Proposals for conceptual design of the CLIC DR RF system at 2 GHz

20/10/2010

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Acknowledgements

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Outline

1. Introduction
2. Low stored energy design option
3. High stored energy design options
    1. Normal conducting ARES-type cavity
    2. Superconducting elliptical calls cavity
4. Summary

CLIC DR parameters

Y. Papaphilippou

New DR parameters

Parameter	DR @ 1GHz	DR @ 2 GHz
Circumference [m]	420.56*	
Harmonic number	1402	2805
Energy Loss/turn [MeV]	4.20	
Damping times [ms]	(1.88,1.91,0.96)	
Number of wigglers	52	
0-current emittances [nm,nm,eVm]	(280,3.7,4400)	
0-current mom. spread/bunch length [%/mm]	0.11/1.4	
RF Voltage/Stat. phase [MV/deg]	4.9/59	4.4/73
Momentum compaction factor	7.6 x 10^{-5}	
Steady state emittances [nm,nm,eVm]	(480,4.5,5960)**	
St. state mom. spread/bunch length [%/mm]	0.13/1.6	
Space charge tune-shift	-(0.006,0.12)	
Peak/Average current [A]	0.66/0.145	1.3/0.145
Peak/Average power [MW]	2.8/0.6	5.5/0.6
Kicker rise / revolution time [ns]	545/1403	1246/1403

* The ring circumference was shortened after relaxing longitudinal parameters in order to reduce space-charge

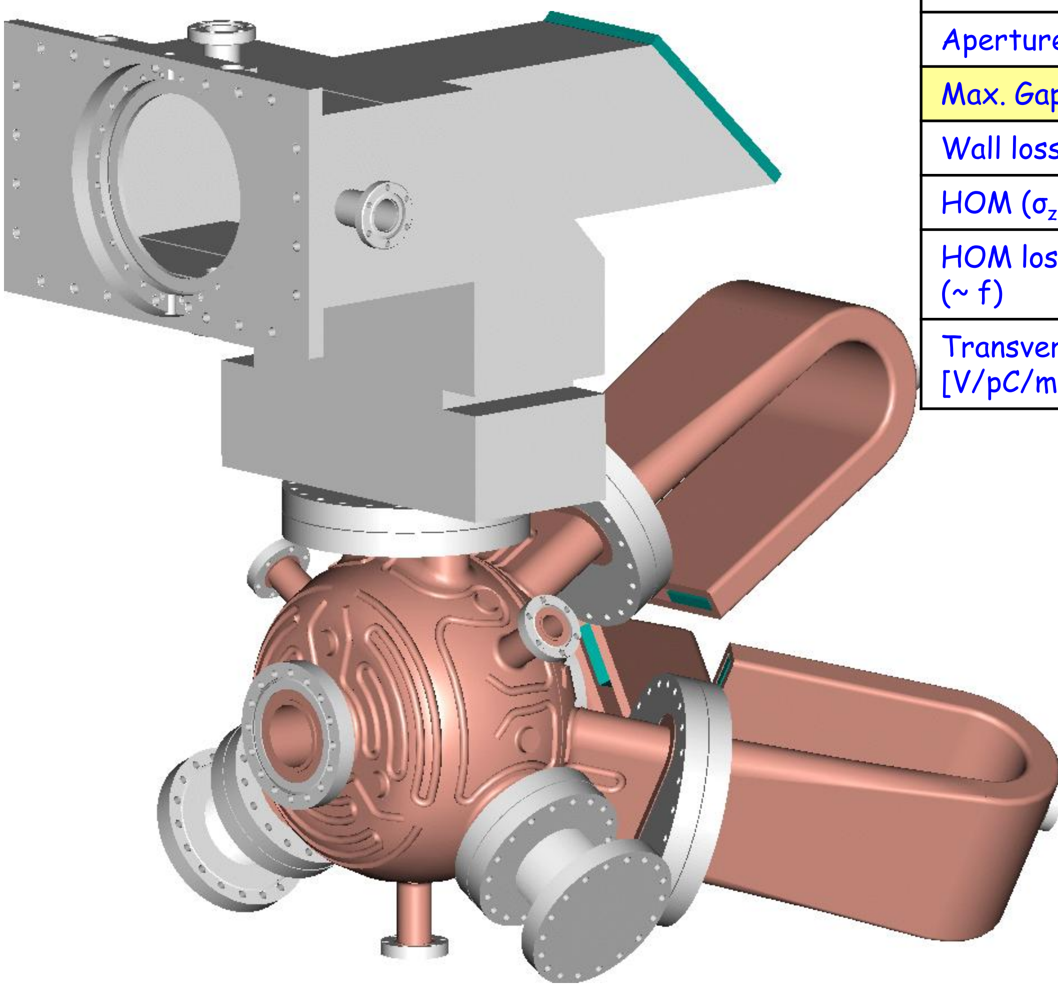
** Using Bane approximation. Piwinski theory gives (310,4.4,6100)

“A la linac”-type rf system

(low stored energy option)

Scaling of NLC DR RF cavity

From PAC 2001, Chicago
AN RF CAVITY FOR THE NLC DAMPING RINGS
R.A. Rimmer, et al., LBNL, Berkeley, CA 94720, USA



NLC DR RF cavity parameters		CLIC DR RF	
Frequency: f[GHz]	0.714	2	1
Shunt impedance: R_g [MΩ] (~ 1/√f)	3	1.8	2.5
Unloaded Q-factor: Q_0 (~ 1/√f)	25500	15400	21500
Aperture radius: r [mm] (~ 1/f)	31	11	22
Max. Gap voltage: V_g [MV] (~ $1/f^{3/4}$)	0.5	0.23	0.39
Wall loss per cavity: $V_g^2/2R_g$ [MW]	0.042	0.015	0.03
HOM (σ_z=3.3mm)			
HOM loss factor: $k^{\|\|}_l$ [V/pC] (~ f)	1.1	3.08	1.54
Transverse HOM kick factor: k^T_t [V/pC/m] (~ f^2)	39.4	309	77.3

From PAC 1995,
Collective effects in the NLC DR designs
T. Raubenheimer, et al.,

Cavity parameters

Number of cavities: $N = V_{rf}/V_g = 4.4/0.23 = 19.1 \sim 20 = 10 \times$ 2-cells cavities

Gap voltage: $V_g = V_{rf}/N = 4.4/20$ $= 0.22$ MV

Total wall losses [MW] : $P_0 = V_{rf}^2/2NR = 4.4^2/(2*20*1.8)$ $= 0.27$ MW

Peak beam SR power [MW]: $P_b = U_0*I_b =$ 4.2*1.3 $= 5.46$ MW

Matching condition:

Total power lost in the cavities when the beam is in: $P_{in} = P_b + P_0$ $= 5.73$ MW

Cavity coupling: $\beta = Q_0/Q_{ext} = P_{in}/P_0 = (P_b+P_0)/P_0$ $= 21$

External Q-factor: $Q_{ext} = Q_0/\beta = 15400/21$ $= 733$

Filling time: $t_f = Q_l/f = Q_{ext}/(1+1/\beta)/f = 733/(1+1/21)/2$ GHz $= 350$ ns

Klystron bandwidth: ∂f

$\partial f \gg 1/t_f = 1 / 350 = \mathbf{3}$ MHz.

