Dark Current in PIP2 SRF Linac

HB650 and LB650

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Motivation

- Dark current (DC) electrons in SRF linac when lost produce radiation affecting
  - beam-line components and cables inside cryo-module (CM)
  - electronics outside of CM in the linac tunnel
  - electronics and personnel in the service parts of the linac enclosure

- Extensive investigation of DC radiation is required during design of SRF linac
  - protect accelerator components from radiation damage
  - optimize thickness and coast of radiation shield
Dark Current Model

• We consider Field Emission (FE) as the main source of Dark Current (DC) in the SRF cavities of HB650 and LB650 sections of PIP2 linac
  
  ‣ uniform distribution of emitters over the cavity surface
    
    - sample emitter location from uniform distribution in coordinate along the cavity axis (z) and then multiply by geometric weights $W_G = r*\sqrt{1+(dr/dz)^2}$ which take into account variation of elementary area of cavity surface

  ‣ number of emitted particles at each location varies according to Fowler-Nordheim model (H. Padamsee et al, *RF Superconductivity for Accelerators*):
    
    - $W_{FN} = N_{FN}(\beta_{FN}E)^2exp(-B_{FN}\varphi^{3/2}/\beta_{FN}E)$, where $B_{FN}=6.83 \cdot 10^3$, $\varphi=4.2$ eV, $E$ in MV/m; typical value of “field enhancement factor” $\beta_{FN}=100$
    
    - Normalization constant $N_{FN}$ is selected in such a way that $W_{FN}(E_{max}) = 1.0$, where $E_{max}$ is the maximum surface field

  • Maximum surface field is proportional to the cavity voltage (energy gain) $V_{acc}(\beta_G)$; $E_{max}/V_{acc}(\beta_G)$ depends on cavity geometry and can be found from RF simulation of cavity

  ‣ select particles with $W_{fn} > 0.01$
Dark Current Model

- Total weight assigned to simulated particles is $W_{tot} = \text{Norm} \times W_G \times W_{FN}$
  
  - Norm factor is determined from the nominal DC value (1 nA) exiting cavity

- Emitted particles are tracked through the linac until they lost or exit linac

- When calculating average physical quantities (energy deposition, power loss, intensities etc) each simulated particle contribute with the weight $W_{tot}$

  - for some quantity $A$: $\langle A \rangle = \text{sum}(W_{tot}A)/N$, where $N$ is the total number of simulated particles
Particle Tracking in Linac

- Cavity EM fields are calculated using RF simulation code (SuperLANS, CST Studio, HFSS)
- Electric field time dependence: \( E \sim \cos(\omega t + \varphi) \)
  - for each emitter location random initial field phase \( \varphi \) is sampled from uniform distribution in the range from 0 to \( 2\pi \)
- Track particles in RF field inside cavity volume using Runge-Kutta integrator of 4th order
  - time step is fixed at 10ps (~150 RF periods) to provide reasonable efficiency and tracking accuracy
- Track particles in focusing magnets using RK4
  - assume static quadrupole field \( B_x = G y, B_y = G x \), where field gradient \( G > 0 \) for focusing quads and \( G < 0 \) for defocusing quads
- LB650 beta=0.61 section: 11 cryo-modules, 33 cavities (3 cavities per CM)

- 150 mm space added for gate valve flange and magnet flange.
Linac Layout

- HB650 beta=0.92 section: 4 cryo-modules, 24 cavities (6 cavities per CM)

HB Section

10.97 m

SC Cryomodule

1.44 m

Cavity Field Map

Cavity Field Map

Cavity Field Map

Cavity Field Map

Cavity Field Map

Cavity Field Map

0.6 m 1.316 m 1.525 m

NC Doublet

1.429 m

0.2 m

NC Doublet

150 mm space added for gate valve flange and magnet flange.
Cavity geometry parameters

- Parameterization of cavity geometry (all dimensions are in mm)

<table>
<thead>
<tr>
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<th>LB650 beta=0.61</th>
<th>HB650 beta=0.92</th>
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</table>
Cavity Gradient

