SCRF System Studies for CEPC APDR and Booster

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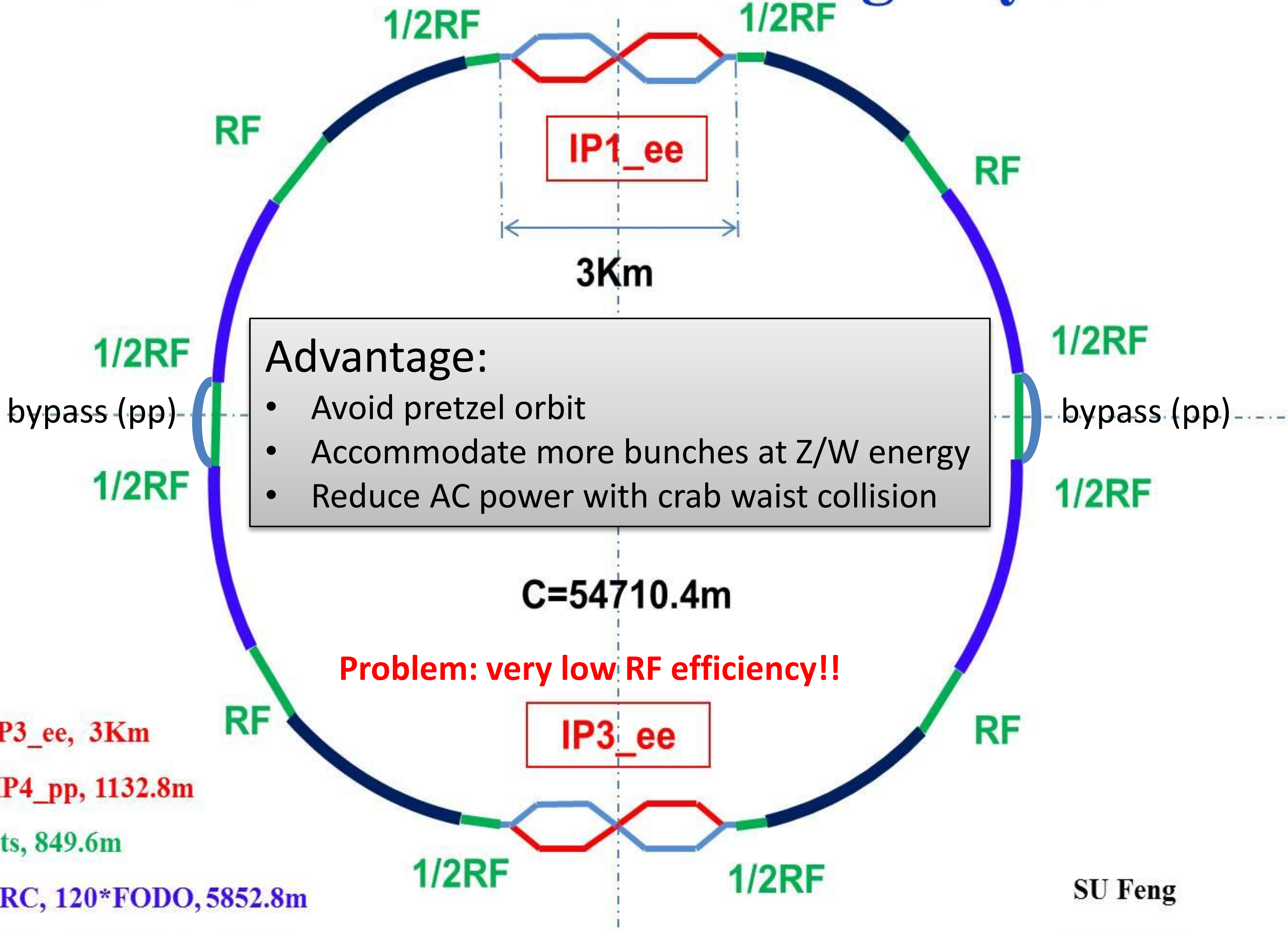
2016-8-18

Outline

- APDR SRF scheme
- Cavity requirement
- Phase and voltage analysis
- Booster

CEPC Partial Double Ring Layout



Advantage:

- Avoid pretzel orbit
- Accommodate more bunches at Z/W energy
- Reduce AC power with crab waist collision

Problem: very low RF efficiency!!

IP1_ee/IP3_ee, 3Km

IP2_pp/IP4_pp, 1132.8m

4Straights, 849.6m

4Long ARC, 120*FODO, 5852.8m

4Short ARC, 100*FODO, 4908.8m

SU Feng

2015.10.12

New idea： APDR

IHEP-AC-LC-Note2016-002

ILC-物理-2016-02

May 20th, 2016

The advanced partial double ring scheme for CEPC

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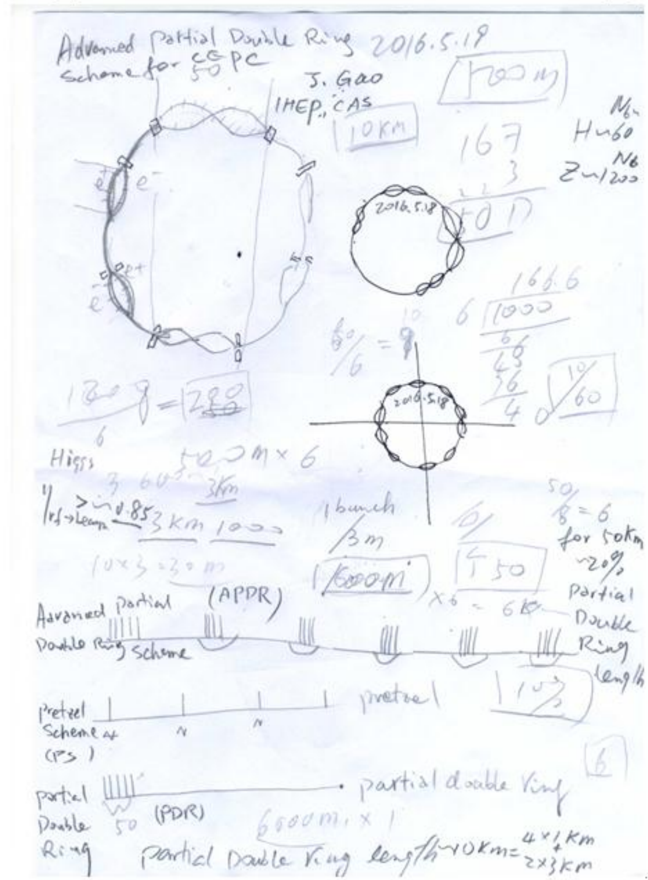
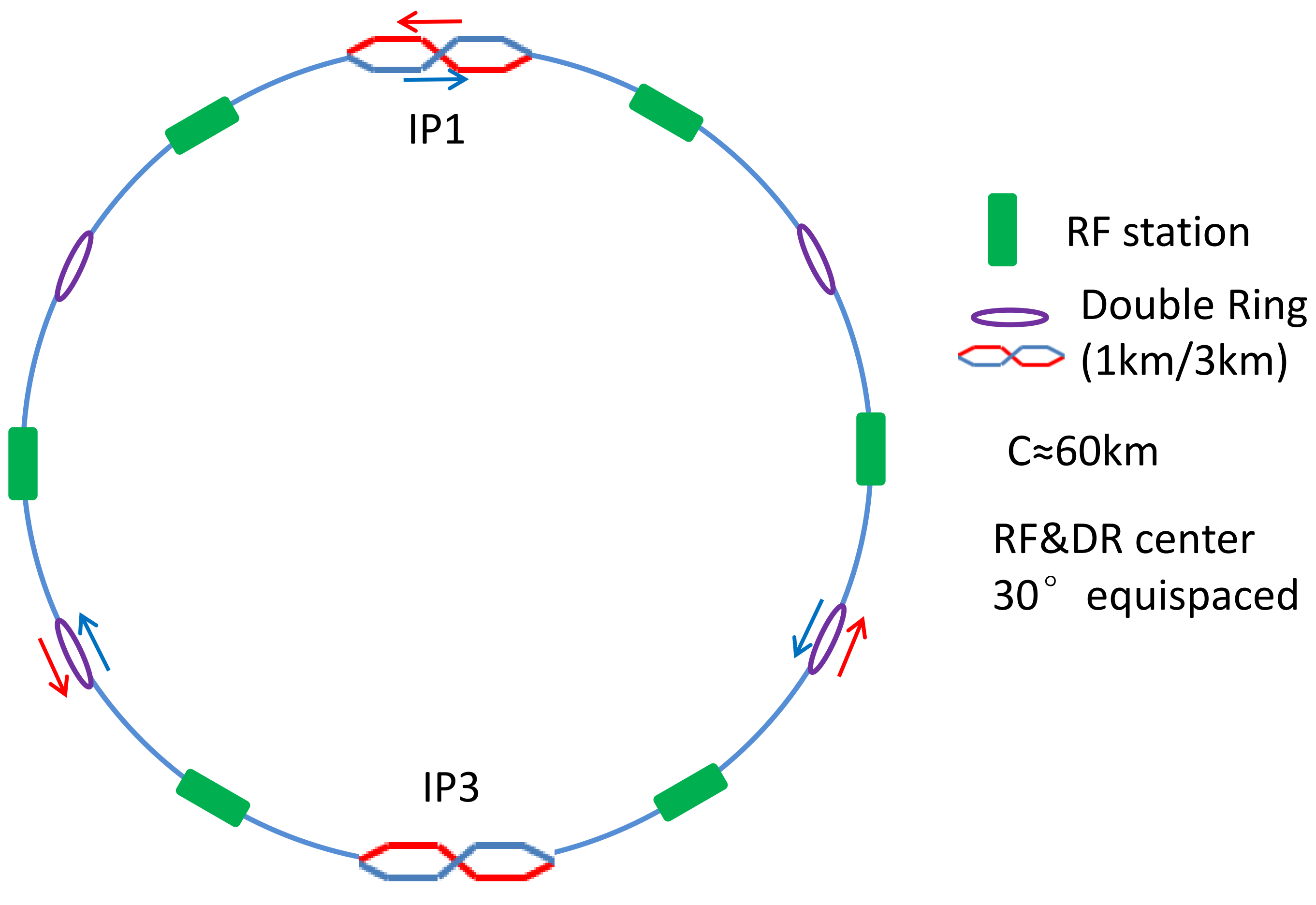
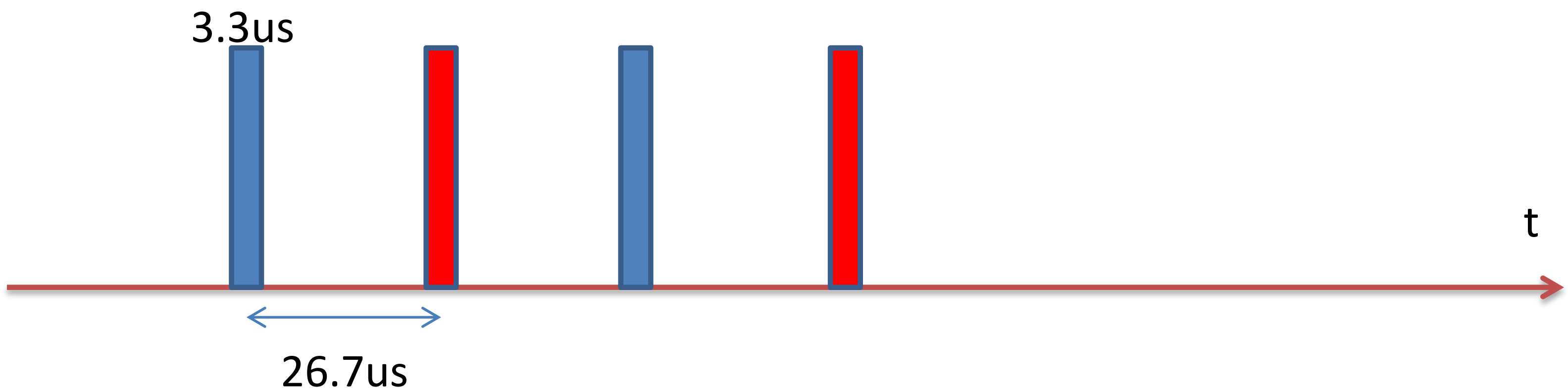


