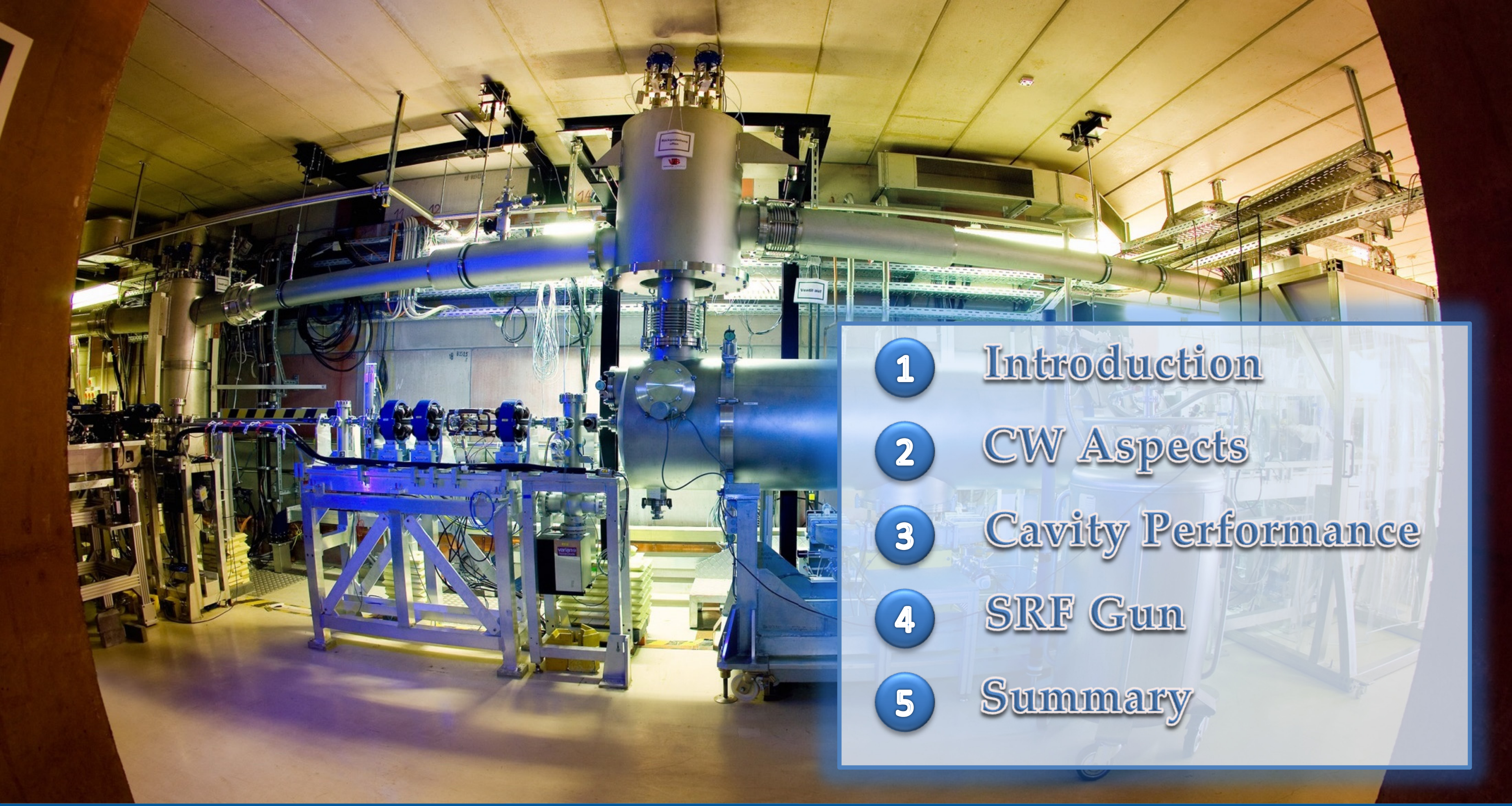


More than 15 years of CW SRF operation at ELBE

André Arnold on behalf of the whole ELBE team

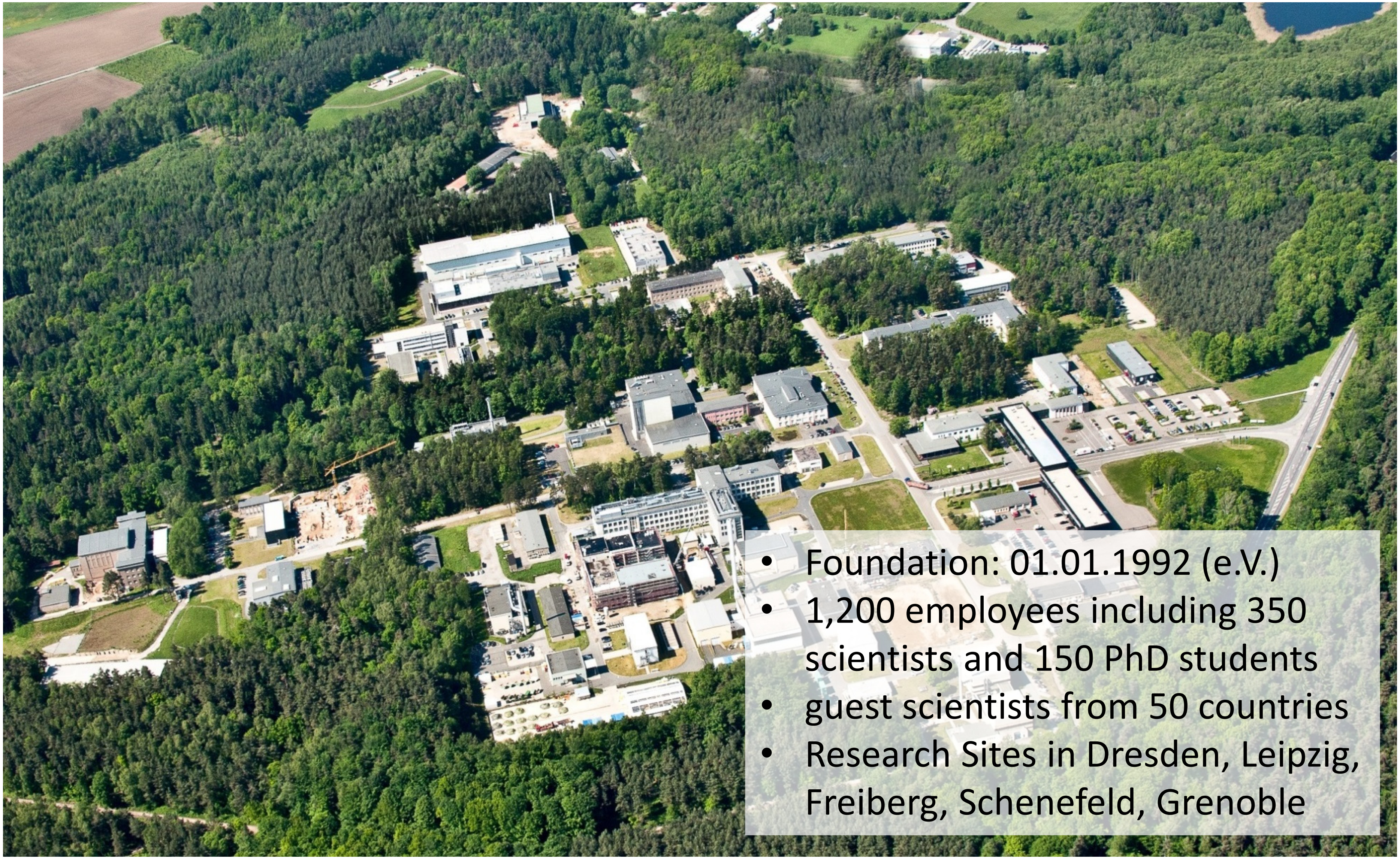
Partner von DRESDEN concept exzellenz-dresden.de

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Introduction into ELBE

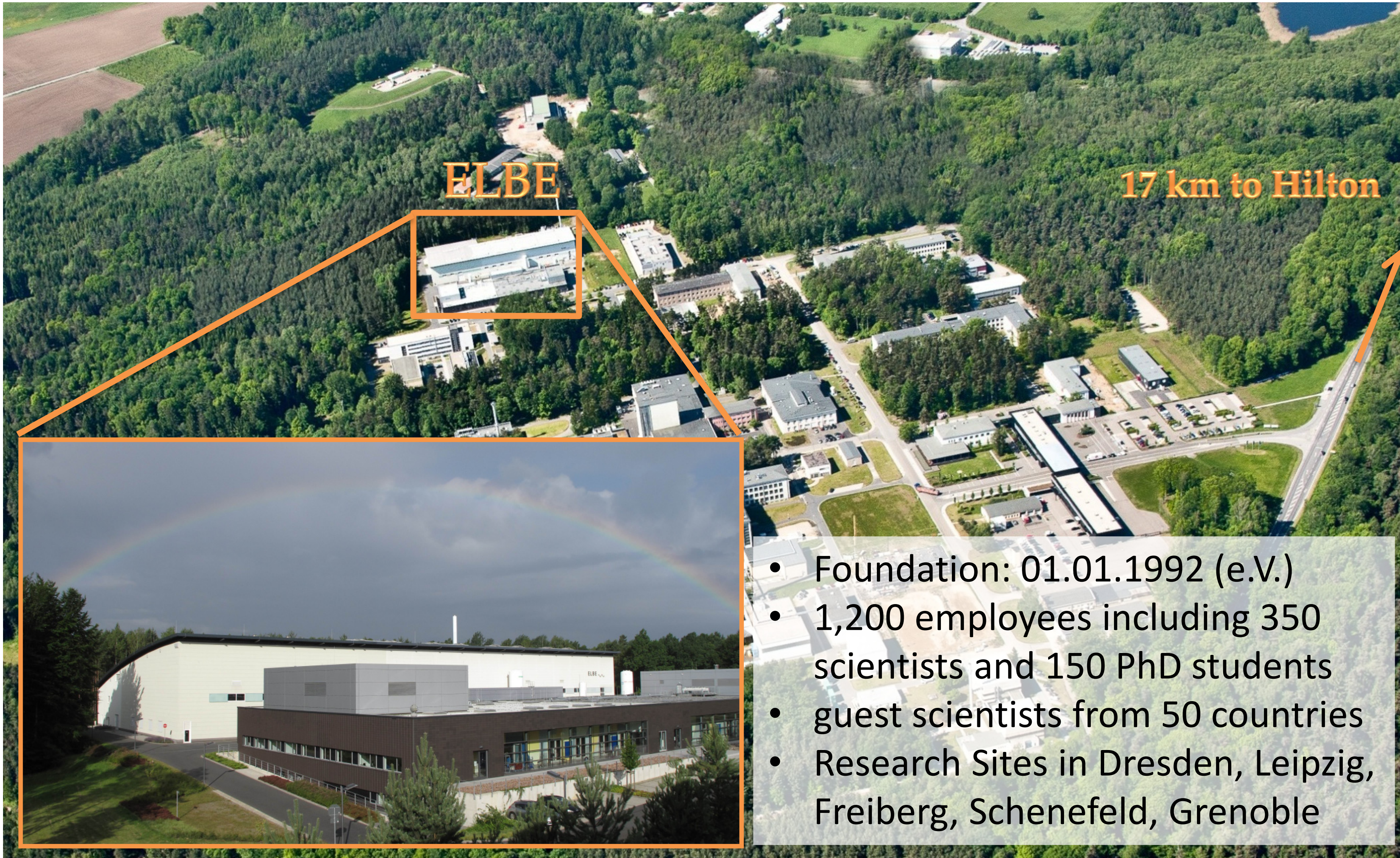
Electron Linear accelerator with high Brilliance and low Emittance



- Foundation: 01.01.1992 (e.V.)
- 1,200 employees including 350 scientists and 150 PhD students
- guest scientists from 50 countries
- Research Sites in Dresden, Leipzig, Freiberg, Schenefeld, Grenoble

