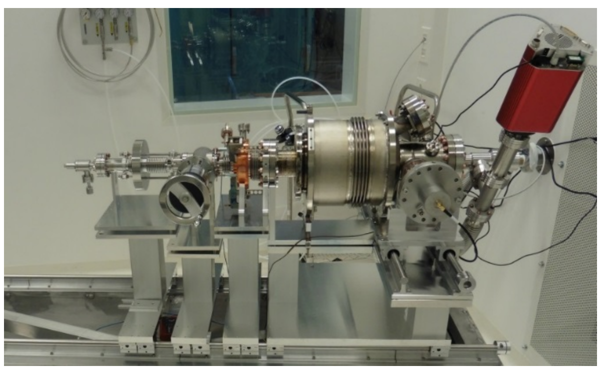
The bERLinPro SRF Photoinjector system - From design to first RF commissioning results

Axel Neumann

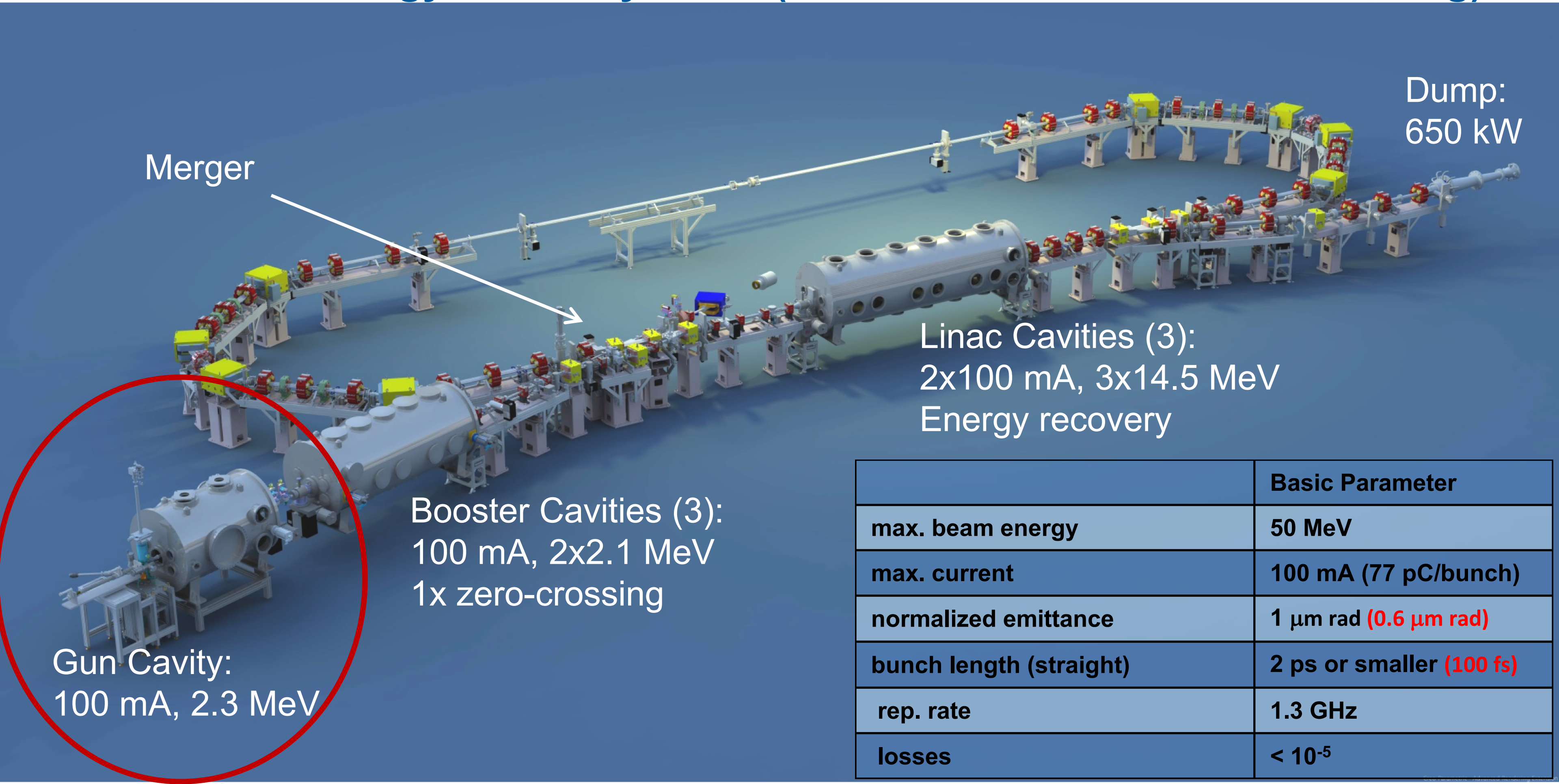


Do ERLs dream
of SRF guns?

For the bERLinPro team and collaborators

ERL 2017, CERN, Geneva
WEIDCC004

bERLinPro: Demonstrator for a low emittance, high brilliance Energy Recovery Linac (see talk A. Jankowiak this morning)

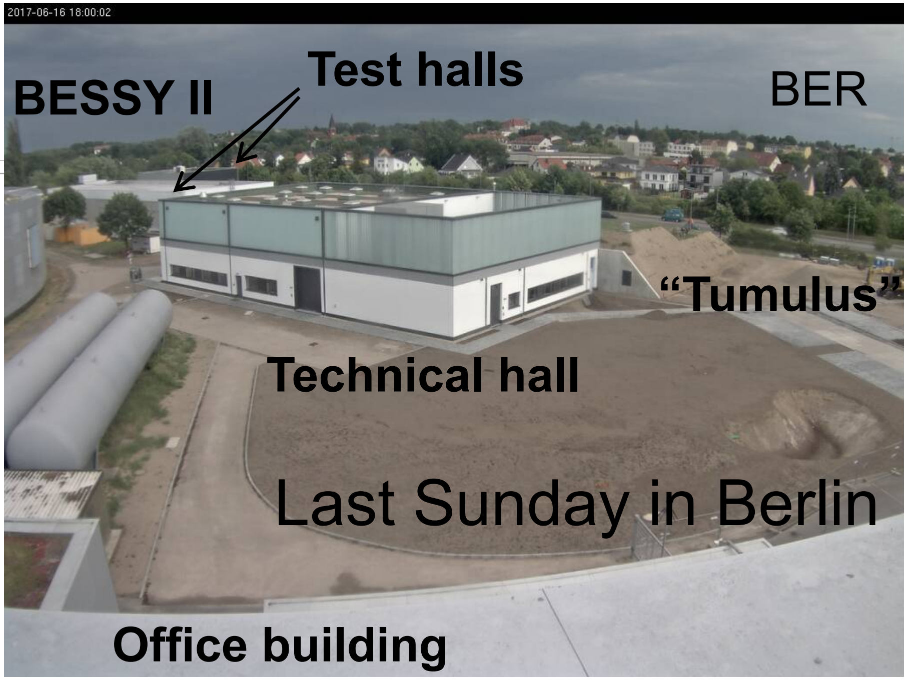


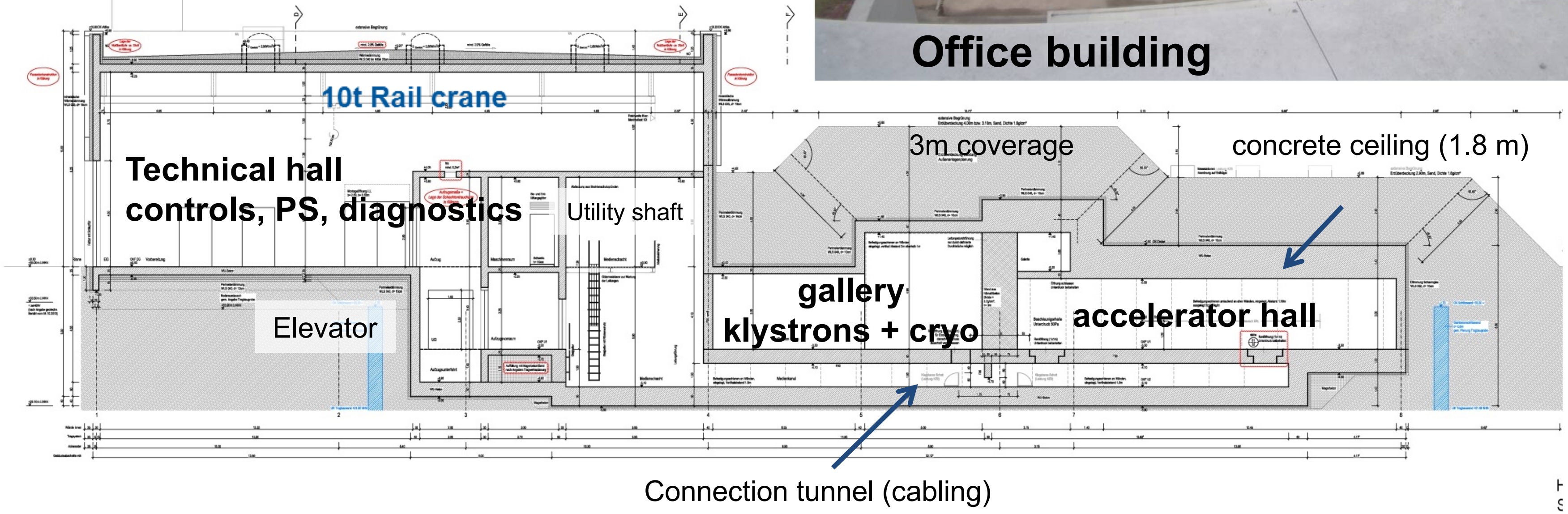
	Basic Parameter
max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
normalized emittance	1 µm rad (0.6 µm rad)
bunch length (straight)	2 ps or smaller (100 fs)
rep. rate	1.3 GHz
losses	$< 10^{-5}$

Main goal:
High current, low emittance ERL operation using CW SRF technology

Motivation

Fully funded project (41 Mio€)
Building construction in progress (very close to be completed)

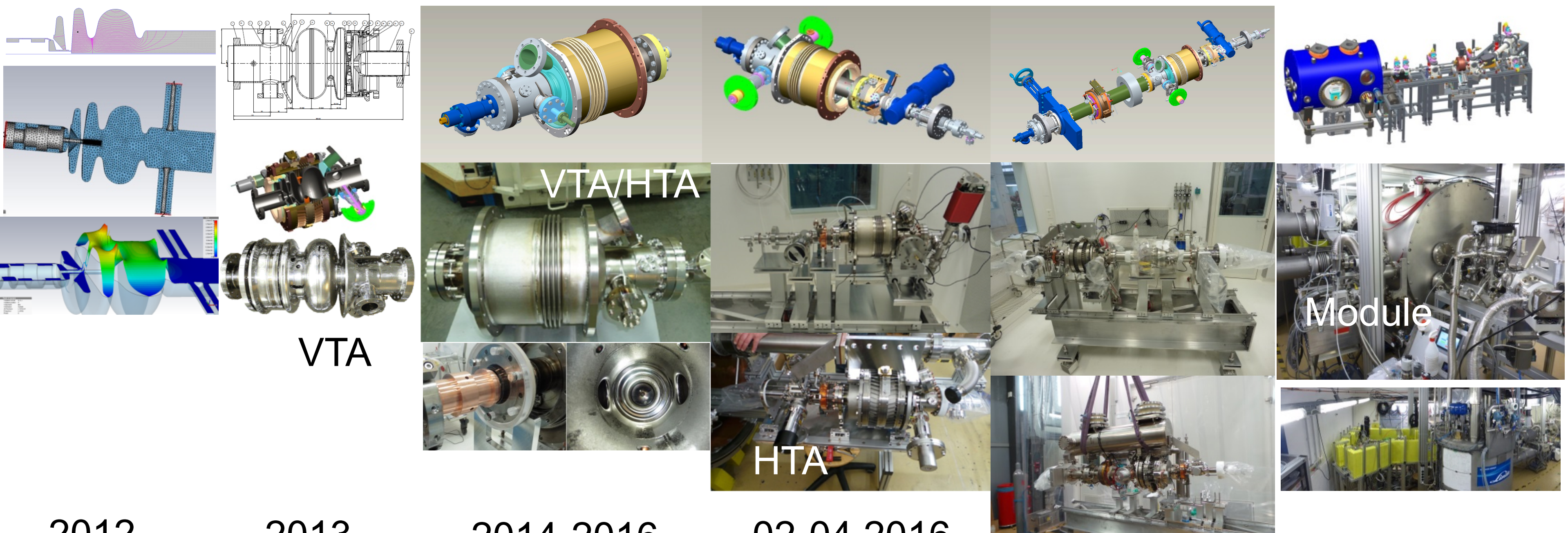




Gun, from the cradle to the….modul!

Cleanroom HoBiCaT

HZB | Jefferson Lab Thomas Jefferson National Accelerator Facility | HZB | Cleanroom | Gunlab



2012 | 2013 | 2014-2016 | 02-04 2016

Time | 04-10 2016 | 11 2016-today

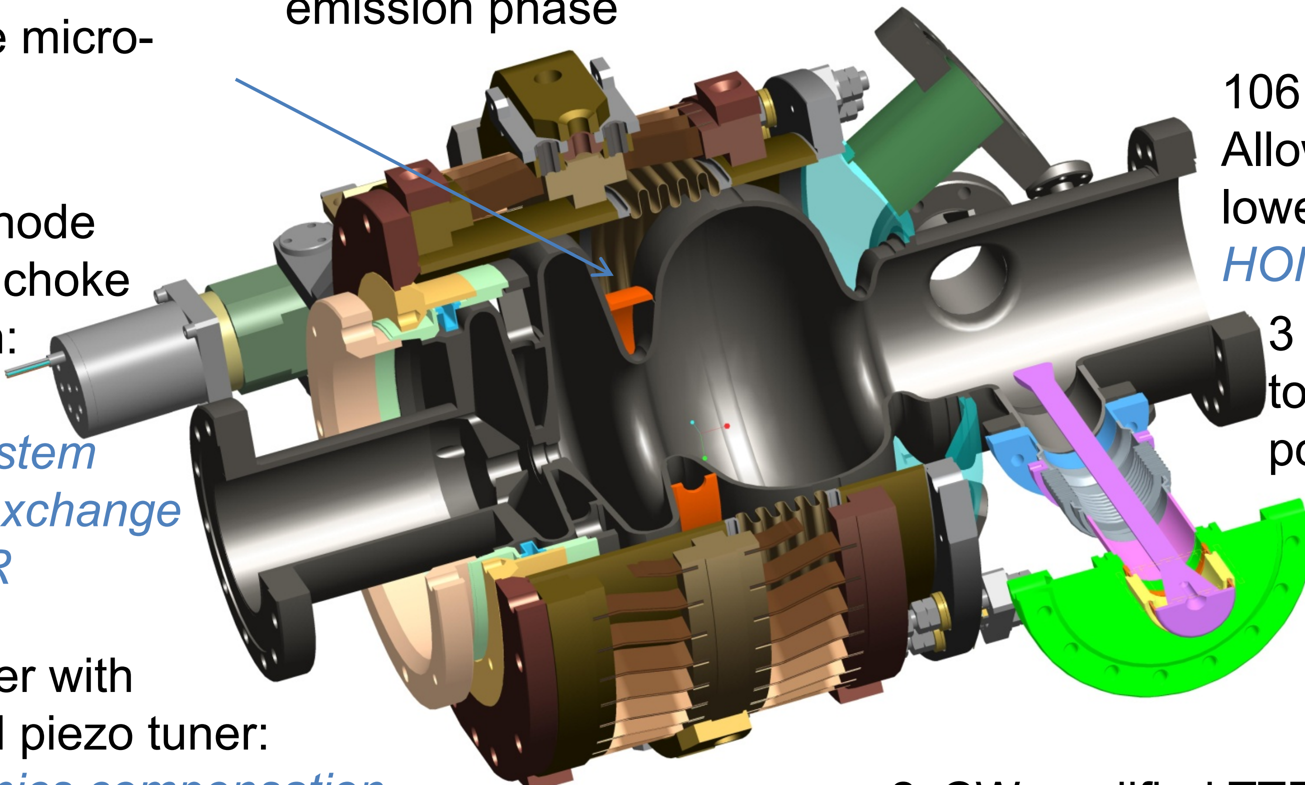
G. Ciovati, A. Burrill, P. Kneisel, A. Frahm. M. Schuster, J. Ullrich, F. Göbel, F. Glöckner, M. Schmeißer, A. Matheisen, M. Schmökel, O. Kugeler, S. Klauke, P. Echevarria, A. Ushakov, Y. Tamashevich, T. Kamps, D. Böhlick + Gunlab team and HZB co-workers

Overall layout of the cavity: Medium power prototype

Stiffening ring:
$\Delta f/\Delta P$ minimized to reduce micro-phonics

0.4·λ/2 cell + full cell:
Optimized emission phase

Chimney 22 cm²~35 W at 1.8 K
about E_{peak}=45 MV/m at $Q_0=3.5\cdot10^9$



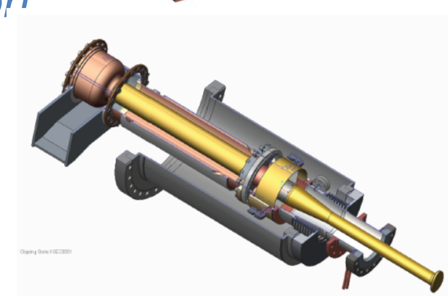
HZDR cathode insert and choke cell design:
Proven system
Cathode exchange with HZDR

