Reverse-phasing mode for FCC-ee RF system

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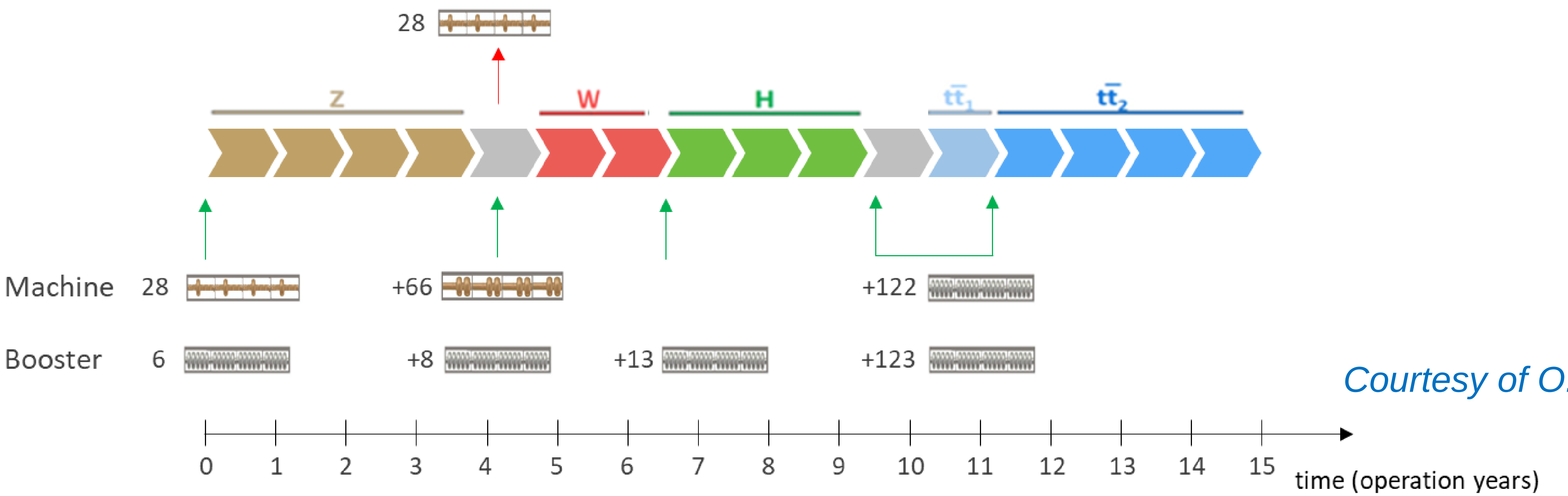
Baseline RF system configuration

	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1283	0.079
W	80	135	1.05
H	120	26.7	2.1
$t\bar{t}$	182.5	5	11.67

K. Oide, 29.05.2024



Courtesy of O. Brunner

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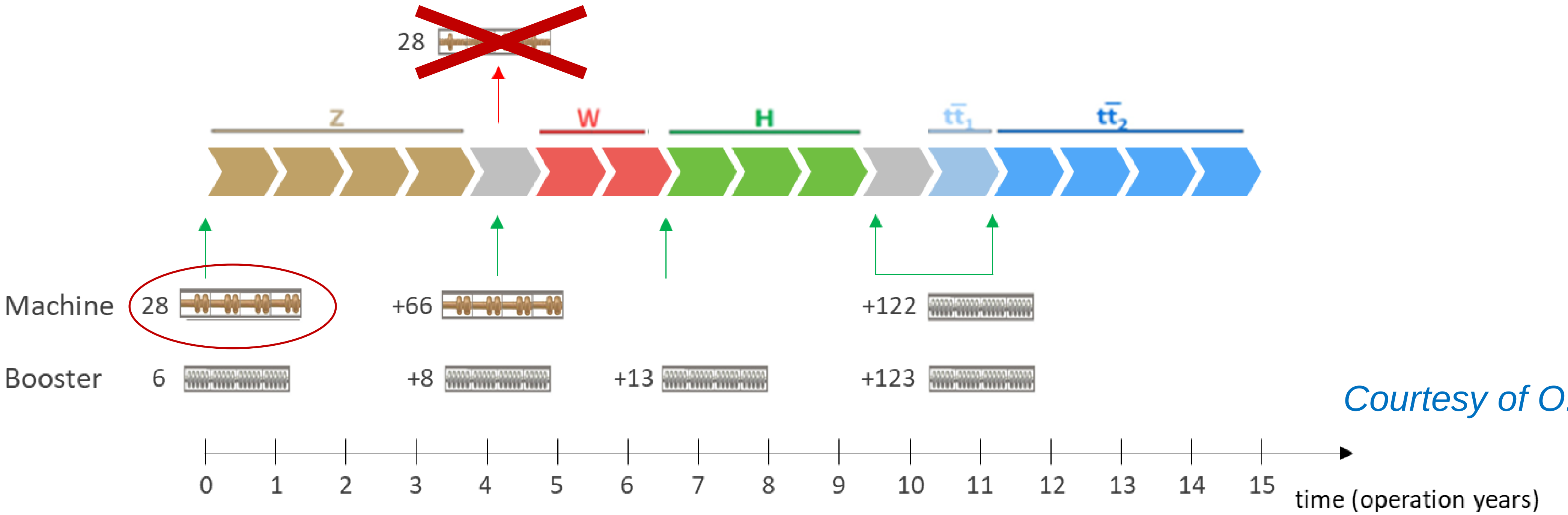


