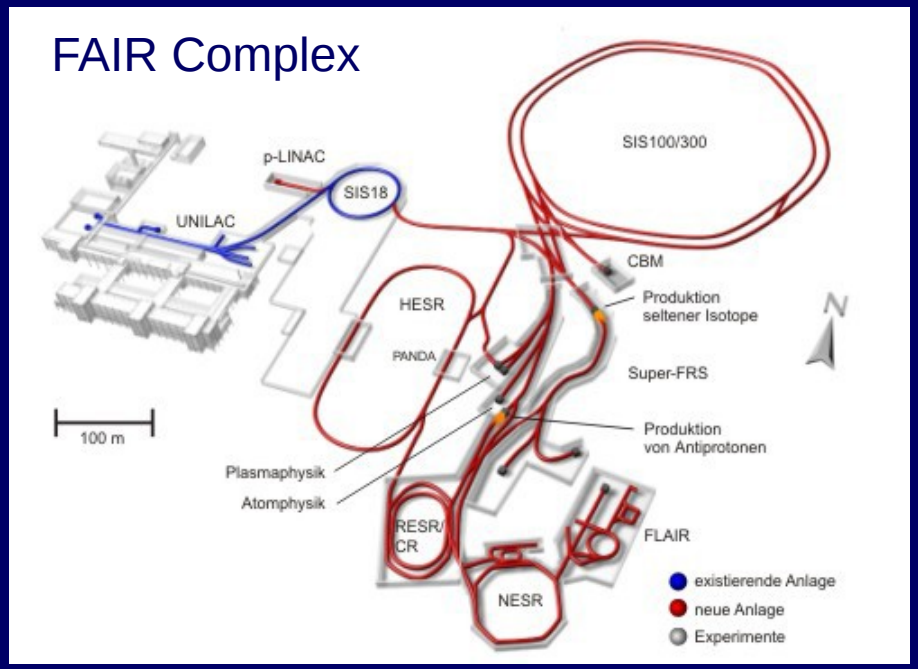
FLUKA Studies of Beam Loss Monitors for the SIS100 at FAIR/GSI:

General Diagnostics and Quench Prevention of Superconducting Magnets

Sanja Damjanovic

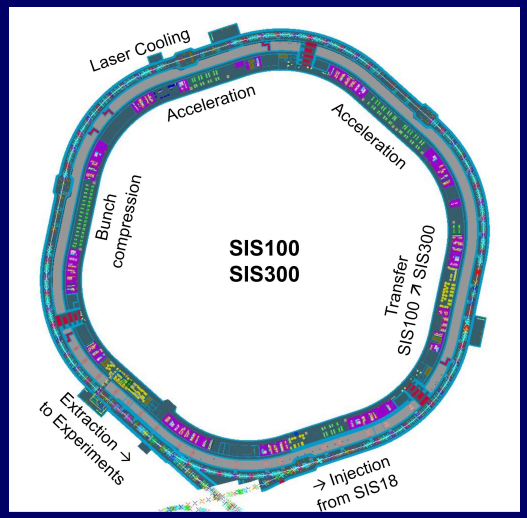
FC2WG Meeting, GSI, 18 November 2015

Superconducting Synchrotron SIS100 at FAIR/GSI



The SIS100 will provide world-wide unique operation with high-intensity intermediate charge-state heavy ions, e.g. 5×10^{11} U^{28+} per synchrotron pulse up to 2.7 GeV/u

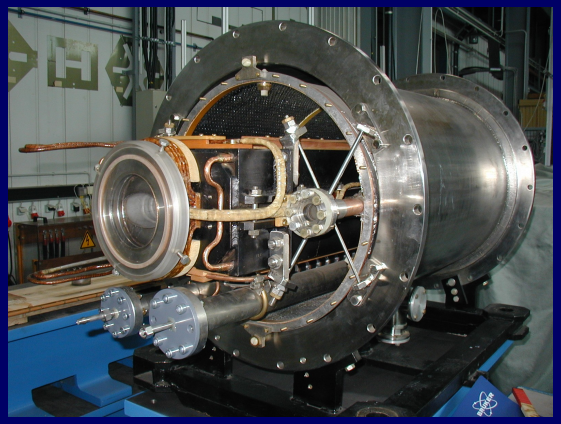
To achieve the goal of delivering high intensity beams, the SIS100 is designed as a superconducting synchrotron with short cycling times (1 Hz) and ramping rates of 4 T/s up to 1.9 T