106 mm beam tube:
Allows propagation of lowest TM_{110} mode:
HOM studies

3 pick-up antennas to measure HOM polarization

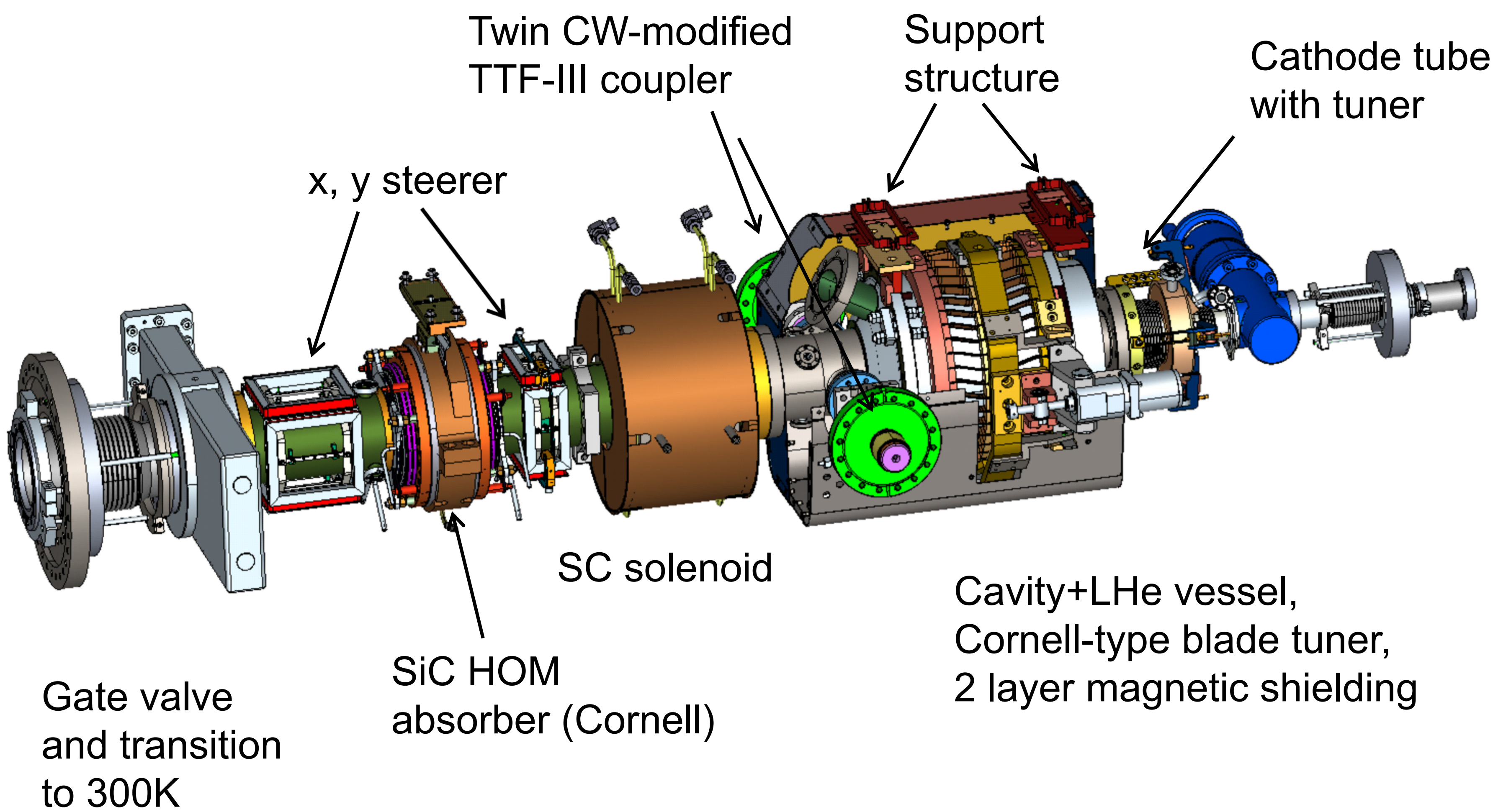
Blade tuner with motor and piezo tuner:
Microphonics compensation

Modified KEK-based FPC
Goal: 120 kW CW



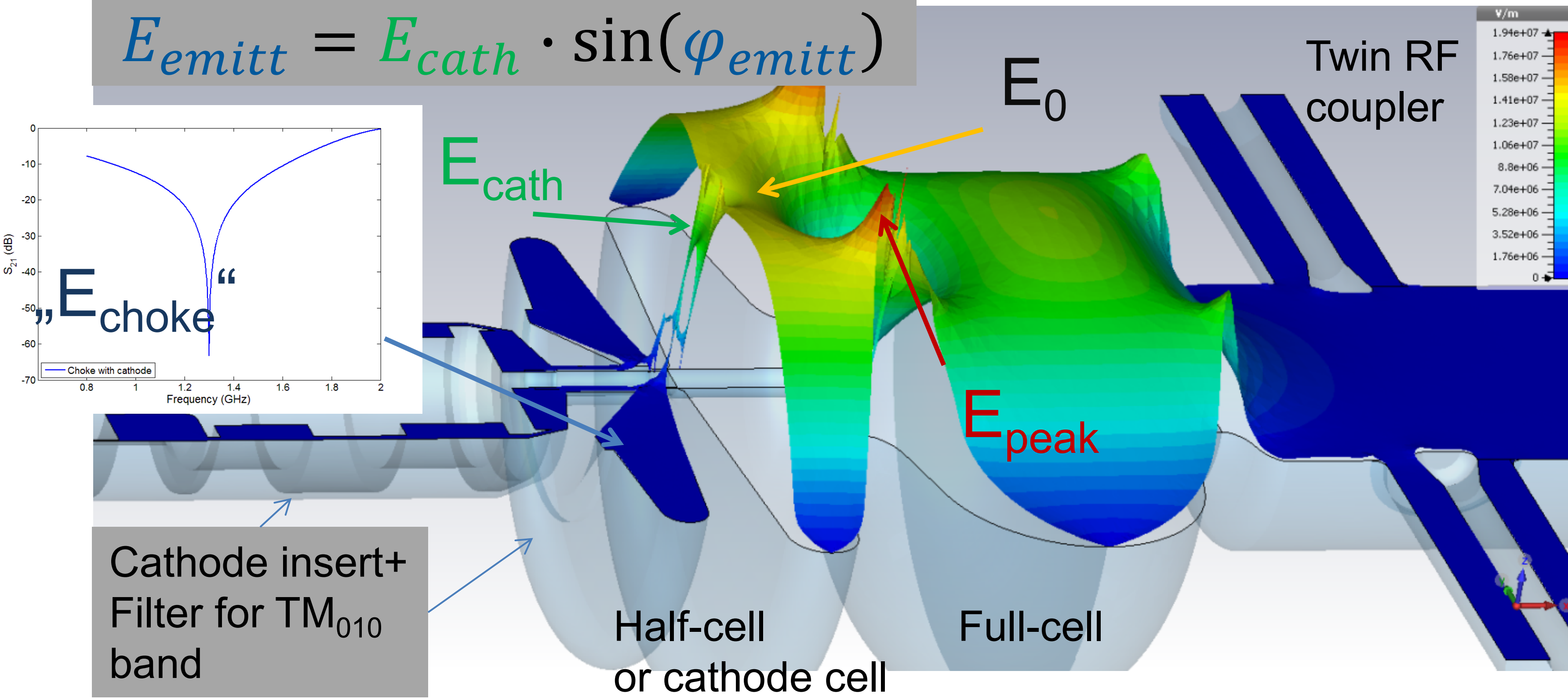
2xCW modified TTF-III Coupler: Q_{ext} $3.6\cdot10^6$
for up to I_{avg}=4 mA,
10 kW each
Study 2 coupler operation
→ High power version next step

Cold String layout



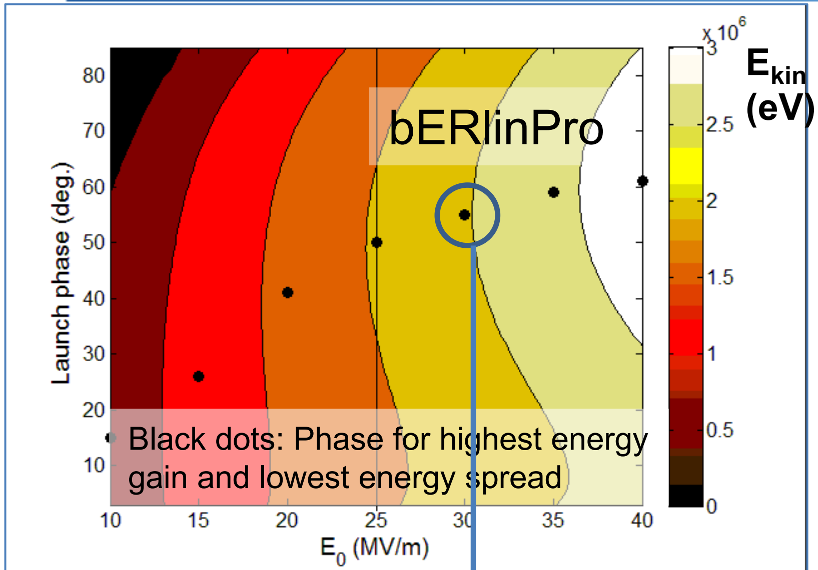
Optimization goals for RF properties

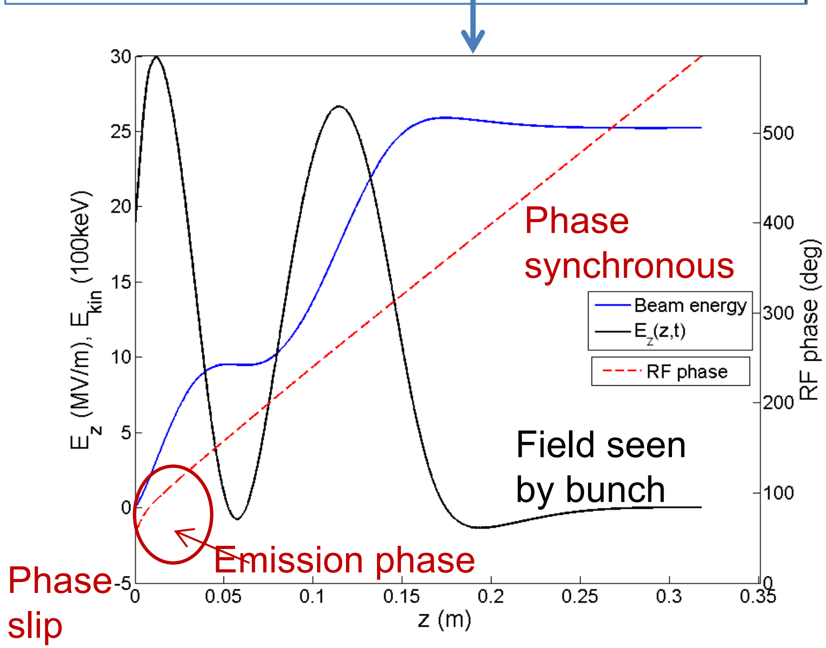
$$E_{emitt} = E_{cath} \cdot \sin(\varphi_{emitt})$$

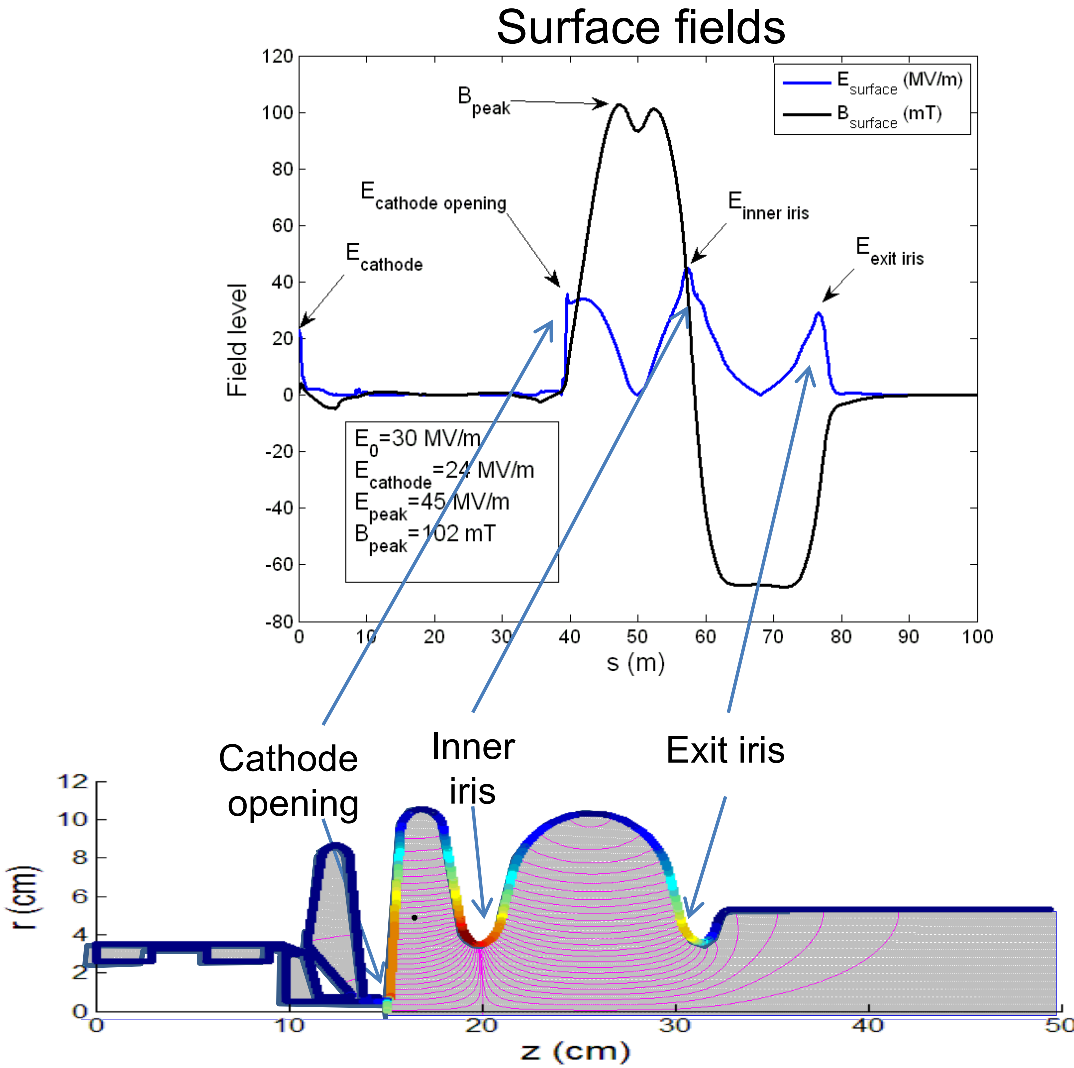


- Highest E_{emitt} favorable, but cathode also functions as field emitter (low work function)
  → highest on-axis field E_{max} few mm behind cathode to reduce dark current and still allow high performance
  → Length of half-cell optimized for high emission phase φ_{emitt}
  → By retractable cathode and backwall inclination E_{cath}<E_{max} and focussing RF effect increased
- Any losses and thus field in insert area minimized by filter (Choke cell)

Design parameters and results achieved

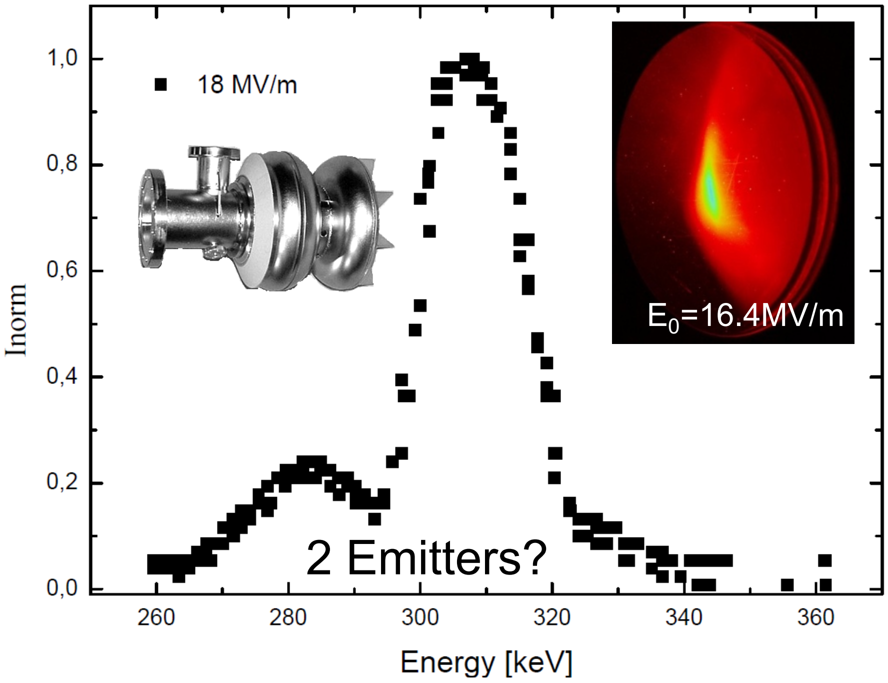






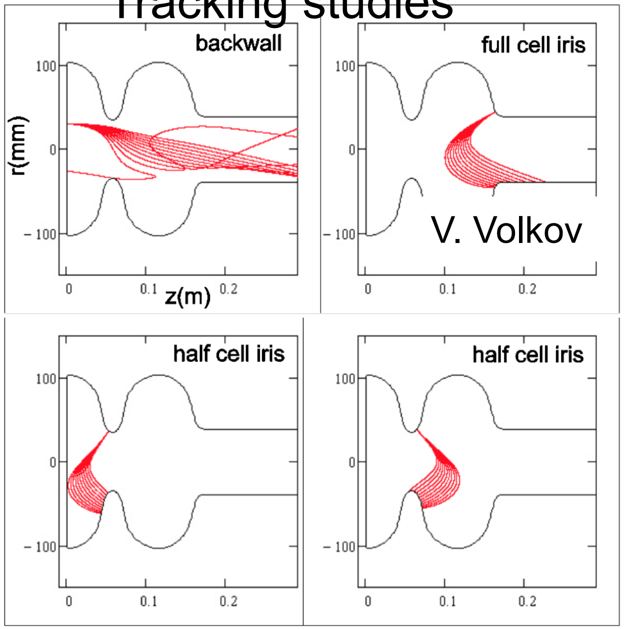
Peak electric field shifted to inner iris wall pointing to cathode
Here field emitted electrons do not leave cavity

Field emission and dark current issues

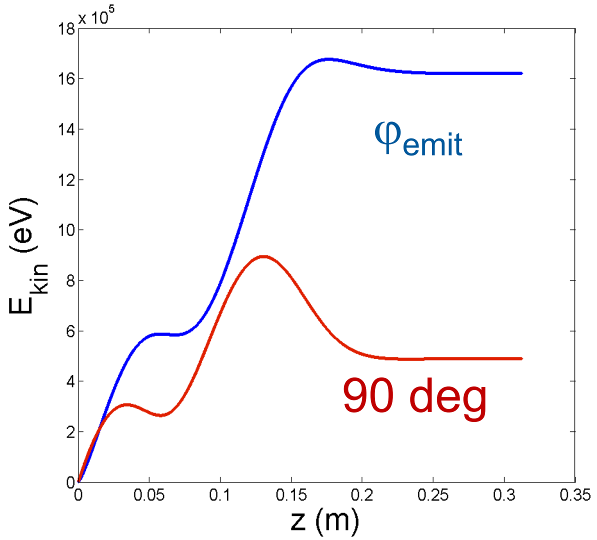


Example of 1.6 cell Nb Pb cathode gun cavity dark current measurement.