Courtesy of O. Brunner

Steady-state beam loading

RF power for SRF cavities with circulators is minimized for optimal parameters:

Optimal detuning $\Delta\omega_{\mathrm{opt}} = -\frac{\omega_{\mathrm{rf}}(R/Q)|F_b|I_{b,\mathrm{dc}}\sin\phi_s}{2V_{\mathrm{cav}}}$

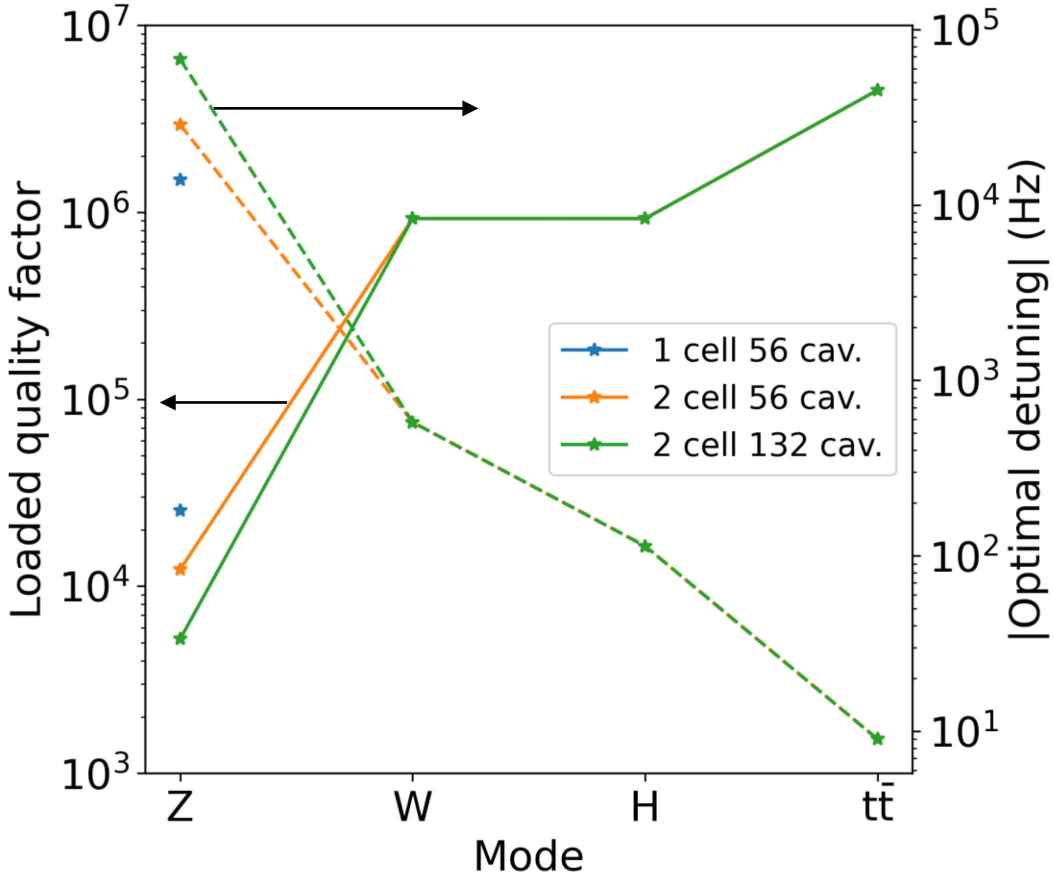
Optimal quality factor $Q_{\mathrm{ext,opt}} = \frac{V_{\mathrm{cav}}}{|F_b|(R/Q)I_{b,\mathrm{dc}}\cos\phi_s}$

Keeping 2-cell cavities for Z, W, H, (and $t\bar{t}$):

→ Large range for $Q_{\mathrm{ext,opt}}$ adjustment (a factor of ~75-600) starting from $\sim 5\times10^3$: possible FPC solutions under study *(S. Gorgi Zadeh and E. Montesinos, CERN SRF, 2024; see also slides of F. Gerigk, FCC Week 2024)*
→ Incresed detuning enhances instability due to fundamental mode

Can the voltage per cavity be increased for Z mode?

