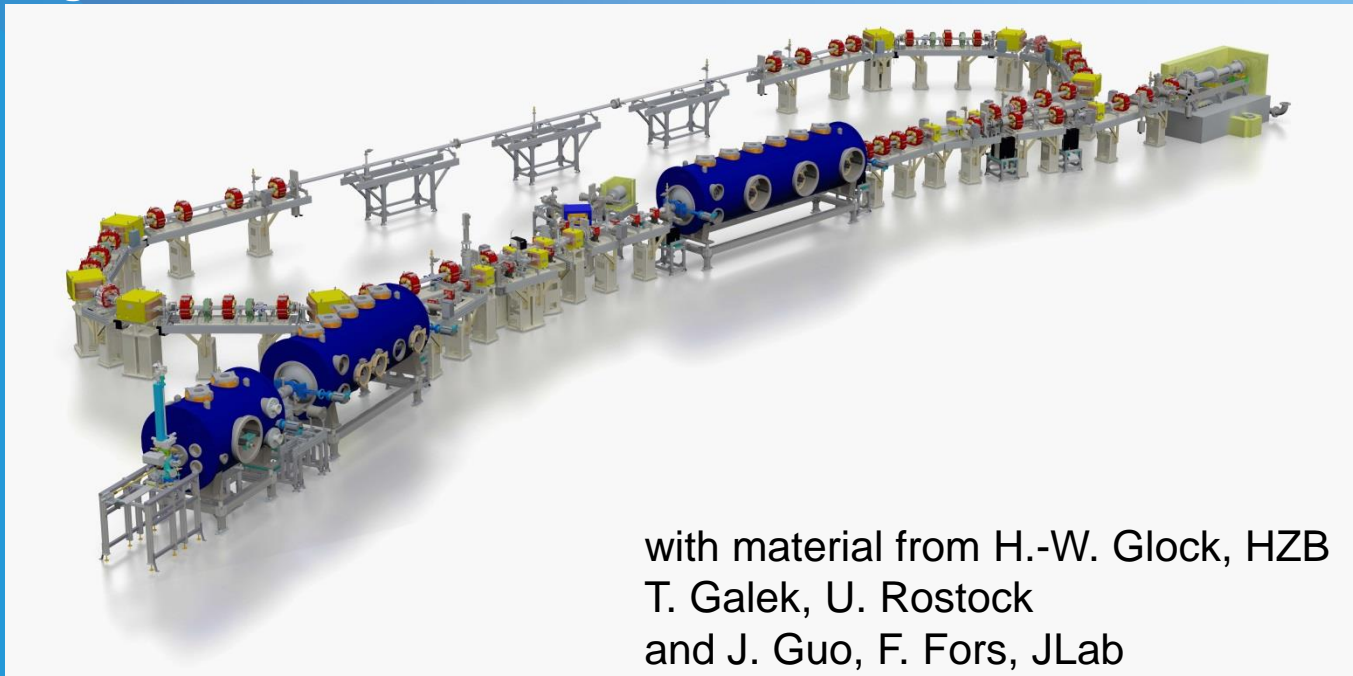


HOM damping concepts of the bERLinPro Energy Recovery Linac Project

A. Neumann, ICFA Mini Workshop on HOMs in SC Cavities 22-24
August 2016, Warnemünde

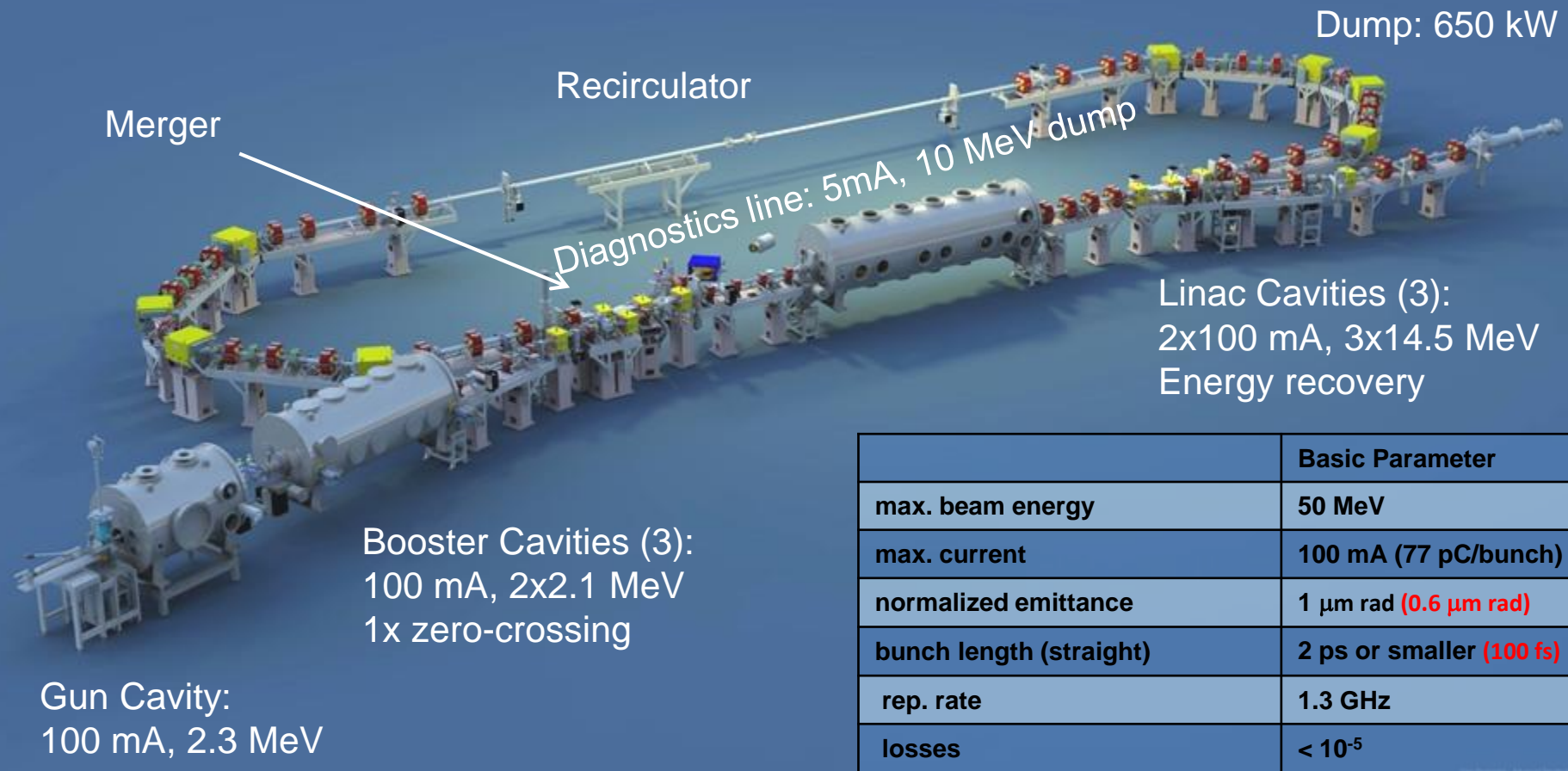


with material from H.-W. Glock, HZB
T. Galek, U. Rostock
and J. Guo, F. Fors, JLab

For the bERLinPro team and collaborators

Motivation

bERLinPro: A demonstrator for a low emittance, high brilliance Energy Recovery Linac

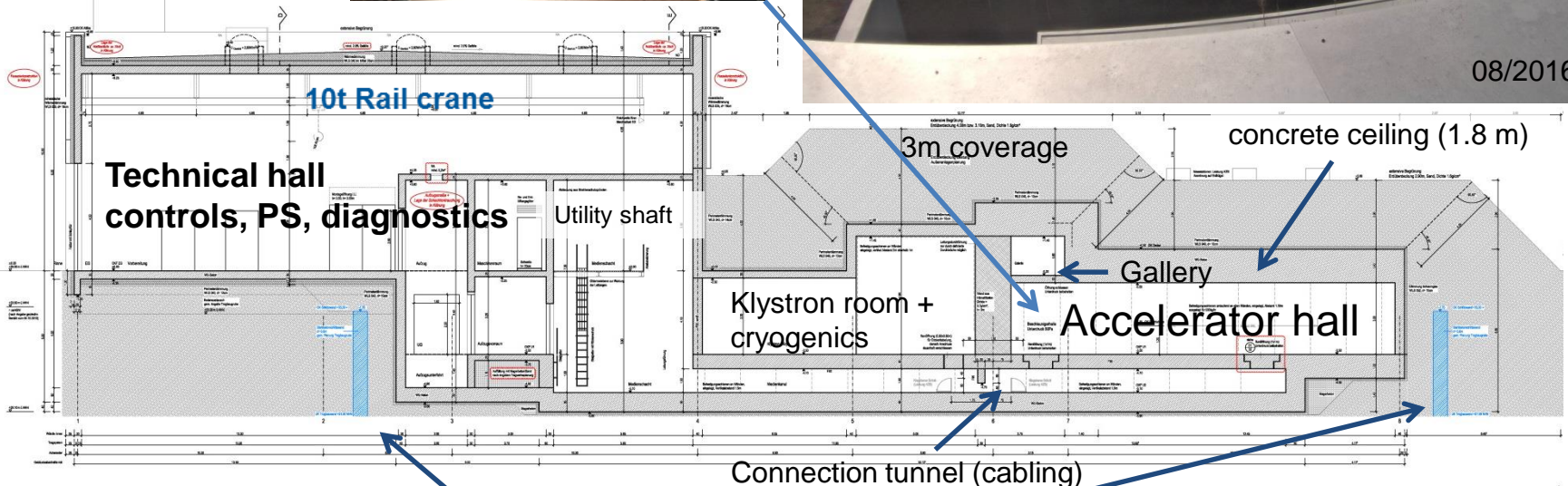
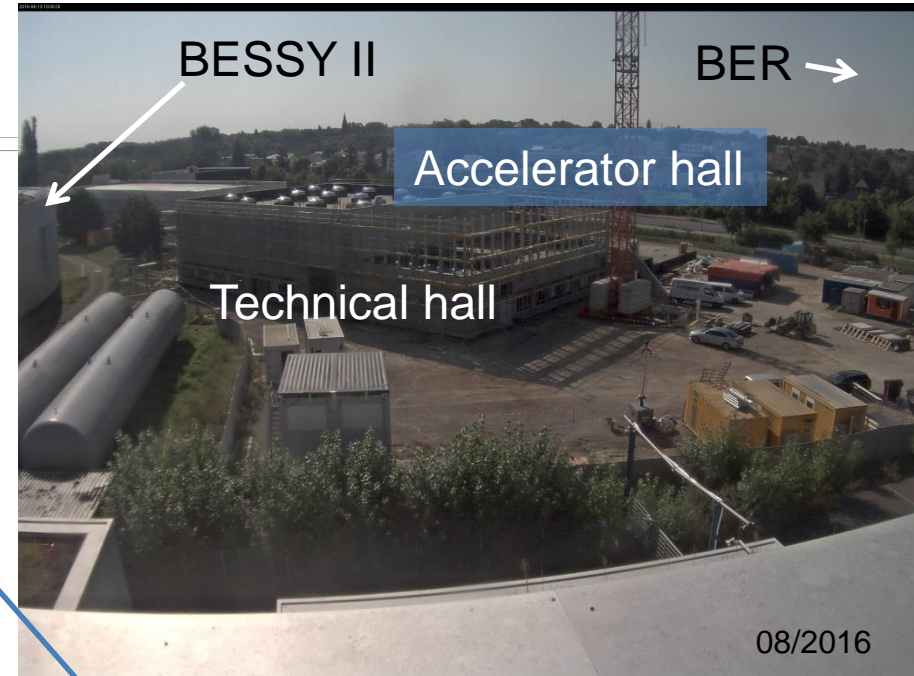
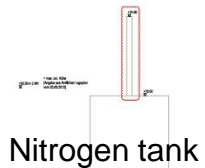


Main goal: Demonstrate **high current** **low emittance** operation using **CW SRF** energy recovery linac

Motivation

Fully funded project (41 M€)
Building construction in progress

chimney for air exhaust
accelerator hall



Courtesy O. Schüler

Trough

-1.5 m ground water level (Berlin used to be a glacial valley)

Next Milestones

- This fall completion of Gun modul and setup of dedicated testlab called Gunlab: Characterize SRF Gun, beam parameters, cathode studies, etc....

→until Fall 2017



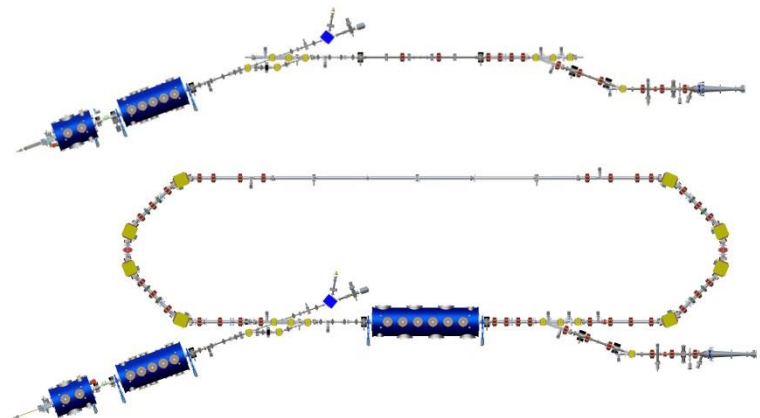
limited to 5 μ A avg. beam current by radiation protection

- Order Booster parts and Linac prototype
- Beginning of 2018 installation of magnets and vacuum system

- Move gun modul to bERLinPro accelerator hall, first beam at bERLinPro about Spring 2018. 2.5 MeV – 3 MeV, up to 5mA

- Fall 2018 installation of booster module and first beam into high power dump, 6.5 MeV

- Later.....



bERLinPro: 3 different cavity types for different requirements

Beam tube absorbers
Fixed coupling
high power coupler

5 Waveguide absorber (25W/load)
1 Variable coupler + 2 beam tube in module

Cavity prototype
Production readiness phase

~~Coupler ordering
Module design~~

Main Linac Cavity (7-cell)

- Preserve emittance
- High beam current
- Zero beam power
- High field level
- Multi-pass beam
- High $Q_L \rightarrow$ Microphonics
- Recovery issues

Booster Cavity (2-cell)

- Preserve emittance
- High beam current
- High beam power
- Intermediate field level

SRF Gun (1.4 cell)

- Low emittance beam
- High beam current
- High beam power
- Intermediate field level
- High on-axis peak fields

Final module assembly

Major project challenge: 3 different type of cavities and modules

All cavities can be considered as prototypes and are manufactured only in small numbers (funding)