Introduction into ELBE

Electron Linear accelerator with high Brilliance and low Emittance



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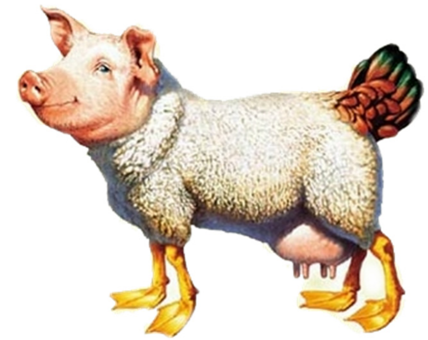
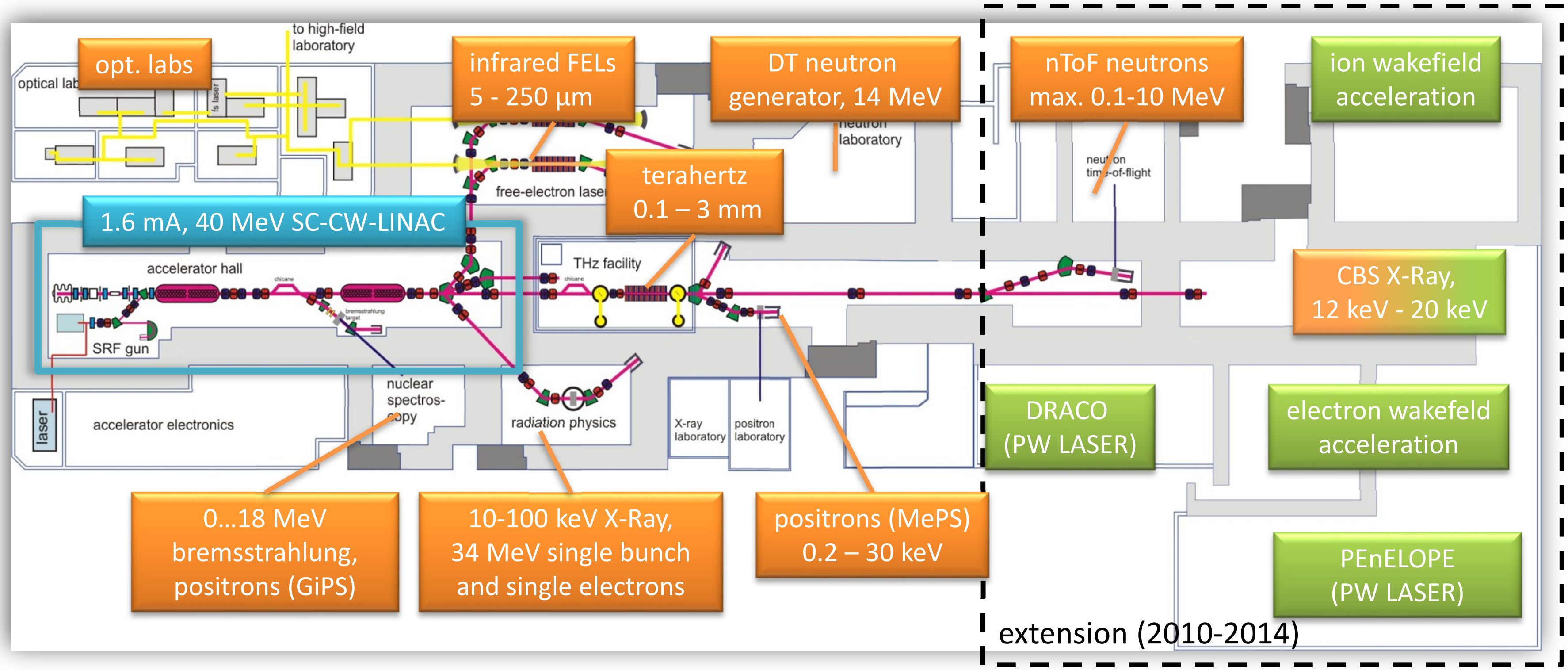
Introduction into ELBE

Electron **L**inear accelerator with high **B**rilliance and low **E**mittance

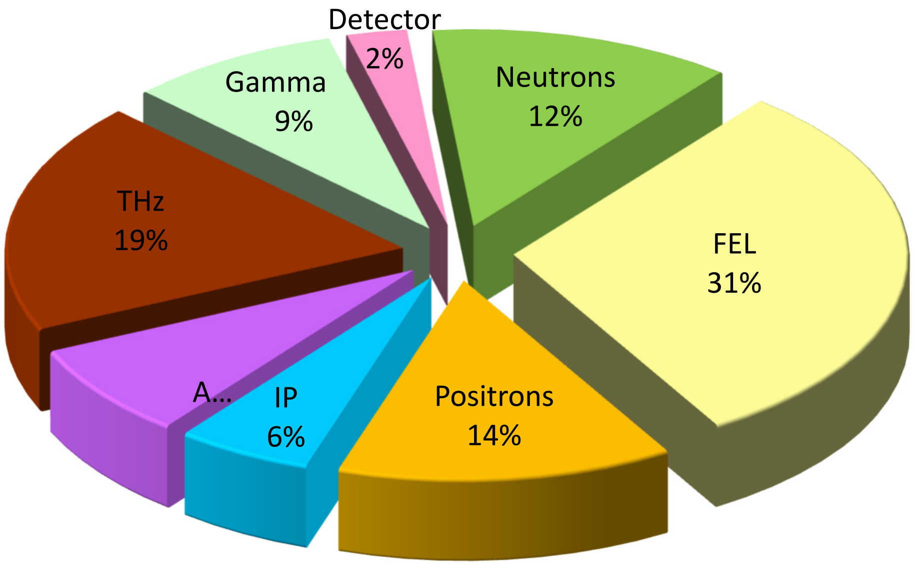
- electron accelerator is based on **4** superconducting **1.3 GHz 9-cell TESLA** cavities driven in **CW operation**
- average current **≤ 1.6 mA**, beam energy **≤ 40 MeV**, rep. rate **≤ 13 MHz**, bunch charge **≤ 77 pC** for thermionic gun and **≤ 300 pC** for SRF gun (currently at 100 kHz)
- 100 m long, 100 M€ investment, ~50 FTE



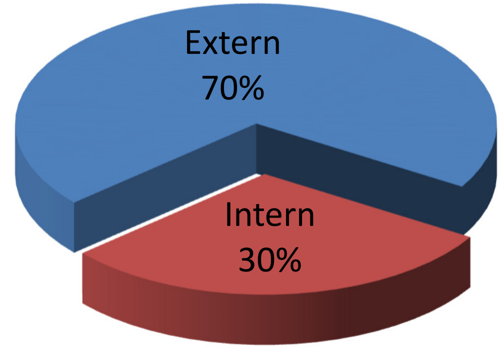
„eierlegende Wollmilchsau“



Typical beam time statistics (2018/2019)



ELBE beam time usage 2018/19



Mid IR FEL: 5 – 45 µm, ≤ 45 W, 13 MHz, 77 pC, 1 mA

Far IR FEL: 30 – 250 µm, ≤ 65 W, 13 MHz , 77 pC, 1 mA

THz: 0.1 – 3 THz, ~ 4 µJ/pulse, 100 kHz, 200 pC, 20 µA

Gamma: < 20 MeV, 10^5 1/s·cm^2, 13 MHz, 77 pC, 1 mA

Neutrons: < 10 MeV, 10^4 n/s·cm^2, 400 kHz, 77 pC, 30 µA

Positron: 0.5-30 keV, $5\cdot10^6$ 1/s, 1.6 MHz, 77 pC, 120 µA

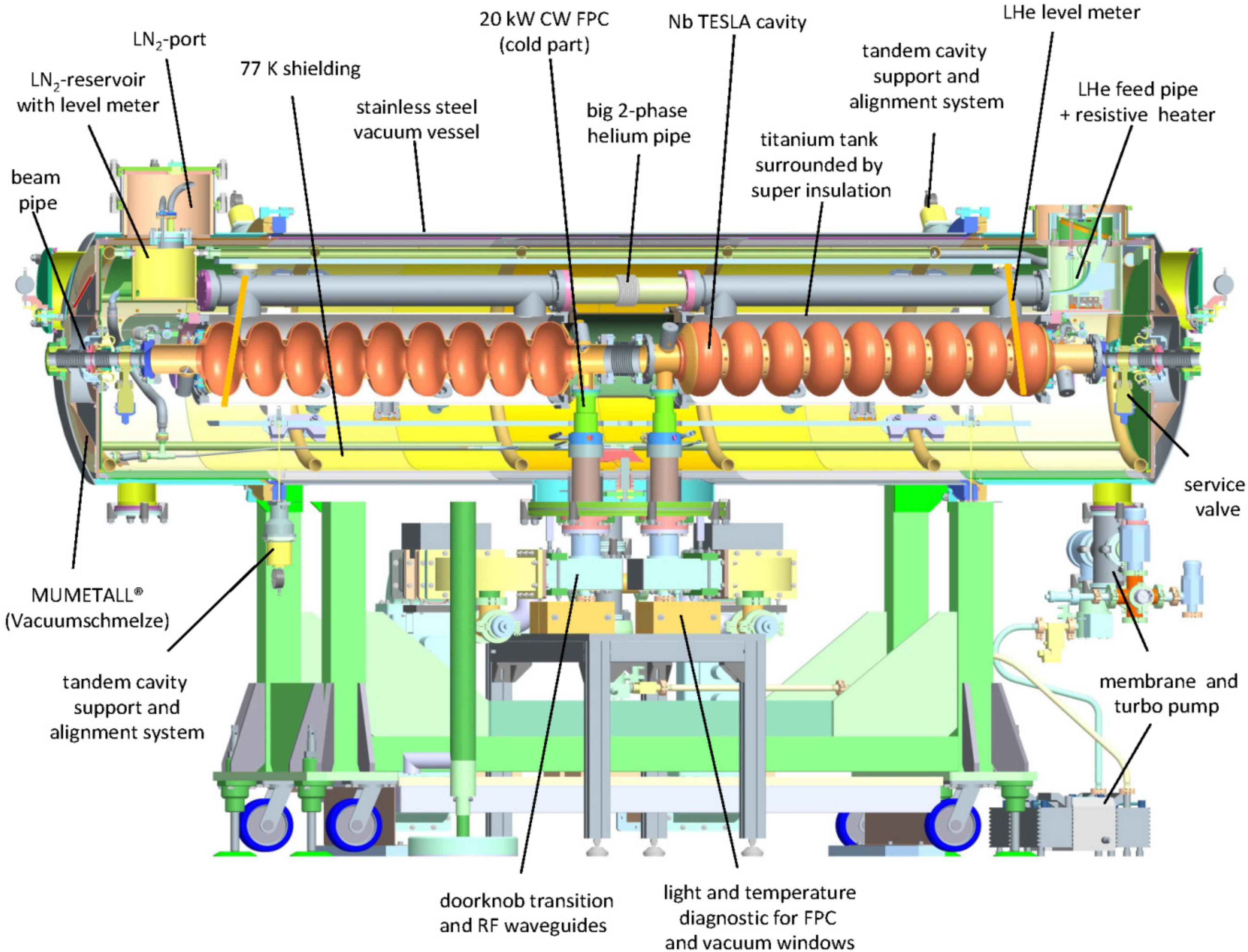
Operation statistics:

Scheduled	6084 h
Used	5777 h
Availability	95%
External users:	~70 %

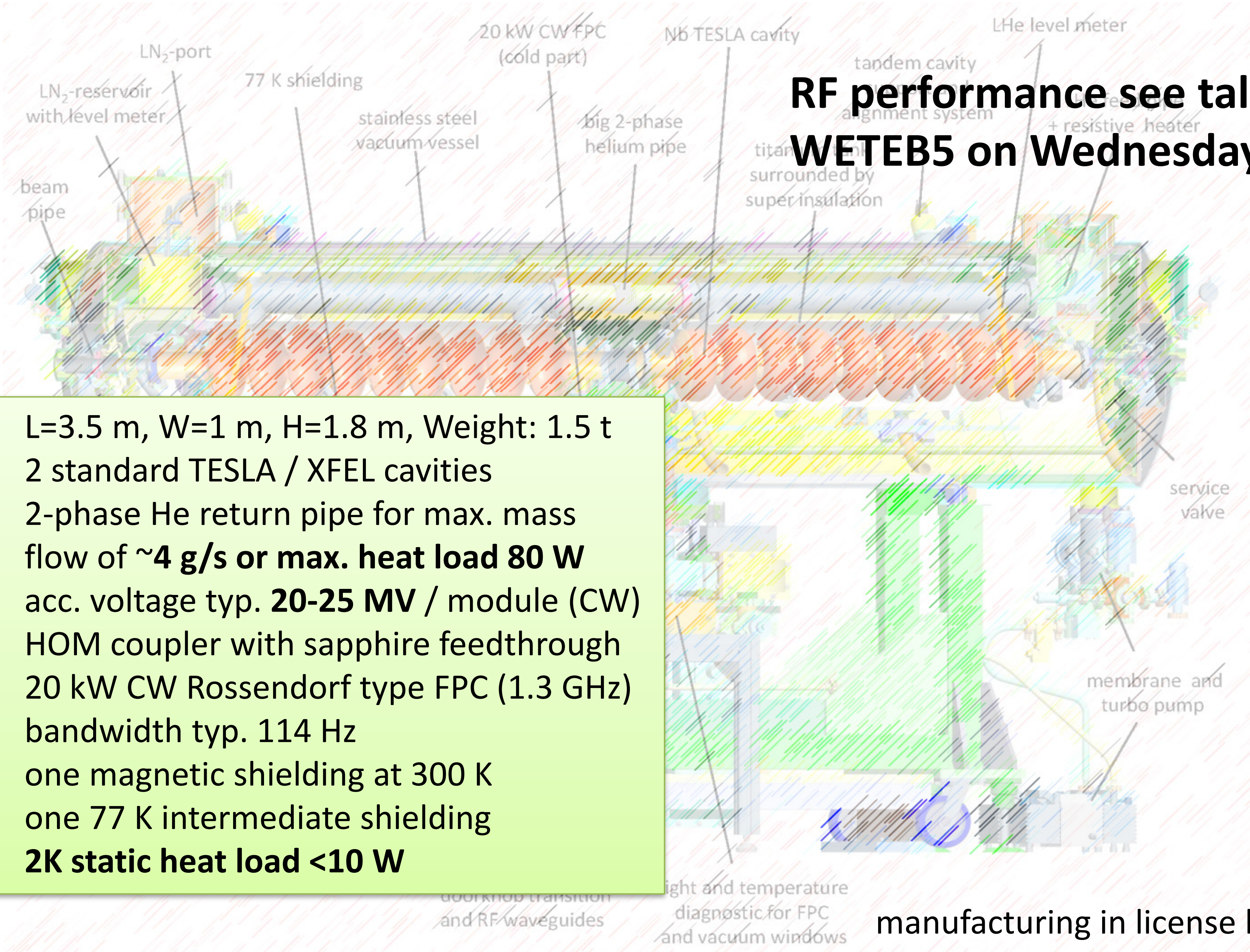
24/7 – real CW SRF operation

Courtesy of P. Michel

The compact ELBE cryomodule



The compact ELBE cryomodule



RF performance see talk WETEB5 on Wednesday

- 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 shielding
- **2K static heat load <10 W**

manufacturing in license by RI

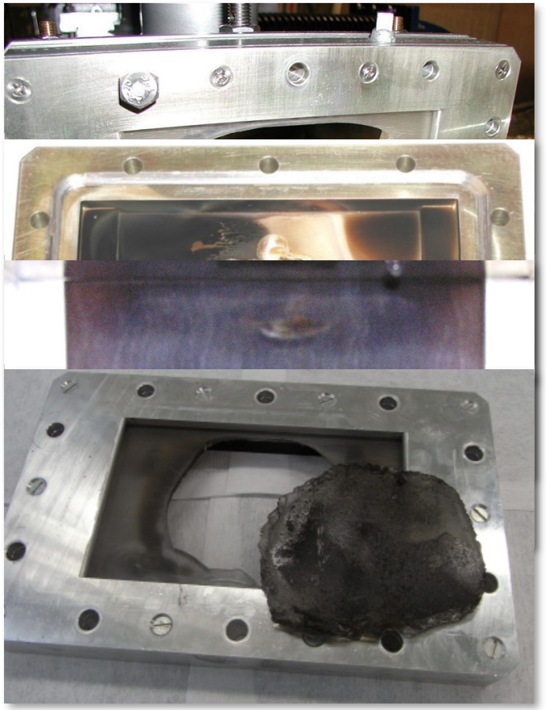
CWRF power amplifiers

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)

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 coupler windows



Rexolite/Quartz WR650 (MEGA)

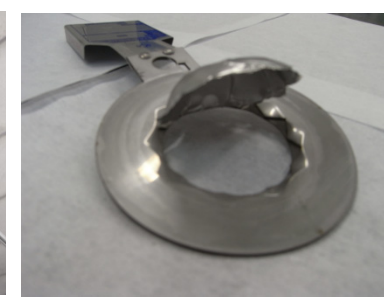
We lost in total 4 warm waveguide windows within last 18 years:

- 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 too 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!

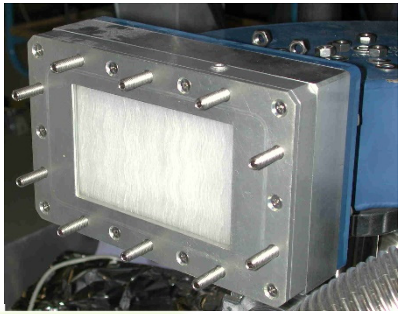
In all cases we had luck because beamline vacuum not broken and only warm coupler parts had to be repaired.

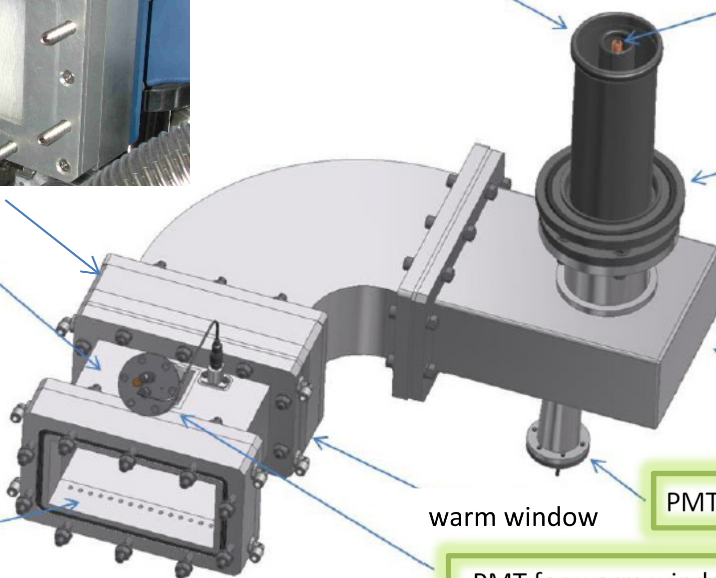


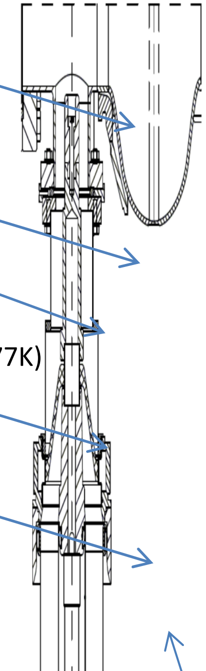




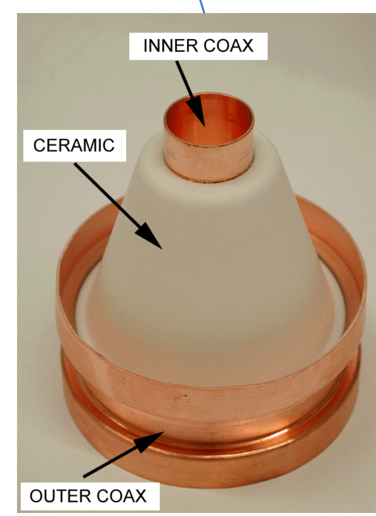
Diagnostics to protect the FPCs







note: left picture taken from RIs MESA module description



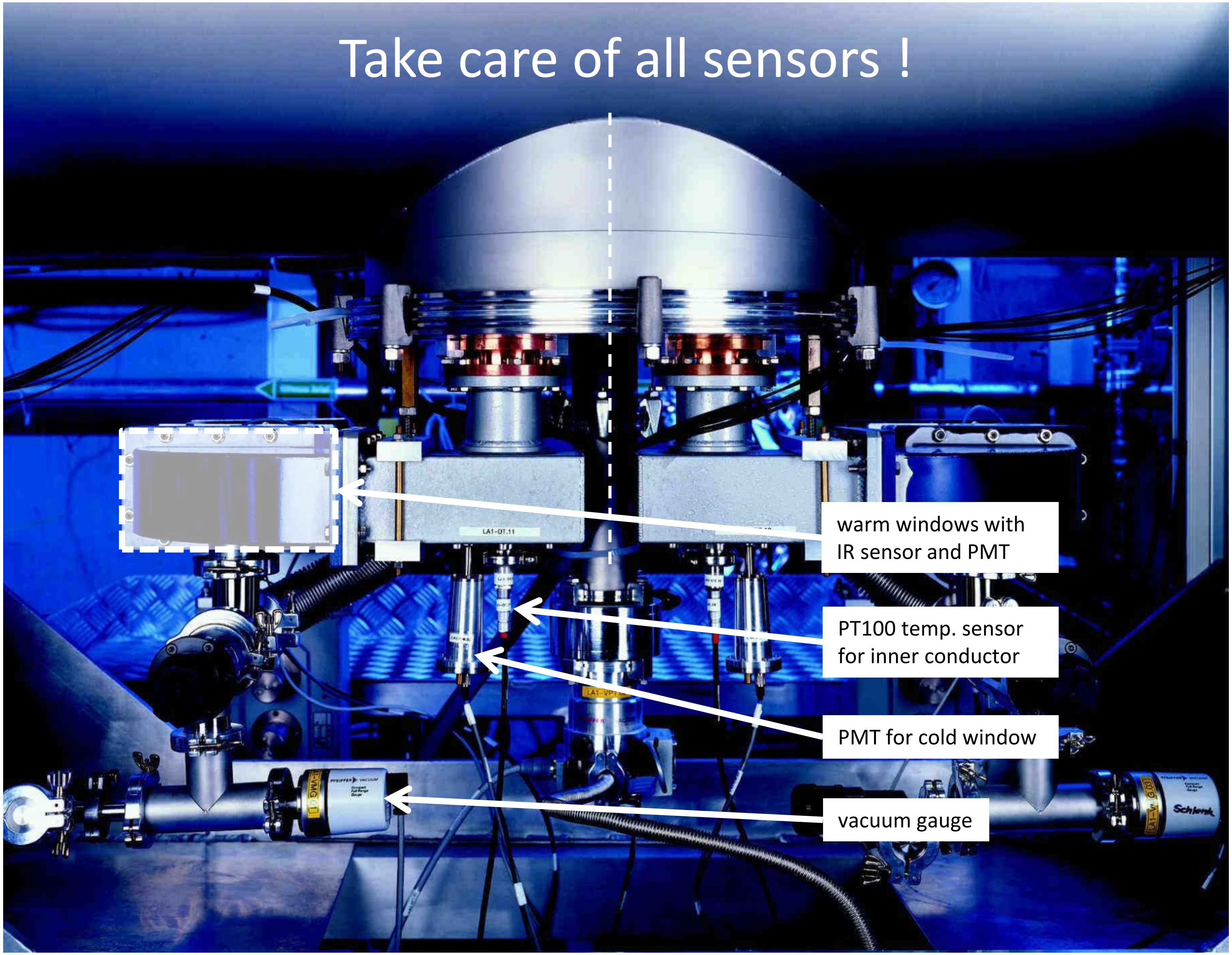
ELBE Coupler Interlock for 20kW CW at 1.3 GHz per cavity

- 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).

