Outlook on Future Hydrodynamic-Tunnelling Studies and Scope of Discussion

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Workshop on coupling simulation of beam impact on accelerator components

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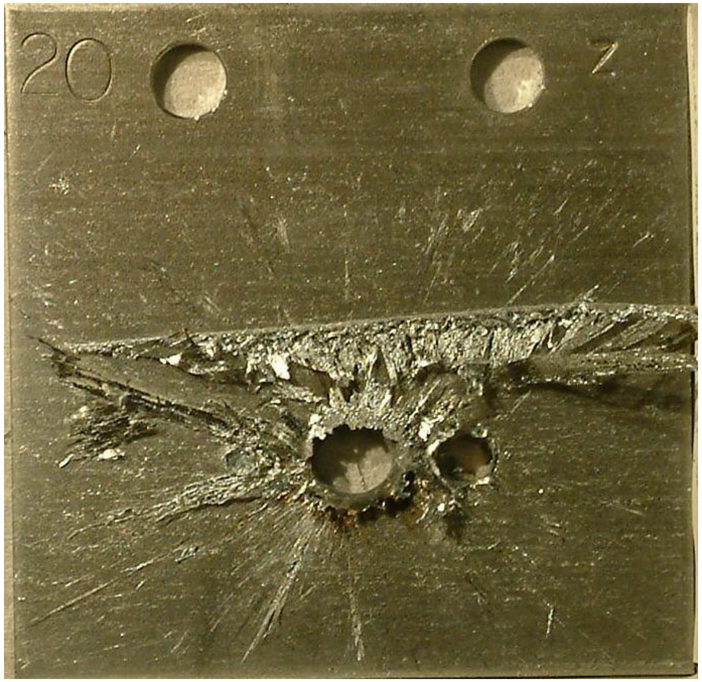
Outline

1) Introduction
2) Failures cases and previous studies
3) Possible future hydrodynamic-tunnelling studies
4) Questions for discussion

Introduction

- Evaluation of machine protection functionality requires estimate of failure *consequences*
- For *extreme failure cases* this might require hydrodynamic-tunnelling studies
- Extreme failure cases are usually *“beyond-design failures”*

