Possible failures on LHC magnets and time constants of their effect on the beam

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Outline

- *Motivation*
- *Considered failures*
- *Evaluation criteria*
- *Assumptions*
- *Results*
- *Conclusions*
- *First simulations*

Motivation

- *BLMs will detect the losses after they happen: in some cases, need of detecting failures before beam losses*
- *Add redundancy with respect to BLMs*

$\Rightarrow$ FMCMs have to be installed in critical magnets

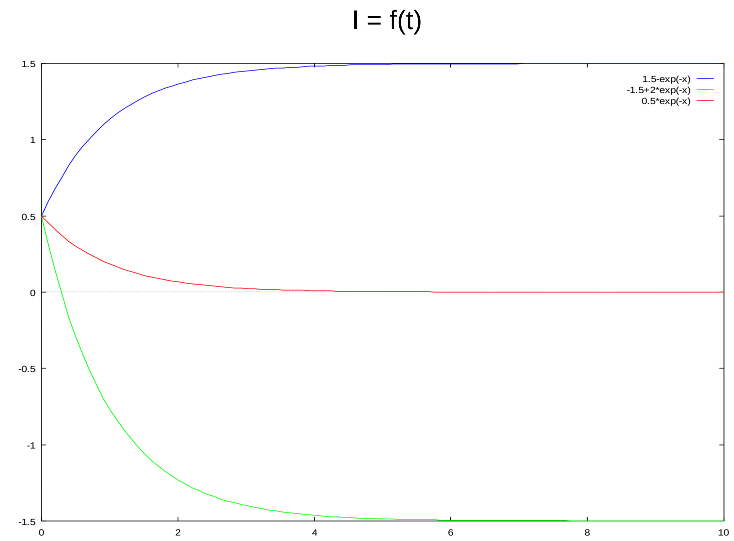
- *Study the timing of the beam losses induced by failures $\Rightarrow$ determine most critical magnets*

- *Set priorities for more detailed further studies (simulations)*

Considered failures (I)

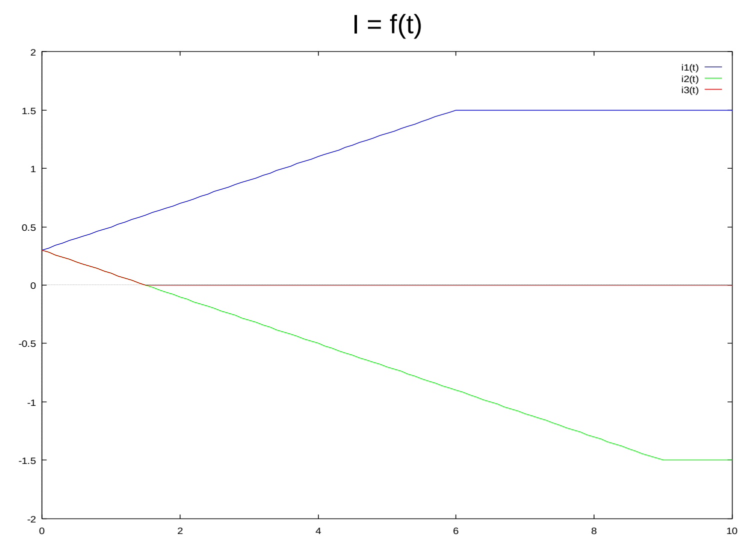
Constant voltage from PC

- Worst case. PC internal failure: maximum voltage difference ($\Delta V = V_{fail} - V_{nom}$)
- Short circuit (sets $V_{fail} = 0$)
- Most relevant in warm magnets



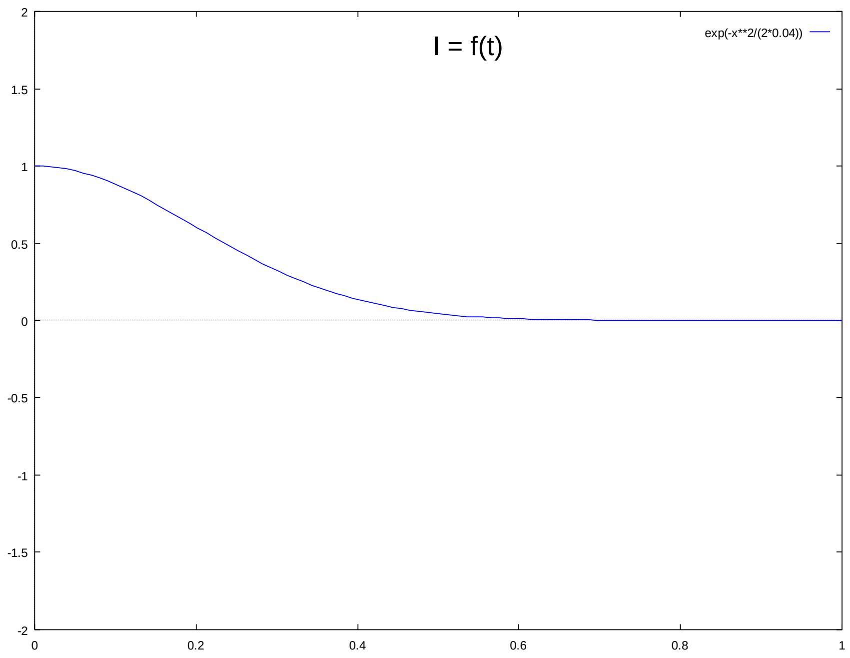
Constant dI/dt from PC

- The PC sets by mistake the ramping dI/dt
- Not concerned by the time constant of the circuit (more critical for SC magnets)



Quench

- Current decay modeled by a gaussian
- σ_c = 200 ms at 7 TeV
- σ_i = 2000 ms at 450 GeV



Other failures…

- Thought to be extremely unlikely and/or have very slow effects in relation to those above

Evaluation criteria

Bending magnets

Time for Δx to reach $6\sigma_{beam}$

Time to reach 1.15 10^{11} particles beyond aperture

Focusing magnets

Time for ΔQ to reach *0.01*

Time to reach 1.15 10^{11} particles beyond aperture

Assumptions

The worst case scenario is assumed

$\Rightarrow$ some results may be too pessimistic

Power converter:

- *Includes extra 10 % on peak voltage (maximum possible over voltage)*

Beam:

- *Only transverse planes*
- *Worst possible phase differences and beta values*

Losses:

- *The missteered beam hits a primary collimator*

Warm bending magnets

	Injection (450 GeV)					
	Short circuit		Constant dI/dt		Max ΔV	
	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBXW	80	**34**	926	404	**3.2**	**1.4**
MBW (IR3)	85	**36**	527	230	**2.5**	**1.1**
MBW (IR7)	110	**47**	791	346	**2.5**	**1.1**
MCBWH	328	113	3736	1633	**7.7**	**3.4**
MCBWV	321	111	3665	1602	**7.6**	**3.3**

	Collision (7 TeV)					
	Short circuit		Constant dI/dt		Max ΔV	
	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBXW	**3.9**	**1.7**	707	309	**3.9**	**1.7**
MBW (IR3)	**21**	**9.3**	2081	909	**21**	**9.3**
MBW (IR7)	**27**	**12**	3121	1364	**14**	**6.5**
MCBWH	62	**26**	14738	6443	**20**	**9.0**
MCBWV	61	**25**	14455	6319	**20**	**8.8**

Results (II)