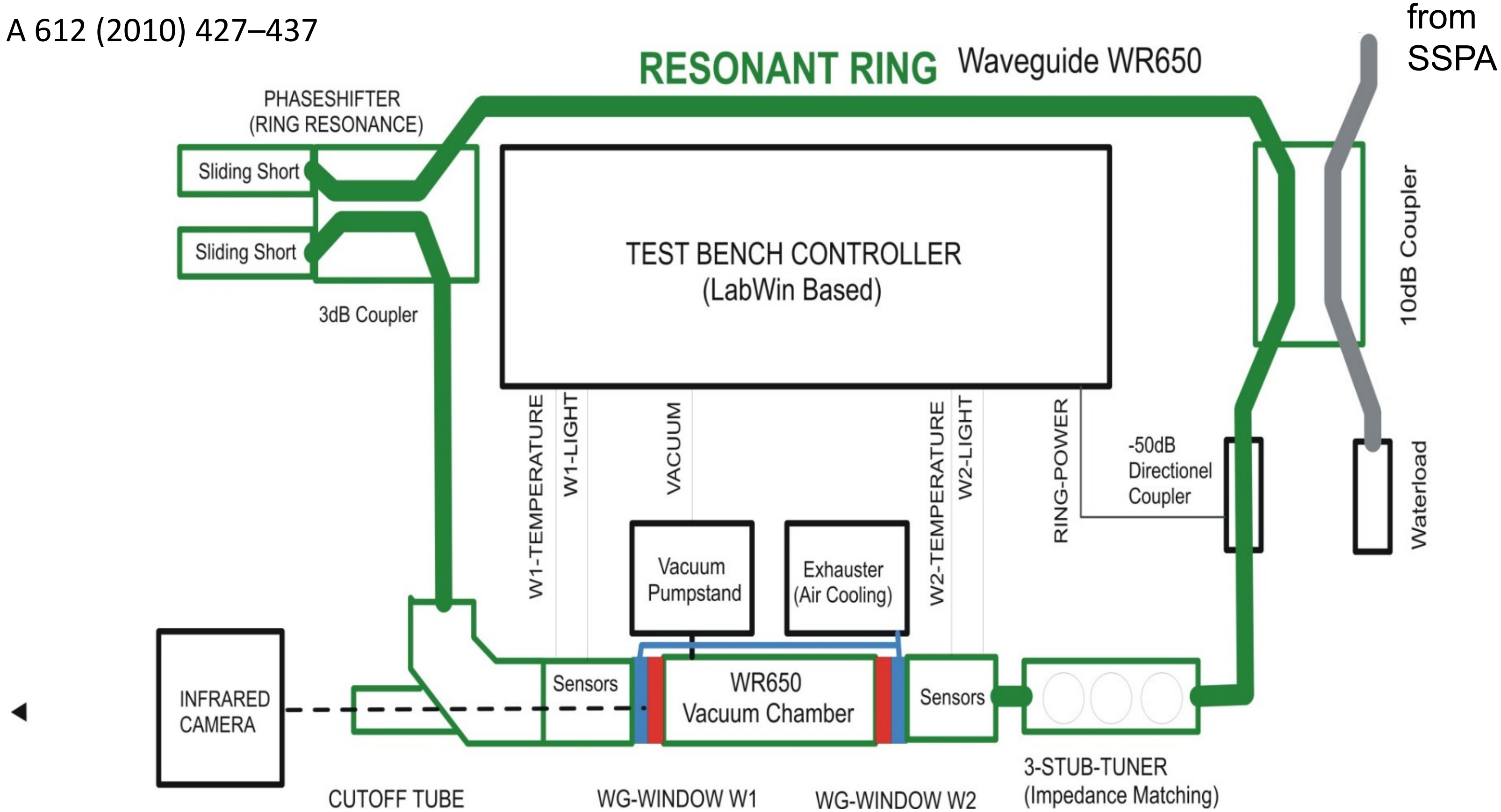
Mitglied der Helmholtz-Gemeinschaft
Dr.-Ing. André Arnold | Institut für Strahlenphysik | www.hzdr.de

Diagnostics to protect the FPCs



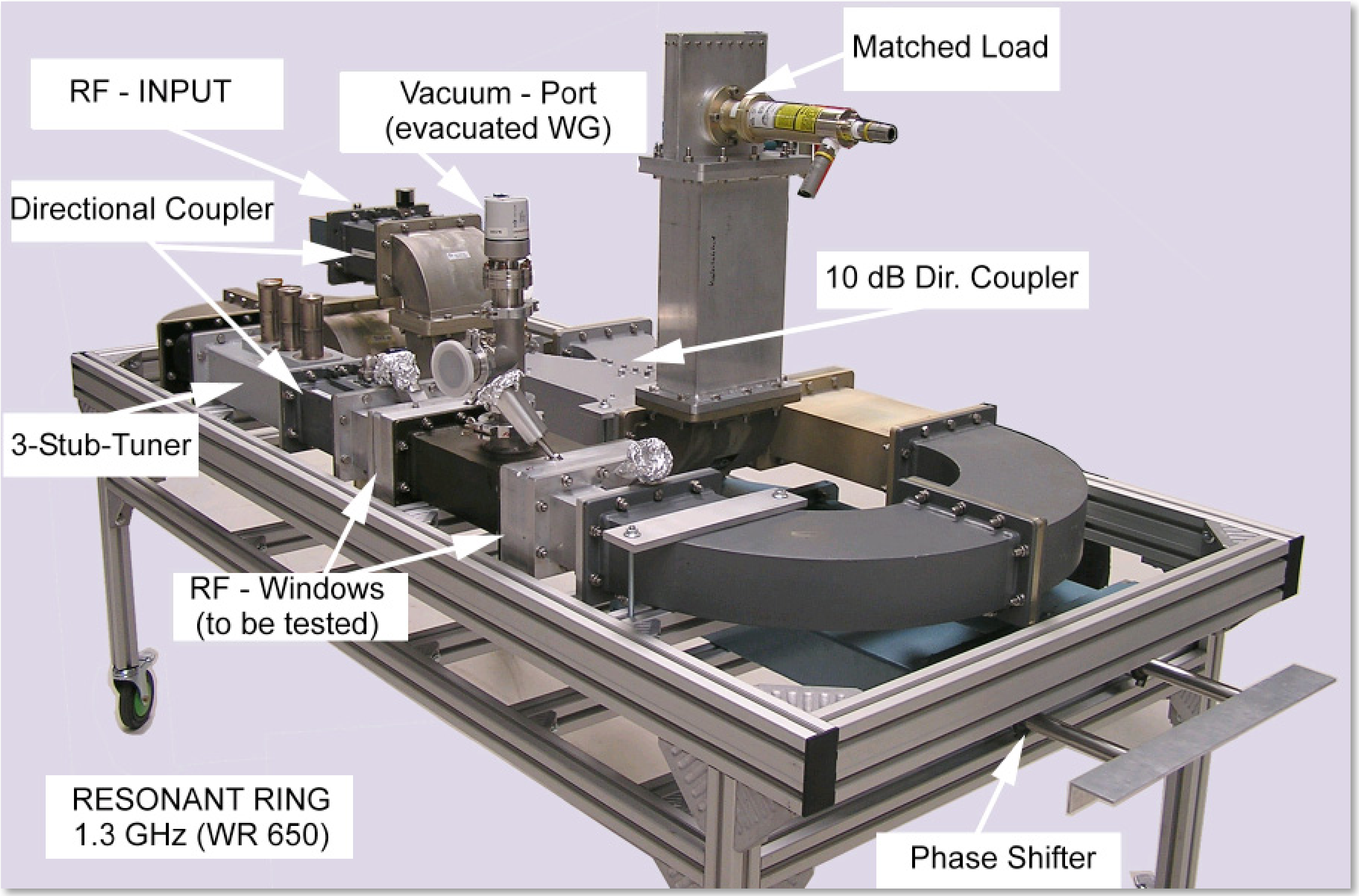
Resonant ring for high power CW RF component tests

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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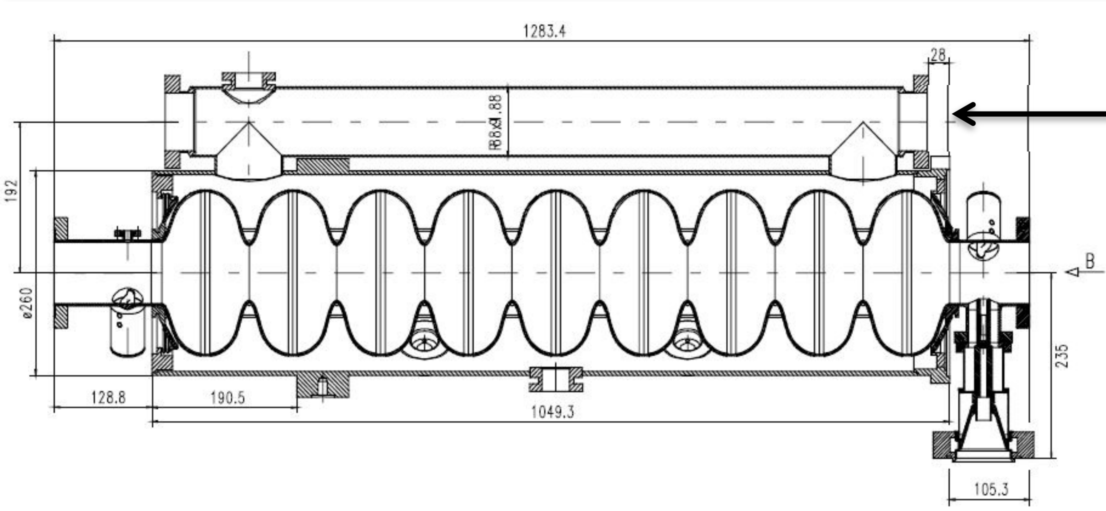
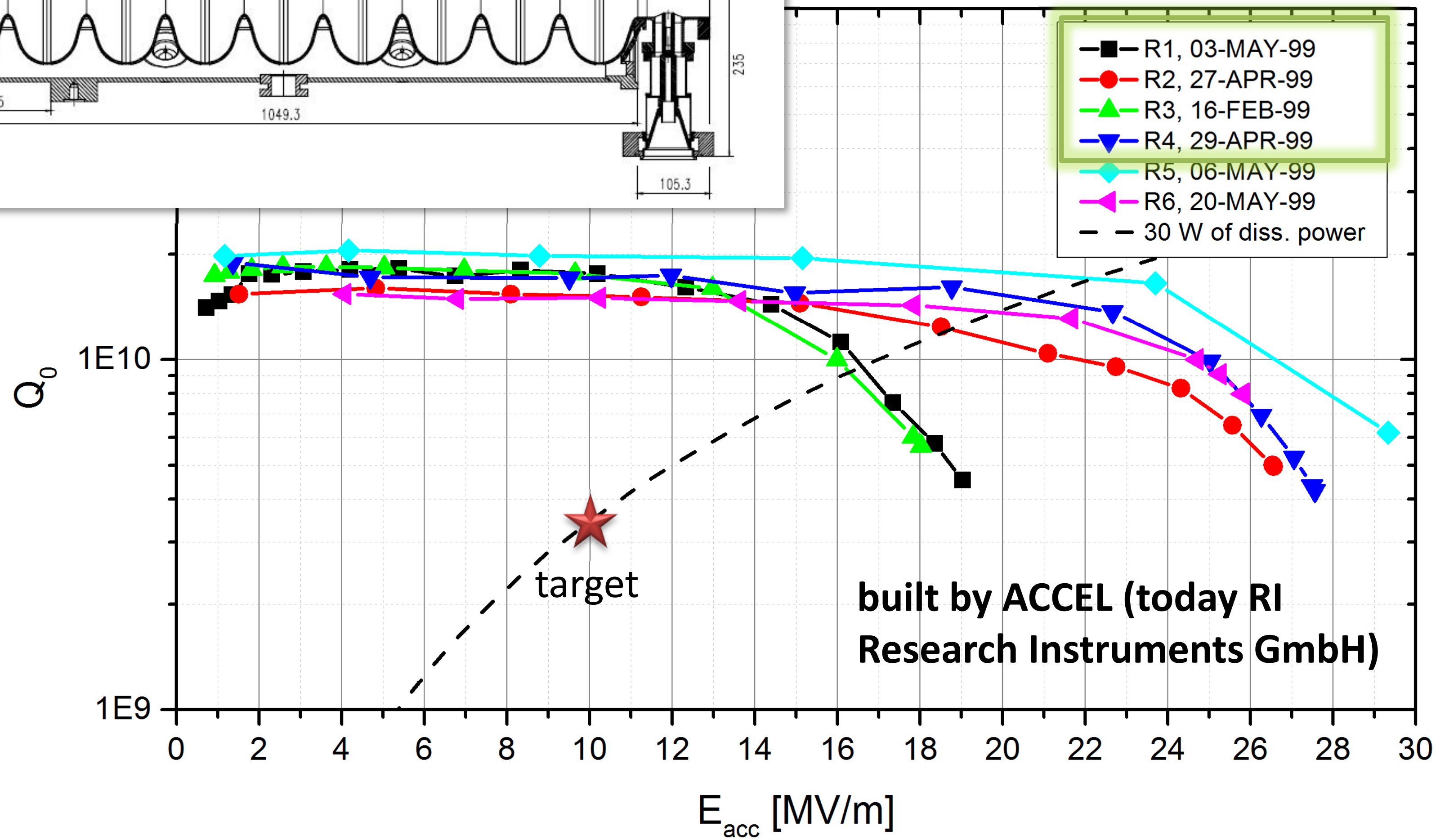
Vertical tests of cavity R1 – R6, 20 years ago



