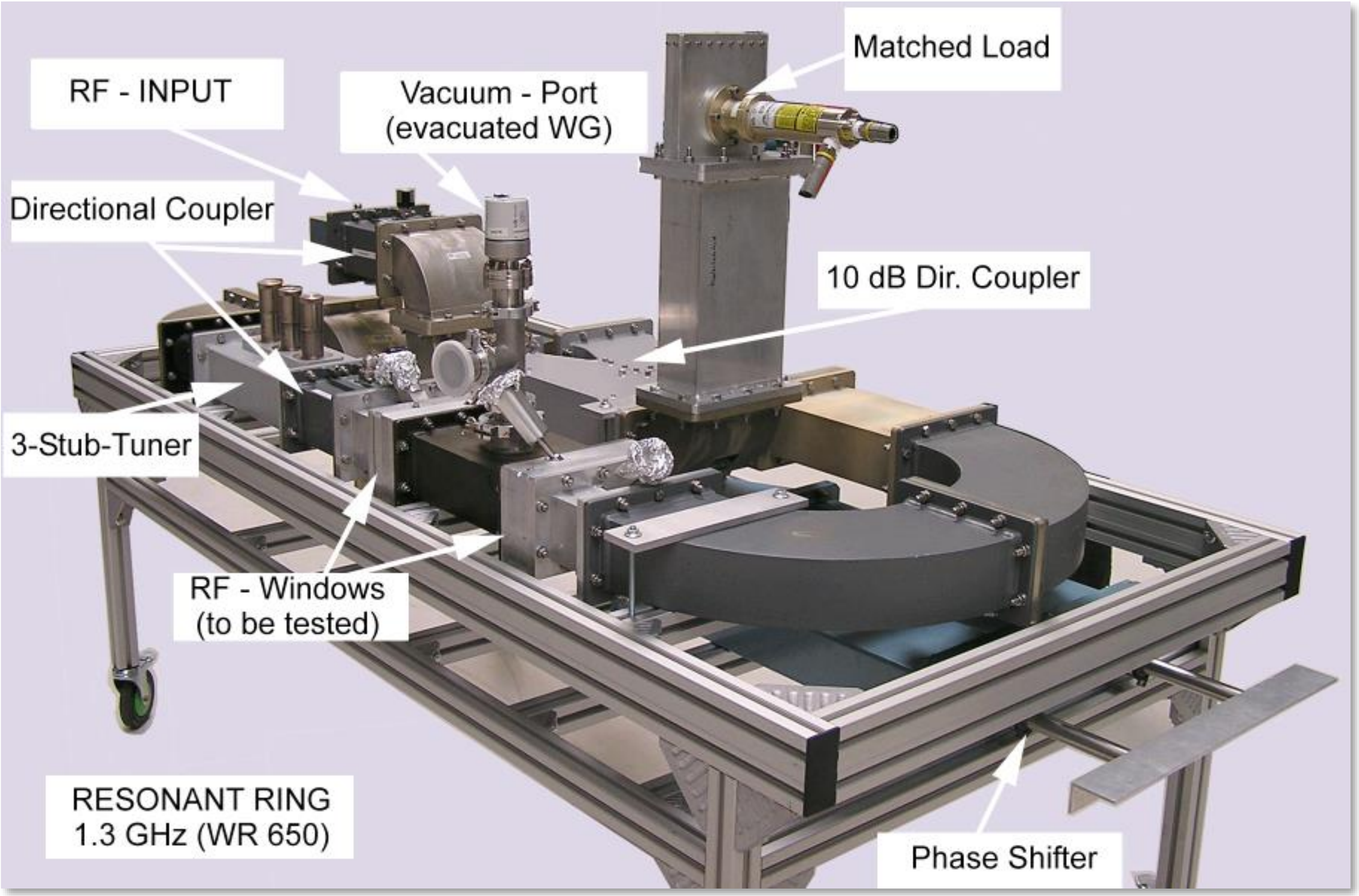
Resonant ring for high power CW RF component tests

NIM A 612 (2010) 427–437



- traveling wave resonator based on WR650 waveguides, phase shifter for resonance tuning
- driven by a 10 kW SSPA, that is coupled into the ring via 10 dB WR650 directional coupler
- in a straight section we can introduce warm windows and FPC, 3-Stub-Tuner for matching
- Diagnostics based on temperatures, vacuum, arc discharges by PMT to switch off RF power
- max. gain w/o insertions ~20 (corr. 200 kW), with insertions ~10 → **100 kW CW for tests**

Resonant ring for high power CW RF component tests



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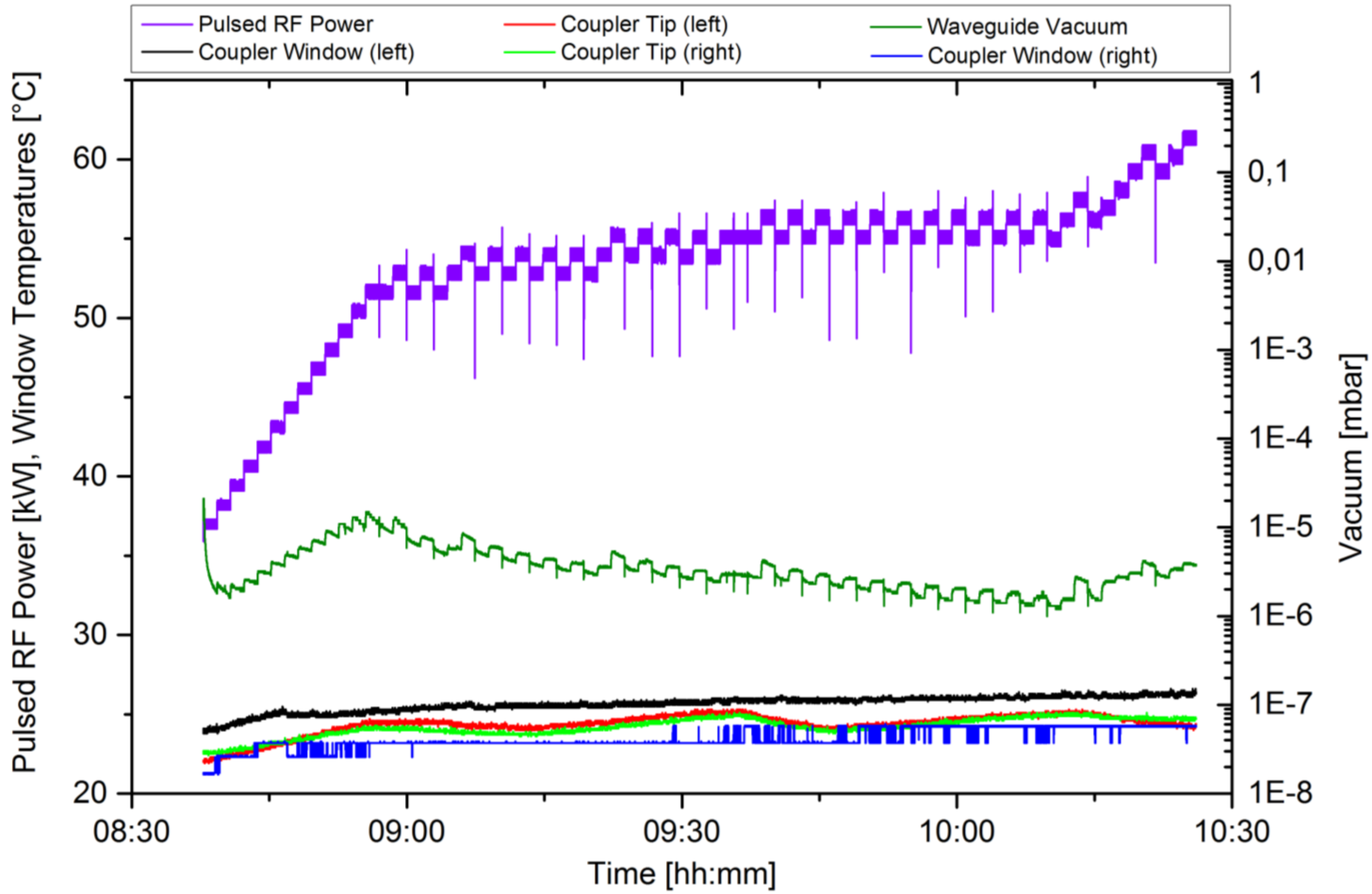
Resonant ring for high power CW RF component tests



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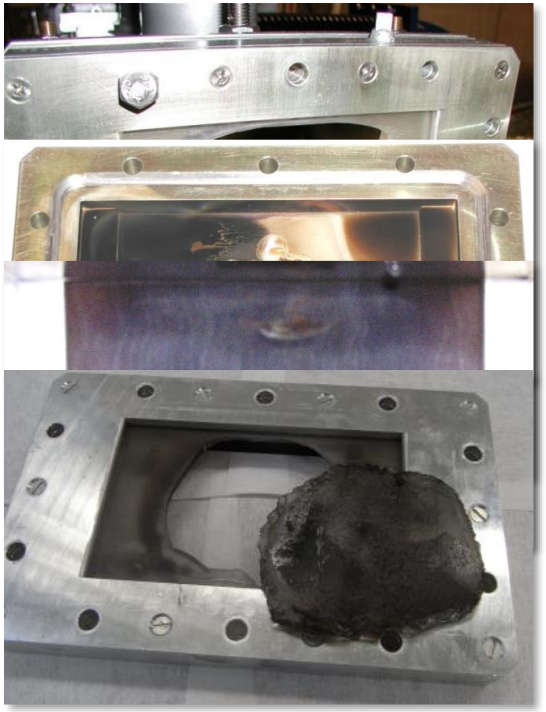
- Diagnostics based on temperatures, vacuum, arc discharges by PMT to switch off RF power
- max. gain w/o insertions ~20 (corr. 200 kW), with insertions ~10 → **100 kW CW for tests**

CW Issues or experiences with coupler windows

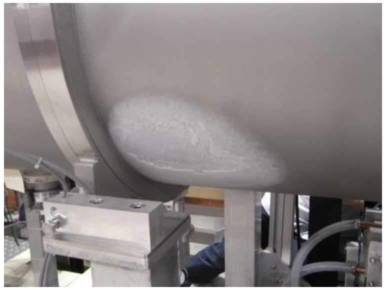


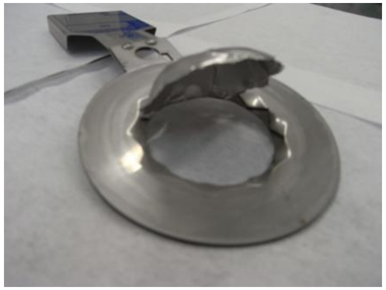
Rexolite/Quartz WR650 (MEGA)

We lost in total 4 warm waveguide windows within last 20 years:

- Jan. 2001: light discharge due to bad /unknown vacuum
  -> coupler diagnostic added
- Nov. 2001: self-excitation of klystron (gain ~70dB), interlock fired but no effect -> circulator added at the klystron input
- Feb. 2009: light discharge due to sensor mal function
  -> automated sensor tests introduced
- May 2014: human error during maintenance work (RF generator connected by mistake to SSPA input directly)
  -> be aware, „Murphy“ is almost everywhere!

In all cases we had luck because beamline vacuum not broken and only warm coupler parts had to be repaired.





