ILC Main Linac Failure Modes

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Intro

- We have studied different failure modes for the ILC main linac
  - Beam loss in
    1. Study (2006)*: ML cavities
    2. Study (ongoing): BDS collimators and spoilers
  - Failure of
    - Klystrons (voltage and phase errors)
    - Quadrupoles, correctors, BPMs
  - Estimating the damage/particle densities

*EUROTeV-Report-2006-040

Beam loss in ML - Method

2006 Model

- A realistic model for an already commissioned, working linac with remaining alignment errors in the order of a few 100 μm.
- One-to-one steering
- 302 quadrupoles with corrector dipoles
- 302 klystrons - each klystron feeds 24 cavities contained in 3 cryomodules

Misalignments

Quads: $\sigma_{x,y}$ = 300 μm
σ_{rot_Z} = 300 μrad
Cavities: $\sigma_{x,y}$ = 300 μm
σ_{rot_Z} = 300 μrad
Cryomods: $\sigma_{x,y}$ = 200 μm

We have considered

- Quad failures
- Klystron phase shifts

Beam loss in ML - Quad Failures

- Estimate
  - Quad failures modify the FODO β-function. We use a simple, multiple scattering ansatz to estimate the average offset

$$\langle \Delta x^2 \rangle = \sum_{i=1,n} (n-i)^2 L^2 \langle \Delta \Theta^2 \rangle > 35\,mm$$

$\Delta\theta = ka \approx 20\,\mu\,rad$

quad strength $k \approx 0.06\mathrm{m}^{-1}$

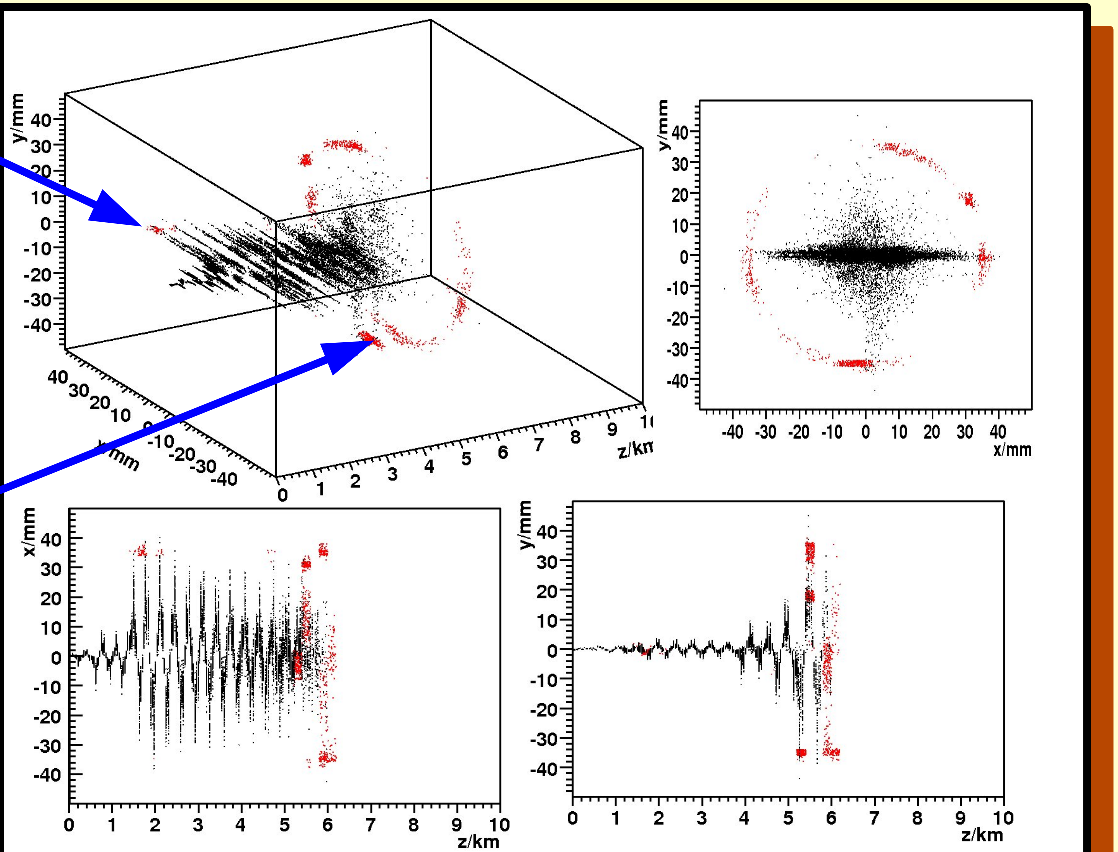
quad offset $a \approx 400\,\mu$

  - At n = 18 this becomes larger than the cavity iris
- Simulation
  - No beam loss for a single quad failure
  - On average 7-8 randomly distributed quad failures are necessary to lose the beam (50% particles)

