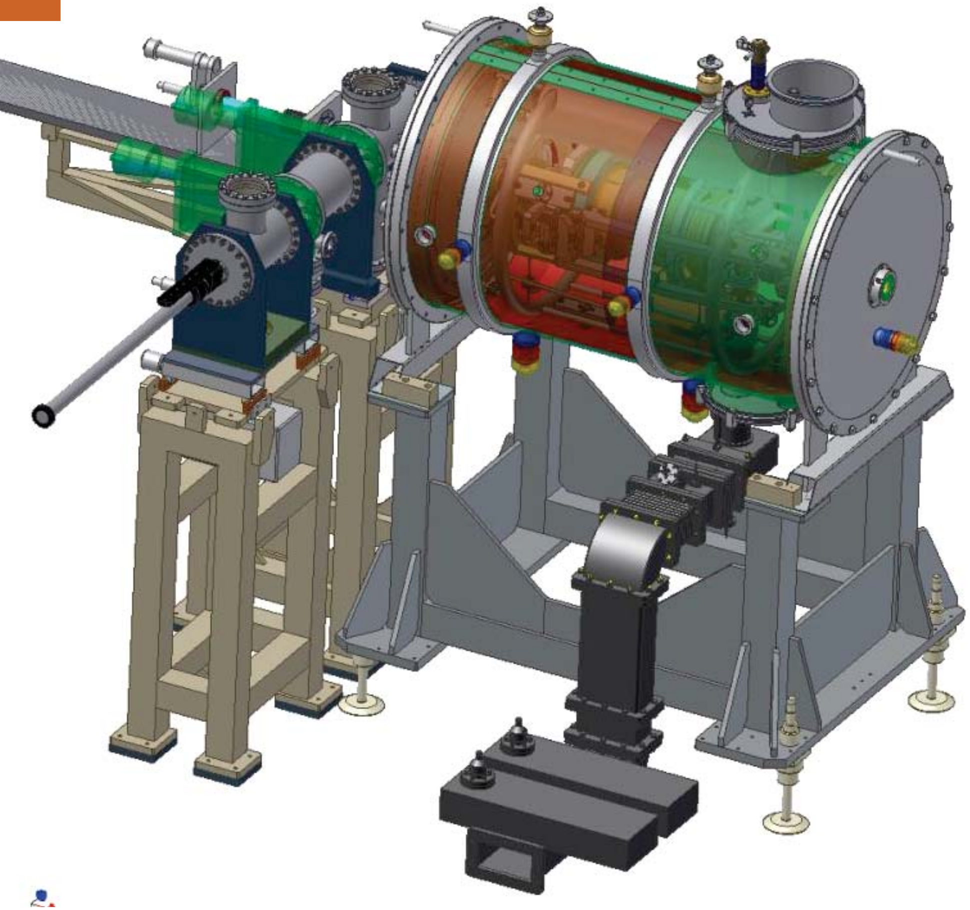


Commissioning and First RF Results of the 2nd 3.5 Cell SRF Gun for ELBE

André Arnold
for the SRF gun crew

Workshop on Energy Recovery Linacs

June 7-12, 2015, Brookhaven

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Outline

1. Design of SRF gun II
2. Cavity and cryomodule assembly
3. Commissioning
4. Cavity contamination
5. Summary

Summary of ELBE SRF gun I

CAVITY

- In operation from Sept. 2007 until April 2014
- Gradient limited by FE

PHOTOCATHODES

- Long lifetime in SRF gun (>1 yr, total charge 264 C @ QE ≈ 0.6 %)
- No cavity degradation during first 4 years
- Multipacting at the cathode stalk, suppression with DC Bias
- High dark current with similar properties as the photo beam

OPERATION @ ELBE

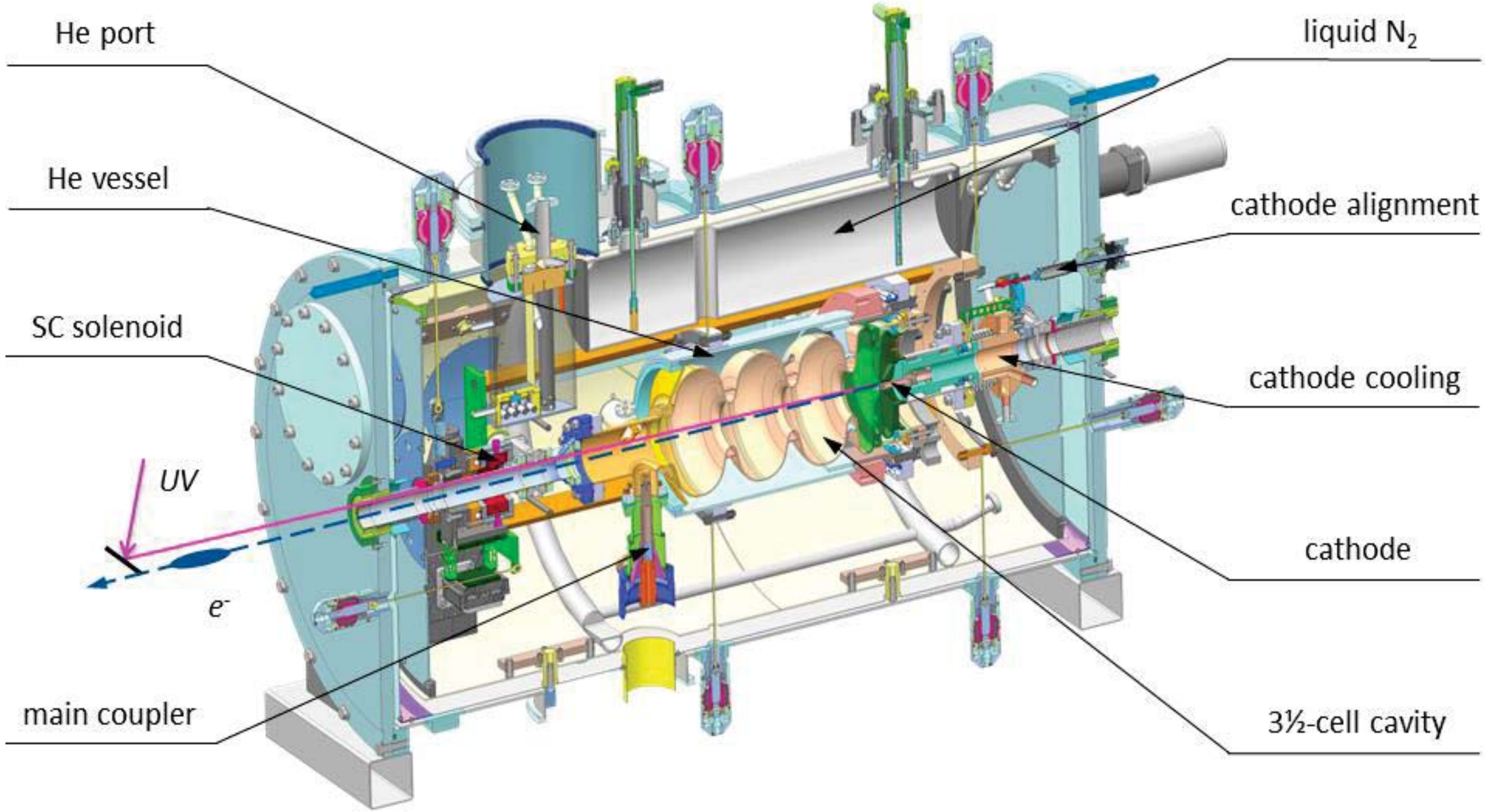
- Despite of low gradient successful experiments and measurements:

  Far-IR FEL operation, Compton-backscattering with TW laser, Superradiant THz radiation, Slice emittance, Longitudinal phase space measurements

FUTURE

- Refurbish ELBE SRF gun I to have a spare part

Design of the ELBE SRF gun II



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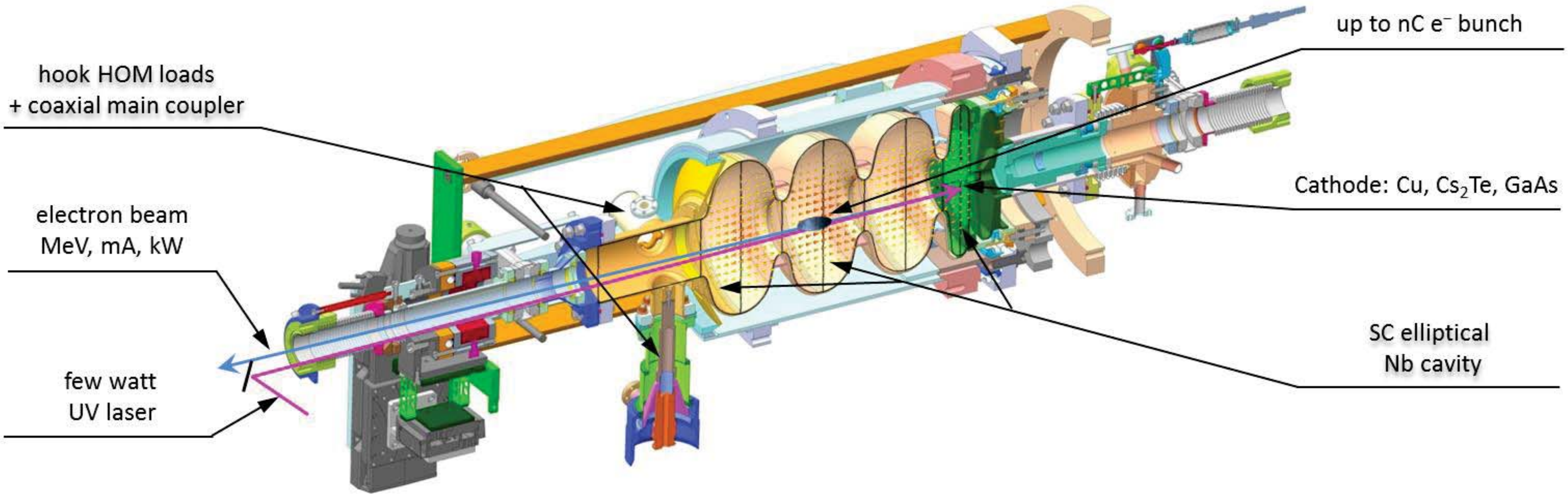

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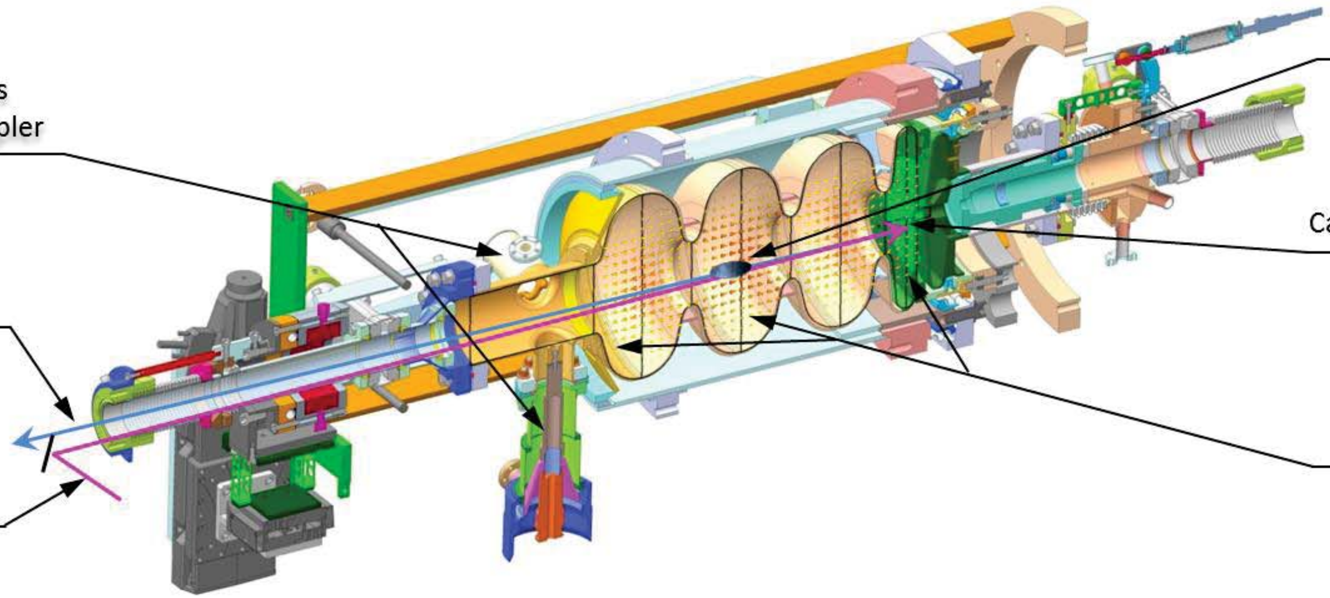

- Cs_2Te, Cu, GaAs, Mg cathode
- Cooled by LN2 to 77 K
- Therm. and electr. isolated from cavity
- Up to 7 kV DC bias for MP suppression
- Moveable and tiltable by remote stepper

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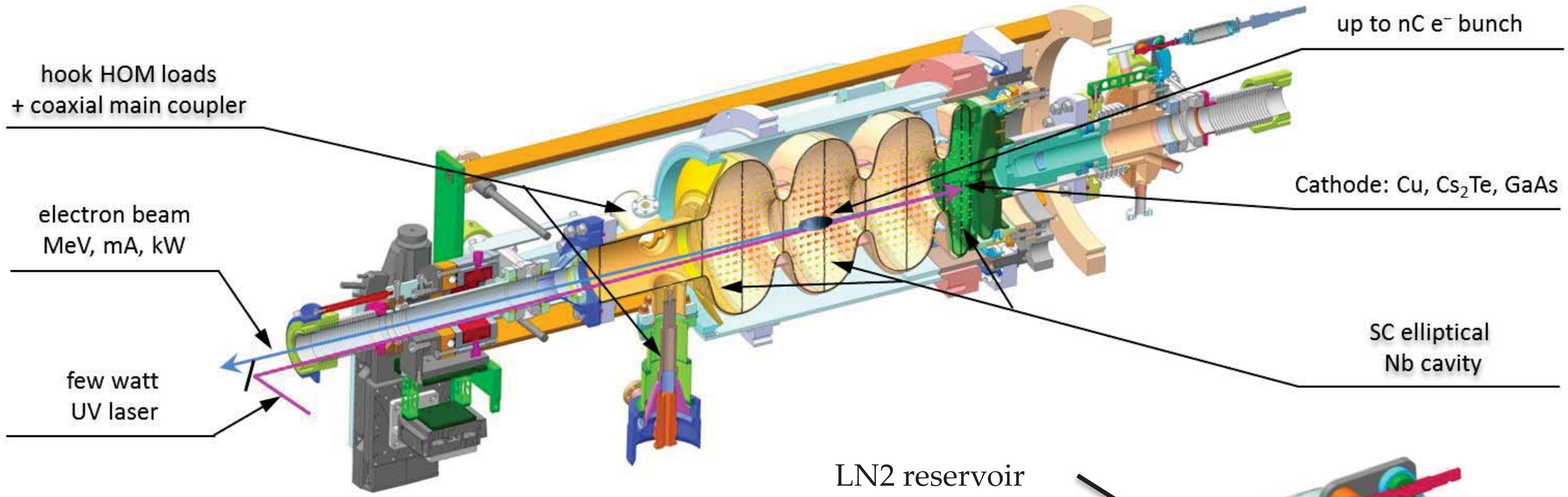

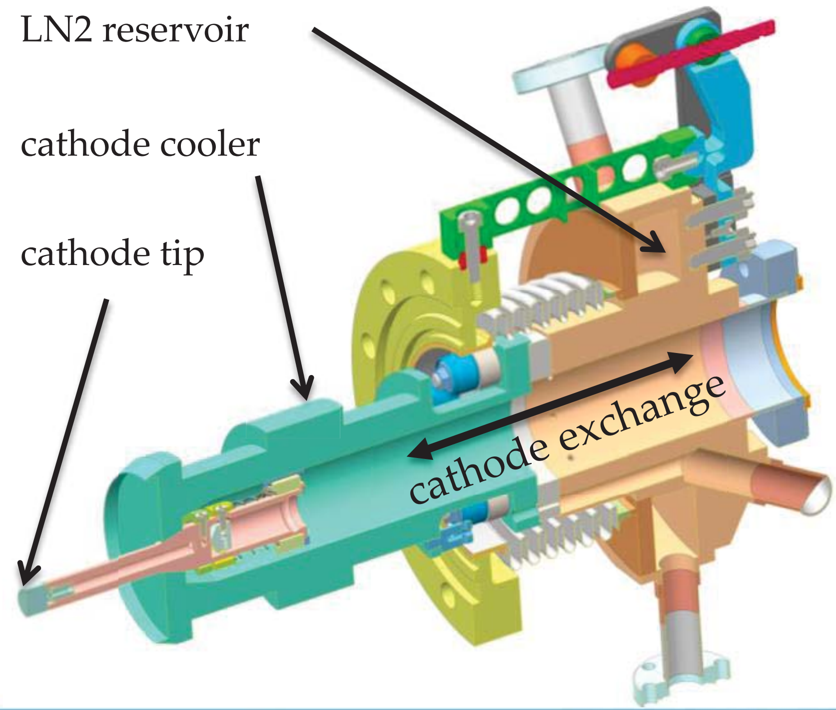

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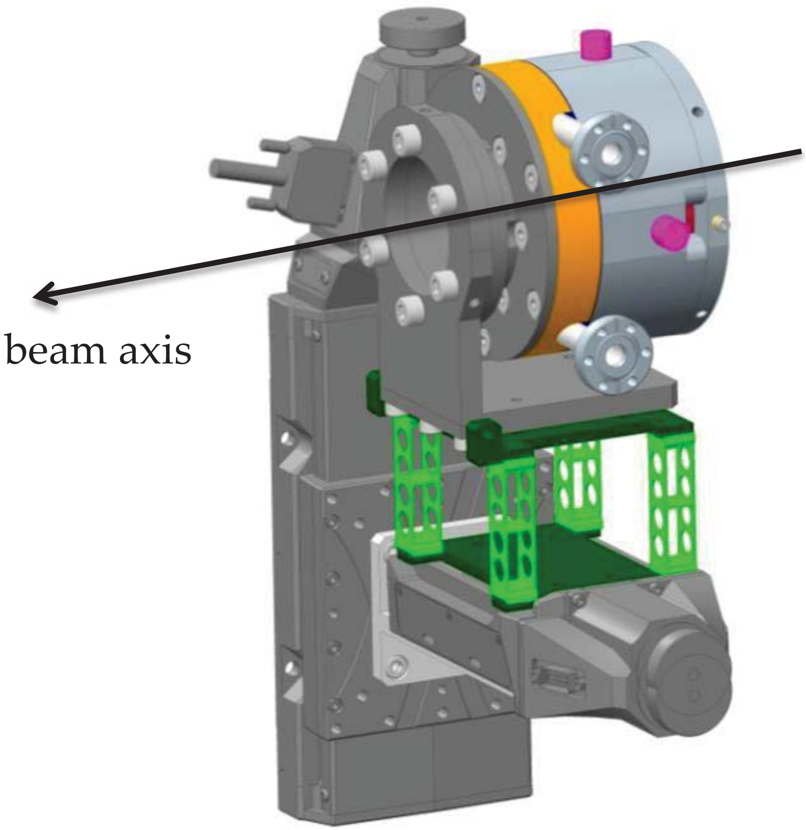
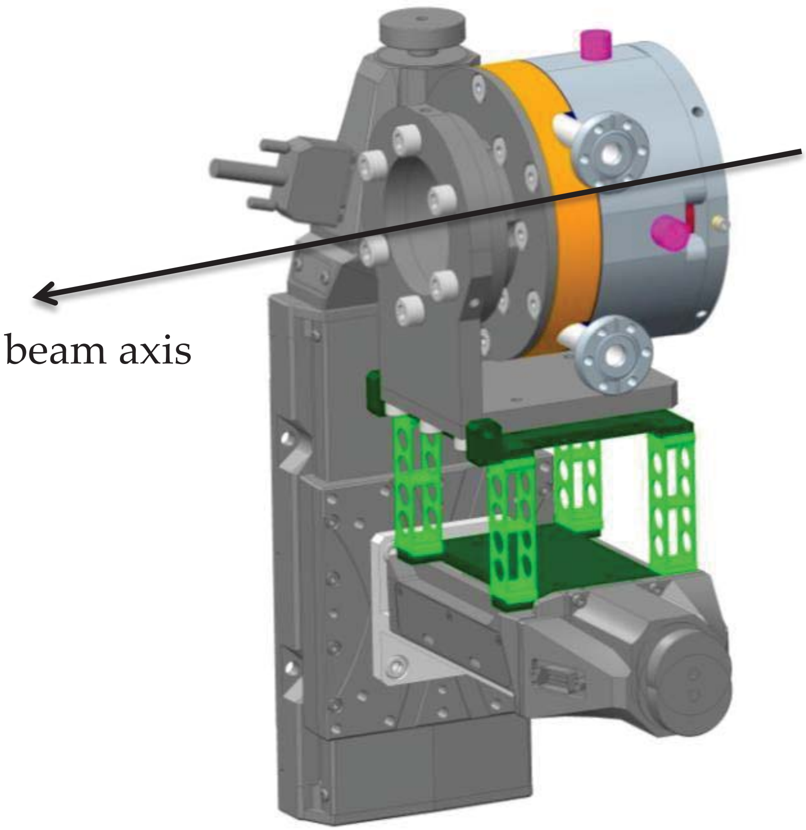


- SC solenoid by Niowave Inc. (2 K)
- Remote controlled xy-table (77 K)
- Field mapping at room temperature
- On axis field profile ⇒ $B_{z,max}$=449 mT @ 10 A

Design of the ELBE SRF gun II



- Additional half-cell stiffening (light green) to reduce Lorentz force detuning, microphonics and pressure sensitivity
- Larger cathode boring to avoid contact with cathode tip
- Modified pickup for better cleaning and clean room assembly

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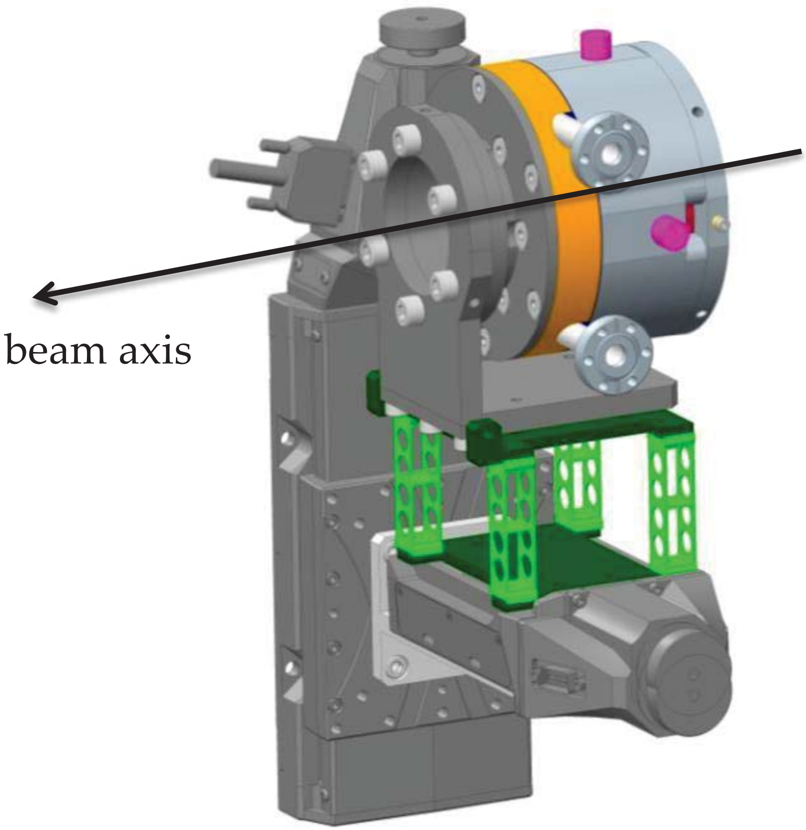

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A stony path to a new cavity

- Fabrication and vertical test of two new cavity in in collaboration with JLab **(P. Kneisel and co-workers)**
- A RRR300 fine grain and a large grain cavity
- **Main objective: achieve design value of E_{pk}=50 MV/m**

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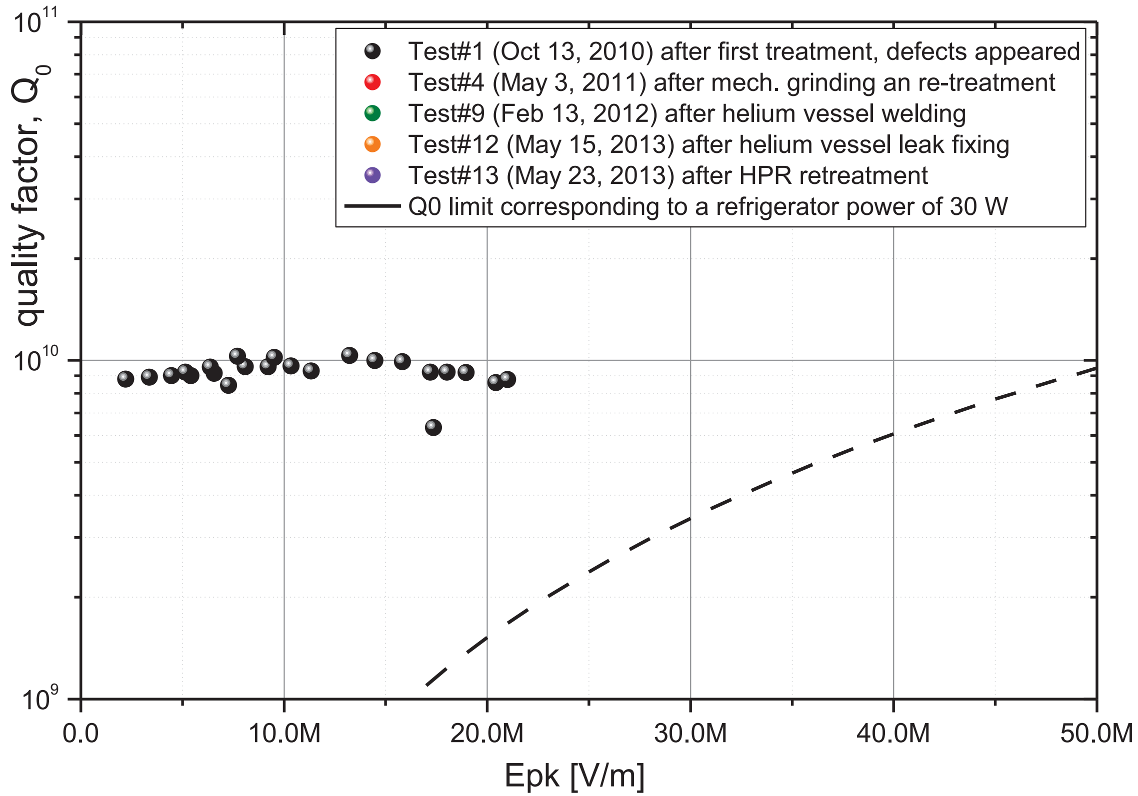

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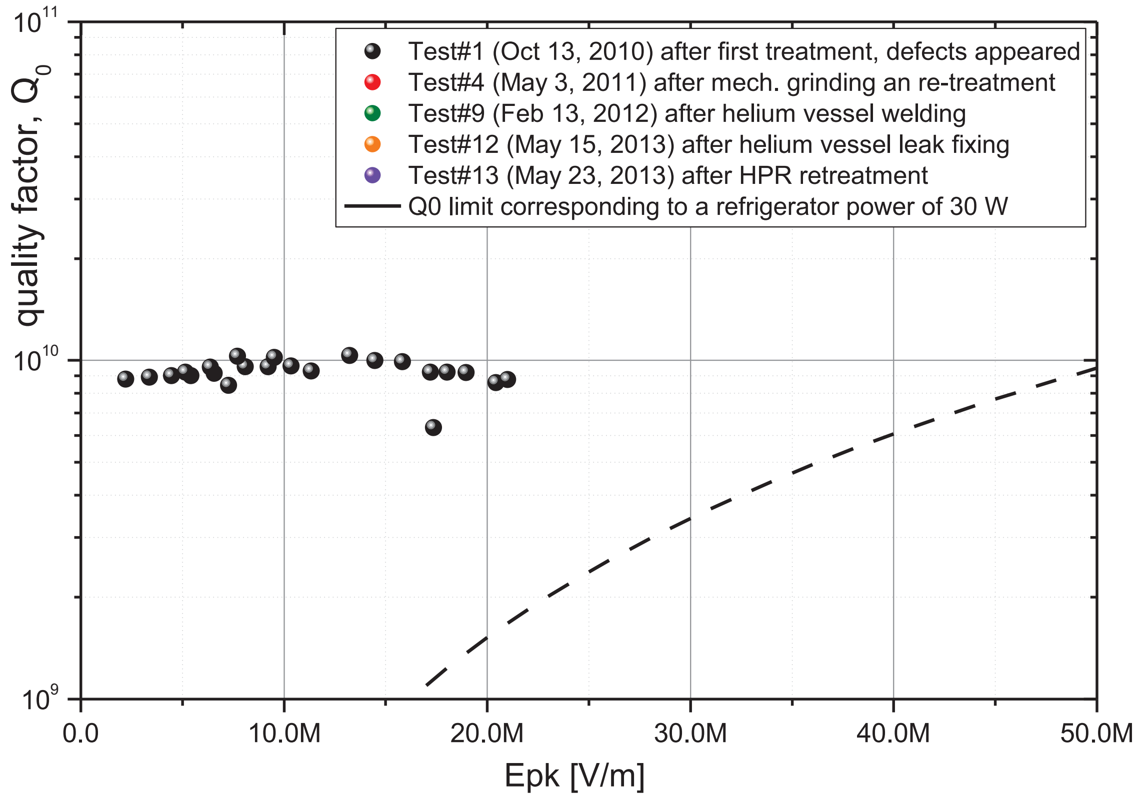

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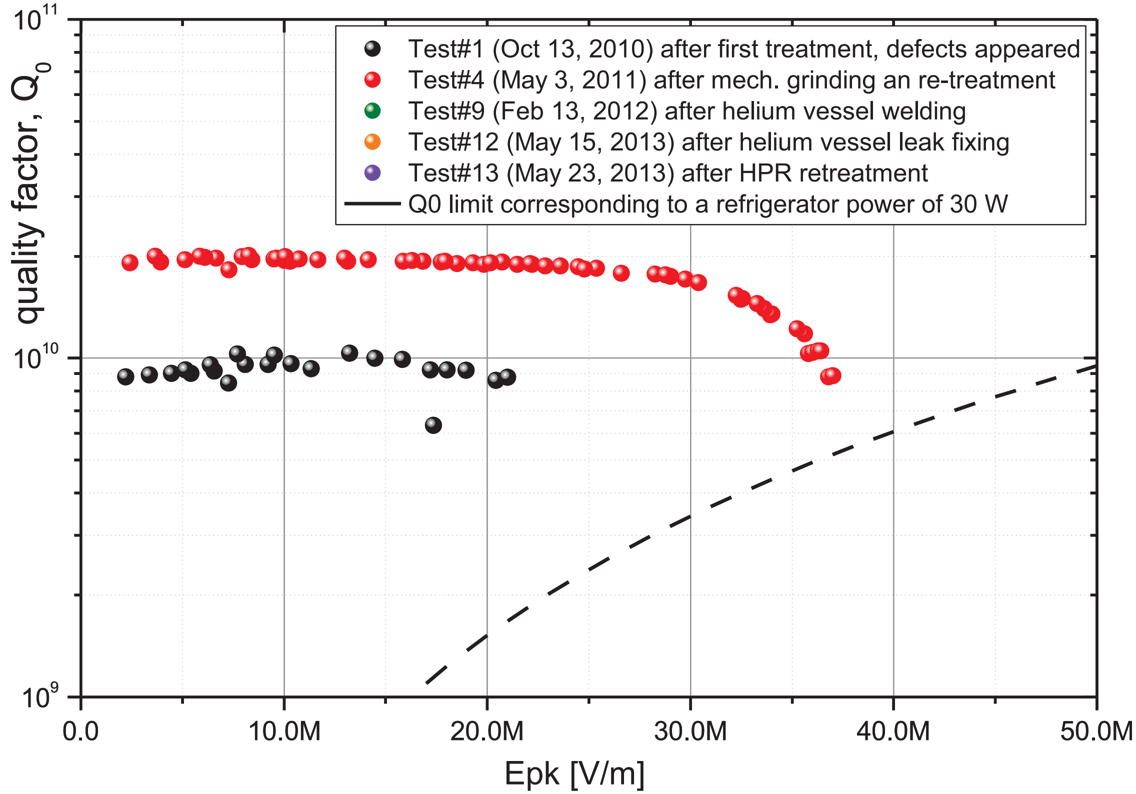

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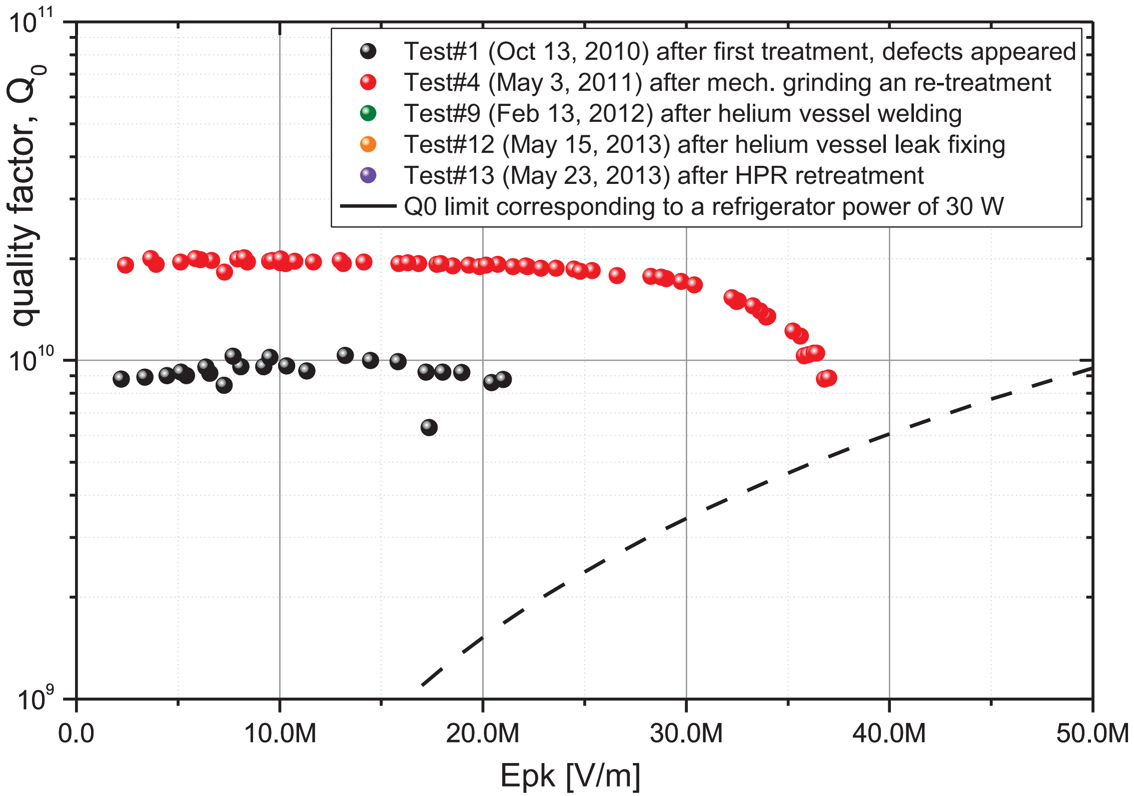

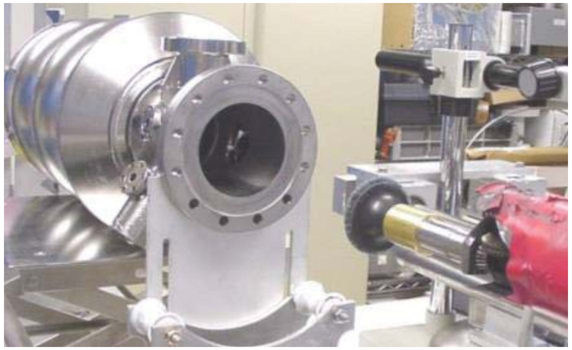

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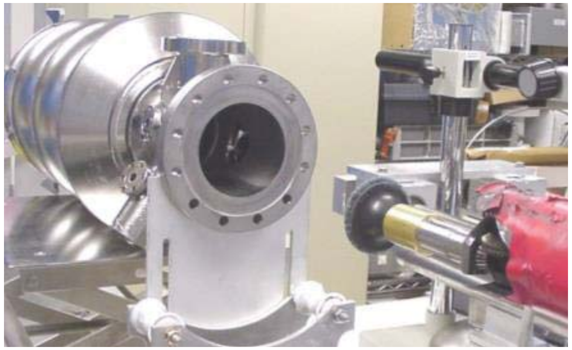

