CLIC DR RF system
Baseline and Alternatives

A.Grudiev

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Acknowledgements for useful discussions to:
K.Akai, S.Belomestnykh, W.Hofle, E.Jensen

Outline

- Introduction
- Beam loading effect
- Baseline
- 1 GHz alternatives
  - SC option
  - Option with RF frequency mismatch
  - Option with strong input power modulations
- 2 GHz alternatives (will not be presented in details due to lack of time)
- Summary

CLIC DR RF system evolution

- 2008,
  - CLIC08, (Oct. 2008), 2 GHz RF system issues were raised for the first time, recommendations were given, 1 GHz was proposed as possible alternative.
- 2009,
  - ACE (May 2009), Issues were presented to ACE and partially addressed. ACE recommended to develop concept for RF system.
- 2010,
  - ACE (Feb. 2010), progress was reported.
  - CLIC meting (March 2010) 1 GHz RF system with 2 bunch trains adopted for CLIC baseline
  - Real work on the DR RF system conceptual design started
  - IWLC (Oct. 2010), new DR parameters were presented (more favorable for RF system), several options for conceptual design of 2 GHz RF system were presented
- 2011,
  - New parameter set for the DR: even more favorable for RF
  - Conceptual design for the baseline at 1 GHz and several alternatives at 1 and 2 GHz are proposed for the CDR.

CLIC DR parameters

CLIC DR		
RF frequency: f [GHz]	1	2
Circumference: C [m]	427.5	
Energy : E [GeV]	2.86	
Momentum compaction: α_p	**1.28×10^{-4}**	
Bunch population: N_e	4.1×10^9	
Number of bunches: N_B	312	
Number of trains: N_T	2	1
Energy loss per turn: eV_A [MeV]	**3.98**	
Energy spread in the bunch: σ_E/E [%]	0.12	
Bunch length: σ_Z [mm]	1.8	1.6
RF voltage: V_C [MV]	**5.1**	**4.5**
Calculated RF parameters		
Harmonic number: h	1426	2852
Synchronous phase : ϕ [°]	38.7	27.8
Synchrotron frequency: f_s [kHz]	3.45	4.58
Energy acceptance: $\Delta E/E$ [%]	2.34	1.01
Bucket length $2\Delta Z$ [mm]	70	35

F. Antoniou and Y. Papaphilippou
Last update on 18 Jan. 2011

Synchrotron motion: small amplitude harmonic oscillation in longitudinal phase space

Specifications from RTML

Specification on the bunch-to-bunch spacing variation along the train:

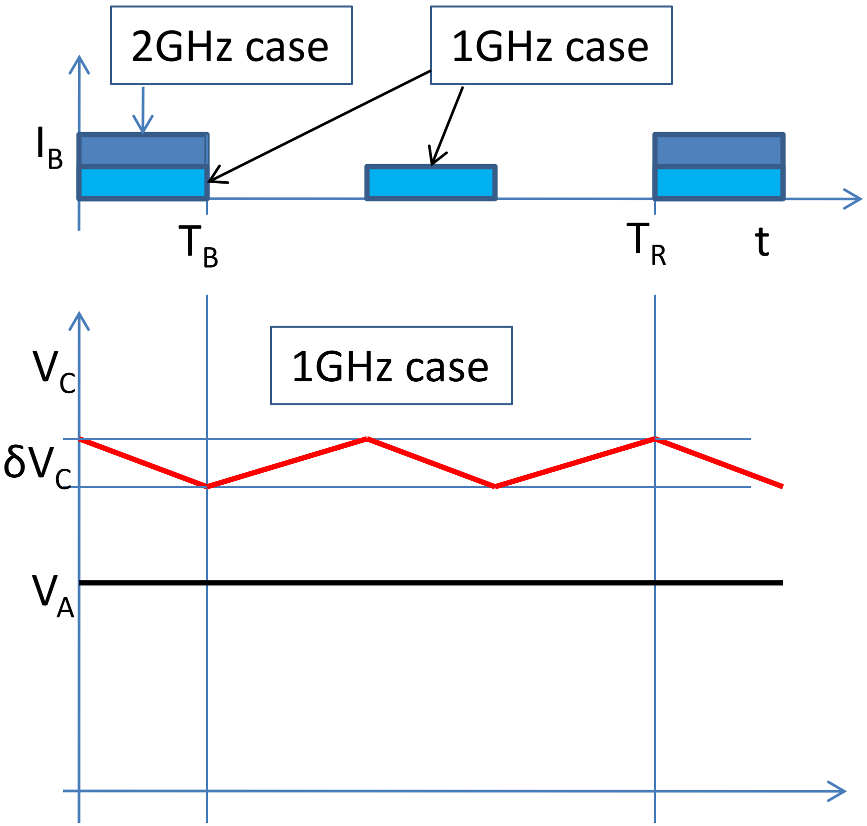
0.1 degree at 1 GHz corresponds to 280 fs; or 84 µm;

Specification on the bunch-to-bunch variation of the bunch length (σ_Z) along the train:

RMS{σ_Z}/σ_Z < 2%

N.B. At the equilibrium, mean energy and the energy spread are the same for all bunches. Only the bunch spacing and the bunch length are significantly affected by the beam loading transient within each revolution period. It is the scope of this presentation to address this effect.
Slow (compared to the revolution period) variations are **outside** of the scope of this presentation. Slow feedback system will take care of this.

Beam loading effect (1/3)



Variation of the stored energy and rf voltage due to beam loading ($\delta V_C/V_C << 1$):

$$U = \frac{V_C^2}{2\omega R/Q}; \quad \frac{\delta U}{U} = 2\frac{\delta V_C}{V_C}$$

$$\frac{dU}{dt} = -\left(P_B - \langle P_B \rangle\right) = \frac{\delta U}{T_B}$$

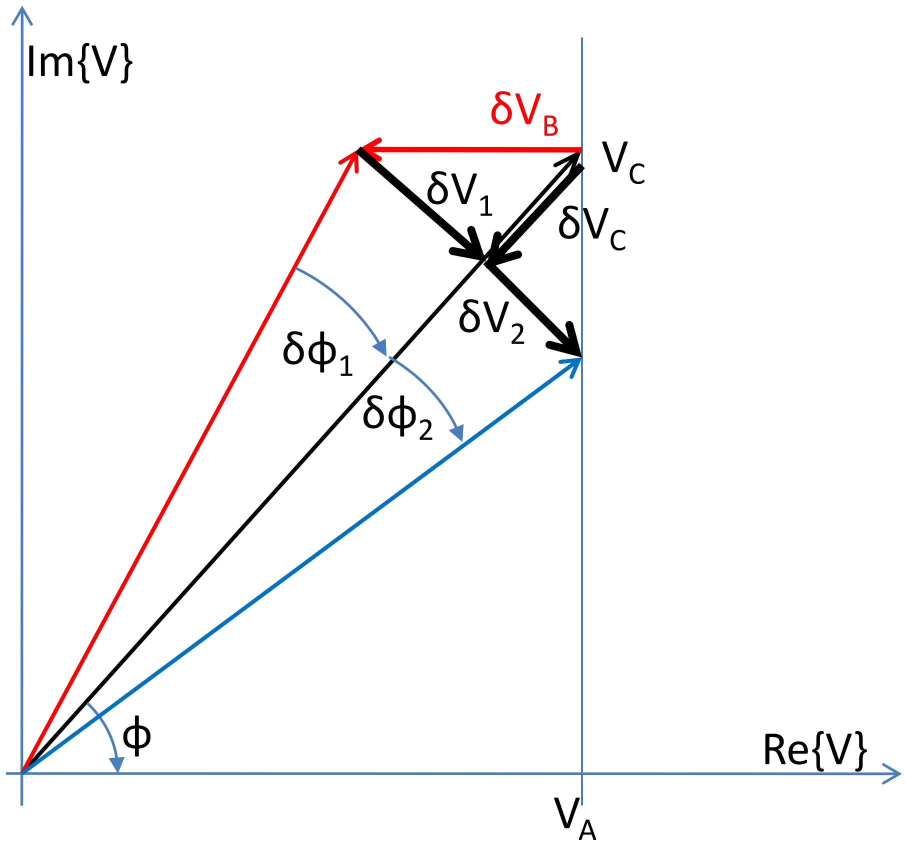
$$\delta U = -\left(P_B - \langle P_B \rangle\right)\frac{N_B T_R}{N_T h}$$

$$= -\frac{N_B N_e e V_A}{N_T}\left(1 - \frac{N_B}{h}\right)$$

Condition to keep RF voltage variation small in an RF system with constant input rf power:

$$|\delta U| << U; \qquad \frac{N_B N_e e V_A}{N_T}\left(1 - \frac{N_B}{h}\right) << \frac{V_C^2}{2\omega R/Q}$$

Beam loading effect (2/3)



Variation of the bunch phase due to rf voltage variation ($\delta V_C/V_C << 1$):

