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MODEL OF DARK CURRENT IN SRF LINAC

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Abstract

Currently, few linacs based on 9-cell TESLA-type SRF cavities are being designed or bult, including XEFL, LCLS-II and ILC. Dark current electron generated by field emission in SRF cavities can be captured and accelerated in the linac up to hundreds MeV before they removed by focusing magnets. Lost dark current electrons interact with the materials surrounding SRF cavities and magnets, produce electromagnetic showers and contribute to the radiation in the linac tunnel. In this paper we present a model of dark current in a linac based on TESLA cavities. We show preliminary results of the simulation applied to ILC main linac.

INTRODUCTION

In superconducting radio-frequency (SRF) cavities electrons can be emitted from the surface of the cavity in the region of the high electric field via field emission (FE). Emitted electrons are then may be captured in accelerating regime and contribute to the dark current (DC). Because of their broad angular, space and phase distribution, large fraction of dark current particles is lost downstream of the originating cavity, in subsequent cavities of the linac, focusing magnets and other beam line components. Lost particles may cause additional heat and RF loading on superconducting cavities. If lost electrons from DC have large enough energy, they produce electromagnetic showers of secondary particles which irradiate cables and electronic components inside the cryostat (cryo-module, CM) containing cavities. Radiation penetrating beyond CM walls may affect electronics in the linac tunnel and personnel and electronics in the service part of the tunnel. Thus, design of SRF linacs requires extensive investigation of DC radiation in order to protect accelerator components from radiation damage and optimize thickness and cost of the radiation shields. Some of the recent studies of DC in SRF linacs are listed in [1–4].

In this paper we describe a model of dark current in SRF linac. Our model combine tracking of electrons in RF field of cavities and magnetic field of focusing magnets with simulation of interactions of lost particles with the materials of the accelerator components.

MODEL

We use MARS package to simulate interaction of DC particles with the materials of linac components and surrounding infrastructure. In order to understand average and maximum radiation conditions and minimize time consuming MARS simulation, we separate our study into following steps:

- Losses inside individual cavity. Radiation from particles lost inside the same cavity where they were emitted. The normalized level of radiation is the same for each cavity in the linac.
- Losses from DC produced by a single cavity. We assume that only one cavity in a string of cavities between focusing magnets[1] contributes to DC. In a worst case emitting cavity is located next to the magnet. Survived DC electrons are accelerated through the string and lost in the next magnet.
- Losses from DC generated by all cavities.

In this paper we focus on steps 1 and 2 and leave step 3 for the future studies.

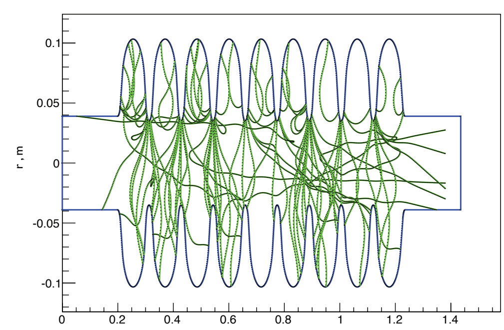

Figure 1: Trajectories of the FE electrons.

Field Emission Model

We use SuperLANS code to calculate RF field in the 9-cell TESLA-type cavity. Time dependence of the electric field is assumed to be $E \sim \cos(\omega t + \phi)$, where RF phase ϕ varies from 0 to 2π. Emitter locations are chosen randomly according to uniform distribution along the cavity surface from the entrance of the 1st cell to the exit of the 9th cell. Each emitted electron is assigned the weight calculated from Fowler-Nordheim model: $W_{FN}(E) = N_{FN}(\beta_{FN}E)^2 \exp(-B_{FN}\varphi^{3.2}/\beta_{FN}E)$, where $B_{FN} = 6.83 \cdot 10^3$, niobium work function $\varphi = 4.2$ eV, and field enhancement factor β has a typical value of 100. Normalization constant N_{FN} is selected such that $W_{FN}(E_{max}) = 1$, where maximum surface electric field in TESLA cavity is $E_{max} = 2E_{acc}$, and E_{acc} is accelerating field on the cavity axis[2]. For subsequent tracking and MARS simulation we select track with $W_{FN} > 0.01$.

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[1] In ILC such a string contains 3 CM and 26 cavities, while in LCLS-II it is 1 CM and 8 cavities

[2] For ILC $E_{acc} = 31.5$ MV/m and $E_{max} = 63$ MV/m.

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Dark Current Model

Electrons generated in each cavity can be separated in 3 groups: 1) particles lost inside cavity; 2) survived electrons leaving cavity in the direction opposite to the main beam; 3) survived DC particles leaving cavity in the direction of the main beam. In ILC distance between adjacent cavities in CM is 5.75λ (and 3λ between CM), which allows capture and acceleration of DC only in the direction of the main beam[3]. Survived DC particles are tracked through cavities and focusing magnets until they lost. Total normalization is obtained at the end of CM by the equation $\sum W_{FN} = I_{DC}$, where I_{DC} is the nominal value of dark current, 50 nA in ILC and 10 nA in LCLS-II.

