ILC ML failure modes

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Fermilab

- Failure modes in Bunch Compressor
- Energy acceptance of BC1 (BC2)
- Dark current models
- Future work

ITB meeting
Dec.9,2014

Failure modes in BC1

RF system (3 CM's powered by 1 klystron):

- Klystron amplitude is wrong (limited by klystron power)
- Phasing is wrong (master oscillator of LLRF system failed)

→energy off by ~ 0.5 GeV max (most dangerous scenario)

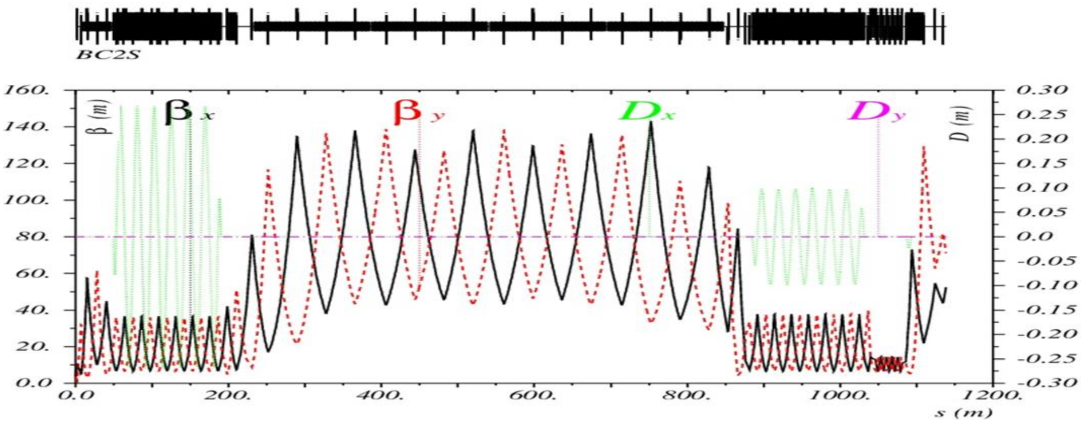
Diagnostics: BMP offsets
Action: send beam (~300 bunches) to dump by fast kicker.
Look: beam propagation through BC2 or even through ML (possible emergency extraction to BC2 dump)

Focusing Quads in CM (3) or in wiggler are failed

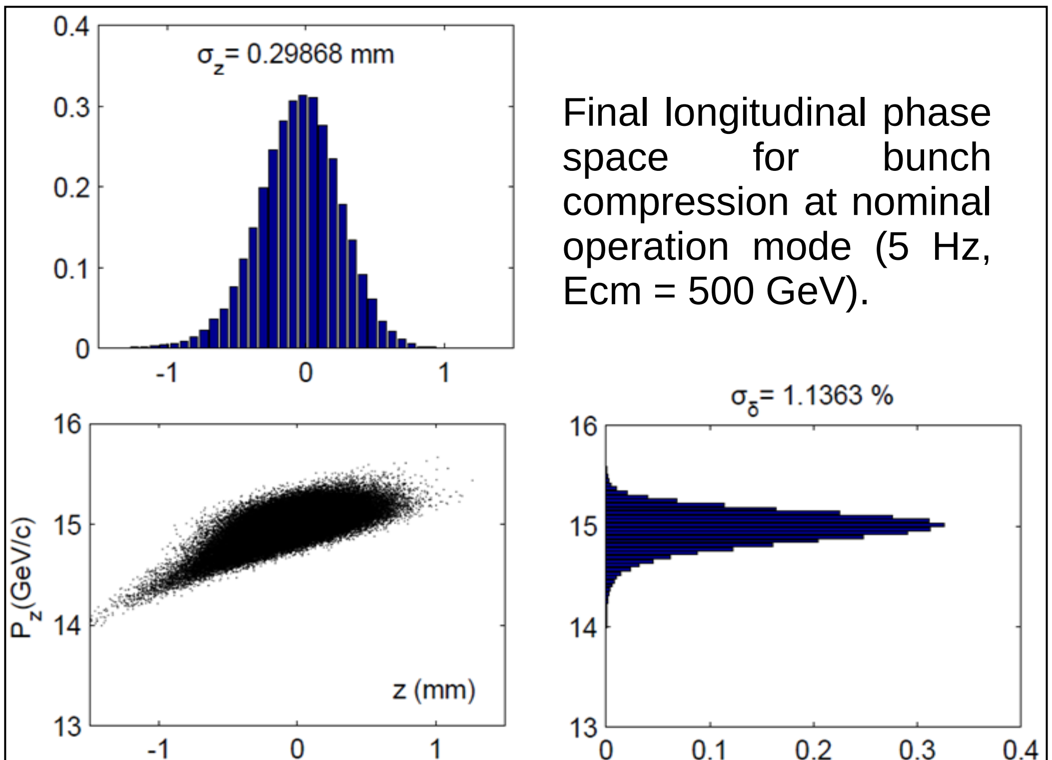
Bending magnets failed

BPM failure

2-stage Bunch Compressor (back to RDR design)



2 stage BC design was updated for TDR design (more tunability, shorter bunch ~ 150μm is possible).



