Bus-Bar Quench Studies

Summary of Available Calculations

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Input from: A. Verweij

Calculations based on the FLUKA Team IR7 Layout

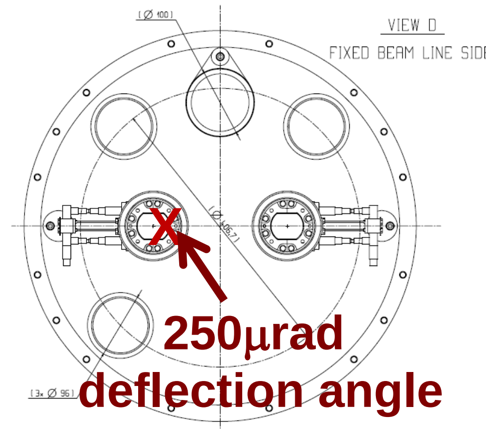
The Studied Cases: Loss Source

General

- Beam-2 case assuming orbit bump at MQ locations
- Two general cases studied for various locations:

(a) Point-like loss in the beam-screen to get peak in the downstream interconnect/empty-cryostat or magnet

(b) assuming a distribution (equal) along the element

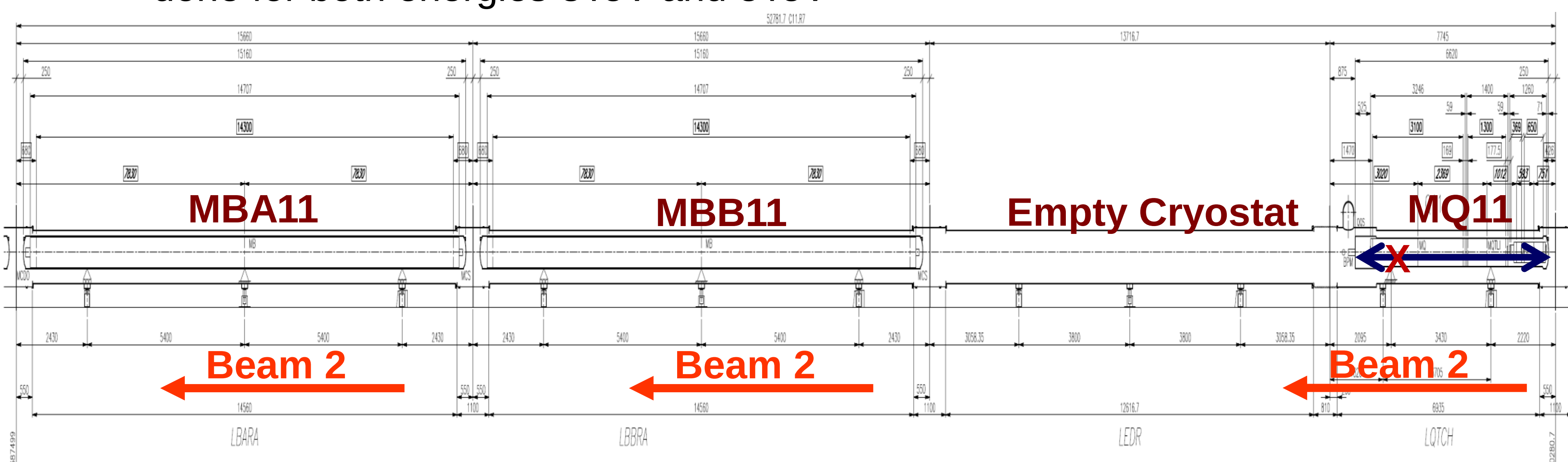


(1) Loss in the Empty Cryostat

- aiming to get peak energy deposition in the empty cryostat and the downstream magnets (5TeV magnets)

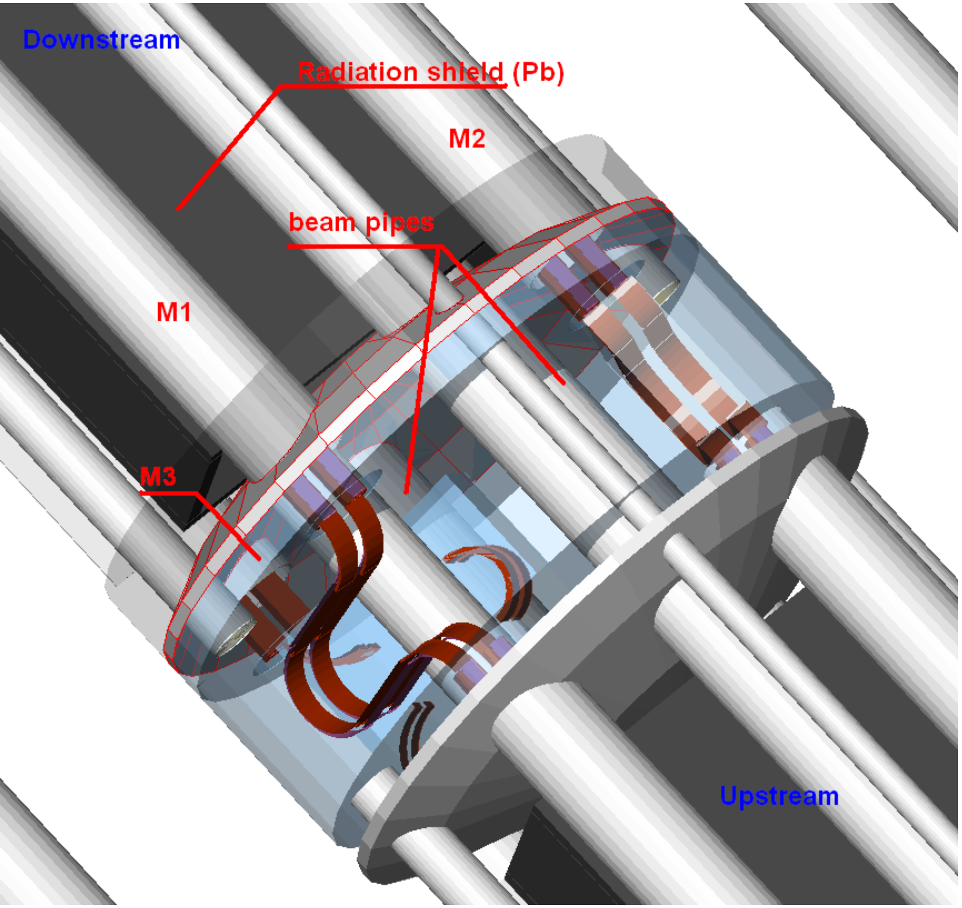
(2) MQ12

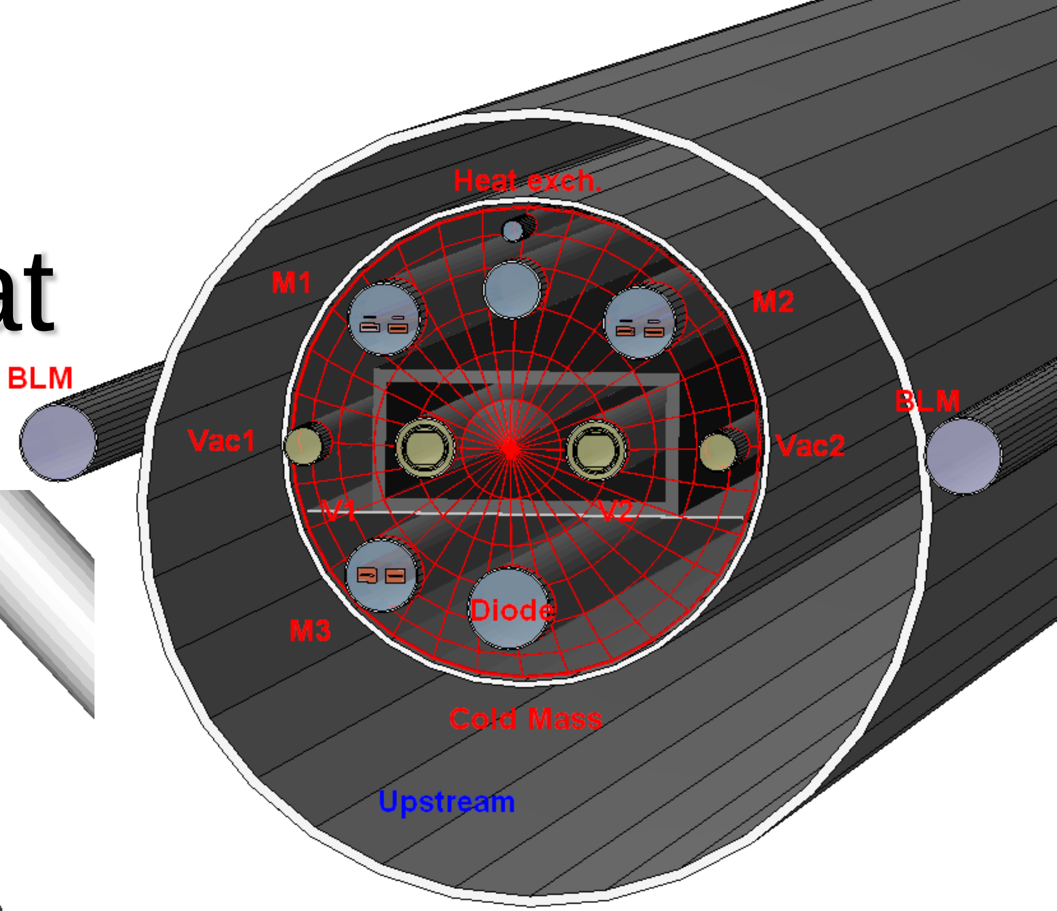
- aiming to get peak energy deposition in the following interconnect, empty cryostat (5TeV only)
- done for both energies 3TeV and 5TeV



Models:

Empty Cryostat



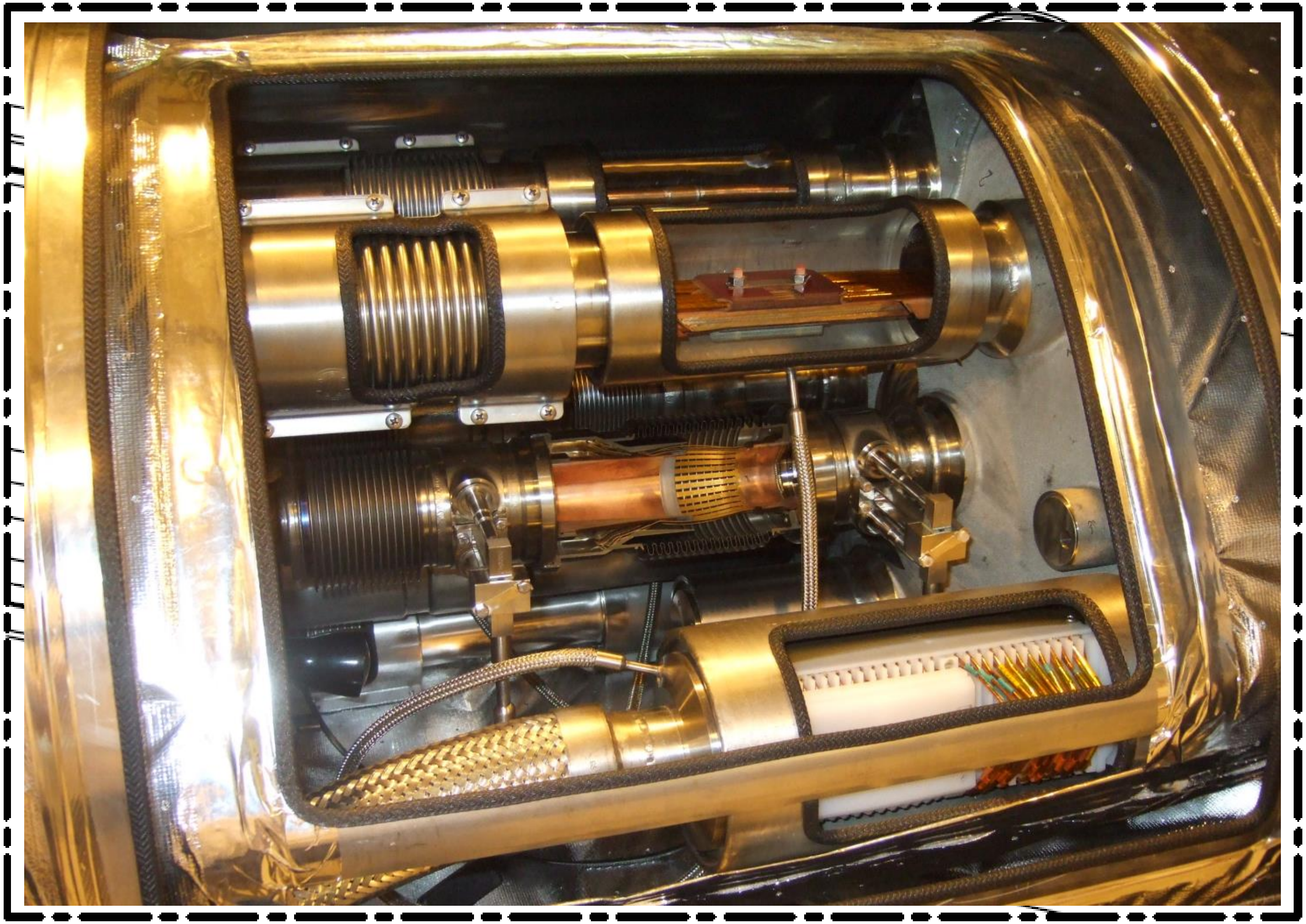


- Energy deposition on the busbars per unit length
- Energy deposition on the lyra
- BLM particles spectra and energy deposition. -> BLM signal