SC bending magnets - Injection

	Injection (450 GeV)							
	Short circuit		Constant dI/dt		Max ΔV		Quench	
	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MB (arc 3-4)	25830	11340	145	64	110	**48**	317	210
MBRB	2357	1027	552	242	60	**26**	479	316
MBRS	2992	1300	763	335	84	**37**	564	372
MBRC	2160	938	1178	518	94	**41**	569	375
MBX	1739	755	844	371	**44**	**19**	568	374
MCBH	125546	35260	5446	2392	1831	799	3429	1817
MCBV	128138	36413	5383	2364	1811	791	3385	1804
MCBCH	24079	9114	2563	1126	644	282	2017	1241
MCBCV	33125	11826	3236	1421	814	356	2366	1414
MCBXH	62082	17456	5440	2389	701	306	3425	1816
MCBXV	34897	10170	5241	2302	412	180	3288	1775
MCBYH	43314	16349	2805	1232	878	384	2035	1250
MCBYV	42919	16223	2785	1223	794	348	2026	1246

Results (III)

SC bending magnets - collision

	Collision (7 TeV)							
	Short circuit		Constant dI/dt		Max delta V		Quench	
	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MB (arc 3-4)	6504	2857	568	250	457	201	16	**11**
MBRB	601	264	2215	973	389	171	24	**16**
MBRS	763	334	3072	1349	576	252	28	**19**
MBRC	165	72	1423	625	165	72	16	**10**
MBX	91	**40**	701	308	59	**26**	13	**8.6**
MCBH	18552	7658	21478	9434	5258	2270	132	85
MCBV	19246	7949	21292	9352	5279	2281	131	84
MCBCH	4312	1846	8707	3824	1477	643	85	56
MCBCV	6501	2746	12832	5636	2194	951	105	68
MCBXH	2107	912	5340	2345	524	229	63	**42**
MCBXV	1237	536	5144	2260	308	135	62	**41**
MCBYH	3565	1547	4504	1978	1025	449	58	**38**
MCBYV	3554	1542	4490	1972	954	418	58	**38**

Results (IV)

Experimental dipoles

	Injection (450 GeV)					
	Short circuit		Constant dI/dt		Max ΔV	
	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBAW	Not reached	17846	44205	19326	687	295
MBWMD	Not reached	2409	26633	11644	157	68
MBXWT	10118	625	7120	3113	17	**7.6**
MBLW	28026	5446	21766	9516	426	184
MBXWH	Not reached	1572	32304	14123	**47**	**21**
MBXWS	Not reached	Not reached	64241	28086	**31**	**13**

	Collision (7 TeV)					
	Short circuit		Constant dI/dt		Max ΔV	
	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBAW	1548	647	52101	22779	532	229
MBWMD	332	141	34149	14930	127	55
MBXWT	70	30	6937	3033	**14**	**10**
MBLW	1567	656	50803	22211	617	265
MBXWH	658	258	115921	50680	135	58
MBXWS	202	81	88525	38703	**35**	**15**

Results (V)

Warm quadrupoles

	Injection (450 GeV)					
	Short circuit		Max ΔV		Constant dI/dt	
	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]
MQWA (avg)	366	350	0.3	**10**	0.3	**10**
MQWB (worst)	Not reached	Not reached	60	58	60	58

	Collision (7TeV)					
	Short circuit		Max ΔV		Constant dI/dt	
	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]
MQWA (avg)	356	340	356	340	356	340
MQWB (worst)	Not reached	Not reached	1435	1256	1435	1256

SC quadrupoles - Injection

	Injection (450 GeV)							
	Short circuit		PC worst failure		Constant dI/dt		Quench	
	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]
MQF 23	7605	124581	31	420	2194	28996	1930	1888
MQM	89105	81337	1028	993	17899	17298	3797	3628
MQMC	Not reached	Not reached	1403	1356	28689	27725	Not reached	Not reached
MQML	14683	14090	267	258	6661	6438	1725	1690
MQY	93818	87381	1510	1458	15974	15437	3309	3194
MQXA/MQXB	46542	44893	1089	1052	8004	7735	934	917
MQXA (Q1)	27805	25883	215	207	1369	1323		
MQXB	40771	38785	620	599	15934	15399		
MQT	Not reached	Not reached	1381	1326	85484	82613	Not reached	Not reached
MQTLH	Not reached	Not reached	1287	1242	56859	54949	Not reached	Not reached
MQTLI	Not reached	Not reached	1210	1168	21888	21153	Not reached	Not reached
MQS	Not reached	Not reached	2854	2750	52715	50944	Not reached	Not reached
MQSX	Not reached	Not reached	2943	2783	303405	293213	Not reached	Not reached

SC quadrupoles - collision

	Collision (7 TeV)							
	Short circuit		PC worst failure		Constant dI/dt		Quench	
	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]
MQF 23	7342	122286	518	7046	36332	487960	189	185
MQM	66527	62020	28870	27570	246616	238332	328	317
MQMC	Not reached	Not reached	35273	33628	386963	373964	Not reached	Not reached
MQML	4447	4289	2135	2062	35547	34353	95	93
MQY	6133	5918	4808	4641	28530	27572	85	83
MQXA/MQXB	2324	2245	1390	1343	6544	6324	**21**	**21**
MQXA (Q1)	601	581	109	105	837	809		
MQXB	1093	1056	525	507	9295	8983		
MQT	Not reached	Not reached	Not reached	Not reached	1294769	1251276	Not reached	Not reached
MQTLH	Not reached	Not reached	Not reached	Not reached	1005083	971320	Not reached	Not reached
MQTLI	Not reached	Not reached	24049	22273	313613	303078	Not reached	Not reached
MQS	Not reached	Not reached	Not reached	Not reached	820021	792475	Not reached	Not reached
MQSX	Not reached	Not reached	1007	967	165627	160063	Not reached	Not reached

Results (VIII)

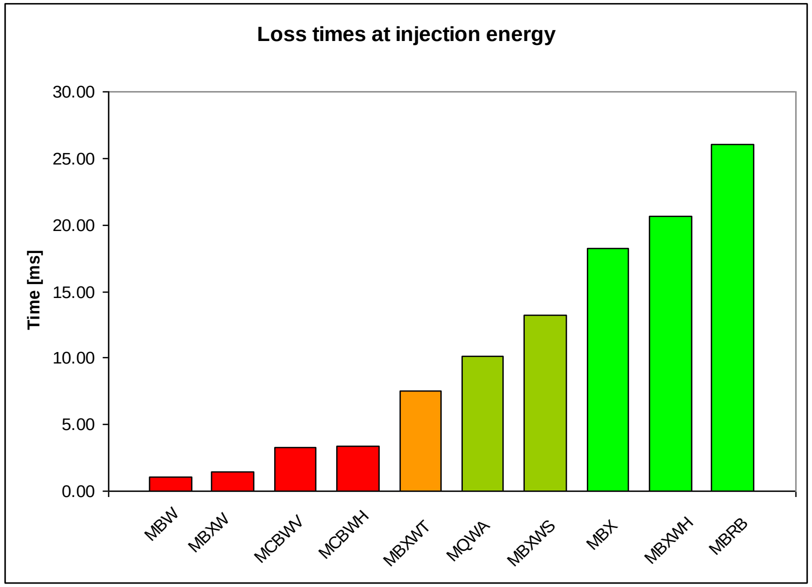
Quadrupoles – 1 mm offset (4 mm MQXA/B)