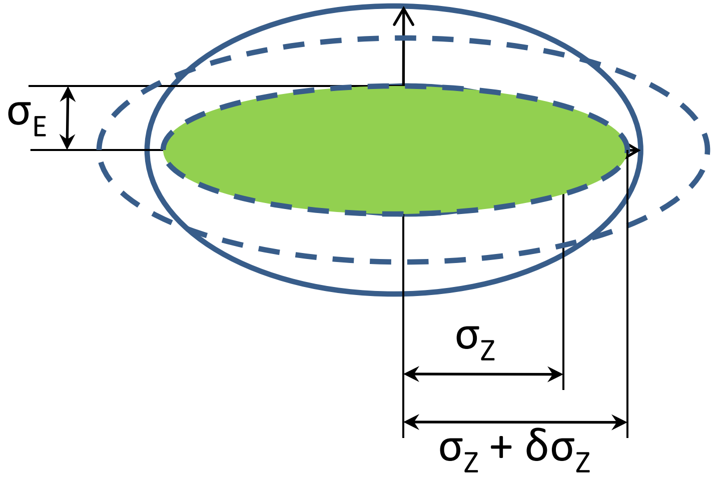
$$\delta\phi_B = \delta\phi_1 + \delta\phi_2$$

$$\delta\phi_1 = \frac{\delta V_1}{V_C} = \frac{\delta V_C}{V_C}\tan\phi$$

$$\delta\phi_2 = \frac{\delta V_2}{V_C} = \frac{\delta V_C}{V_C}\frac{1}{\tan\phi}$$

$$\boxed{\begin{aligned}\delta\phi_B &= \frac{\delta V_C}{V_C}\left(\tan\phi + \frac{1}{\tan\phi}\right)\\ &= \frac{\delta V_C}{V_C}\frac{1}{\cos\phi\sin\phi}\end{aligned}}$$

Beam loading effect (3/3)



Variation of the bunch length due to rf voltage variation ($\sigma_E \ll \Delta E$):

$$\sigma_Z \omega_S \sim \frac{\sigma_E}{E} = const, \quad \omega_S \sim \sqrt{V_C \sin\phi}$$

$$\sigma_Z^4 \cdot \left(V_C^2 - V_A^2\right) = const$$

$$4\sigma_Z^3 \delta\sigma_Z \cdot \left(V_C^2 - V_A^2\right) + \sigma_Z^4 \cdot 2V_C \delta V_C = 0$$

$$\boxed{\frac{\delta\sigma_Z}{\sigma_Z} = -\frac{1}{2}\frac{\delta V_C}{V_C}\frac{1}{\sin^2\phi}}$$

Baseline solution (basic parameter chose)

1. RF frequency is 1 GHz
2. It is designed in a way that the stored energy is so high that the RF voltage variation is kept small to minimize the transient effect on the beam phase to be below the specifications
3. ARES-type cavity developed for the KEK B-factory RF system is used after scaling to 1 GHz and some modifications

- $\delta\phi_b$ = 0.1 degree RMS correspond to 0.3 degree peak-to-peak variation
- $\delta V_C/V_C = \delta\phi_b \cos\phi \sin\phi = 0.26$ %
- $\delta U/U = 2\delta V_C/V_C = 0.52$ %
- $\delta U = N_b N_e e V_A (1-N_b/h)/N_T = 0.318$ J
- $U = \delta U/(\delta U/U) = 0.318 / 0.0052 = 61.2$ J;
- $R/Q = V_C^2/2\omega U = 33.8\ \Omega$

Baseline solution (cavity parameter chose)

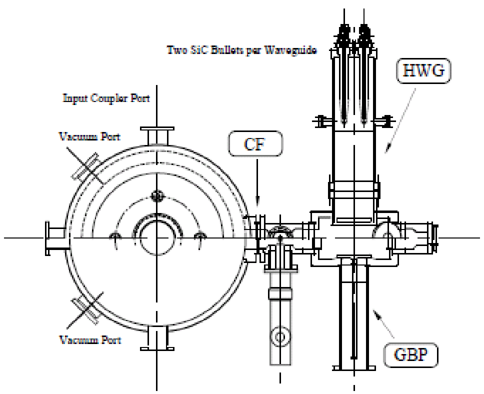


Table 1: RF design parameters of the ARES production model, and the high-power test records achieved with the production prototype ARES96.

f_{RF} = 508.887 MHz
$Ua : Us$ = 1 : 9
R / Q = 15 Ω
Q = 1.1×10^5 †

Pc = 150 kW per ARES Cavity generating
Vc = 0.5 MV (KEKB Design)

High-Power Performance
Maximum Continuous: Pc = 380 kW
Maximum for 20 minutues: Pc = 450 kW

†: in high-power operation with Pc = 150 kW

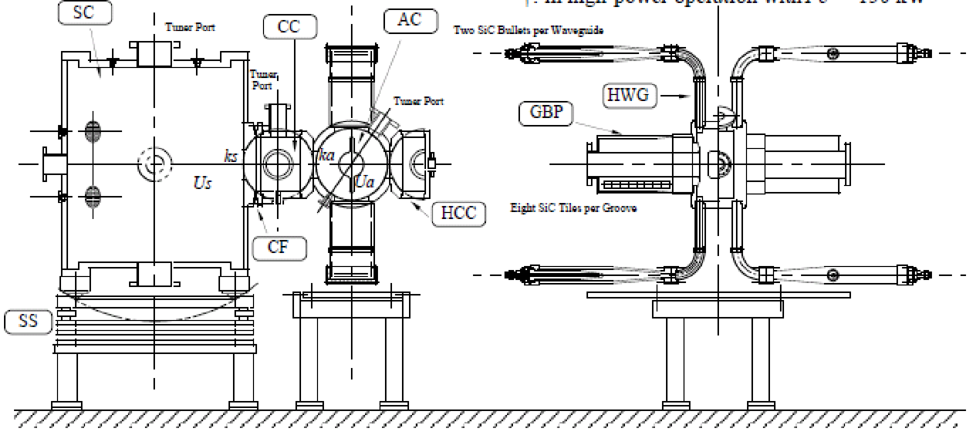


Figure 1: A schematic drawing of the ARES production model based on the prototype ARES96.

~2.5 m

Kageyama et al, APAC98

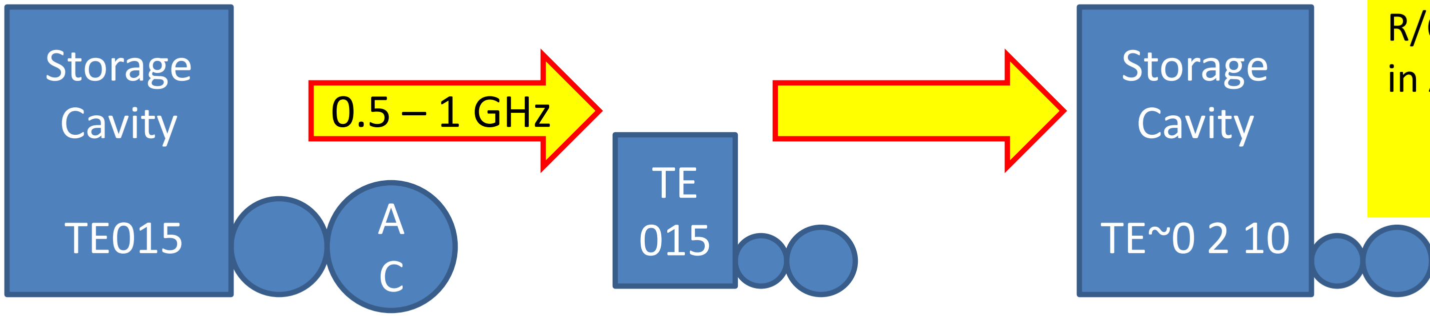
Proposed in 1993 by Shintake, cavities of this type (ARES-type cavities utilizing TE015 mode in storage cavity) are used in KEK B-factory in both low and high energy rings. It is equipped with tuning and HOM damping features.

Frequency: f[GHz]	**0.509**
Normalized shunt impedance (circuit): R_g/Q [Ω]	7.4
Unloaded Q-factor: Q	110000
Aperture radius: r [mm]	80
Power range: $P_g=V_g^2/2R_g$ [MW] Nominal – Maximum tested	0.15 – 0.45
Gap voltage range: V_g [MV] Nominal – Maximum tested	0.5 – 0.866

Baseline solution (cavity parameter chose)

Cavity scaling from 0.5 to 1 GHz

1 GHz cavity modification to reduce R/Q



$R/Q = V^2/2\omega(U_a+U_s)$
in ARES $U_s = 9U_a$
$R/Q \sim 1/f^3$
$Q \sim v/s \sim f$

Scaling V_g to keep EM field amplitude constant :
$V_g \sim f^{-1}$

$V_g \sim f^{0}$

Frequency: f[GHz]	**0.509**	**1**		**1**
Normalized shunt impedance (circuit): R_g/Q [Ω] ($\sim f^0$)	7.4	7.4	($\sim f^{-3}$) x 1/8	**0.925**
Unloaded Q-factor: Q ($\sim f^{-1/2}$)	110000	78000	($\sim f^{1}$) x 2	156000
Aperture radius: r [mm]	80	40		40
Gap voltage range: V_g [kV] Nominal – Maximum tested	500 – 866	250 – 433	same	250 – 433

In our case, an intermediate modification of the cavity is chosen to have comfortable voltage per cavity V_g = 5100 kV / 16 = **319 kV** and the reduced R_g/Q = 33.8 Ω / 16 = **2.11 Ω**

Baseline solution (final parameter table)

- Classical rf system
- No issues
- Constant input rf power matched to the average beam power and power loss in the cavity walls
- Only standard feedback system, for example, like in KEK-B LER
- Remaining (minor) R&D is the rf design of the modified ARES-type cavity with reduced R/Q of 2.1 Ω.