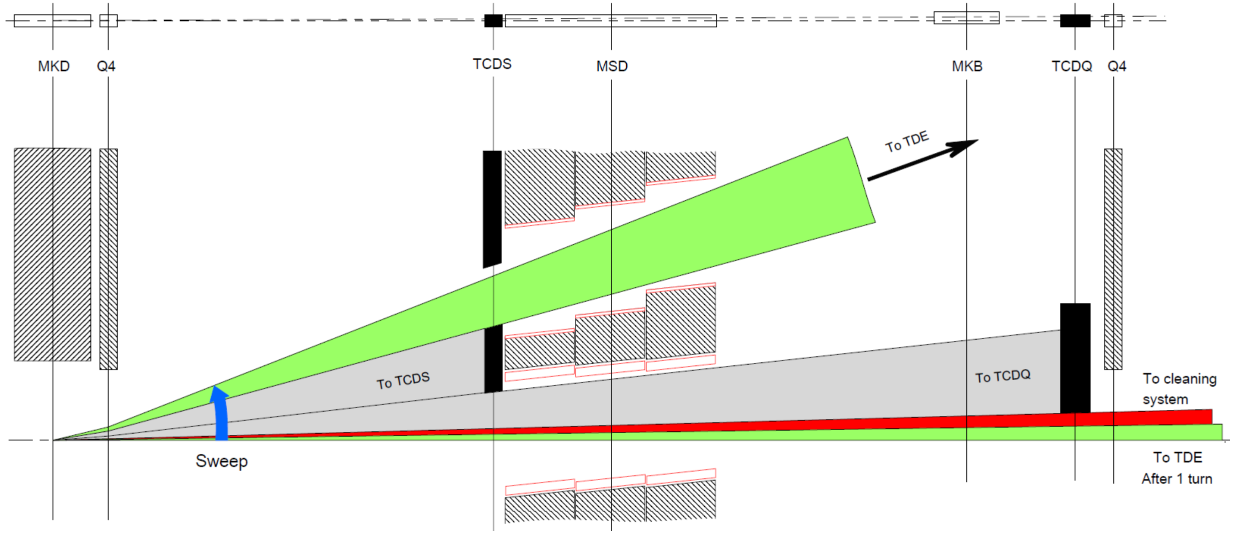


Beam damage experiment, SPS beam, 2004, V. Kain/R. Schmidt

LBDS failure cases

"Acceptable (Design) Fault Cases"	"Unacceptable (Beyond Design) Fault Cases"
Asynchronous beam dump	MKDs not firing upon request
One missing extraction kicker (MKD)	Wrong energy information in BETS → beam can impact on machine/TCDQ
Missing dilution kicker	Complete dilution failure with high-intensity beam
…	…

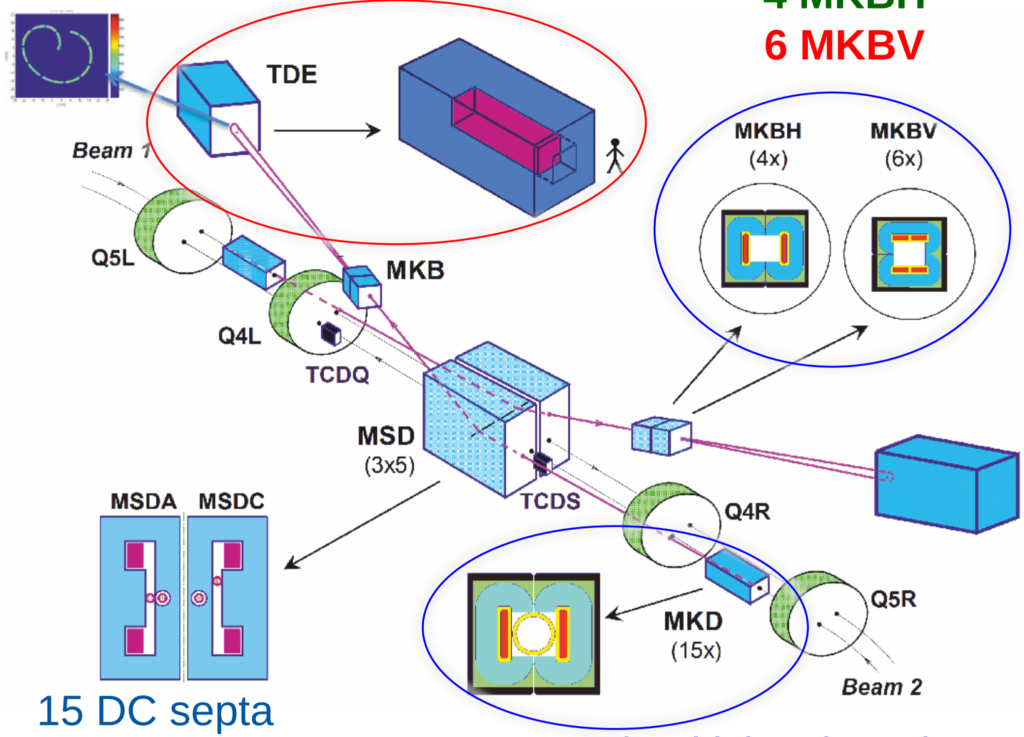
[LHC Design Report, Chap. 17]



LHC dilution system

Beam dump (TDE)

