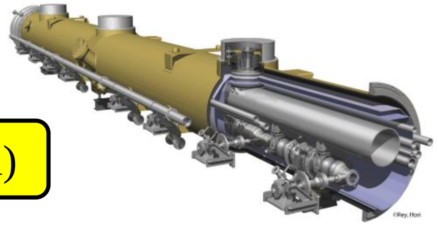
Piezo tuner & Power coupler for ILC

International Linear Collider (ILC)

- Higgs factory machine
- Staging scenario (250 → 500 → 1000 GeV)
- SRF technology for beam acceleration
- Nano-beam technology for high luminosity

x ~8000

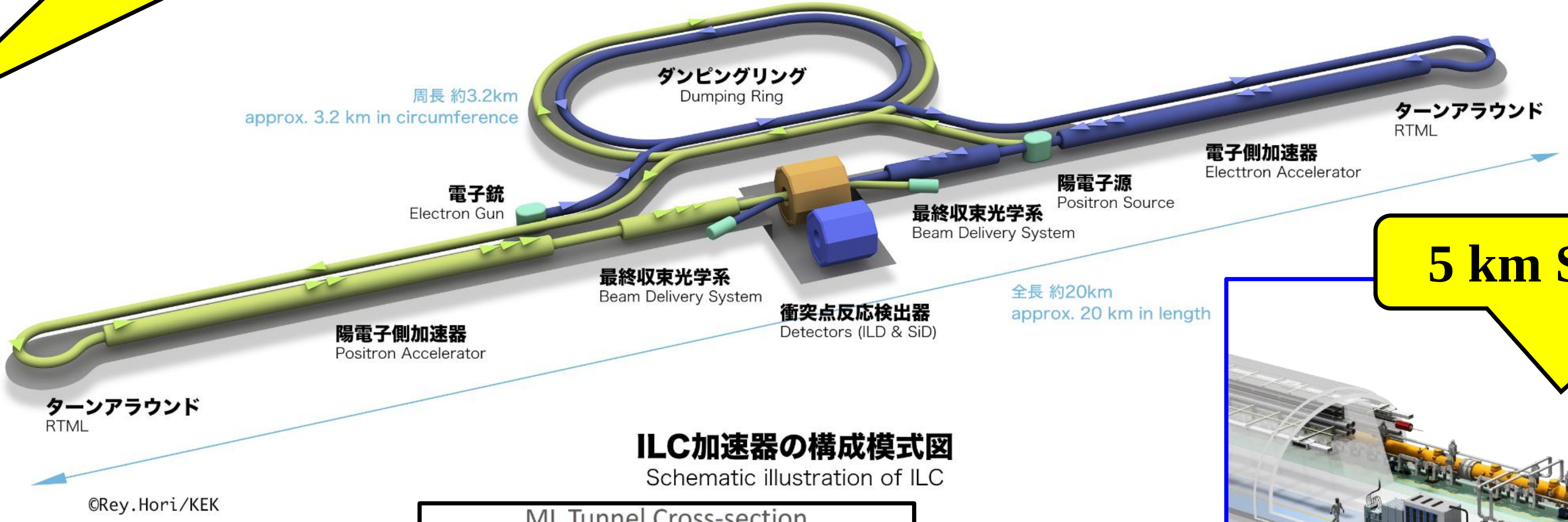


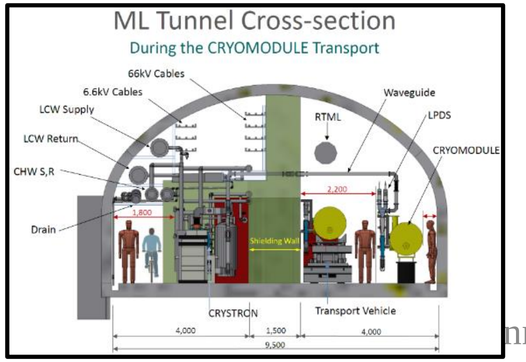
x ~750

	VT	CM
E_{acc}	35.0 MV/m	31.5 MV/m
Q_0	0.8 x 10^{10}	1.0 x 10^{10}
Yield	≥ 90%	~100%

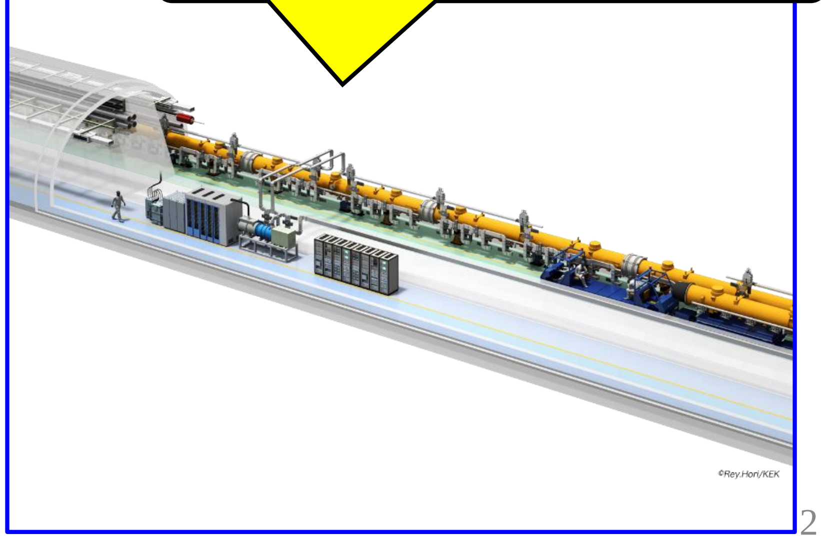
岩手県一関市の資料をもとに作製

Candidate site (geologically suited)





5 km SRF linac for each!



Recent status:
- ☐ Foundation of ILC Japan
- ☐ International Expert Panel
- ☐ Time critical WPs

Summary of key specifications for SRF Main linac

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	±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%	

Piezo also works by pulsed mode of 5Hz

RF repetition rate: 5Hz

Tuner

Specifications on tuner system in TDR

Table 3.8
Main specifications of the frequency tuner.

Tuner	Parameter	Specifications
Slow tuner		
	Tuning range	> 600 kHz
	Hysteresis	$< 10\,\mu$m
	Motor characteristics	Step motor, power-off holding, magnetically shielded
	Motor location	Inside 5K shield, accessible from outside
	Magnetic shield	$<$ 20mG
	Heat load by motor	< 50 mW at 2 K
	Motor lifetime	$> 20 \times 10^6$ steps
Fast tuner		
	Tuning range	$>$1KHz at 2 K
	LFD residuals	$<$ 50 Hz at 31.5 MV/m flat-top
	Actuator	Piezo actuator, located inside 5K shield, Two actuators for redundancy
	Heat load by actuator	$<$ 50 mW at 2 K
	Magnetic shield	$<$ 20mG
	Actuator lifetime	$> 10^{10}$ pulses

for fine tuning

Summary of tuner systems and their specifications

Revised Table 2.12 "Various tuners investigated in the Technical Design Phase." 12/Apr/2021 Revised by Yuriy + Kirk

