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Cosecant Energy-Phase Ramp for Linear Response RF Cavities

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Abstract: For RF cavities where V_s, the on-axis voltage scaling factor, relates to V_{eff}, the effective voltage upon the beam through a linear constant, this note demonstrates a method to rapidly change cavity energy by coupling cavity voltage to a phase parameter.

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1 Introduction

In [1] while analyzing the (non) linear response of different linac cavities at ISAC, I briefly treated the example of debunching. In this note, I consider a general booster cavity whose accelerating profile is small or neutral ($\beta_f \sim \beta_i$), a case which is broadly representative of many linear-response RF cavities at ISAC, where:

$$V_{\mathit{eff}}(V_s) \approx kV_s \tag{1}$$

In other words the effective voltage response is linear to the on-axis field scaling factor V_s over the range of operational parameters for the latter. Such cavities include the ISAC RF booster [2], the ISAC DTL bunchers [3], the HEBT 11 and 35 MHz bunchers [4], the DSB buncher[1] and the SCRF resonators [5].

In any cavity for which (1) holds, if an operator measures the minimum voltage V_0 and associated phase ϕ_0 for which a certain debunching effect can be achieved, for any cavity phase setting ϕ, by setting V_s to:

$$V_s(\phi) = \frac{V_0}{\cos(\phi - \phi_0)} \tag{2}$$

This condition will produce a monotonic energy variation spanning the range of available cavity output energies, from full deceleration up to maximum acceleration, all the while keeping the longitudinal energy spread minimized [1]. Another way to understand V_0: it is the minimum voltage for which an energy focus can be achieved at a downstream target. If needed, the time spread of the beam distribution can be used instead of energy, for example on a time-of-flight monitor. The angle $\phi \in [-\pi/2, \pi/2]$, produces asymptotes to infinity for V_s; the angle ϕ should be kept away from the edges!

It is clear that this is a very important relationship for variable output energy cavity operation, the norm at TRIUMF-ISAC. In this note, this relationship (2) and the resulting output energy-phase ramp it produces, is demonstrated in TRANSOPTR.

2 Single Cavity E-ϕ Coupling

A two-gap linear response RF cavity, whose on-axis longitudinal field $\mathcal{E}(s)$ [6] is shown in Figure 1 was used to demonstrate this energy-phase ramp in TRANSOPTR. For a beam of ^{22}Ne^{4+} at injection energy of 33.66 MeV, the output energy configuration space and output inverse energy spread are shown in Figure 2.

[1] the DSB buncher is identical in design to the 35MHz HEBT buncher.

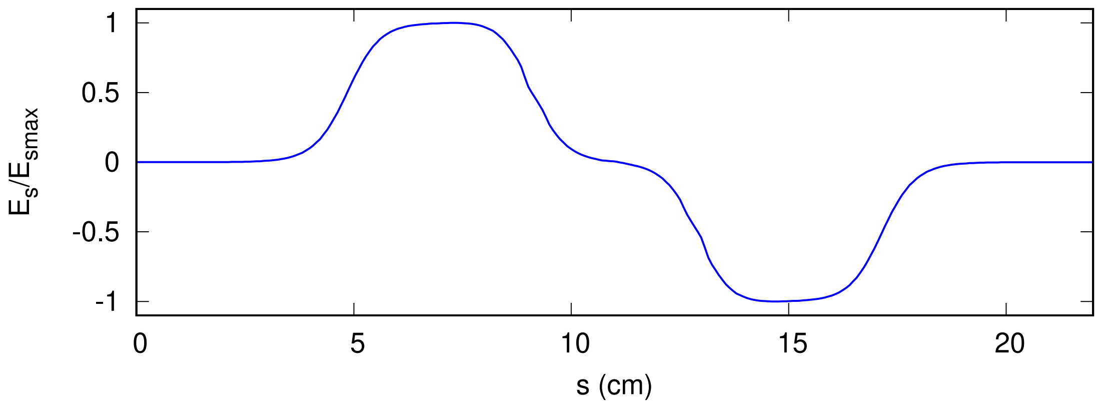


Figure 1: Longitudinal electric field distributions $\mathcal{E}(s)$ for the two-gap resonators used in this note for `TRANSOPTR` with subroutine `linac`.