Tracking studies



Field emission originates from cathode area mainly



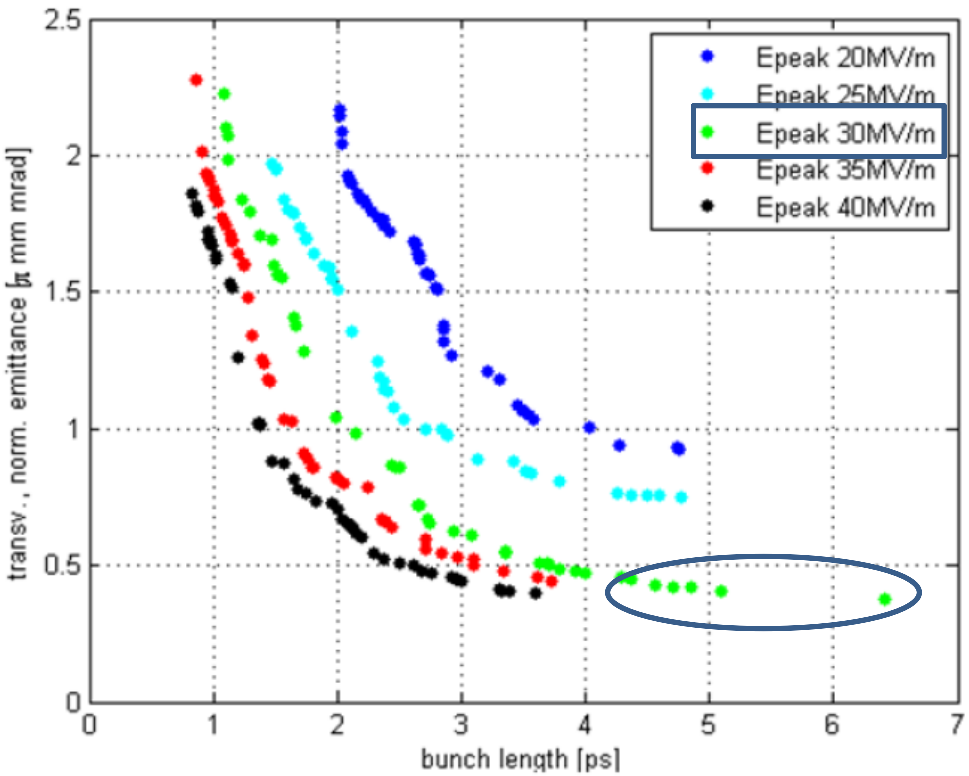
Here peak of dark current emission is well separated in energy from primary beam, as φ_{emitt} << 90 deg

→ Emittance optimized cavity has launch phase closer to peak dark current phase, populate similar phase space (see talk M. McAteer, Thursday)

Eva Panofski, IPAC17 Kobenhavn, THPAB009

EVOLUTIONARY MULTI-OBJECTIVE OPTIMIZATION

optimizing 6 parameter:
laser spot size / pulse length / cathode positon / phase / amplitude / solenoid



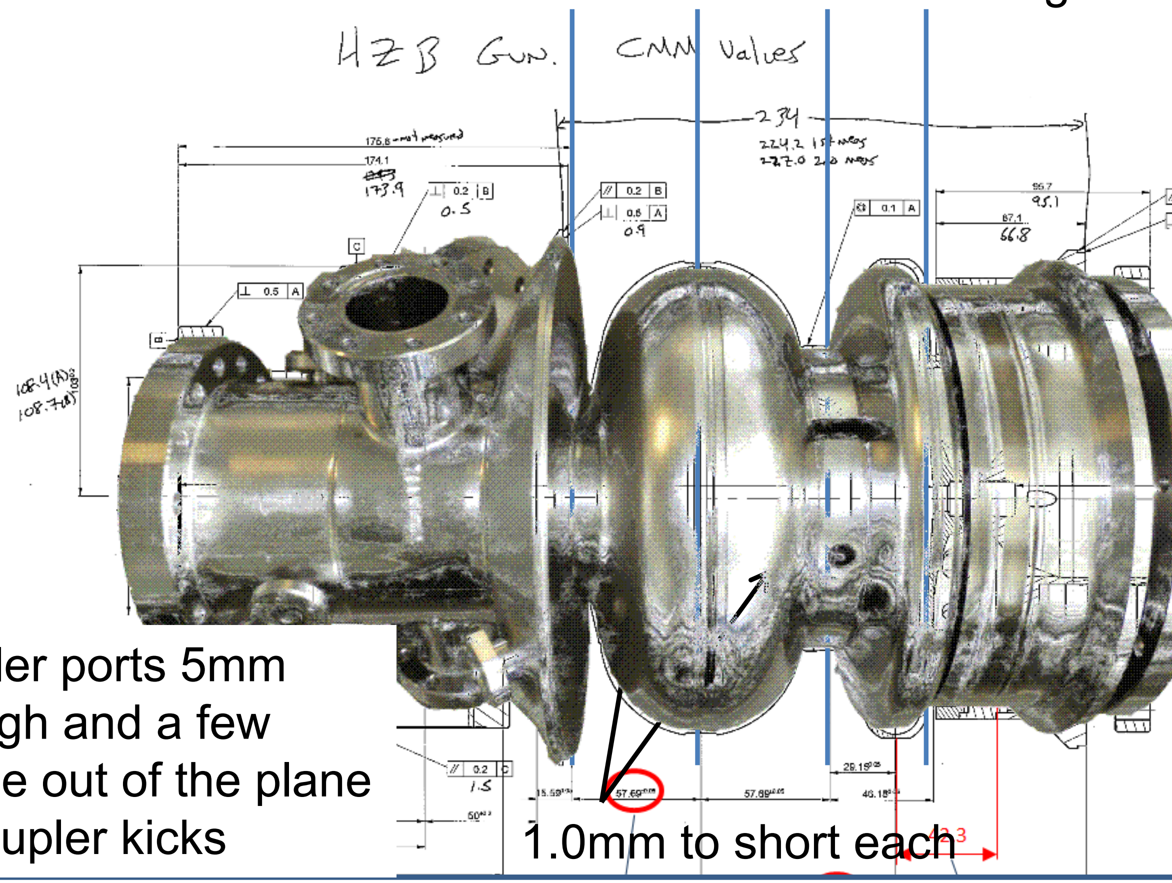
After 50 generations
of the evolution process.

absolut emittance minimum

ε_{min} = 0.31 π mm mrad at z = 2.82 m
for Q_b=77 pC

Reality check: Production status after welding

Half-cell → After tuning 5.7 mm too short



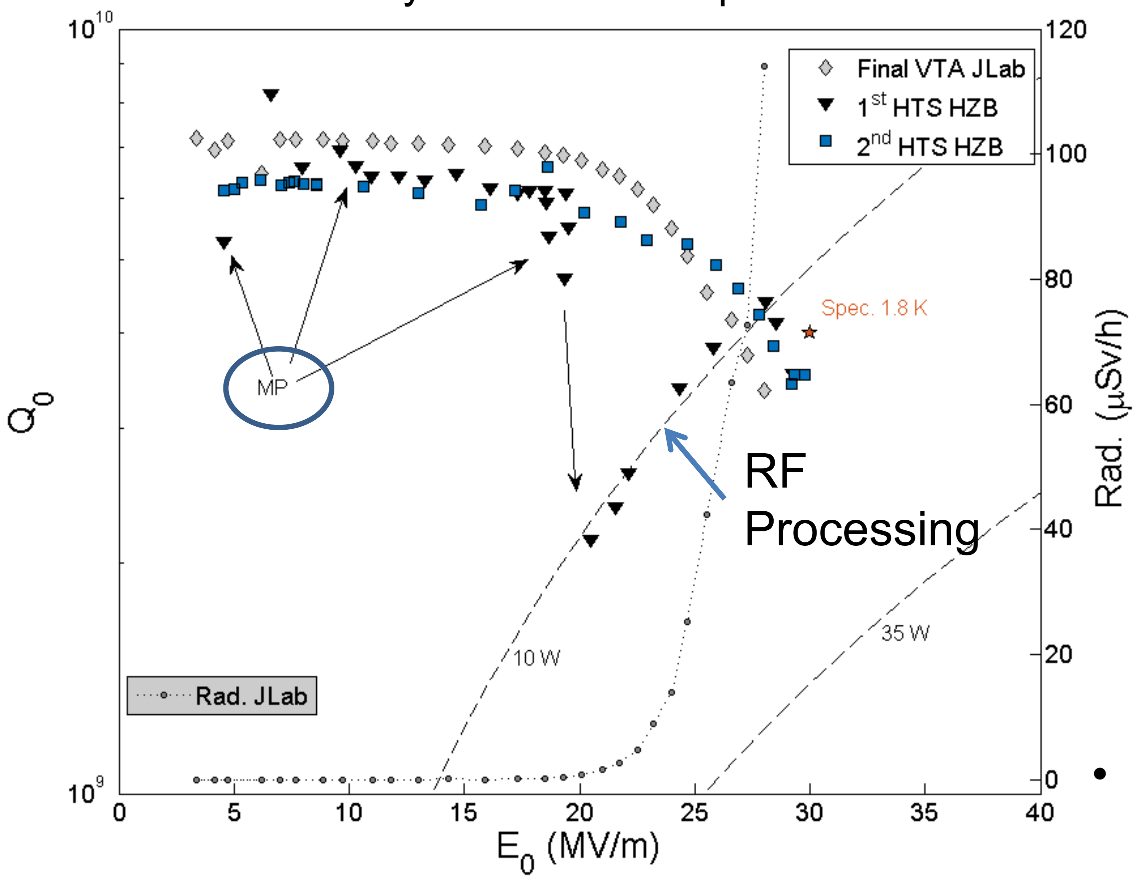
Coupler ports 5mm too high and a few degree out of the plane → Coupler kicks

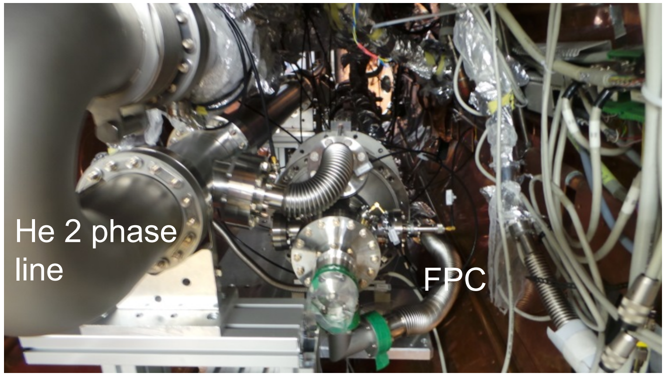
Design	Produced
f TM_{010} π-Mode (MHz)	
1298.823	1298.85
R/Q (Ω)	
150.4	**132.5**
G (Ω)	
174	**156.7**
B_{peak}/E_0 (mT/(MV/m))	
2.27	2.18
E_{peak}/E_0	
1.45	**1.66**
E_{cath}/E_0	
0.743	0.743
$E_0/E_{acc}(\beta=1)$	
1.79	1.82

- Cavity was first of its kind: prototype, complicated structure → unfortunately the design geometry was not fully met
- Half cell too short → implications on beam dynamics and peak field ratios

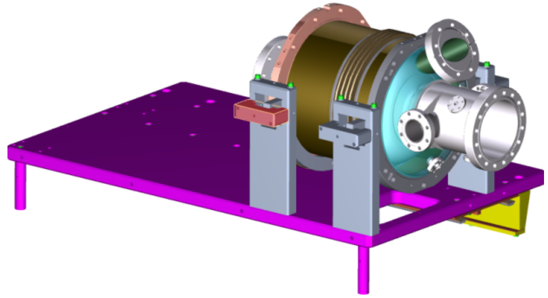
Series of Horizontal Gun1.0 tests at HoBiCaT

First test after delivery from JLab compared to last vertical test





Set up in HoBiCaT



The strong multipacting seen at 18-20 MV/m was also seen by oscillating superleak transducers in vertical test.
→ Multipacting reconstructed by simulations

- Main design criterion is the on-axis peak field E_0
  → Cathode field during emission
- RF losses are of less impact, but low dark current required
- Test at HoBiCaT under vertical test configuration ($\beta_c \simeq 1$)

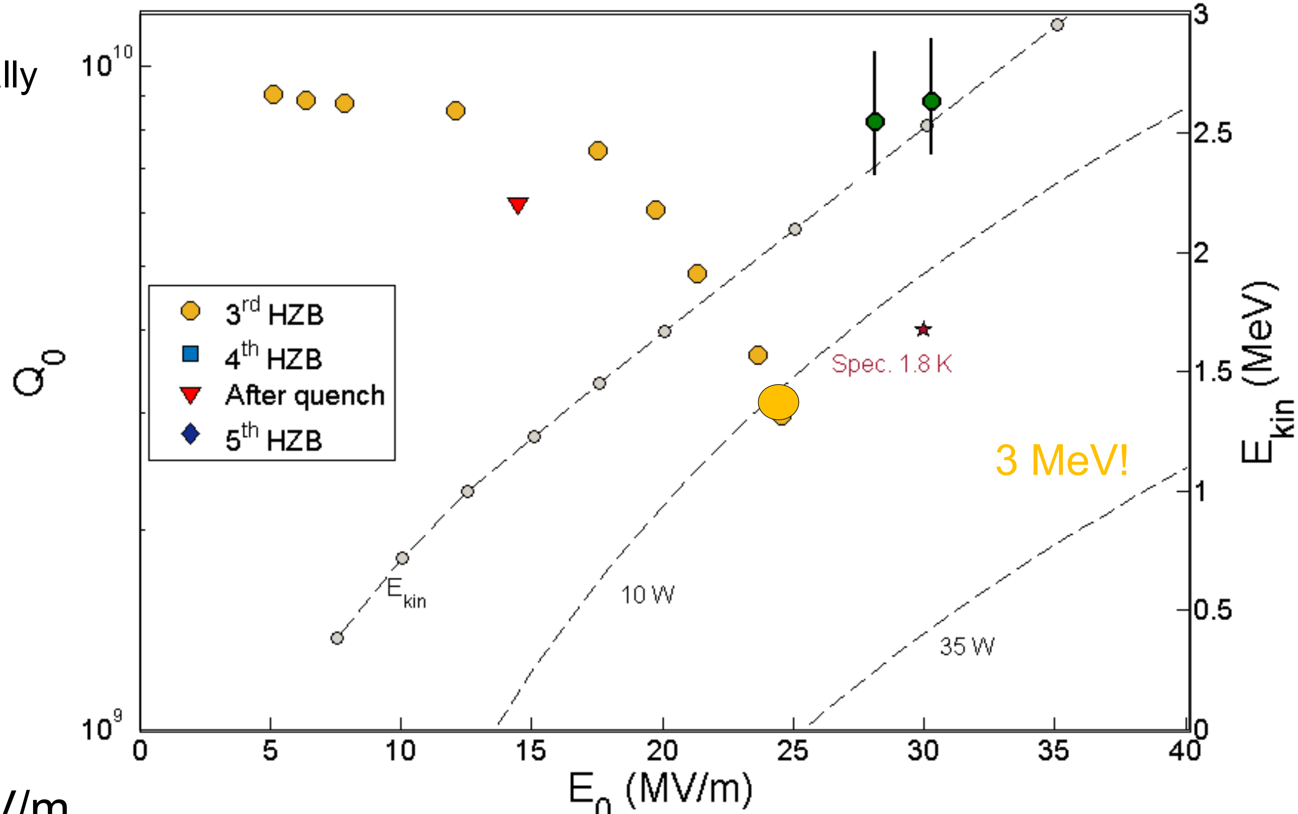
2nd test series after workshop modifications

After work on the helium vessel a further test was required:

- Unfortunately the cavity was vented by a short vacuum hose
- Cavity multipacted and eventually quenched at low fields
- This was overcome by RF processing (yellow dots)→ finally quenched at 35 MV/m
- The cavity was recovered by thermal cycle above T_C and achieves the design field of bERLinPro

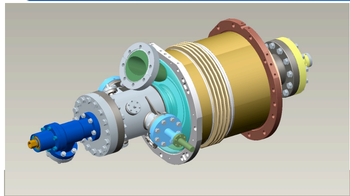
Peak fields achieved:
E_{peak}=57.3 MV/m
B_{peak}=110.4 mT
Corresponds to E_{acc}=26 MV/m of a TESLA cavity

