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*):
    - $W_{FN} = N_{FN}(\beta_{FN}E)^2 \exp(-B_{FN}\varphi^{3/2}/\beta_{FN}E)$, 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 $W_{FN}(Emax) = 1.0$, where Emax is the maximum surface field
      - Maximum surface field is proportional to the cavity voltage (energy gain) $Vacc(\beta_G)$; $Emax/Vacc(\beta_G)$ depends on cavity geometry and can be found from RF simulation of cavity
  - select particles with Wfn > 0.01

Dark Current Model

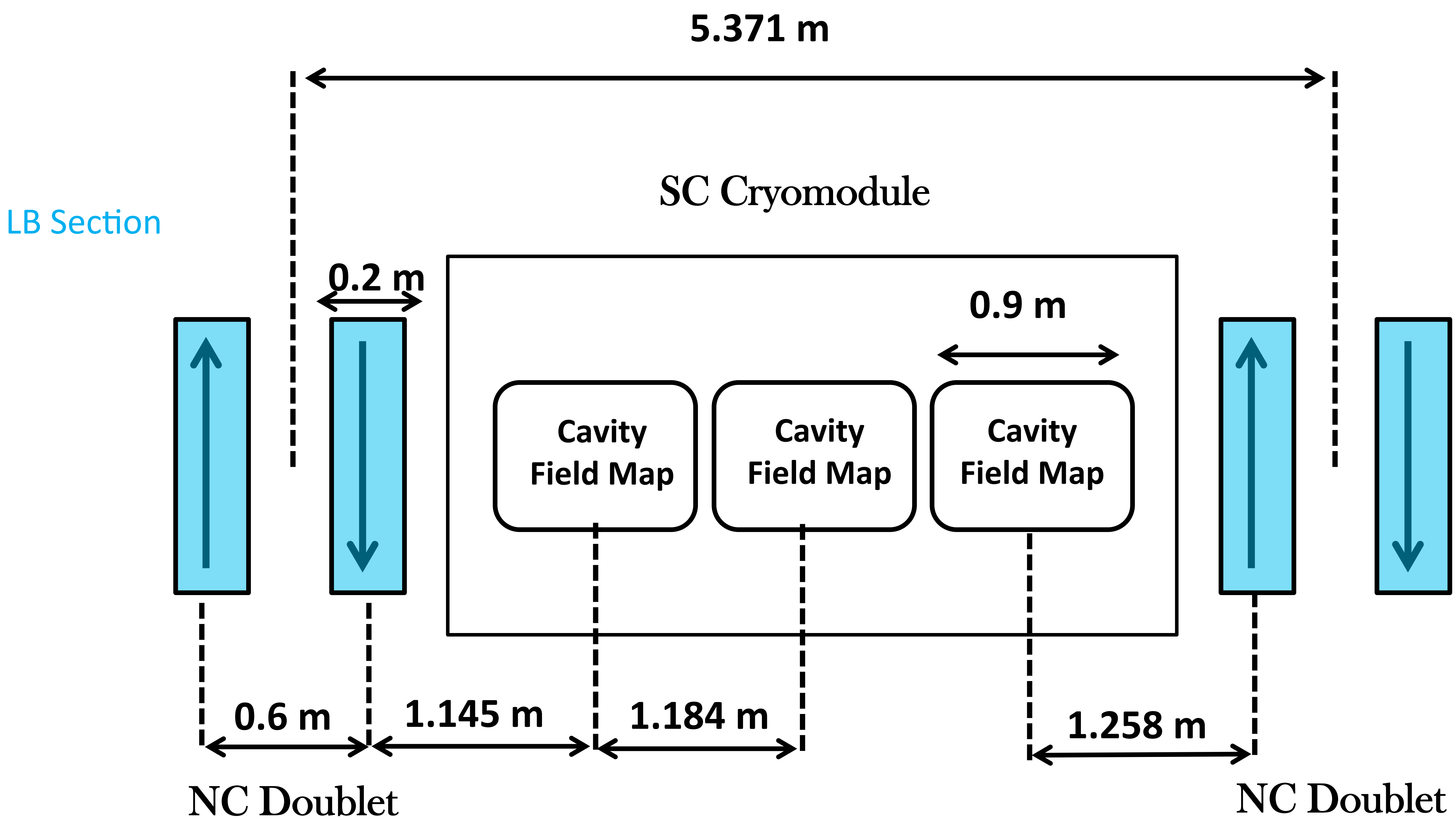
- Total weight assigned to simulated particles is W_{tot}=Norm* W_G* W_{FN}
  - Norm factor is determined from the nominal DC value (1 nA) exiting cavity
- Emitted particles are tracked through the linac until they lost or exit linac
- When calculating average physical quantities (energy deposition, power loss, intensities etc) each simulated particle contribute with the weight W_{tot}
  - for some quantity A: <A> = sum(Wtot*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 ~ Cos(ωt+φ)
  - for each emitter location random initial field phase φ is sampled from uniform distribution in the range from 0 to 2π
- 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 Bx = G*y, By = G*x, where field gradient G>0 for focusing quads and G<0 for defocusing quads

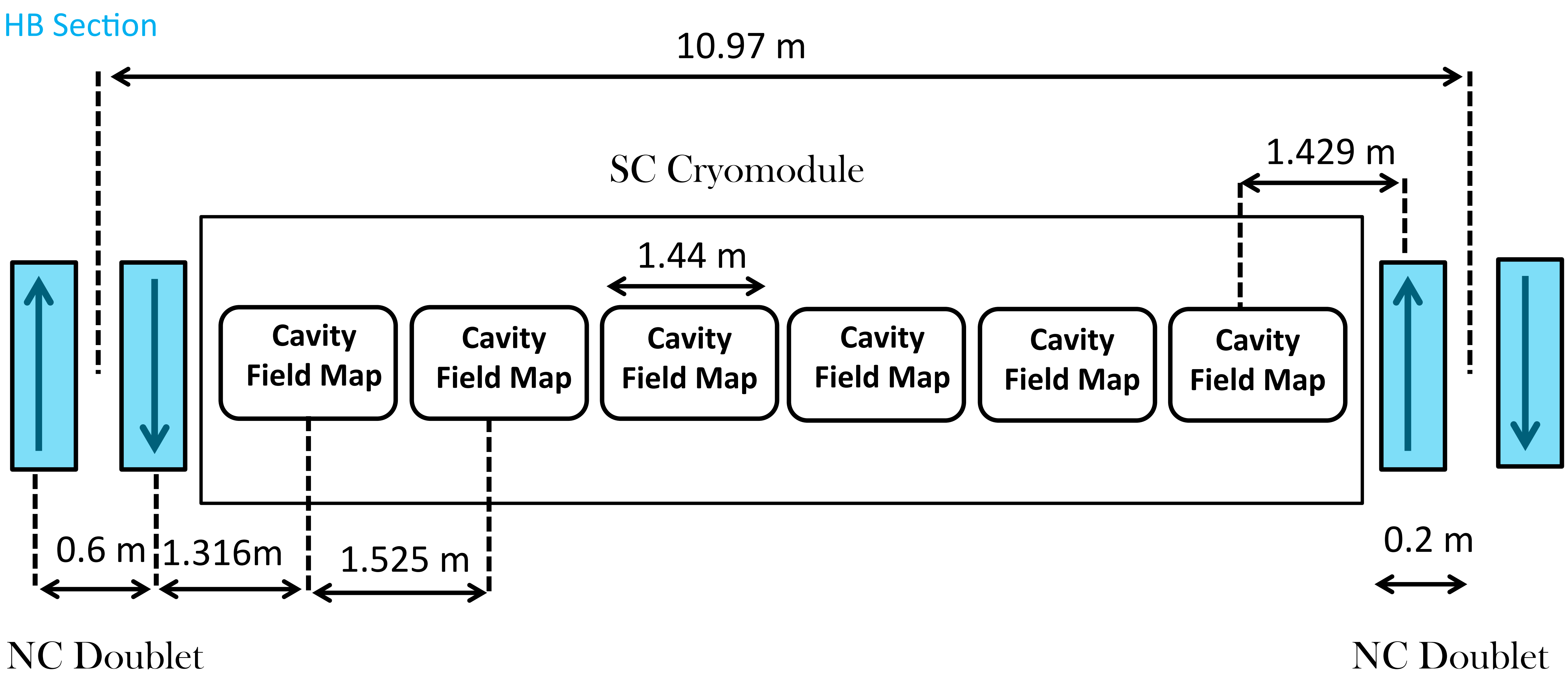
Linac Layout

- LB650 beta=0.61 section: 11 cryo-modules, 33 cavities (3 cavities per CM)