Number of Quads	% lost particles
6	37
8	73
10	80
12	95

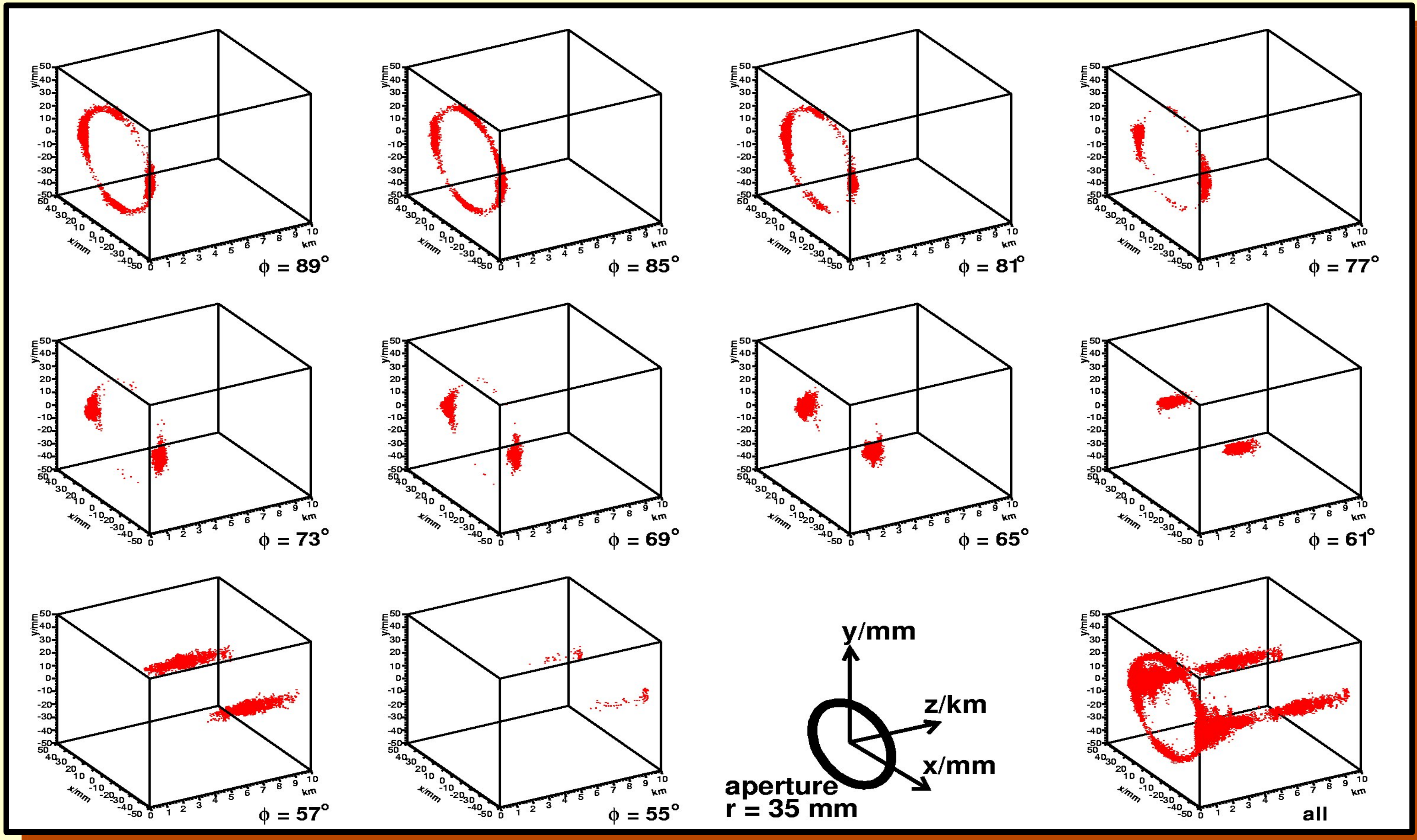
Beam loss in ML - Quad Failures

- A single failure may introduce strong betatron oscillation but only the combined effect of several failures is
- sufficient to reach the aperture.



Beam particles (black) and lost particles (red). An example with 14 randomly failed quads along the linac. Several failures are necessary to kick the beam beyond the aperture.

Beam loss in ML - Klystron Phase Shifts



Spatial distribution of lost particles in the main linac for different klystron phases.