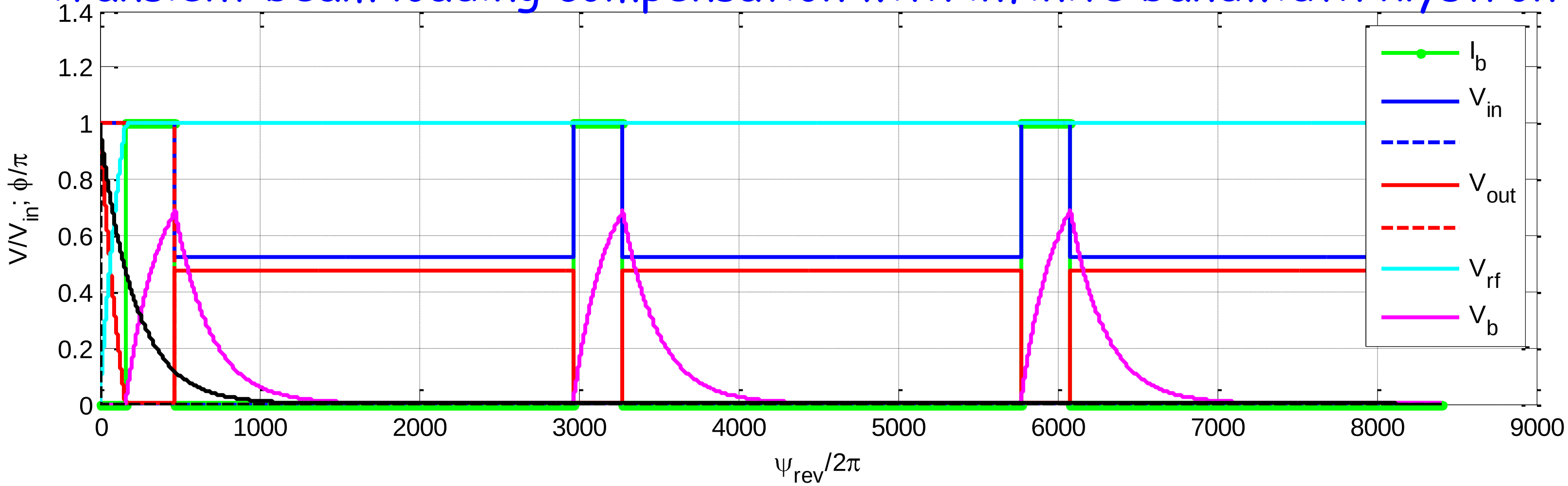
AND

$\partial f \gg 1/t_{gap} = 1 / (1402-156) = 0.8$ MHz; where t_{gap} – time between the bunch trains