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

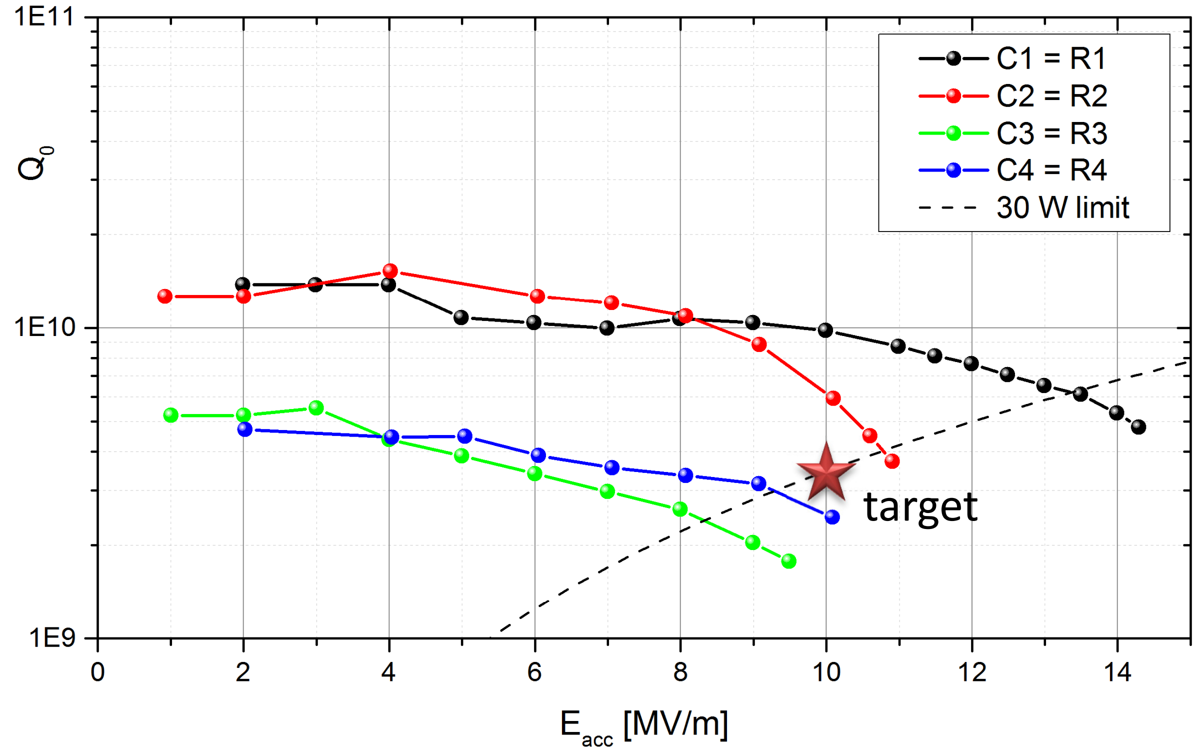


built by ACCEL (today RI Research Instruments GmbH)

Reality – cavity performance today

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

More details have been discussed during TTC Meetings Milano 2018 and Vancouver 2019

High power (pulsed) RF processing (HPP)

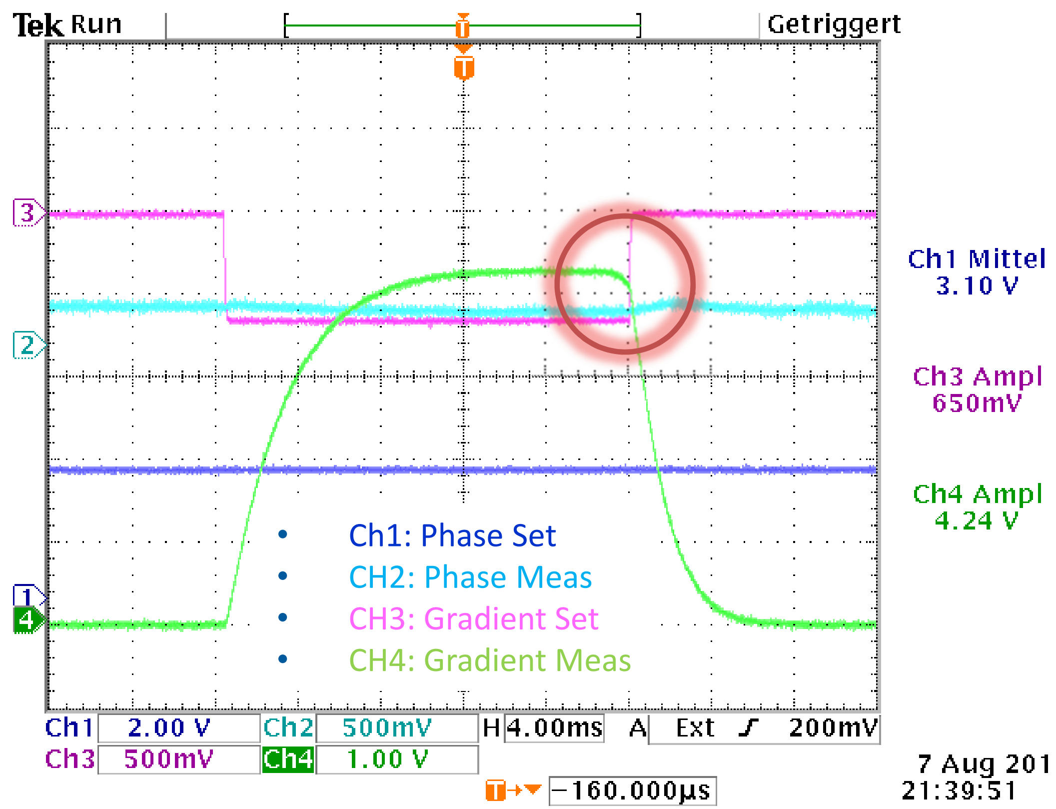
- HPP done in a PLL regime to modulate an external RF generator to follow LF-detuning
- Constant RF power is stepwise increased up to 14-17 MV/m (depending on cavity)
- HPP stopped if reproducible thermal breakdown or high average helium consumption
- Field amplitude as well as vacuum, temp., dose and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

all magnets off

duty cycle 20 / 600 ms

RF power up to 20 kW

τ = 2-3 ms, BW ~ 112 Hz



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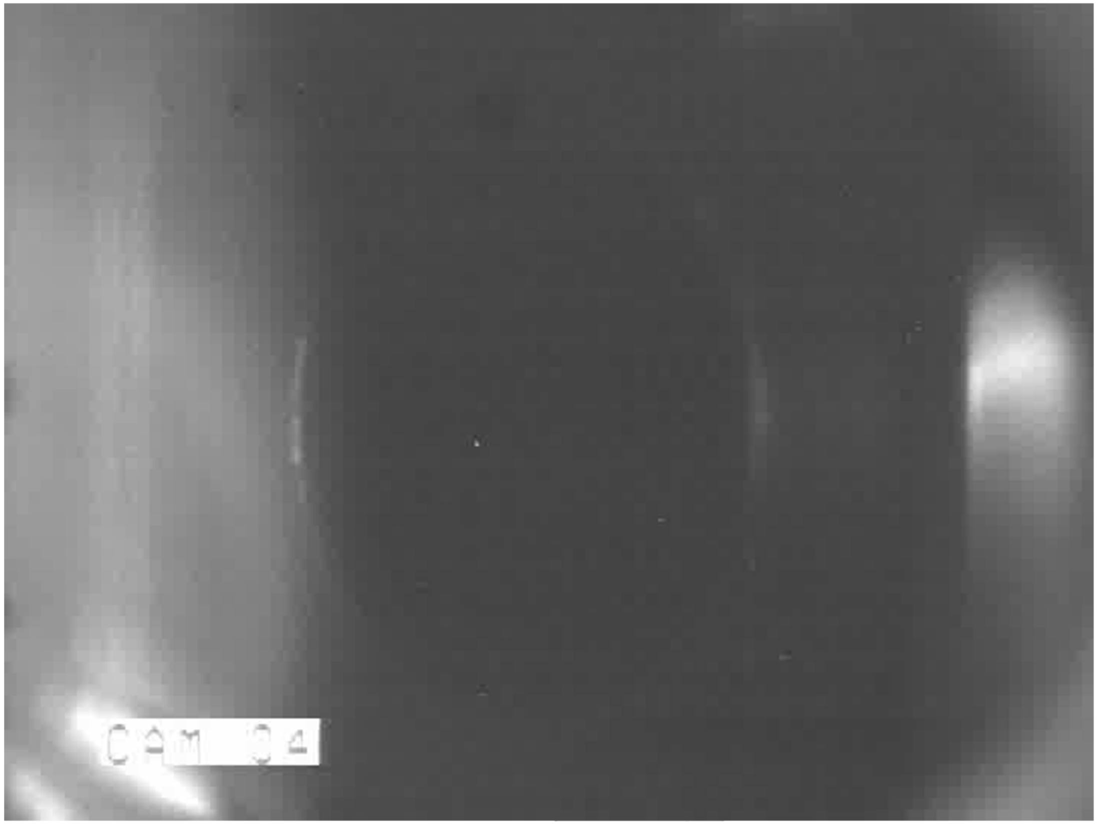
all magnets off

