Thermal and mechanical requirement

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Coupler worshop. LCWS2013

Outline

- ILC TDR specification
- Power requirements for Eacc=31.5 MV/m ± 20%
  - *QL tuning range*
  - *Power overhead*
  - *Effect of gradient distribution*
- Requirements for cryogenic losses
- Mechanical requirements
- Conclusion

TDR specifications

TDR v3-II. Table 3.7

Main specifications of the input coupler. The parameters represent the approximate maximum expected values during operation, **including possible high L upgrades.**

Average power ~ 3.3/**6.6 kW**
400kW x 5/10 Hz x 1.65ms

- Low energy regime requires 10 Hz operation for electron linac at reduced gradient.
- Bunch compressor at lower gradient will not compress beam to nominal size. Is it OK?

Parameter	Specifications
Frequency	1.3 GHz
Operating pulse length	1.65 ms
Operating Repetition rate	5 Hz / 10 Hz
Maximum beam current	8.8 mA
Accelerating gradient of cavity	31.5 MV/m ± 20%
Required RF power in operation	400 kW
Range of external Q value	$(1÷10)\cdot10^6$ (tunable)
RF process in cryomodule	> 1200 kW for ≤ 400 μs > 500 kW for ≥ 400 μs
RF process in HTS	> 600 kW for 1.6 ms
RF process time	< 50 hours in warm state < 20 hours in cold state
Approximate heat loads	< 0.01 W /0.02 W (2K static/dynamic) < 0.07 /0.12 W (5K static/dynamic) < 0.1 /1.6 W (40K static/dynamic)
Number of windows	2
Bias Voltage capability	Required

Simple approach: Beam Power

	I_b = 6 mA	I_b = 9 mA
G_a = 25 MV/m	175 kW	236 kW
G_a = 31.5 MV/m	196 kW	294 kW
G_a = 38 MV/m	237 kW	355 kW

Minimum power that needs to be handled.

Specification set by the "worst case" (355 kW)

True requirement is higher than this, and depends on choice of fill time (t_{fill}) and Q_{ext}.

Impact of ±20% gradient spread

- **Maximising voltage from an RF unit requires so-called P_k and Q_L (~Q_{ext}) control.**
- **As a result, most cavities will not be "matched" and power is reflected**
  - this has to be added to the beam power for the coupler
  - Equivalent power (transmission mode power → V_{SW})

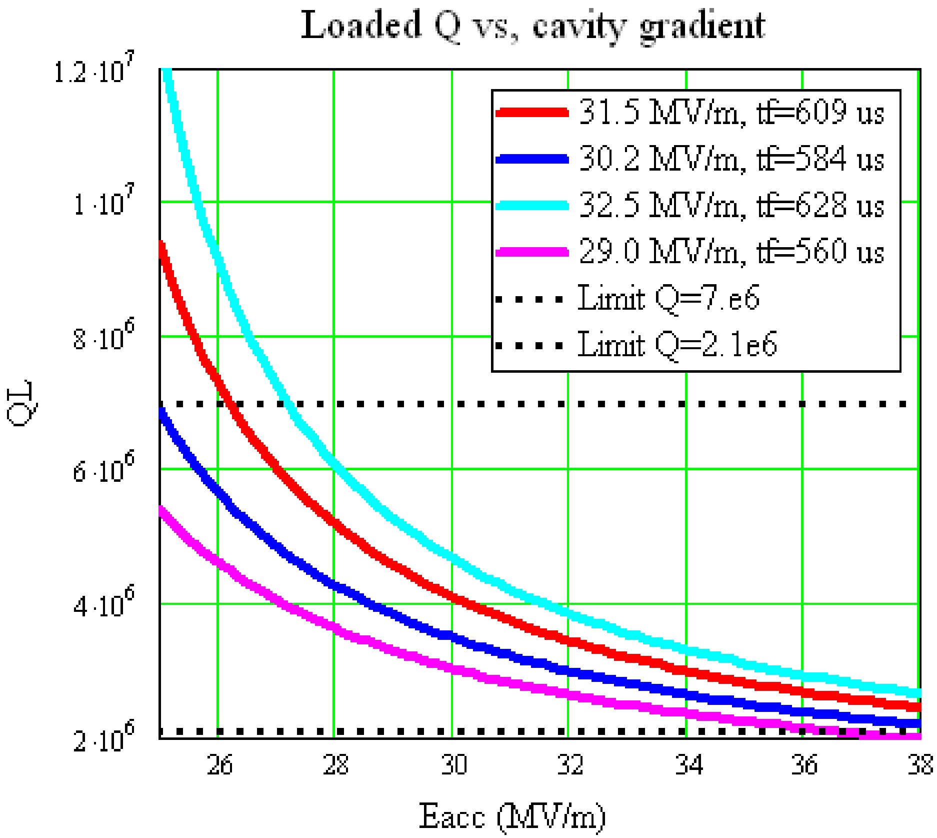
Maximum power $$P_{t,eff} = P_{for} + P_{ref} + 2\sqrt{P_{for}P_{ref}}$$

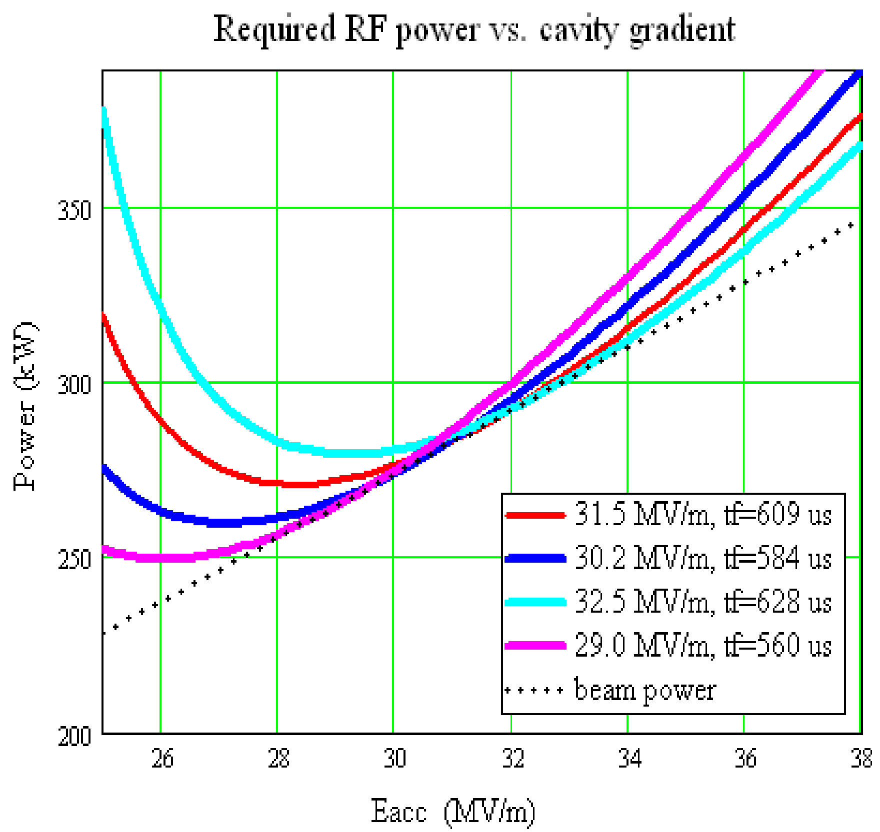
Average power $$P_{t,eff} = P_{for} + P_{ref}$$

- **This overhead is linked to the choice of Q_{ext} range, t_{fill} and overall klystron power overhead.**

Impact of 20% gradient spread

Flat-top operation (Pk,QL solution) *for* 8.8 mA; Gradient = 31.5 MV/m ± 20%





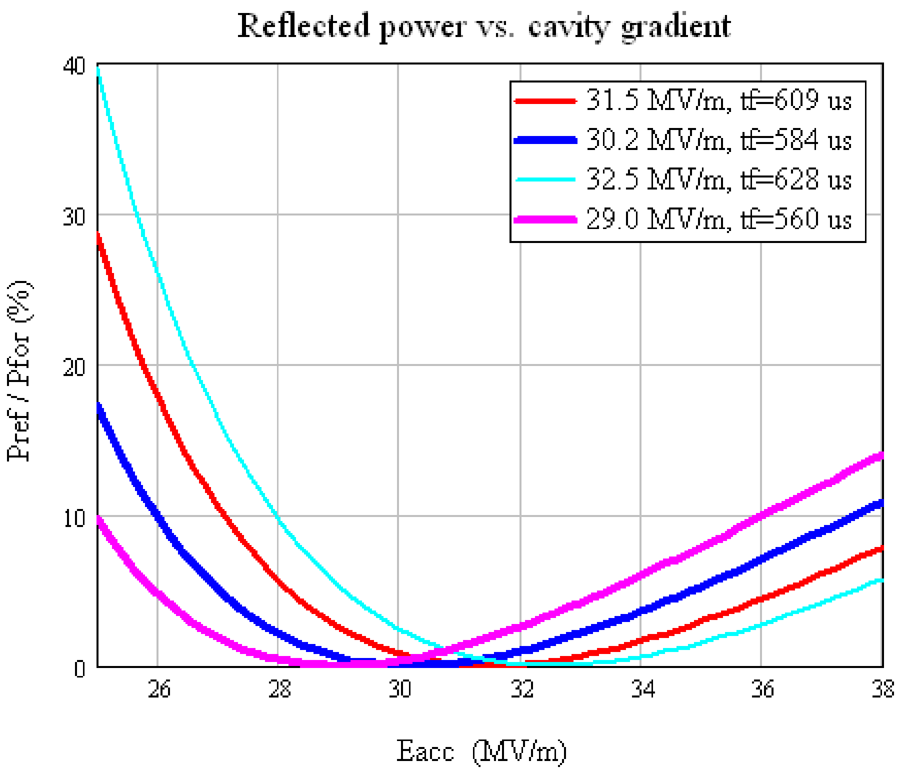
Loaded Q (left) and required power vs. cavity gradient for different matching gradient