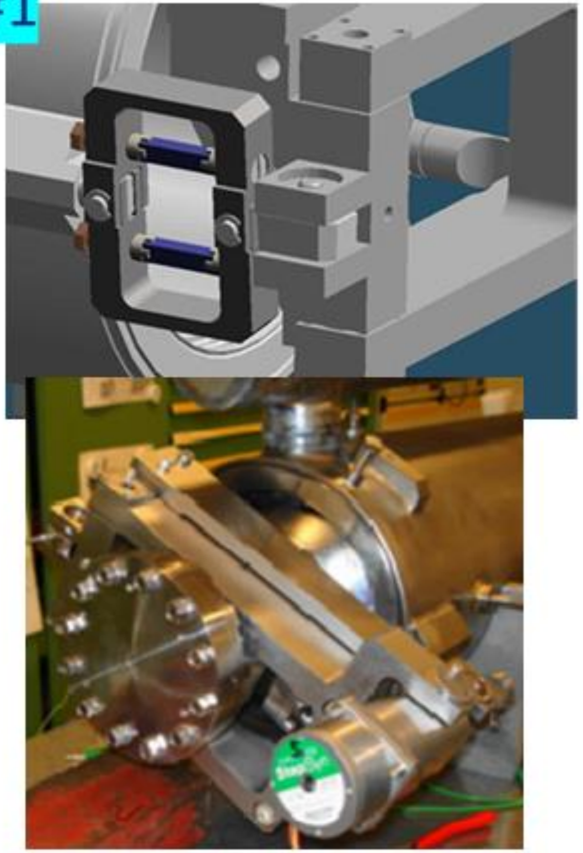
	(SLIM) Blade tuner [1]	Saclay/DESY tuner [2]	Slide-jack tuner [3]	Double-lever tuner [4]
Type	Coaxial	Lateral-Pick-up side	Coaxial and lateral coupler side	Lateral-Pick-up side
(fit to) Beampipes of TESLA Cavity	short-short, short-long	short-long	short-short, short-long	short-short, short-long
Cavity/Tuner system stiffness	30 kN/mm	30 kN/mm	70 kN/mm	40 kN/mm
Drive unit	Inside vessel	Inside vessel	Outside vessel	Inside vessel
	Stepper motor	Stepper motor	Stepper motor	Stepper motor
	Harmonic Drive	Harmonic Drive	both manual or stepper motor actuation	Planetary Gear Drive
Nominal frequency	1.3 GHz	1.3 GHz	1.3 GHz	1.3 GHz
Nominal tunable range	600 kHz	500 kHz	900 kHz	800 kHz
Nominal sensitivity	1.5 Hz/step	1 Hz/step	3 Hz/step	1.4 Hz/step
Coarse tuner hystersis	*100Hz*	*100Hz*		*45Hz*
Piezo	2, thin-layer (0.1 mm), dim. 10 x 10 x 40 mm^3	2, thin-layer (0.1 mm), dim. 10 x 10 x 36 mm^3	1, thick-layer (2 mm), dim. diameter 35 x 78 mm^2	2 , thin-layer (0.1 mm), dim. 10x 10 x 36 mm^3
Piezo Voltage	200 V	120 V	1000 V, operated at 500 V	120 V
Nominal piezo stroke at R.T.	55 μm	40 μm	40 μm	40um
Nominal piezo capacitance at R.T.	8 μF	13 μF	0.9 μF	13 μF
Nominal tunable range (tested at 2K)	2,000 Hz	800 Hz	~600 Hz @500 V	3,000 Hz
Capability to repair (motor + piezo)	No	No	OK	OK
# of tuner operated in accelerators	8 @FNAL/FAST	800 @E-XFEL	14 @STF-2, Quantum Beam	320+180 @LCLS-II (HE)
# of tuner operated in S1-Global	2	2	4	

[1] https://lss.fnal.gov/archive/2011/conf/fermilab-conf-11-101-td.pdf
[2] LLRF Tests of XFEL Cryomodules at AMTF: First Experimental Results (cern.ch)
[3] Cryomodule Tests of Four Tesla-Like Cavities in the STF Phass-1.0 for ILC (cern.ch)
[4] https://accelconf.web.cern.ch/IPAC2015/papers/wepty035.pdf

Tuners serving *(significant amount of)*1.3GHz elliptical cavities

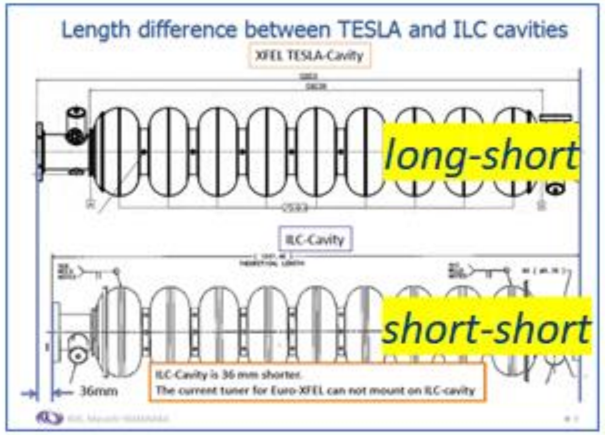
XFEL/Saclay I
N=800 units

#1



#4

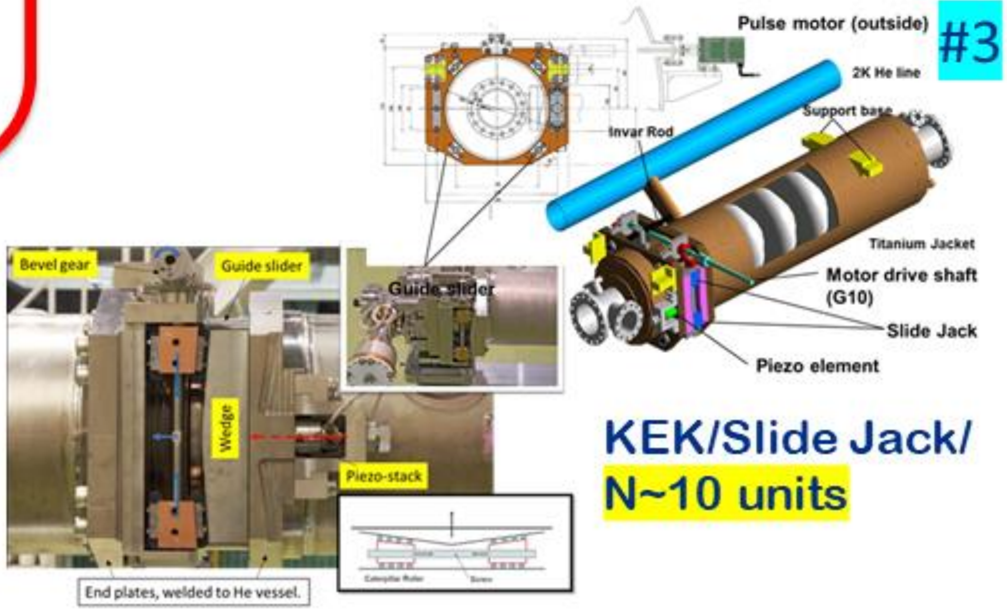
LCLS II (HE)/FNAL's
N=320 units+ 180units



SLIM Blade Tuner
(N=10 units at FNAL's CM2/FAST)

#2

#3



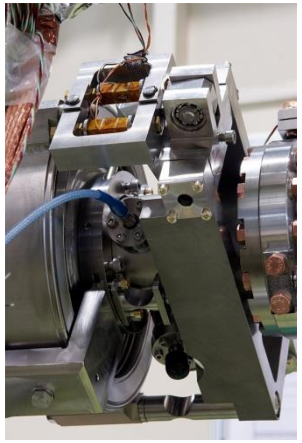
KEK/Slide Jack/
N~10 units

"S1-Global" project as global collaboration

- Done at GDE era
- Global collaboration
- Comparison of performance

TESLA Cavity (DESY/FNAL)

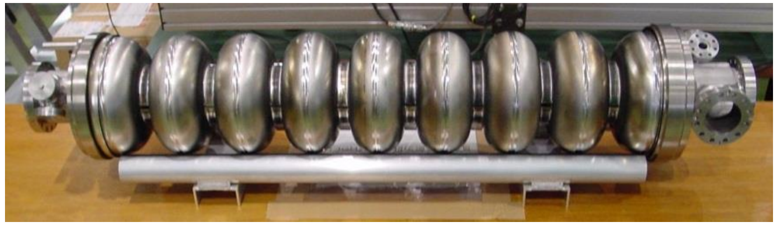
Blade Tuner (FNAL/INFN)