Particle Tracking

We implement Runge-Kutta method for particle tracking within cavities and in the vacuum chamber of the focusing magnets. Typical trajectories calculated in cavity with E_{acc} = 31.5 MV/m RF field are shown in Fig. 1.

RESULTS FOR ILC MAIN LINAC

For simulation of dark current in ILC main linac we consider basic accelerator period from one focusing quadrupole to the next. Such a period contains 26 cavities, arranged in 4 CM.[4] We simulated 100k FE electrons by sampling their z-coordinate and RF phase from uniform distributions along the cavity length and one RF period, respectively, and applying requirement $W_{FN} > 0.01$.

Particles Lost In The Same Cavity

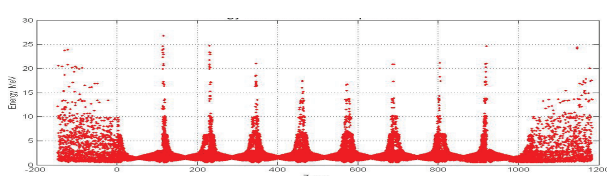

Figure 2: Distribution of energy of particles lost in cavity as function of impact z-coordinate.

Out of all emitted particles 92% are lost in the same cavity. Figure 2 show distribution of the energy of lost electrons as a function of z-coordinate of the impact. Energy of the lost electron can reach as high as 25 MeV. As one may expect, majority of particles are lost at the cavity irises. Energy spectrum of the lost particles is shown in Fig. 3. The structure of the spectrum corresponds to the electrons which are lost in the same cavity cell, where they originate, or propagate to the next cell, or 2nd to the next on so on. After subjecting the lost electrons to MARS simulation, we are able to estimate radiation level outside CM, which is found to be well below safety regulation limits. Only very few highest energy electrons penetrate CM walls. We need to increase

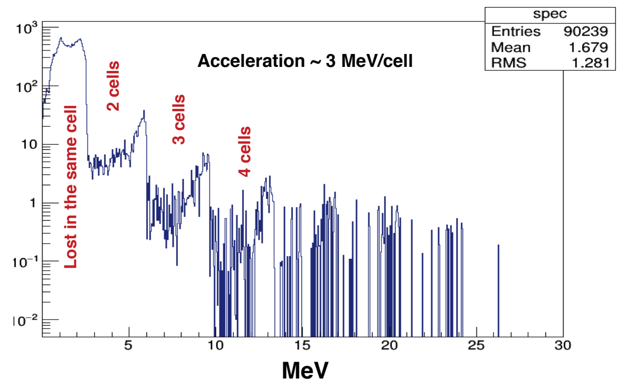

Figure 3: Energy spectrum of particles lost inside cavity.

statistics considerably, especially for the high energy part of the spectrum, in order to map radiation outside CM.

Particles Leaving Emitting Cavity

Eight percent of emitted particles are captured in acceleration and leave cavity, with the half (4%) going in direction of the main beam and the other half (4%) traveling in the direction opposite to the beam. As discussed earlier, particles going against the main beam have wrong phase in the next cavity they enter, therefore they decelerate and will be lost. For now we do not consider these electrons in our model.

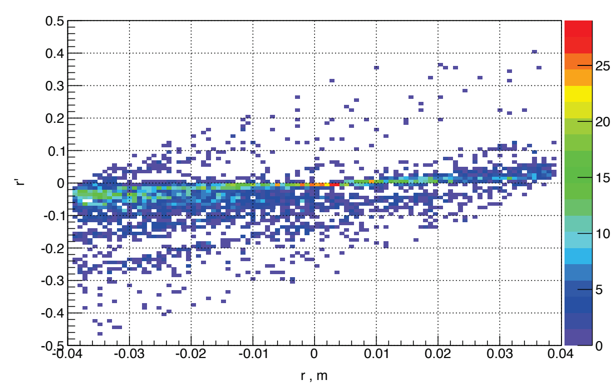

Figure 4: Transverse phase space distribution for electrons leaving emitting cavity. Color scale corresponds to the energy in MeV.

We track survived 4% of particles through the string of 25 remaining cavities and the focusing quadrupole at the end of the string. Figure 4 shows transverse phase space distribution of these electrons at the exit of the emitting cavity. One can see, that DC particles fill most of the beam line aperture and have long tail in angular distribution corresponding to the low energy electrons. Energy spectrum in shown in Fig. 5.

Figure 6 show losses in the string of cavities between focussing quadrupoles. Only 50% of all electrons which exit the emitting cavity reach end of the string. Losses are mostly concentrated at the cavity irises. The energy of the electrons reaching end of the string can be as high as 800 MeV.