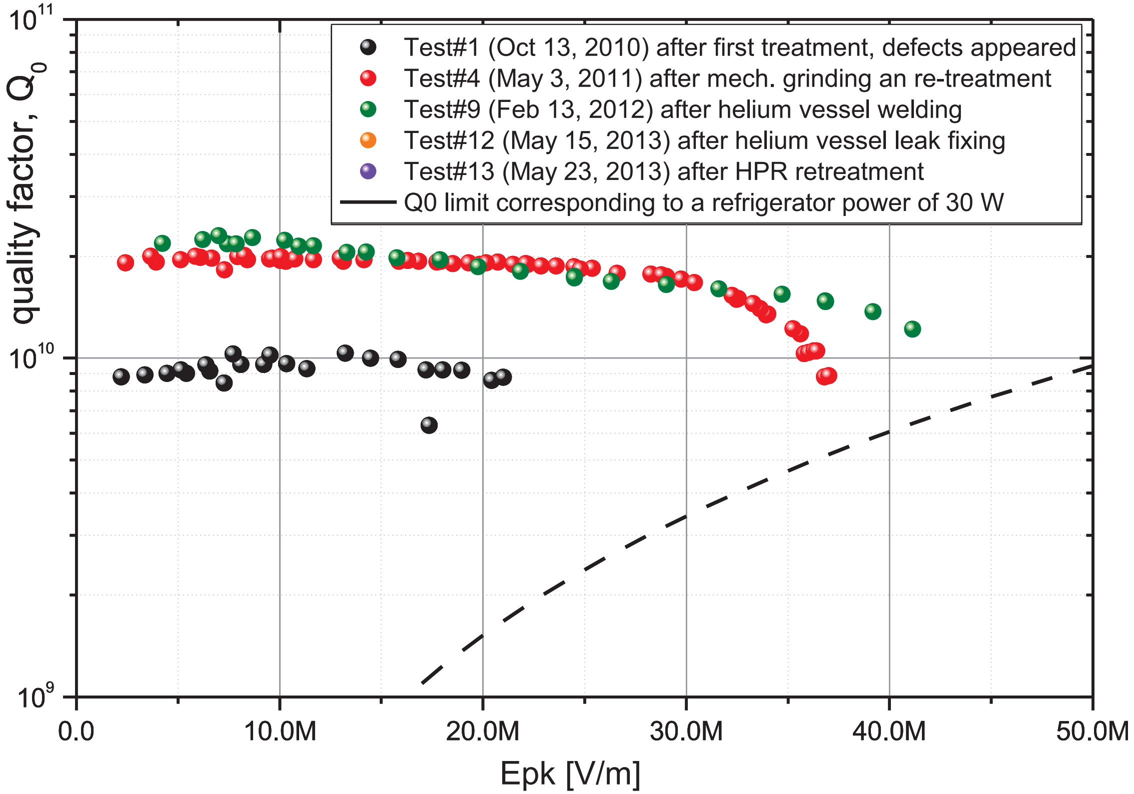

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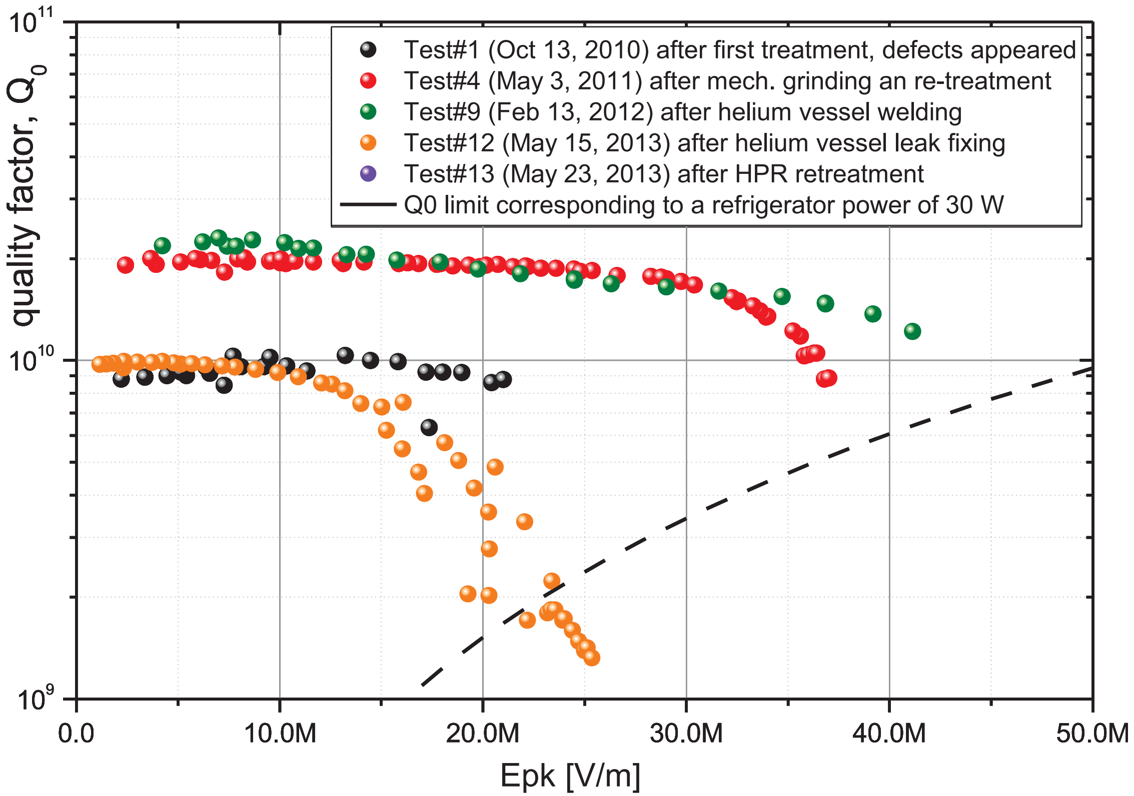

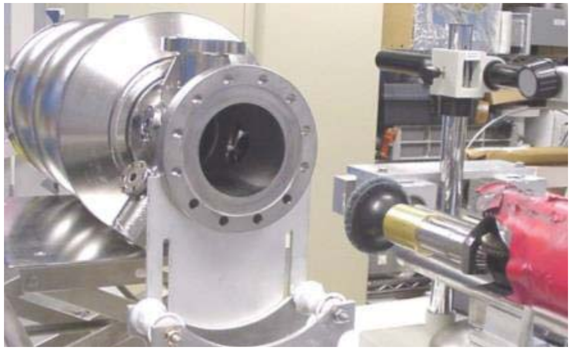

DRESDEN concept HZDR

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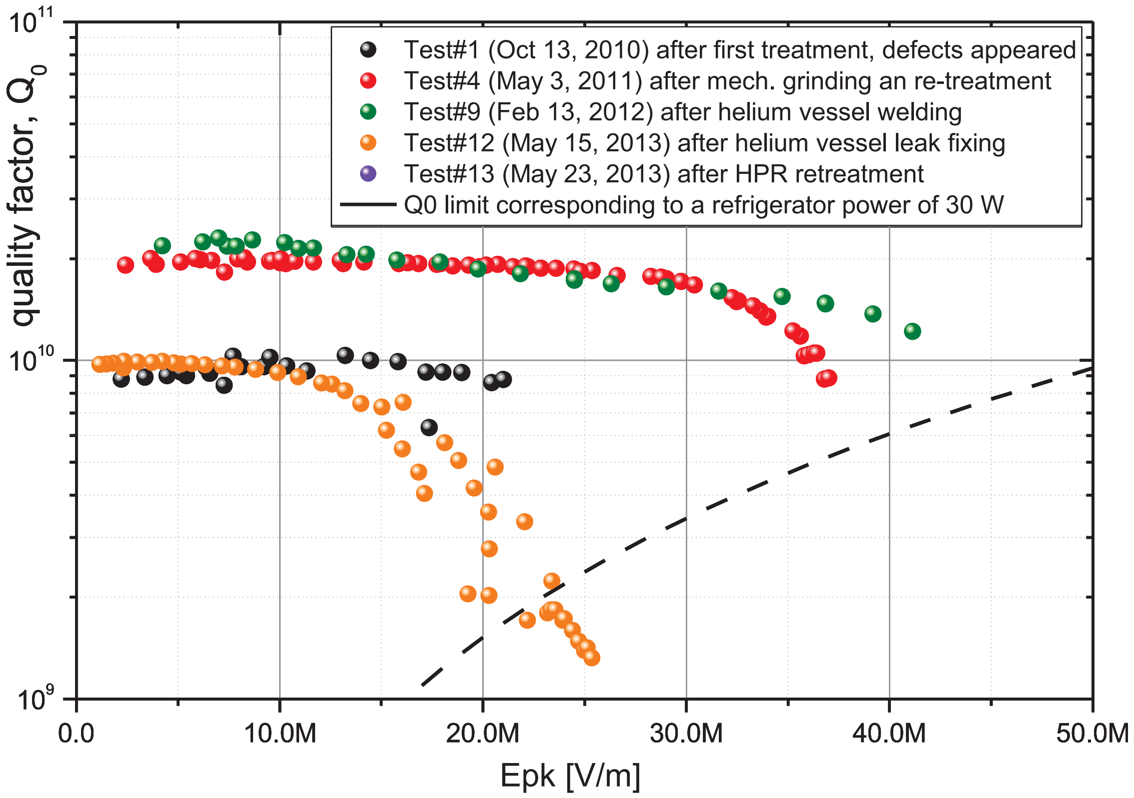

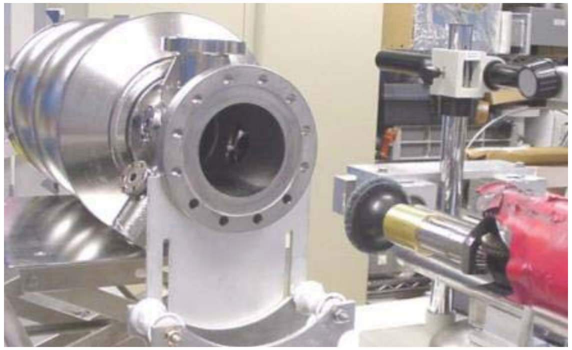

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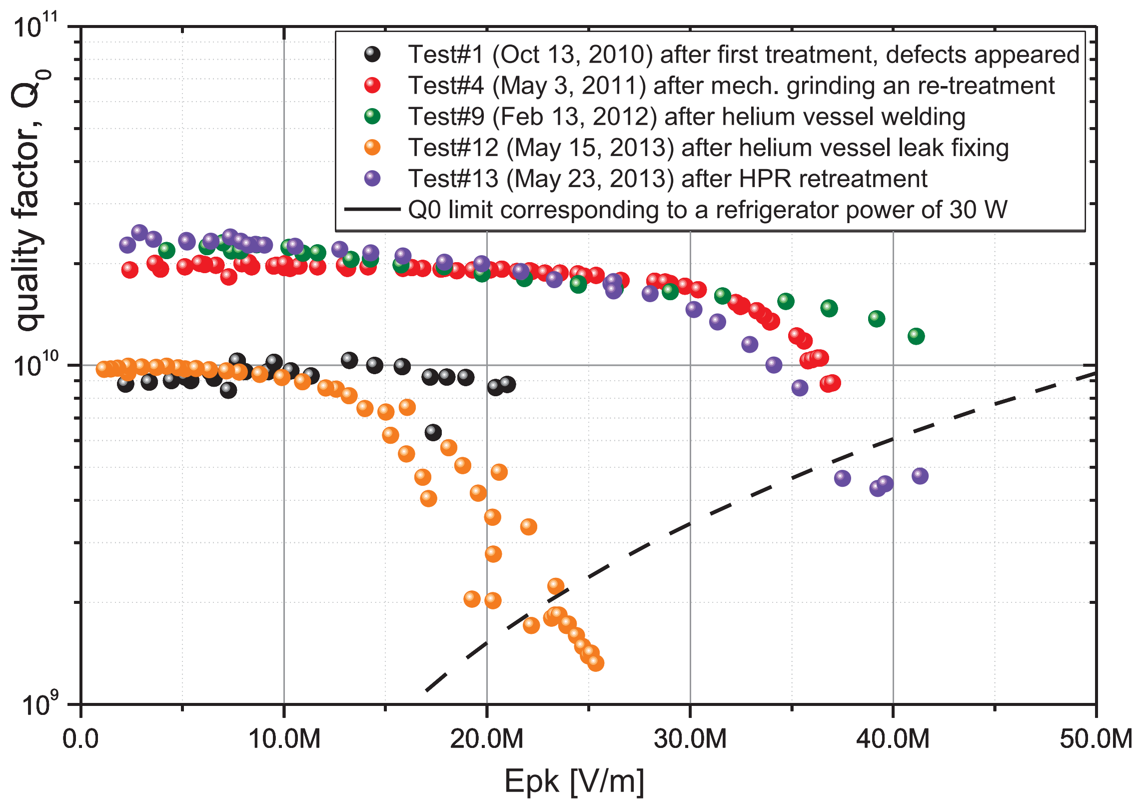

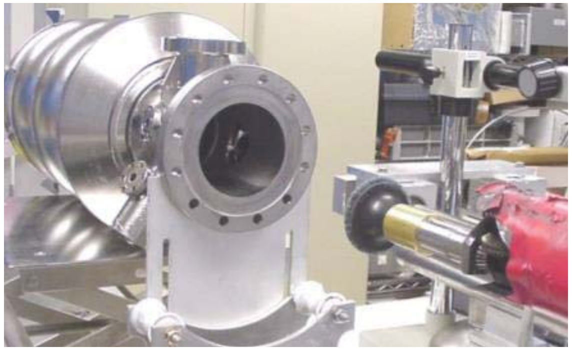

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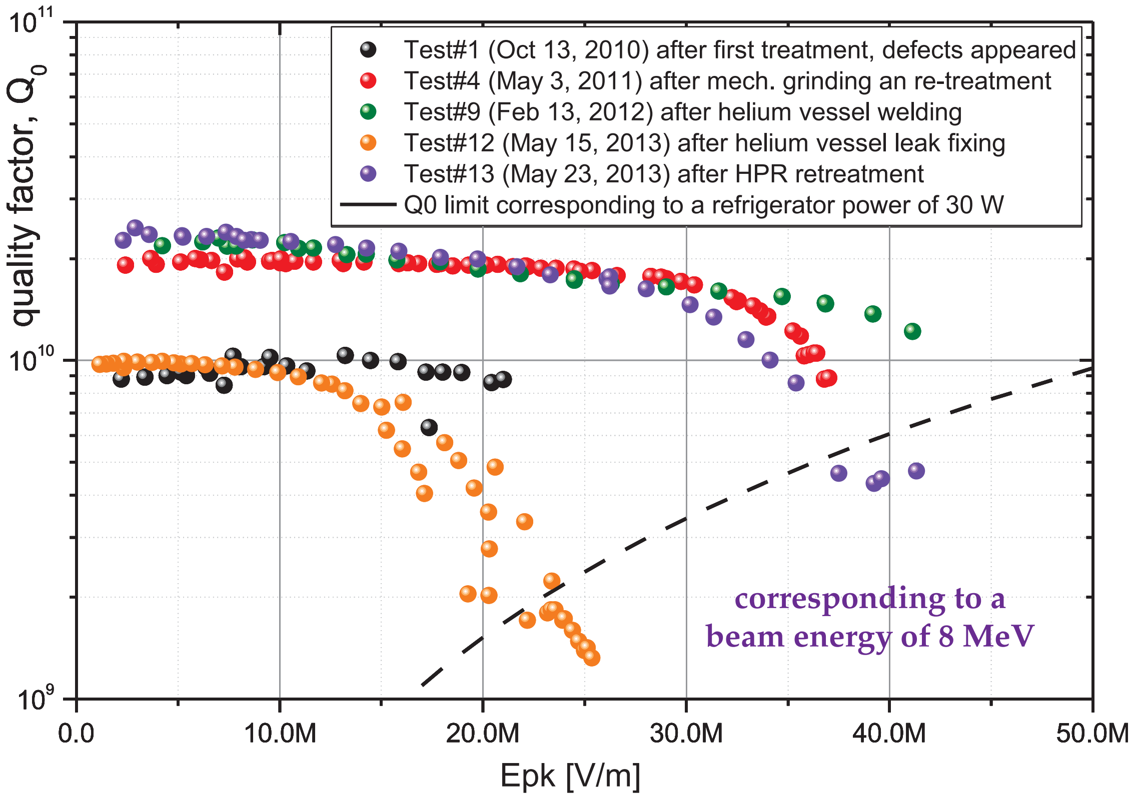
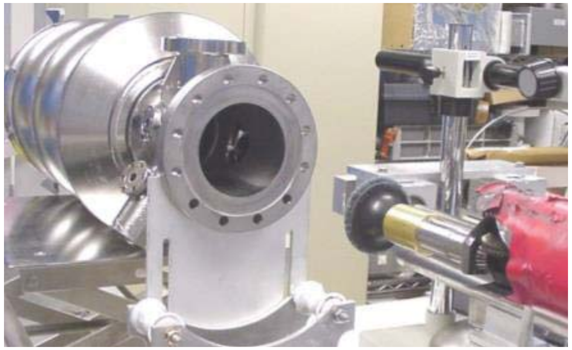
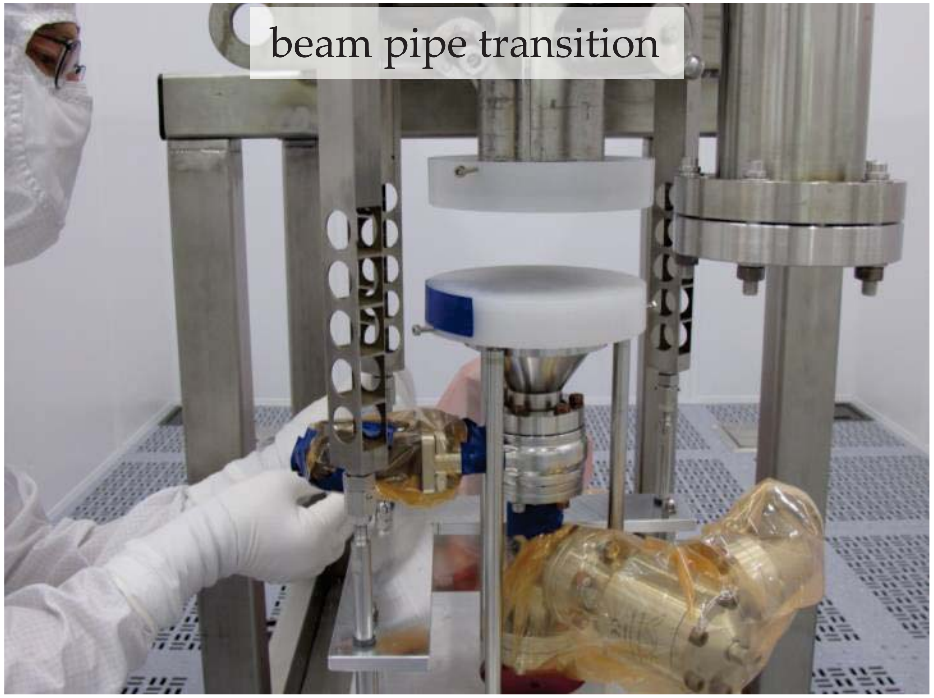




Cold mass cleanroom assembly at JLab



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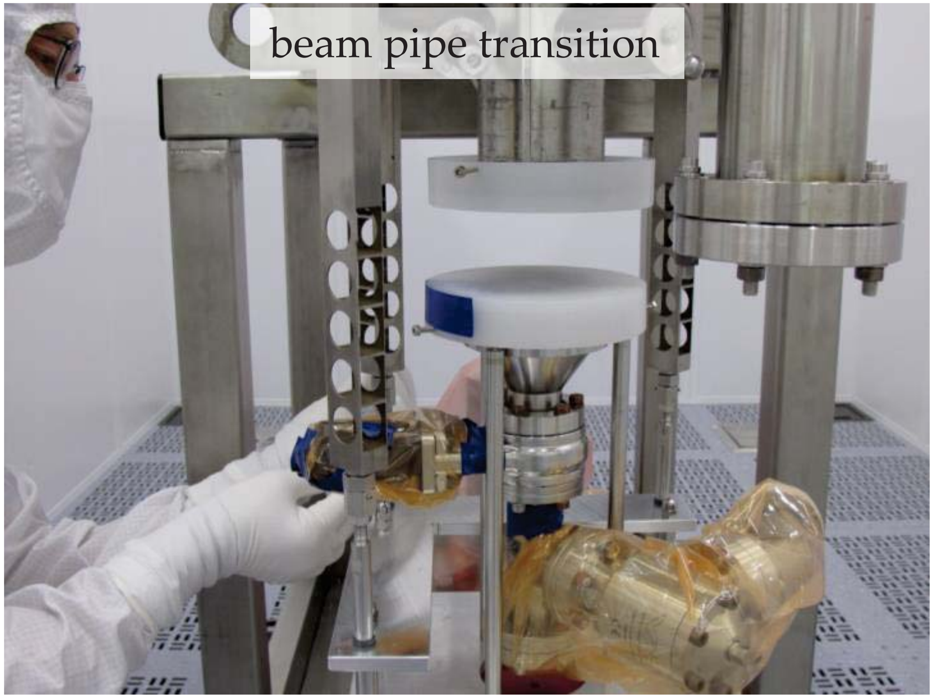

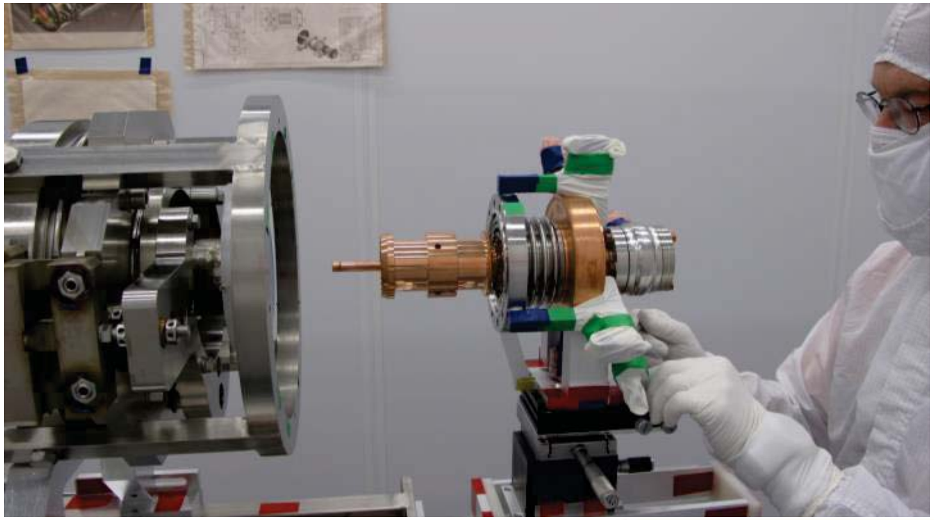

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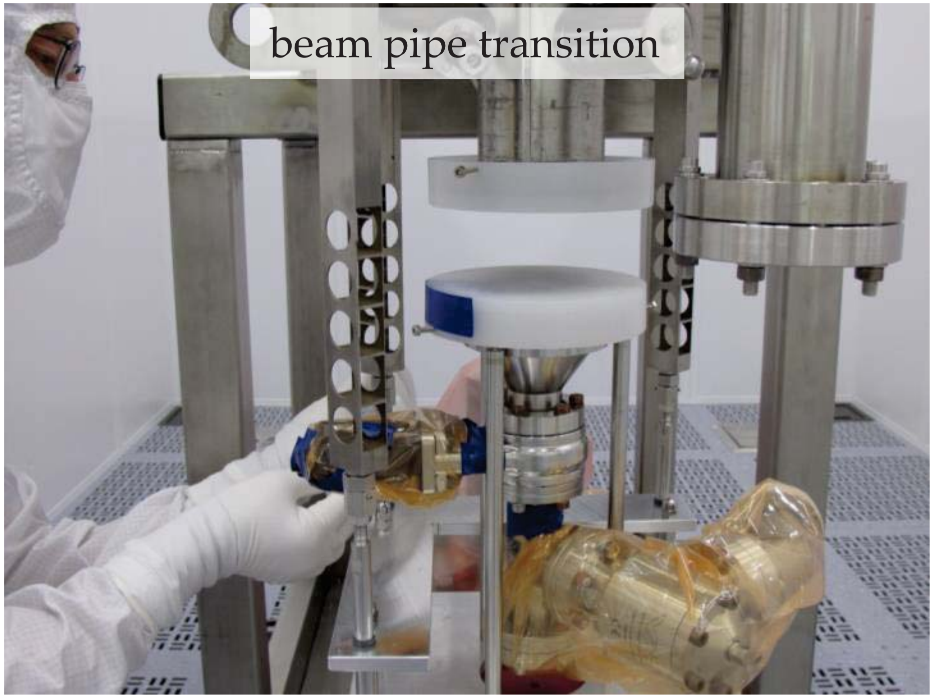

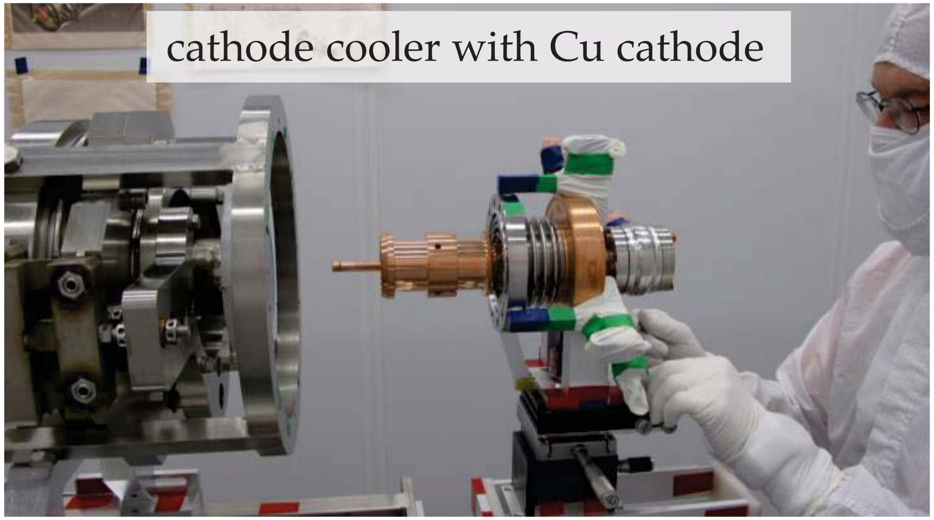

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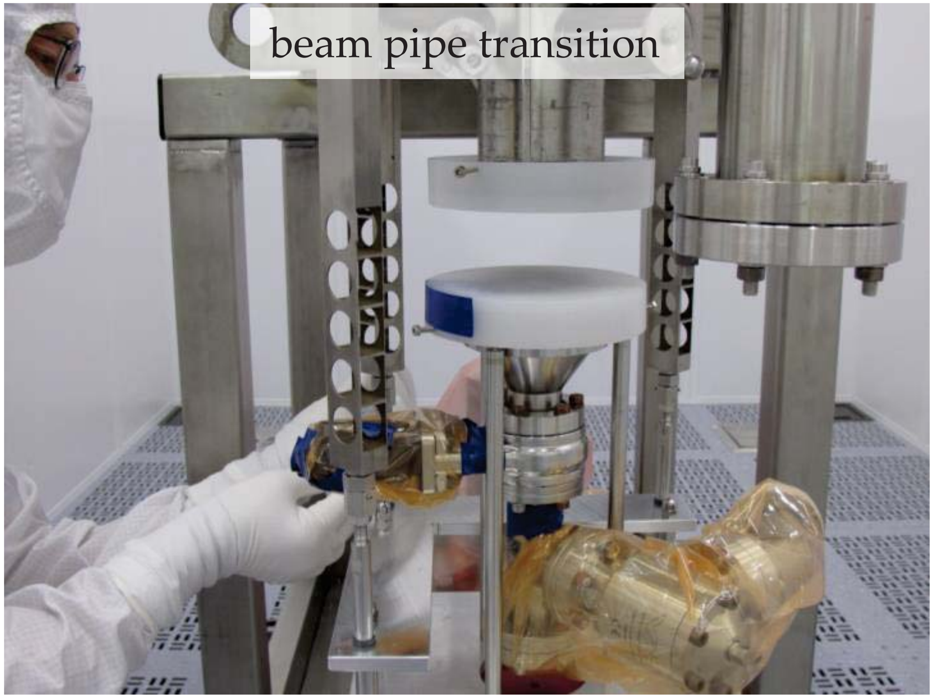
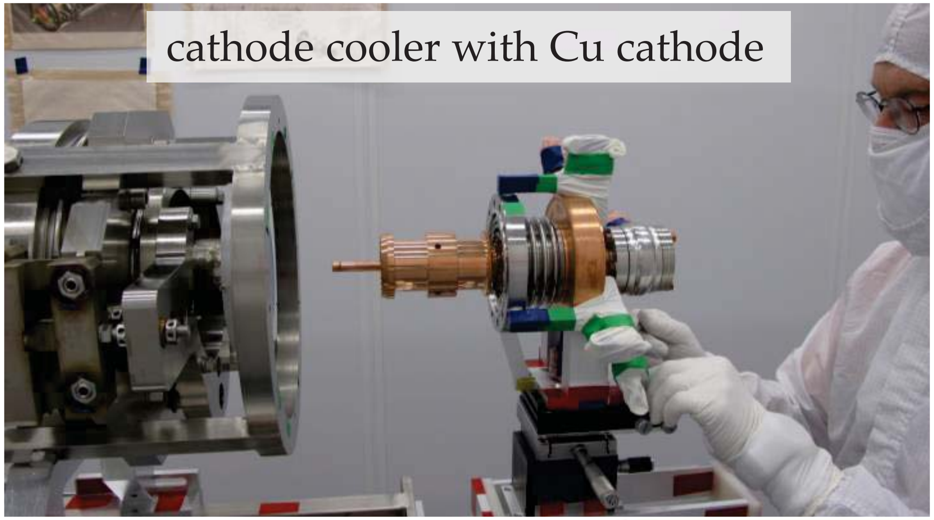


beam pipe transition



cathode cooler with Cu cathode

DRESDEN concept

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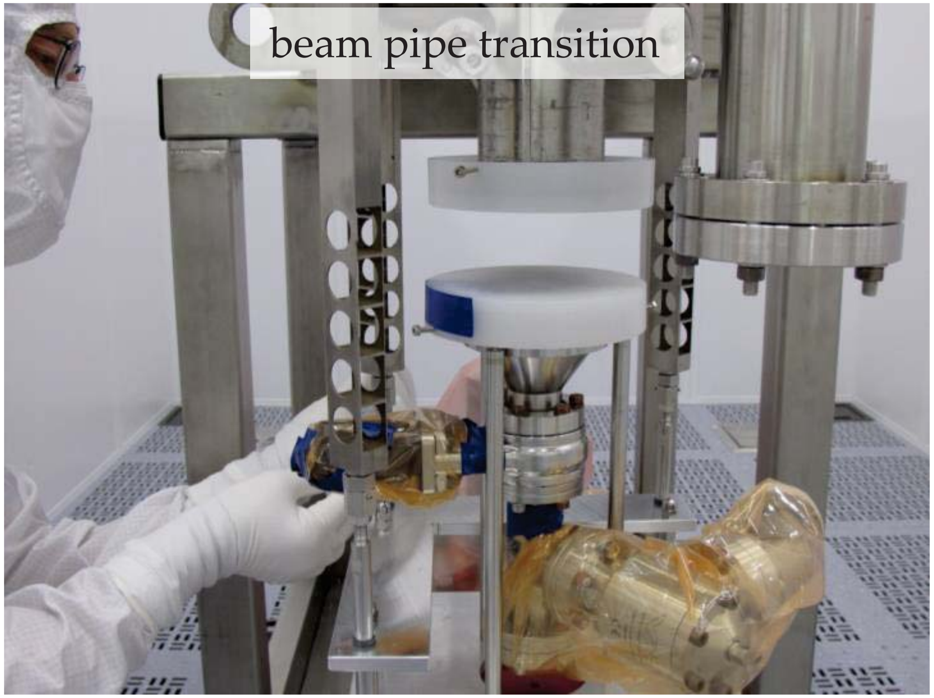

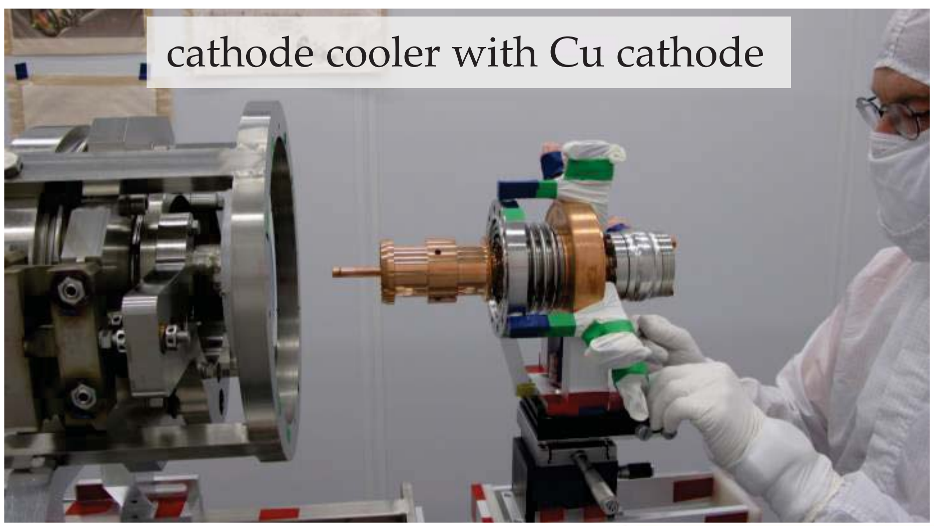

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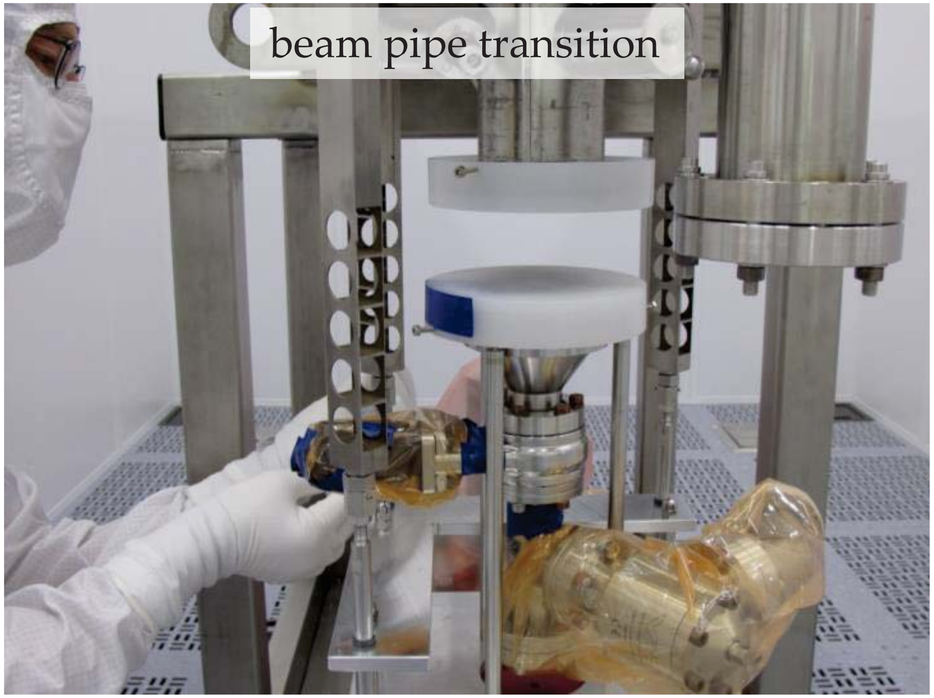

