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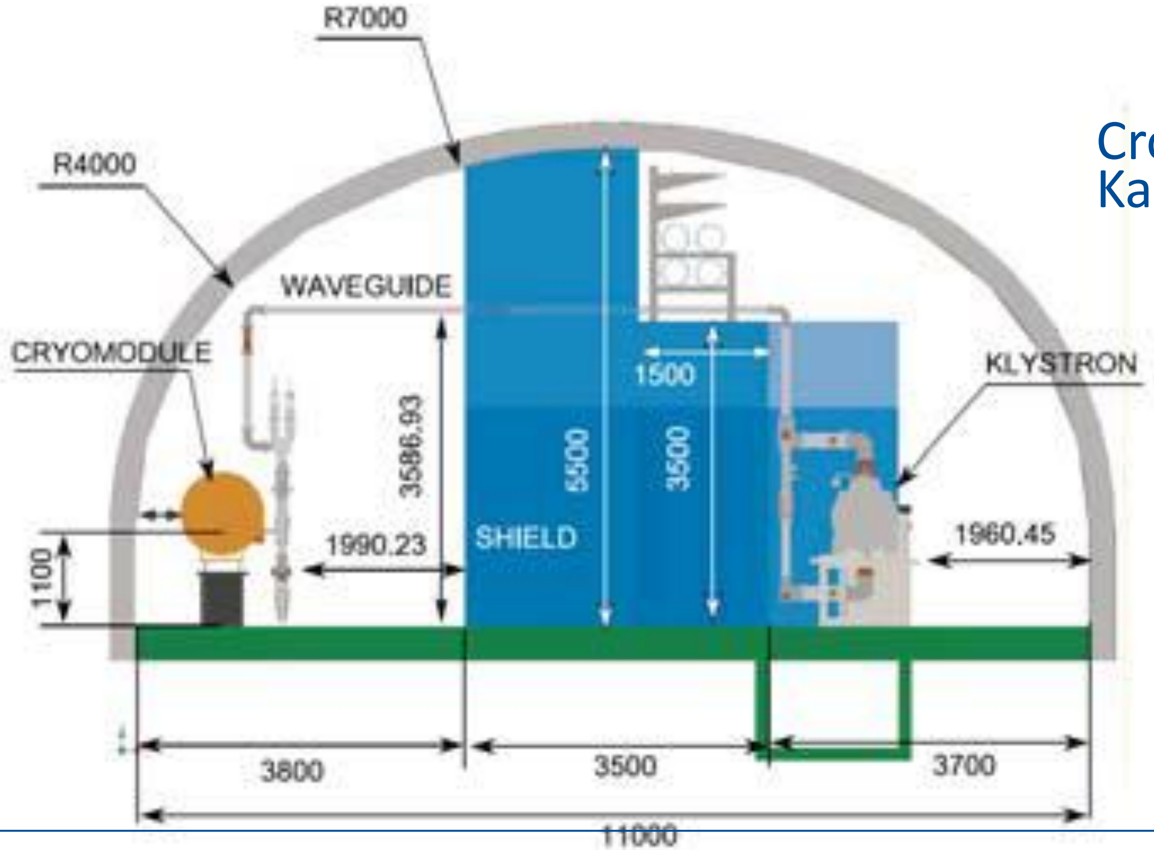
Update on Dark current generation in ILC Main Linac

N.Solyak, A.Sukhanov

Motivation

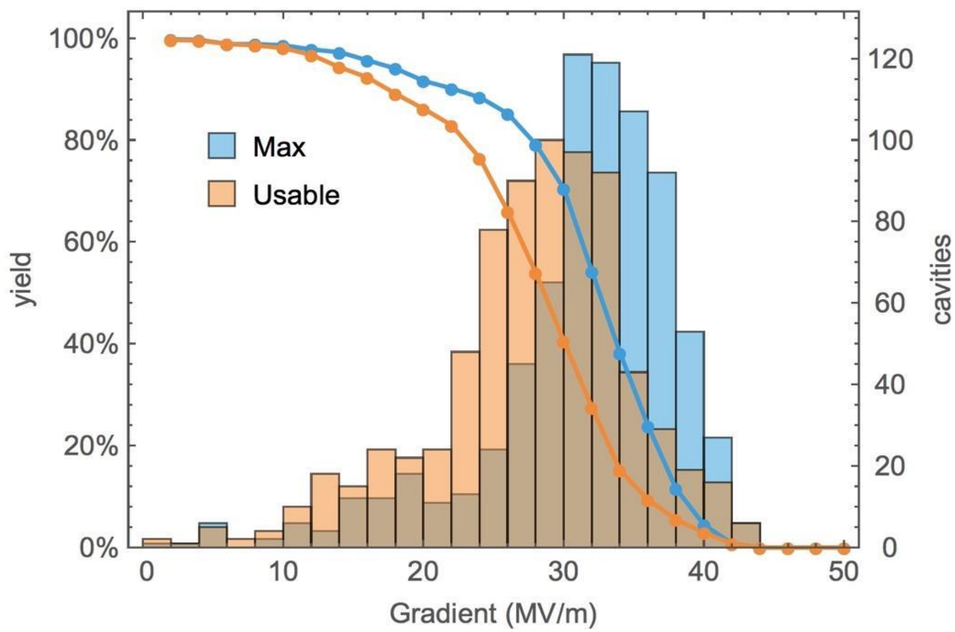
In current design 3.5m wall between main and service tunnels. Reduction of wall thickness is cost effective solution.



Cross section of Kamaboko tunnel

Thickness of wall (1.5-3.5m) separating service and operational facility is determined by max beam losses in tunnel

XFEL cavities as received (VT) and in CM



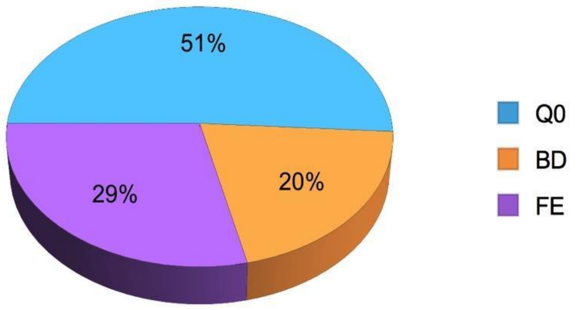
		Max	Usable
Average	MV/m	31.4	27.7
RMS	MV/m	6.8	7.2
Median (50%)	MV/m	32.5	28.7
Yield ≥20 MV/m		92%	86%
Yield ≥26 MV/m		85%	66%

N. Walker et al., PERFORMANCE ANALYSIS OF THE EUROPEAN XFEL SRF CAVITIES, FROM VERTICAL TEST TO OPERATION IN MODULES

typical individual error: 10%

- Include operations spec
  - $Q0 \geq 1 \times 10^{10}$
  - FE threshold (X-ray)

→Usable Gradient



After retreatment of bad cavities:

	Ncavs	Average	RMS
VT	815	28.3 MV/m	3.5
CM	815	27.5 MV/m	4.8

Dark current is less frequent than FE

Field Emission (E=31.5 MV/m)

- uniform distribution of emitters over the cavity surface
- Fowler-Nordheim model

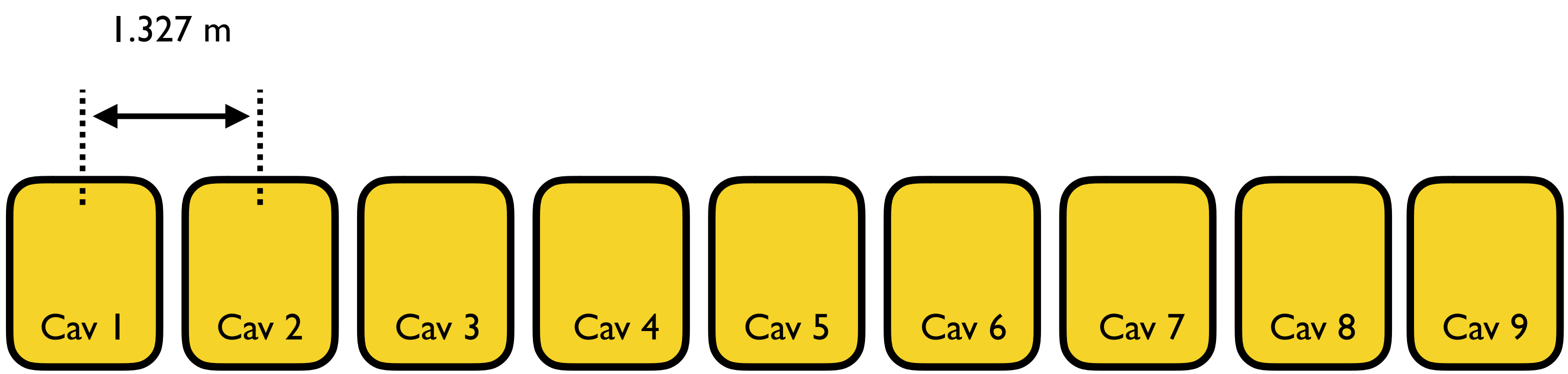
$$W_{FN} = N_{FN}(\beta_{FN}E)^2\exp(-B_{FN}\varphi^{3/2}/\beta_{FN}E)$$

$\beta_{FN}=100$
$B_{FN}=6.83\cdot 10^3$, $\varphi=4.2$ eV,
E in MV/m, I in Amp;

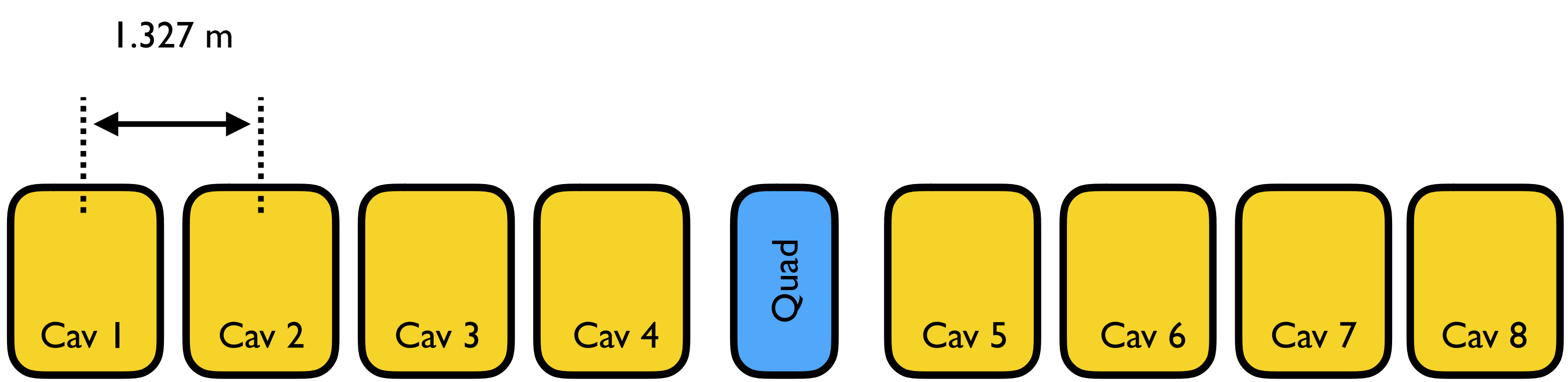
- Norm factor is determined from the nominal DC value (50nA) exiting cavity
  - Norm = 4.79e12 e-/s (taking into account RF duty factor 10Hz*1ms=0.01)

ILC CM Layout

- Type A: 9 1.3 GHz 9-cell TESLA type cavities



- Type B: 4 cavities, magnet package, 4 cavities

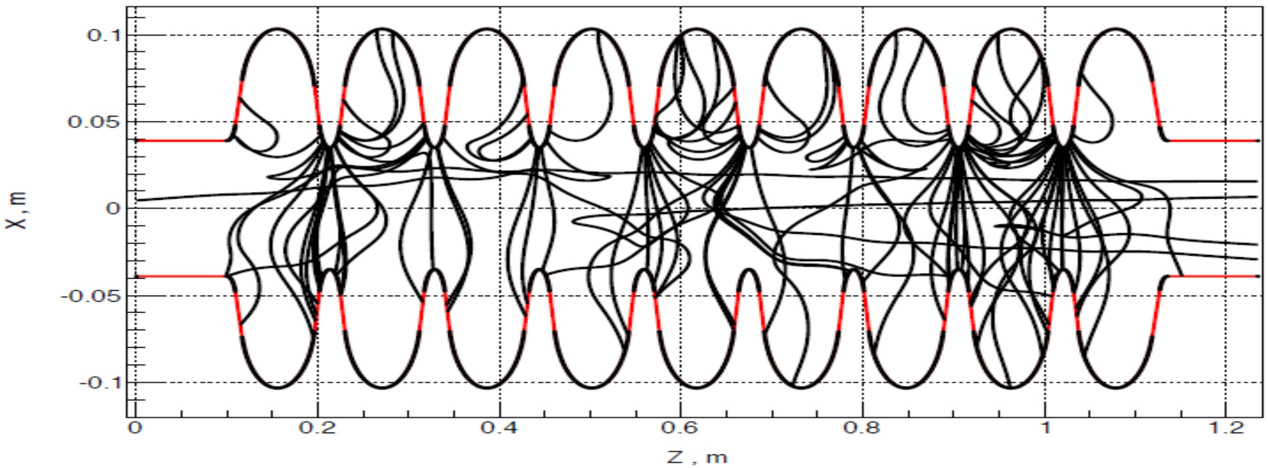


FE: uniform distribution vs. localize source

FE in cavity (uniform distribution)

- Particle trajectories (Eacc = 16 MV/m)

4%

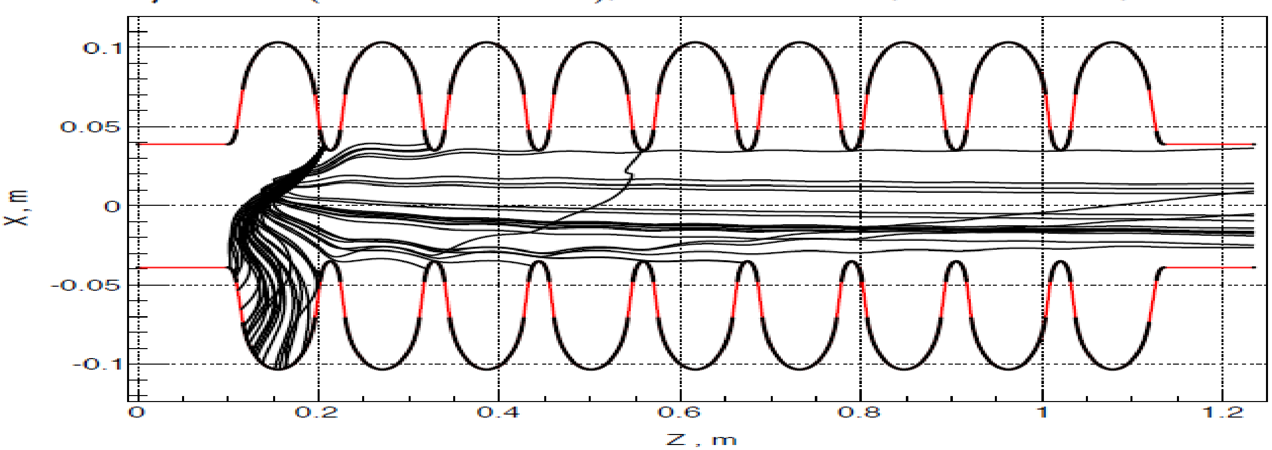


4%

FE in cavity (localized source)