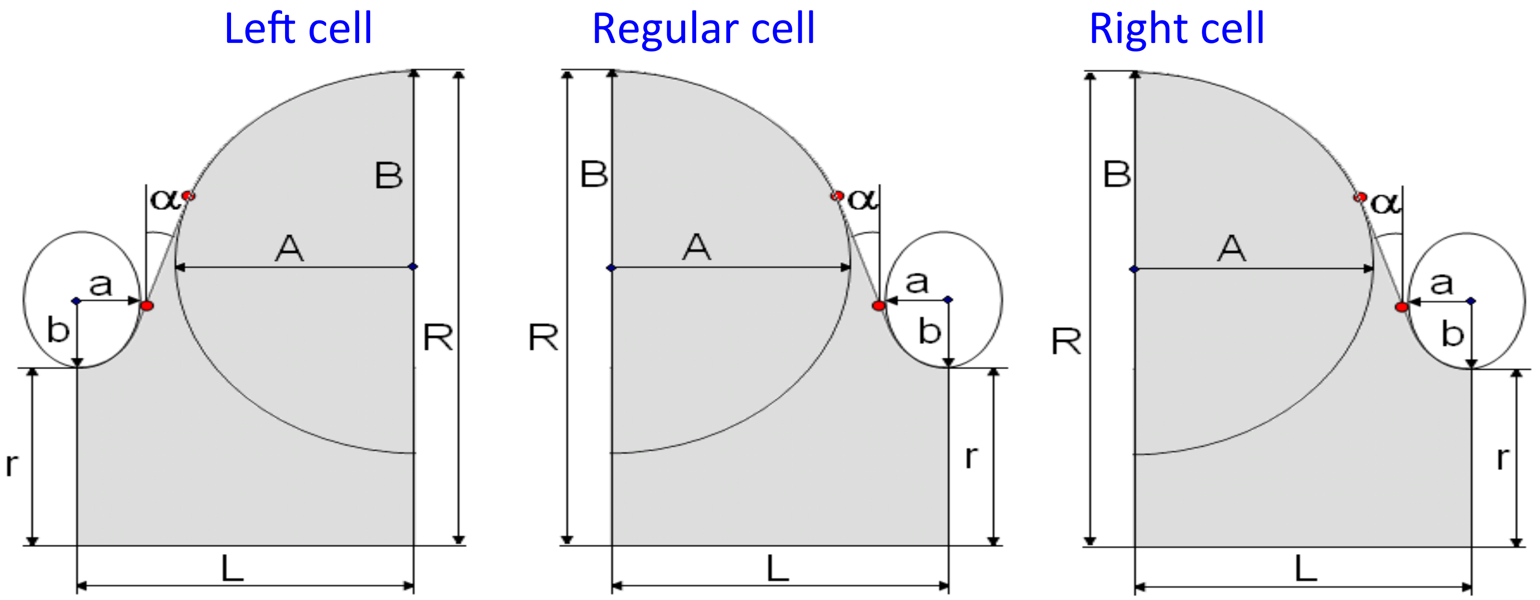
Linac Layout

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



Cavity geometry parameters

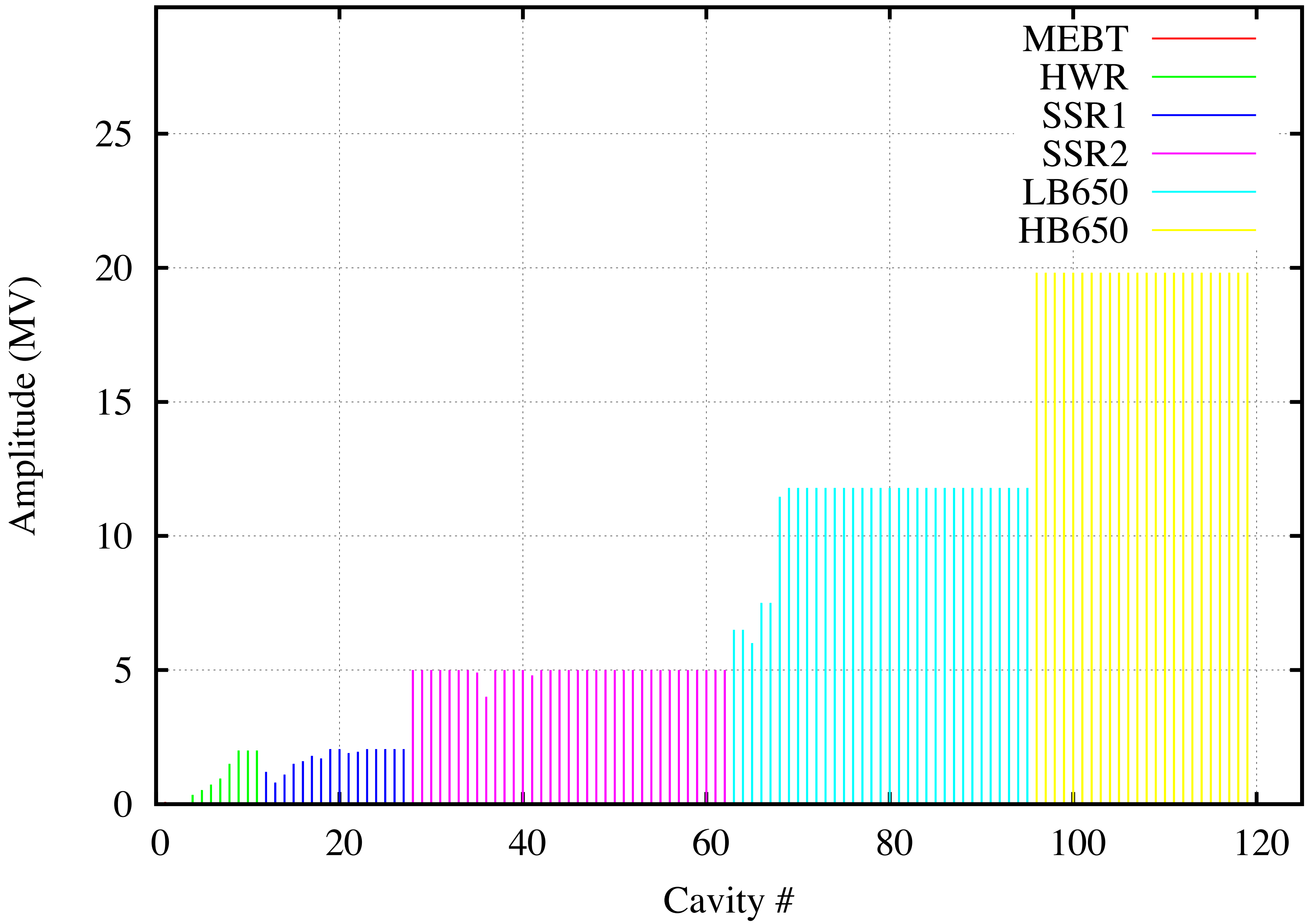
- Parameterization of cavity geometry (all dimensions are in mm)



	LB650 beta=0.61			HB650 beta=0.92		
	Left cell	Reg cell	Right cell	Left cell	Reg. cell	Right cell
r	59	41.5	59	59	59	59
R	194.952	194.952	194.952	200.052	200.052	200.052
L	68.365	70.34	68.365	97.555	106.08	97.555
A	54	54	54	84	85	84
B	48	58	48	90	78	90
a	14	14	14	13	20	13
b	26	25	25	28	33	28
alpha	0.7	2	0.7	1.3	1.9	1.3

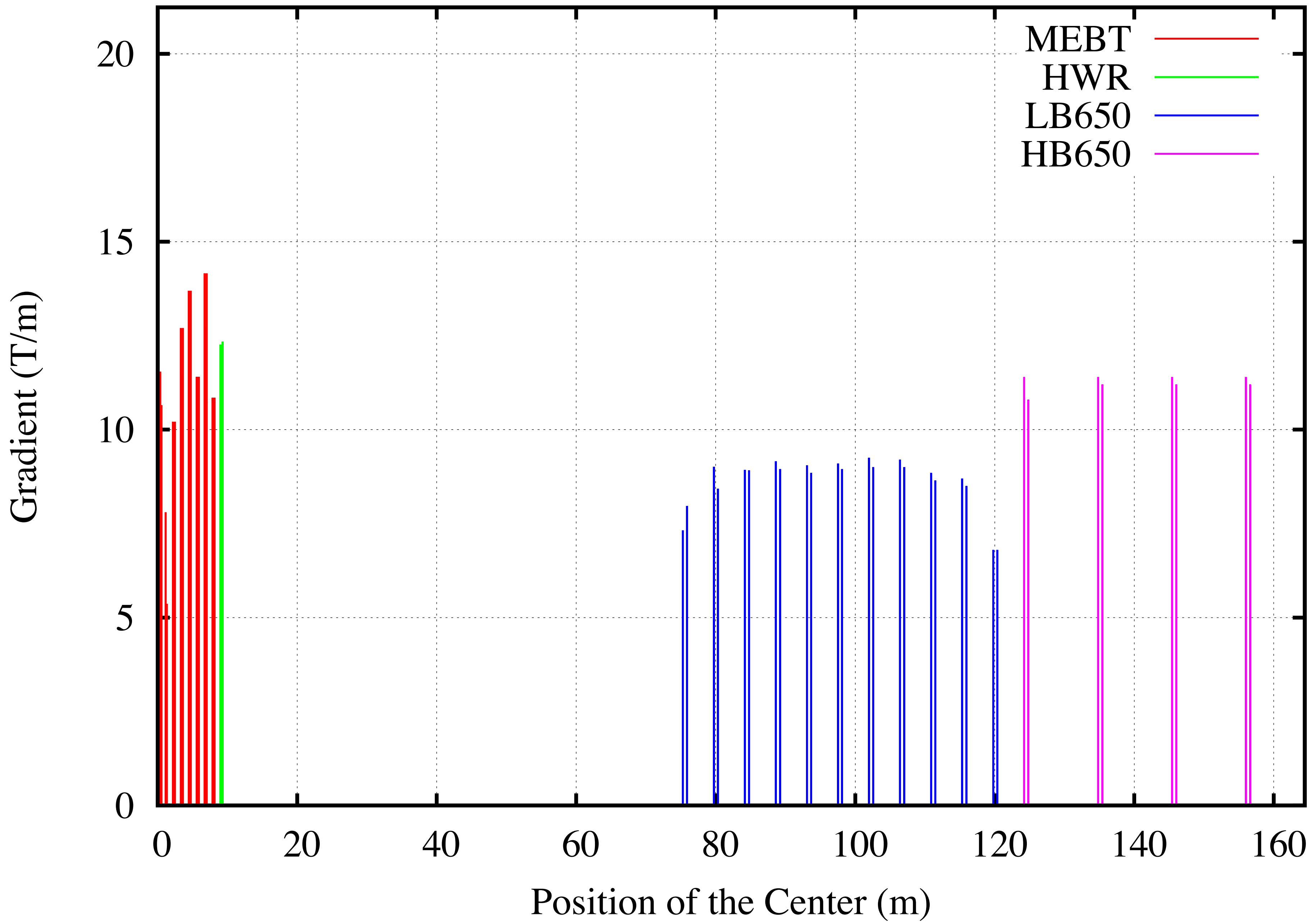
Cavity Gradient

- 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



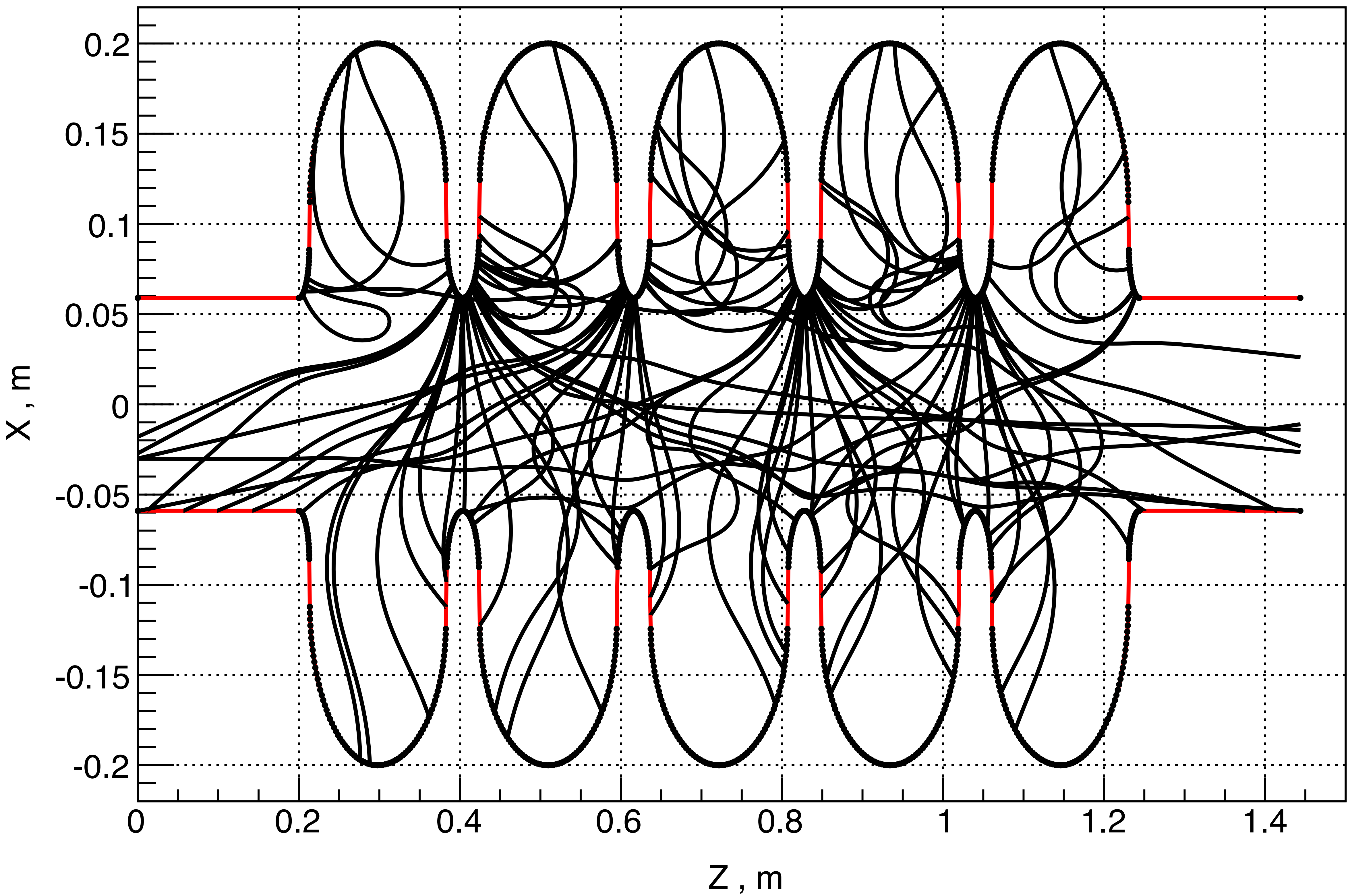
Quad Gradient

- HB650 quads G=12 T/m
- LB650 quads 1/2 G=7.5 T/m; quads 3/4-19/20 G=9 T/m; quads 21/22 G=7 T/m



