Fast Beam Losses due to Equipment Failures

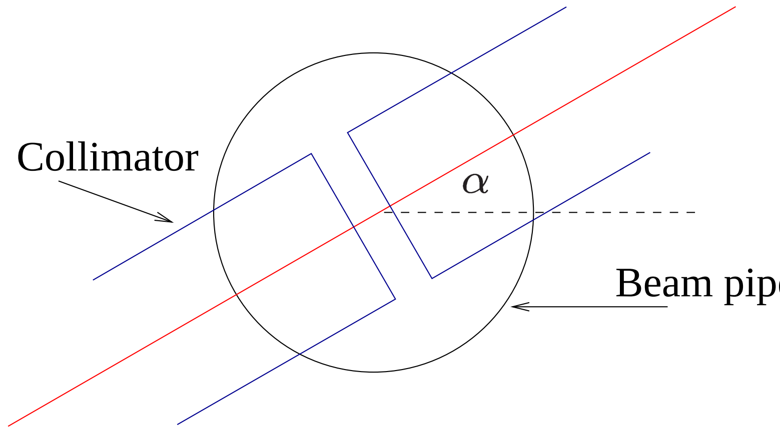
- Introduction: Beam Loss, Collimation
- Magnetic Field Errors: Dipole Field Errors
- Time depending field errors: particle tracking
- D1 separation magnets, main dipole magnets

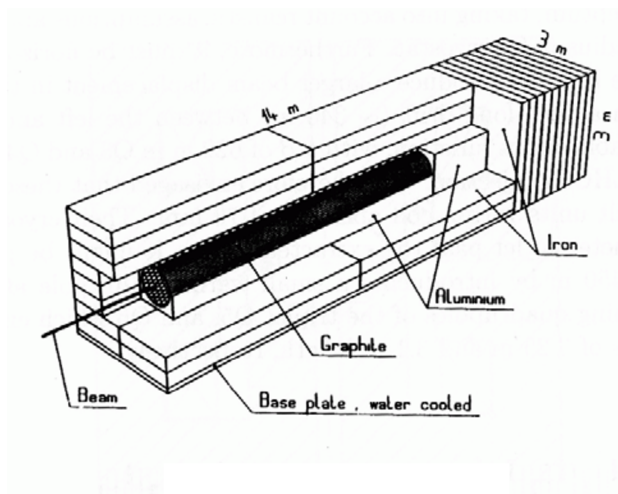
Beam Losses in the LHC

- **continuous** beam loss:
  - proton-proton collisions
  - beam-gas collisions

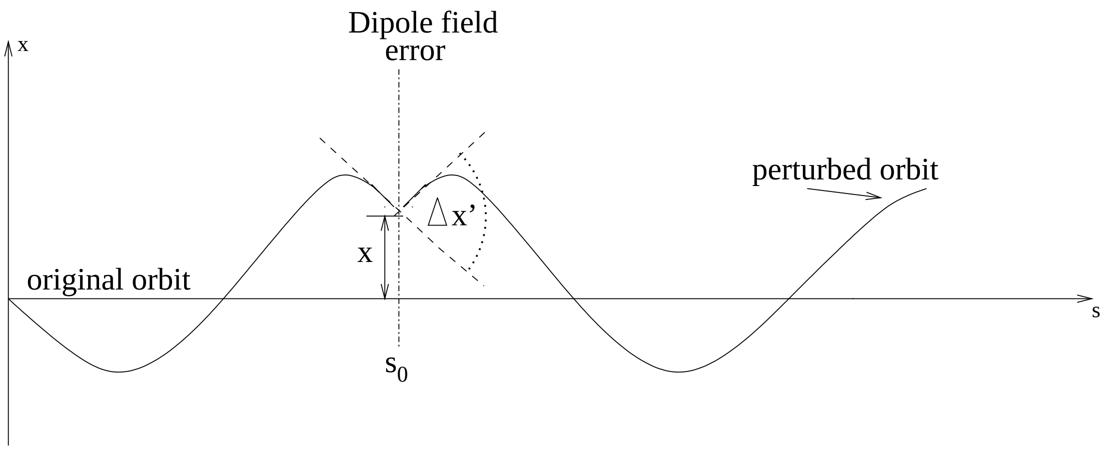
  Outside the insertions: expected loss rate $\sim 2.4 \cdot 10^9$ p/s

- **irregular** beam loss: Equipment failures, operational errors → significant reduction of **Beam Lifetime**.