Parameters of CLIC DR rf system at 1 GHz (baseline)		KEK-B LER
Rf frequency [GHz]	1	0.509
Total stored energy [J]	61.2	106
Total R/Q: [Ω]	33.8	148
Cavity voltage: V_g [kV]	319	500
Number of cavities	16	20
R_g/Q per Cavity: [Ω]	**2.1**	7.4
Q-factor	120000	110000
Total wall loss power [MW]	3.2	3.1
Average beam power [MW]	0.6	4.5
Total rf power [MW]	3.8	7.6
Number of klystrons	8	10
Required klystron power [MW]	> 0.5	> 0.8
Total length of the rf system [m]	16 x 2 = 32	20 x 2.5 = 50
Bunch phase modulation p-p [deg]	0.3 (train 22%)	3.5 (gap 5%)

K.Akai, et.al, EPAC98

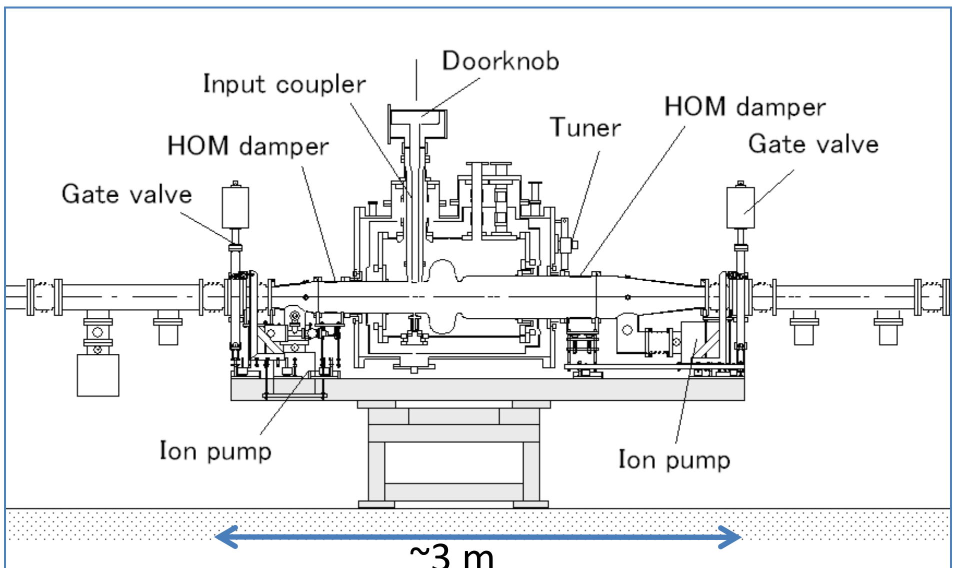
Alternative solutions (motivations)

- Alternative solutions at 1 GHz
    - Improve efficiency
    - Reduce size/cost
- Alternative solutions at 2 GHz
    - No train interleaving after the DR
    - Improve efficiency
    - Reduce size/cost

Alternative solutions 1.1
(superconducting cavity at 1 GHz)

Superconductive RF system will be more efficient but **not** smaller or cheaper. Two options :

1. **Superconducting ARES-type cavity**. Since it is beyond present state-of-the-art in the SC RF technology an extensive R&D and prototyping will be necessary. It is **not considered** further.
2. **Elliptical cavity**. An example, is SCC used in KEK-B HER. It is equipped with tuners and HOM dampers. Must be scaled and modified to reduce R/Q.



Y. Morita et al, IPAC10

Frequency: f[GHz]	**0.509**
Normalized shunt impedance (circuit): R_g/Q [Ω]	46.5
Unloaded Q-factor: Q	~1e9
Aperture radius: r [mm]	110
Beam loading Power range: [MW] Nominal – Maximum tested	0.25 – 0.4
Gap voltage range: V_g [MV] Nominal – Maximum tested	1.5 – 2
Stored energy range: U_g [J] Nominal – Maximum tested	7.7-13.7

Alternative solutions 1.1
(superconducting cavity at 1 GHz)

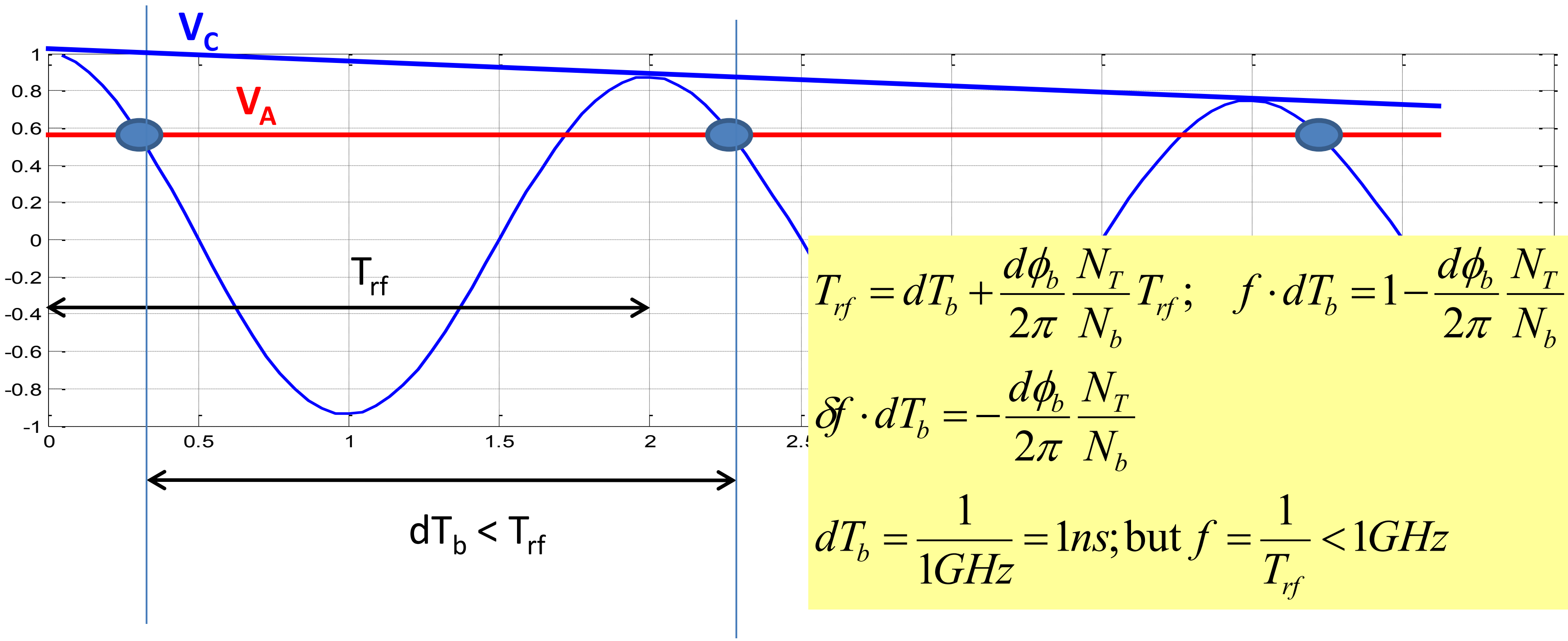
Elliptical cavity. Must be scaled and modified to reduce R/Q. This is done in two steps similar to ARES-type cavity scaling and modification:

1. Scaling by frequency ratio and keeping the same EM field amplitude: V~1/f, $U \sim 1/f^3$.
2. Increasing aperture to reduce the R/Q from **46.5 to 0.94 Ω** but assuming that the stored energy is constant. This is the main issue for this alternative. **It is not obvious that the solution exists …**

Parameters of CLIC DR rf system at 1 GHz (baseline)		Alternative 1.1
Rf frequency [GHz]	1	
Total stored energy [J]	61.2	
Stored energy per cavity [J]	3.8	1.7
Number of cavities	16	36
Total R/Q: [Ω]	33.8	
R_g/Q per gap: [Ω]	**2.1**	**0.94**
Gap voltage: V_g [kV]	319	142
Q-factor	120000	~1e9
Total wall loss power [MW]	3.2	~0
Average beam power [MW]	0.6	
Total rf power [MW]	3.8	0.6
Number of klystrons	8	9
Required klystron power [MW]	> 0.5	> 0.07 (IOT?)
Total length of the rf system [m]	16 x 2 = 32	36 x 3 = **108**

Alternative solutions 1.2
(mismatch of rf frequency and 1 GHz)

1. RF frequency is **close to** 1 GHz
2. It is designed in a way that the stored energy is intermediately high, so that the rf voltage variation is kept small to minimize the transient effect to be below the specifications for the **bunch length only**
3. The remaining variation of the bunch phase is above the specification but it is linear and is compensated by reducing the rf frequency



$$T_{rf} = dT_b + \frac{d\phi_b}{2\pi}\frac{N_T}{N_b}T_{rf}; \quad f \cdot dT_b = 1 - \frac{d\phi_b}{2\pi}\frac{N_T}{N_b}$$

$$\delta f \cdot dT_b = -\frac{d\phi_b}{2\pi}\frac{N_T}{N_b}$$

$$dT_b = \frac{1}{1GHz} = 1ns; \text{but } f = \frac{1}{T_{rf}} < 1GHz$$

Alternative solutions 1.2
(mismatch of rf frequency and 1 GHz)
Basic parameters chose based on the bunch length specs