Design Parameter	Gun	Booster	Linac
Type of operation	CW, high beam power, high peak on-axis field	CW, high beam power, intermediate acc. field	CW, high beam current high acc. field
Number of cells	$1.4 \times \lambda/2$	$2 \times \lambda/2$	$7 \times \lambda/2$
TM _{010-π} frequency (MHz)	1300	1300	1300
Operating temperature (K)	1.8	1.8	1.8
Beam current (mA)	100 (4)	100	2 × 100
HOM absorber	beam tube	beam tube	waveguide + beam tube
FPC type	twin modified c-ERL (TTF-III)	twin modified c-ERL	single modified TTF-III
Energy gain/cavity (MeV)	2.3 (3.5)	2.1	14.8
Beam emission or RF phase (deg)	40-60	-90 and 0	-15
$R/Q_{ }$ for $\beta = 1$ (Ω)	150 (132.5)	219	788
Geometry factor G (Ω)	174 (154)	261	266
$E_{\text{peak}}/E_{\text{acc}}$ ¹	1.45 (1.66)	2.02	2.08
$B_{\text{peak}}/E_{\text{acc}}$ ¹ (mT/MV m ⁻¹)	3.2	4.44	4.40
Q_{loaded} for TM _{010-π}	$1.1 \cdot 10^5$ ($3.6 \cdot 10^6$)	$1.05 \cdot 10^5$	$5 \cdot 10^7$
Max. Q_{ext} 1 st TM dipole band	$11 \cdot 10^3$	170, 7300	$\leq 8 \cdot 10^3$
P_{forward} at $\Delta f = 0$ (kW)	230 (up to 5.8)	230	1.4
$\Delta f/\Delta P$ (Hz/mbar)	20	5	not calculated yet
Measured Properties with HV	Gun	Booster	Linac
Peak on axis electric field (MV/m)	34.5	34-40	NA
Peak surface electric field (MV/m)	57.3	34.4-40.4	NA
Peak magnetic field (mT)	110.4	75.5-89	NA

See A. Neumann et al., SRF 2015

High power

High current
High field



Overall layout of the cavity

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

$0.4 \cdot \lambda/2$ cell + full cell:
Optimized
emission phase

Chimney $22 \text{ cm}^2 \sim 35 \text{ W}$ at 1.8 K
about $E_{\text{peak}} = 45 \text{ MV/m}$ at $Q_0 = 3.5 \cdot 10^9$

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

3 pick-up antennas
to measure HOM
polarization

HZDR cathode
insert and choke
cell design:

Proven system
Cathode exchange
with HZDR

Blade tuner with
motor and piezo tuner:

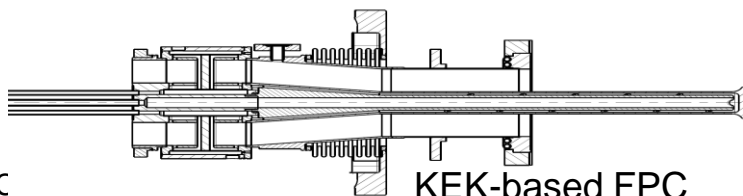
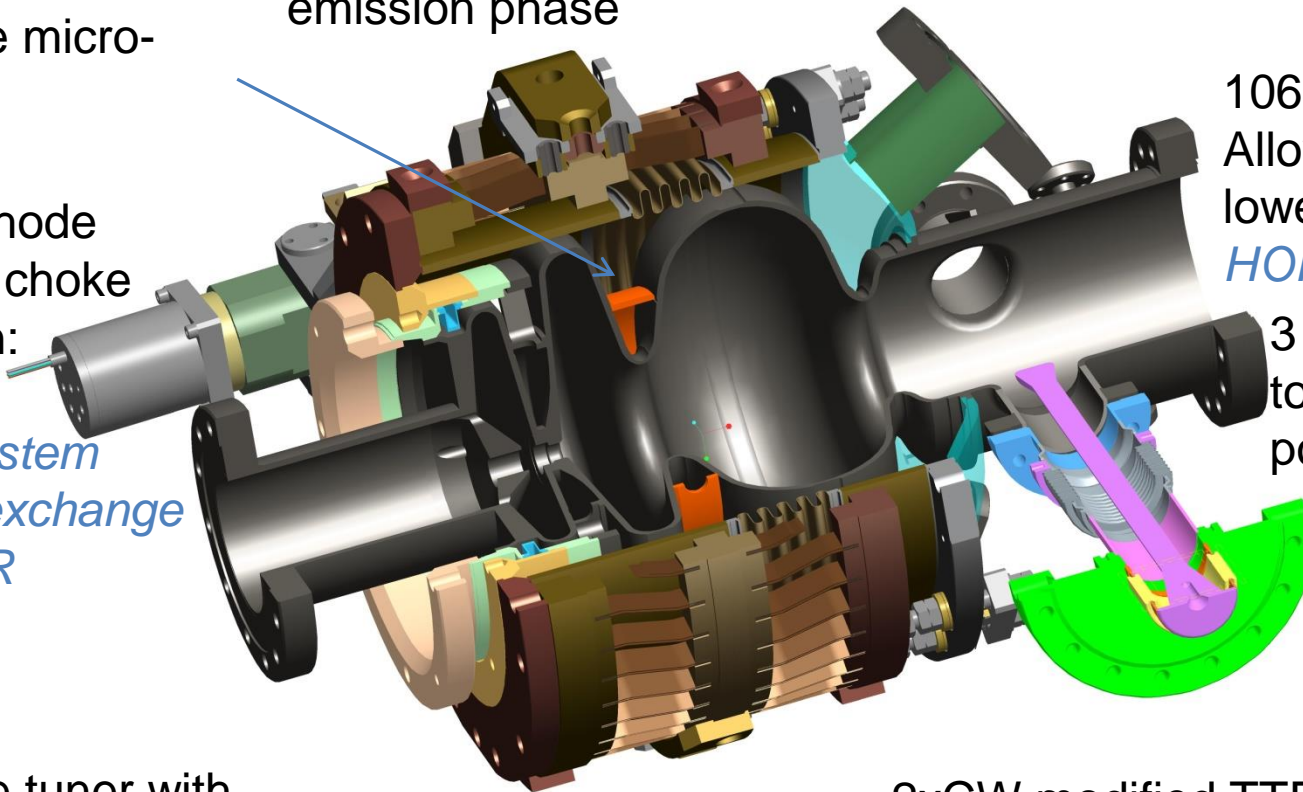
Microphonics compensation

2xCW modified TTF-III

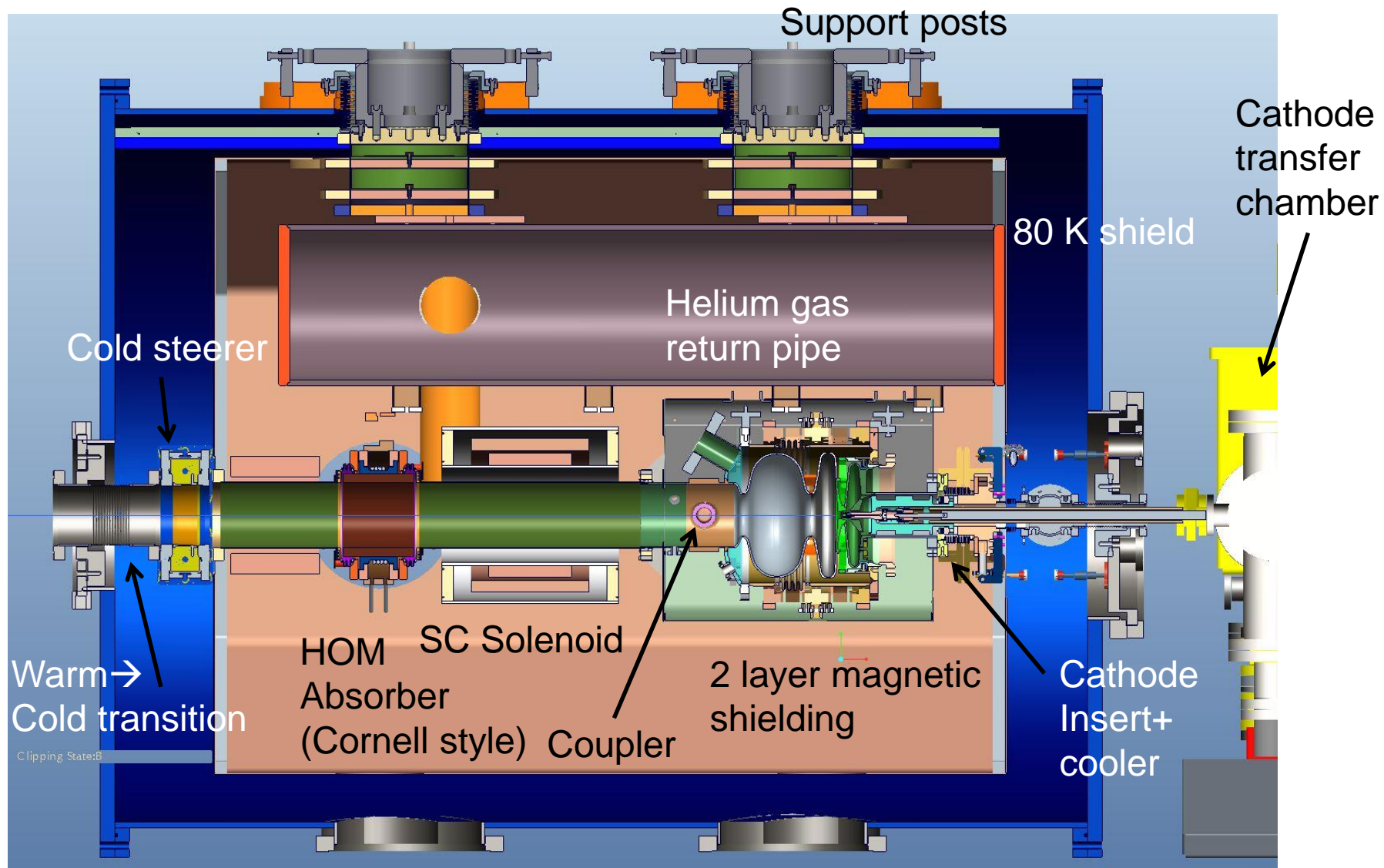
Coupler: $Q_{\text{ext}} 3.6 \cdot 10^6$
for up to $I_{\text{avg}} = 4 \text{ mA}$,
10 kW each

Study 2 coupler operation

→ High power version next step 8

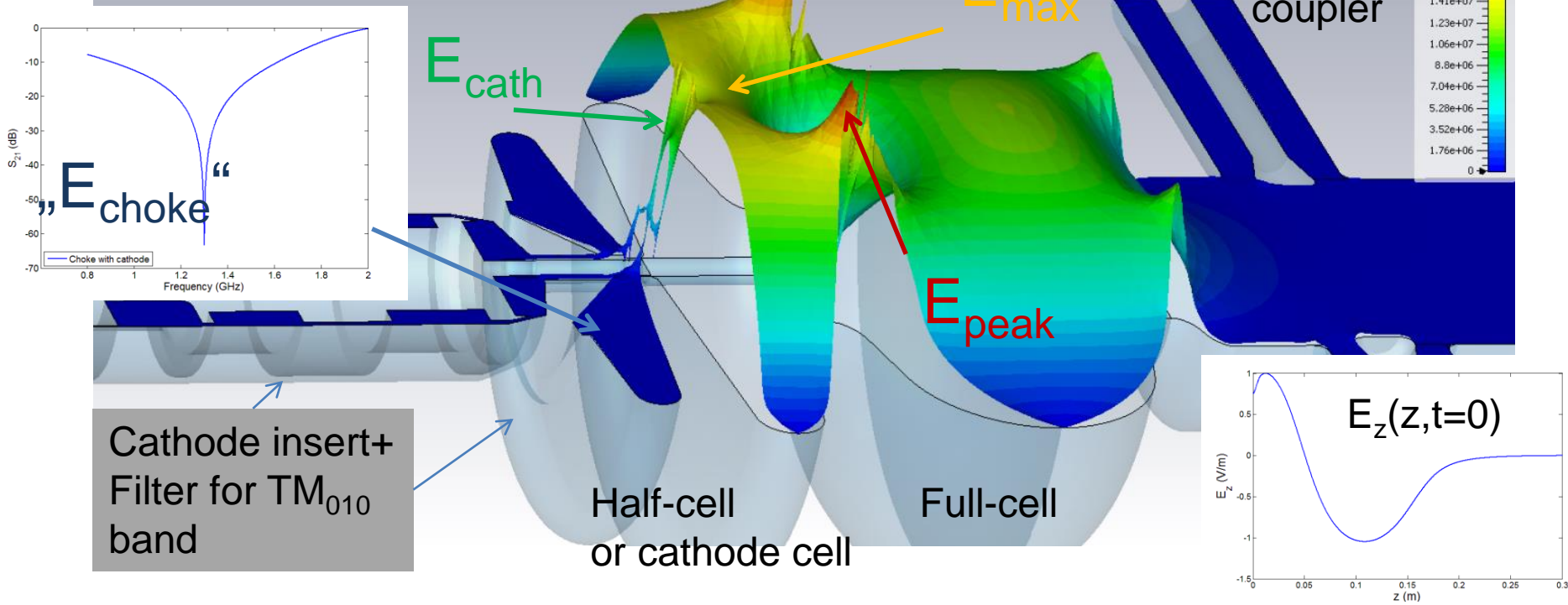


Integration into cryo-module



Optimization of RF properties: Beam dynamics + dark current

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



- Highest E_{emitt} favorable, but cathode also functions as field emitter
 → 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)

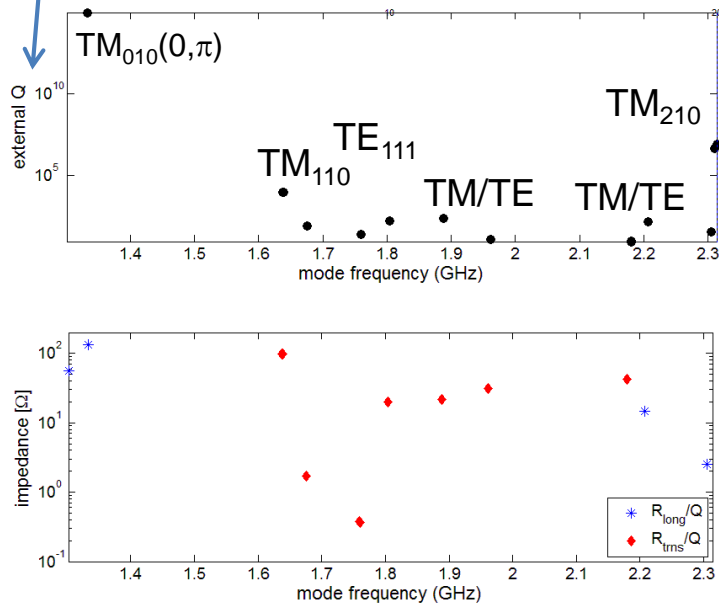


For $E_0=40$ MV/m about 80 mW losses in beam tube by TM_{010}

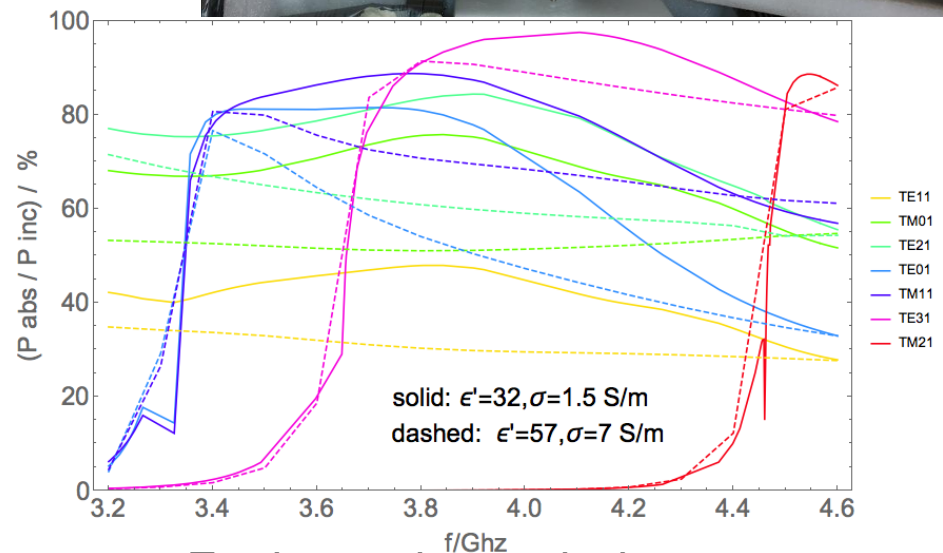
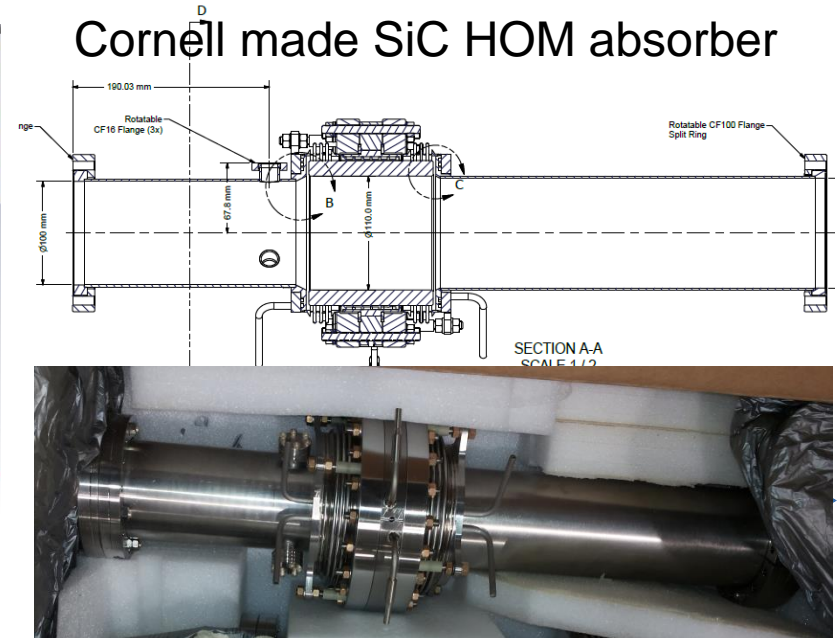
$|E|$ for $U=1$ J

