Superconducting design of CLIC DB Linac

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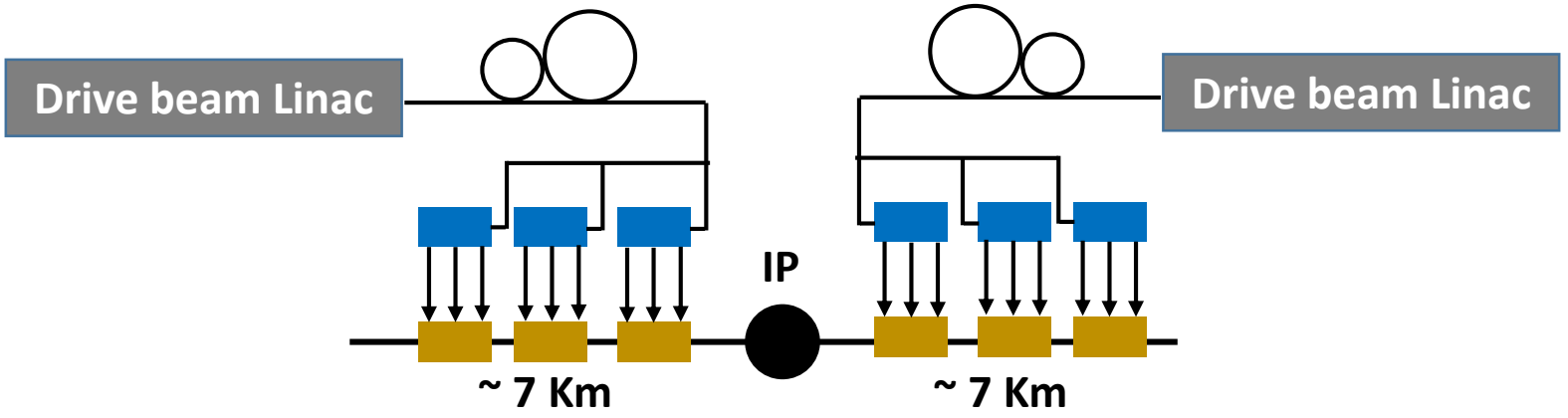
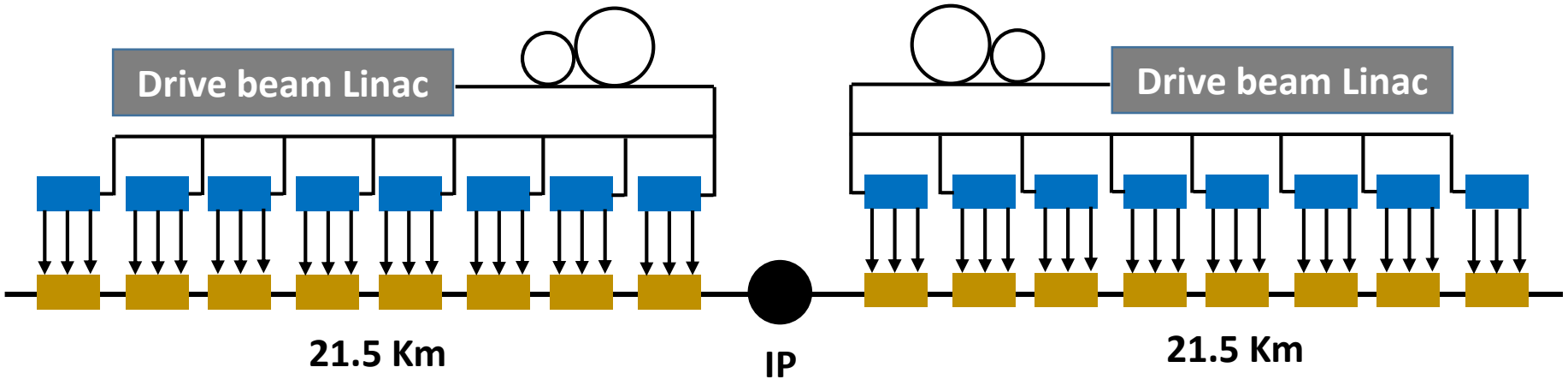
CLIC drive beam linac in different stages

Stage 1: 375 GeV



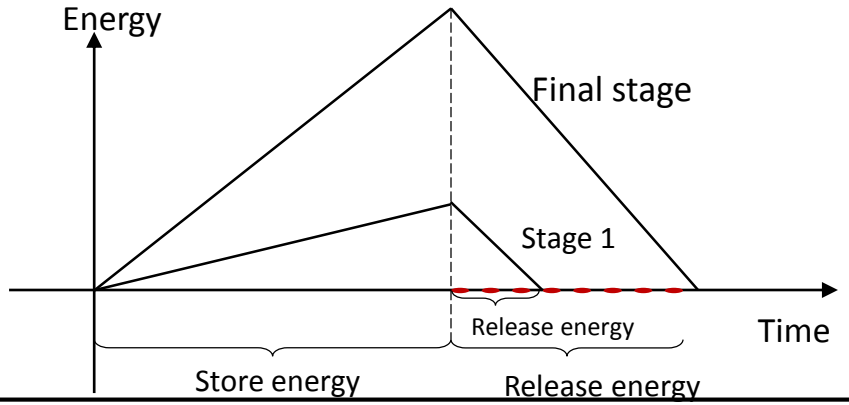
Fianl Stage: 3 TeV

21.5 Km



Motivations

- Run in CW mode (need super conducting).
- The SRF cavities store energy and release them when beam comes.
- Save costs for stage 1.



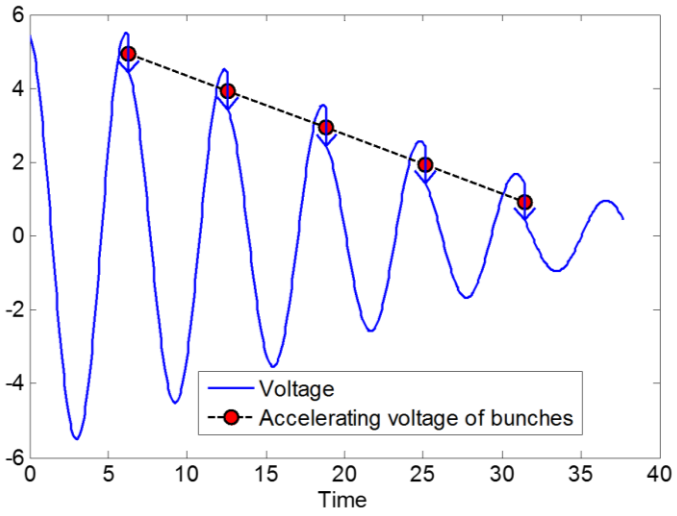
	Normal conducting (CDR)	Super conducting
For 375 GeV	**Very expensive entry cost !!**  540 Klystrons, 22 MW, 35 us; 35 us; CLIC drive beam accelerator; 2.5 km; 2.37 GeV For e+; 2.37 GeV For e-	36 Klystrons, 0.4 MW, CW; 17.5 us; CLIC drive beam accelerator; 2.37 GeV For e+; 0.35 km; 17.5 us; CLIC drive beam accelerator; 2.37 GeV For e-; 36 Klystrons, 0.4 MW, CW
For 3000 GeV	540 Klystrons, 22 MW, 140 us; 140 us; CLIC drive beam accelerator; 2.37 GeV For e+; 2.5 km; 140 us; CLIC drive beam accelerator; 2.37 GeV For e-; 540 Klystrons, 22 MW, 140 us	220 Klystrons, 0.4 MW, CW; 140 us; CLIC drive beam accelerator; 2.37 GeV For e+; 2.1 km; 140 us; CLIC drive beam accelerator; 2.37 GeV For e-; 220 Klystrons, 0.4 MW, CW

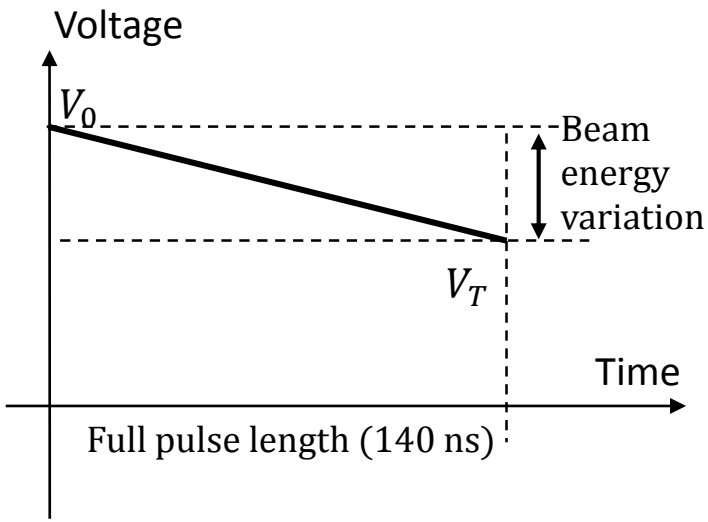
Basic concept for final stage

- Beam loading effect →Voltage change.
- Need more store energy to keep the voltage.
- Energy store factor : η_s= Max stored energy/1.4 MJ;
- Structure length = 1.43 Km * η_s
- No compensation? $\eta_s \approx \frac{V_0/2}{V_0 - V_T}$, for 1% energy variation, $\eta_s = 50$ (Length = 72 Km, Too long)

Cavity frequency	500 MHz
Cavity temperature	4 K
Q_0	5×10^{10}
Max Cavity store energy	980 J/m
Total beam energy per pulse	1.4 MJ
Repetition/Filling time	50 Hz (20 ms)