The Interconnect ‘Challenge’

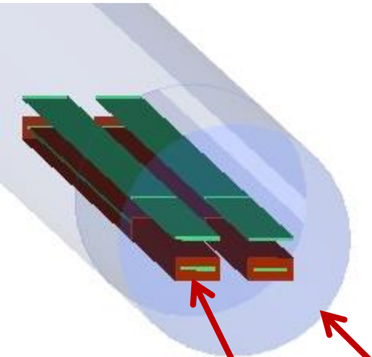
Interconnection: LE-11R / LQ-11R

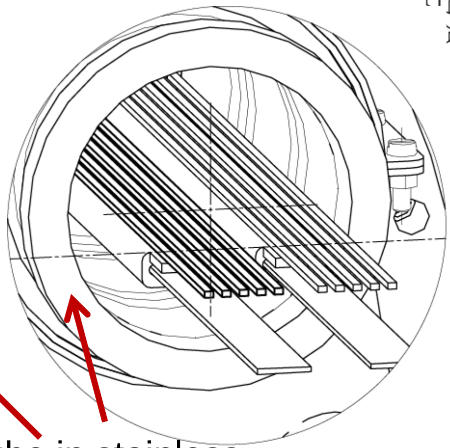
in scale

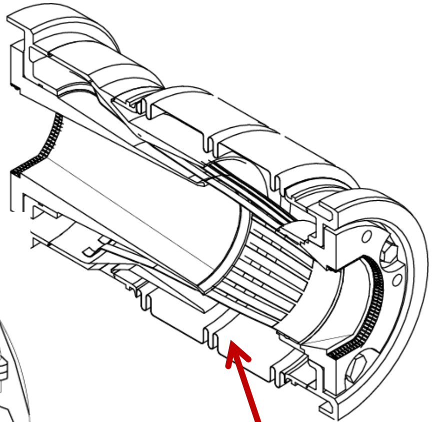


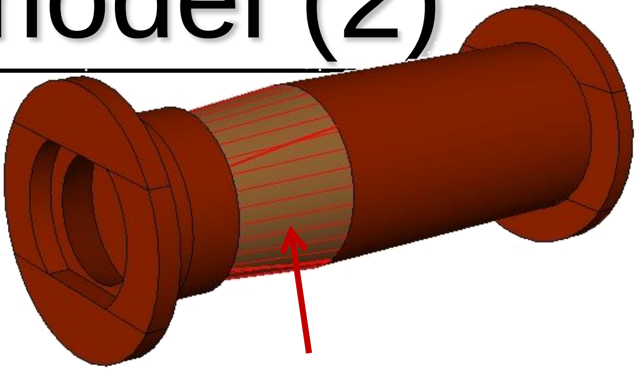
Interconnect: FLUKA model (2)

Beam Line & Bus bar described in detail with respect to the dimensions and materials

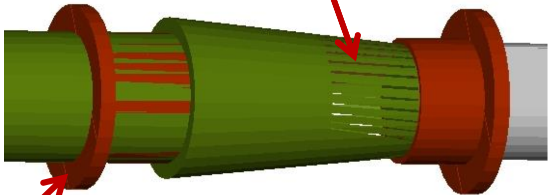






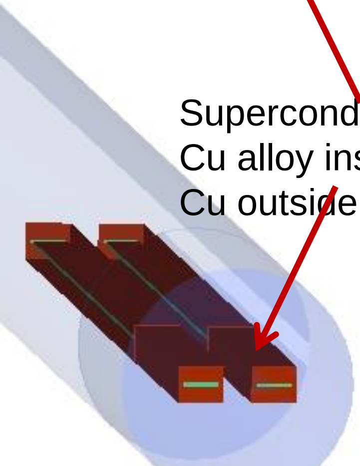


RF contact development
in Cu alloy C17410
with 5µm Au coating

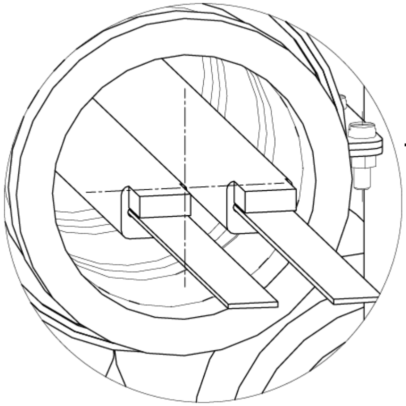


Tube in stainless
steel 316LN

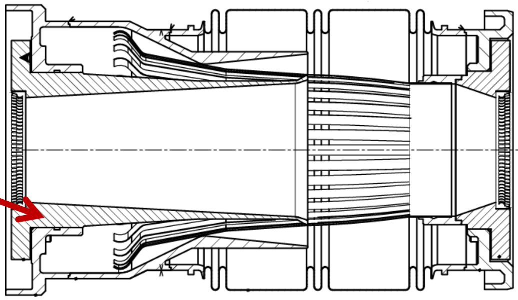
Tube in stainless
steel 316LN



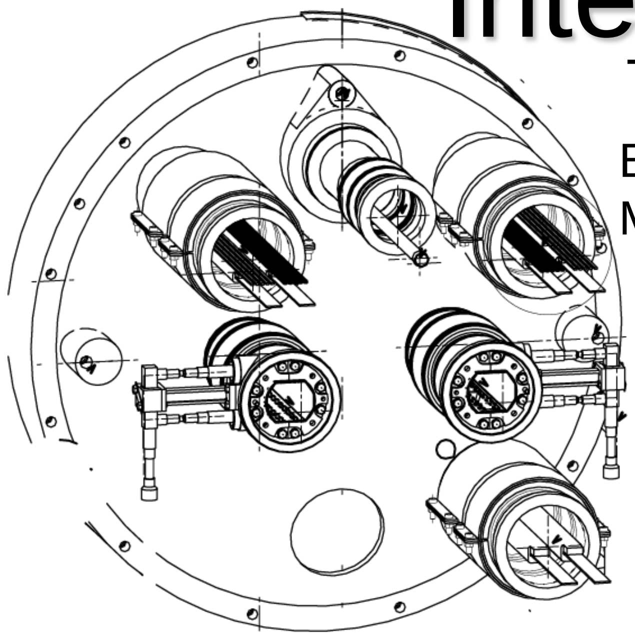
Superconducting cables
Cu alloy inside
Cu outside

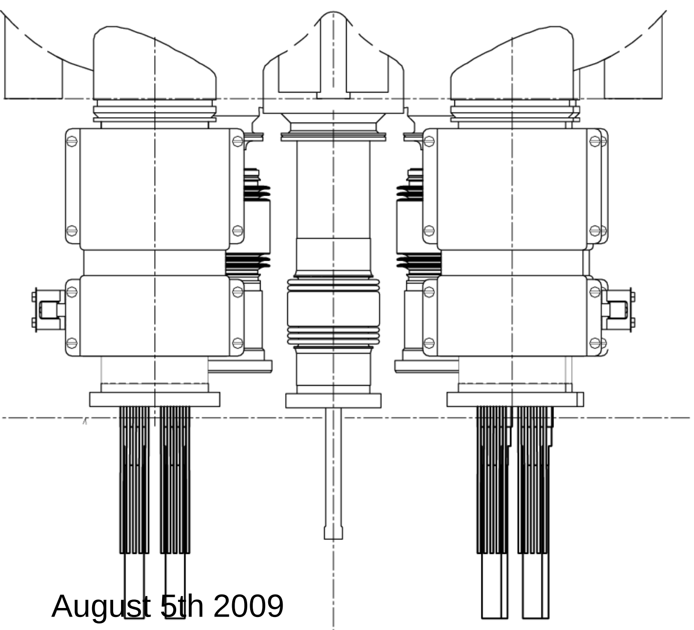


Transition tube
in Cu



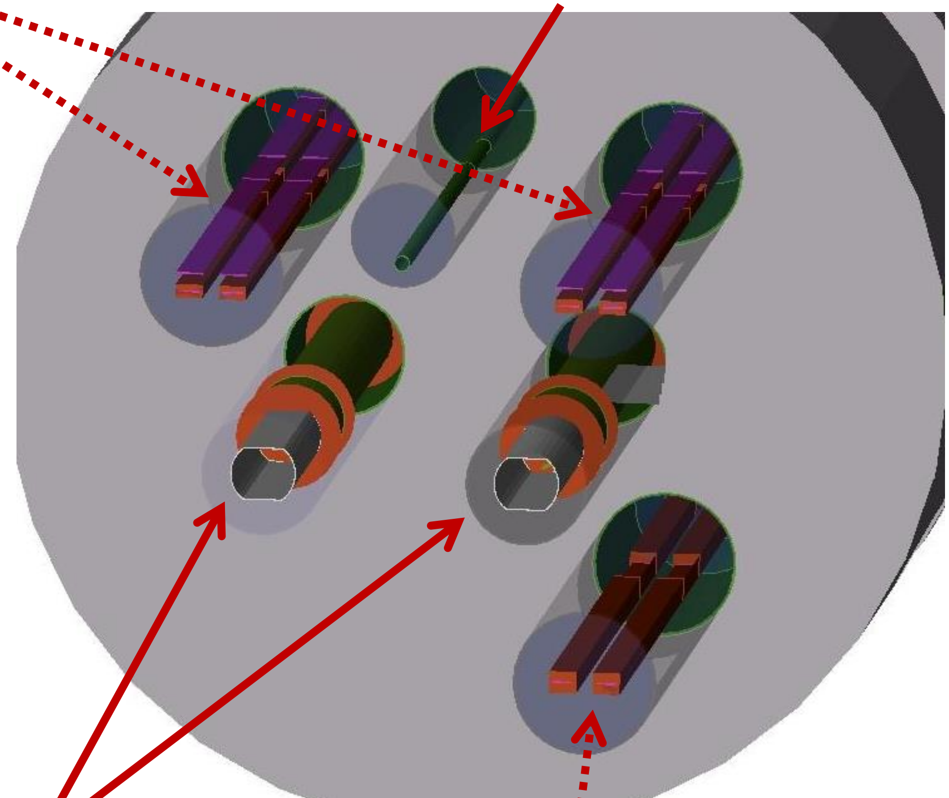
Interconnect: FLUKA model





Bus Bar Quadrupole Line M1 & M2

Linear Heat Exchanger X & Y



Beam Line V1 & V2

Bus Bar Dipole Line M3

Assumptions for Quench & Heating

MB/MQ Quench Limits (for transient case)

- 1mJ/cm^3 (preliminary assumption -> update needed)
- peak energy deposition in magnet coils:
  cell size (r/ϕ/z): ~1cm / 2deg / 10cm

Busbar Quench Limits (transient)

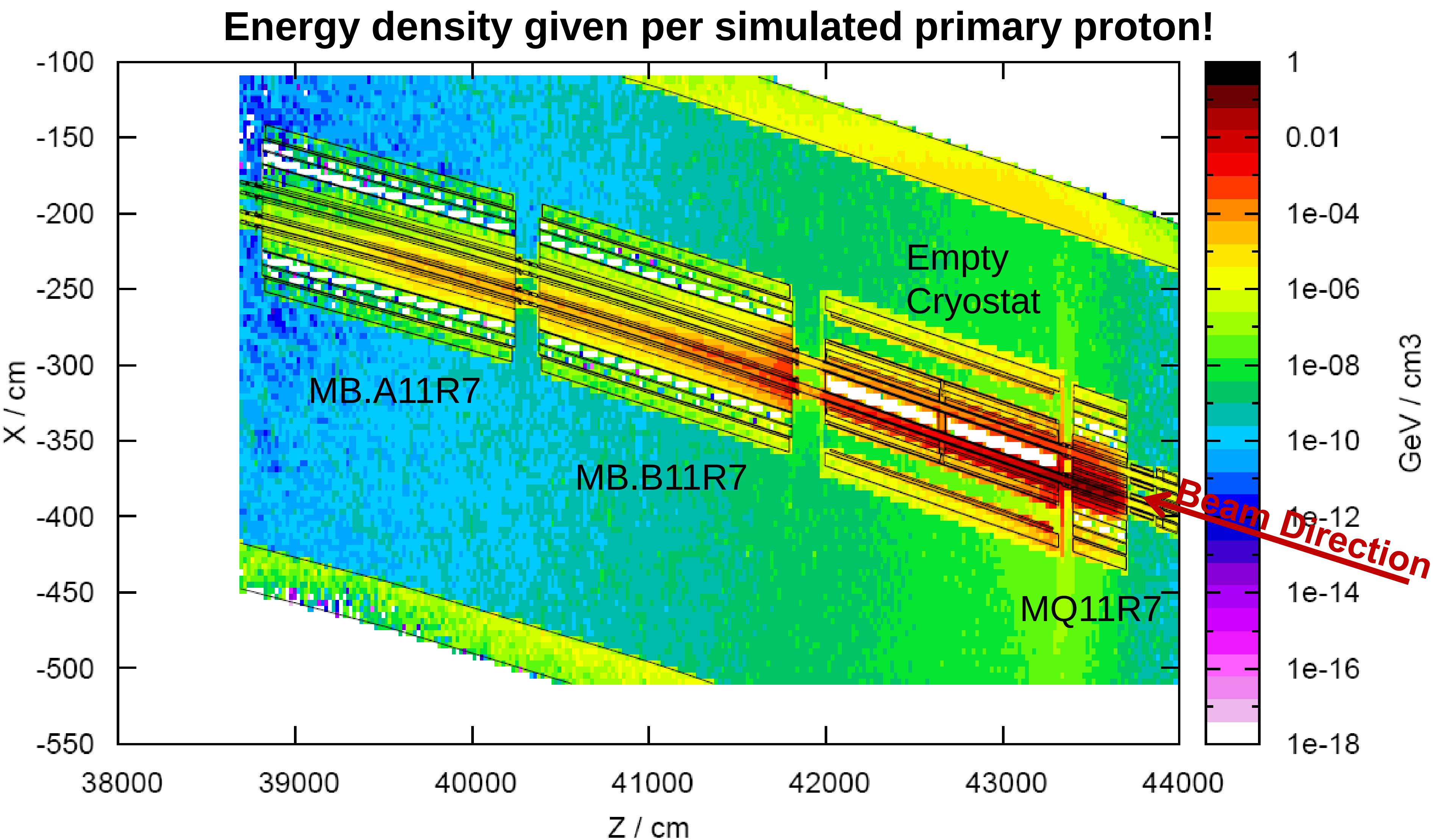
- 10mJ/cm (preliminary assumption -> update needed)
- transversal average over
  - MQ: 160mm^2 (M1, M2 as shown in layout before)
  - MB: 280mm^2 (M3)
- in the moment peak value with:
  - ~ 1cm longitudinal average for the busbars
  - ~ peak value in the Lyra (not averaged!)
- adiabatic assumption

!!! The Results SCALE with these Assumptions !!!