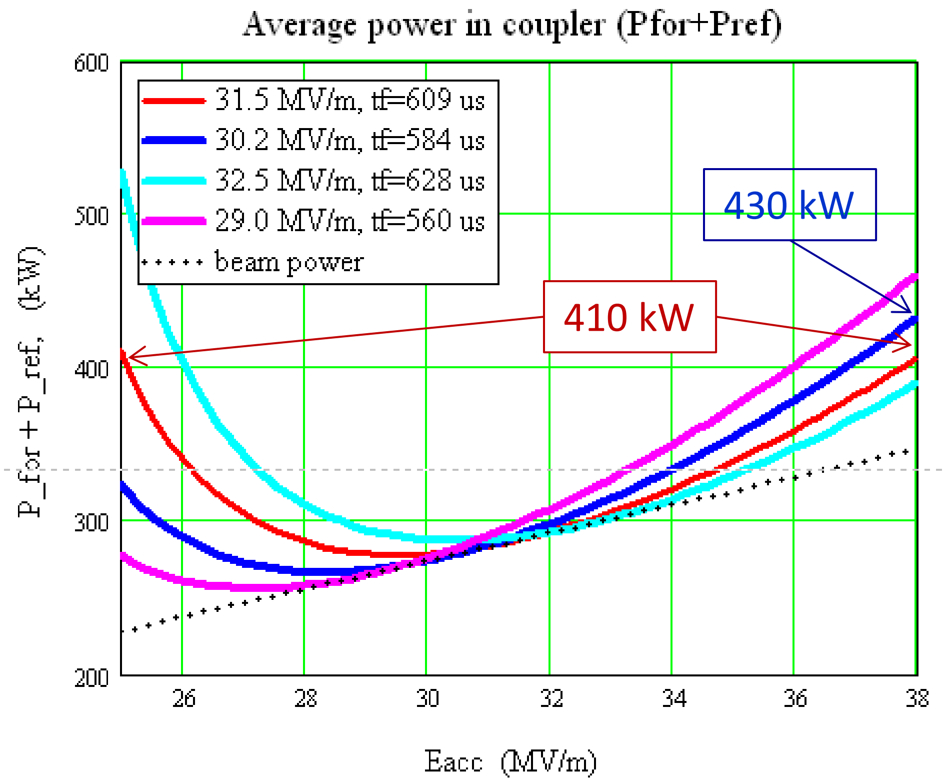
Constraint : QL ≤ $7 \cdot 10^6$ → Matched Gradient ≤ 30.2 MV/m

For G_{match} = 30.2 MV/m:

- smaller QL tuning range (2÷7) $\cdot 10^6$
- Maximum RF power : 390 kW (@38MV/m)

Reflected power (@ flat-top) and power losses in coupler





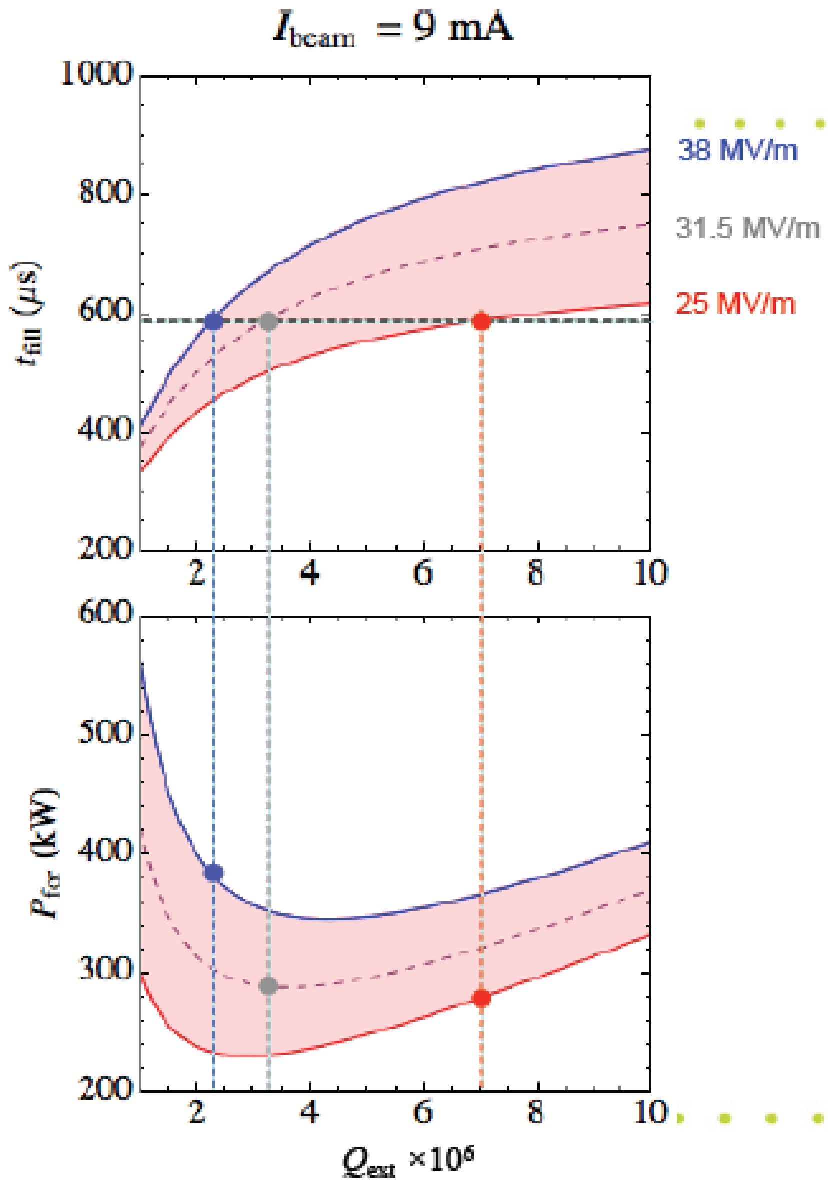
Maximum power losses in coupler corresponds to ~430kW transmitted power (blue curve). Power reflection ~11%

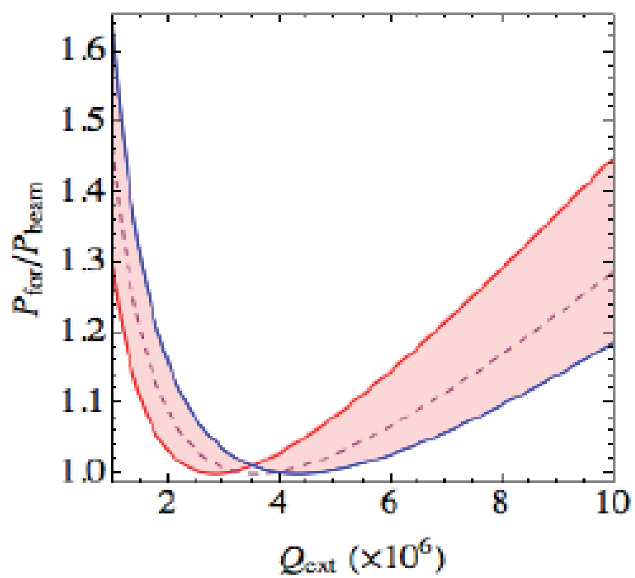
P_K Q_L solutions

Worst case 9 mA

Constrained $Q_{ext} \leq 7\times10^6$

t_{fill} = 585 μs (set by 25 MV/m cavity)





Nick Walker and Wolf-Dietrich Moeller presentation

Summary

I_{beam} =	5.8	matched @ 31.5 MV/m						$Q_{ext} \le 7\times10^6$					
Gradient MV/m	P_{beam} kW	Q_{ext} $\times10^6$	t_{fill} µs	t_{pulse} ms	P_{for} kW	P_{ref} kW	$P_{t,eff}$ kW	Q_{ext} $\times10^6$	t_{fill} µs	t_{pulse} ms	P_{for} kW	P_{ref} kW	$P_{t,eff}$ kW
25.0	151	14.2			211	60	384	7.0			159	9	244
31.5	190	5.4	923	1.65	190	0	190	3.756	824	1.55	196	7	275
38.0	229	3.7			248	20	407	2.767			274	45	543