1.4 cell

Solenoid
beam tube with copper coating



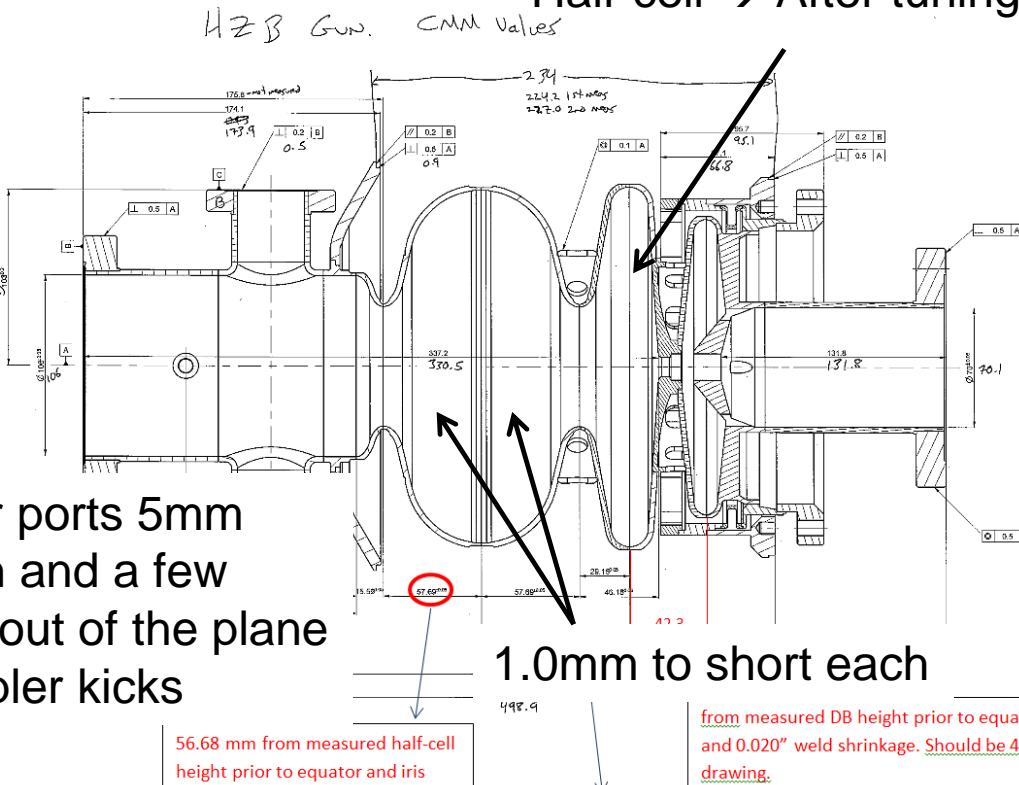
Cornell made SiC HOM absorber



Further wake analysis
Required for 100 mA gun cavity

Reality check: Production status after welding (2013)

Half-cell → After tuning 5.7 mm too short



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} (β=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
- Created much extra work to adapt cathode insert tube, magnetic shielding, couplers, tuning mechanism, etc...

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
- First cavity multipacted and eventually quenched at low fields (as seen by PIC simulations and OSTs during VTS test)
- 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

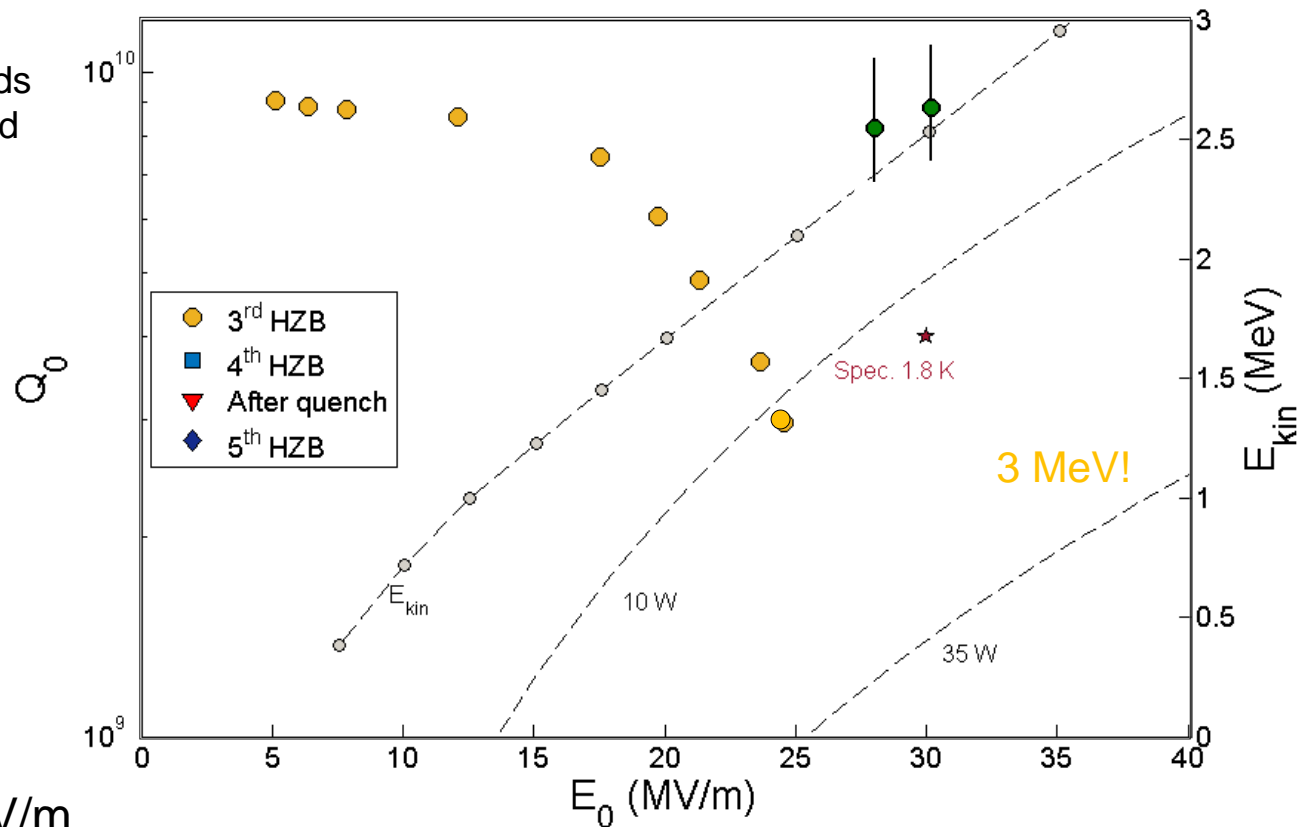
Peak fields achieved:

$$E_{\text{peak}} = 57.3 \text{ MV/m}$$

$$B_{\text{peak}} = 110.4 \text{ mT}$$

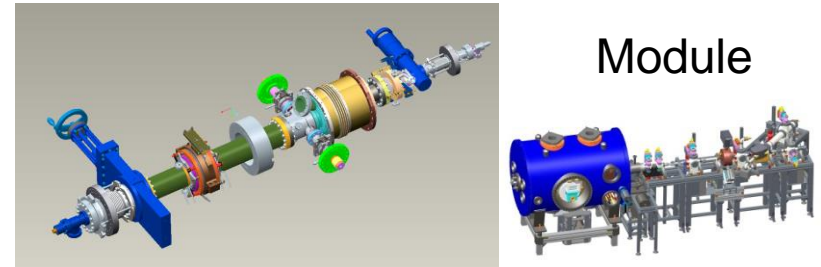
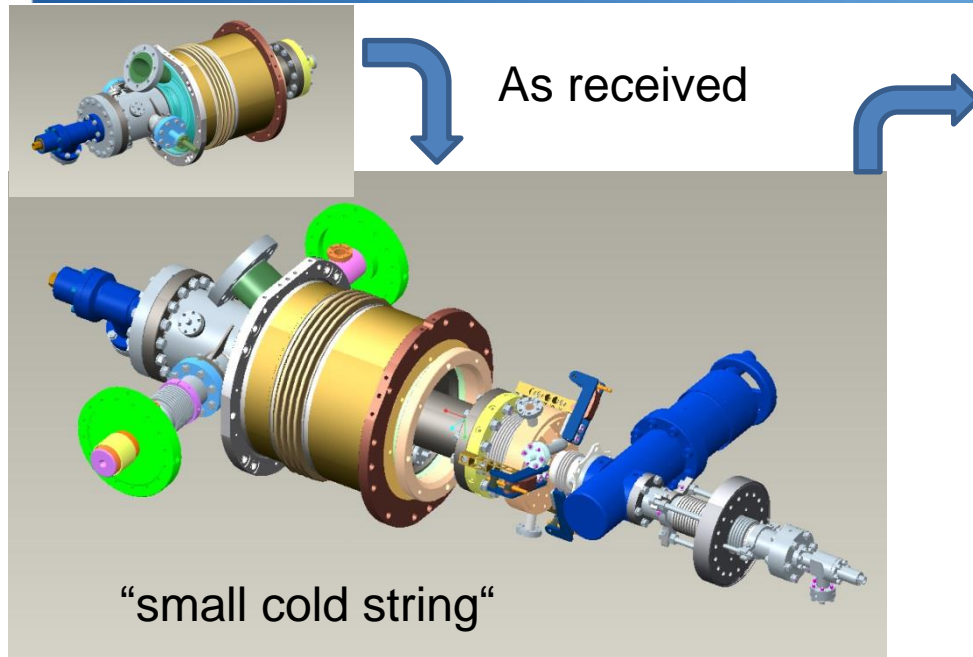
Corresponds to $E_{\text{acc}} = 26 \text{ MV/m}$
of a TESLA cavity

Green data points:
 Q_0 measured by helium evaporation



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

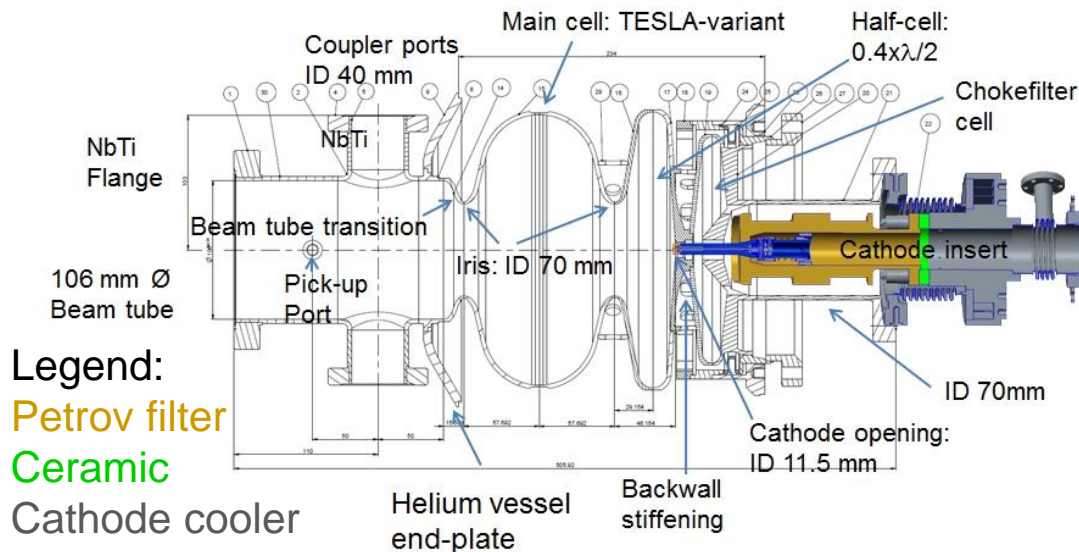
Cold mass assembly



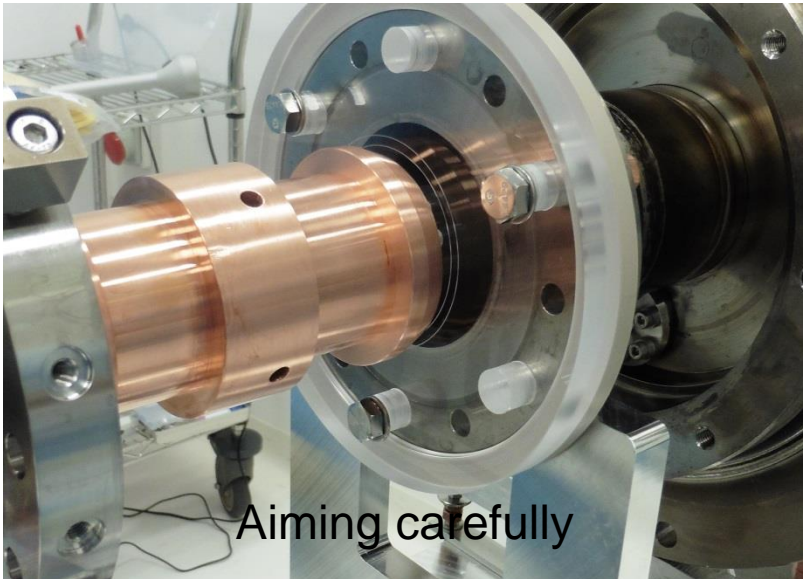
- After horizontal acceptance test assembly of small cold string in ISO4/5 clean room:

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

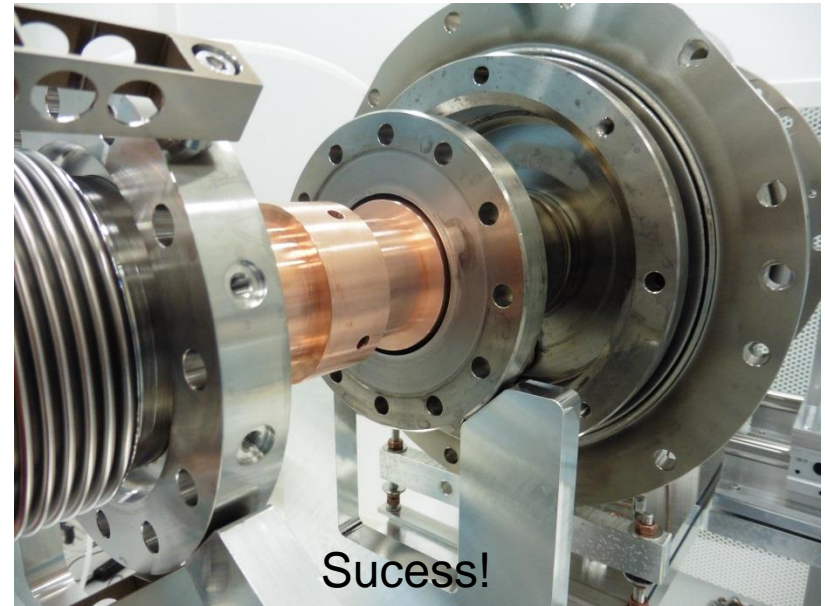
- Follow up horizontal test in module configuration to check if cavity “survived” procedure



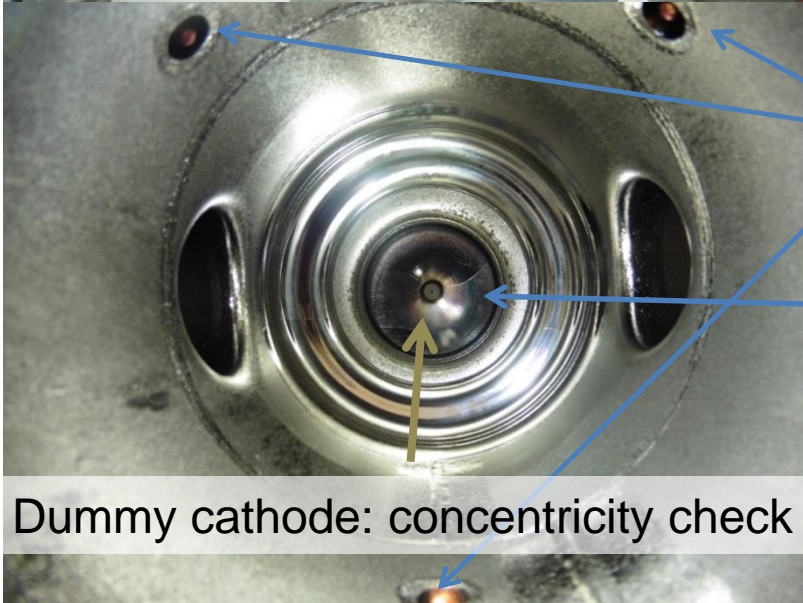
Mounting of the Petrov filter and cathode carrier



Aiming carefully



Success!



Dummy cathode: concentricity check

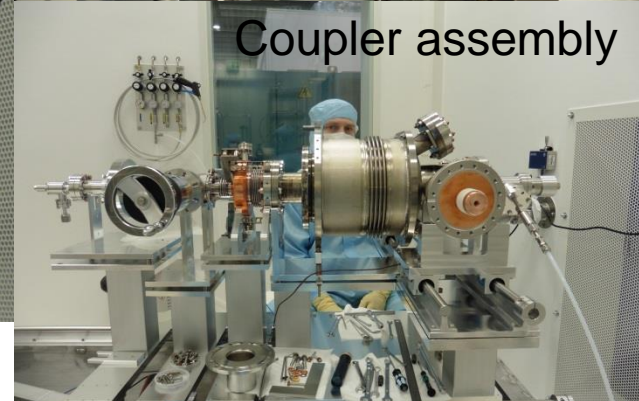
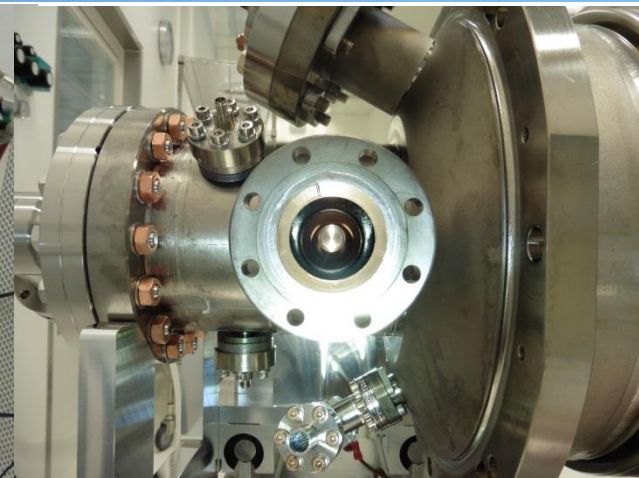
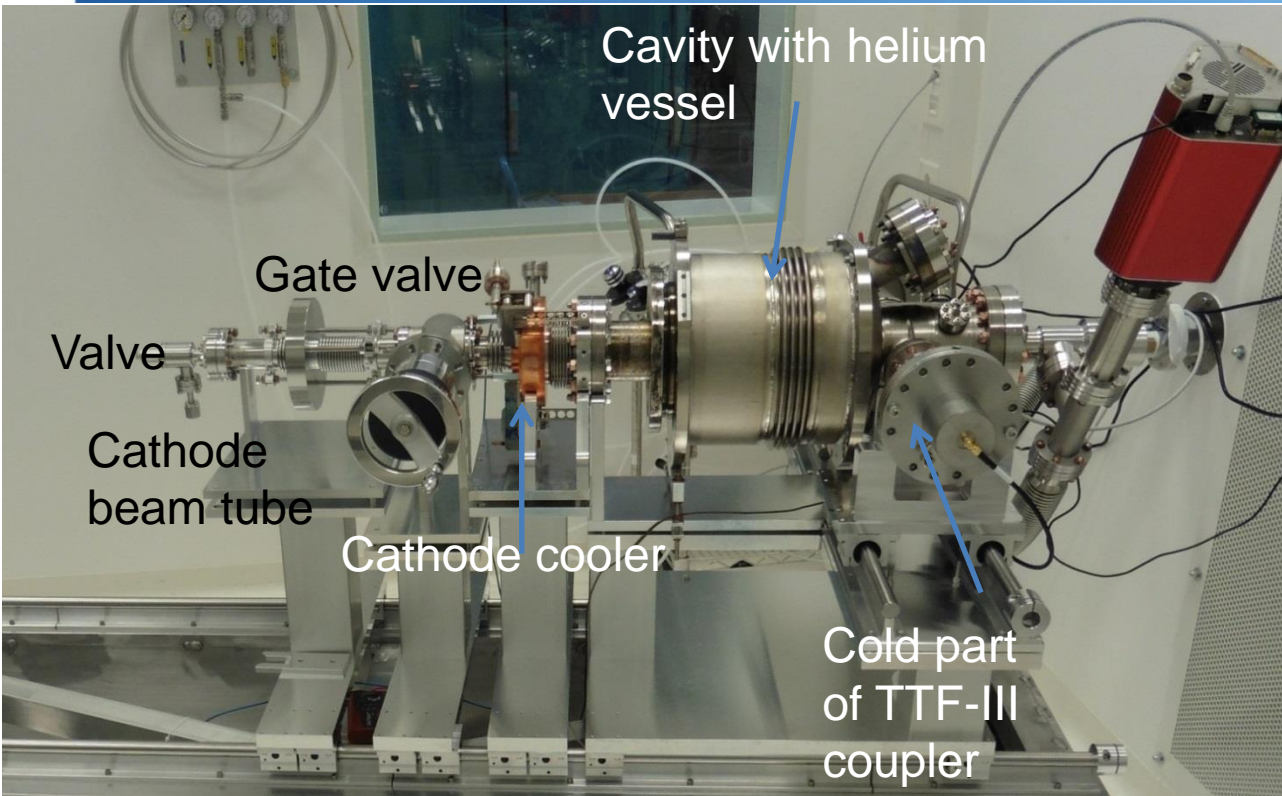
What do you see here:
3 pick-up antennas

Ports for twin coupler arrangement
Part of half-cell back wall, large grain
Niobium, grain boundaries visible

Used N_2 overflow
for all steps.

Flow direction: Assuming
Cavity being the most clean part

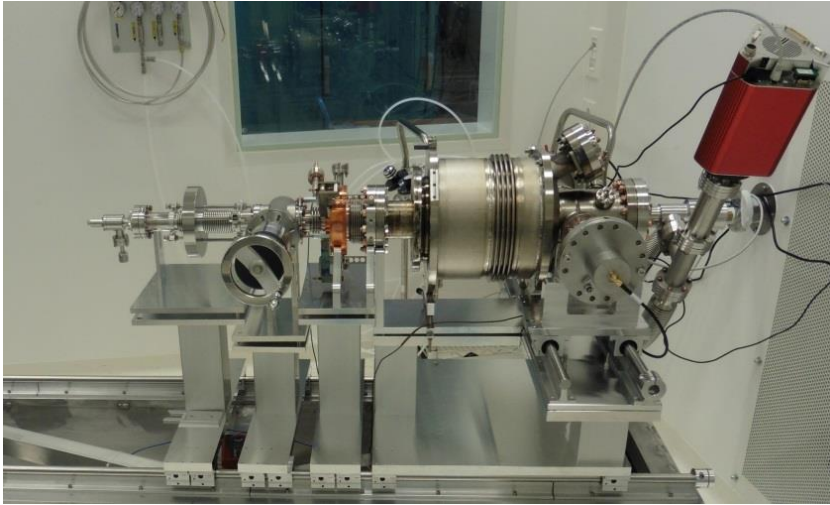
Final steps and done



Special thanks to DESY MKS-3:
Axel Matheisen, Manuela Schmökel, Marco
Schalwat, Birte van-der-Horst et al.
for training, support, discussion and
participation in cold mass assembly!



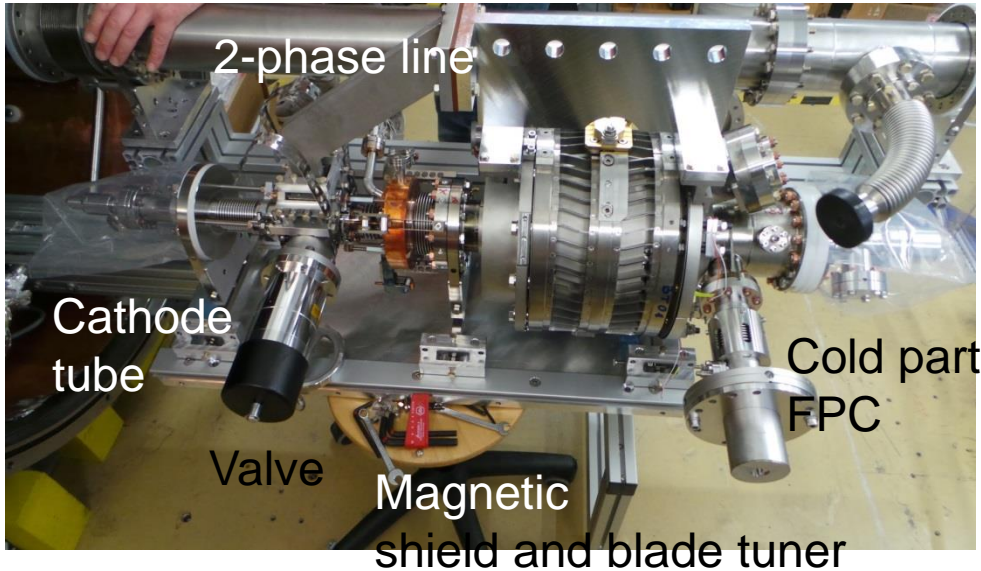
Horizontal acceptance test



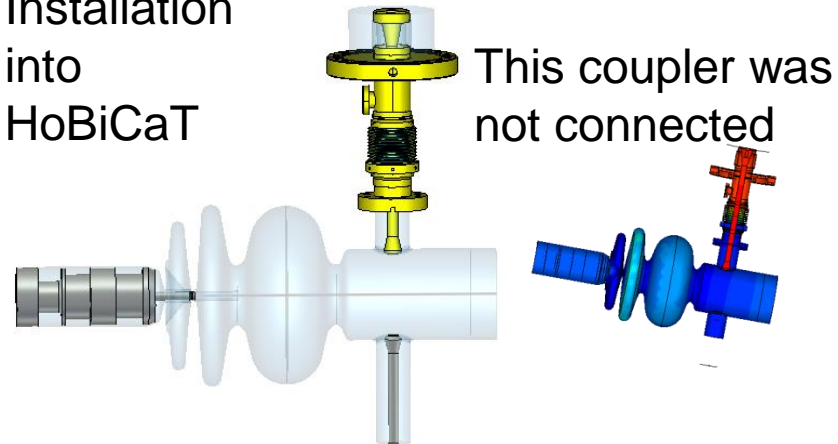
Small cold string after assembly and during pump down in clean room



Final acceptance test at HoBiCaT before completion of string with:
Beam tube and HOM absorber, Solenoid, valves and transition bellow

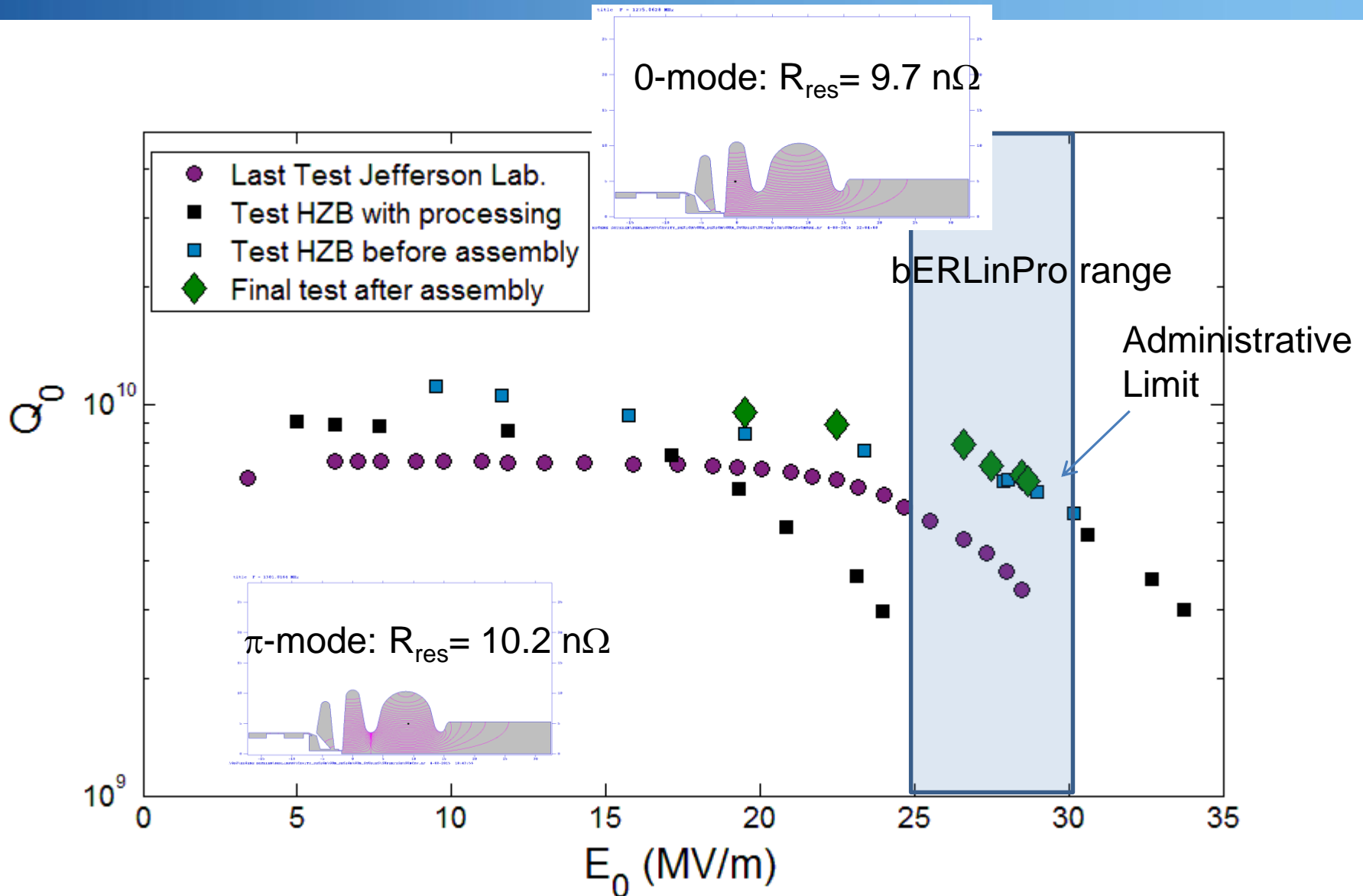


Prior to
Installation
into
HoBiCaT



Active coupler, limited to 2 kW avg

Horizontal acceptance test: Performance kept!