(Pre)Heating-up 80K

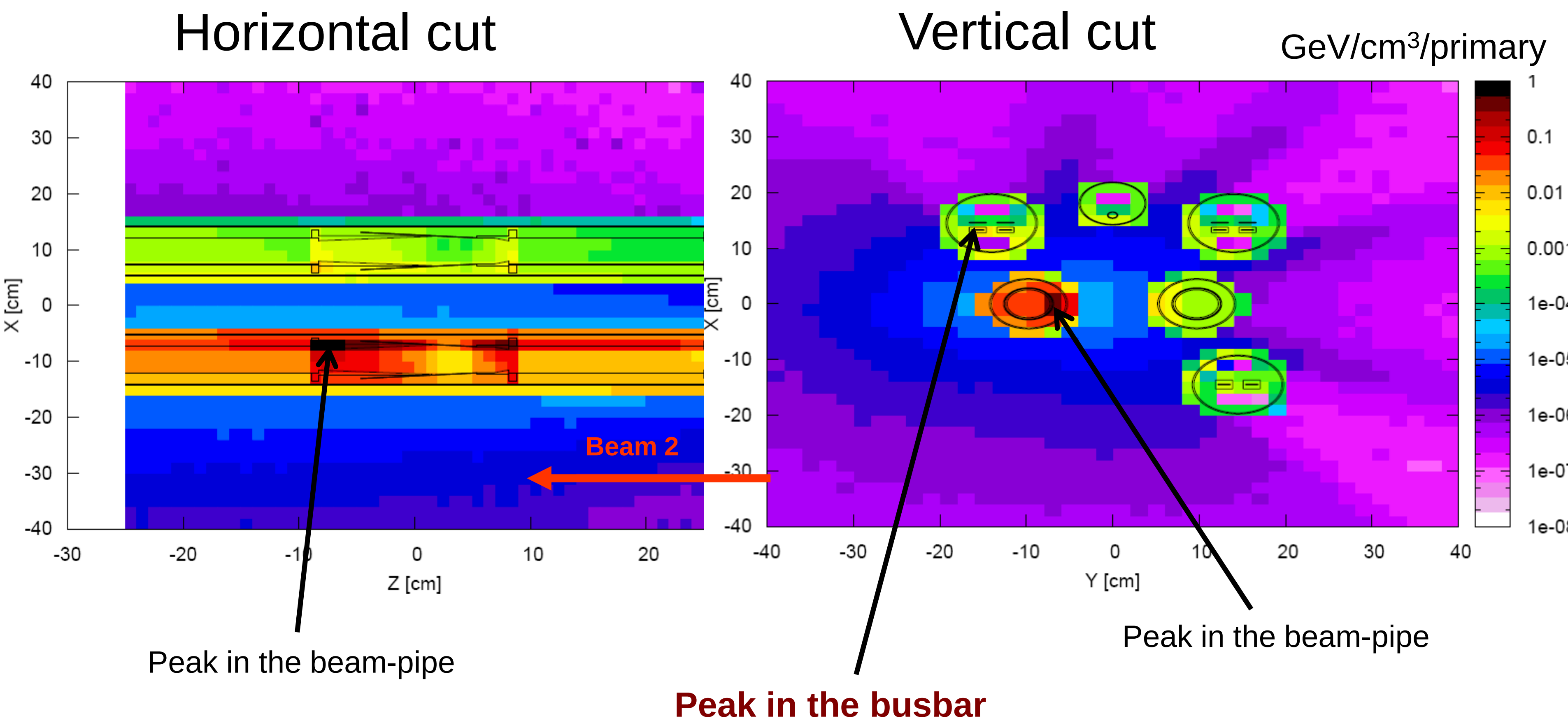
- 80K: 92 J/cm for the MQ, (*c.f.*, A.Verweij)
  (preliminary assumption -> possible update needed)

Example: Distributed Loss in MQ11



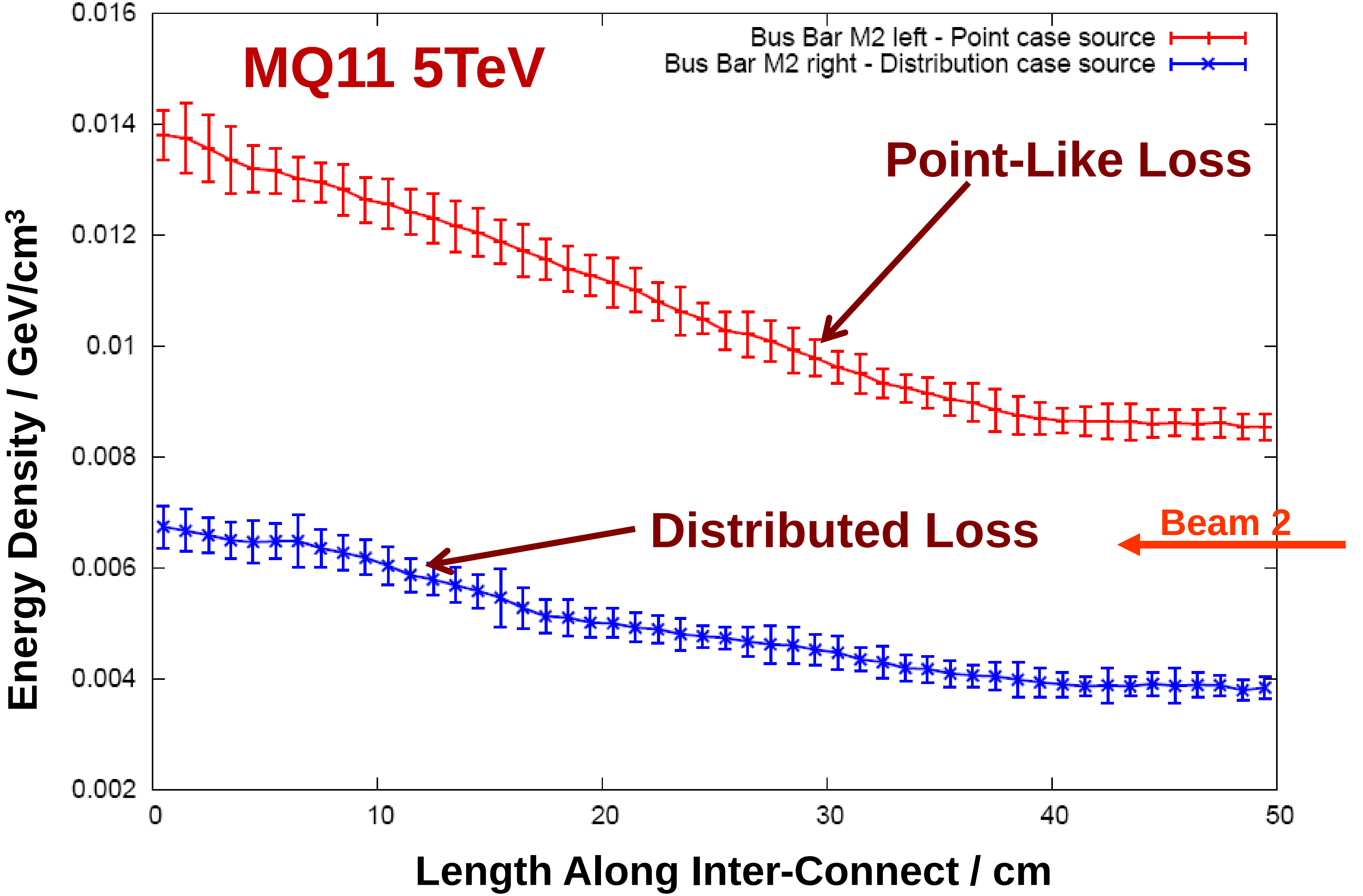
Inter-Connect: Energy deposition

Interconnect located after the MQ11 (point-like loss)