Optimal parameters for different scenarios

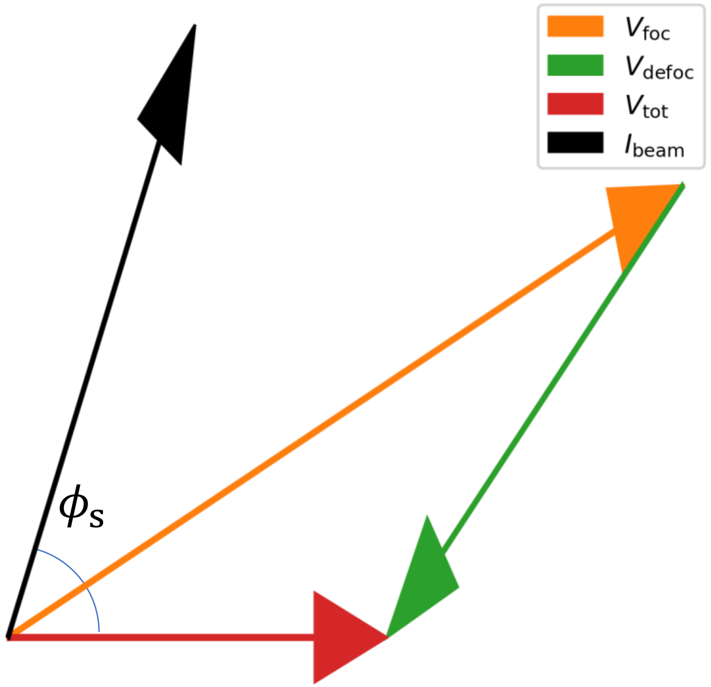


Reverse phase operation

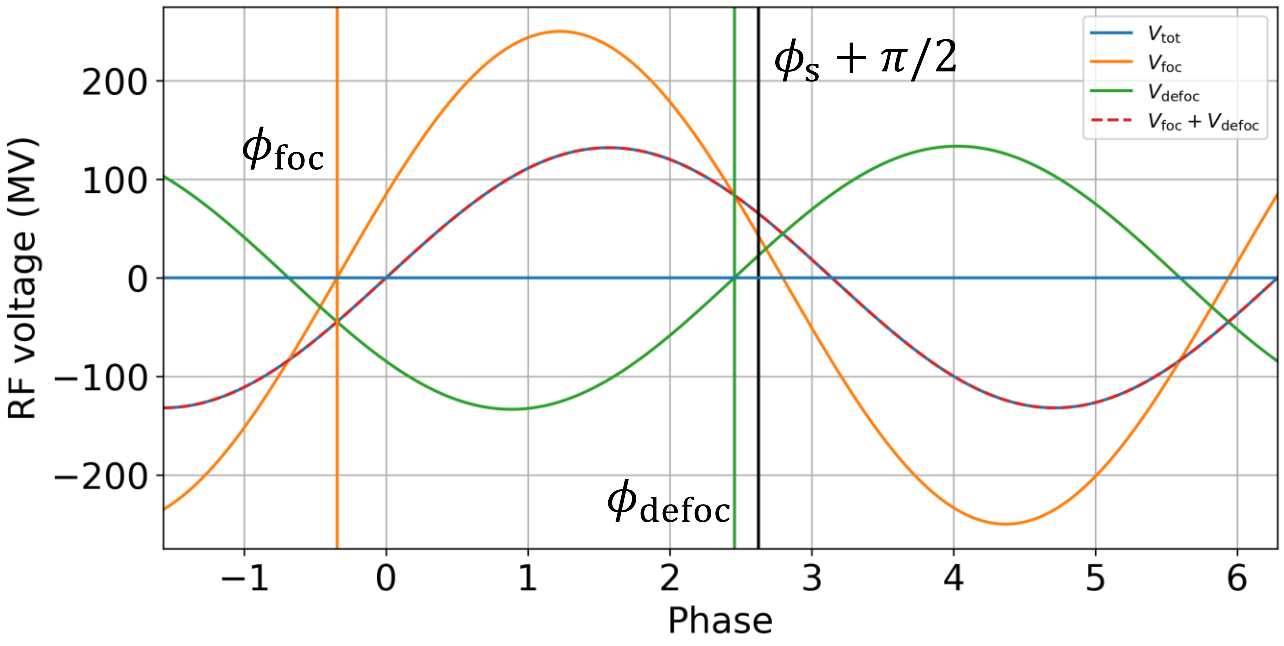
Reverse phase operation (RPO) mode allows increasing RF cavity voltage *(Y. Morita et al., SRF, 2009)*