SIS100 Lattice Structure

- hexagonal geometry
- altogether 280 SC main magnets (D and QP), and 144 SC correctors (steerers, sextupoles, multipoles) arranged in lattice cells: D-DQ-Corrector-FQ-D
- circumference about 1km

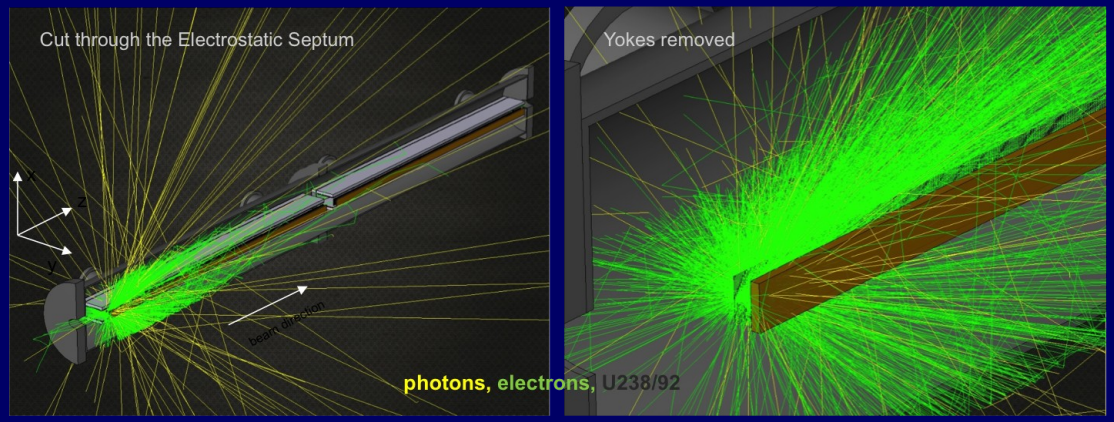
NUCLOTRON type magnets



Principal aim of the present studies

Beam losses unavoidable during the operation of any accelerator. Mechanism for the losses at SIS100 during normal operation: slow extraction (interaction of the beam with the wires of the electrostatic septum), ionization (charge exchange), beam halo generation

single event of an interaction of a U beam with the wires of the electrostatic septum



BLMs essential for diagnostics:

without them, blindness to beam losses and no possibility to verify whether the losses are acceptable

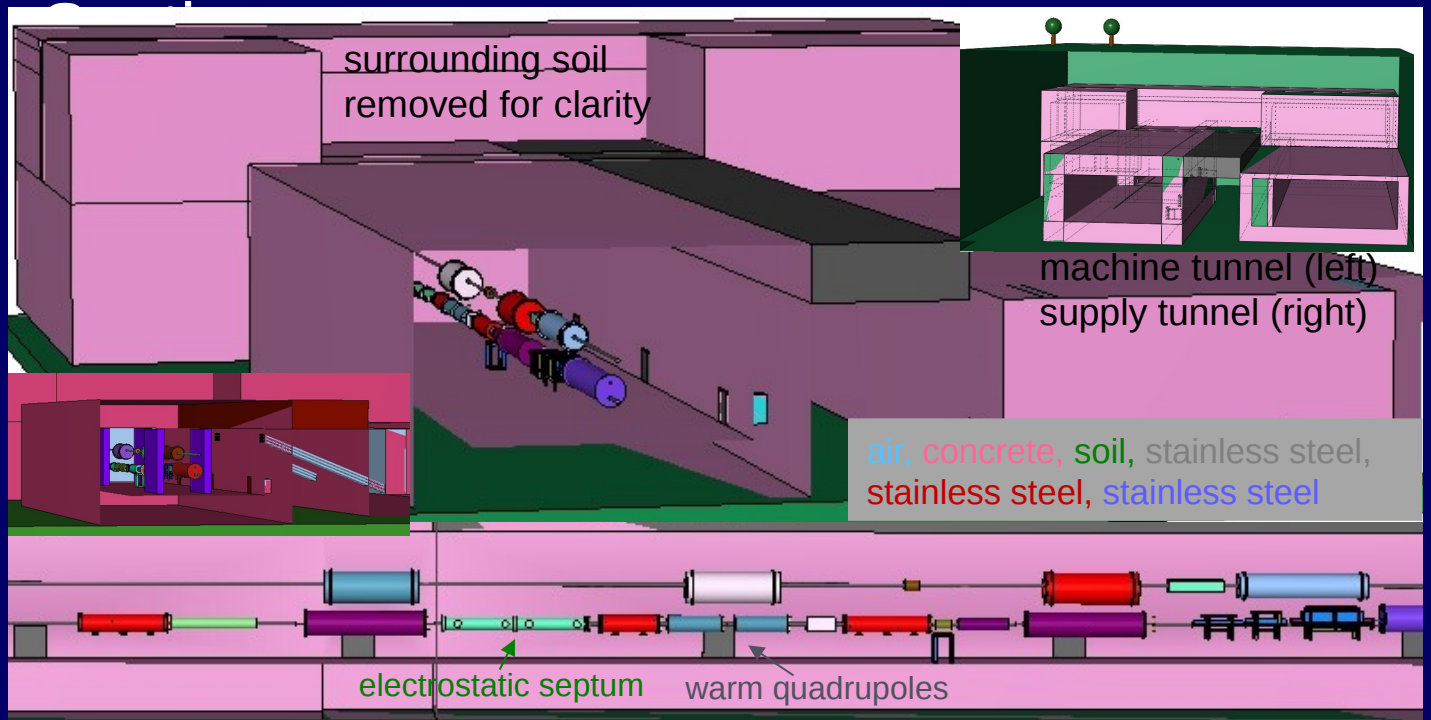
Recent decision: to install about 180 LHC-IC type BLMs along the whole SIS100 circumference