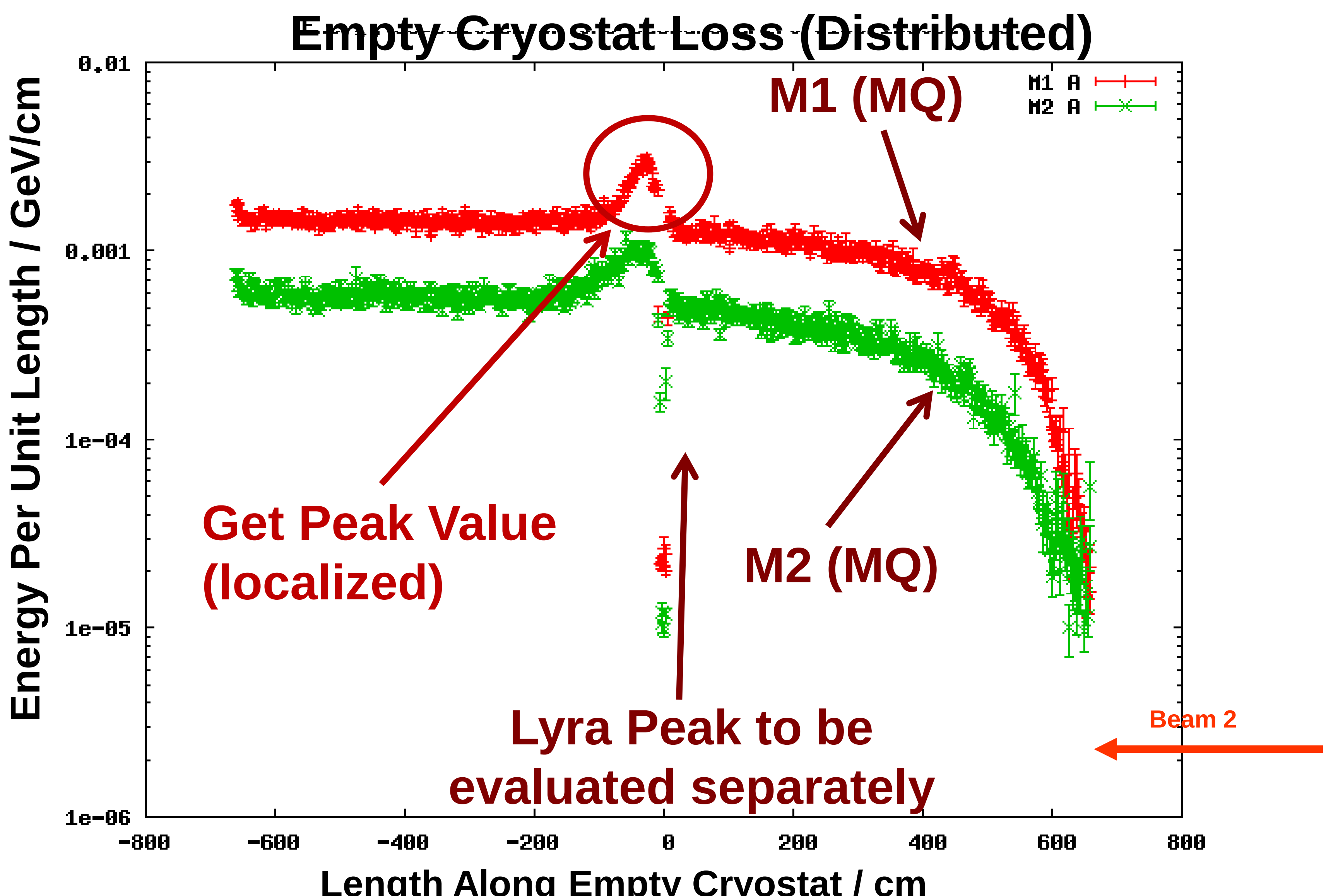


Coarse binning for Visualisation only

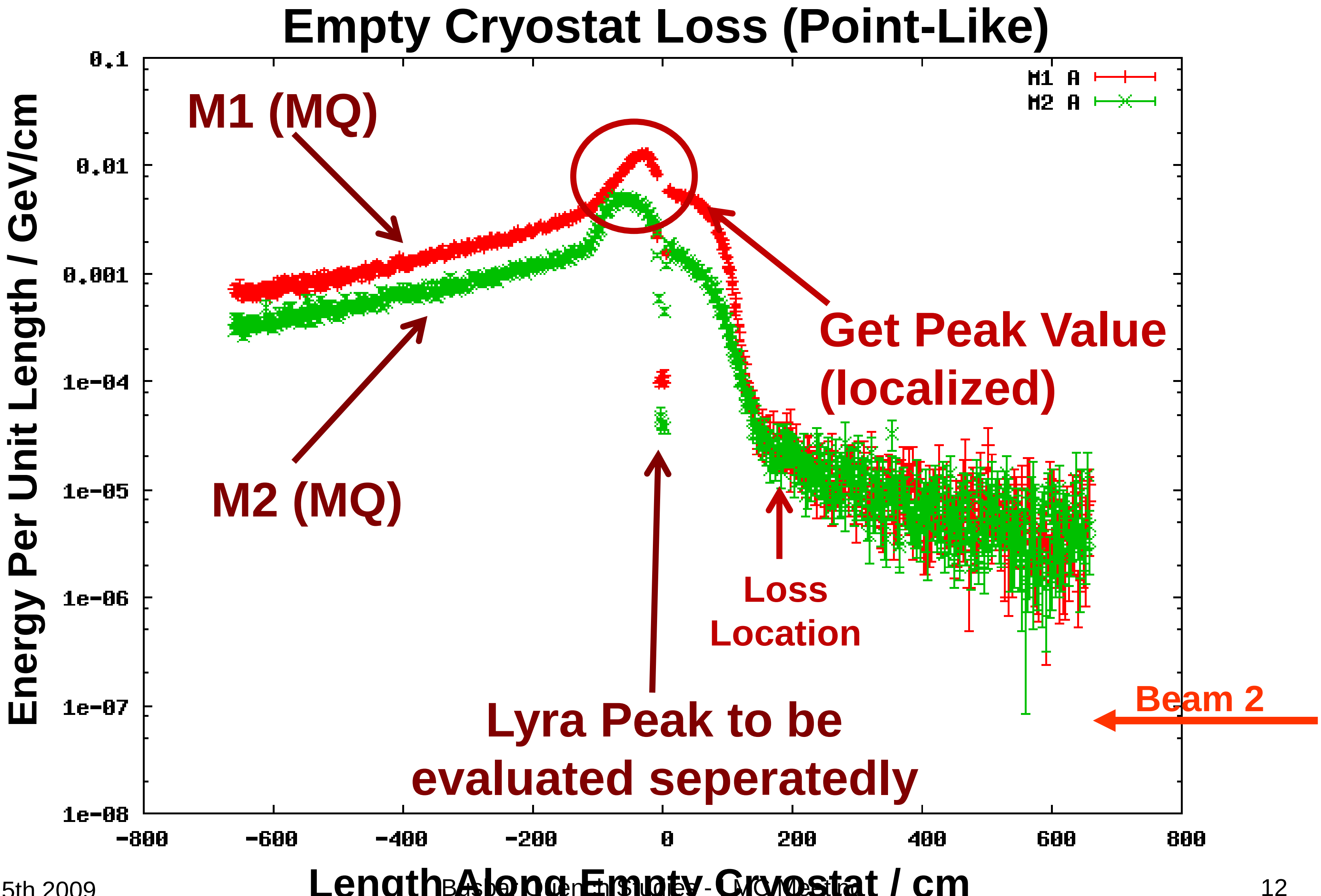
Inter-Connect: Energy Deposition



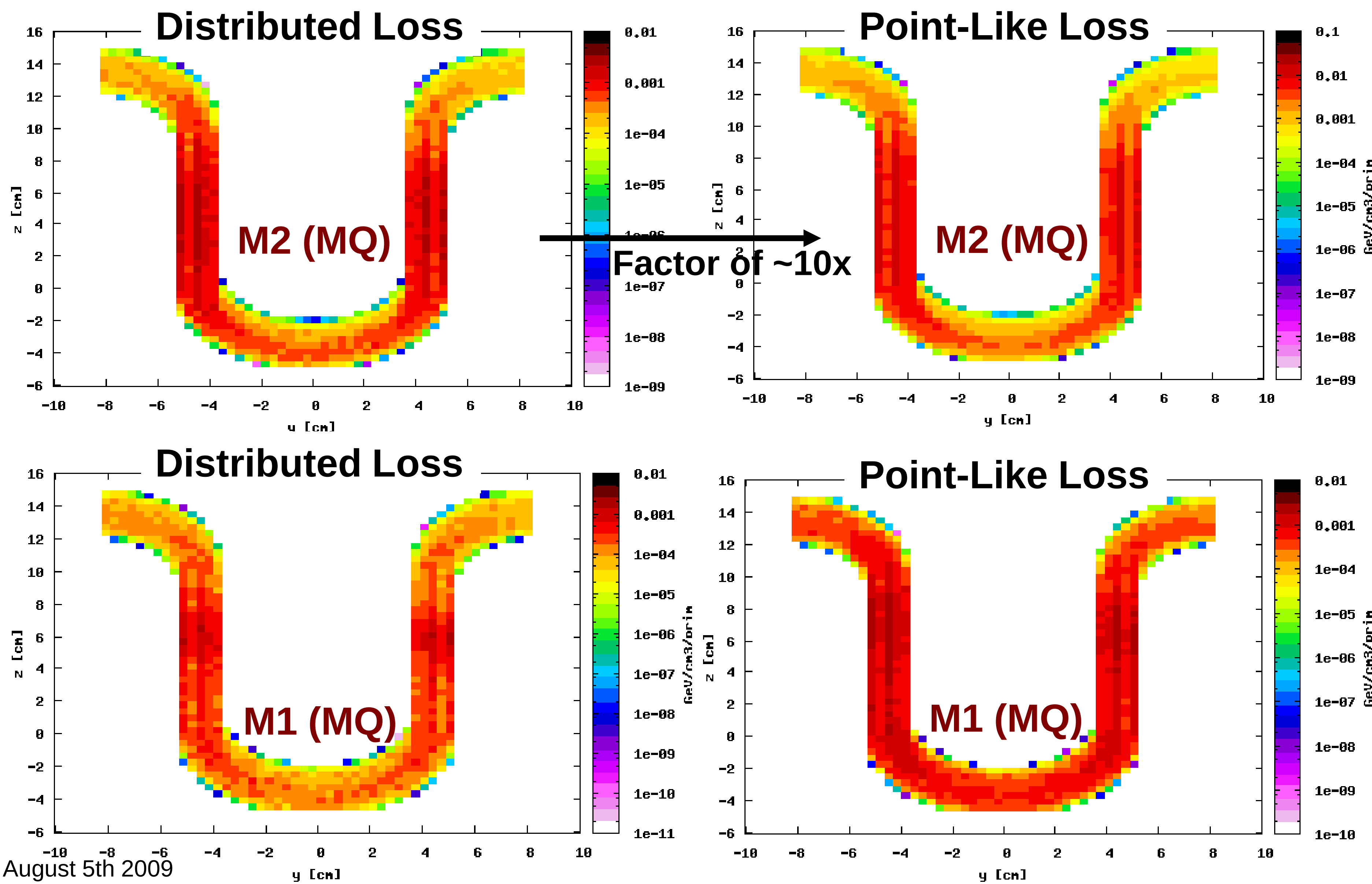
Empty Cryostat: Energy deposition



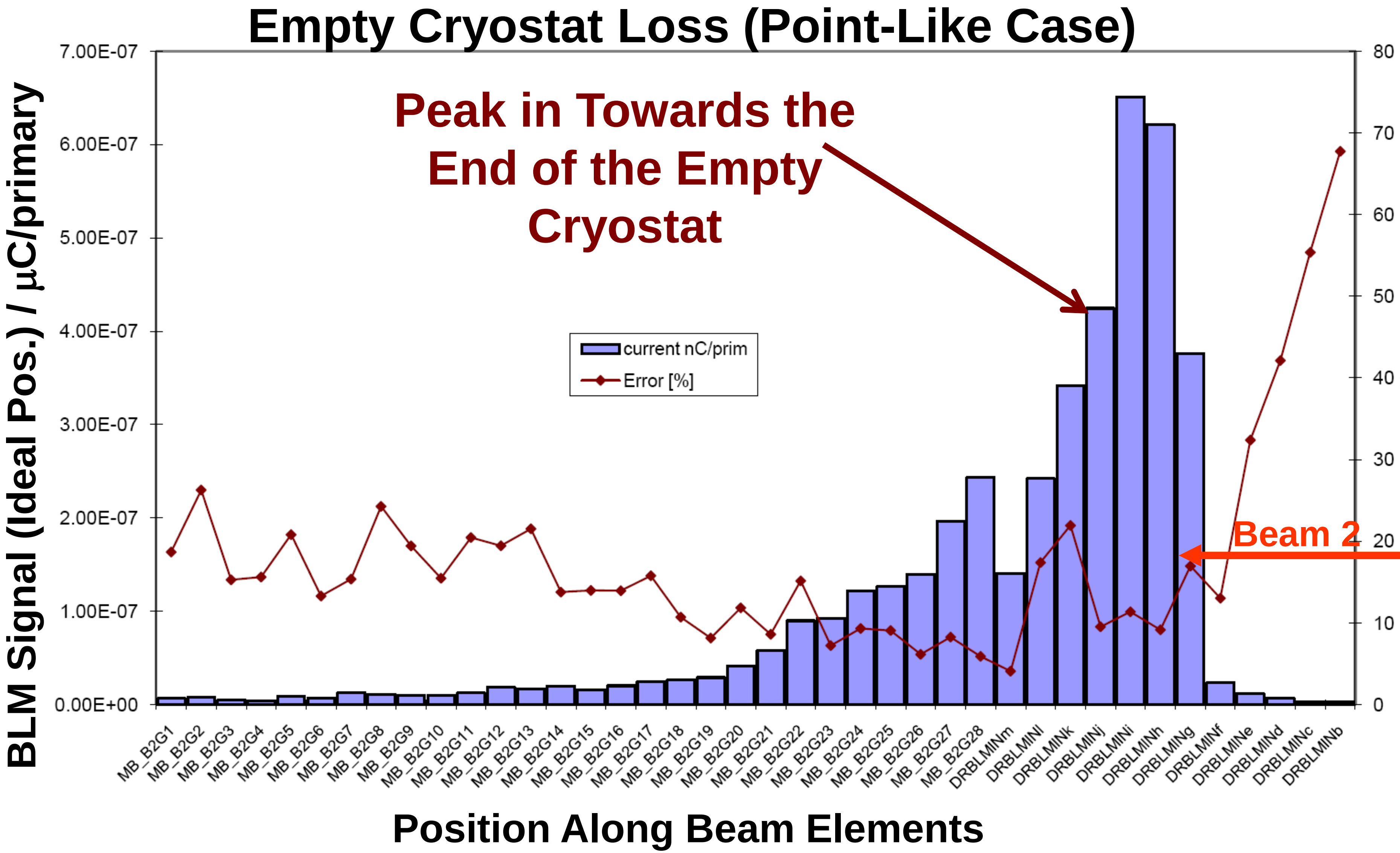
Empty Cryostat: Energy deposition



Empty Cryostat: Energy deposition

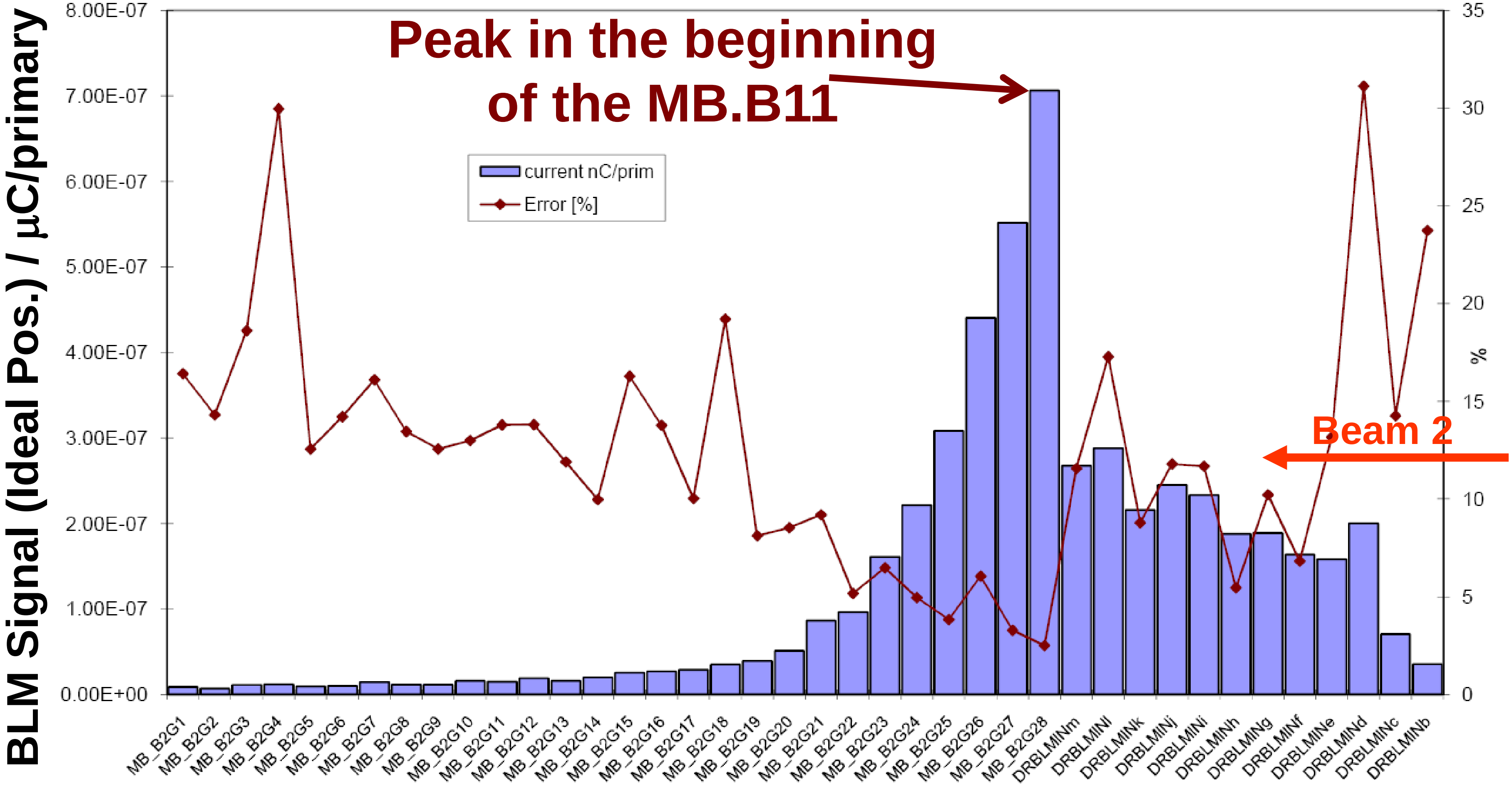


BLM Signal Empty Cryostat



BLM Signal Empty Cryostat

Empty Cryostat Loss (Distributed Case)