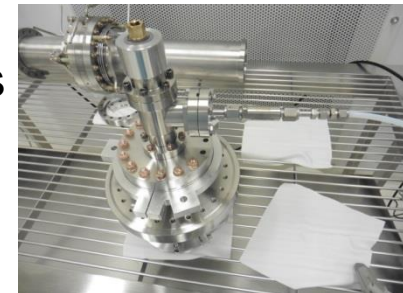
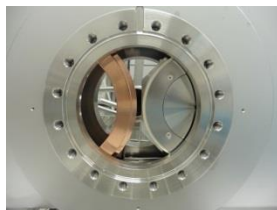


Unfortunately cryo-plant break down → no unloaded HOM test!

Latest assembly attempts: HOM load



- Losses by fundamental mode in stainless steel tube no problem, $< 0.8 \text{ W}$ (add cooling braids)
- Resistive wall wakes of an issue? 75 mW losses at 5 mA , 77 pC , $\sigma_z 3\text{mm} \rightarrow \text{ok}$
Influence on the beam: 0.196 V/pC instead of $0.03 \text{ V/pC} \rightarrow \text{ok}$
Also observed surface roughness $\rightarrow \text{ok}$
 $100\mu\text{m}$ would lead to 1.15 W at 5 mA (worst case)



Next: Finalize string!

Next step: Install module into Gunlab



Cathode camera
+ laser diagnostics

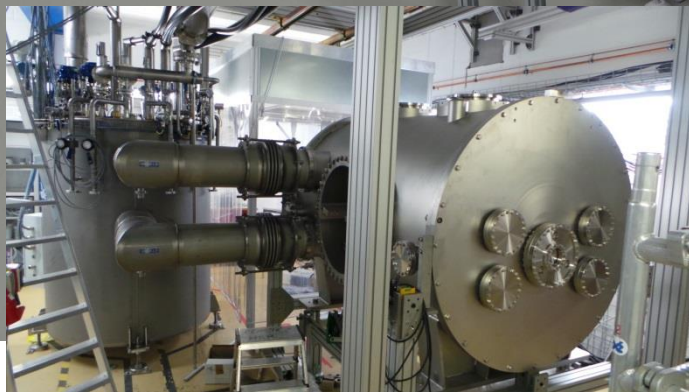


Screen stations

Transverse deflecting
Cavity TM_{110}

Dipole
magnet

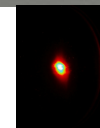
Capacitive
Cathode positioning
system



Stripline
BPM
Integrating current
transformer

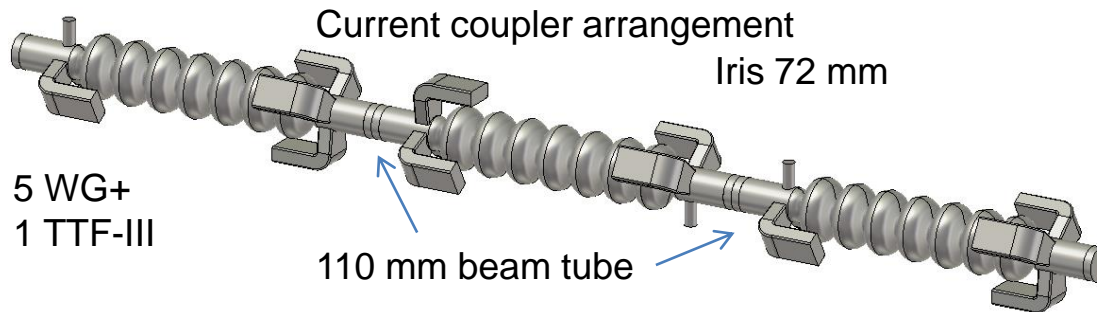
Faraday
cups

First beam for Christmas!?



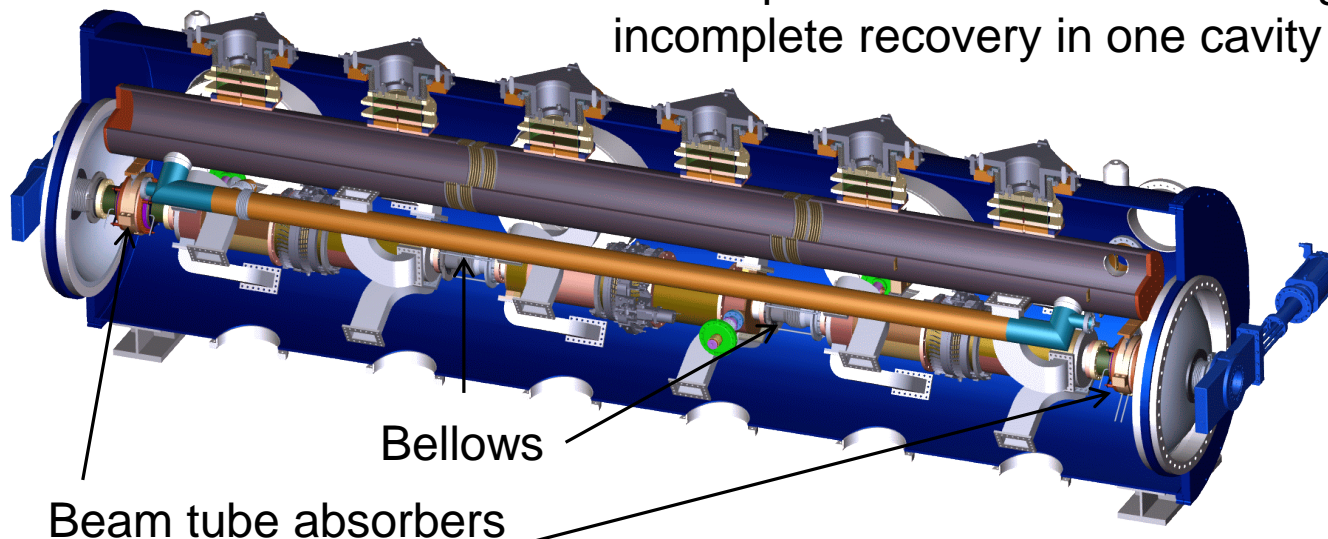


Linac module requirements



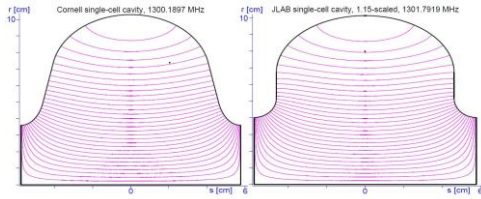
- Low to zero beam power, thus high Q_L operation at low power possible → High mechanical stability required ($Q_L \cdot 5 \cdot 10^7$, $\Delta f / \Delta P \sim 0$)

- The string needs to deliver 14.8 MV per cavity, thus $E_{acc} \simeq 20$ MV/m
- Strong HOM damping required because of interaction with two 100 mA beams
 Q_{ext} lowest dipole $\leq 5 \cdot 10^4$
- Beam is injected with 6.5 MeV, still soft → coupler kicks and emittance preservation need to be considered.....further power overhead and tuning because of incomplete recovery in one cavity



Bellows and absorbers required but also risk for cavity operation (Wakes, dust)

Design concept



Single cell + cavity study:

Wake+ eigenmode analysis

→ Study RF properties

Peak field ratios, losses

→ HOM damping

→ Beam break-up analysis

→ Coupler kicks

Module based RF studies:

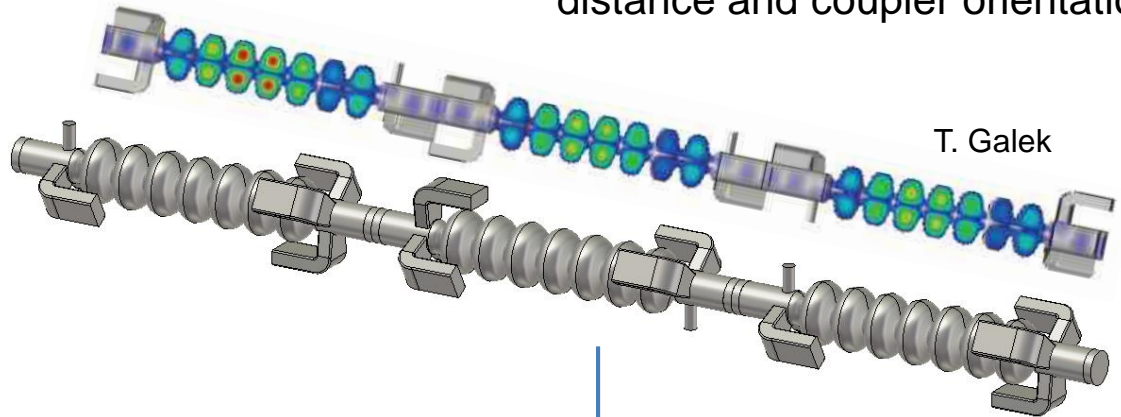
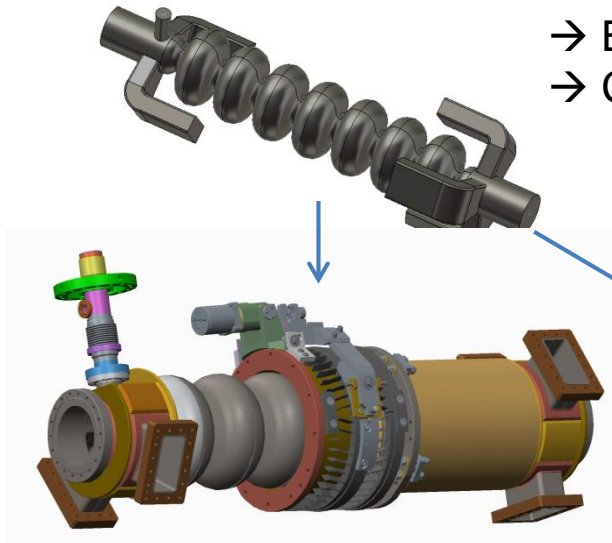
→ Coupled system analysis:

Wake, concatenation (U
Rostock), HOM orientation

→ Coupler kicks

→ Dark current studies

Affects: Cavity-to-cavity
distance and coupler orientation



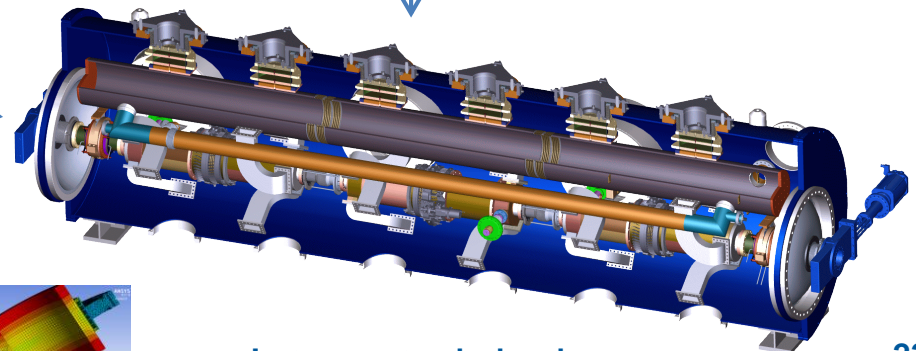
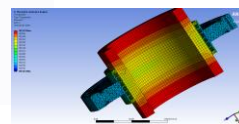
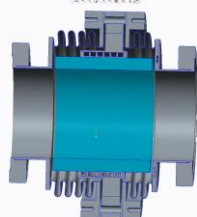
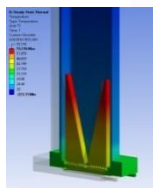
Cavity construction:

→ Thermal management

TM₀₁₀ losses, intercepts

→ Mechanical studies

→ HOM design



Integrated design

TTF-III for variable coupling:
High Q_L
operation possible

5 waveguides
to cover HOM
polarizations:
Well defined
cutoff

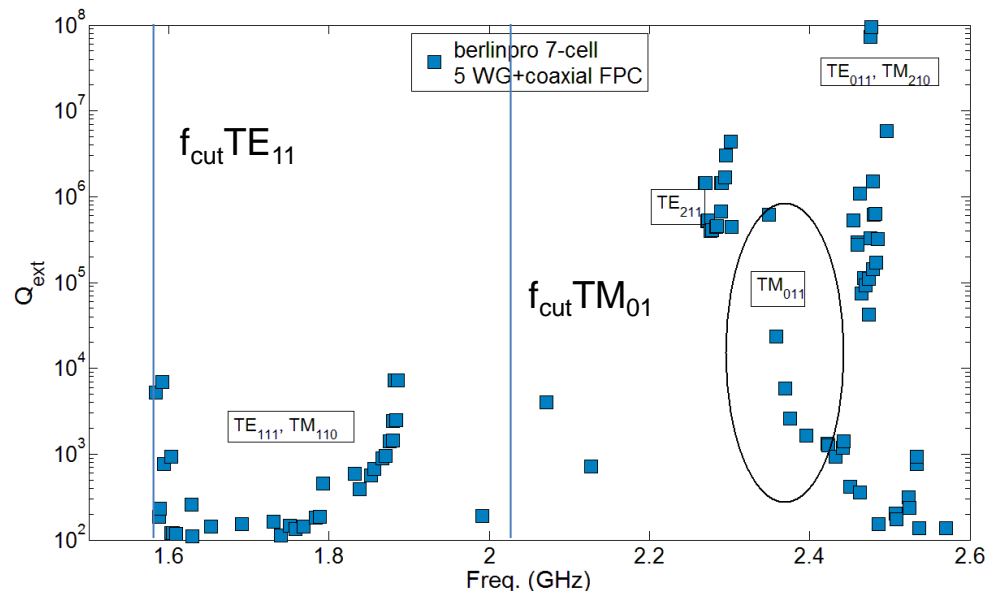
7 cell:
Cornell's ERL
mid-cell + modified end-cells
(asymmetric)