- Particle trajectories (Eacc = 16 MV/m); emitter in HC 1, 6 mm off iris, 1 mm wide

<0.01 %



Up to 40%
(FE location)

Particle Tracking in Cavity RF Field

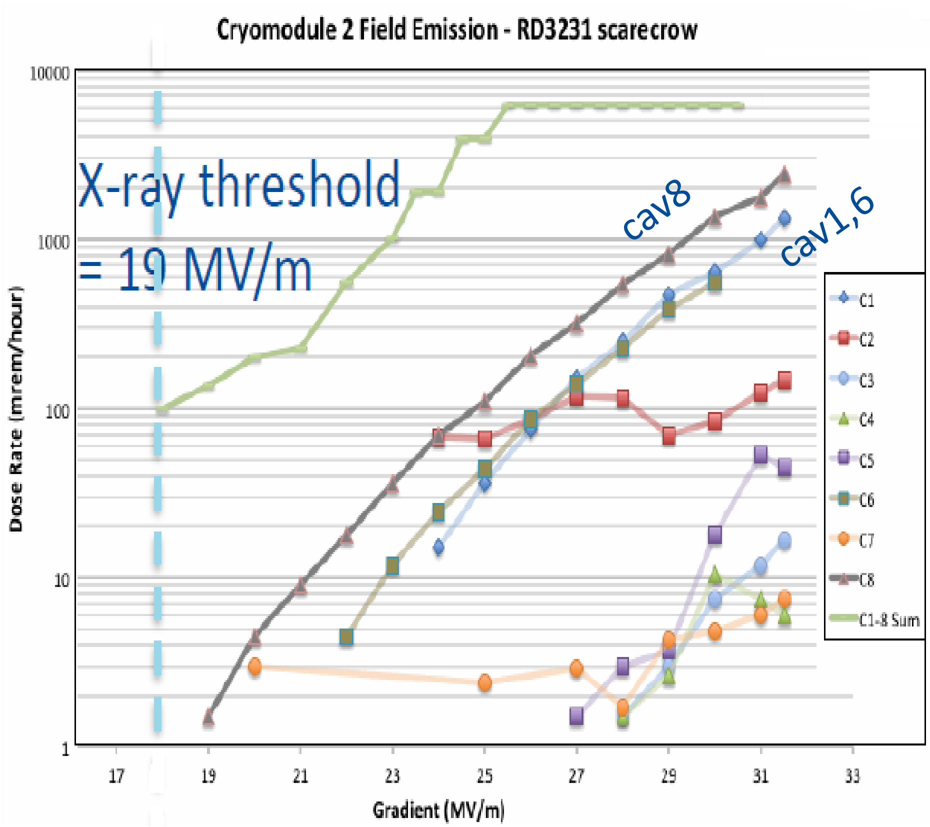
- 92% of emitted particles are absorbed in the same cavity
- 4% of particles are captured into acceleration, exit cavity in the direction of the main beam into the next cavity
  - continue tracking of these particles through cavities down stream until they are lost or reach next quadrupole
- 4% of particles exit cavity up stream, in the direction opposite to the main beam, and enter previous cavity
  - continue tracking of these particles through cavities up stream until they are lost or reach previous quadrupole

- Add emission and tracking for all 26 cavities between quads

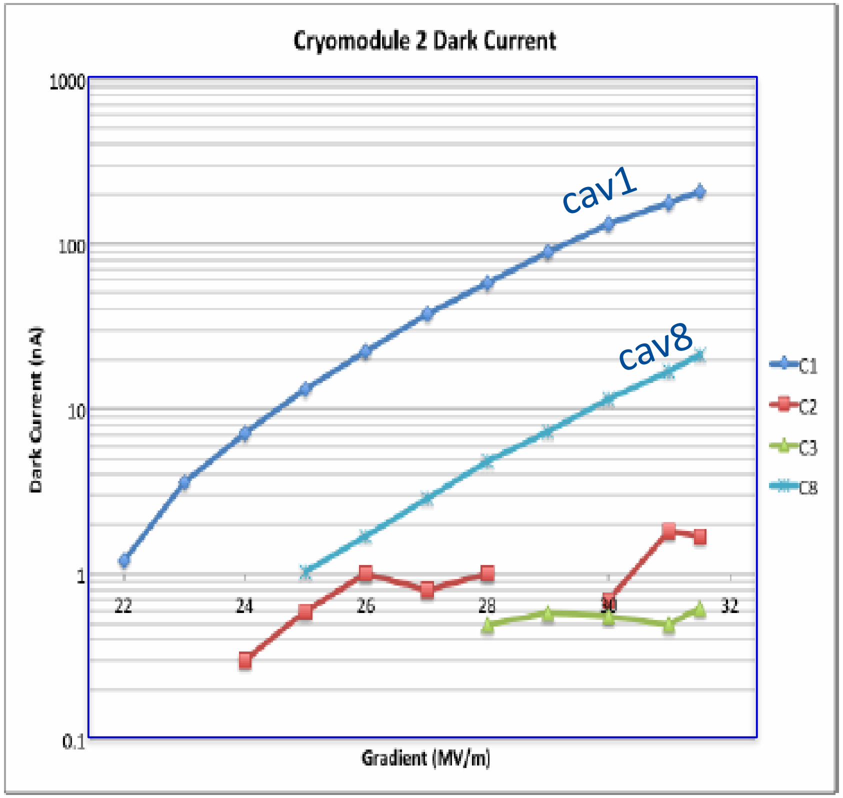
RF phasing between cavities in ILC linac prevents acceleration of the dark current particles in downstream direction

NML CM2 with ILC gradients 31.5 MV/m in all cavities

Radiation

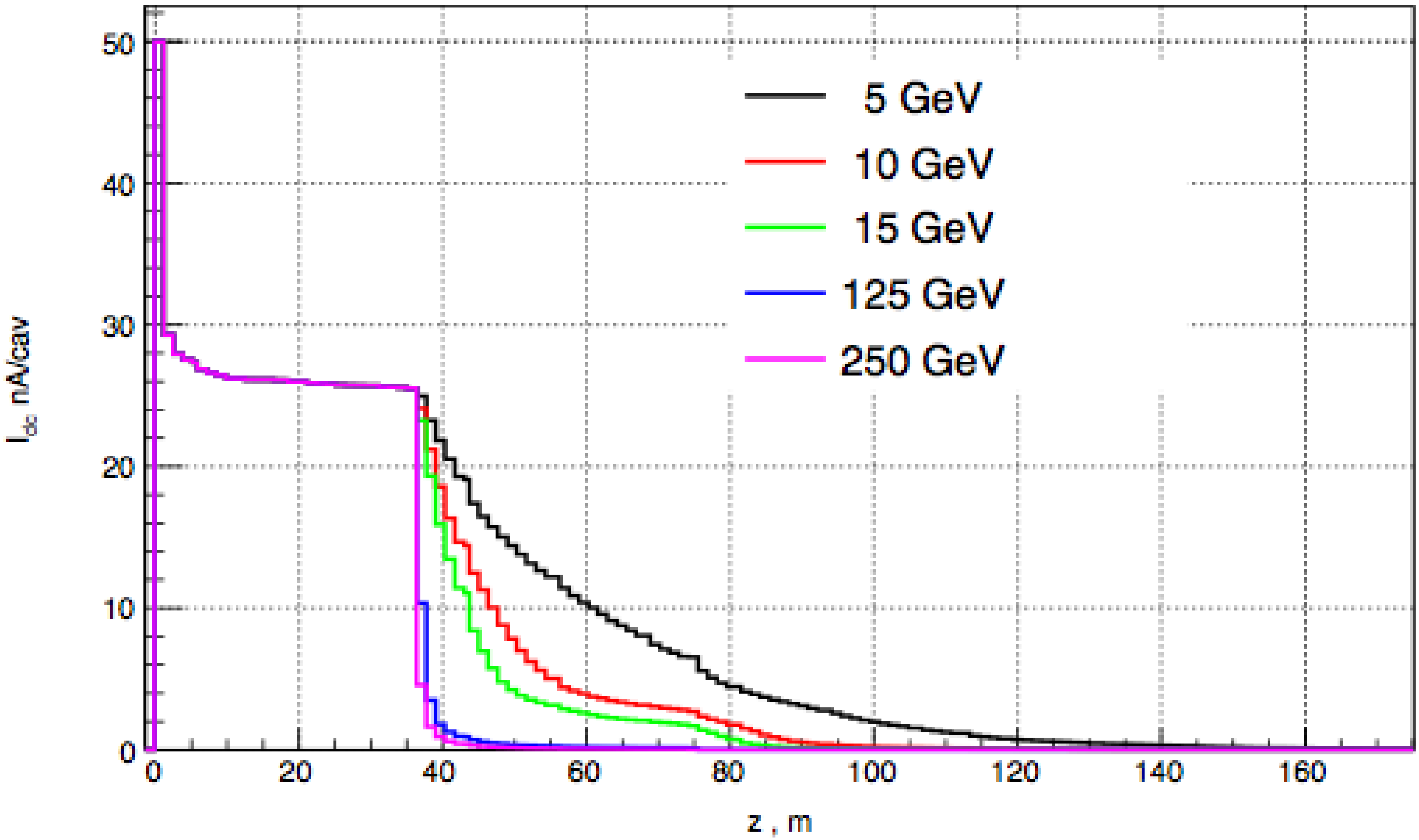


Dark Current



slope = (3.5-4.5)MV/m per decade

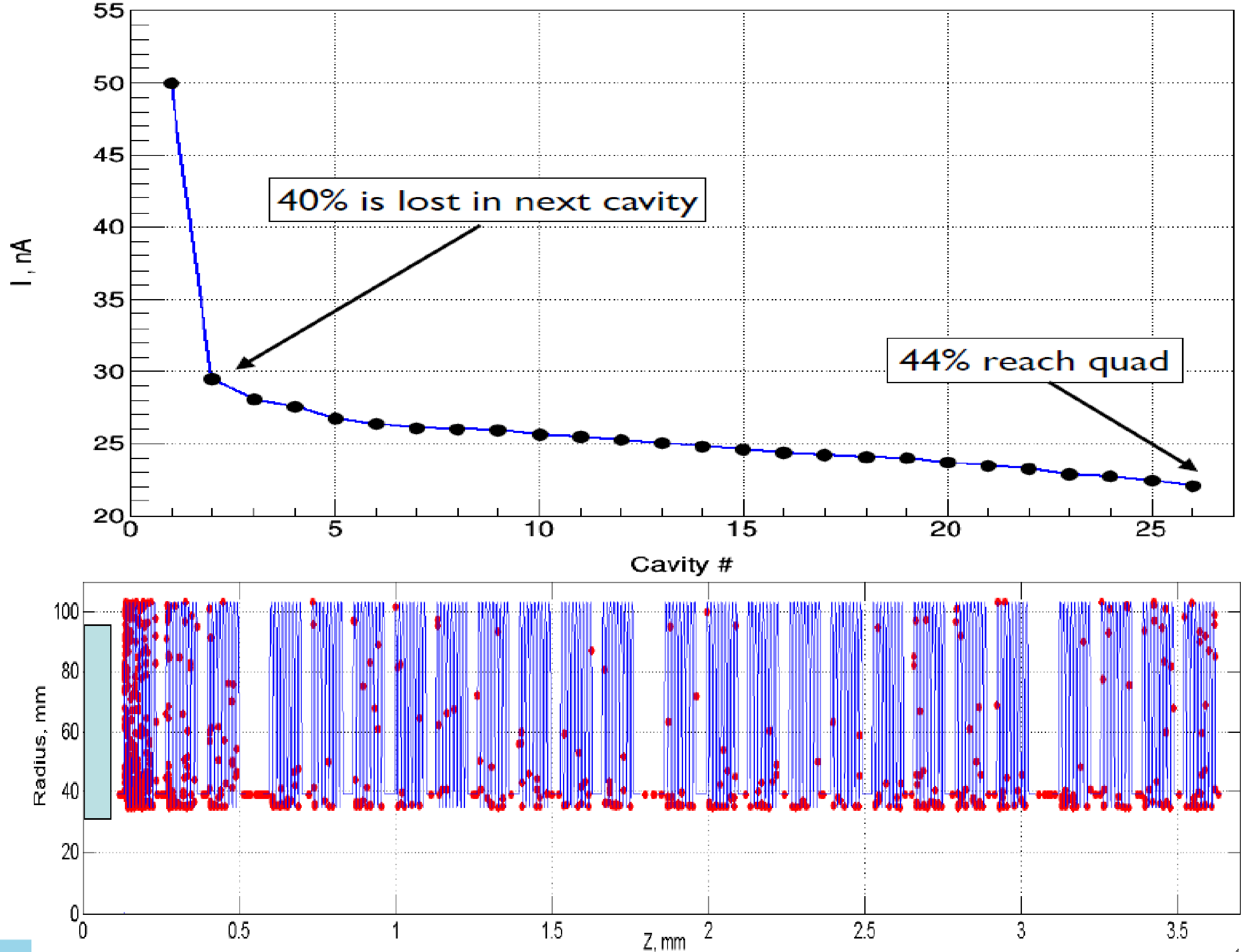
Dark current distribution from single cavity