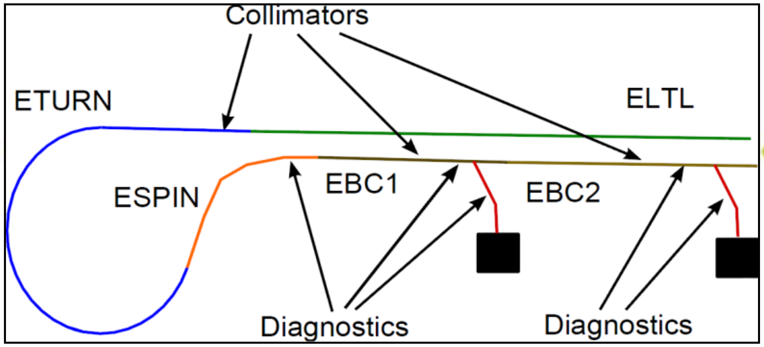
Final longitudinal phase space for bunch compression at nominal operation mode (5 Hz, Ecm = 500 GeV).

Modifications (for TDR):

- 3 CM's with quads for BC1 (ILC design instead of XFEL).
- 16 RF units in BC2 RF (48 CM's; 416 cavities) to reduce gradient.
- New parameter optimization of BC wigglers (S. Seletskiy)
- New output parameters from DR is used.
- New treaty point from RTML to ML

Extraction lines

Will be used to extract beam in case of failure in BC

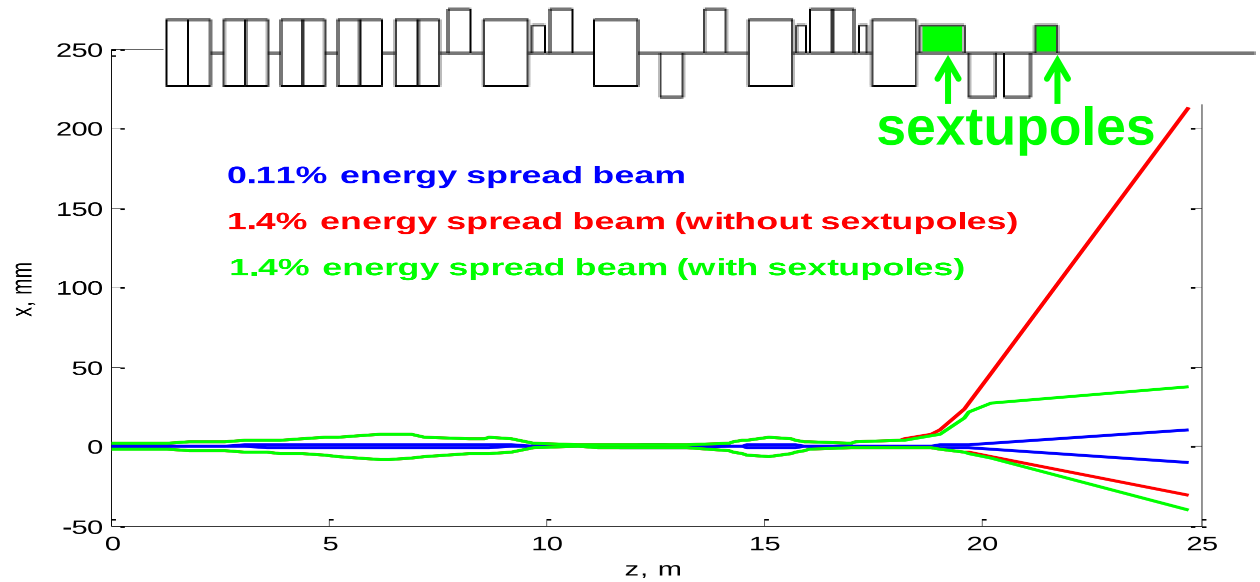


- Extraction System can extract full beam for tune up or make fast bunch extraction.
- Extraction lines in BC1 can dump entire beam (220 kW, @ 5GeV). Extraction line in BC2 can only dump 1/3 of beam power (@ 15 GeV).
- Extraction line at BC1 can dump compressed and uncompressed beam (E=4.8-5 GeV, s_E = 0.11-1.42%), while the one at BC2 needs large energy acceptance.
- *BC1 extraction lines was re-designed based on ideas developed for BC1S (single stage BC)* For the renovated extraction lines we are combining the best features of both designs. *(more details in S. Seletskiy talk, LCWS' 2012, Albuquerqe).*
- *BC2 extraction line will be modified to increase energy acceptance*

Renovated BC1 extraction line (w/o collimators)

- After BC1 the energy spread of compressed beam is small the nonlinear effects are weak and the beam can be contained with only two sextupoles (no collimators).
- Beam size on the dump window is 19.5mm² for both low energy spread beam. High energy spread beam are in dump window of 12.5cm diameter.
- The Extraction Line is 24.7m long, Dump is separated from the main beamline by 5.1m (alcove with radiation enclose)

The renovation of the BC2 extraction line is in progress.