3rd order
spline nose
transition
to low
cutoff
beam tube

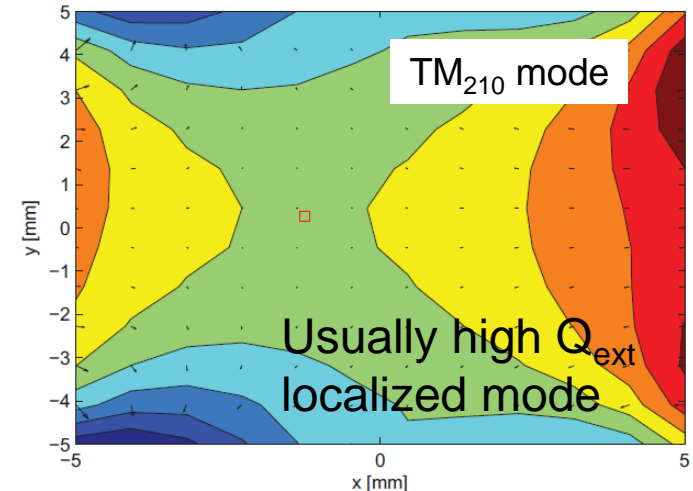
Number of cells	7
R/Q_{\parallel}	788 Ω
$f_{TM_{010}} - \pi$	1.3 GHz
$E_{\text{peak}}/E_{\text{acc}}$	2.08
$B_{\text{peak}}/E_{\text{acc}}$	4.4 mT/MVm ⁻¹
Q_{ext} TM ₁₁₀ dipole	$\leq 8 \cdot 10^3$
Beam tube TE ₀₁ cutoff	1.596 GHz
Waveguide TE ₁₀ cutoff	1.576 GHz
Q_L for TM ₀₁₀ - π	$1 \cdot 10^7 - 1 \cdot 10^8$
P_{forward} at $Q_L = 5 \cdot 10^7$ ($\Delta f = 0$)	1.4 kW

Combine Cornell's low peak
field design with JLab's HOM
damping approach

Number of cells	7
R/Q_{\parallel}	788Ω
$f_{\text{TM}_{010}} - \pi$	1.3 GHz
$E_{\text{peak}}/E_{\text{acc}}$	2.08
$B_{\text{peak}}/E_{\text{acc}}$	4.4 mT/MVm^{-1}
$Q_{\text{ext}} \text{ TM}_{110} \text{ dipole}$	$\leq 8 \cdot 10^3$
Beam tube TE_{01} cutoff	1.596 GHz
Waveguide TE_{10} cutoff	1.576 GHz
Q_L for $\text{TM}_{010}-\pi$	$1 \cdot 10^7 - 1 \cdot 10^8$
P_{forward} at $Q_L = 5 \cdot 10^7 (\Delta f = 0)$	1.4 kW

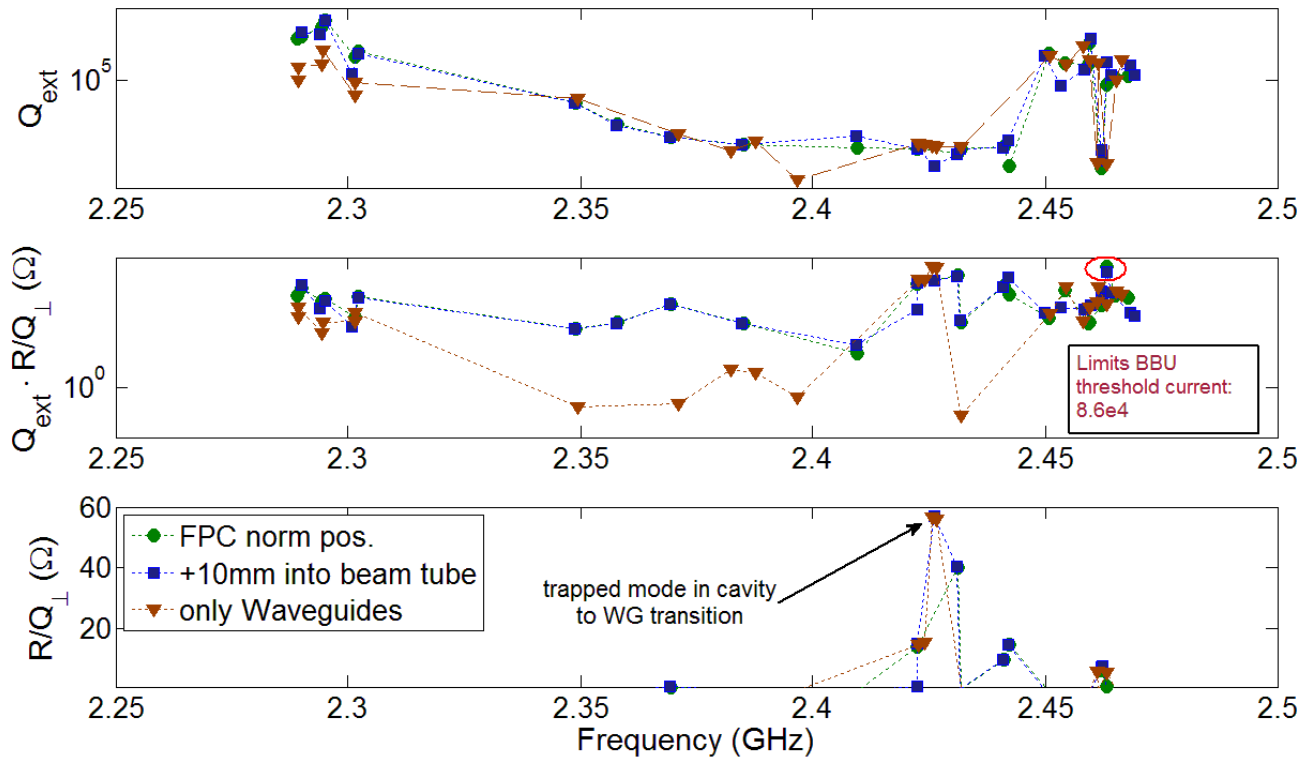


- Final RF design obtained by quasi optimization for field-flat, high R/Q_{\parallel} , low field ratios, but low HOM Q_{ext} design
Basis: Cornell ERL shape
- Low Q_{ext} for all dipole modes within reach of calculation (3D)
- However, problem of dipole-like transverse R/Q component on-axis for TM_{mnp} $m \geq 2$ still unresolved



Multipole decomposition of several integration paths

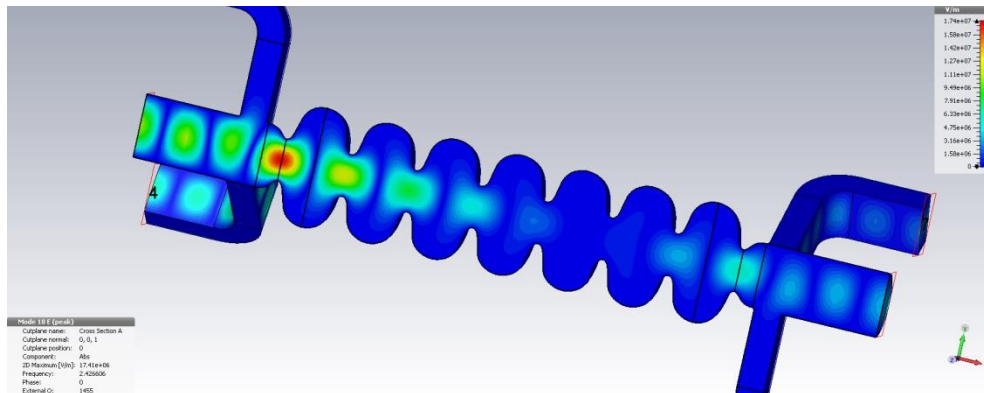
Obstacles of first end-group section



Compare 5WG + coaxial FPC system (2 coupler depths) with 6WG system

Current limit by TM_{210}

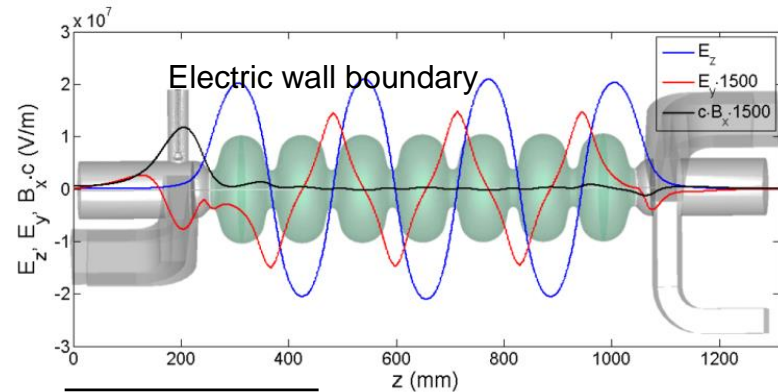
→ Does not appear in 6 WG structure



Trapped modes appeared in transition from iris to Y-shaped waveguide → Gives strong dipole kick, second strongest BBU limiting mode

This section needed to be reworked

Obstacles of first end-group section: Coupler kick

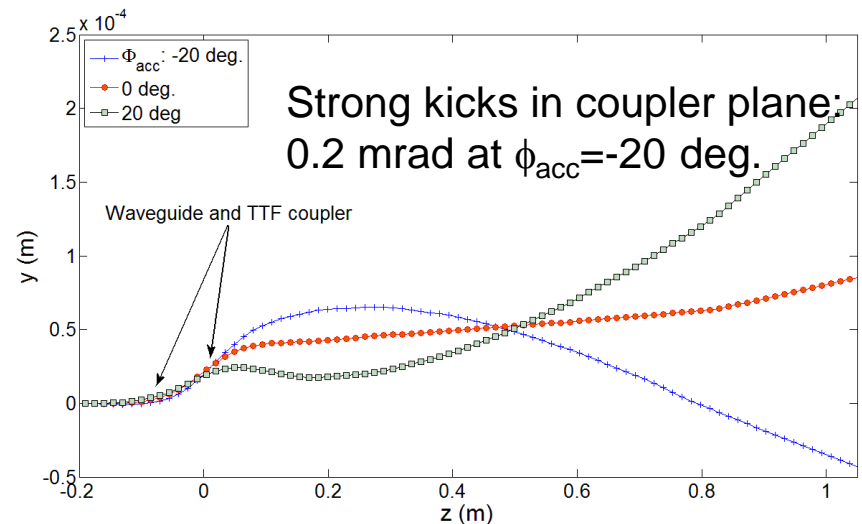
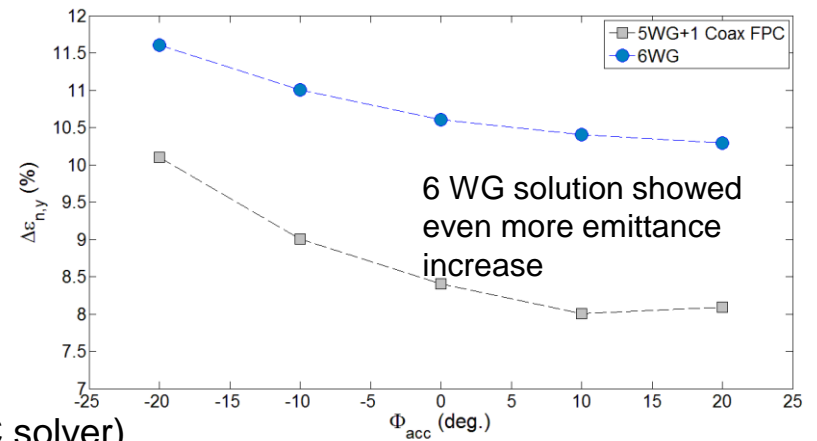
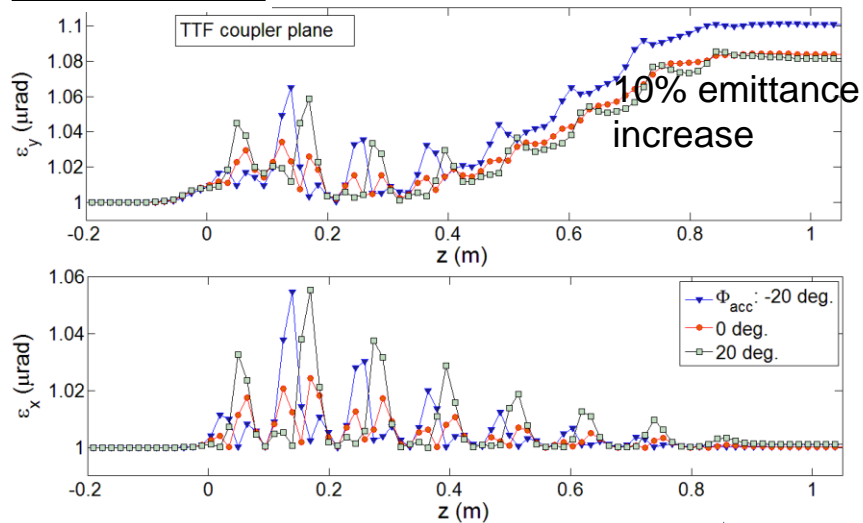


$\epsilon_{n,y,x}$	1 mm mrad
σ_t	5 ps rms
$\sigma_{y,x}$	≈ 0.7 mm rms
$I_{\text{avg,beam}}$	100 mA
$E_{\text{kin,ini}}$	6.5 MeV
V_{acc}	15 MV
E_{acc}	18.56 MV/m
Φ_{acc}	-20 to 20 deg

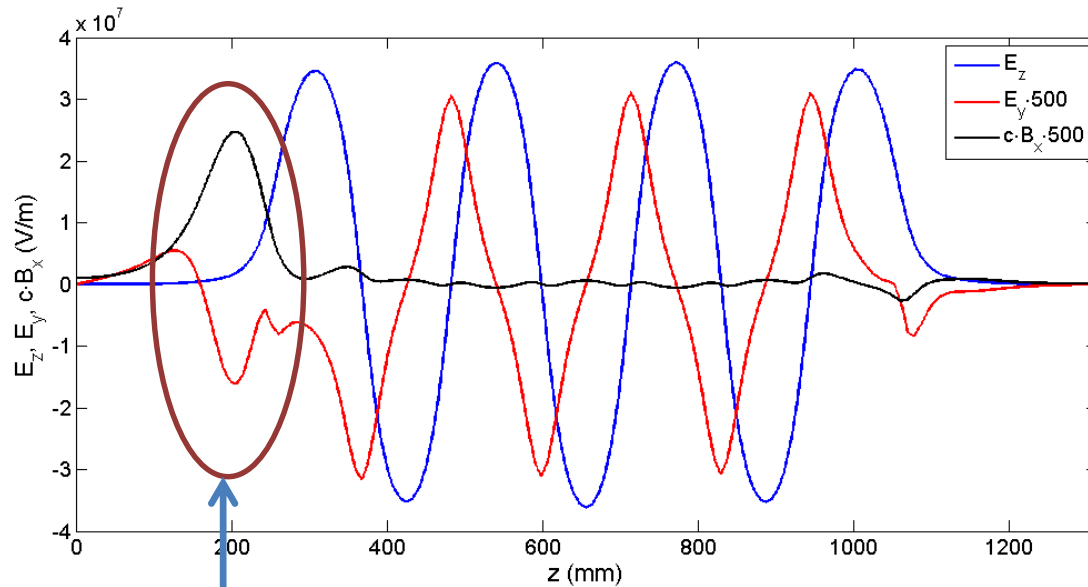
Beam and cavity

Parameters for simulation (EM + PIC solver)