However, given the lower sensitivity threshold of the LHC-IC type monitors of ~10 pA, and inconclusive previous experience with the SIS18 machine, the question arose what level of beam losses at SIS100 could be detected by these monitors

In order to answer the question, use FLUKA simulations to calculate the response of these detectors to the expected (steady) beam losses at SIS100

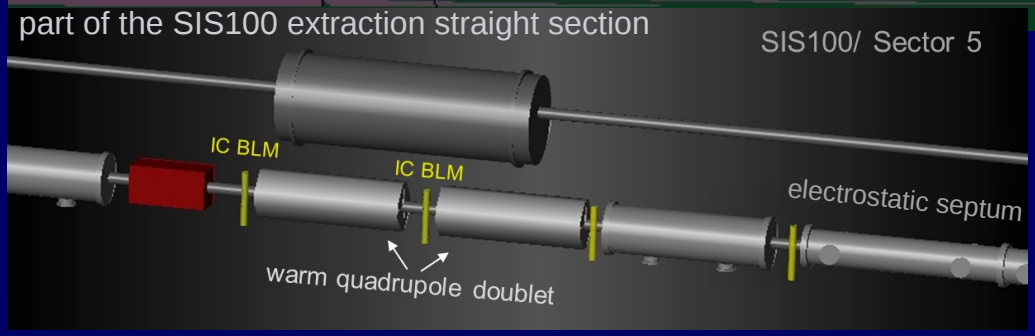
Since the BLM system can not only be used for diagnostics, but could also play an essential role in the machine protection system, the FLUKA simulations were extended to estimate the BLM quench prevention thresholds for use in an interlock system (as done at the LHC)

FLUKA Geometry of the SIS100 Extraction Straight Section



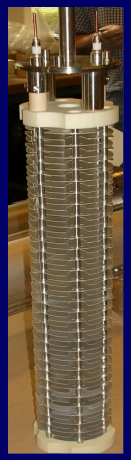
SIS100 extraction straight section comprises many different components

slow, fast and emergency extraction combined in one single straight section

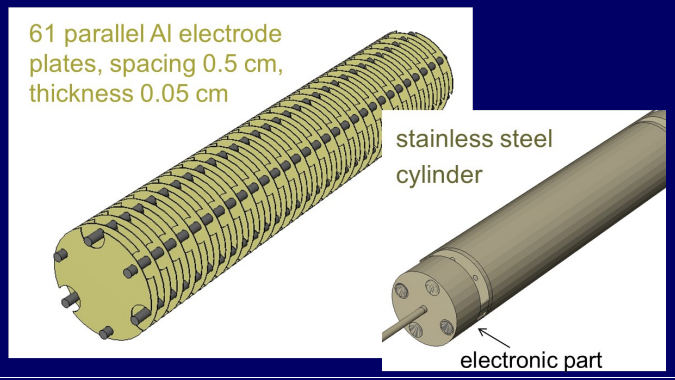


FLUKA geometry of the LHC-IC type BLM

(source: FLUKA team)