Beam loss in ML - Klystron Phase Shifts

- Common Klystron phase shift as an example
  - Gradient becomes smaller and thereby the energy along the linac

$$E(z) = E_0 + \frac{z}{L}(E_F - E_0)\cos\phi$$

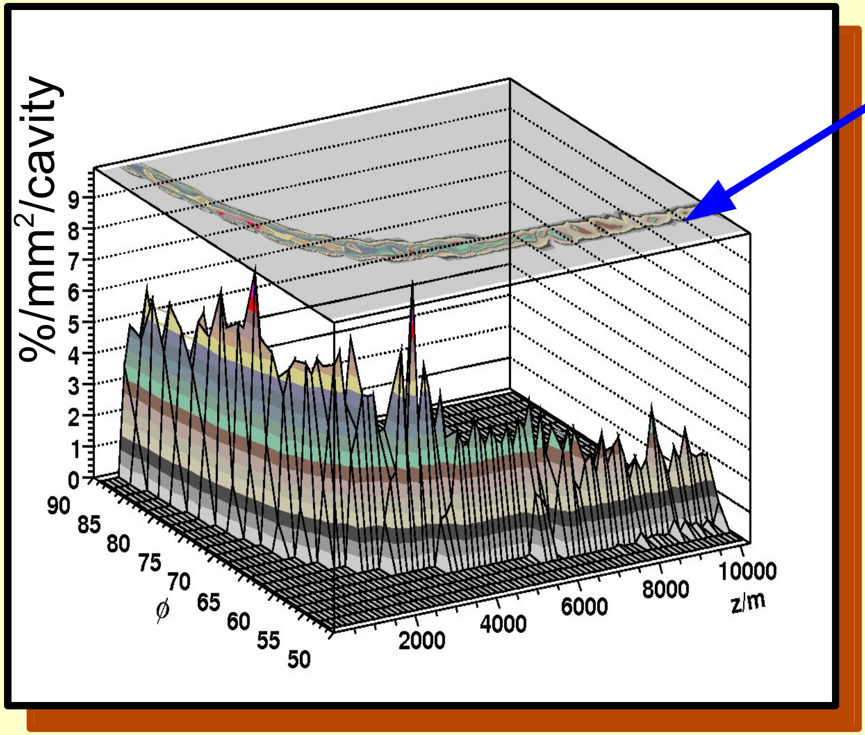
  - FODO stability criterion

$$|\tfrac{1}{2} Tr[M_{FODO}]| < 1$$

  - will be violated at:

$$z(E_F - E_0)(1 - 2\cos\phi) = E_0 L$$

$E_0 = 15\text{GeV},\ E_F = 250\text{GeV},\ L\ \textit{linac length}$



- Particle density never exceeds 10%/mm^2/cavity (100 random seeds)
- SC module with 9 cells, $2 \cdot 10^{10}$ particles per bunch, 2625 bunches per train
- 10% x $2 \cdot 10^{10}$ x 2625 / 9 = $6 \cdot 10^{11}$/mm^2
- typical particle density to generate a hole is 10^{13}/mm^2 for Cu.

Failure Modes in ML+BDS

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A study of the impact of the following failure modes on the beam in the BDS:

- Problems with the **klystron**:
  - **Phase** error (changed from ϕ=3.8° up to 7.8°, nominal is 5.3°)
  - **Voltage** errors (changed to ± 1% klystron voltage error)
- Problems due to
  - failing **quadrupoles**

Simulation parameters

Simulation done with **Merlin**:

- **Lattice:** ILC2006c with different collimator settings taken from A.I.Drozhdin, X.Yang ("ILC BDS Aperture Definition from the Collimation Point of View", May 15, 2006, to be found on the web: http://www-ap.fnal.gov/users/drozhdin/prdriver/pap_ILCFF9_aperture_short.pdf)
- Beam parameters:

  $\sigma_x^* \approx 600$ nm

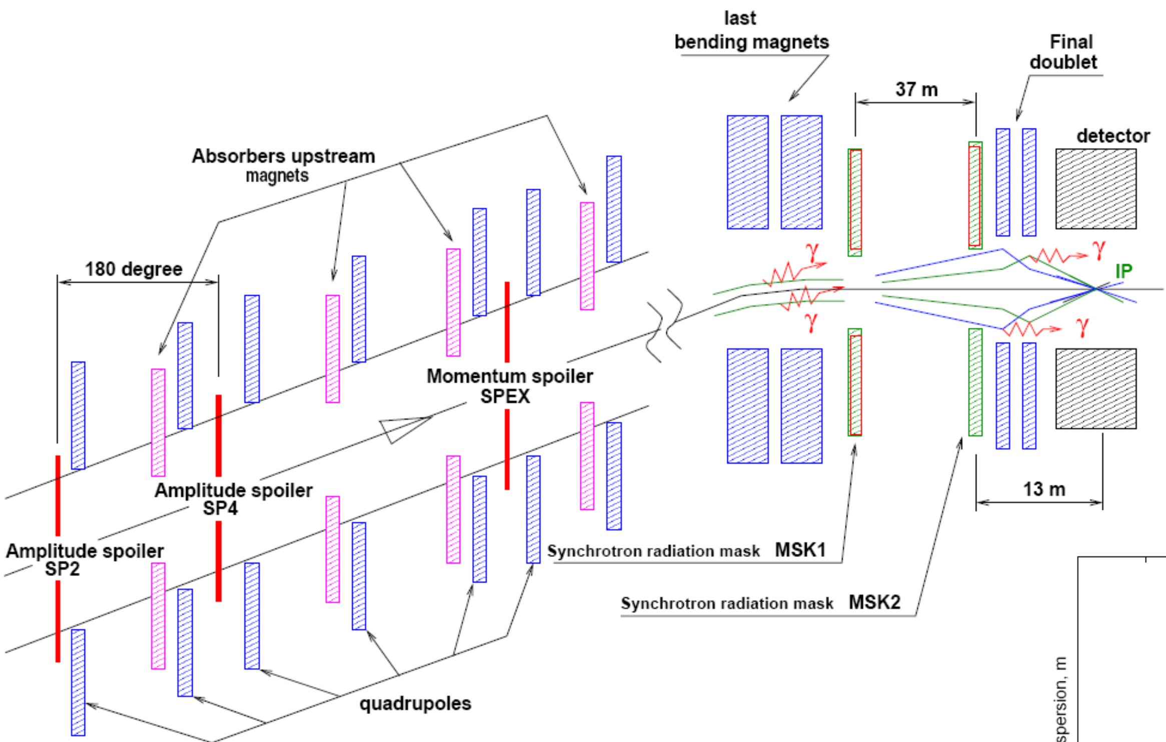
  $\sigma_y^* = 5.1$ nm

  $\gamma\varepsilon_x = 8$ mm•mrad

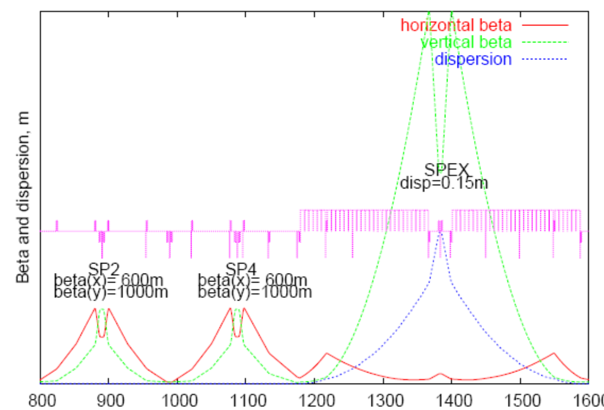
  $\gamma\varepsilon_y = 0.02$ mm•mrad
- Additional parameters:

  10^5 particles -> 50k per beam, 10 random seeds (misalignment configurations)
- Accelerator errors in Merlin:
  - Main Linac:
    - Quadrupole transverse errors: 300 μm x 300 μm
    - Cavity transverse errors: 300 μm x 300 μm
  - BDS:
    - Quadrupole transverse errors: 200 μm x 200 μm
- 1-2-1 steering