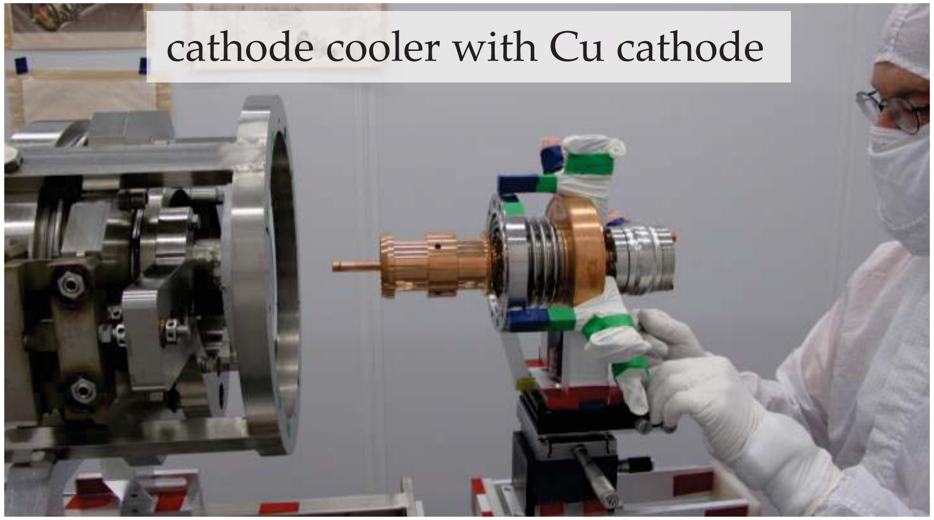

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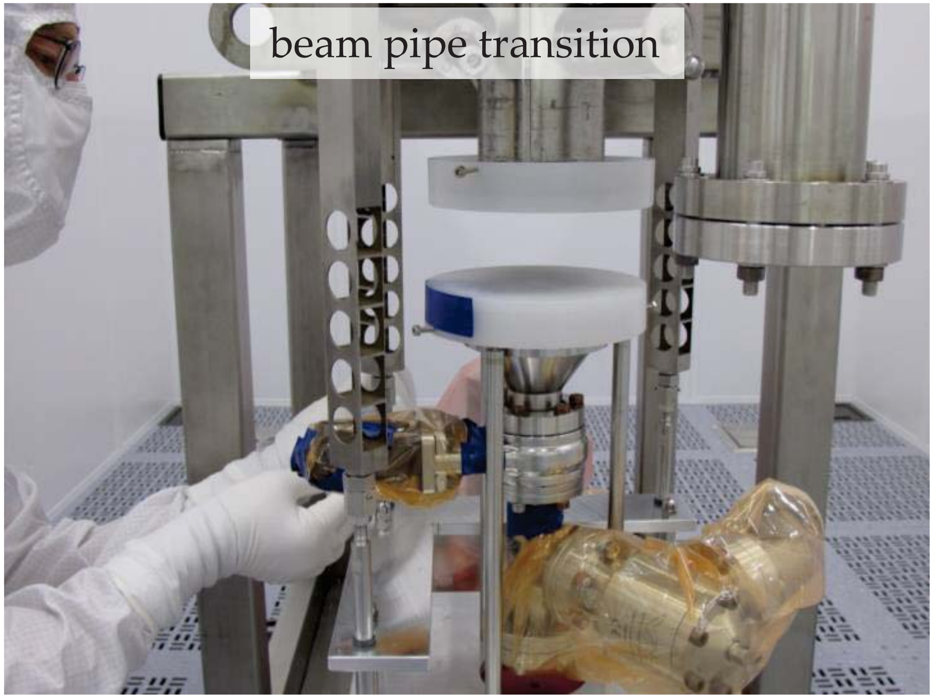
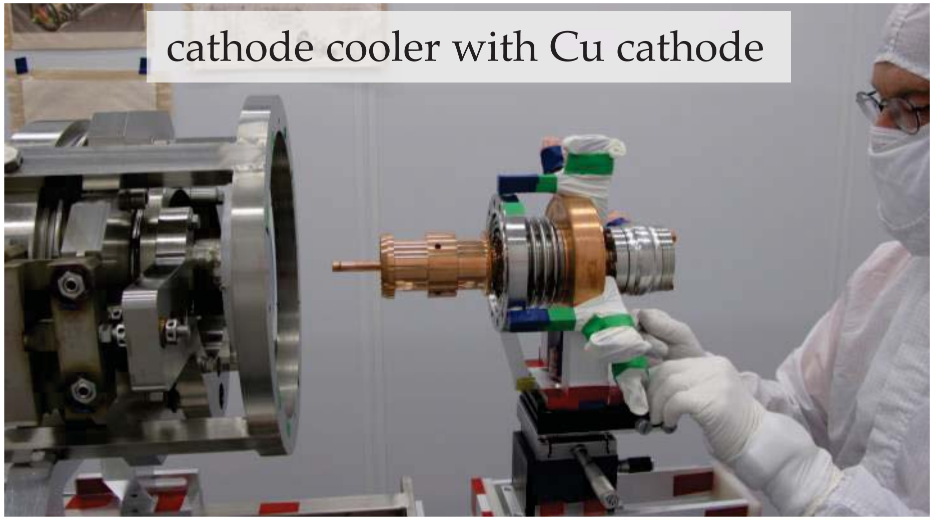
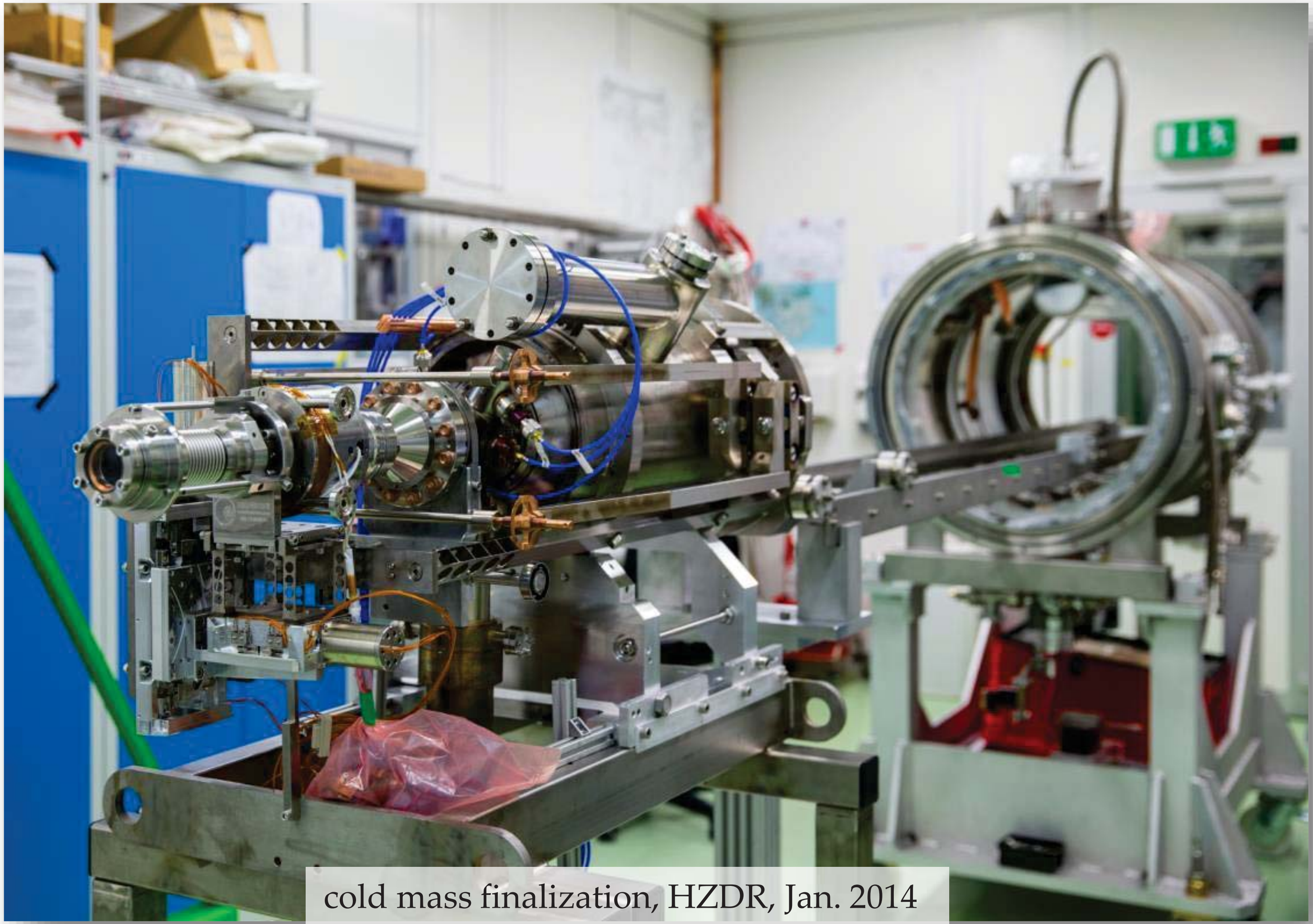




Cryomodule assembly at Rossendorf



cold mass finalization, HZDR, Jan. 2014

Cryomodule assembly at Rossendorf

cryomodule assembly, HZDR, Feb. 2014

Cryomodule assembly at Rossendorf

cryomodule assembly, HZDR, Feb. 2014

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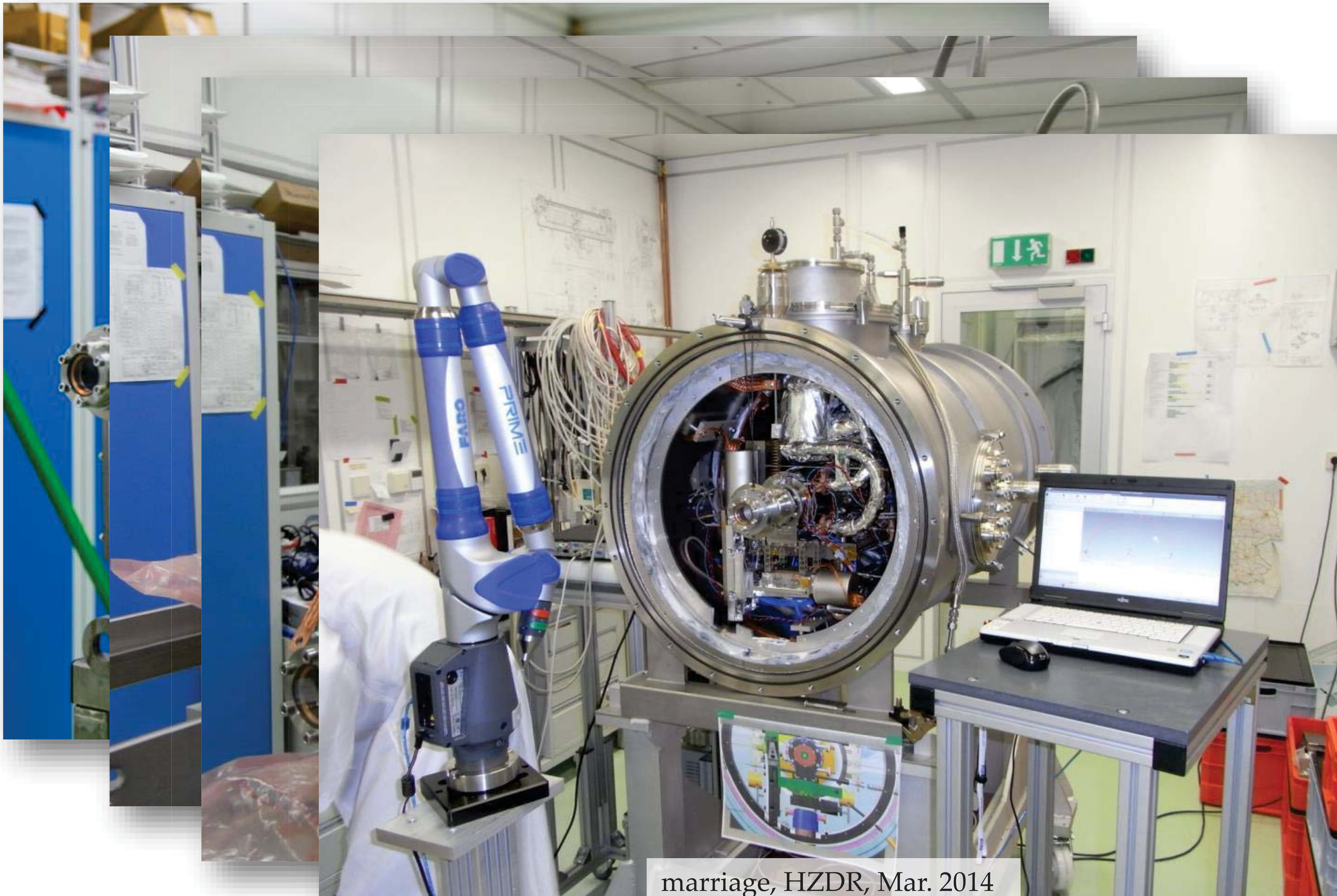


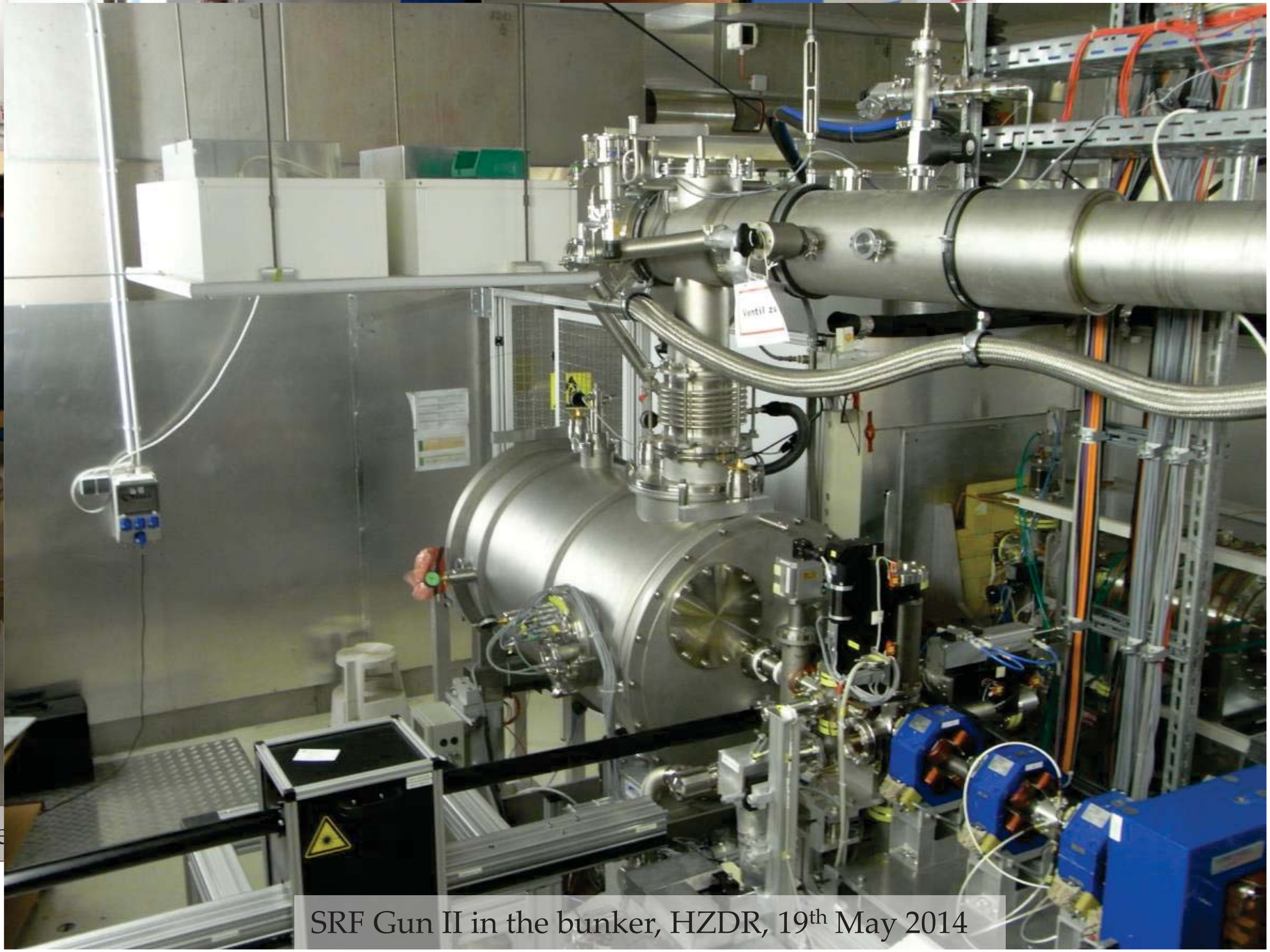
marriage, HZDR, Mar. 2014

Procession of SRF gun II into the bunker

“procession” of SRF Gun II into the bunker, HZDR, 5th May 2014

Procession of SRF gun II into the bunker

“proce



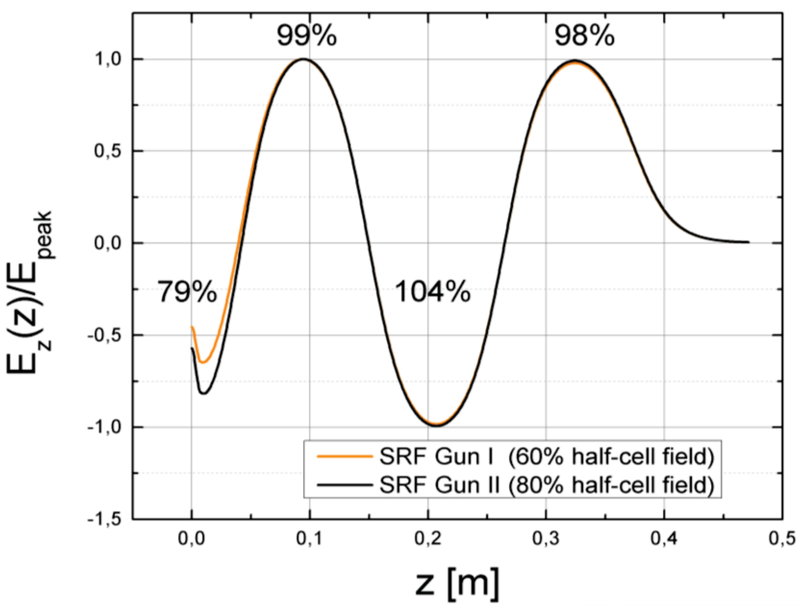
SRF Gun II in the bunker, HZDR, 19th May 2014

field profile

- TM_{010} frequencies in combination with latest bead pull results used to estimate the field profile of the accelerating mode

Table 2: Frequency and bandwidth of all TM_{010} modes.

π-mode	1/4	2/4	3/4	4/4
f_0 / MHz	1267.667	1282.794	1294.762	1300
b /Hz	17	147	271	140



Field profile and external Q's

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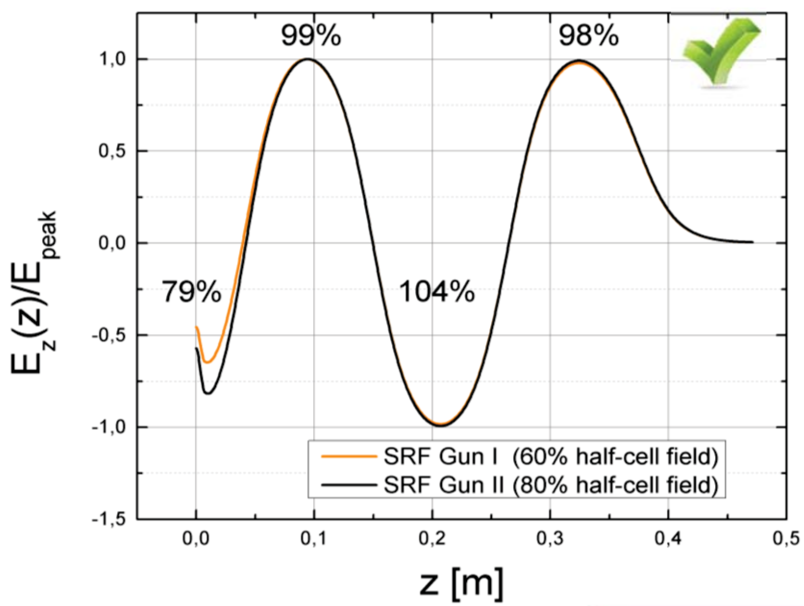

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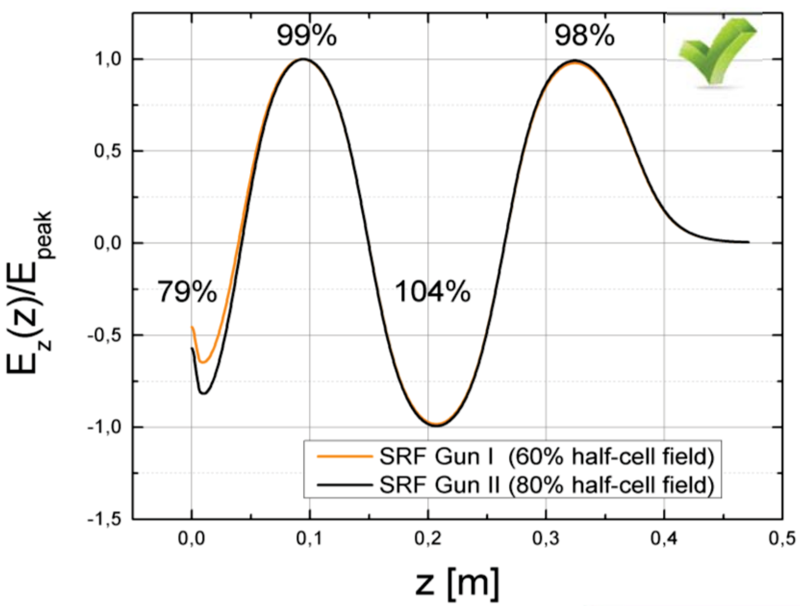

external Qs

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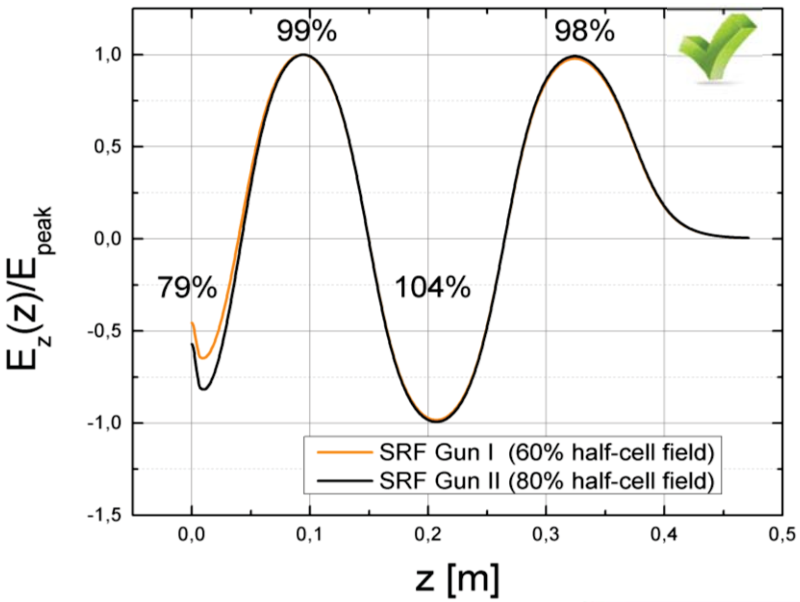

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FPC:	9.3×10^{06}	1.3×10^{07}
F-Pickup:	2.7×10^{11}	~2×10^{11}
Choke:	4.3×10^{10}	~2×10^{11}
HOM1:	2.3×10^{12}	>2×10^{11}
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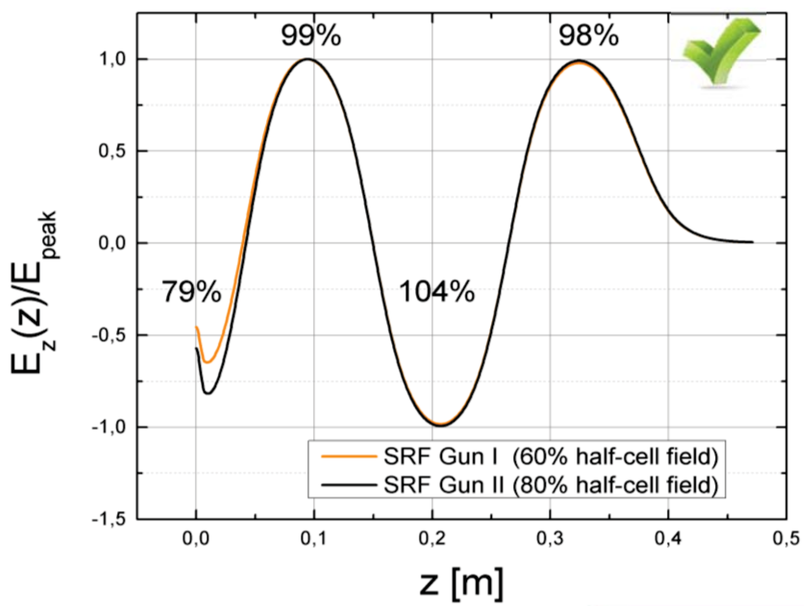

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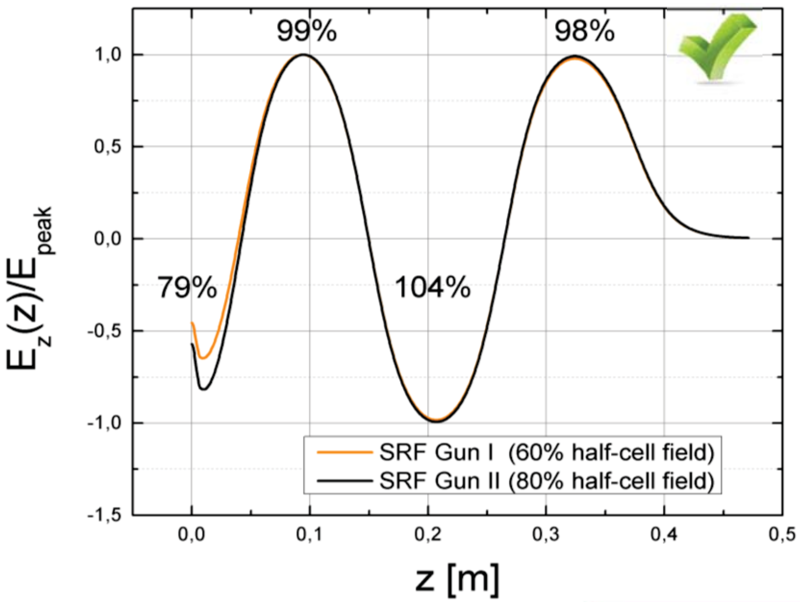

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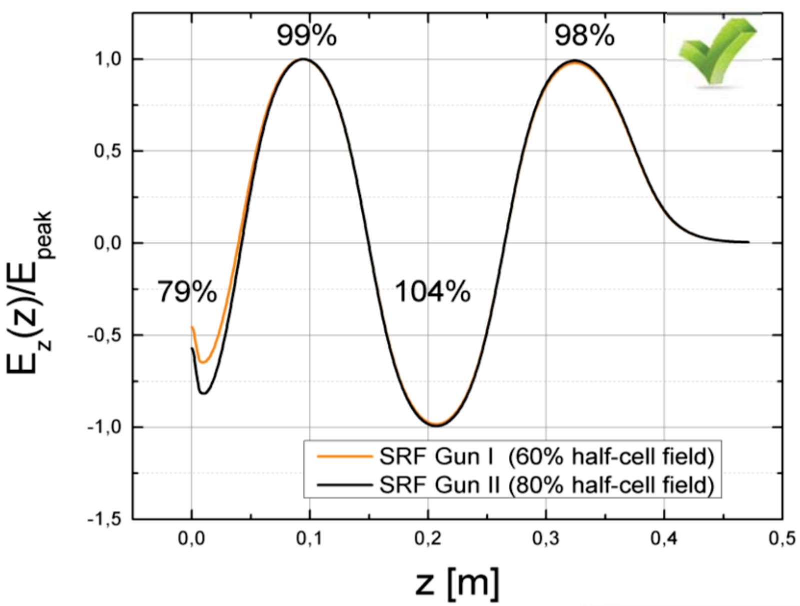

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HOM1:	2.3×10^{12}	$> 2 \times 10^{11}$
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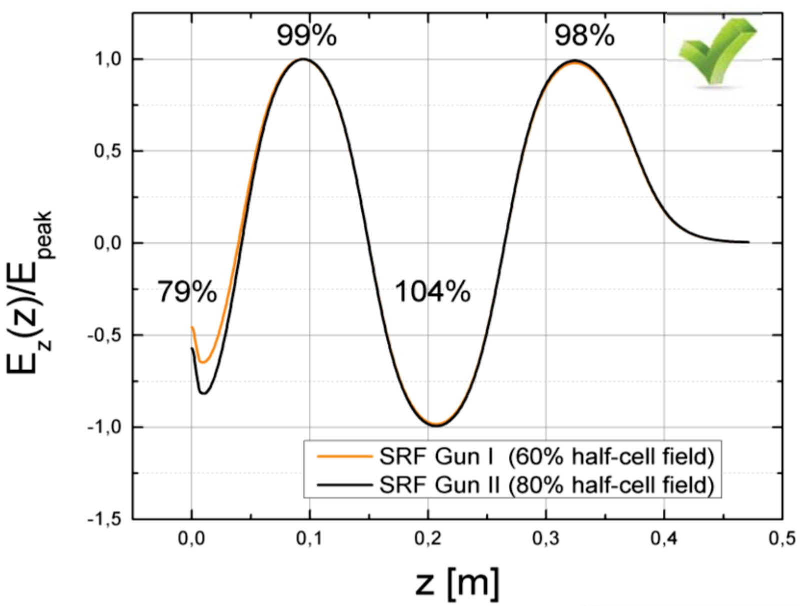
Field profile and external Q's

field profile

- TM_{010} frequencies in combination with latest bead pull results used to estimate the field profile of the accelerating mode

Table 2: Frequency and bandwidth of all TM_{010} modes.

π-mode	1/4	2/4	3/4	4/4
f_0 / MHz	1267.667	1282.794	1294.762	1300
b /Hz	17	147	271	140



external Qs

- 16 kW CW main coupler with fixed coupling by bandwidth measurement
- HOM coupler and choke pickup by comparing transmitted power with known pickup antenna from vertical test
- All criteria for coupling fulfilled

	meas.	*spec.*
FPC:	9.3×10^{06}	1.3×10^{07}
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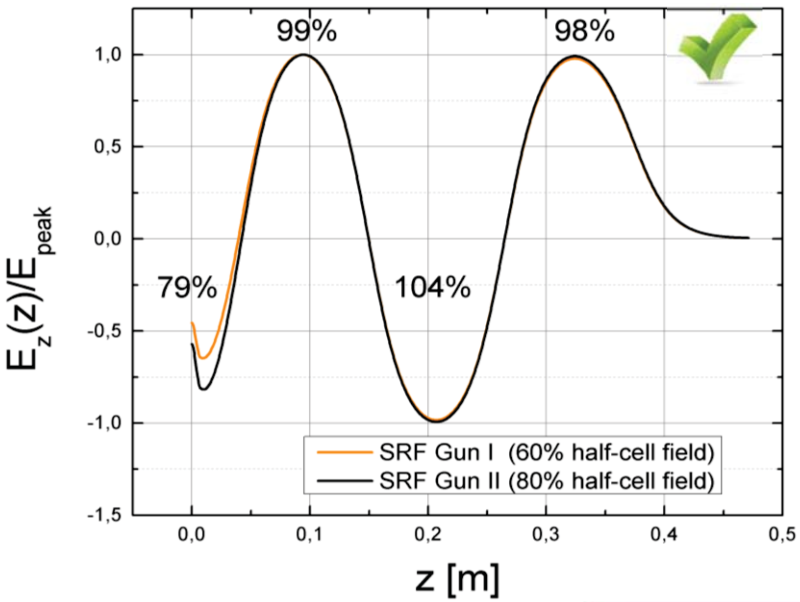

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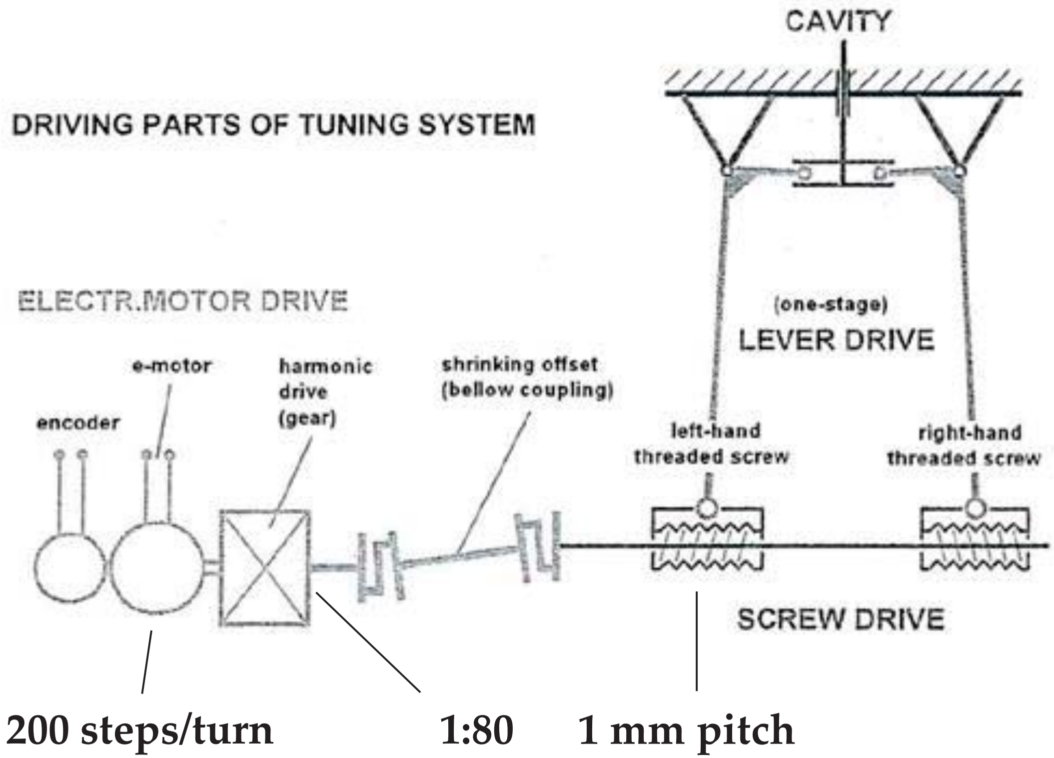
Cavity tuner



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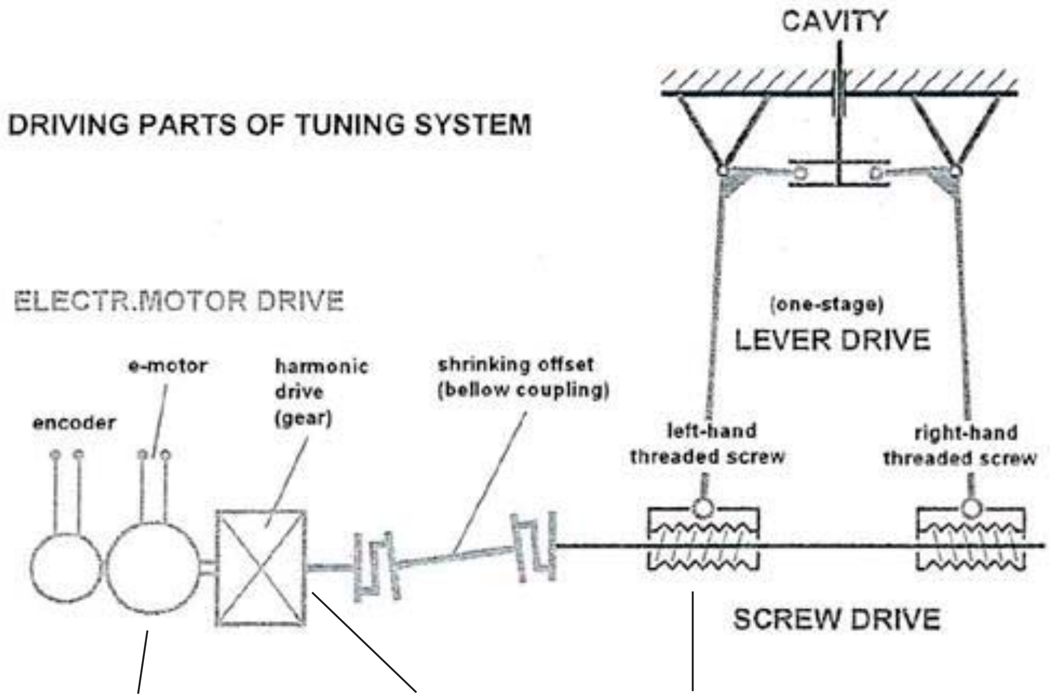
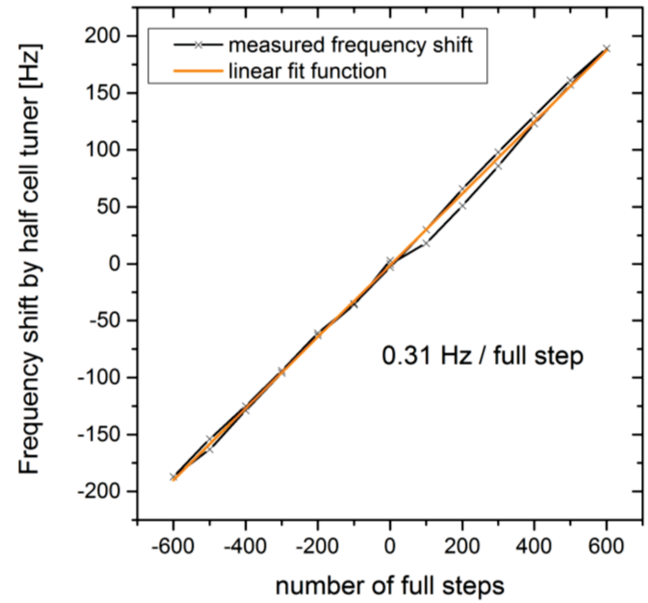


200 steps/turn 1:80 1 mm pitch



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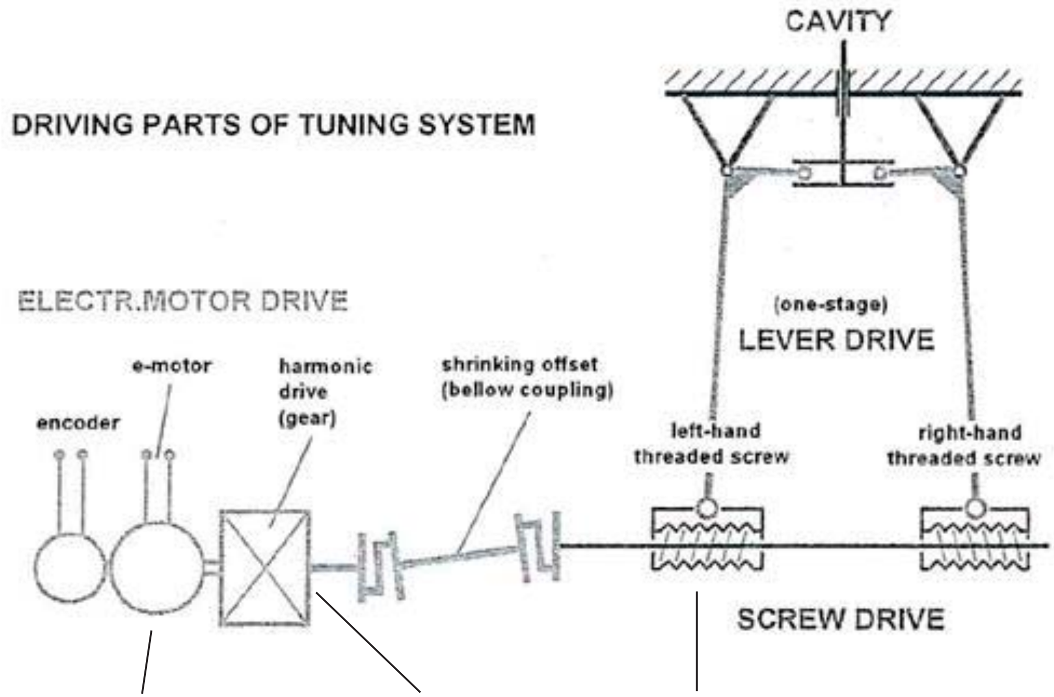

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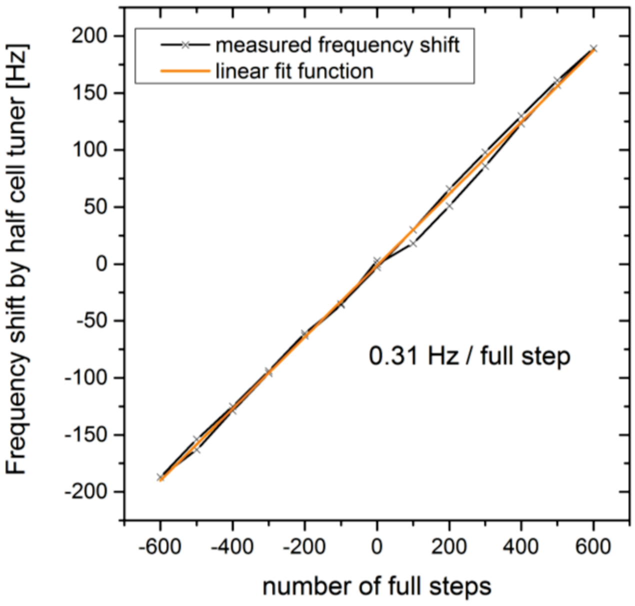