- Experimentally verified with high beam loading in KEKB *(Y. Morita et al., IPAC, 2010)*
- Baseline solution for EIC ESR *(e.g., J. Guo et al., IPAC, 2022)*

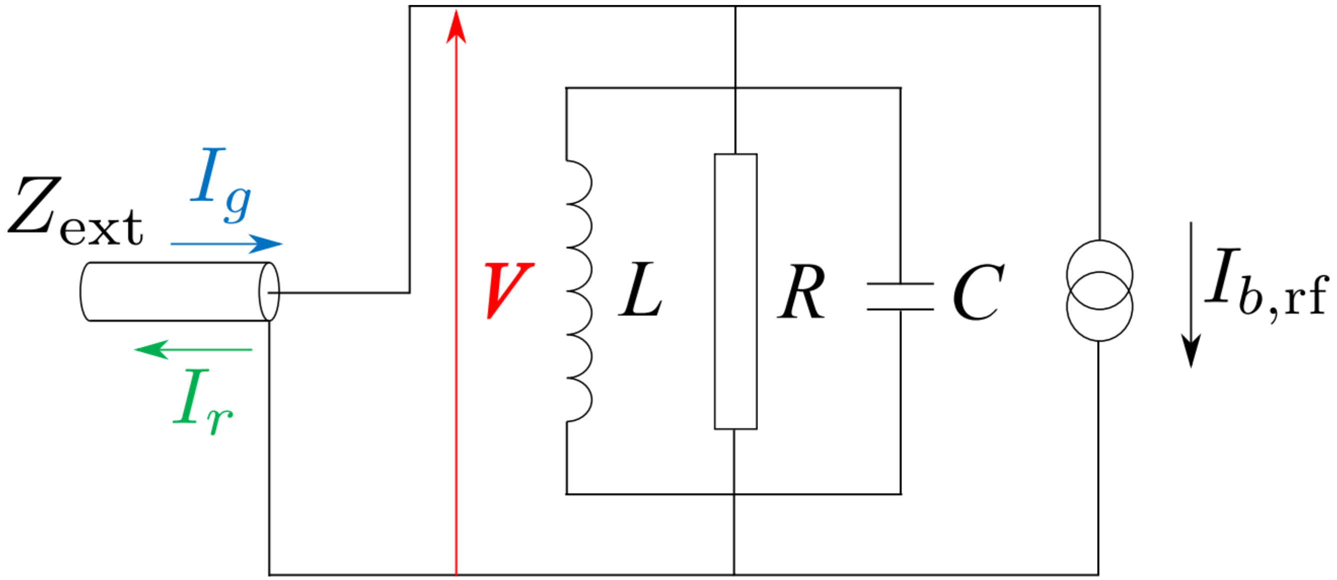
Phasors



RF waves



Beam loading model: main equation



Generator current $$I_g = \frac{V}{2(R/Q)}\left(\frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} - 2i\frac{\Delta\omega}{\omega_{\text{rf}}}\right) + \frac{I_{b,\text{rf}}}{2}$$

Generator power $$P_g = \frac{1}{2}Z_{\text{ext}}\left|I_g\right|^2 = \frac{1}{2}(R/Q)Q_{\text{ext}}\left|I_g\right|^2$$

Fixed parameters are V, (R/Q), Q_0, ω_{rf}, $I_{b,\text{rf}}$, while V, $\Delta\omega$, and Q_{ext} can be adjusted

See, e.g., J. Tückmantel, CERN Report No. CERN-ATS-Note-2011- 002 TECH, 2011

Derivations for arbitrary cavity phase (1/)

Generator current

$$I_g = \frac{V}{2(R/Q)}\left(\frac{1}{Q_0} + \frac{1}{Q_{\mathrm{ext}}} - 2i\frac{\Delta\omega}{\omega_{\mathrm{rf}}}\right) + \frac{I_{b,\mathrm{rf}}}{2}$$

($\frac{1}{Q_0} \rightarrow 0$)

$$F_b = 2\frac{\mathcal{F}[\lambda(t)]_{\omega=\omega_{\mathrm{rf}}}}{\mathcal{F}[\lambda(t)]_{\omega=0}}$$