Green data points:
Q_0 measured by helium evaporation

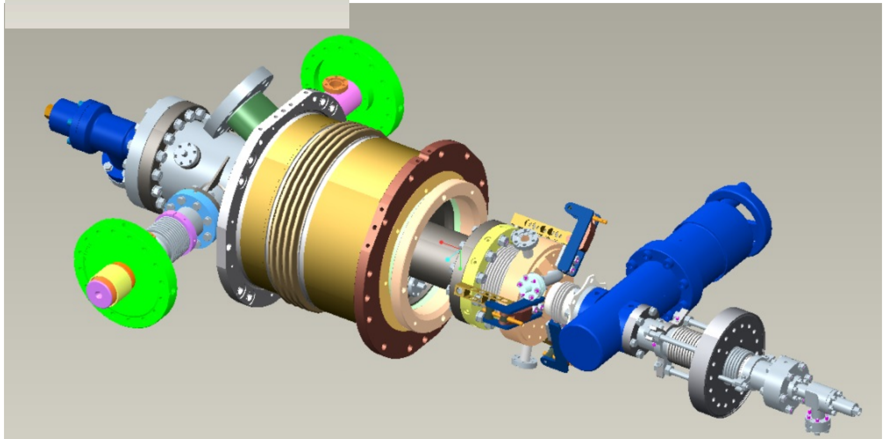


2.5 MeV, $Q_0=5.3 \cdot 10^9$@ 1.8K
Satisfactory

Cold string assembly



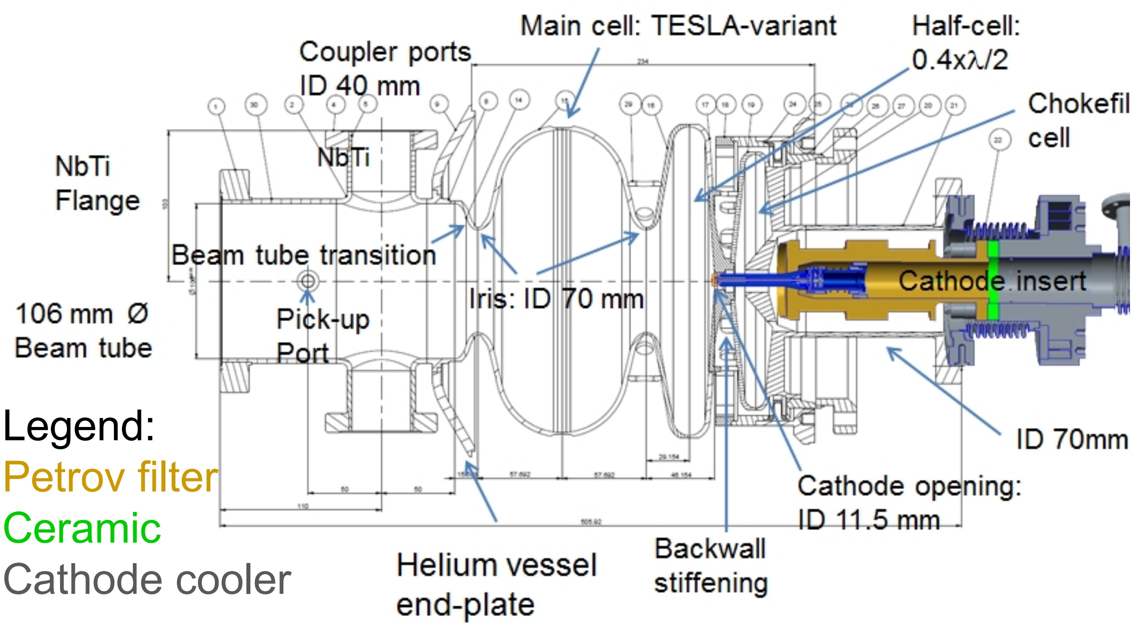
Goal



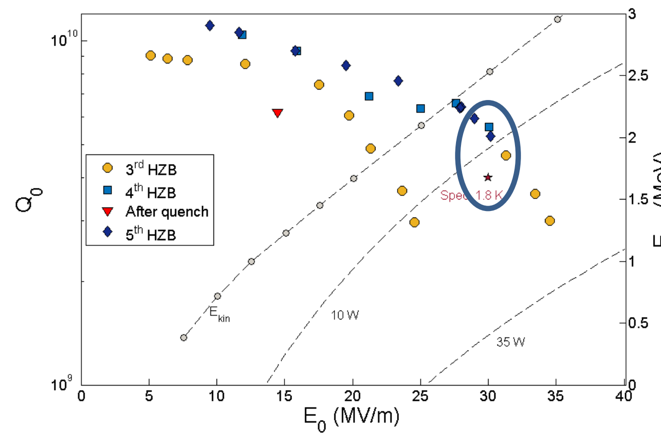
- After horizontal acceptance test assembly of small cold string in ISO4/5 clean room:

  Valve, RF coupler, Cavity, cathode cooler with Petrov filter, gate valve and cathode tube with corner valve

- Follow up horizontal test in module configuration to check if cavity “survived“ procedure, achieve bERLinPro goal



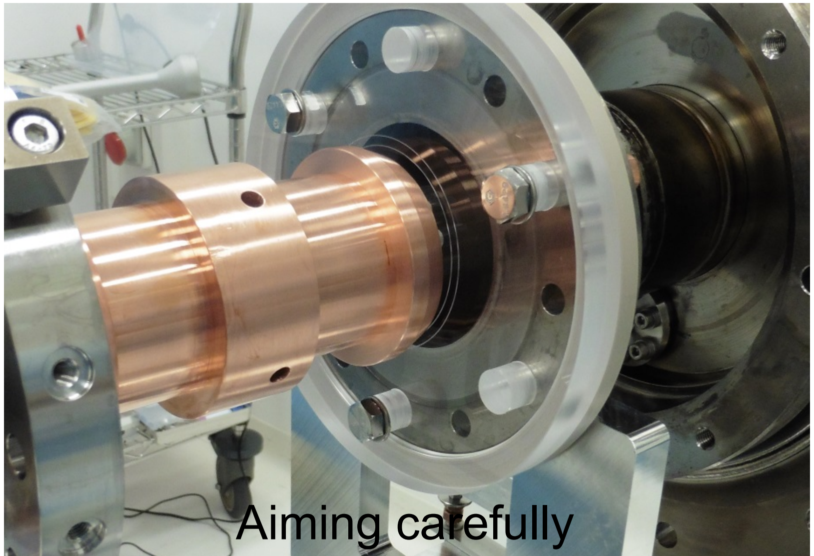
Legend:
Petrov filter
Ceramic
Cathode cooler



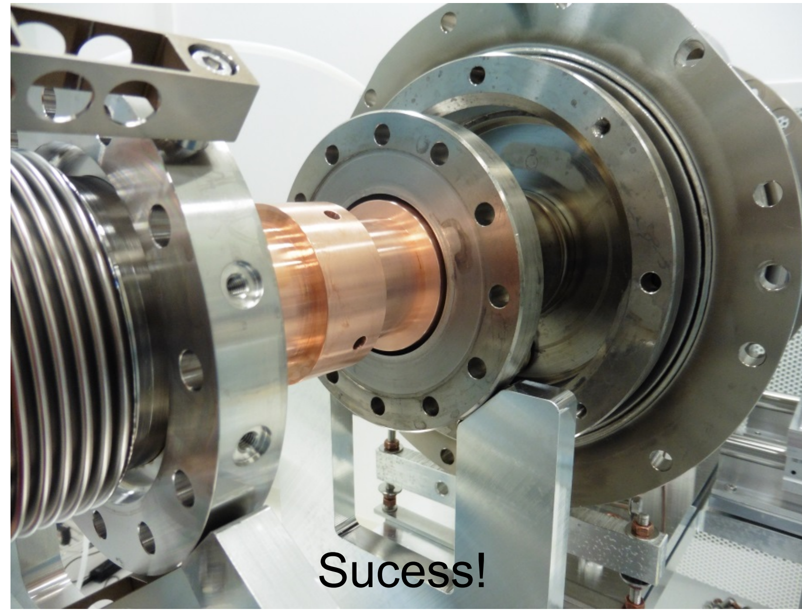
Critical: Insertion of Petrov filter and cathode cooler

Impressions of the assembly

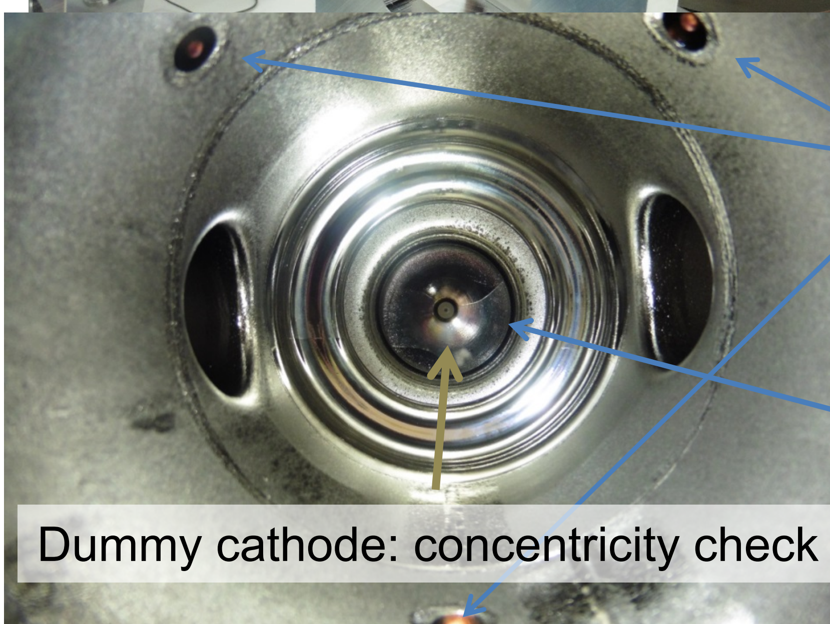
Mounting of the Petrov filter and cathode carrier



Aiming carefully



Sucess!



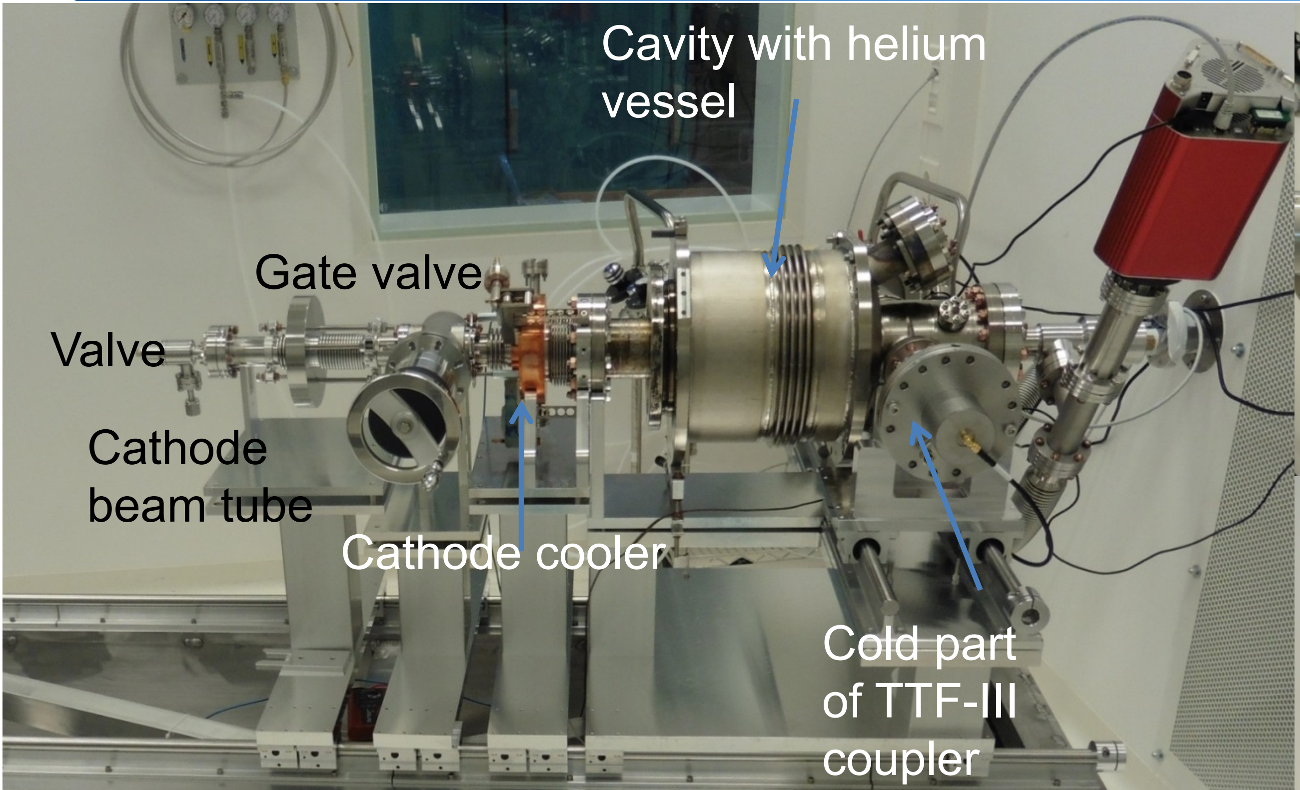
Dummy cathode: concentricity check

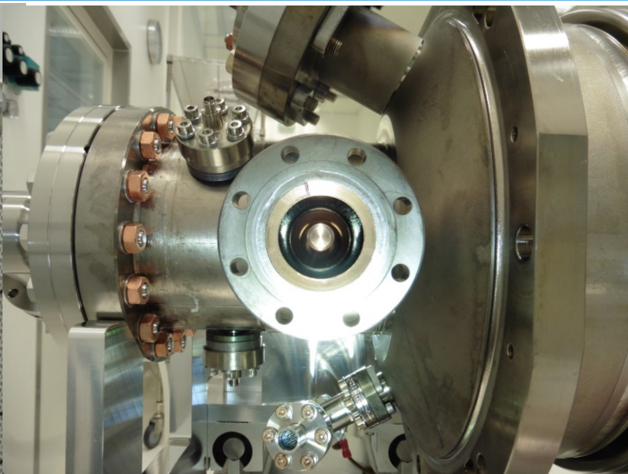
What do you see here:
3 pick-up antennas

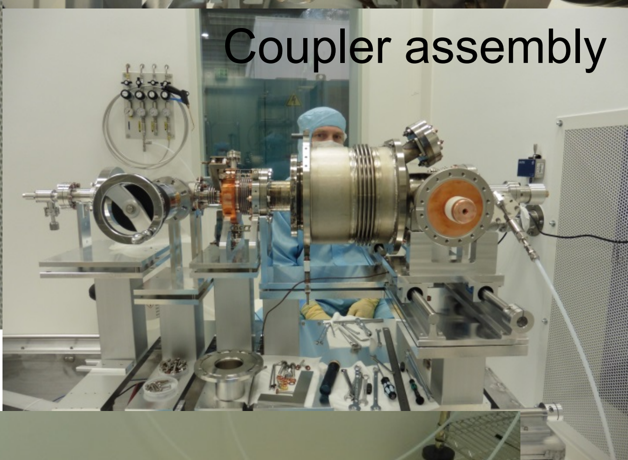
Ports for twin coupler arrangement

Part of half-cell back wall, large grain Niobium, grain boundaries visible

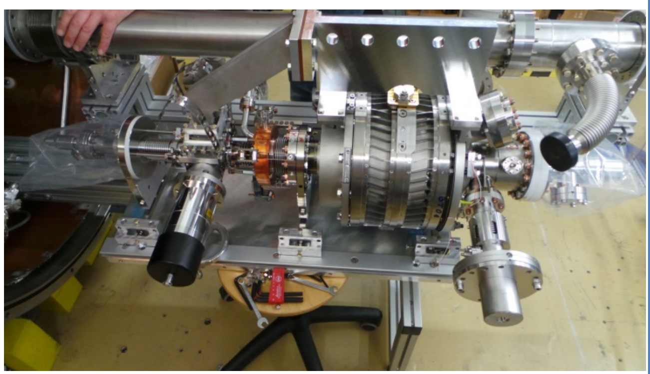
Final steps of assembly





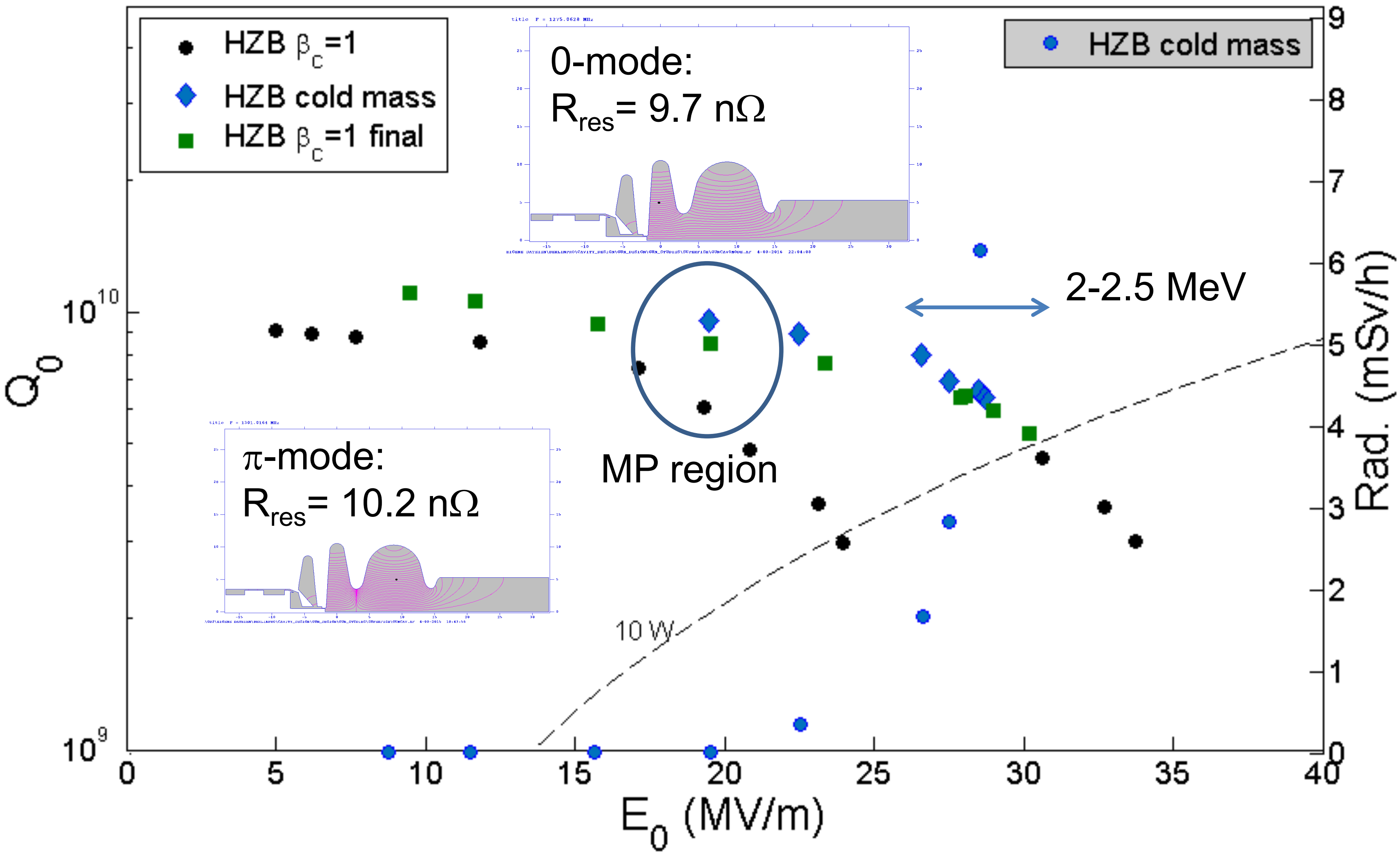


→Install cold string for horizontal acceptance test



Special thanks to DESY MKS-3: A. Matheisen, M. Schmökel, for training, support, discussion and participation in cold string assembly!

