RF system issues due to pulsed beam in ILC DR

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RF system parameters

Frequency f	650 MHz
Cavity type	single-cell SRF
Cavity R/Q, accelerator definition	89 Ohm
Number of cavities per ring N_c	18
Accelerating voltage per cavity V_c	1.33 MV
Beam power per cavity P_b	194 kW
Beam current I_b	400 mA
Energy loss per turn per cavity $\Delta E/e$	0.485 MV
Overvoltage factor η	2.742
Synchronous phase φ_0	68.6°
Cavity input coupler external quality factor Q_{ext}	1.024×10^5

Main constrains

- 10 Hz beam repetition rate, 50 ms beam on/off time, ~1 ms injection/extraction time to fill/empty the ring
- Available klystron power: 1 MW or 250 kW per cavity
- RF window power handling

RF power demand

The RF power in the presence of beam can be expressed as

$$P_{\text{forw}} = \frac{V_{\text{c}}^{\ 2}}{4R/Q \cdot Q_{\text{ext}}} \cdot \frac{(\beta+1)^2}{\beta^2} \cdot \left\{ \left[1 + \frac{I_{\text{b}}\, R/Q \cdot Q_{\text{L}}}{V_{\text{c}}} \cos\varphi_0 \right]^2 + \left[\tan\psi + \frac{I_{\text{b}}\, R/Q \cdot Q_{\text{L}}}{V_{\text{c}}} \sin\varphi_0 \right]^2 \right\} \approx$$

$$\approx \frac{V_{\text{c}}^{\ 2}}{4R/Q \cdot Q_{\text{L}}} \cdot \left\{ \left[1 + \frac{I_{\text{b}}\, R/Q \cdot Q_{\text{L}}}{V_{\text{c}}} \cos\varphi_0 \right]^2 + \left[\tan\psi + \frac{I_{\text{b}}\, R/Q \cdot Q_{\text{L}}}{V_{\text{c}}} \sin\varphi_0 \right]^2 \right\}, \qquad (1)$$

where $\beta >> 1$ is the coupling factor, Q_L is the cavity loaded quality factor, φ_0 is the beam phase relative to the crest of RF wave (a.k.a. synchronous phase), ψ is the cavity tuning angle.

The first term includes active part of beam loading (due to particle energy loss), the second term includes reactive beam loading. The latter is usually compensated by appropriate cavity detuning with a mechanical tuner so that the second term in square brackets is always zero. And then for maximum beam current and optimal quality factor the power demand is simply equal to the beam power per cavity (194 kW).

RF power demand (2)

However, it is not possible to tune the cavity mechanically fast enough to compensate reactive portion of the beam loading during injection (~1 ms).

For the DR parameters we get

$$\tan\psi = 2Q_{\mathrm{L}}\frac{\Delta f}{f} = -2.553,\ \ \Delta f = -8.1\ \ \mathrm{kHz}$$

And, assuming that the cavity is appropriately detuned to compensate the beam current, the power demand when the beam is ejected becomes

$$P_{\mathrm{forw}} = \frac{V_{\mathrm{c}}^{\ 2}}{4\,R/Q\cdot Q_{\mathrm{L}}}\cdot\left[\ 1+\left(\tan\psi\right)^{2}\right] = 365\ \ \mathrm{kW},$$

which (i) exceeds the power available from the klystron and (ii) being fully reflected from the cavity, creates standing wave pattern thus creating a power handling problem for an RF window/coupler and transmission line.

Below we present several approaches on how to deal with this problem and what additional studies are necessary.

Option #1: lower overvoltage factor

Alessandro Gallo (DAFNE RF system, LNF) performed further analysis and derived

$$\tan\psi_{\max} \approx -\frac{(R/Q)Q_{ext}I_{b_{\max}}}{V_c}\sin\varphi_0 = \frac{(R/Q)Q_{ext}I_{b_{\max}}}{V_c}\sqrt{1-\frac{1}{\eta^2}} \underbrace{=}_{eq.2} \sqrt{\eta^2-1}$$

$$P_{FWD}(I_b=0) = P_{beam_{\max}}\left[\frac{1}{4}+\frac{\tan^2\psi_{\max}}{4}\right] = \left(\frac{\eta}{2}\right)^2 P_{beam_{\max}}$$

where η is the overvoltage factor. One can see that for $\eta \le 2$ the cavities can be operated at fixed detuning while the power demand for zero beam current does not exceed the maximum beam power.

Questions:

- □ Is it possible to reduce the overvoltage factor?
- □ How it was chosen in the first place?