Dilution Kicker:
4 MKBH
6 MKBV

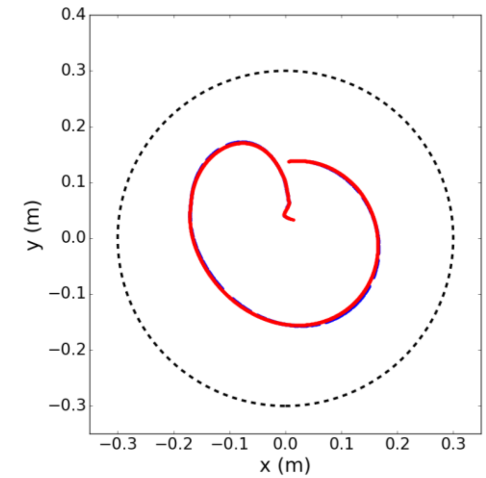


15 DC septa magnets (MSD)

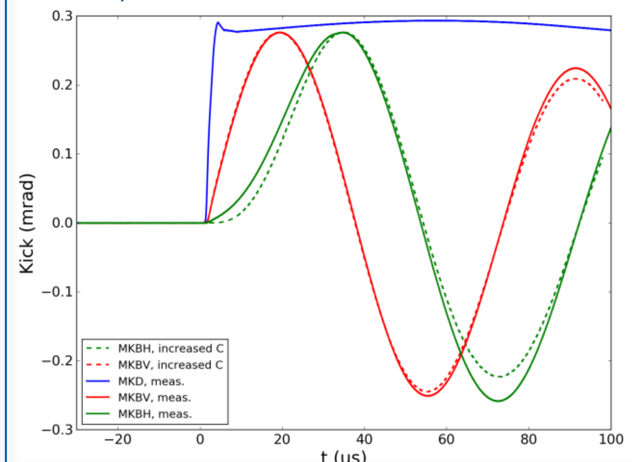
15 extraction kicker (MKD)