New SRF layout-6 ring



bunch



Phase

- The bunches in a bunch train will be accelerated at different Vc_i
- The bunches in a bunch train will be accelerated at different synchrotron phase to keep constant energy gain.
- $Va_i=Vc_i*\cos\varphi s_i=C$

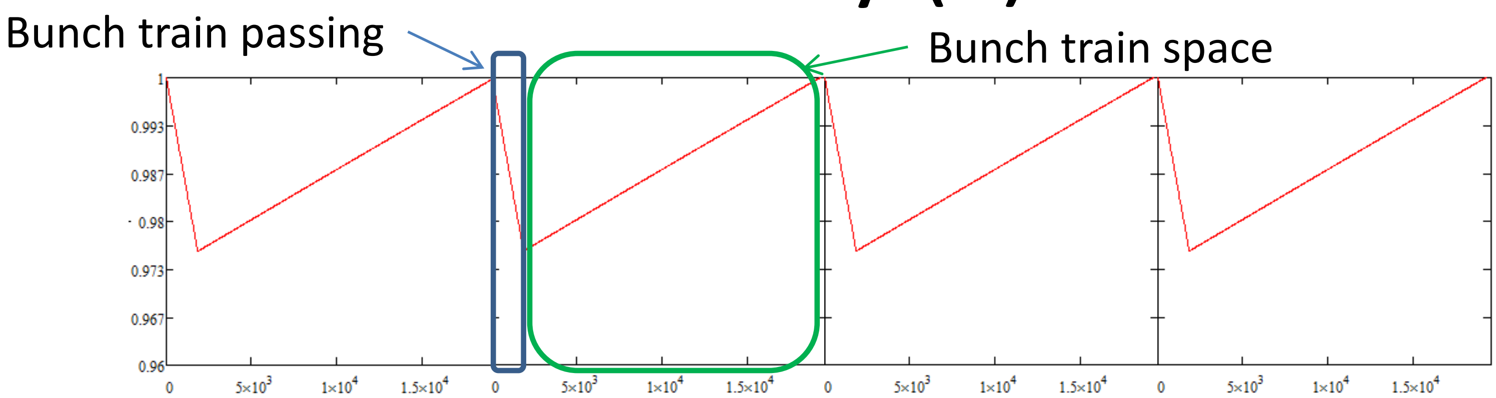
parameter for CEPC partial double ring

（wangdou20160325）

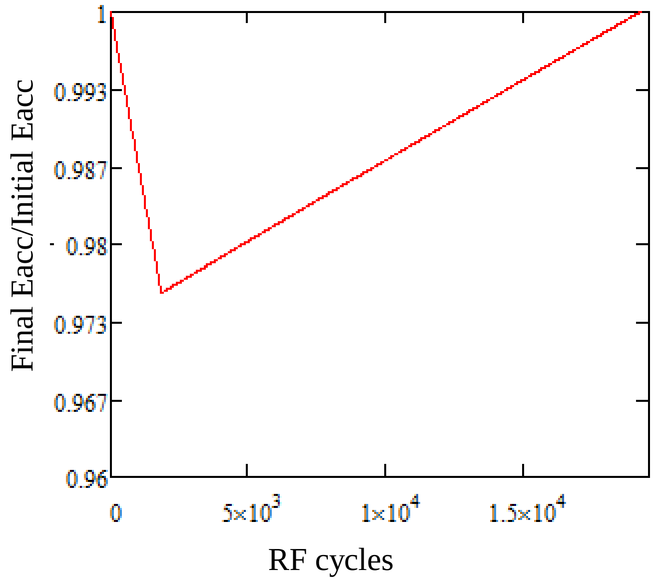
	Pre-CDR	*H-high lumi.*	*H-low power*	*W*	*Z*
Number of IPs	2	2	2	2	2
Energy (GeV)	120	120	120	80	45.5
Circumference (km)	54	54	54	54	54
SR loss/turn (GeV)	3.1	2.96	2.96	0.59	0.062
Half crossing angle (mrad)	0	15	15	15	15
Piwinski angle	0	2.5	2.6	5	7.6
N_e/bunch (10^{11})	3.79	2.85	2.67	0.74	0.46
Bunch number	50	67	44	400	1100
Beam current (mA)	16.6	16.9	10.5	26.2	45.4
SR power /beam (MW)	51.7	50	31.2	15.6	2.8
Bending radius (km)	6.1	6.2	6.2	6.1	6.1
Momentum compaction (10^{-5})	3.4	2.5	2.2	2.4	3.5
β_{IP} x/y (m)	0.8/0.0012	0.25/0.00136	0.268 /0.00124	0.1/0.001	0.1/0.001
Emittance x/y (nm)	6.12/0.018	2.45/0.0074	2.06 /0.0062	1.02/0.003	0.62/0.0028
Transverse σ_{IP} (um)	69.97/0.15	24.8/0.1	23.5/0.088	10.1/0.056	7.9/0.053
ξ_x/IP	0.118	0.03	0.032	0.008	0.006
ξ_y/IP	0.083	0.11	0.11	0.074	0.073
V_{RF} (GV)	6.87	**3.62**	**3.53**	**0.81**	**0.12**
f_{RF} (MHz)	650	650	650	650	650
Nature σ_z (mm)	2.14	**3.1**	**3.0**	**3.25**	**3.9**
Total σ_z (mm)	2.65	4.1	4.0	3.35	4.0
HOM power/cavity (kw)	3.6	2.2	1.3	0.99	0.99
Energy spread (%)	0.13	0.13	0.13	0.09	0.05
Energy acceptance (%)	2	2	2		
Energy acceptance by RF (%)	6	**2.2**	**2.1**	**1.7**	**1.1**
n_γ	0.23	0.47	0.47	0.3	0.24
Life time due to beamstrahlung_cal (minute)	47	36	32		
F (hour glass)	0.68	0.82	0.81	0.92	0.95
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.04	2.96	2.01	3.09	3.09

6 double ring	Pre-CDR Zhaijiyuan20160327	PDR(HL) Zhaijiyuan20160327&0408	APDR(HL V_{RF}=3.62)	APDR (H-low power)	APDR (Z)
Number of IPs	2	2	2	2	2
Energy (GeV)	120	120	120	120	45.5
Circumference (km)	54	54	54	54	54
SR loss/turn (GeV)	3.1	2.96	2.96	2.96	0.062
Half crossing angle (mrad)	0	15	15	15	15
Piwinski angle	0	2.5	2.5	2.6	8.5
N_e/bunch (10^{11})	3.79	2.85	2.85	2.67	0.46
Bunch number	50	67	22x3	15x3	367x3
Beam current (mA)	16.6	16.96	17	10.5	45.4
SR power /beam (MW)	53.2	51	50	31.2	2.8
Bending radius (km)	6.1	6.2	6.2	6.2	6.1
V_{RF} (GV)	6.87	**3.65**	**3.62**	**5.16**	**0.357**
f_{RF} (MHz)	650	650	650	650	650
Cavity No.	384	384	384	498	48
Cavity gradient	15.8	20.6	20.6	22.6	16.2
Accelerating phase	63.1	35.2	35.2-32.3	55.5-55	80.2-79.8
CW power/cavity （kW）	275	263.4	260	126	117
Peak power/train (kW)	/	2220	2345	1148	1237
Total Power （MW)	105.6	**382.5**	**100.4**	**62.7**	**5.6**
Cell/cavity	5	2	2	2	2
Cavity/module	4	**6**	**8**	**4(3)**	**4**
Module/station	6	10	8	21	2
Total module	96	64	48	126	12
R/Q (Ω)	514	206	206	206	206
G	268	268	268	268	268
HOM loss factor/cavity (V/pC)	1.8	0.54	0.54	0.54	0.54
HOM power/cavity (kW)	3.6	0.8	0.838	0.485	0.361
Working Temperature（K）	2	2	2	2	2
Q0	4E10	**2E10**	**2E10**	**2E10**	**2E10**
τ（ms）	1.156	0.097	0.811	2.045	2.243
QL	2.36e6	1.97e5	1.656e6	4.18e6	4.58e6
Bandwidth(kHz)	0.28	3.3	0.196	0.077	0.071
Detuning F (kHz)	-0.27	**-1.16**	**-0.138**	**-0.111**	**-0.234**
Stored energy/cavity(J)	158.7	**107.4**	**107.4**	**126.9**	**65.3**
Frev(kHz)	5.484	5.484	5.484	5.484	5.484
Gap length (us)	/	0.3-160	26.7	26.7	26.7
η(RF to beam efficiency)(%)	100	27%	~100	~100	~100
Vc decrease(%)	/	/	3.3	1.3	2.5
TB/τ	/	1.7	0.0158	0.013	0.012

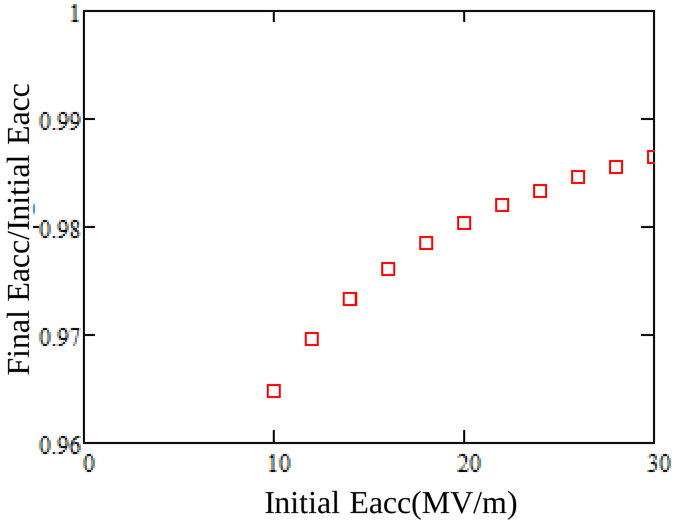
Accelerator gradient decrease in one RF cavity (Z)