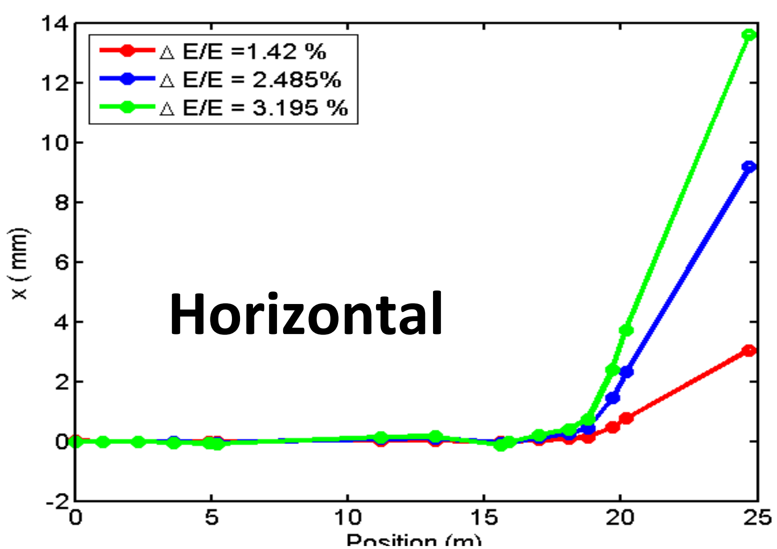


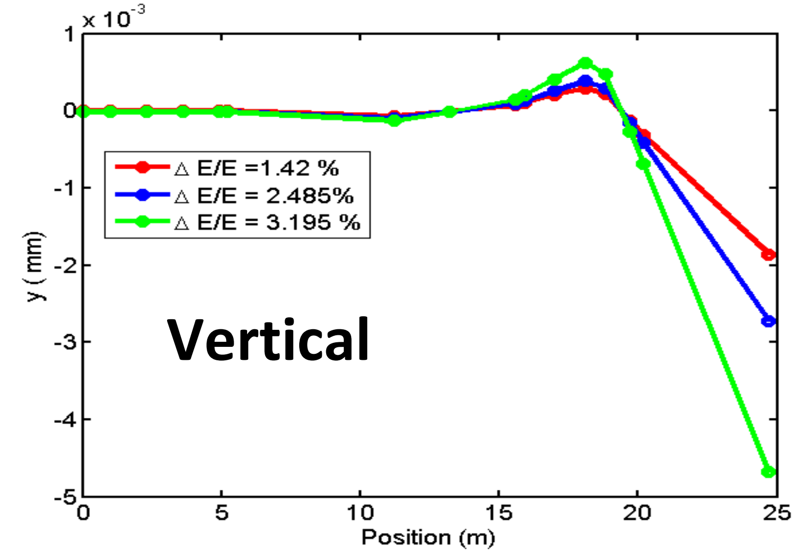
Initial Beam Parameters

- **Beam Parameters at the End of BC1/Beginning of extraction line:**
  - Energy=4.80 GeV, Beam Charge = 3.2nC, RMS Bunch Length = 0.9mm,
  - RMS energy spread: $\boldsymbol{\sigma_E}$= 1.42%
  - Normalized Emittance $\varepsilon_x / \varepsilon_y$ = 800/20 nm · rad.
- **Tracking is performed with Gaussian distribution of 0.5M macro particles.**
- **In order to estimate energy acceptance of BC1 extraction line, initial energy spread is varied and beam losses are checked.**

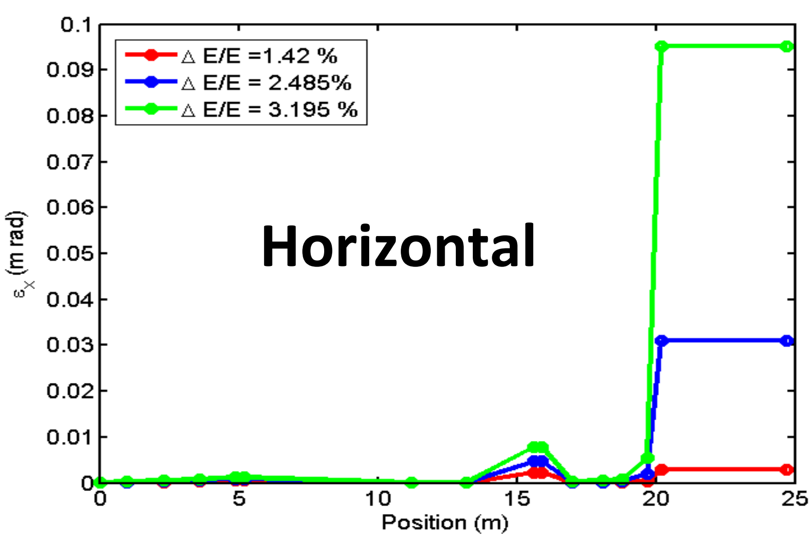
Beam Parameters with varying initial energy spread : Trajectory & Emittances