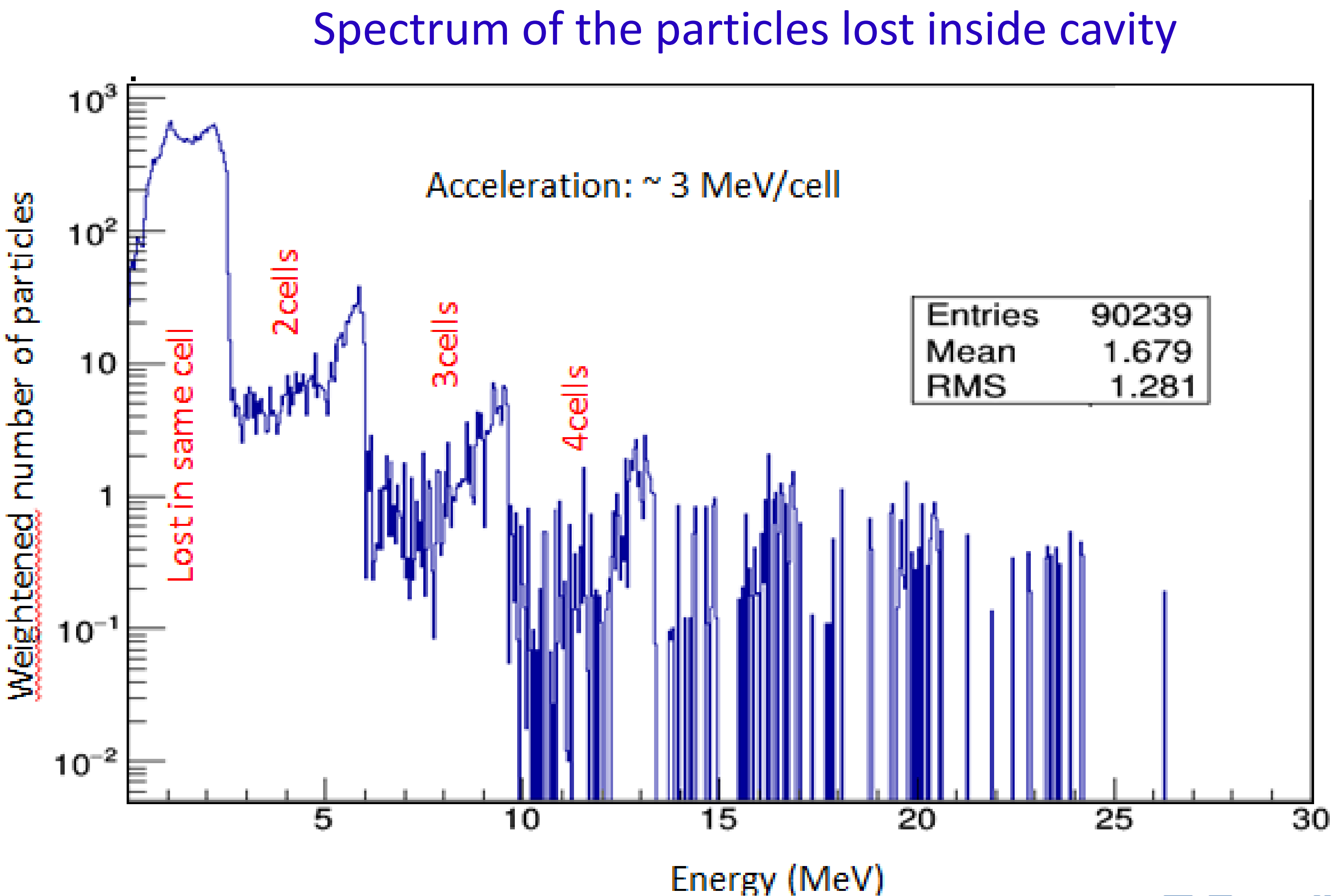
Single cavity (just after focusing quad) emits 50 nA of dark current

DC from Single Cavity

- Distribution of peak DC from single cavity along the string of 26 cavities

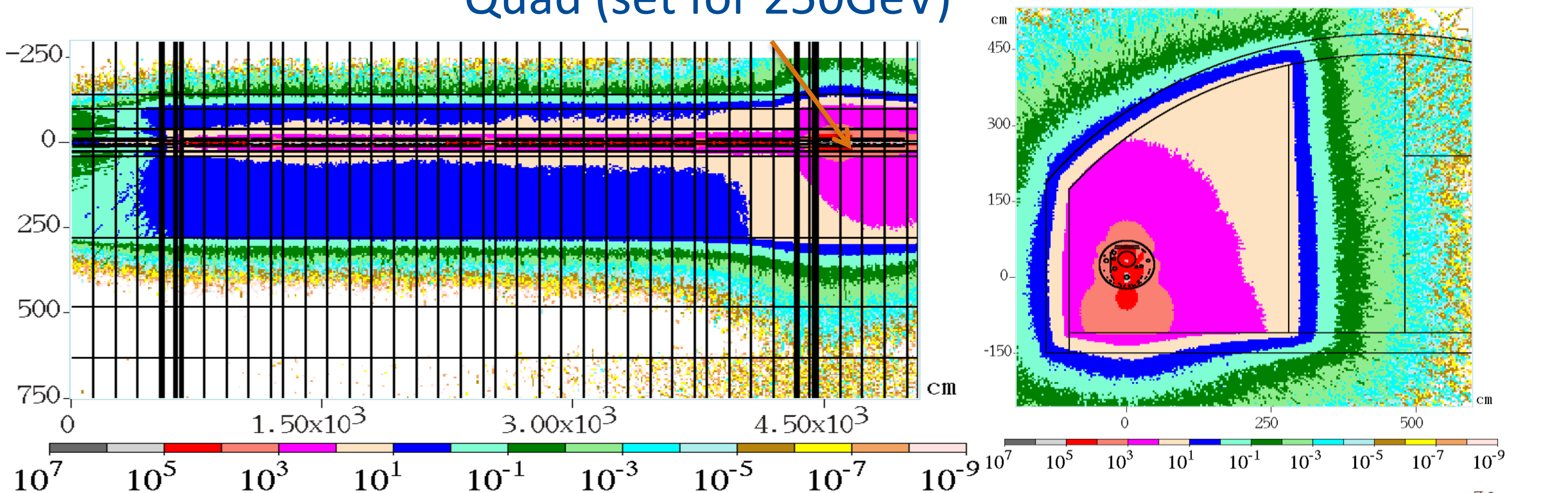


Energy spectrum of lost particles

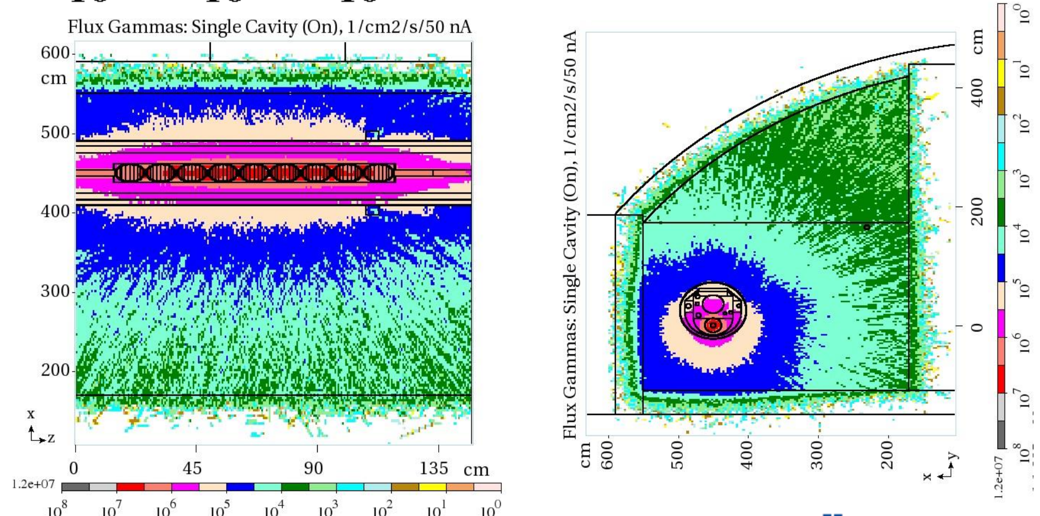


Total prompt dose in 3CMs (top view), mSv/h

Quad (set for 250GeV)



dose in single cavity, mrem/h



1mSv/h=100mrem/h

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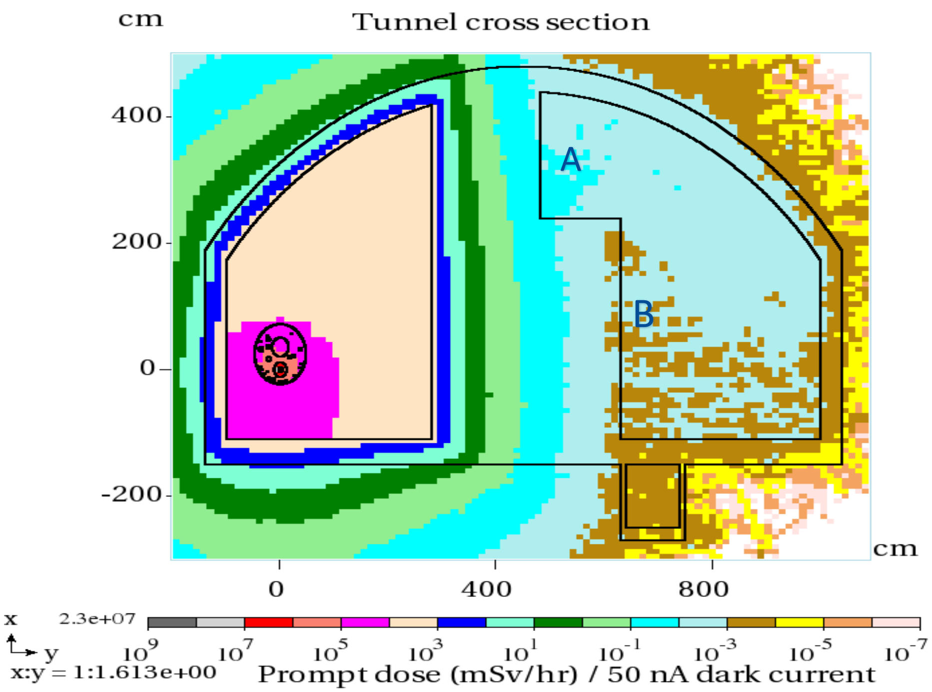
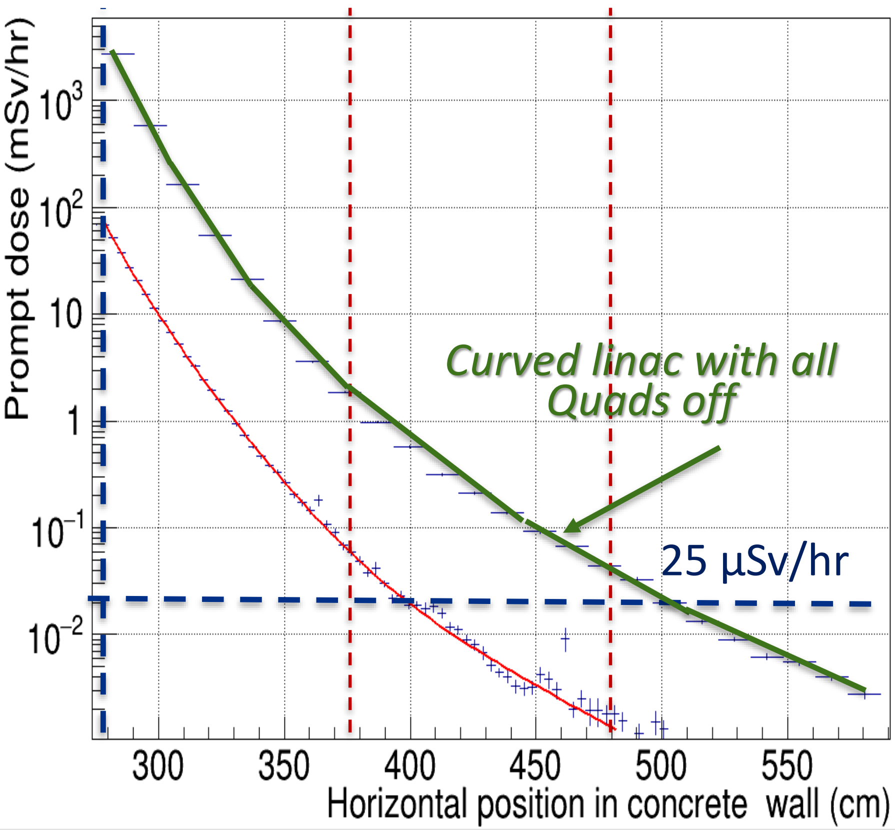
Total prompt dose

Red - Loses at the end of linac with quad ON (250GeV); T_{max}= 0.8 GeV (~3 CM's)

Green – Curved linac with quads OFF; Correctors are set to tune misaligned linac; T_{max}=19.2 GeV





factor of 20 compared to the red line

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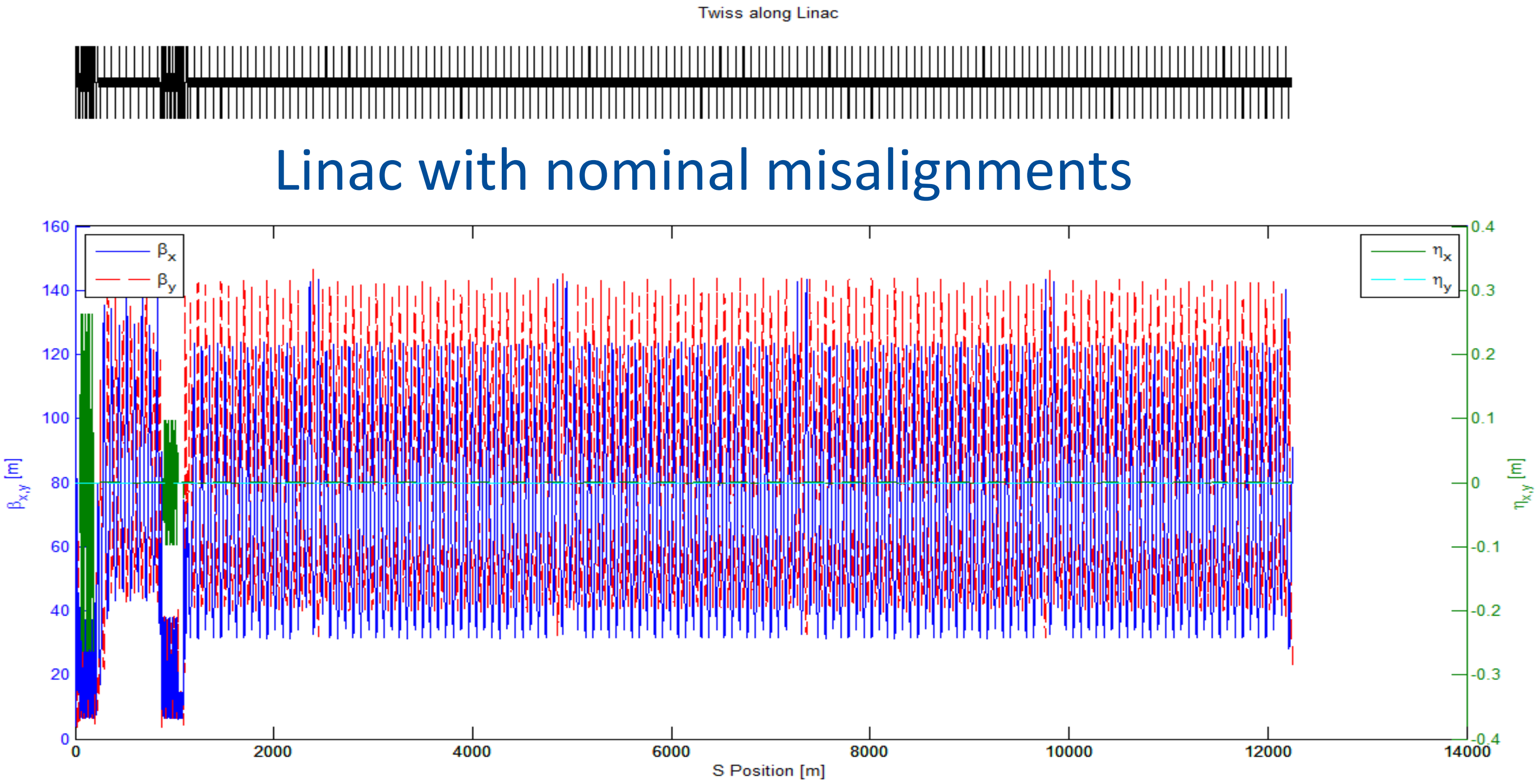
Worst case scenario

Linac with focusing quads OFF (commissioning scenario)

Twiss Parameters in BC and ML (TDR 2016 lattice file)

- Sections are well-matched.
- No residual dispersion in main linac section.