Option #2: optimal detuning

This is also due to Alessandro Gallo's analysis. For an arbitrary detuning one can derive

$$P_{FWD}(I_b) \approx \frac{I_{b_{\max}} V_{loss}}{4} \left[\left(1 + \frac{I_b}{I_{b_{\max}}}\right)^2 + \left(\tan\psi - \frac{I_b}{I_{b_{\max}}} \tan\psi_{\max}\right)^2 \right] =$$

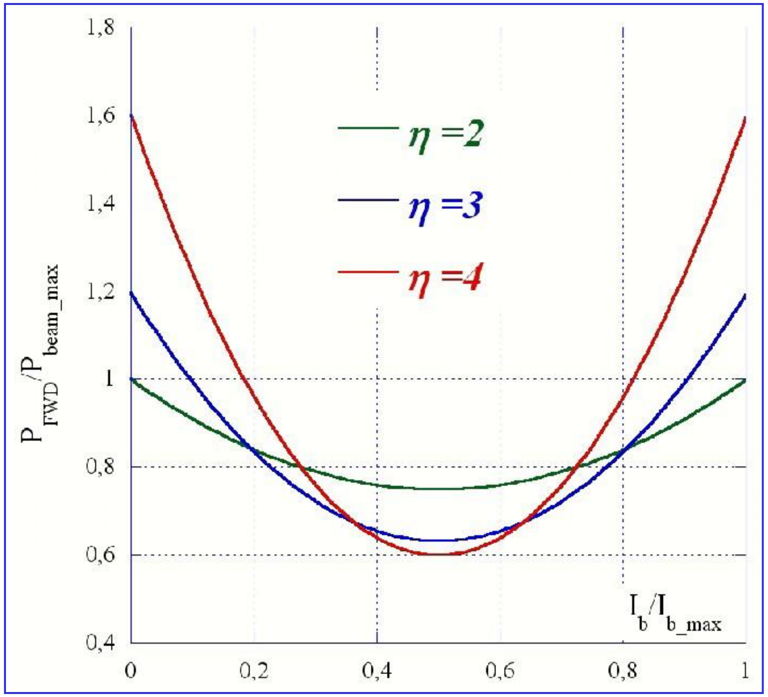
$$= P_{beam_{\max}} \left[\left(\frac{1 + I_b / I_{b_{\max}}}{2}\right)^2 + \frac{\tan^2\psi}{4} \left(1 - \frac{I_b}{I_{b_{\max}}} \frac{\tan\psi_{\max}}{\tan\psi}\right)^2 \right]$$

For $\eta > 2$ the cavities can be operated at an optimal detuning that is different from maximum detuning and is derived from a condition $P_{FWD}(0) = P_{FWD}(I_{bmax})$:

$$\tan\psi_{opt} = \frac{3 + \tan^2\psi_{\max}}{2\tan\psi_{\max}} = \frac{2 + \eta^2}{2\sqrt{\eta^2 - 1}}$$

The power demand increase factor is

$$\left.\frac{P_{FWD}(I_b = 0)}{P_{beam_{\max}}}\right|_{\psi = \psi_{opt}} = \left.\frac{P_{FWD}(I_{b_{\max}})}{P_{beam_{\max}}}\right|_{\psi = \psi_{opt}} = \frac{\eta^2 (8 + \eta^2)}{16 (\eta^2 - 1)}$$



Option #2: optimal detuning (2)

No we can compare maximum detuning case with optimal detuning

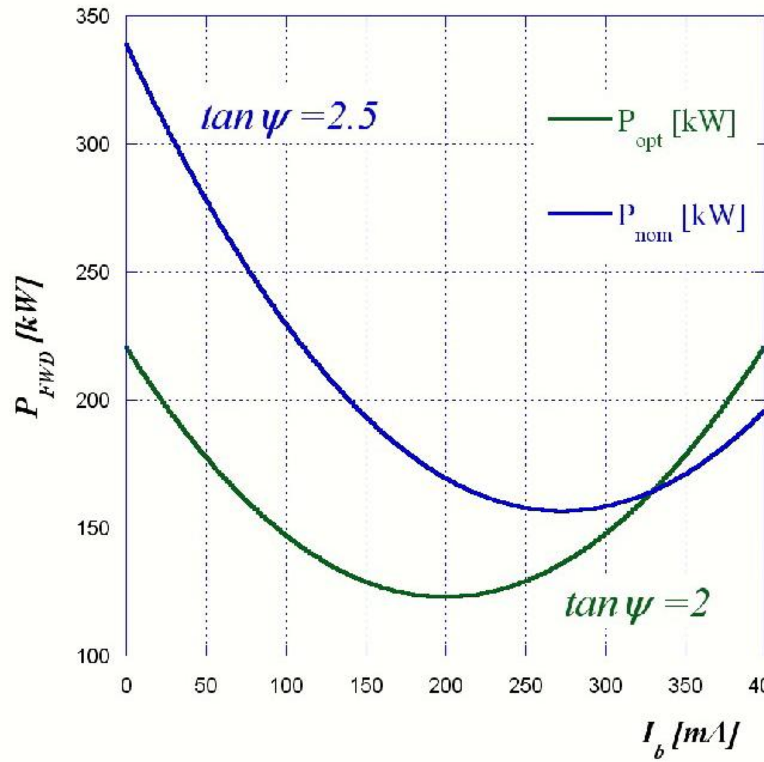
$$\left.\frac{P_{FWD}(I_b)}{P_{beam_{\max}}}\right|_{\psi=\psi_{opt}} = \left(\frac{1+I_b/I_{b_{\max}}}{2}\right)^2 + \frac{\left(3+\tan^2\psi_{\max}\right)^2}{16\tan^2\psi_{\max}}\left(1-\frac{I_b}{I_{b_{\max}}}\frac{2\tan^2\psi_{\max}}{3+\tan^2\psi_{\max}}\right)^2 =$$