duty cycle 20 / 600 ms

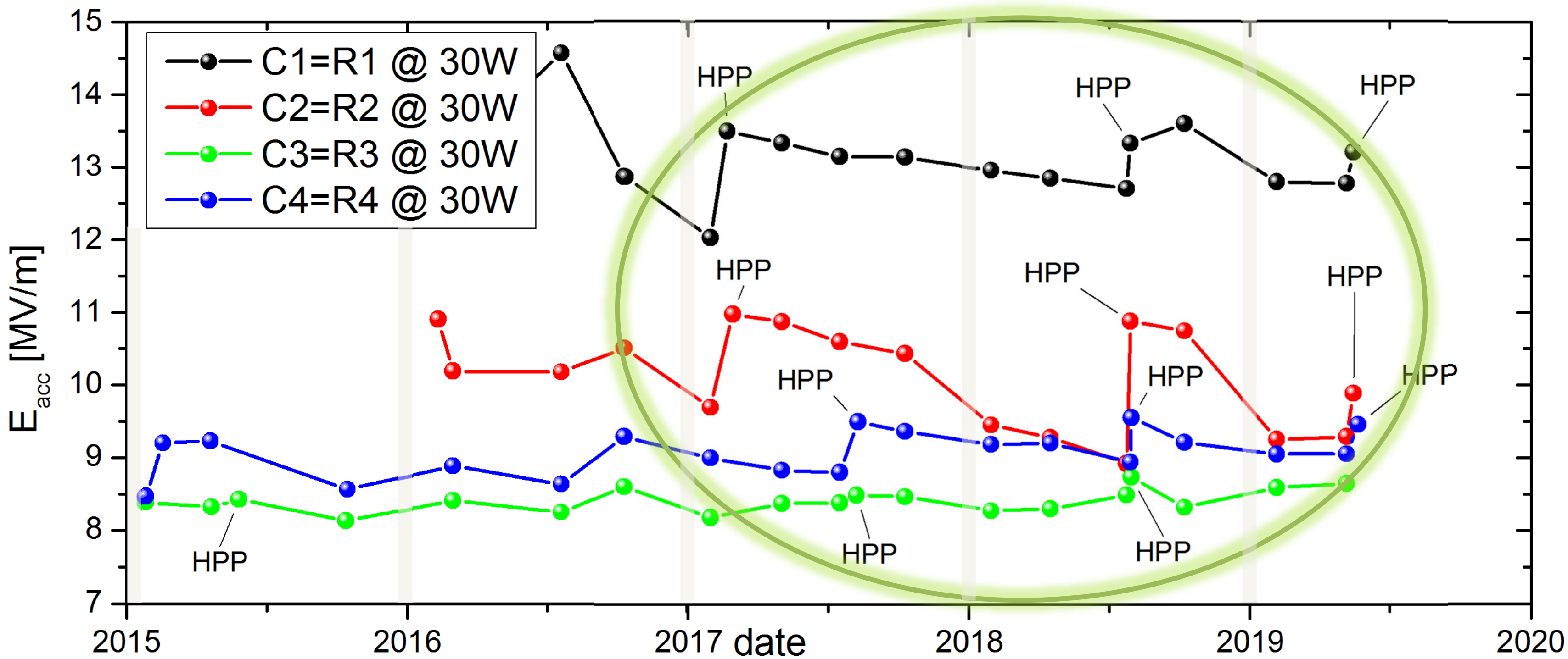
RF power up to 20 kW

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



Cavity degradation over time



- Evaluation of the max. usable acc. gradient for dissipated power of 30 W (each)
- Frequent HPP needed to recover cavity to its initial performance → **no miracles**
- Continuous degradation of all cavities over time in btw. HPP
- No improvement by complete therm. cycle done once a year (maintenance)

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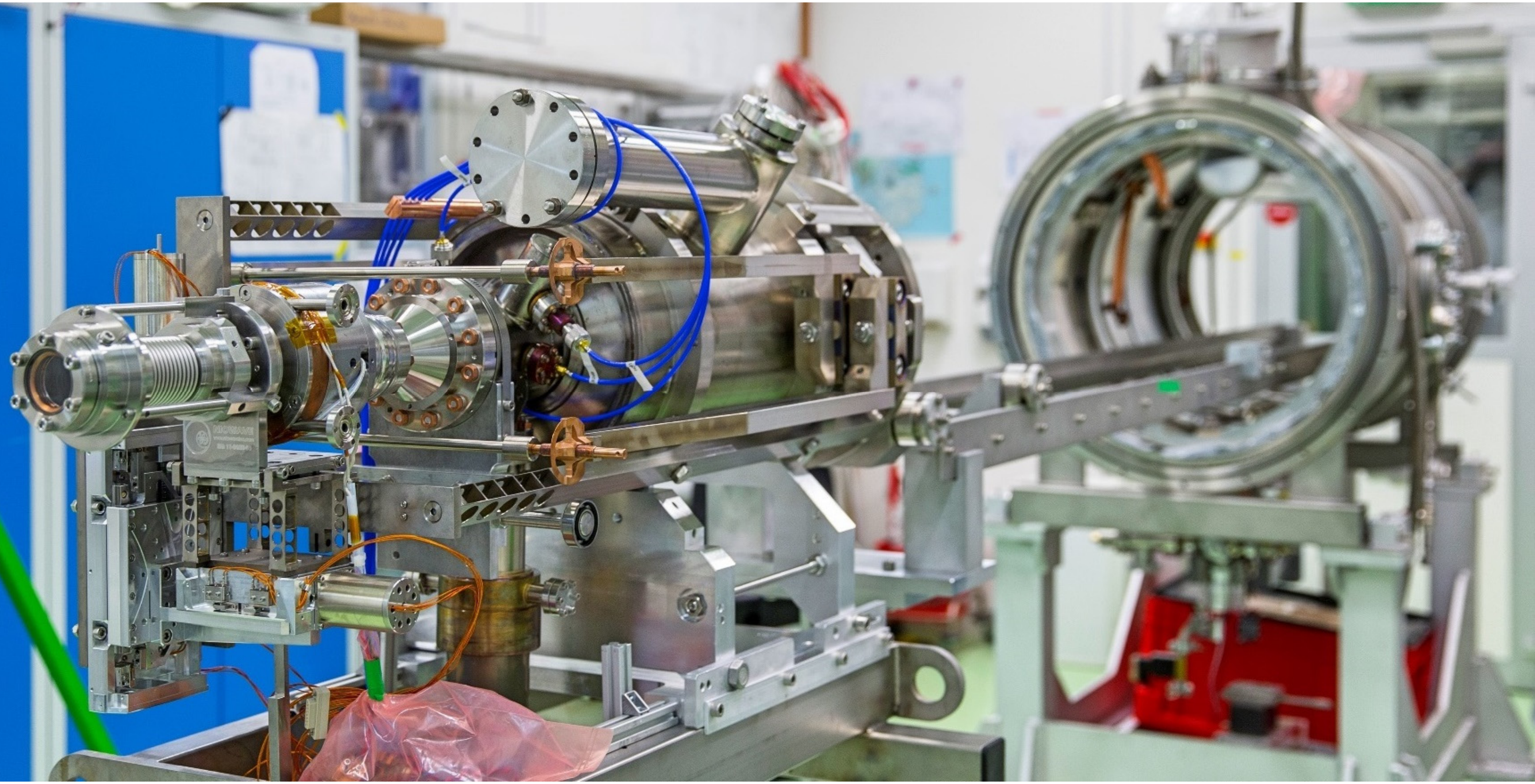
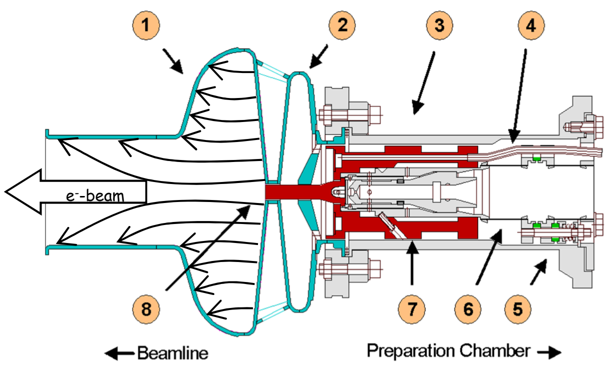
SRF Gun development at HZDR

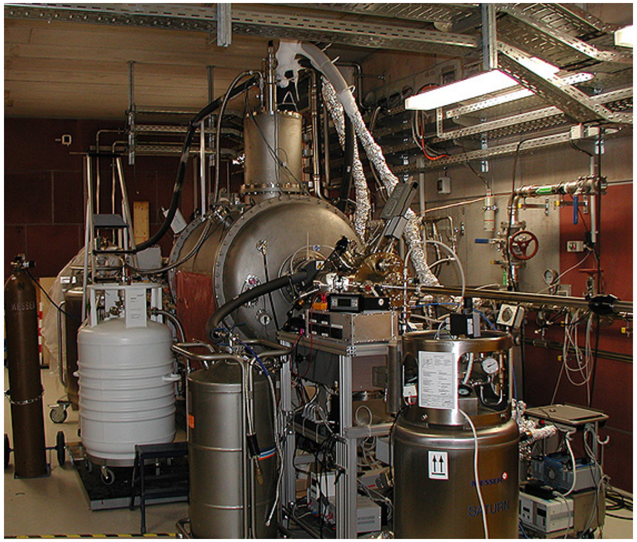


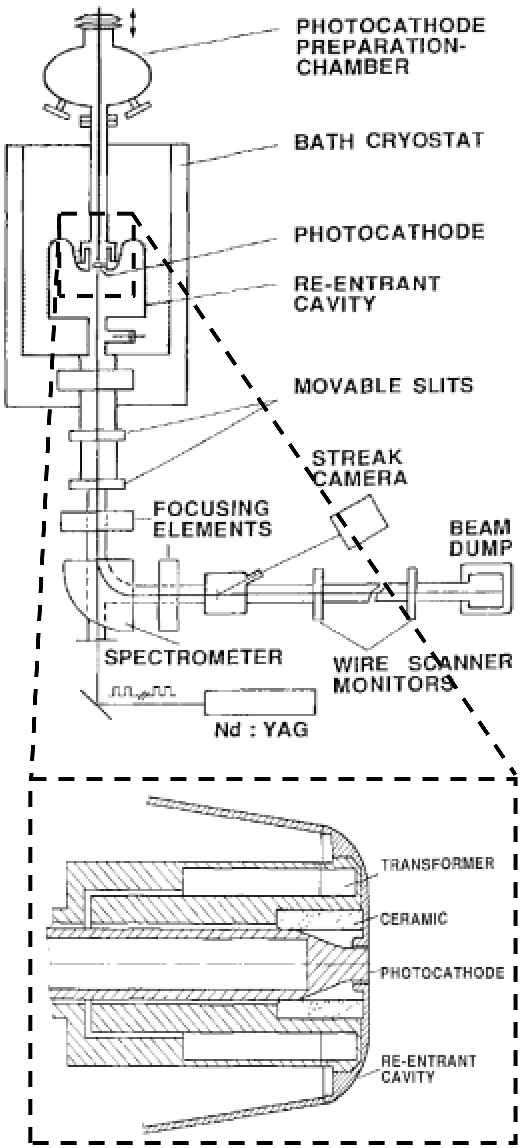
Historical overview - Pioneering work at HZDR

History		
1988	first proposal	H. Piel et al., 10th FEL conf. Jerusalem, 1988
1991	first experiments	A. Michalke, PhD thesis, univ. Wuppertal, 1992
2002 [1)]	first electron beam	D. Janssen et al., NIM A, Vol. 507 (2003) 314
2010	first LINAC acceleration	R. Xiang, et al., Proc. of IPAC'10, Japan, 2010
2013 [2)]	first lasing of IR FEL	J. Teichert, et al., NIM A, Vol. 743 (2014) 114
Since 2018 [3)]	(friendly) user operation for THz and neutron users	Hassan A. Hafez, et al., Nature Vol. 561, 507–511 (2018)

[1)] Drossel (half cell cavity) [2)] SRF gun I (3.5 cell cavity) [3)] SRF gun II (3.5 cell cavity)