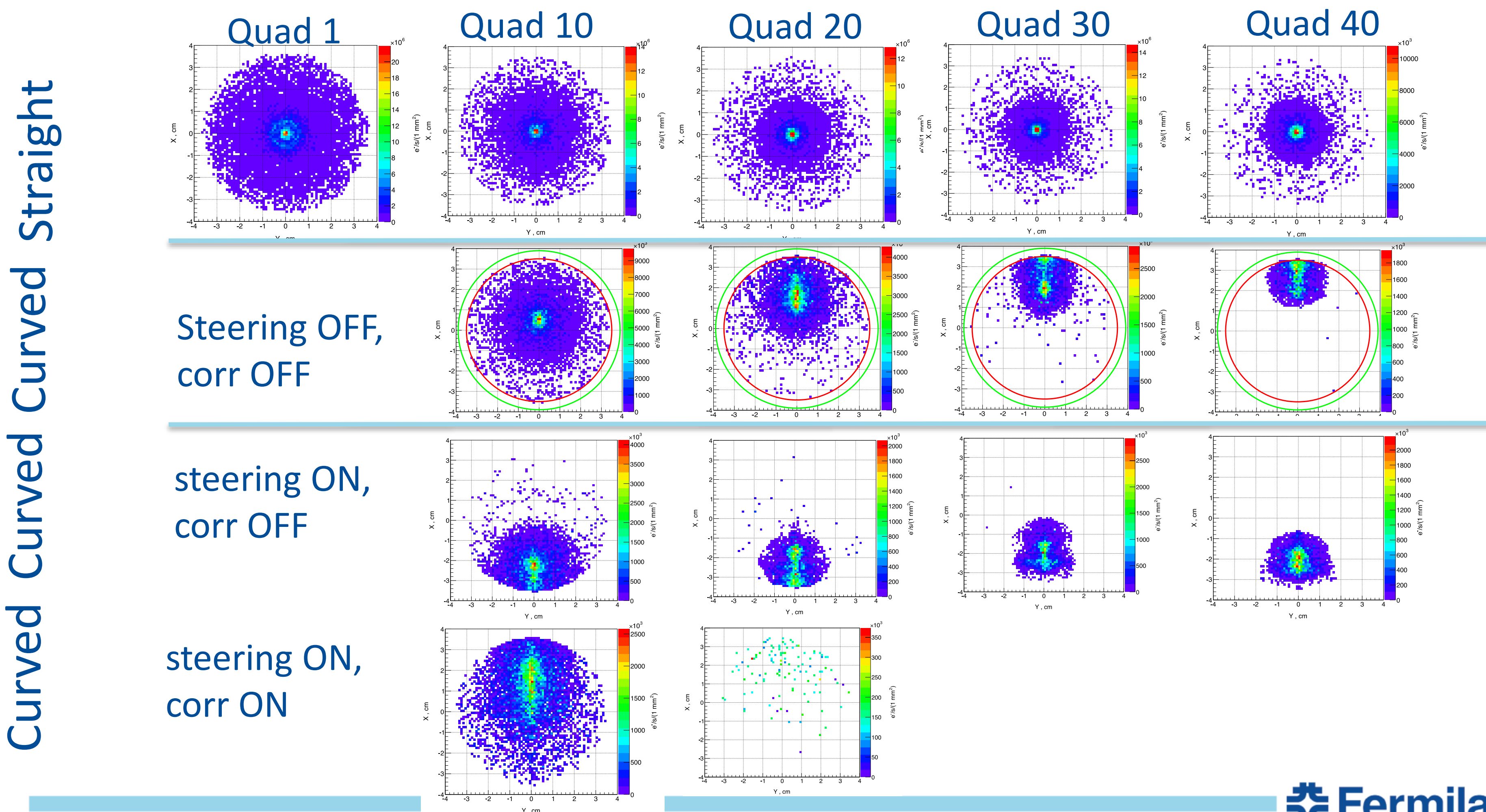
Worst case Models for Dark Current

Tracking through 40 periods of the linac (each period consists of 26 cavities and quad/correcting magnet). Focusing quads are turned OFF

- **Consider 4 scenarios:**
  - Straight linac with correcting magnets turned OFF (Bunch compressors);
  - Curved linac (follows Earth curvature) with steering/correcting magnets turned OFF
  - Curved linac with steering magnets ON, correctors OFF
  - Curved linac with steering magnets ON and correctors ON

Straight and curved sections, quads/correctors OFF

- 40 periods (120 CM’s, ~1600m)
- Spatial distribution at the exit of quads 1,10,20,30,40 (source: single cavity)



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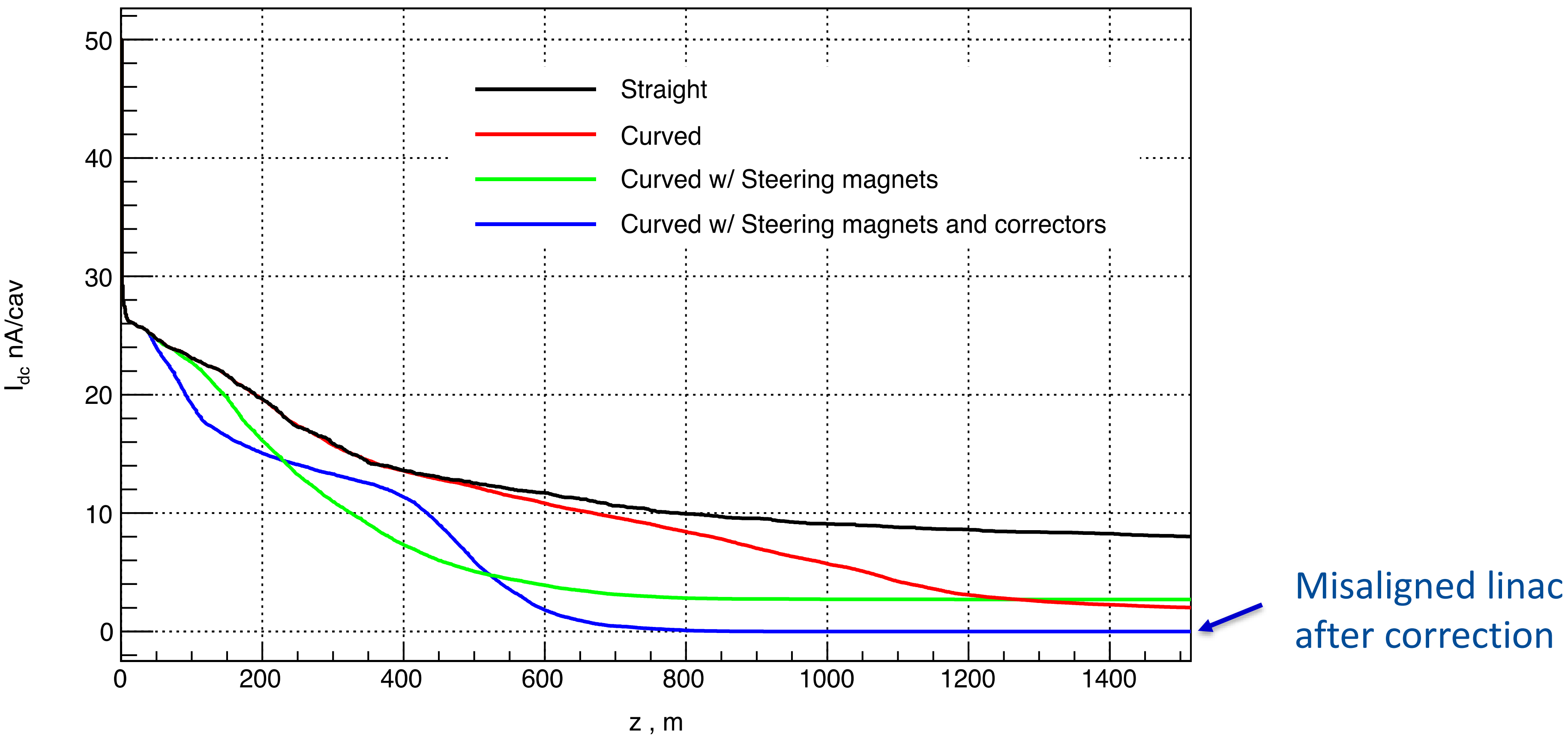
Dark current from single cavity

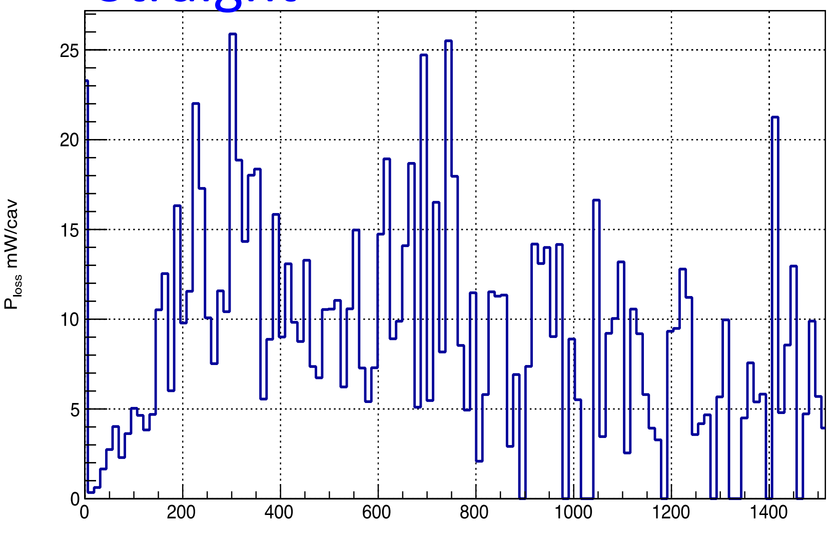
- DC from single cavity (50 nA) at the beginning of linac section of 40 periods for 4 different configurations

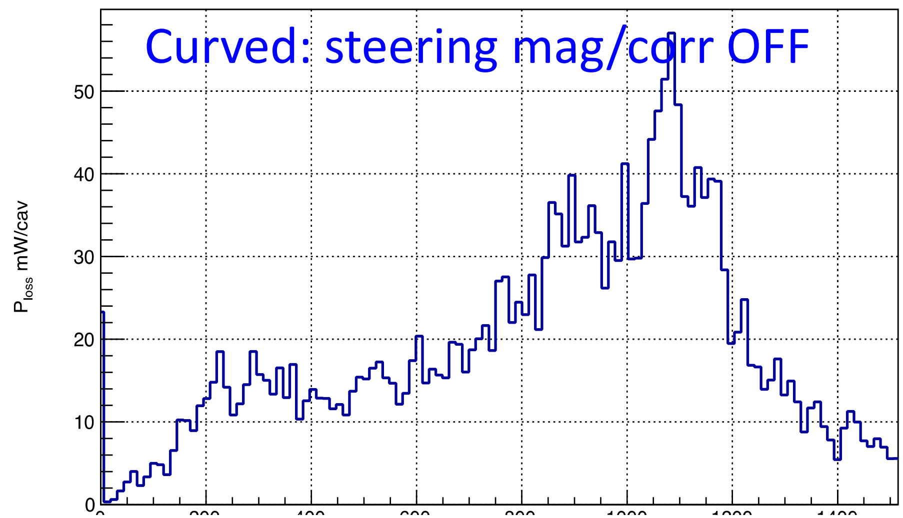


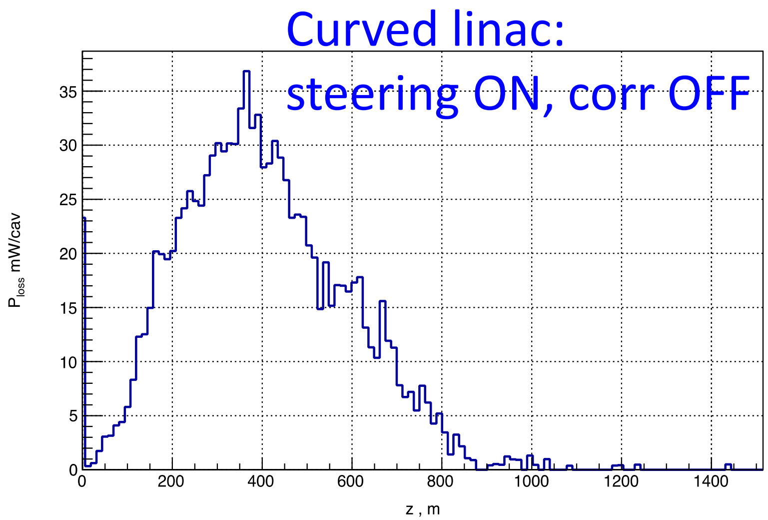
Power losses per CM: single cavity FE, quads OFF