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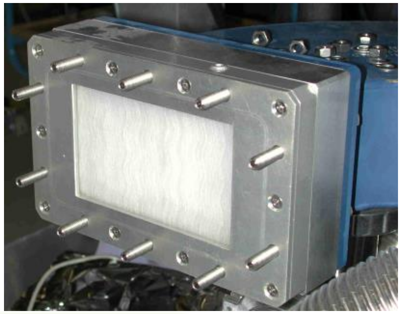
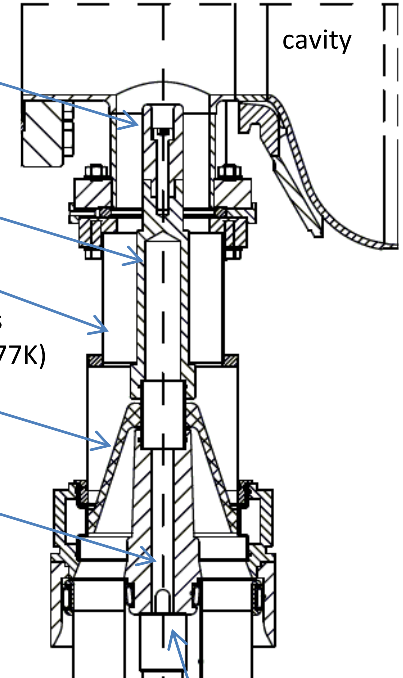
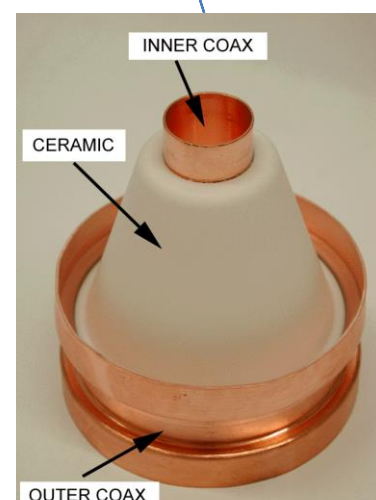
Diagnostics to protect the FPCs





note: left picture taken from RIs MESA module description

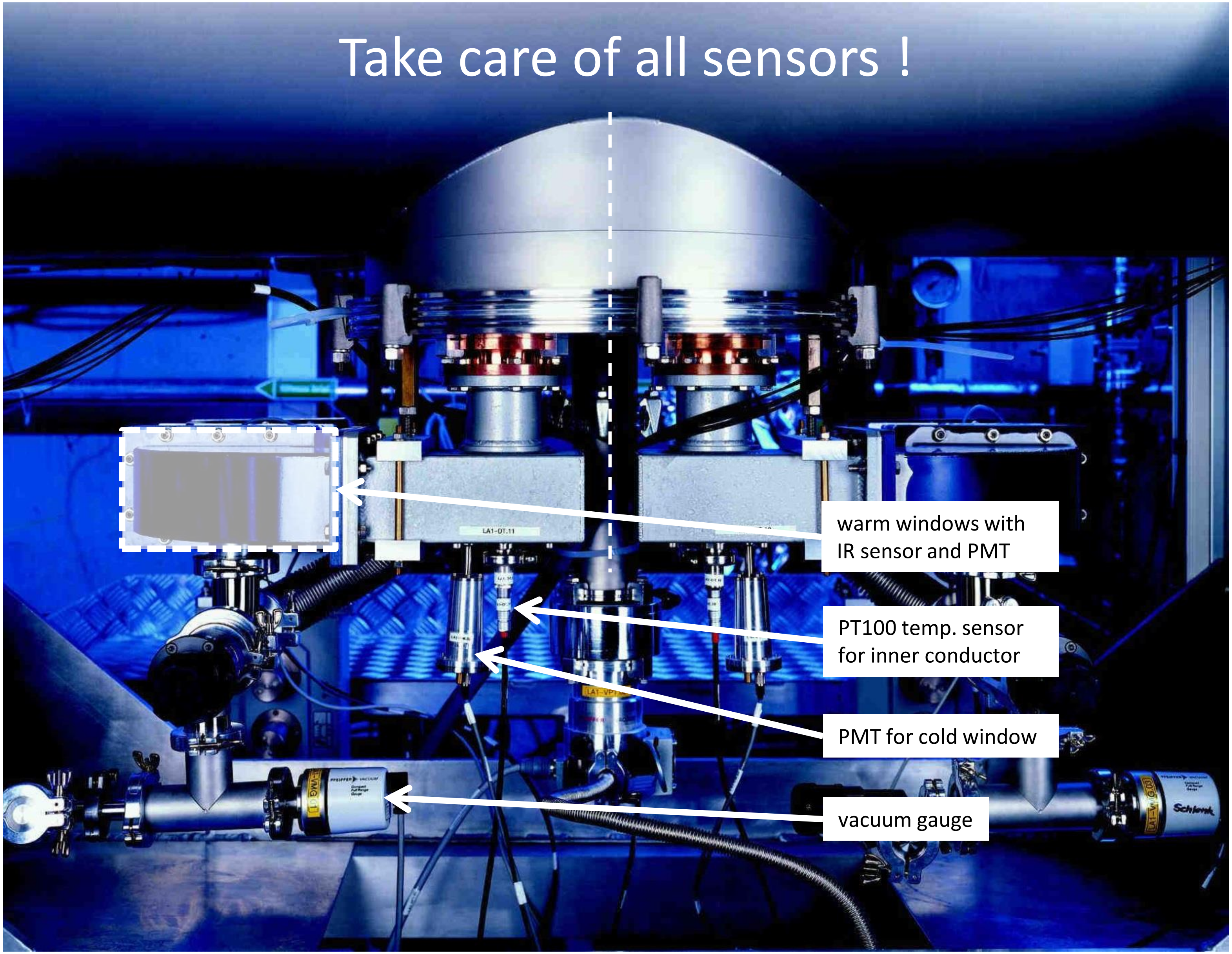


ELBE Coupler Interlock for 20kW CW at 1.3 GHz per cavity

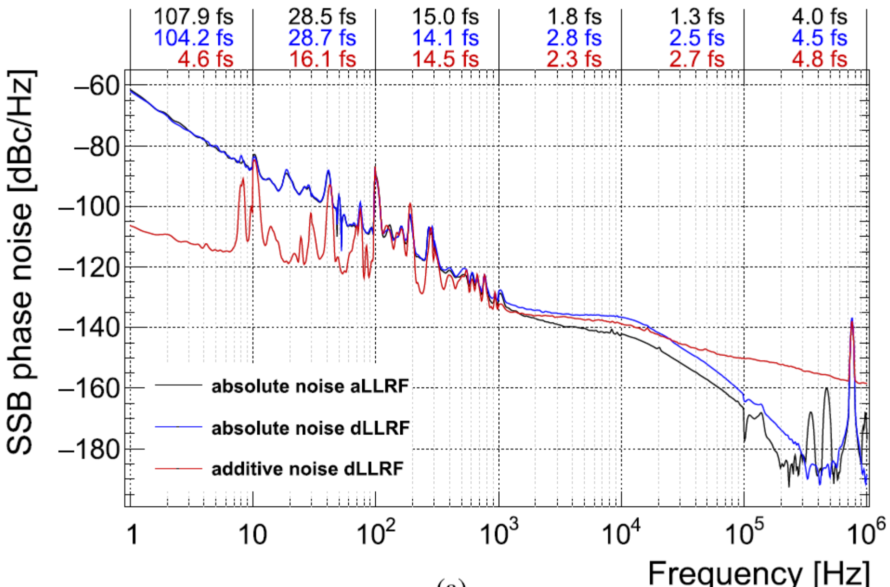
- 2 PMTs, 1 for cold an 1 for warm window (H5783 or H11901 from Hamamatsu)
- 1 vacuum gauge (Pfeiffer IKR060) per FPC to monitor coupler vacuum
- 1 IR temp. sensor (Raytech) for warm window, cooled by fan-discharge duct
- 1 PT100 for inner conductor of the FPC, cold windows cooled by LN

RF is switched off whenever a certain thresholds of at least one sensor is exceed. Shutdown time <1 ms (limited by Siemens SPS, electronics and PMTs are faster).

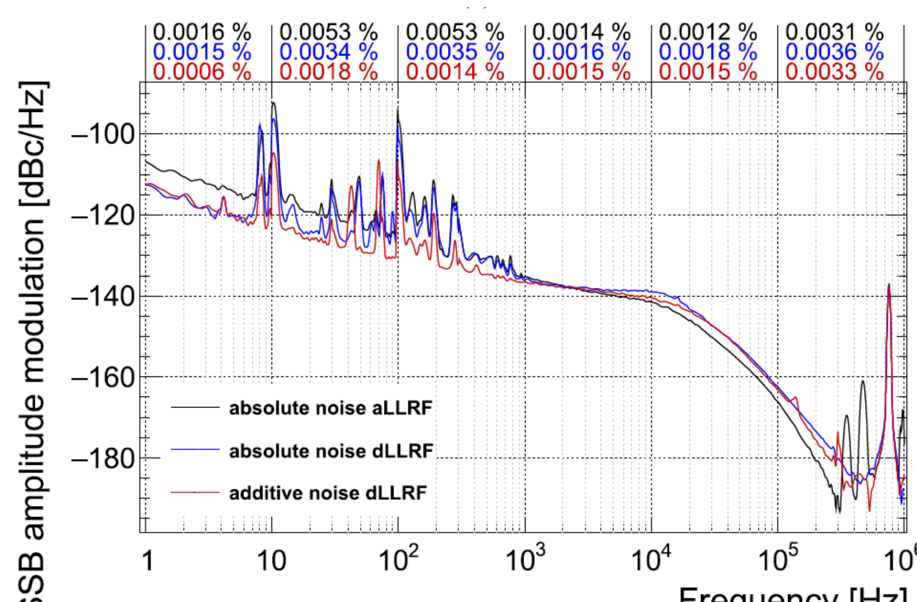
Diagnostics to protect the FPCs



RF Stability



(a)



(b)

RMS INTEGRATED PN FOR DIFFERENT FREQUENCY RANGES

	aLLRF	dLLRF	
	absolute noise [fs]	absolute noise [fs]	additive noise [fs]
1 Hz – 10 Hz	107.9 ± 1.9	104.2 ± 1.8	4.6 ± 0.2
1 Hz – 100 Hz	111.6 ± 1.9	108.1 ± 1.8	16.8 ± 0.9
1 Hz – 1 kHz	112.6 ± 1.8	109.0 ± 1.7	22.2 ± 0.8
1 Hz – 10 kHz	112.6 ± 1.8	109.1 ± 1.7	22.3 ± 0.9
1 Hz – 100 kHz	112.6 ± 1.8	109.1 ± 1.7	22.5 ± 0.9
1 Hz – 1 MHz	112.7 ± 1.8	109.2 ± 1.7	23.0 ± 0.9

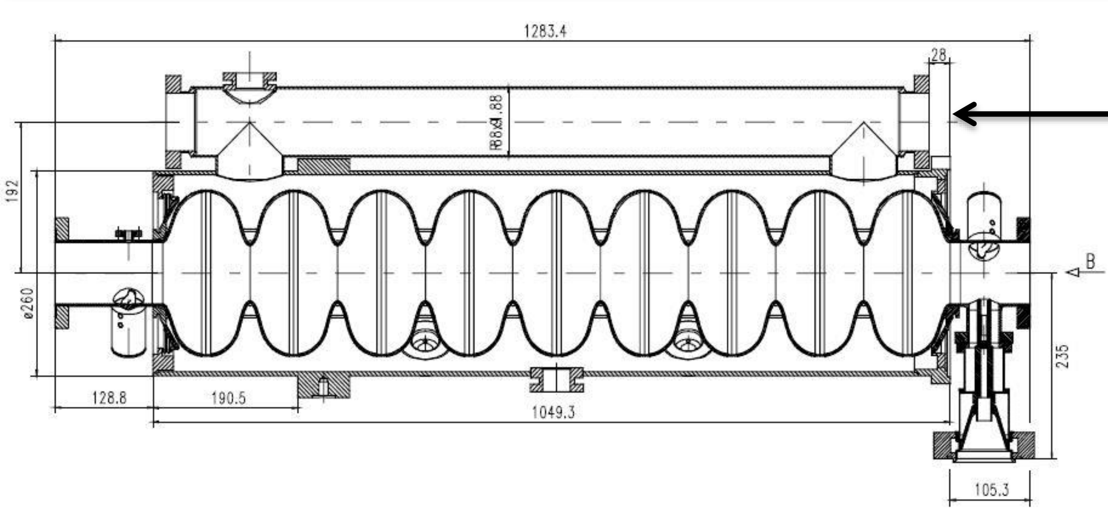
RMS INTEGRATED AM FOR DIFFERENT FREQUENCY RANGES

	aLLRF	dLLRF	
	absolute noise [%]	absolute noise [%]	additive noise [%]
1 Hz – 10 Hz	$(1.6 \pm 0.1) \times 10^{-3}$	$(1.5 \pm 0.1) \times 10^{-3}$	$(6.0 \pm 0.2) \times 10^{-4}$
1 Hz – 100 Hz	$(5.5 \pm 0.5) \times 10^{-3}$	$(3.7 \pm 0.3) \times 10^{-3}$	$(1.9 \pm 0.1) \times 10^{-3}$
1 Hz – 1 kHz	$(7.6 \pm 0.4) \times 10^{-3}$	$(5.1 \pm 0.2) \times 10^{-3}$	$(2.4 \pm 0.1) \times 10^{-3}$
1 Hz – 10 kHz	$(7.8 \pm 0.4) \times 10^{-3}$	$(5.3 \pm 0.2) \times 10^{-3}$	$(2.8 \pm 0.1) \times 10^{-3}$
1 Hz – 100 kHz	$(7.9 \pm 0.4) \times 10^{-3}$	$(5.6 \pm 0.2) \times 10^{-3}$	$(3.2 \pm 0.1) \times 10^{-3}$
1 Hz – 1 MHz	$(8.5 \pm 0.4) \times 10^{-3}$	$(6.6 \pm 0.3) \times 10^{-3}$	$(4.6 \pm 0.2) \times 10^{-3}$