FE in cavities

- HB650 beta=0.92 example of particle trajectories

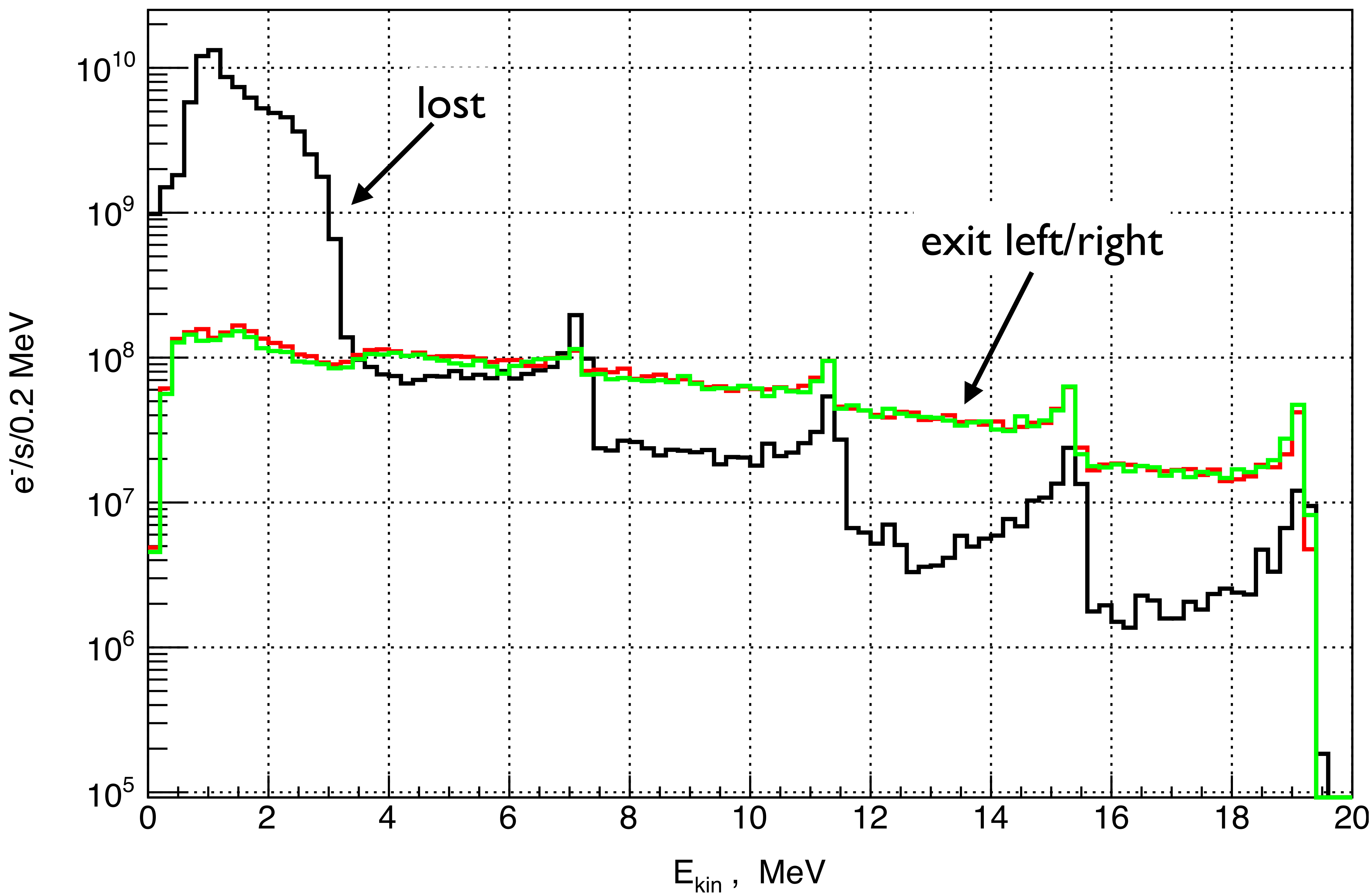


Normalization

- 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)
    - Norm(current) = 4.541e-7 A; Norm(e-) = 2.838e12 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)
    - Norm(current) = 2.567e-7 A; Norm(e-) = 1.604e12 e-/s

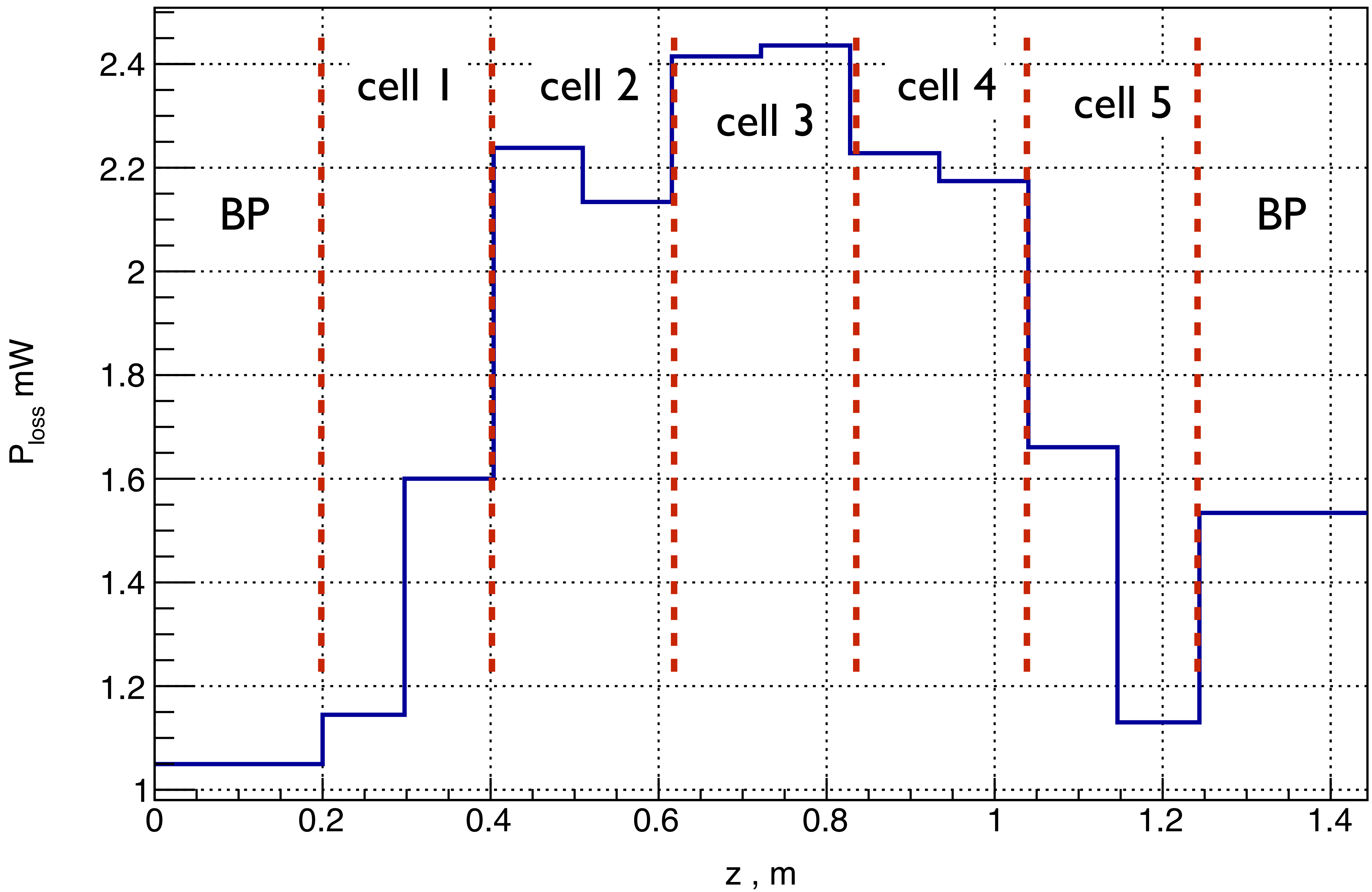
HB650 losses in the same cavity

- energy of lost particles (black) and particles exit to the left (red) and right (green)