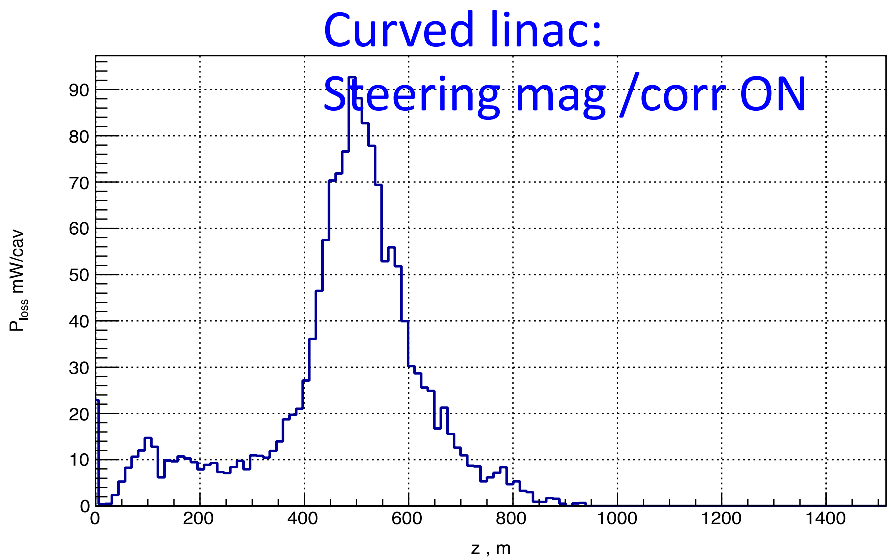
Quad/Correctors/steering=OFF

Straight



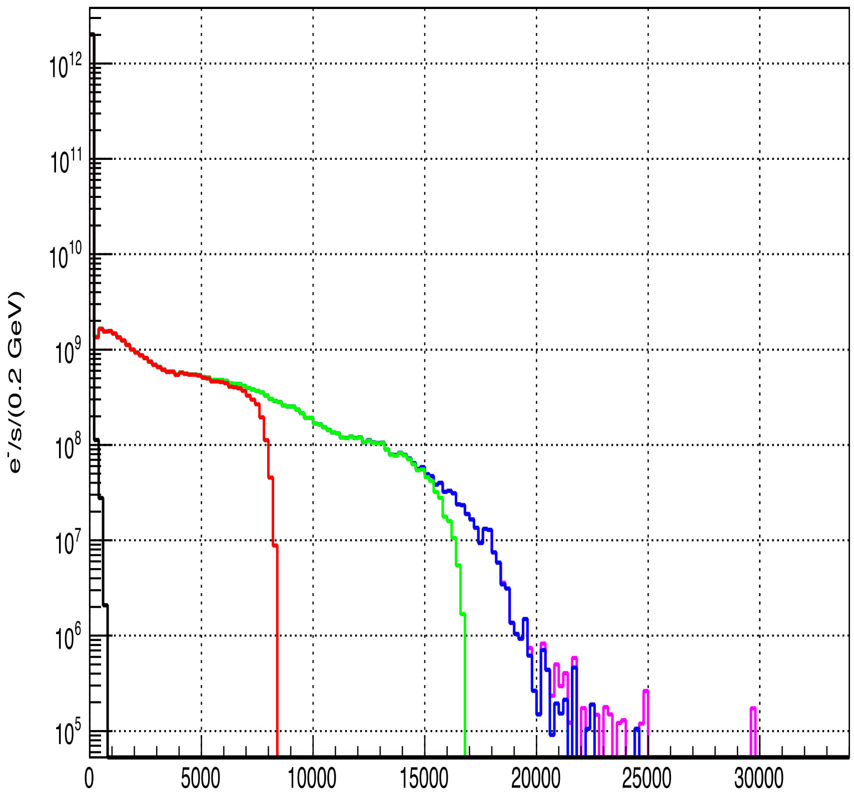


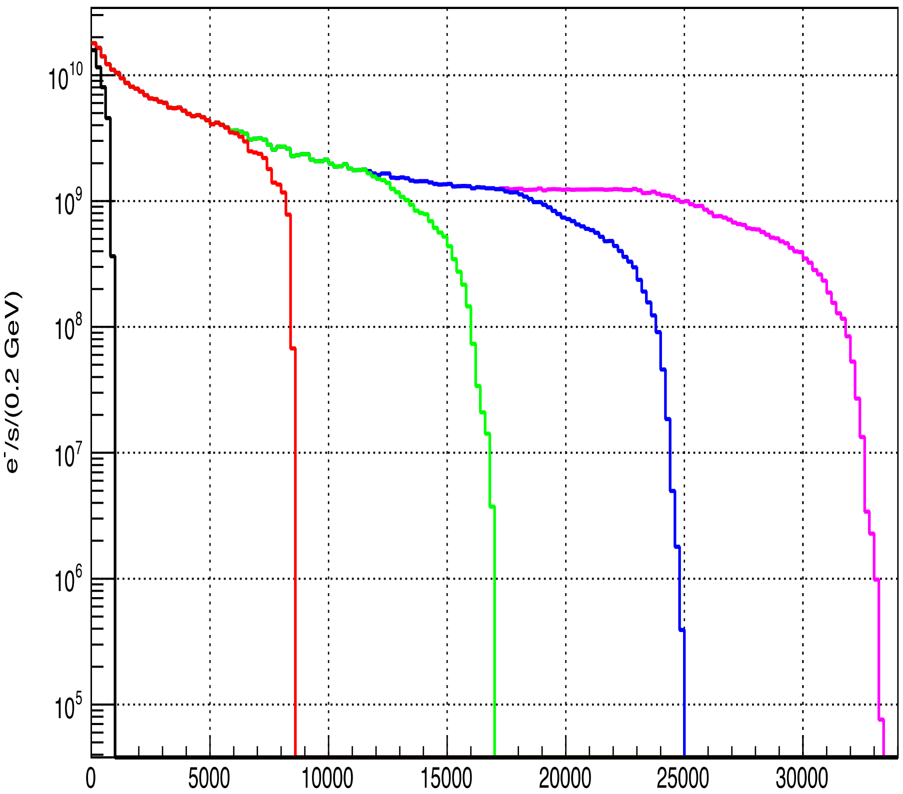




Energy spectrum, lost/propagating particles (corr OFF)

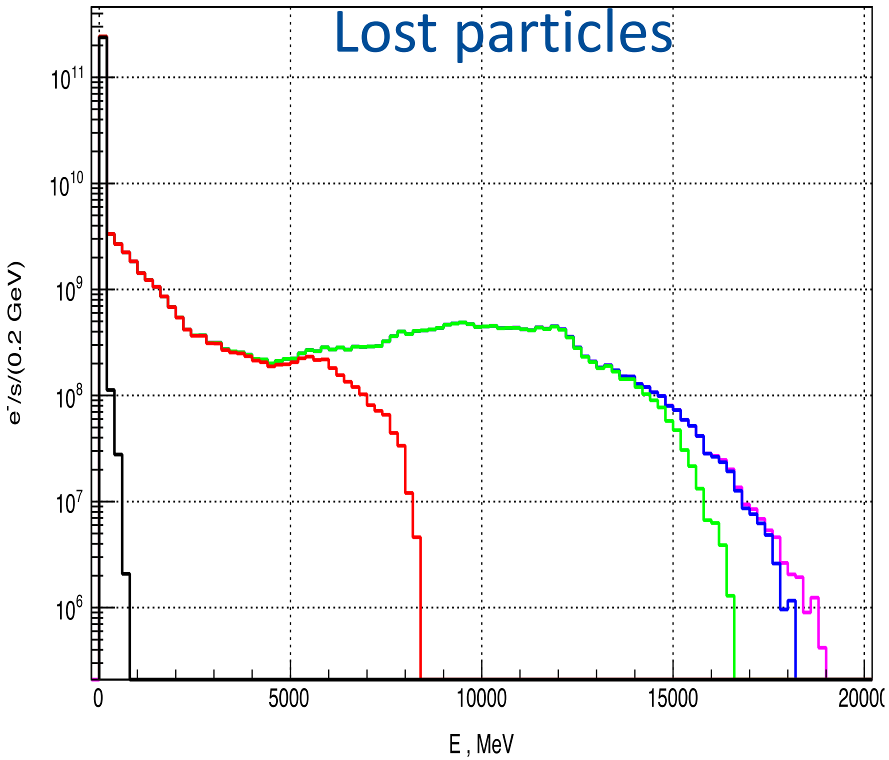
- Energy spectrum of lost/propag electrons (per period)
- Black – 1st period, red – 10th period, green – 20th period, blue – 30th period, magenta – 40th period

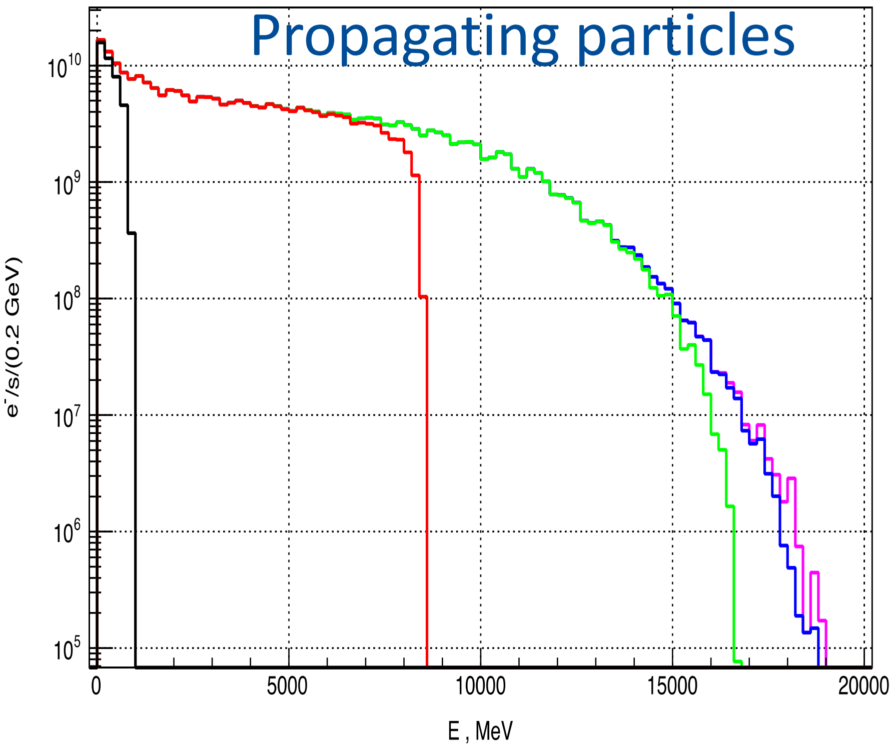




Energy spectrum of lost and propagating electrons (corr 0N)

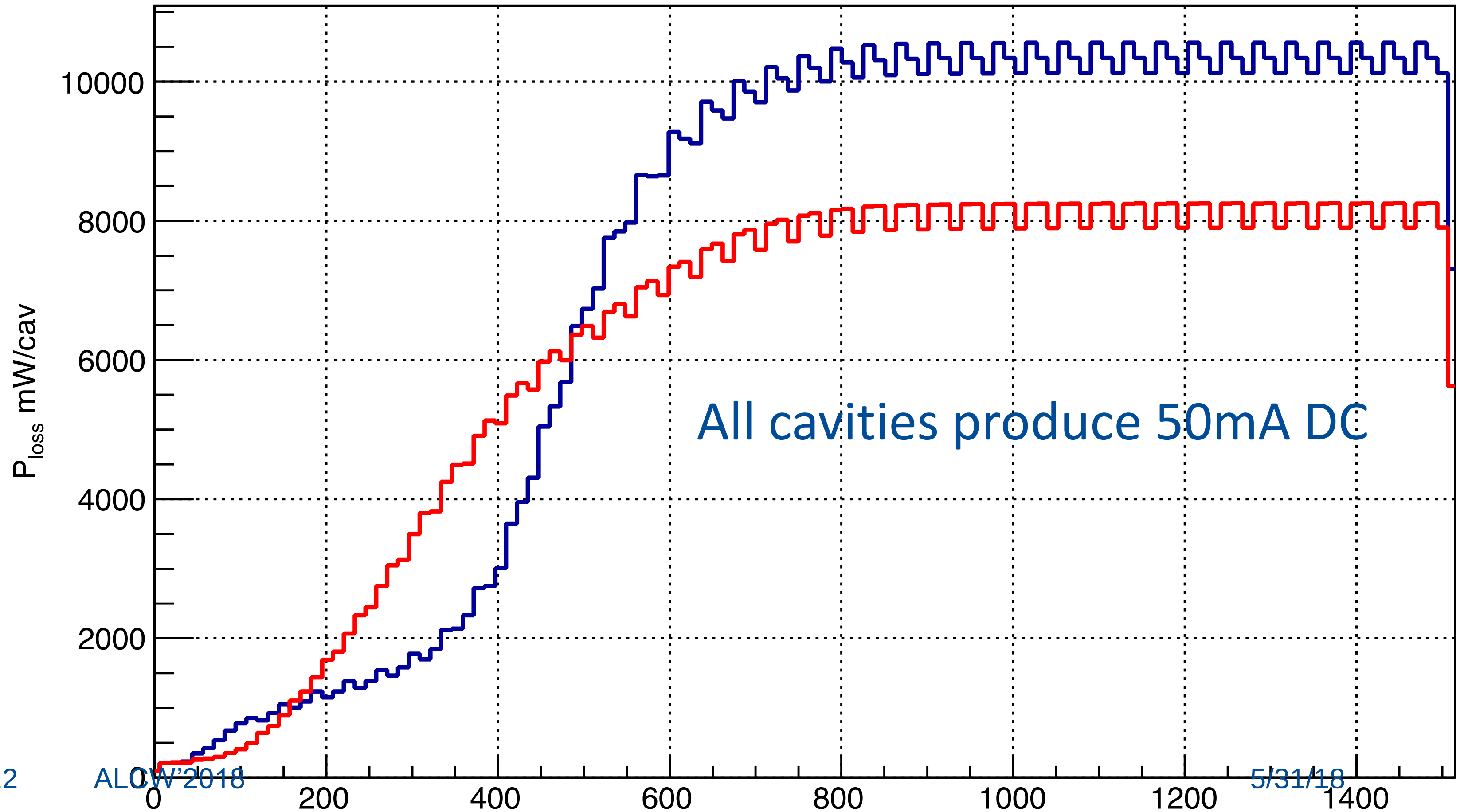
- Energy spectrum of lost/propagating electrons at the end of each RF period (per period)
- Black – 1st period, red – 10th period, green – 20th period, blue – 24th period, magenta – 30th period, periods from 31 to 40 look the same as 30th





Power loss along curved Linac

- Power loss at the linac cryomodules
  - Red line – steering magnets ON, correctors OFF
  - Blue line - steering magnets ON, correctors ON