Alternative 1.2

- $\delta\sigma_Z/\sigma_Z$ = 2% RMS correspond to 6% degree peak-to-peak variation
- $\delta V_C/V_C = -2\delta\sigma_Z/\sigma_Z \sin^2\phi = 2\cdot6\% \cdot\sin^2 38.7^o = 4.7\ \%$
- $\delta U/U = 2\delta V_C/V_C = 9.4\ \%$
- $\delta U = N_b N_e e V_A(1-N_b/h)/N_T = 0.318$ J
- $U = \delta U/(\delta U/U) = 0.318 / 0.094 = 3.4$ J;
- $R/Q = V_C^2/2\omega U = 608\ \Omega$

Baseline

- $\delta\phi_b$ = 0.1 degree RMS 0.3 degree peak-to-peak
- $\delta V_C/V_C = 0.26\ \%$
- $\delta U/U = 0.52\ \%$
- $\delta U = 0.318$ J
- $U = 61.2$ J;
- $R/Q = 33.8\ \Omega$

Alternative solutions 1.2(parameter table)

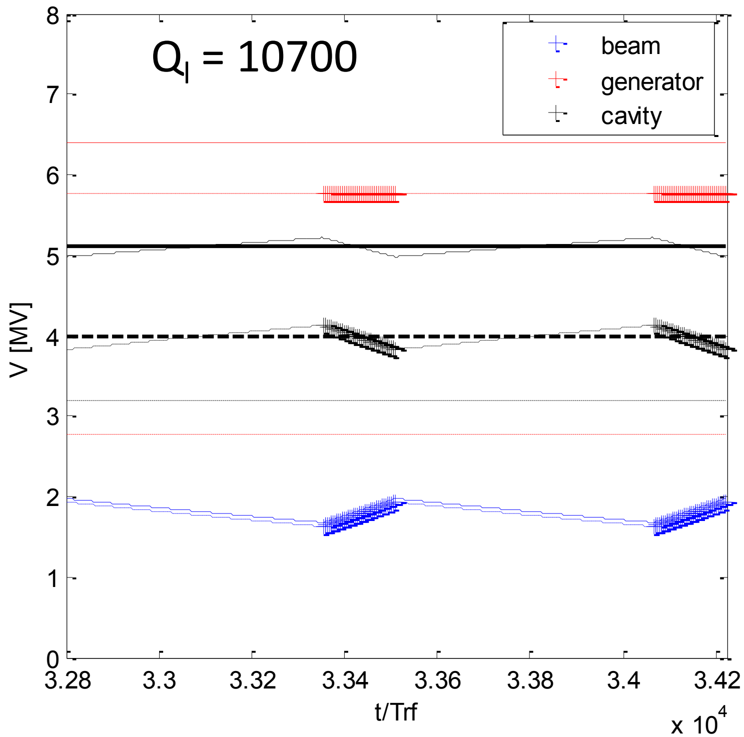
- Classical rf system with one exception: the rf frequency is slightly reduced to correct the bunch spacing to be exactly 1 ns.
- This frequency mismatch is bunch intensity dependent
- Remaining R&D:
1. the cavity design (conventional)
2. an MD to demonstrate this compensation in an existing ring. (unless it is already done ?)
- Advantages:
1. More efficient
2. More compact
3. Less expensive

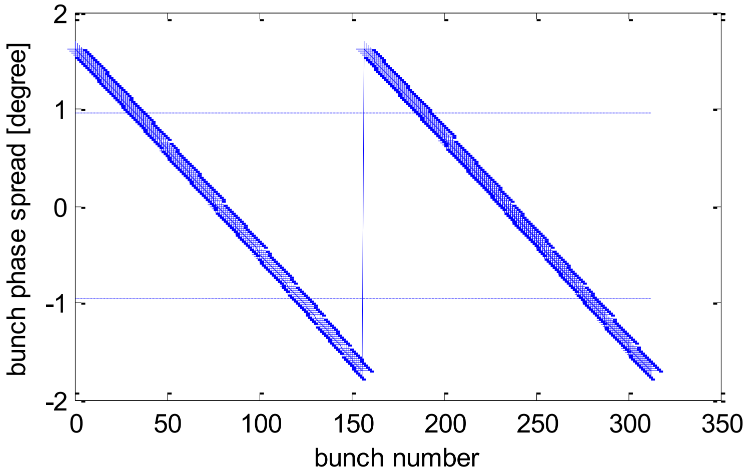
Parameters of CLIC DR rf system at 1 GHz (baseline)		Alternative 1.2
Rf frequency [GHz]	1	
Total stored energy [J]	61.2	3.4
Total R/Q: [Ω]	33.8	608
Gap voltage: V_g [kV]	319	319
Number of cavities	16	16
R_g/Q per gap: [Ω]	**2.1**	38
Q-factor	120000	~30000
Total wall loss power [MW]	3.2	~0.7
Average beam power [MW]	0.6	
Total rf power [MW]	3.8	**1.3**
Number of klystrons	8	4
Required klystron power [MW]	> 0.5	> 0.35
Total length of the rf system [m]	16 x 2 = 32	16 x 1 = **16**
Bunch phase modulation p-p [deg] uncompensated	0.3	5.5
Relative frequency mismatch δf/(1GHz)		1e-4
Corresponding MRP (ρ=50m) shift [mm]		5

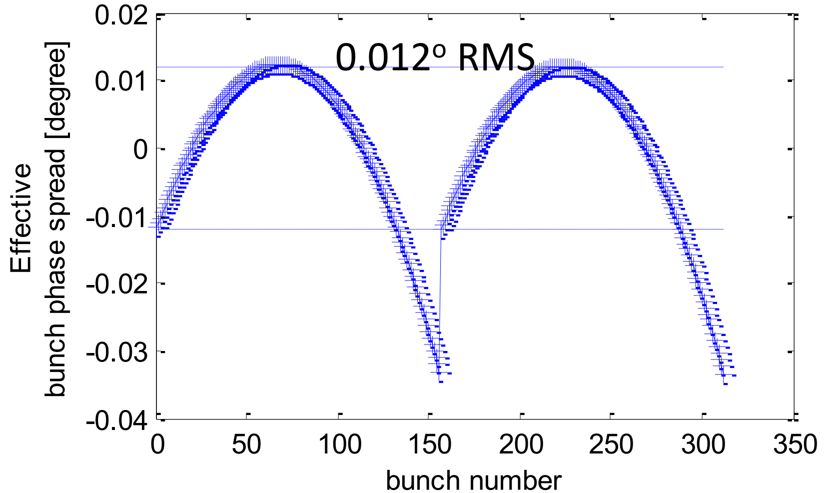
Alternative solutions 1.2

(mismatch of rf frequency and 1 GHz)

Bunch phase variation due to second order effects

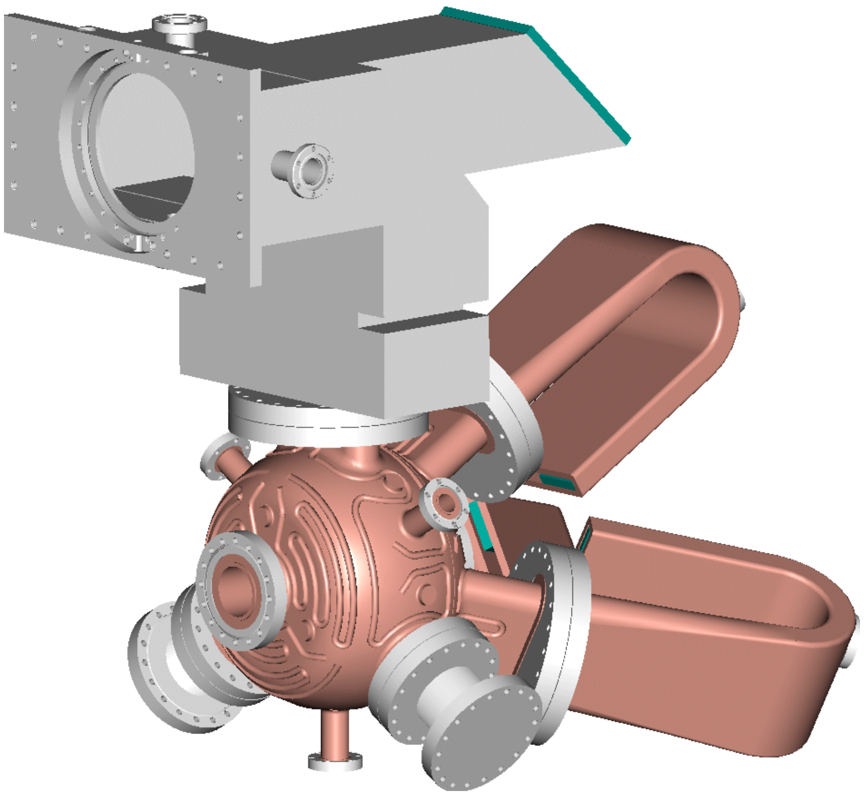






Alternative solutions 1.3
(Input RF power modulation at 1 GHz)

1. RF frequency is 1 GHz
2. It is designed in a way that the stored energy is low.
3. The variation of the RF voltage are compensated by the modulation of the input RF power which is matched not to the average beam power but to the peak beam power, like in a linac



AN RF CAVITY FOR THE NLC DAMPING RINGS, R.A. Rimmer, et al., PAC01.