Possible BLM Positions Along Beam Elements

Analysis, *e.g.*, MQ11 - Point-Like Case

Beam Element	Peak E-Dep [GeV/cm3/pp] [GeV/cm/pp]	Peak E-Dep [mJ/cm3/pp] [mJ/cm/pp]	Quench Limit [mJ/cm3] [mj/cm]	#of Protons required for Quench	Peak BLM [nC/pp]	Peak BLM in case of MQ11 Quench [nC]
MQ.10R7.B1	8.04E-05	1.29E-11	1	7.77E+10	2.37E-09	0.002
MQTLI.10R7.B1	7.80E-05	1.25E-11	1	8.01E+10		
MB.A11R7.B1	4.68E-04	7.49E-11	1	1.34E+10	4.52E-09	0.003
IC3.DS10R7.B1	4.37E-05	6.99E-12	10	1.43E+12		
MB.B11R7.B1	1.26E-02	2.02E-09	1	4.96E+08	5.53E-08	0.04
IC1.DS12R7.B1	6.67E-04	1.07E-10	10	9.37E+10		
DRFT.11R7.B1 (Busbar)	1.97E-02	3.15E-09	10	3.17E+09	5.01E-06	3.4
DRFT.11R7.B1 (Lyra)	3.59E-02	5.75E-09	10	1.74E+09	5.01E-06	3.4
IC2.DRFTR7.B1	2.41E-02	3.86E-09	10	2.59E+09		
MQ.11R7.B1	9.27E+00	1.48E-06	1	6.74E+05	4.66E-07	0.3

- Magnet quenches ~3 orders of magnitudes earlier than the busbars in the adjacent inter-connect or empty cryostat
- BLM signal in the order of nC (if in the optimum position) in the case of the MQ11 quench
- Consider important uncertainties due to the loss assumptions and simulation statistics (digits are not significant)

Analysis, *e.g.*, MQ11 - Distributed Case

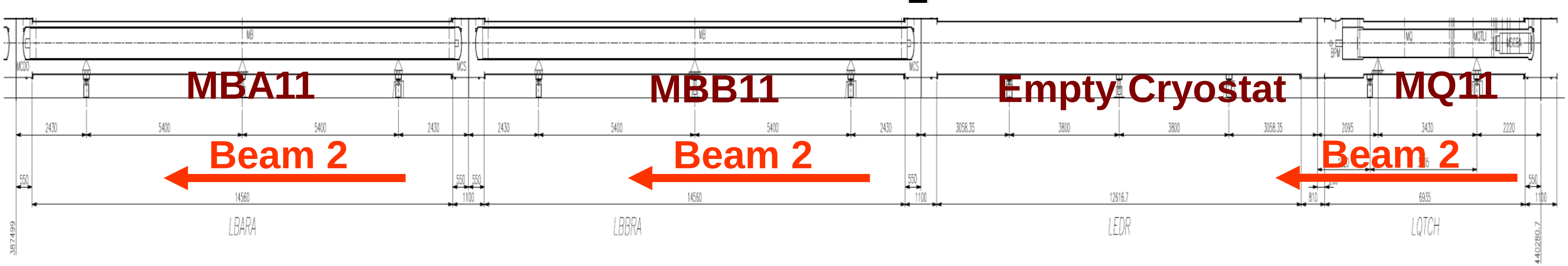
Beam Element	Peak E-Dep [GeV/cm3/pp] [GeV/cm/pp]	Peak E-Dep [mJ/cm3/pp] [mJ/cm/pp]	Quench Limit [mJ/cm3] [mj/cm]	#of Protons required for Quench	Peak BLM [nC/pp]	Peak BLM in case of MQ11 Quench [nC]
MQ.10R7.B1	4.55E-05	7.28E-12	1	1.37E+11	4.43E-09	0.01
MQTLI.10R7.B1	1.61E-04	2.58E-11	1	3.88E+10		
MB.A11R7.B1	7.54E-04	1.21E-10	1	8.29E+09	6.01E-09	0.02
IC3.DS10R7.B1	9.50E-05	1.52E-11	10	6.58E+11		
MB.B11R7.B1	1.07E-02	1.71E-09	1	5.85E+08	3.79E-08	0.1
IC1.DS12R7.B1	5.98E-04	9.57E-11	10	1.04E+11		
DRFT.11R7.B1 (Busbar)	1.00E-02	1.60E-09	10	6.25E+09	1.06E-06	**3.4**
DRFT.11R7.B1 (Lyra)	3.10E-02	4.96E-09	10	**2.02E+09**	1.06E-06	**3.4**
IC2.DRFTR7.B1	1.15E-02	1.85E-09	10	**5.42E+09**		
MQ.11R7.B1	1.92E+00	3.07E-07	1	**3.25E+06**	6.73E-07	**2.2**

- Magnet quenches 2-3 orders of magnitudes earlier than the busbars in the adjacent inter-connect or empty cryostat
- BLM signal in the order of nC in the case of the MQ11 qench

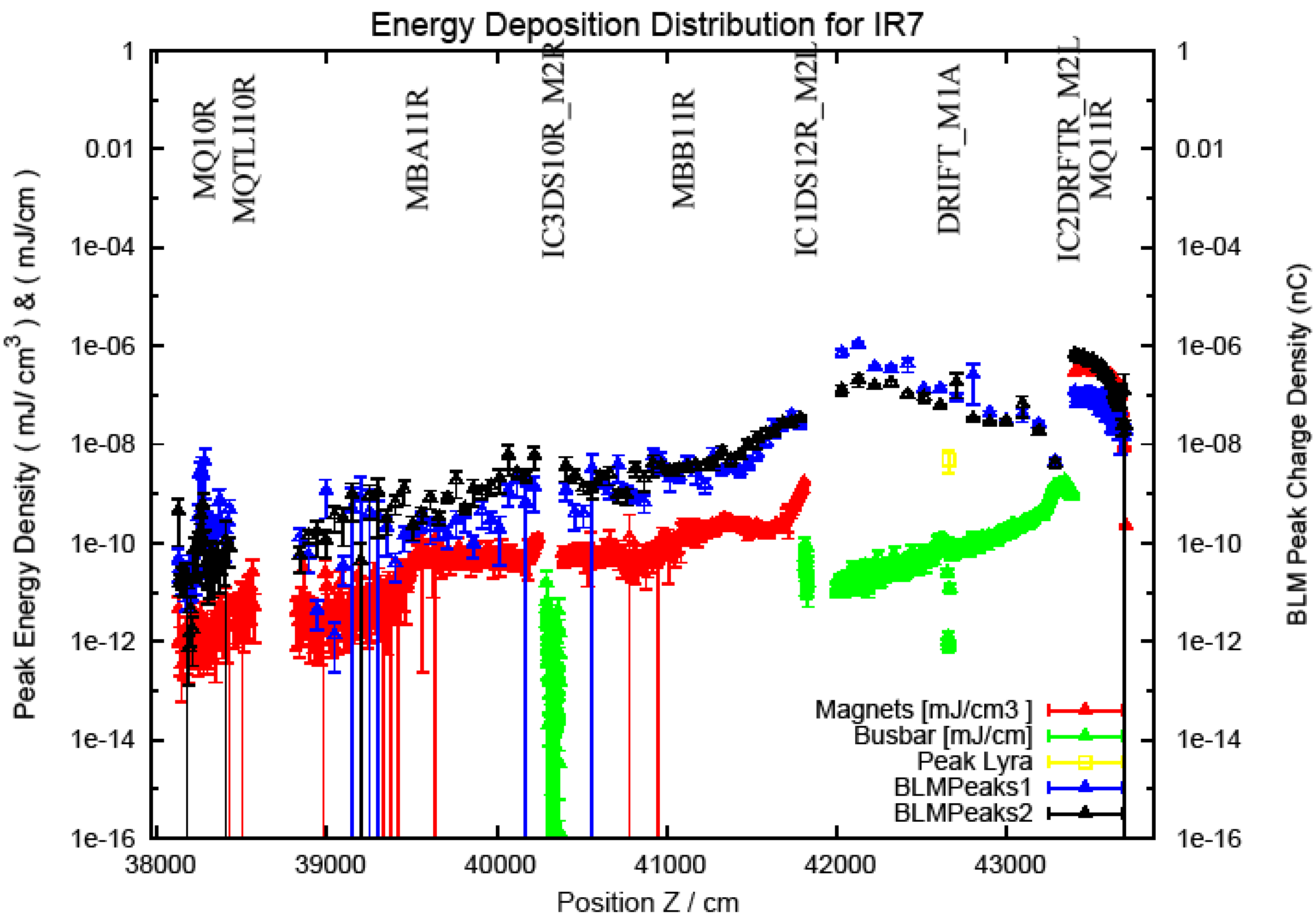
Number Of Protons To Quench Both

MQ11 5TeV

		MBB11R	IC	DRIFT_322	IC	MQ11R	
Point-like Loss in the MQ11							
for	1 proton	2.00E-09		5.70E-09	3.90E-09	1.50E-06	[mJ/cm3]
for	1.75E+09 # of protons	3.51		10.00	6.84	2631.58	[mJ/cm for Busbars]
Distributed Loss in the MQ11							
for	1 proton	1.70E-09		5.00E-09	1.80E-09	3.10E-07	[mJ/cm3]
for	2.00E+09 # of protons	3.40		10.00	3.60	620.00	[mJ/cm for Busbars]



Analysis Plots. MQ11. Dist. Loss



Analysis, *e.g.*, Empty C. Point Loss

Beam Element	Peak E-Dep [GeV/cm3/pp] [GeV/cm/pp]	Peak E-Dep [mJ/cm3/pp] [mJ/cm/pp]	Quench Limit [mJ/cm3] [mj/cm]	#of Protons required for Quench	Peak BLM [nC/pp]	Peak BLM in case of DRFT Quench [nC]
MQ.10R7.B1	4.87E-05	7.78E-12	1	1.28E+11	1.95E-09	0.9
MQTLI.10R7.B1	1.40E-04	2.24E-11	1	4.47E+10		
MB.A11R7.B1	3.68E-03	5.88E-10	1	1.70E+09	1.72E-08	8.2
IC1.DS11R7.B1	2.67E-04	4.28E-11	10	2.34E+11		
IC3.DS10R7.B1	3.20E-04	5.13E-11	10	1.95E+11		
MB.B11R7.B1	6.09E-02	9.75E-09	1	1.03E+08	2.43E-07	116.4
IC1.DS12R7.B1	2.47E-03	3.95E-10	10	2.53E+10		
DRFT.11R7.B1 (Busbar)	1.30E-02	2.08E-09	10	4.81E+09		
DRFT.11R7.B1 (Lyra)	1.31E-01	2.09E-08	10	4.79E+08	6.50E-07	311.3

- Magnet quenches about at the same time as the busbars in the empty cryostat

(Note: the Lyra quench level refers to the peak value)

Analysis, *e.g.*, Empty Cryos. Dist. Loss

Beam Element	Peak E-Dep [GeV/cm3/pp] [GeV/cm/pp]	Peak E-Dep [mJ/cm3/pp] [mJ/cm/pp]	Quench Limit [mJ/cm3] [mj/cm]	#of Protons required for Quench	Peak BLM [nC/pp]	Peak BLM in case of DRFT Quench [nC]
MQ.10R7.B1	8.15E-05	1.30E-11	1	7.67E+10	4.21E-09	6.8
MQTLI.10R7.B1	2.01E-04	3.22E-11	1	3.11E+10		
MB.A11R7.B1	4.39E-03	7.02E-10	1	1.42E+09	2.95E-08	47.5
IC1.DS11R7.B1	2.45E-04	3.91E-11	10	2.56E+11		
IC3.DS10R7.B1	2.25E-04	3.61E-11	10	2.77E+11		
MB.B11R7.B1	1.32E-01	2.12E-08	1	**4.73E+07**	7.06E-07	**1139.0**
IC1.DS12R7.B1	6.44E-03	1.03E-09	10	9.71E+09		
DRFT.11R7.B1 (Busbar)	3.09E-03	4.95E-10	10	2.02E+10		
DRFT.11R7.B1 (Lyra)	3.87E-02	6.20E-09	10	**1.61E+09**	2.88E-07	**464.2**