Complex quantities: I_g, V, and $I_{b,\mathrm{rf}}$ → $I_g = |I_g|e^{i\phi_L}$, $V = |V_{\mathrm{cav}}|e^{i\phi_c}$, $I_{b,\mathrm{rf}} = |F_b|I_{b,\mathrm{dc}}e^{-i\phi_s}$

$$|I_g|e^{i\phi_L} = \frac{|V_{\mathrm{cav}}|e^{i\phi_c}}{2(R/Q)}\left(\frac{1}{Q_{\mathrm{ext}}} - 2i\frac{\Delta\omega}{\omega_{\mathrm{rf}}}\right) + \frac{|F_b|I_{b,\mathrm{dc}}e^{-i\phi_s}}{2} \qquad \Big| \times e^{-i\phi_c}$$

$$|I_g|e^{i\phi_L - i\phi_c} = \frac{|V_{\mathrm{cav}}|}{2(R/Q)}\left(\frac{1}{Q_{\mathrm{ext}}} - 2i\frac{\Delta\omega}{\omega_{\mathrm{rf}}}\right) + \frac{|F_b|I_{b,\mathrm{dc}}e^{-i\phi_s - i\phi_c}}{2}$$

Then splitting in real and imaginary parts:

Derivations for arbitrary cavity phase (2/2)

$$|I_g|e^{i\phi_L - i\phi_c} = \frac{|V_{\text{cav}}|}{2(R/Q)Q_{\text{ext}}} + \frac{|F_b|I_{b,\text{dc}}\cos(\phi_s + \phi_c)}{2} - i\left[\frac{|V_{\text{cav}}|}{(R/Q)}\frac{\Delta\omega}{\omega_{\text{rf}}} + \frac{|F_b|I_{b,\text{dc}}\sin(\phi_s + \phi_c)}{2}\right]$$

$$P_g = \frac{1}{2}(R/Q)Q_{\text{ext}}|I_g|^2$$

$$= \frac{1}{2}(R/Q)Q_{\text{ext}}\left[\frac{|V_{\text{cav}}|}{2(R/Q)Q_{\text{ext}}} + \frac{|F_b|I_{b,\text{dc}}\cos(\phi_s + \phi_c)}{2}\right]^2$$

→ Minimized for $Q_{\text{ext,opt}} = \frac{|V_{\text{cav}}|}{|F_b|(R/Q)I_{b,\text{dc}}\cos(\phi_s+\phi_c)}$

$$+ \frac{1}{2}(R/Q)Q_{\text{ext}}\left[\frac{|V_{\text{cav}}|}{(R/Q)}\frac{\Delta\omega}{\omega_{\text{rf}}} + \frac{|F_b|I_{b,\text{dc}}\sin(\phi_s + \phi_c)}{2}\right]^2$$

→ = 0 for $\Delta\omega_{\text{opt}} = -\frac{\omega_{\text{rf}}(R/Q)|F_b|I_{b,\text{dc}}\sin(\phi_s+\phi_c)}{2|V_{\text{cav}}|}$

Setting $\phi_c = 0$ recovers classical equations for optimal parameters
Adjusting ϕ_c, $Q_{\text{ext,opt}}$ can be modified to meet certain constraints

The minimum power $$P_{g,\text{opt}} = \frac{|V_{\text{cav}}||F_b|I_{b,\text{dc}}\cos(\phi_s + \phi_c)}{2} = \frac{P_{\text{SR}}}{N_{\text{tot}}}$$

Reverse phasing mode equations

Constraints:
- The same $Q_{\text{ext,opt}}$ for all cavities to avoid a movable fundamental power coupler design
- The same $P_{g,\text{opt}}$ to have the identical power sources and uniform power distribution (role of variations is under study)

$$Q_{\text{ext,opt}} = \frac{|V_{\text{cav}}|}{|F_b|(R/Q)I_{b,\text{dc}}\cos(\phi_s+\phi_c)}$$

$$P_{g,\text{opt}} = \frac{|V_{\text{cav}}||F_b|I_{b,\text{dc}}\cos(\phi_s+\phi_c)}{2}$$

→ Cavity voltage must be the same for all cavities: $\cos(\phi_s+\phi_{\text{foc}}) = \cos(\phi_s+\phi_{\text{defoc}}) \rightarrow \phi_{\text{foc}} = -2\phi_s - \phi_{\text{defoc}}$