NLC DR RF cavity parameters		CLIC DR RF
Frequency: f[GHz]	0.714	1
R_g/Q [Ω] ($\sim f^{0}$)	120	120
Unloaded Q-factor: Q_0 ($\sim f^{-1/2}$)	25000	21000
Aperture radius: r [mm] ($\sim f^{-1}$)	31	22
Gap voltage: V_g [MV] ($\sim f^{-1}$) Nominal -	0.5 -	0.35 -

The same voltage per cavity and so the same number cavities as for the baseline solution is assumed: 16.

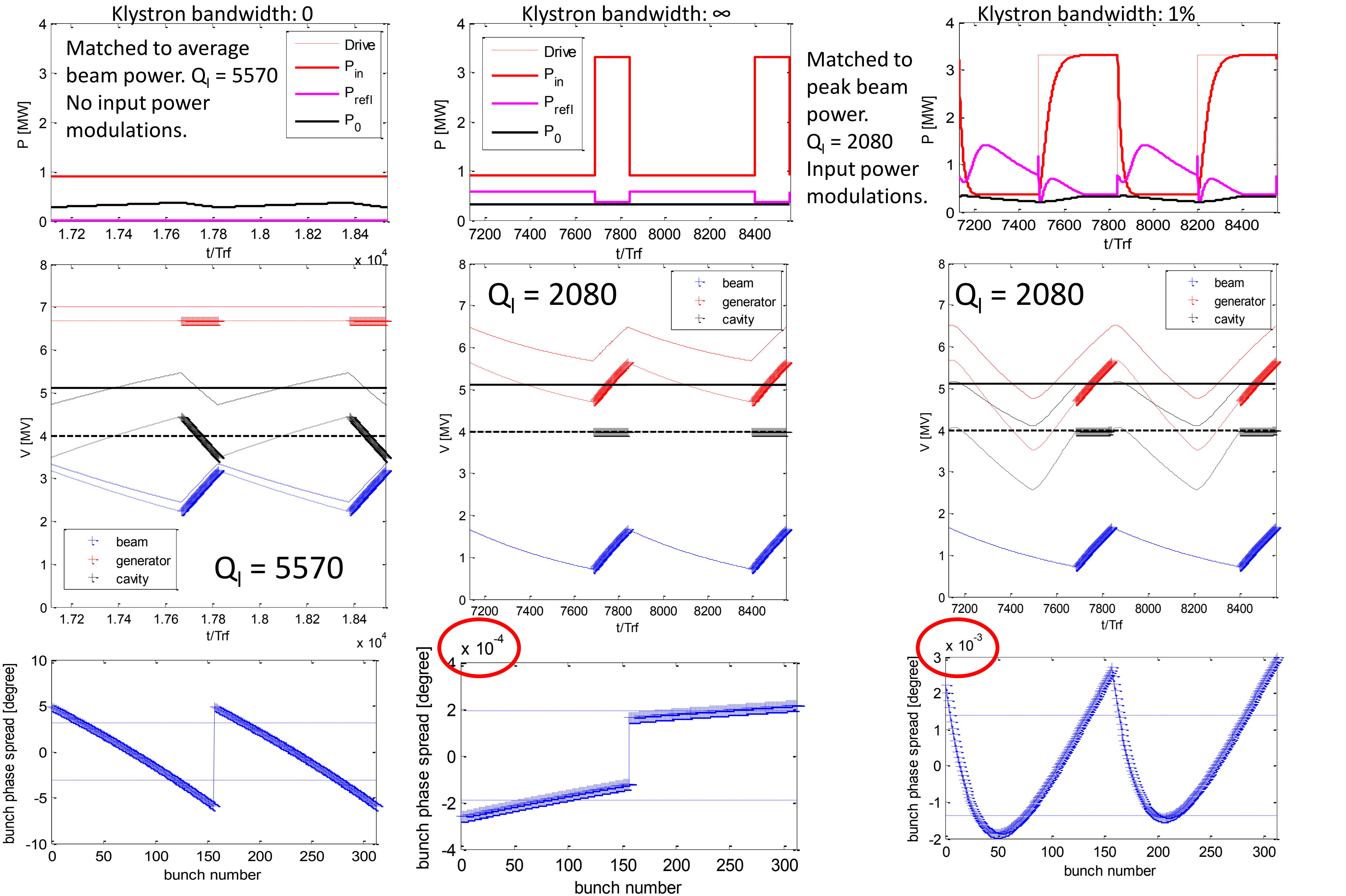
Alternative solutions 1.3(parameter table)

- An rf system similar to the linac rf system with repetition rate equivalent to the revolution frequency.
- Strong input power modulations are essential
- This requires an RF power source with larger bandwidth ~1% which is OK.
- This requires more sophisticated fast feedback and/or feed-forward systems
- A lots of R&D culminating in building a prototype and testing it in a ring are probably necessary:
- Advantages:

1. Slightly more efficient
2. **More compact**
3. Maybe less expensive

Parameters of CLIC DR rf system at 1 GHz (baseline)		Alternative 1.3
Rf frequency [GHz]	1	
Number of cavities	16	
Gap voltage: V_g [kV]	319	
R_g/Q per gap: [Ω]	**2.1**	120
Total R/Q: [Ω]	33.8	1920
Total stored energy [J]	61.2	1.1
Q-factor	120000	21000
Total wall loss power [MW]	3.2	0.3
Reflected power [MW]	0	0.4
Average beam power [MW]	0.6	
Peak beam power [MW]		2.6
Total rf power [MW]	3.2+0.6=3.8	**0.3+0.4+2.6=3.3**
Number of klystrons	8	8
Required klystron power [MW]	> 0.5	> 0.4
Total length of the rf system [m]	16 x 2 = 32	16 x 0.5 = **8**

Alternative solutions 1.3 (transients)



2 GHz alternatives

Huge advantage for all these alternatives is **no train interleaving after the DR**

Alternative solution 2.0 (basic parameter chose)

1. RF frequency is 2 GHz
2. It is designed in a way that the stored energy is so high that the RF voltage variation is kept small to minimize the transient effect on the **beam phase** to be below the specifications
3. ARES-type cavity developed for the KEK B-factory RF system is used after scaling to 2 GHz and some modifications

Alternative 2.0

- $\delta\phi_b$ = 0.2 degree at 2 GHz RMS correspond to 0.6 degree peak-to-peak variation
- $\delta V_C/V_C = \delta\phi_b \cos\phi \sin\phi = 0.43$ %
- $\delta U/U = 2\delta V_C/V_C = 0.86$ %
- $\delta U = N_b N_e e V_A(1-N_b/h)/N_T = 0.725$ J
- $U = \delta U/(\delta U/U) = 0.725 / 0.0086 = 84.3$ J;
- $R/Q = V_C^2/2\omega U = 9.6\ \Omega$

Baseline

- $\delta\phi_b$ = 0.1 degree RMS 0.3 degree peak-to-peak
- $\delta V_C/V_C = 0.26$ %
- $\delta U/U = 0.52$ %
- $\delta U = 0.318$ J
- $U = 61.2$ J;
- $R/Q = 33.8\ \Omega$

Summary table

	1 GHz	2 GHz, **no train interleaving after DR**
Classical RF system based on the NC ARES-type cavities	Baseline P_{RF} = 3.8 MW; L = 32 m; Cavity design: OK	Alternative 2.0 P_{RF} = 5.9 MW; L = 48 m; Cavity design: ok?
Classical RF system based on the SCC cavities	Alternative 1.1 P_{RF} = **0.6** MW; L = 108 m; Cavity design: **ok?**	Alternative 2.1 P_{RF} = **0.6** MW; L = **800** m; Cavity design: **NOT OK**
RF system with RF frequency mismatch	Alternative 1.2 P_{RF} = **1.3** MW; L = **16** m; Cavity design: **OK**	Alternative 2.2 P_{RF} = 2.1 MW; L = 24 m; Cavity design: OK
"A-la-linac" RF system with strong input power modulations	Alternative 1.3 P_{RF} = 3.3 MW; L = **8** m; Cavity design: **OK**	Alternative 2.3 P_{RF} = 5.8 MW; L = **12** m; Cavity design: **OK**

- ❑ Baseline solution is safe
- ❑ Alternative with a RF frequency mismatch is very attractive both at 1 GHz and 2 GHz.
- ❑ Alternative 2.2 certainly can be taken as a baseline at 2 GHz. Why not?