C. Bracco et al., LHC Performance Workshop, Chamonix, 26/01/2016

Nominal dilution pattern

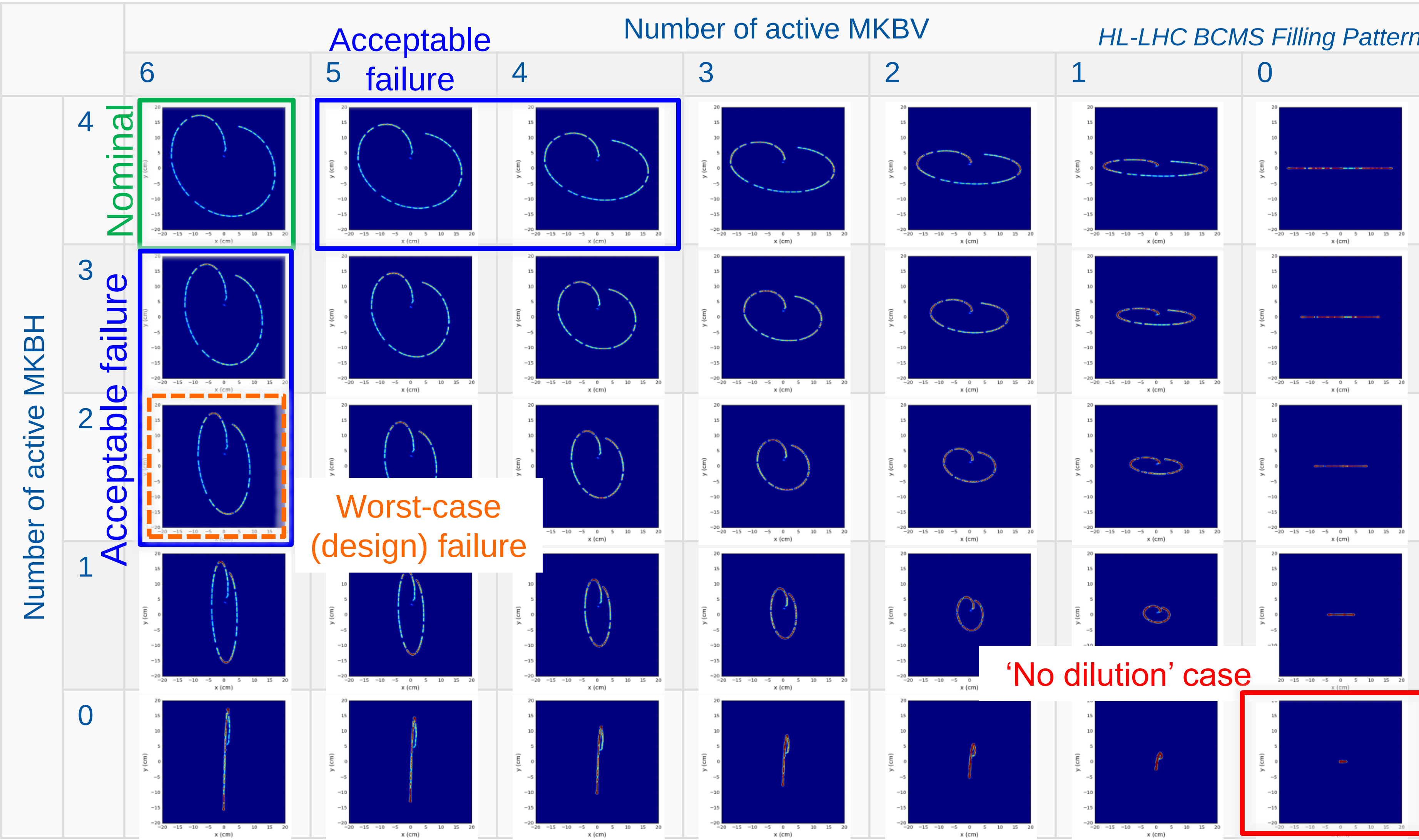


MKD, MKBH and MKBV waveforms



Dilution failures

- Worst case (design) failure: high-voltage flashover of 2 MKBH
- Failure beyond design: complete loss of dilution



For the discussion of a new potential worst-case dilution failure see C. Wiesner et al., 170th MPP, 28.9.2018

Dilution failures: energy deposition

- Peak energy deposition in LHC dump core:

STD

kJ/g		number active MKBV						
		6	5	4	3	2	1	0
number active MKBH	4	3.20	3.28	3.42	4.34	5.94	9.18	15.77
	3	4.02	4.08	4.20	4.50	6.18	9.87	18.22
	2	5.34	5.45	5.59	5.81	6.62	10.84	22.15
	1	7.86	8.17	8.54	9.03	9.70	13.30	32.46
	0	15.11	16.42	18.29	21.17	26.15	37.92	107.31

Worst-case (design) failure

'No dilution' case

- Corresponding maximal temperature increase:

STD

K		number active MKBV						
		6	5	4	3	2	1	0
number active MKBH	4	1827	1865	1931	2358	>3000	>3000	>3000
	3	2211	2237	2294	2432	>3000	>3000	>3000
	2	2807	2859	2922	>3000	>3000	>3000	>3000
	1	>3000	>3000	>3000	>3000	>3000	>3000	>3000
	0	>3000	>3000	>3000	>3000	>3000	>3000	>3000

Worst-case (design) failure

'No dilution' case

	STD
$\epsilon^n_{x,y}$	2.08 μm·rad
I_b	2.3×10^{11}
Filling Scheme	R3-STD
Nominal beam intensity	6.32×10^{14} p+

FLUKA calculations from: *M. Frankl, Energy deposition table for dilution failures, LIBD, 20.6.2017*

Previous studies

- HiRadMat experiment: **440 GeV**, p+ on **copper** target
  - Hydrodynamic tunnelling simulated with FLUKA+BIG2 and with FLUKA+Autodyn
  - Good agreement between experiment and both hydrodynamic codes

[F. Burkart]

TABLE I. Summary of hydrodynamic tunneling studies for the SPS, the LHC, and the FCC.