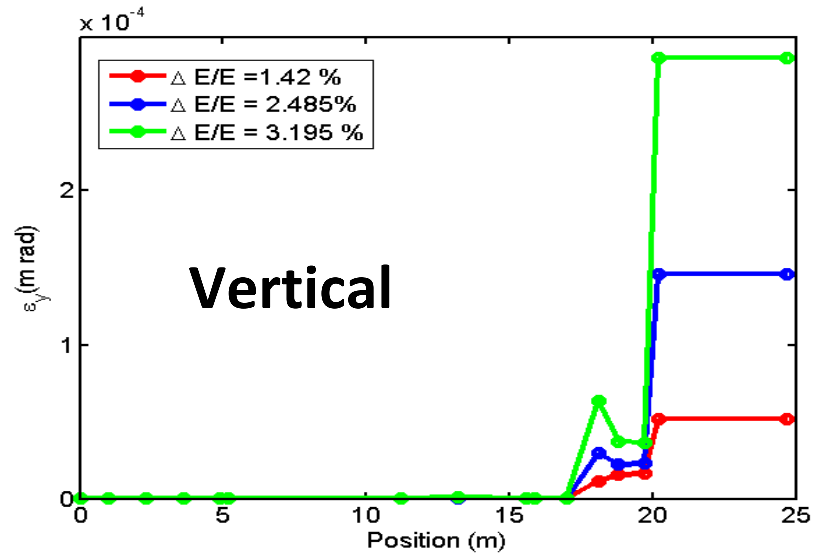
Beam Trajectory



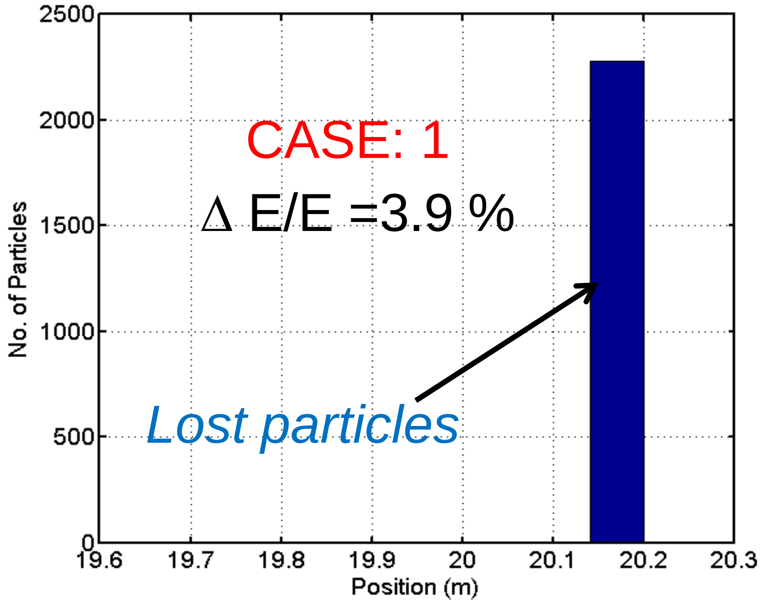


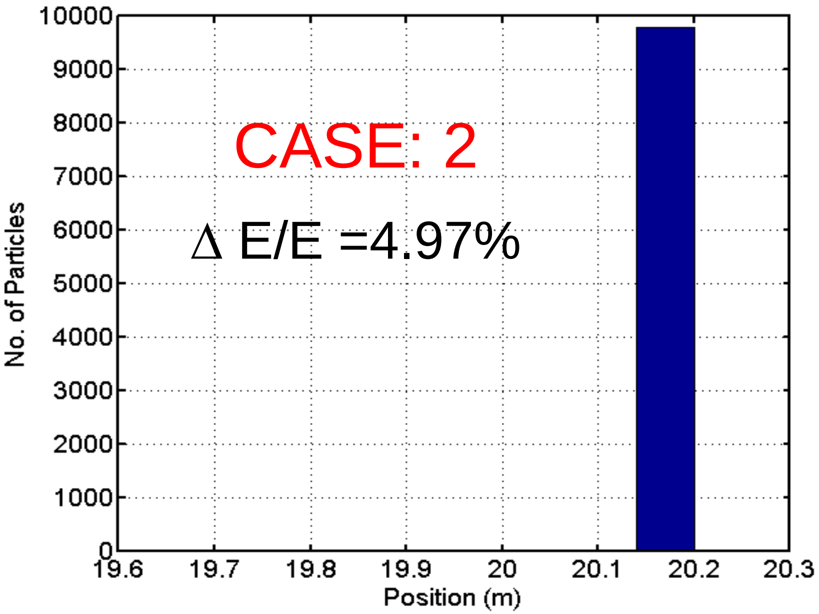
Beam Emittance

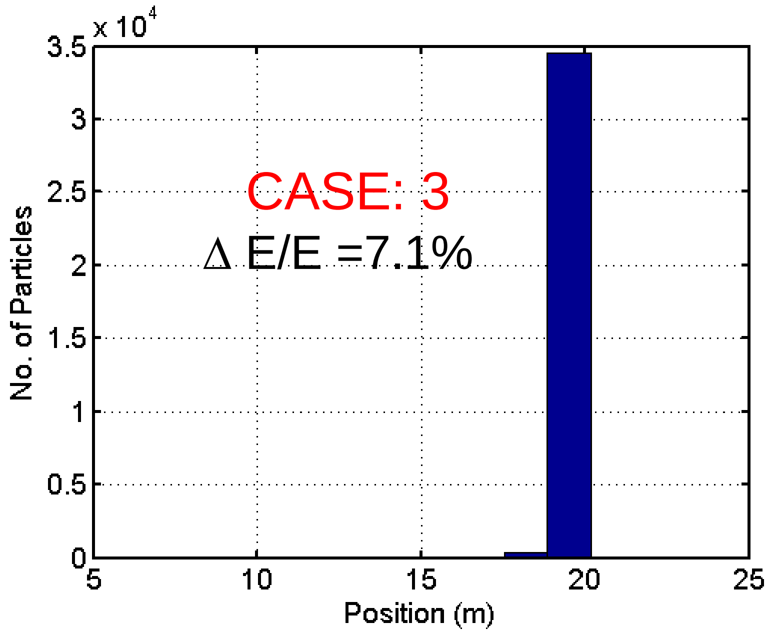




Losses Distribution for various initial beam energy spread







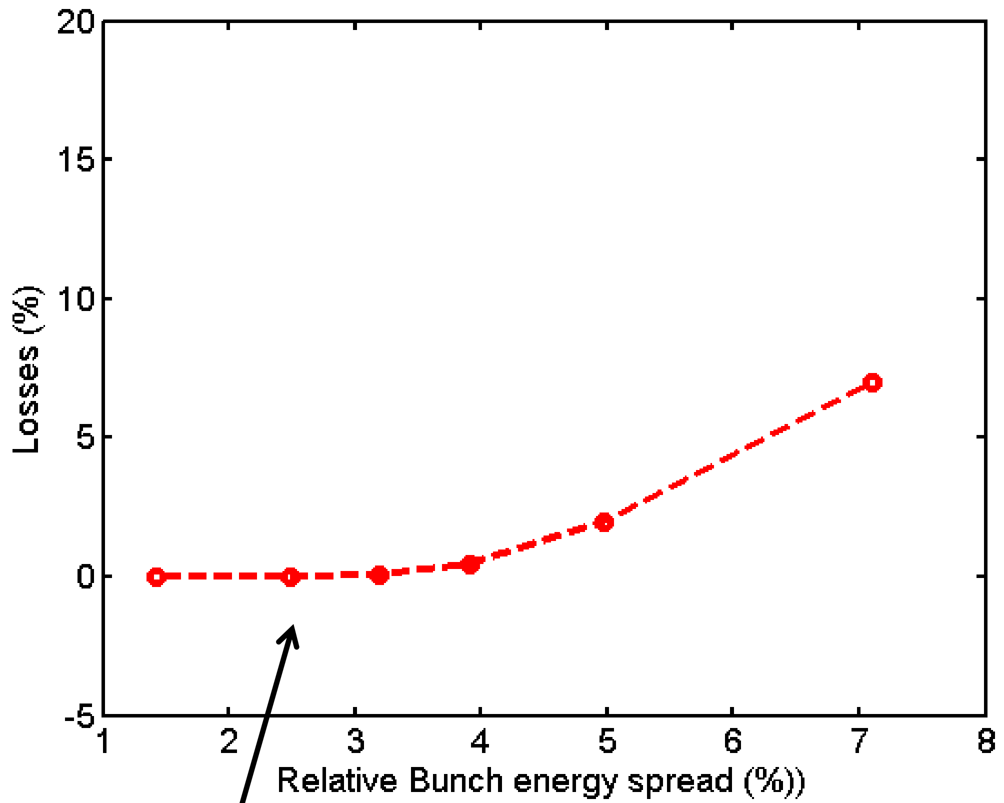
Nominal energy spread = 1.42 %