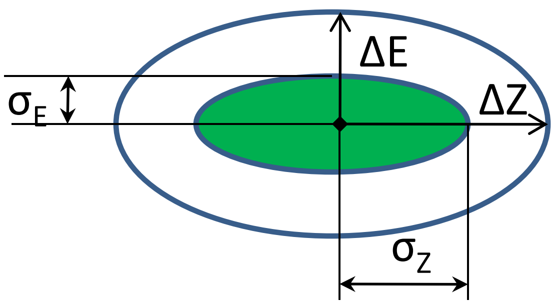
Spare slides

Synchrotron motion

Hamiltonian equations for longitudinal beam dynamics :

$$\frac{d}{dt}(\delta\phi)=\frac{h\eta\omega_R}{pR}\left(\frac{\delta E}{\omega_{rev}}\right);\quad \frac{d}{dt}\left(\frac{\delta E}{\omega_R}\right)=\frac{eV_C}{2\pi}\left(\cos(\phi+\delta\phi)-\cos\phi\right);\quad \cos\phi=\frac{V_A}{V_C}=\frac{\text{acceleration}}{\text{rf voltage}}$$

Separatrix , Bucket length 2ΔZ and Bucket height ΔE : $\Delta E=\Delta E_0\sqrt{\sin\phi-\phi\cos\phi}$



$$\Delta E_0=\left.\sqrt{\frac{2e\beta^2 V_C E}{\pi h|\eta|}}\right|_{v\approx c}\approx\sqrt{\frac{2eV_C E}{\pi h|\alpha_p|}}$$

$$\left.\Delta\phi\right|_{\phi<\frac{\pi}{4}}\approx 3\phi;\quad \left.\Delta Z\right|_{\phi<\frac{\pi}{4}}\approx\frac{3\phi}{2}\frac{c}{\omega}$$

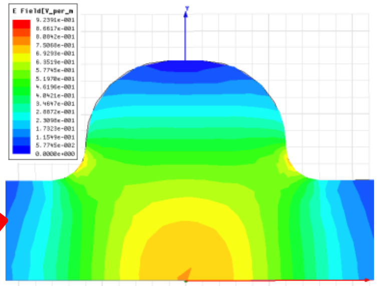
Small amplitude synchrotron oscillation (σ_E<< ΔE):

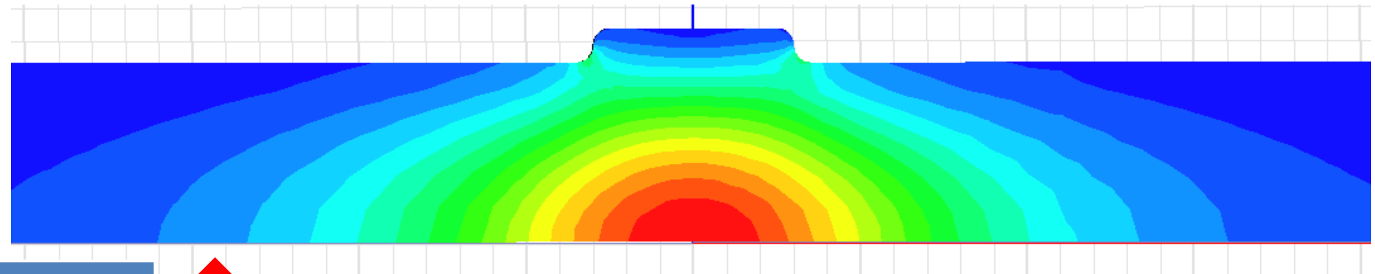
$$\delta\phi=\delta\phi_{\max}\sin\omega_S t;\quad \delta E=\delta E_{\max}\cos\omega_S t;\quad \omega_S=\left.\sqrt{\frac{h|\eta|\omega_R eV_C\sin\phi}{2\pi Rp}}\right|_{v\approx c}\approx\omega_R\sqrt{\frac{h|\alpha_p|eV_C\sin\phi}{2\pi E}}$$

$$\delta\phi_{\max}=\frac{h\eta}{pR}\frac{\delta E_{\max}}{\omega_S};\qquad \sigma_Z=\left.\frac{c}{\omega}\frac{h\eta}{pR}\frac{\sigma_E}{\omega_S}\right|_{v\approx c}\approx\frac{c\alpha_p}{\omega_S}\frac{\sigma_E}{E}$$

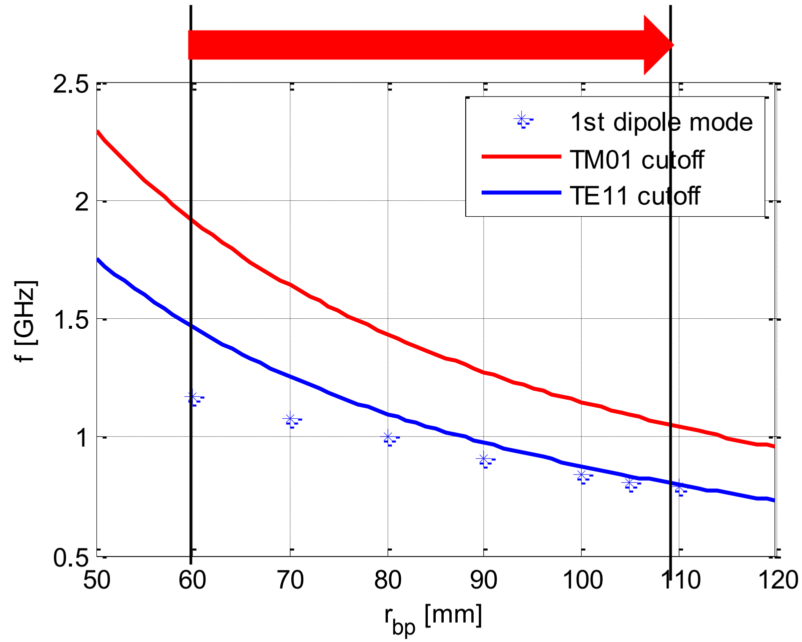
Alternative solutions 1.1
(superconducting cavity at 1 GHz)

Elliptical cavity at 1 GHz with reduced R/Q from **46.5 to 0.94 Ω.**





R_{bp}[mm]	R/Q [Ω]	f_1 [GHz]
60	**42.5**	1.17
70	33	1.08
80	22.5	1.00
90	13.8	0.91
100	6.3	0.84
105	2.84	0.81
106	2.47	
107	1.80	
108	**1.13**	
109	**0.59**	
110	0.16	0.79



Issues:

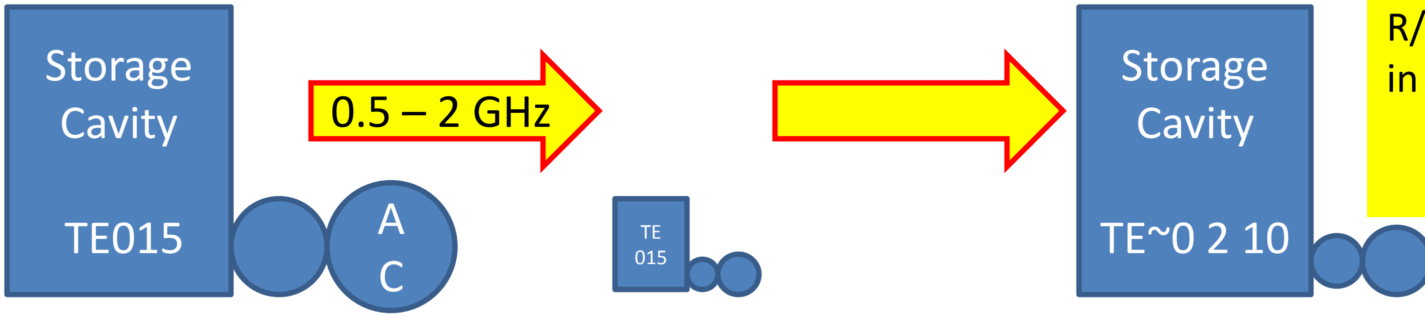
1. Longer cavity
2. More sensitive to the dimensional errors
3. Dipole mode frequency is lower than the fundamental (SOM-damping)

All these **may** make this solution unusable in practice, t.b.s.

Alternative solution 2.0 (cavity parameter chose)

Cavity scaling from 0.5 to 2 GHz

2 GHz cavity modification to reduce R/Q



$R/Q = V^2/2\omega(U_a+U_s)$
in ARES $U_s = 9U_a$
$R/Q \sim 1/f^3$
$Q \sim v/s \sim f$

Scaling V_g to keep EM field amplitude constant : $V_g \sim f^{-1}$

$V_g \sim f^{0}$

Frequency: f[GHz]	**0.509**	**2**		**1**
Normalized shunt impedance (circuit): R_g/Q [Ω] ($\sim f^0$)	7.4	7.4	($\sim f^{-3}$) x 1/64	**0.116**
Unloaded Q-factor: Q ($\sim f^{-1/2}$)	110000	55000	($\sim f^{1}$) x 4	220000
Aperture radius: r [mm]	80	20		20
Gap voltage range: V_g [kV] Nominal – Maximum tested	500 – 866	125 – 216	same	125 – 216

In our case, an intermediate modification of the cavity is chosen to have comfortable voltage per cavity V_g = 4500 kV / 24 = **188 kV** and the reduced R_g/Q = 9.6 Ω / 24 = **0.4 Ω**

Alternative solution 2.0 (final parameter table)

- Classical rf system similar to 1 GHz baseline
- No showstoppers
- Few issues remains:

1. RF design of the low R/Q = 0.4 Ω cavity of ARES-type
2. Total rf power is **1.5** times higher than in the Baseline
3. Total length is **1.5** times bigger

- …

Parameters of CLIC DR rf system at 2 GHz alternative 2.0		Baseline pars
Rf frequency [GHz]	2	1
Total stored energy [J]	84.3	61.2
Total R/Q: [Ω]	9.6	33.8
Cavity voltage: V_g [kV]	188	319
Number of cavities	24	16
R_g/Q per Cavity: [Ω]	**0.4**	**2.1**
Q-factor	200000	120000
Total wall loss power [MW]	**5.3**	3.2
Average beam power [MW]	0.6	0.6
Total rf power [MW]	**5.9**	3.8
Number of klystrons	12	8
Required klystron power [MW]	> 0.5	> 0.5
Total length of the rf system [m]	24 x 2 = **48**	16 x 2 = 32

Alternative solutions 2.1
(superconducting cavity at 2 GHz)

Elliptical cavity. Must be scaled and modified to reduce R/Q. This is done in two steps similar to ARES-type cavity scaling and modification:

1. Scaling by frequency ratio and keeping the same EM field amplitude: V~1/f, U~1/f³.
2. Increasing aperture to reduce the R/Q from **46.5 to 0.024 Ω** but assuming that the stored energy is constant. This is the main issue for this alternative. It is not obvious that the solution exists …
3. Total length of the system is **HUGE**. Here multiple cell cavity could be considered.

Parameters of CLIC DR rf system at 1 GHz (baseline)		Alternative 2.1
Rf frequency [GHz]	1	2
Total stored energy [J]	61.2	84.3
Stored energy per cavity [J]	3.8	0.21
Number of cavities	16	**400**
Total R/Q: [Ω]	33.8	9.6
R_g/Q per gap: [Ω]	**2.1**	**0.024**
Gap voltage: V_g [kV]	319	11.3
Q-factor	120000	1e9
Total wall loss power [MW]	3.2	~0
Average beam power [MW]	0.6	
Total rf power [MW]	3.8	0.6
Number of klystrons	8	10
Required klystron power [MW]	> 0.5	> 0.06 (IOT?)
Total length of the rf system [m]	16 x 2 = 32	400 x 2 = **800**

Alternative solutions 2.2

(mismatch of rf frequency and 2 GHz)

Basic parameters chose based on the bunch length specs

- $\delta\sigma_Z/\sigma_Z$ = 2% RMS correspond to 6% degree peak-to-peak variation
- $\delta V_C/V_C = -2\delta\sigma_Z/\sigma_Z \sin^2\phi = 2\cdot 6\% \cdot\sin^2 27.8^o = 2.6\ \%$
- $\delta U/U = 2\delta V_C/V_C = 5.2\ \%$
- $\delta U = N_b N_e e V_A(1-N_b/h)/N_T = 312\cdot 4.1e9\cdot 1.6e\text{-}19\cdot 3.98e6\cdot(1-312/2850)/1 = 0.725$ J
- $U = \delta U/(\delta U/U) = 0.725 / 0.052 = 14$ J;
- $R/Q = V_C^2/2\omega U = 58\ \Omega$

Alternative solutions 2.2(parameter table)

- Classical rf system with one exception: the rf frequency is slightly reduced to correct the bunch spacing to be exactly 1 ns.
- This frequency mismatch is bunch intensity dependent
- Remaining R&D:

1. the cavity redesign ARES-type (minor)
2. an MD to demonstrate this compensation in an existing ring. (unless it is already done ?)

- Advantages:

1. More efficient
2. More compact
3. Less expensive
4. **No train interleaving after DR**

Parameters of CLIC DR rf system at 1 GHz (baseline)		Alternative 2.2
Rf frequency [GHz]	1	2
Total stored energy [J]	61.2	14
Total R/Q: [Ω]	33.8	58
Gap voltage: V_g [kV]	319	188
Number of cavities	16	24
R_g/Q per gap: [Ω]	**2.1**	2.4
Q-factor	120000	~120000
Total wall loss power [MW]	3.2	~1.5
Average beam power [MW]	0.6	
Total rf power [MW]	3.8	**2.1**
Number of klystrons	8	6
Required klystron power [MW]	> 0.5	> 0.35
Total length of the rf system [m]	16 x 2 = 32	24 x 1 = **24**
Bunch phase modulation p-p [deg] uncompensated	0.3	3.6
Relative frequency mismatch δf/(1GHz)		3e-5
Corresponding MRP (ρ=50m) shift [mm]		1.5

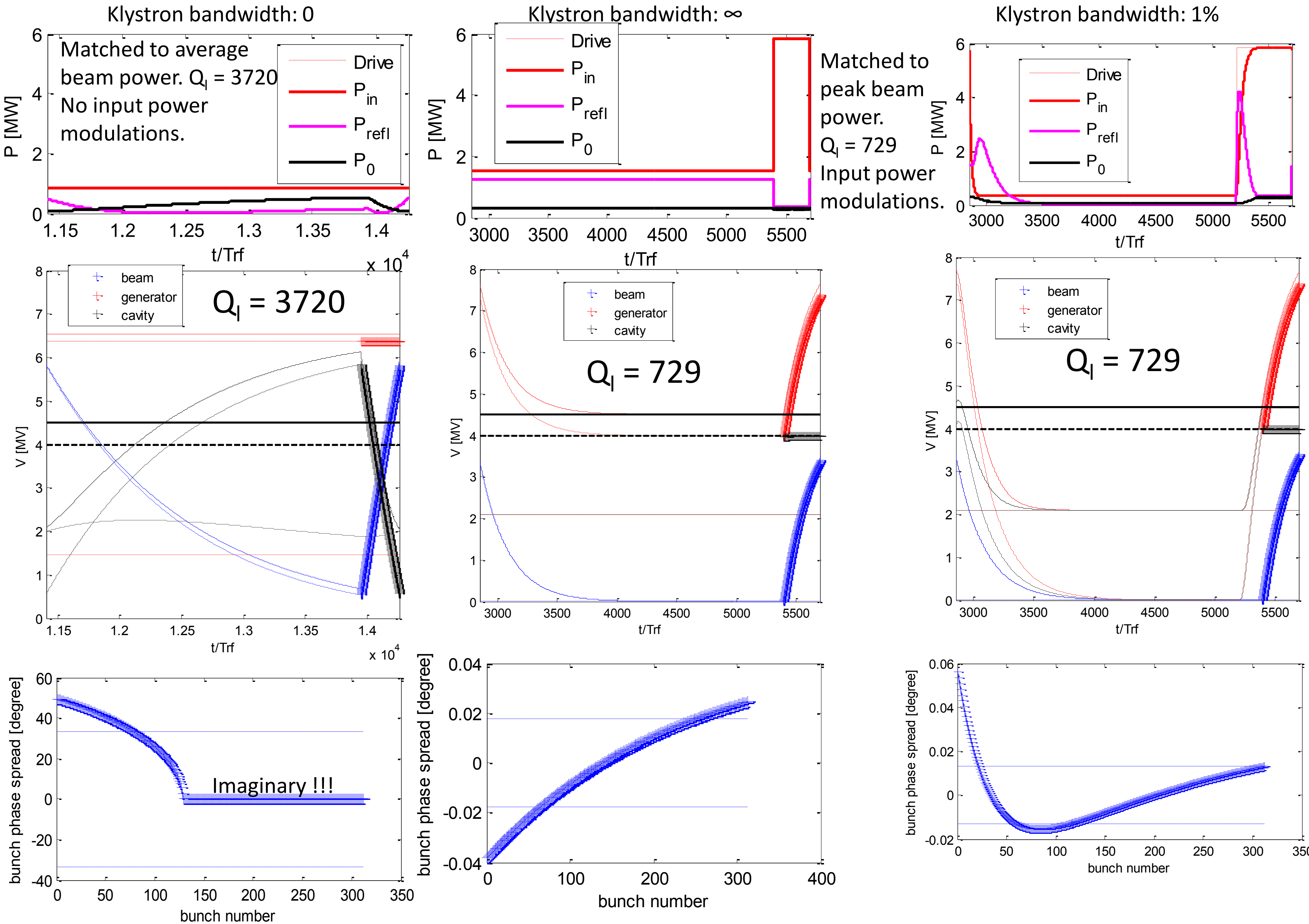
Alternative solutions 2.3(parameter table)

- An rf system similar to the linac rf system with repetition rate equivalent to the revolution frequency.
- Strong input power modulations are essential
- This requires an rf power source with larger bandwidth ~1%, which is OK.
- This requires more sophisticated fast feedback and/or feed-forward systems
- A lots of R&D culminating in building a prototype and testing it in a ring are probably necessary:
- Advantages:

1. **More compact**
2. Maybe less expensive
3. **No train interleaving after DR**

Parameters of CLIC DR rf system at 1 GHz (baseline)		Alternative 1.3
Rf frequency [GHz]	1	2
Number of cavities	16	24
Gap voltage: V_g [kV]	319	188
R_g/Q per gap: [Ω]	**2.1**	120
Total R/Q: [Ω]	33.8	2880
Total stored energy [J]	61.2	0.28
Q-factor	120000	15000
Total wall loss power [MW]	3.2	0.2
Reflected power [MW]	0	0.4
Average beam power [MW]	0.6	
Peak beam power [MW]		**5.2**
Total rf power [MW]	3.2+0.6=3.8	**0.2+0.4+5.2=5.8**
Number of klystrons	8	12
Required klystron power [MW]	> 0.5	> 0.5
Total length of the rf system [m]	16 x 2 = 32	24 x 0.5 = **12**