$$= \left(\frac{1+I_b/I_{b_{\max}}}{2}\right)^2 + \frac{\left(2+\eta^2\right)^2}{16\left(\eta^2-1\right)}\left(1-\frac{I_b}{I_{b_{\max}}}\frac{2\left(\eta^2-1\right)}{2+\eta^2}\right)^2$$

For the DR parameters $\tan\psi_{opt}$ = 1.864 and power demand is 217kW.

Concern:

The RF system will have to operate half of the time on a wrong side of the resonance, where it is unstable (the first Robinson criterion). 50 ms is long enough time for the instability to develop. A direct RF feedback around the cavity may help, but a careful study and simulations are required to determine if it is possible to develop such a feedback for the ILC DR case.



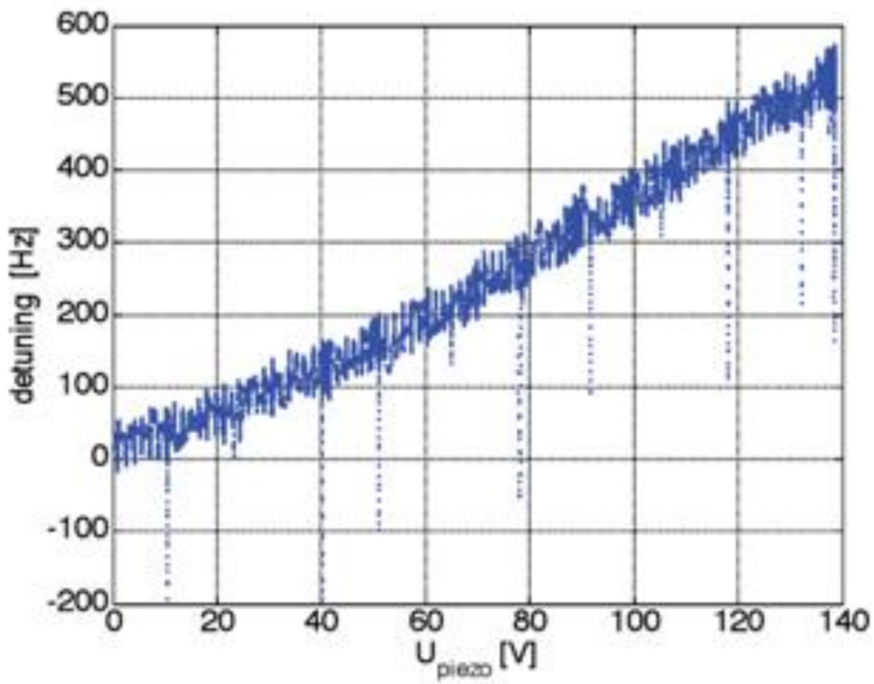
f_{RF} =	650 MHz
R/Q =	89 Ω
V_{cav} =	1.33 MV
V_{loss} =	0.485 MV/turn
Q_{ext} =	102000
$\cos\varphi_s$ =	0.365
$\sin\varphi_s$ =	-0.931
$\tan\psi$ =	2.5

Option #3: fast frequency tuner

With a fast frequency tuner (piezoelectric or magnetostrictive) one can detune the cavity fast enough to follow the beam current increase during injection/extraction. The only known to me storage ring, where piezo tuner were used in routine operation on superconducting cavities, is TRISTAN. I don't have the parameters of that system though. CESR B-cell cryomodules are equipped with piezo tuners, which were used in experiments to study microphonic noise and feedback, but the piezos were not intended to cover large detuning and hence the range is limited:

Further studies/concerns:

- This approach will need further studies of achievable tuning range and speed.
- Tuning in ~1 ms is within the technology state of the art
- But excitation of mechanical resonances could be a limiting factor.
- Alternative tuning schemes (reactive coupling?)