- Case 1: 2.75 x 1.42 = 3.905 %
- Case 2: 3.5 x times of nominal
- Case 3 : 5 x times of nominal

Large fraction of Beam losses happen at last sextupole (at ~20 m) with aperture of 100 mm

Note: 500,000 macro particles

Beam Losses with Initial energy spread



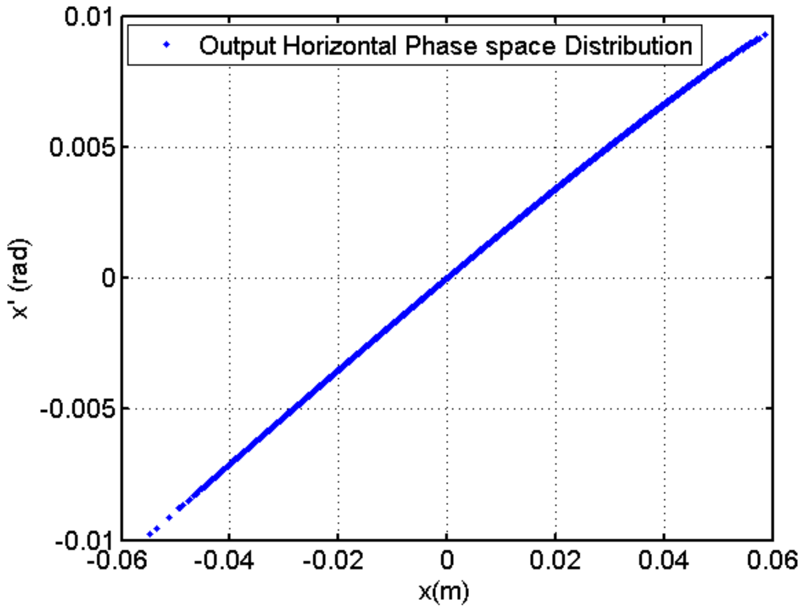
Δ E/E =2.485% is estimated energy acceptance of extraction line