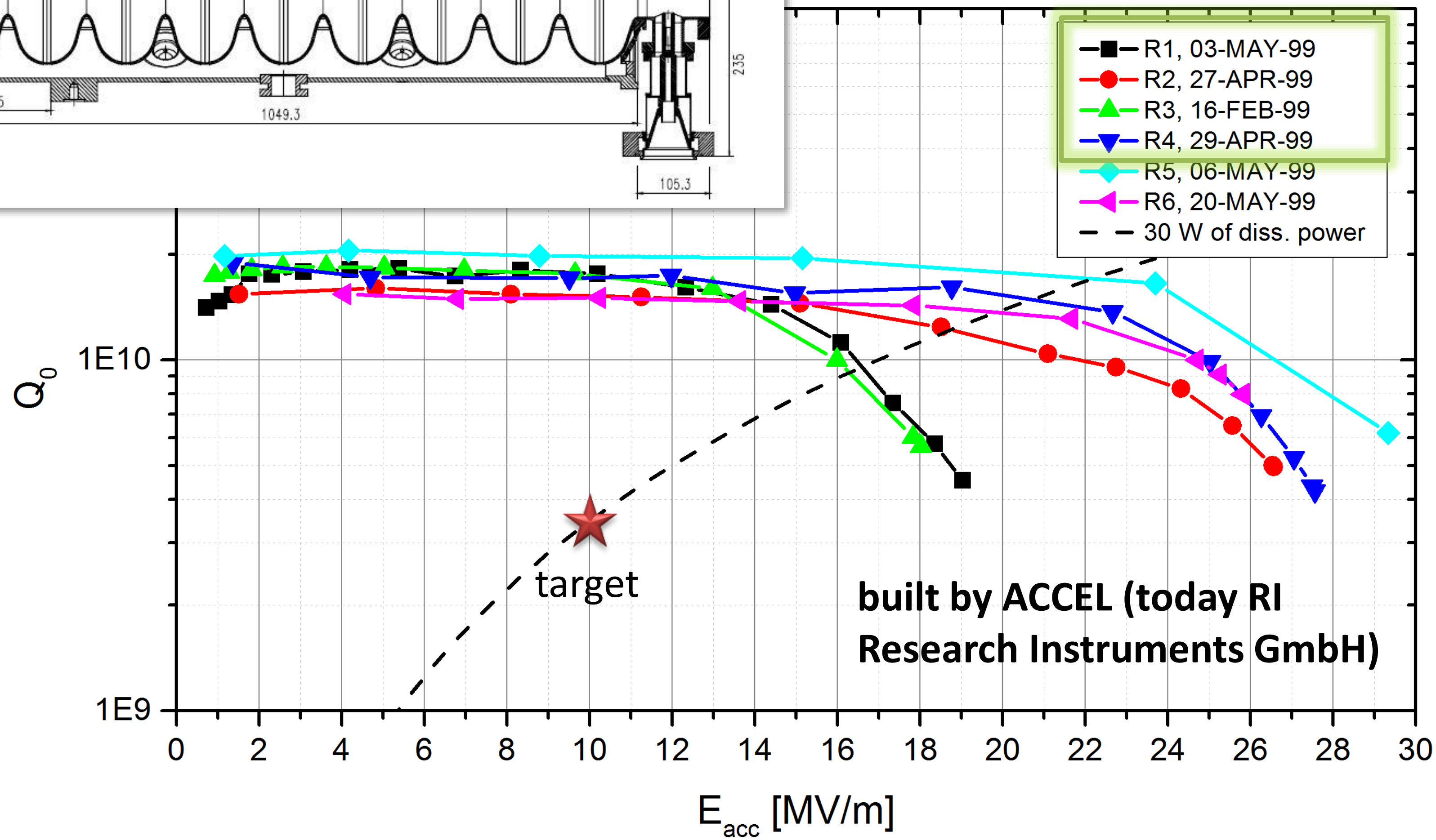
- comparison of the PN and the AM between the aLLRF and the dLLRF at 6 MV/m. Numbers shown on top represent the integrated noise over the frequency decade. (a) PN. (b) AM.
- additive noise measurement resulting in a stability of **0.01° in phase** and **0.005% in amplitude** (both rms), values are almost the same for both aLLRF and dLLRF controller

K. Zenker *et al.*, in *IEEE Transactions on Nuclear Science*, vol. 68, no. 9, pp. 2326-2333, Sept. 2021, doi: 10.1109/TNS.2021.3096757.

Vertical tests of cavity R1 – R6, 20 years ago



2-phase He return pipe for max. mass flow of **~4 g/s (80 W)**



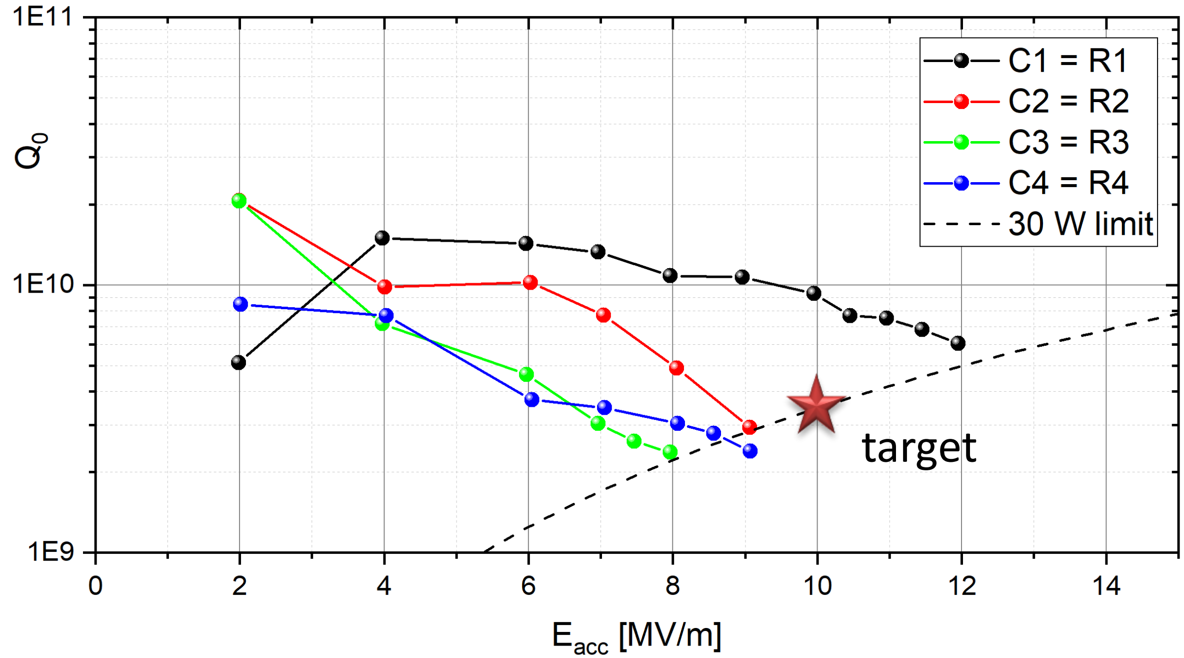
built by ACCEL (today RI Research Instruments GmbH)

Reality – cavity performance today (Jan. 2022)

DRESDEN concept

HZDR

From the very beginning all cavities limited in the tunnel by FE to about 50% of the achieved field in vertical tests!



Suspects being discussed:

1. Particulate contamination during cleanroom and beamline assembly?
   → Possible, but we are following DESY standards in our ISO 4 cleanroom!
2. EPDM gate valves in the modules and in the entire accelerator are not hydrocarbon-free
   → Possible, but we could not found hydrocarbons in the machine (anymore)!
3. Particulates contamination produced by movable beamline elements close to the cavity in combination with transport mechanism that allows them to migrate into the cavities.
   → Partially proven by monitoring the cavity performance over the last years

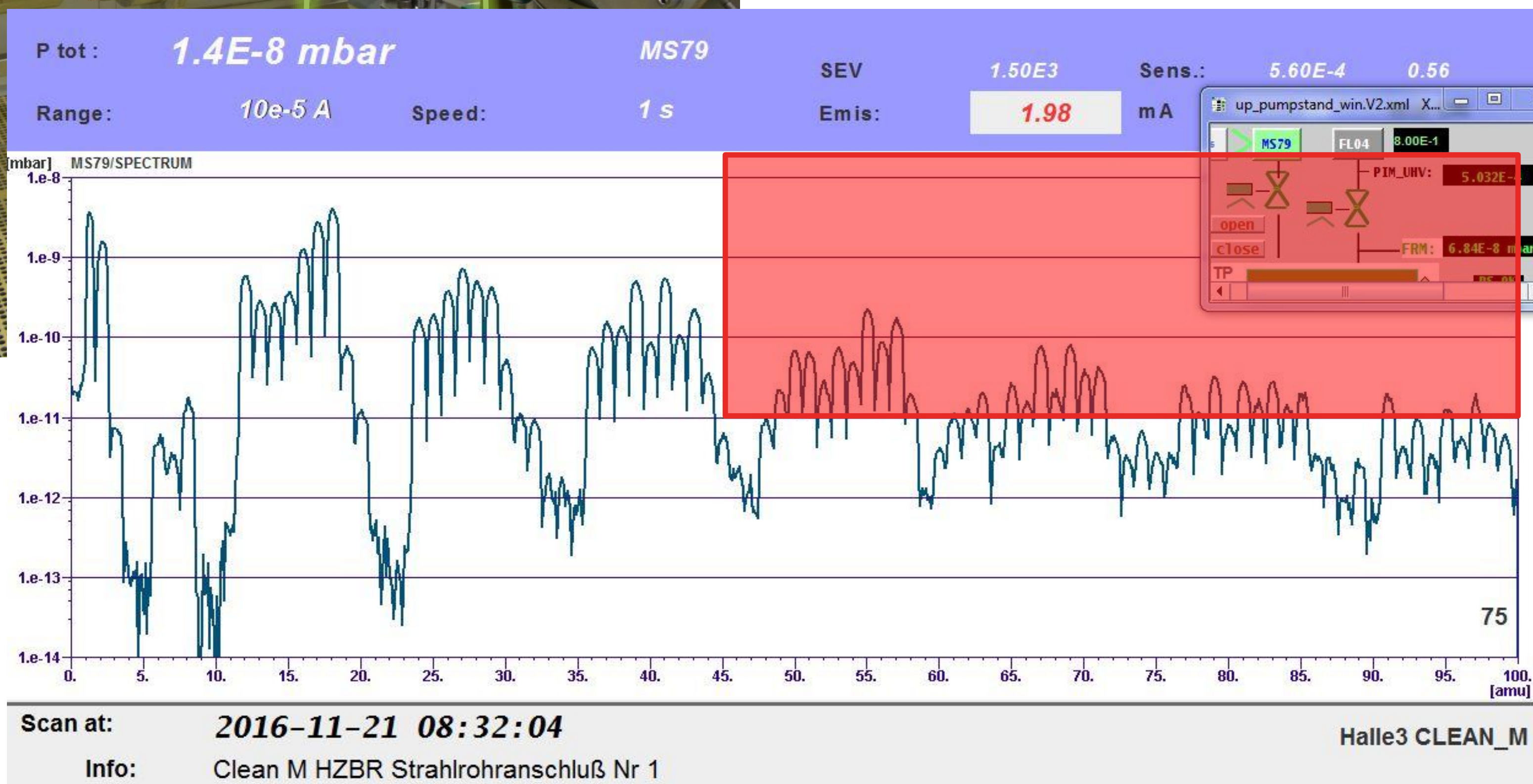
Cleanroom preparation of BL elements

- cavity assembly in ISO4 cleanroom
- beamline assembly in the tunnel with local cleanroom (class >ISO4)
- 3x pump and purge before open the gate valves
- UHV cleaning
  - pre-cleaning with dishwasher for degreasing
  - ultra sonic bath with Tickopur R33
  - ultra pure water rinsing (up to 6 Mohm)
  - drying in vacuum oven up to 100°C
  - blow off with ionized N2 to <10 particle @ 0.3 µm