	Injection (450 GeV)						Collision (7 TeV)					
	PC worst failure		Short circuit		Quench		PC worst failure		Short circuit		Quench	
	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MQWA	**35**	**15**	284	110			284	110	284	110		
MQWB	307	119	NR	NR			NR	NR	2519	391		
MQF 23	1702	746	NR	292135	NR	4331	7876	3430	128422	48840	243	144
MQM	1393	607	NR	33791	NR	2339	8671	3623	15490	6216	158	100
MQMC	3638	1568	NR	NR	NR	NR	21752	8501	87659	23498	360	186
MQML	1005	438	NR	28021	NR	2384	3503	1500	7441	3097	123	79
MQY	4946	2129	NR	NR	NR	NR	12110	5058	15691	6455	135	87
MQXA/B	781	343	32859	14122	785	515	1102	484	1842	808	**19**	**12**
MQXA	110	**48**	9787	3729	1973	1218	71	**31**	393	172		
MQXB	205	90	10524	4379	1232	795	227	100	473	207		
MQT	7386	1895	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
MQTLH	721	312	NR	18971	NR	3357	2221	931	8422	3077	224	135
MQTLI	3752	1541	NR	NR	NR	NR	14240	4793	NR	47667	NR	488
MQS	2667	1126	NR	NR	NR	NR	9899	3735	NR	28854	NR	348
MQSX	NR	3051	NR	NR	NR	NR	6360	1499	NR	NR	NR	NR

Conclusions

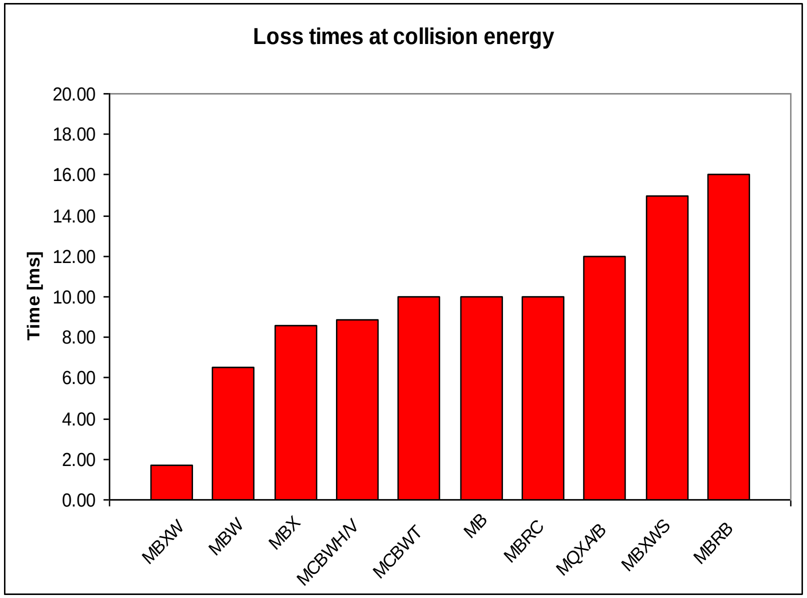
450 GeV

Magnet		T_{loss} [ms]	Failure
MBW	D3,D4 in IR3, IR7	1.1	Max ΔV
MBXW	D1 in IR1, IR5	1.4	Max ΔV
MCBWV	Warm dipole correctors	3.3	Max ΔV
MCBWH		3.4	Max ΔV
MBXWT	ALICE orbit comp.	7.9	Max ΔV
MQWA	Q4, Q5 in IR3, IR7	11	Max ΔV
MBXWS	LHCb orbit comp.	13	Max ΔV
MBX	D1 in IR2, IR8	18	Max ΔV
MBXWH	LHCb orbit comp.	21	Max ΔV
MBRB	D4	26	Max ΔV



7 TeV

Magnet		T_{loss} [ms]	Failure
MBXW	D1 in IR1, IR5	1.7	Max ΔV
MBW	D3,D4 in IR3, IR7	6.5	Max ΔV
MBX	D1 in IR2, IR8	8.6	Quench
MCBWH/V	Warm correctors	9.0	Max ΔV
MBXWT	ALICE orbit comp.	10	Max ΔV
MB	Main dipole	10	Quench
MBRC	D2	10	Quench
MQXA/B	Inner triplets	12	Quench (4mm)
MBXWS	LHCb orbit comp.	15	Max ΔV
MBRB	D4	16	Quench



First simulations

- Tracking done with MAD-X
  - *Relatively few turns: the simulation speed is not an important issue*
  - *Changing B field: madX is versatile*
  - *Easy to obtain the beam twiss parameters with a changing magnetic field*
  - *Code modification to record the losses and take into account skew collimators*
- Only with collimators used in phase 1
- No statistical alignment or field errors, no crossing angles

RD1.LR1 (MBXW) at 7 TeV:

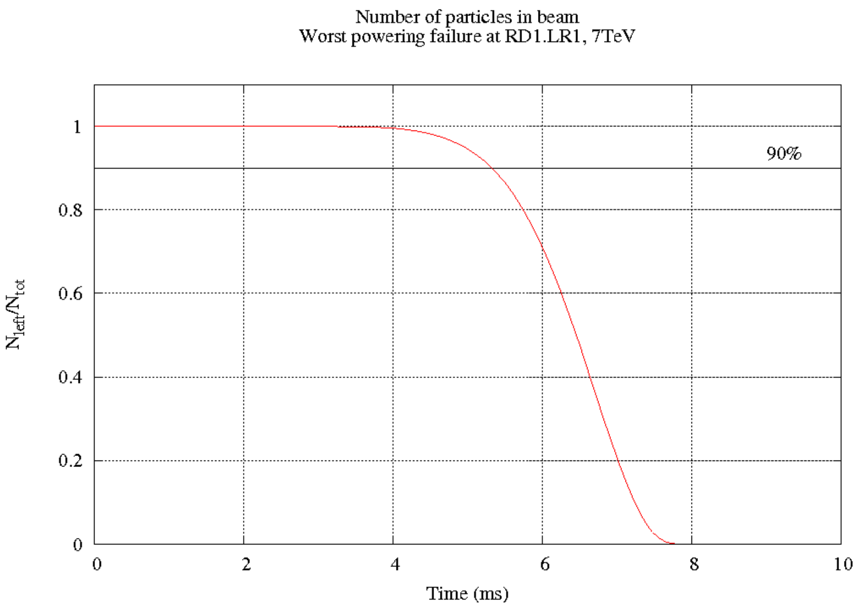
Study: $t_{loss} \geq 1.7$ ms

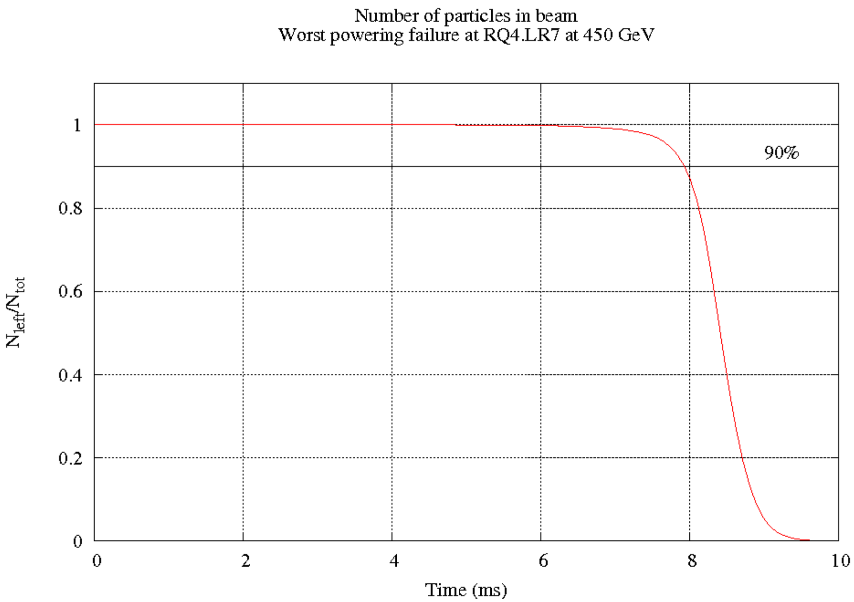
Simulation: $t_{loss} = 3.0$ ms

RQ4.LR7 (MQWA) at 450 GeV:

Study: $t_{loss} \geq 10$ ms

Simulation: $t_{loss} = 5.2$ ms

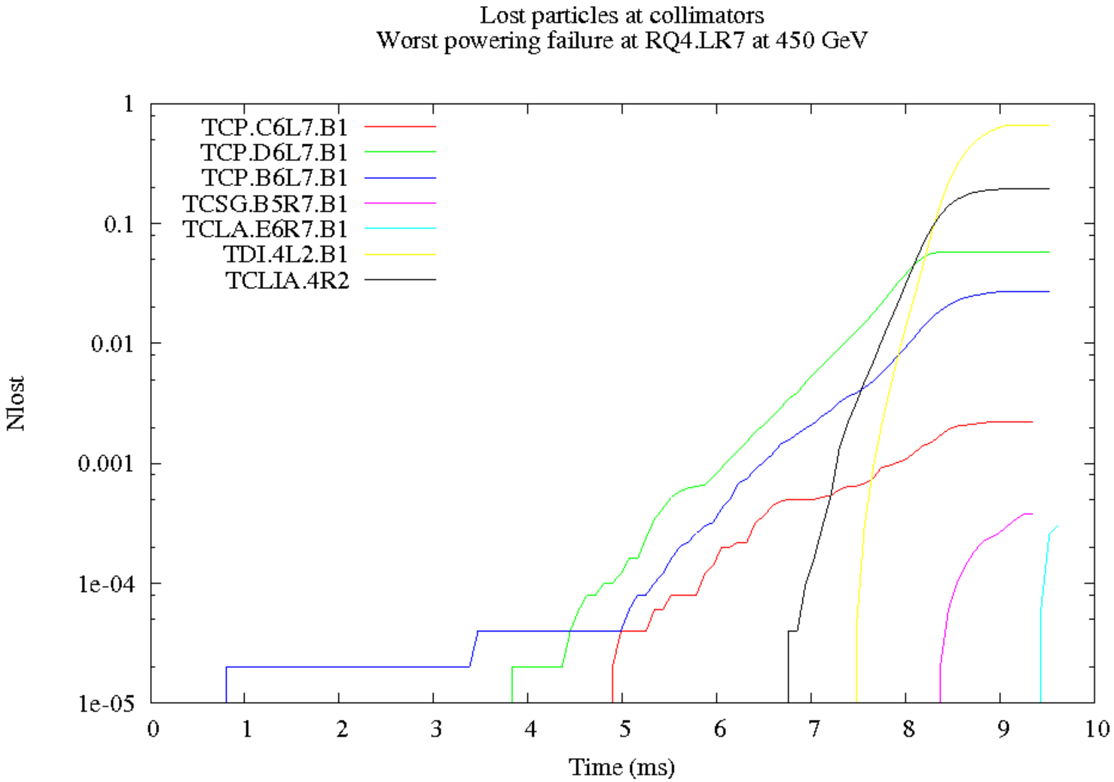




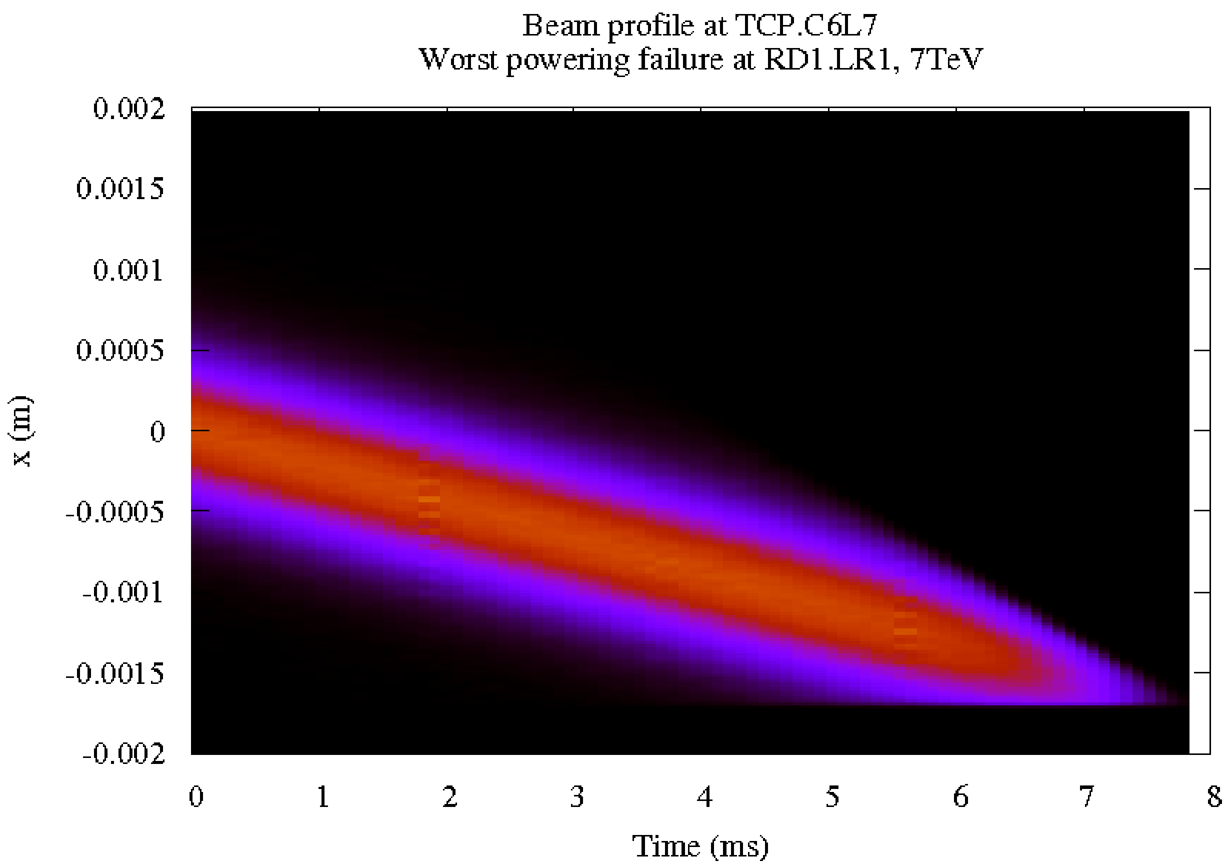
Assumed losses in a single location -> not realistic for quadrupoles: distributed losses