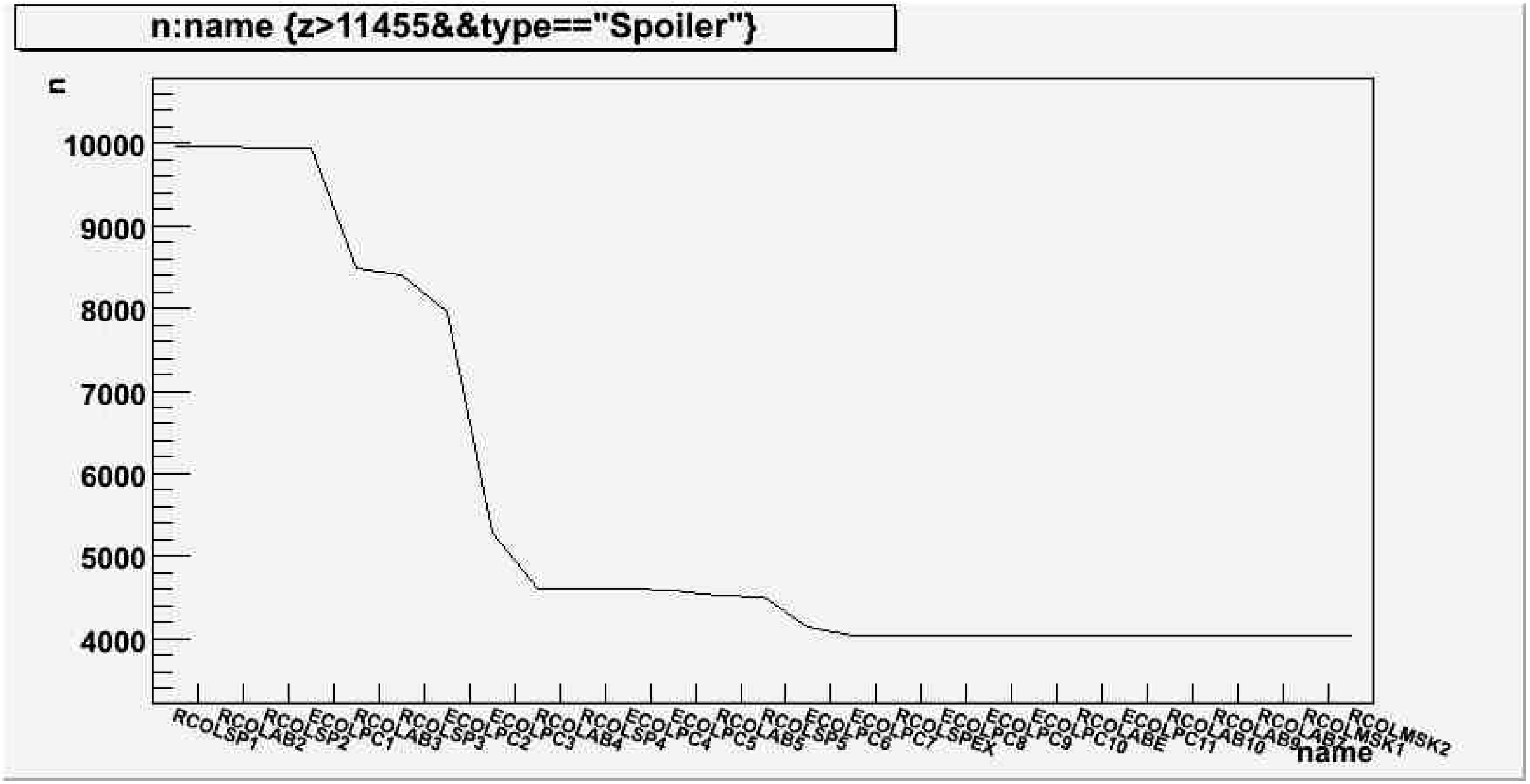
Layout of the last part of the BDS



taken from
A.I.Drozhdin, X.Yang



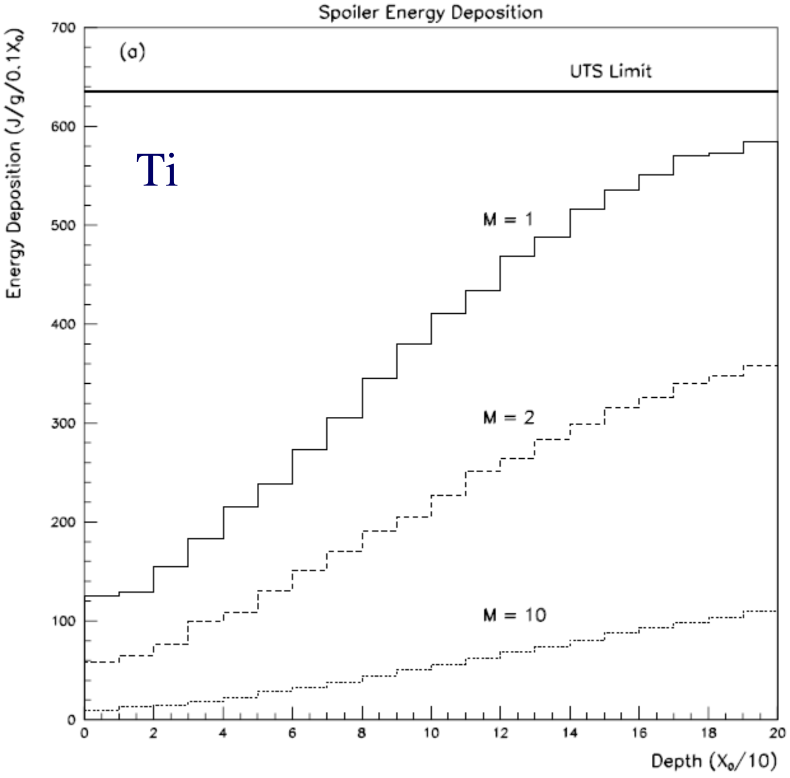
Particles in BDS



Failure limit for spoilers

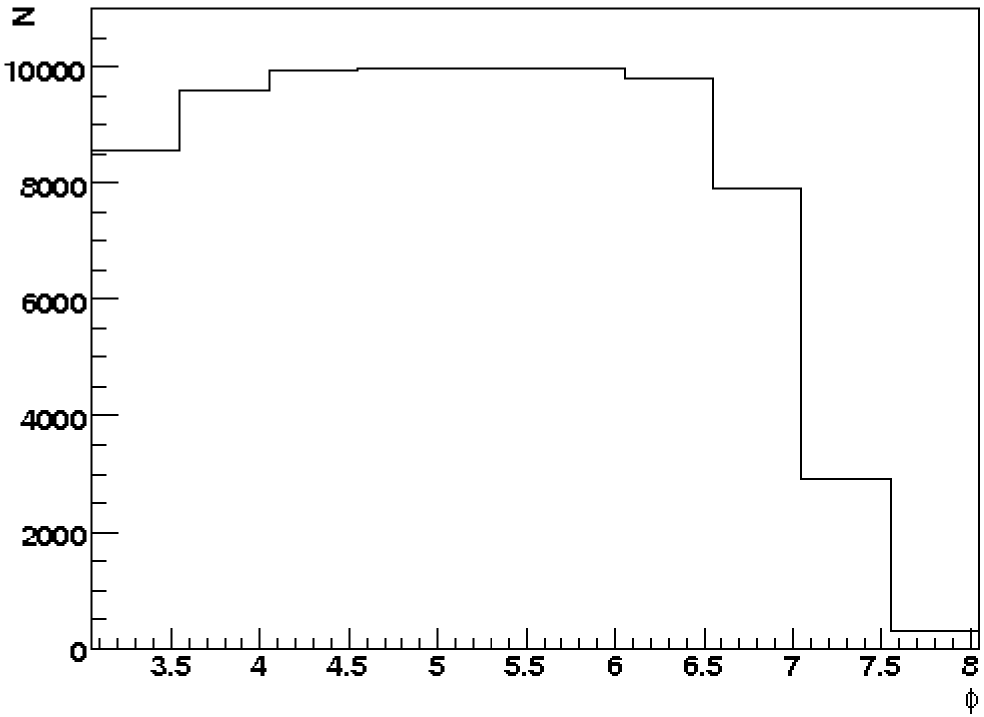
From TESLA-Note 01-12:

For beam with σ_x=130$\sqrt{M}$ μm, σ_x=7$\sqrt{M}$ μm (similar values for ILC beam at spoilers SP2, SP4 and SPEX):