Assume matching

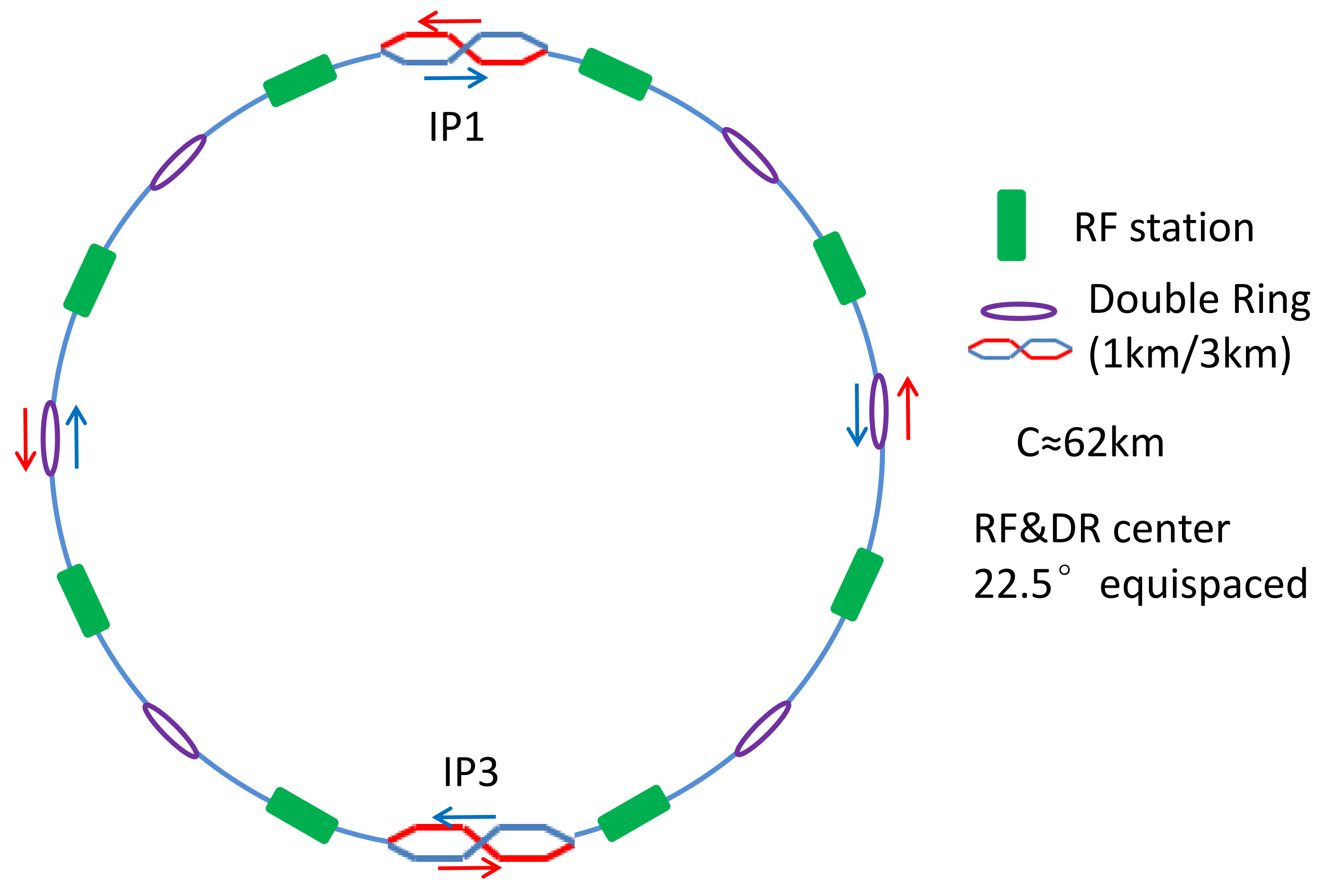


Field evolution in cavity

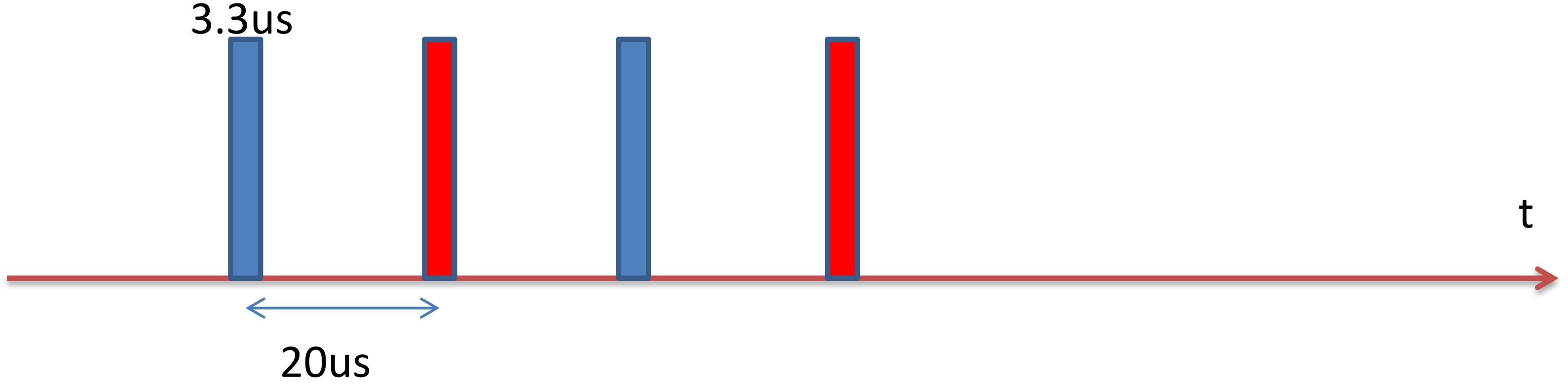


Field decrease vs. various initial field gradient of the cavity

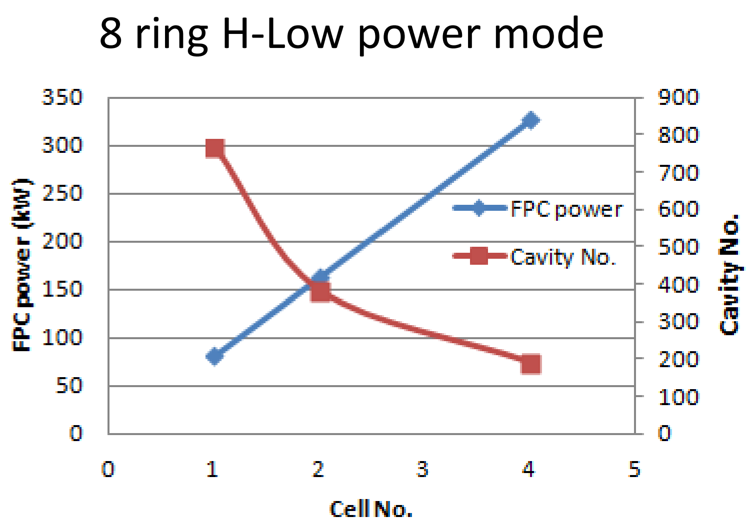
New SRF layout-8 ring

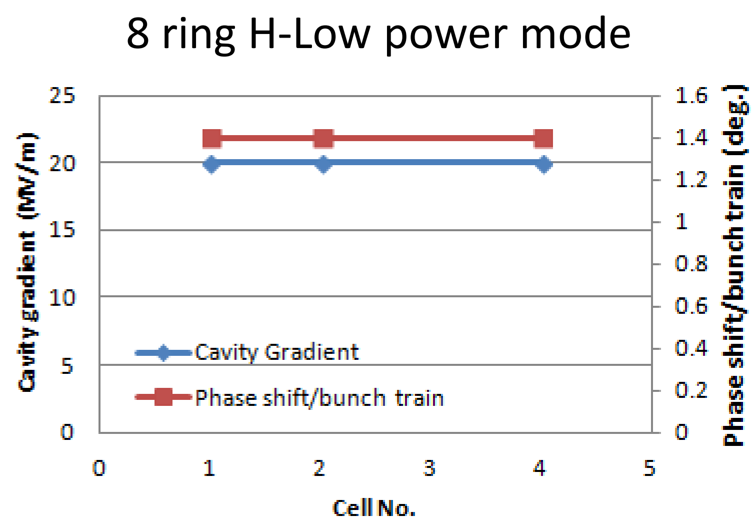


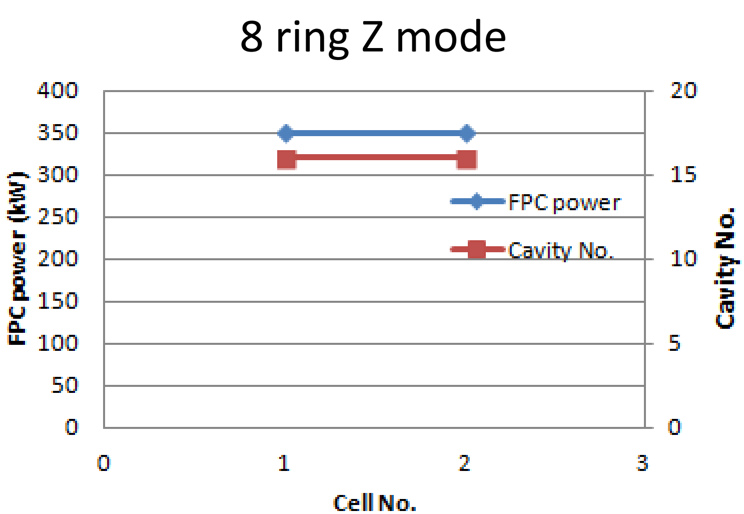
bunch

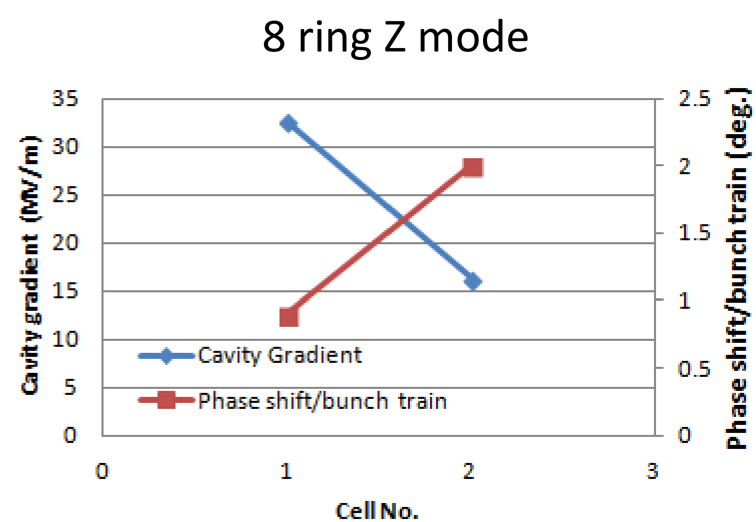


8 double ring	Pre-CDR Zhaijiyuan20160327	PDR(HL) Zhaijiyuan20160327&0408	APDR(HL V_{RF}=3.62)	APDR (H-low power V_{RF}=3.53)	APDR (H-low power)	APDR (Z)
Number of IPs	2	2	2	2	2	2
Energy (GeV)	120	120	120	120	120	45.5
Circumference (km)	54	54	54	54	54	54
SR loss/turn (GeV)	3.1	2.96	2.96	2.96	2.96	0.062
Half crossing angle (mrad)	0	15	15	15	15	15
Piwinski angle	0	2.5	2.5	2.6	2.6	8.5
N_e/bunch (10^{11})	3.79	2.85	2.85	2.67	2.67	0.46
Bunch number	50	67	17x4	11x4	11x4	275x4
Beam current (mA)	16.6	16.96	17	10.5	10.5	45.4
SR power /beam (MW)	53.2	51	50	31.2	31.2	2.8
Bending radius (km)	6.1	6.2	6.2	6.2	6.2	6.1
V_{RF} (GV)	6.87	**3.65**	**3.62**	**3.53**	**5.16**	**0.357/0.12/0.12**
f_{RF} (MHz)	650	650	650	650	650	650
Cavity No.	384	384	384	384/768/192	498	48/16/16
Cavity gradient	15.8	20.6	20.6	20/20/20	22.6	16.2/16.3/32.6
Accelerating phase	63.1	35.2	35.2-33	33-31.6/33-31.6/33-31.6	55.3-55	80.1-79.9/58.9-56.9/58.9-58
CW power/cavity （kW）	275	263.4	260	163.3/81.6/326.6	126	117/350/350
Peak power/train (kW)	/	2220	1389	843	843	884
Total Power （MW）	105.6	**382.5**	**100.4**	**62.7**	**62.7**	**5.6**
Cell/cavity	5	2	2	2/1/4	2	2/2/1
Cavity/module	4	**6**	**6**	**6/12/3**	**6(3,2)**	**6/2/2**
Module/station	6	10	8	8/8/8	10(11）	1/1/1
Total module	96	64	64	64/64/64	126	8/8/8
R/Q (Ω)	514	206	206	206/103/412	206	206/206/103
G	268	268	268	268	268	268
HOM loss factor/cavity (V/pC)	1.8	0.54	0.54	0.54/0.27/1.08	0.54	0.54/0.54/0.27
HOM power/cavity (kW)	3.6	0.8	0.838	0.485/0.24/0.97	0.485	0.36/0.36/0.18