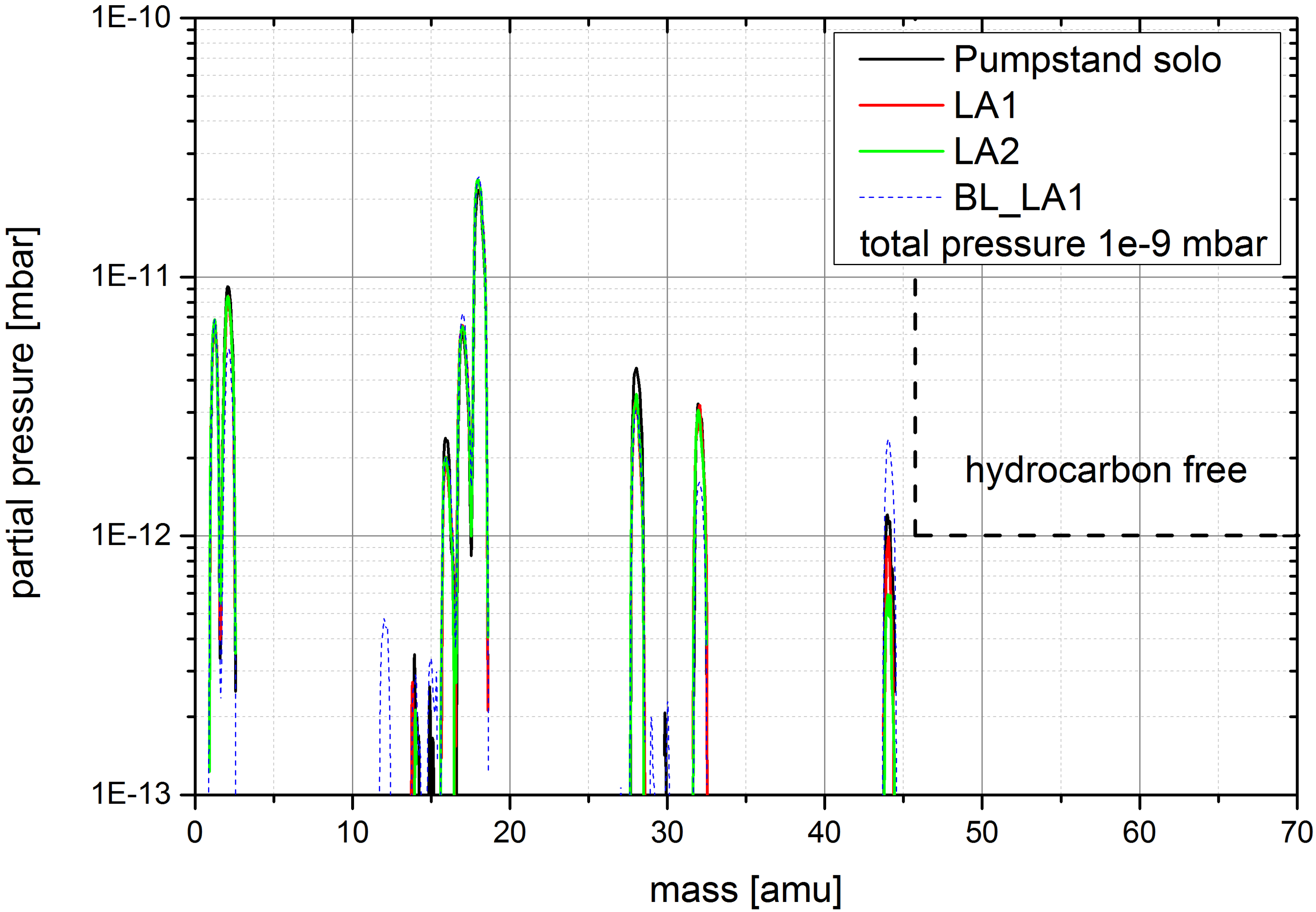
Mass spectrum of our EPDM gate valves

Series 010 | Mini UHV gate valve
DN40, EPDM sealing material

according to „DESY Spezifikation Nr.: Vakuum 005/2008“ parts are hydrocarbon free if partial pressure beyond AMU 45 are at least 3 orders less than total pressure



Mass spectra at different positions in the BL



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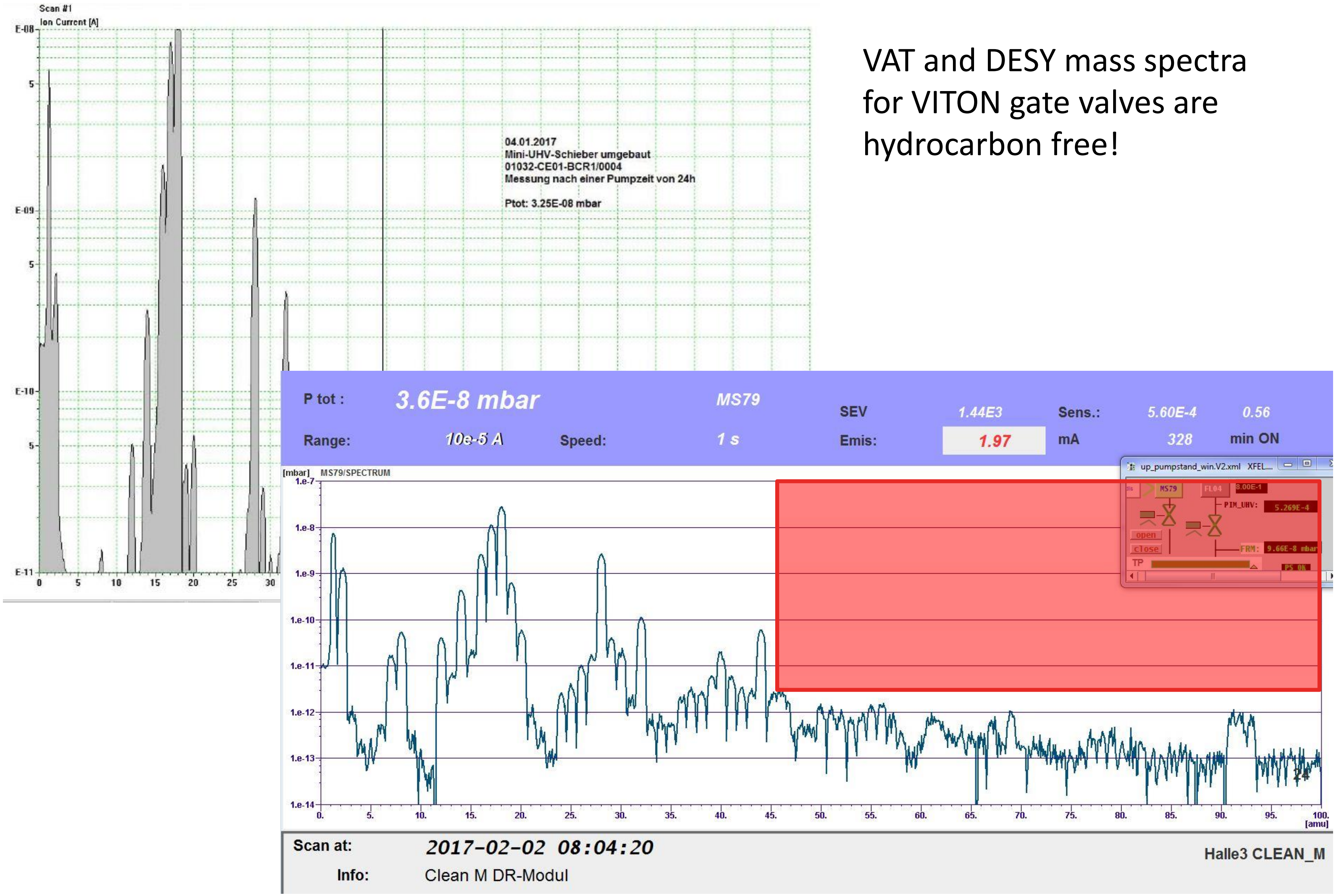
VITON gate valves for next modules



VAT and DESY mass spectra for VITON gate valves are hydrocarbon free!

Beamline elements close to LINAC 1

gate valve EPDM (3.5 m)

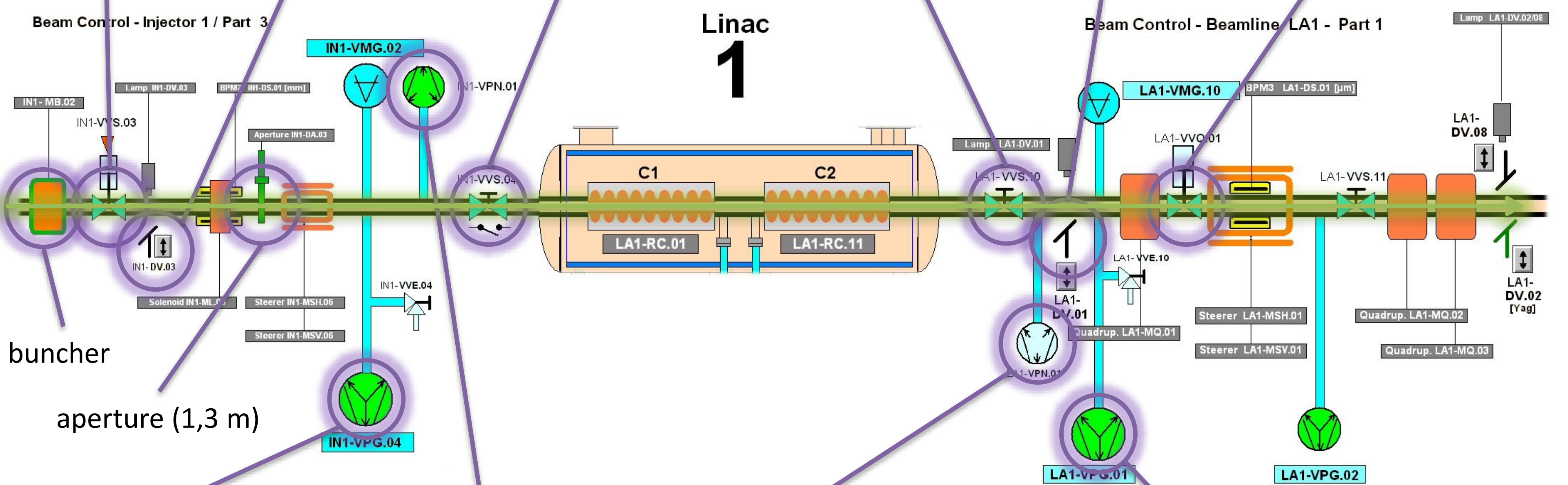
view screen (0,9 m) YAG or Cromox

gate valve (0,8 m) full metal

gate valve (0,7 m) full metal

OTR view screen Al foil (0.9 m)

fast closing valve Viton (1.0 m)



buncher

aperture (1,3 m)