Preservation of energy gain

$$N_{\text{foc}}|V_{\text{cav}}|\cos(\phi_s+\phi_{\text{foc}}) + N_{\text{defoc}}|V_{\text{cav}}|\cos(\phi_s+\phi_{\text{defoc}}) = V_{\text{tot}}\cos\phi_s$$

Preservation of synchrotron tune

$$N_{\text{foc}}|V_{\text{cav}}|\sin(\phi_s+\phi_{\text{foc}}) + N_{\text{defoc}}|V_{\text{cav}}|\sin(\phi_s+\phi_{\text{defoc}}) = V_{\text{tot}}\sin\phi_s$$

$$|V_{\text{cav}}| = \frac{V_{\text{tot}}}{N_{\text{tot}}}\sqrt{\frac{U_0^2}{V_{\text{tot}}^2} + \left(1-\frac{U_0^2}{V_{\text{tot}}^2}\right)\frac{N_{\text{tot}}^2}{(N_{\text{foc}}-N_{\text{defoc}})^2}}$$

See, also *A. Blednykh et al, EIC-ADD-TN-33, 2022*

The aim is to keep V_{cav}, $P_{g,\text{opt}}$, and $Q_{\text{ext,opt}}$ for Z, W, and H modes

Preliminary results

```
Total number of cavities 132, change wrt baseline 0.00 %
Number of focusing cavities 71.0, number of defocusing 61.0
RF power per cavity 378.79 kW, change wrt baseline 0.00 %
Q_L opt 9.21e+05 for V_cav 7.95 MV change to baseline -0.087 %
V_Z actual 0.088 GV, change wrt baseline 12.000 %
V_W actual 1.049 GV, change wrt baseline 4.908 %
V_H actual 2.098 GV, change wrt baseline 0.391 %
Q_s Z: computed 0.0311, change wrt baseline 7.54 %
Q_s W: computed 0.0833, change wrt baseline 2.86 %
Q_s H: computed 0.0343, change wrt baseline 0.93 %
RF acceptance Z: computed 1.20, change wrt baseline 14.20 %
RF acceptance W: computed 3.50, change wrt baseline 4.57 %
RF acceptance H: computed 2.10, change wrt baseline 2.56 %