Working Temperature（K）	2	2	2	2	2	2
Q0	4E10	**2E10**	**2E10**	**2E10**	**2E10**	**2E10**
τ（ms）	1.156	0.097	0.811	1.242	2.045	2.243/0.76/0.76
QL	2.36e6	1.97e5	1.656e6	2.53e6	4.18e6	4.58e6/1.55e6/1.55e6
Bandwidth(kHz)	0.28	3.3	0.196	0.128	0.077	0.071/0.209/0.209
Detuning F (kHz)	-0.27	**-1.16**	**-0.138**	**-0.083**	**-0.111**	**-0.234/-0.347/-0.347**
Stored energy/cavity(J)	158.7	**107.4**	**107.4**	**100**	**126.9**	**65.3/65.3/133**
Frev(kHz)	5.484	5.484	5.484	5.484	5.484	5.484
Gap length TB (us)	/	0.3-160	20	20	20	20
η(RF to beam efficiency)(%)	100	27%	~100	~100	~100	~100
Vc decrease(%)	/	/	2.5	1.6	1	1.7/5.3/2.5
TB/τ	/	1.7	0.025	0.0098	0.0098	0.0089/0.0263/0.0263


8 ring H-Low power mode
FPC power (kW)
Cavity No.
FPC power
Cavity No.
Cell No.

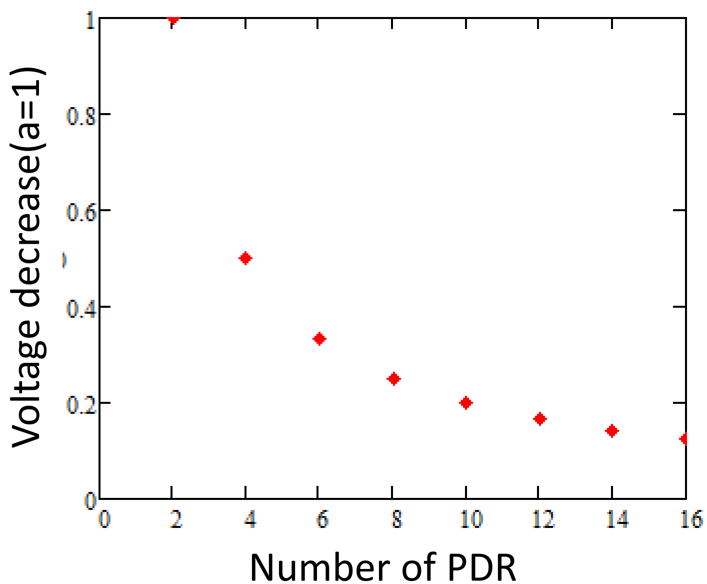

8 ring H-Low power mode
Cavity gradient (MV/m)
Phase shift/bunch train (deg.)
Cavity Gradient
Phase shift/bunch train
Cell No.


8 ring Z mode
FPC power (kW)
Cavity No.
FPC power
Cavity No.
Cell No.


8 ring Z mode
Cavity gradient (MV/m)
Phase shift/bunch train (deg.)
Cavity Gradient
Phase shift/bunch train
Cell No.

What is the best number of PDR?

- $P_{cw} << P_{pulse}$ case:
- There are 2n PDR in the circumference（n=1,2…).
- Assume the voltage decrease in the 2 PDR design is a.
- The voltage decrease in the 2n PDR design is a/n.

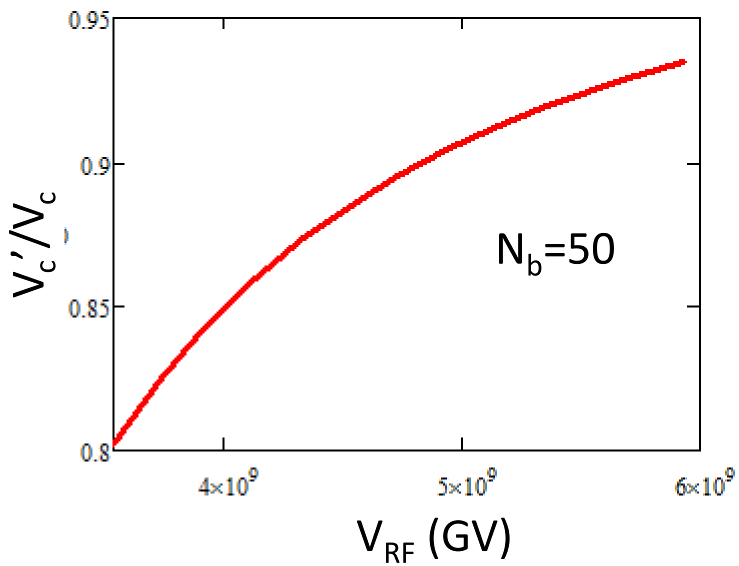


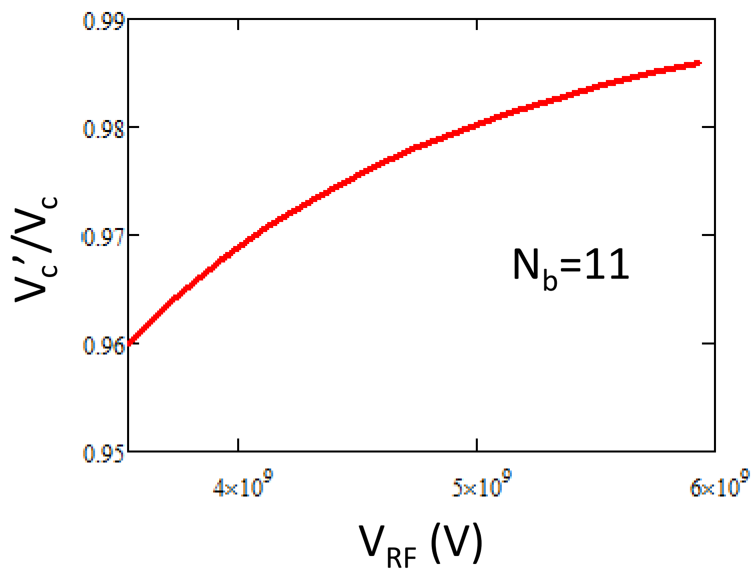
What is the best voltage?

- R/Q=Vc^2/ωU, assume $P_{pulse} >> P_{cw}$

$$\frac{V_c'}{V_c} = \sqrt{1 - \frac{(V_{SR}/dN_{cav})q\omega(R/Q)N_b}{(V_{RF}/N_{cav})^2}}$$

- d, cavity effective length, q bunch charge, N_b bunches per train, N_{cav} cavity number.
- H-low power case:
  - q=42.8nC,Vsr=2.96GV, N_{cav} =384
- Assume matching



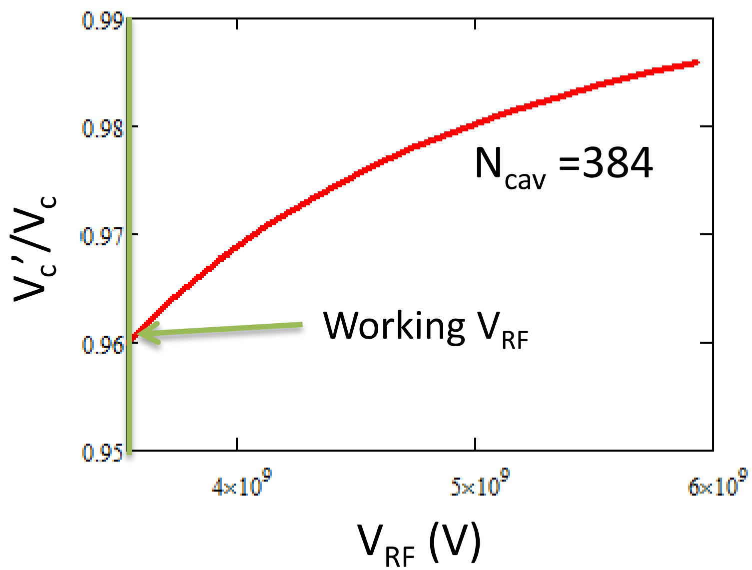


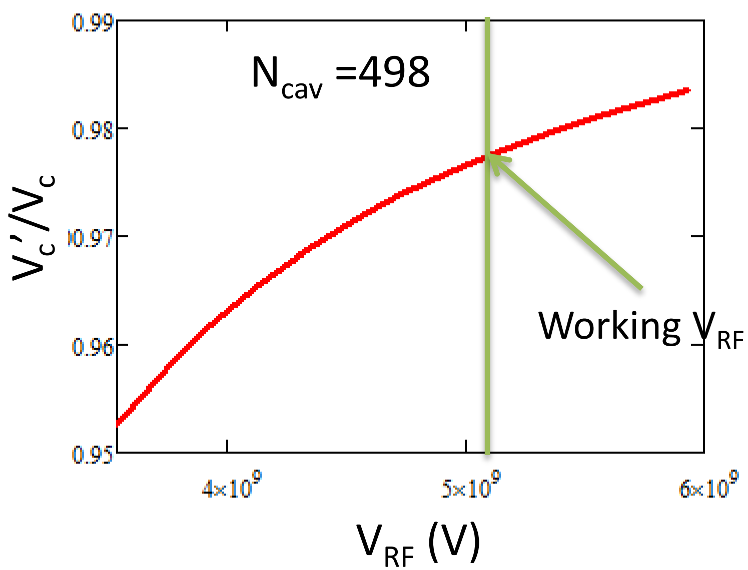
What is the best voltage?