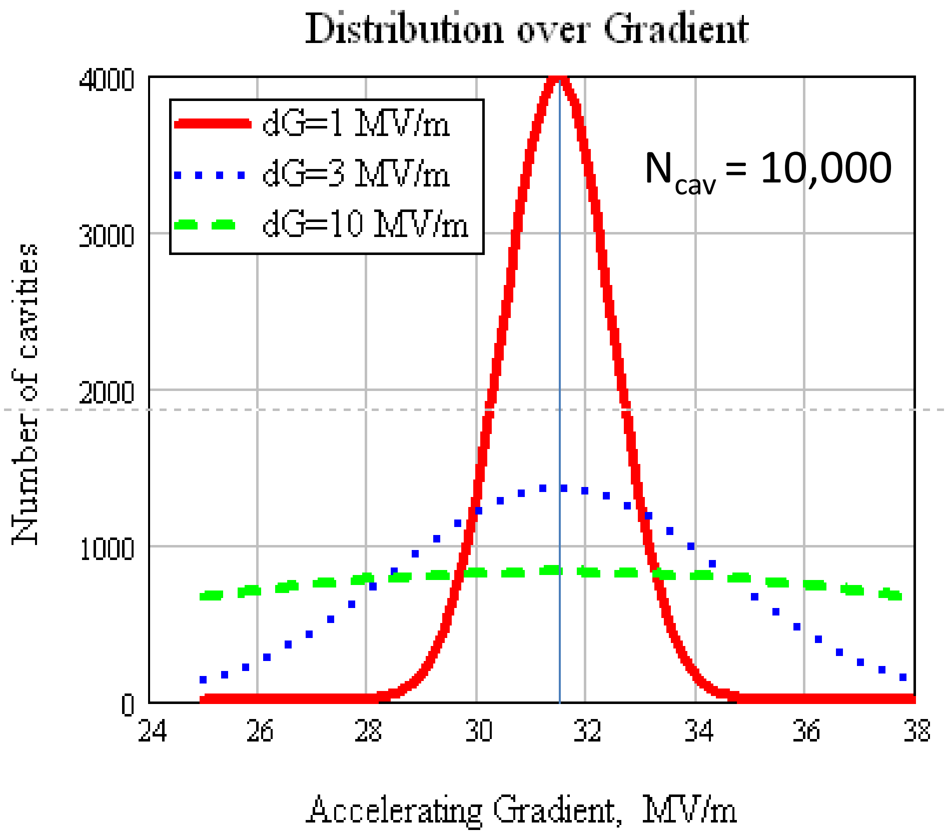
I_{beam} =	8.8	matched @ 31.5 MV/m						$Q_{ext} \le 7\times10^6$					
Gradient MV/m	P_{beam} kW	Q_{ext} $\times10^6$	t_{fill} µs	t_{pulse} ms	P_{for} kW	P_{ref} kW	$P_{t,eff}$ kW	Q_{ext} $\times10^6$	t_{fill} µs	t_{pulse} ms	P_{for} kW	P_{ref} kW	$P_{t,eff}$ kW
25.0	228	9.4			320	91	753	7.0			278	49	562
31.5	288	3.6	609	1.57	288	0	288	3.1	585	1.55	289	1	330
38.0	347	2.4			377	30	617	2.2			389	42	686

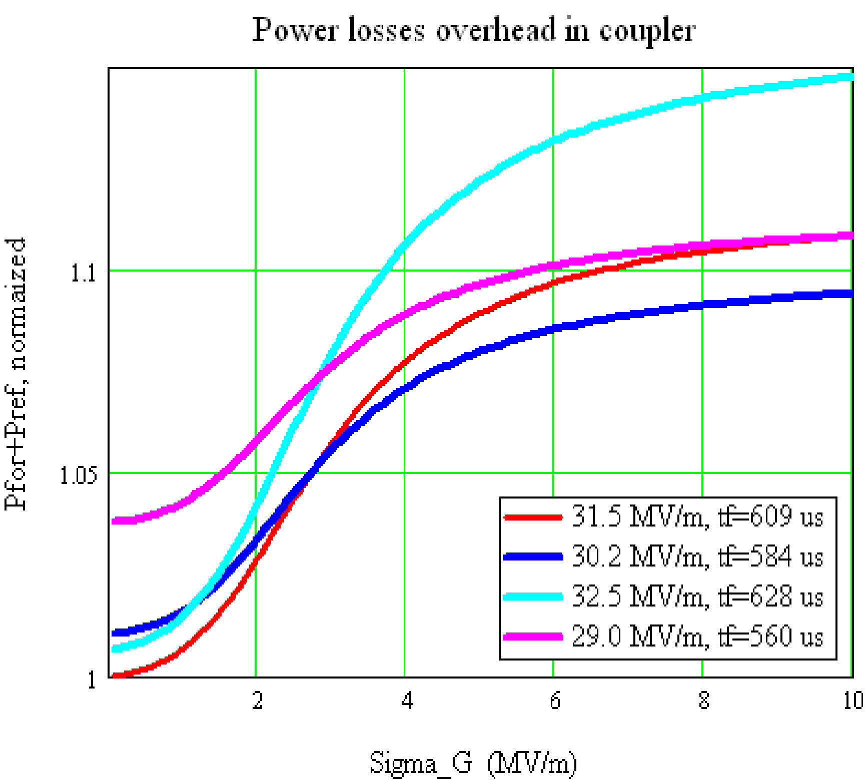
~410kW **~430kW**

Maximum pulse repetition rate: 10 Hz
(covers L upgrade scenarios)

<u>Conclusion:</u>
In case of large gradient spread ±20% it is beneficial to chose lower matched gradient (~30 MV/m , -4%). It will reduce filling time and required QL range. Drawback is higher forward power and higher losses in coupler, partially compensated by shorter RF pulse.

Effect of accelerating gradient distribution



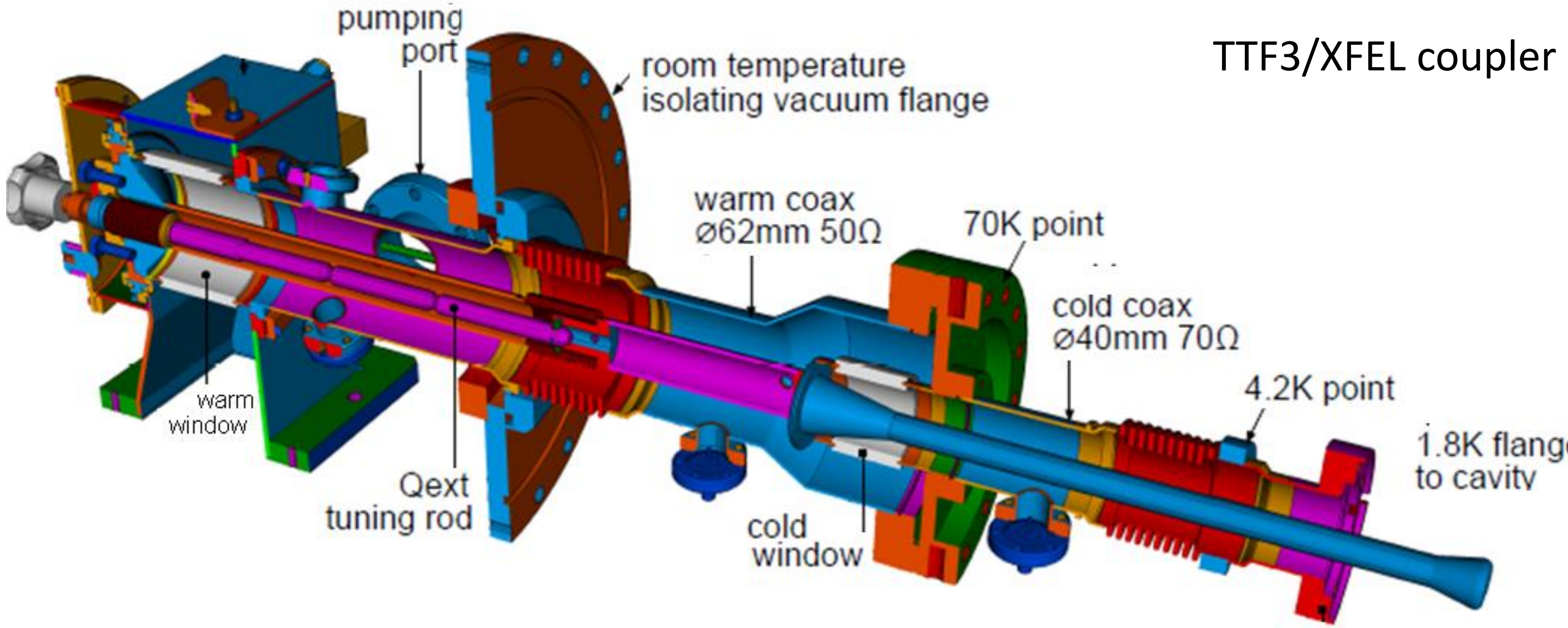


$$n(x,\sigma) := Nc \cdot \frac{e^{-\left(\frac{x-31.5}{\sqrt{2}\cdot\sigma}\right)^2}}{\int_{25}^{38} e^{-\left(\frac{x-31.5}{\sqrt{2}\cdot\sigma}\right)^2} dx}$$

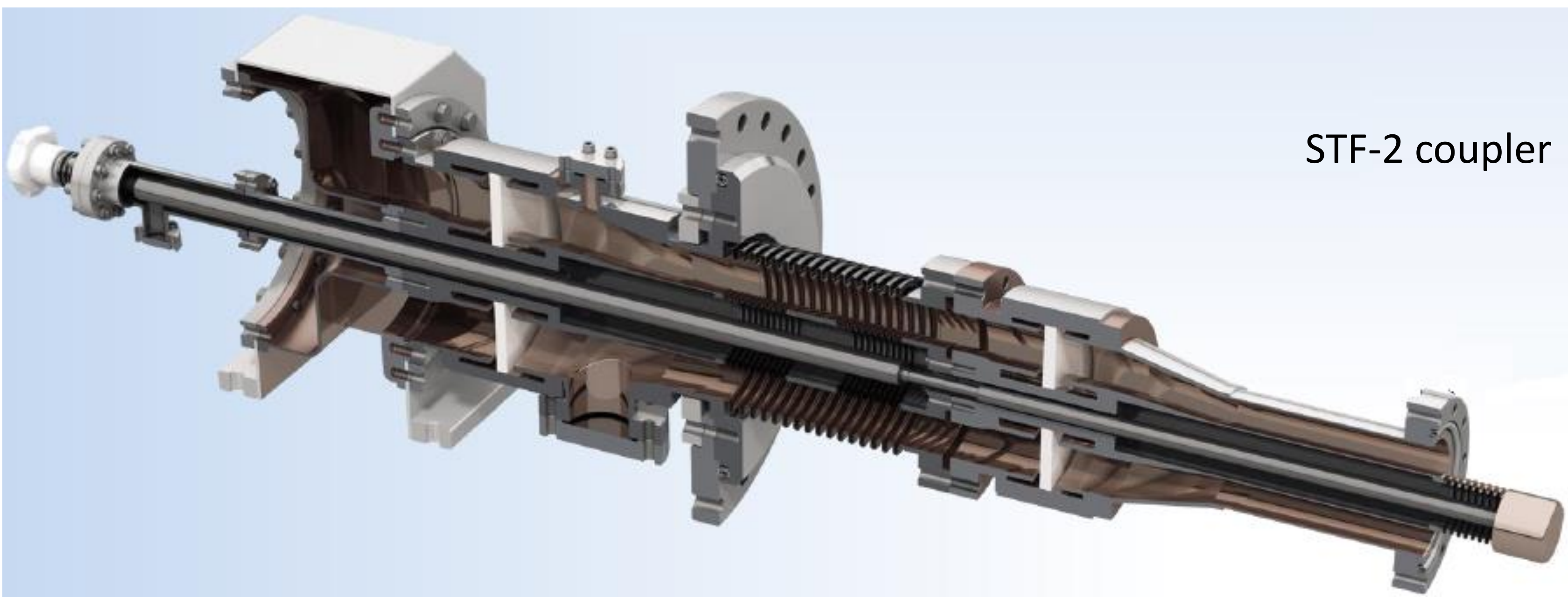
Power losses in coupler normalized to losses for the case without gradient spread. (need small correction for filling time).