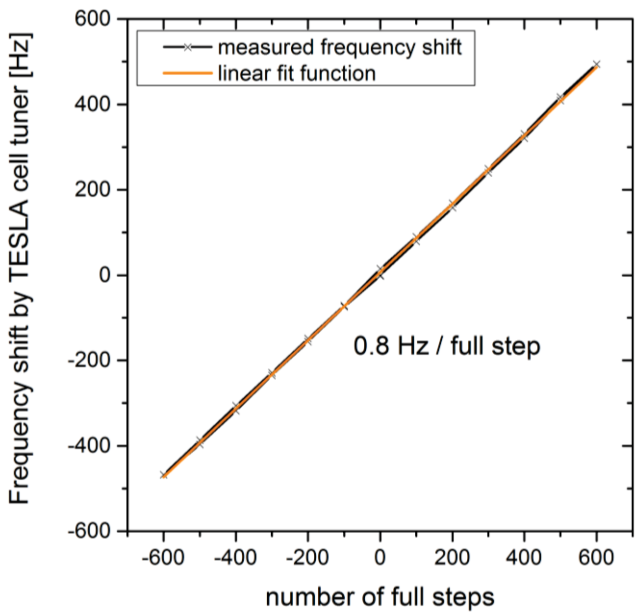

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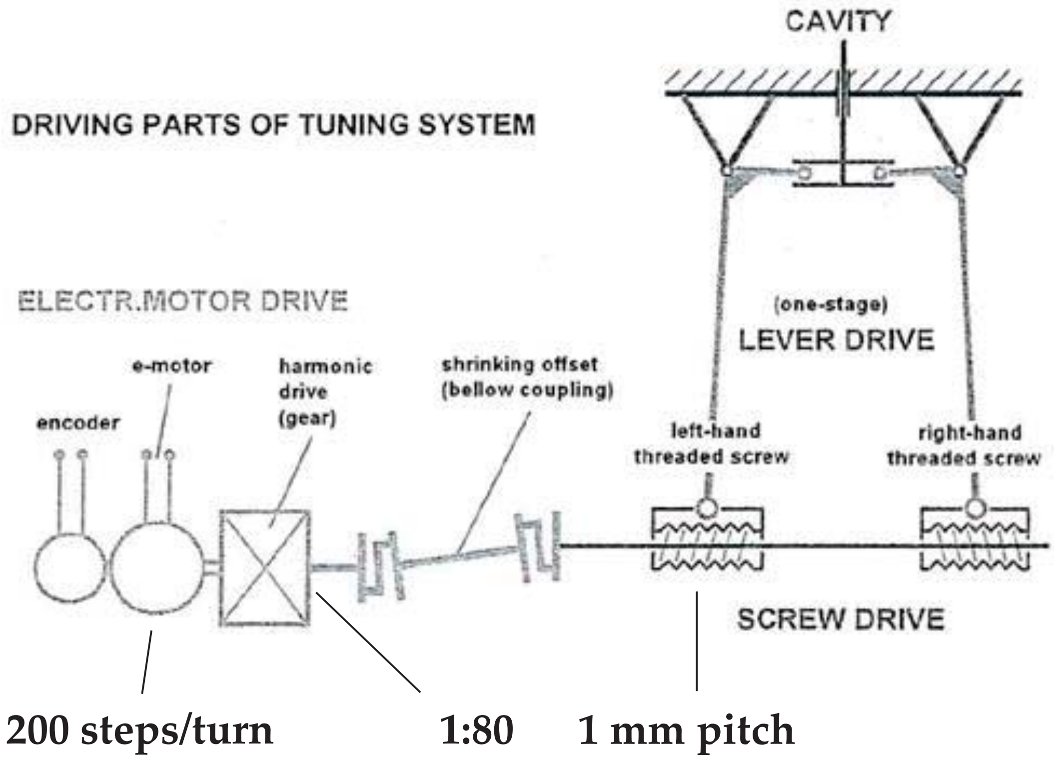

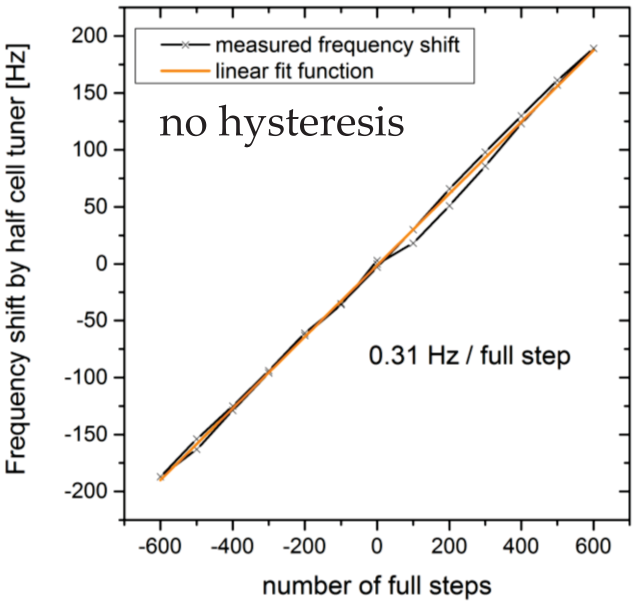

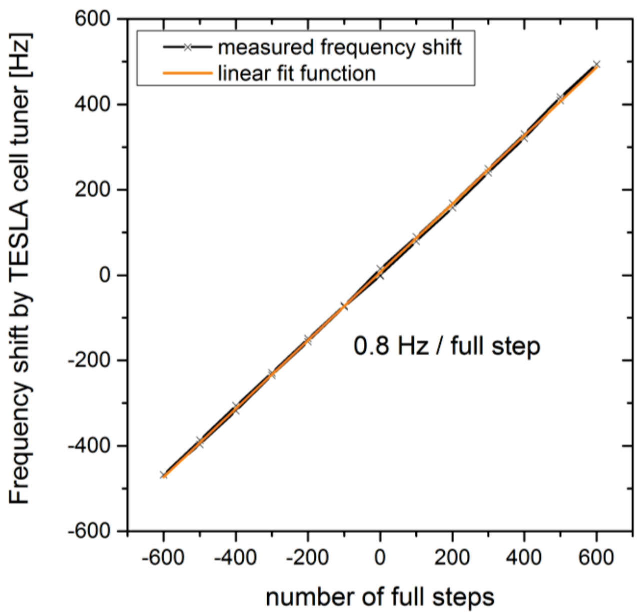

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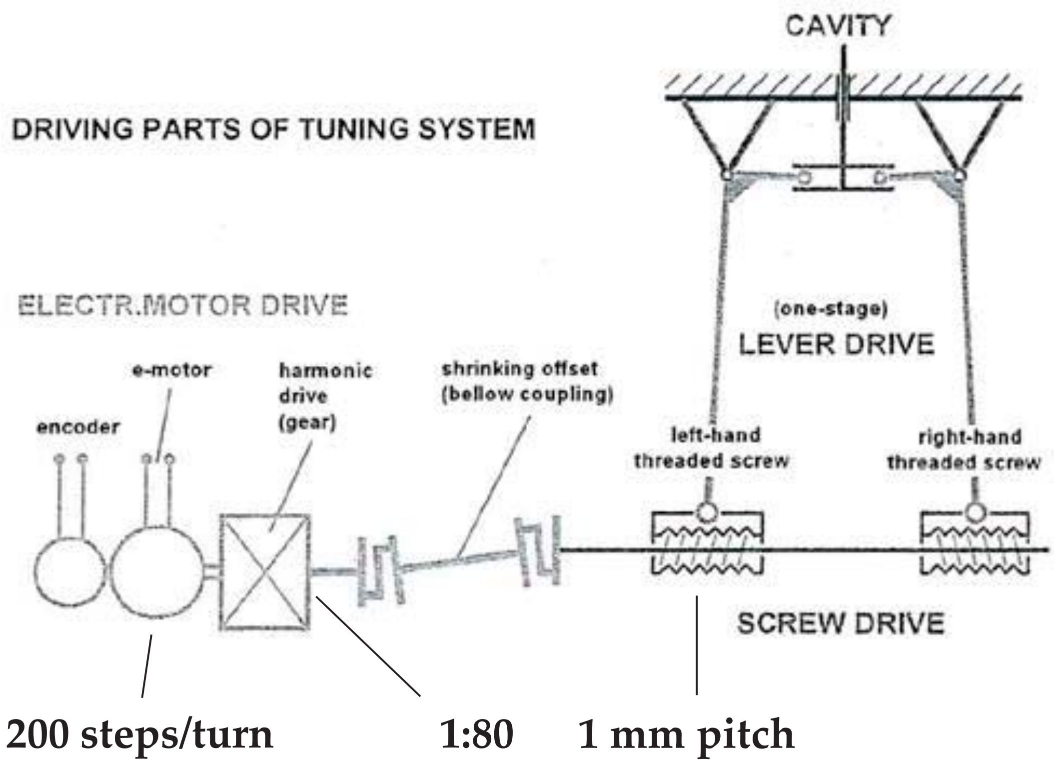

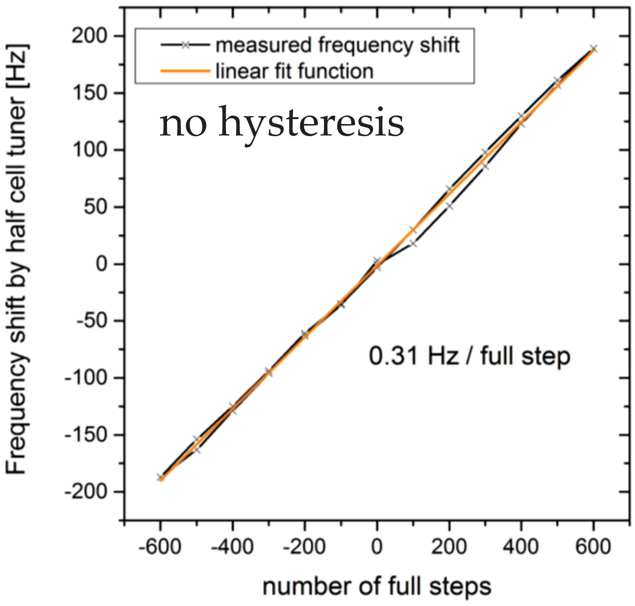

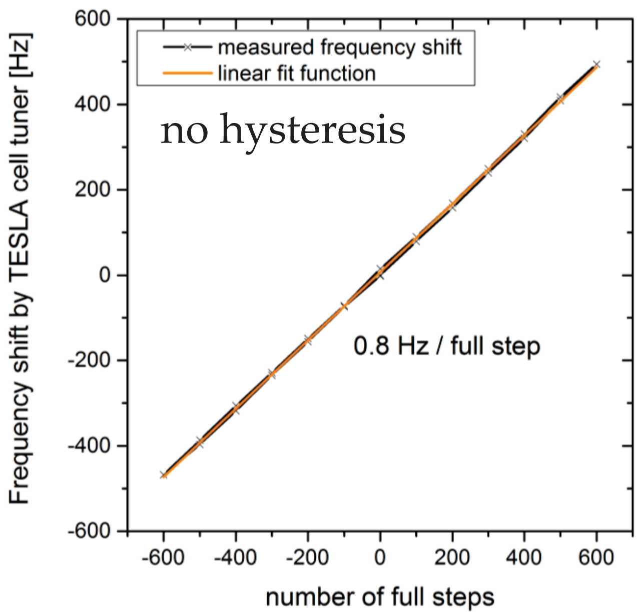

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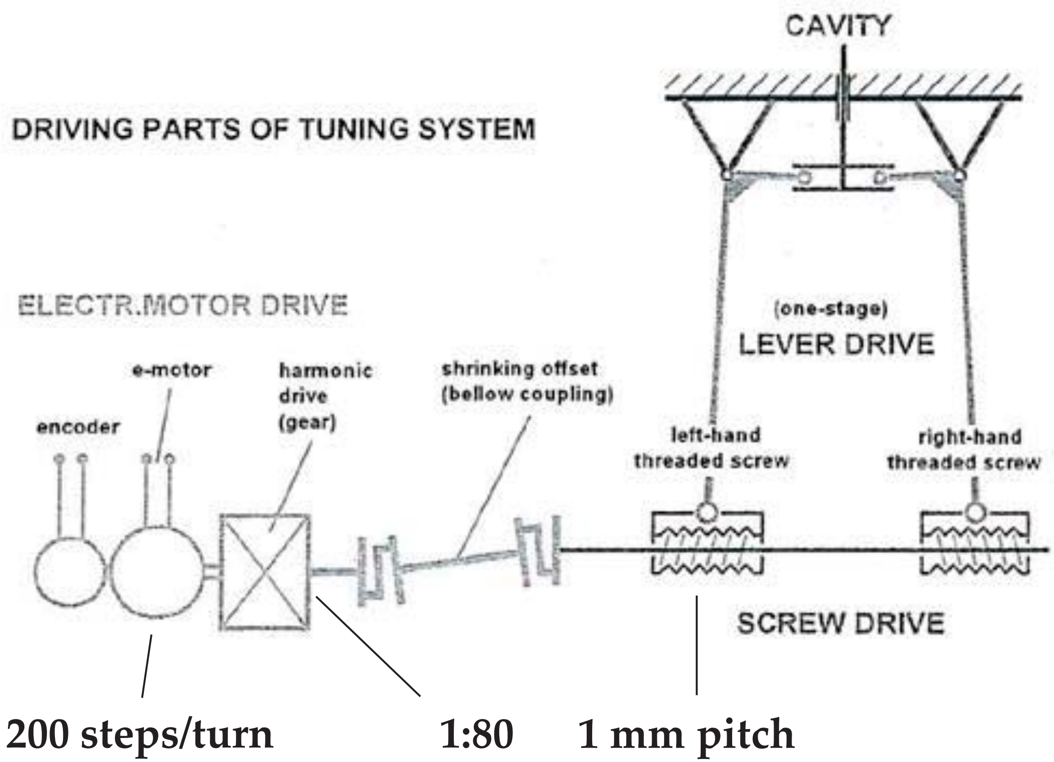

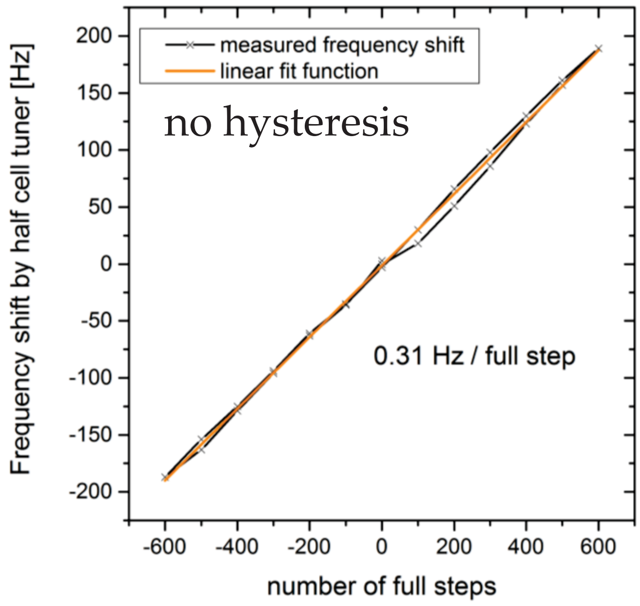

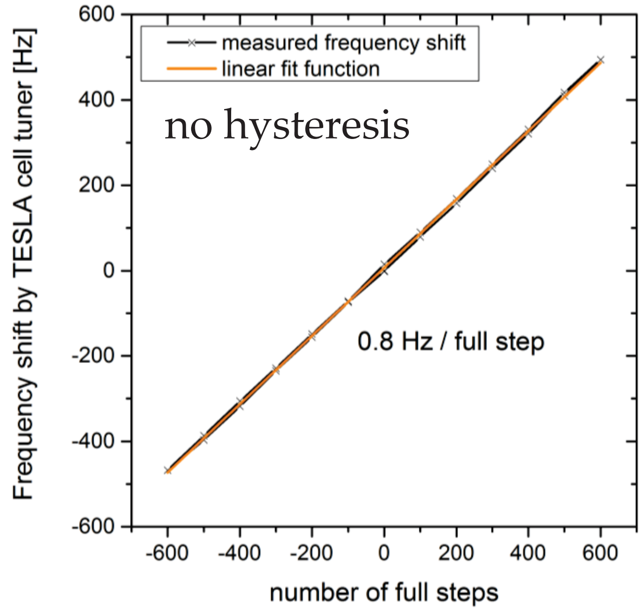

tuner parameter	unit	cold test	
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load path	mm	±0.30	±0.30
frequency const.	kHz/mm	257	650
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mech. resolution	nm/step	1.25	1.25
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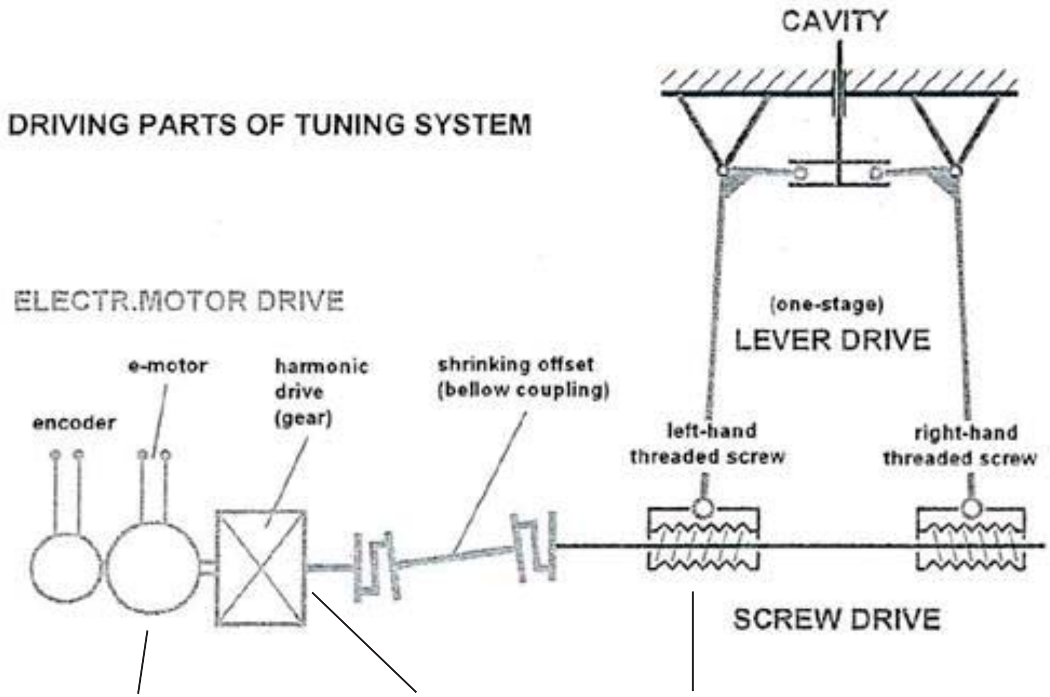

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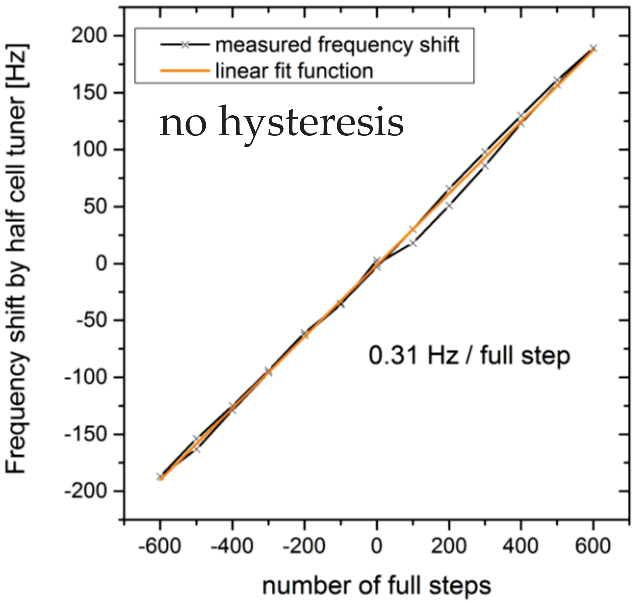

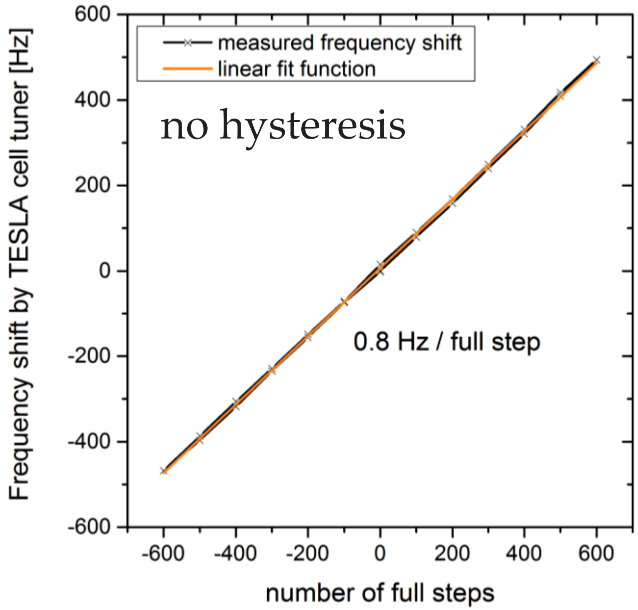

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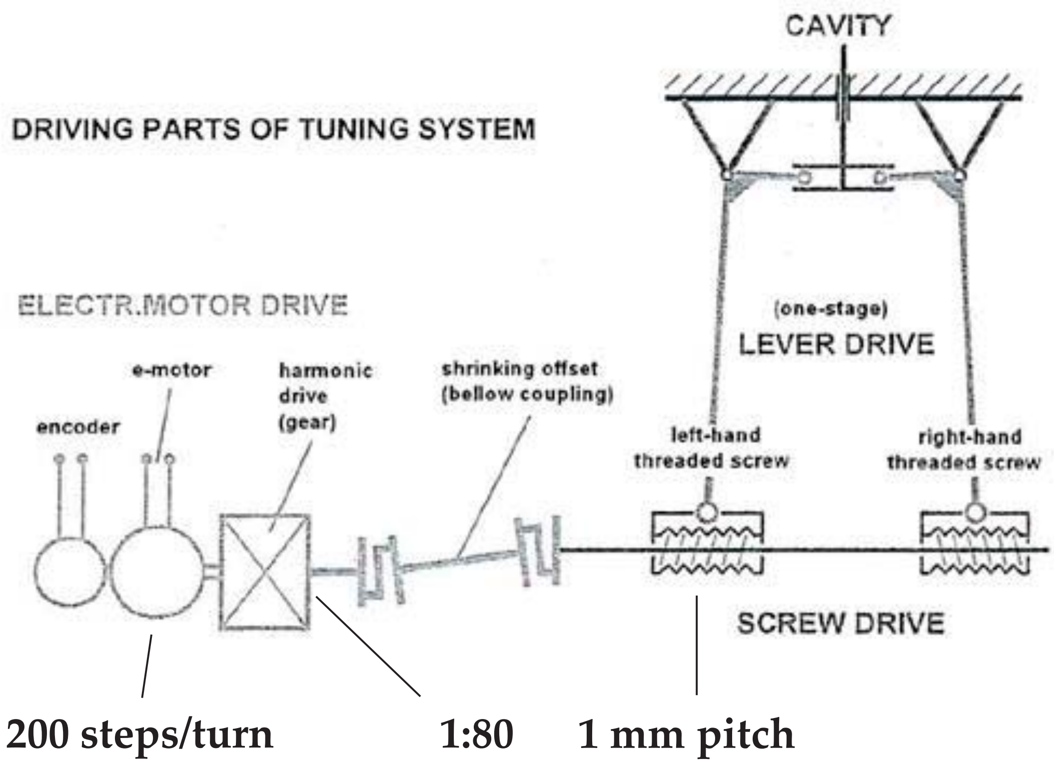

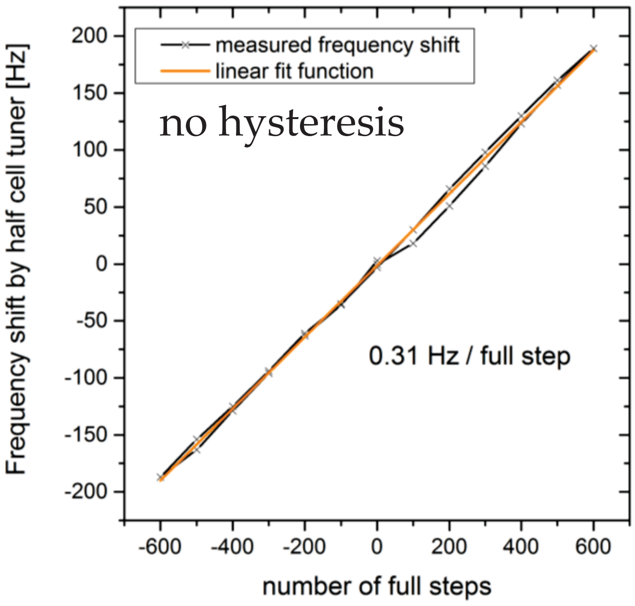

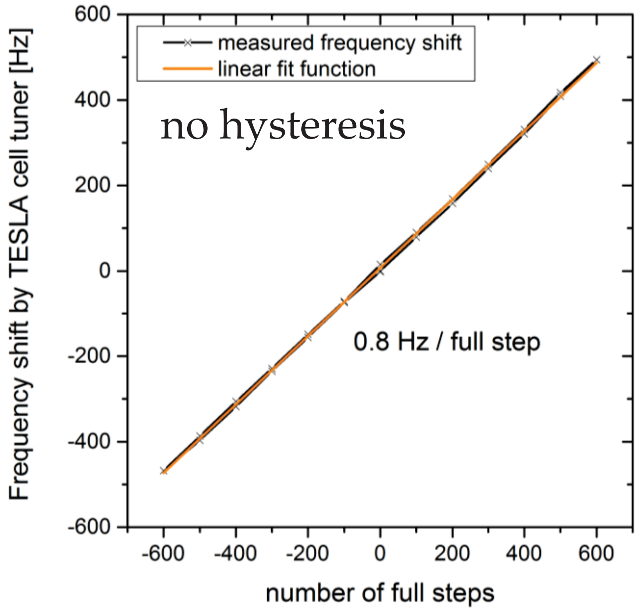

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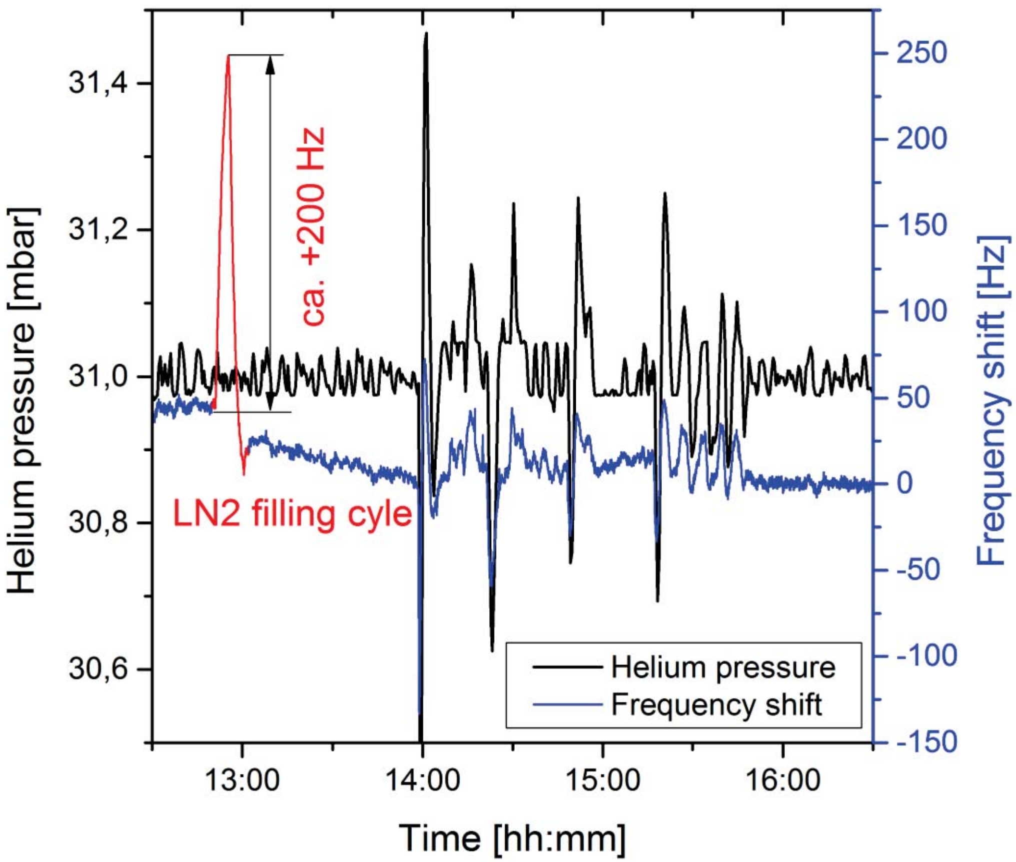
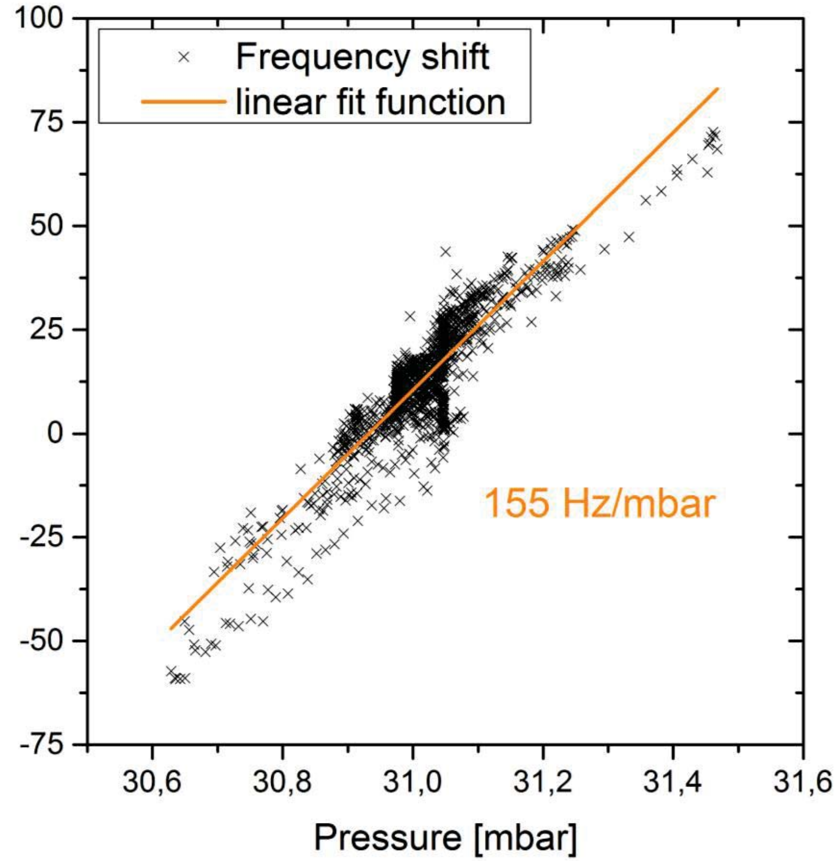
Pressure sensitivity





- **Pressure sensitivity relatively high** but because of high stability of helium machine (<0.1 mbar) not critical for stable RF operation
- Nevertheless, filling cycle of **LN2 shield cooling causes a frequency shift** of about 200 Hz, which needs to be compensated by automatic cavity tuning

DRESDEN concept HZDR

Closed loop microphonics

- Measurement of closed loop phase noise time signal
- Calculation and integration of PSD to separate main frequency components
- Calculation of total frequency detuning using BW, K_p and σ_{phase}

Parameters

- loop gain: 127
- bandwidth: 300 Hz
- gradient: 9 MV/m

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Results

- σ_{phase} = 0.02° (RMS)
- $\sigma_{frequency}$ = 6.6 Hz (RMS)

- main contributors:
  10 Hz, 24 Hz (pumps)
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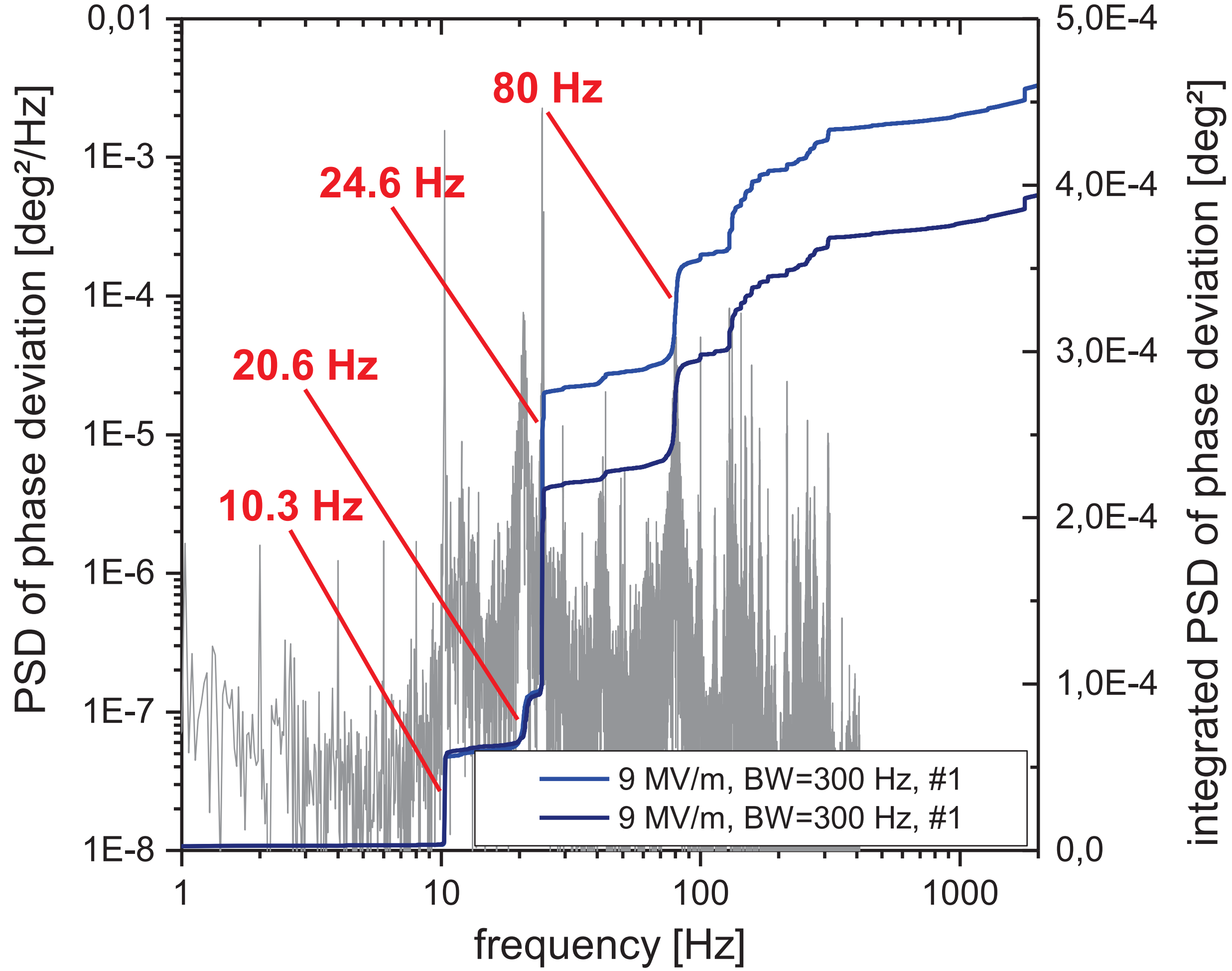

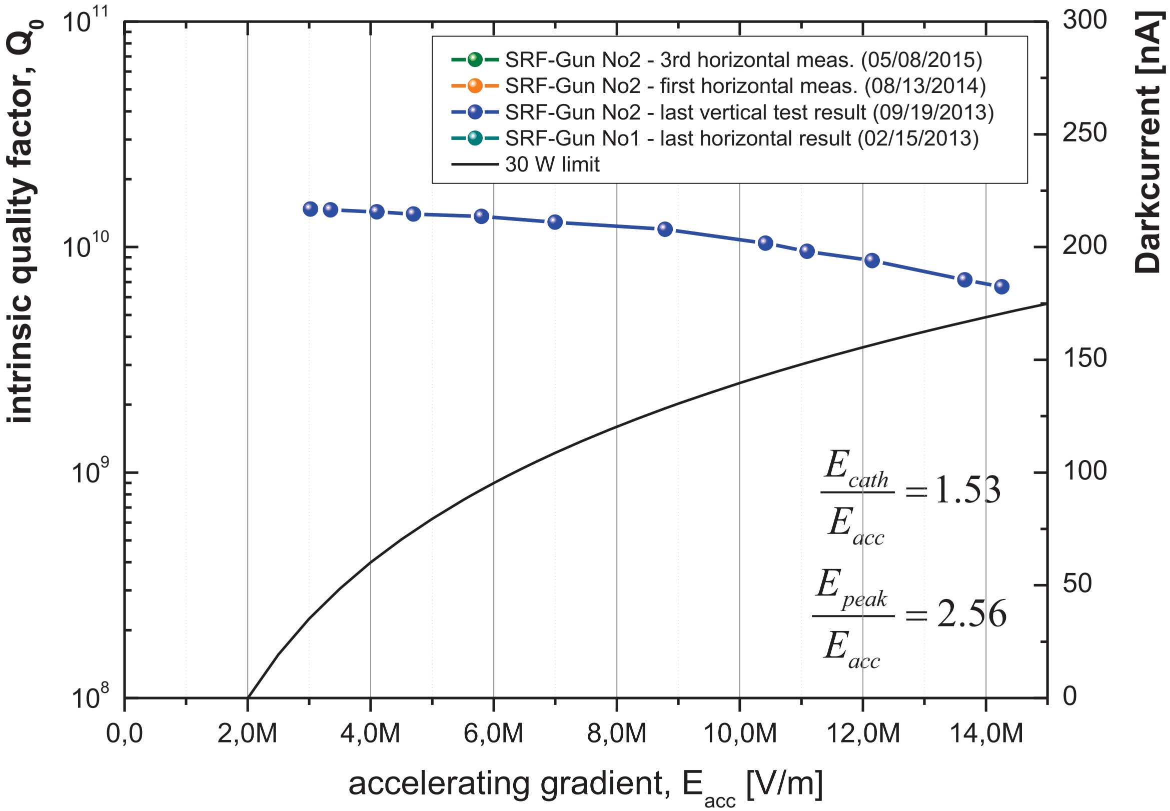

Formulas:

$$E_{acc} = \frac{1}{L}\sqrt{2 r_s Q_t P_t}$$

$$E_{acc} \overset{\beta\,\square\,1}{=} \frac{1}{L}\sqrt{2 r_s Q_L 4 P_i}$$

$$Q_0 = \frac{Q_t P_t}{P_d}$$

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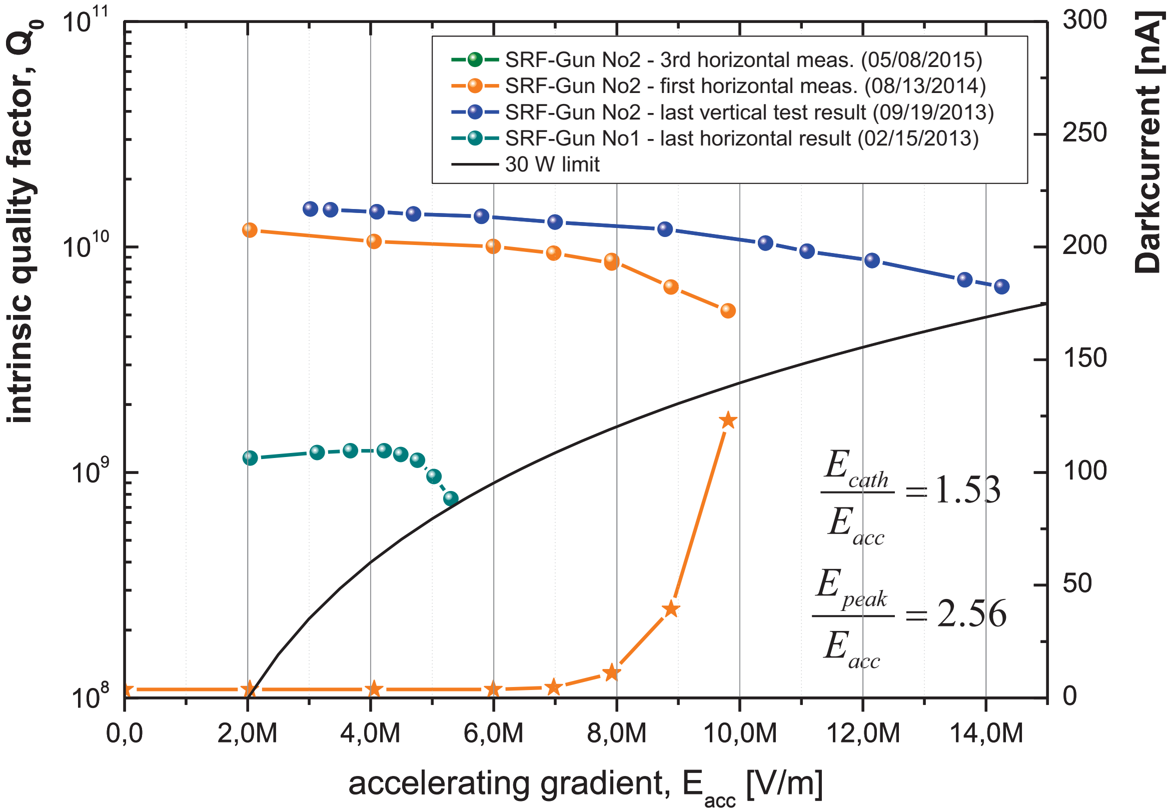
Q_0 vs E_{acc}