Ultimate Tensile Strength (UTS) limit reached for nominal (M=1) beam with the 2nd bunch.

Klystron failure: bandwidth for phase errors



N: Number of electrons reaching the IP
(simulation starts with 10k e in the ML)

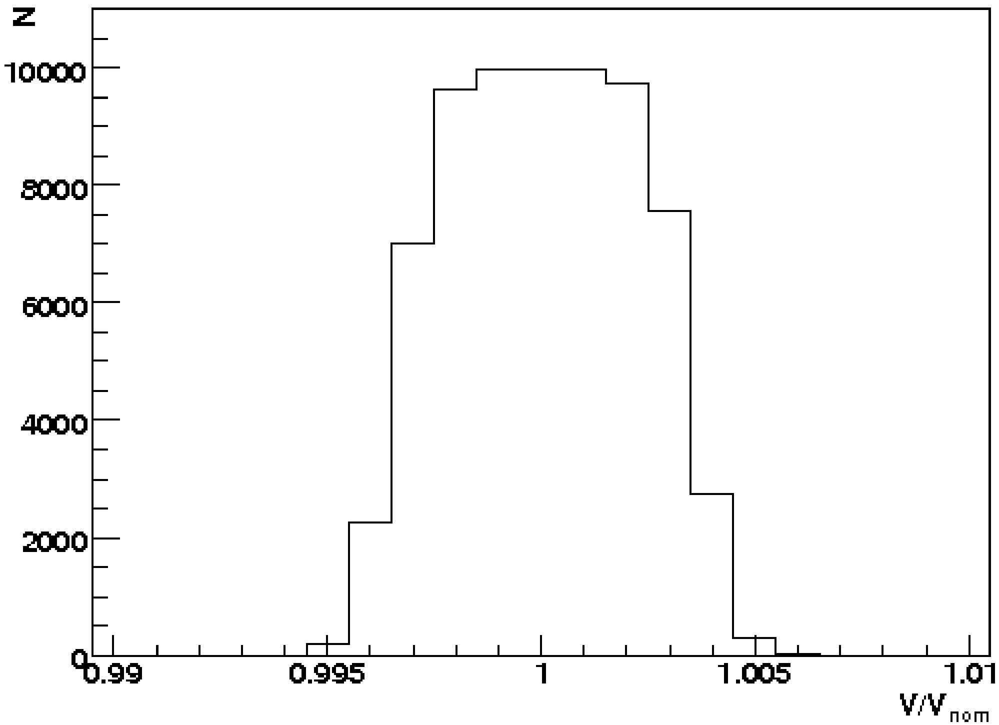
Same phase fluctuation factor for all klystrons.

Beam spoiled by SPEX, then absorbed in the following absorbers.
Beam size @ SPEX:
σ_x = 120 μm, σ_y = 10 μm

Safe for one bunch!