- R/Q=Vc^2/ωU, assume P_{pulse}>>P_{cw}

$$\frac{V_c'}{V_c}=\sqrt{1-\frac{(V_{SR}/dN_{cav})q\omega(R/Q)N_b}{(V_{RF}/N_{cav})^2}}$$

- d, cavity effective length, q bunch charge, N_b bunches per train, N_{cav} cavity number.
- H-low power case:
  - Nb=11,q=42.8nC,Vsr=2.96GV,
- Assume matching & same gradient



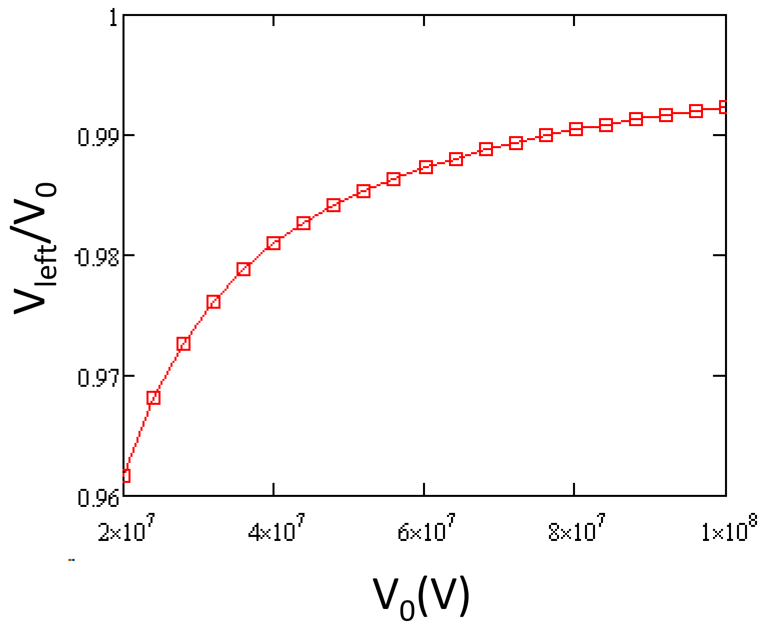


LEP

After the passage of the first bunch (bunch a) the voltage left in an RF unit located before an intersection point is given by:

$$V_{\mathrm{left}} = \sqrt{(V_0 \cos\varphi_e)^2 - 2\pi I_b V_0 h R_s Q^{-1} \cos\varphi_e \sin(\varphi_s + \varphi_{align})}$$

- Assume:
  - ϕ_e= 1deg., φ_s=116deg., φ_{align}=3deg., I_b=0.45mA, h=31324, Q=40000, R_s=774MΩ（14 cavities）
  - V_0 (initial peak voltage)from 20MV-100MV
  - 2.3MV/cavity(acc. voltage)



Voltage decrease:

1 bunch ~1%

4 bunches ~4%

APDR:

8 DR: 2.5%(HL)5.3/2.5%(Z)

6 DR: 3.3%(HL)

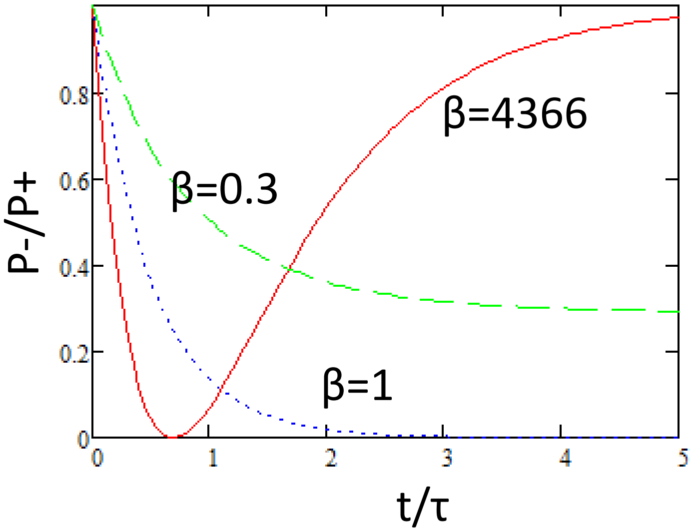
Voltage drop is acceptable!

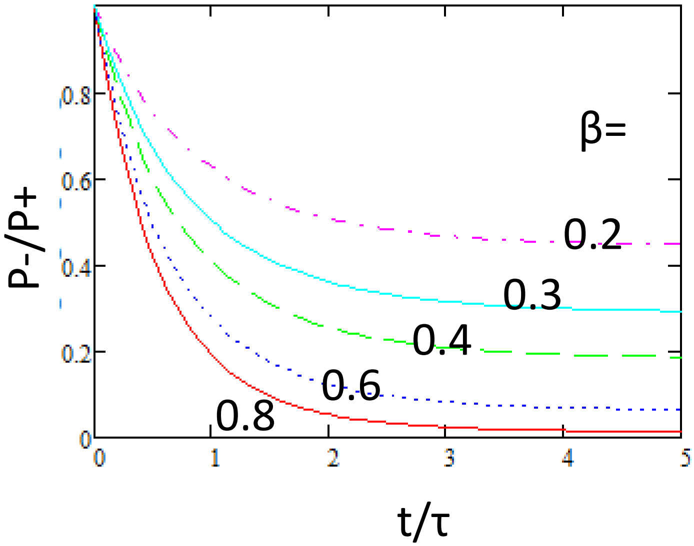
CEPC APDR SRF Design

APDR SRF Challenge	Difficulty	Methods	CDR
Phase stability	☆☆☆	Feedback control, injection control, phase stability, SR damping,…	±0.1%
Voltage control	☆☆☆	Feedback control,	±1%
BBU	☆☆	Variation on bunch current, Low wake field excitation at bunch train length, High damping SC cavity, Radiation damping(wiggler), bunch spacing, feedback,…	>500mA (Z>1A)
HOM damping	☆☆	Single cell beam pipe/slotted cavity(multi-cell), …	1-3kW
Longitudinal instability	☆☆		
Transverse instability	☆☆		
Impact bunch position control	☆☆☆		
Input coupler	☆☆		130kW(1cell),260kW(2cell); Z:350kW(2cell),175kW(1cell)
Q_0	☆☆	EP is very important	2E10
Cavity gradient	☆☆☆	20.6MV/m&Q_0=2E10@2K (☆☆) 32.6MV/m&Q_0=2E10@2K (☆☆☆, lower the Q_0)	H mode:2E10 Z mode:> 5E9

Cavity requirement

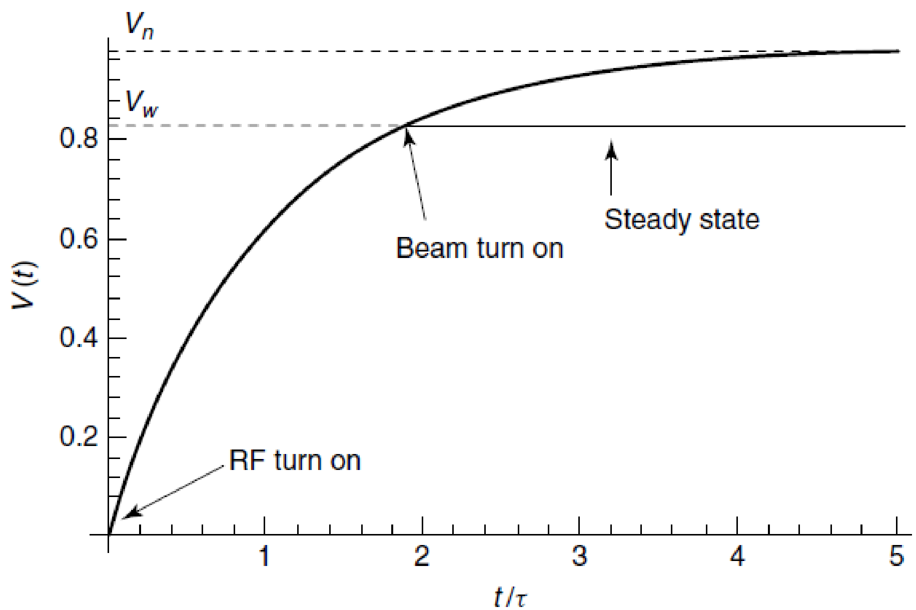
What is the best β？





P-, reflection power; P+, forward power.

$$t_b = -\tau \ln(1 - V_w/V_n)$$



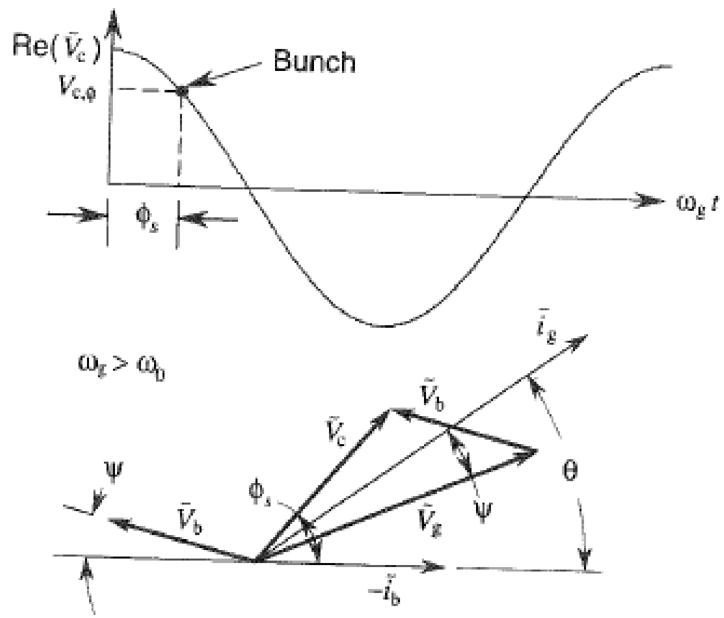
What is the best cavity for APDR?