RF system total length: 10 x 1 m = 10 m

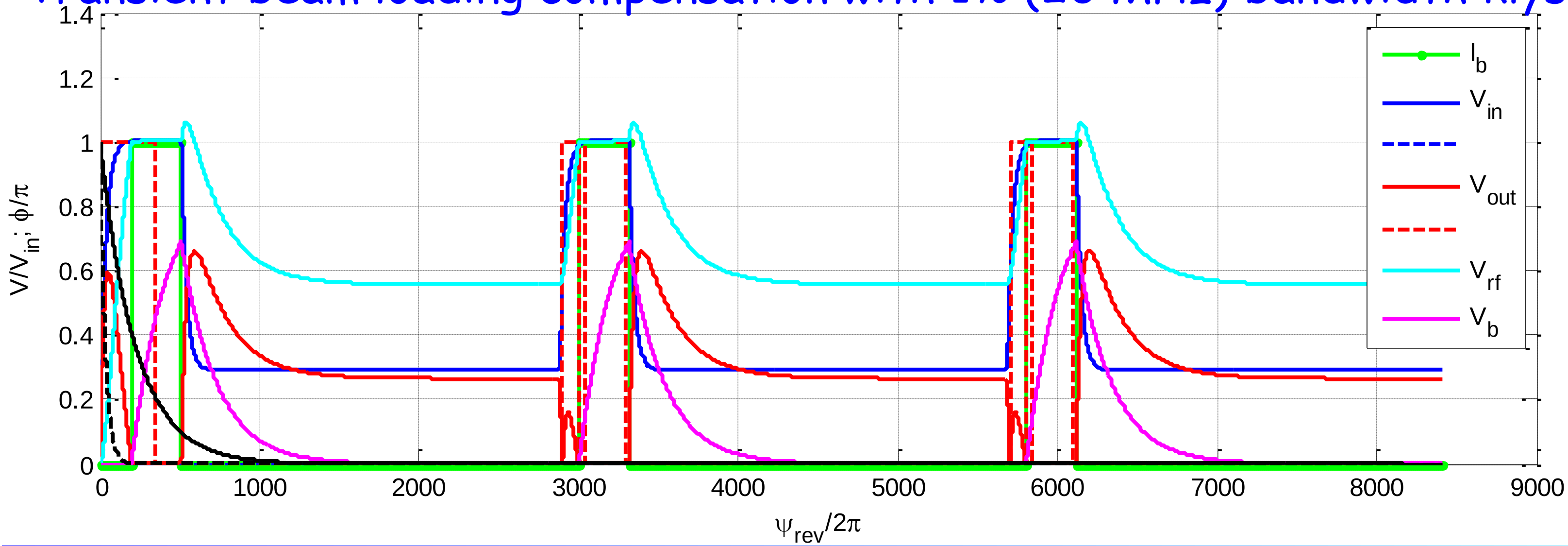
Transient beam loading compensation

Transient beam loading compensation with infinite bandwidth klystron



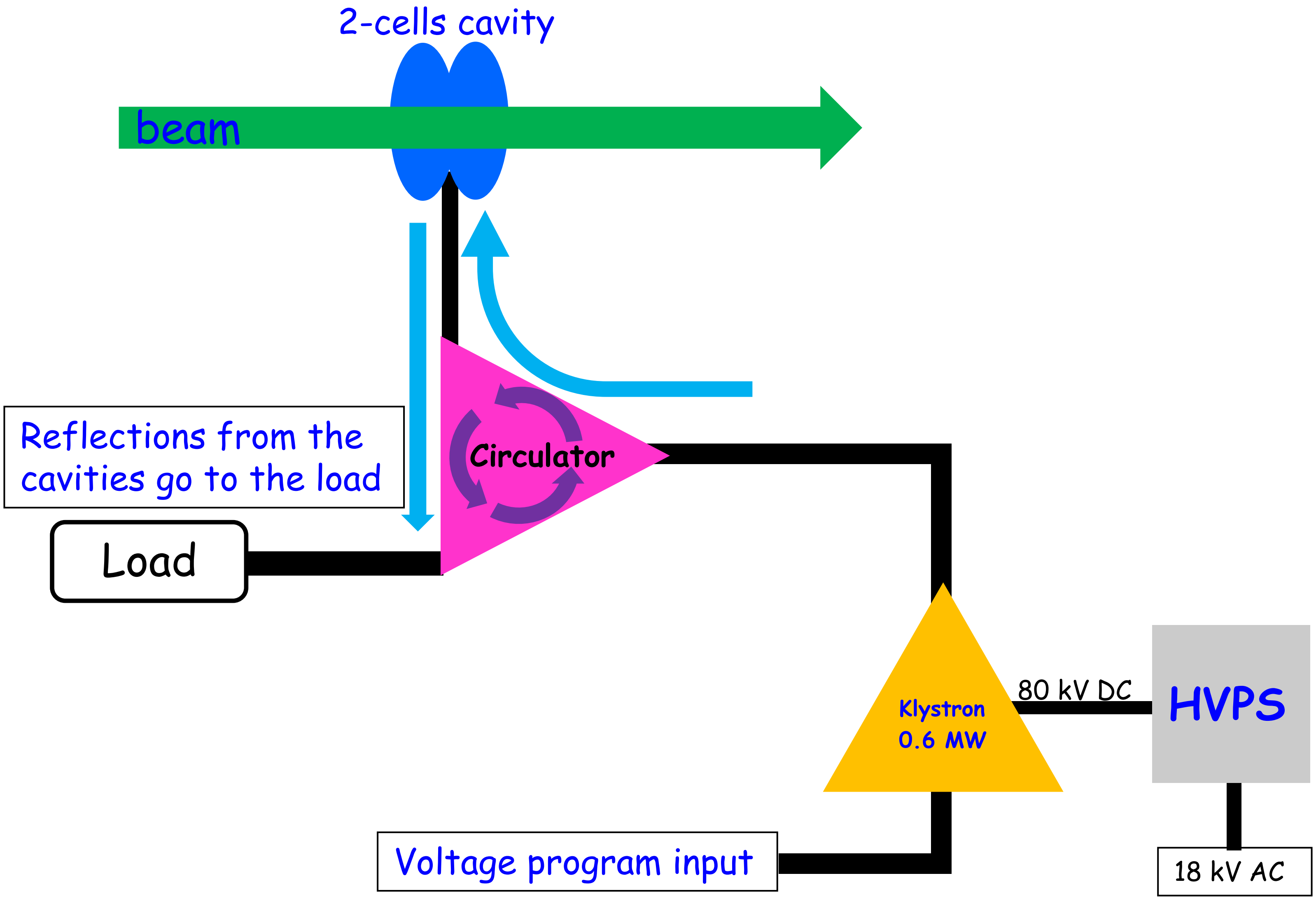
Amplitude modulation from 1 to 0.55 is necessary (see V_{in})

Transient beam loading compensation with 1% (20 MHz) bandwidth klystron

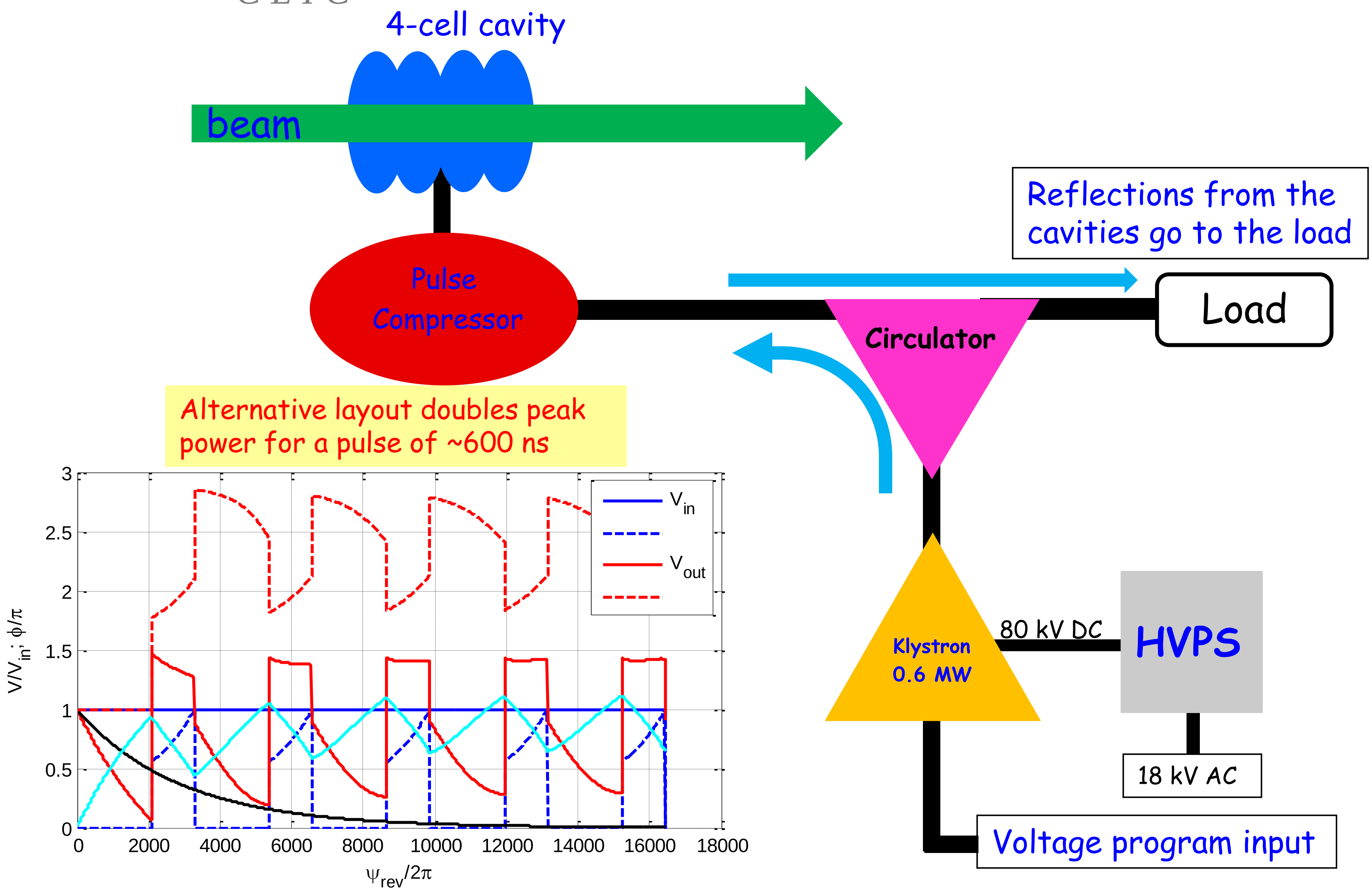


Amplitude modulation from 1 to 0.3 is necessary (see V_{in})