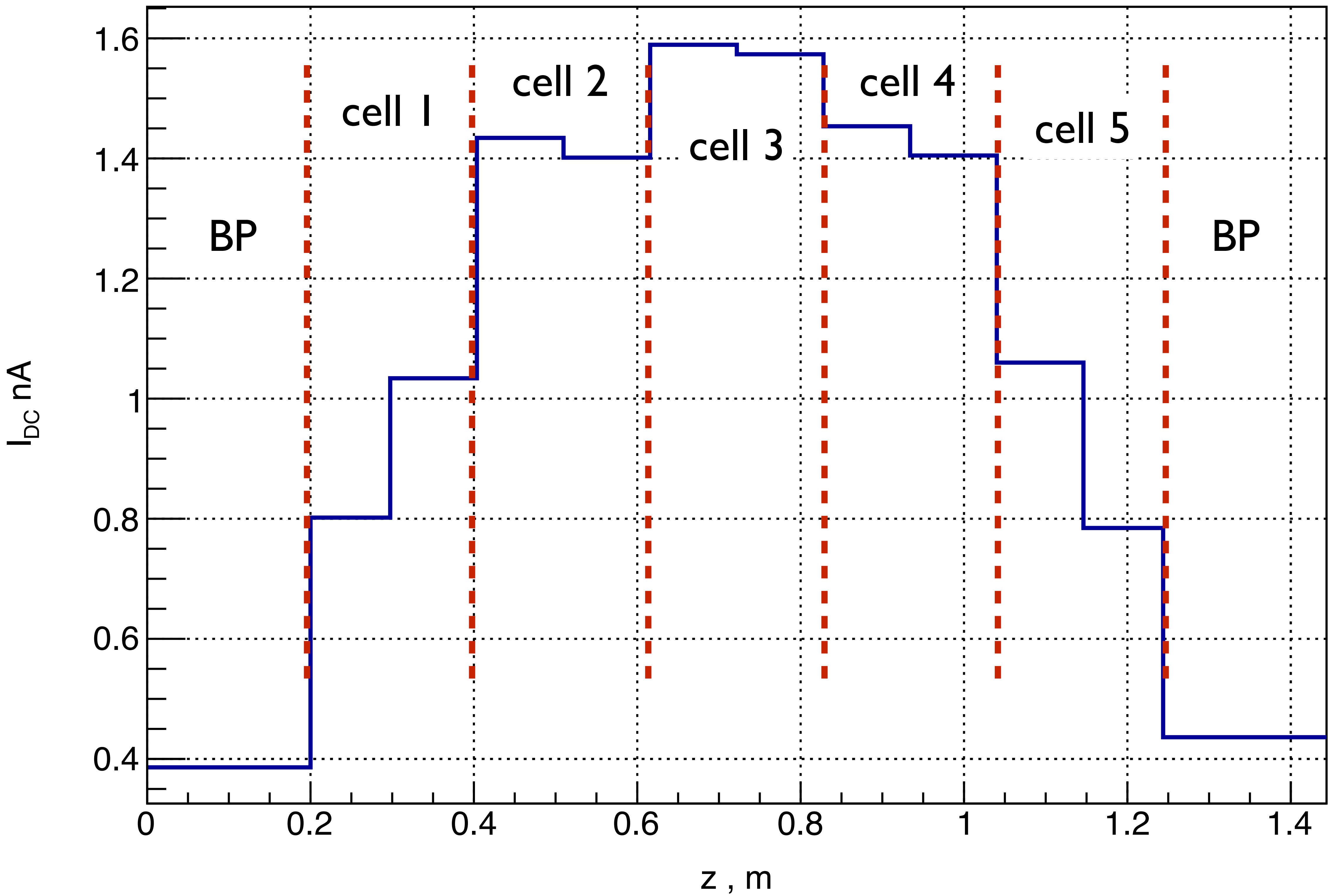
HB650 losses in the same cavity

- power loss - total power loss is 22 mW



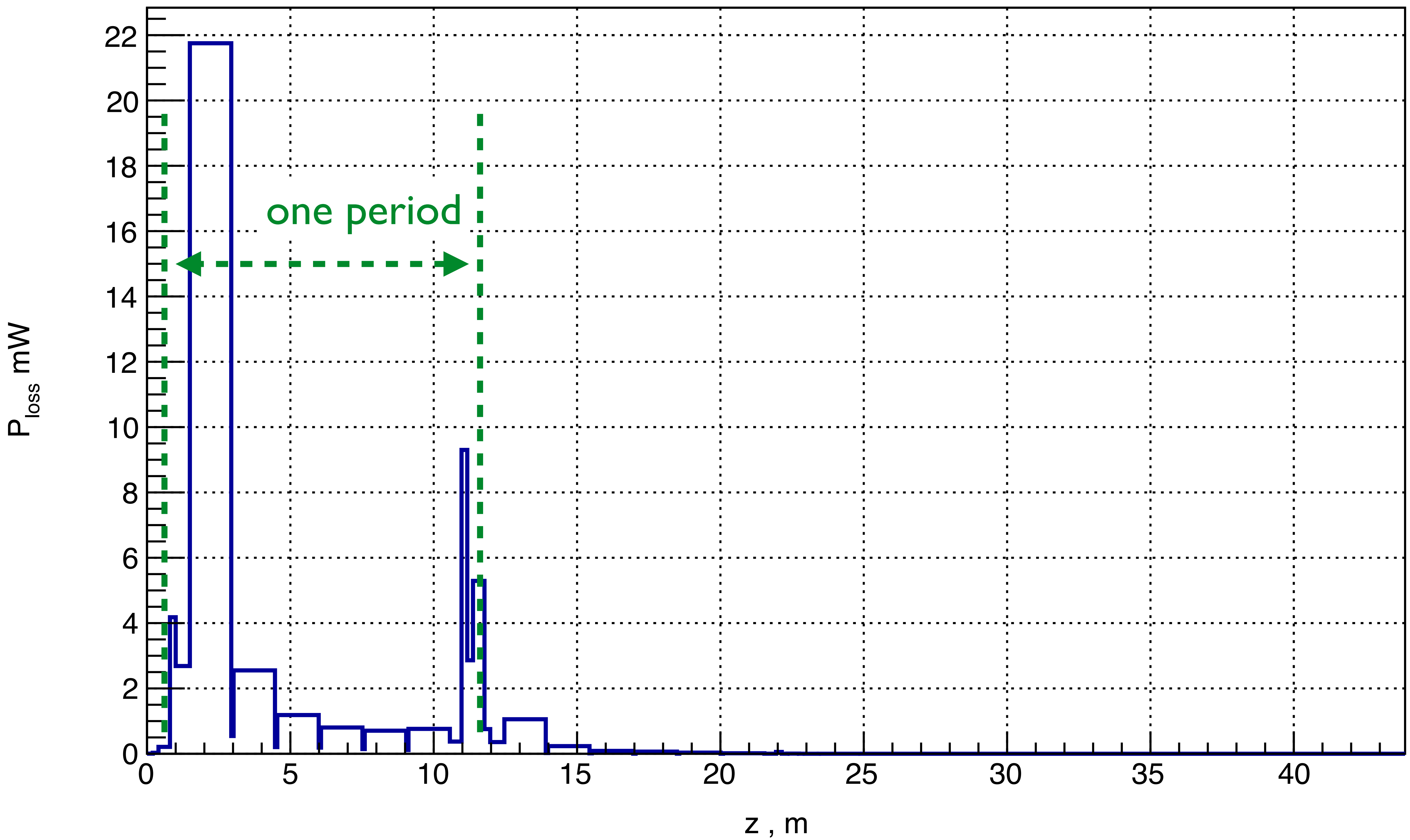
HB650 losses in the same cavity

- lost current - total current lost in cavity is 13 nA



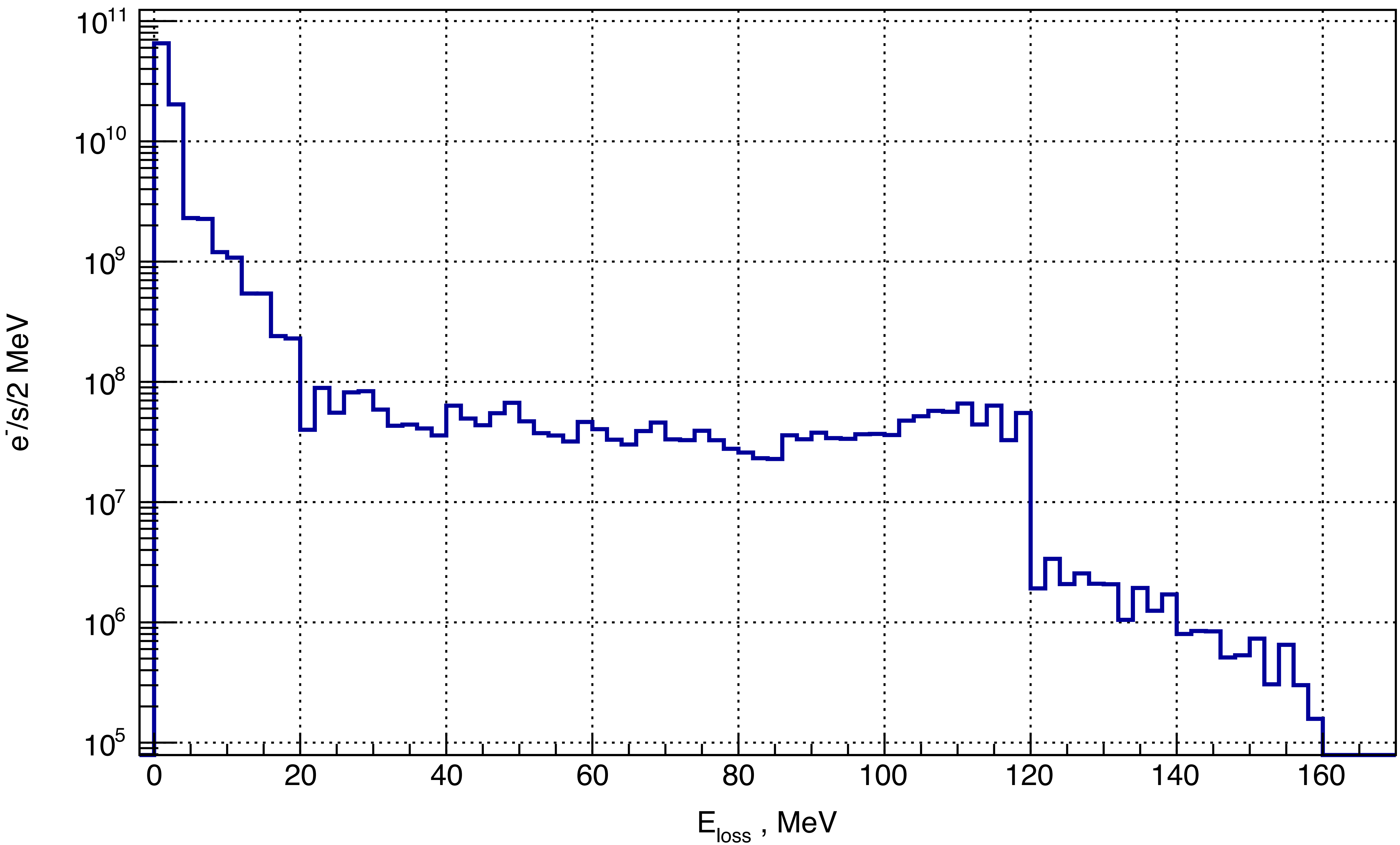
HB650 losses in linac, single cavity

- power loss



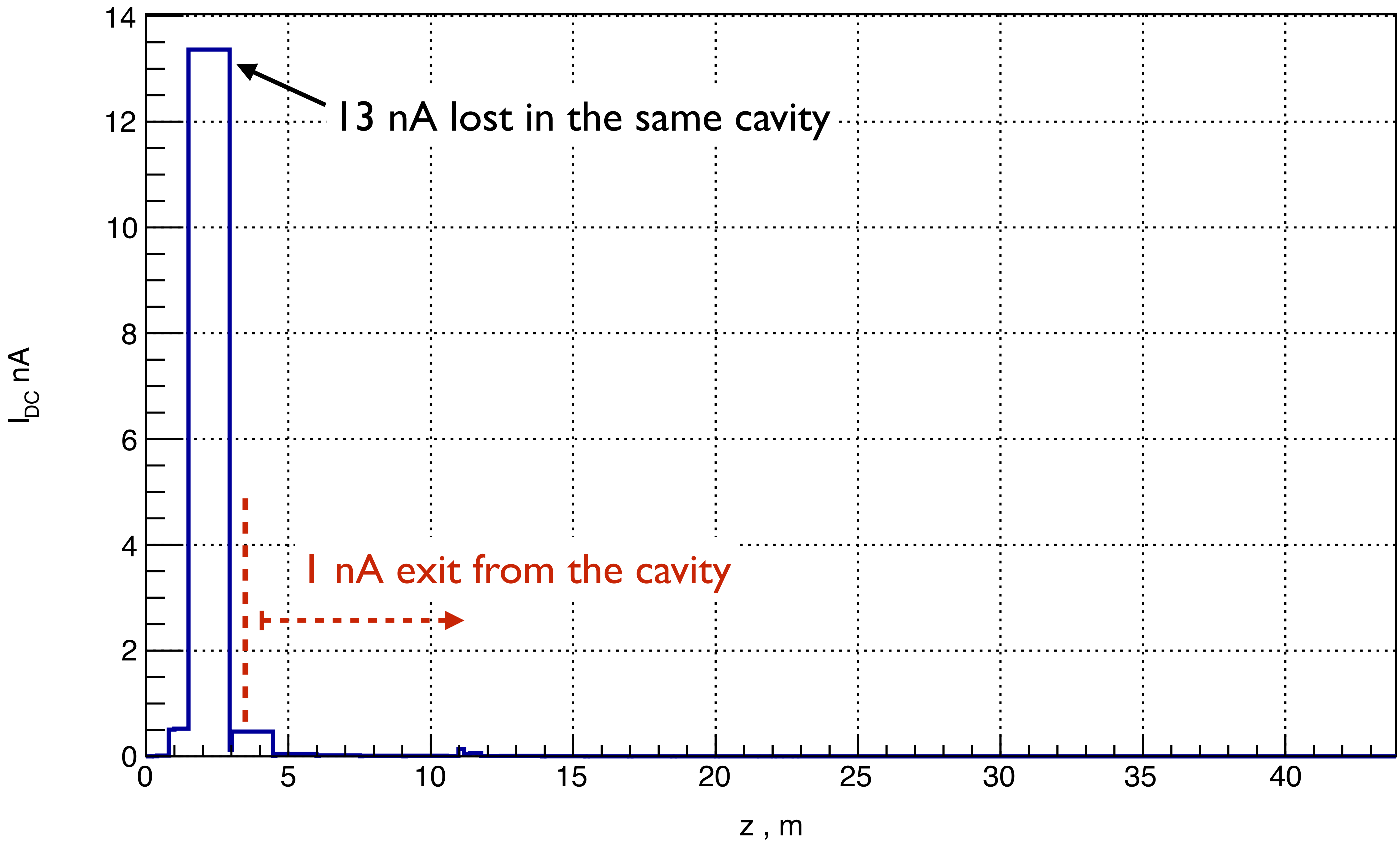