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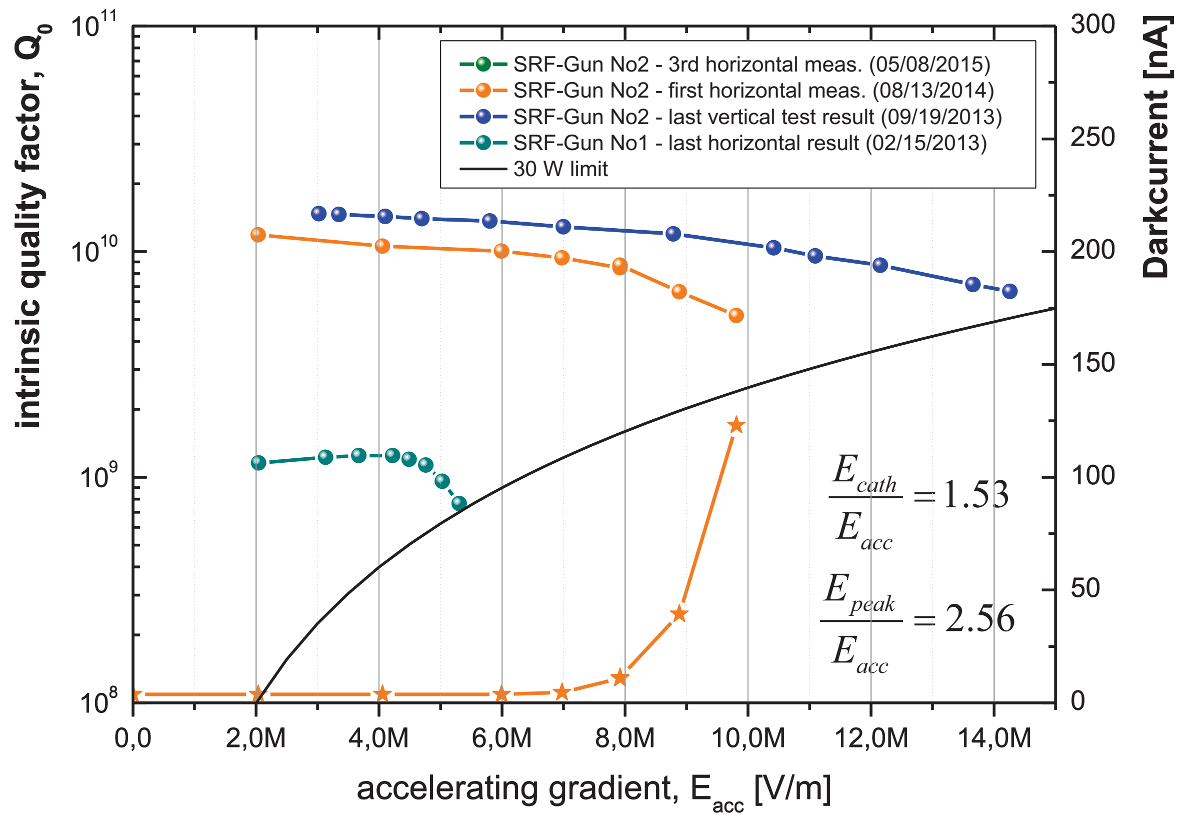

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- both quantities were determined independently by measuring P_i and P_d or P_t and P_d
- **30% performance loss** compared to the last vertical test, but twice the gradient of SRF gun I
- no further degradation after Cu cathode transfer **but tremendous loss with Cs_2Te cathode**

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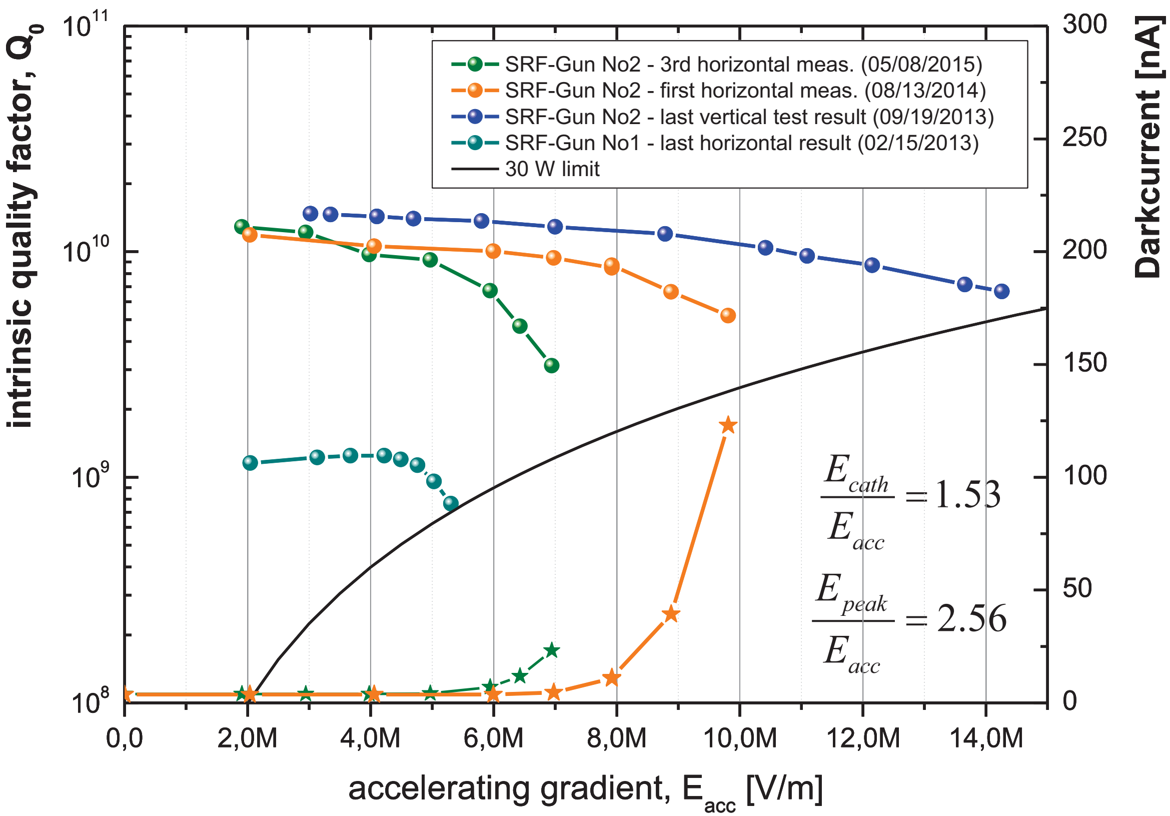

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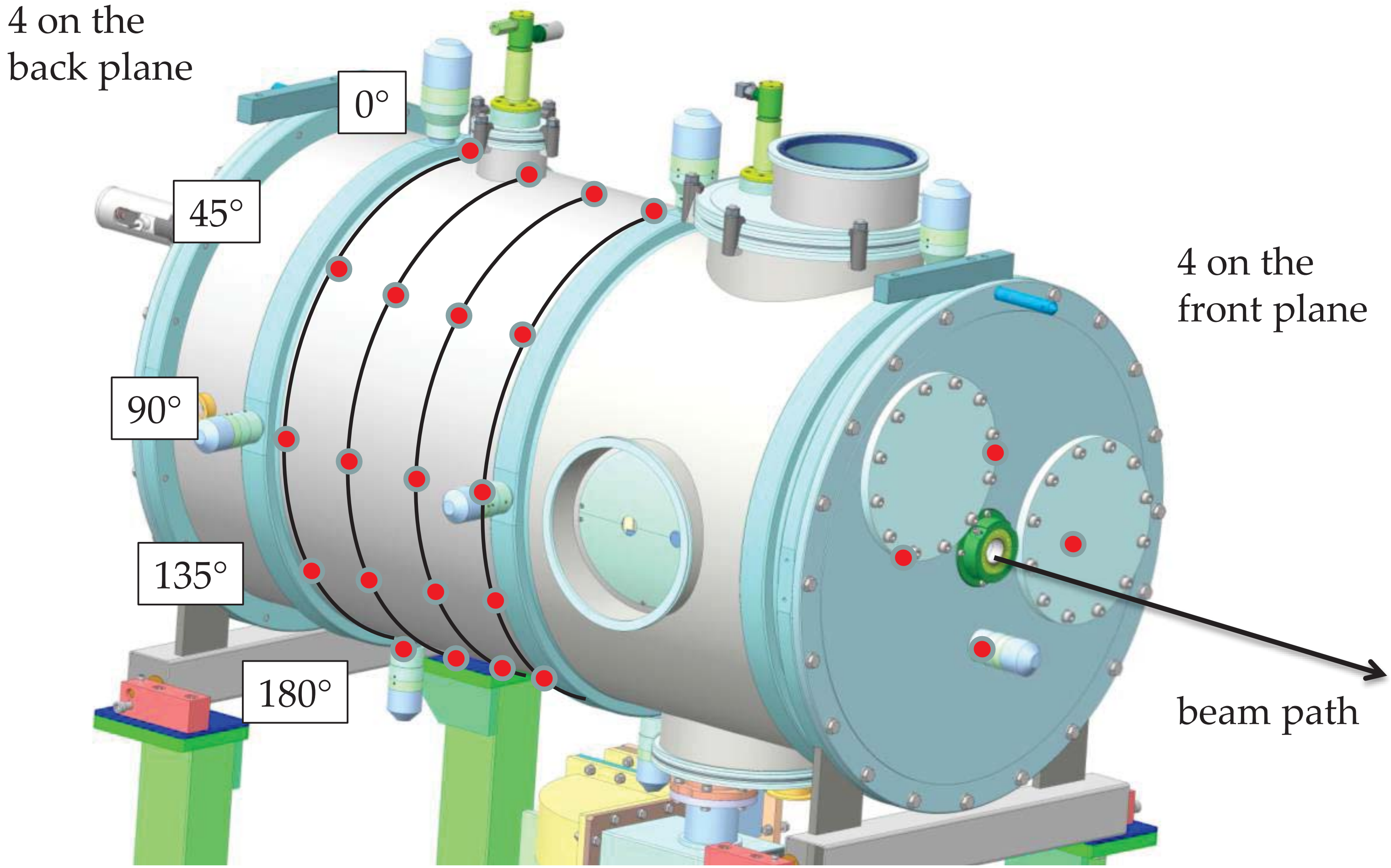
Analysing spatial distribution of radiation

- 40 OSL (Optically Stimulated Luminescence) dosimeters around the cryostat
- 8 at the circumference of each cavity cell, 4 on the front, 4 on the back plane
- exposed 90 min at 7.1 MV/m (maximum gradient)



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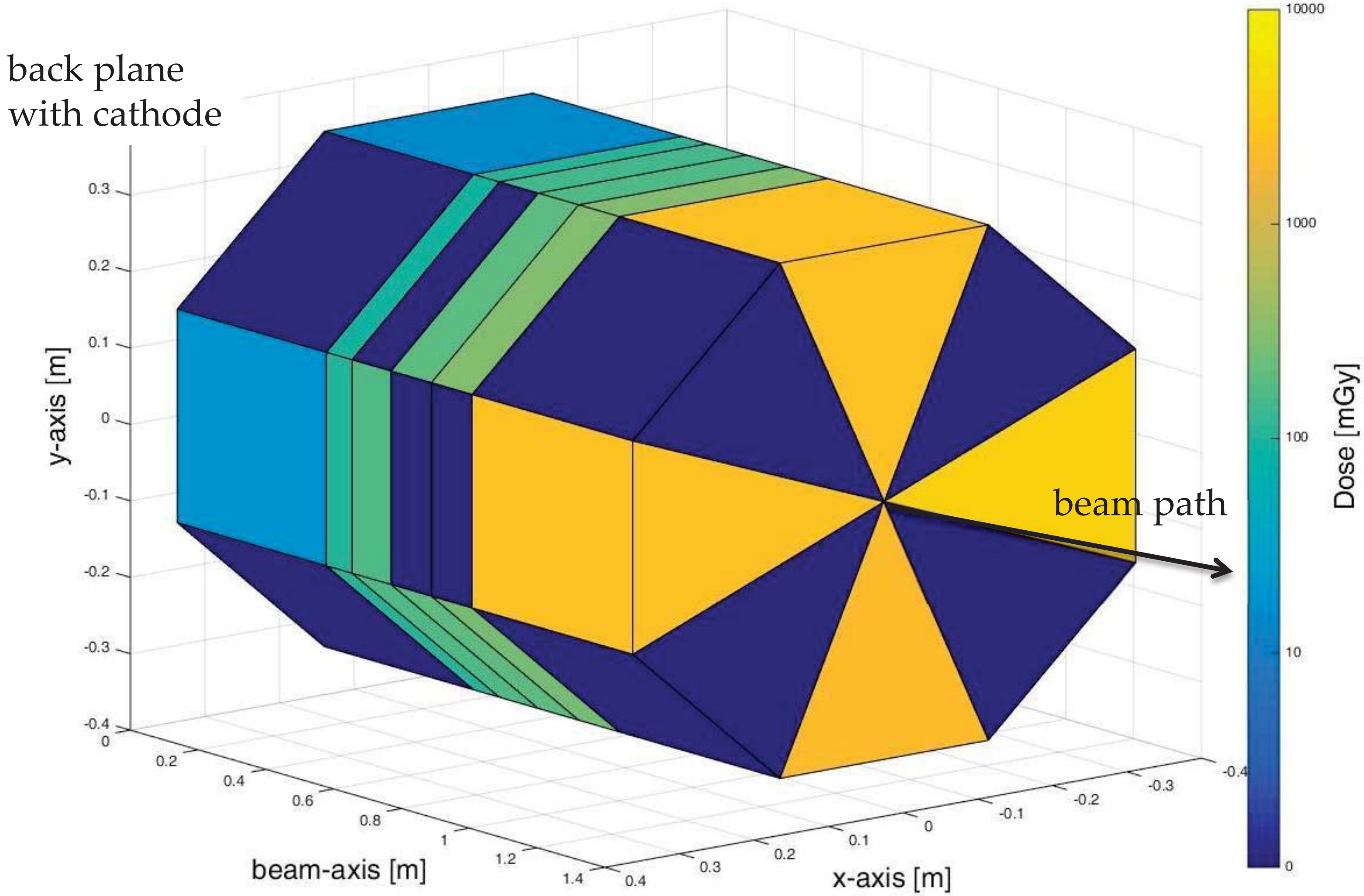

QvsE in each cell for all modes

- external quality factor of the pickup antenna for all 4 TM_{010} passband modes

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f_0 [MHz]	1267.677	1282.792	1294.764	1300.000
Tau [ms]	140.4	2.38	1.17	2.2
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	¼ Pi	½ Pi	¾ Pi	Pi
f_0 [MHz]	1267.677	1282.792	1294.764	1300.000
Tau [ms]	140.4	2.38	1.17	2.2
BW [Hz]	2.3	133	272	145
Q_t	1.91E13	2.94E11	1.424E11	2.58E11

- peak electric field in each cell

$$E_{\text{cell}}^{\text{mode}} = k_{\text{cell}}^{\text{mode}} \sqrt{U}$$

- proportional constant from simulation

$$\left[k_{\text{cell}}^{\text{mode}} \right] = \left(\text{MV/m} \right) J^{-1/2}$$

$$Q_0 = \frac{f_0}{BW} \frac{4\beta_{in}}{\beta_{in} + 1} \frac{P_i}{P_d} \quad \text{or} \quad Q_0 = \frac{Q_t P_t}{P_d}$$

QvsE in each cell for all modes

- external quality factor of the pickup antenna for all 4 TM_{010} passband modes

$$Q_t = \left(\frac{1}{\beta_{out}} + \frac{\beta_{in}}{\beta_{out}} + 1 \right) \frac{f_0}{BW} \quad \text{with} \quad \beta_{in} = (S_{11}+1)^2 \frac{P_i}{P_d} \; ; \; \beta_{out} = \frac{P_t}{P_d}$$

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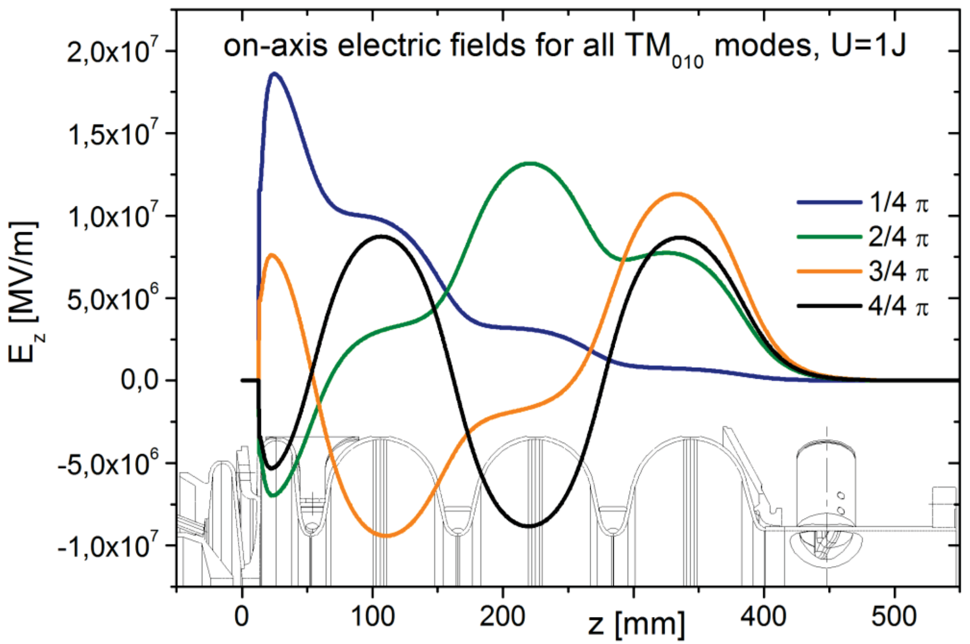

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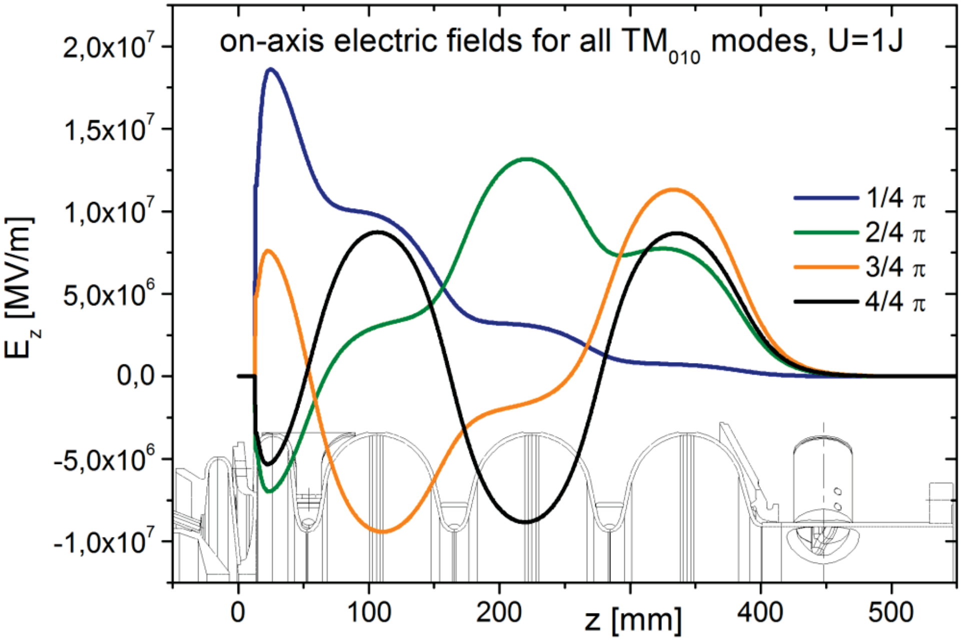

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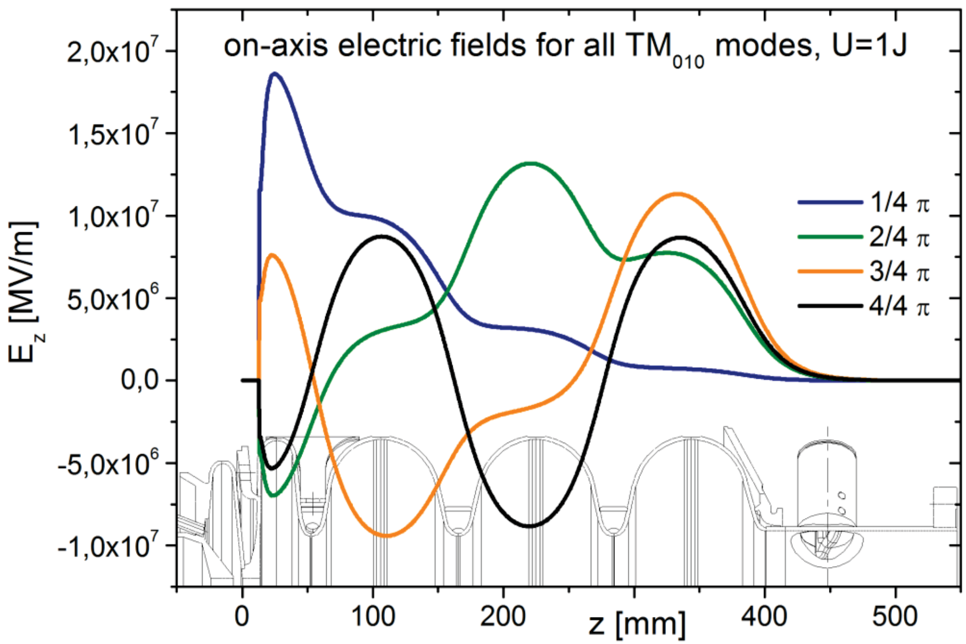

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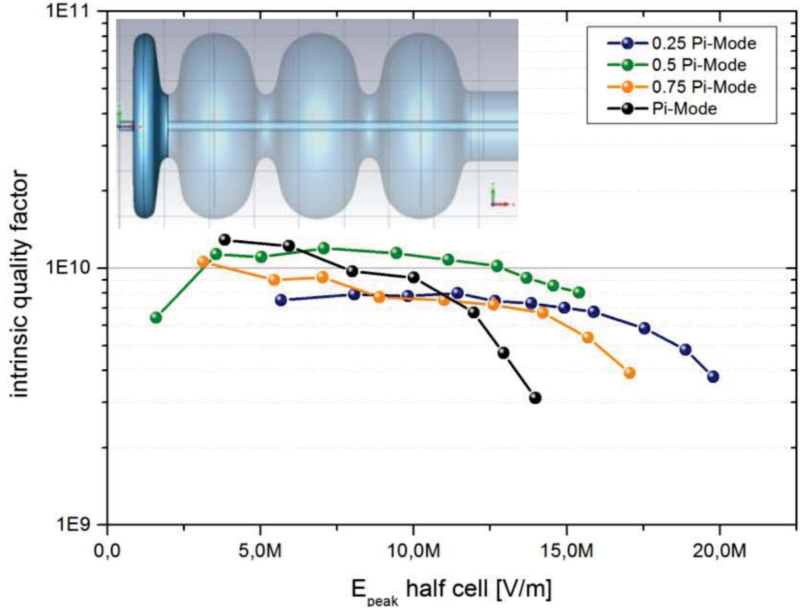

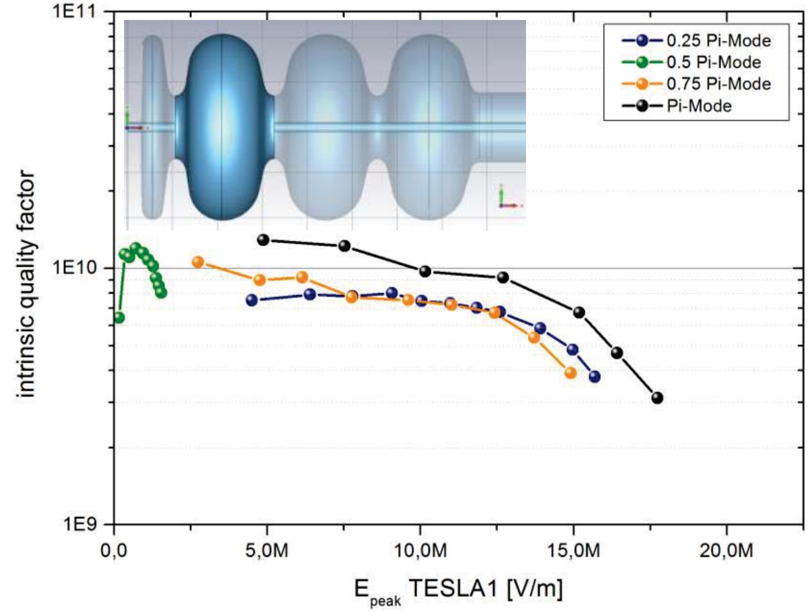

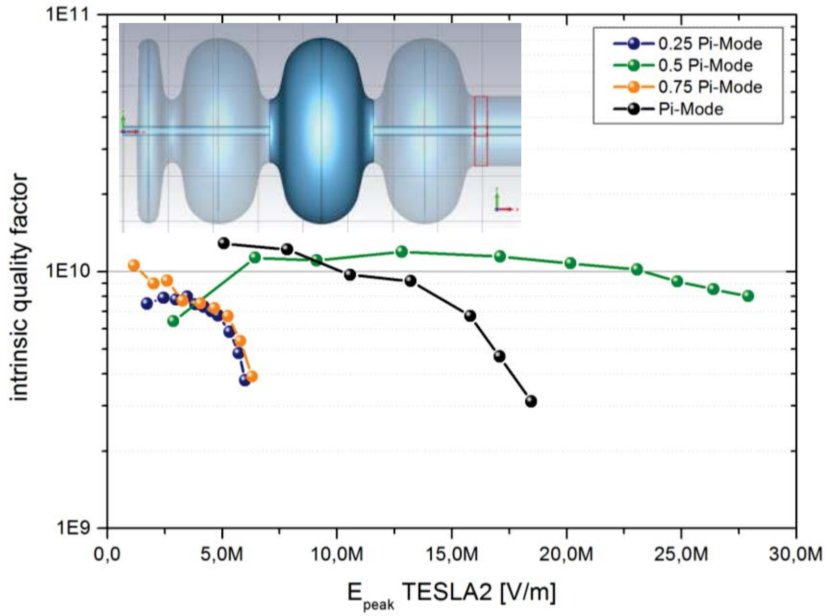

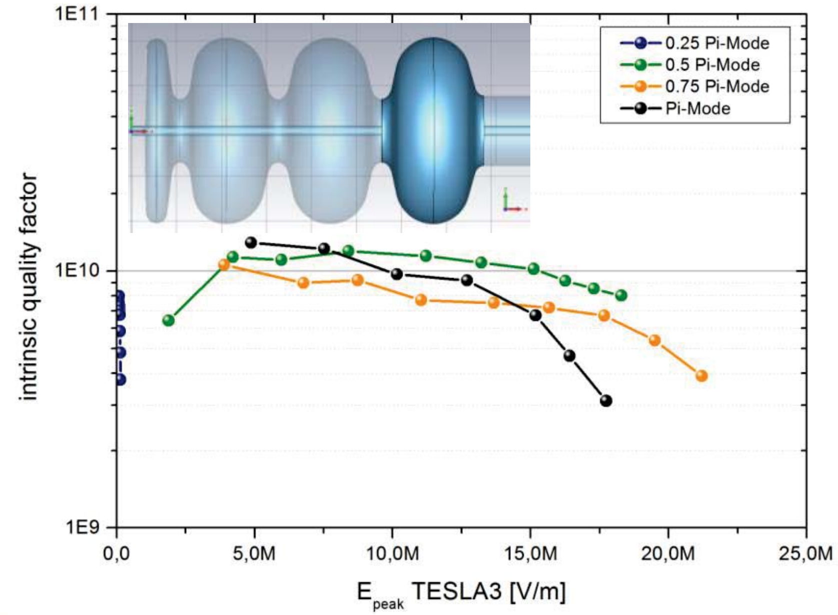

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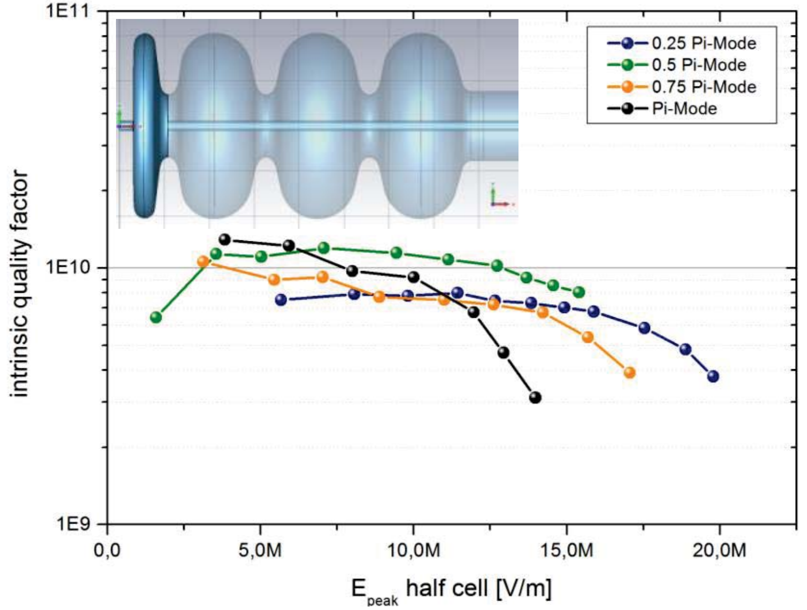
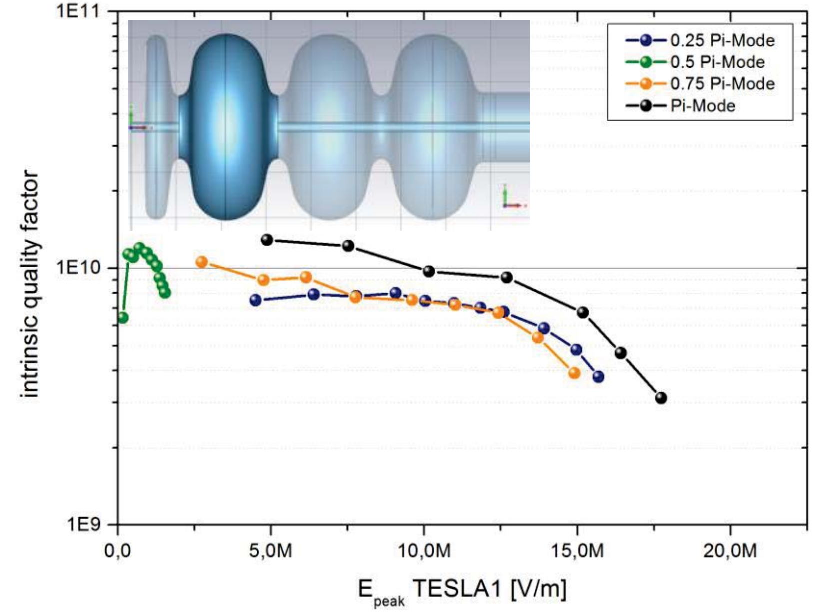
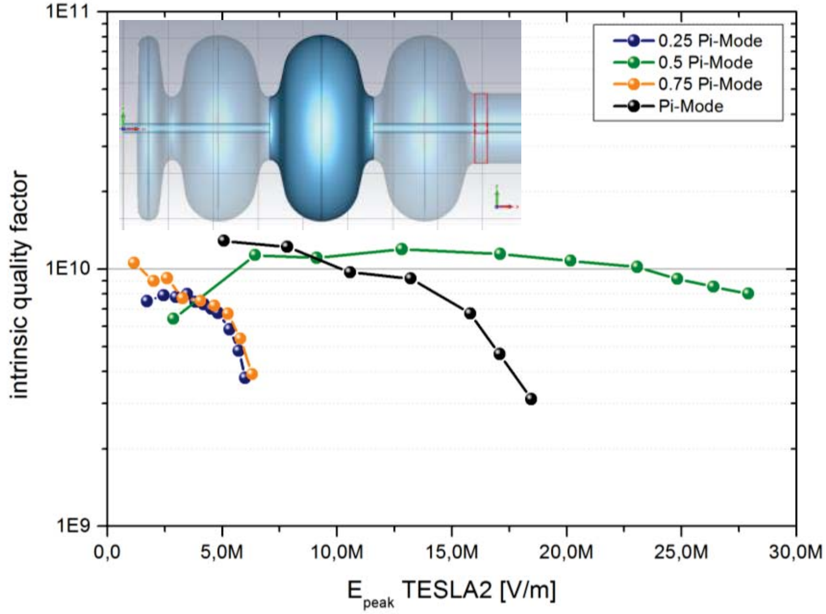
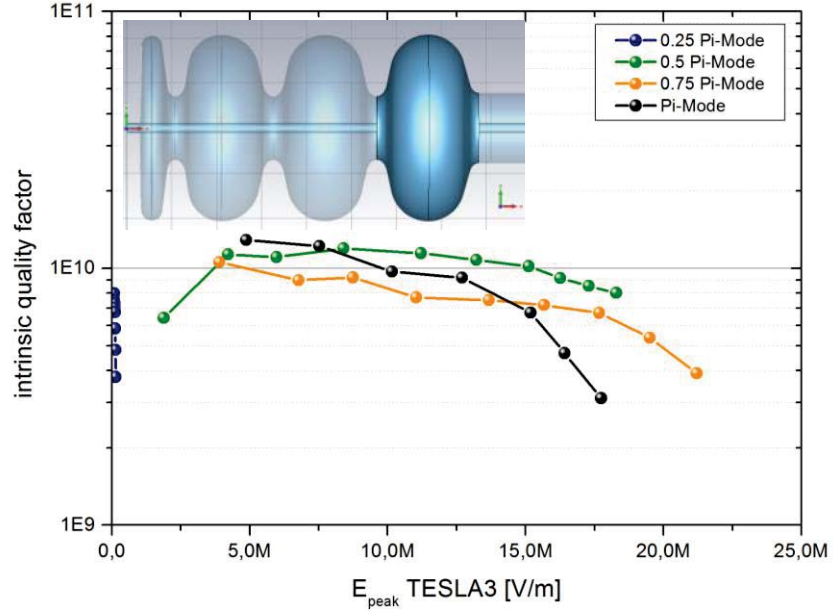
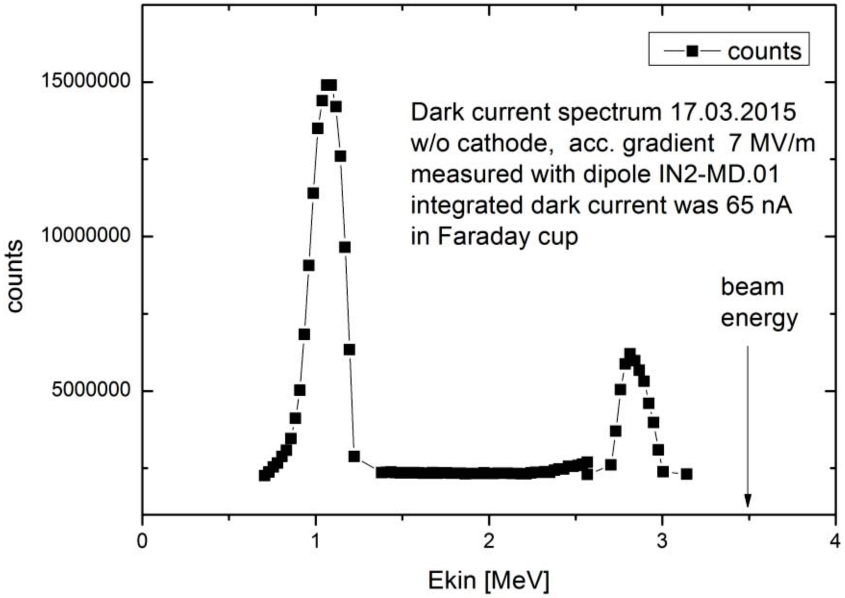