Cryogenic losses are scaled as power losses (max increase ≤ 10%)

Cryogenic requirements



TTF3/XFEL coupler

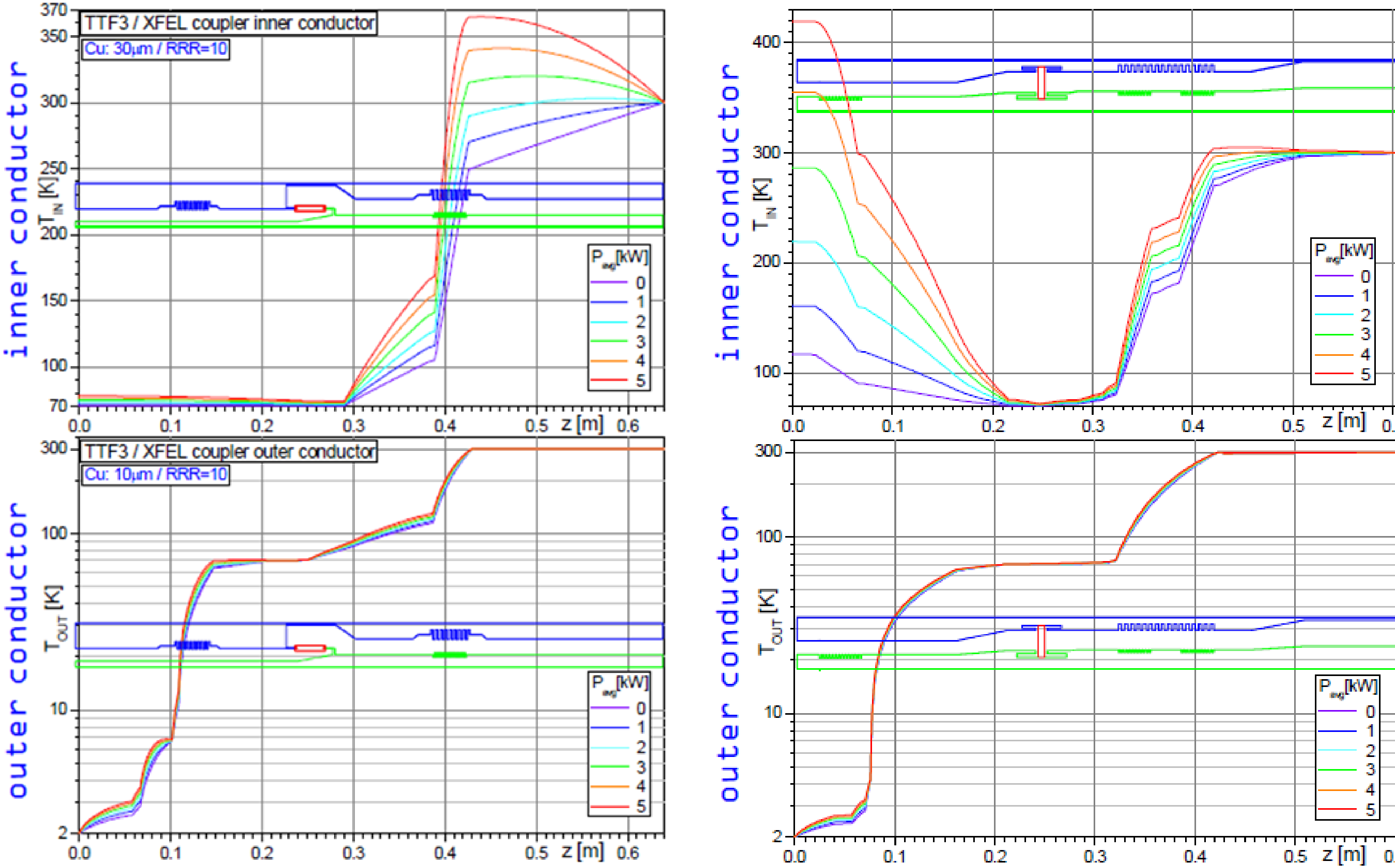


STF-2 coupler

TTF3/XFEL

STF-2 coupler

Denis Kostin /DESY



Thermal analysis done for 2 designs for different power levels, thickness of Cu and RRR

Summary of cryogenic losses simulation

		2K	4K	70K
STF-2 (cod/warm) in=25um, out=10/25 um; RRR=20/50	Static	0.025	0.64	2.86/2.91*
	+Dynamic 5kW	0.036	0.17	6.75 /6.27*
XFEL/TTF3 in =30um, out=10 um; RRR=10	Static	0.02	0.2	1.9
	+Dynamic 5kW	0.05	0.23	6.23

*Increase internal conductor coating h 10→50 um; increase total losses ~0.8W @ 2kW

- RF power simulated up to 5 kW (40 MV/m, 10 Hz, 1.65 ms, 6 mA ; margin 25%)
- KEK S1-G and STF-2 couplers are compared to TTF3 / XFEL coupler.
  - *Designs are very close by cryogenic losses.*
  - *STF-2 coupler has higher static losses*
  - *STF-2 design has 5% less total RF losses (~25% less RF losses on the ceramic window) compared to TTF3 DESY design.*

Cryogenic losses in TDR

Table 3.9
Average heat loads per module in a ML unit, for the baseline parameter in Table 3.1. All values are in watts [27].

	2 K		5–8 K		40–80 K	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
RF Load		8.02				
Radiation Load			1.41		32.49	
Supports	0.60		2.40		18.0	
Input coupler	0.17	0.41	1.73	3.06	16.47	41.78
HOM coupler (cables)	0.01	0.12	0.29	1.17	1.84	5.8
HOM absorber	0.14	0.01	3.13	0.36	-3.27	7.09
Beam tube bellows		0.39				
Current leads	0.28	0.28	0.47	0.47	4.13	4.13
HOM to structure		0.56				
Coax cable (4)	0.05					
Instrumentation taps	0.07					
Diagnostic cable			1.39		5.38	
Sum	1.32	9.79	10.82	5.05	75.04	58.80
Total	11.11		15.87		133.84	
Coupler contribution	5%		30%		43%	
@7 kW	6%		30%		57%	

Average power ~3kW → Input coupler

26/3 = 8.67 cavities per CM an average

Both designs of coupler meet requirements. For 7 kW power requirement should be corrected

Modification TTF3 coupler for operation at 7 kW average power

Power limited by **overheating of the inner bellows >130°C**

Cure: increase thickness of copper plating of inner conductor to ≥50 um

Proposed for Project X, LCLS-II

Cu coating (μm)		Cu RRR	case	Power W	Power W	Power (W)				T_{max} °K
						in	out	window	total	
in	out			2K	4K	70K				
30	10	10	Static	0.02	0.2	0.85	1.06	0	2.13	
			Dynamic	0.07	0.32	5.95	1.74	1.35	9.47	420
50			**Static**	**0.02**	**0.2**	**1.2**	**1.06**	**0**	**2.48**	
			Dynamic	**0.07**	**0.32**	**5.9**	**1.74**	**1.35**	**9.42**	**376**
100			Static	0.02	0.2	1.95	1.06	0	3.23	
			Dynamic	0.07	0.32	5.75	1.74	1.35	9.32	327
30		100	Static	0.095	0.5	0.88	0.73	0	3.06	
			Dynamic	0.025	0.157	5.93	1.63	1.35	8.14	396
50			Static	0.095	0.5	1.24	0.73	0	3.42	
			Dynamic	0.025	0.157	6.02	1.63	1.35	8.23	364
100			Static	0.095	0.5	2.05	0.73	0	4.23	
			Dynamic	0.025	0.157	6.15	1.63	1.35	8.37	322