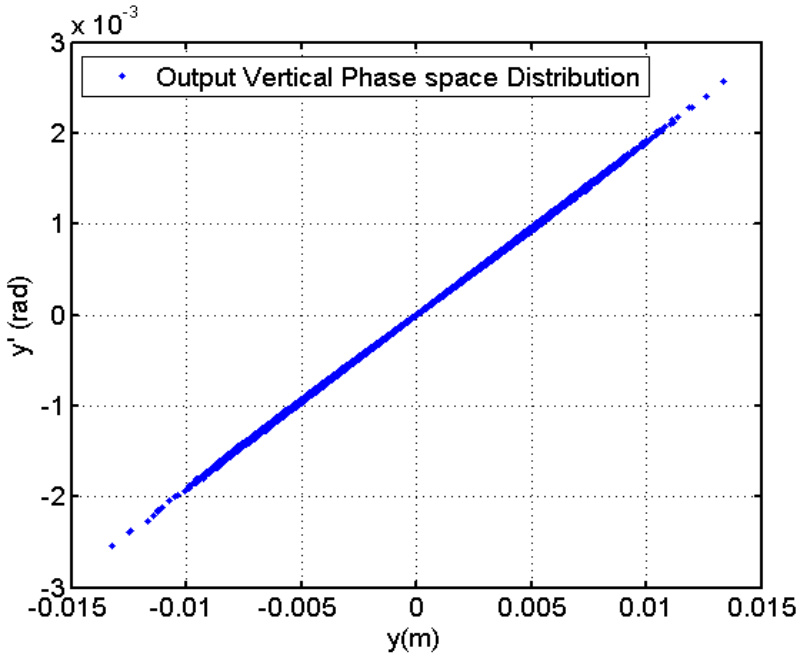
No Beam losses for initial rms relative energy spread equal to 1.75 times of nominal spread. (1.75x σ_E =2.485 %). σ_E = 1.42%

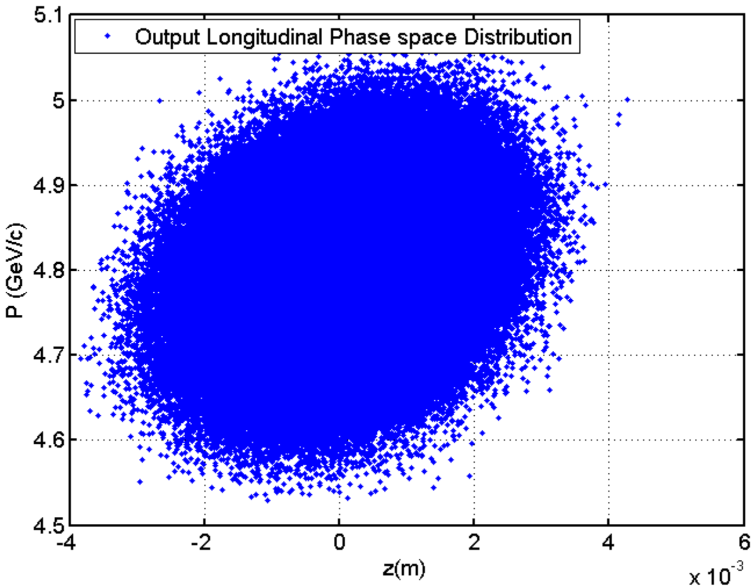
7 % beam is lost in extraction line for initial rms relative RMS energy spread equal to five times of nominal spread (5xσ_E = 7.1 %).

- In case of wrong rf phase max energy deviation is < 10% (~7σ_E)
- Estimated beam size at the location of sextupole