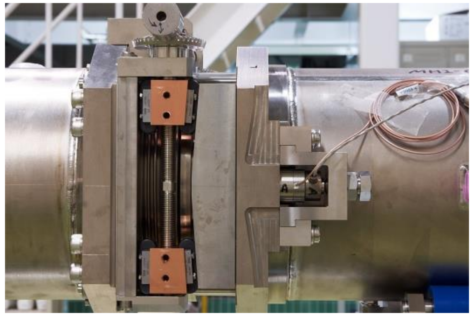
Saclay Tuner (DESY)

TTF-III Coupler (DESY/FNAL)

Comparison of Performance



Tesla-like (KEK)



Slide-Jack Tuner (KEK)

STF-II Coupler (KEK)

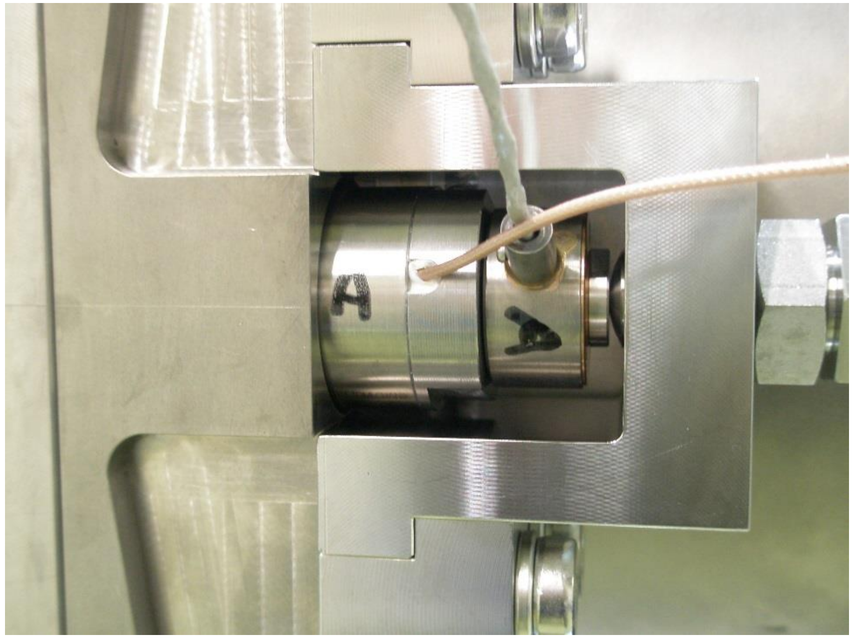
Piezo tuner systems used for S1-Global

Two types of piezo tuner

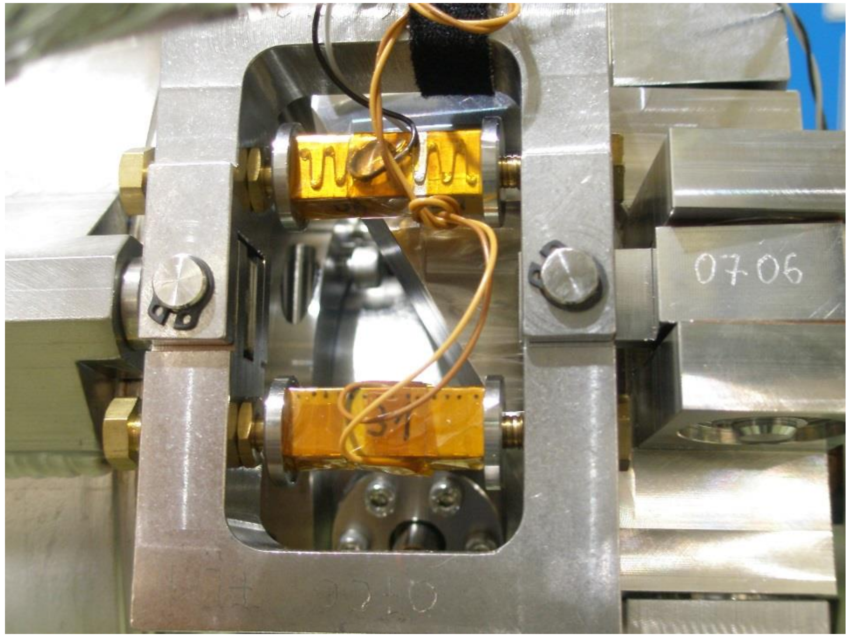
- High voltage (~1 kV): STF
- Low voltage (~200 V): DESY/INFN

Blade tuner

Slide-jack tuner



Saclay tuner



Piezo used for LCLS-II

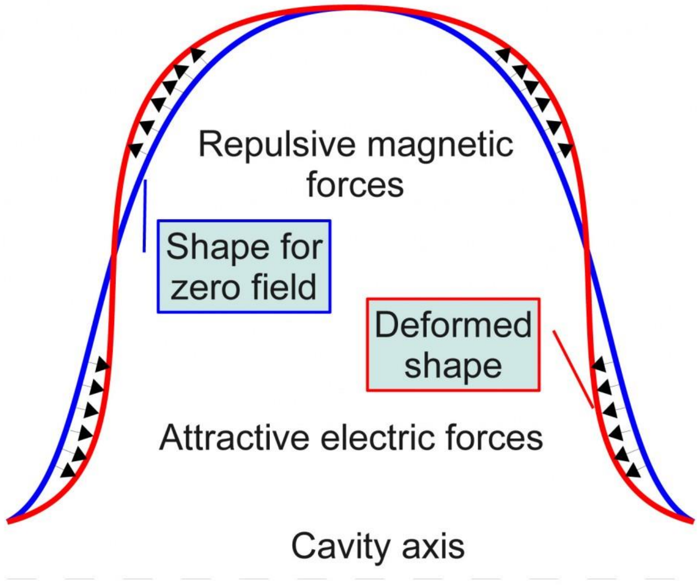
- **Piezo Actuator P-844K075**
  - ***Designed by Physik Instrumente (PI)***
  - ***(with contribution from FNAL) for LCLS II Project.***

Each capsule has inside two (glued) 10*10*18mm PICMA piezos. Piezo, during assembly into capsule, internally preloaded with 800N.

Each Cavity/Tuner system has 4 (four) electrically separate piezo-stacks.
Tuner could operate even after failure of 2 stacks

Lorentz force detuning of SRF cavity at high gradient

- LFD generates at high gradient
  - Not flat accelerating gradient
- Piezo works for compensation of LFD



$$P_s = \frac{1}{4}\left(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2\right)$$