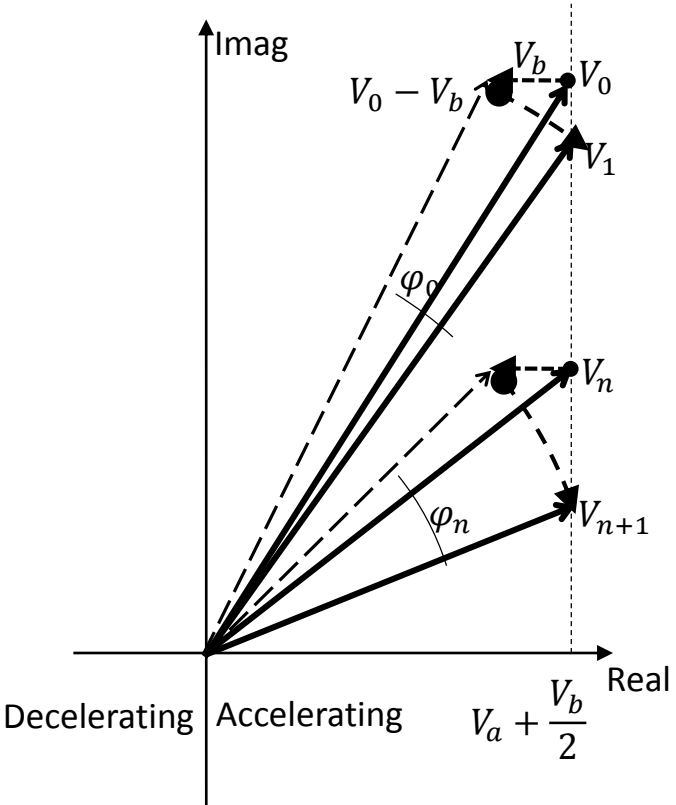
Without compensation

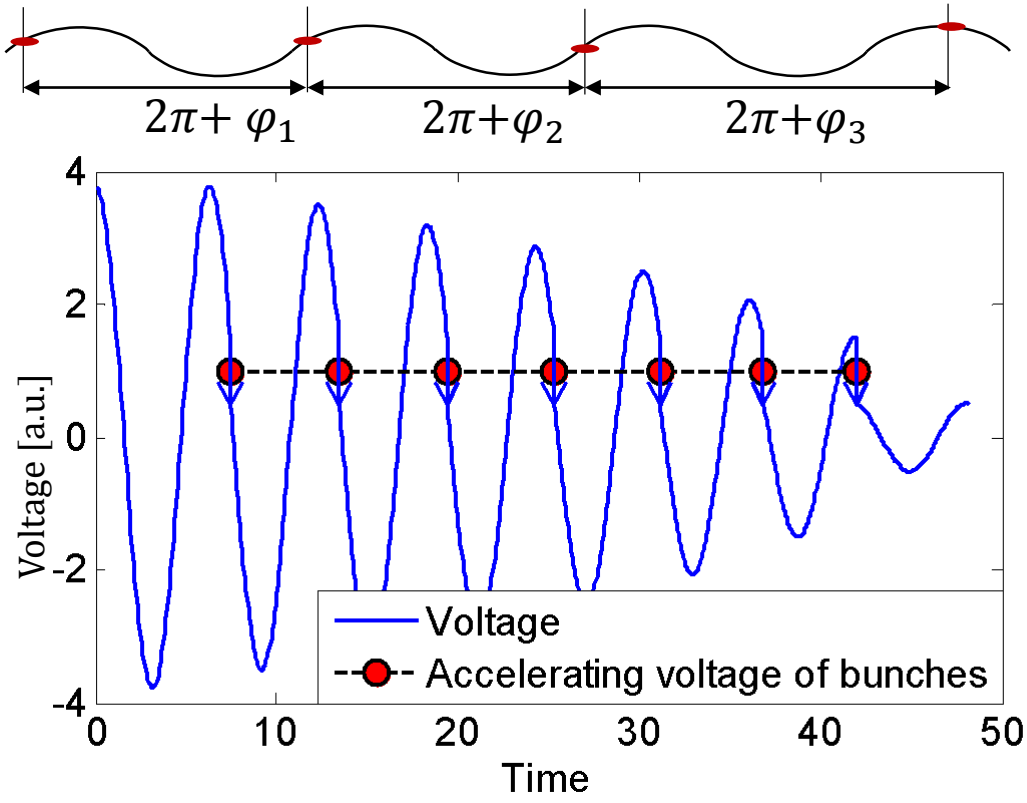




Variable phase modulation for constant voltage

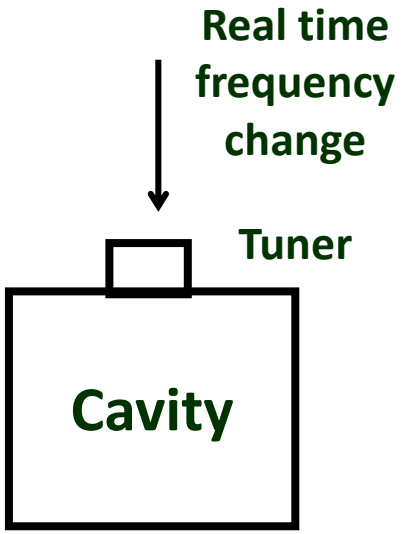
- A proper phase modulation during beam time is able to accelerate all bunches with same voltage:
- During power feeding: f_g(Frequency of Generator)$=$ f_c(Resonate frequency of Cavity) $\neq$ f_b(Bunches)$=$500 MHz
- During beam time: f_g(Frequency of Generator) $\neq$ f_c(Resonate frequency of Cavity) $\neq f_b$(Bunches)$=$500 MHz





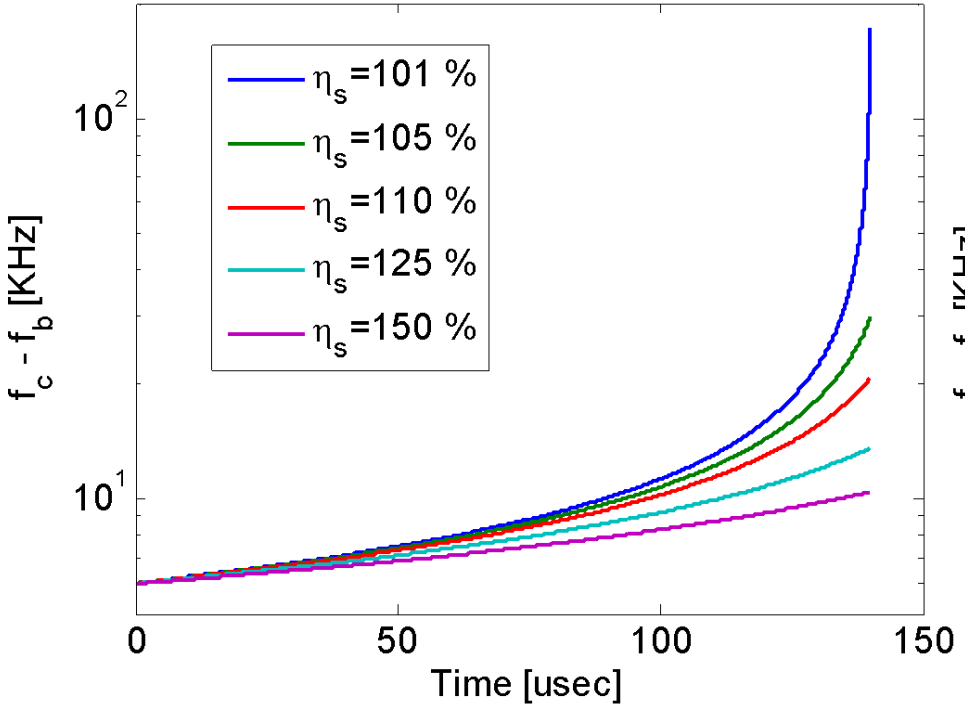
Variable phase modulation

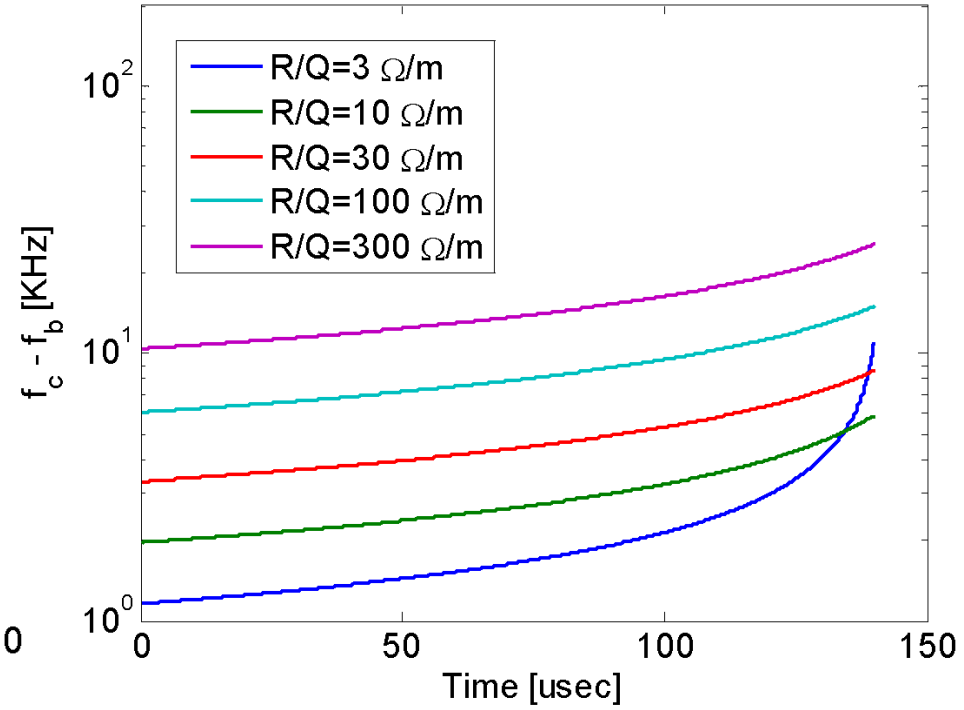
- The frequency change of cavity is continuous during beam time.
- Range and speed of the frequency tuning are strongly depended on R/Q and energy stored factor η_s.
- **Tuning speed** is the key technical parameters for variable phase modulation.