Output Phase Space Distribution: Nominal







- Estimated beam size at the location of sextupole is >> 50μm^2

ML - Beam loss

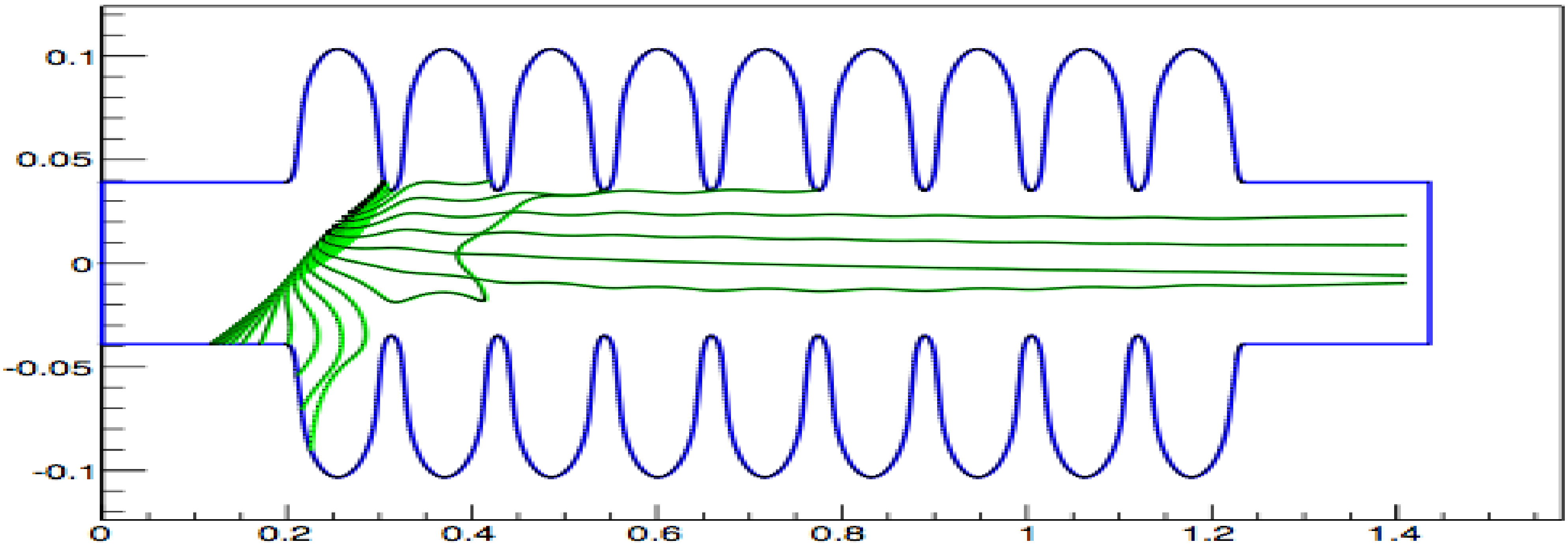
T.Sanami, KEK

- Beam loss: K.Kubo on 2nd ADI-meeing
  - Beam gas coulomb :
    - ML: 2.3e-7/E[GeV] W/m
    - RTML: 1.0e-6 W/m
  - Beam gas Brems. : 3e-9 E[GeV] W/m
  - Dark Current   : 410 MeV, 88 I[nA] mW/quad (I nA for each cavity)
- Suppose 30MV/m、50 nA/Cavity, 38m btw Quad
  - Normal operation (under consideration) - 400MeV, 4.4W (6.875e10eps) at Q magnet
  - System failure (under consideration) - Entire bunch train at one point
  - Amount of normal loss is 10^6 times smaller than total beam power

Dark current studies

- Start with LCLS-II layout and parameters to understand requirements and range of acceptable dark current (cross-check SLAC results)
- Built model to simulate particle losses and acceleration along CM (or few CM's).
- Investigate different scenario of FE (uniform from whole cavity surface or from diaphragm; all /few/ one cavity contribute to FE; effect of field enhancement, ..)
- In all cases dark current was normalized to 1nA at the end of cryomodule.