$$\Delta f_0 = (f_0)_2 - (f_0)_1 = -K\, E_{acc}^2$$

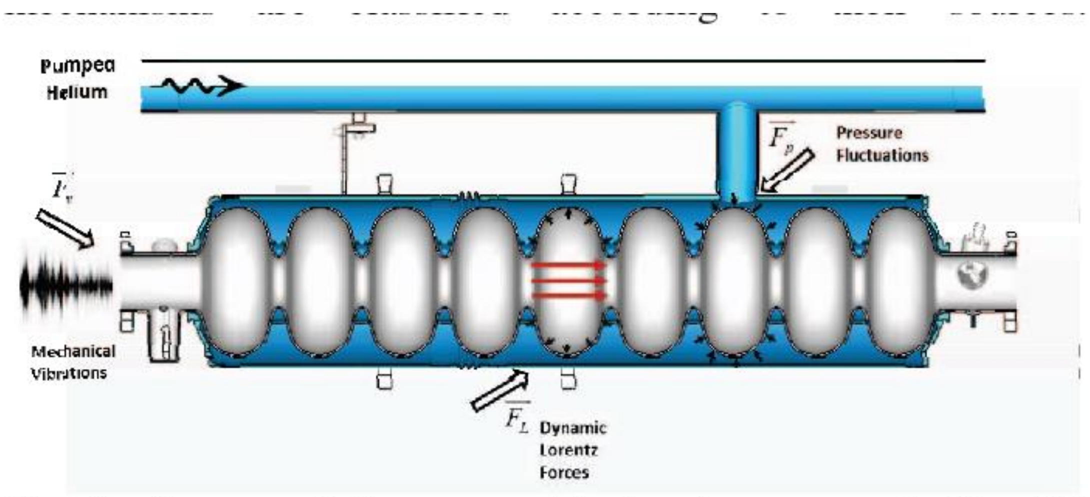
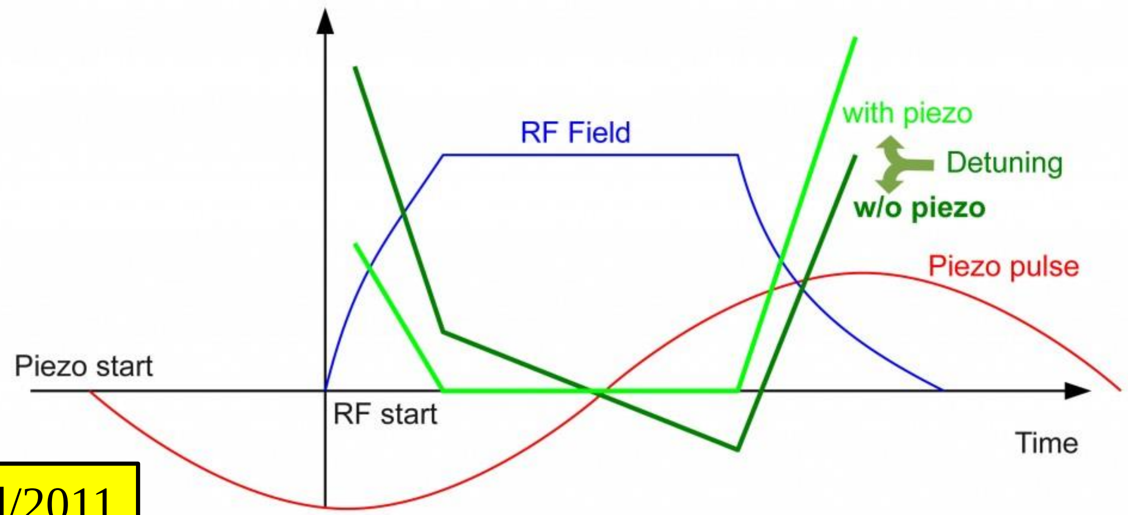


Fig. 1. Sources of frequency detuning in superconducting RF cavities

M.H. Awida, et al.



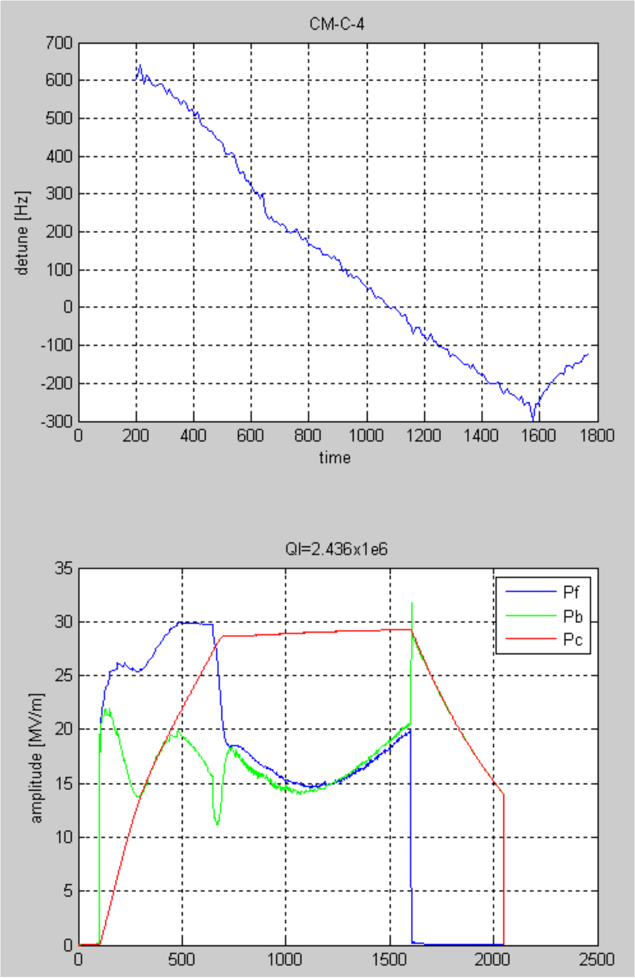
ILC Newsline @7/Jul/2011

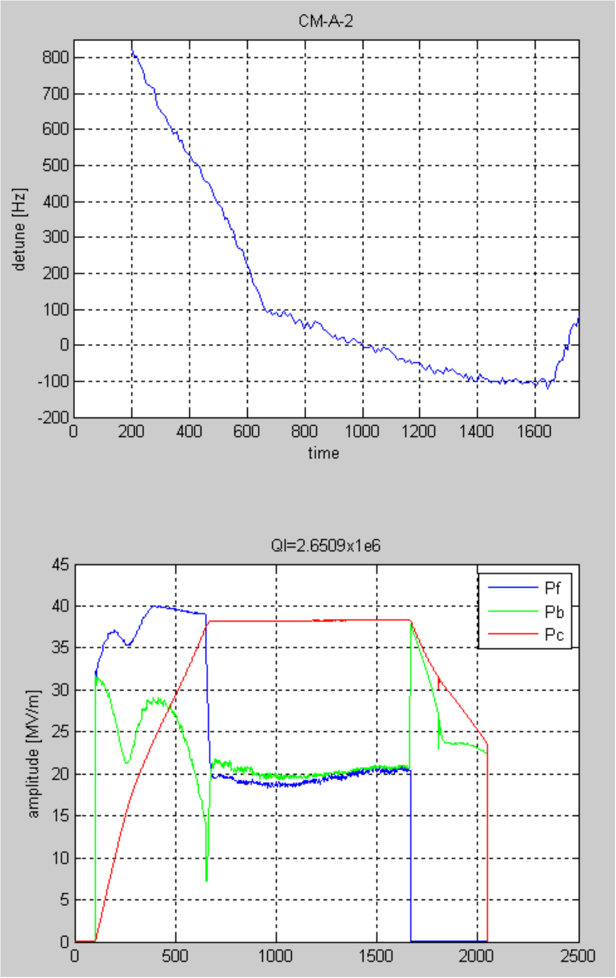
LFD results at S1-Global

C4/Z109 @29MV/m
(TESLA cavity)

A2/MHI-06 @38MV/m
(STF cavity)

- STF cavity has more mechanical stiffness for less LFD effect
  - The frequency change is same for rise-up, but quite different for flat-top between TESLA and STF cavity.