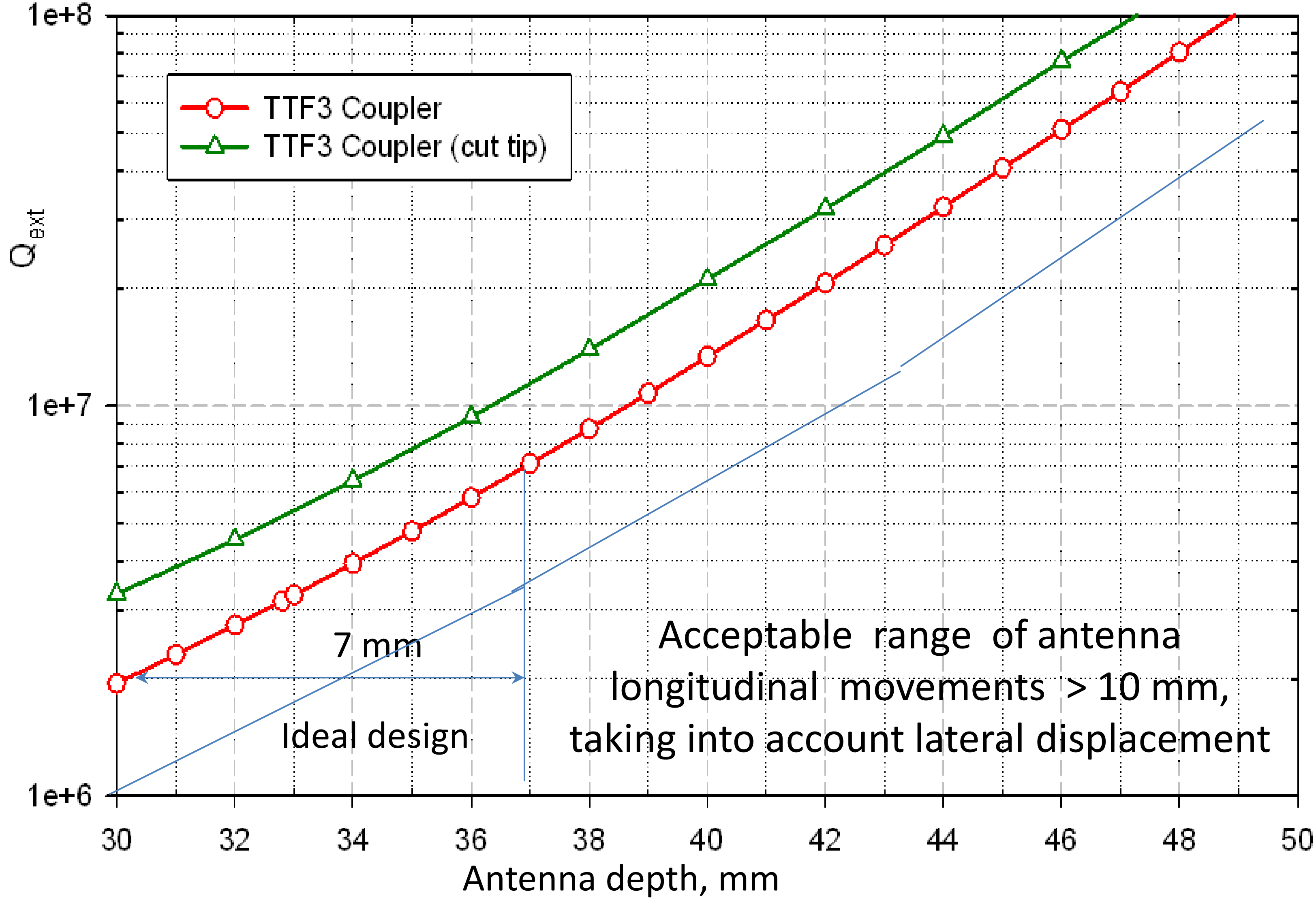
Effect of increase thickness of Cu (only in warn inner part):

increase static losses and decrease of dynamic losses at 70 K

ILC RF Power Coupler design criteria comparison

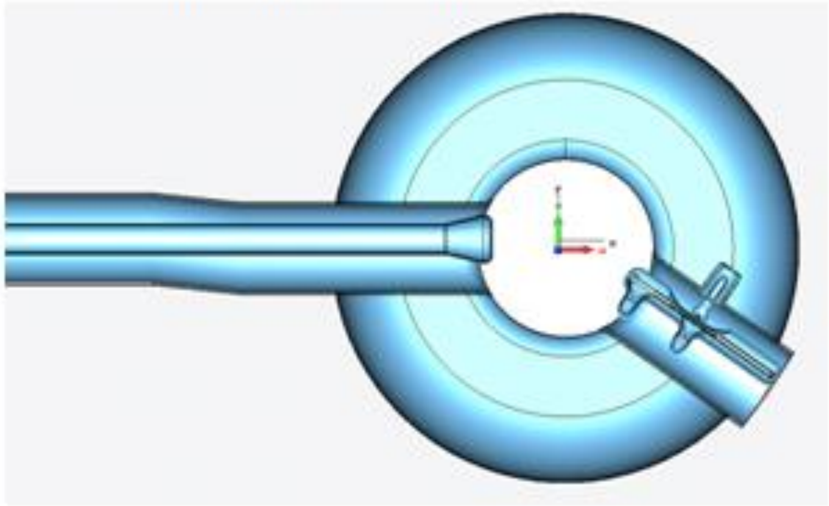
	ILC Spec	TTF3 / XFEL	STF-2
Frequency	1.3 GHz	1.3 GHz	1.3 GHz
Operating pulsed RF power		100 .. 600 kW	
Operating RF pulse length / rep.rate		1.3 ms / 10 Hz	
Max. RF conditioning power (20 .. 500μs)		1 MW	
copper coating inner/outer conductor		30 μm / 10 μm	
copper coating RRR		30 .. 60	
Max. cryogenic losses at 2K / 4.2K / 70K		0.06 / 0.5 / 6 W	
window	2 windows	2 cylindrical	2 disc
Warm coax		60 mm, 50 Ohm	80 mm, 50 Ohm
Cold coax		40 mm, 75 Ohm	60 mm, 50 Ohm
Qext range	**$1.0 – 10 \times 10^6$**	**$1.0 – 15 \times 10^6$**	**$2.0 – 4.0 \times 10^6$**
bias	yes	yes	no
lateral movement	**± 5mm**	± 15mm	± 5mm
max surface field (inner cold part) @500kW TW		1MV/m	0.5MV/m
max voltage, (inner cold part) @500kW TW		14kV	7.5kV
MP levels		150 , 250 , 450 kW	
Insertion loss		less 0.1 dB	