Basic layout of 2 GHz rf station



Alternative layout for 2 GHz rf station DR



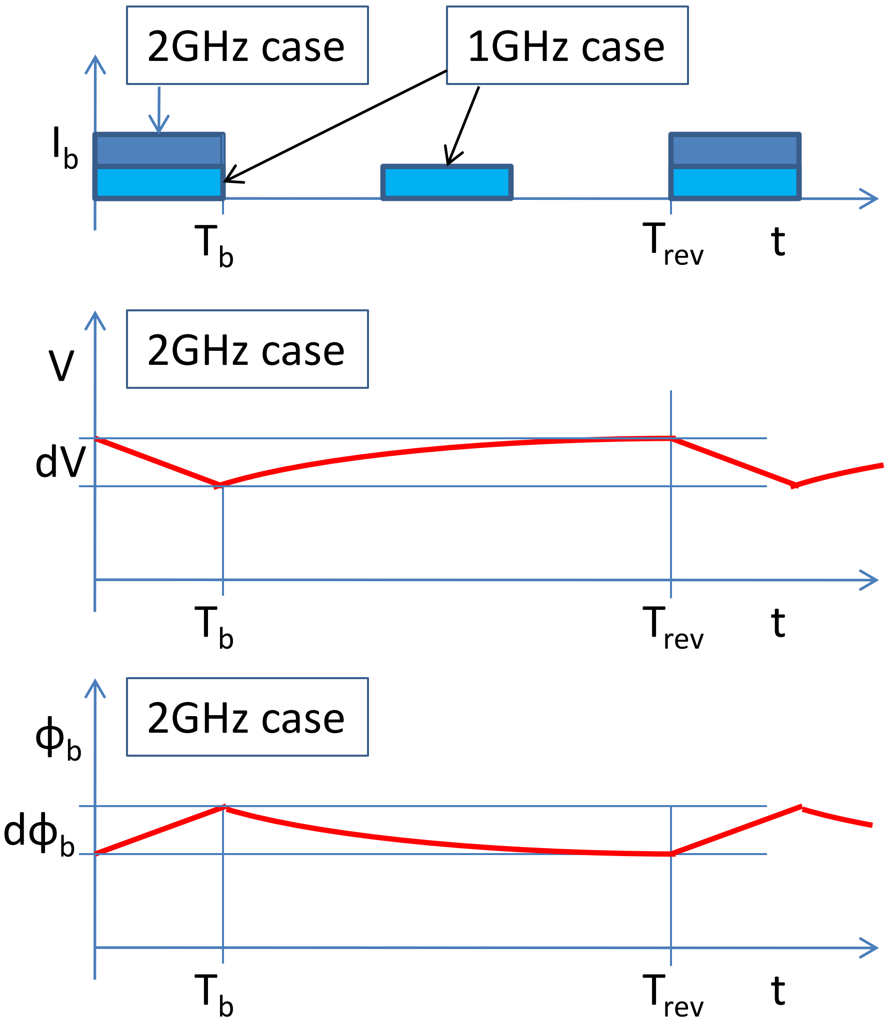
Summary table for "a la linac"-type

Overall parameters		alternative
Total rf power [MW]	6	3
Total length [m]	10	5
Number of HVPS	10	5
Number of klystrons	10	5
High voltage power supply (HVPS)		
Output voltage [kV]	60	
Output current [A]	20	
Voltage stability [%]	0.1	
Klystron		
Output power [kW]	600	
Efficiency [%]	50	
Bandwidth [MHz]	> 1%	
Gain [dB]	~40	

KEKB-type rf system

(high stored energy option)

Beam cavity interaction, dV/V << 1



$W = V^2/\rho\omega$; $dW = dV\ 2V/\rho\omega$

$dW/dt = -P_b + n_{trains} * T_b/T_{rev} * P_b$; $dt \to T_b$

$\mathbf{dV/V = -P_b T_b(1-n_{trains} T_b/T_{rev})\rho\omega/2V^2}$

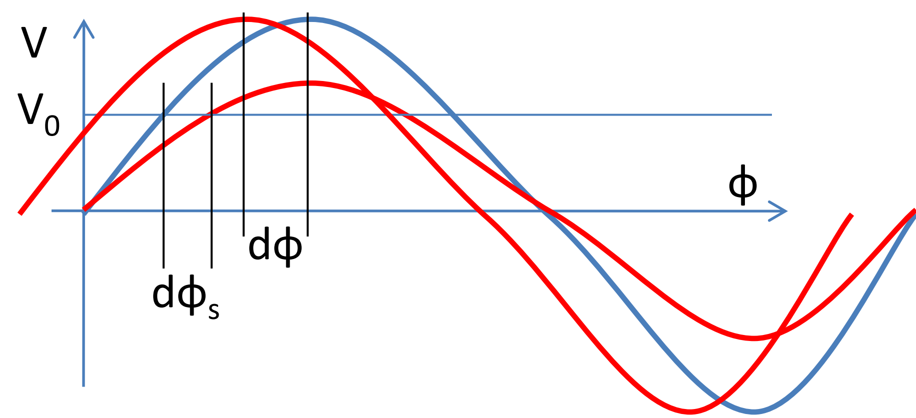
$\mathbf{d\phi\ = dV/V*1/\tan\phi_s)}$

$\mathbf{d\phi_b\ = d\phi + d\phi_s = dV/V*(1/\tan\phi_s - \tan\phi_s)}$

$V_0 = V \sin\phi_s$ = energy loss per turn = const;

$dV_0 = dV \sin\phi_s + V\cos\phi_s\ d\phi_s = 0$

$\mathbf{d\phi_s = -\ dV/V*\tan\phi_s}$



KEKB RF system

K. Akai, et. al, “**THE LOW-LEVEL RF SYSTEM FOR KEKB**”, EPAC98

Table 1: RF-related machine parameters and RF operation parameters.

	LER	HER	
Energy [GeV]	3.5	8.0	
Current [A]	2.6	1.1	
Beam power [MW]	4.5	4.0	
Bunch length [mm]	4	4	
RF frequency [MHz]	508.887	508.887	
Harmonic number	5120	5120	
Cavity type	ARES	SCC	ARES
Number of Cavities	20	8	12
Relative phase	¡	10 degrees	
Total RF voltage [MV]	10	17.9	
R =Q [› /cav.]	14.8	93	14.8
QL £ 10⁴	3.0	7.0	3.0
Input fl	2.7	¡	2.7
Voltage [MV/cav.]	0.5	1.5	0.5
Input power [kW/cav.]	375	250	340
Wall loss [kW/cav.]	154	¡	154
Beam power [kW/cav.]	221	240	173
Number of Klystrons	10	8	6
Klystron power ʏ [kW]	» 810	» 270	» 730

ʏ 7 % loss at waveguide system is included.

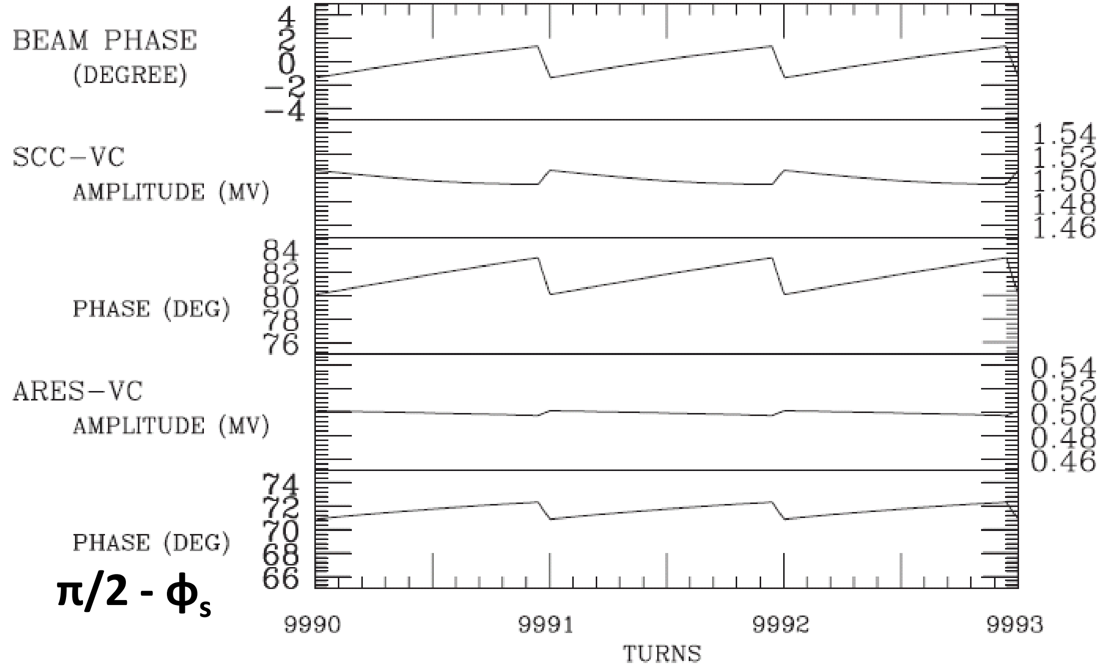


Figure 3: Transient response of the hybrid system in HER to a 5% gap.