getter pump (1,4 m) Varian Diode

NEG pump (1,3 m) SAES-WP1250

NEG pump (1,2 m) SAES-WP1250

getter pump (1,3 m) Varian Noble-Diode

note: additionally two EPDM gate valve inside the cryo module

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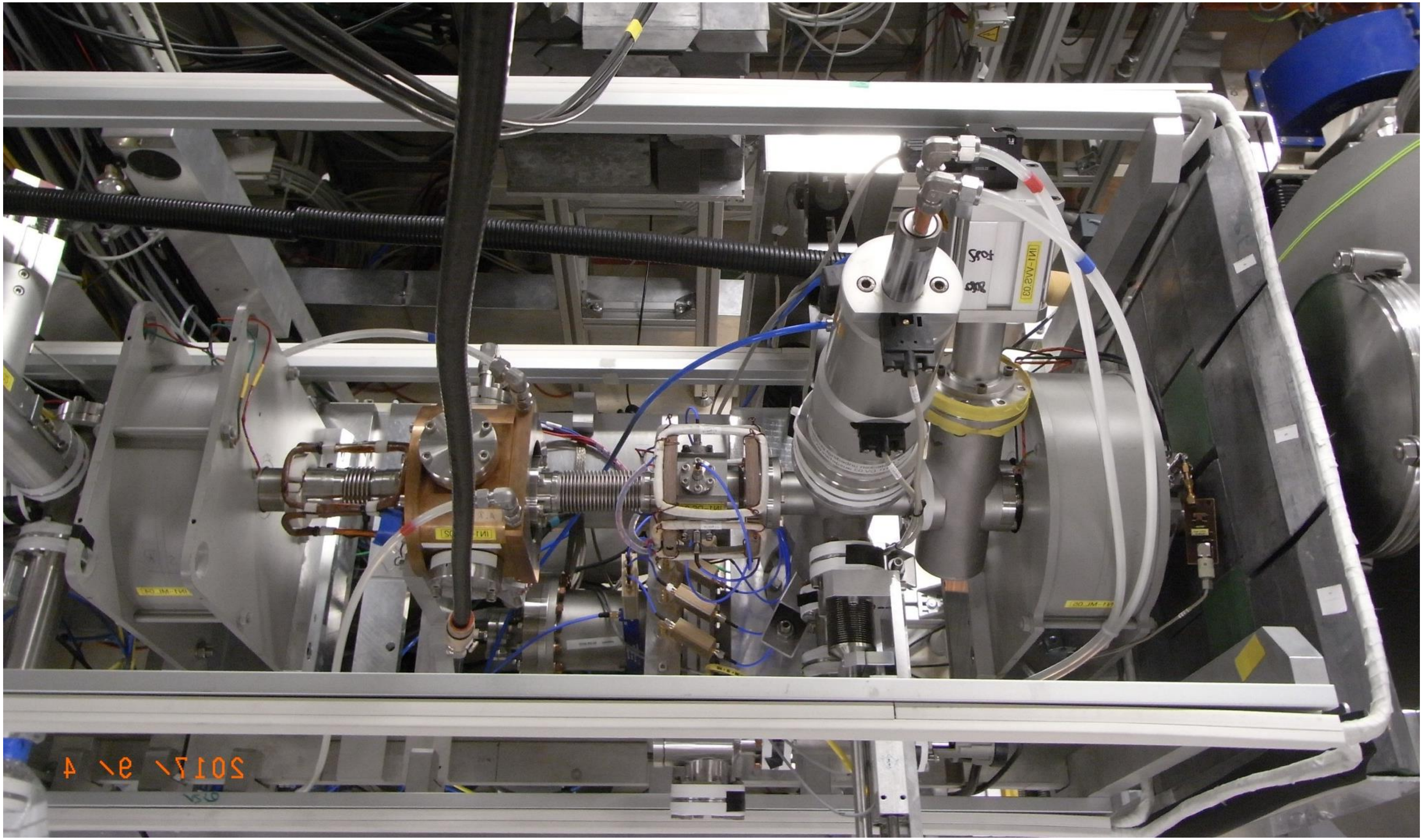
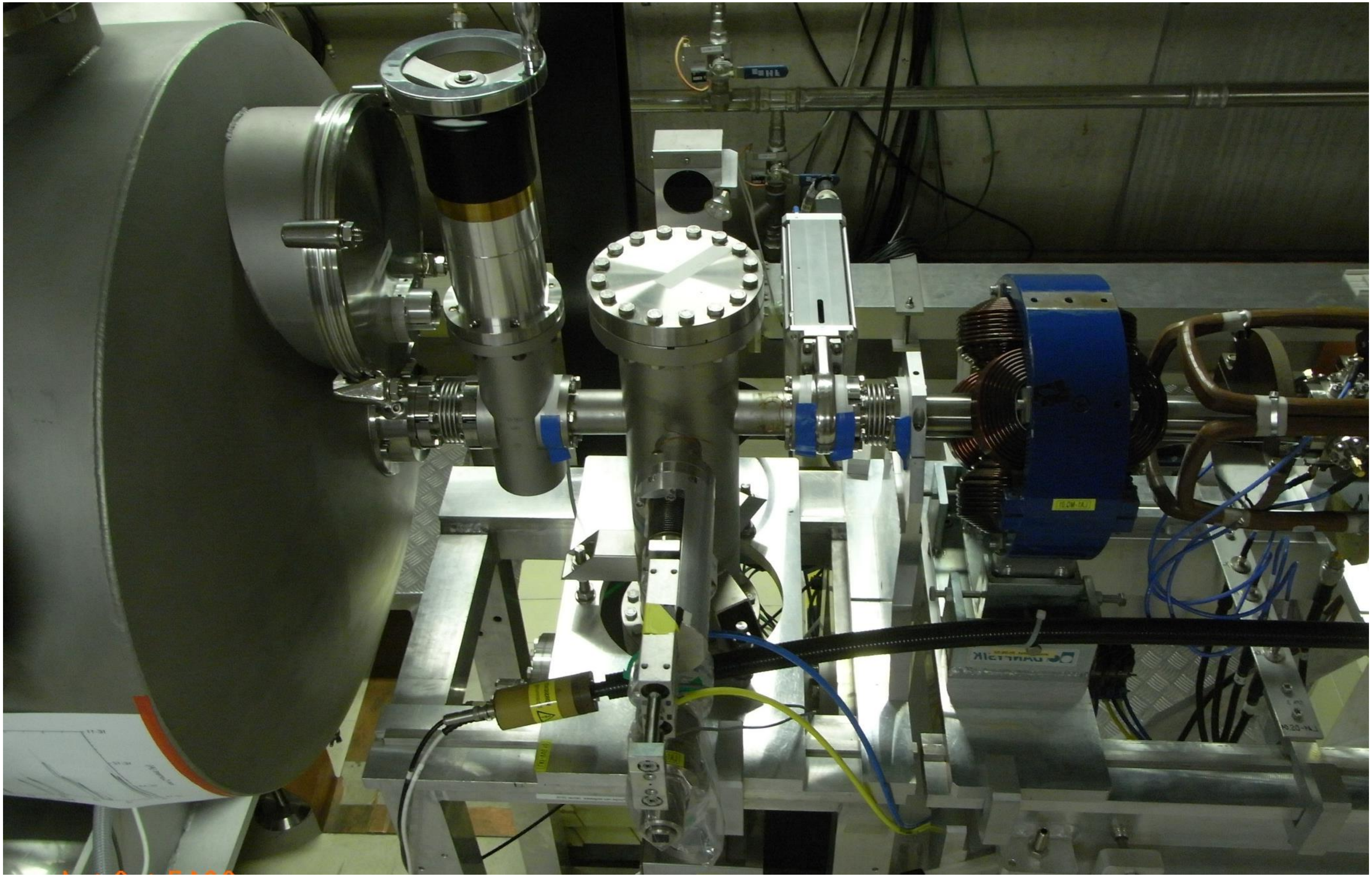
Beamline elements in front of LINAC 1



Beamline elements after LINAC 1



Beamline elements close to LINAC 2

OTR view screen
Al foil (0.9 m)

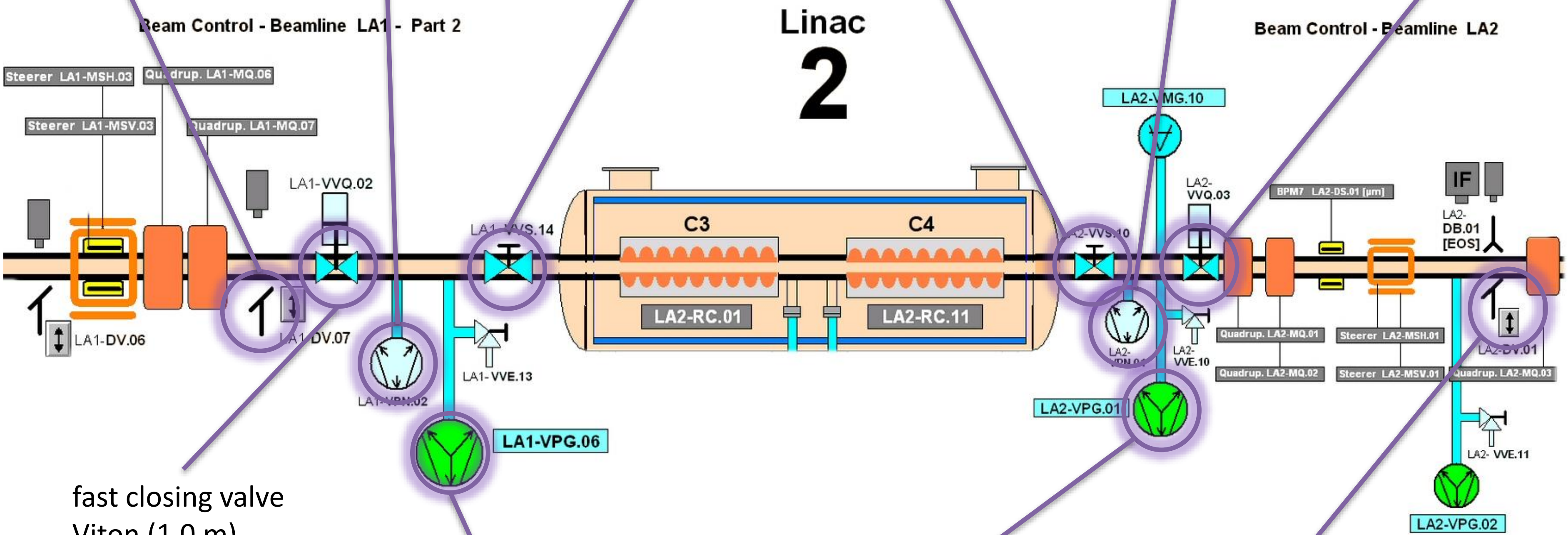
NEG pump (1,2 m)
SAES-WP1250

gate valve (0,7 m)
full metal

gate valve (0,7 m)
full metal

NEG pump (1,2 m)
SAES-WP1250

fast closing valve
(1,0 m) Viton



fast closing valve
Viton (1,0 m)