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```
Total number of cavities 152, change wrt baseline 15.15 %
Number of focusing cavities 81.0, number of defocusing 71.0
RF power per cavity 328.95 kW, change wrt baseline -13.16 %
Q_L opt 7.93e+05 for V_cav 6.88 MV, change wrt baseline -13.571 %
V_Z actual 0.079 GV, change wrt baseline 0.000 %
V_W actual 1.045 GV, change wrt baseline 4.500 %
V_H actual 2.090 GV, change wrt baseline 0.000 %
Q_s Z: computed 0.0289, change wrt baseline 0.00 %
Q_s W: computed 0.0832, change wrt baseline 2.62 %
Q_s H: computed 0.0340, change wrt baseline 0.00 %
RF acceptance Z: computed 1.05, change wrt baseline 0.00 %
RF acceptance W: computed 3.49, change wrt baseline 4.20 %
RF acceptance H: computed 2.05, change wrt baseline 0.00 %
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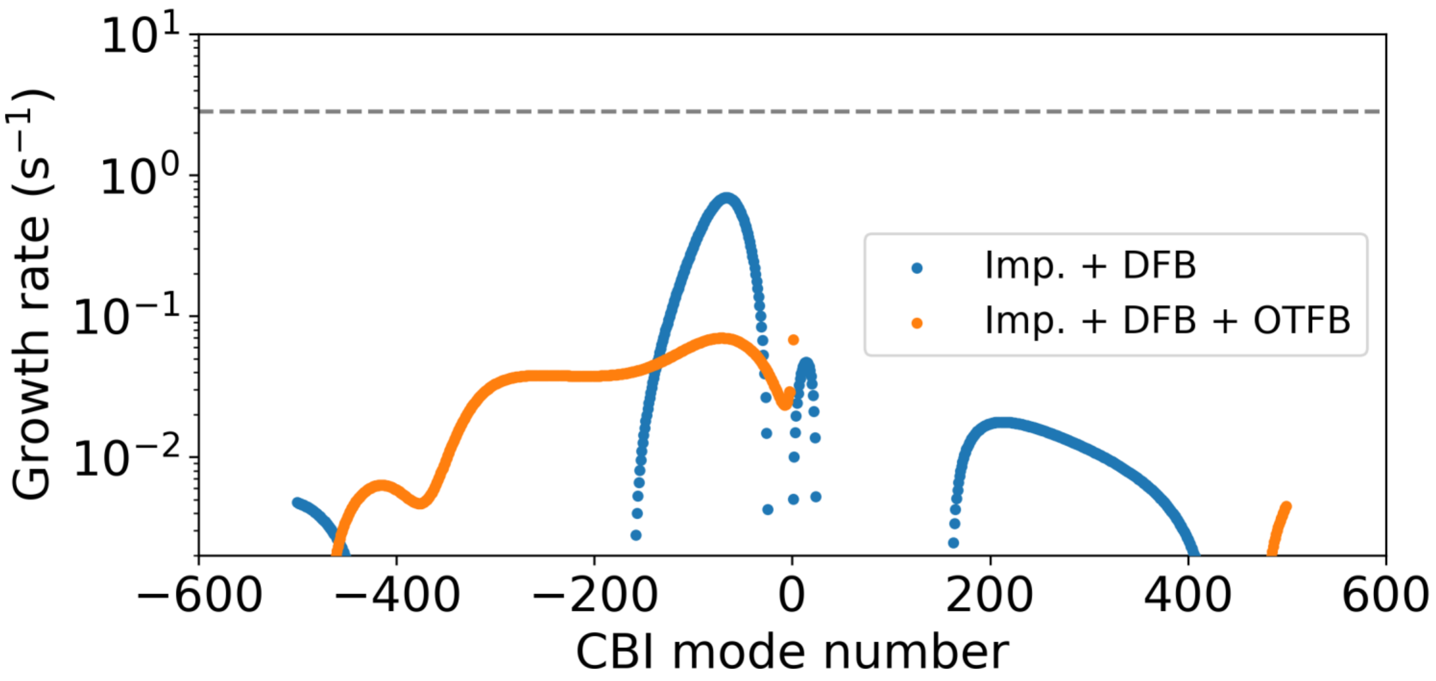
→ RPO is under evaluation potentially allowing for the same optimal quality factor for Z, W, and H modes

Thank you for your attention!

Backup slides

Coupled-bunch instability due to fundamental mode



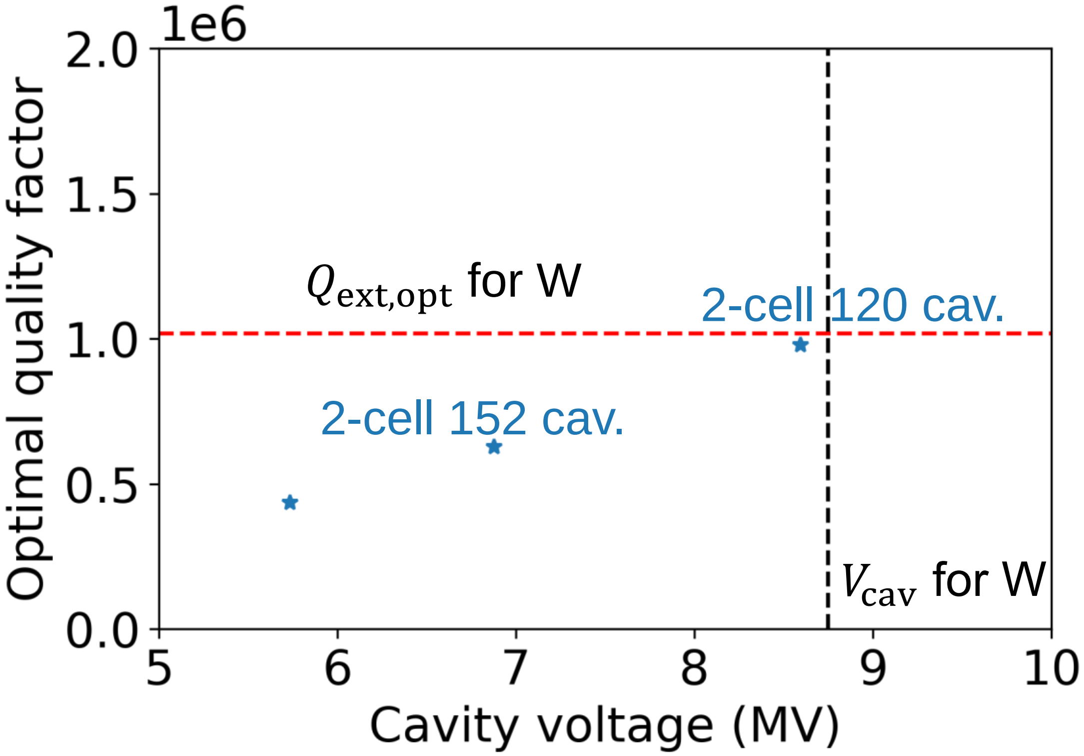
A factor of 4 margin with DRF only, ~40 with additional OTFB

Preliminary results

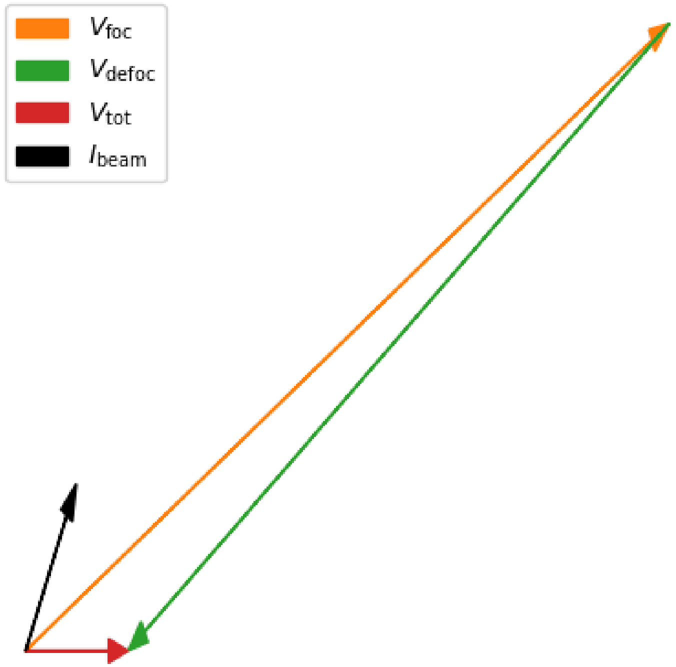
$$|V_{\text{cav}}| = \frac{V_{\text{tot}}}{N_{\text{tot}}} \sqrt{\frac{U_0^2}{V_{\text{tot}}^2} + \left(1 - \frac{U_0^2}{V_{\text{tot}}^2}\right) \frac{N_{\text{tot}}^2}{(N_{\text{foc}} - N_{\text{defoc}})^2}}$$

Optimal quality factor with RPO