- Adjacent magnet quenches ‘only’ ten times earlier than the busbars in the empty cryostat
- significantly higher BLM signal (some 100nC)

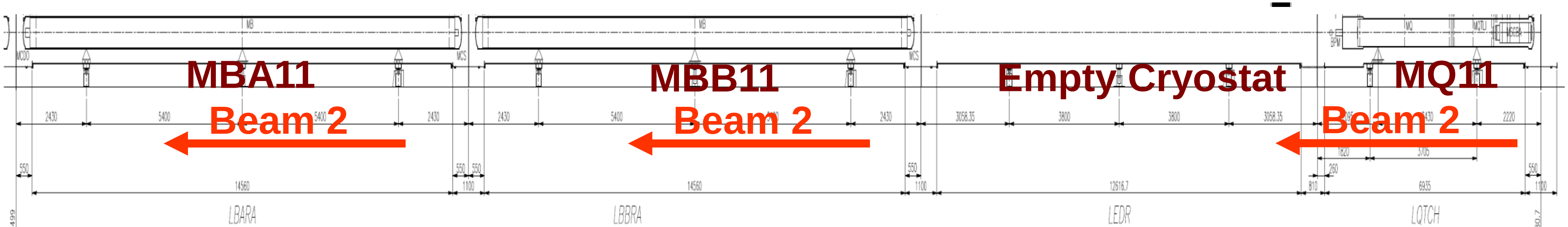
  (Note: the BLM signal refers to the BEST possible location, thus not necessarily the one as installed in the machine)

Number Of Protons To Quench Both

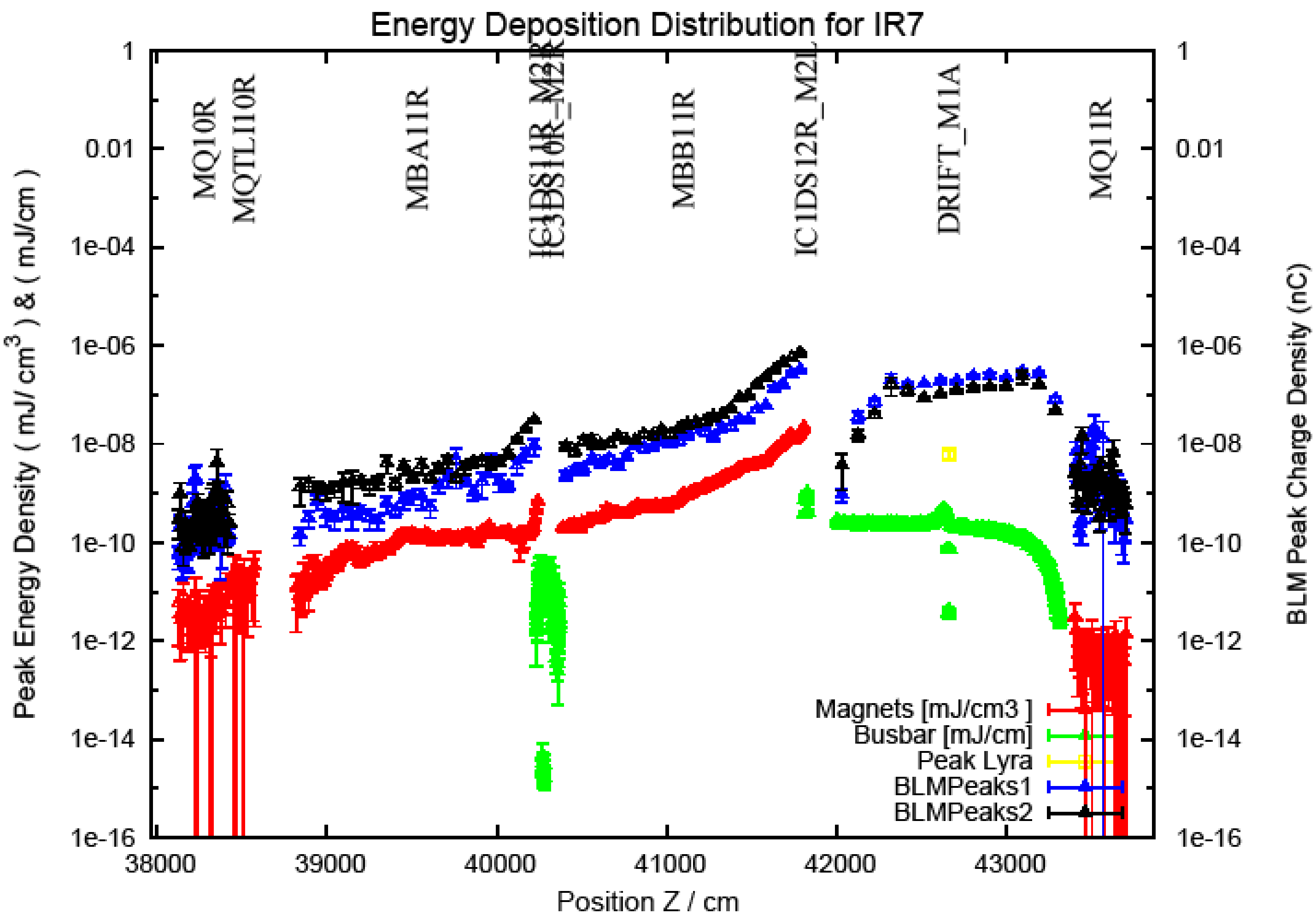
Empty Cryostat 5TeV

Point-like Loss in the Empty Cryostat (5 TeV)						
for	1 proton	5.90E-10	9.70E-09	4.00E-10	2.10E-08	[mJ/cm3]
for	**4.76E+08 # of protons**	0.28	**4.62**	0.19	**10.00**	[mJ/cm for Busbars]
Distributed Loss in the Empty Cryostat (5 TeV)						
for	1 proton	7.00E-10	2.10E-08	1.00E-09	6.20E-09	[mJ/cm3]
for	**1.61E+09 # of protons**	**1.13**	**33.87**	1.61	**10.00**	[mJ/cm for Busbars]

MBA11R IC MBB11R IC DRIFT_322



Analysis Plots. Empty Cryos. Dist. Loss



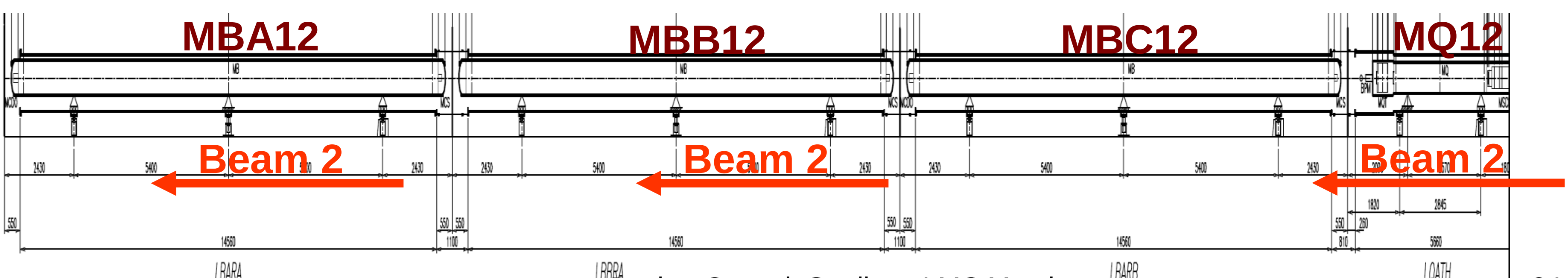
Number Of Protons To Quench Both

MQ12 5TeV

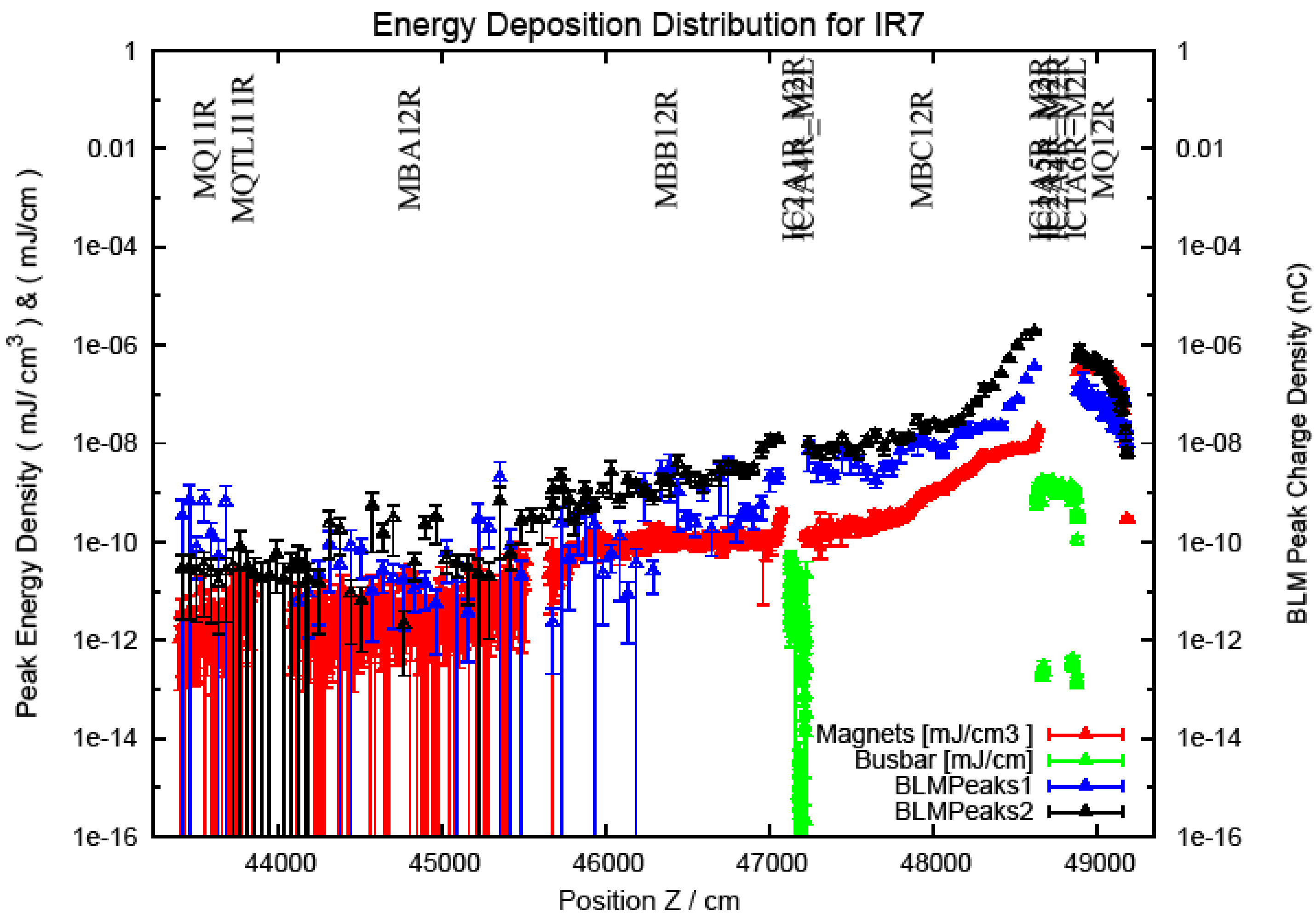
Point-like Loss in the MQ12 (5TeV)						
for	1 proton	2.50E-10	3.90E-08	3.50E-09	1.60E-06	[mJ/cm3]
for	**2.86E+09 # of protons**	0.71	**111.43**	**10.00**	**4571.43**	[mJ/cm for Busbars]

Distributed Loss in the MQ12 (5TeV)						
for	1 proton	3.90E-10	1.90E-08	1.80E-09	3.10E-07	[mJ/cm3]
for	**5.56E+09 # of protons**	**2.17**	**105.56**	**10.00**	**1722.22**	[mJ/cm for Busbars]

MBB12R IC MBC12R IC MQ12R



Analysis Plots. MQ12 5TeV Dist. Loss



Quenches: Summary Table

Loss Element	Loss Scenario	Energy [TeV]	Minimum #ofProtons to quench the Magnet	Minimum #ofProtons to quench the Busbar	Multiple #ofProtons to quench the Busbar	BLM Peak Signal in case of Magnet Quench [nC]	BLM Peak Signal in case of Busbar Quench [nC]	Location of BLM Peak Signal
MQ12	Point	5	6.4E+05	2.8E+09	4476	2.3	10193.8	MB.C12
		3	1.1E+06	4.4E+09	3895	2.3	8885.3	MB.C12
	Distributed	5	3.2E+06	5.7E+09	1751	6.2	10881.2	MB.C12
		3	5.9E+06	1.0E+10	1770	6.8	12067.5	MB.C12
MQ11	Point	5	6.7E+05	1.7E+09	2579	3.4	8708.4	Empty Cryostat
	Distributed	5	3.3E+06	2.0E+09	620	3.4	2136.5	Empty Cryostat
Empty Cryostat	Point	5	1.0E+08	4.8E+08	5	311.3	1452.3	Empty Cryostat
	Distributed	5	4.7E+07	1.6E+09	34	1139.0	38876.8	MB.B11

- **Magnet will quench significantly earlier** than adjacent busbars (in inter-connects or the empty cryostat)
  - (10^8) 10^6 protons sufficient to quench the magnets
  - (10^8) 10^9-10^{10} protons required to quench the busbars
- Energy dependence **between 5 and 3 TeV is about a factor of two** (significantly below the uncertainties due to the loss assumptions)
- Respective **BLM signal is a few nC for the magnet quench** (3-1000nC)
- Loss (point-like) in the empty cryostat is considered as 'worst-case', however direct losses are very unlikely (as compared to the MQs)

