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Minimization of power consumption during charging of superconducting accelerating cavities

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ABSTRACT

The radio frequency cavities, used to accelerate charged particle beams, need to be charged to their nominal voltage after which the beam can be injected into them. The standard procedure for such cavity filling is to use a step charging profile. However, during initial stages of such a filling process a substantial amount of the total energy is wasted in reflection for superconducting cavities because of their extremely narrow bandwidth. The paper presents a novel strategy to charge cavities, which reduces total energy reflection. We use variational calculus to obtain analytical expression for the optimal charging profile. Energies, reflected and required, and generator peak power are also compared between the charging schemes and practical aspects (saturation, efficiency and gain characteristics) of power sources (tetrodes, IOTs and solid state power amplifiers) are also considered and analysed. The paper presents a methodology to successfully identify the optimal charging scheme for different power sources to minimize total energy requirement.

1. Introduction

In particle accelerators charged particles are accelerated to high energies, in specially prepared structures, the cavities, by electromagnetic fields typically in the radio frequency (RF) range (MHz to GHz). In order to supply the same energy to all particles, cavities require the establishment of stable accelerating voltage in them by means of power sources. *In our paper we focus on the cavity charging prior to beam arrival*. When the RF sources start to drive the field into the cavities, a part of the power fed to the cavities is reflected and dissipated in a load, because the cavity without beam behaves like a mismatched load. This effect is highly relevant to superconducting cavities with their extremely high quality factors. While the cavities gradually start to fill with the electromagnetic fields, the reflection reduces, but all the previously reflected power is wasted. In fact, the bandwidth of a pulse with monochromatic carrier and rectangular envelope is non-zero and inversely proportional to the pulse duration because sharp edges of the pulse give rise to a rich harmonic content. At the same time, a superconducting accelerating cavity even dressed with a high-power coupler is very narrowband (in the order of 1 kHz) so that noticeable part of the spectrum of supplied signal lies outside the bandwidth that the cavity can accept and this leads to reflection.

The amount of energy lost during charging of a cavity using step input can be estimated from the RF pulse duration and the cavity filling times. Roughly, a fraction of wasted RF energy is $t_F/2t_p$ of the total RF energy supplied to a cavity provided that the cavity with a beam is critically coupled. Here t_F and t_p are the cavity filling time and RF pulse duration. For European XFEL, using parameter values from [1,2] for nine-cell accelerating TESLA cavity, we get the cavity filling time as 780 μs while it is given that the total RF pulse duration is 1.4 ms. Thus, in this case with step filling we compute that around 25% of the total RF energy will be lost in reflection during cavity charging. For the Spallation Neutron Source (SNS) using parameter values in [3–5] for the medium beta cavities we get the pulse duration as 1.3 ms while the cavity filling time is 288 μs, and in this case around 5% of the total energy will be wasted.

So, it is of importance to devise techniques so that the RF energy losses can be minimized and thus running costs reduced. To this end, we investigate the possibility to tailor the temporal profile of the RF signal applied to a cavity such that most of it contributes to building up the intra-cavity fields, rather than being reflected and compare with step filling of cavities. To the knowledge of the authors, this topic has not been addressed in literature, at the same time at European Synchrotron Radiation Facility (ESRF) filling schemes different from step filling are used [6]. The effect of such minimization of reflected energy on power source requirements, cavity filling time and transit time factor, T, of cavities is also investigated.

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In order to demonstrate a possible gain using our scheme, we consider particular cavity parameters of the superconducting spoke cavities of the European Spallation Source (ESS) [7]. ESS is planned to run for 20 years, 8000 h per year at 14 Hz pulse rate which may be extended to 28 Hz or 56 Hz with shorter pulse lengths. While for the 14 Hz pulse rate energy waste due to reflection is around 3%, as the pulse rate is foreseen to increase in the future with shorter pulses, the energy waste will increase to over 10%. For high β cavities, which supply most of the energy to the beam, this will amount to around 20%. In this regard, it is important to investigate techniques that can make the linac more efficient.

The derivation and comparison of the optimal filling scheme with the step filling scheme requires that the latter be designed optimally as well and so the optimal step charging strategy is presented in Section 2. Once the optimal filling scheme is identified, it is studied and compared with the step filling scheme, with respect to generator power, total required energy and reflected energy in Section 3. The practical conditions, with regard to gain and efficiency characteristics of power sources are also modelled and investigated to compute total energy efficiency of the optimal charging scheme in Section 5.