- All HB650 Vacc(beta_G) = 20 MV (Emax = 40 MV/m)
- LB650 cav 1,2 Vacc = 6.5 MV; cav 3 Vacc = 6 MV; cav 4,5 Vacc = 7.5 MV, cav 6-33 Vacc = 12 MV (Emax = 40 MV/m)
  - neglect FE in cav 1-5
Quad Gradient

- HB650 quads $G=12 \text{ T/m}$
- LB650 quads $1/2 \ G=7.5 \text{ T/m}$; quads $3/4-19/20 \ G=9 \text{ T/m}$; quads $21/22 \ G=7 \text{ T/m}$
FE in cavities

- HB650 beta=0.92 example of particle trajectories
Normalization

• HB650 beta=0.92 - generated 1e6 FE tracks/cavity
  ▸ 842958 tracks lost in cavity
  ▸ 80906 exit to the left; 76136 exit to the right
  ▸ Normalization (1 nA dark current)
    - $\text{Norm(\text{current})} = 4.541 \times 10^{-7} \text{ A}$; $\text{Norm(\text{e-})} = 2.838 \times 10^{12} \text{ e-/s}$

• LB650 beta=0.61 - generated 1e6 FE tracks/cavity
  ▸ 754462 tracks lost in cavity
  ▸ 121835 exit to the left; 123703 exit to the right
  ▸ Normalization (1 nA dark current)
    - $\text{Norm(\text{current})} = 2.567 \times 10^{-7} \text{ A}$; $\text{Norm(\text{e-})} = 1.604 \times 10^{12} \text{ e-/s}$
HB650 losses in the same cavity

- energy of lost particles (black) and particles exit to the left (red) and right (green)
HB650 losses in the same cavity

- power loss - total power loss is 22 mW
HB650 losses in the same cavity

- lost current - total current lost in cavity is 13 nA
HB650 losses in linac, single cavity

- power loss

![Graph showing power loss vs. z, m]

- one period
HB650 losses in linac, single cavity

- energy of lost particles

$E_{\text{loss}}, \text{MeV}$

e$^{-}$/s/2 MeV

$10^{11}$
$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
$10^{6}$
$10^{5}$

0 20 40 60 80 100 120 140 160
HB650 losses in linac, single cavity

- lost current

13 nA lost in the same cavity

1 nA exit from the cavity
HB650 losses in linac, 4 periods, 24 cavities

- power loss - average power loss is 0.2 W per period
HB650 losses in linac, 4 periods, 24 cavities

- energy of lost particles
HB650 losses in linac, 4 periods, 24 cavities

- lost current
LB650 losses in the same cavity

- energy of lost particles (black) and particles exit to the left (red) and right (green)
LB650 losses in the same cavity

- power loss - total power loss is 11 mW

![Graph showing power loss distribution across different cells with peaks at various z positions with labels BP and other possibly cells marked as cell 2, cell 3, cell 4, cell 5.](image-url)
LB650 losses in the same cavity

- lost current - total current lost in cavity is 6 nA
LB650 losses in linac, single cavity

- power loss

![Graph showing power loss vs z, m]
LB650 losses in linac, single cavity

- energy of lost particles

![Graph showing the distribution of energy of lost particles in MeV.](image)
LB650 losses in linac, single cavity

- lost current
LB650 losses in linac, 11 periods, 28 cavities

- power loss - average power loss is 50 mW per period
LB650 losses in linac, 4 periods, 24 cavities

- energy of lost particles
LB650 losses in linac, 4 periods, 24 cavities

- lost current
Summary

• Developed a model of DC in HB650 0.92 and LB650 0.61 sections of PIP2 linac

• Generated and tracked DC particles through linac
  ‣ particles were generated in LB cavities with Vacc=12 (this excludes first 5 cavities of LB section)
  ‣ assumed 1nA DC exiting from cavities

• Average power loss due to DC is 210 mW (HB) / 50 mW (LB) per period

• Energy of lost particles is up to 160 MeV (HB) / 40 MeV (LB)
  ‣ in HB section energy spectrum of the lost particles is flat in the range from 20 to 120 MeV

• Generated particles can be used as a source for Geant4/MARS simulation to estimate radiation levels in linac elements and PIP2 tunnel