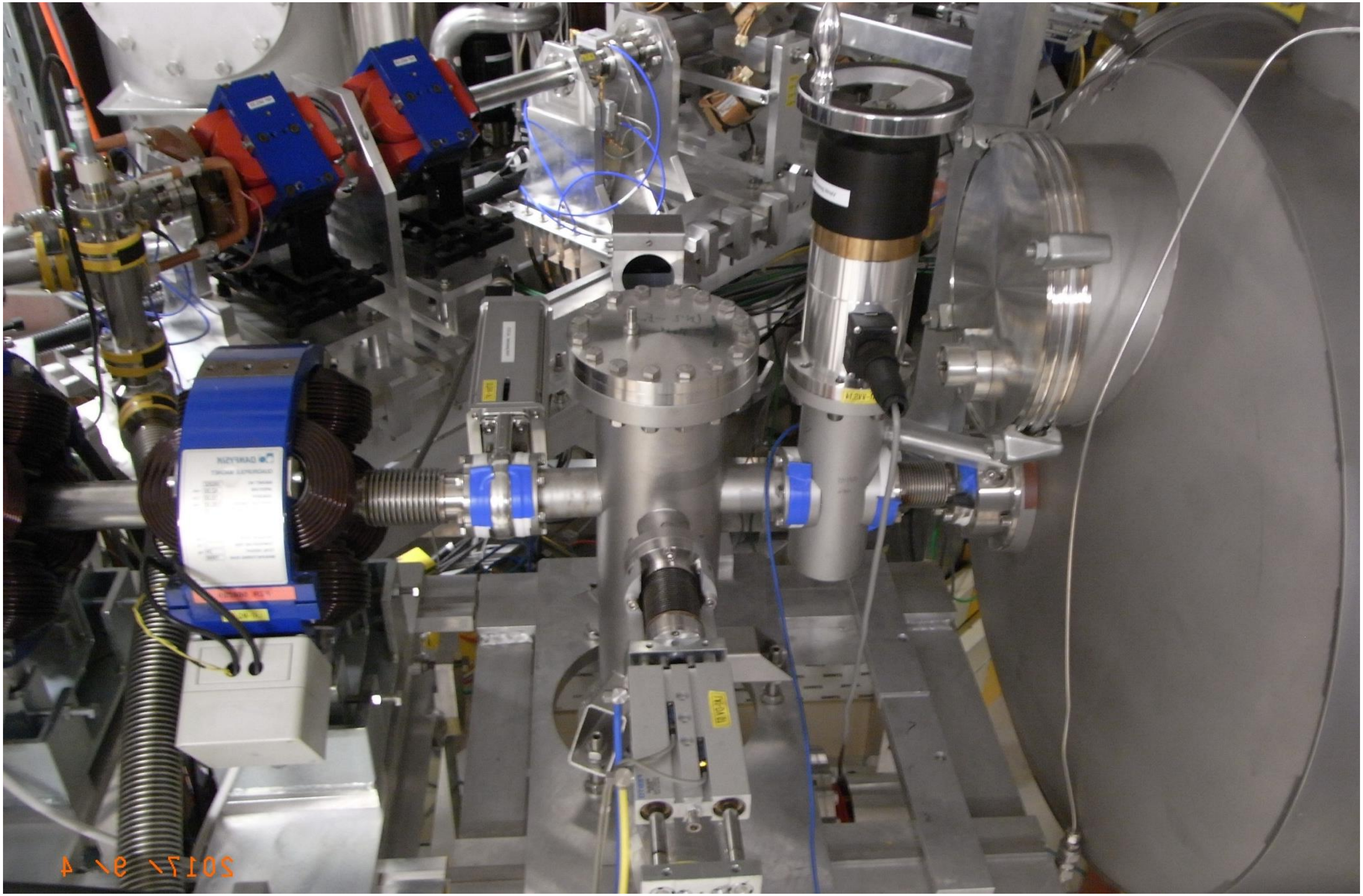
getter pump (1,3 m)
Varian Diode

getter pump (1,3 m)
Varian Noble-Diode

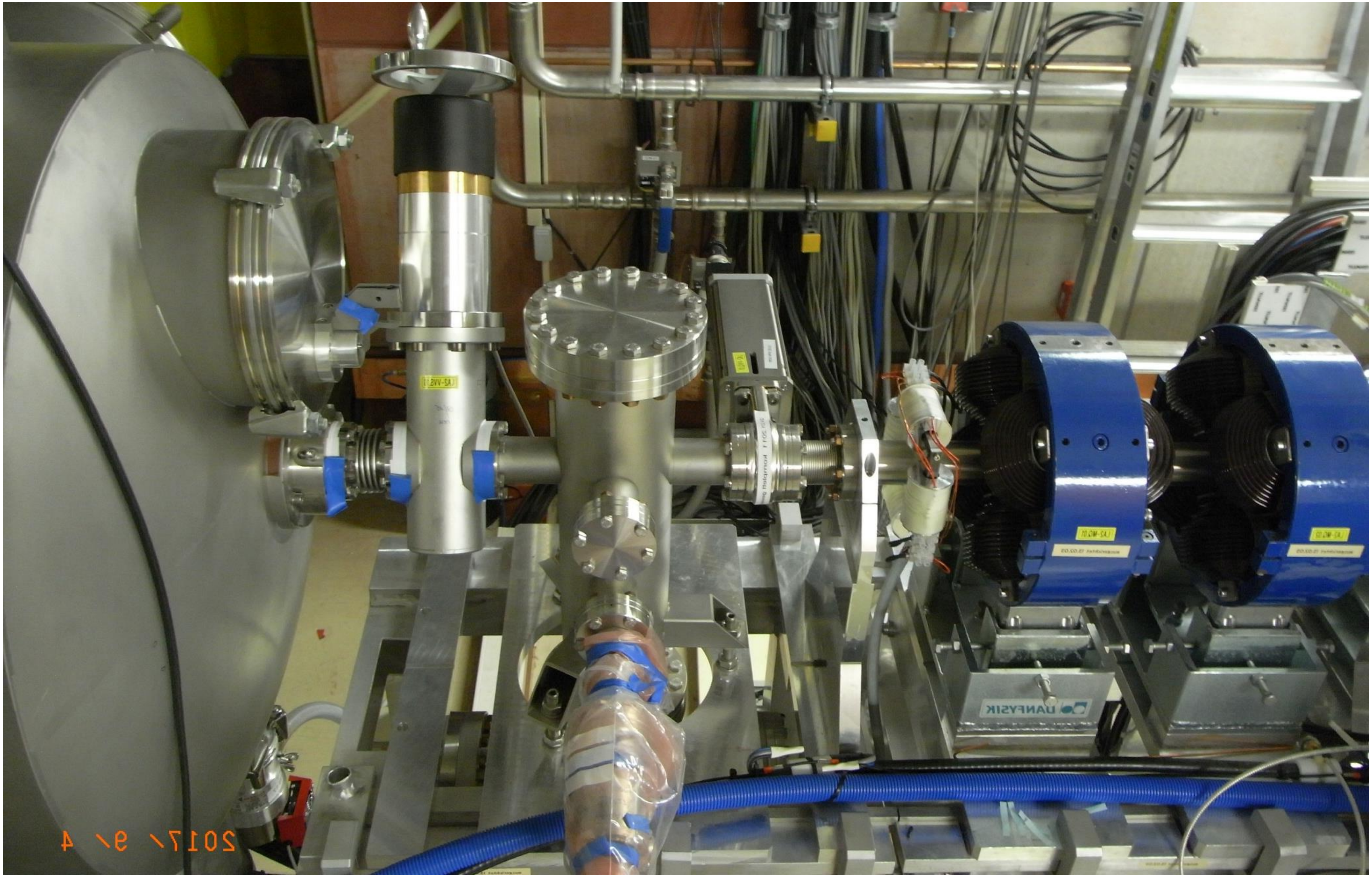
OTR view screen
Al foil (2,1 m)

note: additionally two EPDM gate valve inside the cryo module

Beamline elements in front of LINAC 2



Beamline elements after LINAC 2



Summary beamline elements

- view screens (Cromox ceramic, YAG, Al-OTR) – 1 m
- fast closing valve (Viton) – 1m
- gate valve (full metal) – 0.7 m
- gate valve (EPDM) – in the entire accelerator
- service hand valve (EPDM) – inside module

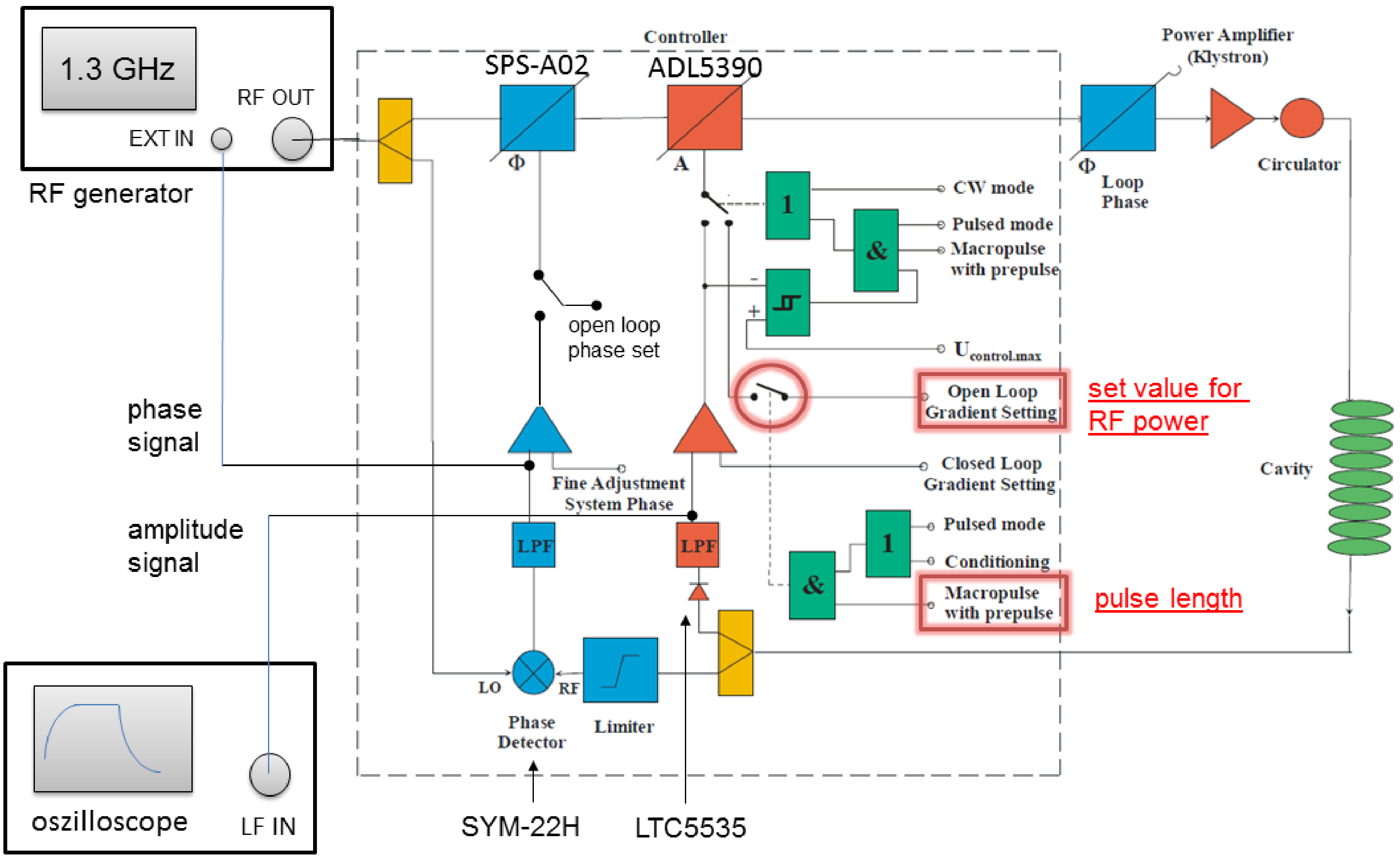
- getter pumps (Varian Noble-Diode, Diode) – 1.3 m
- NEG pumps (SAES-WP1250) – 1.2 m

- NC copper buncher with moving tuner stamps – 2 m

Are these BL elements responsible for degradation?

High power (pulsed) RF processing (HPP)

- phase signal of analog LLRF is used in a PLL regime to modulate an external RF generator
- logic gates and fast switches to pulse and set a constant RF power
- amplitude signal of LLRF as well as vacuum, temp., dose and light sensors for analysis



High power (pulsed) RF processing (HPP)

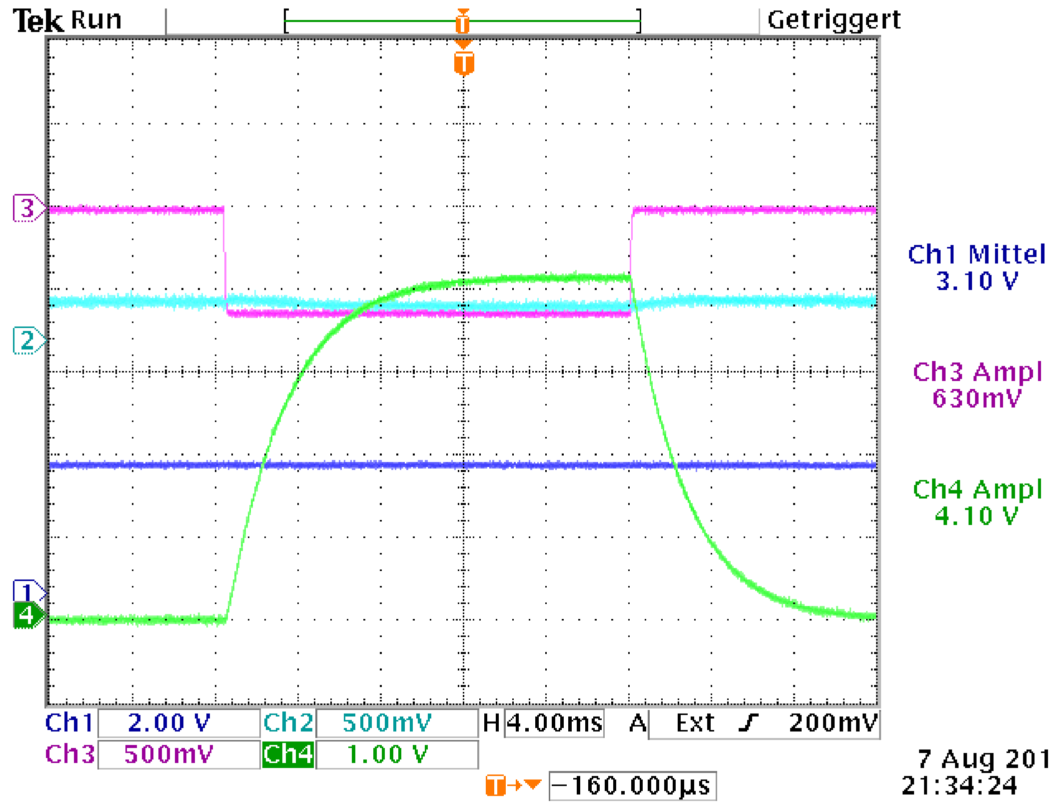
- HPP done in a PLL regime to modulate an external RF generator to follow LF-detuning
- RF power is stepwise increased up to 14-17 MV/m (depending on cavity)
- Field amplitude as well as vacuum, temp., dose and light sensors for analysis / protection
- HPP stopped if reproducible thermal breakdown or high average helium consumption

all magnets off

duty cycle 20 / 600 ms

RF power up to 20 kW

τ = 2-3 ms, BW ~ 112 Hz



- training events are indicated by randomly appearing field drops at high fields or electrons cloud
- not all cavities show same behavior, some benefit more from HPP than others