QL tuning range

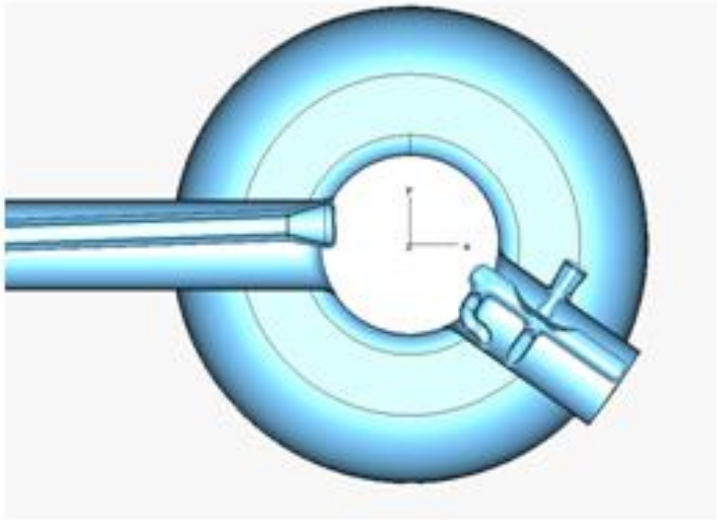


Effect of antenna transverse position in TTF3 coupler

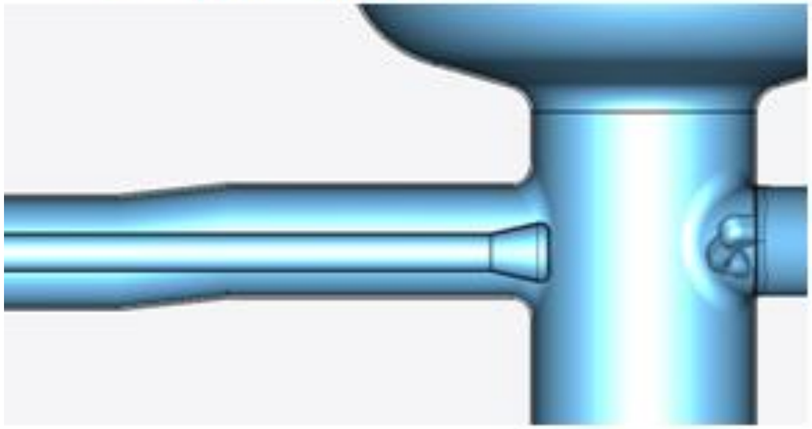
Vertical antenna shift



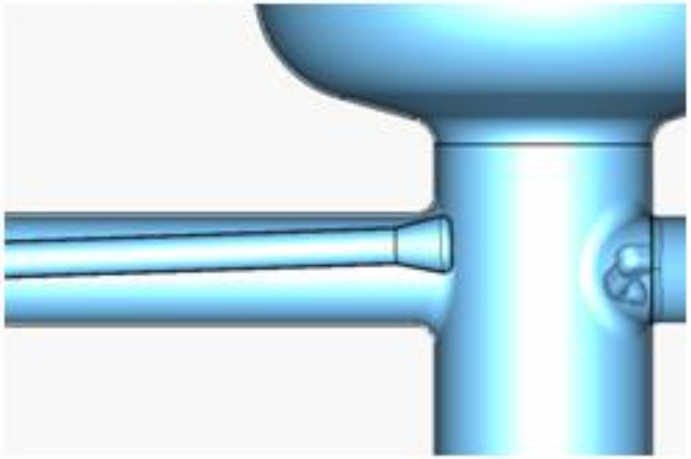
Vertical antenna tilt



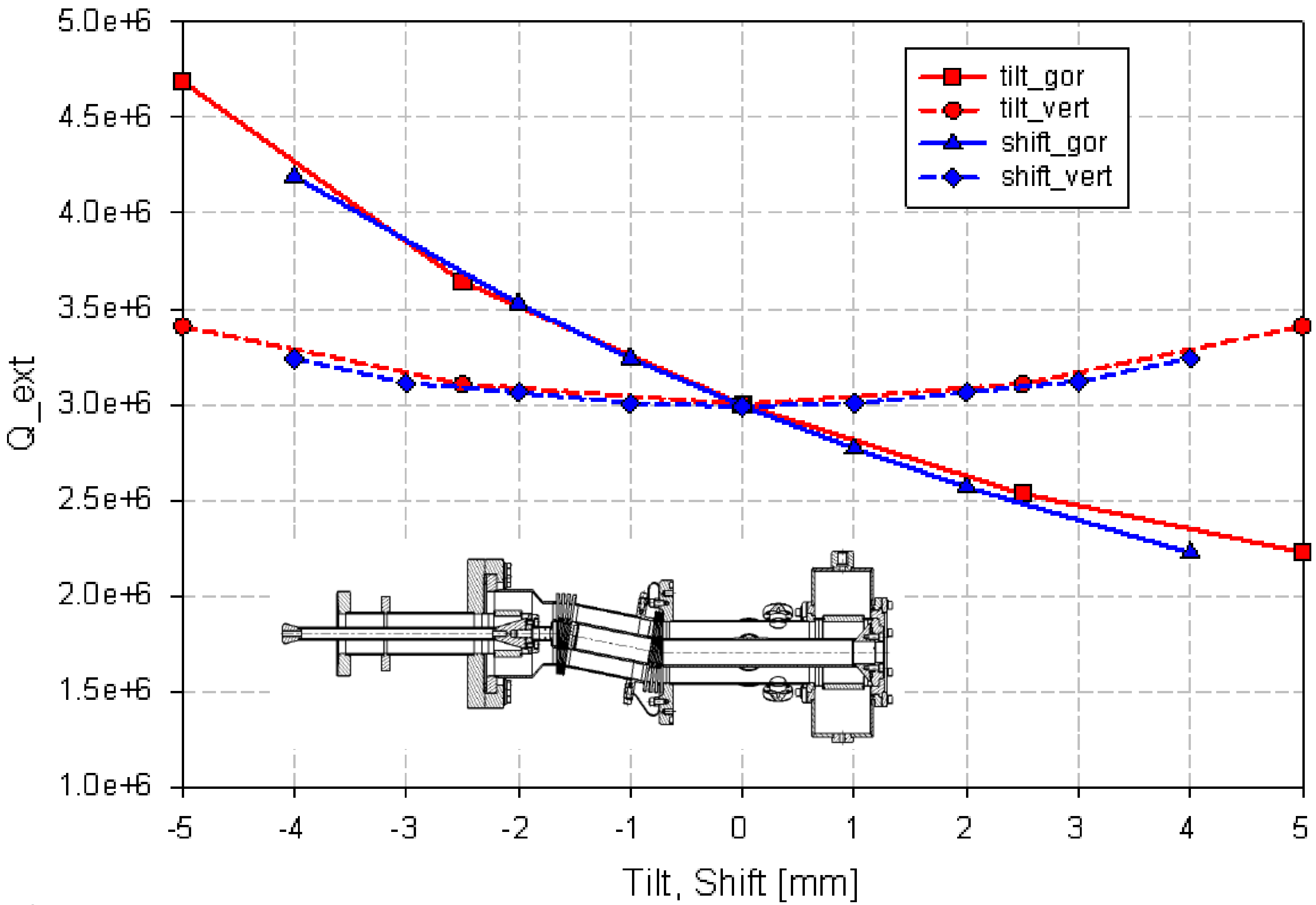
Horizontal antenna shift



Horizontal antenna tilt



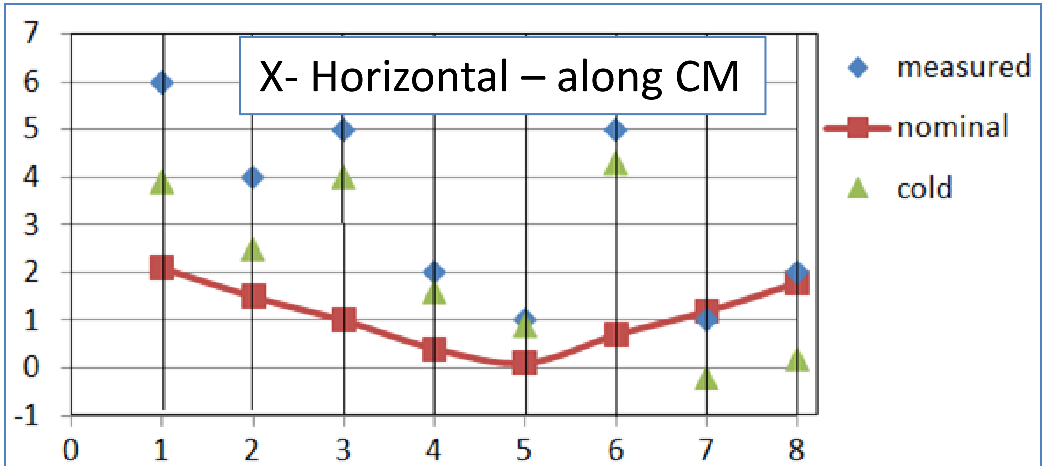
ILC-structure Q-external versus antenna displacements

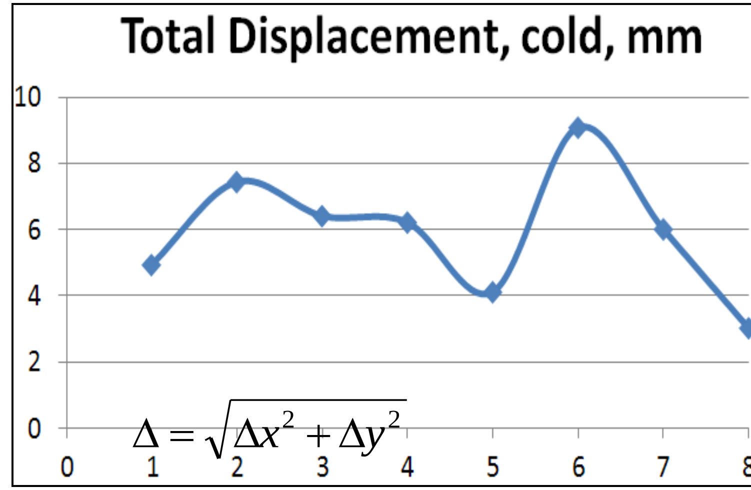


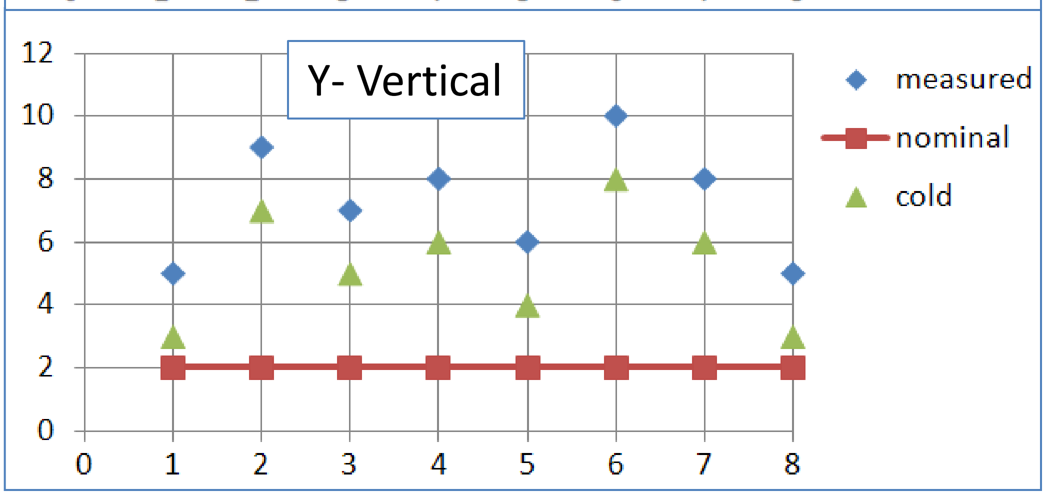
Conclusion

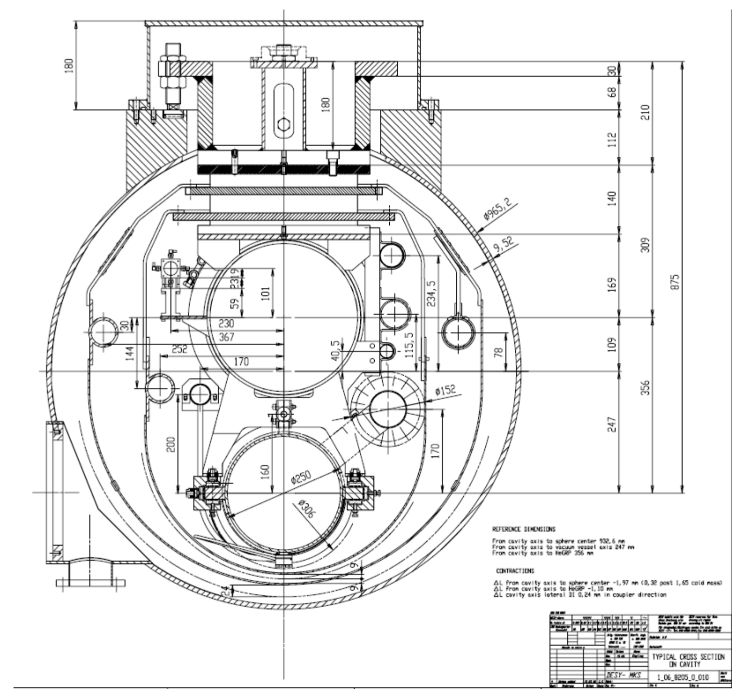
- For TTF3 coupler the most sensitive parameter is a horizontal antenna shift/tilt. 3mm shift change QL by ~20%. Vertical tolerances are relaxed.
- For STF-2 coupler this is not issue, mechanical design guarantee small shift.

