Energy-Optimal Cavity Filling

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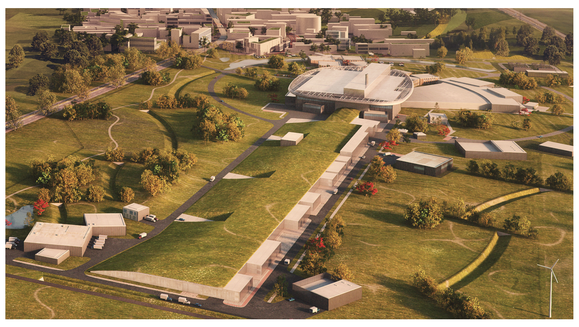
Overview

Pulsed, high-power accelerators consume significant amounts of power to fill the cavities, power which does not contribute to particle acceleration. A recent paper [1] considered how to minimize the *reflected* power during filling, which essentially corresponds to minimizing the energy consumption of an ideal amplifier. We demonstrate how to find optimal filling profiles for *arbitrary* efficiency characteristics, and also in presence of detuning (assumed to be repetitive and known). The results on this poster has been previous published in [2].

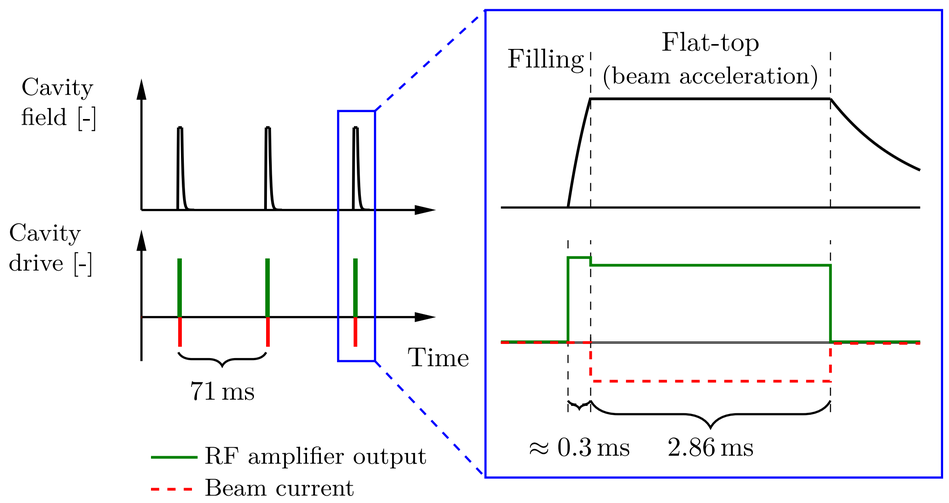
Example: European Spallation Source

ESS Parameters

Beam Current	62.5 A
Pulse length	2.86 ms
Pulse rate	14 Hz
Average Beam Power	5 MW
Final Energy	2 GeV
# SRF Cavities	146
Construction cost	≈2 B€



Pulse structure:



► Total electricity cost for filling the 84 high-β cavities powered by inductive output tubes (IOTs): **100 k€/year**

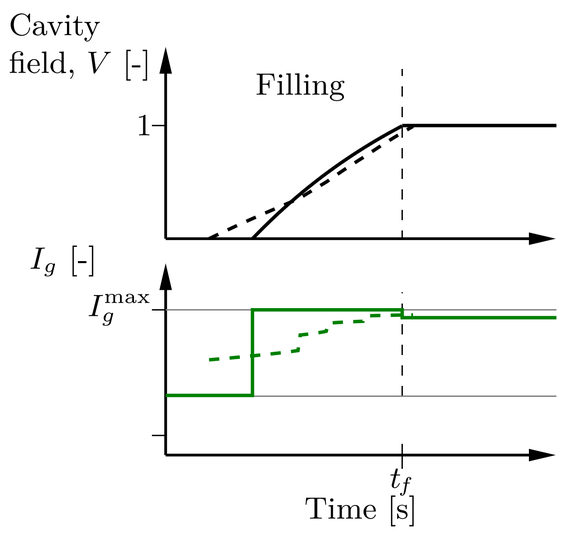
Optimal Control Problem (Amplitude)