R/Q = 300 Ω/m (Reference : KEK-B: 372 Ω/m)

η_s=120 %

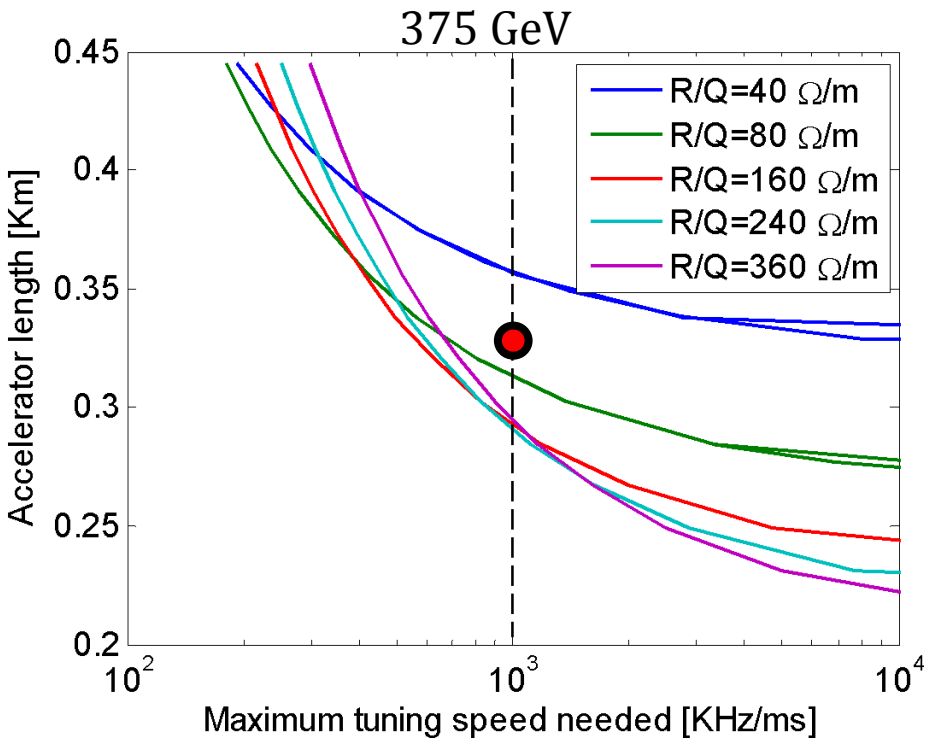


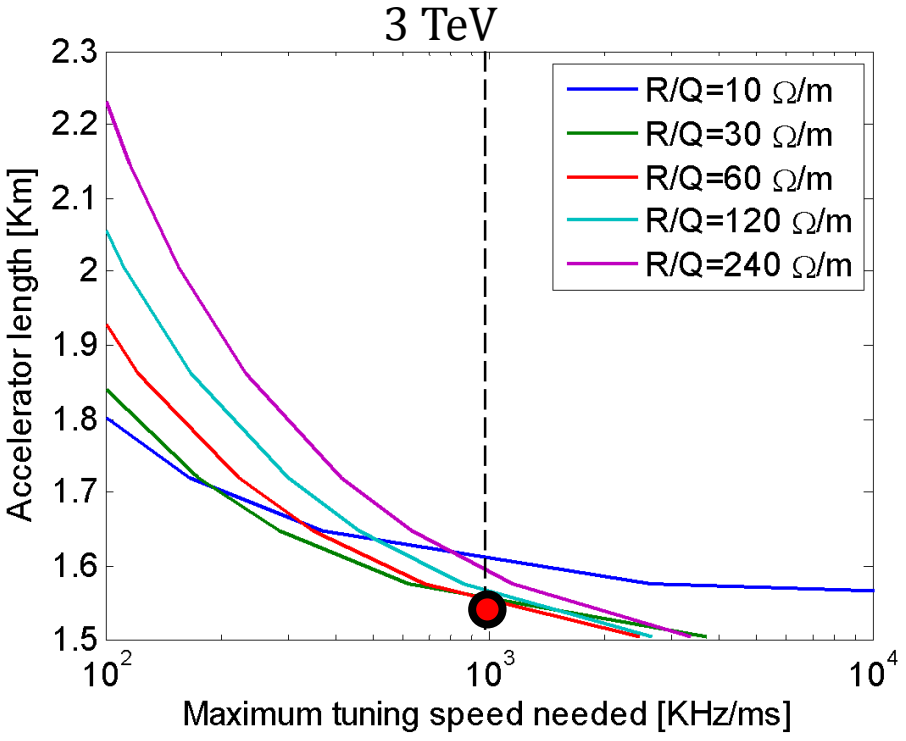


Variable phase modulation

- Reasonable tuning speed Limit: 1 MHz/ms.
- Optimum R/Q = 60 Ω/m for final stage (not optimum for first stage).

Parameters	375 GeV	3 TeV
Acc. Length	328 m	1.55 Km
Frequency range	5.67 KHz	14 KHz
R/Q per length	60 Ω/m	60 Ω/m
Klystron power	8.83 MW CW	76.1 MW CW
Cryogenics power	4.72 MW	15.87 MW
Total AC power	18 MW	130 MW

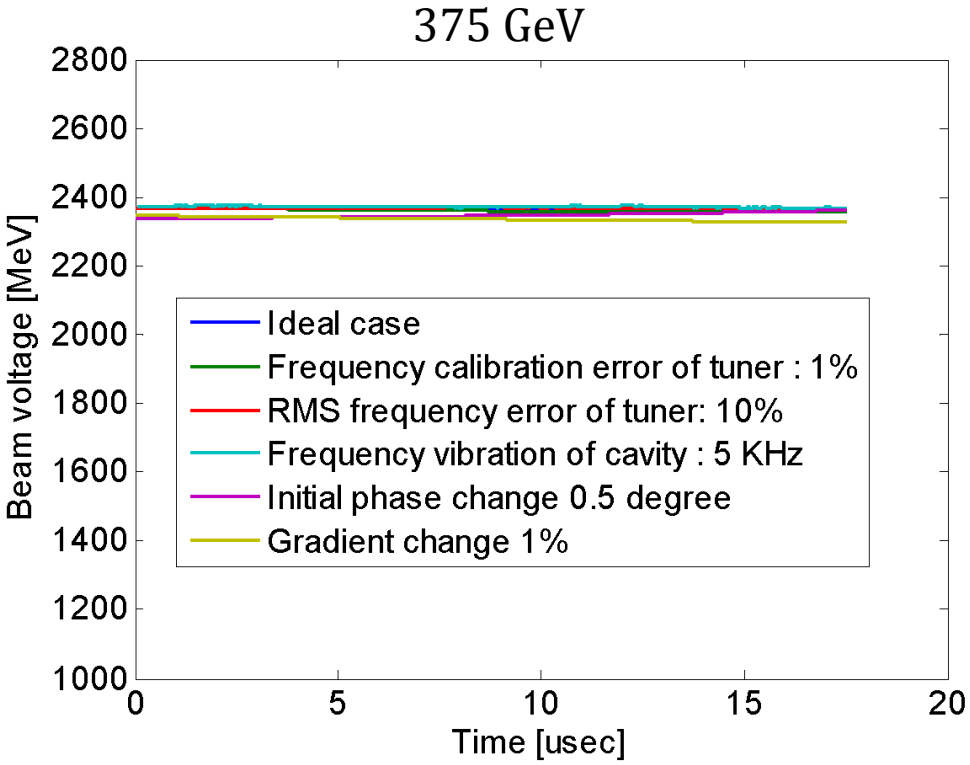


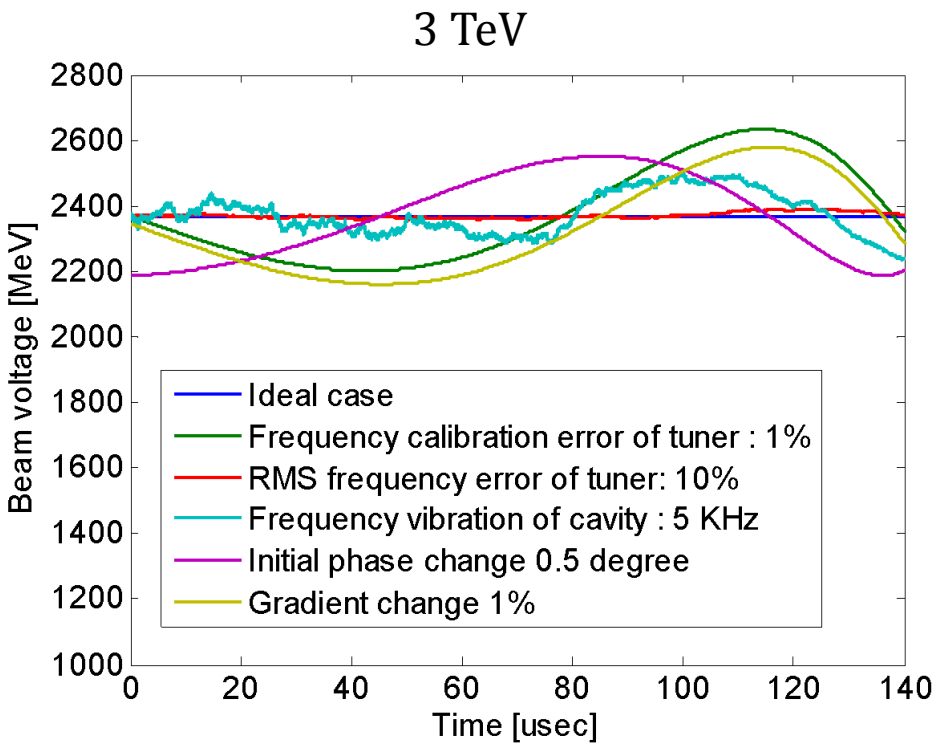


Stability in variable phase modulation

- In order to achieve 0.1% energy flatness, big challenge for the final stage:

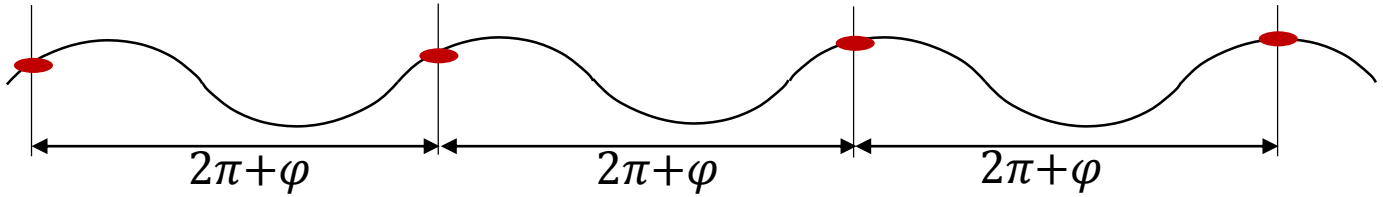
- Frequency calibration error $< 0.01\%$ (RMS $< 1\%$)
- Cavity resonant frequency vibration < 100 Hz
- Initial gradient change $< 0.005\%$
- Initial phase shift $< 0.003°$