Dark current analysis



Dark current analysis

- measurement of the energy spectra of the dark current before (1.0 MeV and 2.8 MeV)
- and after high power pulsed RF processing (only 2.8 MeV and 1/3 of total current)
- photo beam energy is 3.6 MeV

- to identify origin of electrons, energy spectra is simulated for different emission points
- circle source at the inner cavity surface is moved along the z-axis
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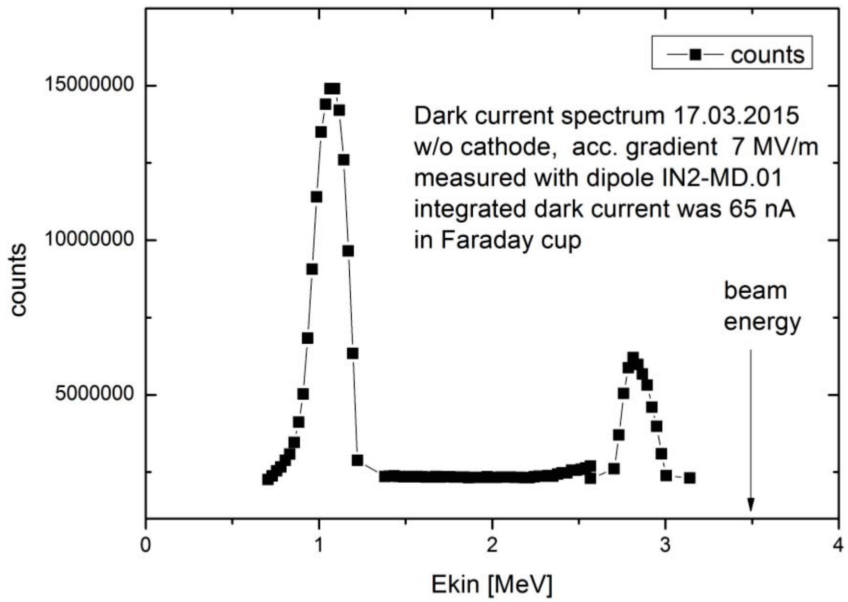
- particle monitor at beam exit counts electrons



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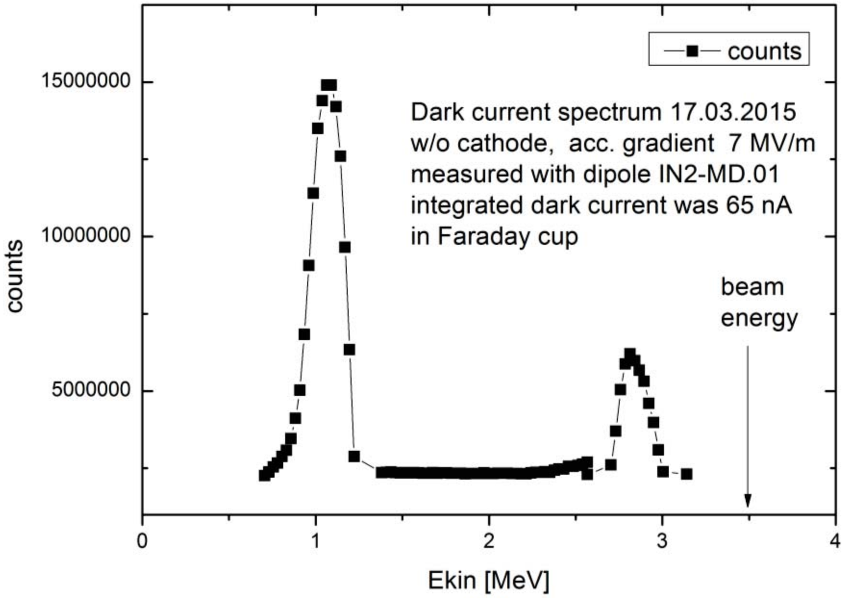

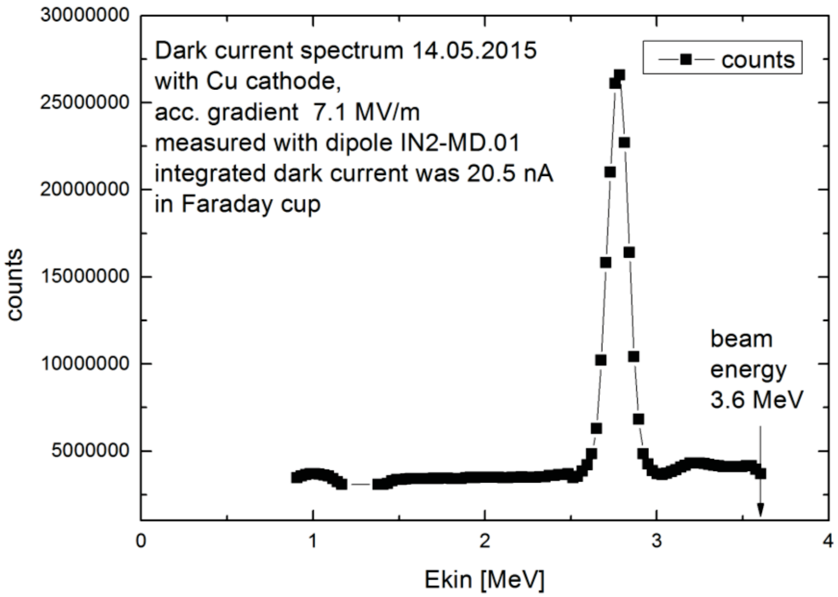

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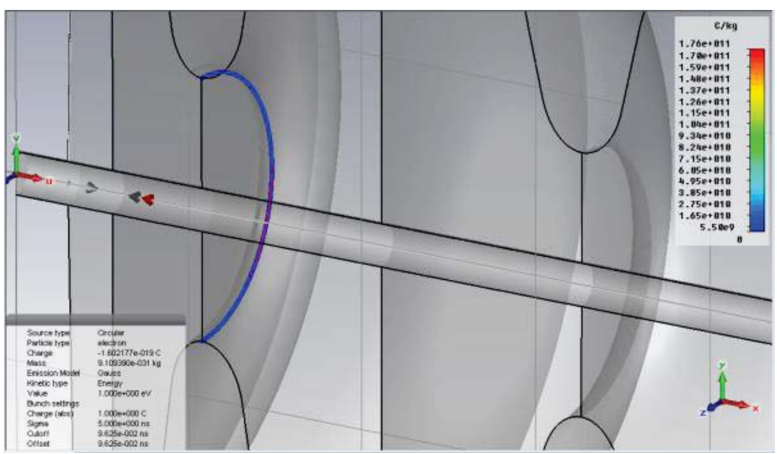

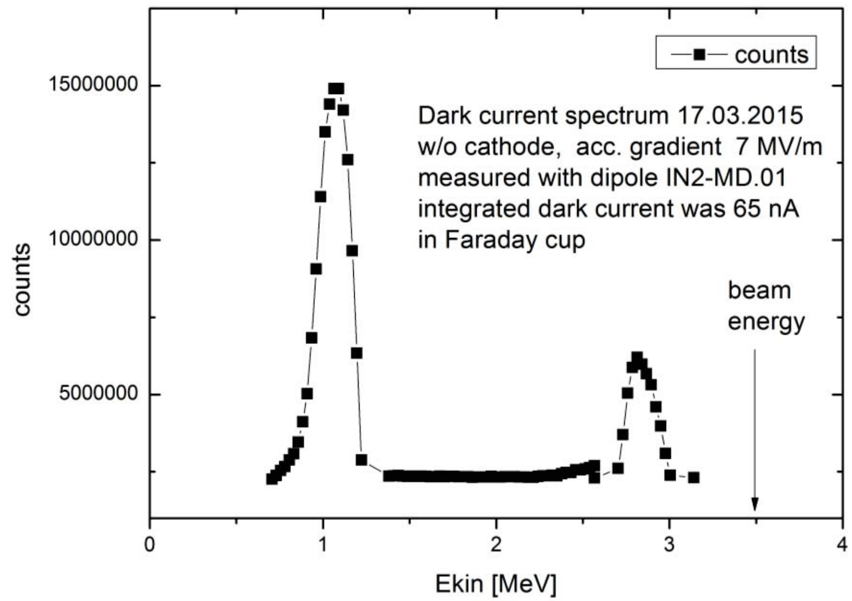

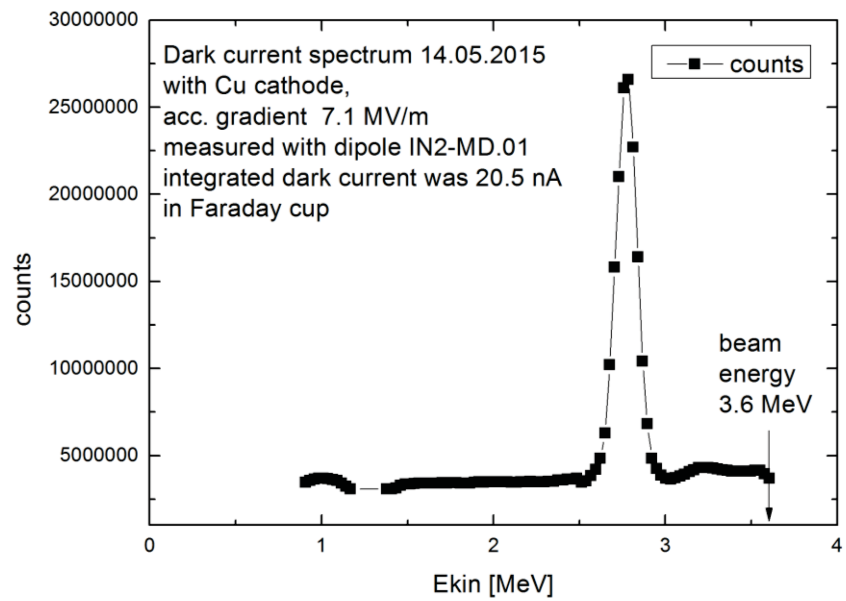

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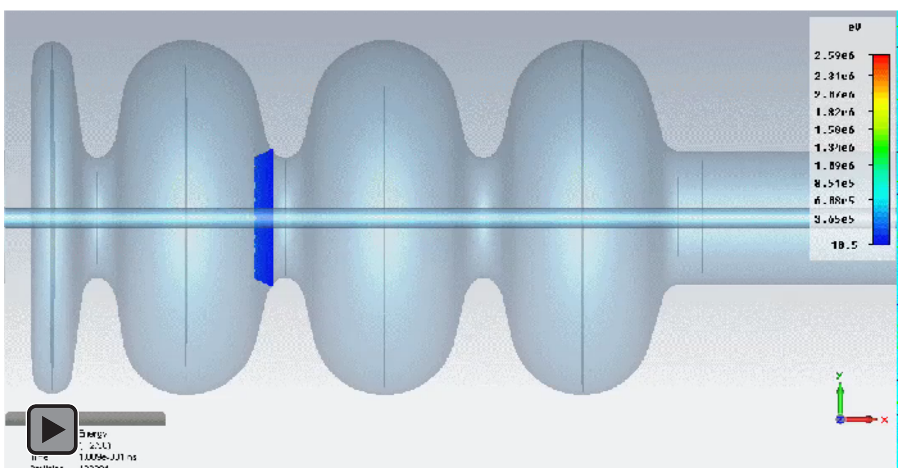

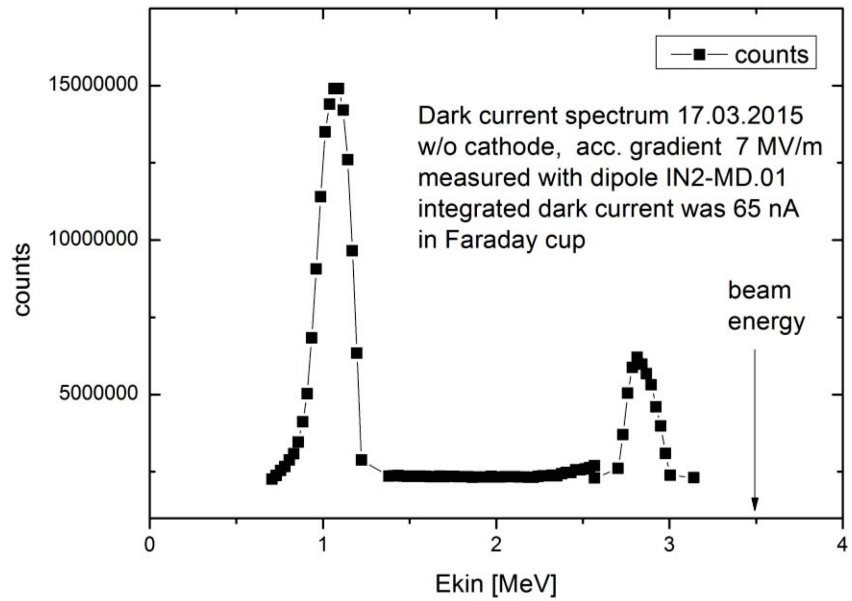

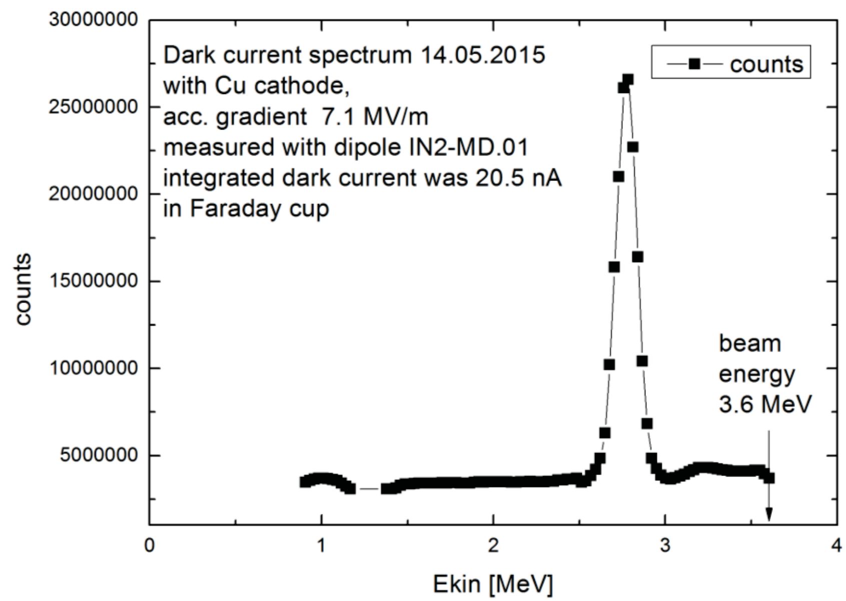

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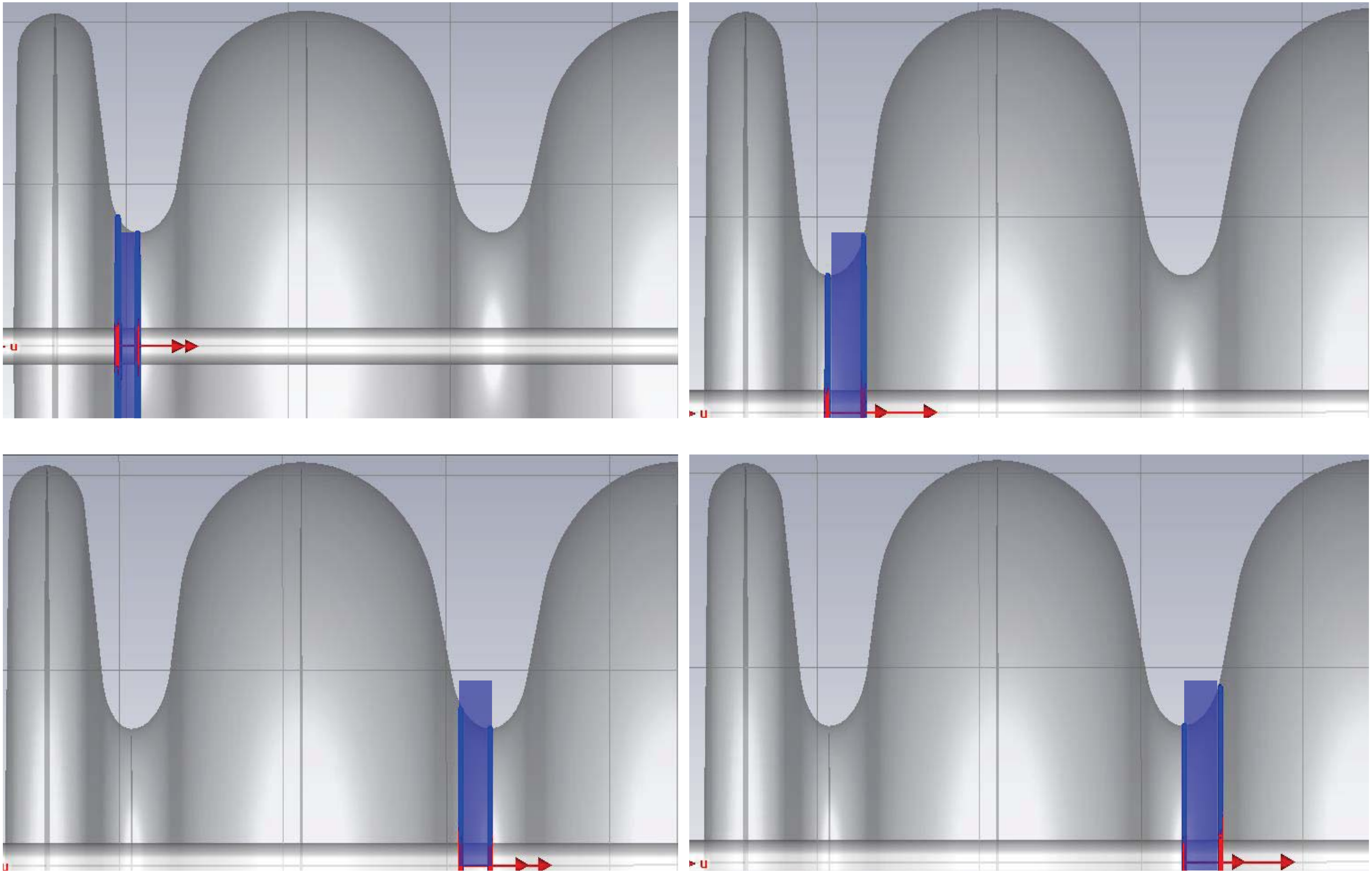

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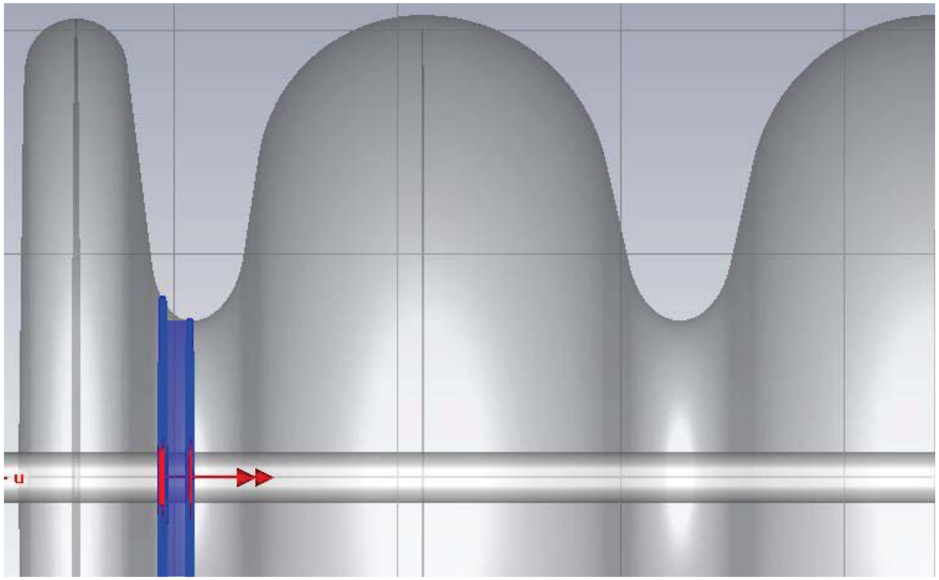

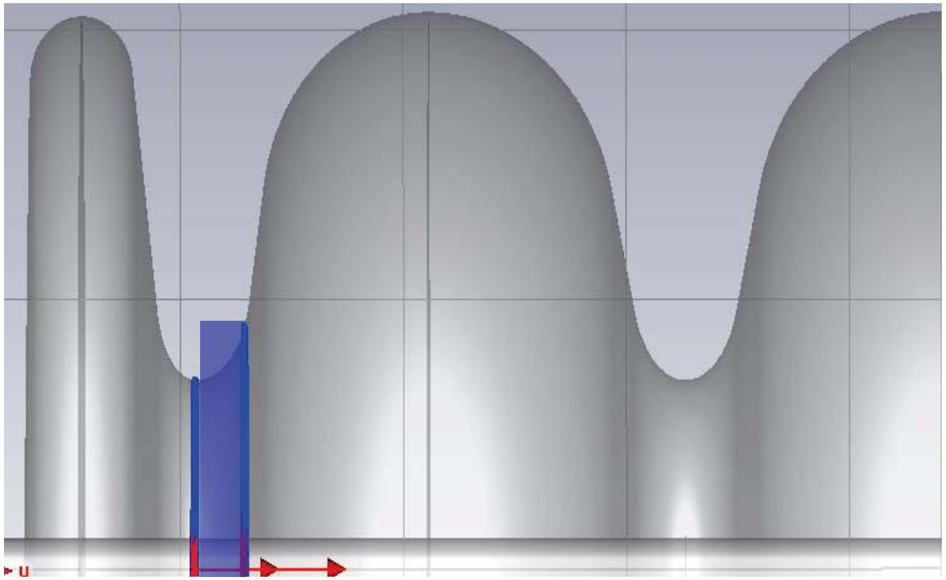

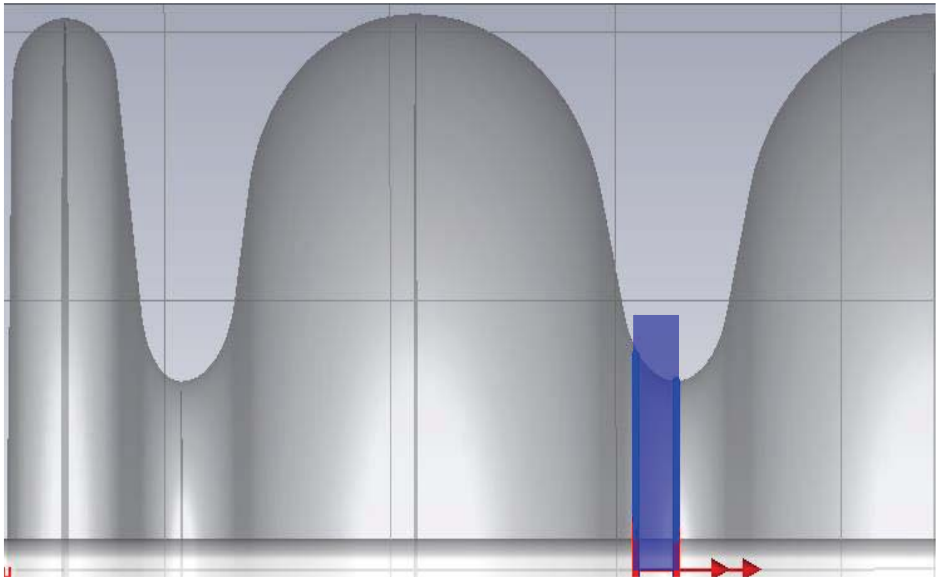

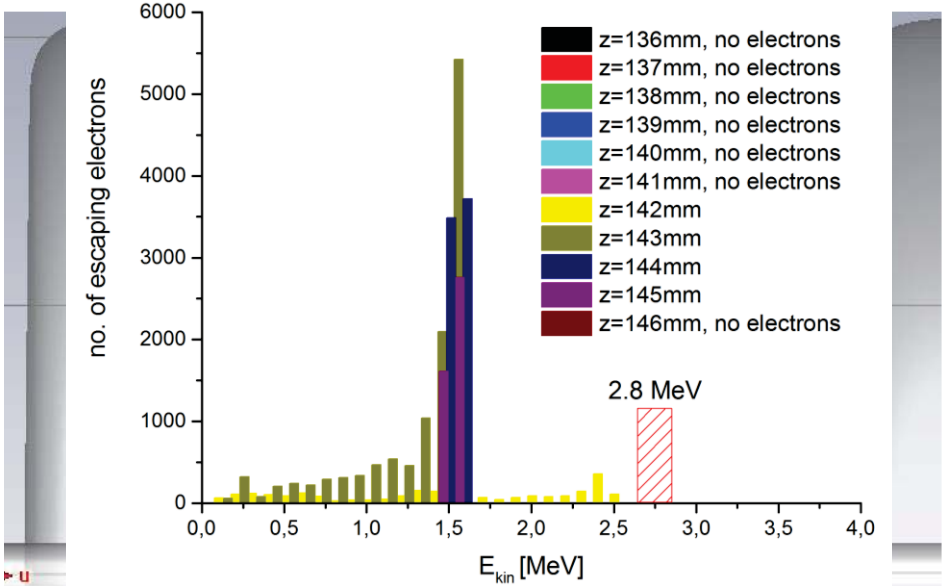

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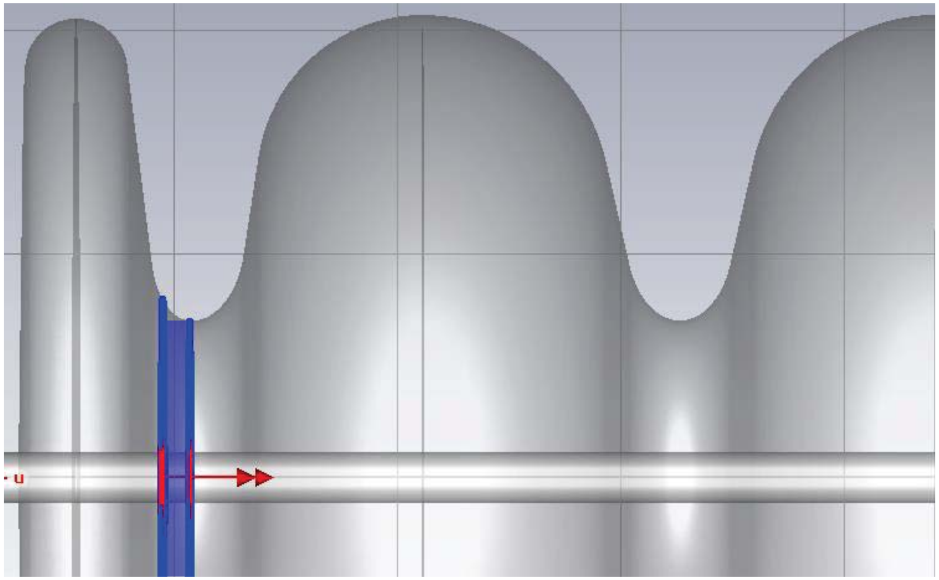

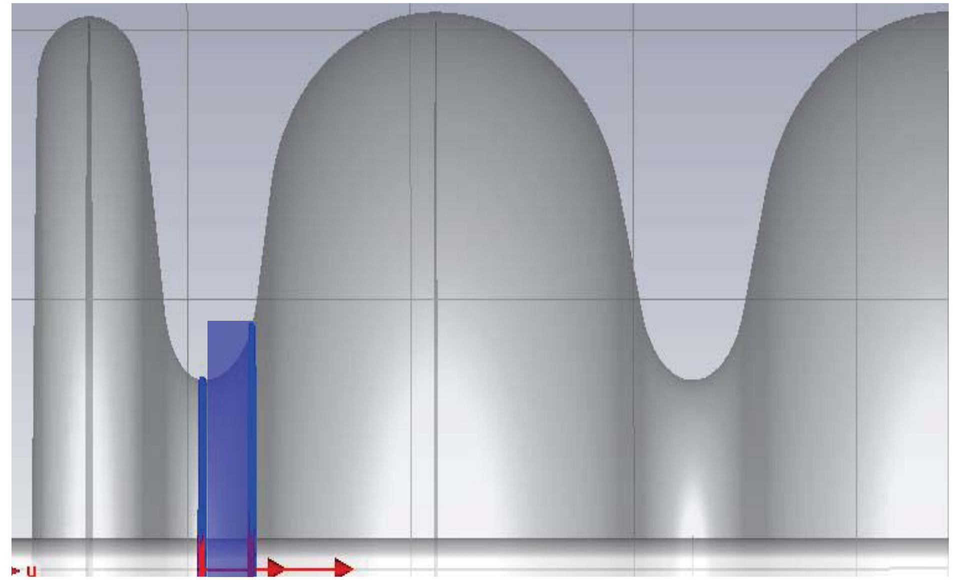

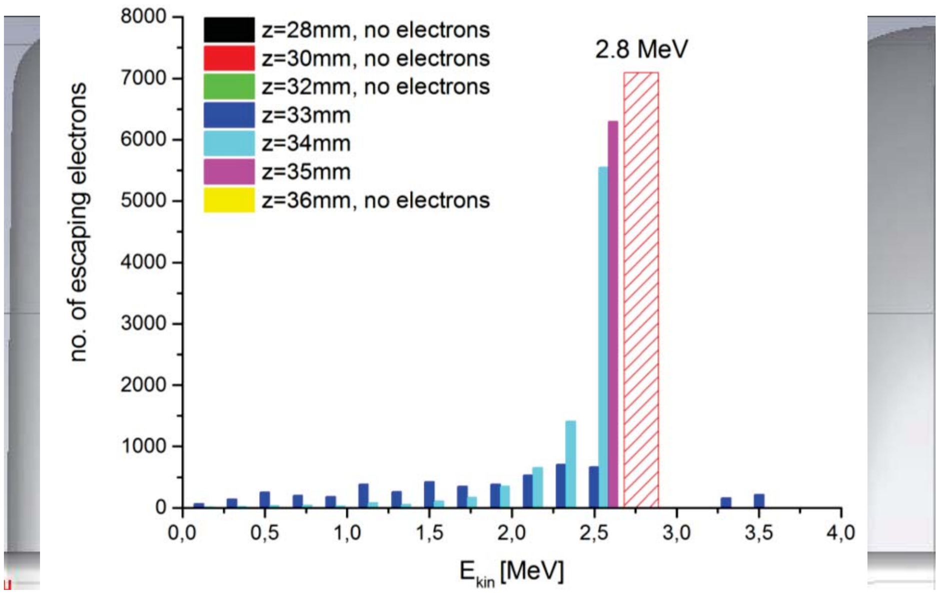

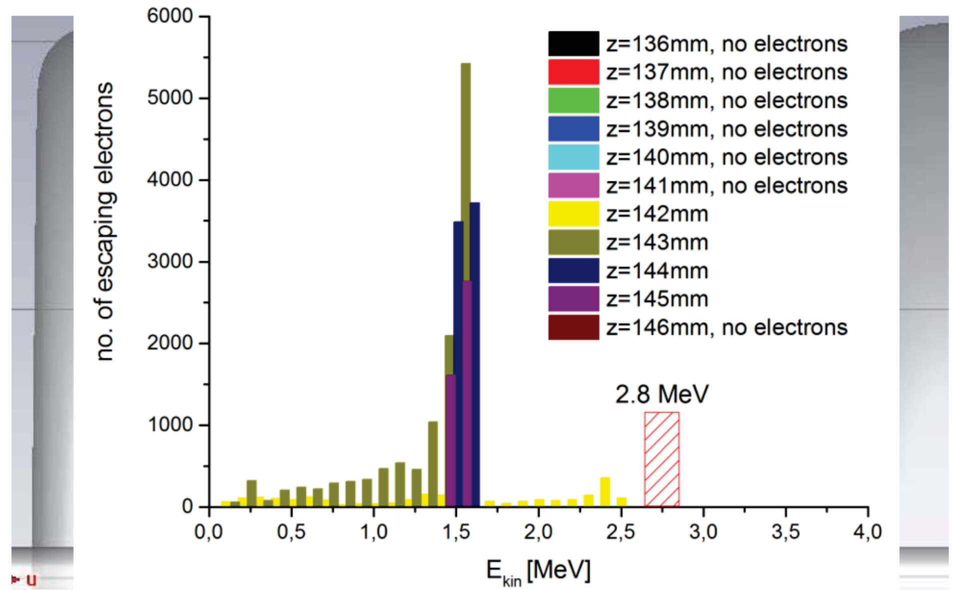

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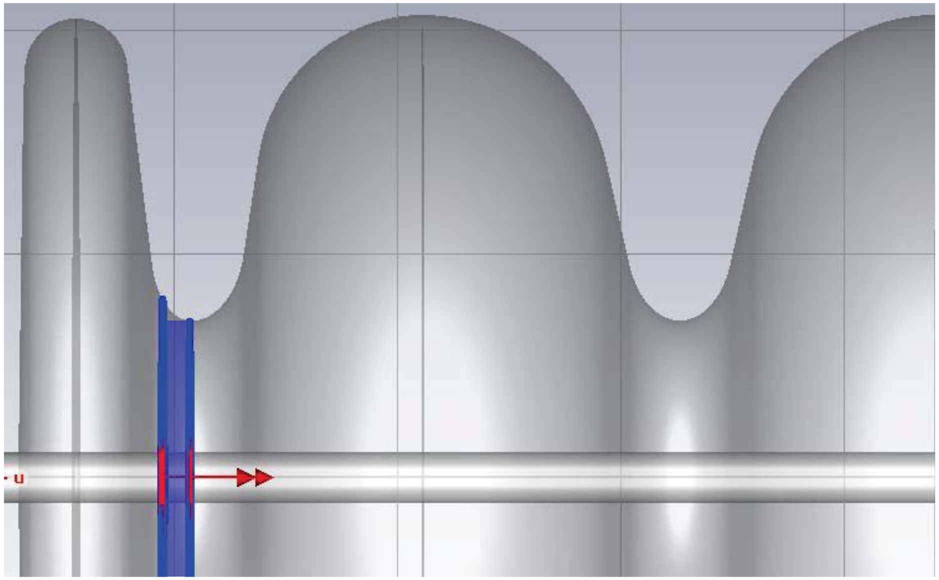

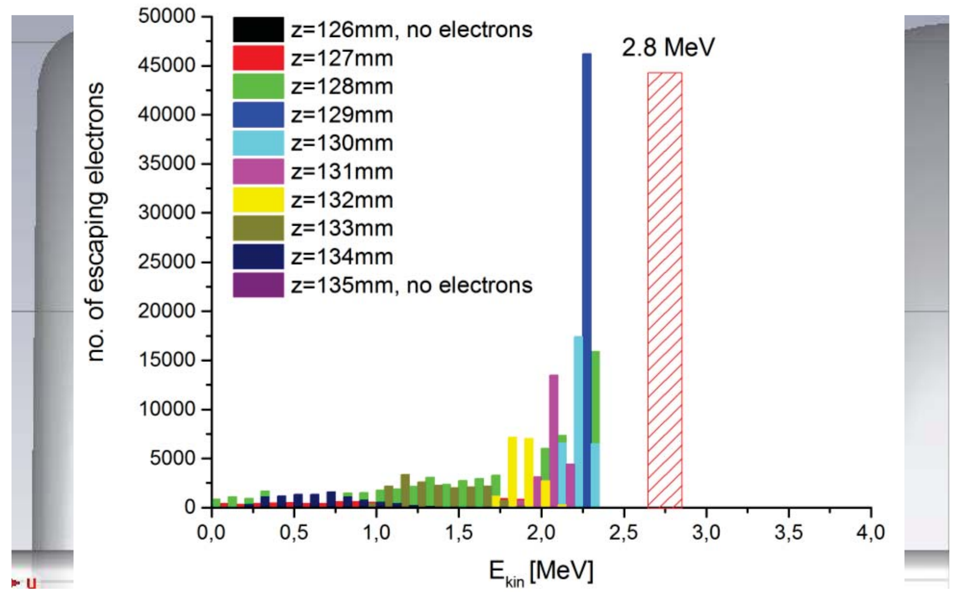

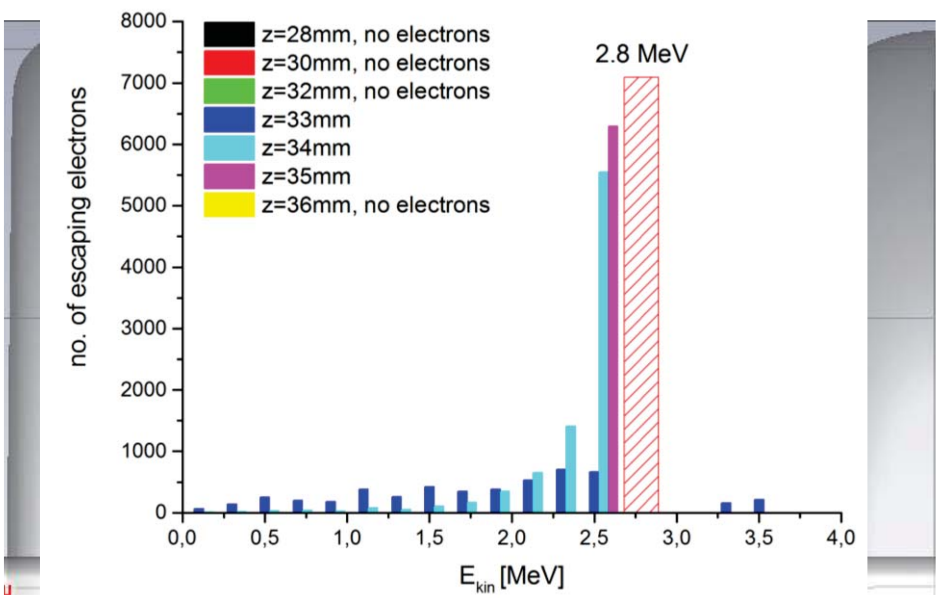

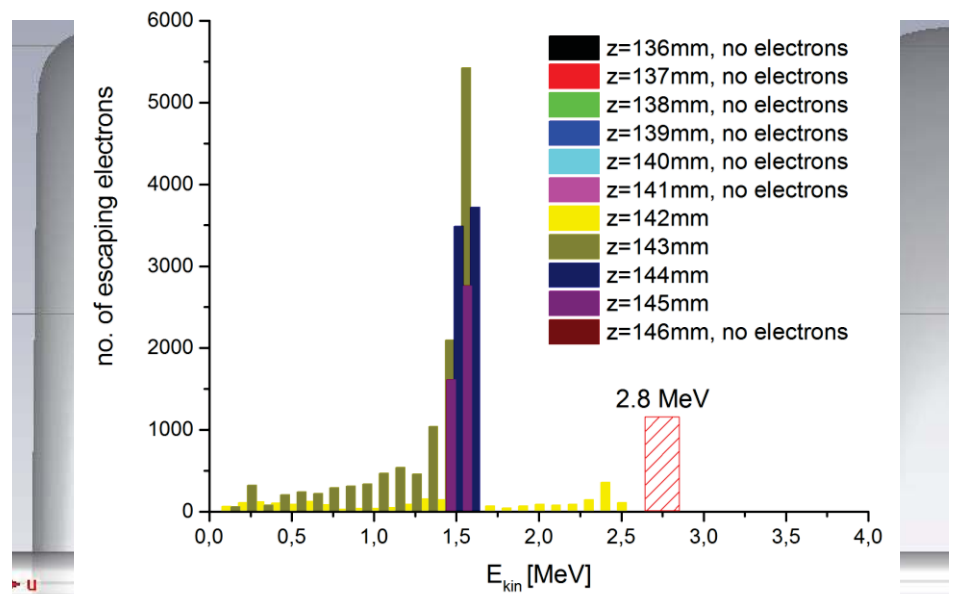

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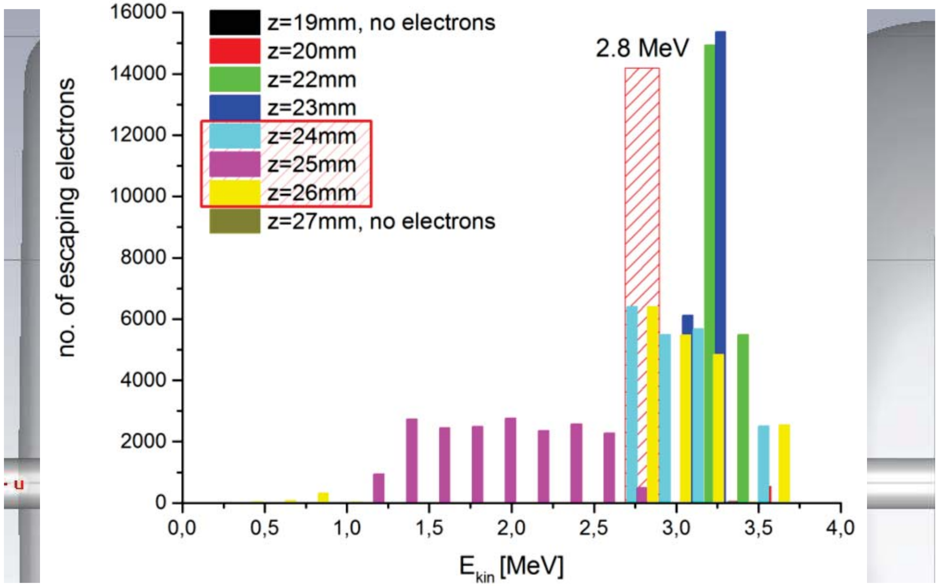