2. Power source–cavity interaction

Resonant modes of standing electromagnetic (EM) waves in cavities can be described by resonant *R–L–C* circuits as shown in Fig. 1, where the circuit elements are defined as

$$C = \frac{1}{T^2\omega(R/Q)} \tag{1}$$

$$L = \frac{T^2(R/Q)}{\omega} \tag{2}$$

and

$$R = Q_0 T^2 (R/Q). \tag{3}$$

Here T is the transit time factor, Q_0 is the quality factor which gives measure of energy lost in a cavity, with the cavity-shape constant (R/Q). The oscillating fields in the cavities create a voltage, $V(t)$, which works on the beam particles that can be described by a model similar to that of a driven harmonic oscillator [8] in the slow varying envelope approximation ($|\mathrm{d}^2V/\mathrm{d}t^2| \ll |\omega^2 V(t)|$). Then the fundamental relation between $V(t)$, and generator current, $I_g(t)$, is given by [9]

$$t_F\dot{V}(t) + \left(1 - i\frac{2\Delta\omega}{\omega}Q_L\right)V(t) = 2Z_L T I_g(t) \tag{4}$$

where the dot denotes time derivative, $t_F = 2Q_L/\omega$ is the cavity time constant or filling time, $\Delta\omega = \omega_0 - \omega$, with the RF excitation frequency ω_0 and the cavity resonant frequency ω respectively. The loaded quality factor, $Q_L = \left(Q_{ext}^{-1} + Q_0^{-1}\right)^{-1}$ where Q_{ext} is the quality factor which gives measure of energy lost through a power coupler, and $Z_L = (R/Q)Q_L$ is the loaded cavity impedance. The reflected current is then given by

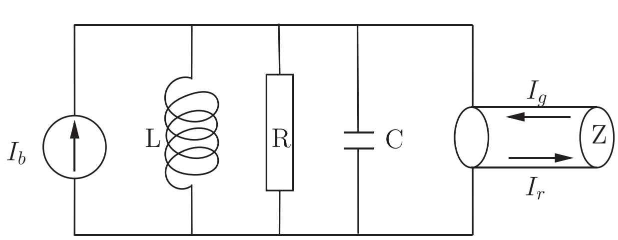

Fig. 1. Resonant cavity modelled as lumped circuit.

$$I_r(t) = \frac{V(t)}{2(R/Q)T}\left(\frac{1}{Q_{ext}} - \frac{1}{Q_0} + 2i\frac{\Delta\omega}{\omega}\right) - \dot{V}(t)\frac{1}{\omega(R/Q)T}. \tag{5}$$

Before a beam is injected into the cavity for acceleration, the voltage in the cavity has to reach the nominal value V_c. We will carry out our analysis for the case $\Delta\omega = 0$ in Eq. (4), since the cavity detuning due to the Lorentz detuning is slow [10] compared to the cavity filling, and the initial detuning can be compensated by slow tuners.

To demonstrate the problem of reflected energy, let us first consider the case of the standard step charging of cavity. Let the beam injection time be t_i, i.e., $V(t) = V_c$ at time $t = t_i$, and $I_g(t) = I_g^0 U(t)$, where $U(t)$ is the unit step function, then Eq. (4) can be solved to obtain $V(t)$ as

$$V(t) = 2Z_L T I_g^0\{1 - \exp(-\tau)\} \tag{6}$$

where $\tau = t/t_F$, with t_F the cavity filling time.

Then, from [11] we obtain that the *optimal beam injection time*, such that the beam induced voltage gradient is perfectly compensated by the gradient of the RF source induced voltage (see Fig. 2), is generally given by

$$t_i = t_F \ln\left(\frac{I_g^0}{I_b^0}\right) \tag{7}$$

while the required generator current is given by

$$I_g^0 = I_b^0 + \frac{V_c}{2TZ_L} \tag{8}$$

where I_b^0 is the DC beam current which is one half of a bunched RF current for short bunches of charged particles. The effect of the beam, I_b^0, is accounted for in the determination of both t_i and I_g^0.

Now, for the estimated value of generator current for $t \le t_i$, the reflected current for such step filling is obtained by solving Eq. (5) to get

$$I_r^s(t) = I_g^0\{1 - 2\exp(-\tau)\}. \tag{9}$$

The time when the reflection reduces to zero is obtained by setting the right hand side of Eq. (9) to zero and solving for t, which gives in the general case,

$$t_r^0 = -t_F \ln(\tfrac{1}{2}) \tag{10}$$

which is different from the optimal injection time given in Eq. (7), for mismatched cavities, and any energy supplied after t_r^0 will be

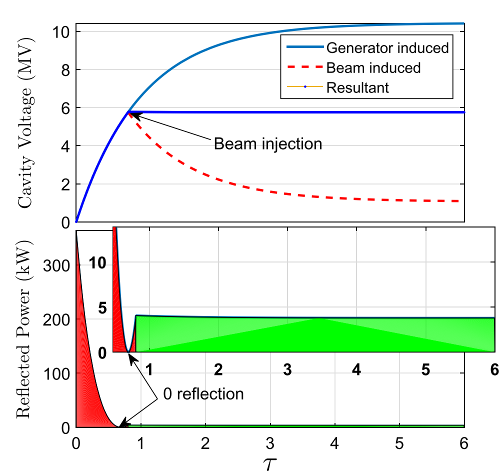

Fig. 2. The reflected energy during step filling, before beam injection is given by the red region, and the power falls exponentially as filling continues. This is what we wish to minimize. After beam injection, due to sub-optimal Q_{ext}, reflection is non-zero, as shown by the green region. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)