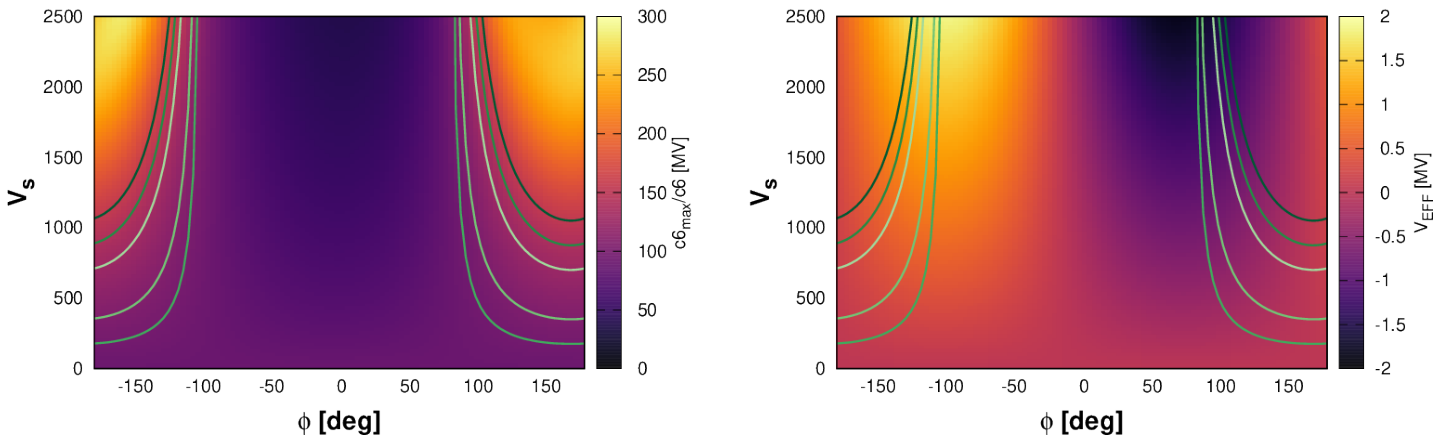


Figure 2: **Left:** `TRANSOPTR` Normalized inverse longitudinal energy spread, as measured at a downstream diagnostic, for the field in Figure 1. (**Right:**) Effective voltage on beam for same field, as measured downstream. Both scans defined on a 100 by 100 grid.

Equation (2) has also been plotted on Figure 2, for arbitrary values of V_0. On the left, we see the different cosecant curves, associated with each V_0, delineate paths of constant debunching through cavity (V_s, ϕ) configuration space. These same curves are evaluated on the mapping for cavity output energy versus (V_s, ϕ), shown in Fig. 2, right, tracing paths for a family of variable energy ramp solutions for the cavity, using a single energy change phase parameter. This phase parameter is referenced to the point of minimum (V_0, ϕ_0).

The python script topology [7] has been adapted to scan the phase associated with Eq. (2) for the subroutine linac. This was first carried out with the two-gap RF cavity, SCB1-1. The simulation started from the start of /acc database sequence scb1_db0.xml and terminated at SEBT:FTM20, the furthest downstream flight time monitor. A beam of ^{22}Ne^{4+} was employed at injection energy 33.66 MeV (1.53 MeV/u). The RF frequency was set to 106.08 MHz. The phase ϕ_0 which produced the minimum P_z, referred to also as the pure bunching phase, was identified. At this ϕ_0, different values of V_0 were arbitrarily chosen, on the 0-2500 EPICS V_s scale. A tuneable phase parameter was then defined as:

$$\theta = \phi - \phi_0 \tag{3}$$

ϕ_0 was found to be roughly -190°, so θ = ϕ + 190. The different phase ramps associated with each V_0 are shown in Figure 3. The the inverse z-momentum and corresponding E(θ) are shown in Figure 4 top and bottom, respectively. The significance of (2) is that it allows an operator to smoothly and rapidly vary the cavity output energy by only changing the cavity phase ϕ, should the voltage be automatically computed at each step.