Alternative solutions 2.3 (transients)

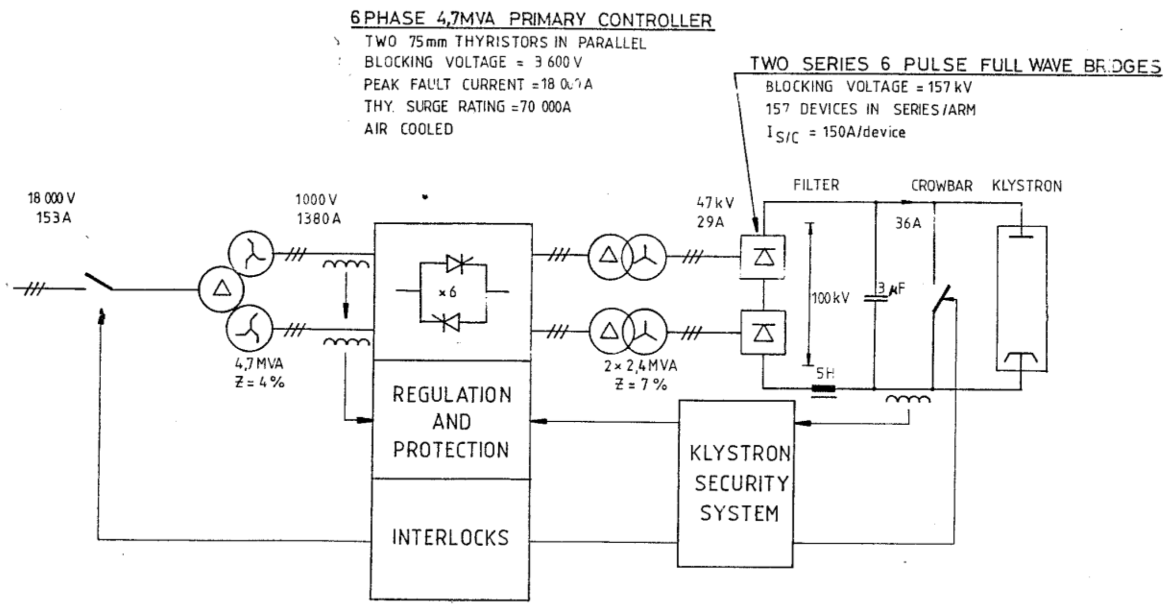


CW klystron power supply

Information provided by D. Siemaszko

LEP klystron power supply

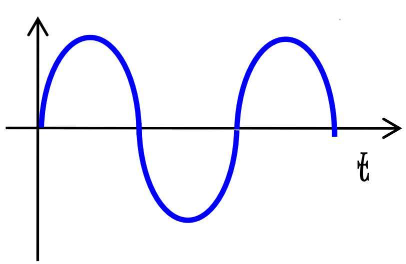
FIG 1 : KLYSTRON SUPPLY 0 – 100 kV AT 36A (CONTINUOUS OUTPUT)



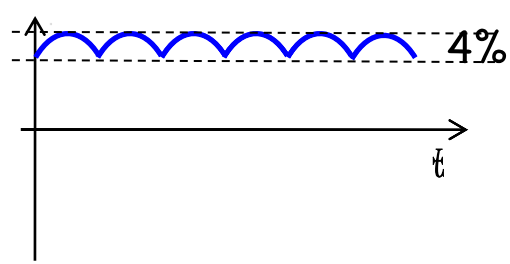
Feedback stabilizes high voltage at lower frequencies to the level of **1-0.1%.**
Limited mainly by the HV measurement accuracy

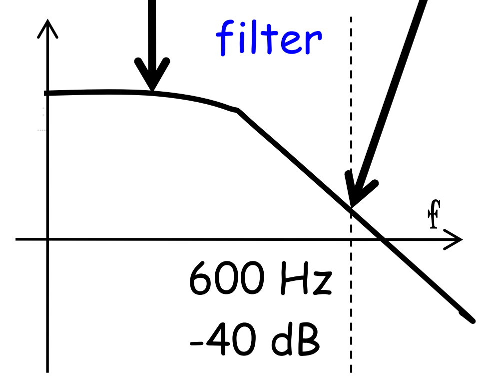
Filter reduce 600 Hz ripples down to $0.04*0.0045 = \mathbf{2*10^{-4}}$

3 phases main



12 phases – 600 Hz ripples





Klystron amplitude and phase stability

TDA Progress Report 42-87 July–September 1986

Long-Term Amplitude and Phase Stability of the 400-kW 2.115-GHz Transmitter

D. J. Hoppe and A. M. Bhanji
Radio Frequency and Microwave Subsystems Section

Results of recent measurements of the long-term phase, amplitude and group delay stability of the 400-kW S-band (2.115-GHz) transmitter are reported. Various control parameters which are responsible for many of the observed instabilities are identified. Further tests to identify the parameters responsible for the remaining instabilities are suggested.

V. Conclusions

In conclusion, the long-term stability tests have shown that the 400-kW transmitter easily meets its specifications for amplitude, phase, and group stability. Two major contributors to the observed instabilities have been determined: (1) the beam voltage with pushing factors of 20 kW/kV and 20 deg/kV at saturation, and (2) the inlet coolant temperature at -0.9 kW/°C and -0.8 deg/°C. Further work is required to determine the contributors to the remaining amplitude, phase, and group delay variations. In particular, a more detailed look at the system of amplifiers driving the klystron would probably be beneficial. If future missions or experiments require greater transmitter stability than was measured during this test, improvements in beam voltage and coolant temperature regulation should be considered.

Beam voltage ~60 kV

Low frequency

high voltage stability: 0.1 %

(0.3 % achieved in Tristan (KEK) DC power supply for 1MW CW klystron, PAC87)

-> 60V -> 1.2 kW rf output power stability

~ 0.3 % power stability

~ 0.15 % amplitude stability

Or

~ 1.2 degree phase stability

This is not sufficient (see RTML specs). Slow RF feedback loop around the klystron is necessary

Klystron bandwidth

NLC DR RF system:
http://www-project.slac.stanford.edu/lc/local/Reviews/cd1%20nov98/RF%20HighPwr_Schwarz.pdf

Klystron

- High power CW klystrons of 1 MW output power and -3 MHz 1 dB bandwidth at 700 MHz were developed by industry for APT.
- New requirement for Damping Ring klystron is order of magnitude wider bandwidth: 65 nano-seconds gap in between bunch trains cause variations in accelerating field level during bunch train, resulting in bunch extraction phase variation. This effect can be counteracted by a fast direct feedback loop with about 30 MHz bandwidth.
- A klystron bandwidth of 20 - 30 MHz is within technical know-how for a 1 MW high power klystron but will result in lower efficiency.

Klystron Dept. Microwave Engineering, H. Schwarz, 1998

http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01476034

A BROADBAND 500 KW CW KLYSTRON AT S-BAND,

Robert H. Giebeler and Jerry Nishida, Varian Associates, Palo Alto, Calif. 1969

klystron amplifier designed for installation 'on the 210 foot steerable antenna. This paper will describe the development of a 500 kilowatt CW S-band at the JPL/NASA deep space instrumentation facility a€ Goldstone, California. This tube is an improved version of the 450 kilowatt unit developed in 1967. Its features include 1-1/2 percent instantaneous bandwidth, 58 dB nominal gain and **53 percent nominal efficiency.**

- Few percent bandwidth is feasible for 0.5 MW CW klystron

Impedance estimate in DR, PDR

Calculated RF cavity parameters HOM	NLC DR	CLIC DR		CLIC PDR	
Frequency: f[GHz]	0.714	1	**2**	1	**2**
Number of cavities: $N = V_{rf}/V_g$	2 (3)	16	**20**	40	**48**
Total HOM loss factor: $k^{\|\|}_l * N$ [V/pC]	2.2	24.6	**61.6**	61.6	**148**
Long. HOM energy loss per turn per bunch [μJ]: $\Delta U = k^{\|\|}_l * N * eN_e^2$	2.8	10	**25**	32	**77**
Incoherent long. HOM loss power [kW]: $P^{\|\|}_{incoh} = \Delta U * N_b f/h$	2	2.2	**5.6**	7.7	**19**
Coherent long. HOM loss power [kW]: $P^{\|\|}_{coh} \sim P^{\|\|}_{incoh} * Q_{HOM} * f/f_{HOM}$ (if the mode frequency f_{HOM} is a harmonic of 2 GHz)	Careful Design of HOM damping is needed				
Total HOM kick factor: $k^T_t * N$ [V/pC/m]	78.8	1240	**6160**	3100	**14800**
Tran. HOM energy loss per turn per bunch [μJ]: $\Delta U = k^T_t * 2\pi f/c * N * eN_e^2 * d^2$ (d – orbit deviation , 10mm assumed)	0.15	1.1	**10.5**	3.3	**32**
Tran. HOM loss power is not an issue: < [kW]					