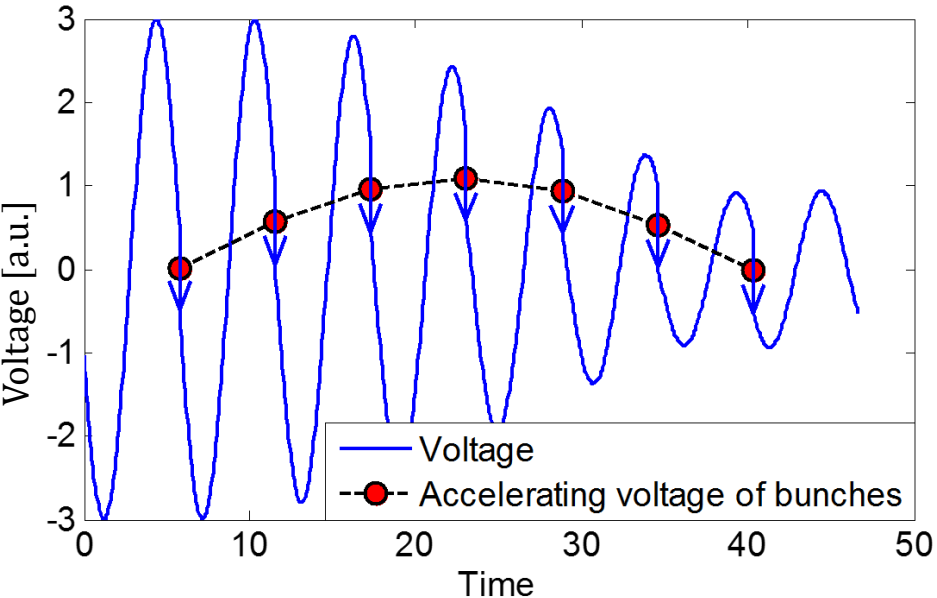


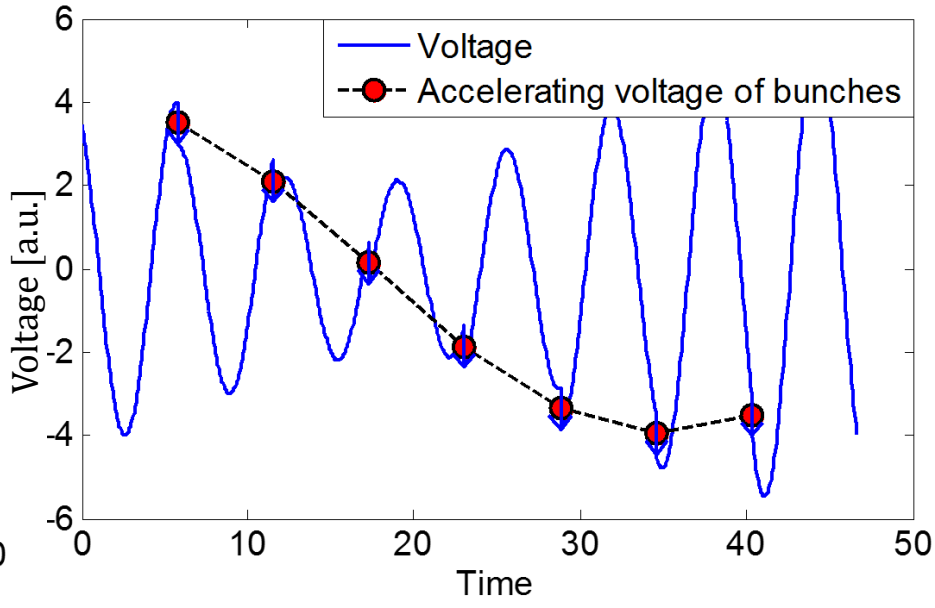


Concept of Linear phase modulation

- f_g(Frequency of Generator)= f_c(Resonate frequency of Cavity) ≠ f_b(Bunches)=500 MHz
- Bunch separation * Resonate frequency of Cavity = $1+\frac{\varphi}{2\pi}$.
- Accelerating voltage : $V_n = e^{j\varphi}(V_{n-1} - V_b) = \left(V_0 - V_b \frac{e^{j\varphi}}{e^{j\varphi}-1}\right) e^{jn\varphi} + V_b \frac{e^{j\varphi}}{e^{j\varphi}-1}$

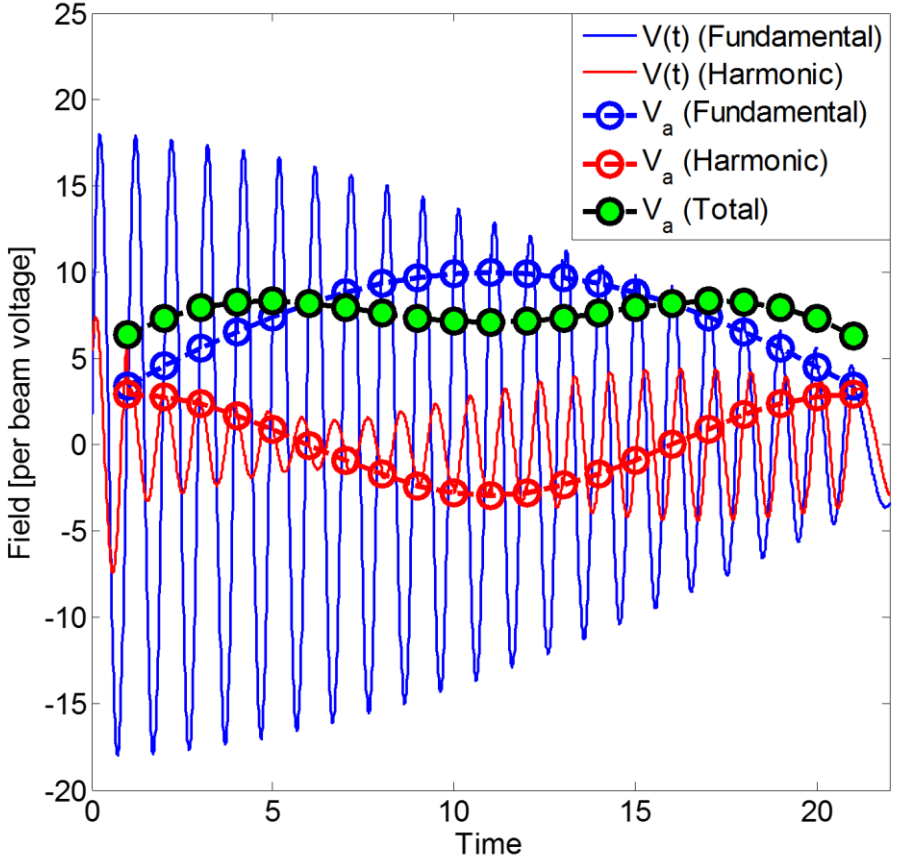






Multi-harmonic phase modulations

- Linear phase modulation provide sine/cosine voltage profile.
- Energy variation → Fourier series → Group of sine/cosine function →Multi-Linear phase modulation.
- So-called Multi-harmonic compensation.



$$f_c^{(0)} - f_b = \frac{140}{360}\frac{1}{T_b} = 2.78 \text{ KHz}$$

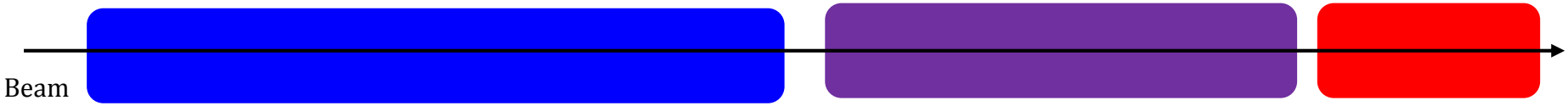
Fundamental structure
Phase shift over all bunch
$= 140°$

$$f_c^{(1)} - f_b = \frac{1}{T_b} = 7.14 \text{ KHz}$$

1-st Harmonic structure
Phase shift over all bunch
$= 360°$

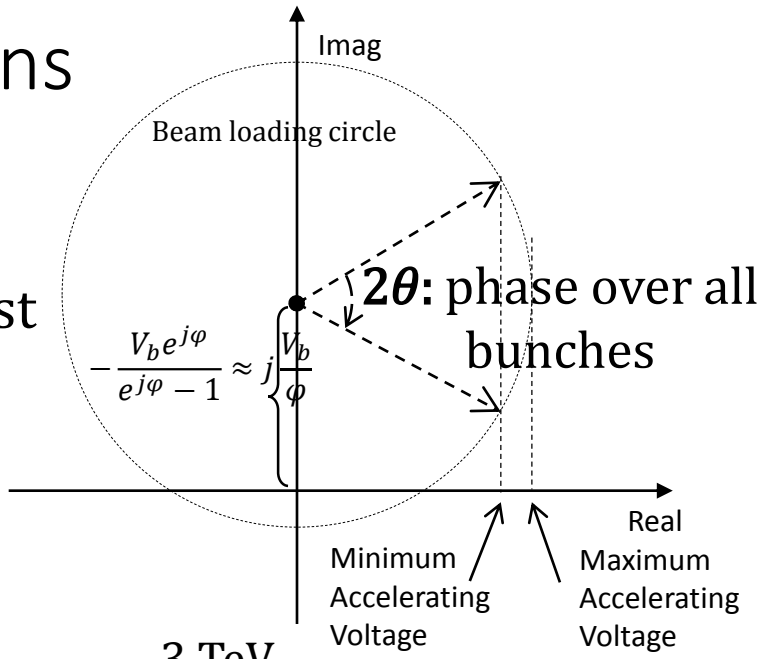
$$f_c^{(2)} - f_b = \frac{2}{T_b} = 14.29 \text{ KHz}$$