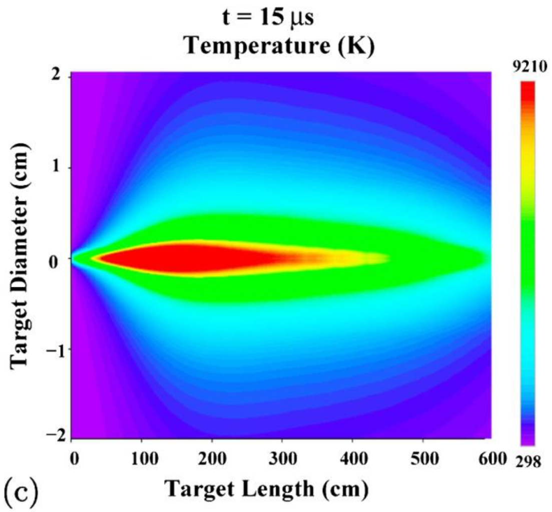
Accelerator	Proton energy	Bunch number	Bunch intensity	Bunch separation	rms beam size	Target material	Tunneling range	Source	
SPS	440 GeV	108	1.5×10^{11}	50 ns	0.2 mm	Copper	0.8 m	Simulation [23]	
SPS	440 GeV	108	1.5×10^{11}	50 ns	0.2 mm	Copper	0.795 m	Experiment [24,25]	
SPS	440 GeV	144	1.5×10^{11}	50 ns	0.2 mm	Copper	0.9 m	Simulation [23]	BIG2 Autodyn
SPS	440 GeV	144	1.5×10^{11}	50 ns	0.2 mm	Copper	0.85 m	Experiment [24,25]	
SPS	450 GeV	288	1.1×10^{11}	25 ns	0.088 mm	Copper	1.3 m	Simulation [11]	
SPS	440 GeV	288	1.15×10^{11}	25 ns	0.2 mm	Copper	1.1 m	Simulation [22]	
SPS	440 GeV	288	1.15×10^{11}	25 ns	0.5 mm	Copper	0.85 m	Simulation [18,22]	
LHC	7 TeV	2808	1.15×10^{11}	25 ns	0.2 mm	Copper	35 m	Simulation [13,17]	
LHC	7 TeV	2808	1.15×10^{11}	25 ns	0.5 mm	Graphite	25 m	Simulation [18]	BIG2
FCC	40 TeV	10600	1.0×10^{11}	25 ns	0.2 mm	Copper	290 m	Simulation [27]	
FCC	50 TeV	10600	1.0×10^{11}	25 ns	0.2 mm	Copper	350 m	Simulation [27]	

Y. Nie et al., PRAB 20, 081001 (2017)

Possible future studies I

1st study: 7 TeV Benchmark with LHC parameters

- Simulation already performed using FLUKA+BIG2
- → Repeat using FLUKA+Autodyn



Temperature distribution calculated with BIG2 for a 7 TeV LHC beam on a carbon target
[N. A. Tahir et al., PRSTAB 15, 051003 (2012)]

Simulation parameters:

- **7 TeV**, 2808b, **1.15e11 ppb**, $\sigma_x = \sigma_y = 0.5$ mm (2d case)
- **Graphite** target (r = 5 cm, l = 6 m, density 2.28 g/cm^3)

Goal:

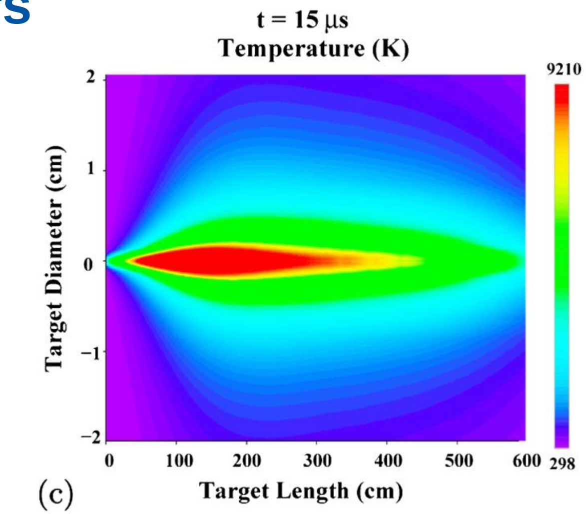
- Establish 2nd simulation benchmark between BIG2 and Autodyn
- Compare physics results for 7 TeV
- Prepare further simulations

Possible future studies I

1st study: 7 TeV Benchmark with LHC parameters

Required steps:

- Set up FLUKA and Autodyn simulations: MPE-PE, EN-STI, EN-MME, and N. Tahir (GSI)
- Study 'automatized' code coupling: MPE-PE, EN-MME
- Physics interpretation of results, discussion and comparison with BIG2 results, together with N. Tahir (GSI)



Temperature distribution calculated with BIG2 for a 7 TeV LHC beam on a carbon target
[N. A. Tahir et al., PRSTAB 15, 051003 (2012)]

Questions for discussion:

- Benefit of benchmark study at 7 TeV?
- Material properties/EoS for graphite?
- How to efficiently couple energy-deposition and hydrodynamic codes? Use of MpCCI?