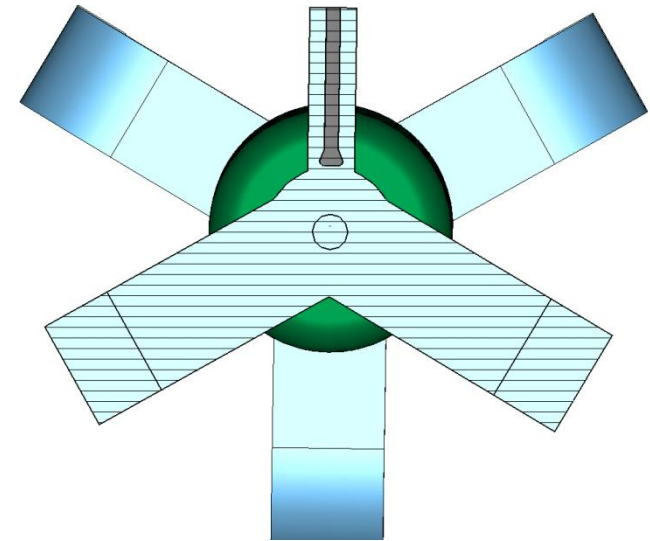
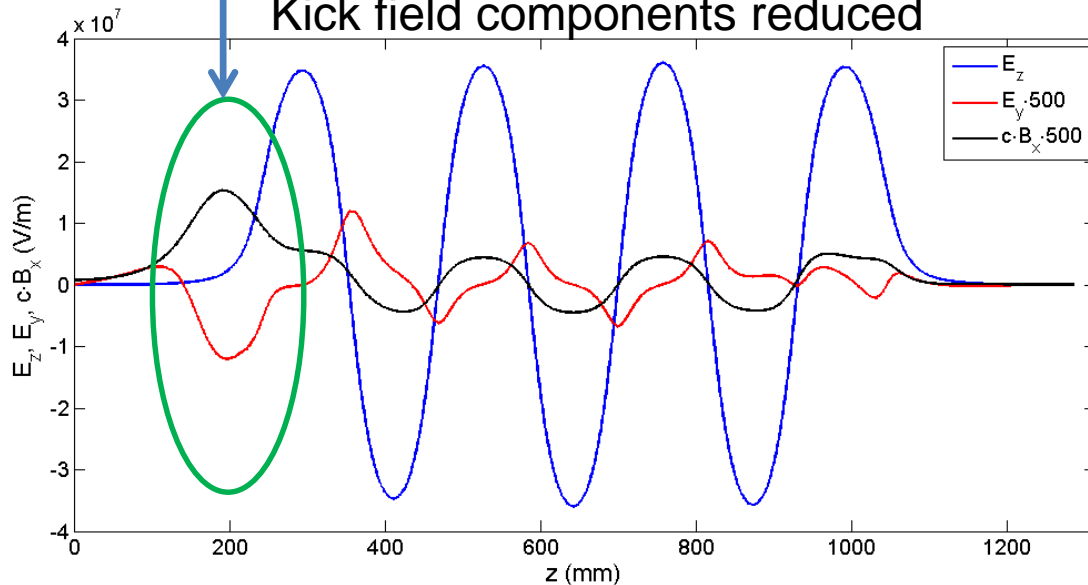
Confirmed with Astra tracking calculations



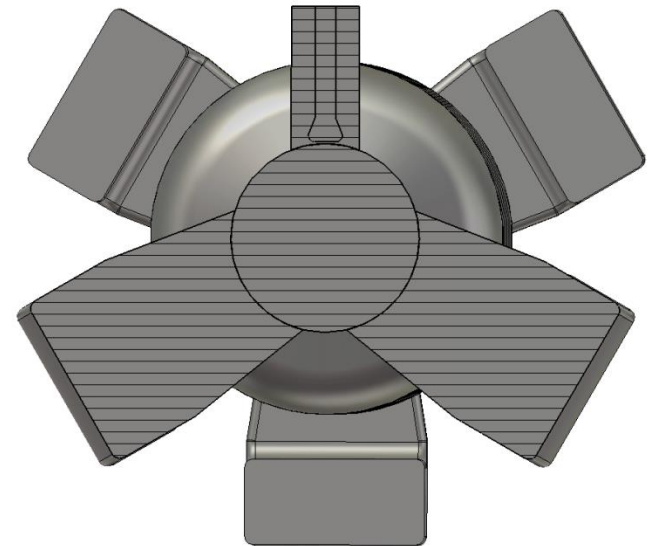
New end-group for kick reduction and trapped mode tuning



Kick field components reduced



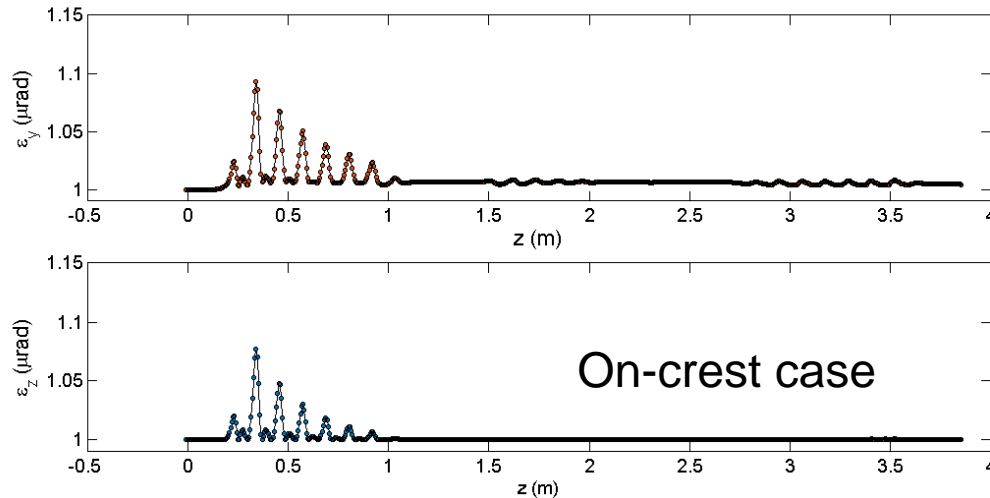
Kept waveguide dimensions, but included tapering



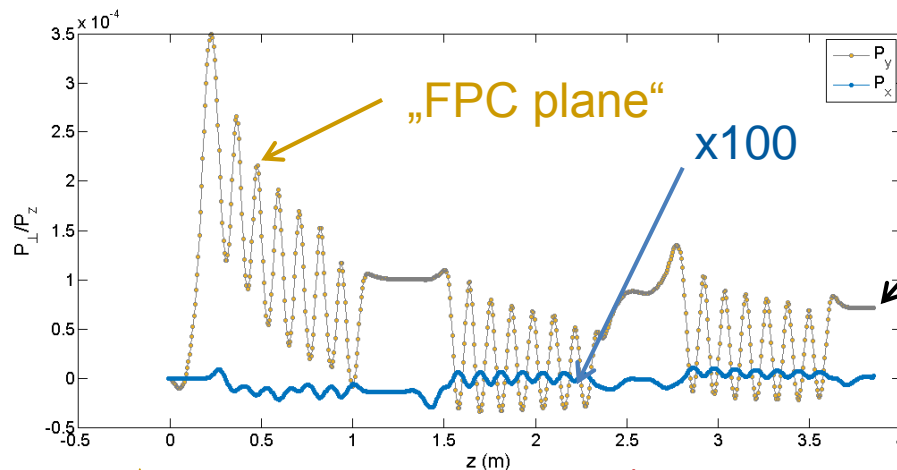
Removes mode in transition

Module based kick analysis

Emittance dilution by variation of field experienced by different slices of bunch → function of bunch length which samples the coupler field during passage

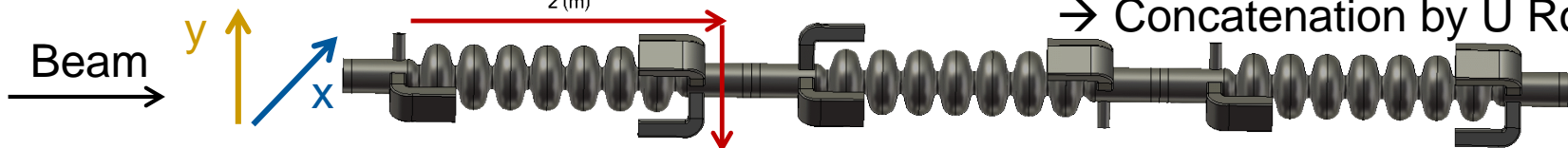


EM and PIC based coupler kick study:
below 0.5%
emittance increase in
both transverse
planes

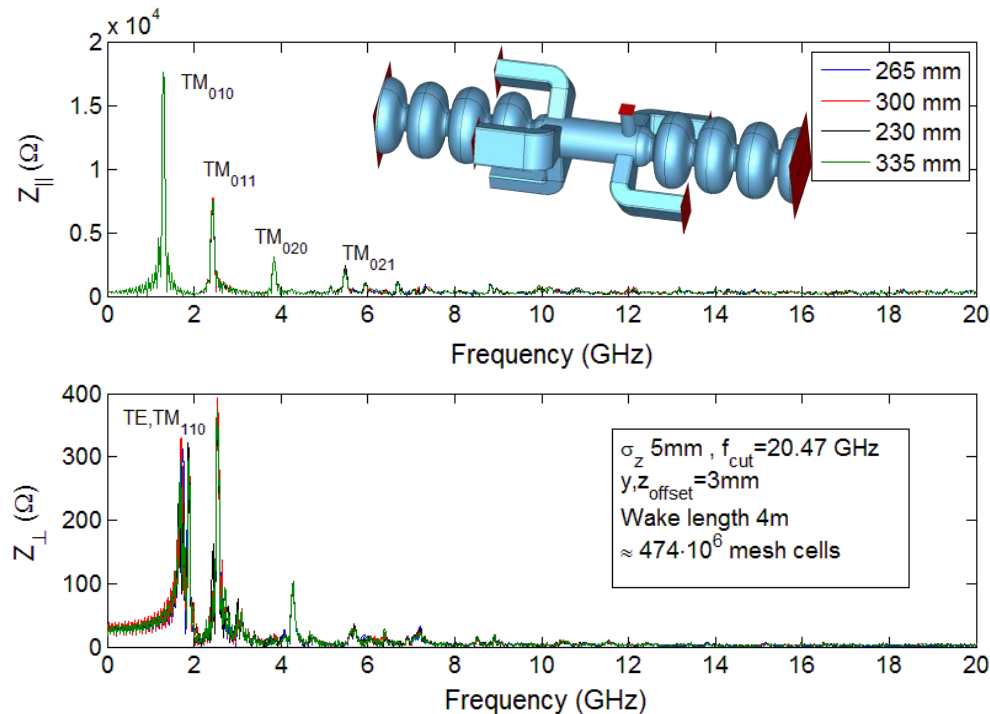


Kick is integral effect on bunch's center of mass, depends on FPC's orientation in string

Triggered study:
Which orientation optimal w.r.t.
coupler kicks and HOM damping
→ Concatenation by U Rostock

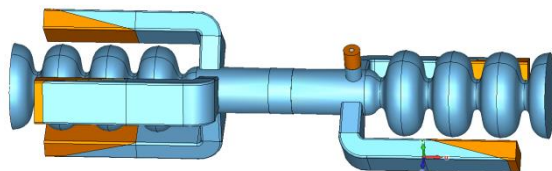


First module based HOM/Wake studies

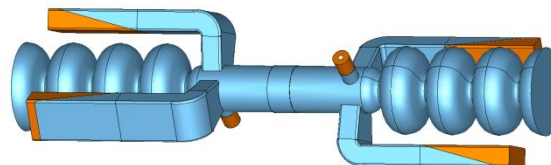


- Study influence of length of interconnecting beam tube on HOM spectrum
- Comparing reference run done with full cavity as half cell open boundary somewhat inaccurate
- Mode of TM_{020} type closed to beam harmonic at 3.9 GHz. Typically they have low impedance because of transit time effect
- Resolution of Wake calculation limited as very high computational effort

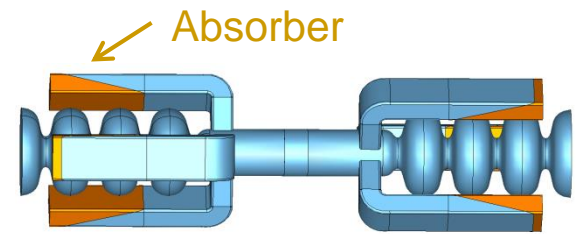
But three different sets of interconnecting groups exist:



5WG+1TTF

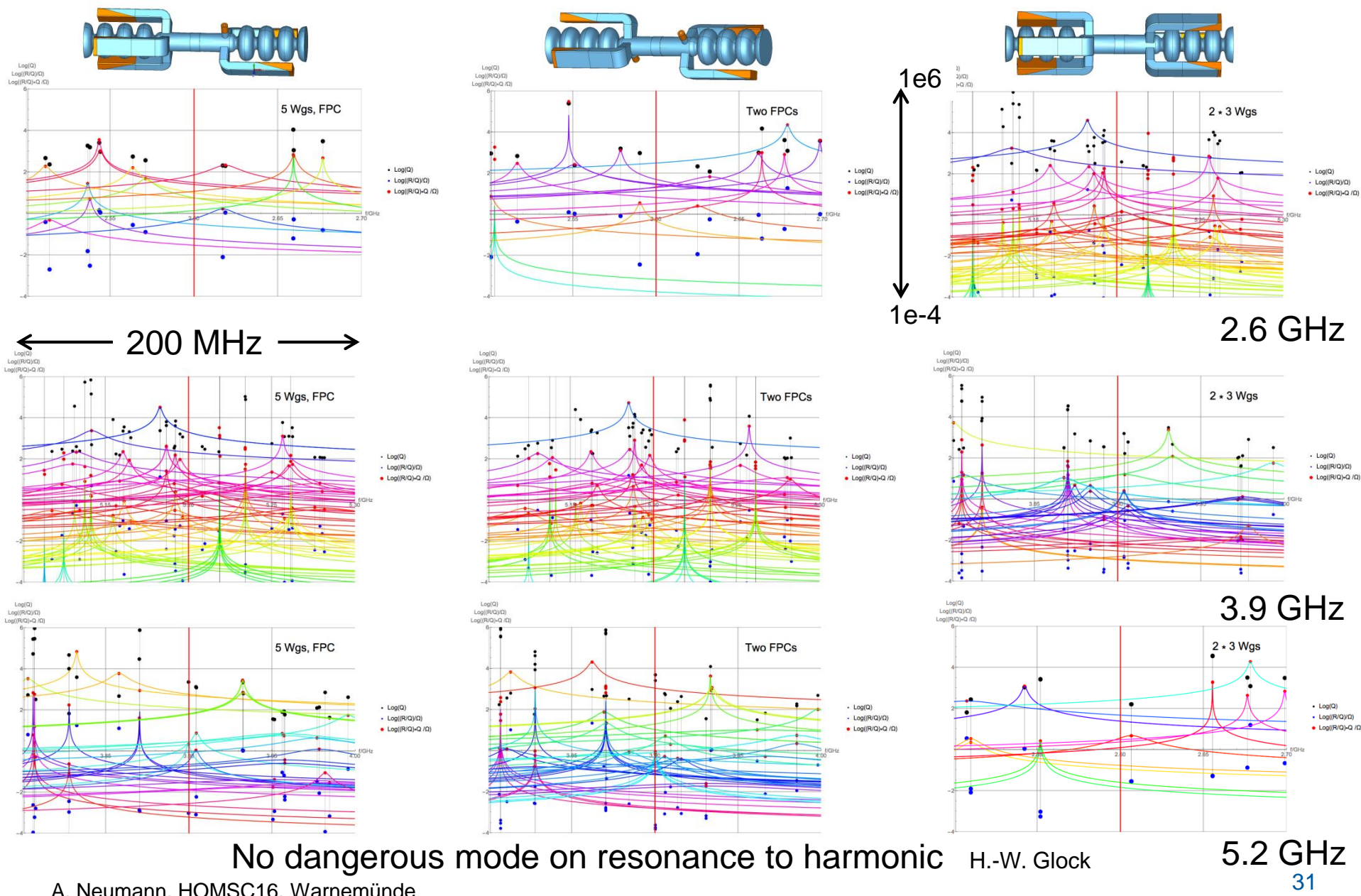


4WG+2TTF

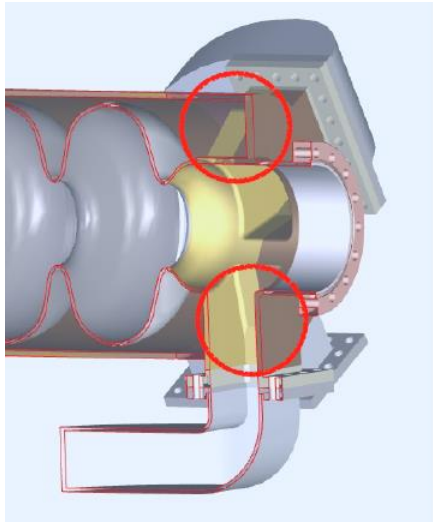


6WG

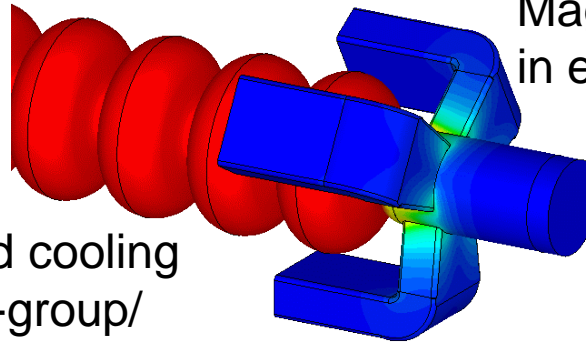
Intense Eigenmode search at beam harmonics



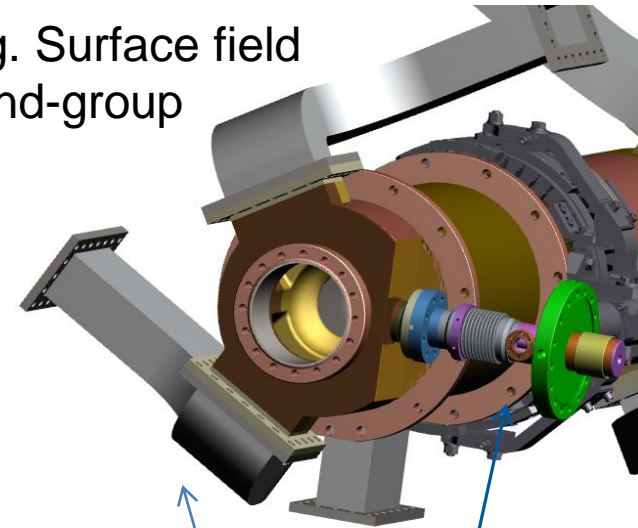
Cavity design issues w.r.t. HOMs



3-sided cooling
of end-group/
waveguides →
Needed to prevent heating
by leaking fundamental
mode

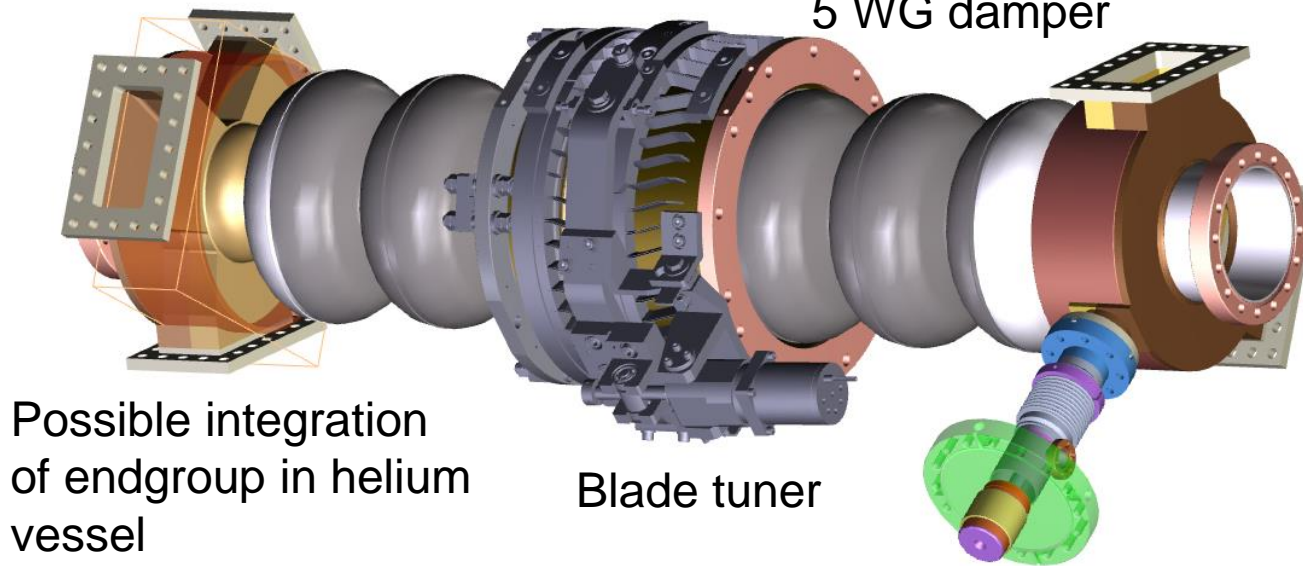


Mag. Surface field
in end-group



Integration of
original TTF-III
coupler design

What type of
flange/flange
material?
Length of
superconducting
section

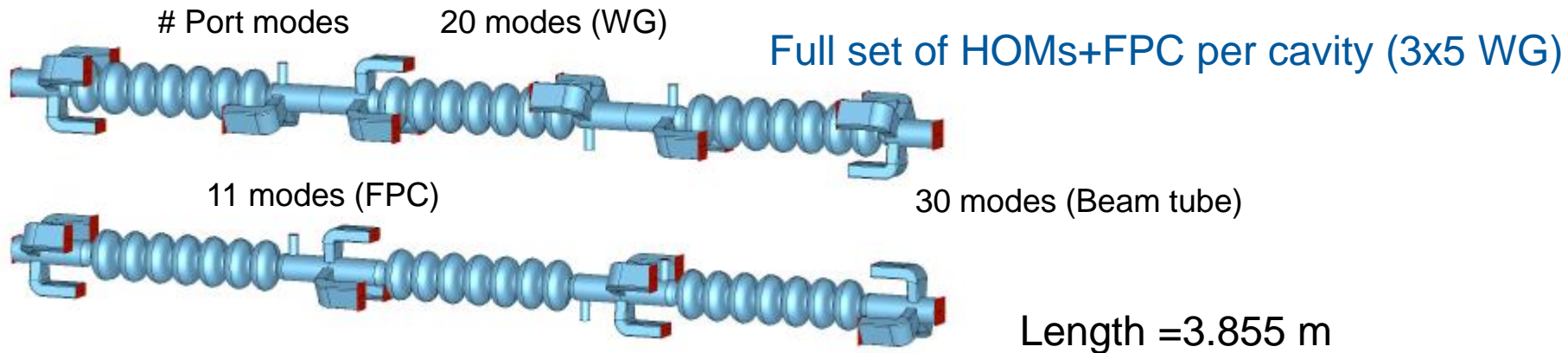


Possible integration
of endgroup in helium
vessel

Blade tuner

TTF coupler

PS Wake Solver based module RF studies



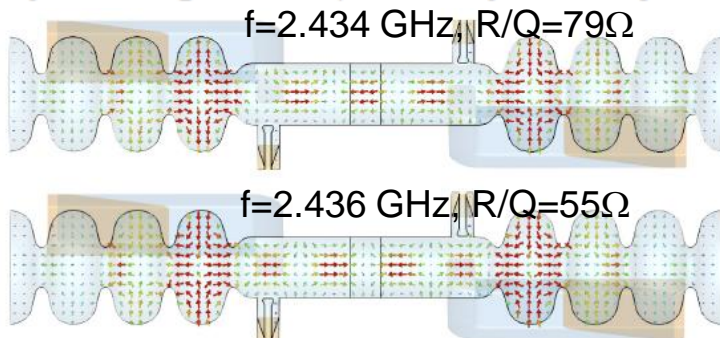
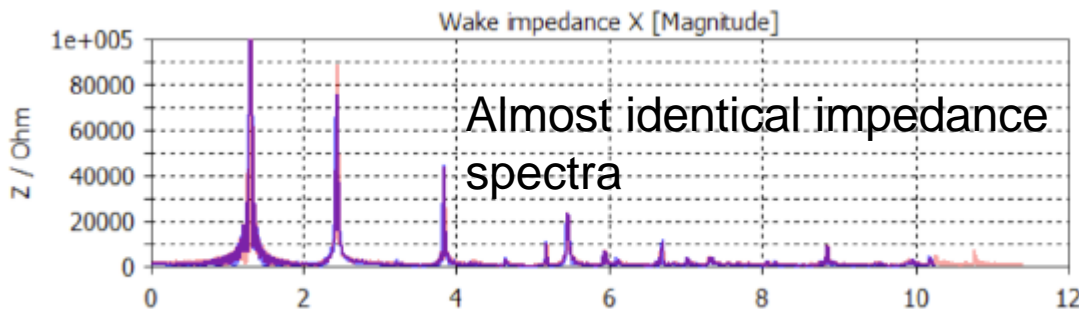
Reduced version:

One waveguide group between cavities (4x3 WG)

Wake solver settings:

$\sigma_s = 9\text{ mm} \rightarrow$ up to 11.3 GHz analyzed, offset 2.1 mm in both transverse planes

158h on a 2 x Xeon2643v2 6-core 256 GB RAM



Strong coupling of beam tube to TM_{011} band, $6/7\pi$ type, localized in end-cells and tube

\rightarrow Complete BBU and long. HOM analysis planned with Rostock data

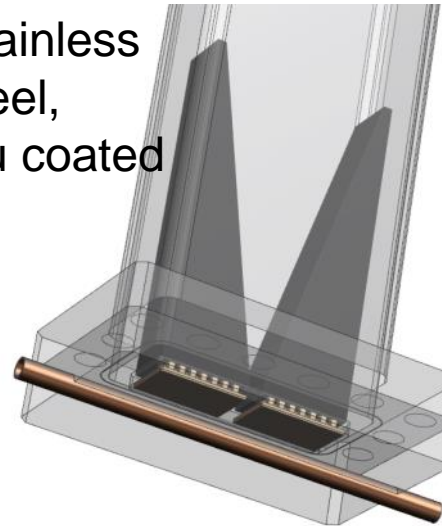
Wake data and EM based fundamental mode data serve as input to HOM load design

Freq (GHz)	TE10	TE11	TM11	TE30	Total (W)
2.6	8.370				
5.2	3.962	2.534	10.482	0.926	
7.8	0.468				
Max power (W/100MHz bin)	8.370	2.534	10.482	0.926	
Total mode power (W)	12.885	2.789	10.738	0.982	27.394
total of modes to sim (W)					26.742

Stainless steel,
Cu coated

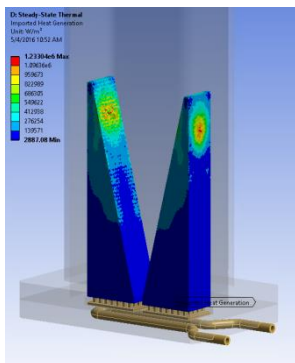
SiC wedges
brazed on Cu
Pegboard

Load designed
for 25 W

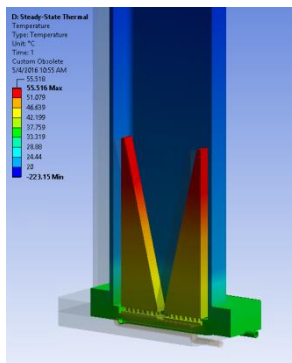


Room temperature
Cooling water channel

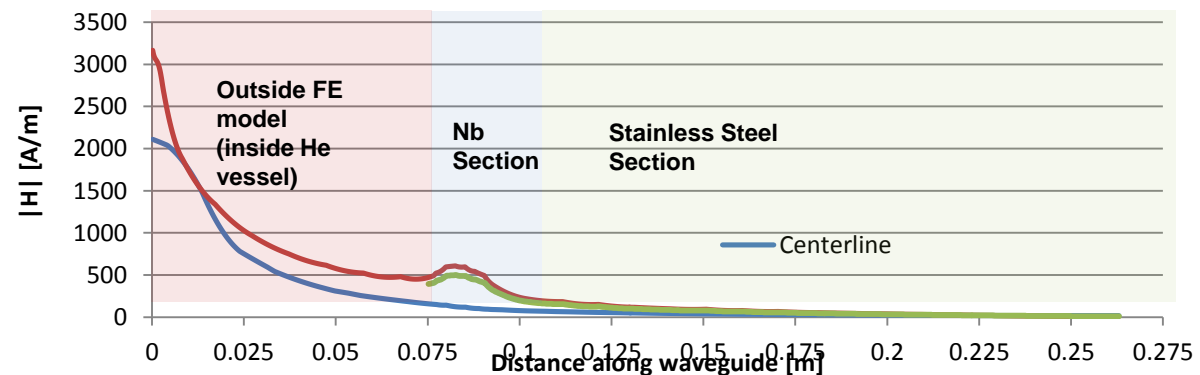
J. Guo, F. Fors, JLab



Imported RF power
losses mapped to
the absorber

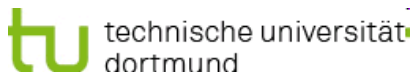
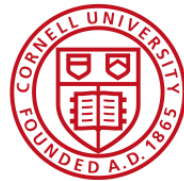


Thermal
analysis
results



Currently: Optimization of intercepts and flange position

Acknowledgements



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, R. Eichhorn, J. Sekutowicz, G. Ciovati, L. Turlington, D. Reschke, A. Matheisen, M. Schmökel, B. van-der-Horst, J. Smedley, V. Volkov, D. Kostin, I. Will, W.-D. Möller, M. Schalwat, U. van Rienen, T. Galek, B. Riemann, T. Weis, K. Brackebusch, T. Flisgen
+ many more

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