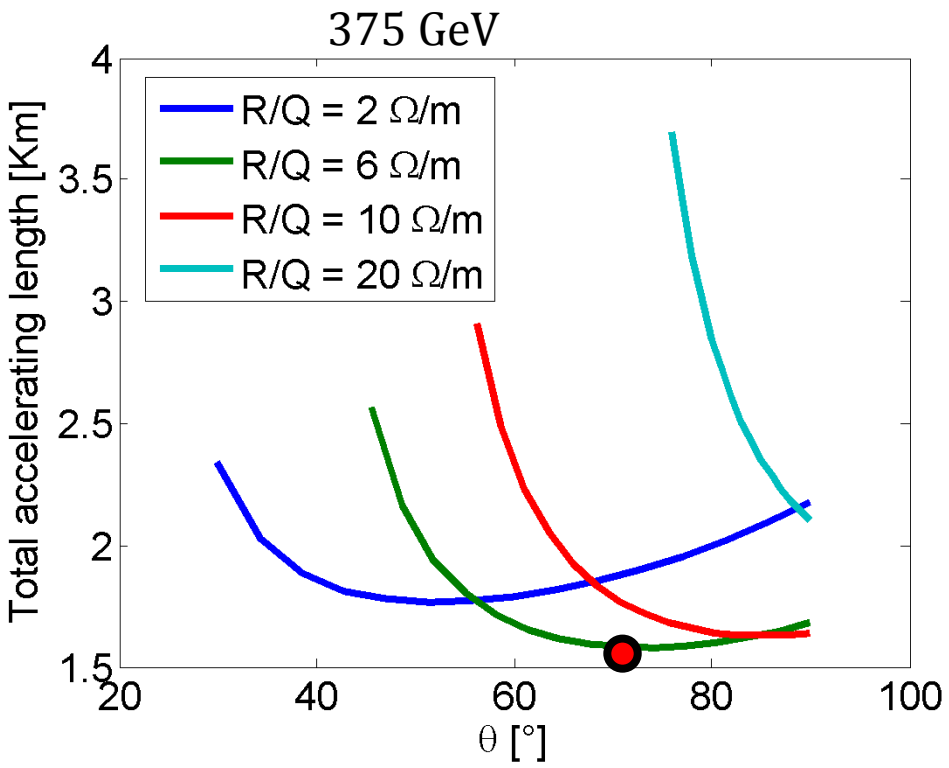
2-nd Harmonic structure
Phase shift over all bunch
$= 720°$

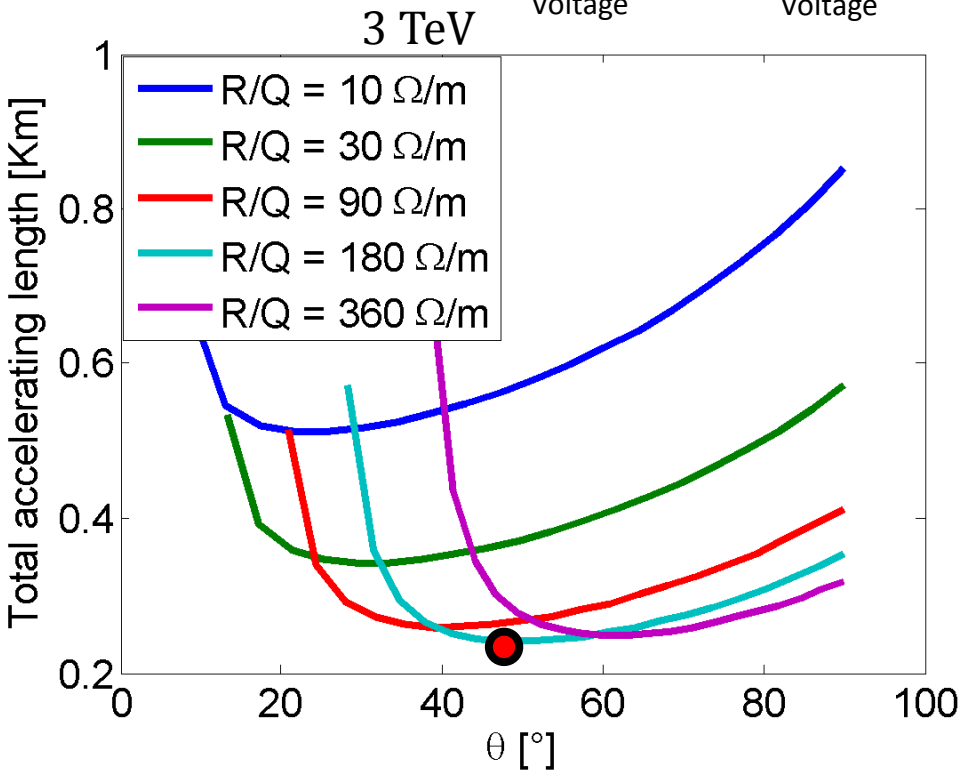


Multi-Harmonic phase modulations

- Important parameters: R/Q, θ of fundamental structure.
- Optimum R/Q for final stage : 6 Ω/m, for first stage : 160 Ω/m (Fundamental structure).
- Upgrade plan: compromise R/Q = 10 0Ω/m for first stage. Reuse them as harmonic structure in final stage.



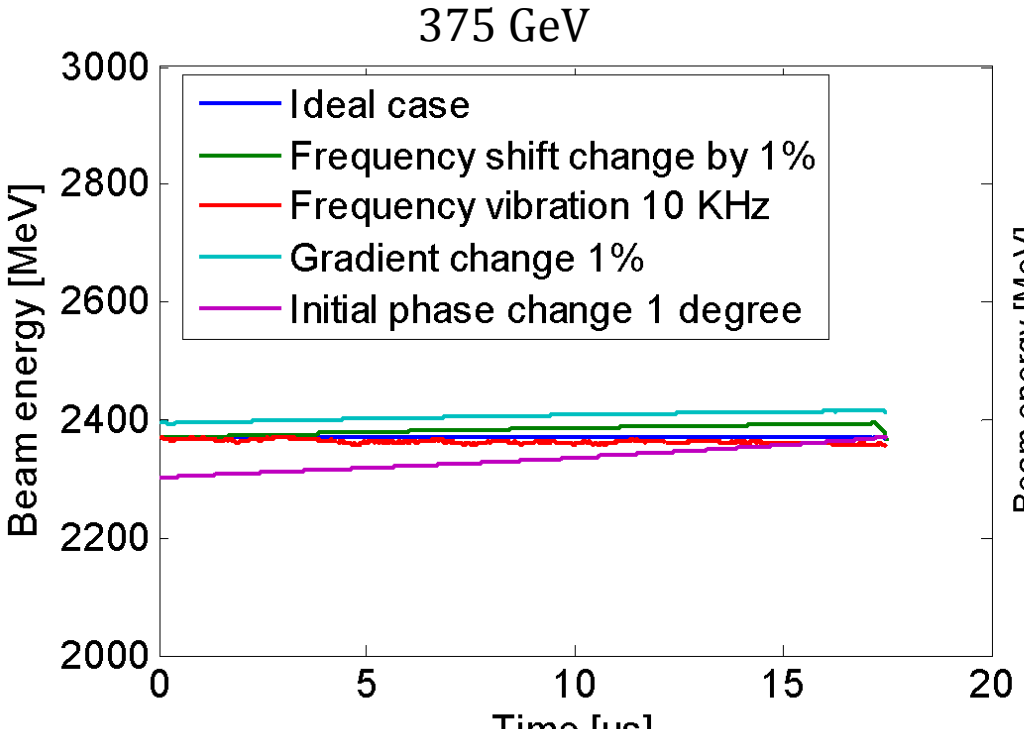


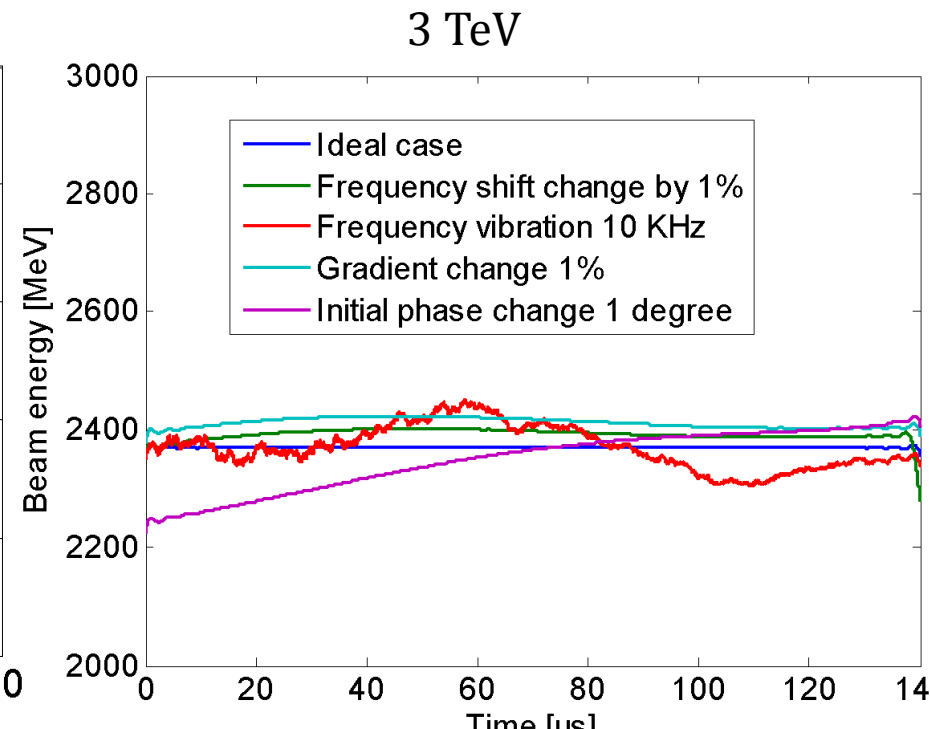


Stability in variable phase modulation

- In order to achieve 0.1% energy flatness, big challenge for the final stage:

- Frequency calibration error < 0.1% (VPM < 0.01%)
- Cavity resonant frequency vibration < 200 Hz (VPM< 100 Hz)
- Initial gradient change <0.1% (VPM< 0.005%)
- Initial phase shift <0.015° (VPM< 0.003°)