$dV/V = P_b T_b (1 - T_b/T_{rev}) \rho\omega / 2V^2$ ~ 1 % it is consistent with simulation presented in Fig 3

$d\phi_b = dV/V^*(1/\tan\phi_s - \tan\phi_s)$ ~ 3° it is consistent with simulation presented in Fig 3

Dominated by direct cavity voltage phase modulation in KEKB case

THE ARES CAVITY FOR KEKB, Kageyama et al, APAC98

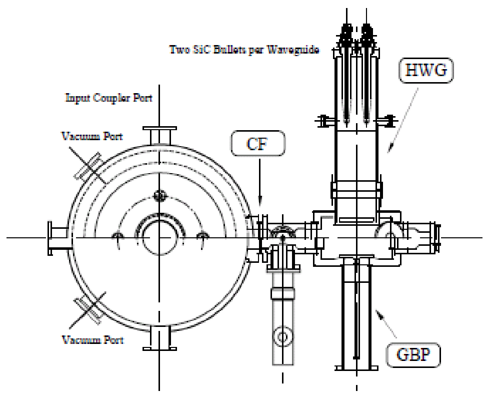


Table 1: RF design parameters of the ARES production model, and the high-power test records achieved with the production prototype ARES96.

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

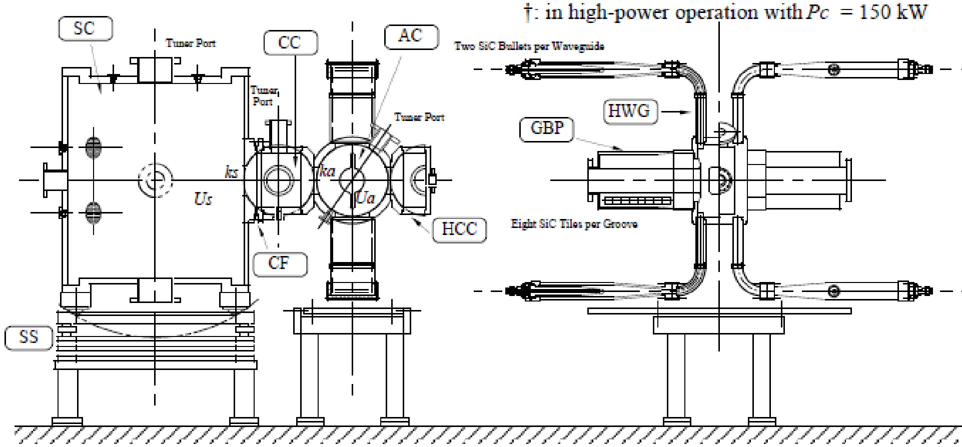


Figure 1: A schematic drawing of the ARES production model based on the prototype ARES96.

~2.5 m

Frequency: f[GHz]	**0.509**	**1**	**2**
Normalized shunt impedance (linac): $\rho_g=R_g/Q$ [Ω] (~f^0)	15	15	15
Unloaded Q-factor: Q (~ $1/f^{1/2}$)	110000	77000	55000
Aperture radius: r [mm] (~ 1/f)	80	40	20
Max. Gap voltage: V_g [MV] (~ $1/f^{3/4}$) Nominal	0.5	0.3	0.18
Max. Gap voltage: V_g [MV] (~ $1/f^{3/4}$) High power tested times sqrt(3)	**0.85**	**0.5**	**0.3**
Wall loss per cavity: $P=V_g^2/R_g$ [MW]	**0.44**	**0.22**	**0.11**

Scaling of the gap voltage is done to keep heat load per meter constant: $P/g = V_g^2/R_g g = V_g^2/\rho_g Q\, g \Rightarrow V_g \sim 1/f^{3/4}$

CLIC DR parameters for scaled ARES cavity

The incoming beam needs to be stable to

$$\sigma_{\varphi,\text{in}} < 0.4\,\text{deg @ 2 GHz and } \sigma_{E,\text{in}}/E_{\text{in}} < 3.8\times10^{-4} \text{(distributed timing reference)}$$

or $$\boxed{\sigma_{\varphi,\text{in}} < 0.1\,\text{deg @ 2 GHz and } \sigma_{E,\text{in}}/E_{\text{in}} < 5.4\times10^{-5} \text{(outgoing pulses as timing reference)}}$$

Specs from RTML
F. Stulle, CLIC meeting, 2010-06-04

Circumference: C [m]	**420.56**	
Energy loss per turn: U_0 [MeV]	4.2	
RF frequency: f_{rf} [GHz]	1	2
RF voltage: V_{rf} [MV]	4.9	4.4
Beam current I_b [A]	0.66	1.3
Train length T_b [ns]	2 x 156	156
Harmonic number: h	1402	2804
Synchronous phase : ϕ_s [°]	59	73
Gap voltage: V_g [MV]	0.3 – 0.5	0.18 – 0.3
Wall loss total [MW]	1.2 - 2.1	0.9 - 1.6
Bunch phase spread for scaled ARES cavity: $d\phi_b$ [°] (ρ_g =15 Ω)	0.7 - 0.4	15 - 9
Factor missing to get the specs	**~10**	**~100**
Specified bunch phase spread: $d\phi_b$ [°]	0.05	0.1