HB650 losses in linac, single cavity

- energy of lost particles



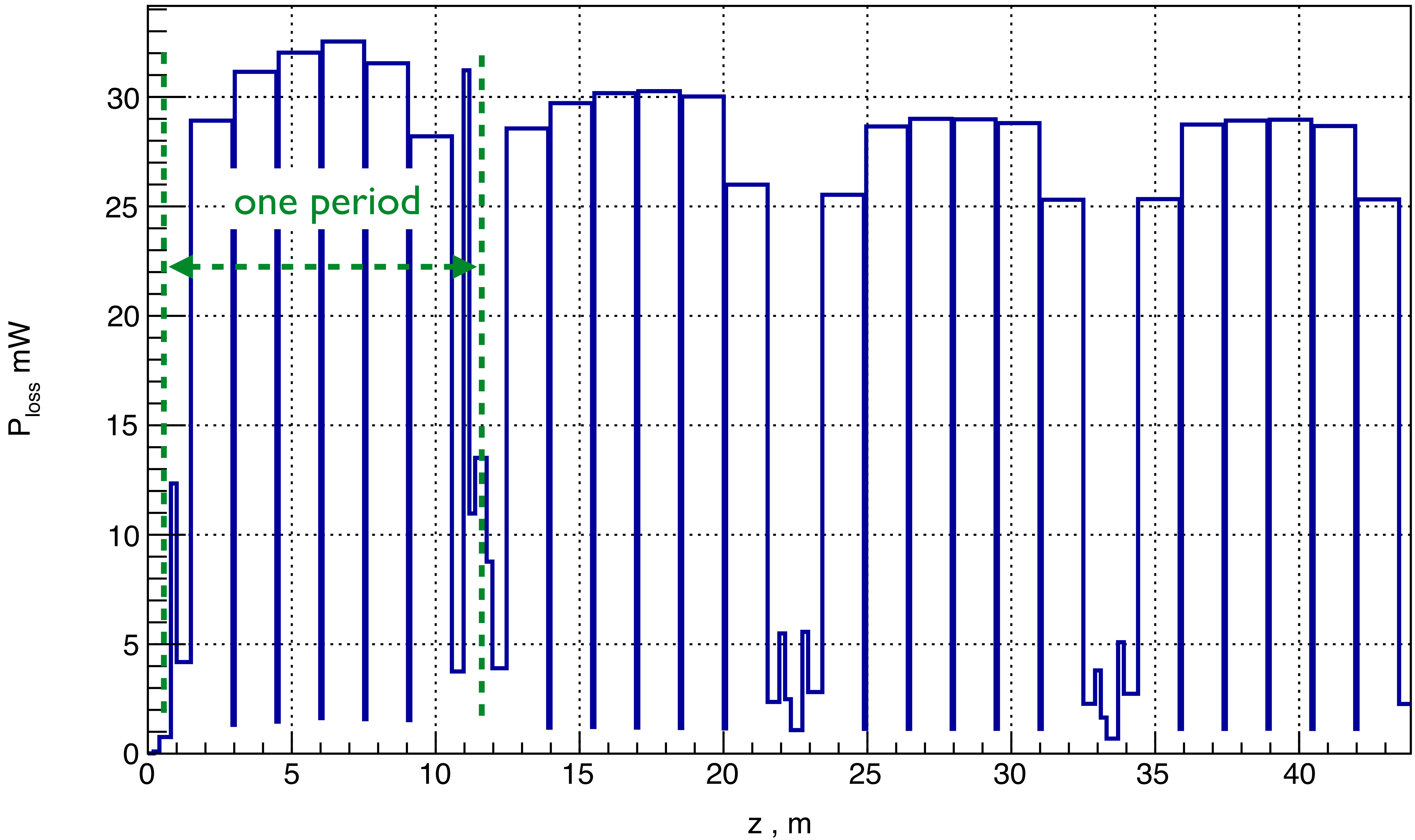
HB650 losses in linac, single cavity

- lost current



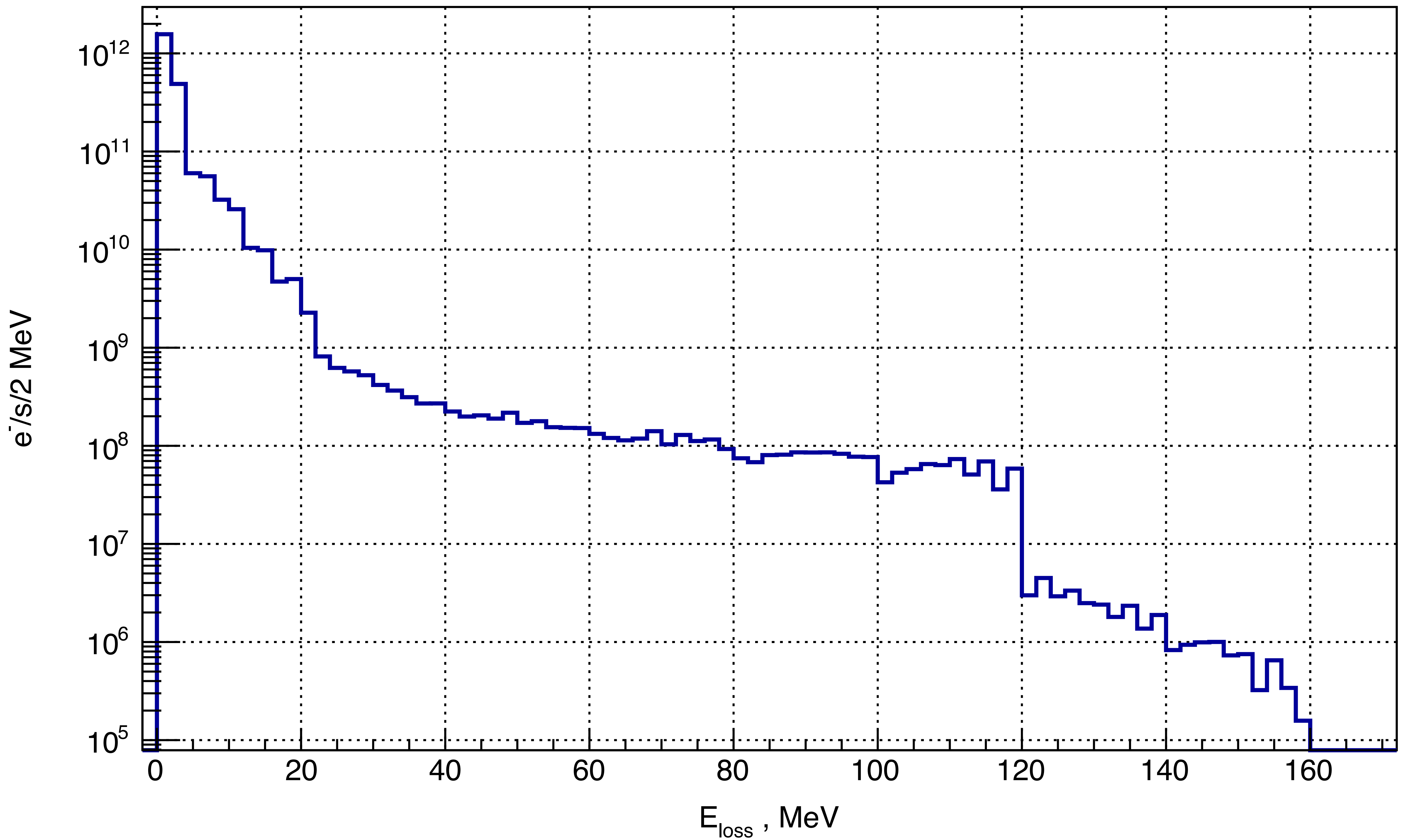
HB650 losses in linac, 4 periods, 24 cavities

- power loss - average power loss is 0.2 W per period



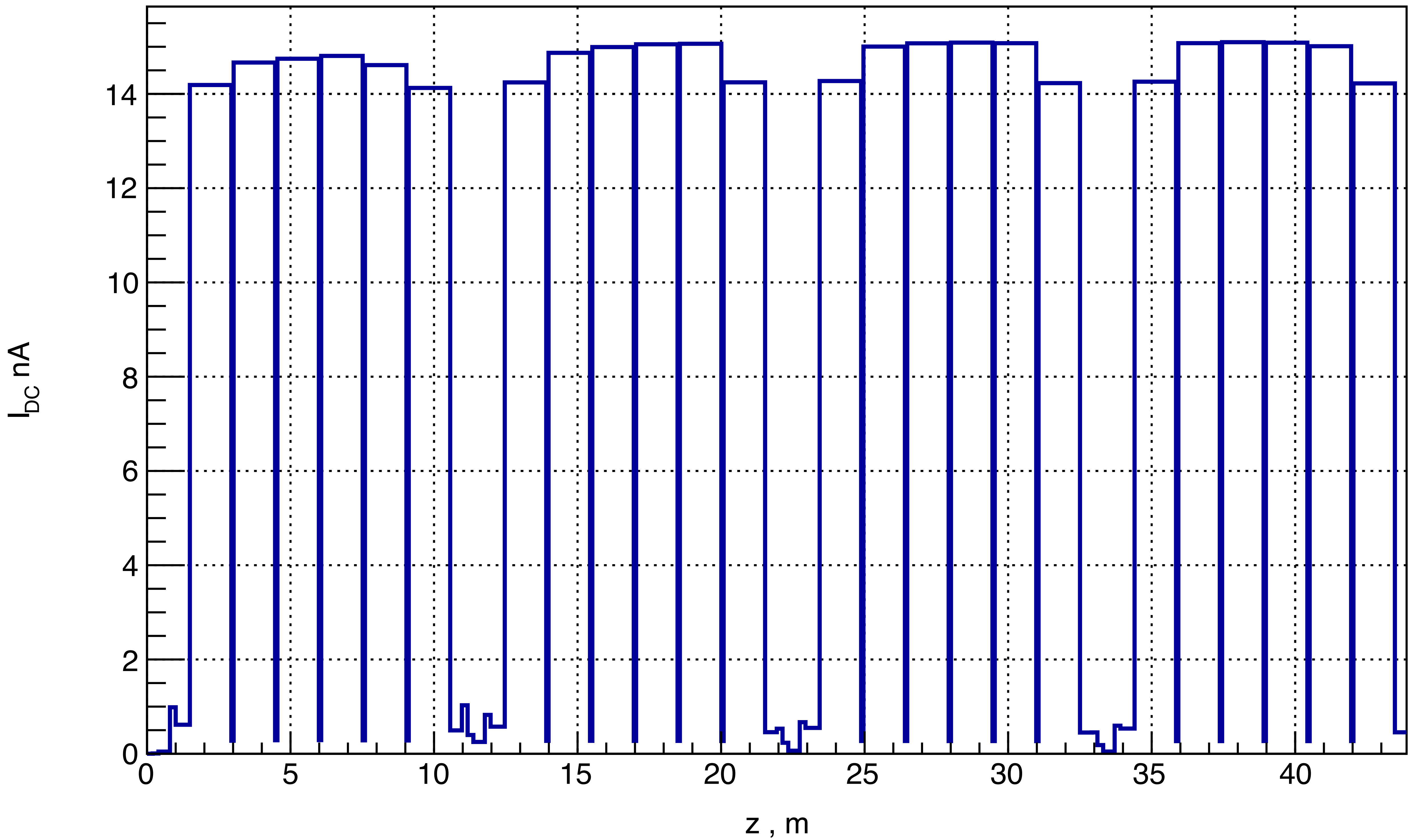
HB650 losses in linac, 4 periods, 24 cavities