Q_0 conserved after cold string assembly

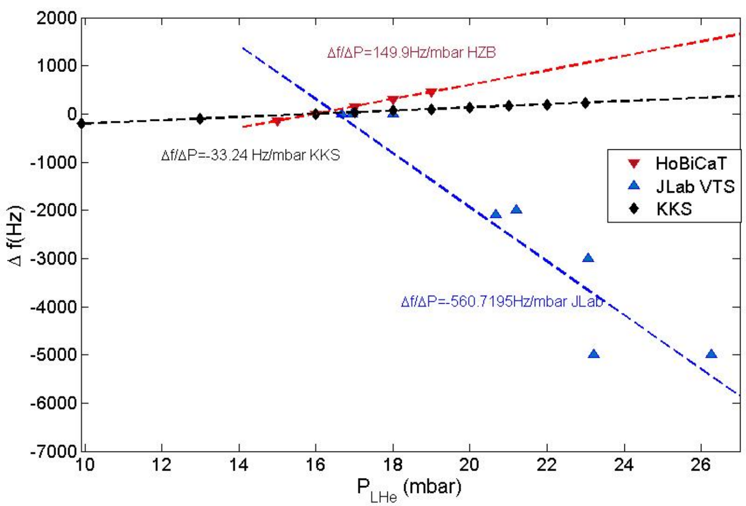


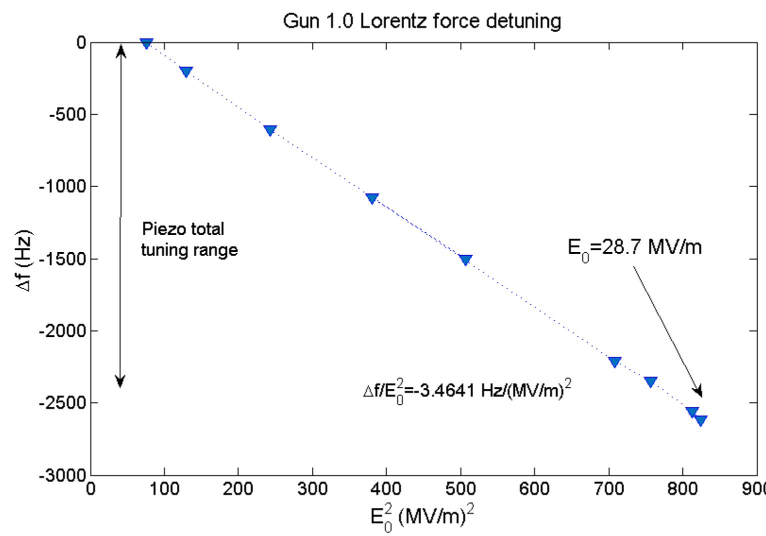
Blue diamonds taken after pulse processing by He 2K gas flow, higher field possible, but not done as of radiation limit

RF properties so far

Parameter	VTA JLab	HTA HZB	Cold string HZB	Module
E_0 (MVm^{-1})	34.9	34.5	28.5§	-
E_{peak} (MVm^{-1})	58	57.3	47.3	-
B_{peak} (mT)	111.8	110.4	91.2	-
low field Q_0	$1.2{\cdot}10^{10}$	$1.1{\cdot}10^{10}$	$9.6{\cdot}10^{9}$	-
$\Delta f/\Delta E_0^2$ (HzMV^{-1}m)^2	-4.7	-3.7	-3.4	-
$\Delta f/\Delta P_{\mathrm{LHe}}$ (Hzmbar^{-1})	-561	150	33	-
$\Delta f/\Delta l$ (Hz/step)	-	-	2.3 (1.8 K)	3.8 (300 K)

SRF properties conserved so far, mechanical properties close to design

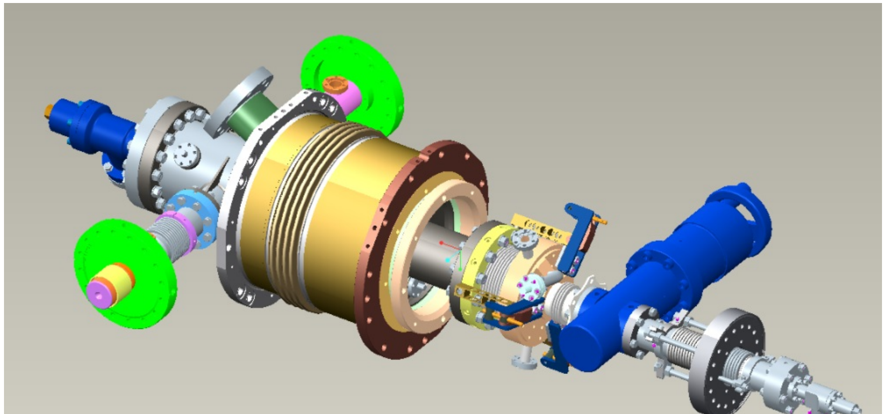




Next steps

It is crucial to evaluate the cavity performance at every major step or change to the system:

- Measure cavity's Q_0 and field level after module assembly, all valves closed (We are here)*
- Measure cavity again after opening of shutter valves to diagnostic beam line and cathode transfer chamber
- Characterize the same properties after insertion of the cathode



Pumping via 11.75 mm opening with low particle pump stand

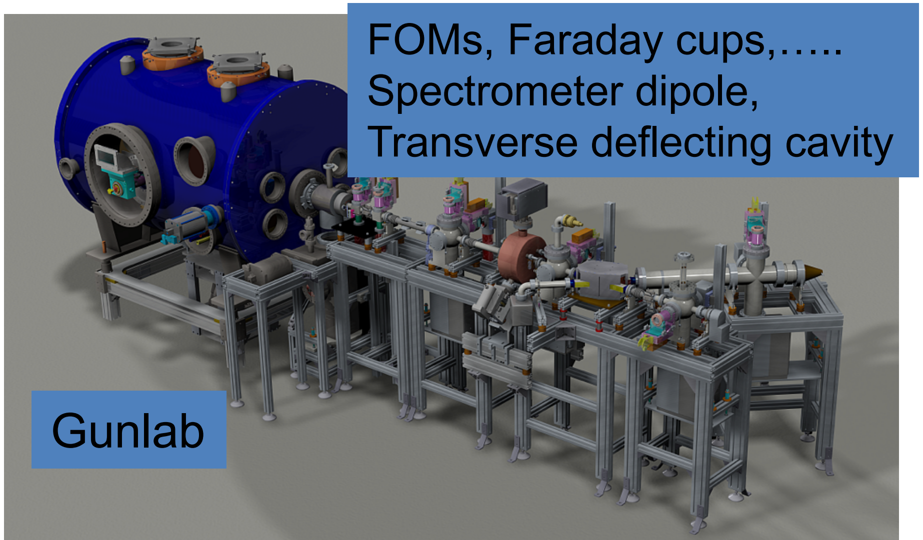
*However, this was risky:

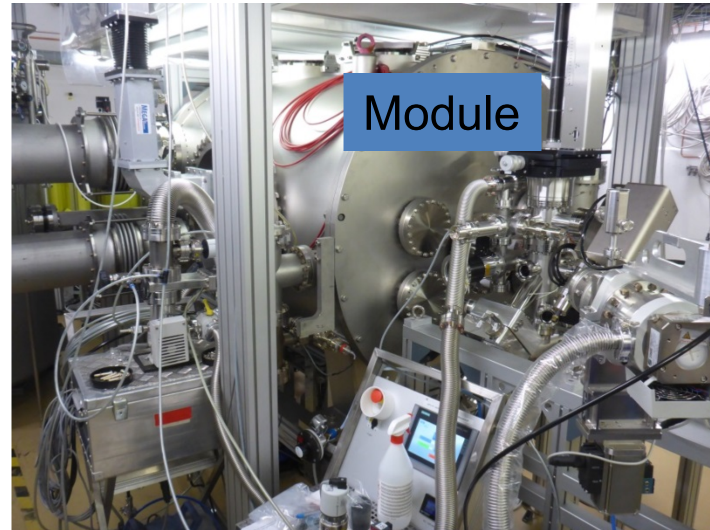
P. Kneisel, SRF 1995, Effect of Cavity Vacuum on Performance of Superconducting Niobium Cavities:

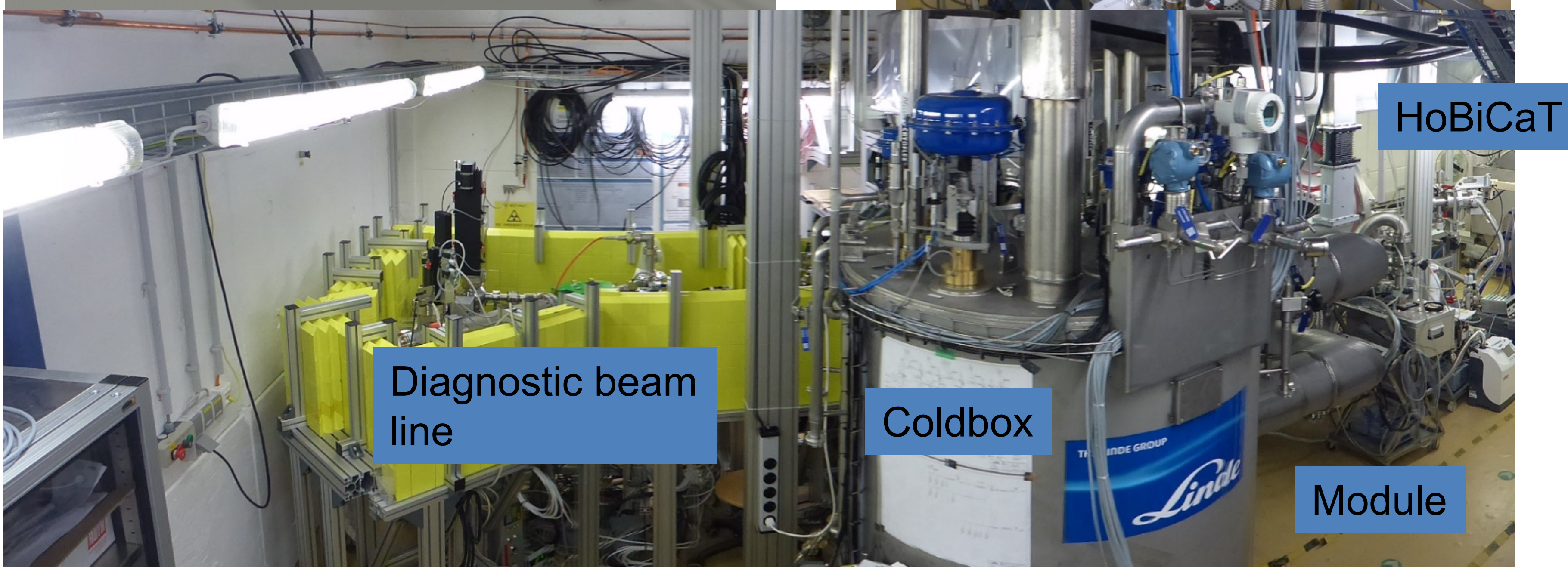
Degradation of electron loaded cavities in surface resistance and field (field emission) if starting pressure $\geq 1 \cdot 10^{-4}$ mbar