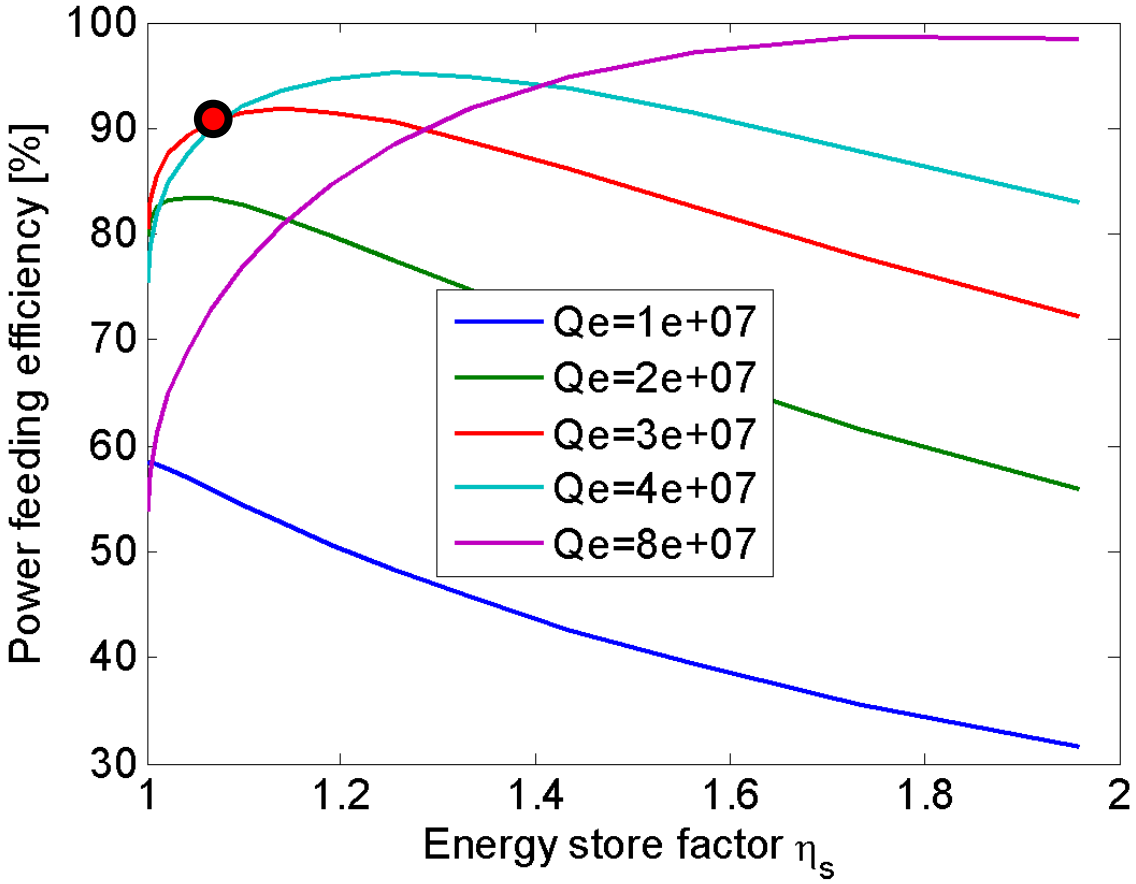
Conclusions for beam loading

- For variable phase modulation: precise tuning at 1 MHz/ms is not realistic. Multi-harmonic phase modulation seems to be the base line design.

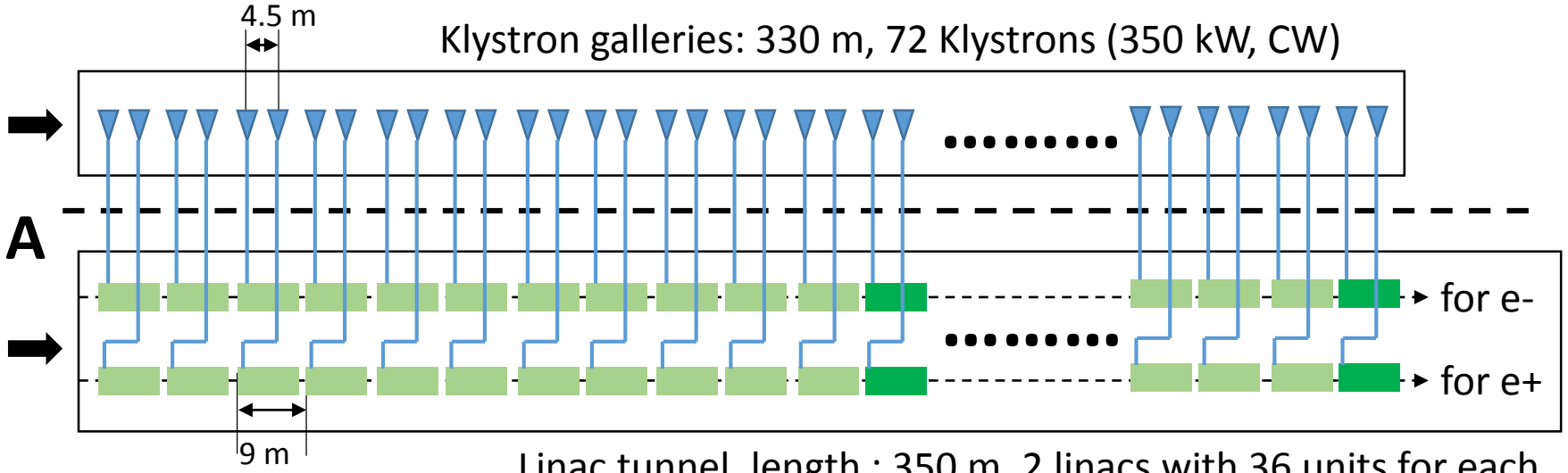
Parameters	Multi-harmonic phase		Variable phase	
	375 GeV	3 TeV	375 GeV	3 TeV
Fundamental Length	268 m	1.44 Km		
Harmonic length	21.8 m	278 m		
Total Length	290 m	1.71 Km	328 m	1.55 Km
R/Q per length for fundamental	100 Ω/m	6 Ω/m		
R/Q per length for harmonic	100 Ω/m	100 Ω/m	60 Ω/m	60 Ω/m
Klystron power	11.77 MW CW	83.3 MW CW	8.83 MW CW	76.1 MW CW
Cryogenics power	3.96 MW	17.25 MW	4.72 MW	15.87 MW
Total AC power	21.1 MW	142.2 MW	18 MW	130 MW

Power feeding issue

- Because of reflection: Klystron power * Filling time ≠ Stored energy in Cavities.
- Power feeding efficiency: $\eta_f = \frac{\Delta U_c}{T_f P_i}$, where ΔU_c: cavity stored RF energy gain (minimum 1.4 MJ); P_i: klystron RF power ; T_f: filling time.



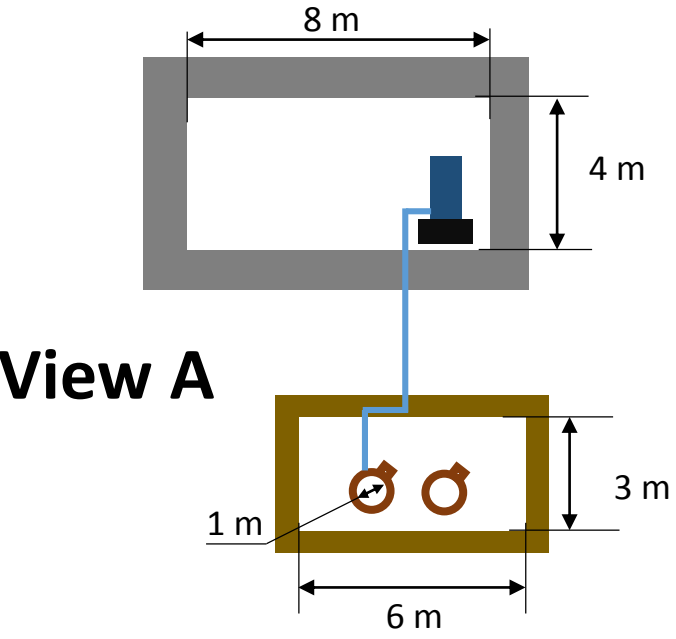
CLIC-SC-Drive Beam Linac-0.375 TeV



Linac tunnel, length : 350 m, 2 linacs with 36 units for each

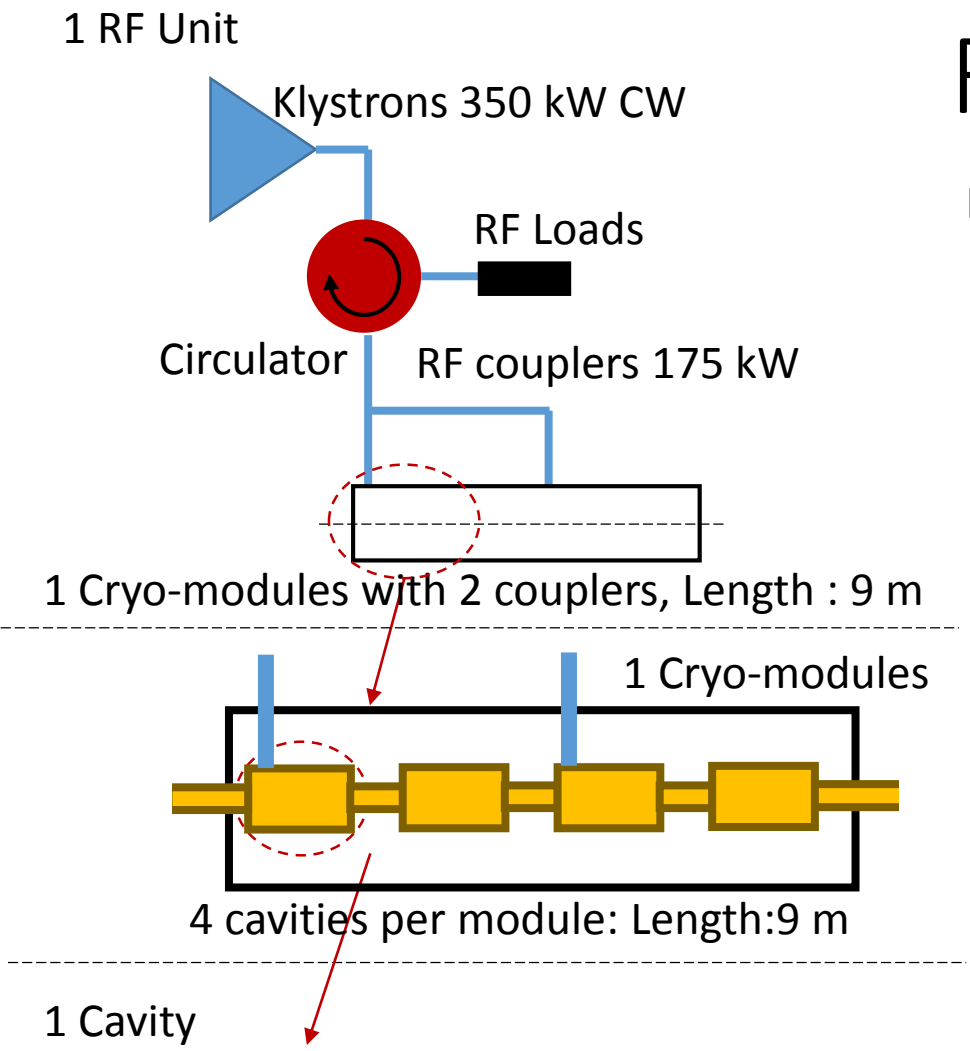
Fundamental structure (Total: 66)