Losses do not happen mainly in a primary collimator

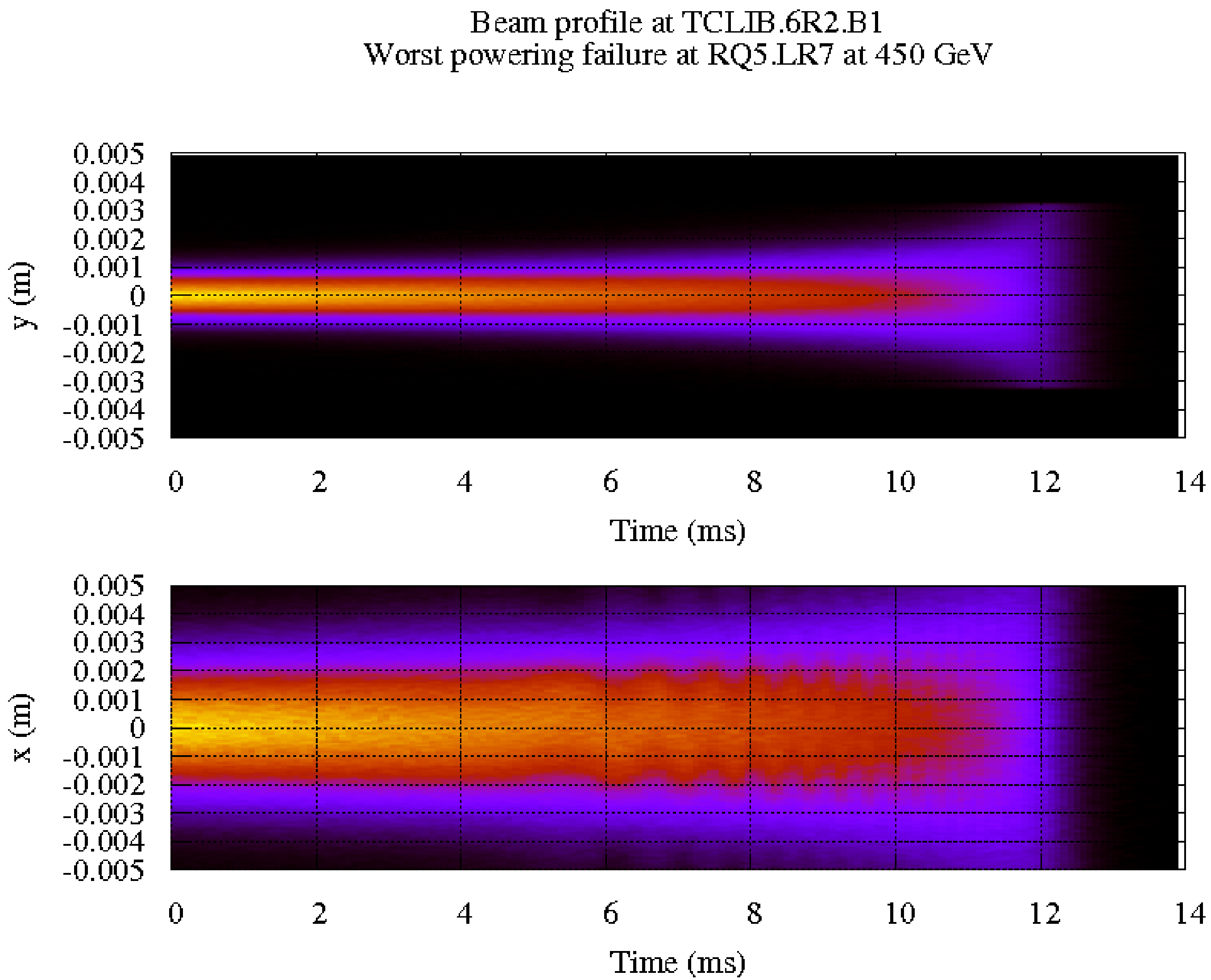
Tune shift not considered in the study



Profile: dipole failure



Profile: quadrupole failure



Outlook

- MAD-X modifications offer a good tool for further loss recording (< 1000 turns is time-reasonable)

- Next simulations to come…
  - *Other critical magnets according to the values obtained from the theoretical study (MBXW, MBXWT, MBX…)*
  - *Groups of circuits - more global powering failures (ex. RQ4 and RQ5 in IR7 fail at the same time)*
  - *Quench of the inner triplets (MQXA/MQXB)*
  - *Addition of statistical alignment and field errors in all the elements, crossing angles, etc.*