We were on the edge, but gave it a try

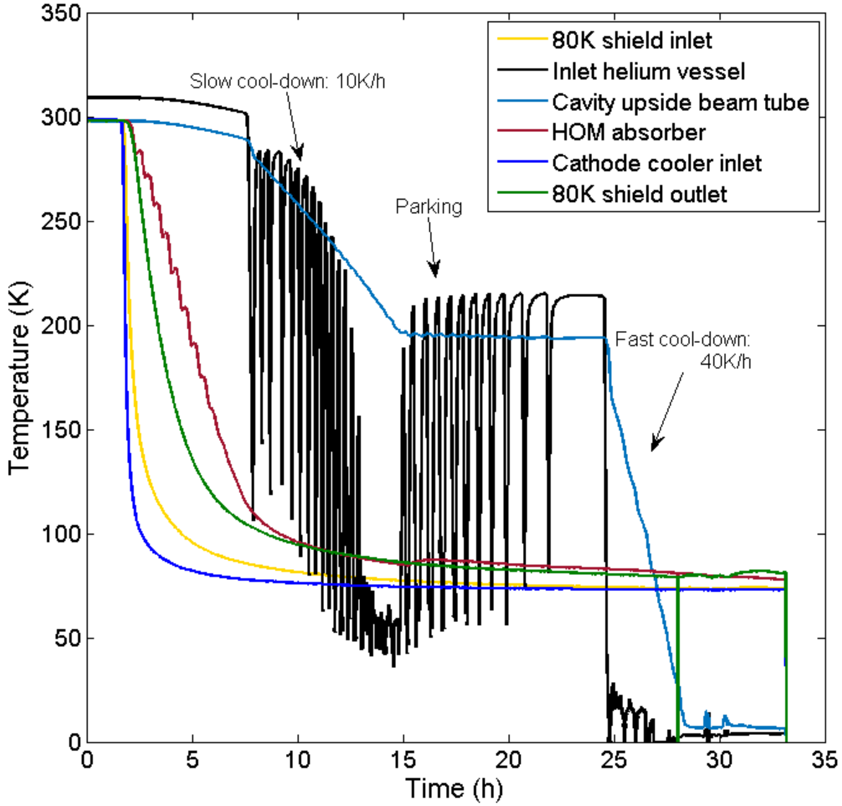
Installation of Gun Module in Gunlab





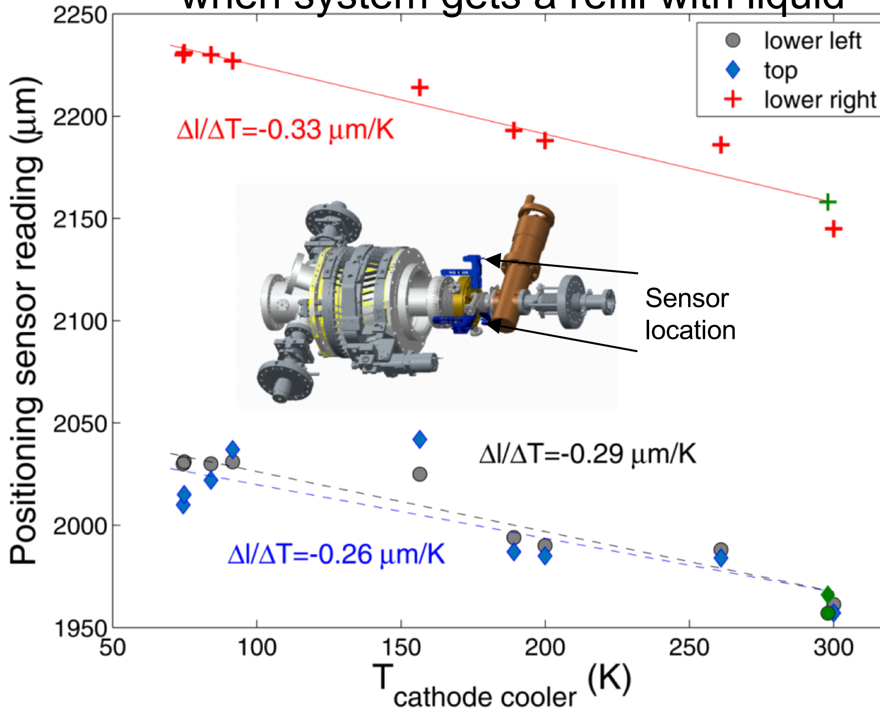


Cooldown results

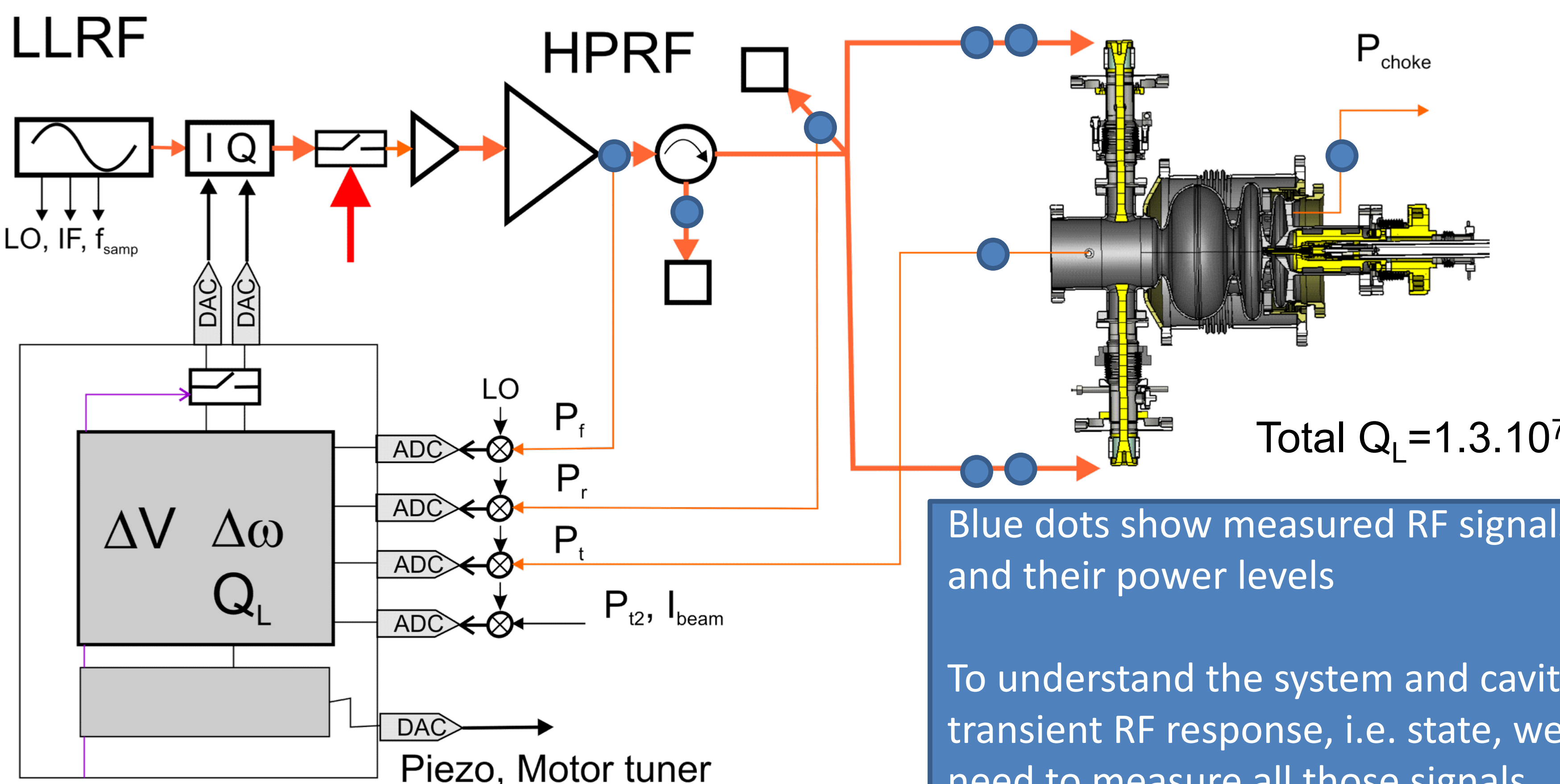


Uniform cathode holder movement during cooldown, about 50µm from 300 K to 80 K
Monitored by cryo compatible capacitive sensors

- Cryo-systems works fine.
- However, thermal bridge between probably 80K system and 2K system observed. Reasons not fully understood→
  HGRP and returned gas in cold-box both showed elevated temperature (25 K)
- Therefore cooling from filling line below cavity (Not JT).
- Some coupling in helium loss data when system gets a refill with liquid



The RF/LLRF measurement set up



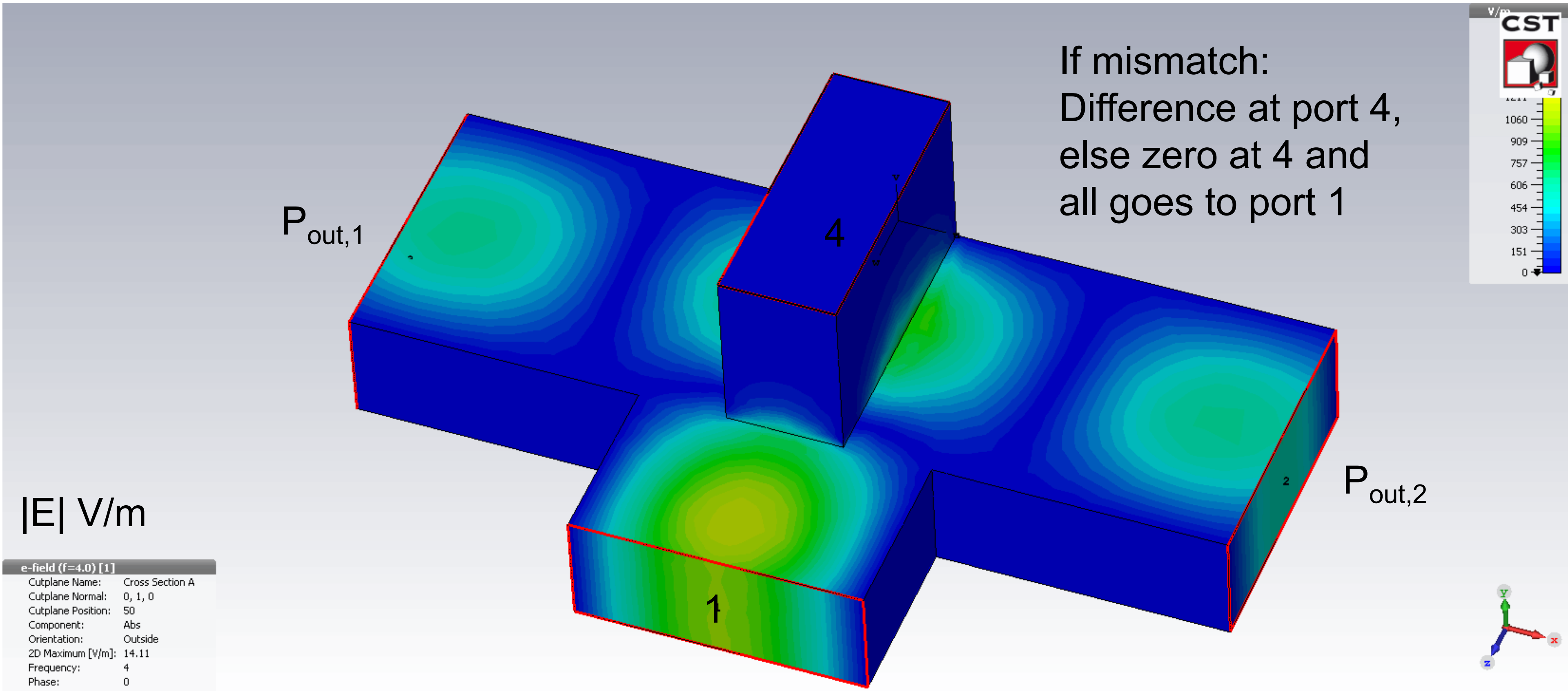
Cavity with blade tuner including four symmetric attached piezo stacks (Cornell type)

Blue dots show measured RF signals and their power levels

To understand the system and cavity's transient RF response, i.e. state, we need to measure all those signals

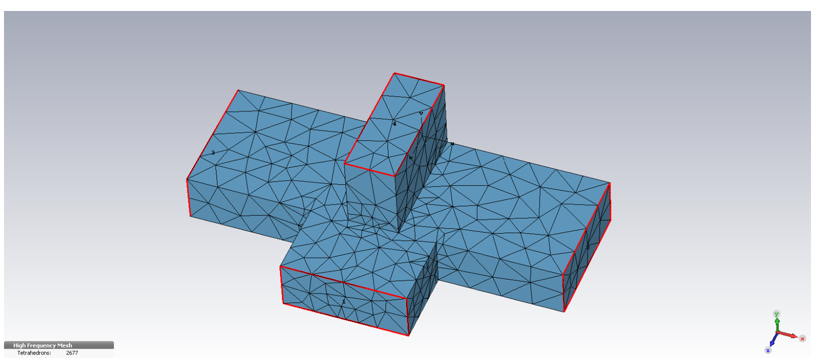
Unfortunately, the couplers were not 100% symmetric assembled because of geometry deviations of ports

Two coupler operation: Magic Tee



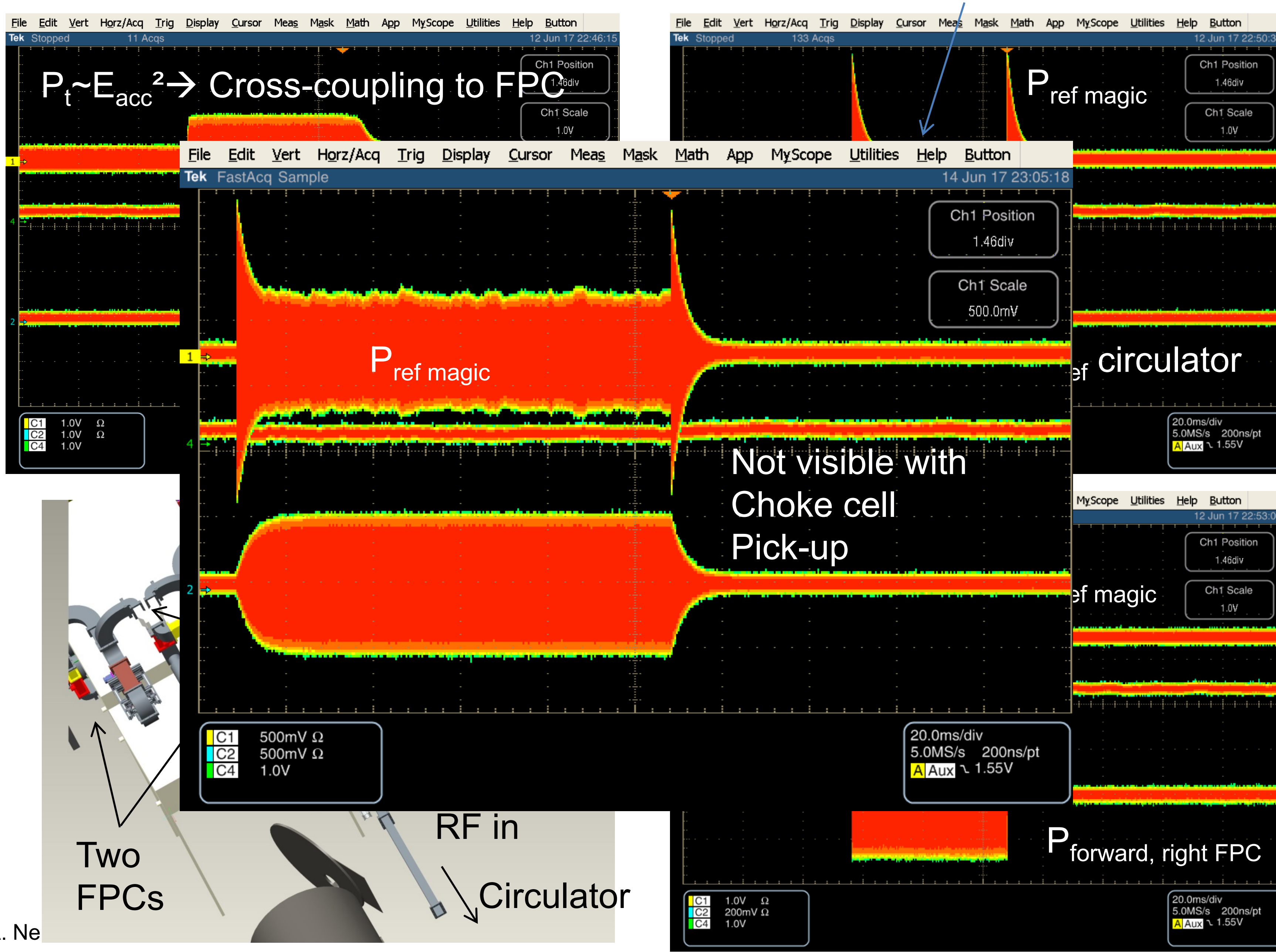
If mismatch:
Difference at port 4,
else zero at 4 and
all goes to port 1

P_{in}



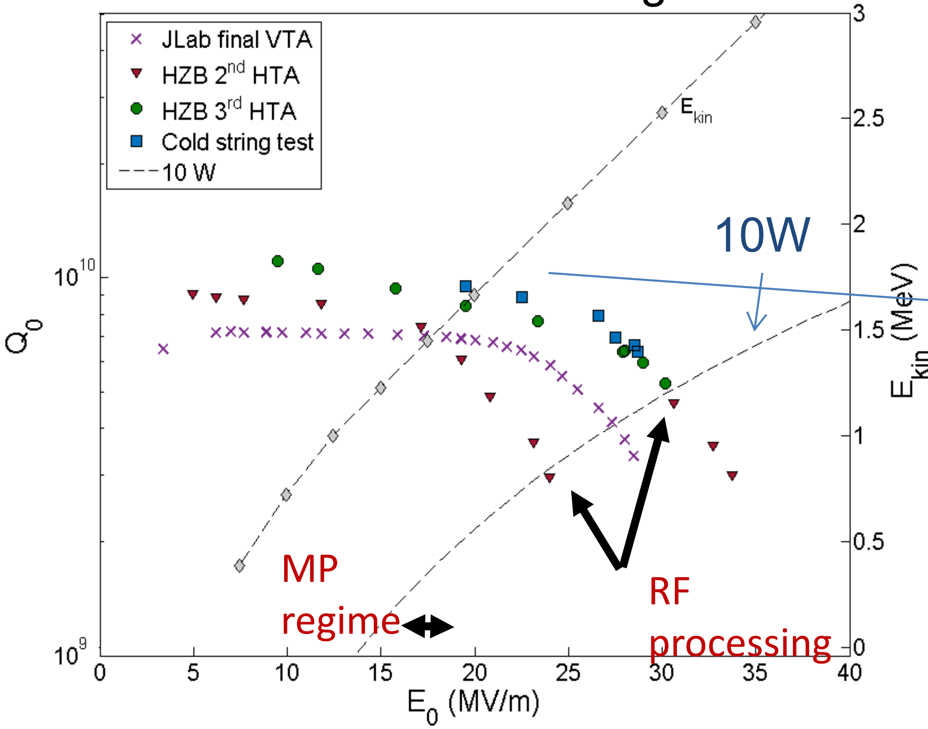
Invented during WWII, published W. A. Tyrell (of Bell Labs) in 1947

It‘s a kind of magic….magic tee pulsed behaviour

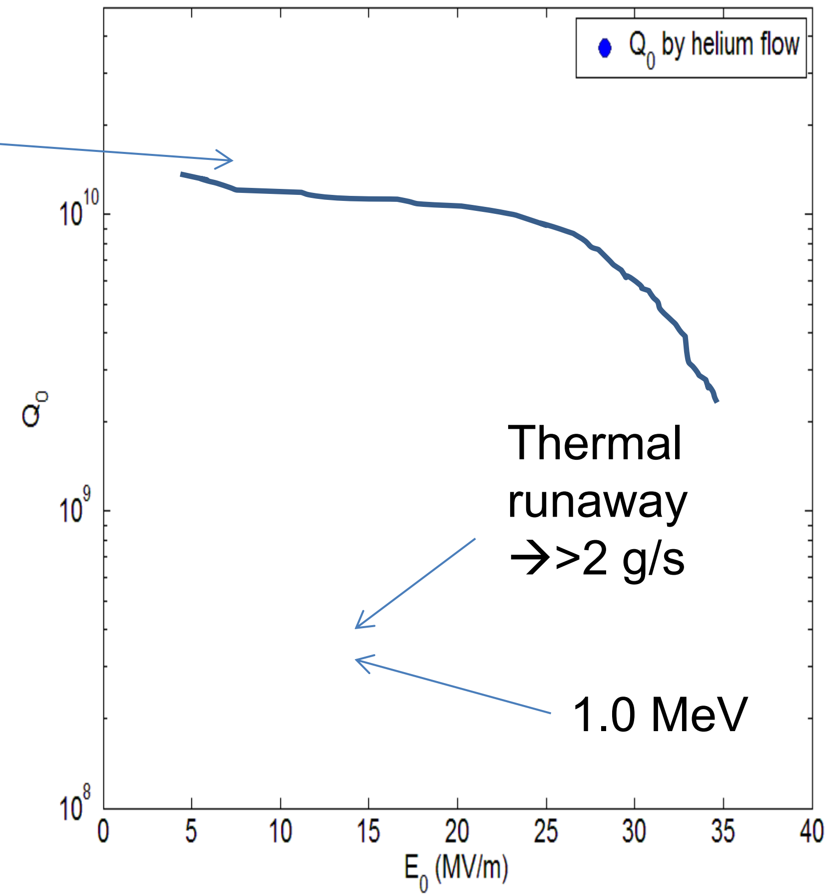


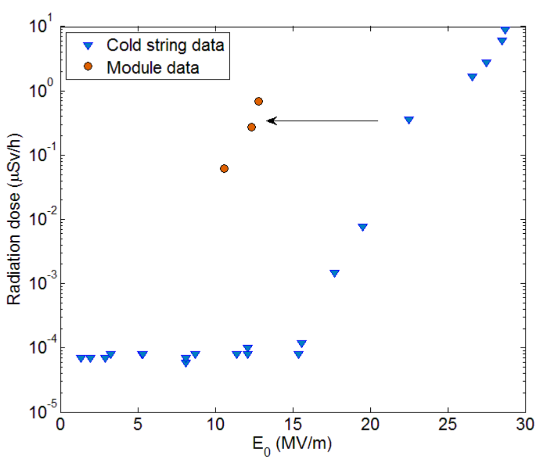
Q_0 and field of first module test (last week)

VTS/HTS+ cold string



First module data





Earlier field emission on-set

The coming weeks:

- Operating license received, opening of gate valve possible
- Warm up to room temperature, establish vacuum system via foreseen pump ports at beam line and transfer chamber
- Cooldown again with proper vacuum condition
- Currently vacuum level low 10^{-10} mbar next to module
- Follow-up cooldown week after ERL17
- First RF test w/o cathode (+dark current)
  → cathode transfer of Cu cathode
  → again RF test with cathode (+dark current)
  → LLRF commissioning
- First beam on screen

Acknowledgments

Incomplete list of people helping with collaborative effort and discussion:

J. Teichert, A. Arnold, P. Kneisel, M. Liepe, R. Rimmer, H. Wang, W. Xu, S. Belomestnykh, E. Zaplatin, E. Kako, T. Konomi R. Eichhorn, J. Sekutowicz, G. Ciovati, L. Turlington, D. Reschke, A. Matheisen, M. Schmökel, B. van-der-Horst, V. Volkov, D. Kostin, I. Will, W.-D. Möller + many more

and the HZB gun cavity and high brightness beam teams + the bERLinPro team members

D. Böhlick, A.B. Büchel, M. Bürger, P. Echevarria, A. Frahm, H.-W. Glock, F. Göbel, S. Heling, K. Janke, T. Kamps, S. Keckert, S. Klauke, G. Klemz, J. Knobloch, G. Kourkafas, J. Kühn, O. Kugeler, B. Kuner, N. Ohm, E. Panofski, H. Plötz, S. Rotterdam, M. Schenk, M.A.H. Schmeißer, M. Schuster, H. Stein, C. Schröder, Y. Tamashevich, J. Ullrich, A. Ushakov, J. Völker +…

Merci beaucoup

Workshop: Reliably operating SRF in a 'Dirty' accelerator

14th -15th September 2017
Helmholtz-Zentrum Berlin

HZB Helmholtz Zentrum Berlin
BESSY VSR

Aim: to gather together the expert community to compile experience with these operating conditions and develop recipes for the reliable operation of high-voltage SRF.