Possible future studies II

2nd study: Full beam impact with HL-LHC intensities

Possible simulations parameters

- **7 TeV**, ~**2.3e11** ppb, $\sigma_x = \sigma_y = \sim 1.2$ mm (2d case)
- **Graphite** target (lower density: 1.1 g/cm^3 – 1 .8 g/cm^3 ?)

Goal

- Estimate tunnelling range for impact of full HL-LHC beam on graphite

Possible future studies II

2nd study: Full beam impact with HL-LHC intensities

Required steps:

- Set up FLUKA and Autodyn simulations
- Continue study for ‘automatized’ code coupling
- Physics interpretation of results and discussion, together with N. Tahir (GSI)

Questions for discussion:

- Material properties/EoS for lower density graphite?

Possible future studies III

3rd study: 'No-dilution case' with MKD overshoots

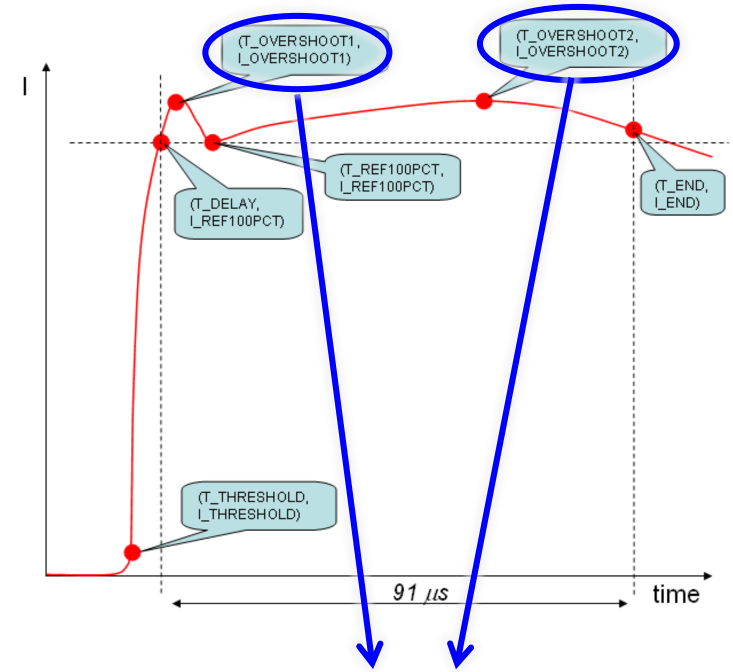
Possible simulation parameters:

- **7 TeV**, ~**2.3e11** ppb, $\sigma_x = \sigma_y = \sim 1.2$ mm
- Different beam impact parameters for each bunch due to MKD deflection (**3d case**)
- **Graphite** target (densities as in TDE)

Goal

- Estimate tunnelling range for impact of 'undiluted' HL-LHC beam on graphite dump

Extraction kicker (MKD) waveform*



MKD overshoots cause horizontal movement of ~2 cm at the dump

*J. Uythoven, Naming of characteristic points of MKD and MKB waveforms, derived quantities and logical tests – Version 2, EDMS No. 910572

Possible future studies III

3rd study: ‘No-dilution case’ with MKD overshoots

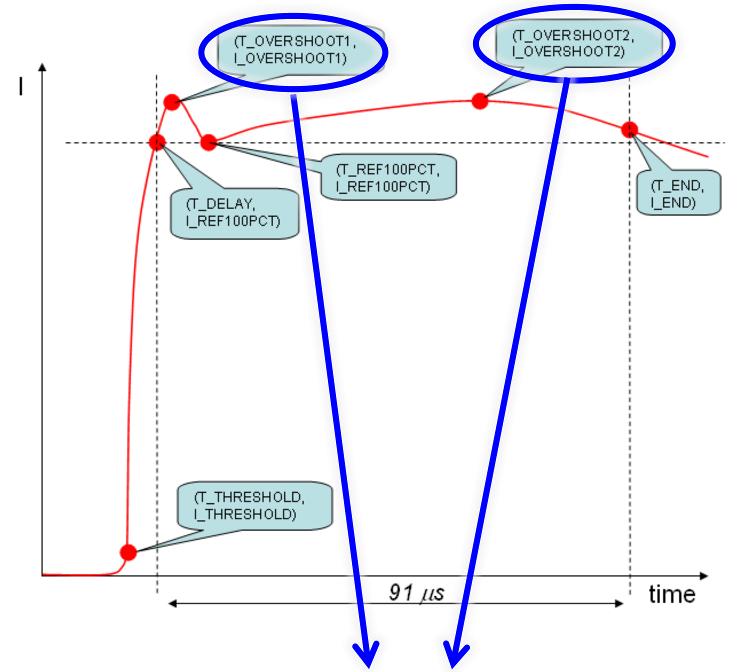
Required steps:

- Agree on simulation parameters: ABT, MPE, EN-STI, …
- Set up FLUKA and Autodyn simulations
- Extend ‘automatized’ coupling to 3d mesh
- Physics interpretation of results and discussion of possible implications

Questions for discussion:

- Material properties/EoS for lower density graphite?

Extraction kicker (MKD) waveform*



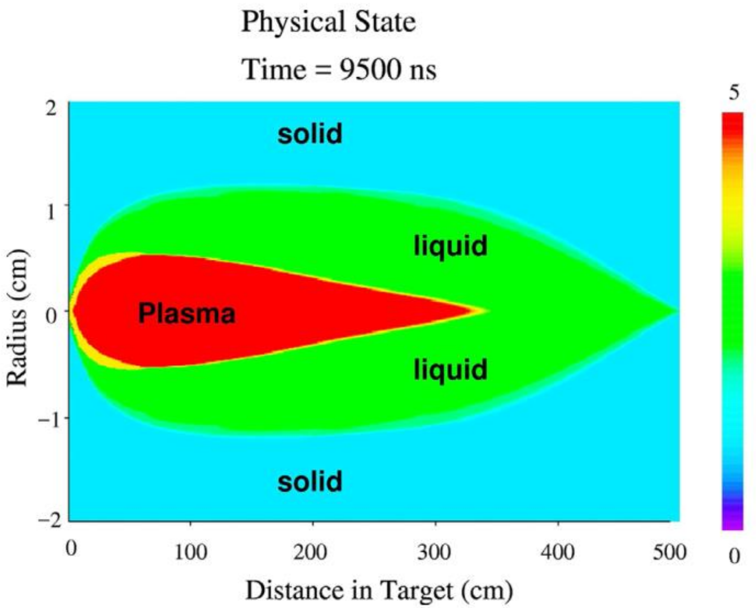
MKD overshoots cause horizontal movement of ~2 cm at the dump

*J. Uythoven, Naming of characteristic points of MKD and MKB waveforms, derived quantities and logical tests – Version 2, EDMS No. 910572

Possible future studies: outlook

Sensitivity studies

- Variation of beam size, beam intensity, material properties?



Physical state of Cu cylinder after impact of 380 LHC bunches, calculated with BIG2 (7 TeV, 1.15e11 ppb, σ = 0.2 mm)
[N.A. Tahir et al., NIM B 427 (2018) 70–86]

Questions for discussion:

- Plasma effects relevant for hydrodynamic tunnelling?
- How to use FLUKA for beam-matter interaction in the regime of plasma?

Questions for discussion

- Do we need a benchmark study BIG2/Autodyn at 7 TeV?
  - *1st study: 7 TeV Benchmark with LHC parameters?*
- Most relevant future studies?
  - *2nd study: Full beam impact with HL-LHC intensities?*
  - *3rd study: ‘No-dilution case’ with MKD overshoots? …*
- How to efficiently couple energy-deposition and hydrodynamic codes? Can MpCCI be used?
- Material properties, equation of state, choice of constitutive models and their influence on results
  - Material properties of graphite? SESAME data base?
- Are there any plasma effects relevant for hydrodynamic tunnelling?
- How to use FLUKA for beam-matter interaction in the regime of plasma?
- …

Thank you for your attention!

LHC Risk Matrix

HL-LHC/ LHC risk matrix		Recovery						
		∞	year	month	week	day	hours	minutes
		S7	S6	S5	S4	S3	S2	S1
Frequency	1 / hour							
	1 / day							
	1 / week							
	1 / month							
	1 / year							
	1 / 10 years							
	1 / 100 years							
	1 / 1000 years							

Risk matrix: J. Uythoven/M. Blumenschein