- energy of lost particles



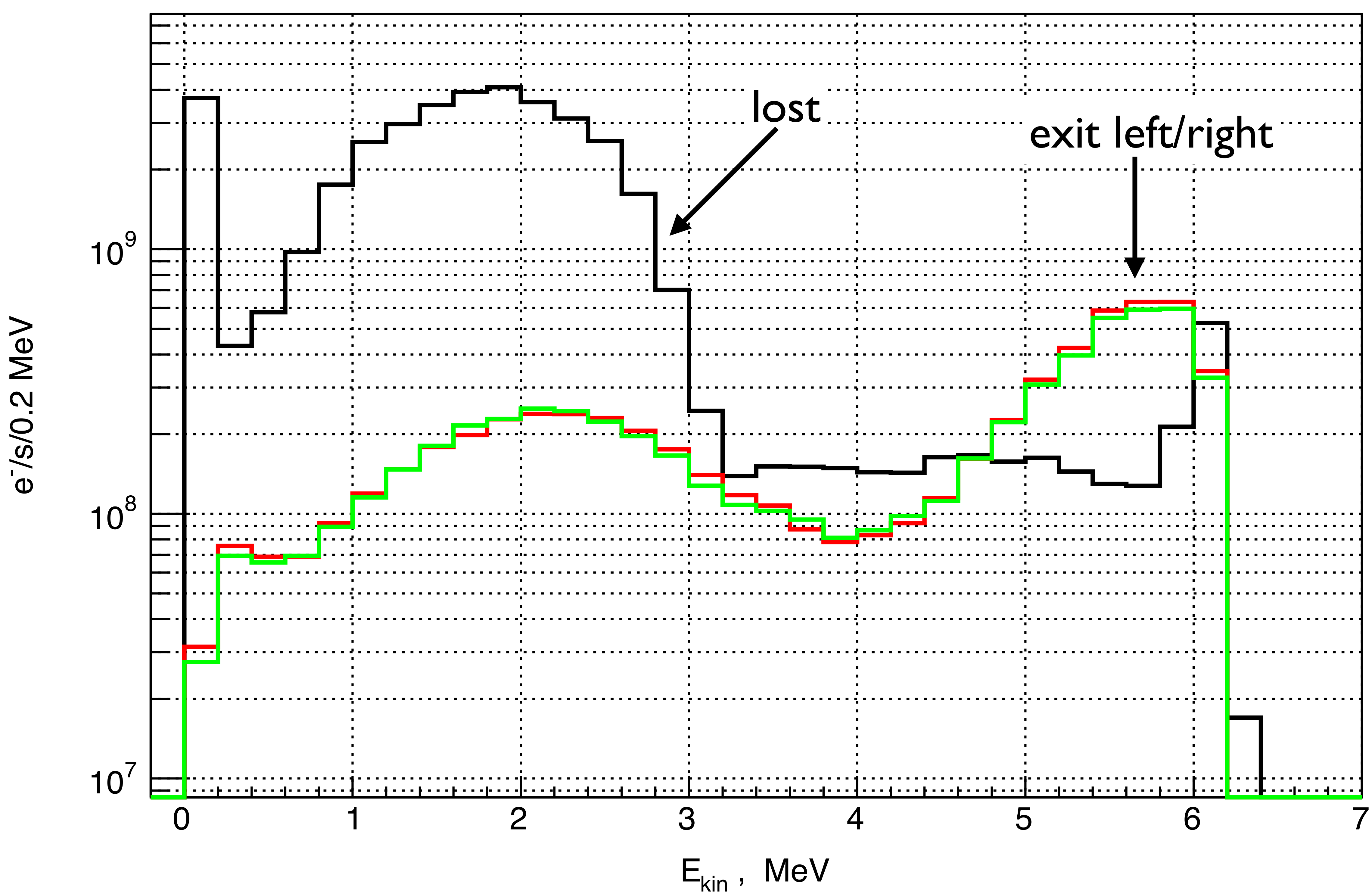
HB650 losses in linac, 4 periods, 24 cavities

- lost current



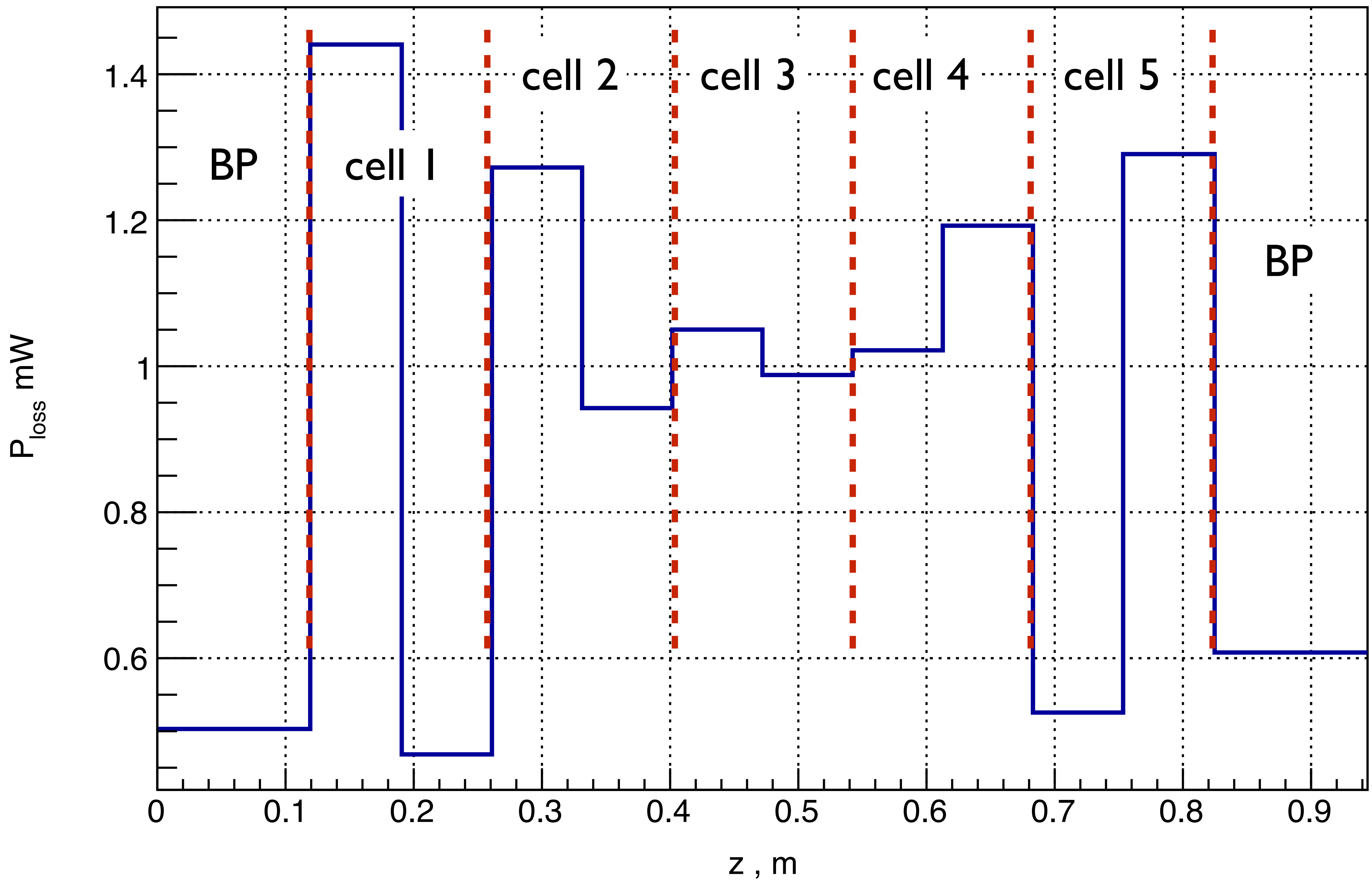
LB650 losses in the same cavity

- energy of lost particles (black) and particles exit to the left (red) and right (green)