DC simulation

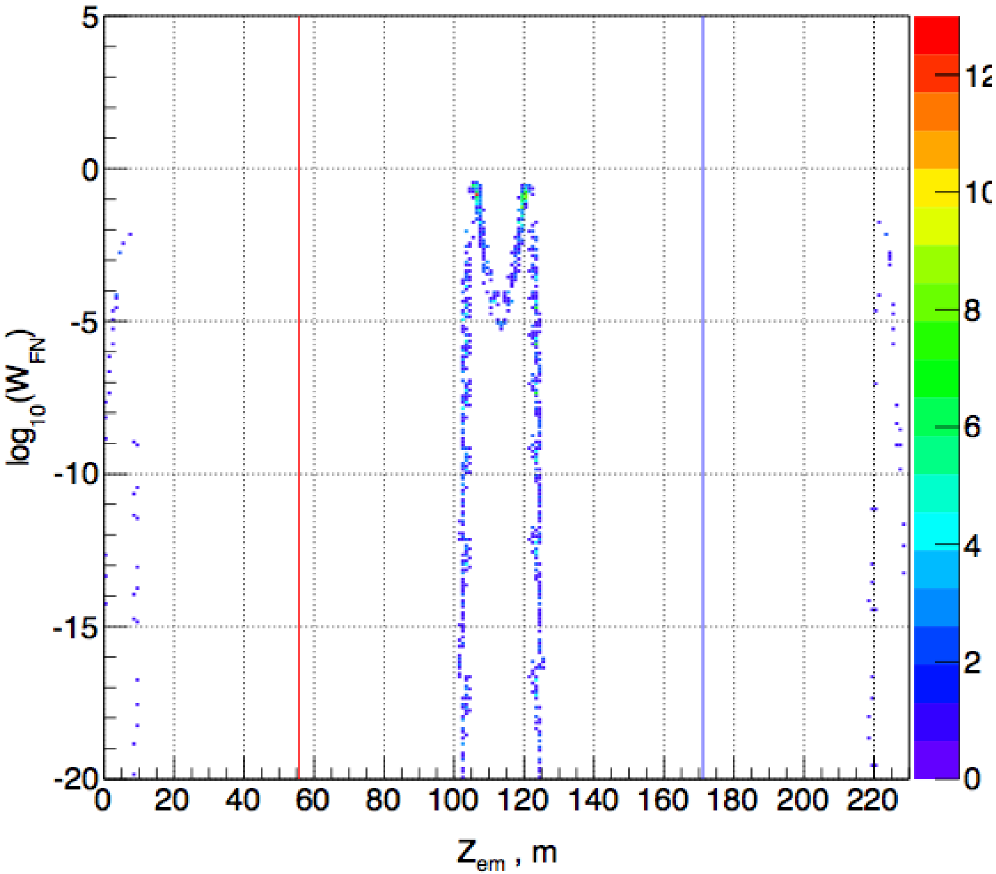


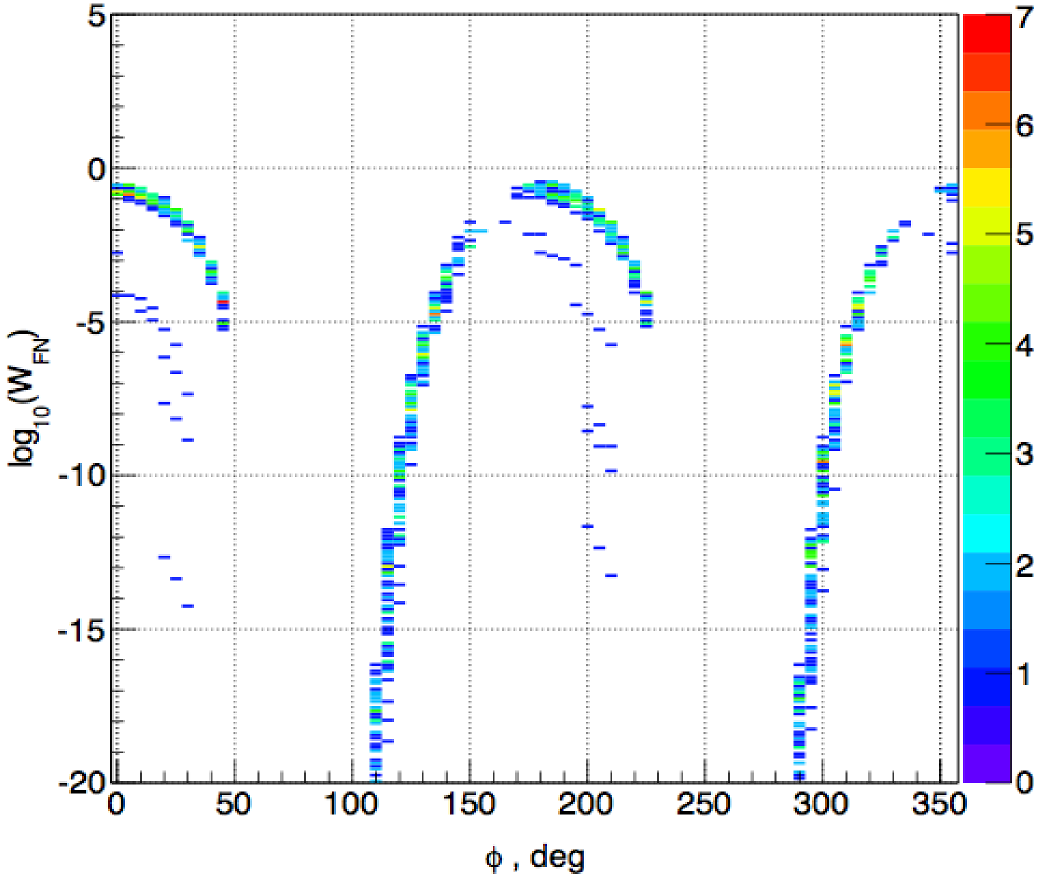
Emitter location: 7 mm us from the 1st iris, RF phases from 0 to 360° with the step of 5°

DC simulation

FN weight VS emitter location/phase for the tracks exiting cavity:

- weight changes from 100% to 1% for z = ±(5-9) mm from iris, max weight at ±7mm
- weight changes from 100% to 1% for the phase +-25°at max field phase (0,180°)





Dark Current simulation

- **Fowler–Nordheim** model (assign weight to each simulated track according to equation**:**

$$I(E) = N_{FN}(\beta_{FN}E)^2 \exp(-B_{FN}\phi^{3/2}/\beta_{FN}E),$$

where: $B_{FN}=6.83\cdot 10^3$, $\phi=4.2$ eV, E in MV/m, I in Amp; we assume $\beta_{FN}=100$ *(H.Padamsee book):*

- Using FN weights and assuming equal FE in all cavities and normalizing DC to 1 nA at the exit of CM (N=0.0138 e)

- Using this normalization we calculate contribution to energy loss/exit from FE in the 1st cavity

- Eacc=17 MV/m, F=1.3GHz
- Total number of field emission (FE) electrons: 80367 (1mm step x 5° phase step)
- N=941 and 17% of energy at cavity exit;
- Track through all other cavities (2-8), see table
- This allows to calculate absolute energy loss in cavities and energy exit cavities
- Last two rows in the table show contribution into total/exit energy per RF period due to FE from the 1st cavity

No weight

	FE	1	2	3	4	5	6	7	8
	80367	941	467	292	247	239	230	223	223
%FE	100.00	1.17	0.58	0.36	0.31	0.30	0.29	0.28	0.28
%upstream	100.00	1.17	49.63	62.53	84.59	96.76	96.23	96.96	100.00
E_{ds}/E_{tot}, %		17.30	73.00	74.30	93.00	99.01	99.19	99.43	100.00
E_{tot}, MeV		**47.70**	**16.80**	**17.60**	**17.50**	**20.40**	**24.10**	**27.70**	**31.10**
E_{ds}, MeV		8.30	12.30	13.10	16.30	20.20	23.90	27.50	31.10

F-N weight

	FE	1	2	3	4	5	6	7	8
E_{tot}, MeV		5.50	2.83	4.07	5.41	6.73	8.03	9.28	10.45
E_{ds}, MeV		1.25	2.62	4.03	5.41	6.73	8.01	9.23	10.45
E_{loss}, MeV		4.25	0.21	0.04	0.00	0.00	0.02	0.05	0.00

0.208 (mW/MeV/RF period)

Dark current energy at the end of CM

- If every cavity has the same dark the total energy at the end of CM is:
  - **152.2 MeV/RF period/side (equal weight for each FE particle) => 30mW /nC**
  - **47.7 MeV/RF period/side (F-N model, β=100) ➔9.6 mW/nC**

Cavity	E_{loss}, mW/nC
1,8	10
2,7	10.9
3,6	11.8
4,5	12.0
Total	89.6

Cavity	E_{loss}, mW/nC
1,8	0.92
2,7	0.96
3,6	0.96
4,5	0.95
Total	7.4

Next steps

- Simulate energy acceptance of BC2
- Finalize model for dark current and simulate input for radiation model (FLUKA)
  - **All cavities are equally contribute in dark current emission 50nA at 31.5 MV/m at each cavity**
  - **One bad cavity define all dc budget – same normalization (?)**
- Start Radiation simulation from dark current losses (cross-check KEK result)
- Further work on failure scenario