Phase needs to be stable to ±1°

Klystron failure: bandwidth for voltage errors



N: Number of electrons reaching the IP
(simulation starts with 10k e in the ML)

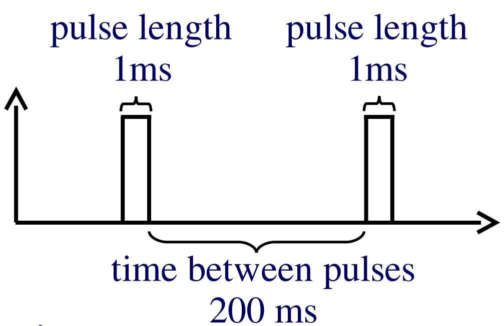
Same voltage fluctuation factor for all klystrons.

Similar to phase error: beam spoiled by SPEX, then absorbed in the following absorbers.
Beam size @ SPEX:
σ_x = 120 μm, σ_y = 10 μm

Safe for one bunch!

Voltage needs to be stable to ±0.1%

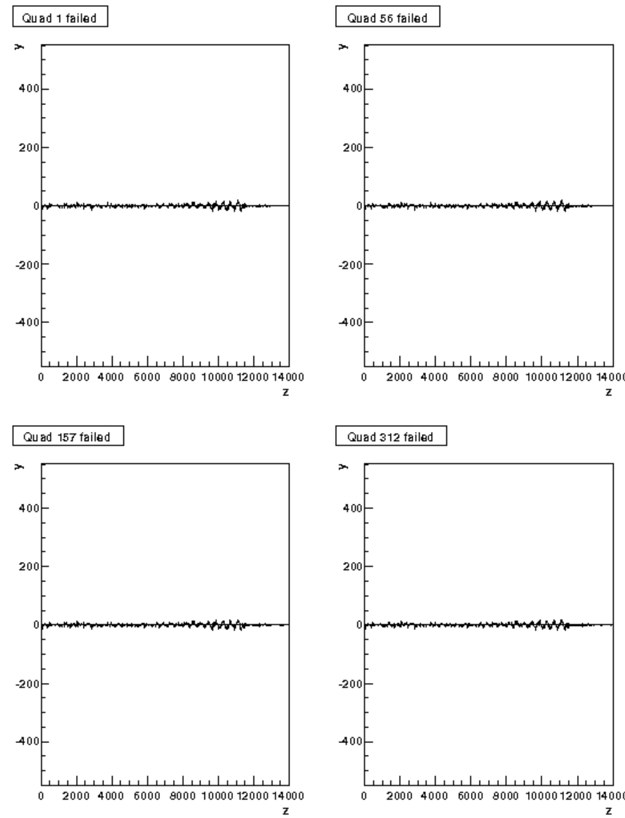
Quadrupole failure in Main Linac



- Characteristic time constant for SC quadrupole to ramp down to 0 is O(ms).
- Bunch interval within pulse: 369.2 ns

2 scenarios:

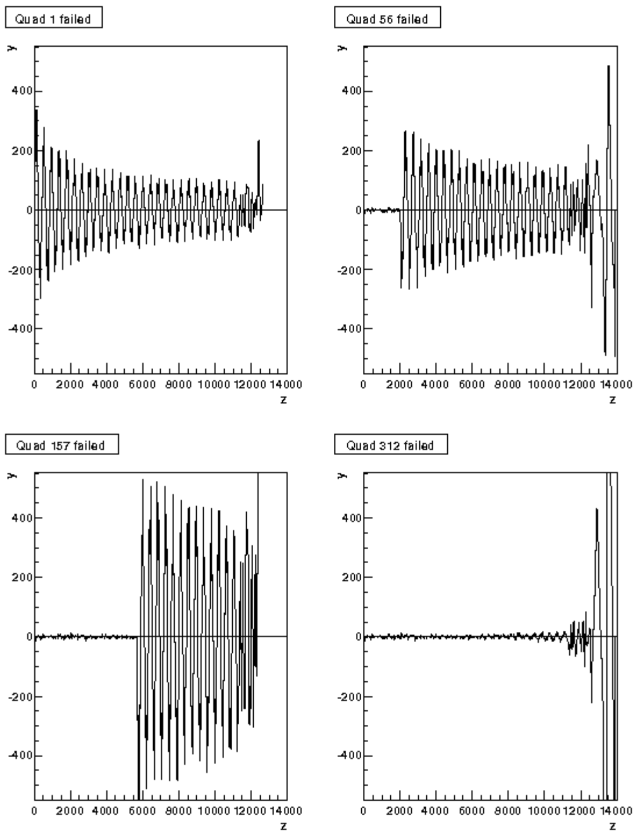
- Quadrupole failure during the time between pulses -> damping ring extraction inhibited.
- Quadrupole failure during pulse -> next bunch will only see small change of field (O(0.04%)) due to long ramp down time



Beam not affected by small field change

Examples for mean y distribution in case of quad failure (0.04% less than nominal field).