Coupler alignment tolerances in CM2



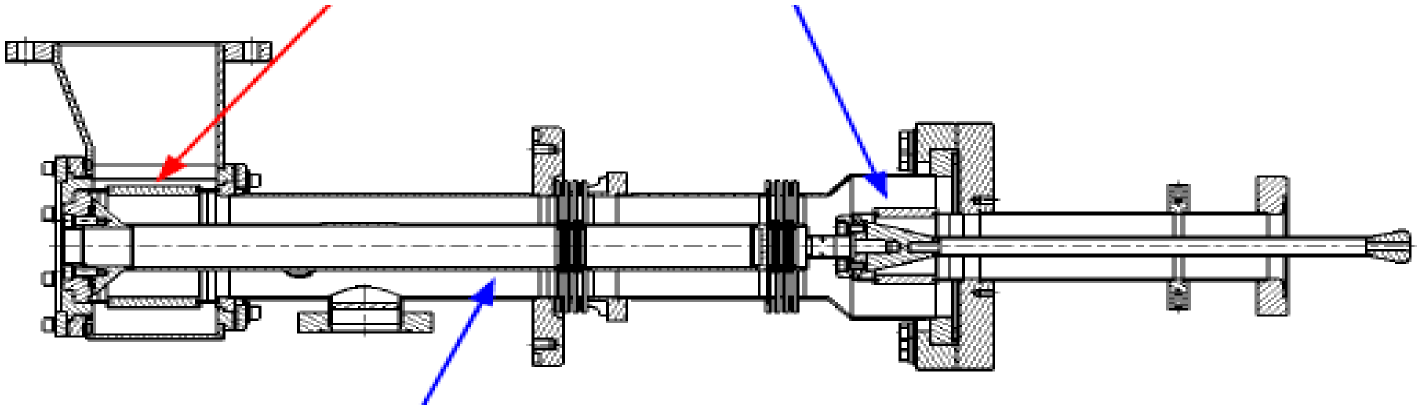


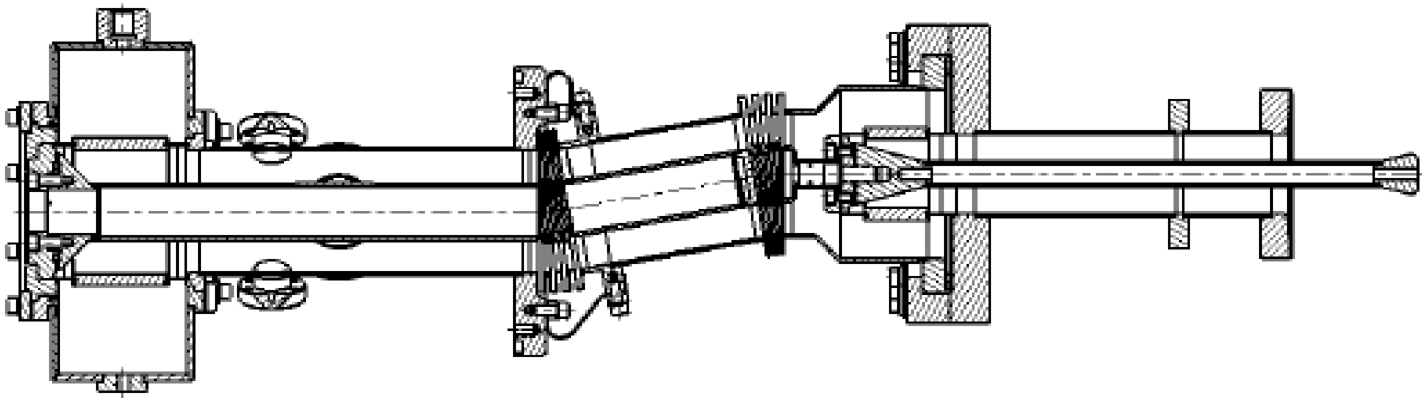




Real position of the antenna is not known. Measurements are done for position of center of 70 K flange.

Lateral movements





With invar rod the expected thermal movement is reduced to 2mm for cavities at the end of CM. Taking into account assembly errors requirements ±(5-7)mm should be acceptable.

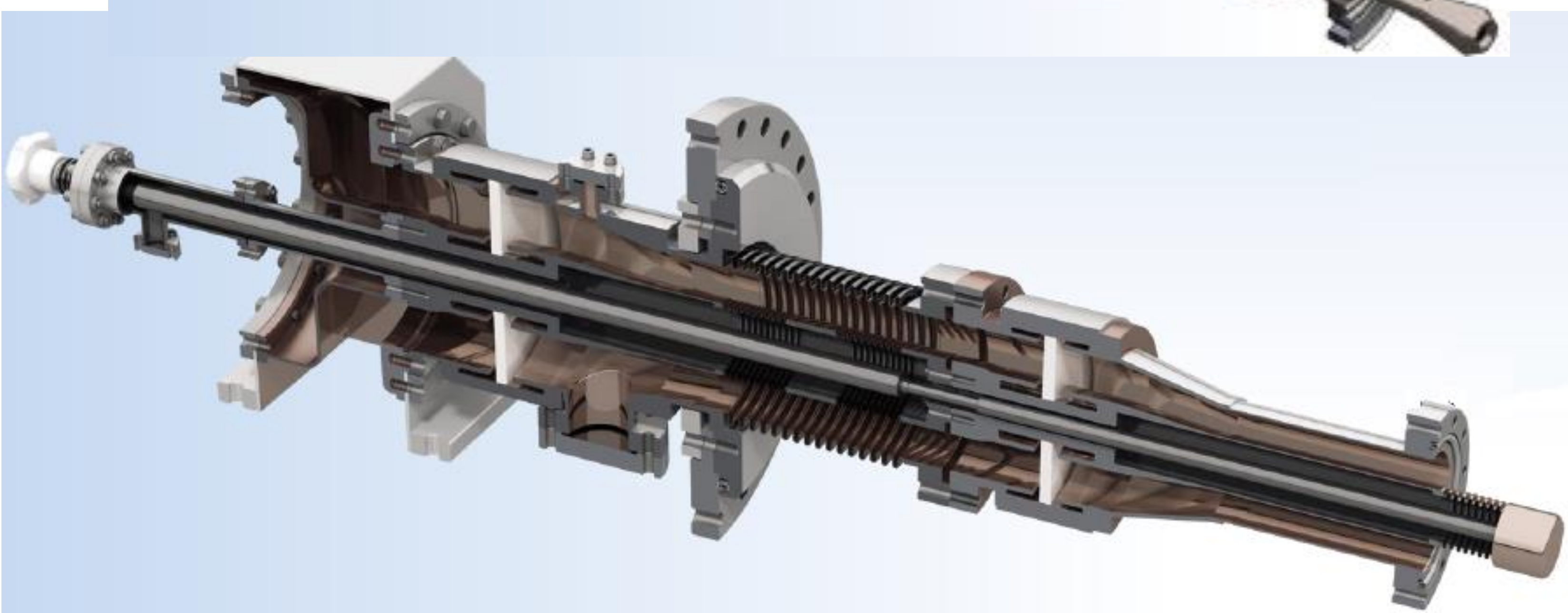
Conclusion

- Requirements for 10 Hz operation with beam current = 8.8 mA and Eacc=31.5 MV/m ±20% is tight:
  - Max coupler power ~400 → 450 kW
  - QL tuning range: $(2\div7)\cdot10^{6} \rightarrow (1\div10)\cdot10^{6}$
  - Matching gradient ~30 MV/m is beneficial for reduction of tuning range and power overhead.
- Coupler contribution to cryogenic losses at 2K is ~5%. Increasing of that value is not critical. 10 Hz operation at full accelerating gradient requires more cryogenic. Major contribution from coupler is 70K.
- Mechanical requirements can be relaxed for lateral movements and longitudinal tuning range. But assembly procedure should guarantee level of alignment errors < (2-3) mm.

Back-up slides

Table 3.1
Summary of key numbers for the SCRF Main Linacs for 500 GeV centre-of-mass-energy operation. Where parameters for positron and electron linacs differ, the electron parameters are given in parenthesis.

Cavity (nine-cell TESLA elliptical shape)		
Average accelerating gradient	31.5	MV/m
Quality factor Q_0	10^{10}	
Effective length	1.038	m
R/Q	1036	Ω
Accepted operational gradient spread	$\pm 20\%$	
Cryomodule		
Total slot length	12.652	m
Type A	9 cavities	
Type B	8 cavities	1 SC quad package
ML unit (half FODO cell)	282 (285)	units
(Type A - Type B - Type A)		
Total component counts		
Cryomodule Type A	564 (570)	
Cryomodule Type B	282 (285)	
Nine-cell cavities	7332 (7410)	
SC quadrupole package	282 (285)	
Total linac length – flat top.	11027 (11141)	m
Total linac length – mountain top.	11072 (11188)	m
Effective average accelerating gradient	21.3	MV/m
RF requirements (for average gradient)		
Beam current	5.8	mA
beam (peak) power per cavity	190	kW
Matched loaded Q (Q_L)	5.4×10^6	
Cavity fill time	924	μs
Beam pulse length	727	μs
Total RF pulse length	1650	μs
RF–beam power efficiency	44%	