Dipole Field Errors



Dipole Field Errors → Orbit Distortions.

$$\Delta x' = \frac{e}{p} \cdot \Delta B \cdot l$$

The **perturbed orbit** depends on

- the error kick at s_0
- the lattice functions at s_C and s_0: beta-function, phase-advance-difference
- the tune Q

If the field error is constant or slowly changing in time, the **equilibrium solution** of the **perturbed orbit** reads:

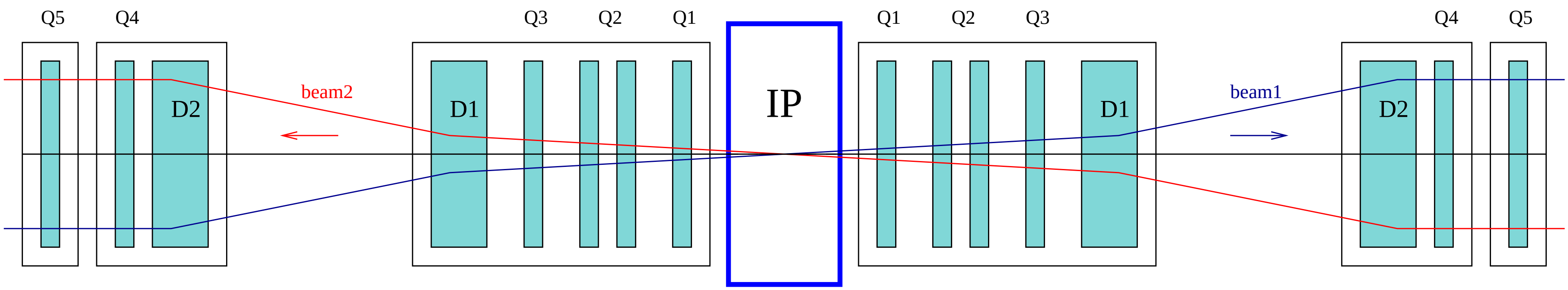
$$x(s_C) = \frac{\Delta x'}{2} \cdot \sqrt{\beta_0 \beta_C} \cdot \frac{\cos(\pi Q - \psi_{s_0 \to s_C})}{\sin(\pi Q)}$$

Slowly changing field: $\Delta x' \rightarrow \Delta x'(t)$

Magnet Failures: $B(t) \sim I(t)$

- power converter fault or power abort: $I(t) = I_{max} \cdot e^{-\frac{t}{\tau}}$, $\tau = \frac{L}{R}$
  $\rightarrow \Delta x'(t) \sim \Delta B(t) \sim (1 - e^{-\frac{t}{\tau}})$
- magnet quench: $I(t) = I_{max} \cdot e^{-\frac{t^2}{2\sigma^2}}$, $\sigma = 200$ ms to 400 ms
  $\rightarrow \Delta x'(t) \sim \Delta B(t) \sim (1 - e^{-\frac{t^2}{2\sigma^2}})$

Short Time Constants



For **warm magnets** the **time constant** τ can be very **small**:

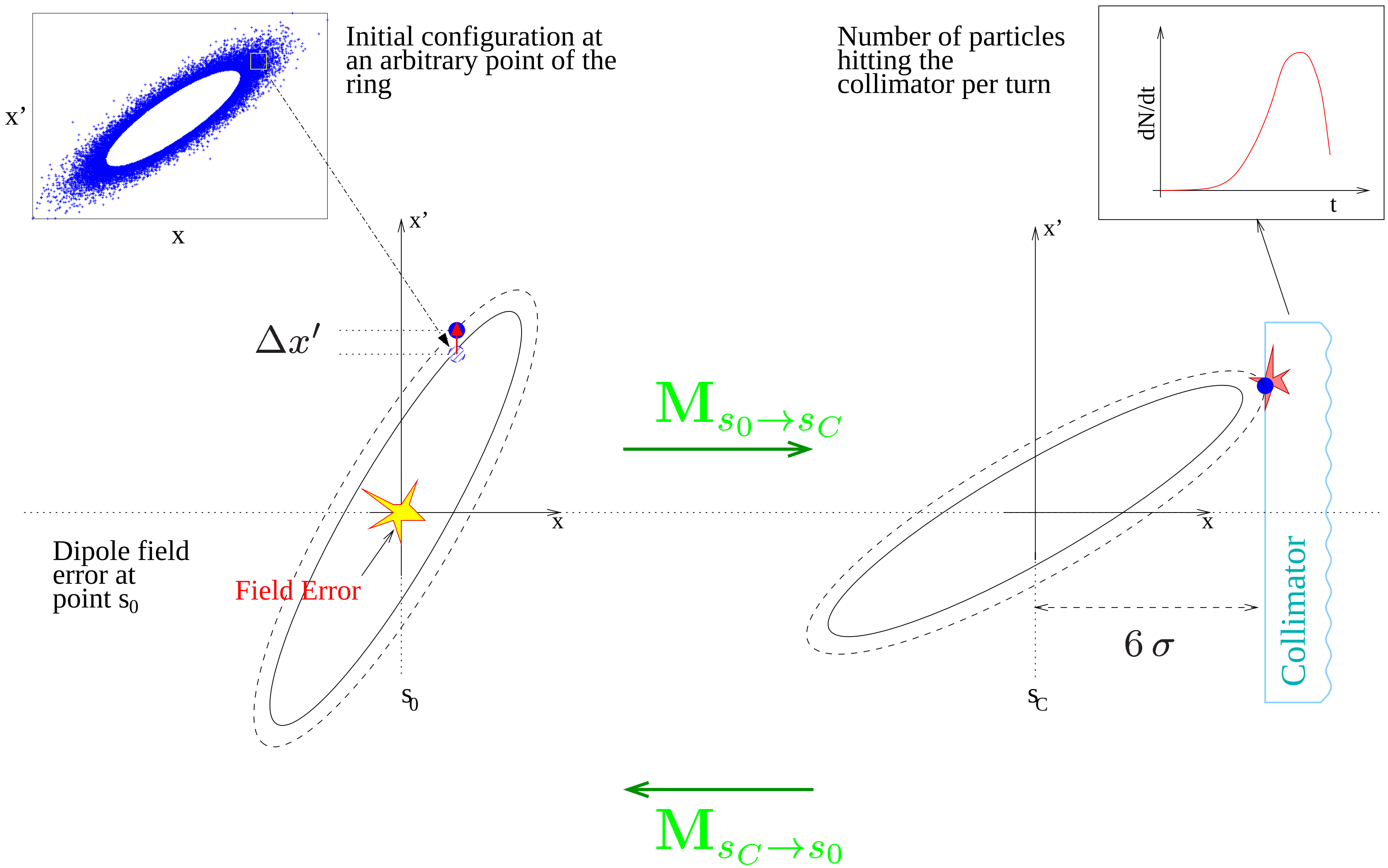
warm D1 separation dipoles: 2.53 s

More accurate result than with orbit formula above:

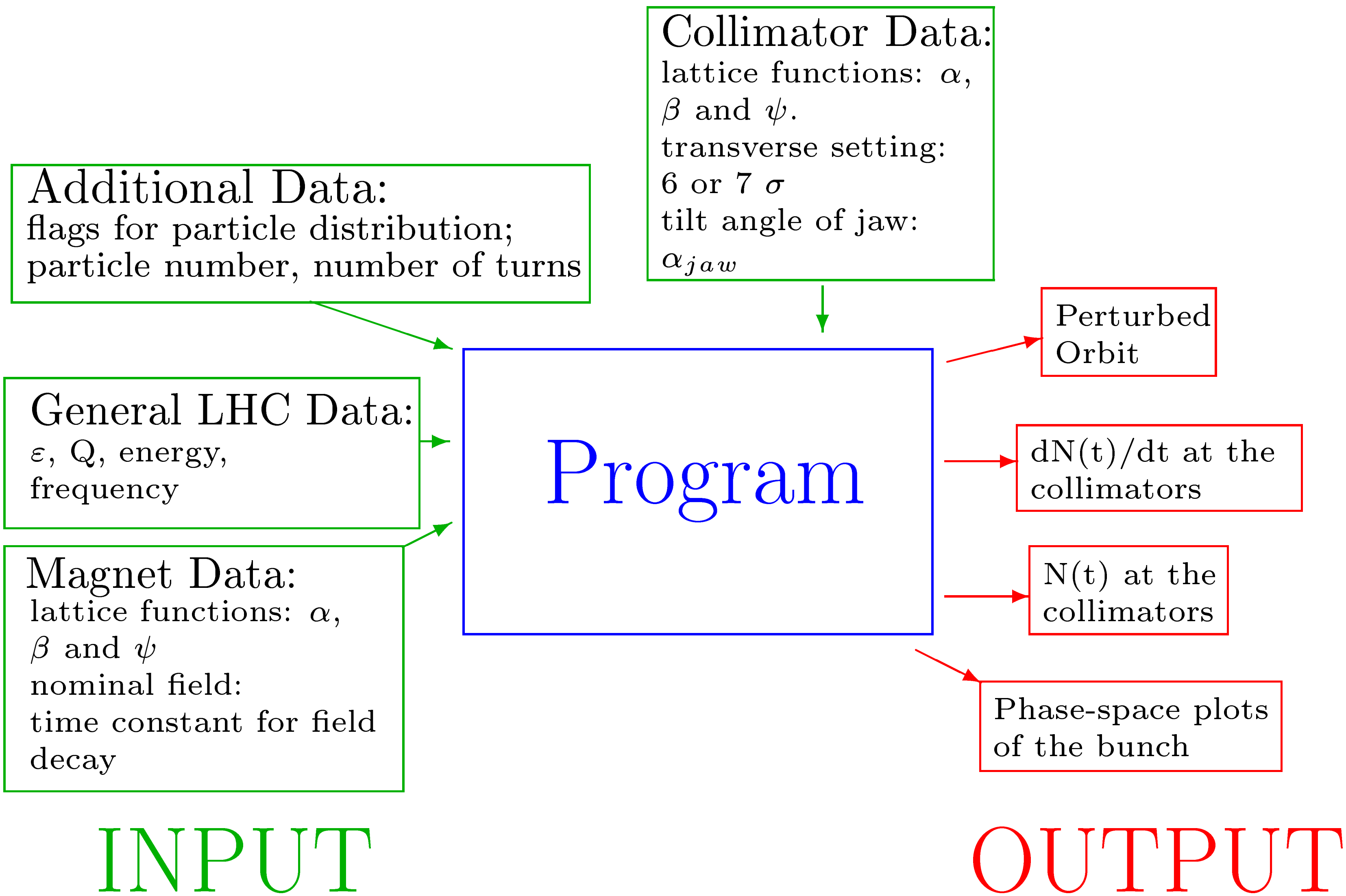
$\rightarrow$ Multi-particle Tracking

Calculating the actual impact on the beam turn by turn in terms of beam loss.

What does the tracking program?



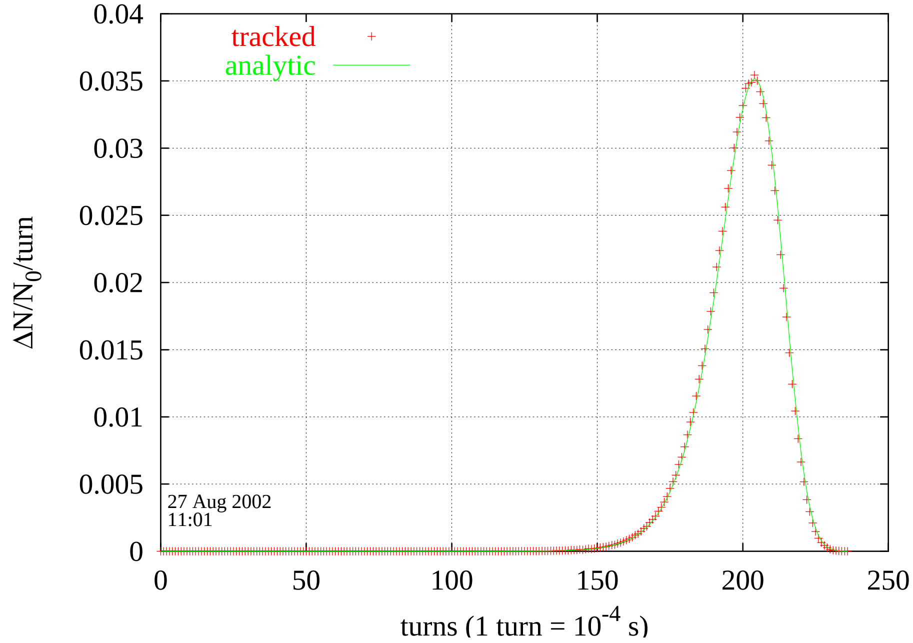
Input and Output of the Tracking Program