- Need of more realistic current decays -> some measurements may be needed here…

Acknowledgements

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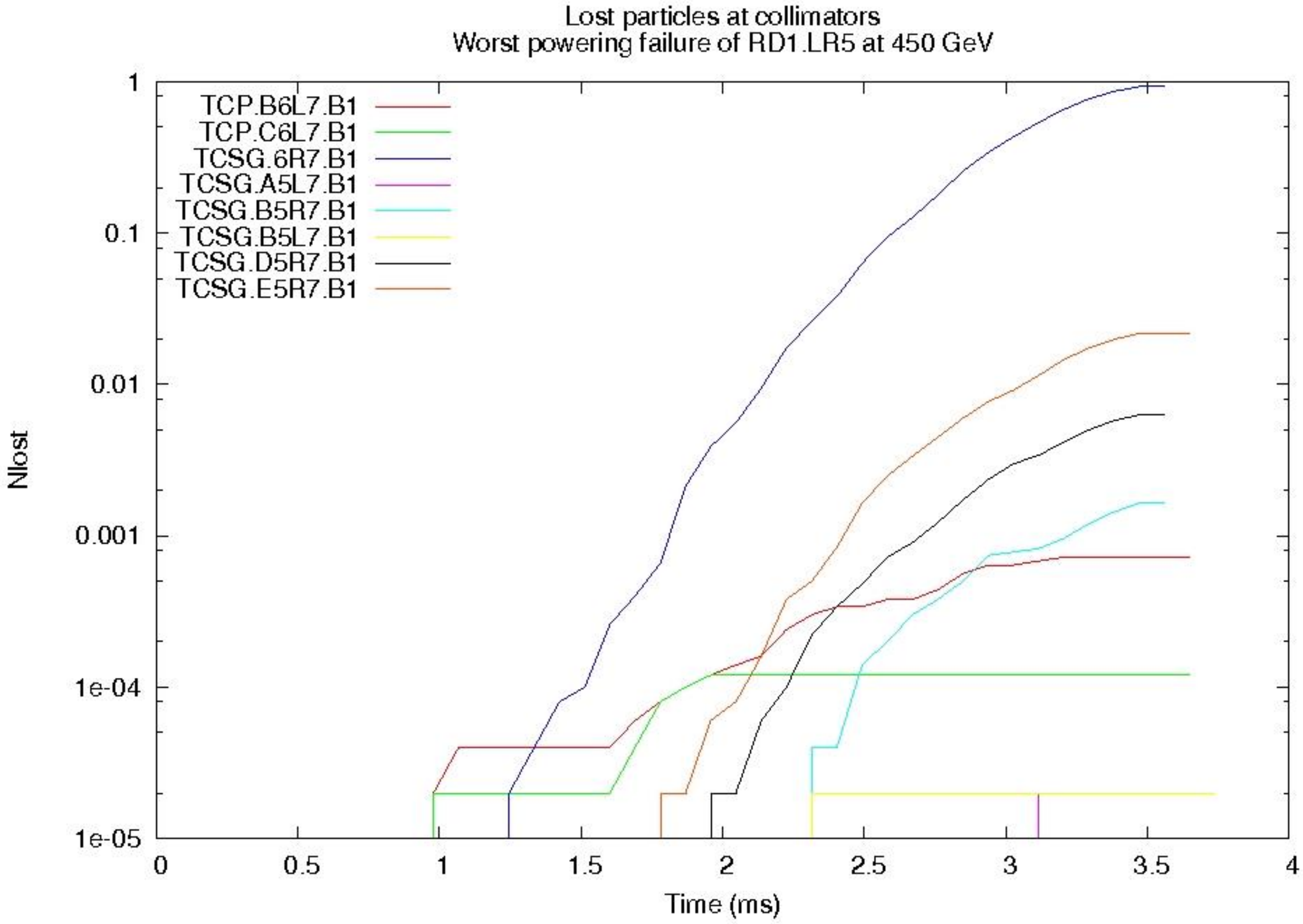
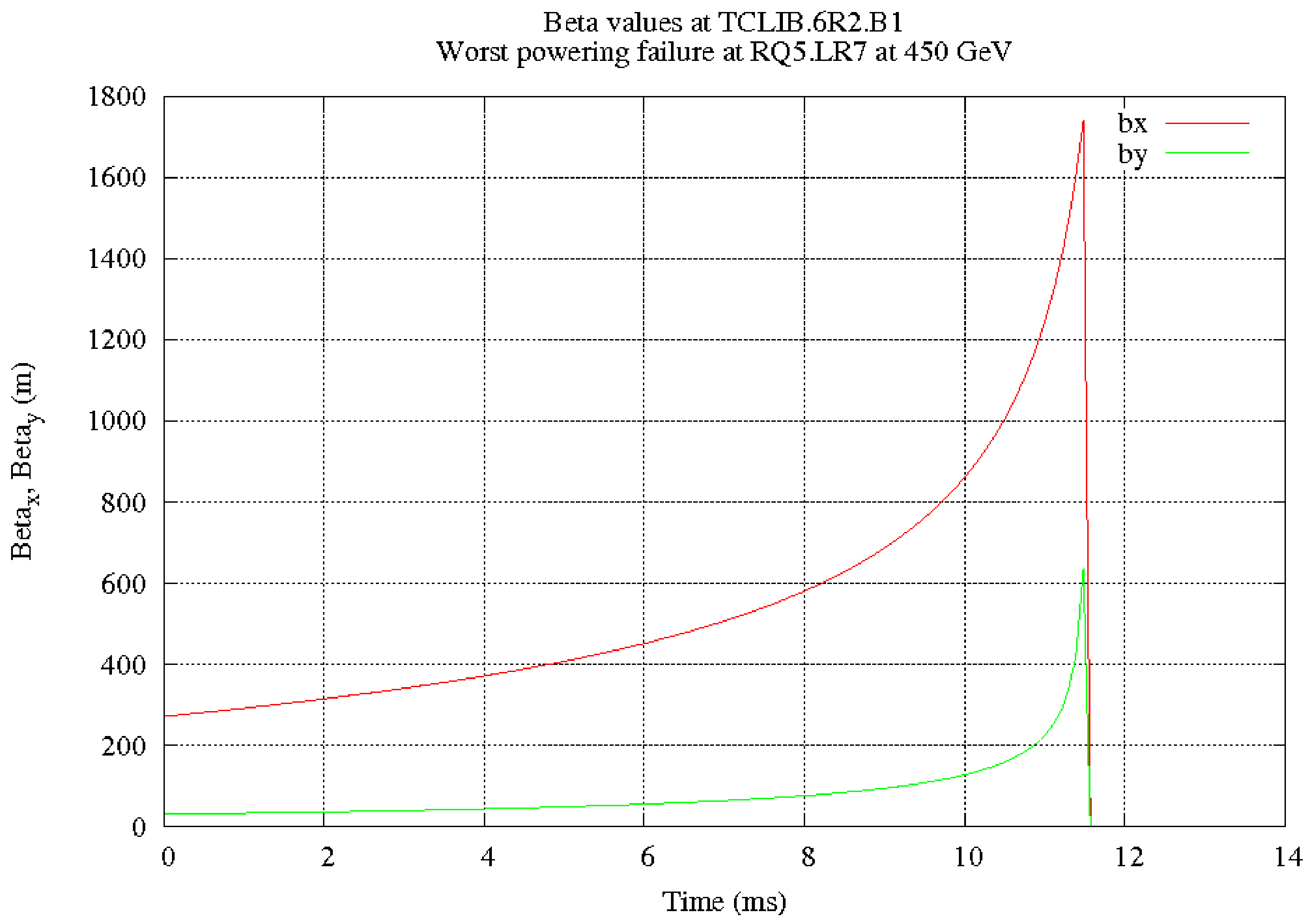
And to **F. Schmidt** and especially **A. Koschik** for their valuable help with MAD-X