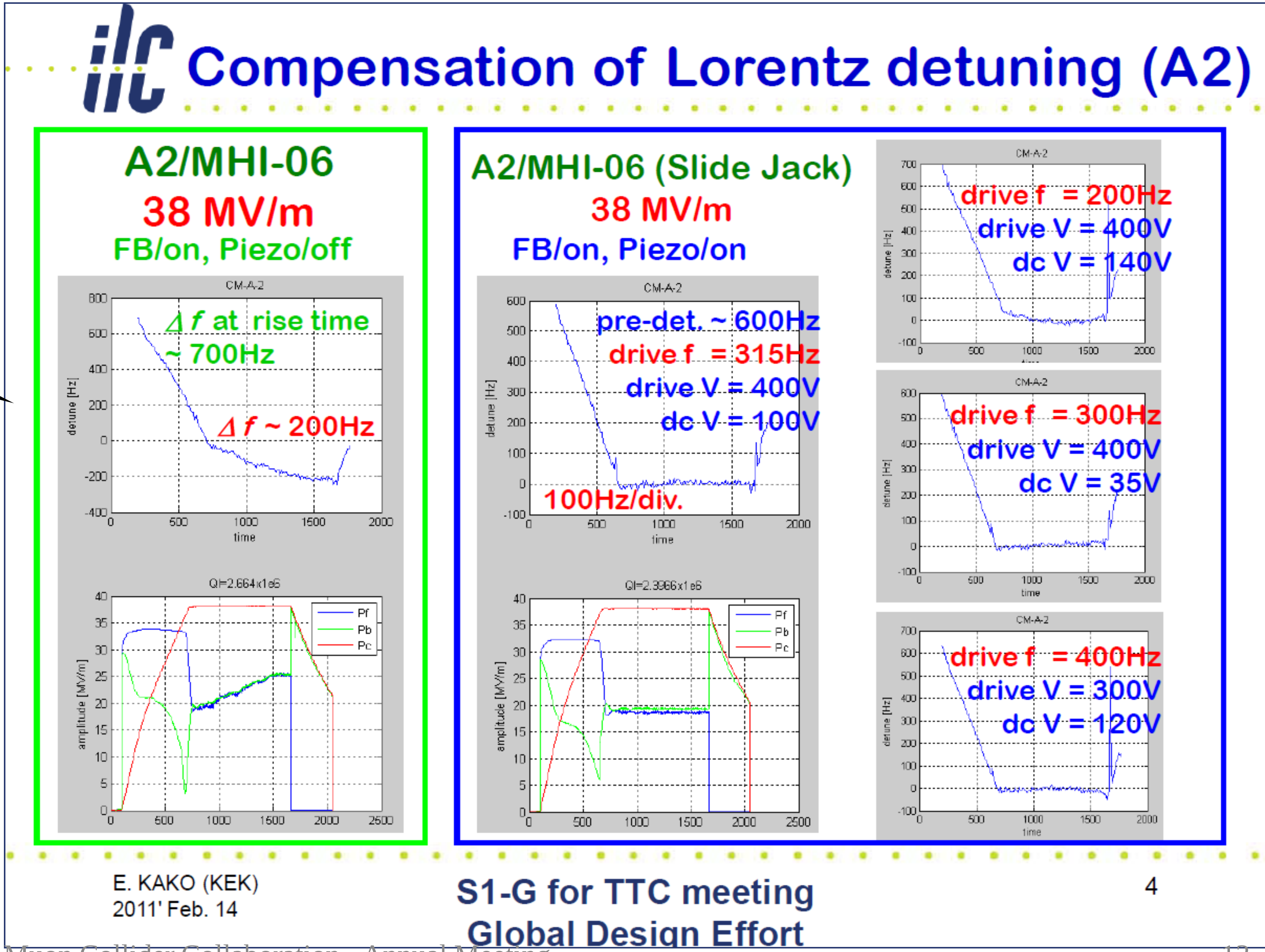




You can consider the balance between the mechanical stiffness and the cost of the cavity