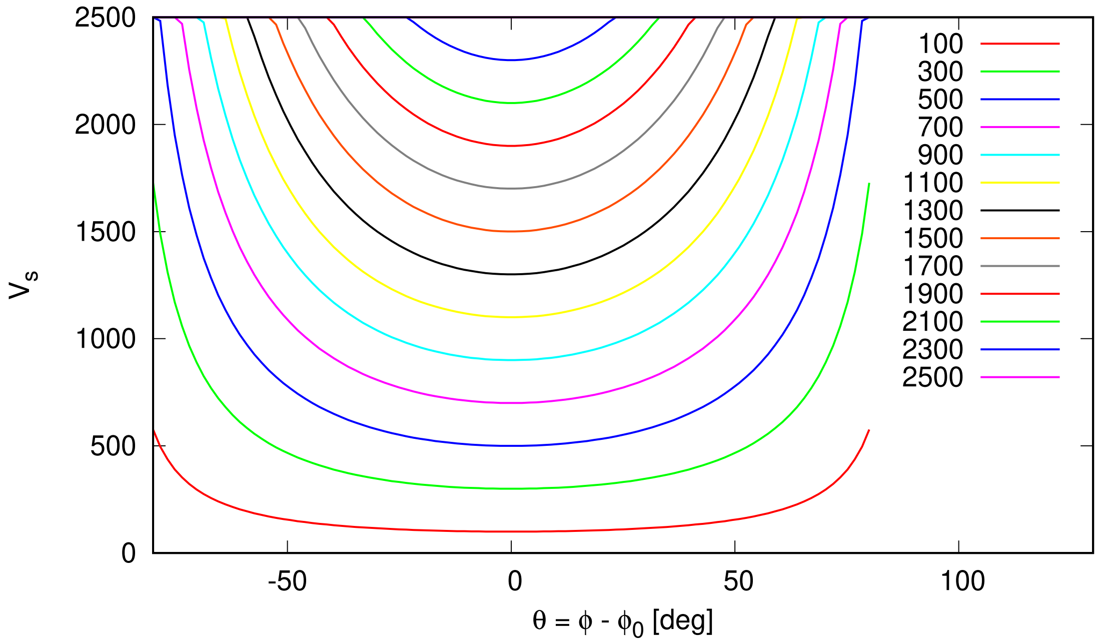
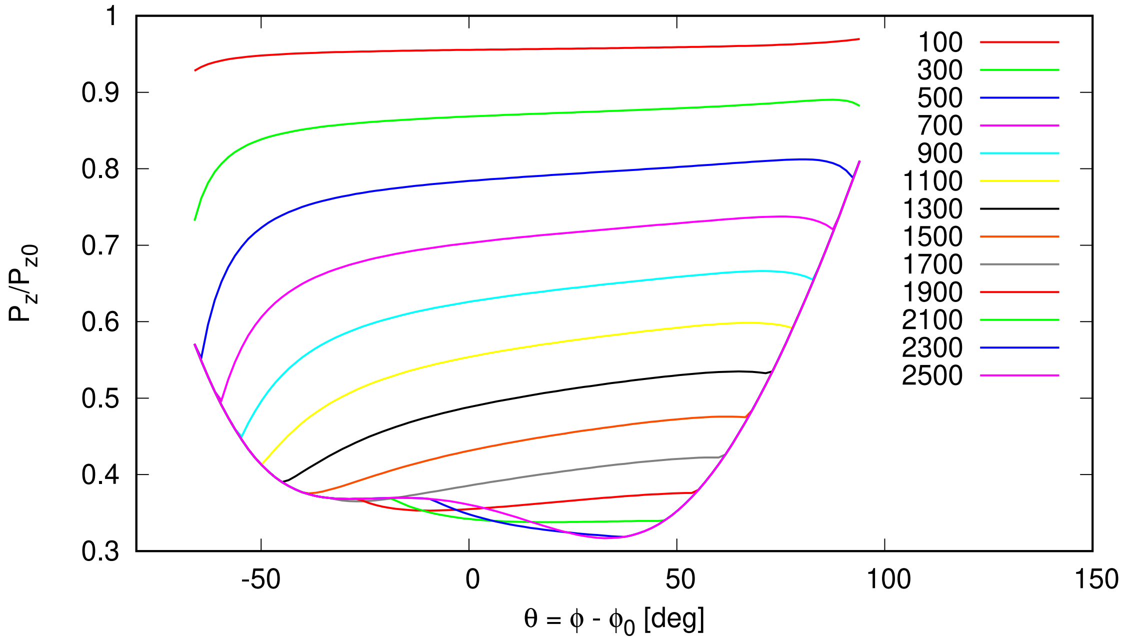


Figure 3: TRANSOPTR-simulated cosecant V_s-ϕ ramp following Equation (2) on the $\mathcal{E}(s)$ in Fig. 1. Factors V_0 associated for each curve shown in legend.