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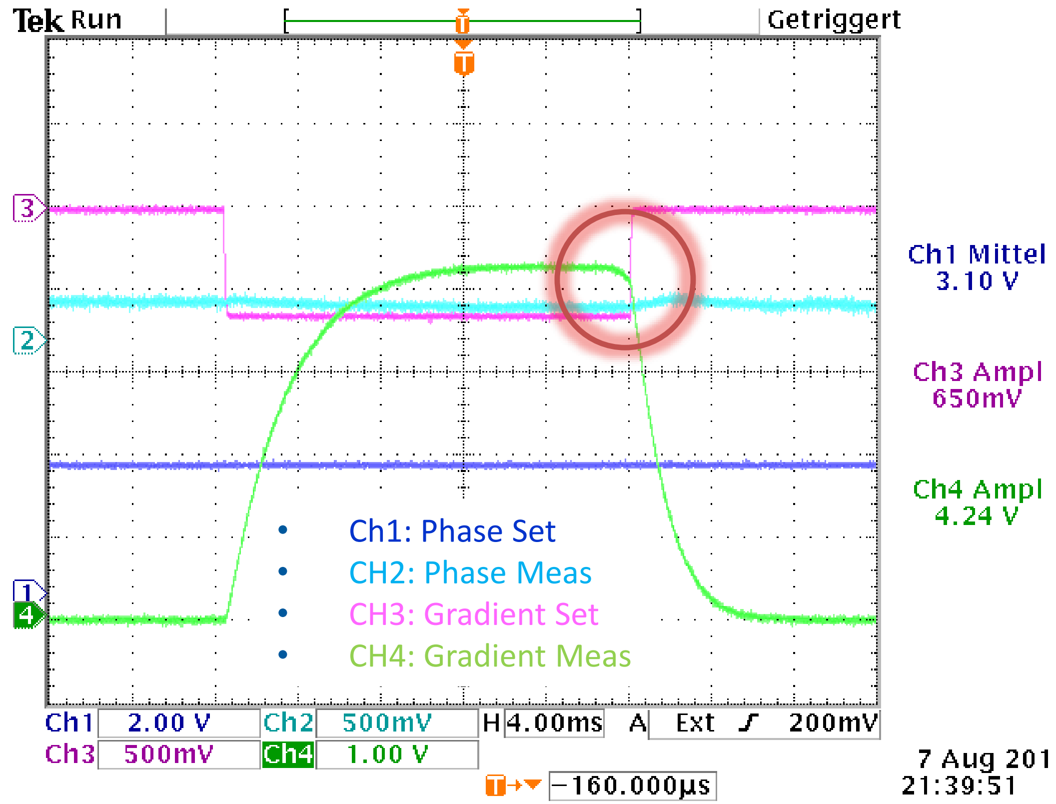
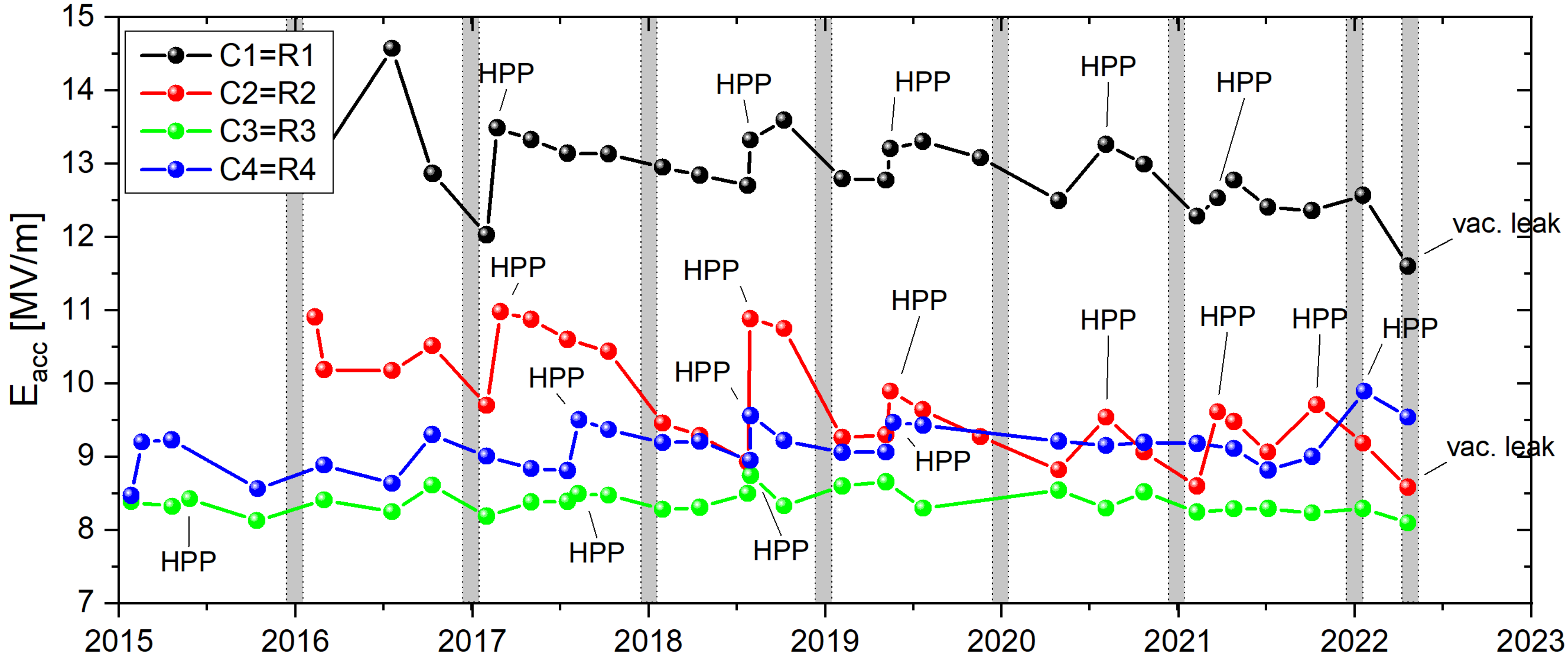


Cavity degradation over time



*note grey bar = thermal cycle

- Evolution of the max. usable acc. gradient for dissipated power of 30 W (each)
- HPP not sustainable, continuous degradation btw. HPP but also beyond
- Frequent HPP needed to mitigate FE but initial performance could not recovered
- No improvement by complete therm. cycle done once a year (maintenance)

What else?

- No helium or plasma processing done, because need for higher gradient is not yet high enough, but of course considered final option

aLLRF

- No dedicated quench protection but if LLRF controller output is reaching max. value -> RF is switched off (τ=100ms)
- No feedforward to compensate beam loading, but as beam is set up in a macro pulsed mode at the nominal bunch charge this results in same beam energy as in CW (with the exception of the first few bunches in each pulse)

dLLRF

- quench protection implemented in firmware but not used at ELBE so far
- learning feed forward to compensate beam loading in macro pulsed mode
- all questions are best directed to dLLRF expert M. Kuntzsch

Summary

- testing before and protection of high power RF components during operation is essential to prevent serious damages

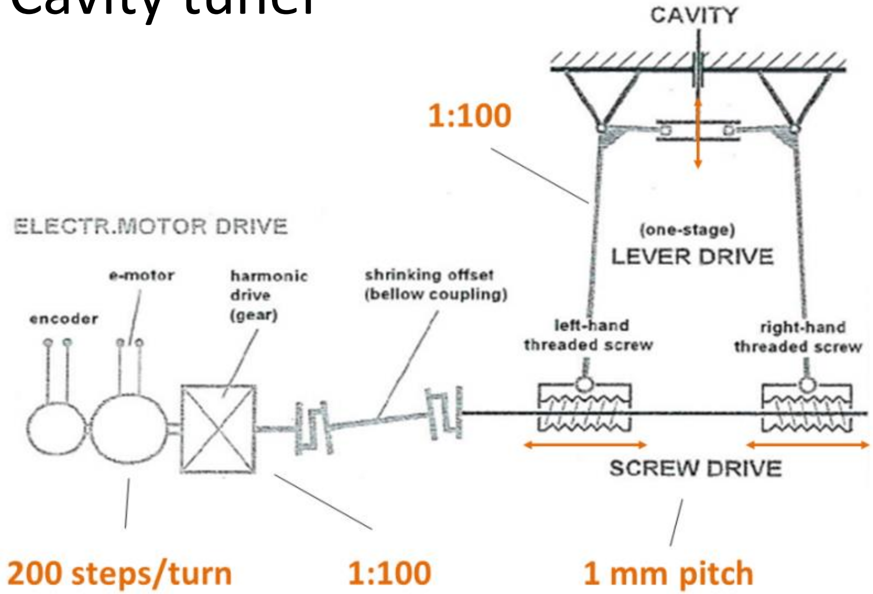
- cavities in the tunnel limited by FE to less than 50% of the achieved field in vertical tests
  - contamination during cleanroom assembly in ISO4 cleanroom
  - activation of field emitters because of hydrocarbons in EPDM gate valves that are installed in the entire accelerator?

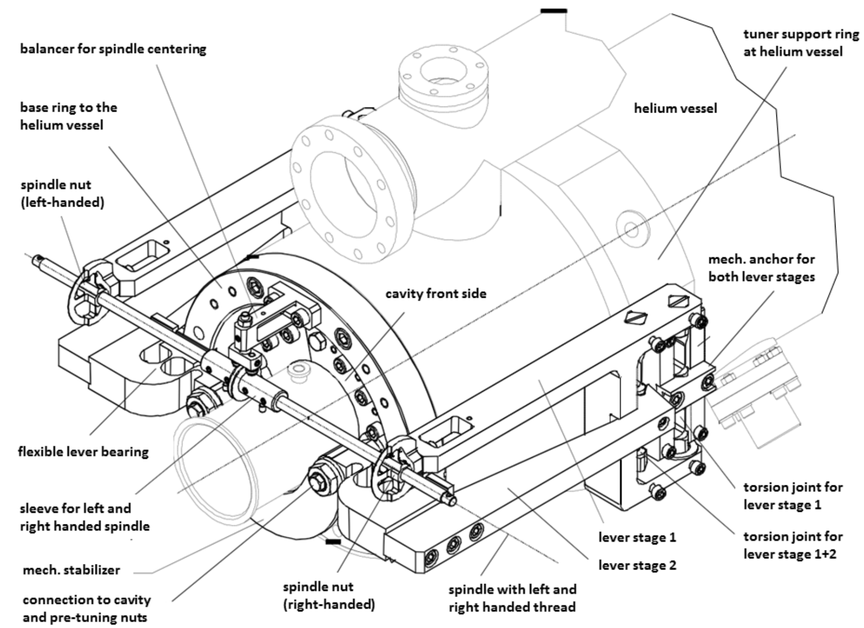
- continuous degradation of all cavities over time
  - particles from BL elements moving into nearby (~1m) cavities?

- mitigation by HPP -> **but no miracles to be expected**
- no improvement by complete therm. cycle done once a year
- helium or plasma processing only considered as final option