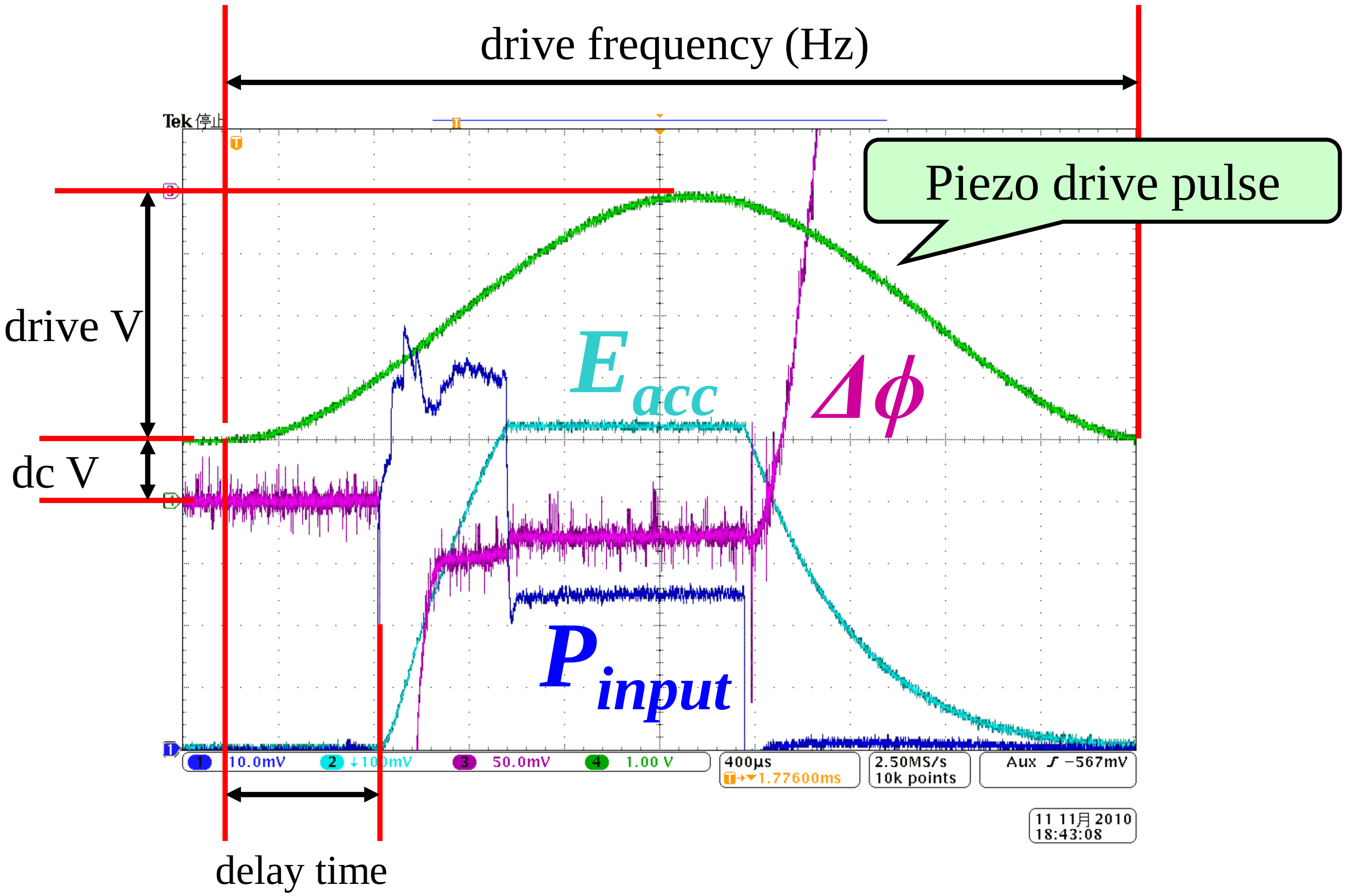
LFD compensation by piezo at S1-Global

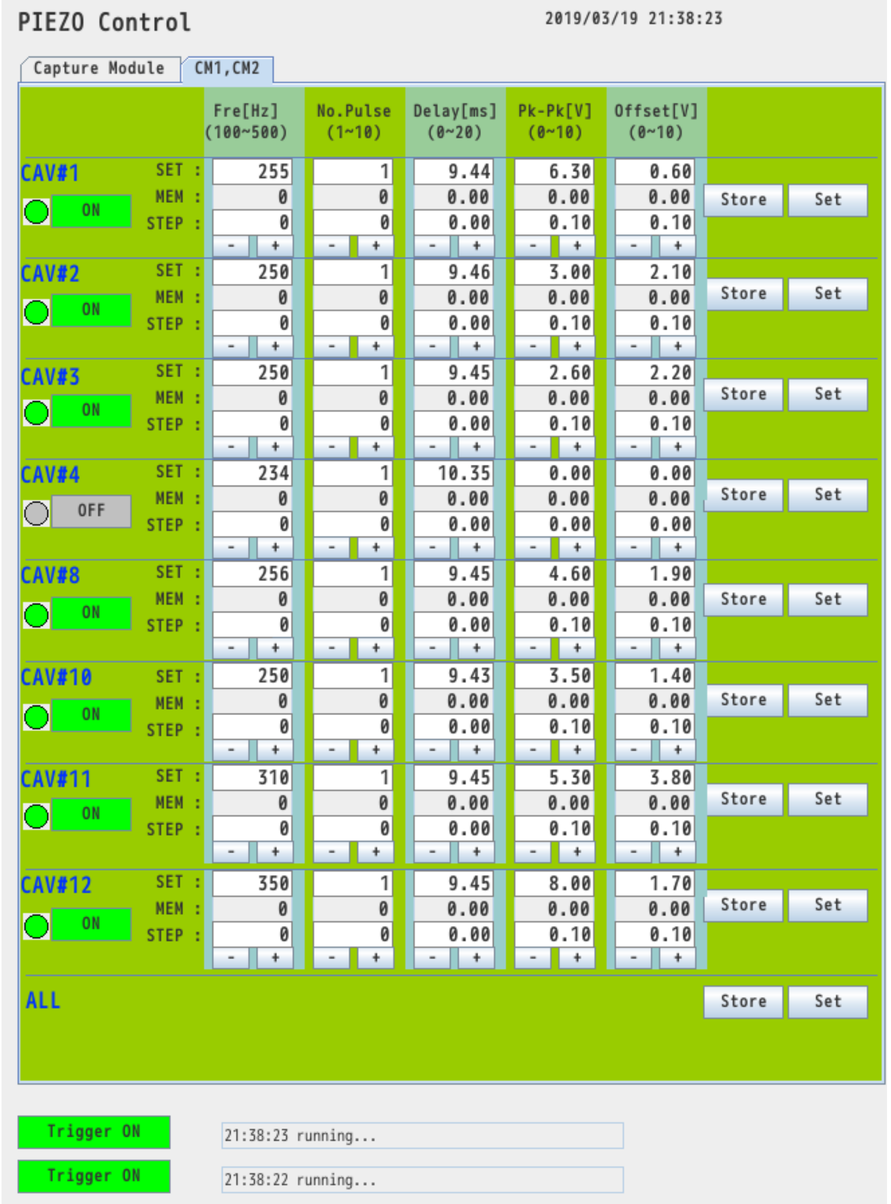
Piezo worked well at 38 MV/m for LFD compensation!



Piezo operation parameters for LFD compensation

Generally, four parameters are available for piezo drive.





RF frequency sweep (example of RCS2)

- RF frequency sweep need in ~1 ms, from injection to extraction
- **$\Delta f/f = \Delta l/(2\pi R) \approx 1.7 \cdot 10^{-6} \rightarrow \Delta f \approx 2.2$ kHz**
- **Reported tuning ranges for TESLA-style cavities**

- **W. Cichalewski et al., ICALEPCS2015, p. 266: $\Delta f \approx 1.2$ kHz**
- **Y. Pischalnikov, ILCX2021-ILC: $\Delta f \approx 3$ kHz**
- **V. Jain, IJAS2020**

As SRF cavity has mechanical inertia, it takes 1 msec to change by 1kHz.

Power coupler

Specifications on power coupler system for ILC

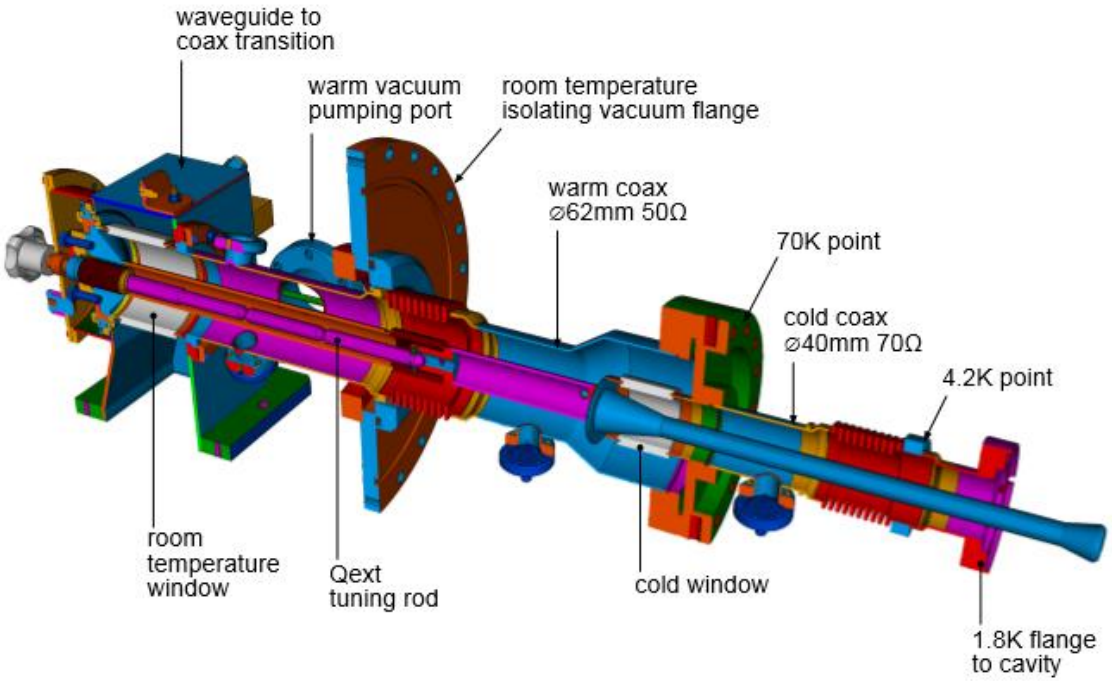
- Based on TTF-III coupler
- Cylindrical RF windows
- Variable coupling (next page)

Thickness of copper plating for outer conductor is 10μm

Table 3.7
Main specifications of the input coupler. The parameters represent the approximate maximum expected values during operation, including possible upgrades.

Parameter	Specifications
Frequency	1.3 GHz
Operation pulse width	1.65 ms
Operation 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	$(1.0 \sim 10.0) \times 10^6$ (tunable)
RF process in cryomodule	> 1200 kW for ≤ 400 μs pulse width > 500 kW for > 400 μs pulse width
RF process with reflection mode in test stand.	> 600 kW for 1.6 ms pulse width
RF process time	< 50 hours in warm state < 20 hours in cold state
Approximate heat loads	< 0.01 mW (2K static) 0.07 W (5K static) 0.6 W (40K static) < 0.02 W (2K dynamic) 0.12 W (5K dynamic) 1.6 W (40K dynamic)
Number of windows	2
Bias voltage capability	Required

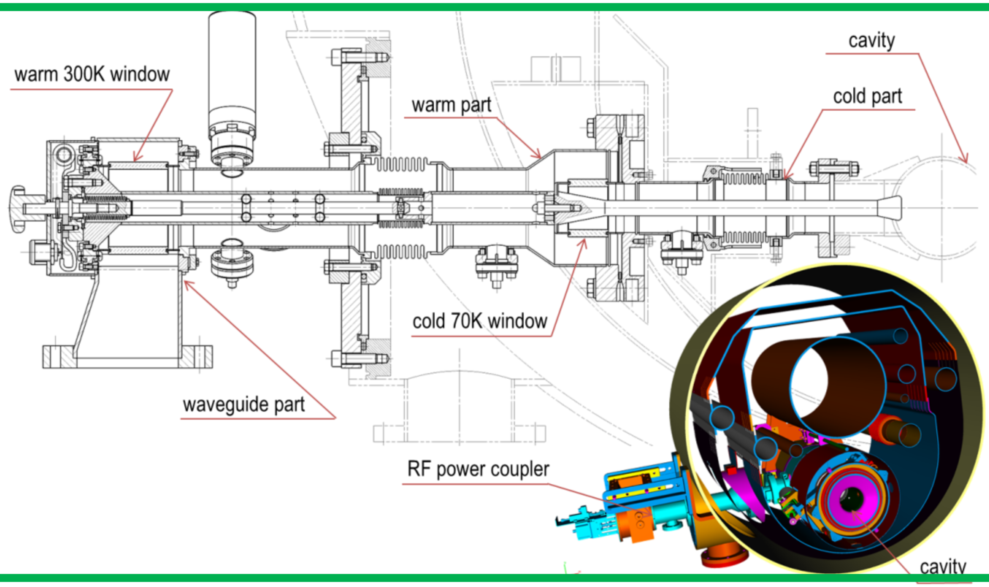
Figure 3.6
Schematic drawing of TTF-III (XFEL) input coupler.