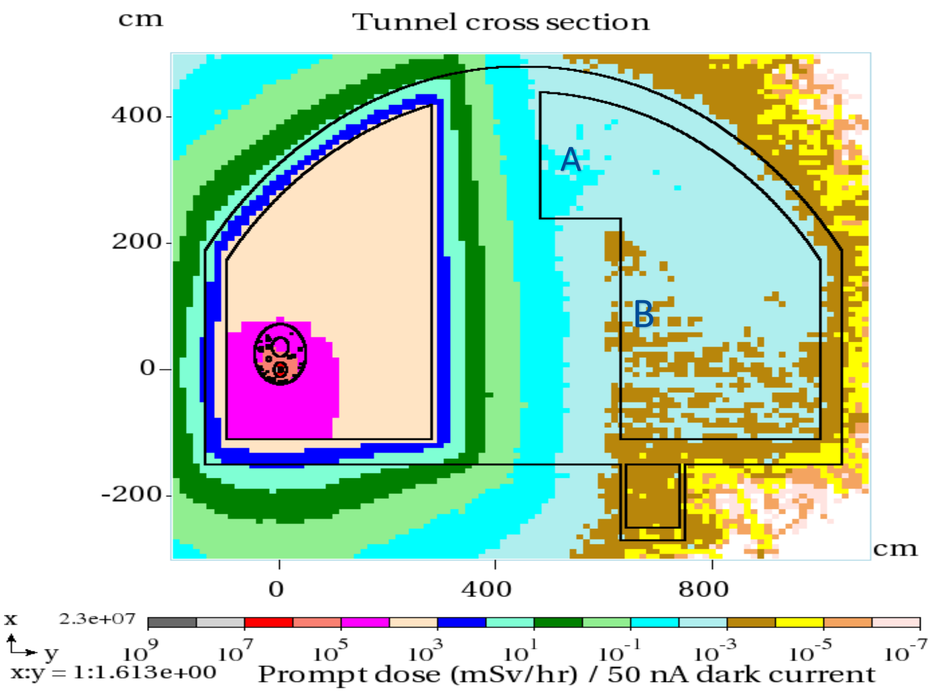


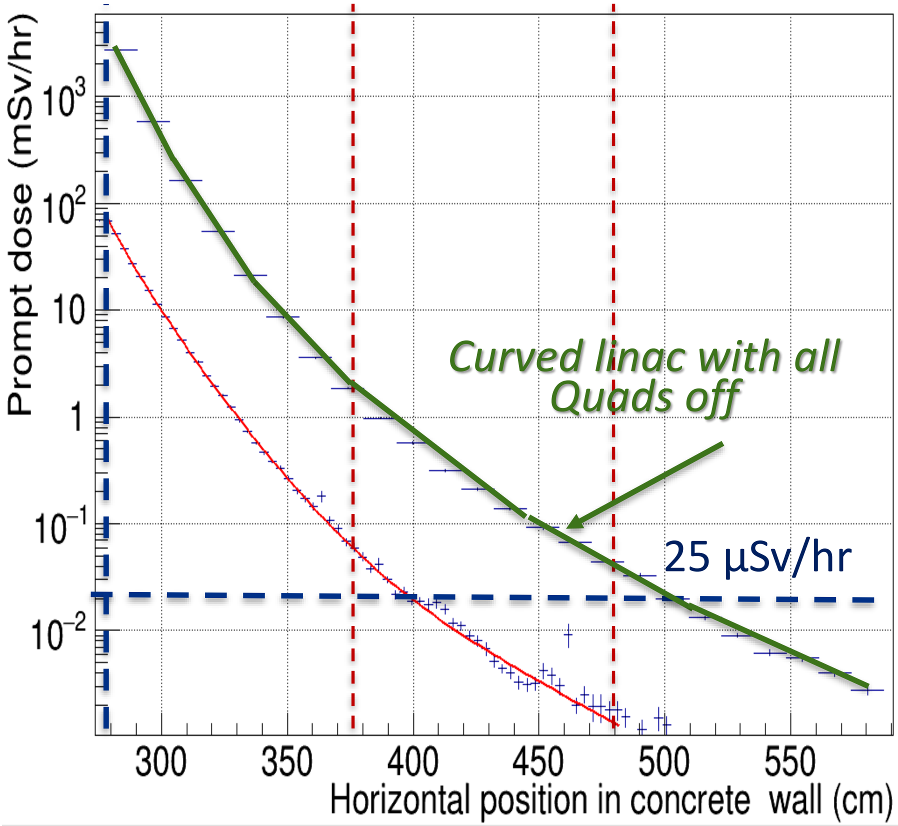
Remarks

- In worst case scenario with 50 nA DC in each cavity, particle losses reaches steady-state regime after ~800m.
- Spectrum of lost particles in steady-state up to ~ 15 GeV.
- Radiation uniformly distributed along the linac
- Level of radiation worst case when quads are switched off is factor of x20 higher than for the case with Quad field sets for 250GeV (end of linac), studied previously

Total prompt dose

Red - Loses at the end of linac with quad ON (250GeV); T_{max}= 0.8 GeV (~3 CM's)
Green – Curved linac with quads OFF; Correctors are set to tune misaligned linac; T_{max}=19.2 GeV





factor of 20 compared to the red line

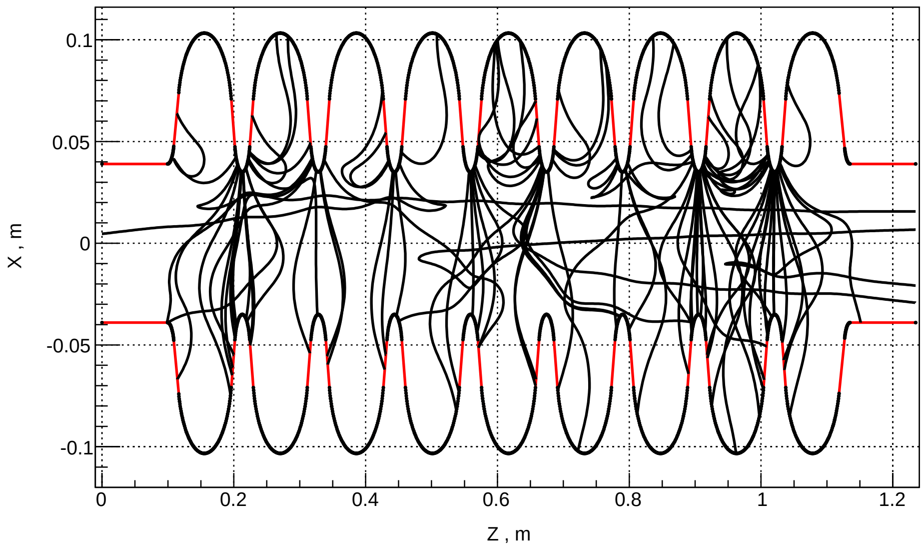
Summary

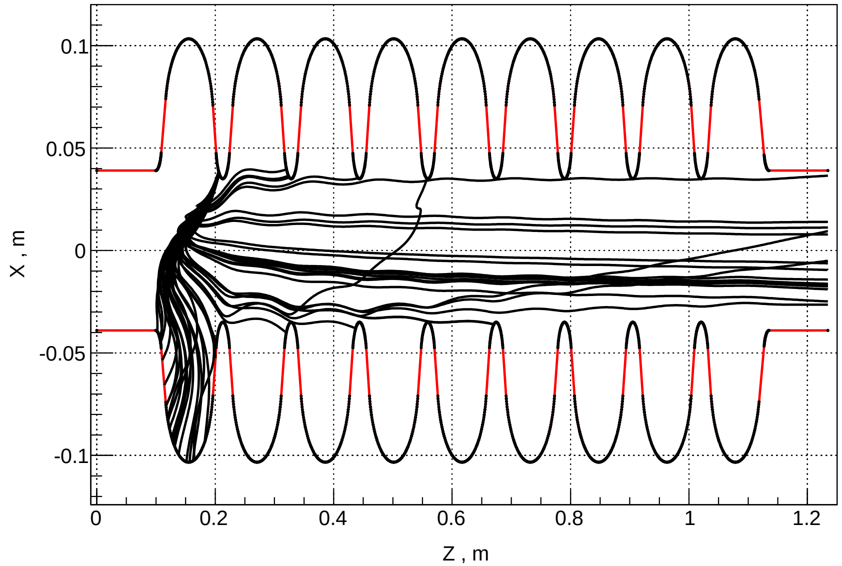
- As expected, largest losses from DC are in the curved linac with steering magnets and corrections for misalignment ON
- With every cavity emitting DC, losses levels after 20 periods (800m)
- Losses are largest in the 1st cavity after magnet and may reach 2.4 W/cavity

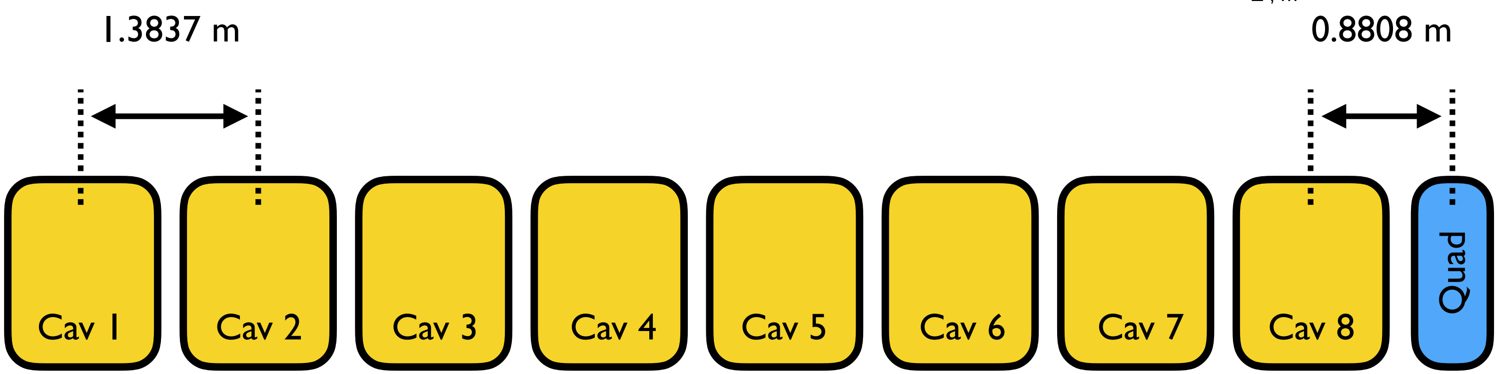
LCLS-II vs. ILC

Dark Current Model (LCLS-II)

- Field Emission (FE) is the source of Dark Current (DC)
  - uniform distribution of emitters over the cavity surface or localized emitter locations
  - number of emitted particles at each location varies according to Fowler-Nordheim model
  - normalize physical values to nominal DC 1 nA at the emitting cavity exit
  - track emitted particles through pCM until they are lost or exit

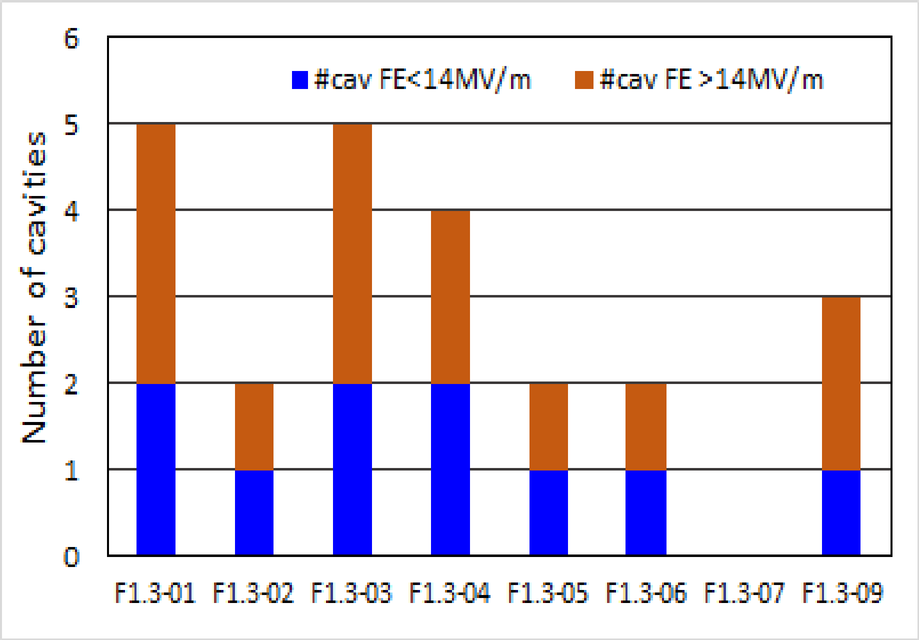


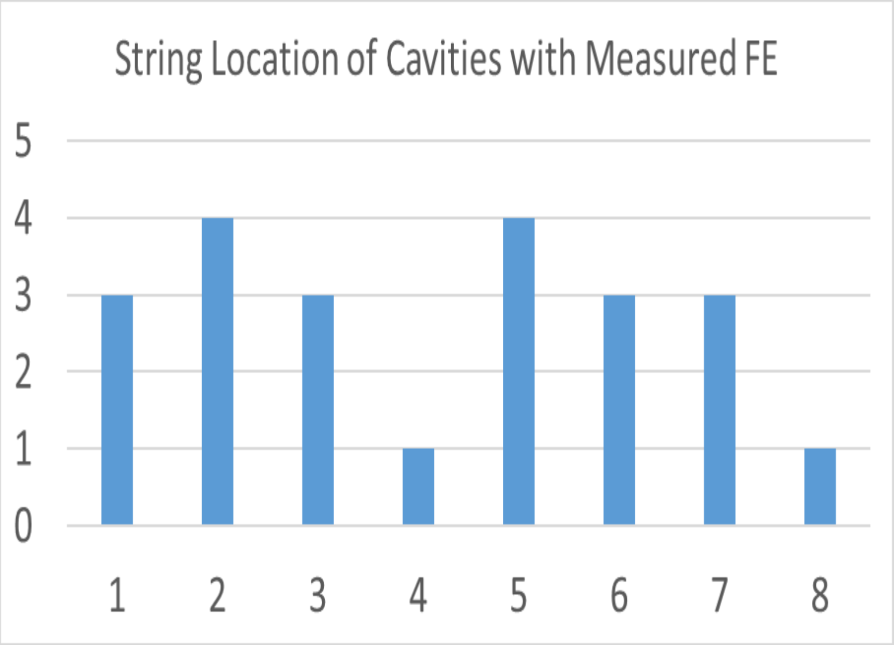




LCLS-II Performance - FE

- Spec: onset of measurable field FE $E_{acc} \geq 14$ MV/m
  - Few cavities not meet spec
  - F1.3-07 first cryomodule with no measured FE
- Usable gradient requires <50 mR/hr measured outside CM
  - Exceeded for most cryomodules
- **Field emission not dependent on location in string**