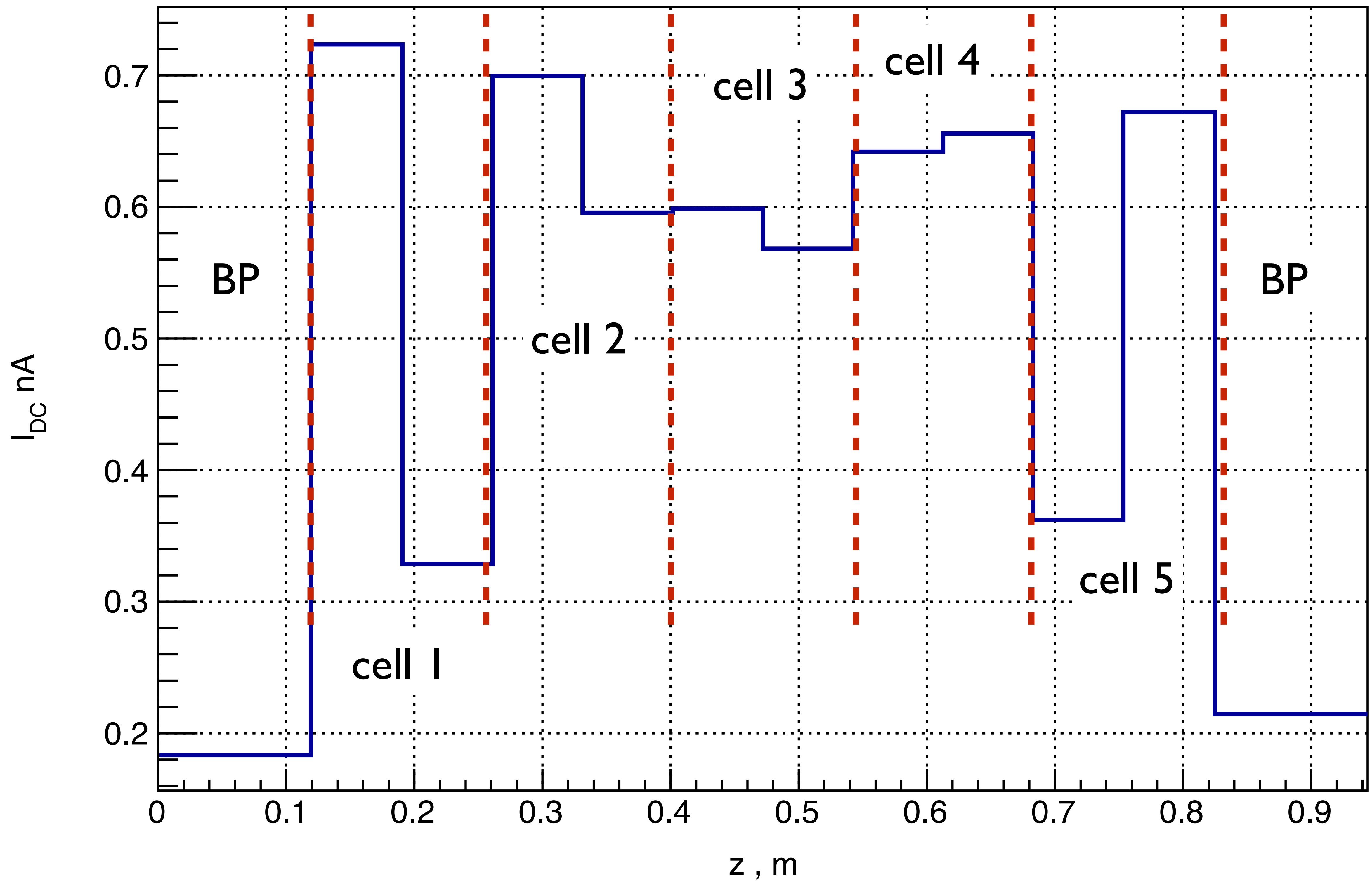
LB650 losses in the same cavity

- power loss - total power loss is 11 mW



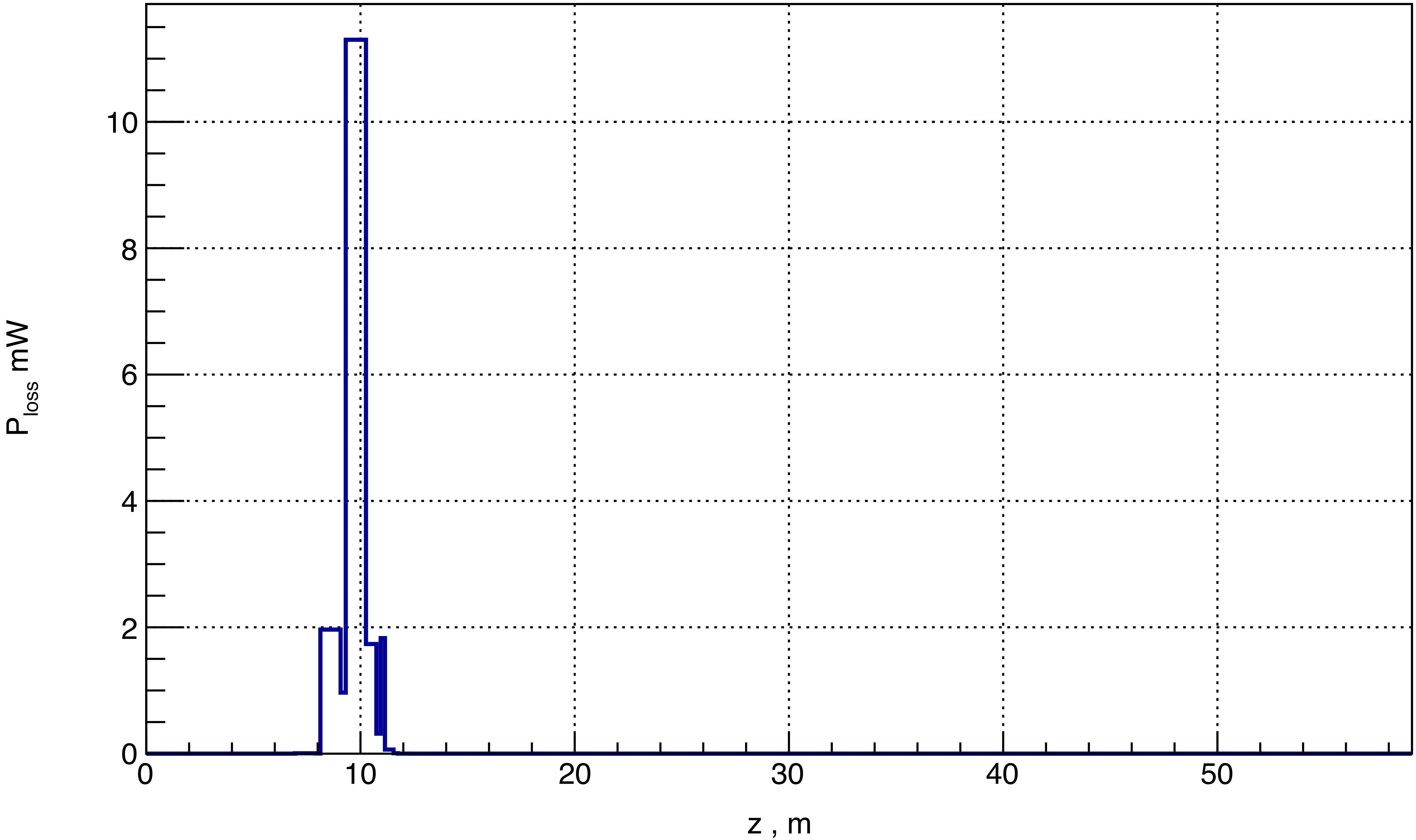
LB650 losses in the same cavity

- lost current - total current lost in cavity is 6 nA



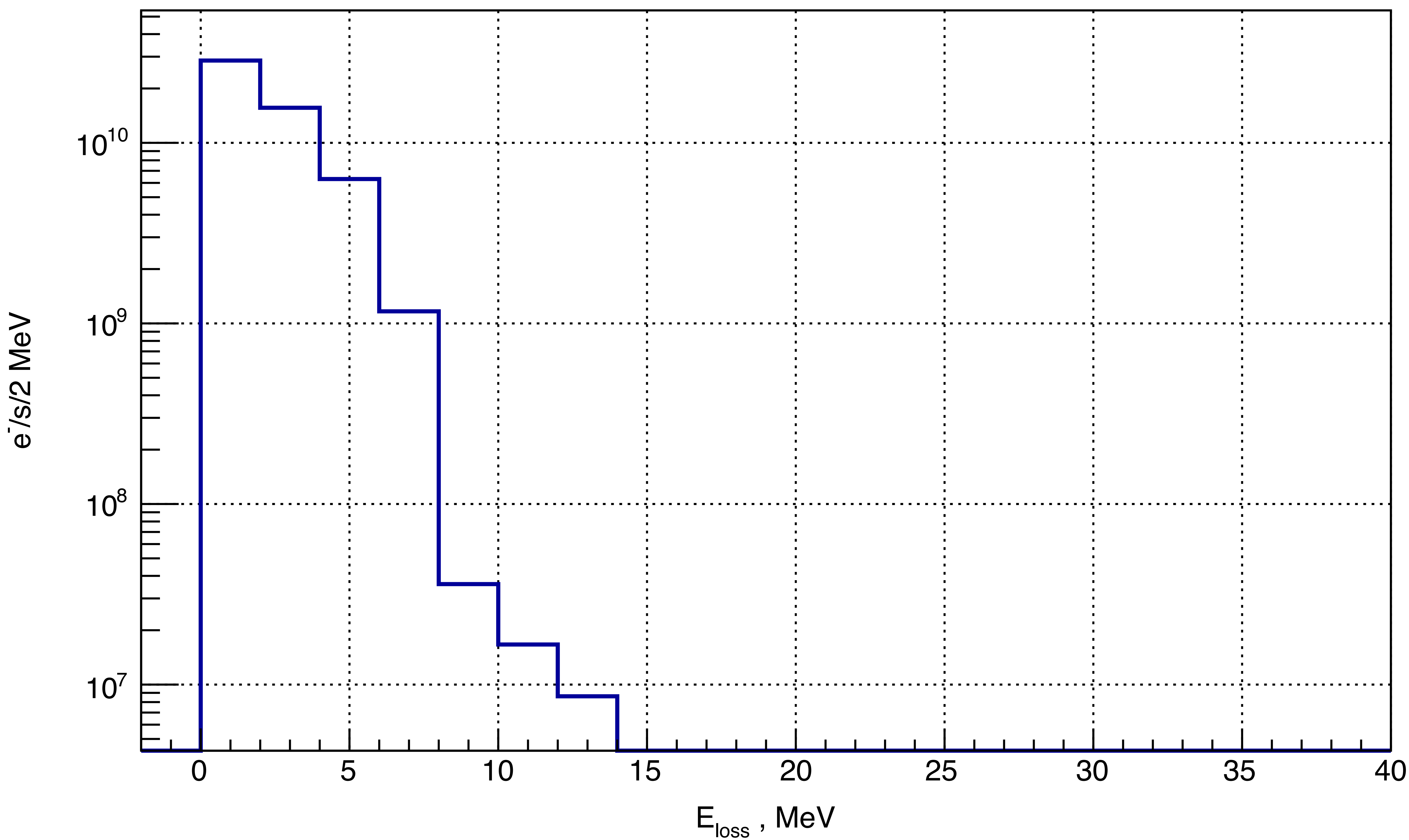
LB650 losses in linac, single cavity

- power loss



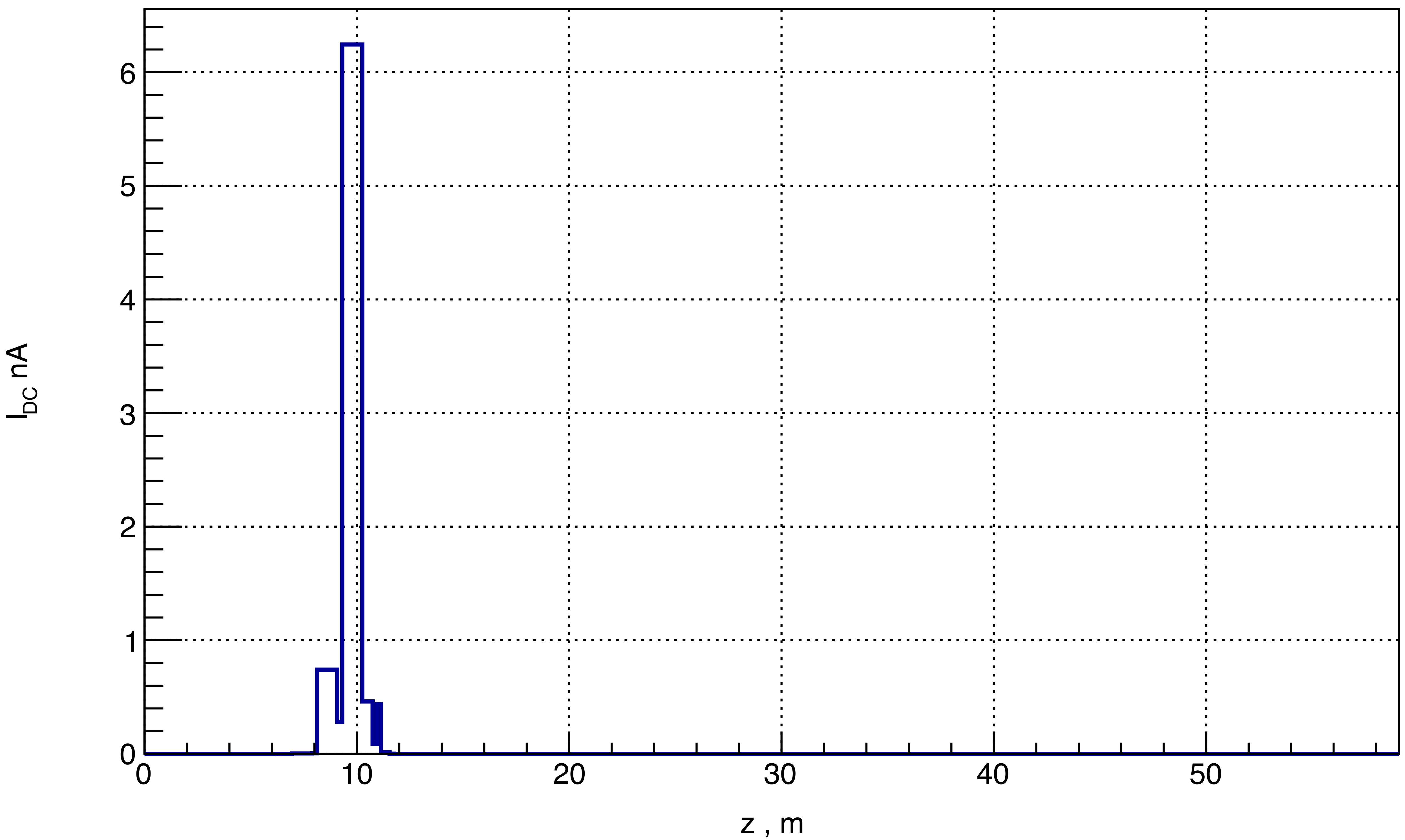
LB650 losses in linac, single cavity