Topics of interest

- Contamination of SRF cavities and how to deal with it.
- Cleanliness of the cavities
- Long-term performance degradation and mitigation schemes
- Dealing with synchrotron radiation
- Particle transport
- Design of cryogenic plant and helium transfer system

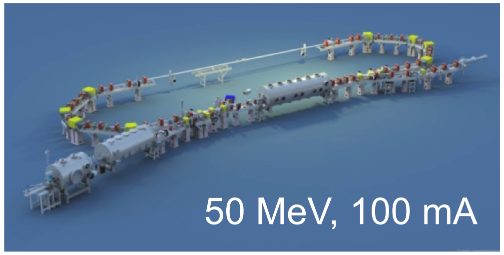
Important Dates

Deadline for submission of abstracts, registration and payment: 31st August 2017

For more information please contact: emmy.sharples@helmholtz-berlin.de
Registration Online now at: https://www.helmholtz-berlin.de/events/operating-srf/index_en.html

Backup slides

What are the challenges for SRF Photoinjector Cavity design?



bERLinPro needs to preserve and recirculate a:

- **Low emittance beam with high peak brightness and high average current**
- **Dark current level as low as possible to mitigate beam Halo**

Low emittance < 1μrad:

- High electric field component at cathode during bunch emission to counteract space charge driven beam expansion
- Sufficient large radial field components for beam RF focusing
- Energy gain of 2.3 MeV at high launch phase using the given forward power level to full extend *coupler limit, transmitter limit*

Peak brightness 77 pC @ 1.3 GHz (see talk J. Kühn on Monday):

- Insert a high quantum efficiency NC semi-conductor cathode in SC environment *SC requires dust free environment, thermal isolation*

High average current 100 mA:

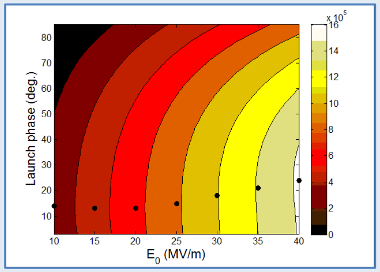
- Achieve good HOM damping capabilities. Absorber as close as possible *solenoid as close as possible, SC solenoid*

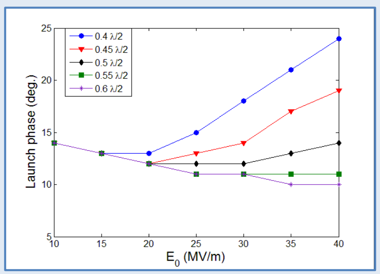
Dark current: Avoid, if possible, highest field on axis on cathode surface and opening of back wall *low emittance, low cathode work function*

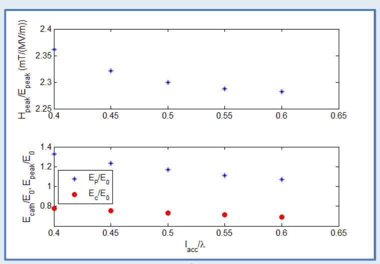
SRF: Keep field ratios low (e.g. B_{peak}/E_{max} as Hc1 Nb about 160mT)

Cavity design flow

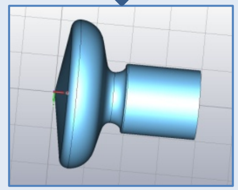
Analyze results, Parameter scan Optimizer

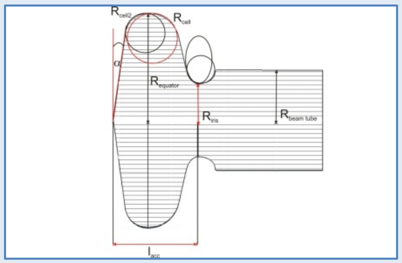






2-D studies: 0.X-cell

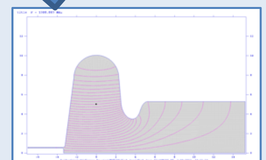




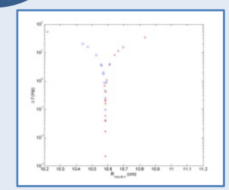
Change geometry parameter

Optimize for
1. Beam dynamics
2. HOM properties
3. SRF parameters

Tune frequency by Golden Section Search Optimizer



Calculate Cavity parameter



Energy-phase-field scan

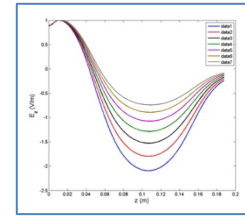
Power limit met?

$$Q_L = \frac{V_{cav}}{\frac{r}{Q} I_b \cos\varphi_b}$$

$$P_f = \frac{V_{cav}^2}{\frac{r}{Q} Q_L 4}\left(1 + \frac{\frac{r}{Q} Q_L I_b}{V_{cav}} \cos\varphi_b\right)^2$$

Results

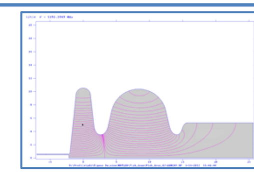
Field distributions

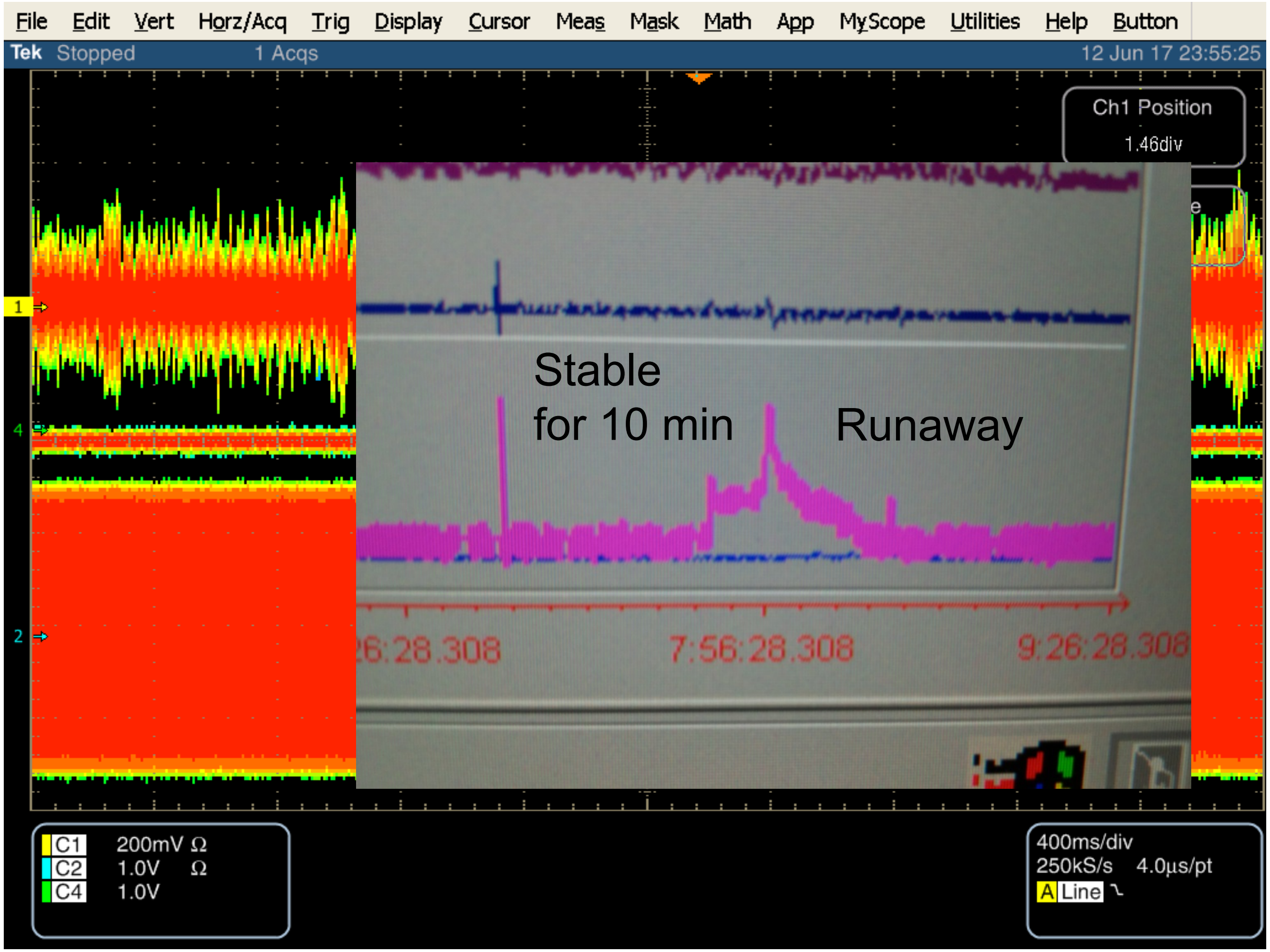


E_z, E_r

External ASTRA scans, MOGA studies High brightness beam group T. Kamps

Need for?
- RF focusing
- Launch phase
- Launch field





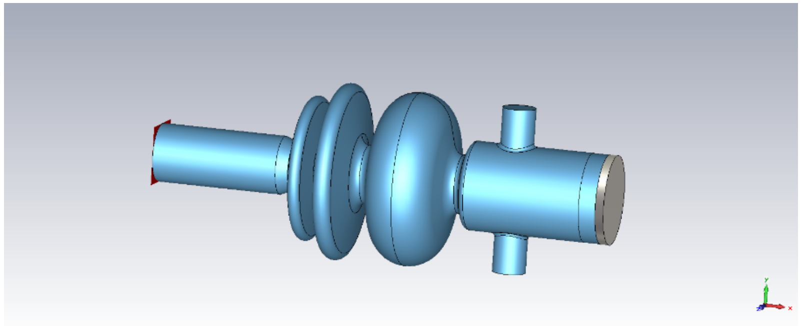
E_0=11.1 MV/m

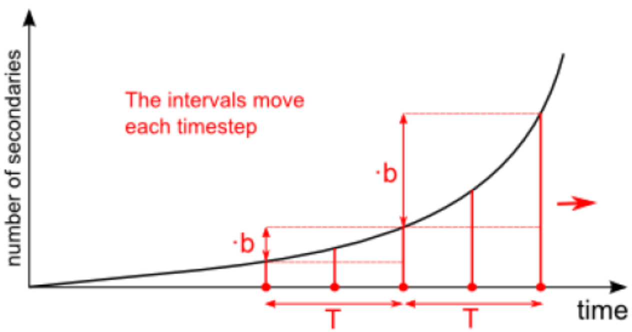
After ten minutes of stable operation these events appeared:
1.25 Hz, some MP?
Field emission remained constant within slow integration time of radiation sensor

Helium losses ran up from 0.63 g/s to 1.2 g/s and increasing→ RF off

$Q_0=1.06\cdot10^9$ decreases to $Q_0=3.65\cdot10^8$

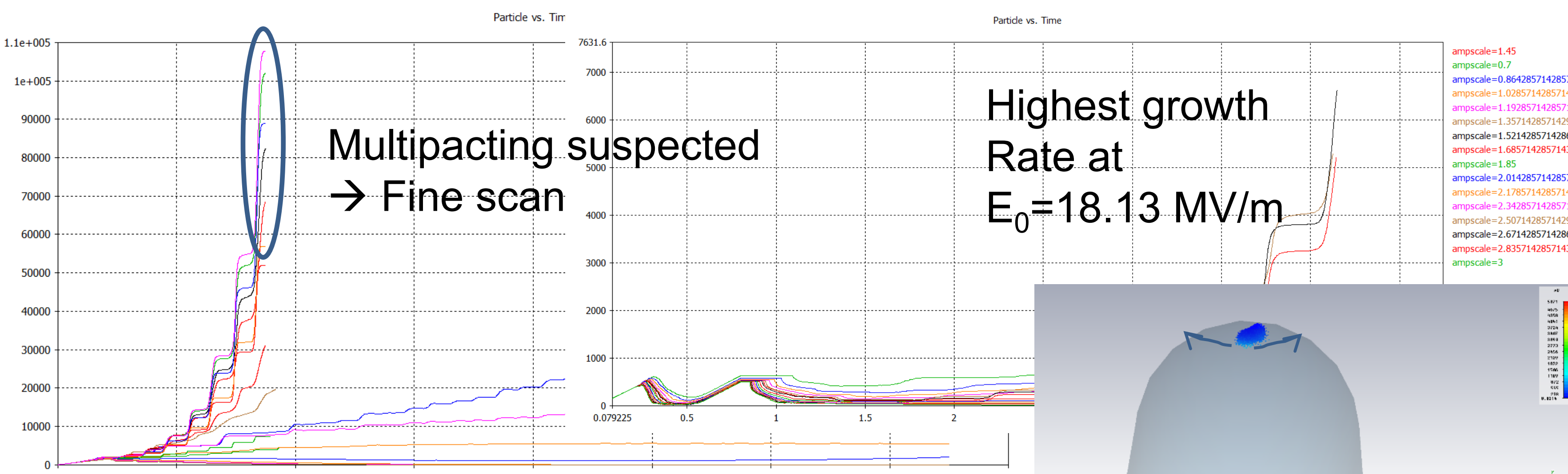
Multipacting in half cell at E_0=18 MV/m





Procedure:

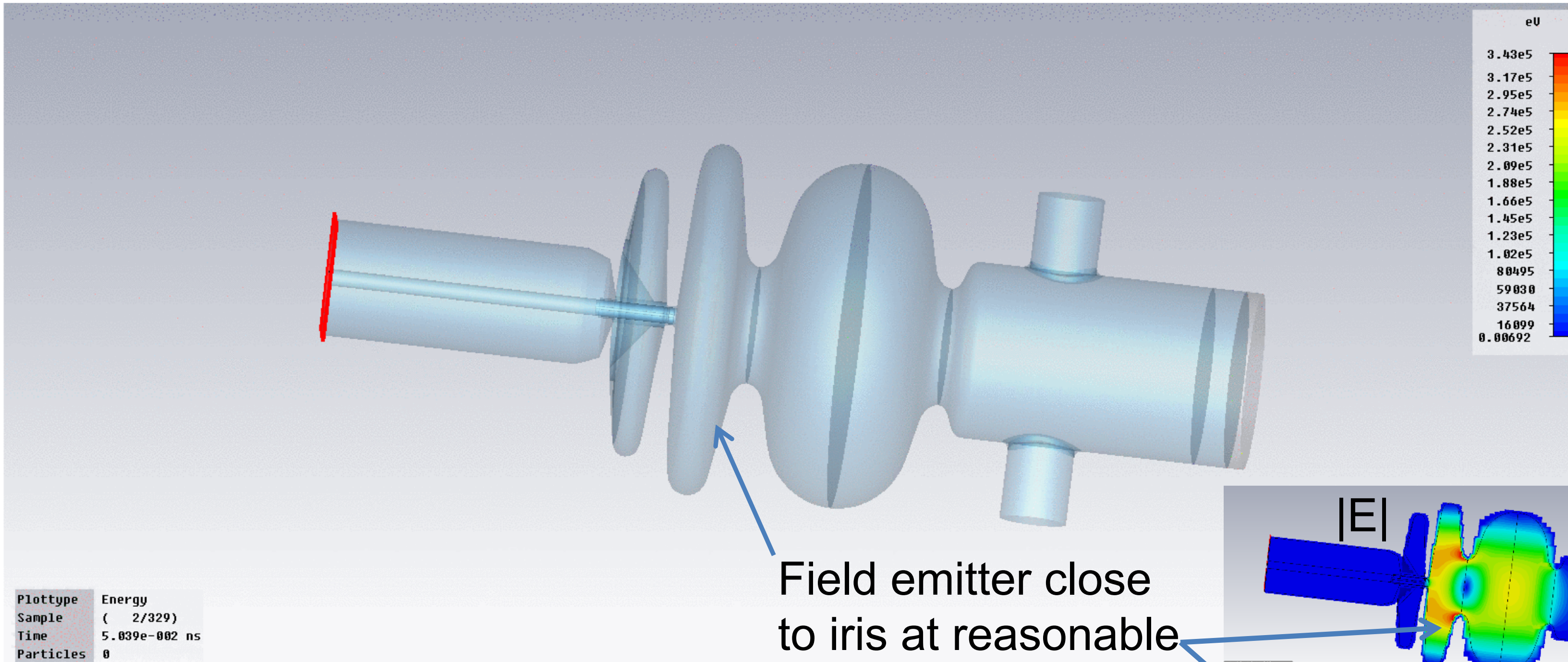
- EM calculation for 3D field distribution (H- and E-field)
- Import of field into PIC simulation
- Placed electron emitter in equator dome of half cell, emits about an RF cycle SEY set to Niobium (300°C Bakeout) (E. Tulu et al., SRF2013, R. Calder et al.)
- Calculation stops when exponential electron growth rate is observed (T_{simu}=18 ns)