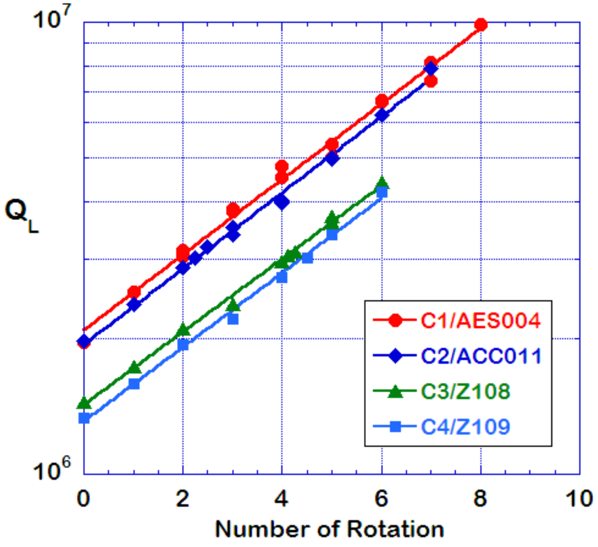


Q_L range measurement at S1-Global

TTF-III coupler satisfied the specification of Q_L range

TTF3 Input Power Coupler





Q_L = 2~10 x 10^6

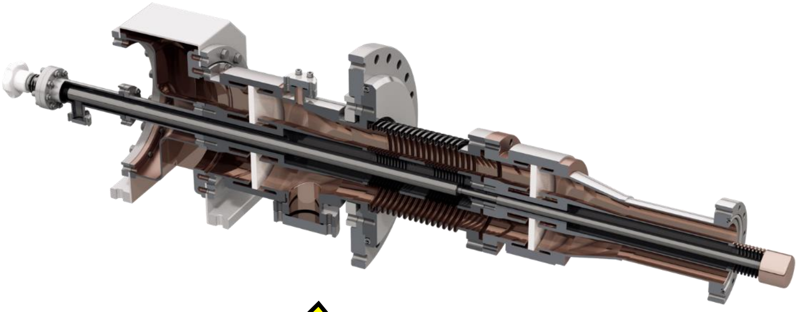
Stroke: ±10 mm

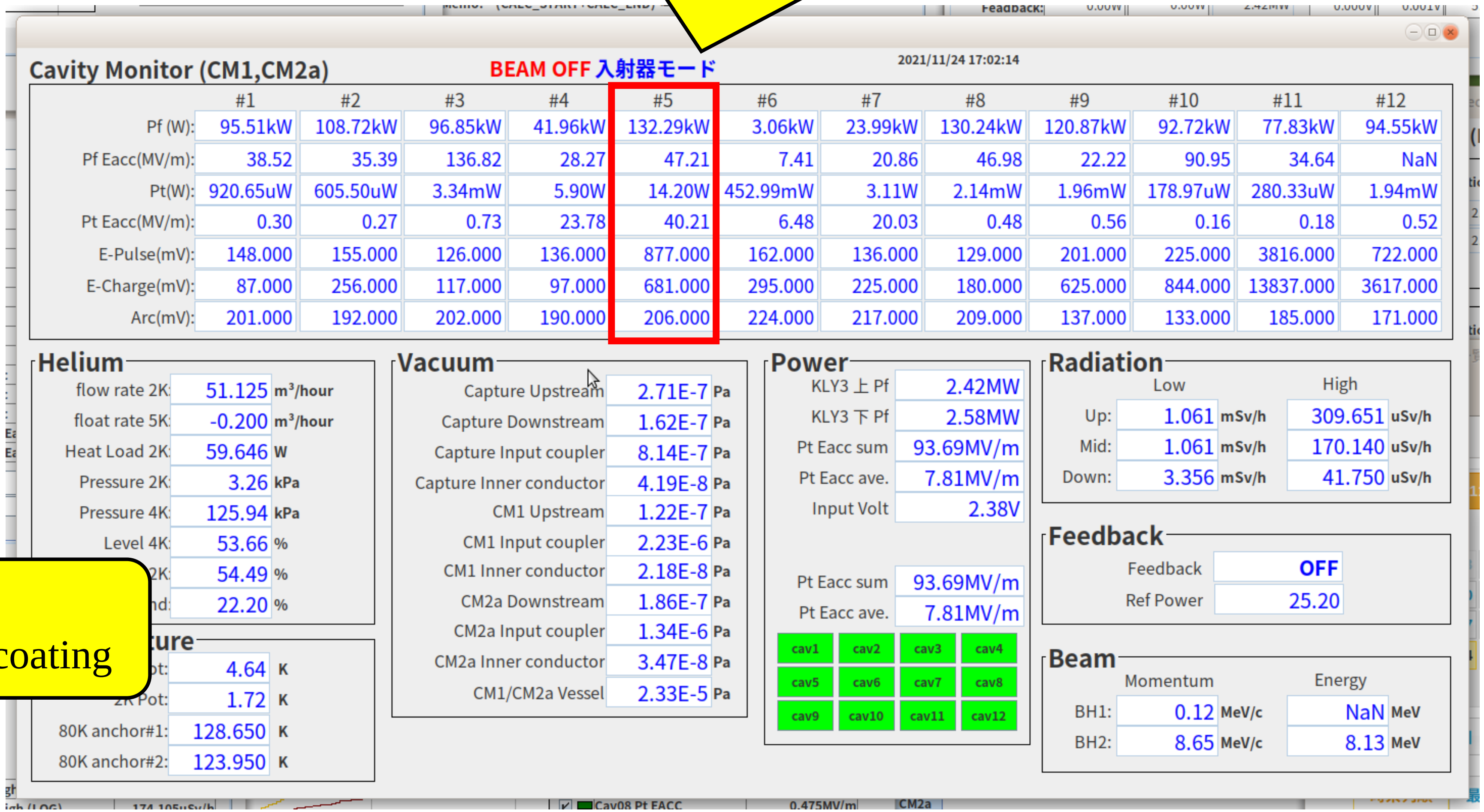
Outer diameter of inner conductor: 12.4 mm
Head of inner conductor: 20.7 mm