Cavity dynamics during filling (no beam), normalized wrt time and amplitude:

$$\dot{V}(t) = -V(t) + I_g(t)$$

Optimal control problem:

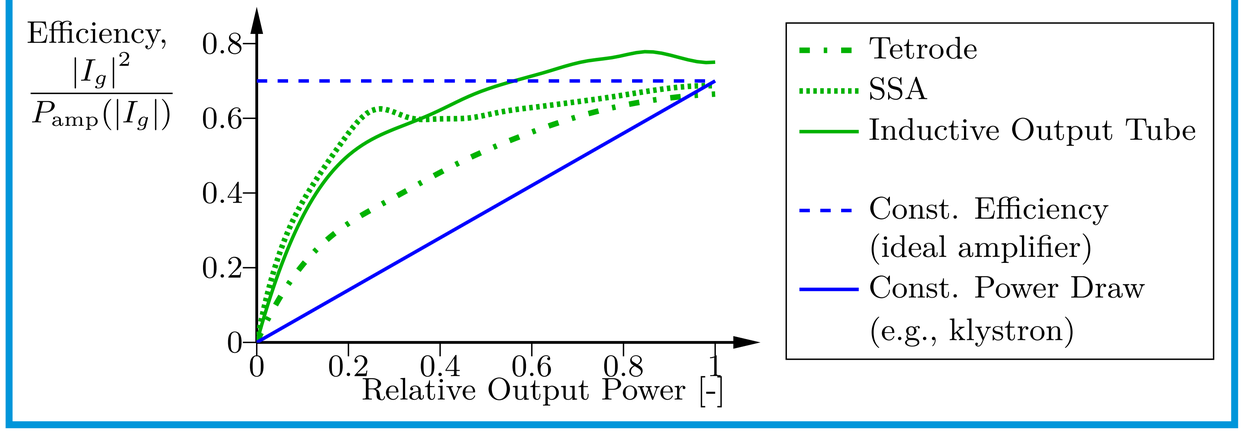
$$\begin{aligned} \underset{I_g,\, t_f}{\text{minimize}} \quad & \int_0^{t_f} P_{\text{amp}}(|I_g|)\, dt \\ \text{subject to} \quad & \dot{V}(t) = -V(t) + I_g(t) \\ & |I_g(t)| \le I_g^{\max} \\ & V(0) = 0 \\ & V(t_f) = 1 \end{aligned}$$



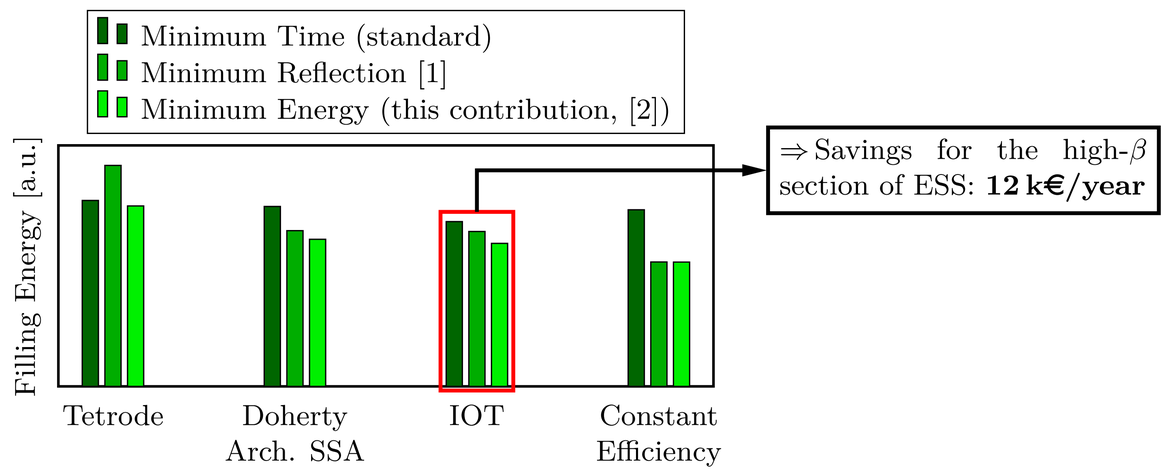
Energy-optimal control signal:

$$I_g^\star(t) = \underset{I_g}{\text{argmax}} \frac{-V(t) + I_g}{P_{\text{amp}}(I_g)}$$