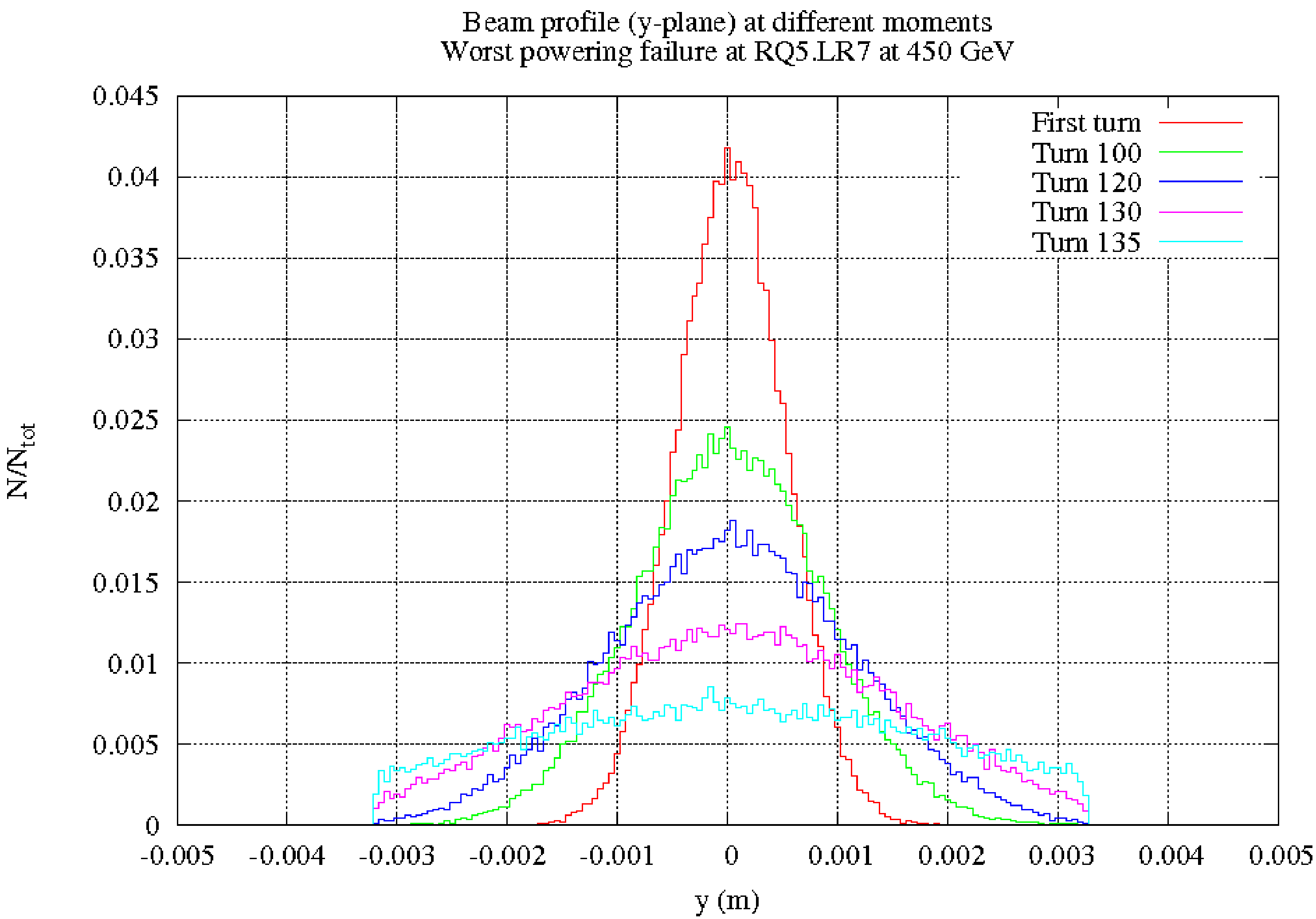
Dipole failure



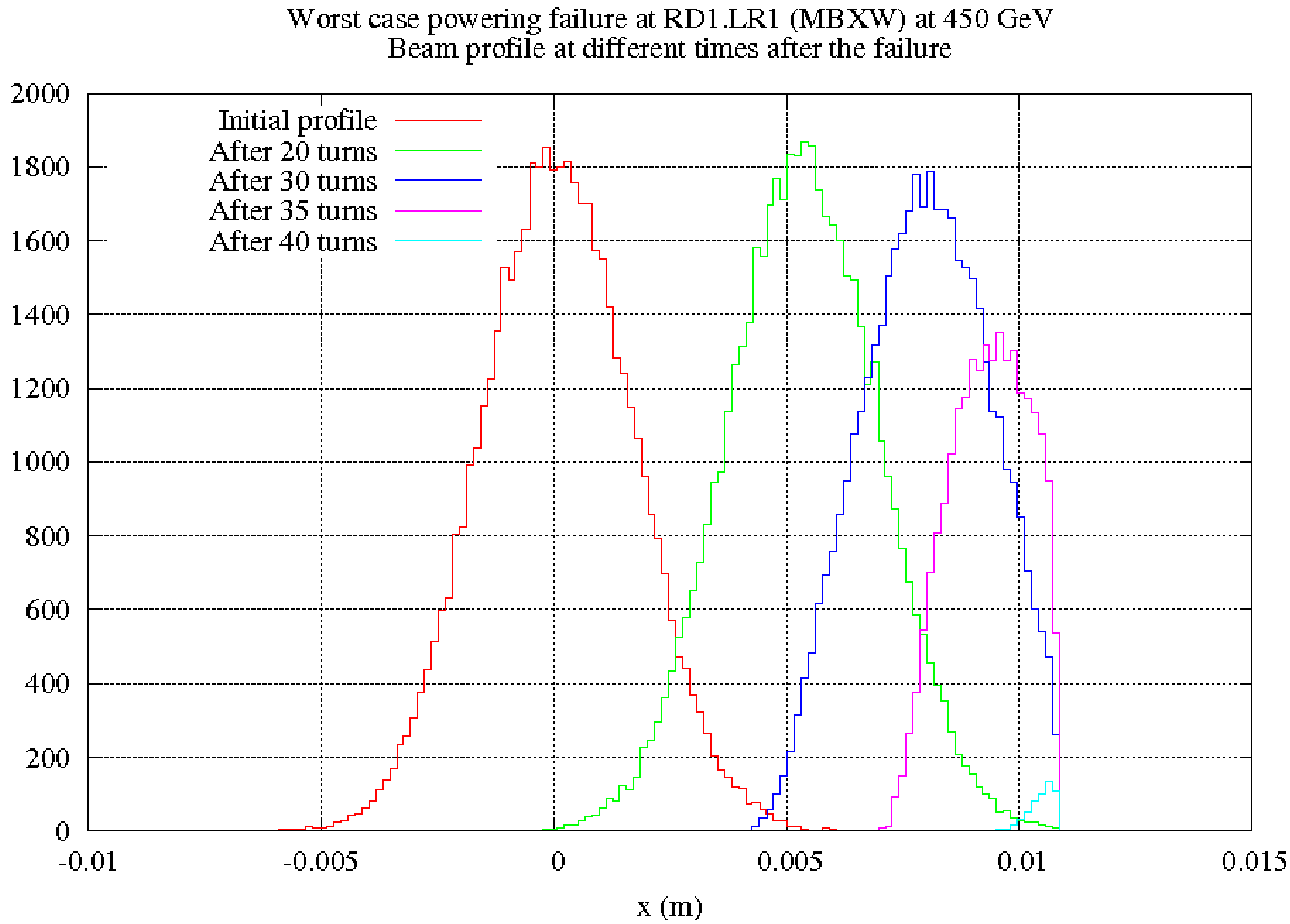
Quadrupole failure



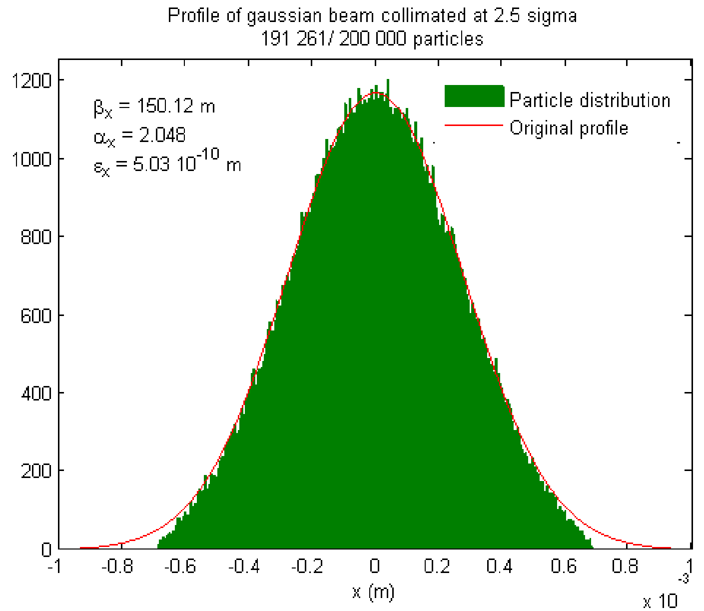
Quadrupole failure

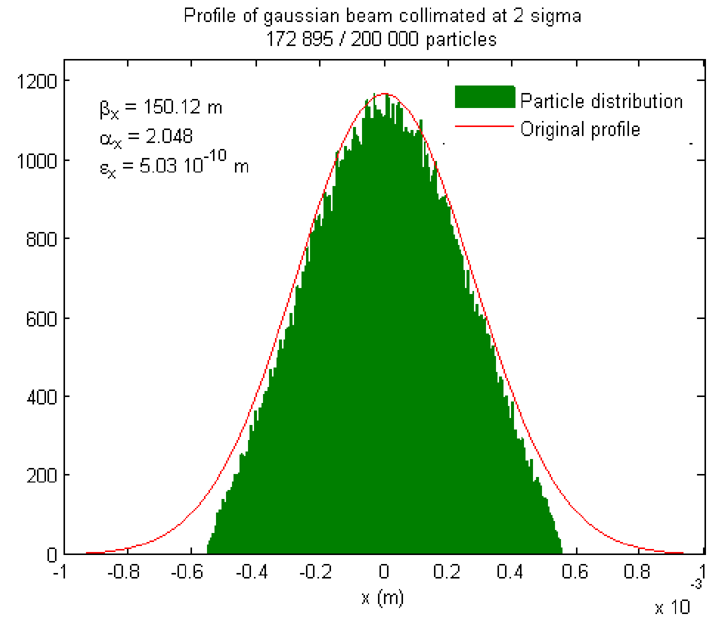


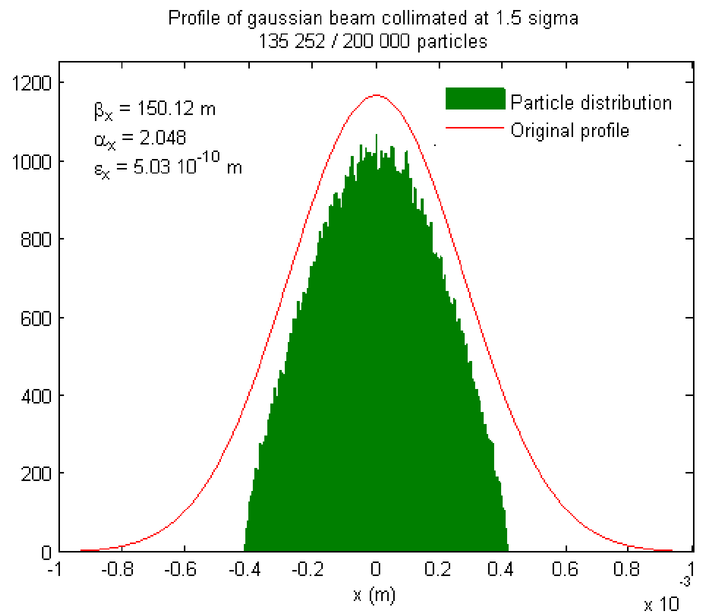
Dipole failure

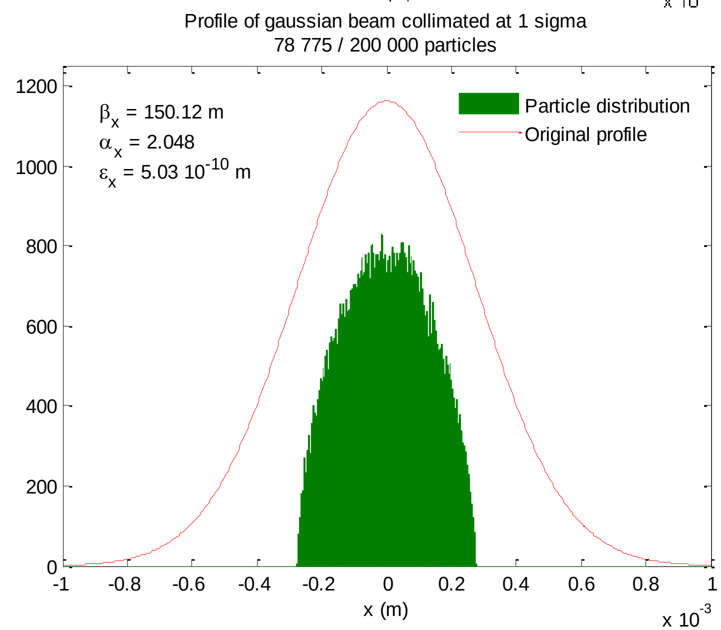


Round cut


Profile of gaussian beam collimated at 2.5 sigma
191 261/ 200 000 particles
β_x = 150.12 m
α_x = 2.048
ε_x = 5.03 10^{-10} m
Particle distribution
Original profile
x (m)
x 10^{-3}


Profile of gaussian beam collimated at 2 sigma
172 895 / 200 000 particles
β_x = 150.12 m
α_x = 2.048
ε_x = 5.03 10^{-10} m
Particle distribution
Original profile
x (m)
x 10^{-3}


Profile of gaussian beam collimated at 1.5 sigma
135 252 / 200 000 particles
β_x = 150.12 m
α_x = 2.048
ε_x = 5.03 10^{-10} m
Particle distribution
Original profile
x (m)
x 10^{-3}


Profile of gaussian beam collimated at 1 sigma
78 775 / 200 000 particles
β_x = 150.12 m
α_x = 2.048
ε_x = 5.03 10^{-10} m
Particle distribution
Original profile
x (m)
x 10^{-3}

Theoretical study (II)

Time calculations for MB powering failures

	Time for $\Delta x = x_m$ (1)
Max ΔV at PC	$t = -\frac{L}{R}\ln\left(1 - \frac{2\sin(\pi Q)Ex_m}{\sqrt{\beta_{ap}\beta_{fail}}ecB_0 l\left(\Delta V / V_0\right)}\right)$
Constant *dI/dt*	$t = \frac{2\sin(\pi Q)Ex_m I_0}{\sqrt{\beta_{ap}\beta_{fail}}ecB_0 l\left(\frac{dI}{dt}\right)}$

Δx for N_{lost} (2):

$$\Delta x = F^{-1}\left(\frac{Nlost}{Ntot};0,\sigma_x\right) + x_{ap}$$