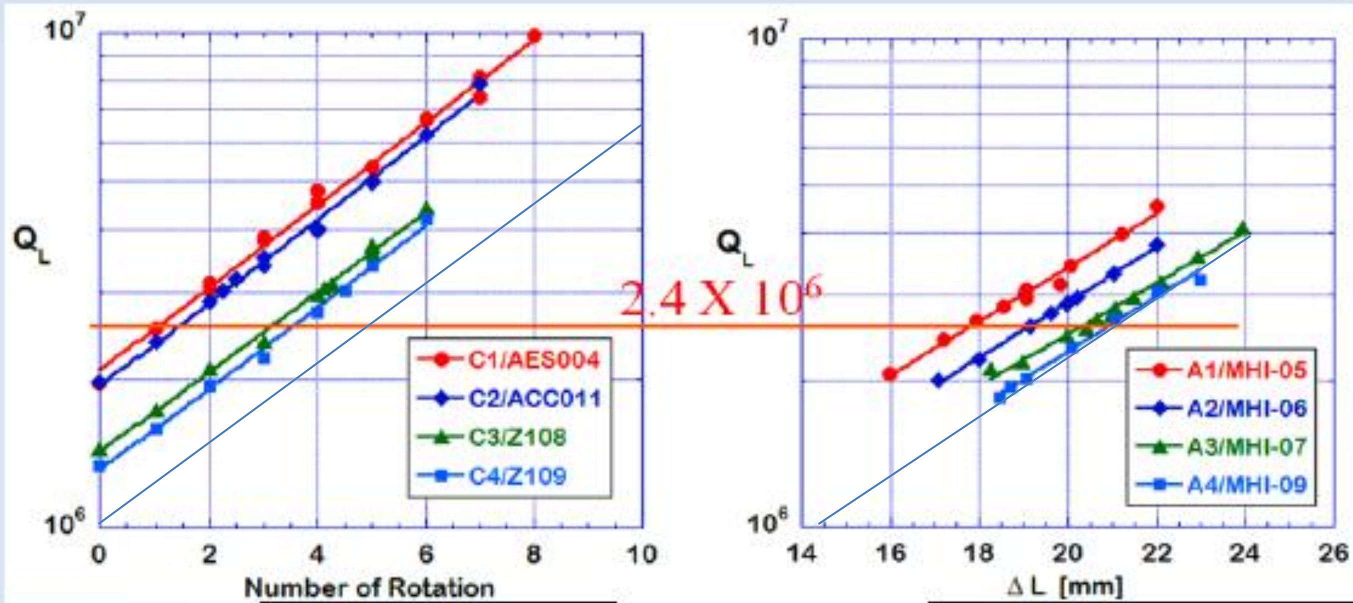
Dynamic loss measurements in S1-G

	TTF-III		STF-2			TTF-III	STF-2				
	C-4	C-1	A-3	A-2	A-2	4 C Cavities	4 A Cavities	4 C Cavities	4 A Cavities	7 Cavities	7 Cavities
Date	Nov. 17	Nov. 19	Nov. 23	Nov. 24	Nov. 25	Nov. 26	Nov. 30	Dec. 2	Dec. 3	Dec. 9	Dec. 10
Gradient	28 MV/m	25.2 MV/m	32.3 MV/m	38 MV/m	32 MV/m	32 MV/m Detune	32 MV/m Detune	20 .0 MV/m	26.9 MV/m	25.4 MV/m	20.4 MV/m
Dynamic Loss	0.84 W	1.44 W	2.8 W	4.8 W	2.6 W			2.7 W	6.9 W	9.6 W	4.8 W
Detuned Loss	0.09 W	0.18 W	0.7 W	1.8 W	1.2 W	0.5 W	4.6 W	0.2 W	2.5 W	2.6 W	1.6 W
Dynamic Loss at Cavity	0.75W	1.26 W	2.0 W	2.9 W	1.3 W			2.5 W	4.4 W	7.0 W	3.2 W
Q_0	8.8E9	4.3E9	4.3E9	4.2E9	6.5E9						
								C1=22.2 C2=18.9 C3=14.9 C4=24.3	A1=15.8 A2=37.6 A3=32.9 A4=21.4	C1=25.2 C2=NA C3=17.6 C4=28.8 A1=15.3 A2=37.4 A3=32.4 A4=20.9	C1=20.1 C2=NA C3=14.1 C4=23.0 A1=12.3 A2=30.4 A3=26.0 A4=16.7

Dynamic losses of KEK couplers was 9 times larger than those of TTF-III couplers.

Couplers Performance

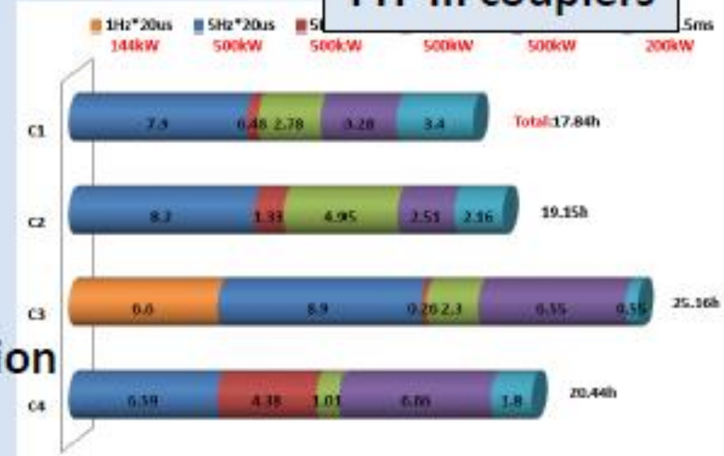
Q_L tuning range

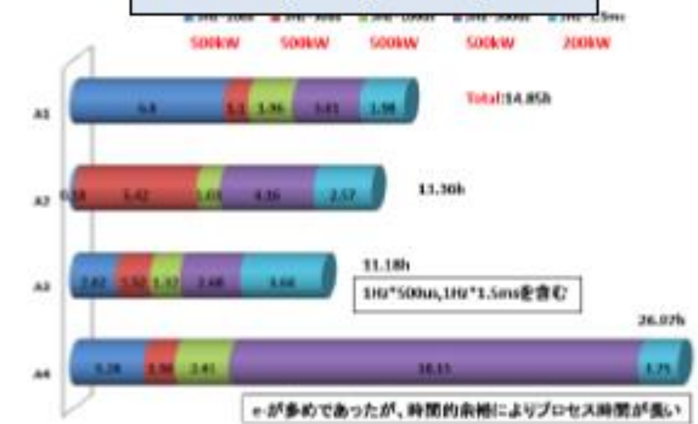


TTF III couplers

STF-2 (KEK) couplers

Process Time After installation

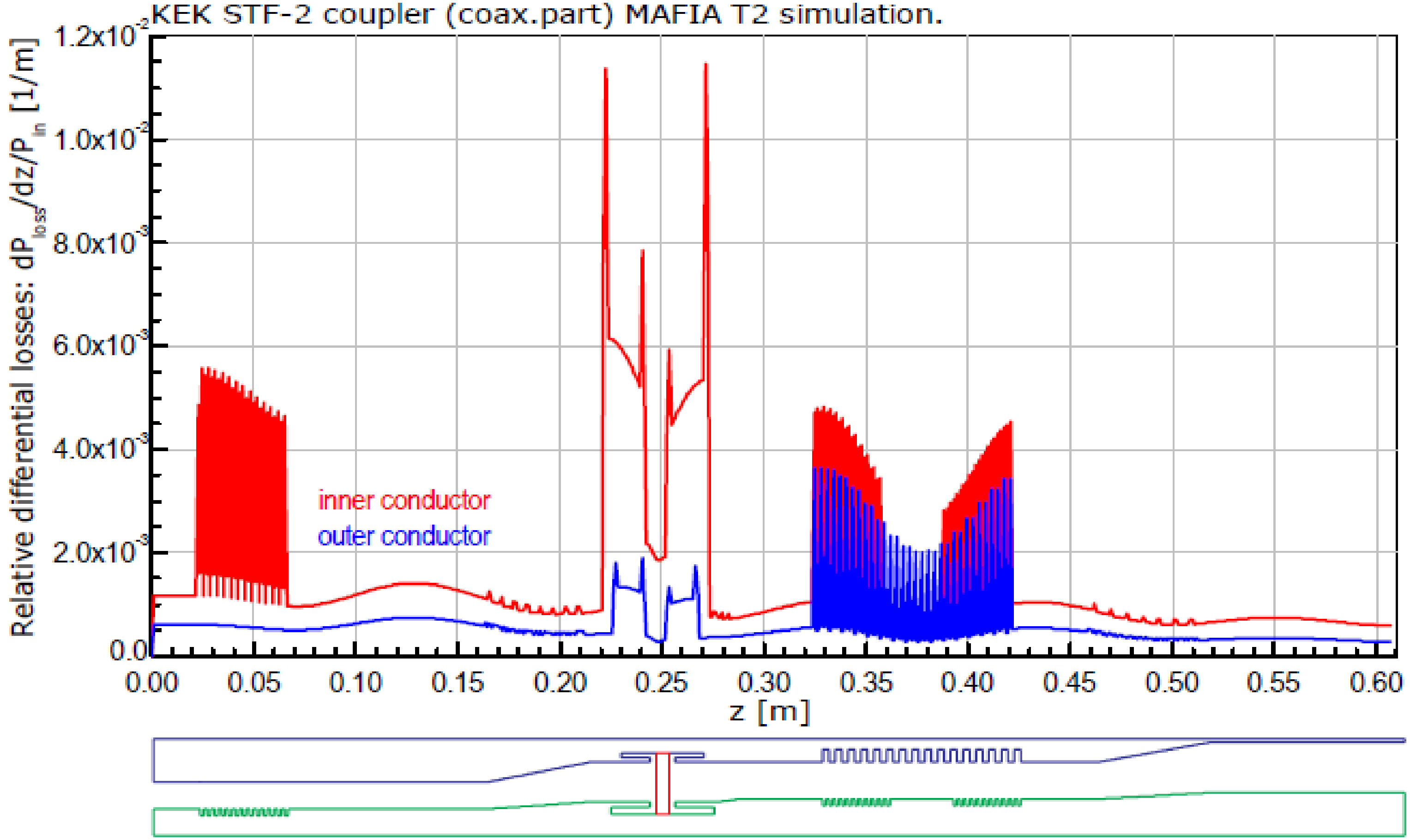




Average process time=21 hours

Average process time=15 hours

Mafia calculation: RF losses



Material: Cu, $\kappa_0 = 5.8\times10^7$ $1/(\Omega\times m)$ (300 K)

Power Losses in the 70K ceramic window

($\varepsilon = 9.2$, $tg\delta = 10^{-4}$): $P_{loss.win}/P_{in} = 1.39\times10^{-4}$