Harmonic structure (Total: 6)



Parameters		Parameters	
RF Frequency	500 MHz	Klystron number	72
Length	350 m	RF Cavities	288
Energy	2.37 GeV		
Peak Beam power	2*10 GW		
Avg Beam power	2*8.6 MW		

RF and Cryogenics



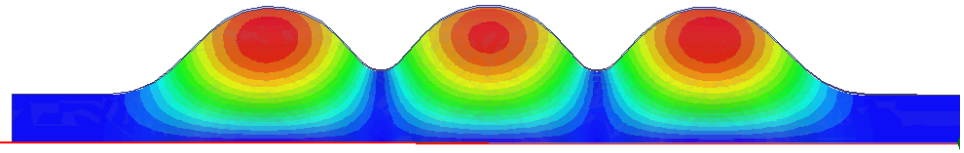
3 cells per cavity : 2.04 m
R/Q : 100 Ohm/m; Store energy: 980 J/m
Max(Esurf) = 56 MV/m, Max(Hsurf) = 140 KA/m

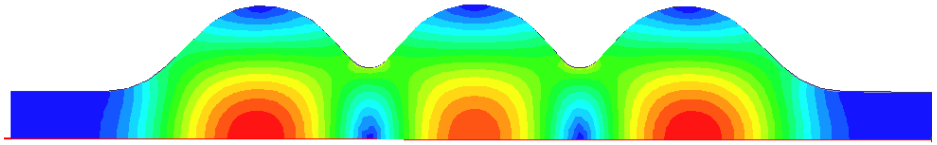
Heat load per cryo-module, total 72modules

Heat load(W)	4K	5-8K	50-75K
RF cavities	350	36	599
Coupler	10		
Static loss	26	111	648
Total	387	147	1247

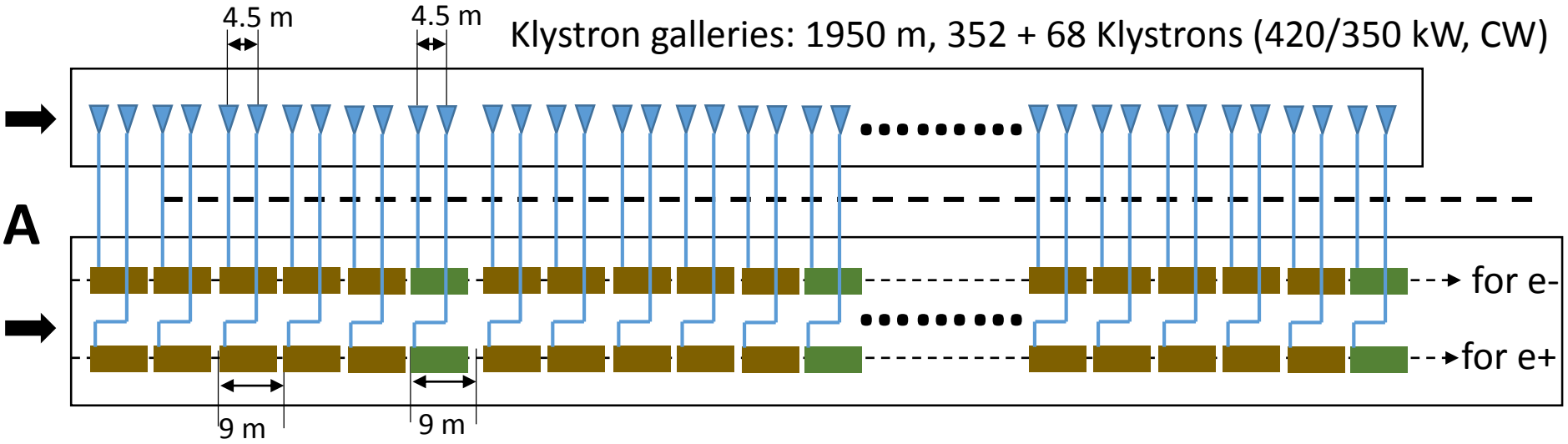
AC power consumption

Item	Power	Eff	Grid power
Cryogenics(4.5K)	34 KW	0.43 %	8 MW
RF	23.5 MW	67 %	35.3 MW
Total			44.3 MW





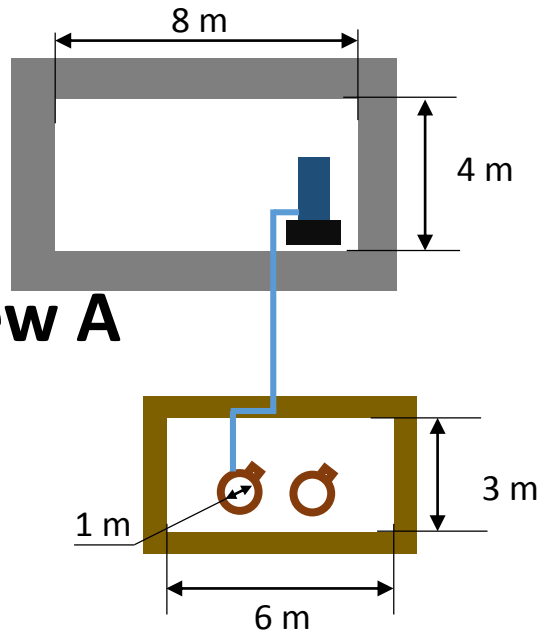
CLIC-SC-Drive Beam Linac-3 TeV



Linac tunnel, length : 2050 m, 2 linacs with 176+ 34 units for each

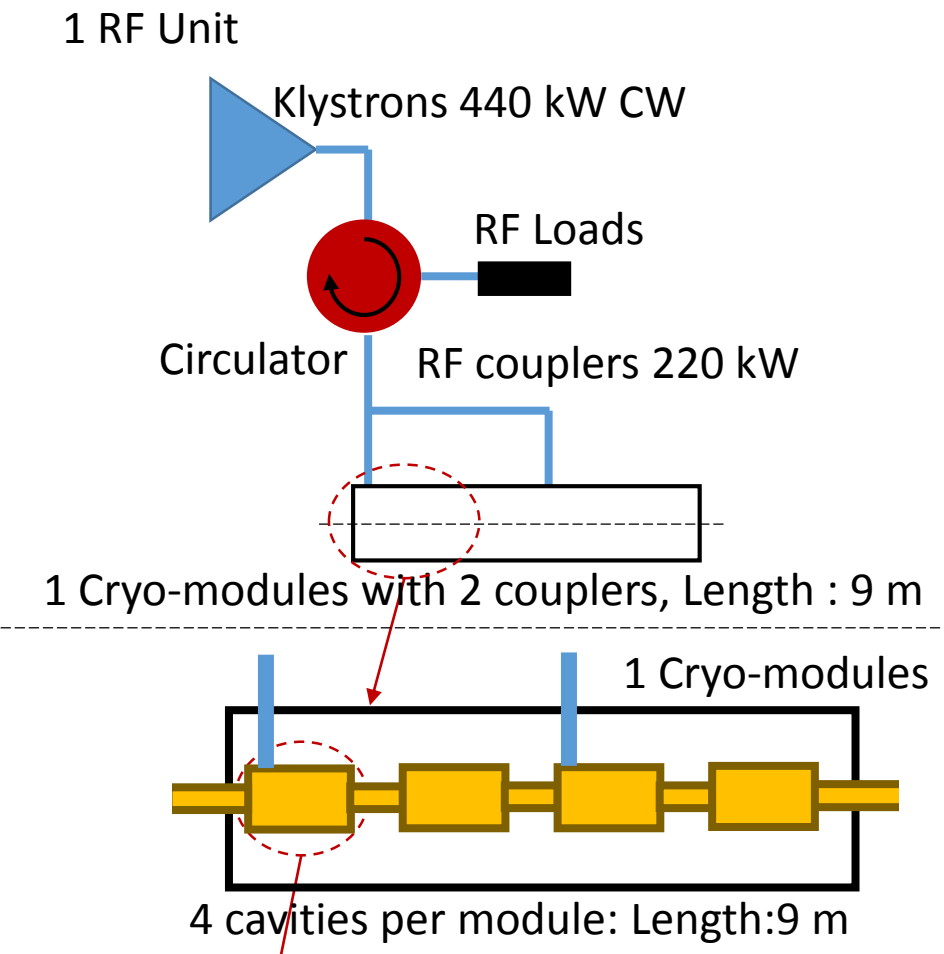
Fundamental structure (new build), count: 352

Harmonic structure (take from 0.375 TeV stage), count: 68



Parameters		Parameters	
RF Frequency	500 MHz	New Klystron	352
Length	2000 m	New RF Cavities	1408
Energy	2.37 GeV		
Peak Beam power	2*10 GW		
Avg Beam power	2*68.8 MW		