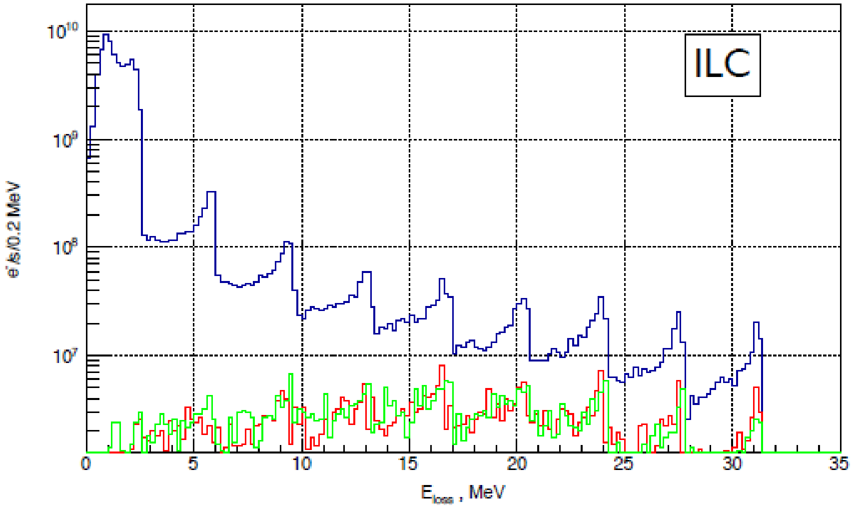


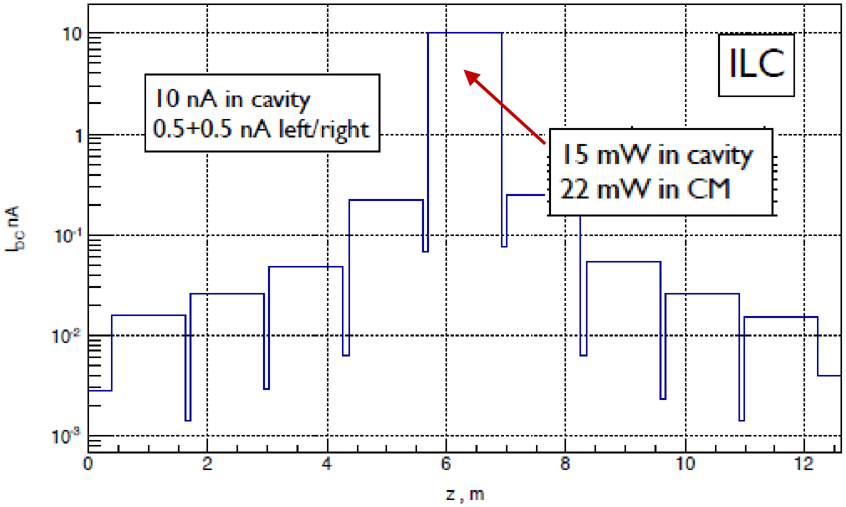


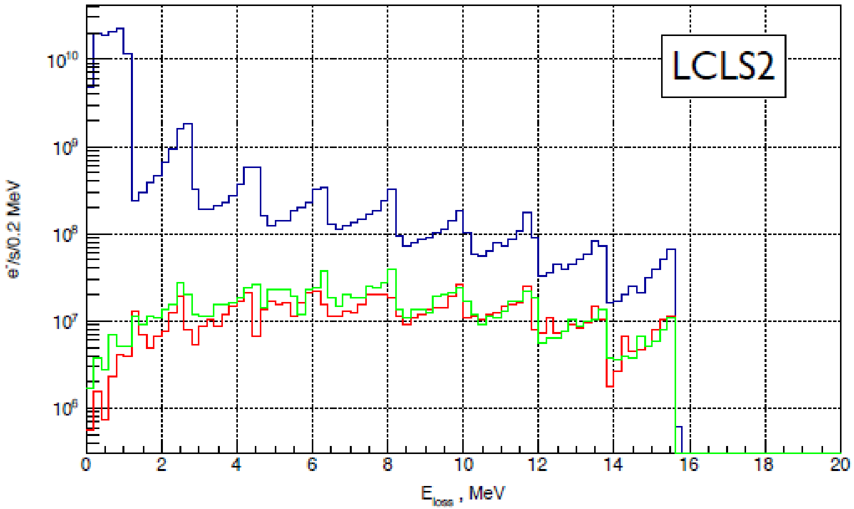
courtesy: Olivier Napoly

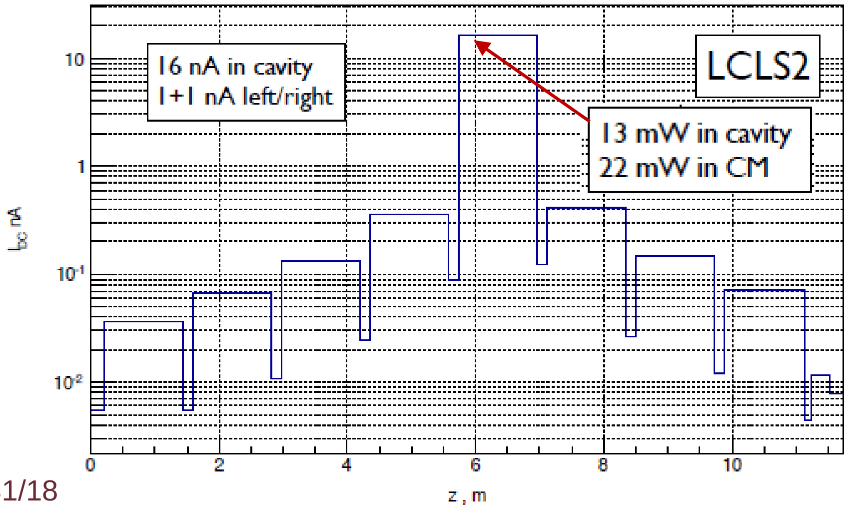
LCLS2 VS ILC

- ILC (50 nA/cavity, DF=0.01) vs LCLS2 (1 nA/cavity, CW)

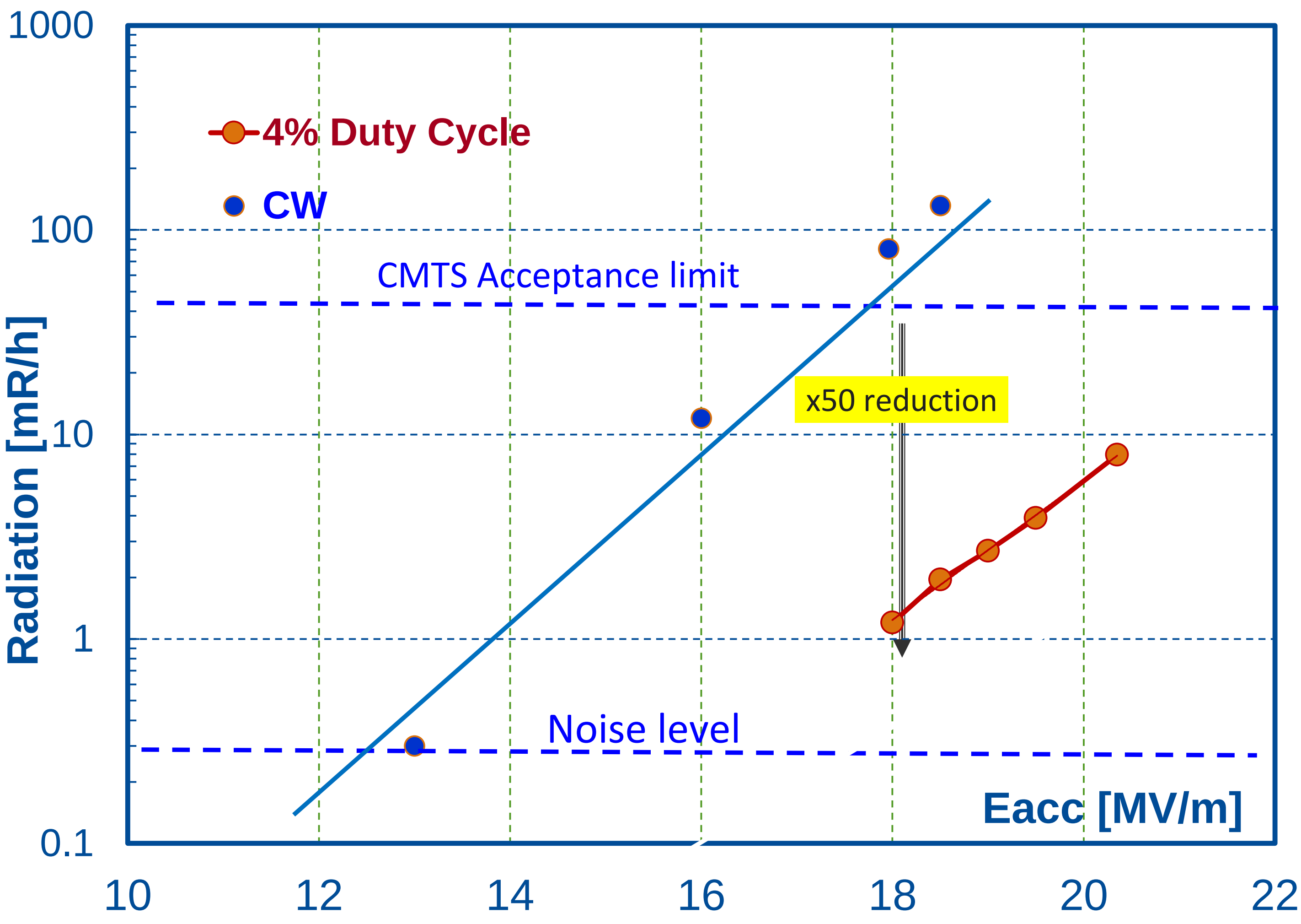






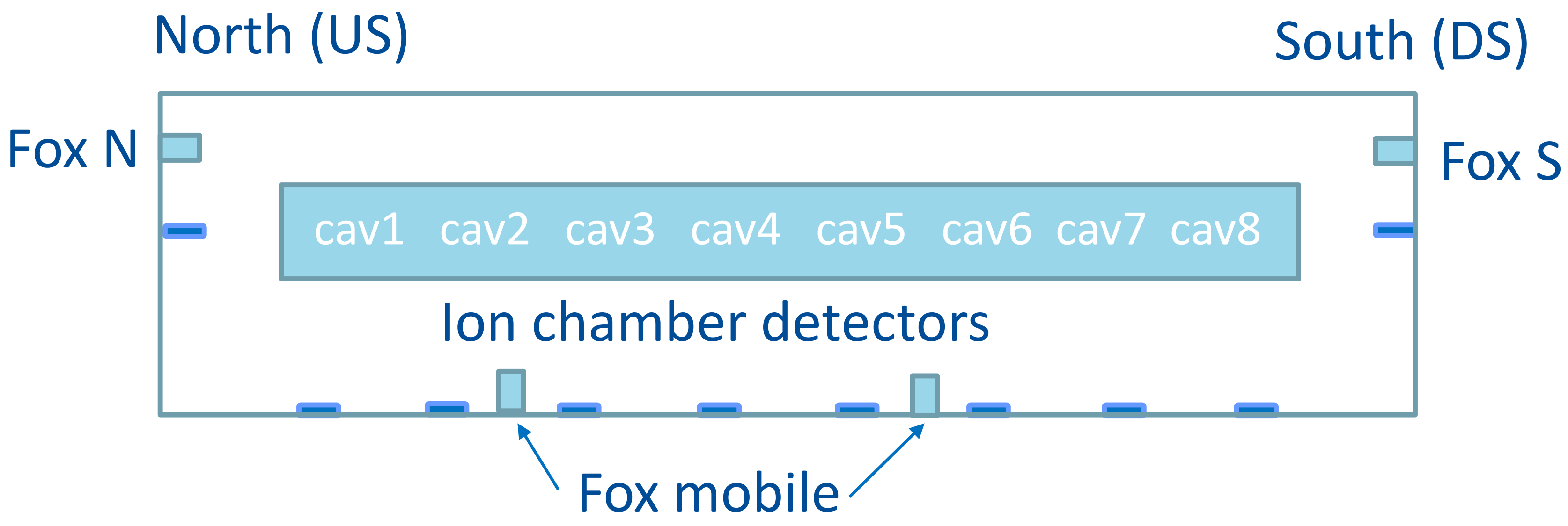


J1.3-01 cav#6: Radiation from FE



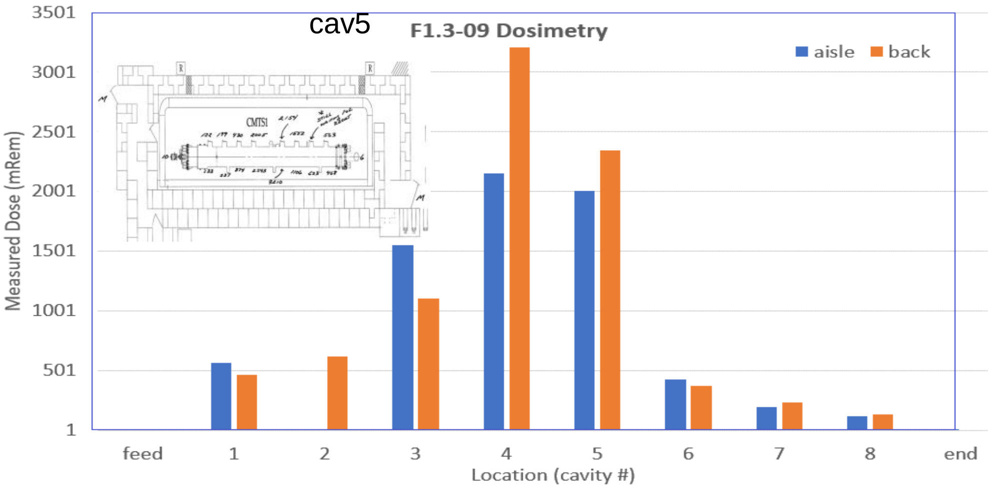
Slope ~ (2.6 -3) MV/m per decade

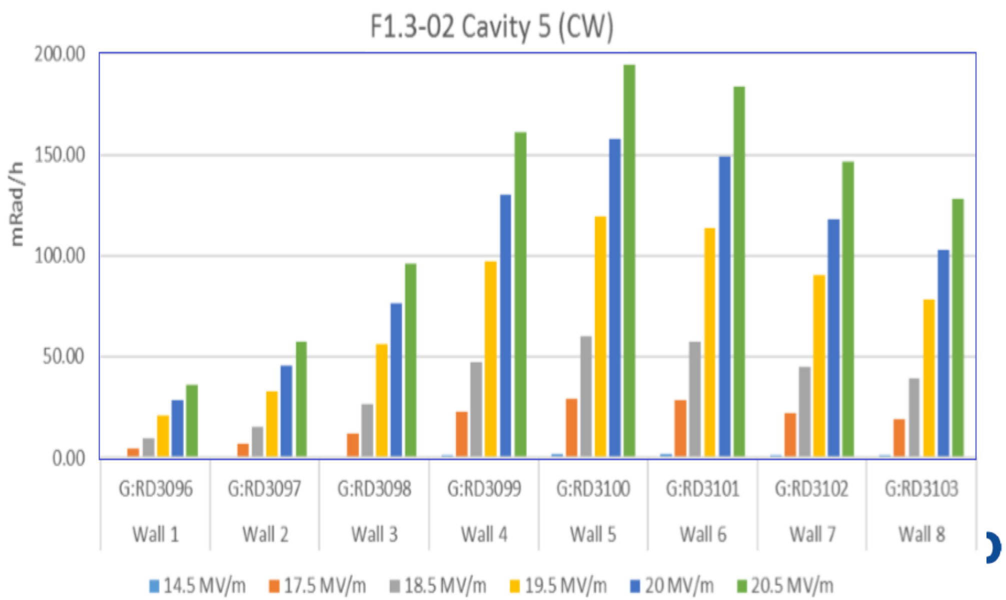
Radiation and DC in LCLS-II CM tests in CMTF