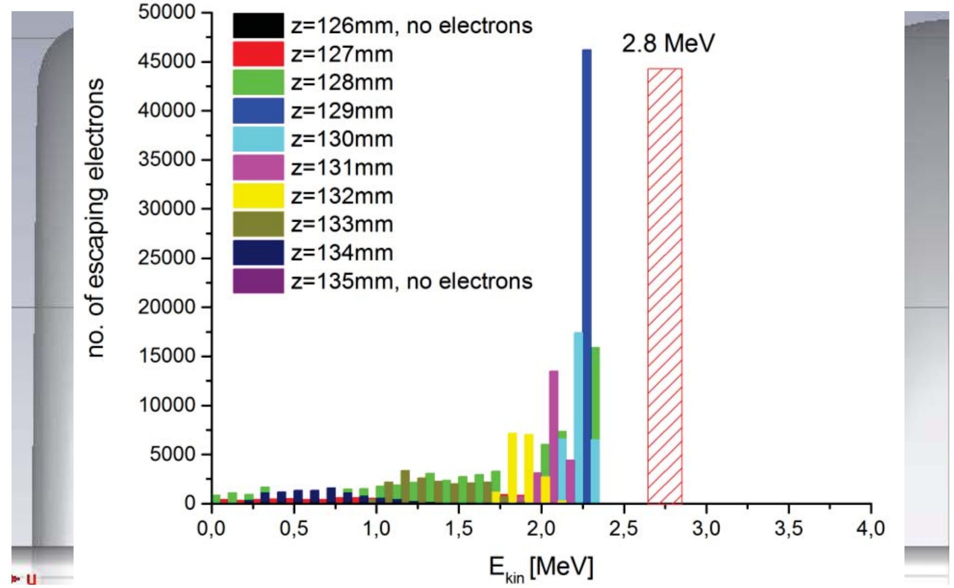

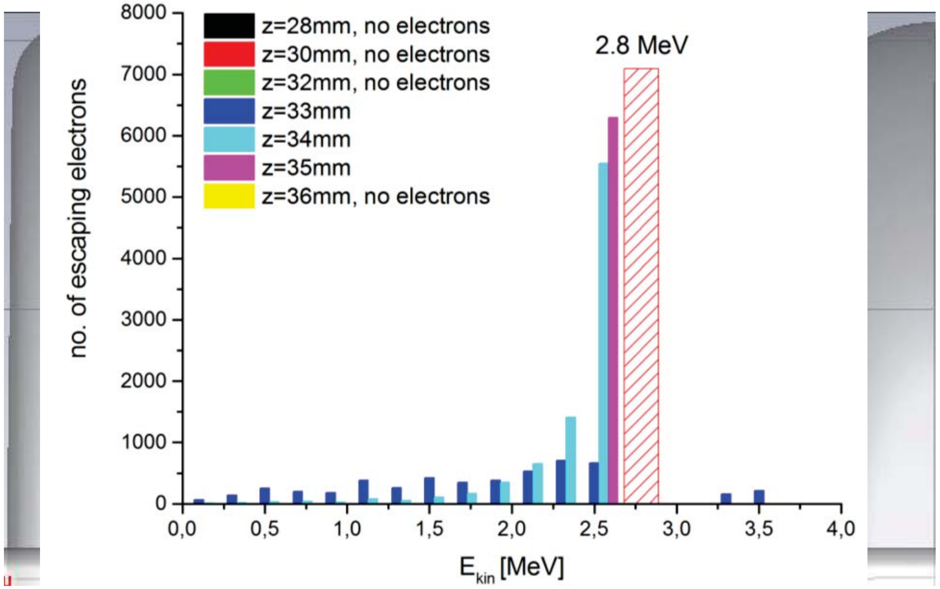

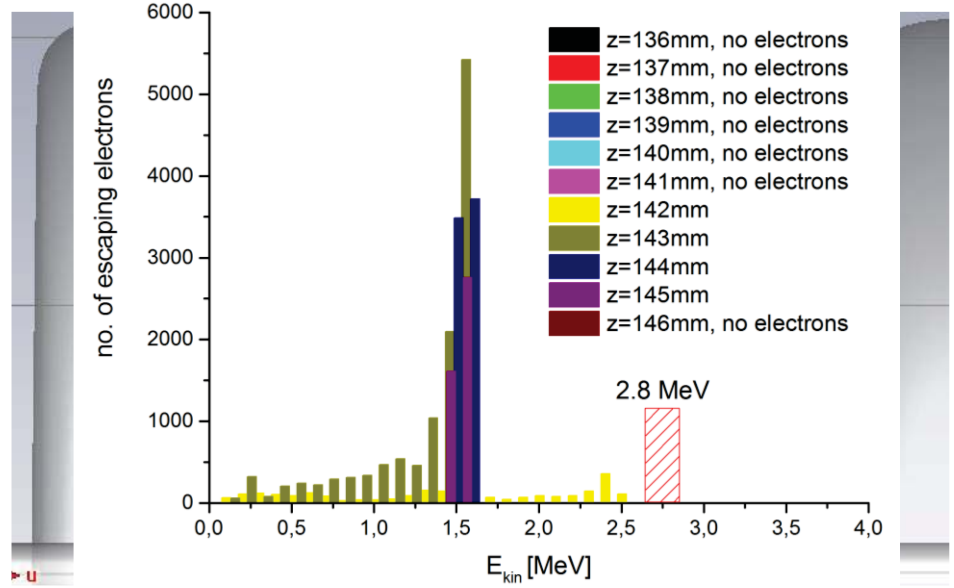

Candidates for contamination

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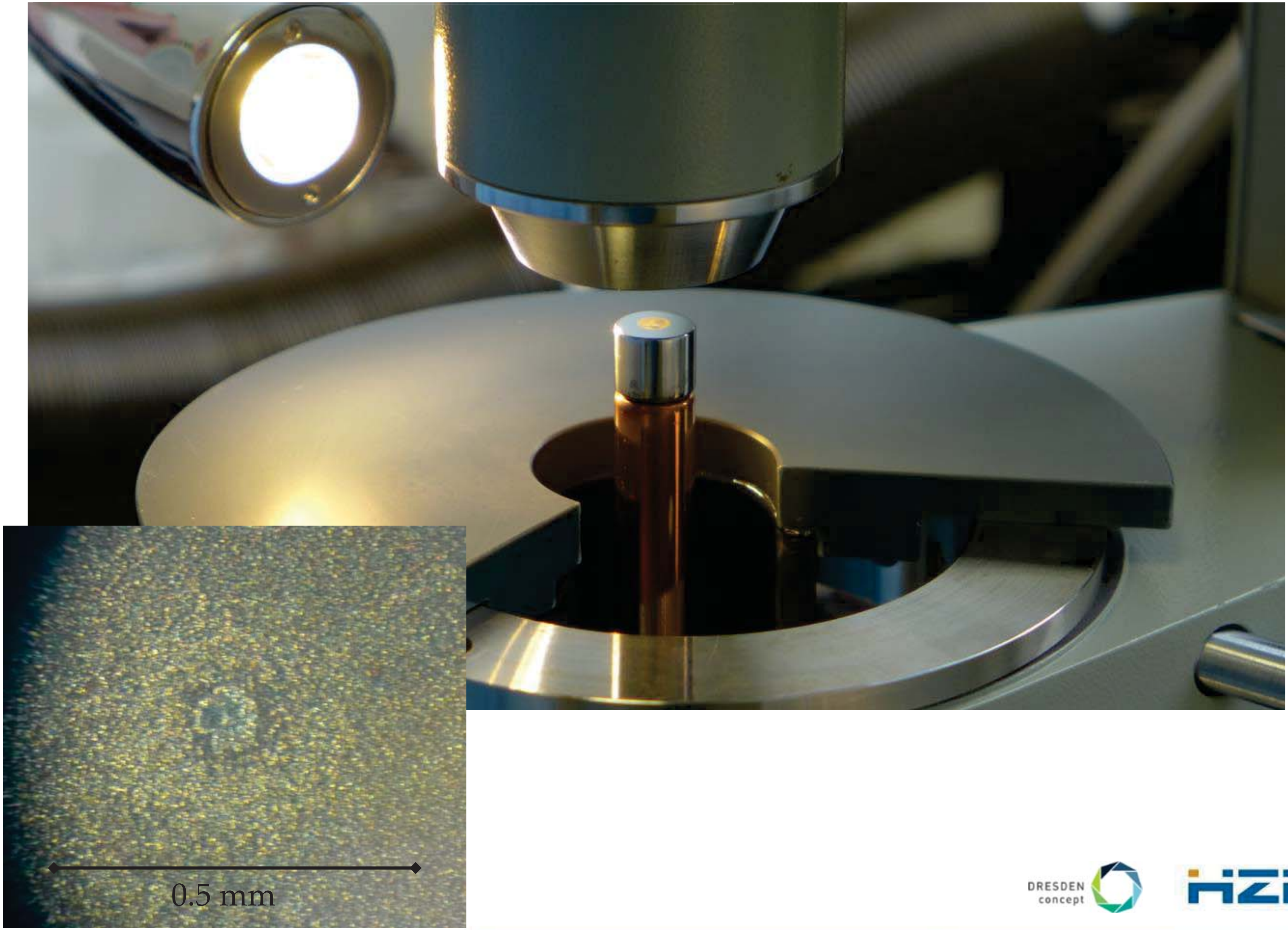

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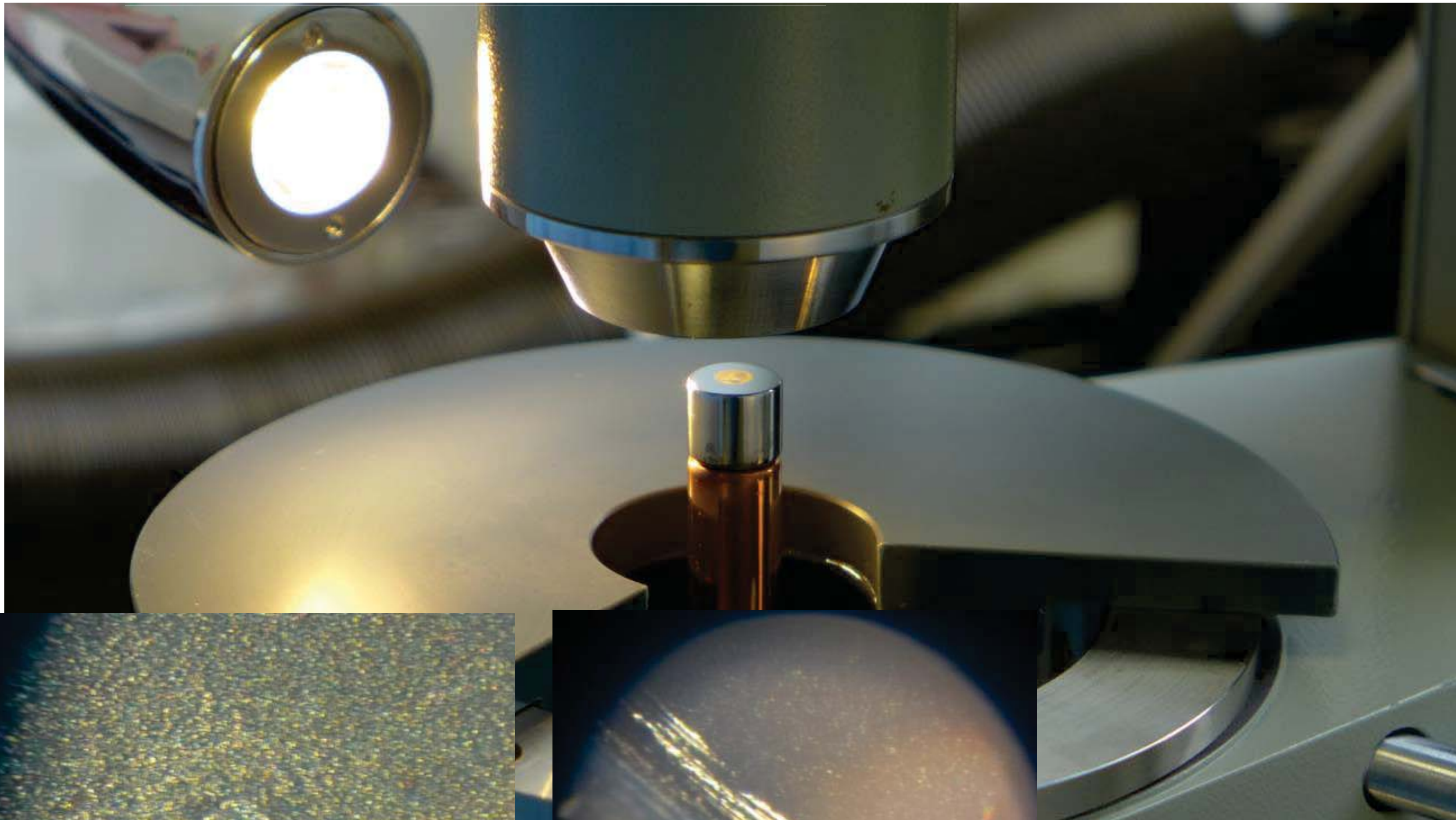

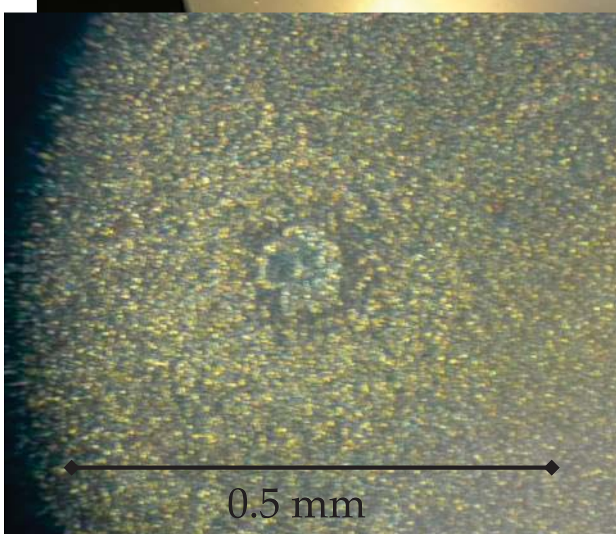

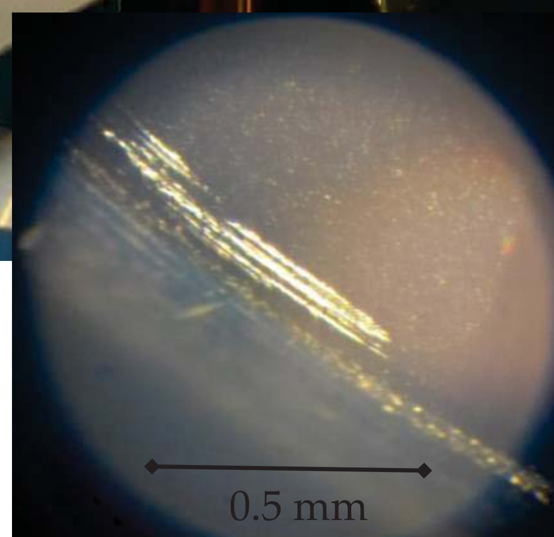

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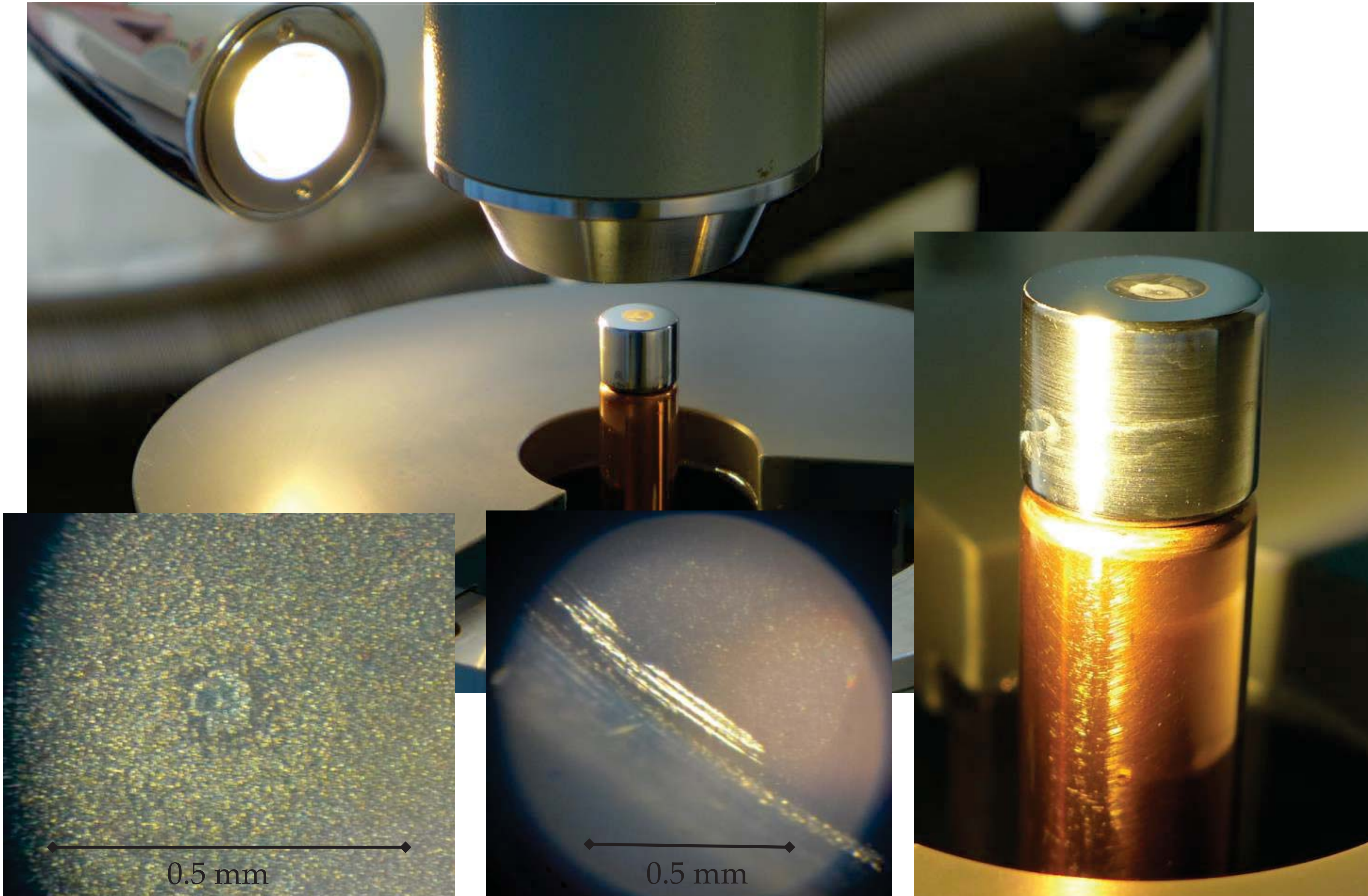


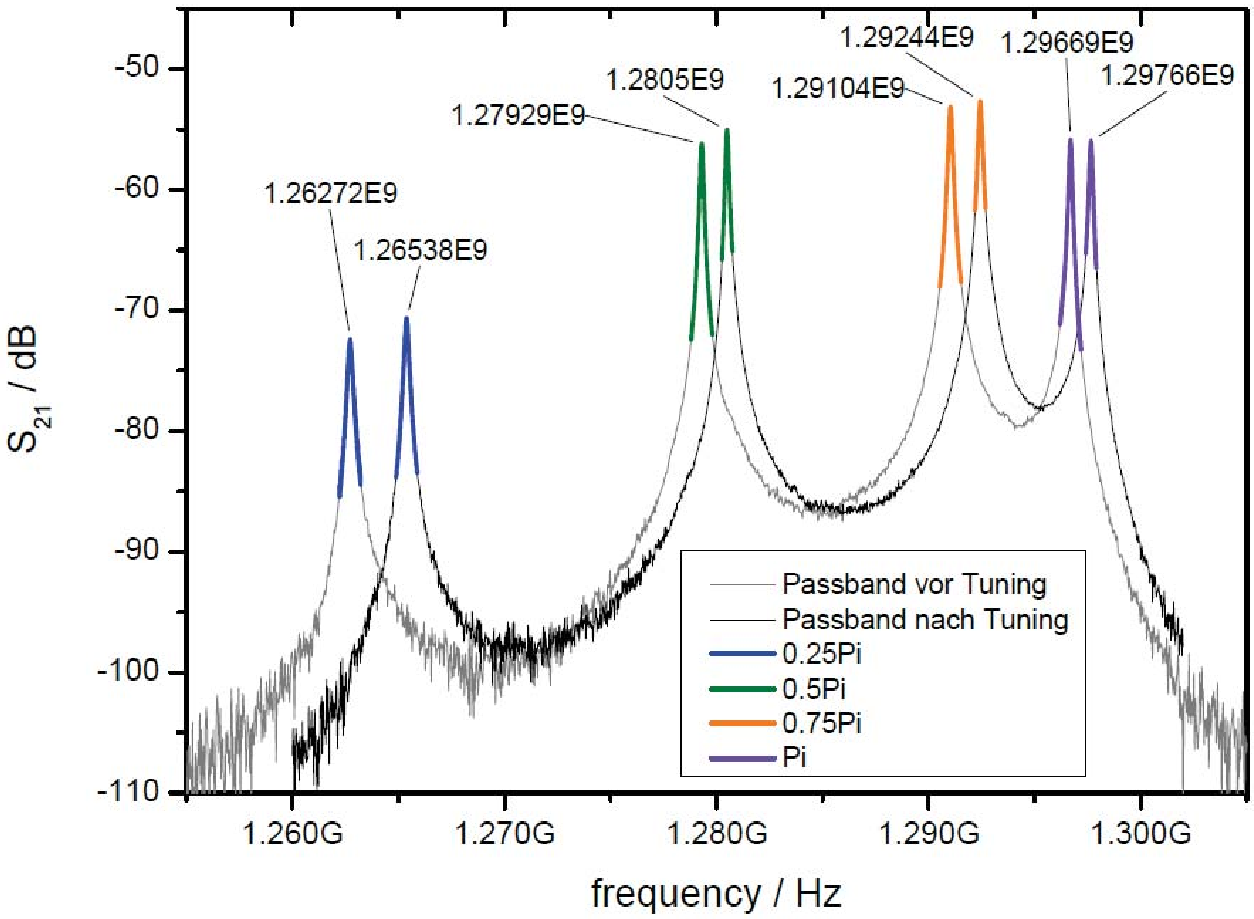
Summary

1. **Still very challenging to build a high gradient SRF gun cavity!!!**
2. Cavity and cryomodule assembly went smoothly because of experiences of gun I
3. 30% loss of usable gradient btw. vertical and horizontal test
4. RF performance twice as high as for gun I and good enough for 1 nC and 1mA
5. **Serious cavity contamination** during 1st Cs_2Te cathode transfer and performance drop by another 30%
6. Reason is probably particle moved from cathode surface to the first iris

Thank you for your attention

Backup Slides

Cryomodule assembly at Rossendorf



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2. field flatness (0.79/0.99/1.04/0.99)
3. HOM coupler tuning (Q_{ext}<1E11)
4. choke tuning (f_{notch}=1253.55 MHz)
5. cavity tuner test (<1 Hz/step, ±300 kHz)
6. earth‘s magnetic field shielding (<2 μT)

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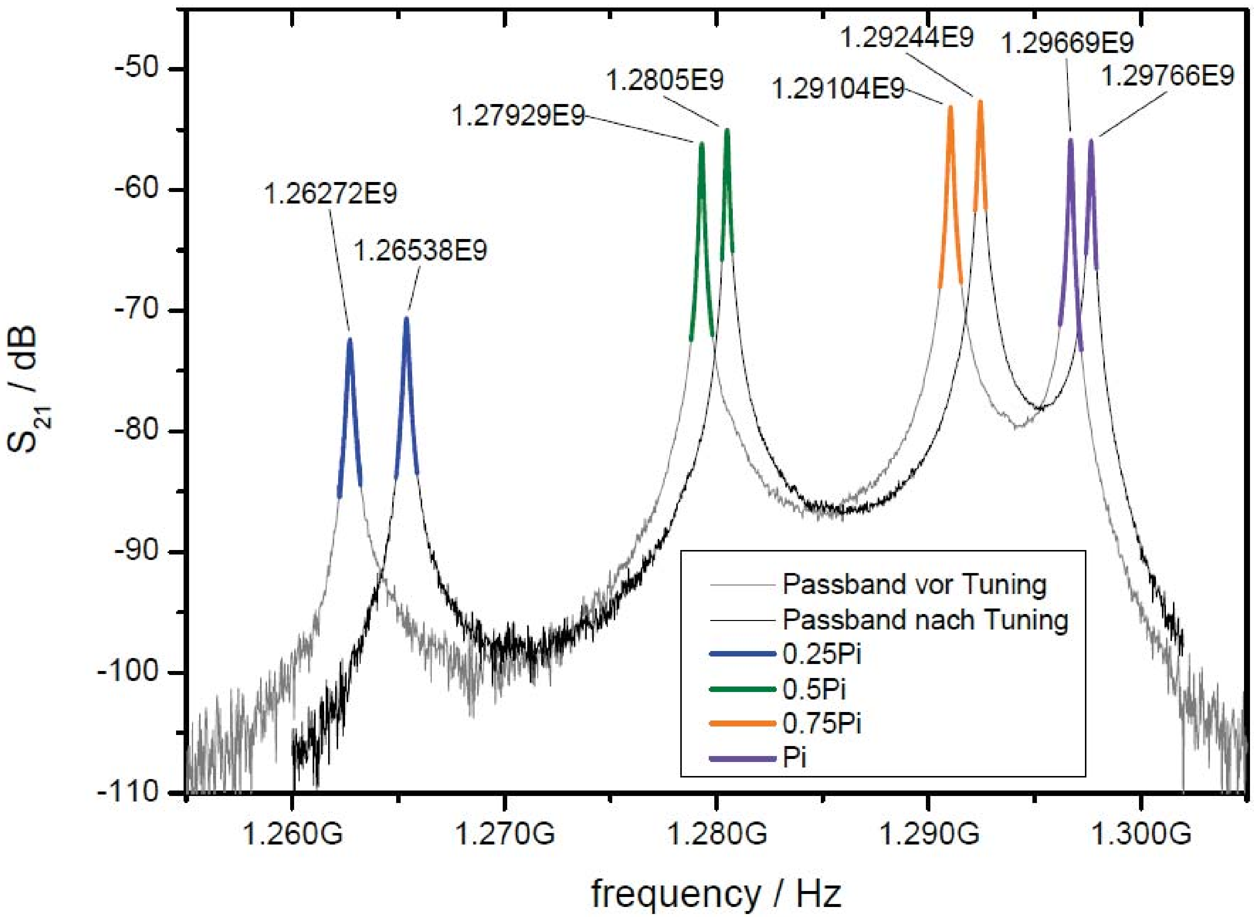

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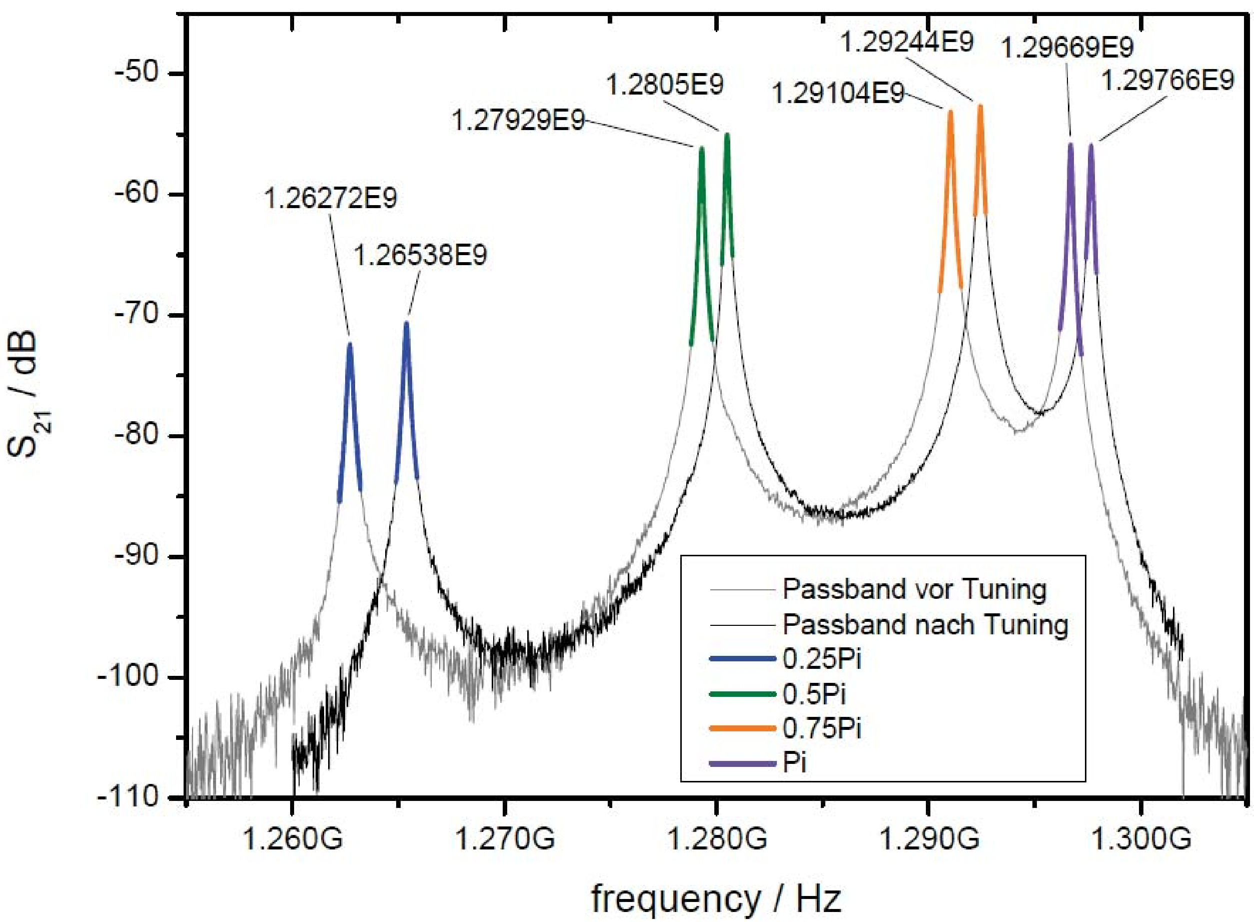

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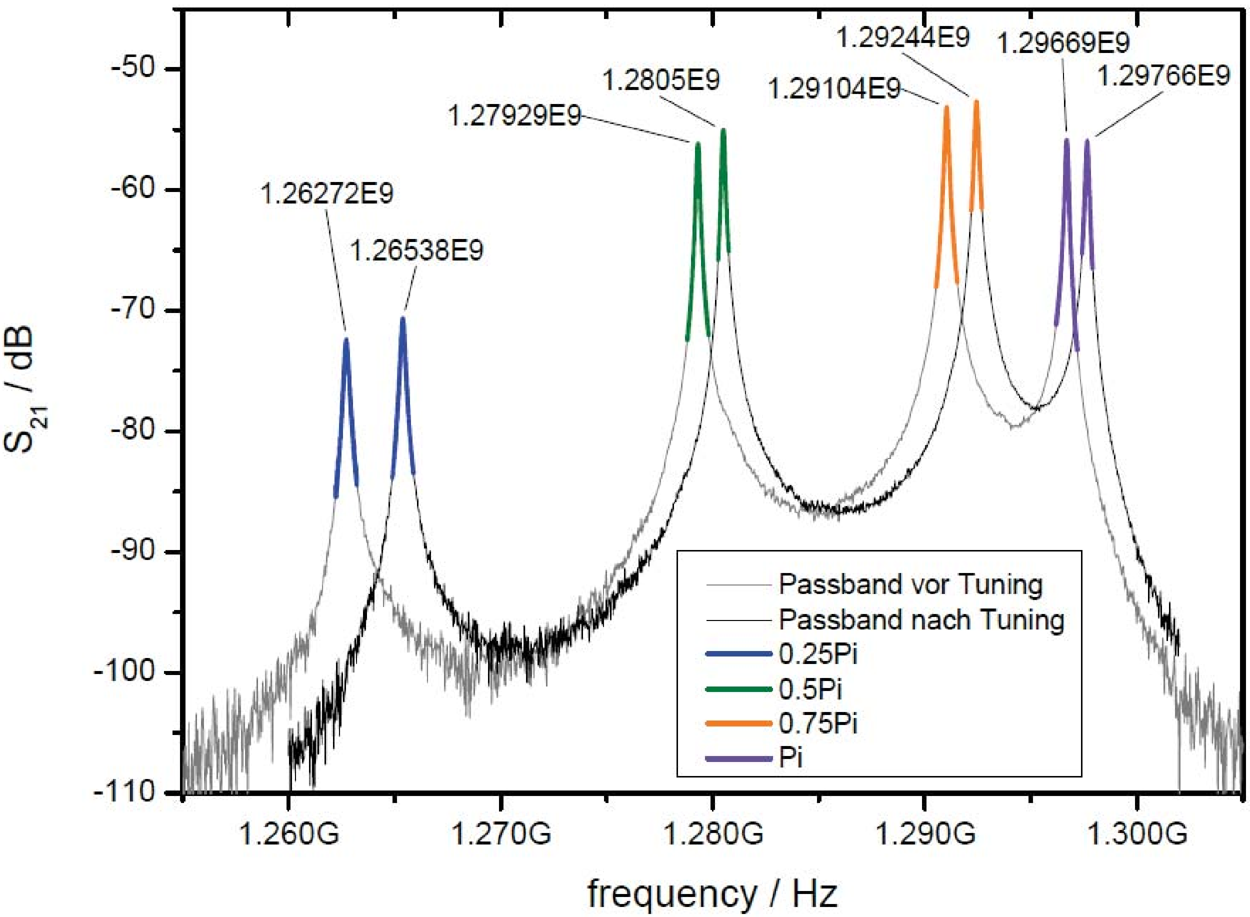