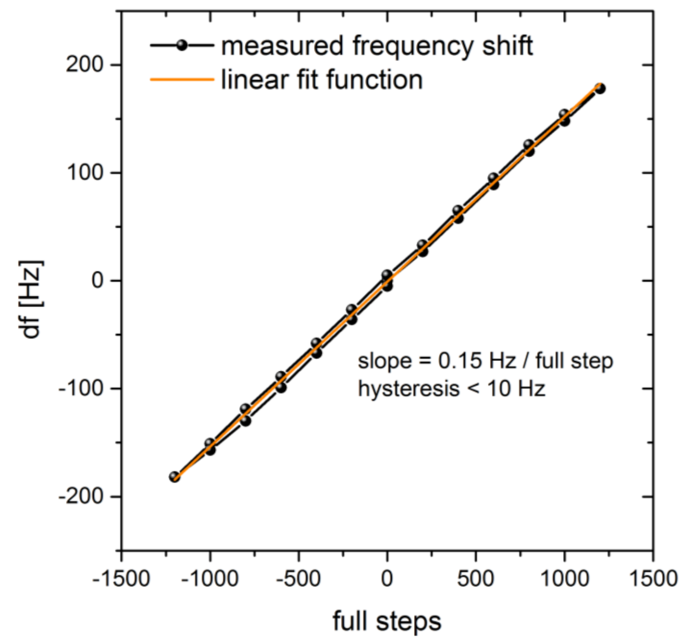
Backup

Cavity tuner



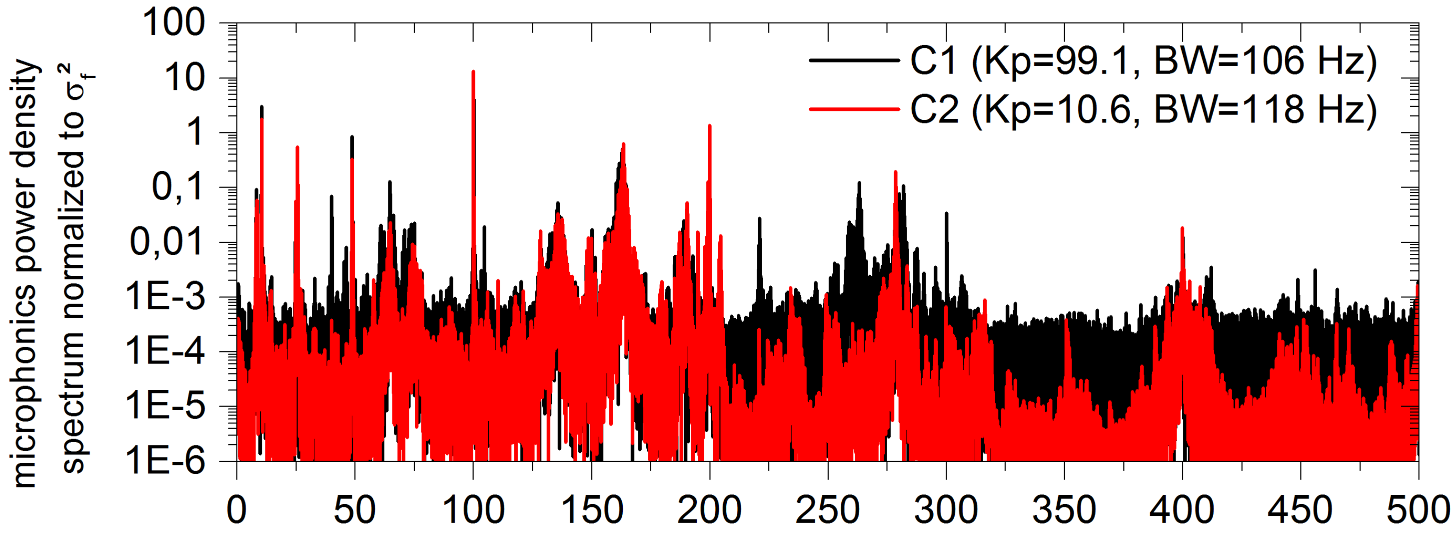


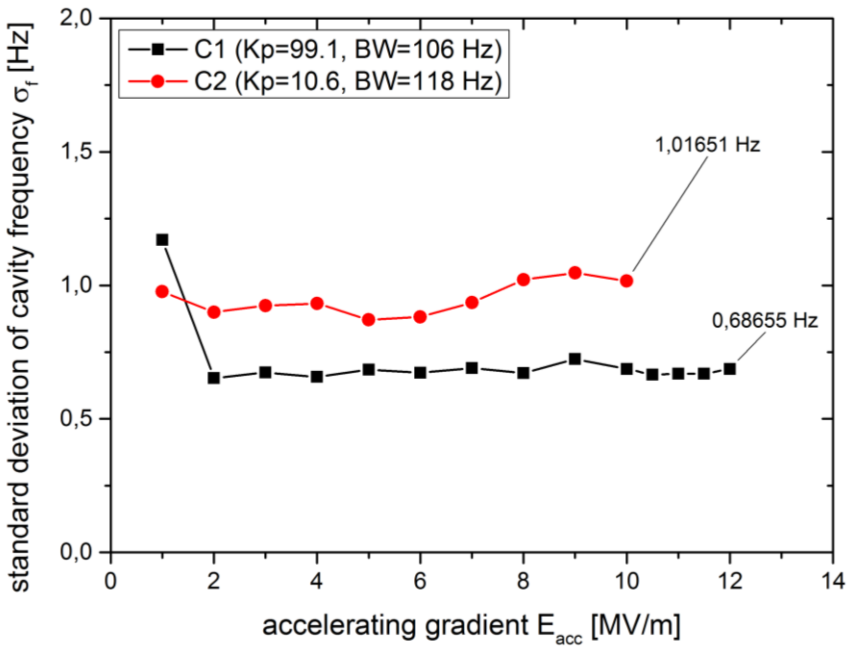
tuner parameter	unit	value
force path	mm	±30
load path	mm	±0.30
frequency const.	kHz/mm	~400
tuning range	kHz	±110
mech. resolution	nm/step	0.5
frequ. resolution	Hz/step	0.15
hysteresis	Hz	<10

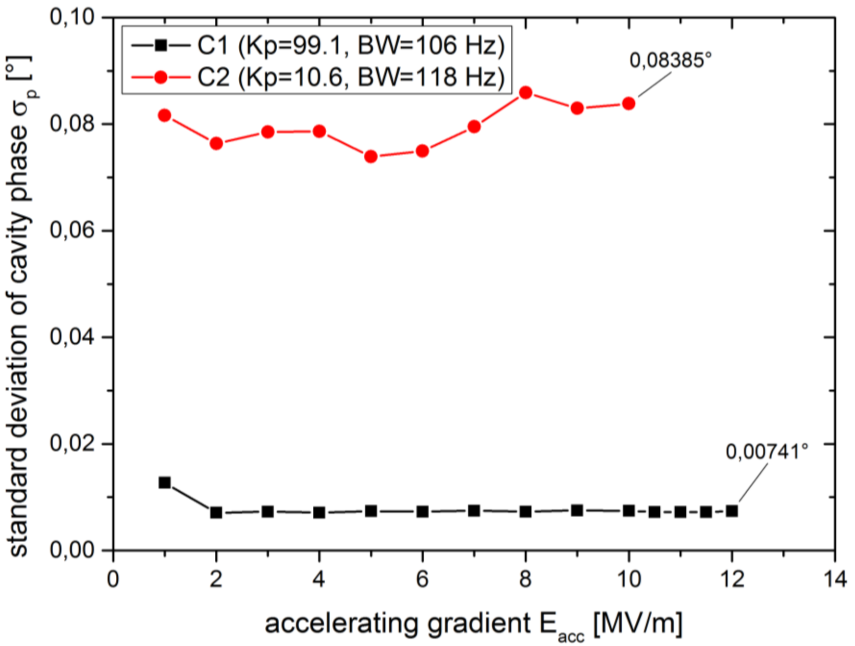


tuner based on 2-stage lever drive with torsion joints for lowest hysteresis and highest precision

Microphonics

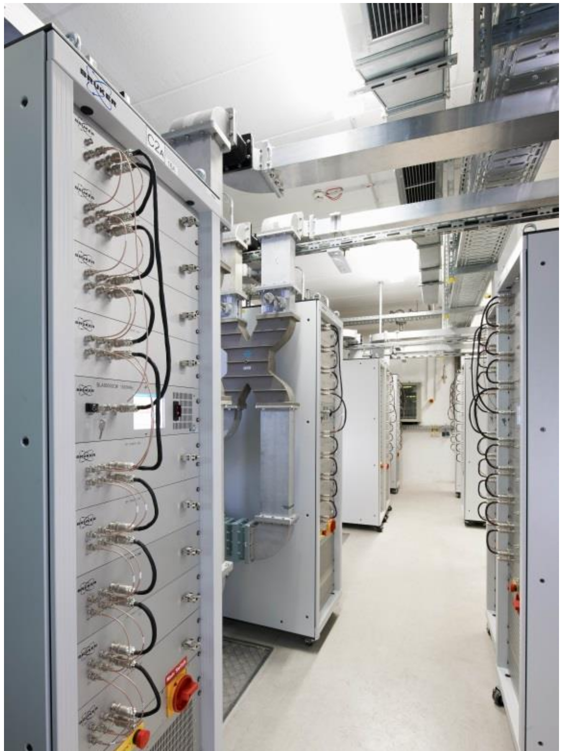






CWRF power amplifiers

2001 – 2011	8kW klystron VKL7811St from CPI
2009	Bruker presented 1st 10 kW class AB solid state power amp. based on 28V LDMOS-FET Transistors at the SRF2009 in Berlin
2010	Delivery of the 1st 10 kW SSPA to HZDR for testing on beam
2012 – today	10x 10 kW SSPA (2 per cavity), reliable and compact system with high redundancy (5 LDMOS died no impact on beam time, 2 times 4 h down time because of power supply failure)



FEBRUARY 2012

Latest version by SigmaPhi Electronics (former Bruker)

- 15kW CW 1300MHz based on 6th gen. 50V LDMOS
- Bandwidth: ±5MHz
- Small Signal Gain: 73dB typ.
- Operating Dynamic: >30dB
- Rise / Fall Time: < 100ns
- Harm. Rejection: 40dBc min.
- Noise Figure: 6dB typ.
- Spurious: 60dBc min.

CW Issues or experiences with high beam power

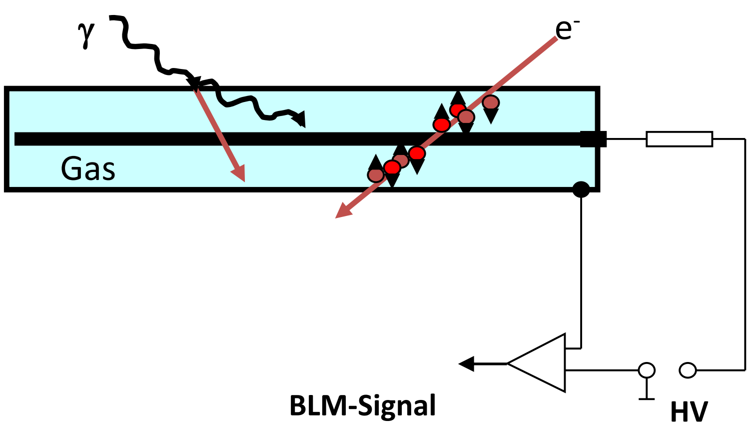
- First attempt to operate ELBE in CW resulted in a hole in the beamline and 2 polluted cavities ☹
  - Estimation for 1mA and 20 MeV (stopped in steel after 1.5 cm), c = 450 J/Kg K, m= 63 mg, T_M=1400 °C

$$Q = P \cdot t = m \cdot c \cdot \Delta T \longrightarrow t_{melt} = \frac{m \cdot c \cdot (T_{melt} - T_0)}{P_{beam}} \approx 2ms$$

- but even much lower lost beam currents may produce leaks

Solution: Beam Loss and Differential Current Monitors (BLM, DCM)

- BLMs are segmented ionization chambers based on HJ4.5-50 Coax (air insulated, radiation hard) along the whole beamline
  - radiation generates charged particles
  - apply high voltage, measure current
  - current proportional to beam loss
  - sensitivity: 0.3 - 3 V per µA beam loss



Diagnostics to protect the machine

Differential Current Monitors

- Based on λ/4 stripline BPM which is co-used by signal splitter as DCM and BPM
- BPM signals after each section are compared with each other by fast electronics
- If difference is higher than certain threshold (typ. 10 µA) beam is switched off

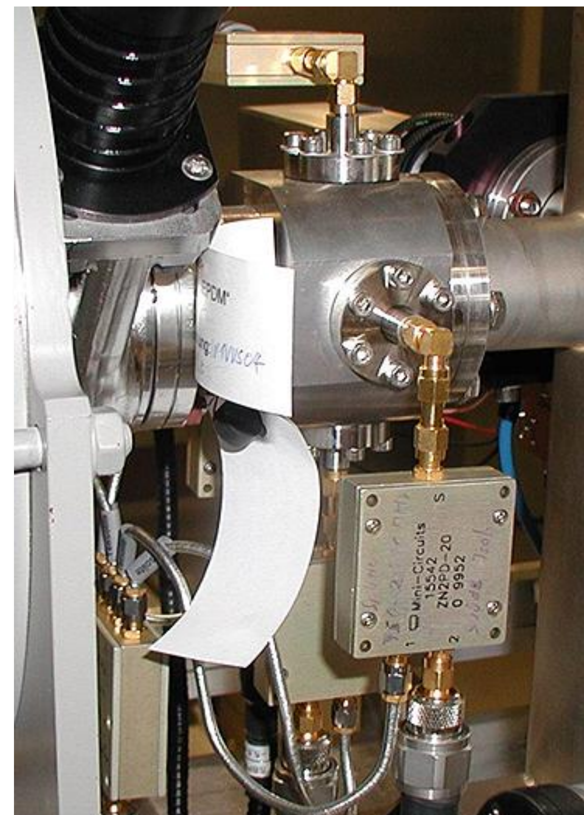
interlock threshold, typ. 10µA

signal proportional to beam current from position Z

signal proportional to beam current from downstream Z

Issues:

1. linearity over dynamic range
2. performance below 13 MHz



CW Issues or experiences with beam dump windows

- 14x Broken Be window, vacuum barrier btw. BL vacuum and graphite beam dump (1 mbar)
- reason (local) overheating, but wobbling also does not fully solved the problem
- thermal stress introduced by 40 kW beam over typ. 2 years caused crack of Be windows
- **Solution: Nb foil (50 µm, 100 € each) instead of Be (0.5 mm, 14000 €) cheaper, more robust!!**