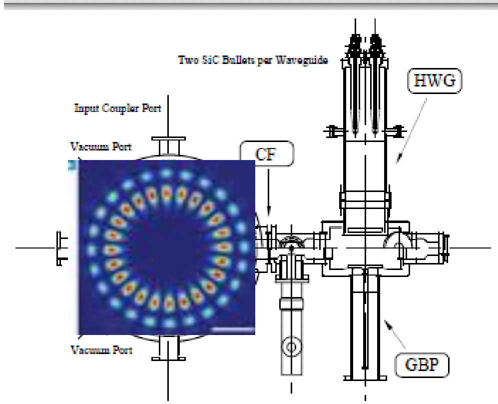
Assuming parameters of ARES cavity from nominal up to tested (150 - 450 kW) and scaled to 1 or 2 GHz

$$dV/V = -P_bT_b(1-n_{trains}T_b/T_{rev})\rho_g\omega/2V_gV$$

$$d\phi_b = dV/V(1/\tan\phi_s-\tan\phi_s)$$

Dominated by cavity voltage modulation -> synchronous phase modulation

Solution 1: Modification of the scaled ARES cavity



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High-Power Performance
Maximum Continuous: Pc = 380 kW
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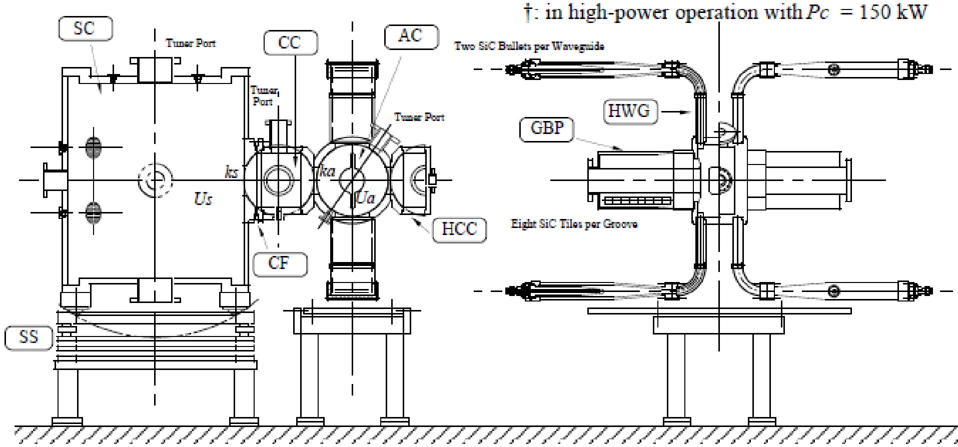

Figure 1: A schematic drawing of the ARES production model based on the prototype ARES96.

$\rho = V^2/\omega(W_a+W_s)$; in ARES $W_s=10W_a$

If we keep the size of the storage cavity the same as for 0.509 GHz when scaling to 1 or 2 GHz: $W_s=10W_a*(f/0.509)^3$

$$\rho = 1/f^3$$

In addition, Q-factor improves $\sim f^{1/2}$

Frequency: f[GHz]	0.509	1	2
Normalized shunt impedance (linac): $\rho_g=R_g/Q$ [Ω] ($\sim 1/f^3$)	15	1.9	0.23
Unloaded Q-factor: Q ($\sim f^{1/2}$)	110000	156000	220000
Aperture radius: r [mm] ($\sim 1/f$)	80	40	20
Max. Gap voltage: V_g [MV] ($\sim 1/f^{5/4}$) Scaled to keep wall loss per cavity constant	**0.85**	**0.35**	**0.15**
Wall loss per cavity: [MW]	**0.44**	**0.44**	**0.44**

Scaling of the gap voltage is done to keep heat load per cavity constant: $P = V_g^2/R_g g = V_g^2/\rho_g Q\, g \Rightarrow V_g \sim 1/f^{5/4}$

- This implies that we go to higher order mode in storage cavity from TE015 to whispering-gallery modes like in the BOC-type pulse compressor.
- Wall loss per cavity increased dramatically what requires gap voltage reduction.

CLIC DR parameters for modified ARES cavity

The incoming beam needs to be stable to

$$\sigma_{\varphi,\mathrm{in}} < 0.4\,\mathrm{deg}\ @\ 2\ \mathrm{GHz\ and}\ \sigma_{E,\mathrm{in}}/E_{\mathrm{in}} < 3.8\times10^{-4}\ \text{(distributed timing reference)}$$

or

$$\boxed{\sigma_{\varphi,\mathrm{in}} < 0.1\,\mathrm{deg}\ @\ 2\ \mathrm{GHz\ and}\ \sigma_{E,\mathrm{in}}/E_{\mathrm{in}} < 5.4\times10^{-5}\ \text{(outgoing pulses as timing reference)}}$$

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Circumference: C [m]	**420.56**	
Energy loss per turn: U_0 [MeV]	4.2	
RF frequency: f_{rf} [GHz]	1	2
RF voltage: V_{rf} [MV]	4.9	4.4
Beam current I_b [A]	0.66	1.3
Train length T_b [ns]	2 x 156	156
Harmonic number: h	1402	2804
Synchronous phase : ϕ_s [°]	59	73
Gap voltage: V_g [MV]	0.2 – 0.36	0.09 – 0.15
Wall loss total [MW]	**3.5 - 6**	**7.5 - 12.8**
Bunch phase spread for modified ARES cavities: $d\phi_b$ [°]	0.1- 0.07	0.5 - 0.3
Specified bunch phase spread: $d\phi_b$ [°]	0.05	0.1

Assuming parameters of ARES cavity in the range from nominal up to tested and modified to 1 or 2 GHz keeping the same storage cavity volume

Performance is almost within specs but the power loss in the cavities is big. It is acceptable for 1 GHz but probably too big for 2 GHz

Solution 2: Detuning rf frequency from bunch frequency

In the presence of linear phase shift of $d\phi_b$ over a period of time T_b :

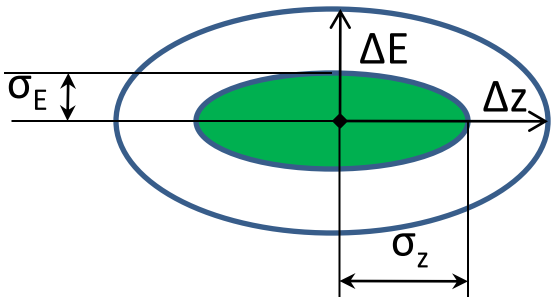
$$f_b = f_{rf} - d\phi_b/2\pi T_b;$$

To compensate $d\phi_b$= dV/V ($1/\tan\phi_s$- $\tan\phi_s$) = **1.7°** at 2 GHz, $\delta V/V$ = **-1%**, ϕ_s=**73°**,

df_{rf}/f_{rf} = -**1.5e-5** is needed, which is very small

BUT the associated voltage reduction $\delta V/V$ results in bucket reduction and consequently in bunch parameters modification. Radiation damping keeps σ_E=const for all bunches in the train so the bunch length varies along the train.

The limit from RTML is that RMS$\{\delta\sigma_z/\sigma_z\}$ < **1%**(F.Stulle)



$\Delta E/\Delta z = \sigma_E/\sigma_z$ => $\Delta E\, \sigma_z = \Delta z\, \sigma_E$

Variation gives $\delta\Delta E\, \sigma_z + \Delta E\, \delta\sigma_z = \delta\Delta z\, \sigma_E + \Delta z\, \delta\sigma_E$

Which results in $\boldsymbol{\delta\sigma_z/\sigma_z = \delta\Delta z/\Delta z - \delta\Delta E/\Delta E}$

$\Delta E^2 \sim V(\cos\phi_s+(\phi_s-\pi/2)\sin\phi_s)$

$\delta\Delta E/\Delta E = ½[\delta V/V+\delta\phi_s/(\tan\phi_s +1/(\phi_s-\pi/2))]$