Pre-Heating to 80K

Loss Element	Loss Scenario	Energy [TeV]	Peak E-Dep [mJ/cm/pp]	Element Name	#of Protons to (pre)heat to 80K
MQ12	Point	5	3.51E-09	IC1.A6R7.B1	2.62E+13
		3	2.26E-09		4.07E+13
	Distributed	5	1.76E-09	IC2.A4R7.B1	5.21E+13
		3	9.59E-10	IC1.A6R7.B1	9.60E+13
MQ11	Point	5	5.75E-09	IC2.DRFTR7.B1	1.60E+13
	Distributed	5	4.96E-09		1.86E+13
Empty Cryostat	Point	5	2.09E-08	DRFT.11R7.B1 (Lyra)	4.40E+12
	Distributed	5	6.20E-09		1.48E+13

- **Only preliminary assumption for the required energy**
  - **92J for 80K** (*c.f.*, A.Verweij)
- 10^{8}-10^{10} protons required to quench the busbar`
- **Some 10^{12}-10^{13} protons required for >80K**
- Considered as less of an issue

Conclusions

- Peak values location (and loss scenario) dependent, however **general conclusions possible to be drawn within the order of magnitudes** (given the assumptions)
- **Combined busbar and magnet quench can not be excluded**
- **Magnet will quench at a significantly lower level** of beam loss than adjacent bus bars (in inter-connects or the empty cryostat)
  - (10^8) 10^6 protons sufficient to quench the magnets
  - (10^8) 10^9-10^{10} protons required to quench the busbars
- Applied **quench 'limits' require an iteration with the magnet experts** – results scale accordingly
- **Energy dependence** between 5 and 3 TeV is **about a factor of two**
- According to the present studies it's **very unlikely to quench the busbar only (not observed in these studies)**
- **Pre-Heating to 80K seems less of an issue**, but required heat assumptions need to be clarified

Supporting Material

Problem Introduction

Motivation

“Quantify the likelihood of quenching the busbar with beam.”

“Verify the respective magnet quenches and levels.”

“Analyse the related BLM signal and positions”

“Study the probability of rising the temperature of the busbar/Cu over 80K before discharging.”

The ‘Problem’

Sufficiently ‘realistic’ representation of the geometrical situation

Proper implementation in the DS/ARC layout

What loss scenario to be condisered

Link between loss scenario, energy deposition (quench) and BLM signal

- simulation layout follows same layout as damage studies proposed before/after Chamonix 2009 (see V. Kain et al.)

The Required (New) Ingredients

Geometry

- FLUKA model of the empty cryostat
- FLUKA model (different lengths) of the interconnects
- BLM 'dummy' regions along magnets

Technical

- Routine allowing for arbitrary losses in beam elements of the DS/ARC
- BLM particle energy spectra scoring as a function of 'Lattice'
- Special LYRA scoring following U-shape and allowing to get only the contribution of the sensitive volume
- Check for particles leaving the area (possible use for post-tracking studies)
- Longitudinal scoring along bus-bars, as well as 3D scoring for visualization

Loss Assumption

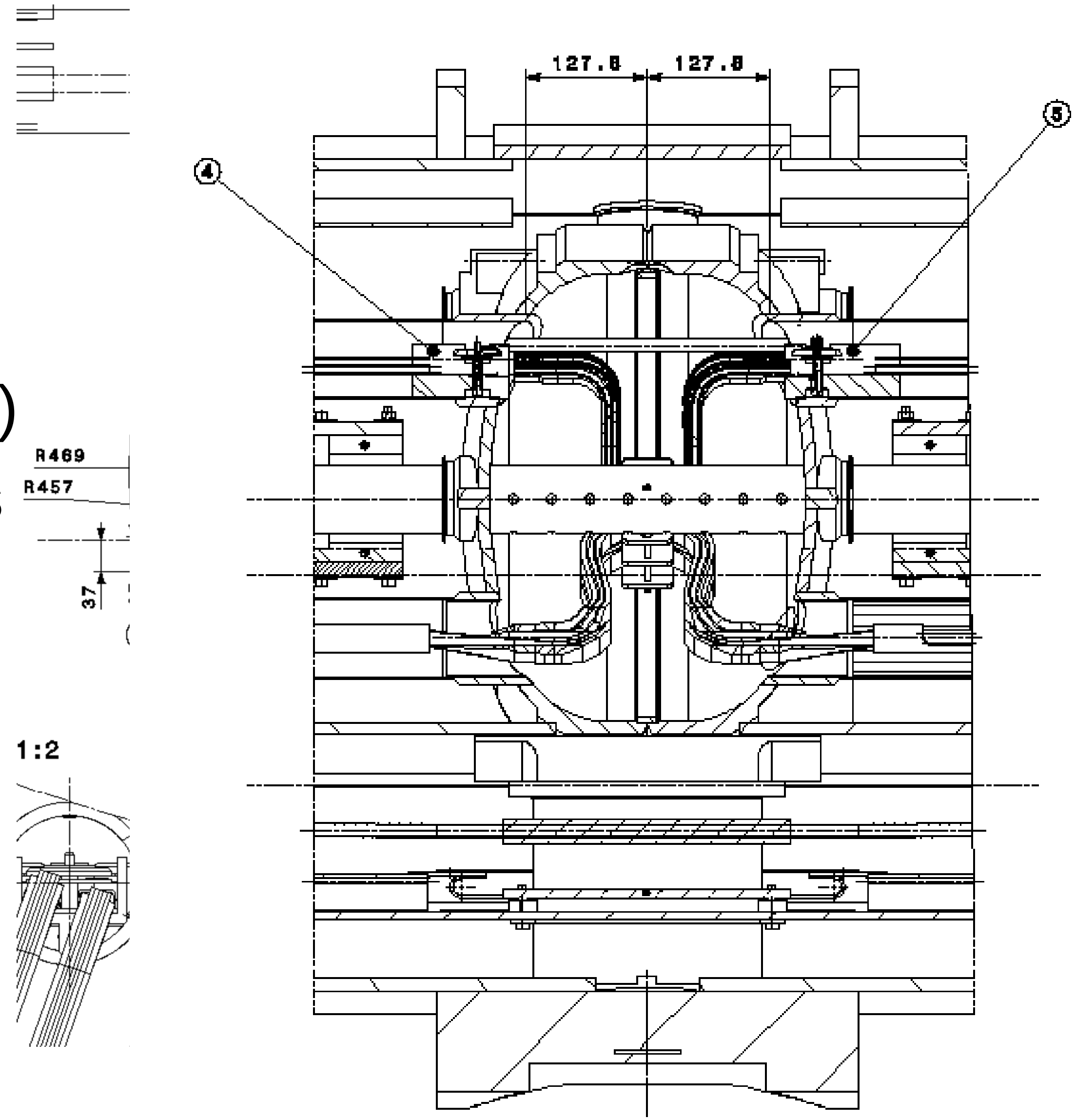
- Different cases studied for various loss locations (MQ12/11/Empty Cryostat) and in some cases also different energies

Quench Levels & Preheating: Values and Conditions

- Normalization assumptions
- Quench conditions to be studied (transient,…)

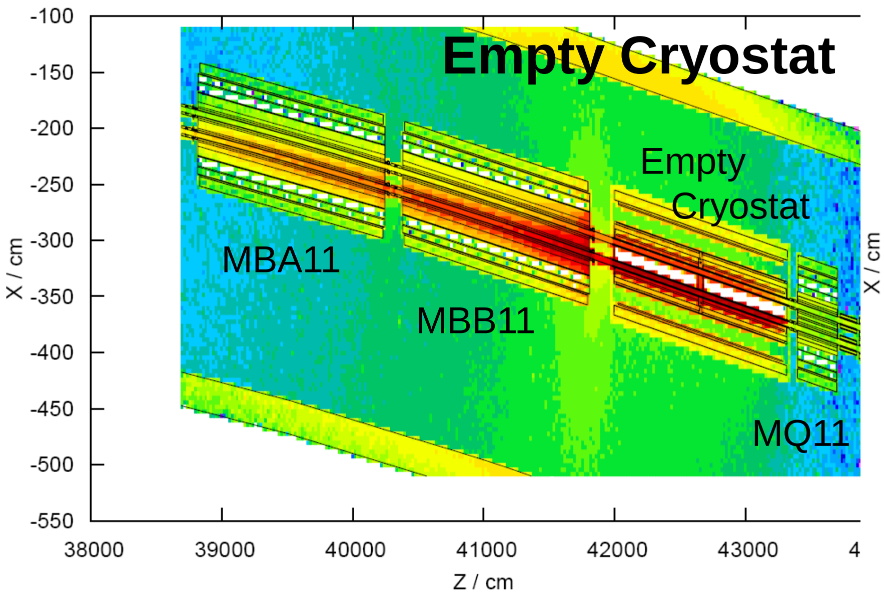
Geometry Models: Empty Cryostat

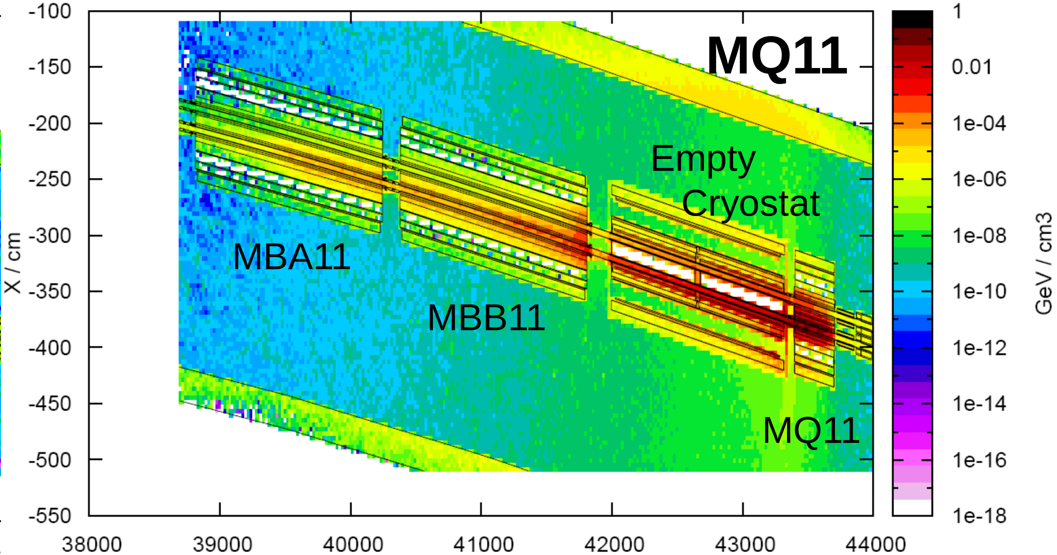
- **Details Included**
  - Lyras (complex implementation through angles,…)
  - Radiation shield (Pb)
  - Beam screens/pipes
  - Central part (He/Steel)
  - Continuous horizontal BLM

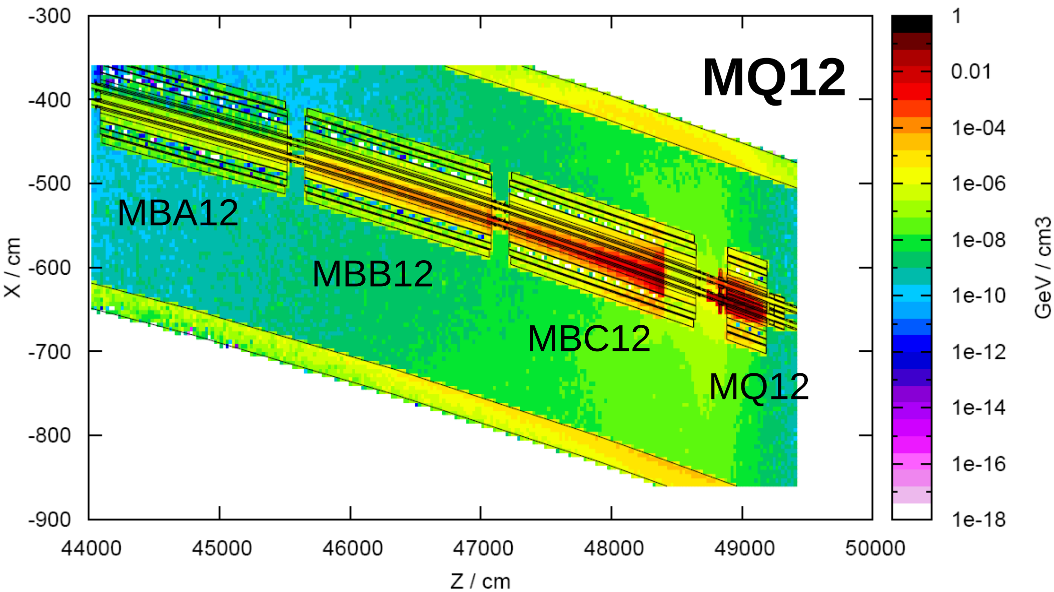


Detail B

Different Locations (distributed loss)