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Option #4: fast coupling change

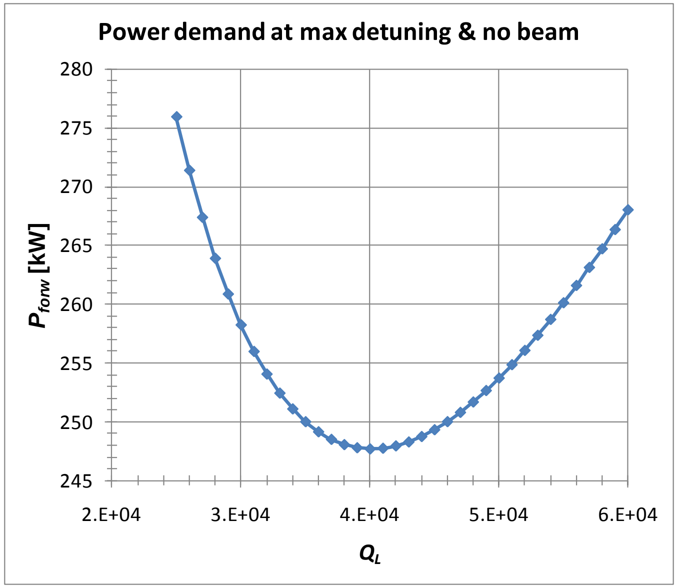
This would involve developing a fast waveguide tuner to change the cavity coupling during injection/extraction and thus decrease the power demand. Such tuners are under development at several laboratories, but are not used in operations yet. Changing the cavity coupling alone is not enough as even in the best case of

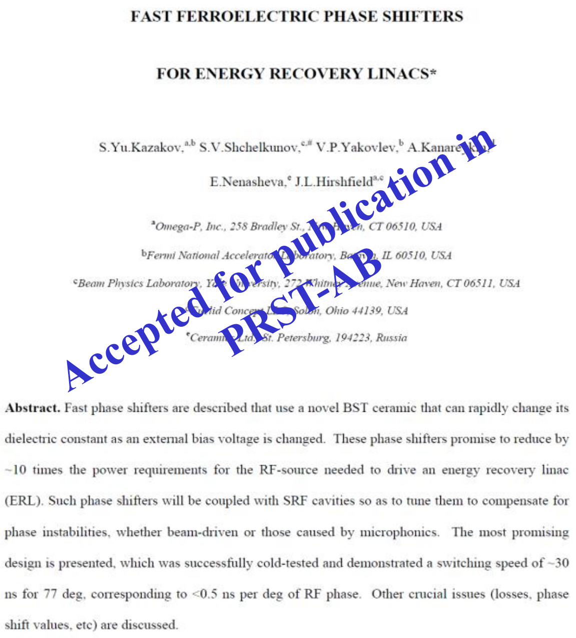
$Q_{ext} = f / (2 \cdot |\Delta f_{max}|) = 4.01 \ \ 10^4$ (maximum detuning, no beam)

the power demand is still high:

$$P_{forw} = |\tan\psi| \cdot P_b = 248 \text{ kW.}$$

It may, however be used in combination with options #2 or #3.





FAST FERROELECTRIC PHASE SHIFTERS

FOR ENERGY RECOVERY LINACS*

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Abstract. Fast phase shifters are described that use a novel BST ceramic that can rapidly change its dielectric constant as an external bias voltage is changed. These phase shifters promise to reduce by ~10 times the power requirements for the RF-source needed to drive an energy recovery linac (ERL). Such phase shifters will be coupled with SRF cavities so as to tune them to compensate for phase instabilities, whether beam-driven or those caused by microphonics. The most promising design is presented, which was successfully cold-tested and demonstrated a switching speed of ~30 ns for 77 deg, corresponding to <0.5 ns per deg of RF phase. Other crucial issues (losses, phase shift values, etc) are discussed.

Further studies:

This approach will need further studies of achievable coupling range, speed and power handling.

Summary

- 10 Hz operation of the ILC Damping Ring RF system seems to be feasible.
- We have presented four different options. Each of them however have challenges.
- Option #3 is the most attractive as the RF power demand is minimal under it. However, it requires extensive R&D.
- Option #1 would be the most easily implementable is the overvoltage factor can be lowered to 2.

Common concerns & studies needed (in addition to those listed for individual options):

- RF window/coupler power handling with full reflection (except option #3)
- Feedforward to mitigate transients during beam injection/extraction
- Pulsed operation of the RF system is worth considering as it will save power and reduce thermal load on RF window/coupler. Two options here: (i) pulsed RF and klystron mod anode; (ii) pulsed klystron HV.