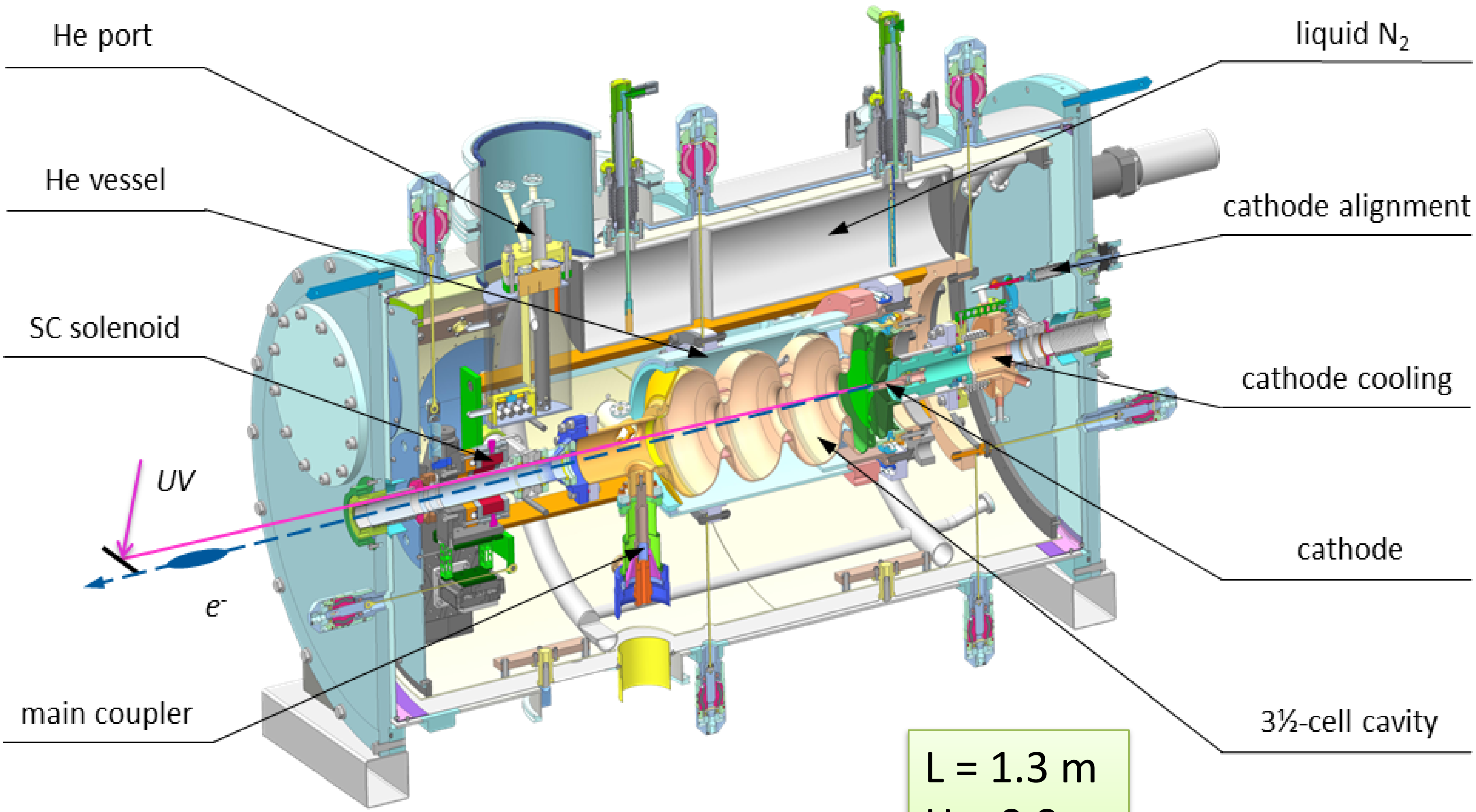






Cavity: Niobium ½ cell, TESLA 1.3 GHz
Cathode: Cs_2Te (262 nm, 1 W laser)
thermally isolated, LN_2 cooled

Design of the ELBE SRF gun II



L = 1.3 m
H = 0.9 m
ø = 0.7 m

designed for E_{kin}=9.5 MeV and $I_{average}$=1 mA

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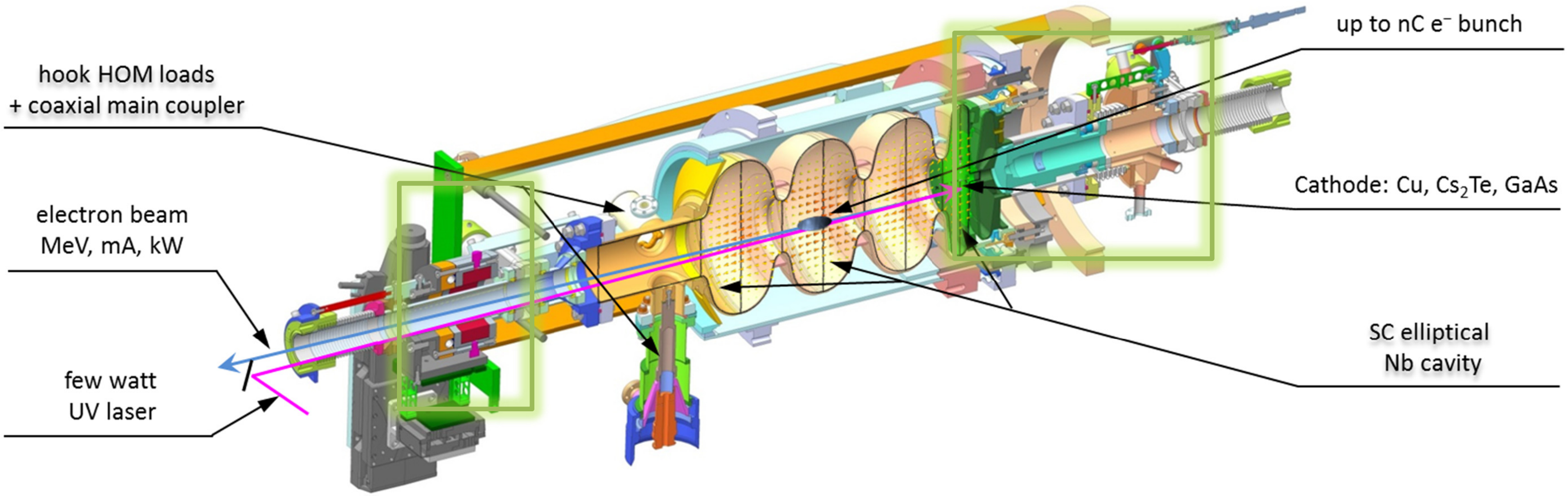
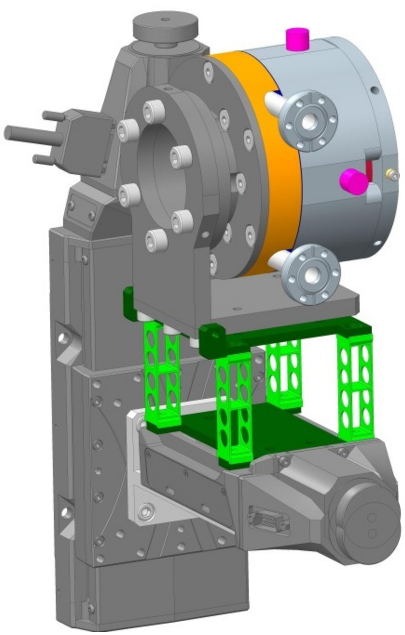
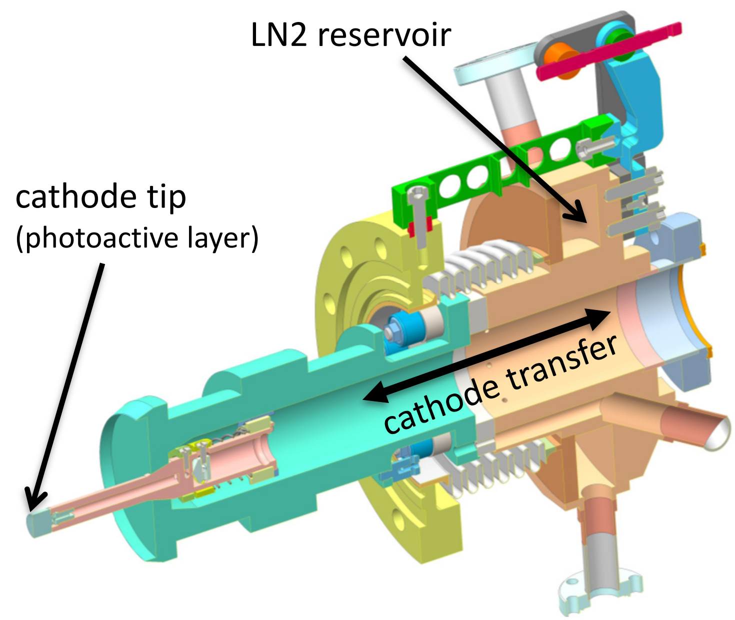
Design of the ELBE SRF gun II



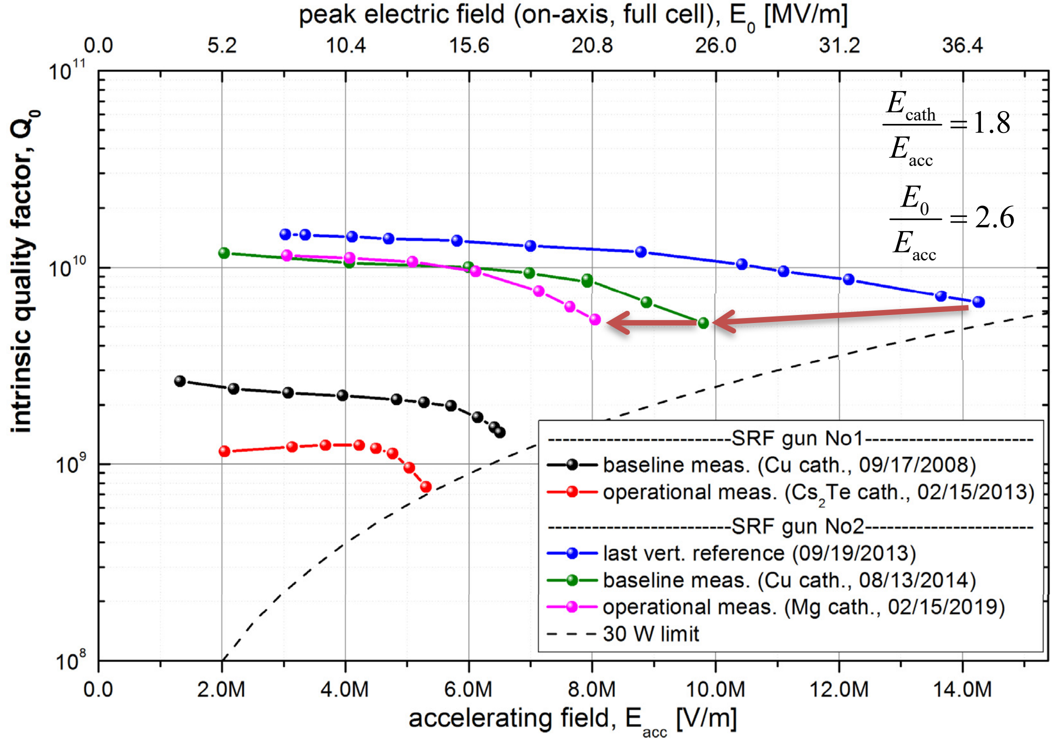


- SC solenoid by Niowave (2K)
  $B_{z,max} = 449\,mT$ @ 10 A
- Remote controlled xy-table (77 K)