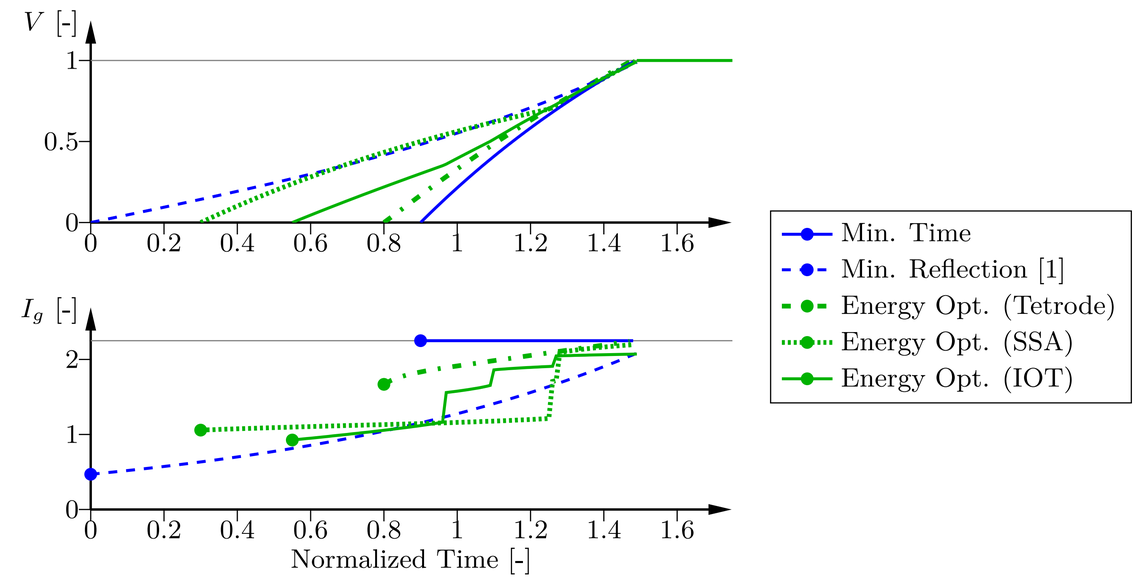
Typical efficiency characteristics



Results



Optimal filling profiles:



Accounting for detuning

Accounting for detuning gives complex-valued cavity dynamics:

$$\begin{aligned} \underset{\mathbf{I_g},\, t_f}{\text{minimize}} \quad & \int_0^{t_f} P_{\text{amp}}(|\mathbf{I_g}|)\, dt \\ \text{subject to} \quad & \frac{d}{dt}\mathbf{V} = (-1 + i\Delta\omega(t))\mathbf{V} + \mathbf{I_g} \\ & |\mathbf{I_g}| \le I_g^{\max} \\ & \mathbf{V}(0) = 0 \\ & \mathbf{V}(t_f) = 1. \end{aligned}$$

Can decouple problem by introducing polar coordinates, $\mathbf{V}(t) = V(t)e^{i\phi(t)}$ and $\mathbf{I_g}(t) = I_g(t)e^{i\theta(t)}$

Optimal angle for control signal:

$$\theta^*(t) = -\int_t^{t_f} \Delta\omega(t)\, dt$$

Remarks

- Due to the longer fill time, the cryogenic load is increased. For ESS: ≈ 1–2 k€/year
- The proposed filling approach requires good knowledge of the system parameters, and that the detuning $\Delta\omega(t)$ is known and repetitive (low gain feedback would reduce the impact of microphonics)

Bibliography

[1] Bhattacharyya, A.K., Ziemann, V., Ruber, R., and Goryashko, V. (2015). "Minimization of power consumption during charging of superconducting accelerating cavities". Nuclear Instruments and Methods in Physics Research A, 801, 78–85.

[2] OT, BoB (2017). "Energy-Optimal Excitation of Radio-Frequency Cavities". Proceedings of the IFAC World Congress 2017.