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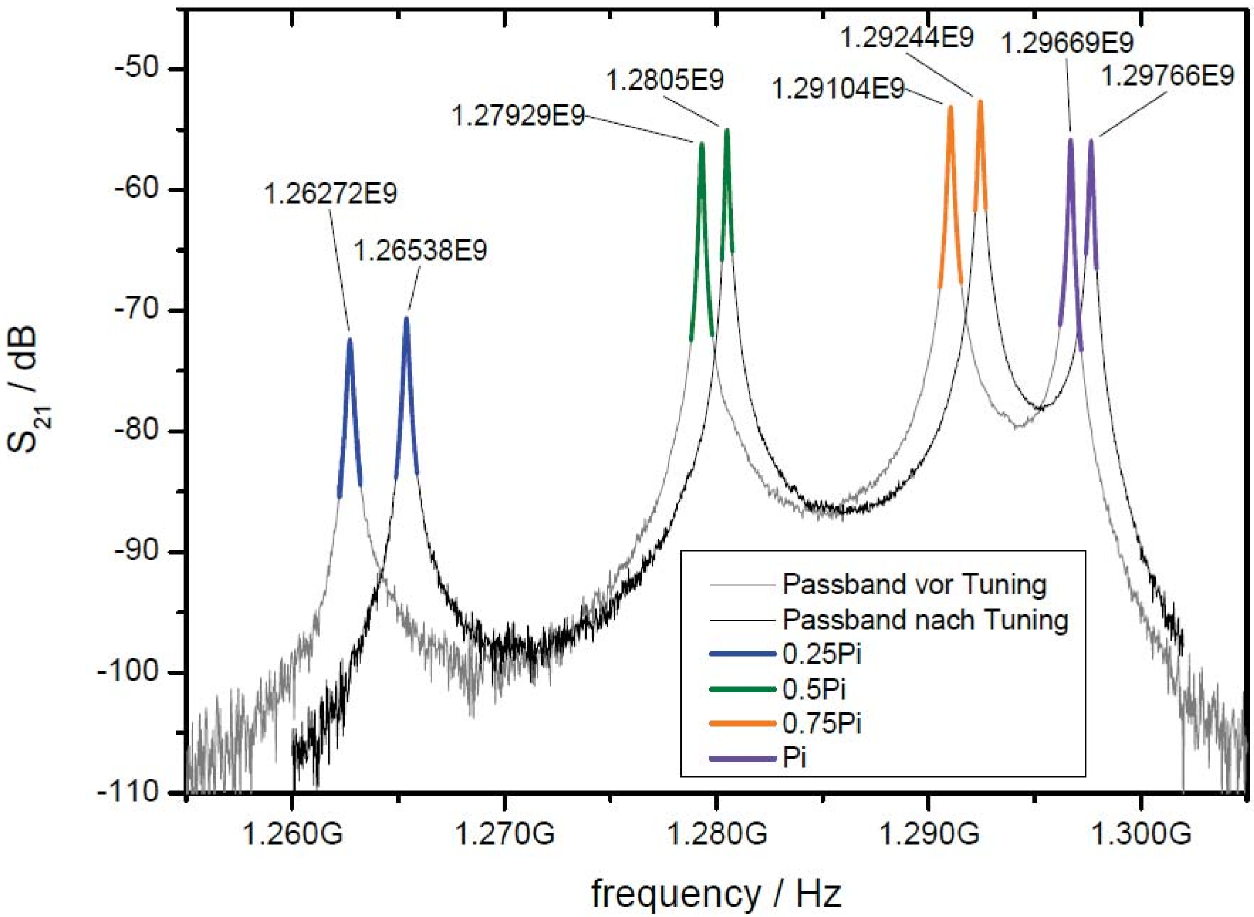
Cryomodule assembly at Rossendorf



1. cavity tuning (f_{RT}=1297.660 MHz) ✔
2. field flatness (0.79/0.99/1.04/0.99) ✔
3. HOM coupler tuning (Q_{ext}<1E11) ✔
4. choke tuning (f_{notch}=1253.55 MHz) ✔
5. cavity tuner test (<1 Hz/step, ±300 kHz)
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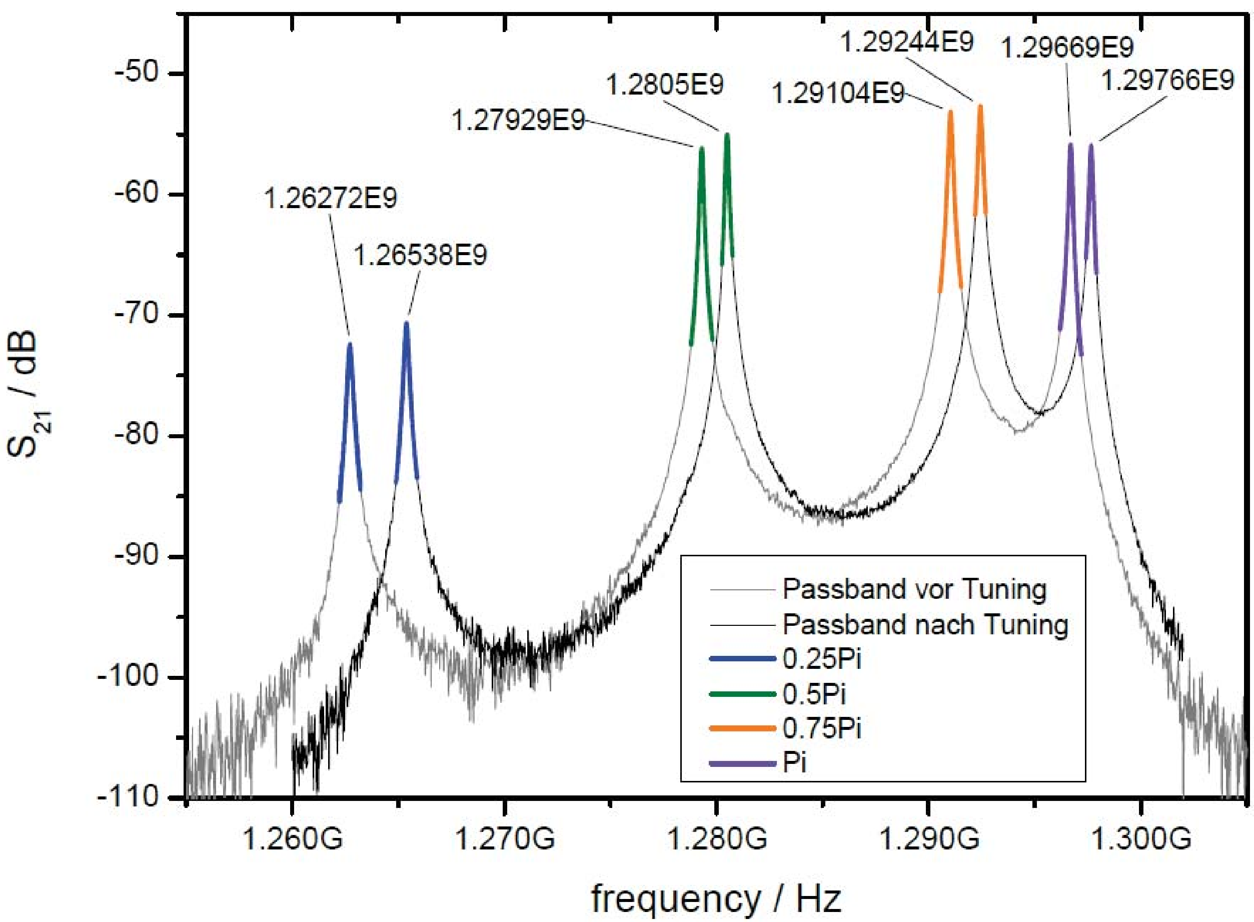

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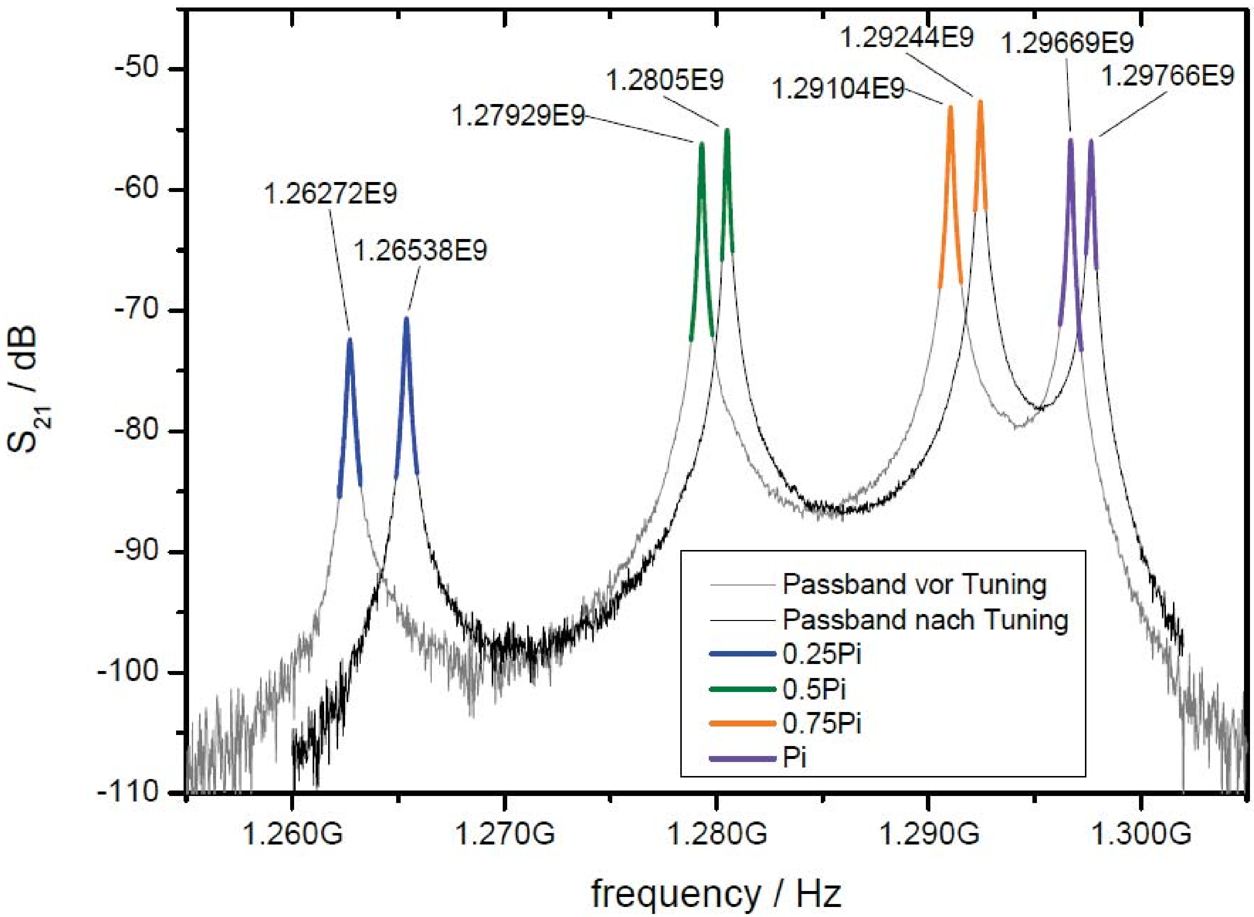

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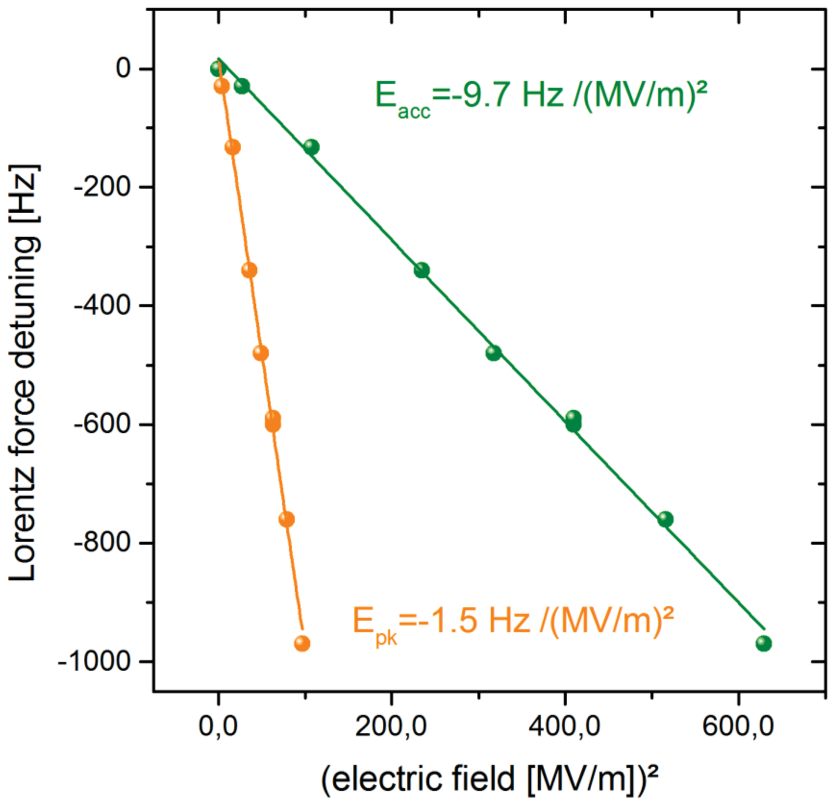
Lorentz force detuning



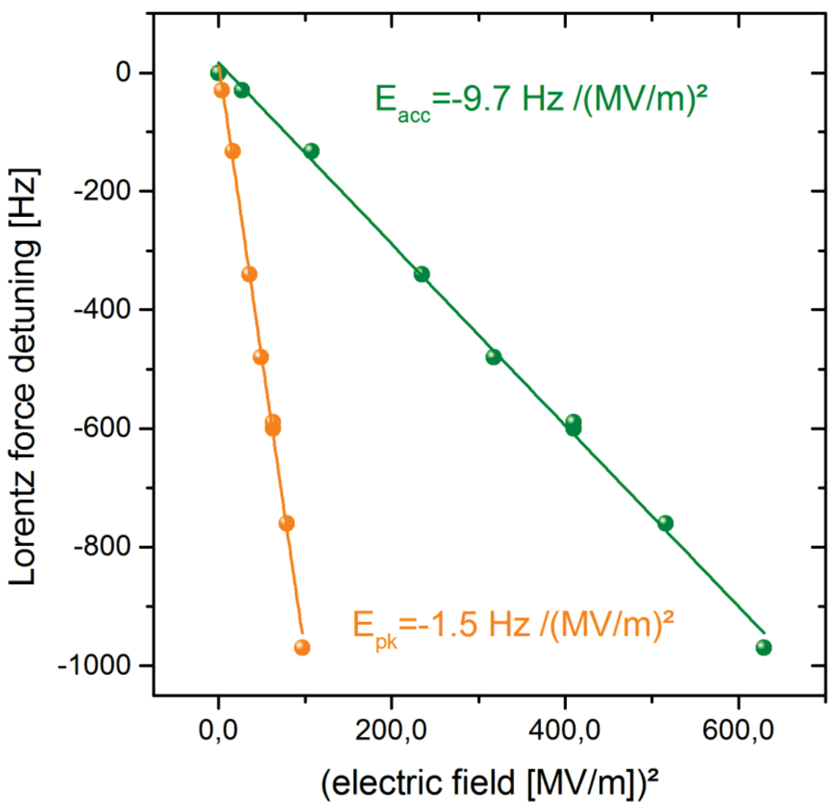
	SRF gun I	SRF gun II	TESLA
k_{acc} / Hz/(MV/m)^2	5	9.7	1
k_{peak} / Hz/(MV/m)^2	0.69	1.5	0.25

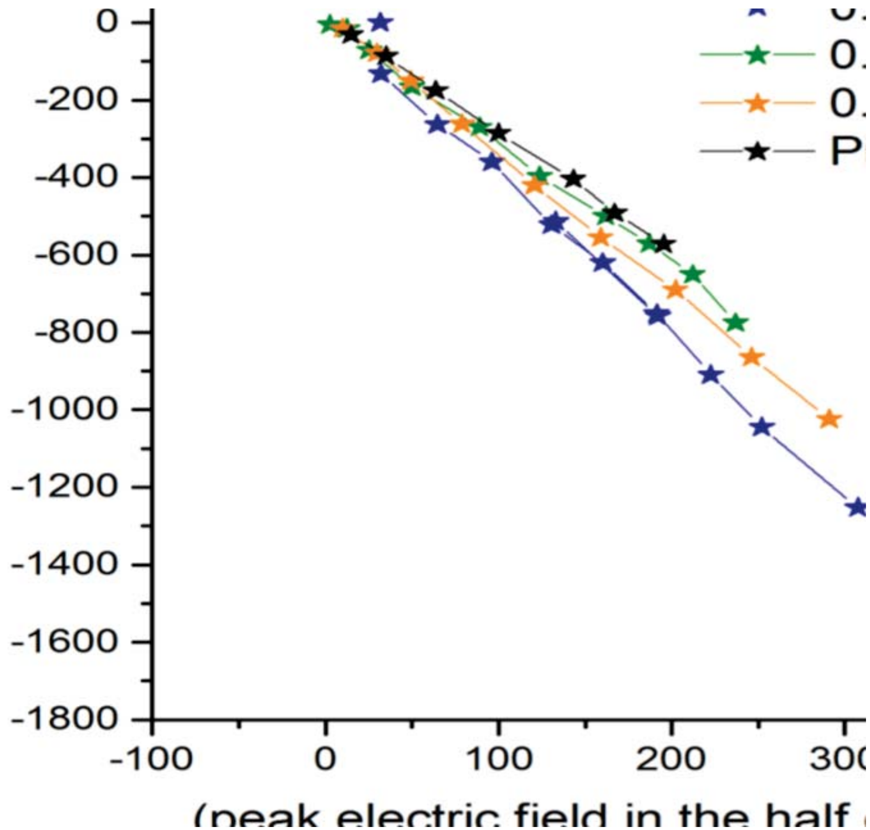
$$k_{acc} = k_{peak} \left(\frac{E_{peak}}{E_{acc}} \right)^2 \qquad \frac{E_{peak}}{E_{acc}} = 2.56$$

DRESDEN concept

HZDR

Lorentz force detuning





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DRESDEN concept

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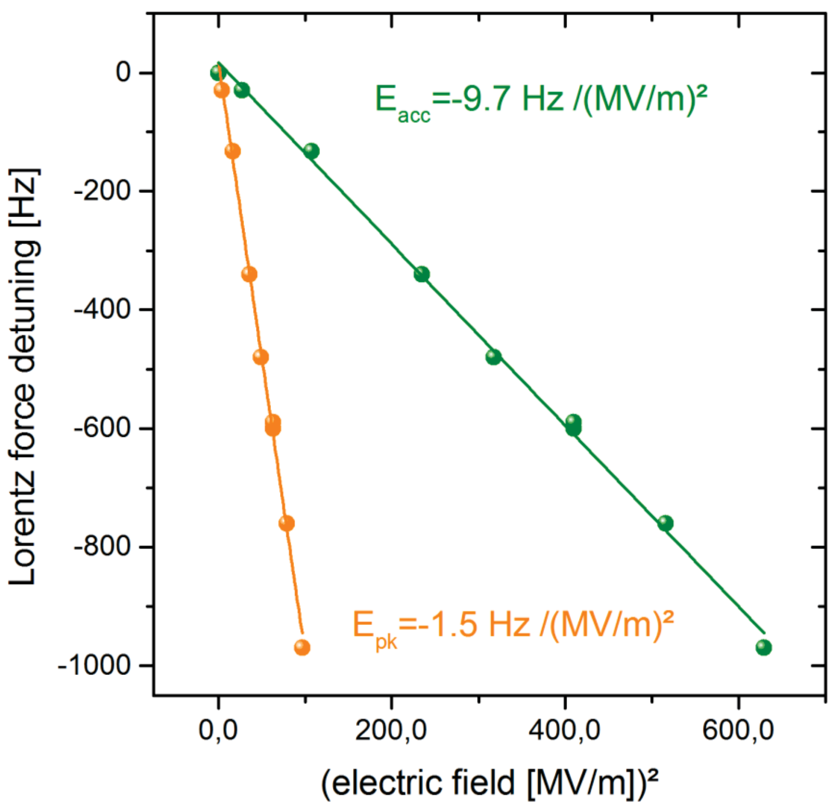

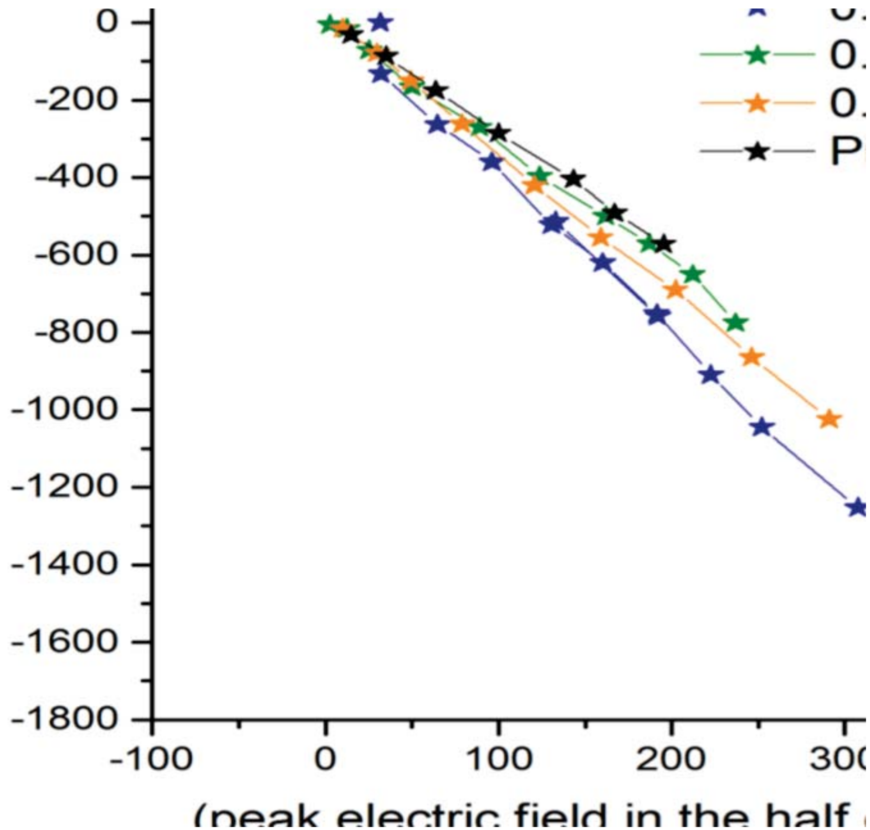

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- LF coefficient is **2x higher** than for gun I
- **3x higher** than in simulation and even
- **6x higher** than for TESLA 9cell cavities

- plotting detuning vs. peak electric fields for each mode clearly point on half cell
- additional stiffeners are not enough

RF window limits the Gradient to 8 MV/m

green: temp
blue: gradient
magenta: vacuum

Problem

RF Waveguide window made from Rexolite (cross linked polystyrene microwave plastic) heats up to ~55°C (limit is 60°C).

New RF window does not limits the Gradient

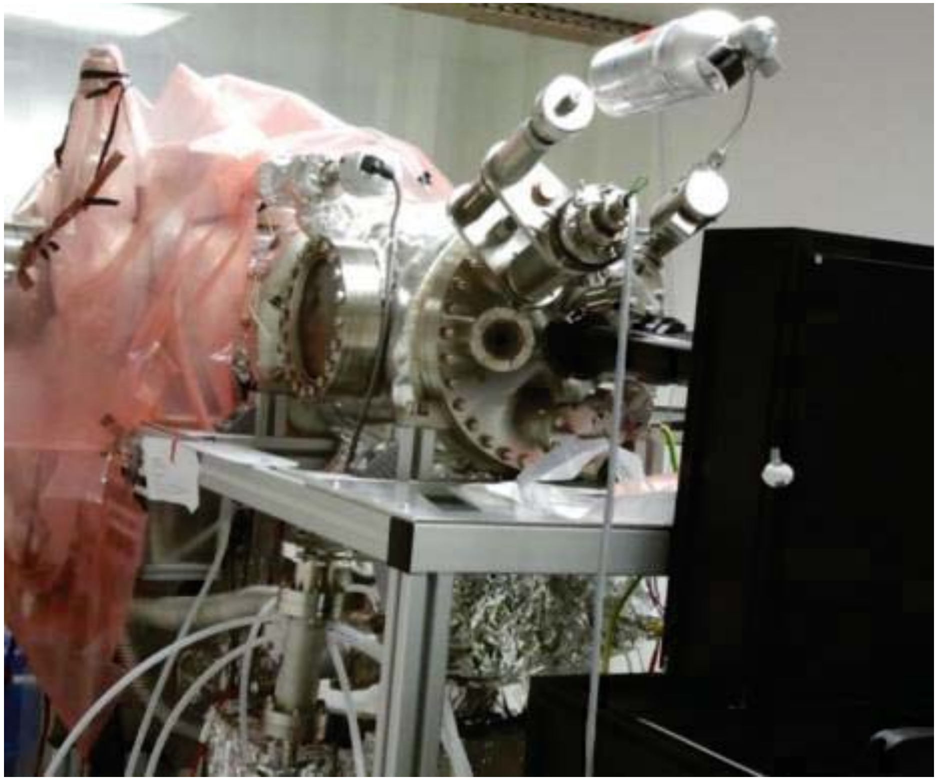
green: temp
blue: gradient
magenta: vacuum

Solution

RF Waveguide window made from Quartz heats up to ~27°C (limit is 60°C) at 8 MV/m.

Preparation of Cs_2Te Cathodes

Inside preparation chamber



Preparation of Cs_2Te Cathodes

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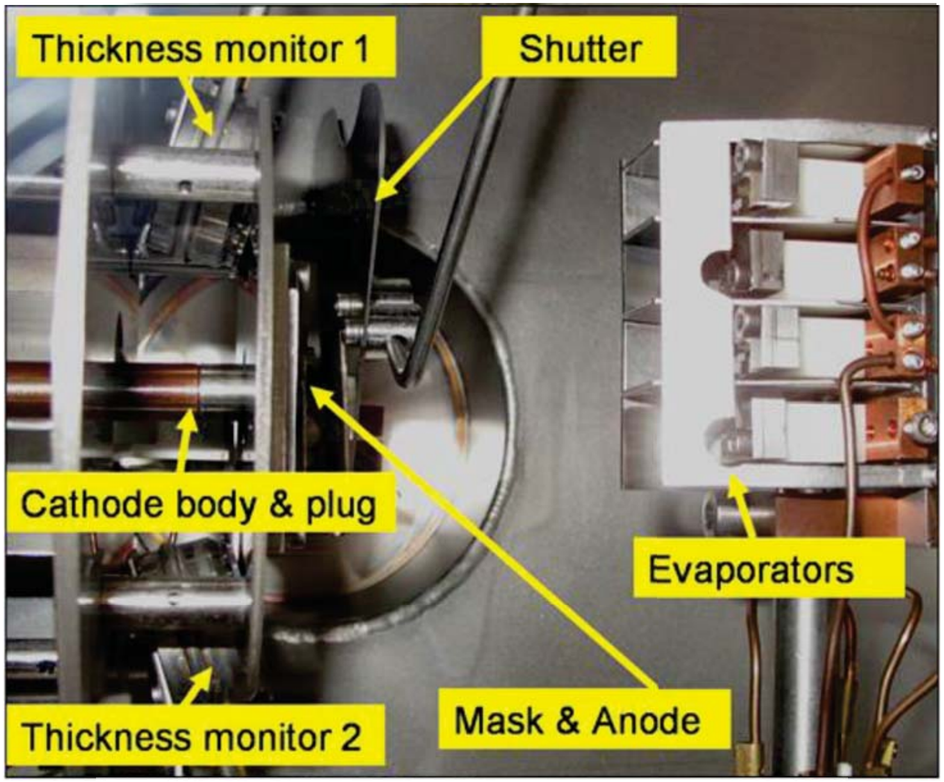
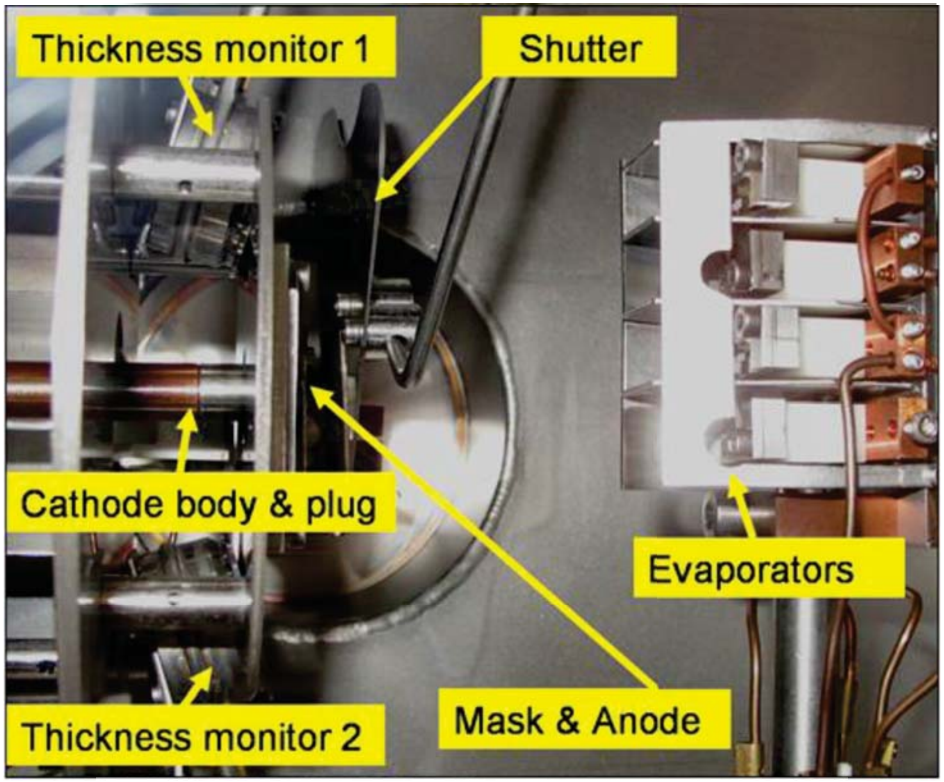
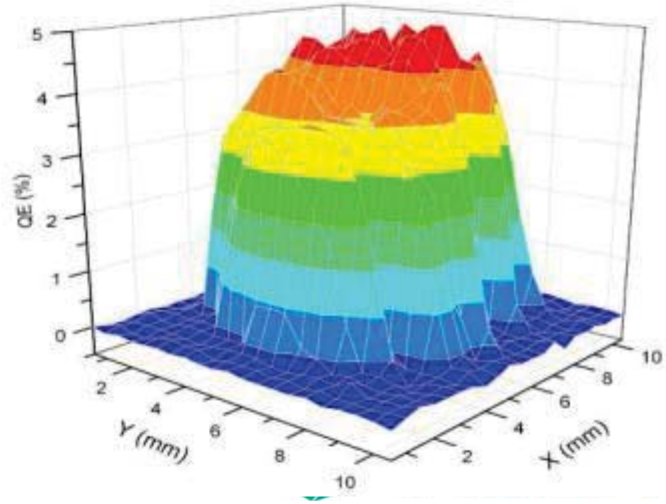


Preparation of Cs_2Te Cathodes

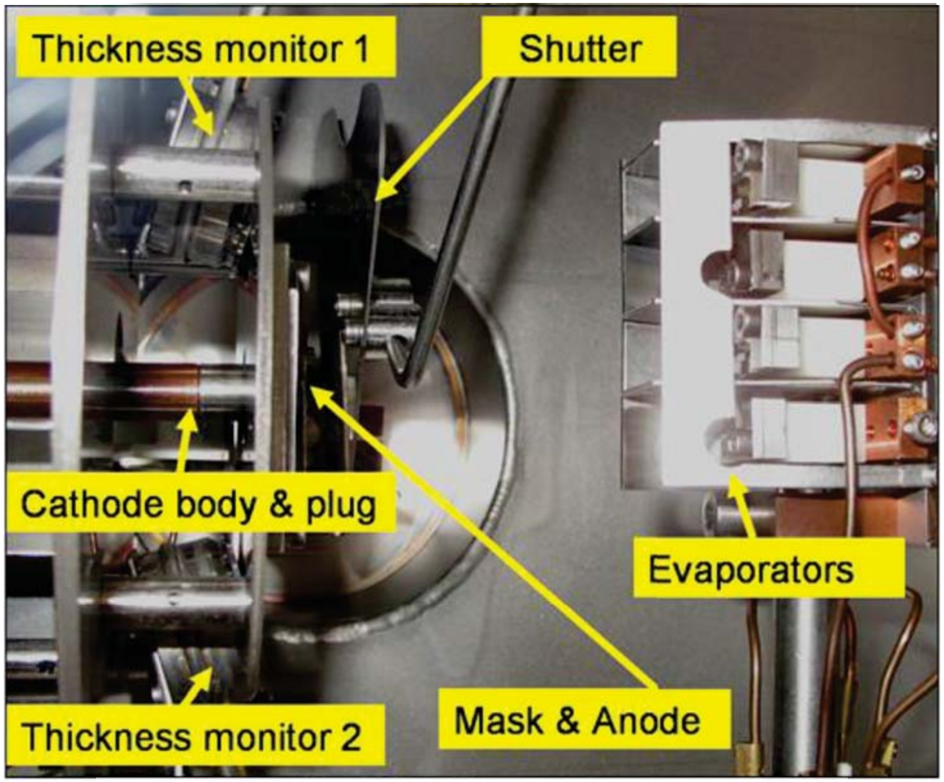
Inside preparation chamber



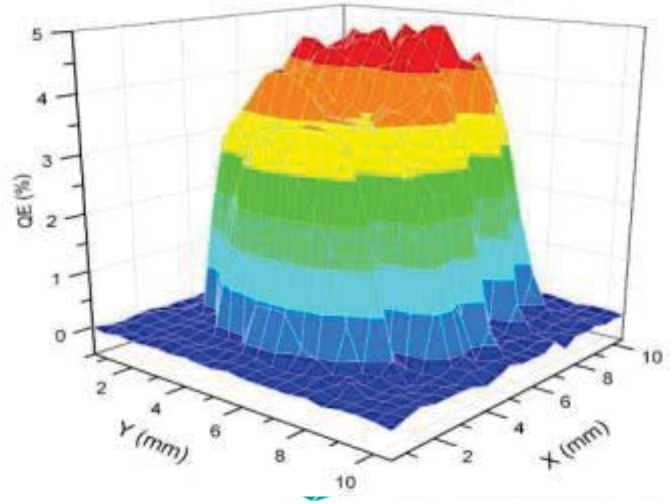


Preparation of Cs_2Te Cathodes

Inside preparation chamber



- Cathodes polished (Ra 10nm) and cleaned with Ar^+
- Heated to 120° C and evaporated with Cs and Te (successive- or simultaneously) until QE saturated
- Online thickness and QE measurement
- QE distribution scan after preparation



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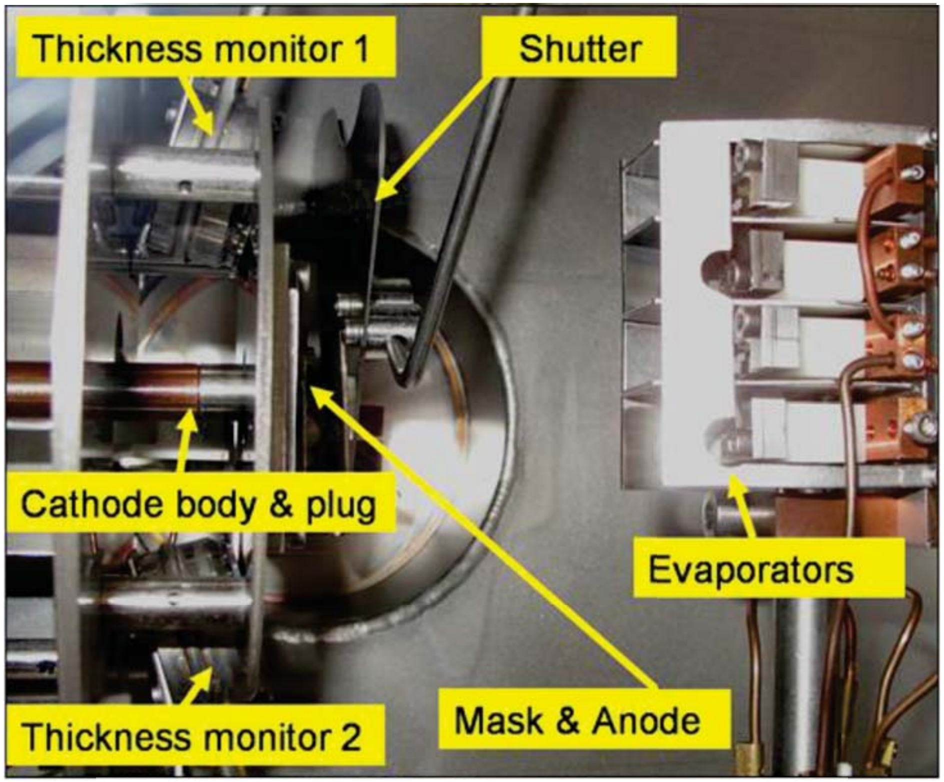

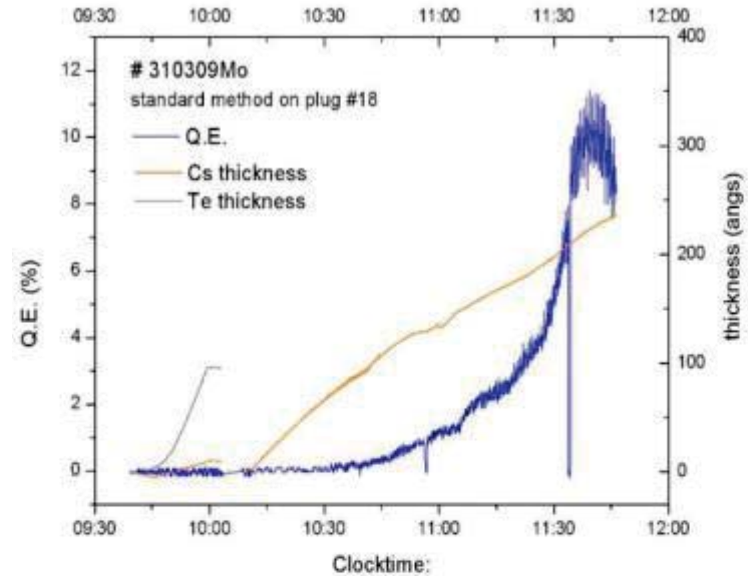

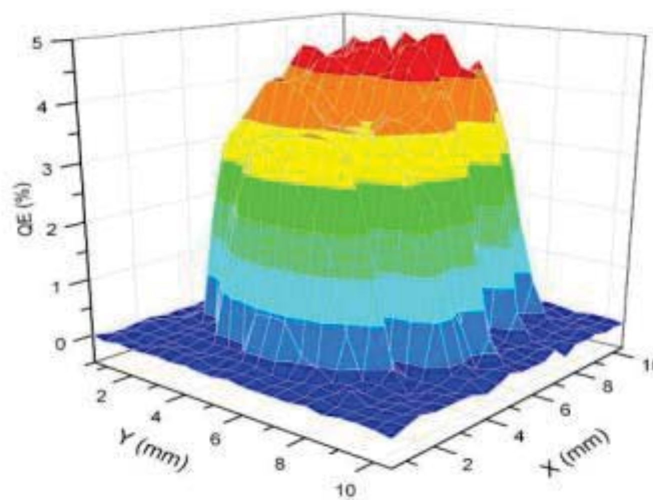

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