$\delta\phi_s = -\delta V/V \tan\phi_s$

$\delta\Delta E/\Delta E = ½\delta V/V[1-1/(1+1/(\tan\phi_s(\phi_s-\pi/2)))]$

$\delta V/V$ = -**1%**, ϕ_s=**73°** => $\delta\Delta E/\Delta E$ = -**17%**

$\Delta\phi \sim (\phi_s-\pi/2)$

$\delta\Delta\phi/\Delta\phi = \delta\phi_s/(\phi_s-\pi/2)$

$\delta\phi_s = -\delta V/V \tan\phi_s$

$\delta\Delta\phi/\Delta\phi =$

$-\delta V/V \tan\phi_s/(\phi_s-\pi/2)$

$\delta V/V$ = -**1%**, ϕ_s=**73°** =>

$\delta\Delta z/\Delta z = \delta\Delta\phi/\Delta\phi$ = -**11%**

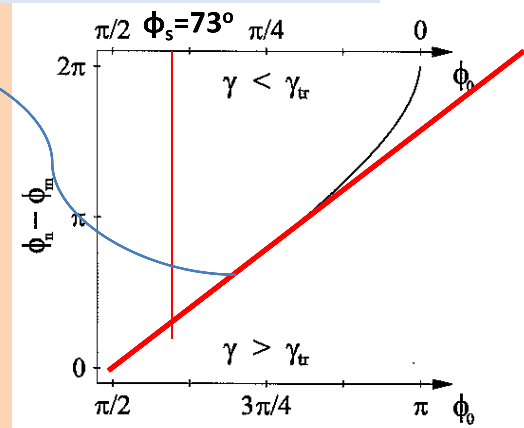


Fig. 2.3: Bucket length $\phi_n - \phi_m$ versus synchronous phase ϕ_0.

Image from H. Damerau, PhD Thesis, 2005

$\delta\sigma_z/\sigma_z = \delta\Delta z/\Delta z - \delta\Delta E/\Delta E$ = -11% + 17% = **6%** (peak-to-peak)

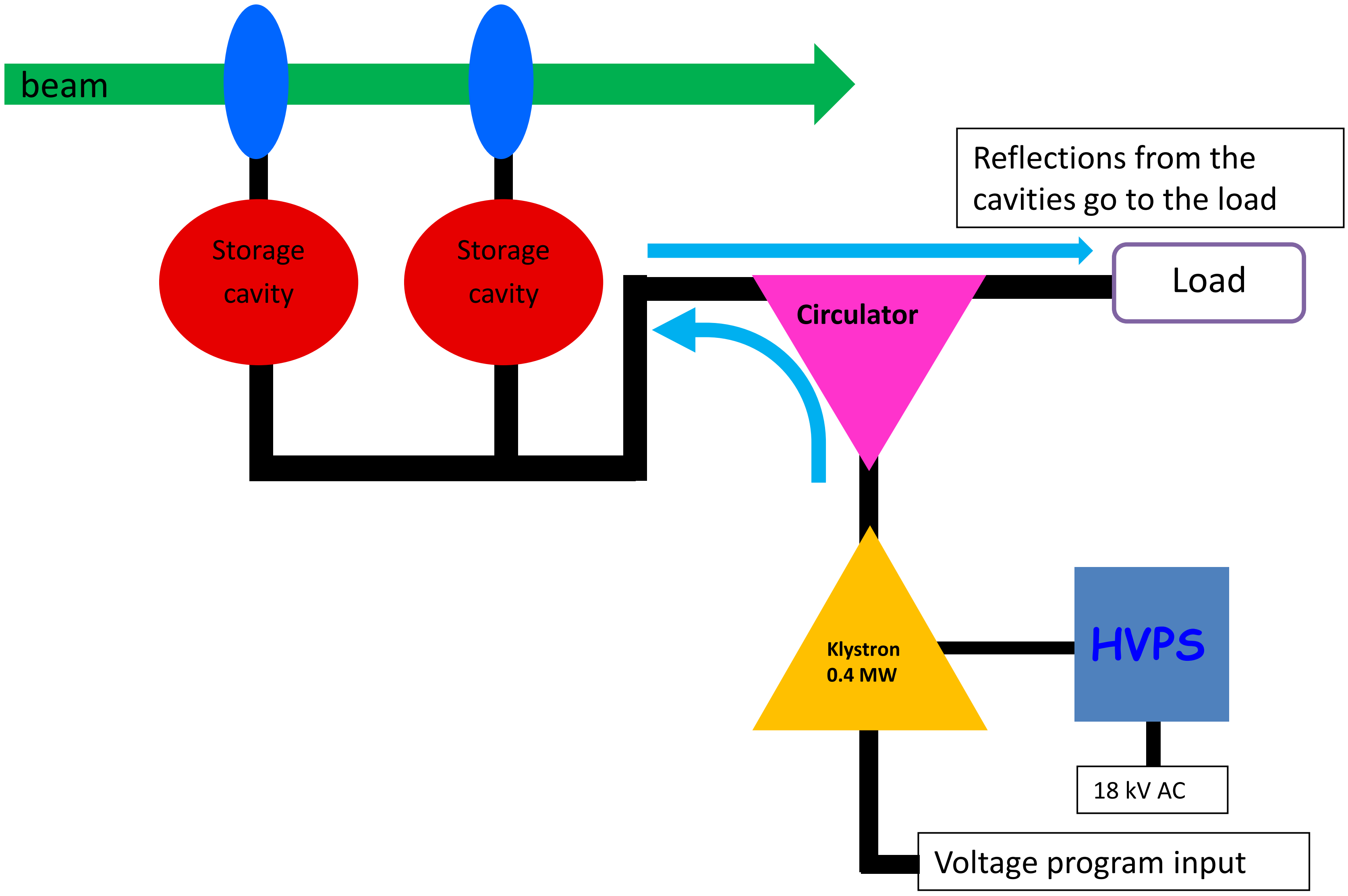
Reducing ϕ_s helps a lot

Proposal for conceptual design at 2 GHz based on the ARES-type cavities

1. Fix the value of acceptable bunch length increase from first to the last bunch to $\boldsymbol{\delta\sigma_z/\sigma_z = 3\%}$
2. This defines allowed voltage reduction $\boldsymbol{\delta V/V = -0.5\%}$, which corresponds to $d\phi_b = dV/V\ (1/\tan\phi_s - \tan\phi_s) = \mathbf{0.85^o}$, $\phi_s = 73^o$
3. To assure this voltage reduction the total normalized shunt impedance: $\rho = -dV/V * 2V^2/(P_b T_b (1-n_{trains} T_b f_{rev})\ \omega) = \mathbf{20\ \Omega}$
4. **Reducing ϕ_s helps a lot**

Parameters of the proposed rf system at 2 GHz	
Gap voltage: V_g [MV]	0.15
Normalized shunt impedance per cavity (linac): ρ_g [Ω]	0.7
Q-factor	~190000
Number of cavities	30
Total stored energy [J]	**77**
Wall loss total [MW]	**~5**
Average beam power [MW]	0.6
Total length of the rf system [m]	**~50**
Bunch phase spread: $d\phi_b$ [^{o}]	0.85
Relative rf frequency detuning: df/f Required for compensation of $d\phi_b$	-0.75e-5
Corresponding mean radius increase: dR=R*df/f [mm]	~0.4