Quadrupole failure in Main Linac



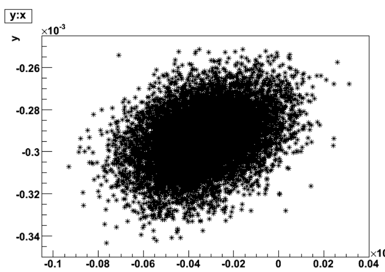
Examples for mean y distribution in case of complete quad failure (field completely 0)

Dependent on the misalignment geometry of the quadrupoles and cavities:
beam might get completely lost at positions where beam size is small enough to cause damage:

Example:

Beam lost in SP1 with:

$\sigma_x = 16\ \mu m$, $\sigma_y = 13\ \mu m$



☛ Damping ring extraction inhibit must be active

Conclusions

- Failure leading to different beam energy causes beam to end up mainly in SPEX (safe for one bunch)
- Quadrupole errors:
  - complete failure: beam needs to be kept in damping ring to prevent damage
  - failure during pulse: slow field change does not affect the beam significantly

To do:

Corrector failure

Failure mode studies will be finished in few weeks.

-> EUROTeV-Report will summarize final results.

Backup transparencies

Backup: collimator settings calculated by Drozhdin

name	thickness		material	aperture					σ beam size	
				code	hor.	ver.	hor.	ver.	hor.	ver.
	mm	rad.len.			mm	mm	σ_x	σ_y	mm	mm
collim.at $8\sigma_x$ X $57\sigma_y$										
AB2	429.0	30	Copper	17	2.0	2.0	18	260	0.1119	0.0077
SP2	8.6	0.6	Copper	18	0.9	0.5	8	65	0.1119	0.0077
PC1	214.5	15	Copper	20	3.0	3.0	-	-	0.0655	0.0016
AB3	429.0	30	Copper	28	2.0	2.0	99	1670	0.0202	0.0012
PC2	214.5	15	Copper	10	3.0	3.0	-	-	0.0617	0.0015
PC3	214.5	15	Copper	22	3.0	3.0	-	-	0.1419	0.0055
AB4	429.0	30	Copper	24	2.0	2.0	18	260	0.1123	0.0077
SP4	8.6	0.6	Copper	25	0.7	0.5	6.2	65	0.1123	0.0077
PC4	214.5	15	Copper	23	3.0	3.0	-	-	0.1373	0.0061
PC5	214.5	15	Copper	11	3.0	3.0	-	-	0.0923	0.0030
AB5	429.0	30	Copper	12	2.0	2.0	47	2200	0.0426	0.0009
PC6	214.5	15	Copper	27	3.0	3.0	-	-	0.0893	0.0023
PDUMP	214.5	15	Copper	56	2.0	2.0	29	328	0.0677	0.0061
PC7	214.5	15	Copper	55	60.0	5.0	1700	289	0.0349	0.0173
SPEX	35.6	1	Titanium	33	1.0	0.8	19	62	0.0516	0.0130
PC8	214.5	15	Copper	19	3.0	3.0	-	-	0.0367	0.0170
PC9	214.5	15	Copper	26	3.0	3.0	-	-	0.0378	0.0123
PC10	214.5	15	Copper	13	3.0	3.0	-	-	0.0606	0.0073
ABE	105.0	30	Tungsten	37	2.0	2.0	22	833	0.0902	0.0024
PC11	214.5	15	Copper	14	3.0	3.0	-	-	0.0400	0.0011
AB10	105.0	30	Tungsten	39	7.0	7.0	18	139	0.3801	0.0502
AB9	105.0	30	Tungsten	40	10	4.5	16	147	0.6449	0.0307
AB7	105.0	30	Tungsten	41	4.4	1.6	171	1230	0.0257	0.0013
MSK1	105.0	30	Tungsten	42	7.8	4.0	16	178	0.4875	0.0225
MSK2	105.0	30	Tungsten	43	7.4	4.5	12	151	0.6076	0.0298

Table 1: ILC collimator aperture, length and material. SP - spoiler, AB - absorber, MSK - photon mask, PC - protection collimator (mask). Version ILCFF9 with enlarged aperture of SPEX to $1 \times 0.8\ mm^2$, PCs to $3 \times 3\ mm^2$ and aperture of absorbers to $2 \times 2\ mm^2$. Aperture of PC7 is $60 \times 5\ mm^2$, ABE, AB10, SB9 and AB7 are as in the Table for "tight" collimation. There is a way for collimation with SPEX at X=1 mm. To do this, it is necessary to decrease aperture of SP4 from $0.9\ X\ 0.5\ mm^2$ to $0.7\ X\ 0.5\ mm^2$. Fig. 2 shows all halo particles and particles passed behind the collimation requirement window. Fig. 3 presents these particles at the SP2, SP4, SPEX and FD entrance. As it is seen from this figures, there is a way to reduce beam size at FD by moving SP4 close to the beam.