- $R/Q=Vc^2/\omega U$
- A lower R/Q can give a high U at the same cavity voltage (or gradient)
- The gradient is more stable at higher U when the input power is not enough at the pulse period.
- It is an opposite design scheme comparing with low-loss cavity or others
- Reduced R/Q can also decrease the detuning frequency
- R/Q ↓ Riris ↑ loss factor ↓
- Cavity can work at a lower gradient with the same U

Phase and voltage analysis

Power coupling

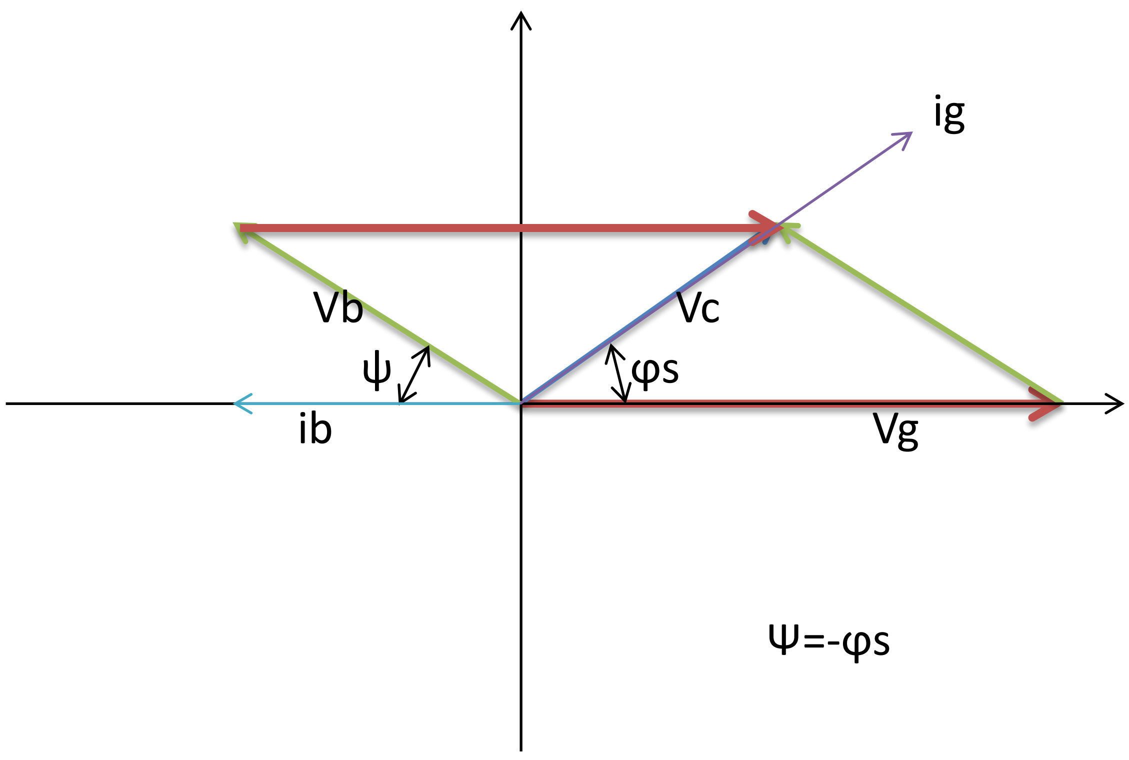
Phasor diagram



$\phi_s \neq 0$ & $\omega_{g>}\omega_0$

Optimum coupling

- With optimum coupling condition



Equispaced bunches

- For equispaced bunches:

$$\tilde{V}_b \approx -\frac{I_0 R_a}{1+\beta}\cos\psi e^{i\psi}$$

- Consider H-Low power case, I_0=0.021mA,R_a=206x2x10^{10}, beta=7.9x10^3, ψ=-33deg.=-0.576

$\mathbf{V}_b$=0.021x206x2x10^{10}xcos(-0.576)$e^{-0.576i}$/(1+7.9x10^3)=-7.7x10^6+5x10^6i

- The amplitude of $\mathbf{V}_b$ is 9.2MV

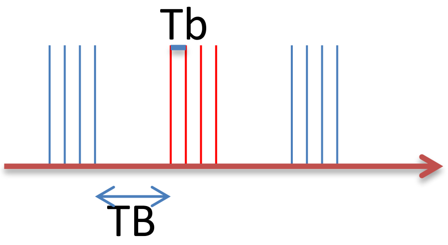
Abs($\mathbf{V}_b$)=9.2MV   Angle($\mathbf{V}_b$)=-0.576

- V_c=20MV/m*0.46m=9.2MV, φ_s=0.576

So, V_b=V_c & ψ=-φ_s

APDR bunches

- Bunch train case, Tb is the bunch time interval in bunch train; TB is the time interval between bunch trains.
- $T_b \neq T_B$.
- Tb<<TB&TB/td<<1
- Tb/td=2.428e-4, TB/td=0.016, φs=33deg., f=650MHz



What is beam loading?

- It is not a beam in the cavity!!!
- It is the beam induced voltage in the cavity!!!
- When TB/Td<<1, the multi-bunches induced a constant V_b

$$V_\mathrm{i} = V_{\mathrm{i},h}\left(1 + \mathrm{e}^{-\rho}\mathrm{e}^{\mathrm{i}\varphi} + \mathrm{e}^{-2\rho}\mathrm{e}^{\mathrm{i}2\varphi} + \cdots\right)$$

$$\rho = \frac{t_\mathrm{b}}{t_\mathrm{d}} \qquad \varphi = \omega_h t_\mathrm{b} - 2\pi m_\mathrm{b}$$

$$V_\mathrm{i} = V_{\mathrm{i},h}\frac{1}{1 - \mathrm{e}^{-\rho}\mathrm{e}^{\mathrm{i}\varphi}}, \qquad V_\mathrm{b} = V_{\mathrm{i},h}\left(\frac{1}{1 - \mathrm{e}^{-\rho}\mathrm{e}^{\mathrm{i}\varphi}} - \frac{1}{2}\right)$$

Non-equispaced bunches

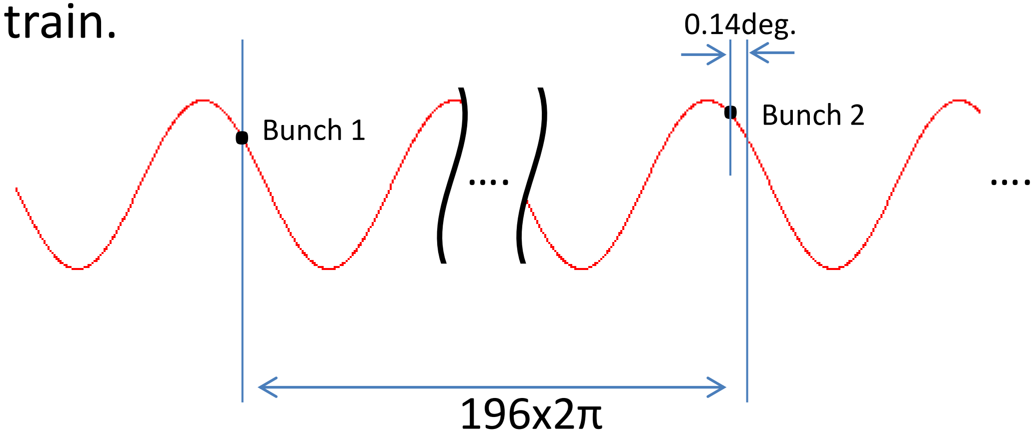
- Consider H-Low power case, it is equal to 11x4bunches, I_0=0.021mA/11=1.91x10^{-3}mA, R_a=206x2x10^{10}, beta=7.9x10^3, ψ=-33deg.=-0.576, f=650MHz, t'_b=196x77/f=2.322x10^{-5}s, Q_0=2x10^{10}

$$\mathrm{V}_{ih} = R_h I_0 \mathrm{t}_b^{'} \frac{\omega_h}{2Q_0} = 1.865\times10^4\,\mathrm{V}$$

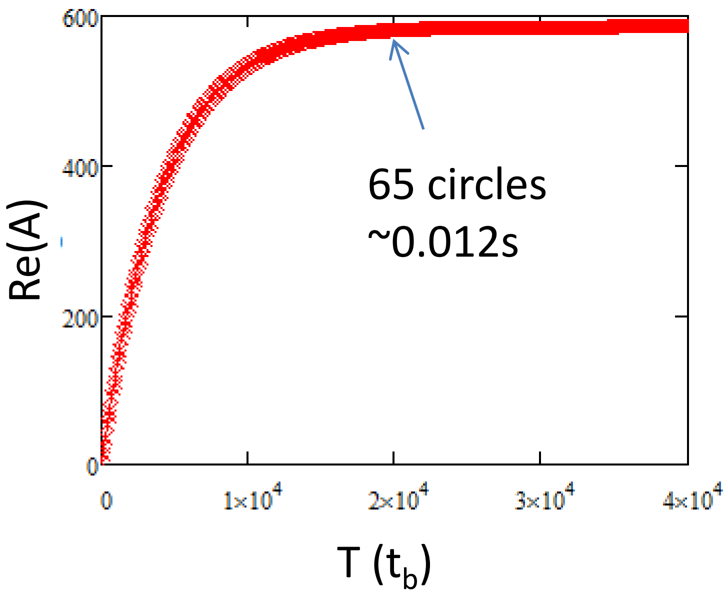
- Phase shift is 1.4deg. with 11 bunches, the phase shift between two bunches is 0.14deg. m_b=196. So t_b=195.999611/f=3.015x10^{-7}s.

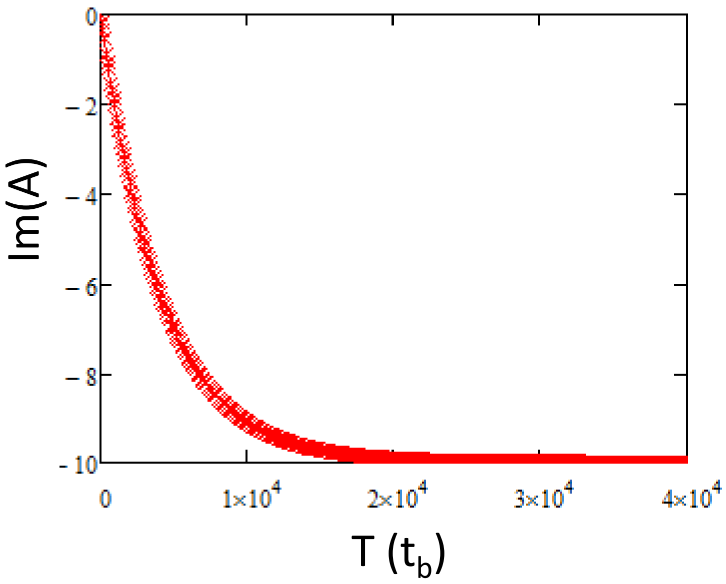
$$\varphi = \omega_h t_b - 2\pi m_b = -2.444\times10^{-3}$$

- Also we need to assume there is no phase shift between the first bunch of each bunch train.