$$Q_{\text{ext,opt}} = \frac{V_{\text{cav}}^2 N_{\text{tot}}}{V_{\text{tot}}(R/Q)|F_b|I_{b,\text{dc}} \cos\phi_s}$$



→ RPO is under evaluation potentially allowing for the same optimal quality factor for Z, W, and H modes


V_{foc}
V_{defoc}
V_{tot}
I_{beam}

Reverse phasing mode equations

Constraints: $|V_{\mathrm{cav}}|$ and $P_{g,\mathrm{opt}}$ are the same for focusing and defocusing cavities

$\rightarrow \cos(\phi_s + \phi_{\mathrm{foc}}) = \cos(\phi_s + \phi_{\mathrm{defoc}}) \rightarrow \phi_{\mathrm{foc}} = -2\phi_s - \phi_{\mathrm{defoc}}$

$$P_{g,\mathrm{opt}} = \frac{|V_{\mathrm{cav}}||F_b|I_{b,\mathrm{dc}}\cos(\phi_s + \phi_c)}{2}$$

Preservation of energy gain

$$N_{\mathrm{foc}}|V_{\mathrm{cav}}|\cos(\phi_s + \phi_{\mathrm{foc}}) + N_{\mathrm{defoc}}|V_{\mathrm{cav}}|\cos(\phi_s + \phi_{\mathrm{defoc}}) = V_{\mathrm{tot}}\cos\phi_s$$

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	RPO	**Classical**
Optimal quality factor	$Q_{\mathrm{ext,opt}} = \dfrac{V_{\mathrm{cav}}^2 N_{\mathrm{tot}}}{V_{\mathrm{tot}}(R/Q)|F_b|I_{b,\mathrm{dc}}\cos\phi_s}$	$Q_{\mathrm{ext,opt}} = \dfrac{V_{\mathrm{cav}}}{|F_b|(R/Q)I_{b,\mathrm{dc}}\cos\phi_s}$
Optimal detuning	$\Delta\omega_{\mathrm{opt}} = -\dfrac{\omega_{\mathrm{rf}}(R/Q)|F_b|I_{b,\mathrm{dc}}}{2V_{\mathrm{cav}}}\sqrt{1 - \dfrac{\cos^2\phi_s V_{\mathrm{tot}}^2}{V_{\mathrm{cav}}^2 N_{\mathrm{tot}}^2}}$	$\Delta\omega_{\mathrm{opt}} = -\dfrac{\omega_{\mathrm{rf}}(R/Q)|F_b|I_{b,\mathrm{dc}}\sin\phi_s}{2V_{\mathrm{cav}}}$