Quenches of the D2 Separation Dipoles

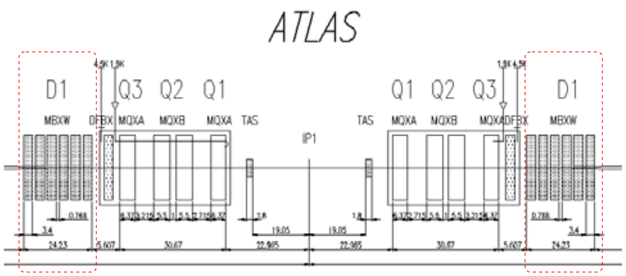
D2 of	@	$10^{-5} \cdot N_0$ [turns]	$3.5 \cdot 10^{-4} \cdot N_0$ [turns]
IP1,L	2	78	121
IP1,R	2	147	183
IP2,L	2	114	141
IP2,R	2	112	136
IP5,L	2	103	129
IP5,R	2	153	196
IP8,L	13	175	206
IP8,R	2*	157	203

Nominal field 2.74 T, magnetic length 9.45 m.

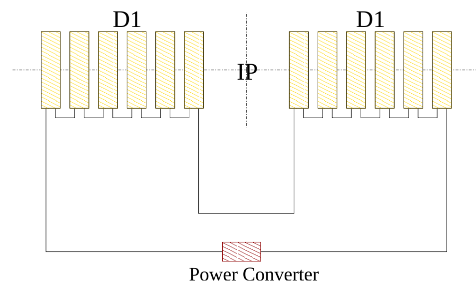


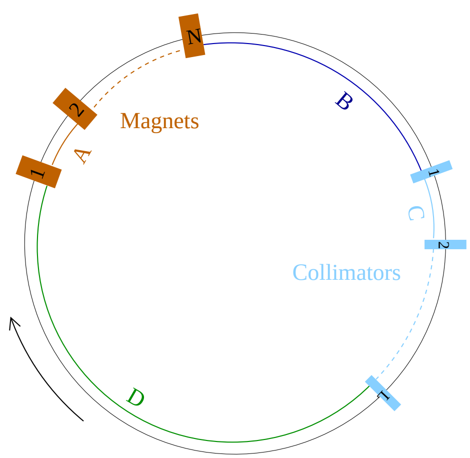
The D1 Separation Dipoles

Warm D1 magnets at the high luminosity experiment insertions

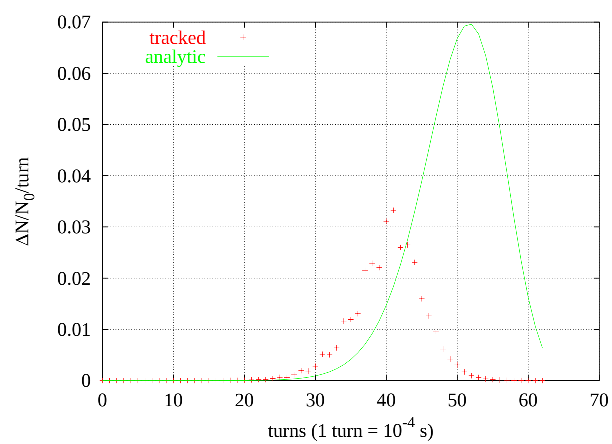


The 12 magnets are powered in series.





Tracking delivers more reliable results.



Results of D1 failures, Parameters

- particle energy: 7 TeV
- number of particles: $N_0 = 10^6$, Gaussian bunches
- time constants: quench $\sigma = 0.2$s; power converter failure $\tau_{cold} = 31.7\,$s, $\tau_{warm} = 2.53\,$s