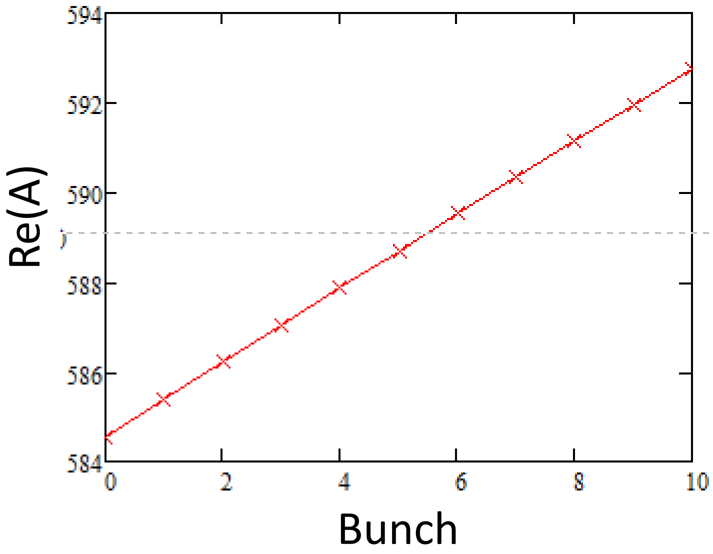
- $V_{br}=V_{ih}*A$

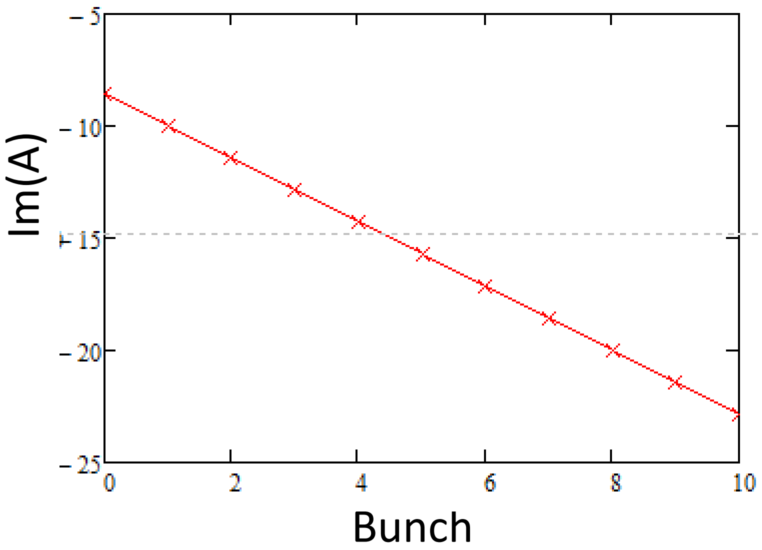




One circle=308t_b

- $V_{br}=V_{ih}*A$, A for bunches in a bunch train after 400000 circles.
- Total phase shift of V_b is 1.37degree for 11 bunches.

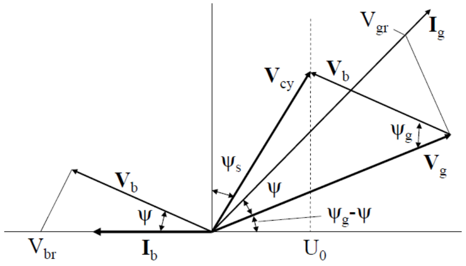




$V_{br} \approx 1.865\text{x}10^4\text{Vx}584.5=1.09\text{x}10^7\text{V}$

With optimum matching of minimum P_g, $\psi=-\varphi_s$

$V_b=V_{br}\cos(-33^\circ)=9.14\text{MV}$ As $V_c=9.2\text{MV}$, so $V_b \approx V_c$

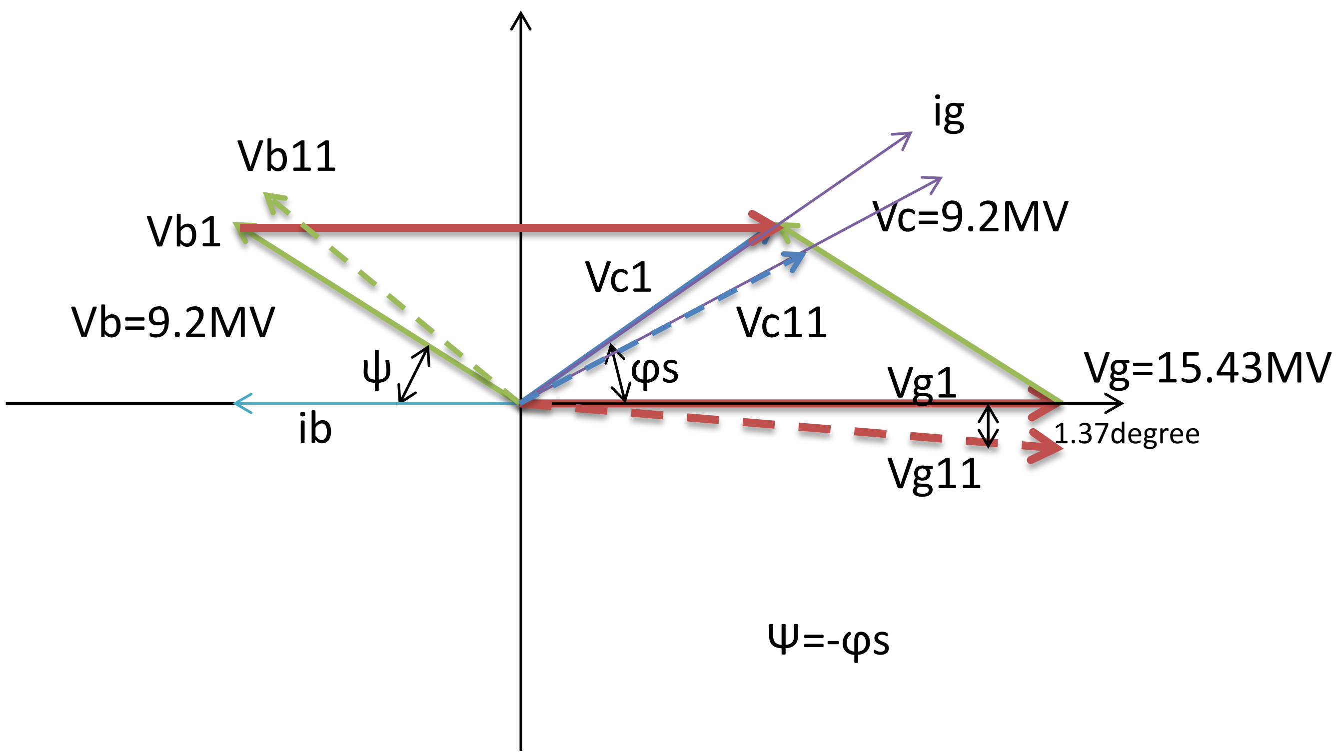


Vg

8-ring: Bunch No.	Re Vb	Im Vb	Re Vc	Im Vc	Re Vg	Im Vg	ABS Vg	Vg	Vg Angle (deg.)	Vg Angle shift (deg.)
1	−7.67E+06	4.98E+06	7.72E+06	5.01E+06	1.54E+07	3.05E+04	1.539E+07	1.0000	0.00	0
2	−7.66E+06	5.00E+06	7.72E+06	4.99E+06	1.54E+07	−6.31E+03	1.537E+07	0.9991	−0.13	0
3	−7.64E+06	5.02E+06	7.72E+06	4.97E+06	1.54E+07	−4.31E+04	1.536E+07	0.9983	−0.27	0
4	−7.63E+06	5.03E+06	7.72E+06	4.95E+06	1.53E+07	−7.98E+04	1.535E+07	0.9974	−0.41	0
5	−7.62E+06	5.05E+06	7.72E+06	4.94E+06	1.53E+07	−1.16E+05	1.533E+07	0.9966	−0.54	0
6	−7.60E+06	5.07E+06	7.72E+06	4.92E+06	1.53E+07	−1.53E+05	1.532E+07	0.9958	−0.68	0
7	−7.59E+06	5.09E+06	7.72E+06	4.90E+06	1.53E+07	−1.89E+05	1.531E+07	0.9949	−0.82	0
8	−7.58E+06	5.10E+06	7.72E+06	4.88E+06	1.53E+07	−2.26E+05	1.530E+07	0.9941	−0.96	0
9	−7.56E+06	5.12E+06	7.72E+06	4.86E+06	1.53E+07	−2.62E+05	1.528E+07	0.9933	−1.09	0
10	−7.55E+06	5.14E+06	7.72E+06	4.84E+06	1.53E+07	−2.98E+05	1.527E+07	0.9924	−1.23	0
11	−7.54E+06	5.16E+06	7.72E+06	4.82E+06	1.53E+07	−3.34E+05	1.526E+07	0.9916	−1.37	0

Phase evolution

- With optimum coupling condition (H low power 8ring)



Bunch No.	Pre CDR (CW, $P_g=P_{avg}$)		PDR (CW, $P_g=P_{pulse}$, very low RF efficiency)		APDR 8 ring (HL, CW, $P_g=P_{avg}$)		APDR 8 ring (H-low power, CW, $P_g=P_{avg}$)		APDR 8 ring (Z, $P_g=P_{avg}$)	
	Vc	Phase shift	Vc	Phase shift	Vc	Phase shift	Vc	Phase shift	Vc	Phase shift
1	1	0	1	0	1	2.00	1	1.40	1	2.0000
2	1	0	1	0	0.9984	1.88	0.9984	1.26	0.9998	1.9927
3	1	0	1	0	0.9969	1.75	0.9968	1.12	0.9996	1.9855
4	1	0	1	0	0.9953	1.63	0.9952	0.98	0.9994	1.9782
5	1	0	1	0	0.9938	1.50	0.9936	0.84	0.9992	1.9709
6	1	0	1	0	0.9922	1.38	0.992	0.70	0.9990	1.9636
7	1	0	1	0	0.9906	1.25	0.9904	0.56	0.9988	1.9564
8	1	0	1	0	0.9891	1.13	0.9888	0.42	0.9987	1.9491
9	1	0	1	0	0.9875	1.00	0.9872	0.28	0.9985	1.9418
10	1	0	1	0	0.9859	0.88	0.9856	0.14	0.9983	1.9345
11	1	0	1	0	0.9844	0.75	0.984	0	0.9981	1.9273
15	1	0	1	0	0.9781	0.25			0.9973	1.8982
17	1	0	1	0	0.9750	0			0.9969	1.8836
50	1	0	1	0					0.9906	1.6436
67			1	0					0.9873	1.5200
275									0.0947	0

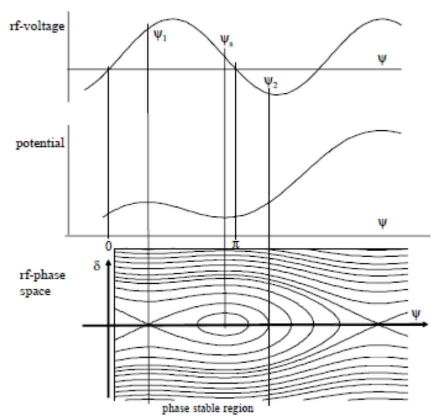
Assume V_{rf} is constant at the first bunch of bunch trains and the change of V_b is negligible.