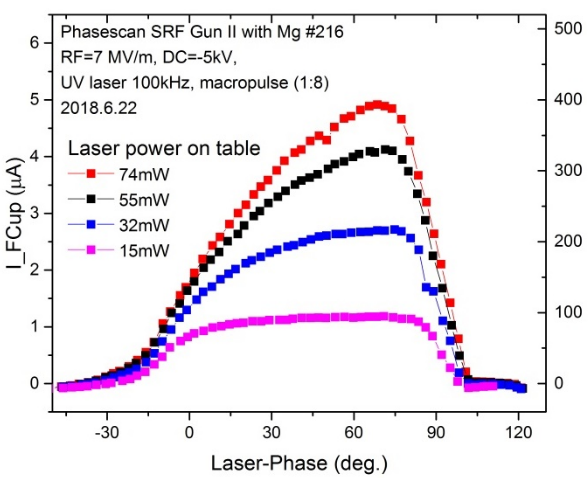
- Cs_2Te, Cu, GaAs, Mg cathodes
- cathode cooling by LN to 77 K
- cathode transfer into the cold gun
- therm. and electrical isolation
- DC bias up to 7 kV to suppress MP
- moveable (±0.6 mm) by remote stepper for best RF focusing

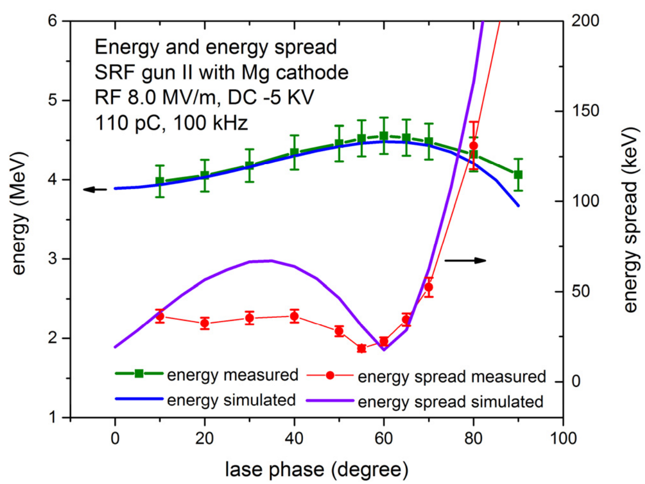


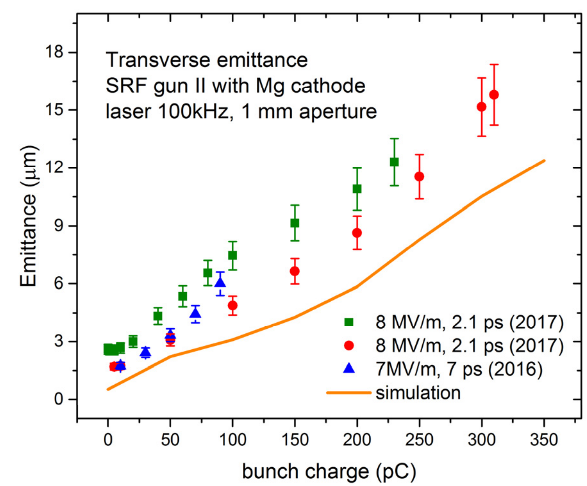
Cavity and gun performance



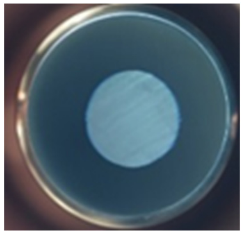
parameter	SRF gun II
energy (pc)	4.5 MeV
SRF gun gradient	8 MV/m
cathode field	14.4 MV/m
bunch charge	0 – 300 pC
transv. emittance	2 – 15 µm
energy spread	5 – 25 keV
micro pulse rate	100 kHz
beam current (CW)	30 µA
laser pulse length	~2 ps
dark current	30 nA



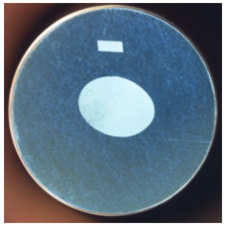




Photocathodes



vs.



Cs_2Te for high average current

- high QE up to 12%, 1-2% in gun
- complex preparation based on INFN recipe (deposition of 10 nm Te + Cs activation) in special UHV chambers (3×10^{-10} mbar)
- special cathode preparation lab in a certain distance to the gun needed
- high vacuum requirement 10^{-10} mbar
- high risk of cavity contamination

Cathode	Days	Σ Charge	QE
#090508Mo	30	< 1 C	0.05%
#070708Mo	60	< 1 C	0.1%
#310309Mo	[illegible]	[illegible]	[illegible]
#040809Mo	[illegible]	[illegible]	[illegible]
#230709Mo	[illegible]	[illegible]	[illegible]
#250310Mo	[illegible]	[illegible]	[illegible]
#090611Mo	65	< 1 C	1.2%
#300311Mo	76	2 C	1.0 %
#170412Mo	447	264 C	~ 0.6 %

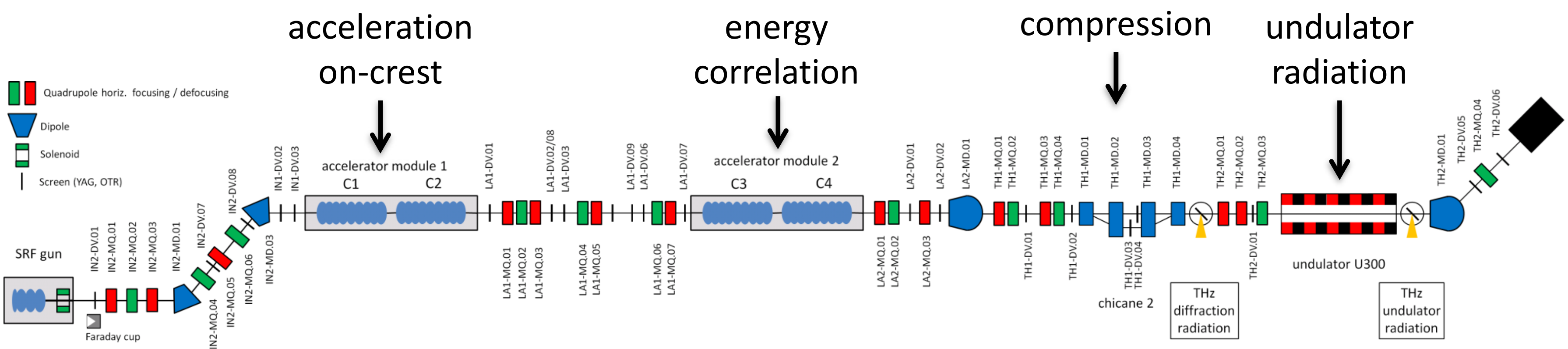
- fresh QE 8.5%, in gun 0.6%
- total beam time 600 h
- extracted charge 264 C
- Max. CW beam current: 400 µA

Mg cathodes for low average current

- low QE of 0.1 - 0.3 % (fresh and in gun)
- relatively simple cathode “cleaning” by melting surface to remove MgO with our focused UV cathode laser (2 W/mm²)
- repeated cleaning for same cathode right next to the gun in transport chamber
- moderate vacuum requirement 10^{-9} mbar
- low risk of cavity contamination

Cathode	Time	Q_b / I_{CW}	QE
Mg 201	Mar. 16 – Aug. 16	200 pC / 20 µA	0.2 %
Mg 207	Nov. 16 – Dec. 16	80 pC / 8 µA	0.1 %
Mg 207	Mar. 17 – May 17	150 pC / 15 µA	0.2 %
Mg 214	Aug. 17 – Jun. 18	300 pC/ 30 µA	0.3 %
Mg 216	Jun. 18 – now	300 pC/ 30 µA	0.2%

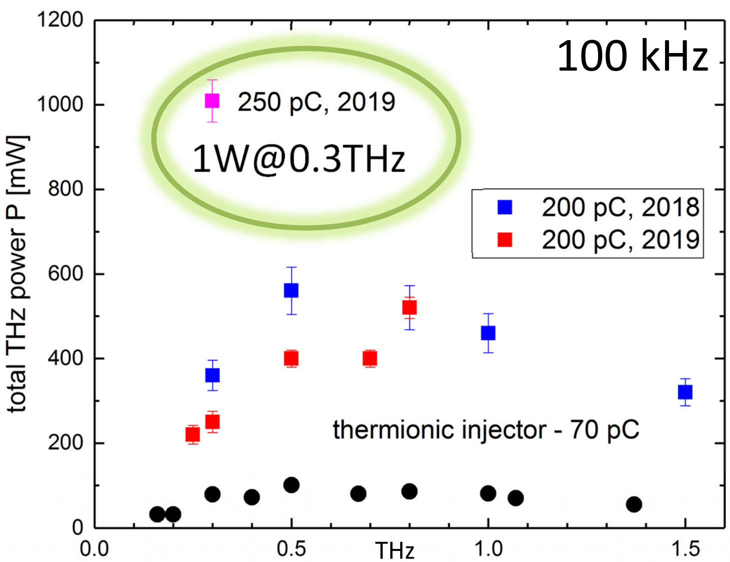
Routine THz user beam time since 2018

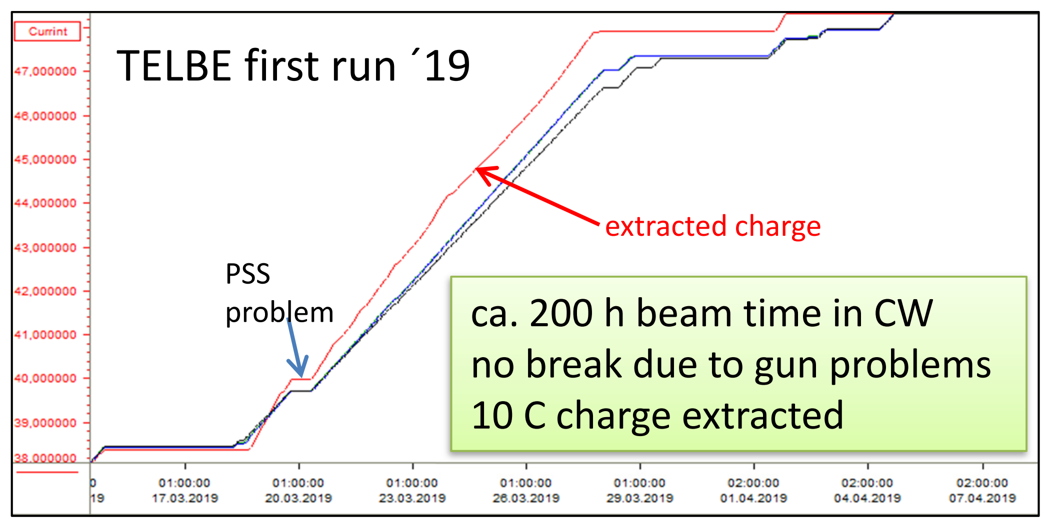


$$\boxed{E_{THz} \sim F(\omega, \sigma_z) N^2}$$

higher bunch charge (200 pC)

shorter bunch length (~100 fs)





ca. 200 h beam time in CW
no break due to gun problems
10 C charge extracted

In 2019: 30 non-stop 12 h shifts for external users + 8 MD shifts (20% of total beam time)

Summary

- 18 year‘s experience of CW SRF with 6 TESLA cavities at 2K
- 100.000 hours SRF operation and 100.000 C acc. charge (~30 Ah)
- Lot of lessons to learn because of issues with high RF and high beam power
  → Be aware Murphy is almost everywhere, but helps to find proper diagnostic!
- SSPA (100 kW installed) worked reliable and with high redundancy last 7 years
- ELBE module has still a to date performance and it is very compact and robust
- From the beginning all cavities in the tunnel limited by FE to about 10 MV/m
- Continuous degradation of all cavities, frequent HPP needed to recover cavity

- Since 2002 HZDR is doing pioneering work on SRF gun development
- We gained enough experience for routine user operation at 200 pC @ 100 kHz