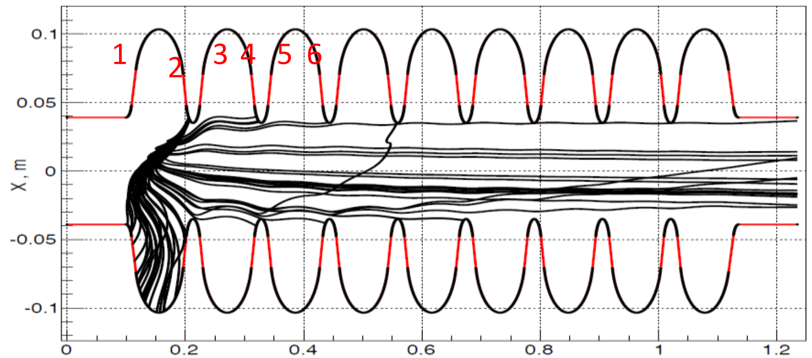
Performance – field emission & dark current

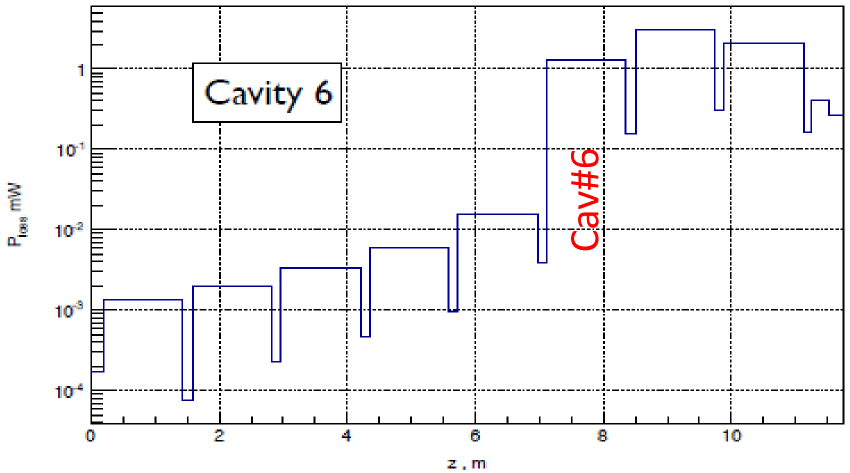
- Field emission seen on at least one cavity of every cryomodule tested - until F1.3-07
- Location and magnitude varies
- ‘Usable gradient’ refers to peak gradient limited by measured FE of 50 mR/hour
- Dark current generally correlated with highest field emitting cavities
- Pulsed Processing has been effective in mitigating some field emitting cavities

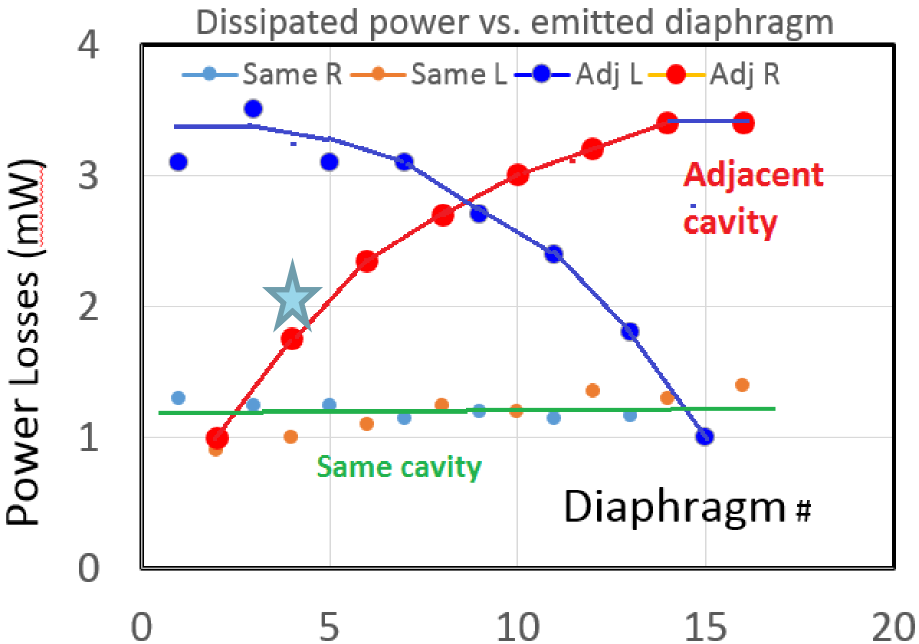


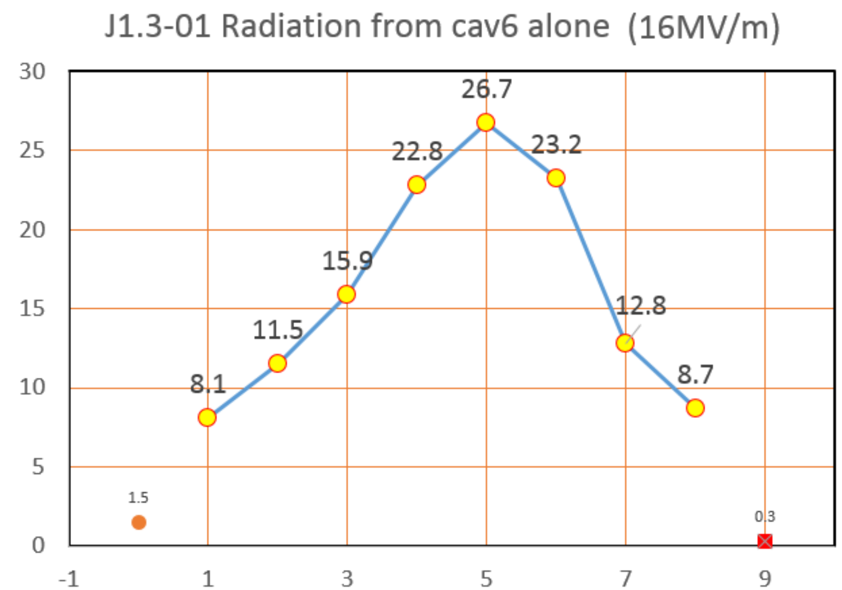


Simulations vs. measurements J1.3-01



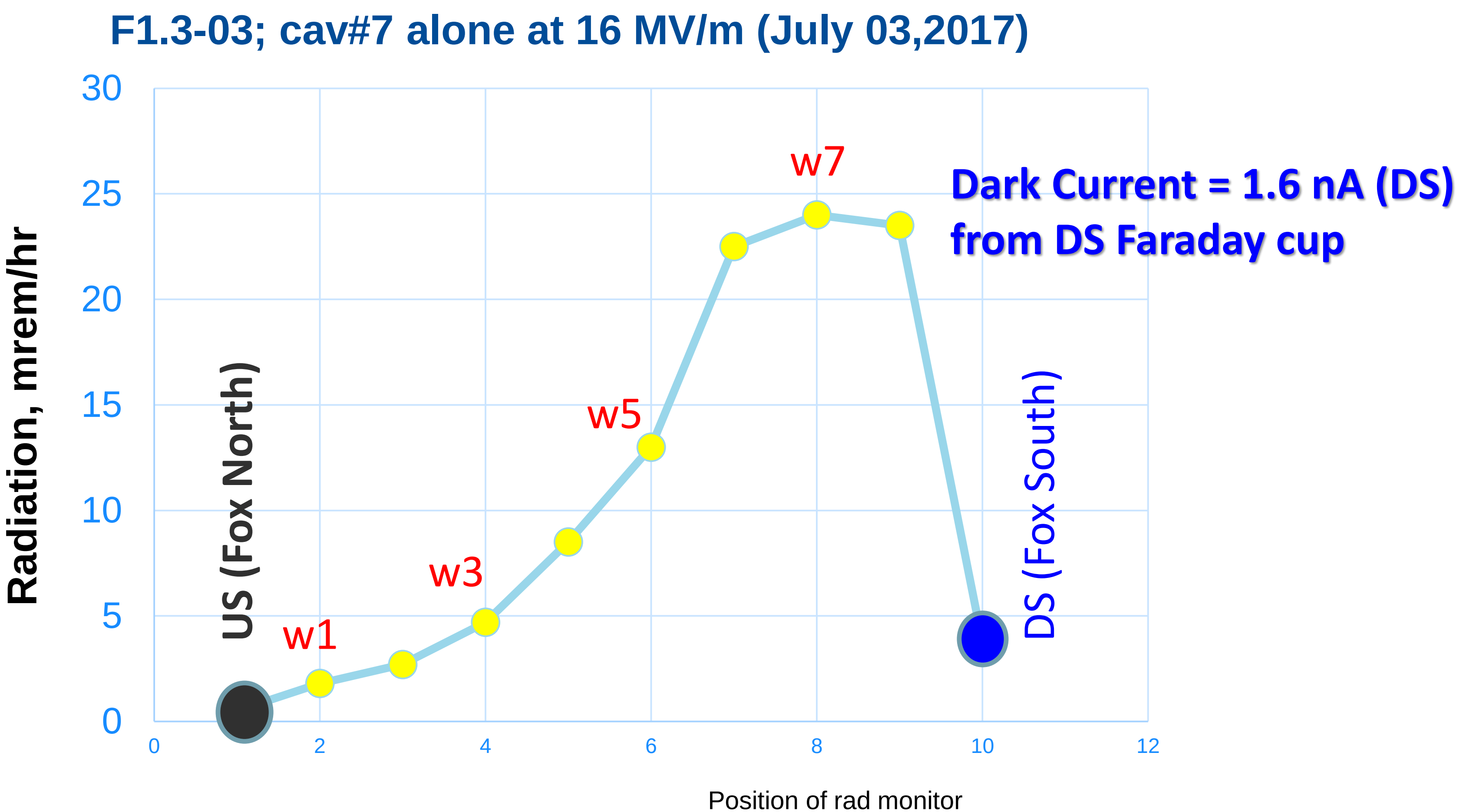






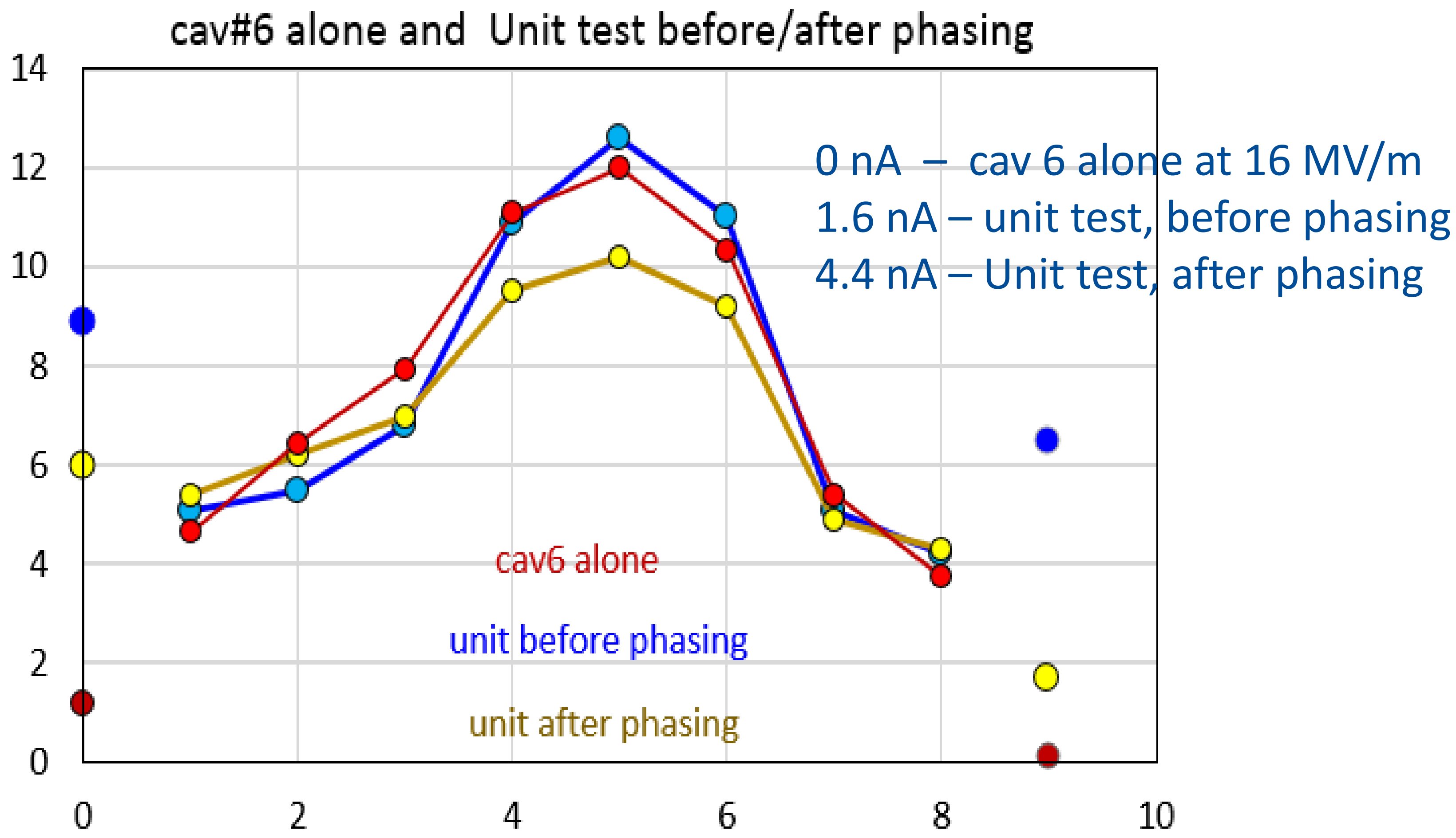
Backup slides

Radiation Data from F1.3-03



Ratio = (max signal)/(max at the end-detectors) ~ 6-7

J1.3-01: Radiation and DC



Dark current