Result at the highest gradient at STF-2

>500 kW (peak power) @40MV/m

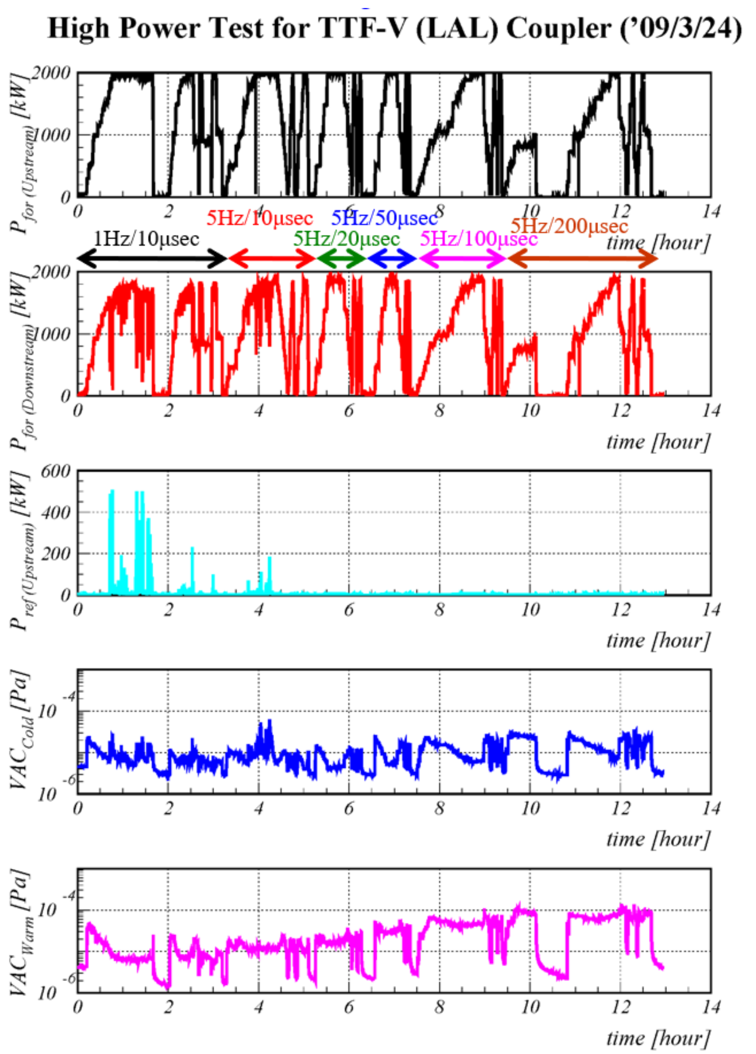
STF-2 Coupler

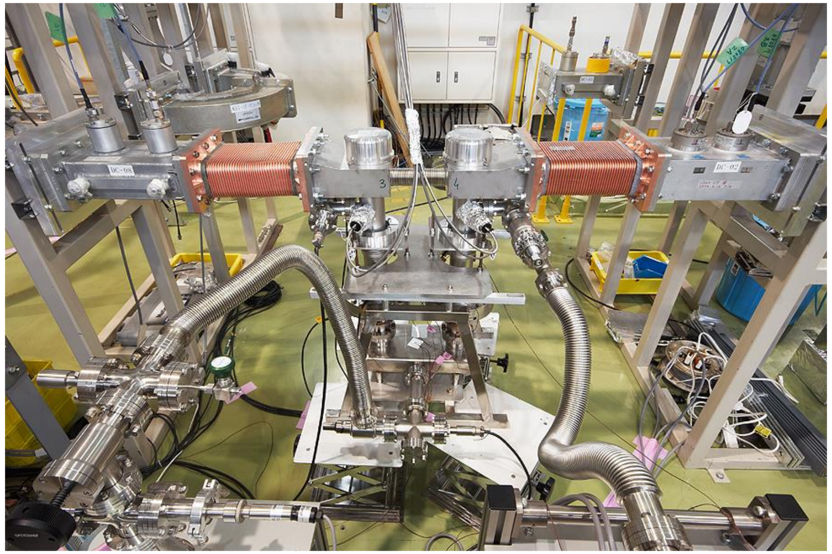


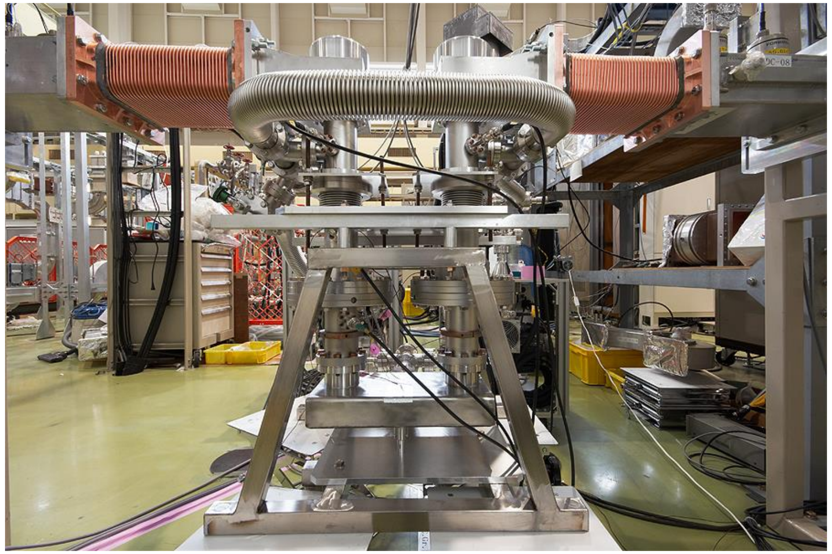


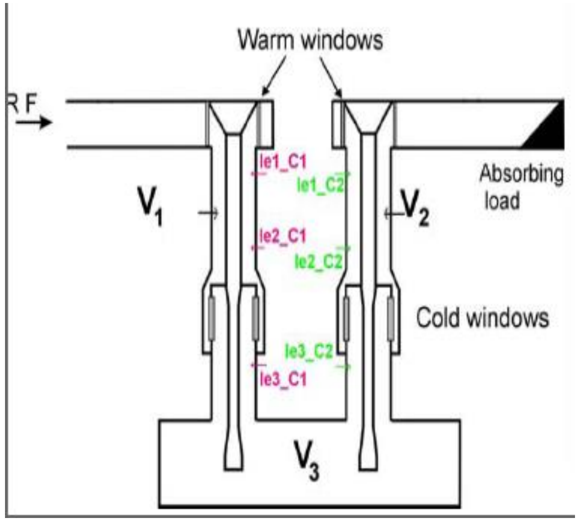
10 µm copper plating
95% purity for alumina w/ 10 nm TiN coating

TTF-V power coupler for ILC as Japan-France collaboration









Result of high power test at test stand	
RF condition	**Achieved power [kW]**
<400 μsec/5Hz	2000
>800 μsec/5Hz	500

Toward higher RF power and longer RF pulse

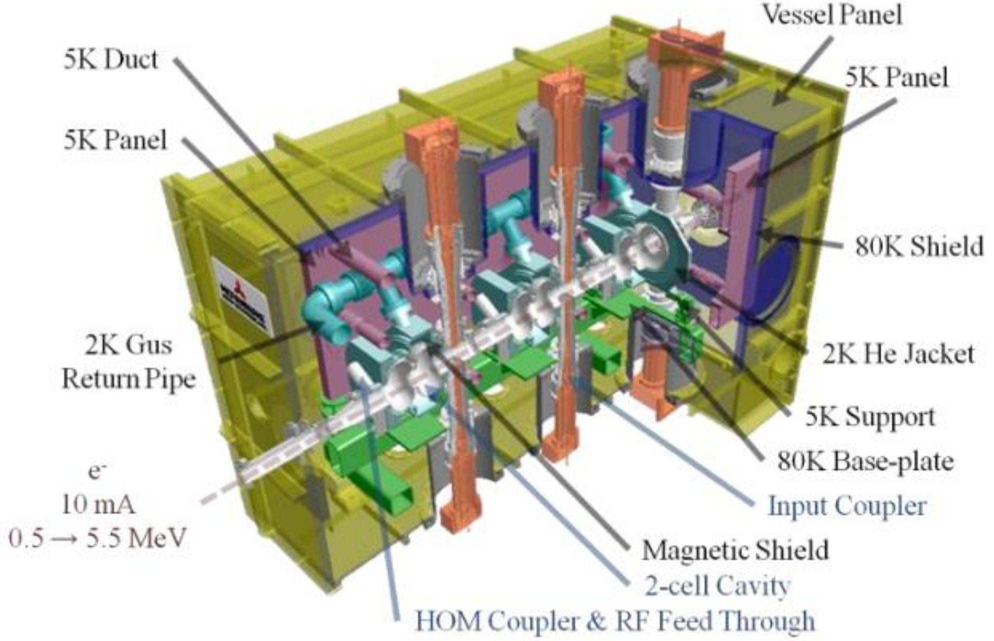
If you think of higher power and longer pulse, you can consider the change of following parameters.

RF power/RF duty	ILC	Higher/Longer
Purity of Al_2O_3	> 95%	> 99%
Dielectric loss tangent	~10^{-4} @1GHz	~10^{-5} @1GHz
Secondary electron emission coefficient	<~2 (w/ TiN coating)	<~2 (w/ TiN coating)
Thickness of copper plating	10 µm	>10 µm

(Additionally) Toward higher beam current

If you think of higher beam current, you can consider power supply from two power couplers.

Injector CM of cERL at KEK



At the GDE era, beam operation of **9 mA** has been done at TTF in DESY.