[3] In LCLS-II linac distance between cavities in CM is 6λ and DC can be captured and accelerated in both directions of the main beam.

[4] 4 cavities in 1st CM before magnet and 4 cavities in the 4th CM after magnet belong to the previos and the next periods.

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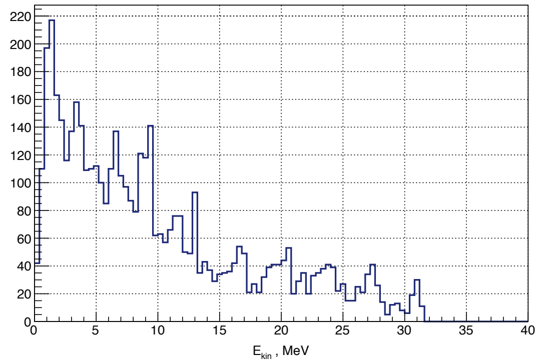

Figure 5: Exit energy.

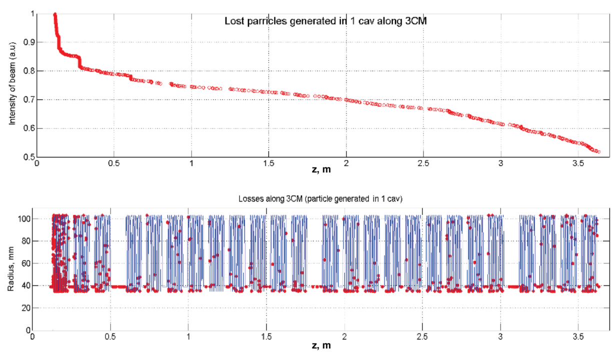

Figure 6: Losses along string of the cavities.

Particles exiting the last cavity of the string are tracked through the focussing quadrupole. Since quadrupole gradient is determined by the energy of the main beam, it will be different along the linac. Here we consider magnets located in the middle of the linac, at the beam energy 125 GeV. At this field strength, 64% of all DC electrons are deflected and lost in the quadrupole, while 36% continue into the next section of the linac.

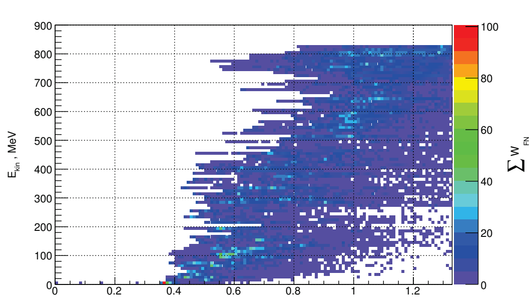

Figure 7: Energy distribution of losses as a function of z-coordinate of impact in the 125 GeV quadrupole.

Energy distribution of losses in quadrupole as a function of z-coordinate of the impact point is shown in Fig. 7. Figures 8 and 9 show transverse phase space and energy distributions for the DC electrons exiting magnet and continuing into the next cavity. Tracking in the cavity next to the magnet

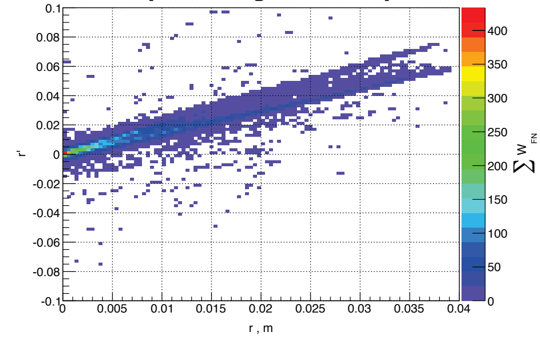

Figure 8: Transverse phase space distribution of DC particles exiting from the 125 GeV quadrupole.

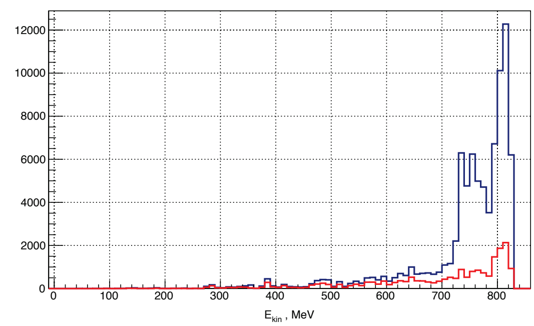

Figure 9: Energy distribution of DC electrons at the exit of 125 GeV quadrupole. In red histogram tracks are weighted with W_{FN} weights.

show that 70% of electrons will continue accelerating along the linac.

CONCLUSION

We describe model of dark current in SRF electron linac based on the TESLA type 9-cell cavities. The model combines tracking of DC particles in the cavities and focusing magnets with MARS simulation of lost particles in the materials of the linac components and in the linac tunnel. We apply this model to study radiation in the ILC main linac tunnel.

ACKNOWLEDGMENT

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