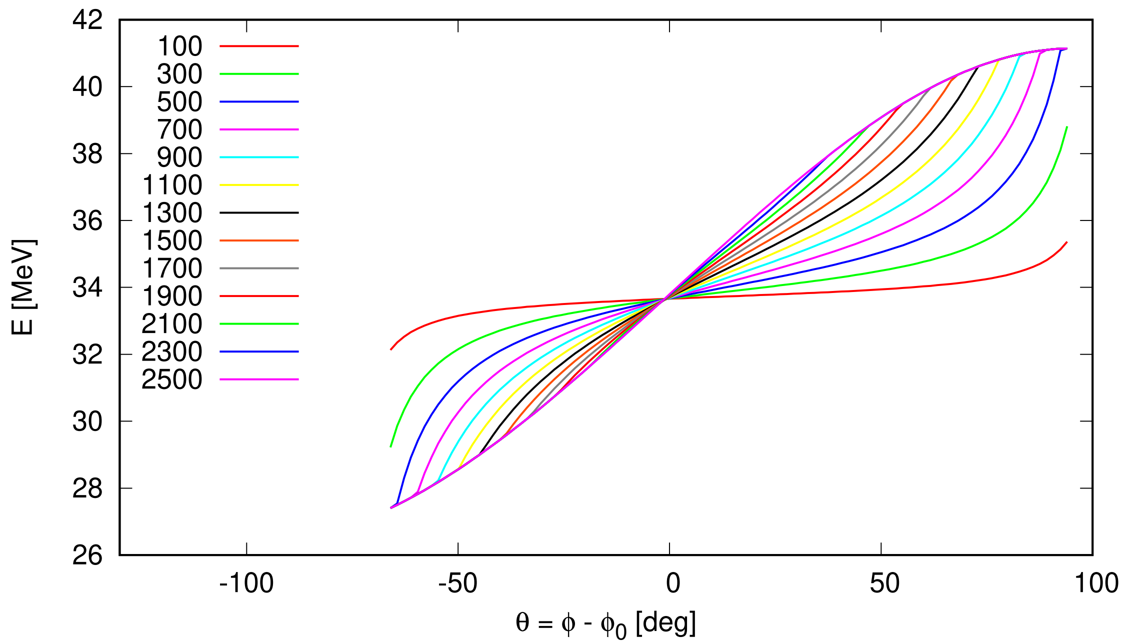


Figure 4: TRANSOPTR-simulated **Top:** normalized longitudinal momentum spread associated with (V_s, ϕ) from Fig. 3. **Bottom:** Resulting phase energy ramp for the cavity. Factors V_0 associated for each curve shown in legend.

3 Conclusion

The energy ramp (2) is of great interest for ISAC RF cavity tuning, particularly given the variable output energy operation requirement. It is clear from Figure 4, bottom, that we should wish to operate cavities at a suitable value of V_0 which produces a sufficiently sensitive energy-phase response, while also providing a useful energy range.

For ISAC-I, this is of interest for the ISAC-RF Booster and more generally any RF cavity excluding the IH DTL accelerating tanks, in addition to a possible use for HEBT experiments. In the case of SCRF, the current operational tuning procedures used for initial SCRF cavity setup record all information needed to parametrise the cosecant ramp.

The energy-phase lines in Figure 4, bottom also produce characteristic curves which can be used to calibrate the parameters (V_s, ϕ) for any of the above-mentioned cavities, not to mention verifying model-machine agreement. The coupling of V_s and ϕ_0 from eq. (2) may provide a novel technique for operators to perform rapid energy changes for any ISAC RF cavity featuring a linear response between V_s and V_{eff} [1].

References

[1] Shelbaya O. Nonlinear RF Cavities. Technical Report TRI-BN-20-05, TRIUMF, 2020.

[2] Robert Laxdal, Zhengting Ang, Thomas Au, Spencer Kiy, Stephanie Rädel, Olivier Shelbaya, Vladimir Zvyagintsev, et al. A 3-gap booster cavity to match ion source potential to rfq acceptance. In *29th Linear Accelerator Conf.(LINAC'18), Beijing, China, 16-21 September 2018*, pages 196–199. JACOW Publishing, Geneva, Switzerland, 2018.

[3] Vasyuchenko A, Feschenko A, Kvasha A, Menshov A, and Paramonov V et al. *Development, Fabrication and Test of Triple Gap Split-Ring Bunchers for the TRIUMF ISAC Facility*. In *Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL*, pages 978–80, 2001.

[4] AK Mitra, PJ Bricault, IV Bylinskii, K Fong, G Dutto, RE Laxdal, RL Poirier, et al. *RF Test and Commissioning of the Radio Frequency Structures of the TRIUMF ISAC I facility*. In *Proceedings of LINAC*, page 106, 2002.

[5] A Facco, V Zviagintsev, R Laxdal, and Enrico Chiaveri. The superconducting medium beta prototype for radioactive beam acceleration at triumf. In *PACS2001. Proceedings of the 2001 Particle Accelerator Conference (Cat. No. 01CH37268)*, volume 2, pages 1092–1094. IEEE, 2001.

[6] R. Baartman. Linac Envelope Optics. Technical Report TRI-BN-15-03, TRIUMF, 2015.

[7] Shelbaya O. Longitudinal Beam Topology with TRANSOPTR. Technical Report TRI-BN-20-01, TRIUMF, 2020.