(1) x_m set to a convenient value ($N\sigma$ or such that a N_{lost} particles hit the collimator)

(2) $N_{lost} = 1.1*10^{11}$. Number of particles in a bunch $F^{-1}(x;\mu,\sigma)$ is the inverse cumulative Gaussian function

Theoretical study (III)

Time calculations for MQ powering failures

	$\Delta Q = \Delta Q_{min}$	$\Delta\beta/\beta = (\Delta\beta/\beta)_{min}$
Max ΔV at PC	$t = -\frac{L}{R}\ln\left(1 - \frac{4\pi\Delta Q_{\min}}{K_0 l \beta_{fail}\frac{\Delta V}{V_0}}\right)$	$t = -\frac{L}{R}\ln\left(1 - \frac{2\sin(2\pi Q)\left(\frac{\Delta\beta_{ap}}{\beta_{ap}}\right)_{\min}}{K_0 l \beta_{fail}\frac{\Delta V}{V_0}}\right)$
Constant dI/dt	$t = \frac{4\pi I_0 \Delta Q_{\min}}{K_0 l \beta_{fail}\frac{dI}{dt}}$	$t = \frac{2\sin(2\pi Q) I_0 \left(\frac{\Delta\beta_{ap}}{\beta_{ap}}\right)_{\min}}{K_0 l \beta_{fail}\frac{dI}{dt}}$

$\Delta\beta/\beta$ for N_{lost}

$$\frac{\Delta\beta}{\beta} = \left(\frac{6\sigma}{\sigma F^{-1}\left(\frac{Nlost}{2Ntot};0,1\right)}\right)^2 - 1$$

Theoretical study (I)

Bending magnets

Deflection angle $$\theta_{kick} = \frac{ec}{E} l \Delta B = \frac{ec}{E} B_0 l \left(\frac{I(t)}{I_0} - 1 \right)$$

Offset at position s $$\Delta x(s) \leq \frac{1}{2\sin(\pi Q)} \sqrt{\beta_s \beta_{fail}} \theta_{kick}$$

Quadrupoles

Tune shift $$\Delta Q = \frac{k_0 l \beta_{fail}}{4\pi} \left(\frac{I(t)}{I_0} - 1 \right)$$

Beta beating $$\frac{\Delta \beta_s}{\beta_s} \leq \frac{k_0 l \beta_{fail}}{2\sin(2\pi Q)} \left(\frac{I(t)}{I_0} - 1 \right)$$