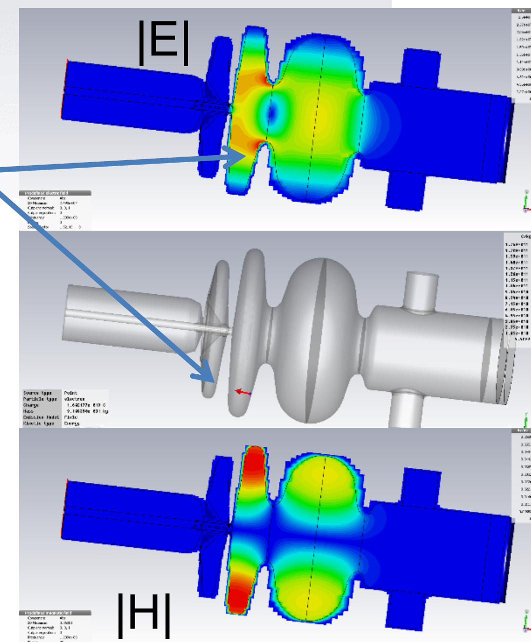
Multipacting suspected
→ Fine scan

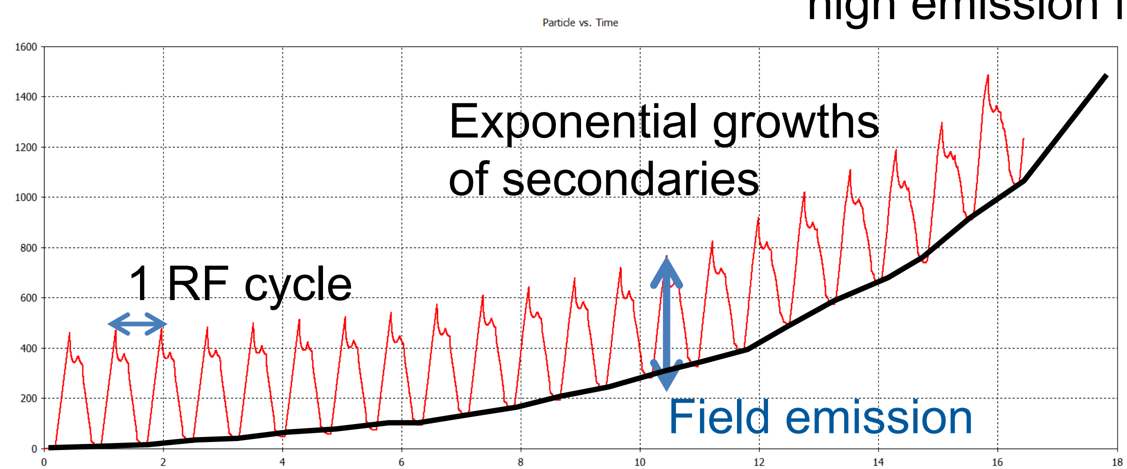
Highest growth
Rate at
E_0=18.13 MV/m

Multipacting triggered by field emission



Field emitter close to iris at reasonable high emission field





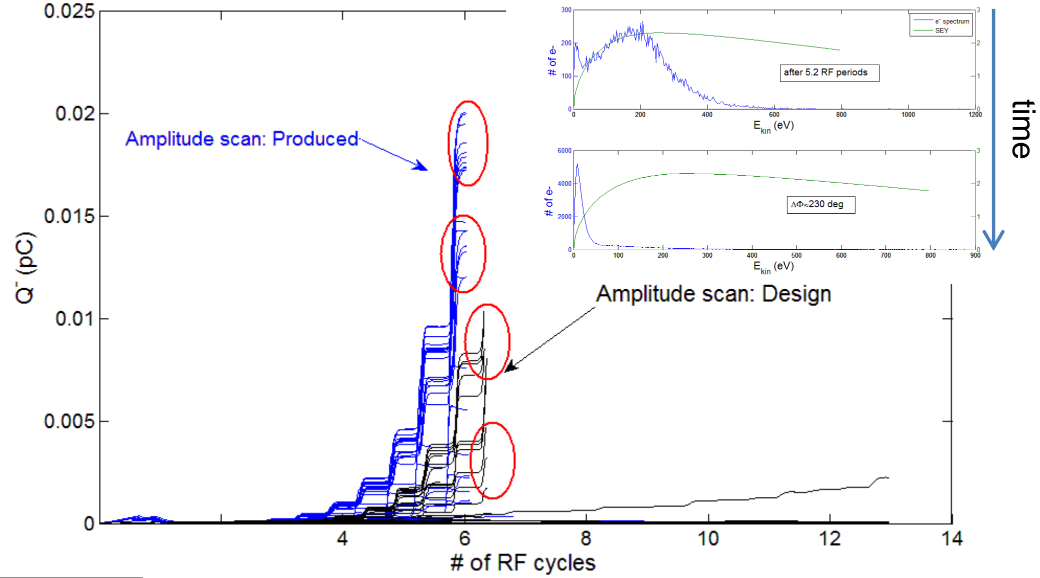
A. Neumann, ERL 2017, CERN, Geneva

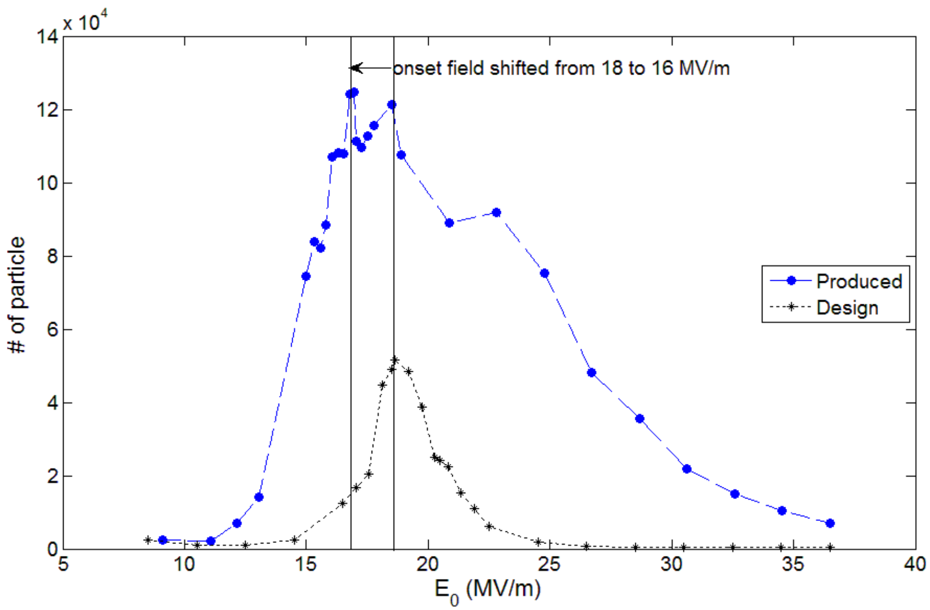
Comparing design and produced model

- SEY of etched and water rinsed Nb surface has a peak of ~2.3 at 250 eV
- Triggered MP by field emitter

2 groups of MP field levels in half cell's dome

distorted geometry:
Factor of 2.5 stronger MP effect

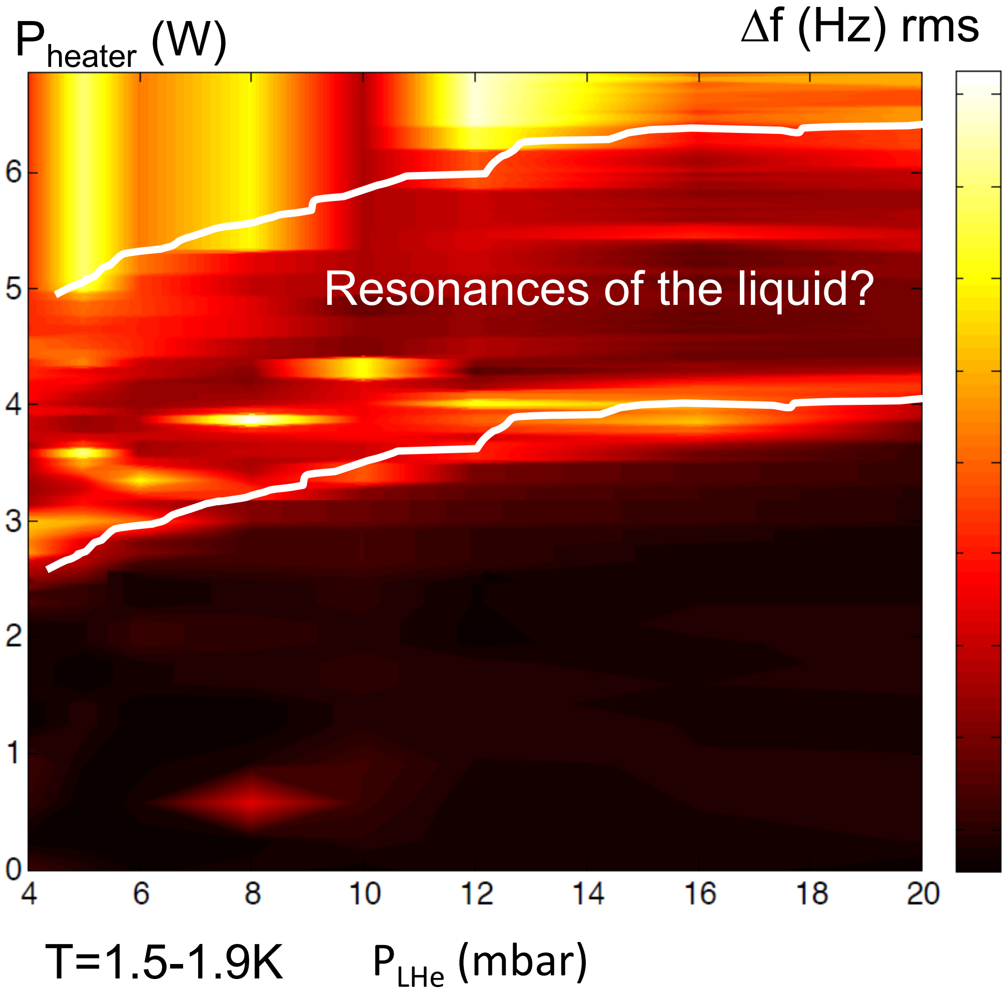


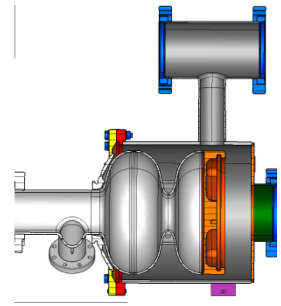


MP shifted by 1-2 MV/m to lower field

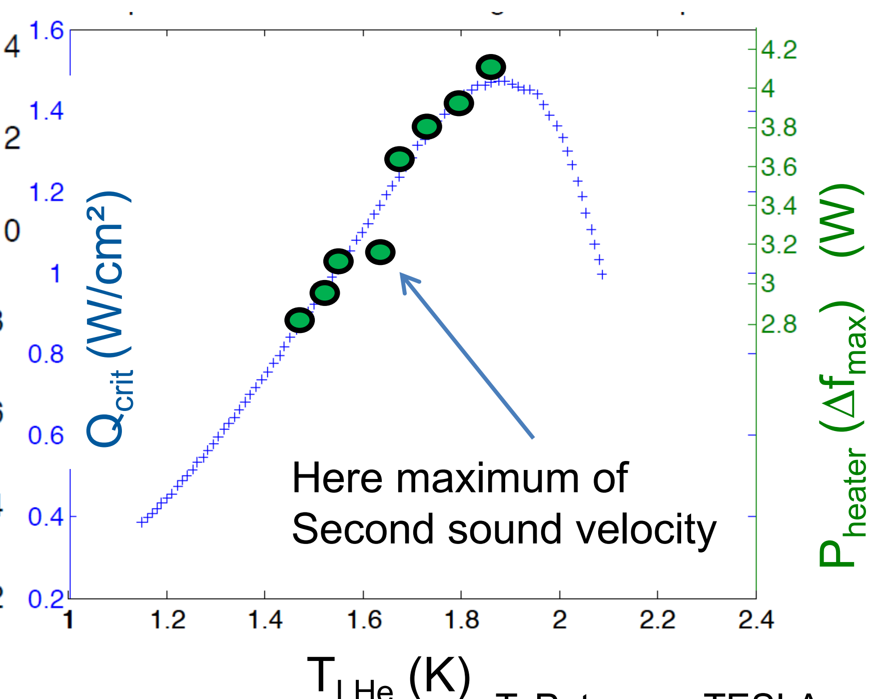
Field range prone to MP much broader

CW operation: A electro-magnetic-mechanical-thermo-acoustic coupled problem?





Device under test:
Nb Pb cathode gun

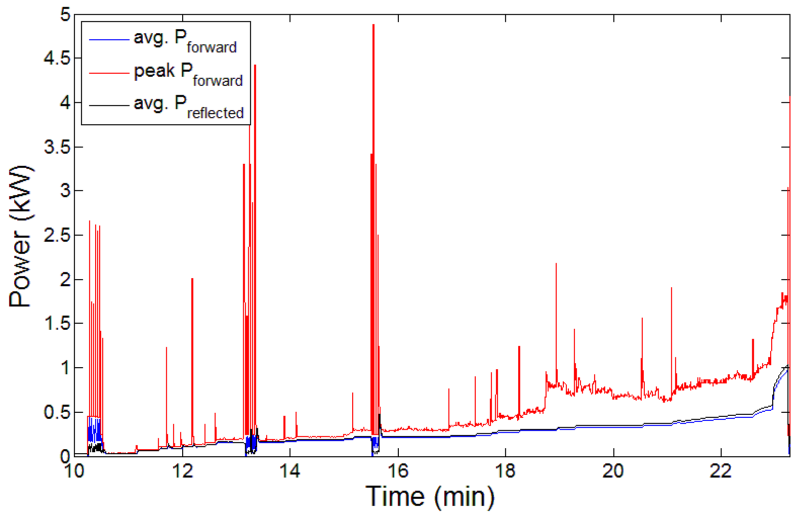


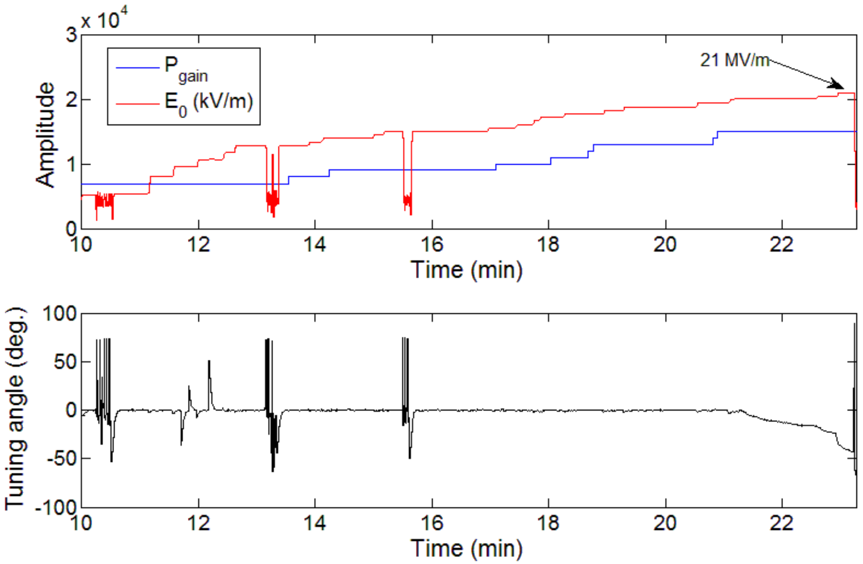
T. Peterson, TESLA-Report 1994-18

Cavity driven by LLRF at E_0=15 MV/m
Piezo compensation in PI loop mode
with low-pass filtering, $Q_L=1.4 \cdot 10^7$

Additional power dissipated in L_{He} bath
by heater (few cm²) within liquid
Microphonics recorded while heater is powered

First LLRF results for cold string





Limited in power to 2 kW average, non optimized loop, ponderomotive effects by large Lorentz force detuning

E_0 (MV/m)	8	15	20.1	8 + construction site
σ_ϕ(deg)	0.06	0.08	0.06	0.55
σ_A/A	2.6e-4	2.6e-4	2.4e-4	5.6e-4
σ_f (Hz)	2.9	5.4	6.5	28.8
K_P	100	118	221	100

A. Neuman

Piezo to RF detuning transfer functions