- energy of lost particles



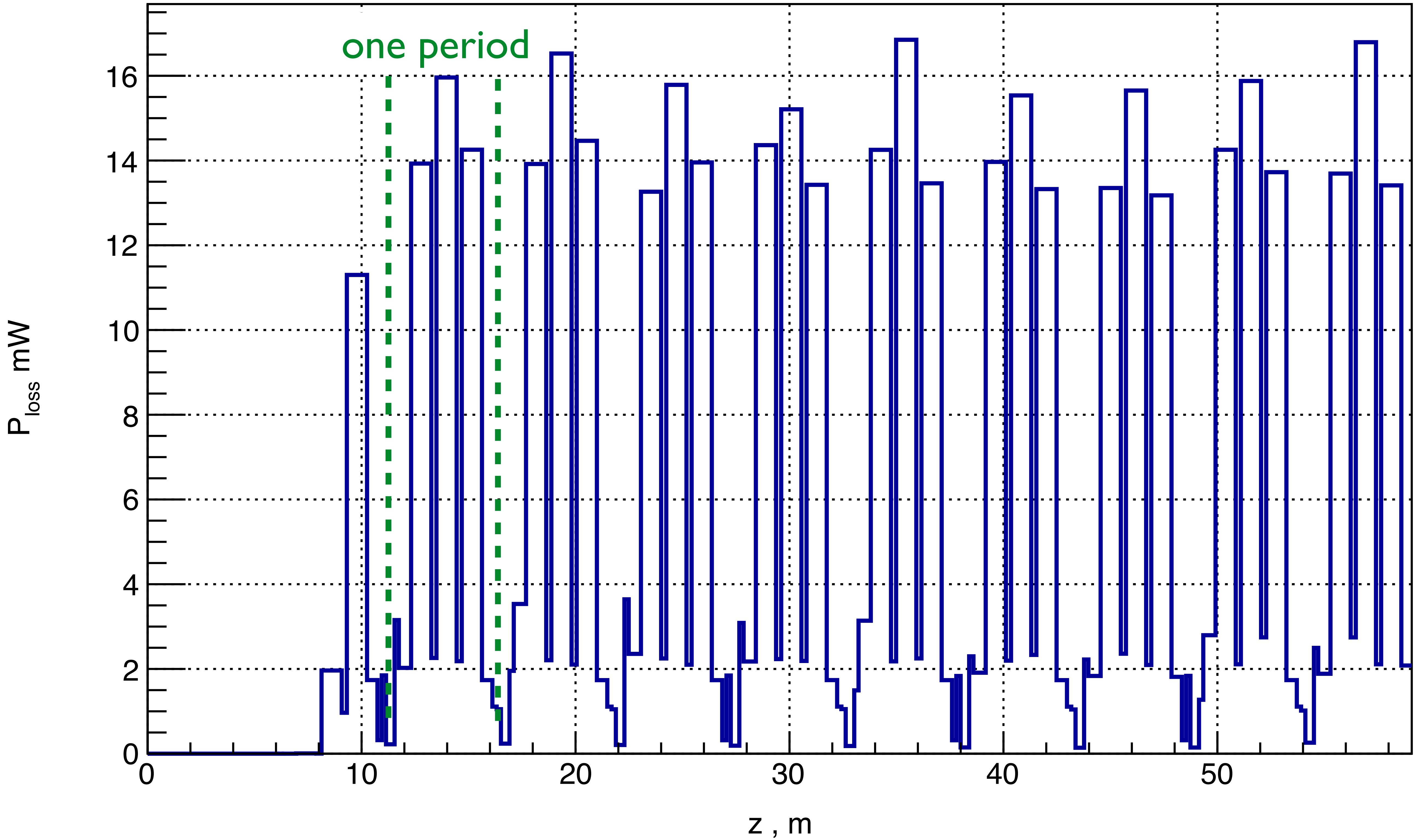
LB650 losses in linac, single cavity

- lost current



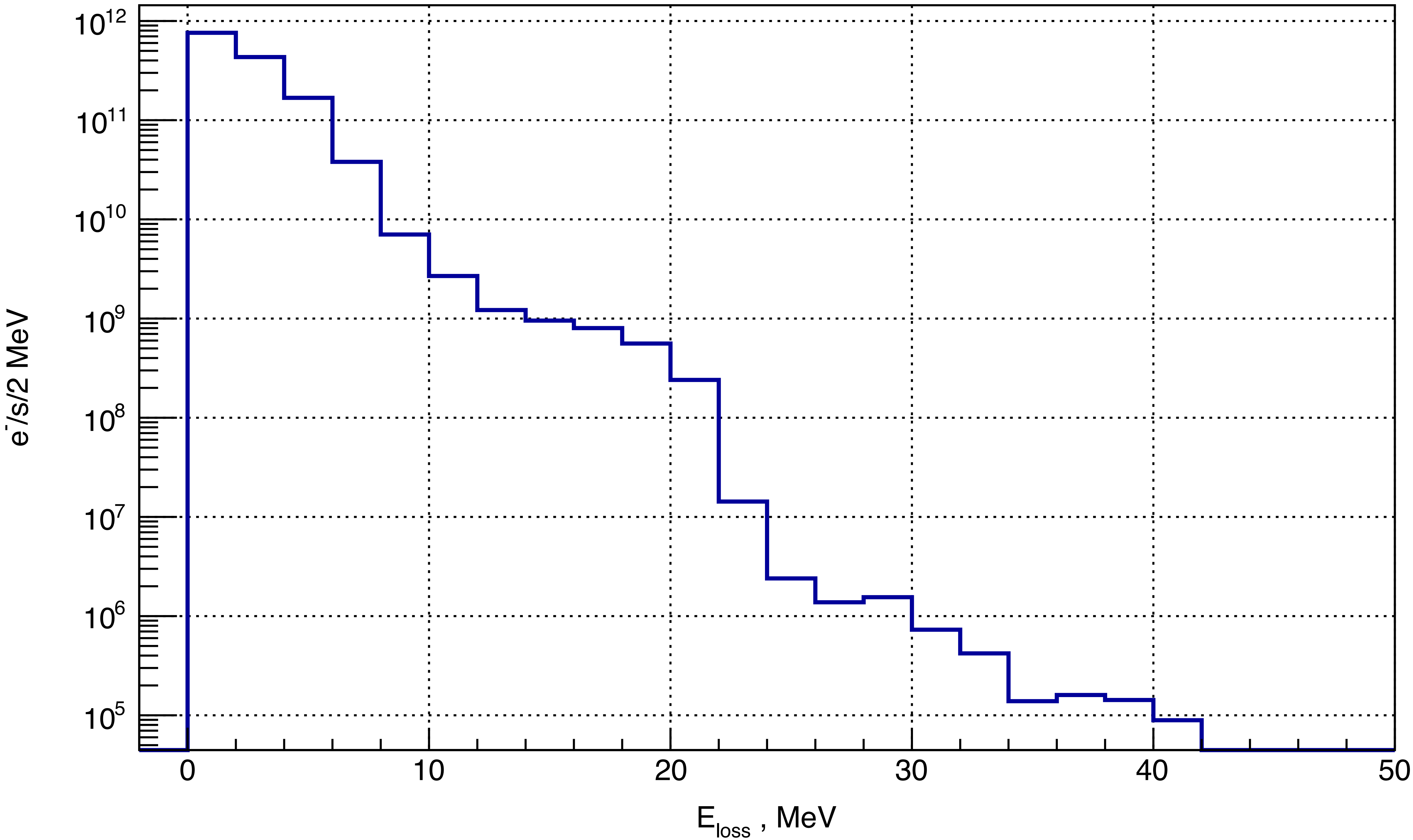
LB650 losses in linac, 11 periods, 28 cavities

- power loss - average power loss is 50 mW per period



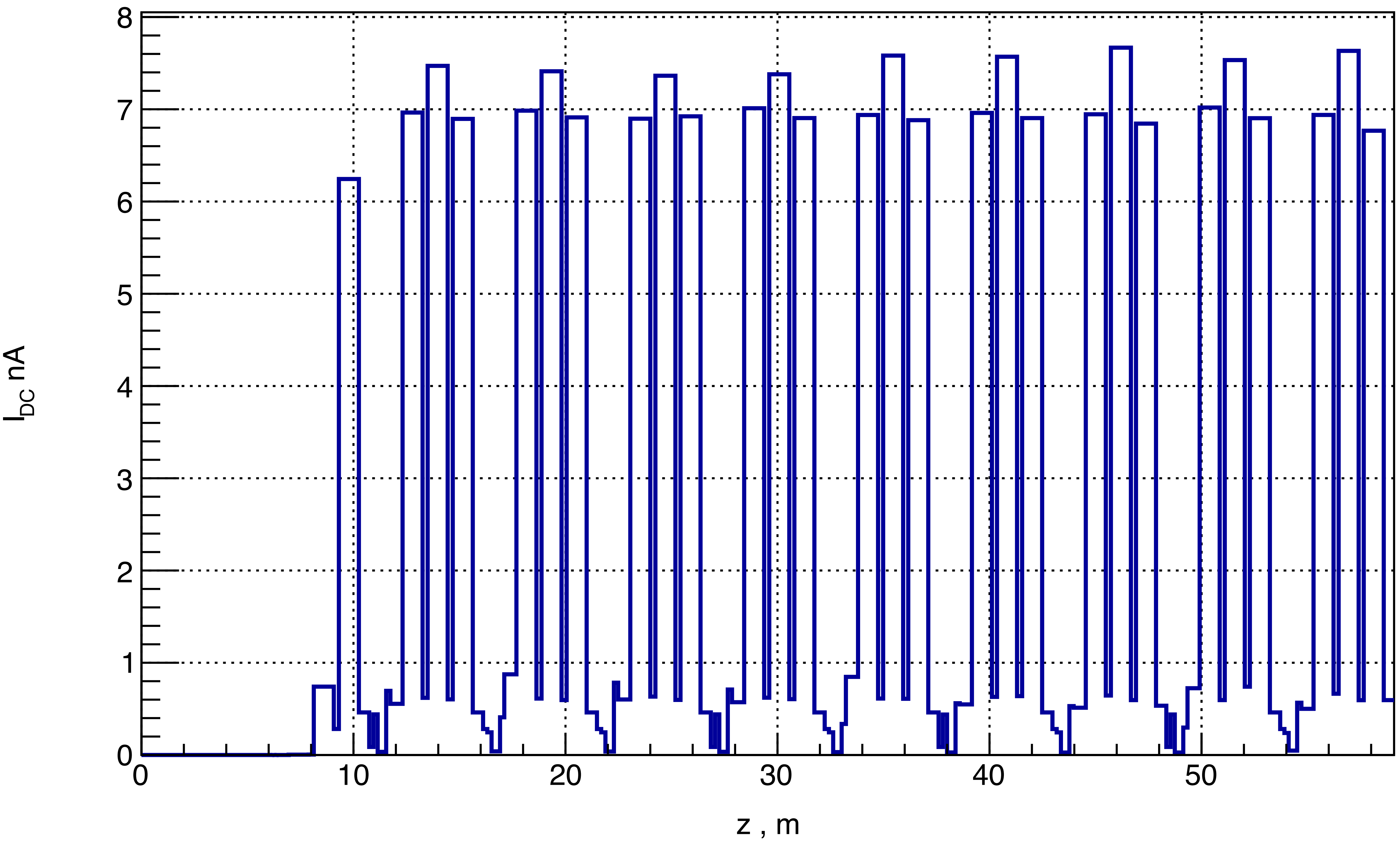
LB650 losses in linac, 4 periods, 24 cavities

- 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