RF and Cryogenics



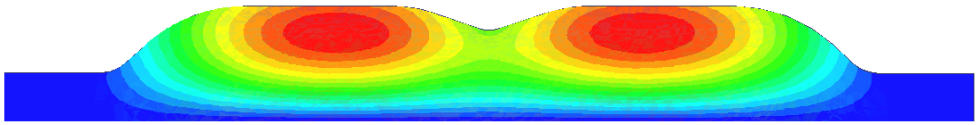
2 cells per cavity : 2.04 m
R/Q : 6 Ohm/m; Store energy: 980 J/m
Max(Esurf) = 20 MV/m, Max(Hsurf) = 138 KA/m

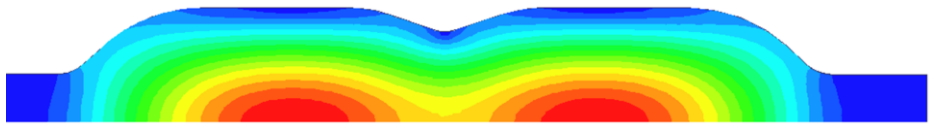
Heat load per cryo-module, total
352 new modules

Heat load(W)	4K	5-8K	50-75K
RF cavities	245	25	416
Coupler	9		
Static loss	18	77	450
Total	272	102	866

AC power consumption

Item	Power	Eff	Grid power
Cryogenics(4.5K)	148 kW	0.43 %	34.5 MW
RF	167 MW	67 %	250 MW
Total			284.5 MW

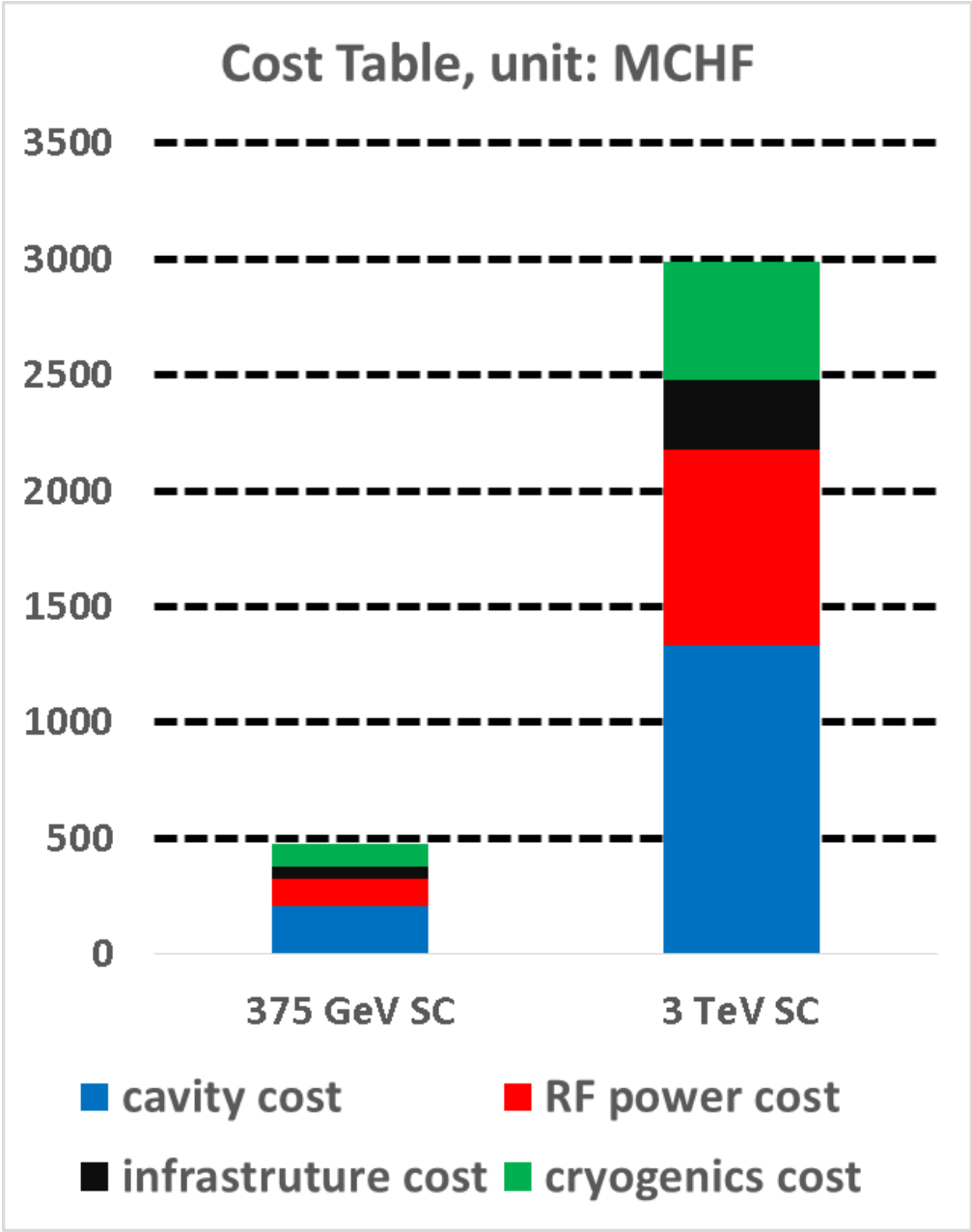




Cost table

- Super conducting scheme save 1 BCHF for entry cost (375 GeV)!
- Super conducting scheme cost more in 3 TeV.
- Further optimization is still possible.

	375 GeV SC	375 GeV CDR	3 TeV SC	3 TeV CDR
cavity cost	204		1331	
RF power cost	123		848	
infrastrutu re cost	51		298	
cryogenics cost	99		515	
Total cost	477	1000~ 1200	2991	2000~ 2500



RF cost (2 linacs) for 375 GeV

	Quantity	Price per unit [kCHF]	Price Total [MCHF]	Reference
Cavities				
Cavity manufacture	288	380kCHF	109.44	SPL : 170 kCHF/m * 1.6 m (effective length) * 1.4 (dimension scale)
Coupler	144	70kCHF	10.08	SPL : 70 kCHF
Tuner	288	80kCHF	23.04	SPL : 80 kCHF/m
Other Cavity cost	144	180kCHF	25.92	SPL [kCHF] LLRF: 30 ; Control: 20; Cabling: 70; Installation: 60
Cryo-module	72	500kCHF	36	
Total Cavity cost			**204.48**	
Klystrons				
Klystron	72	380kCHF	27.36	LHC : 350 kCHF/330 kW * 350 kW
Circulator, Load, Waveguide	72	175kCHF	12.6	LHC : 175 kCHF
LLRF cost	72	50kCHF	3.6	LHC
Electrical distribution, cooling & ventilation	37.6MW	2100kCHF/MW	78.96	
Total RF power cost			**122.52**	
Total RF			**327**	**CDR one DB Linac: 1181 MCHF**

Other cost (2 linacs) for 375 GeV

	Quantity	Price per unit [kCHF]	Price Total [MCHF]	Reference
Beam Line infrastruture				
Accelerating tunnel	350m	25kCHF/m	8.75	
Klystron gallery	330m	32kCHF/m	10.56	
Beam instrumentation	330m	10kCHF/m	3.3	
Magnets	330m	59kCHF/m	19.47	
Vacuum	330m	28kCHF/m	9.24	
Total infrastruture cost			**51.32**	**CDR one DB Linac: 263 MCHF**
Cryogenics cost				
Refrigerator 20 kW	2	24000kCHF	48	
Helium storage	2	2000kCHF	4	
Compresssor hall	1600m2	6kCHF/m2	9.6	SPL : 6 kCHF/m2
Refrigerator hall	400m2	4kCHF/m2	1.6	SPL : 4 kCHF/m2
valve boxes & jumper	72	200kCHF	14.4	
Electrical distribution, cooling & ventilation	9.33MW	2100kCHF/MW	19.593	
Lines and piping	330m	5kCHF/m	1.65	
Total cryogenics cost			**98.843**	
Total cost			**477.163**	**CDR one DB Linac: 1444 MCHF**

RF cost (upgrade from 375 GeV)

	Quantity	Price per unit [kCHF]	Price Total [MCHF]	Reference
Cavities				
Cavity manufacture	1408	380kCHF	535.04	SPL : 170 kCHF/m * 1.6 m (effective length) * 1.4 (dimension scale)
Coupler	704	70kCHF	49.28	SPL : 70 kCHF
Tuner	1408	80kCHF	112.64	SPL : 80 kCHF/m
Other Cavity cost	1408	180kCHF	253.44	SPL [kCHF] LLRF: 30 ; Control: 20; Cabling: 70; Installation: 60
Cryo-module	352	500kCHF	176	
Total Cavity cost			**1126.4**	
Klystrons				
Klystron	352	445kCHF	156.64	
Circulator, Load, Waveguide	352	175kCHF	61.6	LHC : 175 kCHF
LLRF cost	352	50kCHF	17.6	LHC
Electrical distribution, cooling & ventilation	233.2MW	2100kCHF/MW	489.72	
Total RF power cost			**725.56**	
Total RF			**1851.96**	

Other cost (upgrade from 375 GeV)

	Quantity	Price per unit [kCHF]	Price Total [MCHF]	Reference
Beam Line infrastruture				
Accelerating tunnel	1600m	25kCHF/m	40	
Klystron gallery	1600m	32kCHF/m	51.2	
Beam instrumentation	1600m	10kCHF/m	16	
Magnets	1600m	59kCHF/m	94.4	
Vacuum	1600m	28kCHF/m	44.8	
Total infrastruture cost			**246.4**	
Cryogenics cost				
Refrigerator 20 kW	8	24000kCHF	192	
Helium storage	8	2000kCHF	16	
Compresssor hall	6400m2	6kCHF/m2	38.4	SPL : 6 kCHF/m2
Refrigerator hall	2000m2	4kCHF/m2	8	SPL : 4 kCHF/m2
valve boxes & jumper	372	200kCHF	74.4	
Electrical distribution, cooling & ventilation	37.33MW	2100kCHF/MW	78.393	
Lines and piping	1700m	5kCHF/m	8.5	
Total cryogenics cost			**415.693**	
Total update cost			**2514.053**	
Total cost (+ Stage 375 GeV)			**2991.216**	**CDR 2 DB Linacs: 2746 MCHF**