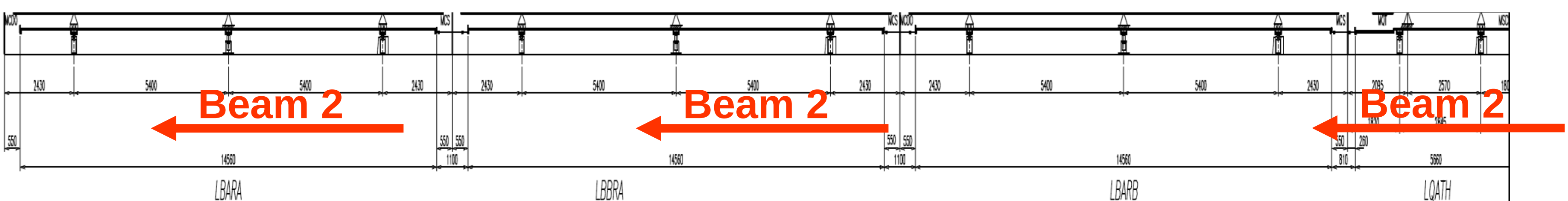


Analysis of peak energy depositions in busbars and magnet coils for the different loss locations and distributions (as well as energy for the MQ12 case)

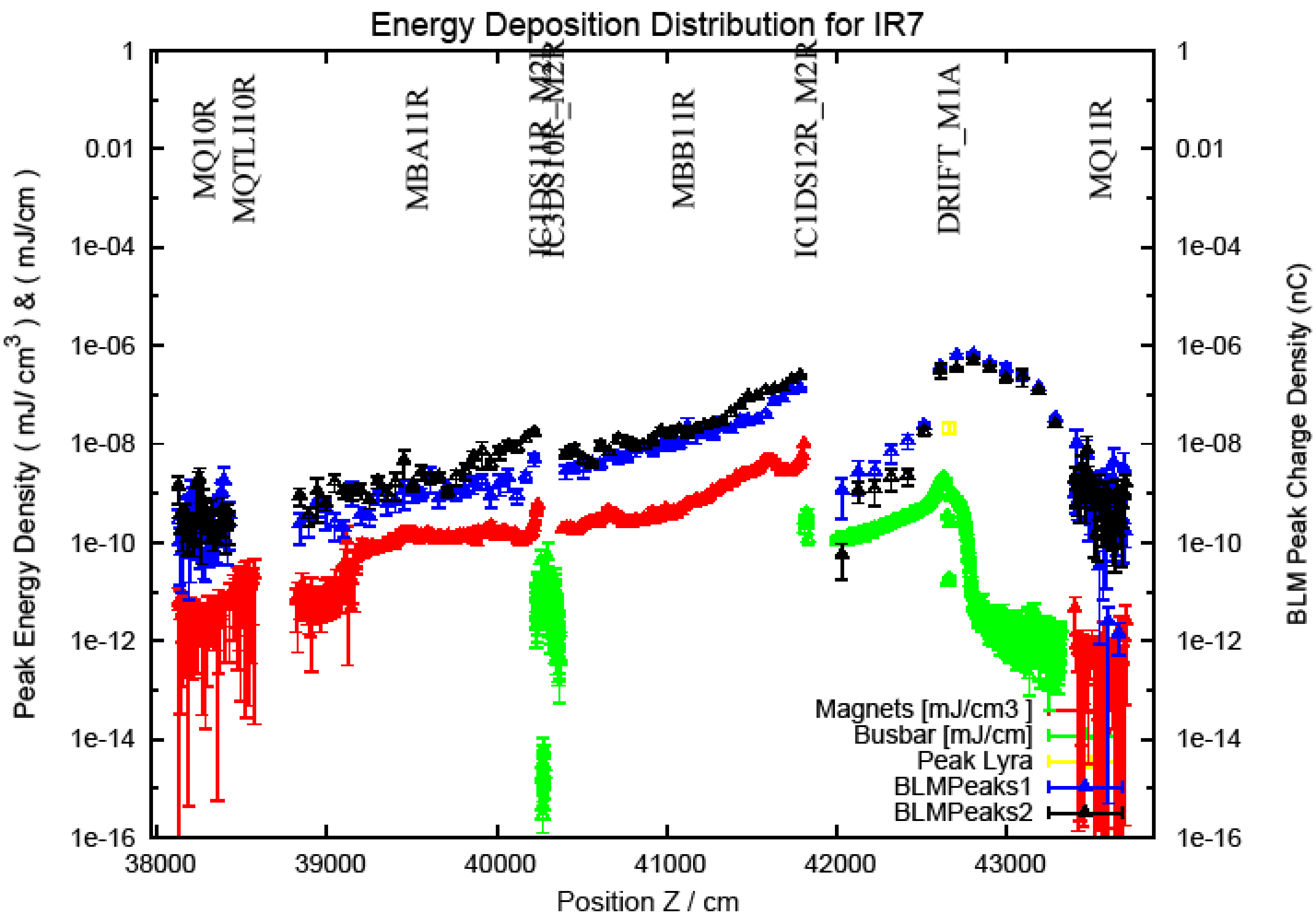
Number Of Protons To Quench Both

MQ12 3TeV

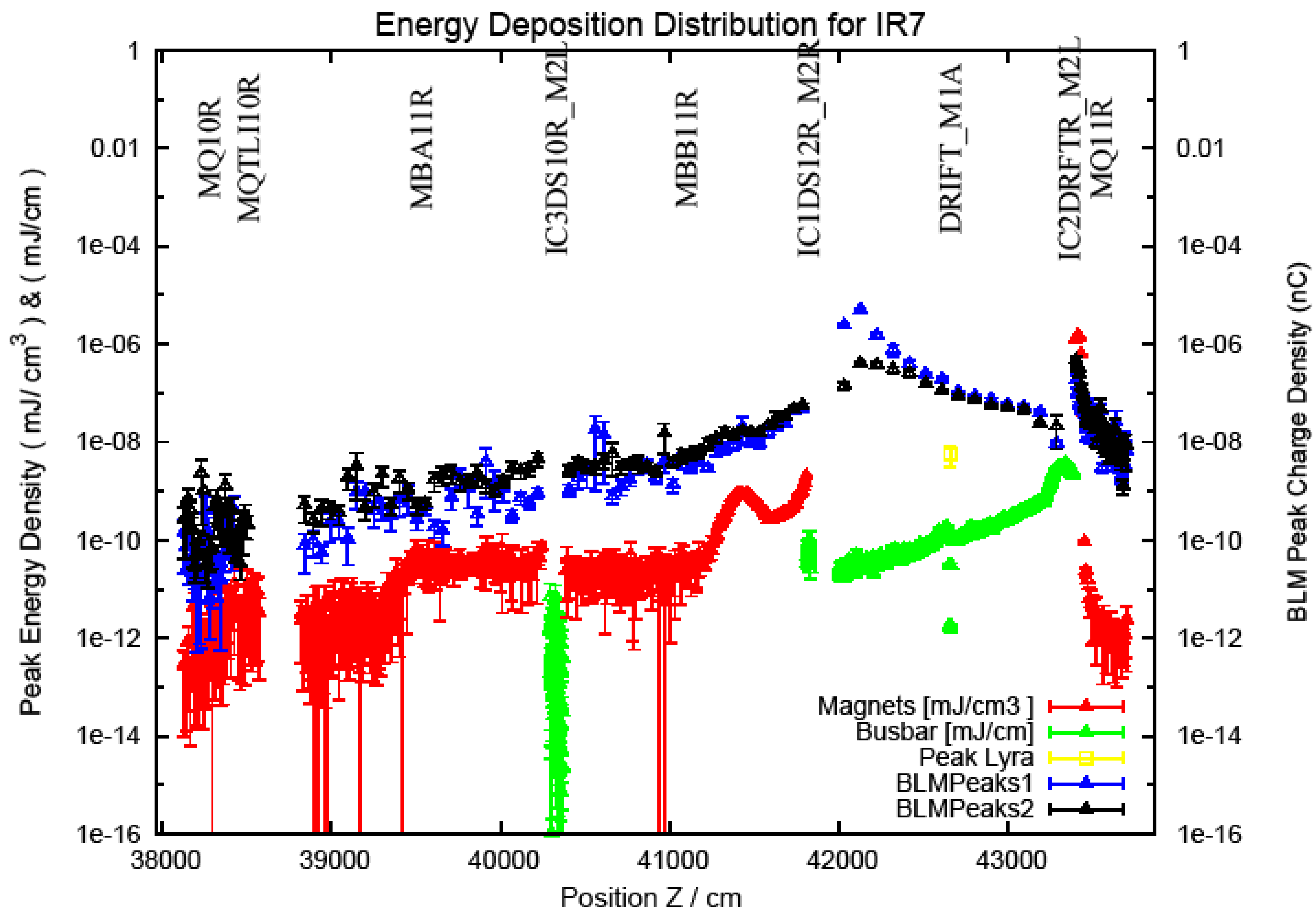
	Point-like Loss in MQ12 (3TeV)					
for	1 proton	1.40E-10	2.10E-08	2.30E-09	8.80E-07	[mJ/cm3]
for	4.35E+09 # of protons	0.61	91.30	10.00	3826.09	[mJ/cm for Busbars]
	Distributed Loss in MQ12 (3TeV)					
for	1 proton	2.60E-10	1.00E-08	1.00E-09	1.70E-07	[mJ/cm3]
for	1.00E+10 # of protons	2.60	100.00	10.00	1700.00	[mJ/cm for Busbars]
		MBB12R	IC MBC12R	IC	MQ12R	



Analysis Plots. Empty Cryos. Point Loss



Analysis Plots. MQ11 Point Loss



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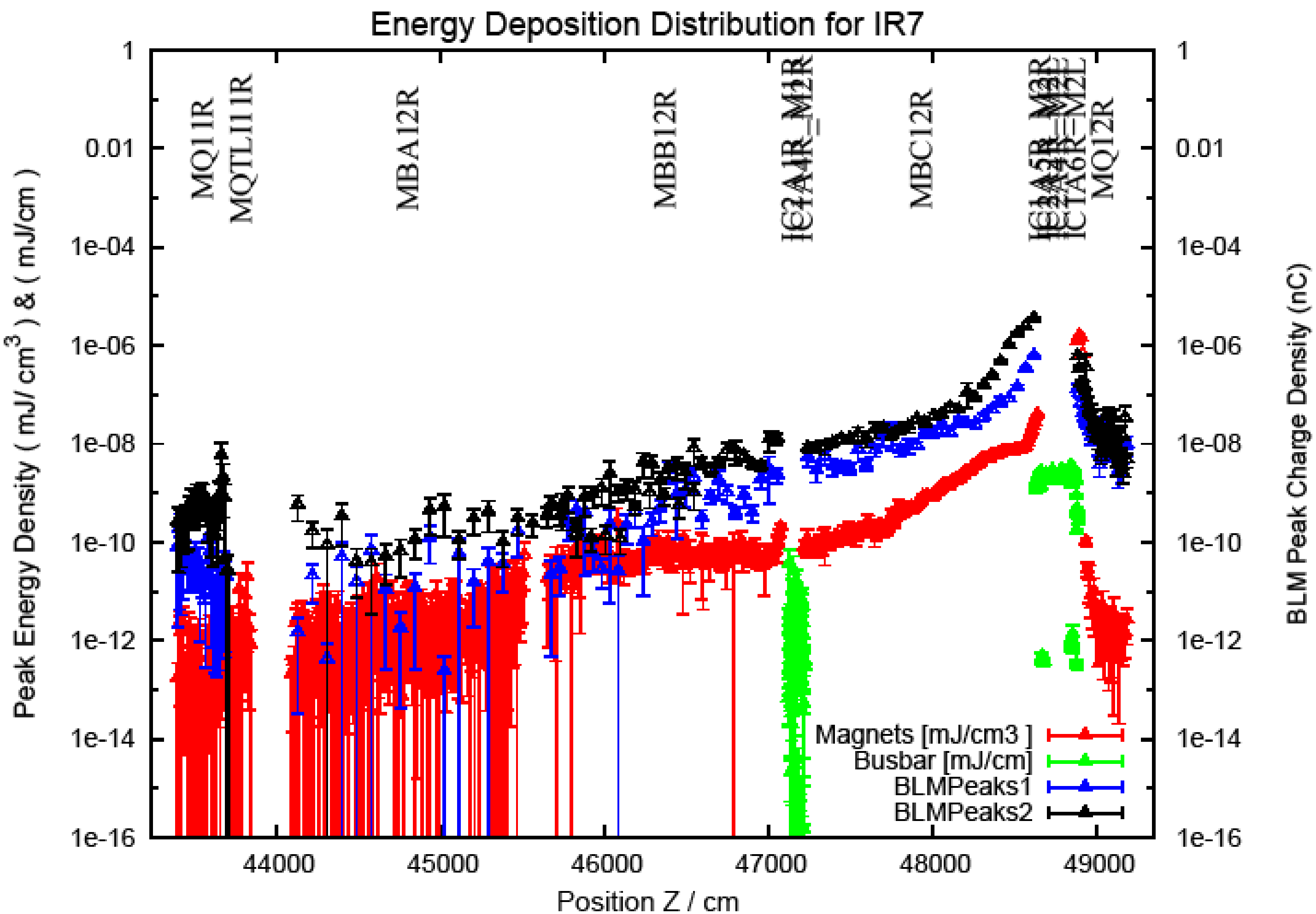

Energy Deposition Distribution for IR7
Peak Energy Density (mJ/ cm^3) & (mJ/cm)
BLM Peak Charge Density (nC)
Position Z / cm
MQ11R
MQTLI11R
MBA12R
MBB12R
MBC12R
MQ12R
Magnets [mJ/cm3]
Busbar [mJ/cm]
BLMPeaks1
BLMPeaks2
1
0.01
1e-04
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
44000
45000
46000
47000
48000
49000