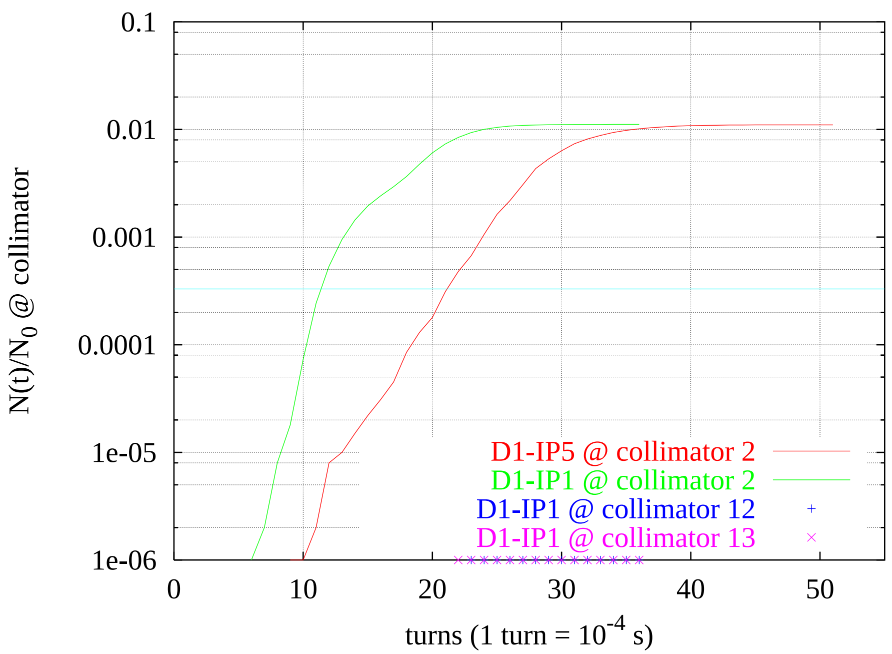
Parameters at operating temperature – MBX		
Nominal field (at 7 TeV)	3.8	T
Nominal current	5800	A
Magnetic length	9.45	m
Parameters at operating temperature – MBXW		
Nominal field (at 7 TeV)	1.38	T
Nominal current	770	A
Magnetic length	3.4	m

Results of cold D1 failures

D1 of		@	$10^{-5} \cdot N_0$ [turns]	$3.5 \cdot 10^{-4} \cdot N_0$ [turns]
IP2,L	powering failure	2	151	237
	quench	2	73	88
IP2,R	powering failure	2	157	235
	quench	2	68	88
IP8,L	powering failure	13	425	530
	quench	13	115	132
IP8,R	powering failure	13	595	752
	quench	13	134	157

Results of warm D1 failures

D1 of	@	$10^{-5} \cdot N_0$ [turns]	$3.5 \cdot 10^{-4} \cdot N_0$ [turns]
IP1	2	8	11
IP5	2	13	21



At starting point of beam loss:

- orbit change at the collimator: $\sim 1.3\,\sigma \sim 0.3\,\mathrm{mm}$
- after 5 turns: $\Delta I/I_0 = 0.0002$

At 450 GeV: a failure would lead to beam loss after $\sim$ 120 turns.

Results for Beam Loss while Main Dipole Failures

The 154 MBs per sector are powered in series.

Time constant τ for fast power abort: **100 s**

Two cases were studied:

1. all 154 MBs quench ($\sigma = 0.2\,\mathrm{s}$)
2. quench ($\sigma = 0.2\,\mathrm{s}$) of one MB followed by a power abort ($\tau = 100\,\mathrm{s}$)

Parameters at operating temperature – MB		
Bending radius	2803.928	m
Nominal current	11796	A
Bending angle	5.1	mrad
Field at 7 TeV	8.33	T
Magnetic length	14.3	m

MBs of	case 1			case 2		
		$10^{-5} \cdot N_0$	$3.5 \cdot 10^{-4} \cdot N_0$		$10^{-5} \cdot N_0$	$3.5 \cdot 10^{-4} \cdot N_0$
	@	[turns]	[turns]	@	[turns]	[turns]
IP1-IP2	2	78	103	13	151	173
IP2-IP3	13	44	50	13	77	90
IP3-IP4	13	43	49	13	78	90
IP4-IP5	2	260	324	2	148	180
IP5-IP6	13	117	133	2	87	130
IP6-IP7	2	143	182	13	124	144
IP7-IP8	13	110	132	13*	156	186
IP8-IP1	2	185	250	2	88	109

Consequences for Machine Protection

- Fastest losses at collimators occur after 5 to 10 turns for powering failure of warm D1 magnets.
- For D1 powering failure: after starting point of beam loss at collimators there are only 5 to 10 turns left until damage threshold of collimators is reached. $\rightarrow$ BLMs and beam dump system must be fast.
- Other methods for triggering beam dump? Failure of MBs: beam loss starts after $\sim$ 40 turns. Then damage threshold of collimators is quickly reached (worst case: $\sim$ 10 turns). Using quench detection for triggering beam dump?

Remaining Questions

- Vertically kicking dipole magnets: corrector magnets: short time constants?
- Thunder storm: power abort for all circuits in the LHC.
- etc.