Possible layout of an RF station with ARES type cavities

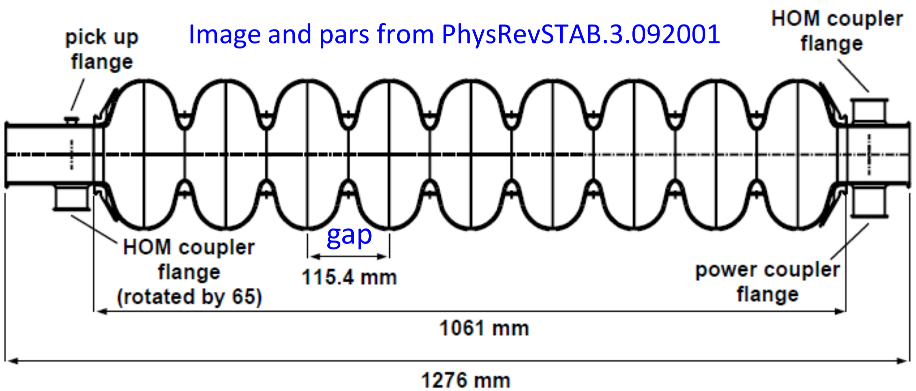


Superconducting RF option

❖Making ARES-type cavity superconducting is probably possible but certainly beyond the present state-of-the-art in SC RF technology

❖Elliptical cavity is an option but it has relatively high normalized shunt impedance. Let's consider TESLA-like cell:

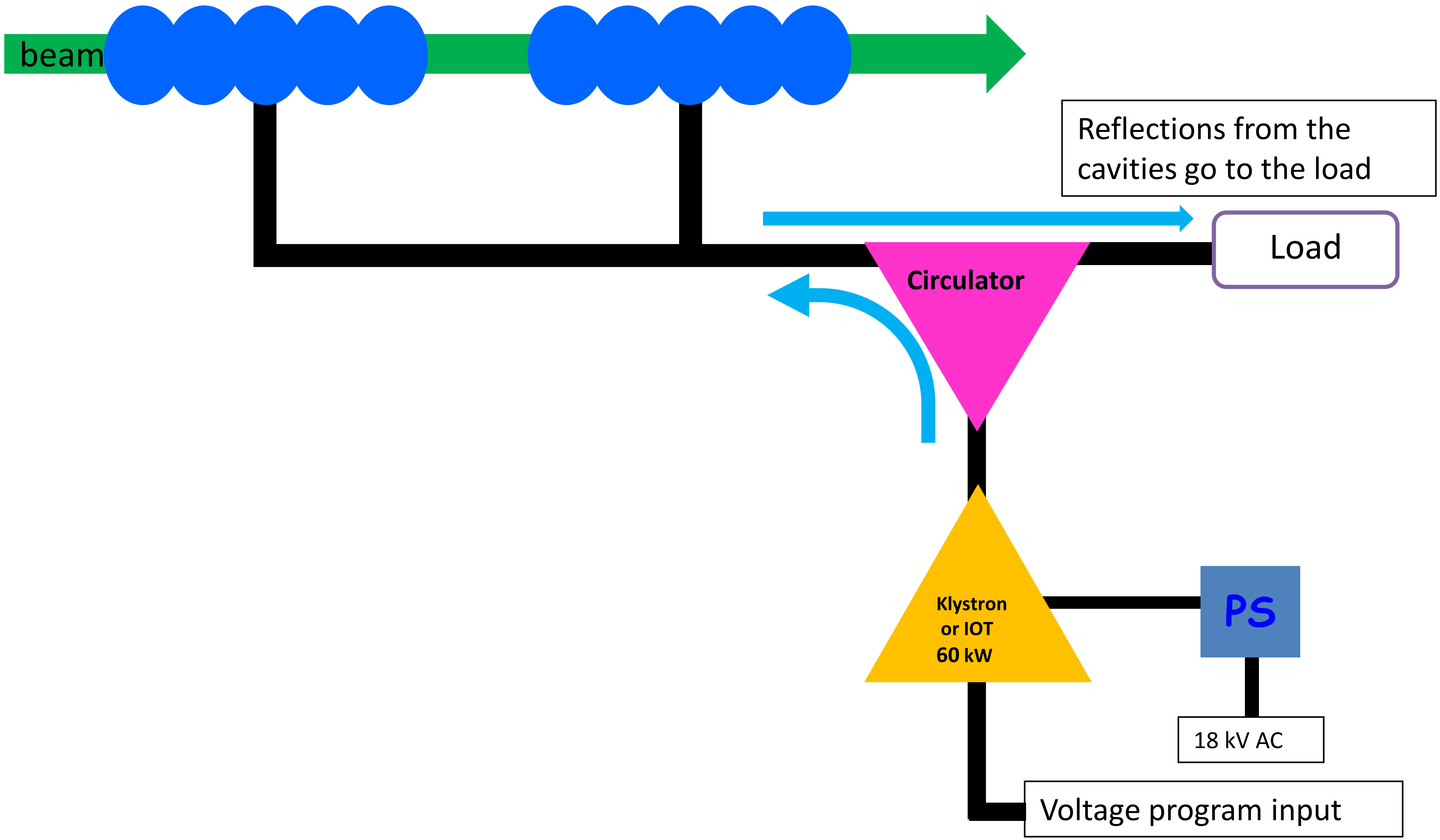
Image and pars from PhysRevSTAB.3.092001



Frequency: f[GHz]	**1.3**	**1**	**2**
Normalized shunt impedance per cell (circuit): $\rho_g = R_g/Q$ [Ω] (const)	58	58	58
Unloaded Q-factor: Q (~ $1/f^2$)	5e9	8e9	2e9
Aperture radius: r [mm] (~ 1/f)	35	46	23
Max. gradient in CW: G [MV/m] Scaled to keep gradient constant	**14**	**14**	**14**
Max. gap voltage: V_g [MV]	**1.6**	**2**	**1**
Stored energy per gap: $V_g^2/2\rho_g\omega$ [J]	**2.7**	**5.5**	**0.7**

Parameters of SC rf system at 2 GHz	
Total stored energy: [J] Needed for dV/V = 0.5%	**77**
Gap stored energy: [J]	0.7
Number of gaps	110
Gap voltage: V_g [MV]	0.04
Normalized shunt impedance per gap (circuit): ρ_g [Ω]	**0.09**
Q-factor	2e9
Wall loss total [W] at 2K	484
Total cryogenic power [MW] at 300K	~0.5
Average beam power [MW]	0.6
Total length of the rf system [m] Dependent on the # of cells per cavity	~22 for 5 cells

RF station layout for SC cavities



Comparison of 3 options

All 3 options seems to be feasible but have different issues summarized below

	"A la linac"		ARES		SC	
Train length [ns]	156	312	156	312	156	312
Total stored energy [J]	0.3		77	154	77	154
Shunt impedance R [MΩ]	36		1.9	0.95	20000	10000
Total rf power [MW]	6 (3)		6	~12	0.6	1.2
Total length [m]	10 (5)		~50	~50	~20	~40
Klystron bandwidth [%]	> 1		< 0.1		< 0.1	
Voltage modulation	Strong: Phase + amplitude		No, or very small phase	Could be stronger	No, or very small phase	Could be stronger
Strong HOM damping	demonstrated		demonstrated		demonstrated in single cell	
Transverse impedance	Highest		Lower		Lowest	
Cryogenic power [MW]	0		0		>0.5	
Main Challenge	Voltage modulation for transient compensation, Low efficiency		Low efficiency Big size		Low R/Q, Rf design both for fundamental and for HOM	

ϕ_s reduction will help a lot here