Bunch No.	Pre CDR (CW, $P_g=P_{avg}$)		PDR (CW, $P_g=P_{pulse}$, very low RF efficiency)		APDR 6 ring (H-low power, CW, $P_g=P_{avg}$)		APDR 6 ring (HL, CW, $P_g=P_{avg}$)		APDR 6 ring (Z, $P_g=P_{avg}$)	
	Vc	Phase shift	Vc	Phase shift	Vc	Phase shift	Vc	Phase shift	Vc	Phase shift
1	1	0	1	0	1	2.20	1	2.60	1	2.6000
2	1	0	1	0	0.9984	2.04	0.9984	2.48	0.9998	2.5929
3	1	0	1	0	0.9968	1.89	0.9969	2.35	0.9996	2.5858
4	1	0	1	0	0.9952	1.73	0.9953	2.23	0.9994	2.5787
5	1	0	1	0	0.9936	1.57	0.9937	2.10	0.9992	2.5716
6	1	0	1	0	0.992	1.41	0.9921	1.98	0.9989	2.5645
7	1	0	1	0	0.9904	1.26	0.9906	1.86	0.9987	2.5574
8	1	0	1	0	0.9888	1.10	0.9890	1.73	0.9985	2.5503
9	1	0	1	0	0.9872	0.94	0.9874	1.61	0.9983	2.5432
10	1	0	1	0	0.9856	0.79	0.9859	1.49	0.9981	2.5361
11	1	0	1	0	0.984	0.63	0.9843	1.36	0.9979	2.5290
15	1	0	1	0	0.9776	0	0.9780	0.87	0.9971	2.5005
22	1	0	1	0			0.9670	0	0.9956	2.4508
50	1	0	1	0					0.9897	2.2519
67			1	0					0.9861	2.1311
367									0.0923	0

Assume V_{rf} is constant at the first bunch of bunch trains and the change of V_b is negligible.

Bunch position

- The e+ and e- bunch trains should be symmetry to the two IPs.
- The phase shift of the synchrotron phase between each bunch in a bunch train is 0.14 degree for the H low power mode. The total phase shift is 1.4 degree.
- After enough synchrotron damping, the bunches will be at its synchrotron phase separately.
- If the transport matrix from cavity to IP is the same for e+ and e- bunch trains, there will be no shift for the position of colliding.



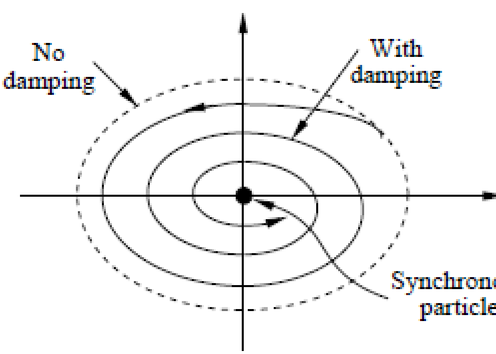


Illustration of energy oscillations with and without radiation damping

RADIATION DAMPING, R.P. Walker

Power reflection

- In resonant operation：

$$P_r = P_g - P_c - P_b$$

- For heavy beam loading, P_c<<P_b,

$$P_r \approx P_g - P_b$$

- For APDR steady state, P_b is constant. We make the first bunch of bunch train at optimal coupling, then P_g=P_b. P_r=0
- The generator power is

$$P_g = \frac{R_a i_g^2}{16\beta} = \frac{P_c}{4\beta}\left[(1+\beta) + \frac{I_0 R_a \cos\phi_s}{V_c}\right]^2$$

- Which simplifies to

$$P_g = \frac{[(1+\beta)P_c + P_b]^2}{4\beta P_c}$$

H. Padamsee, RF superconductivity for accelerators, P387,P396

The first bunch of bunch train working at different synchrotron phase

- The beam induced voltage and generator induced voltage are related with β.

$$\tilde{V}_{\mathrm{br}} = \frac{\tilde{i}_{\mathrm{b}}}{(1+\beta)G_{\mathrm{c}}} = -\frac{I_0 R_{\mathrm{a}}}{1+\beta},$$

$$\tilde{V}_{\mathrm{gr}} = \frac{\tilde{i}_{\mathrm{g}}}{(1+\beta)G_{\mathrm{c}}} = \frac{2\sqrt{R_{\mathrm{a}} P_{\mathrm{g}} \beta}}{1+\beta},$$

$$\tilde{V}_{\mathrm{c}} = \tilde{V}_{\mathrm{gr}} + \tilde{V}_{\mathrm{br}}$$

- Vc can be increased by lower β.
- By increasing Vc and ϕs, keeping Vc*cos (ϕs)=C, →Pb is constant, Pg is constant. So

$$P_r \approx P_g - P_b = 0$$

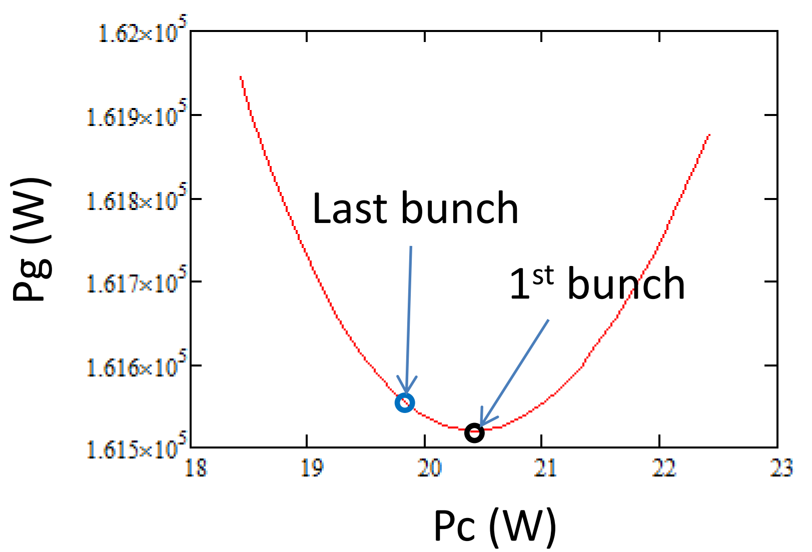
Bunches in a bunch train

- In we set the β optimal to the first bunch, then the β is not optimal to others.

$$P_g = \frac{[(1+\beta)P_c + P_b]^2}{4\beta P_c}$$

- For example, H low power case, If we set β=7914 for the first bunch, keeping P_b constant (161.5kW). Pc=20.42W→Eacc=20MV/m. The last bunch, Pc=19.8W

The Pg needed for the last bunches is a little higher. But **only 0.025%**



Booster Parameters

- **Parameter List for Alternating Magnetic Field Scheme.**

Parameter	Unit	Value
Beam energy [E]	GeV	6
Circumference [C]	km	63.84
Revolutionfrequency[f_0]	kHz	4.69
SR power / beam [P]	MW	2.16
Beam off-set in bend	cm	1.2
Momentum compaction factor[α]		2.33E-5
Strength of dipole	Gs	**-129.18/+180.84**
n_B/beam		50
Lorentz factor [g]		11741.71
Magnetic rigidity [Br]	T·m	20
Beam current / beam [I]	mA	0.92
Bunchpopulation[N_e]		2.44E10
Bunch charge [Q_b]	nC	3.91681
emittance-horizontal[e_x] inequilibrium	m·rad	6.38E-11
injected from linac	m·rad	3E-7
emittance-vertical[e_y] inequilibrium	m·rad	0.191E-11
injected from linac	m·rad	3E-7

Parameter	Unit	Value
RF voltage [Vrf]	GV	0.2138
RF frequency [frf]	GHz	1.3
Harmonic number [h]		276831
Synchrotronoscillationtune[n_s]		0.21
Energy acceptance RF	%	5.93
SR loss / turn [U0]	GeV	5.42E-4
Energyspread[s_d] inequilibrium	%	0.0147
injected from linac	%	0.1
Bunch length[s_d] inequilibrium	mm	0.18
injected from linac	mm	~1.5
Transversedampingtime[t_x]	ms	4.71
	turns	
Longitudinaldampingtime[t_e]	ms	4.71
	turns	

Tianjian Bian

Booster Parameters

- **Parameter List for Alternating Magnetic Field Scheme.**

Parameter	Unit	Value
Beam energy [E]	GeV	120
Circumference [C]	km	63.84
Revolutionfrequency[f_0]	kHz	4.69
SR power / beam [P]	MW	2.16
Beam off-set in bend	cm	0
Momentum compaction factor[α]		2.54E-5
Strength of dipole	Gs	**516.71**
n_B/beam		50
Lorentz factor [g]		234834.15
Magnetic rigidity [Br]	T·m	400
Beam current / beam [I]	mA	0.92
Bunchpopulation[N_e]		2.44E10
Bunch charge [Q_b]	nC	3.91681
emittance-horizontal[e_x] inequilibrium	m·rad	3.61E-9
injected from linac	m·rad	3E-7
emittance-vertical[e_y] inequilibrium	m·rad	0.1083E-9
injected from linac	m·rad	3E-7

Parameter	Unit	Value
RF voltage [Vrf]	GV	6
RF frequency [frf]	GHz	1.3
Harmonic number [h]		276831
Synchrotronoscillationtune[n_s]		0.21
Energy acceptance RF	%	4.57
SR loss / turn [U0]	GeV	2.34
Energyspread[s_d] inequilibrium	%	0.12
injected from linac	%	0.1
Bunch length[s_d] inequilibrium	mm	1.36
injected from linac	mm	~1.5
Transversedampingtime[t_x]	ms	21.76
Longitudinaldampingtime[t_e]	ms	

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Conclusion

- The 8-double ring and 6-double ring are available when using the same parameter as PDR(V_{RF}=3.62GV) for HL. The 8-double ring has a lower phase variation than the 6-double ring .
- The phase region is from 35.2-33 degree for bunches in a bunch train for the 8-double ring HL mode. The phase region is from 35.2-32.3 degree for the 6-double ring HL mode.
- The bunch energy gain in each cavity is constant.
- The RF to beam efficiency is ~100%.
- V_b is 9.14MV with a 1.37deg. phase shift in a bunch train of the APDR H low power of 8 ring case.
- V_b reaches constant value after about 65 circles (I_b=C, ~0.012s).
- Beam can be stored by increasing bunch charges stably (with reflection in low current).
- V_c should keep constant phase and value for each bunch separately.

Thanks!