LHC BLM IC: length 59.9 cm, diameter 8.9 cm, sensitive volume 1.5 l, filled by nitrogen at 1.1 bar



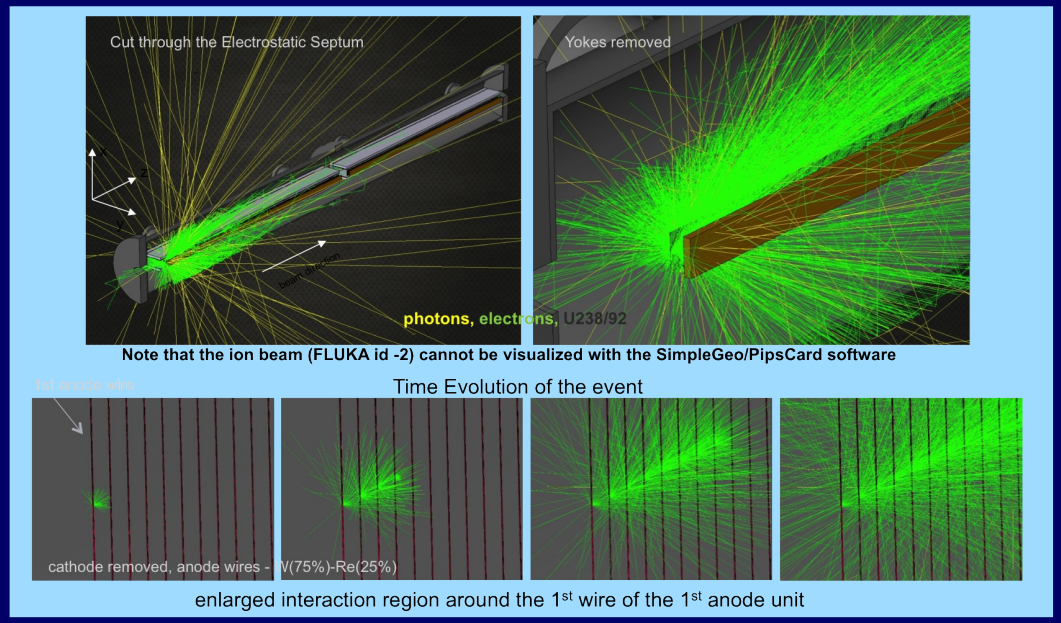
LHC-IC BLM:
lower threshold 10 pA (limited by leakage current through insulator ceramic), dynamic range 10^8 (upper limit: saturation due to space charge)

Sensitivity of Beam Loss Monitors (BLMs) to beam losses at the SIS100 Extraction Straight Section

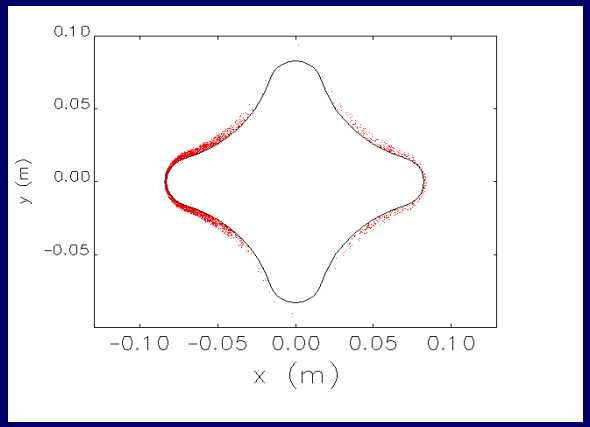
Assumptions for the simulations

- Uranium beam of E_k=0.2 and 2.7 GeV/u
- beam intensity: 5×10^{11} ions/cycle (cycle time 3.2 s)
- source: particles lost during slow extraction intercepted by the two warm quadrupoles (impact at the centers with equal probability)

Tracking a realistic U beam through the electrostatic septum of SIS100 with FLUKA (single event display)



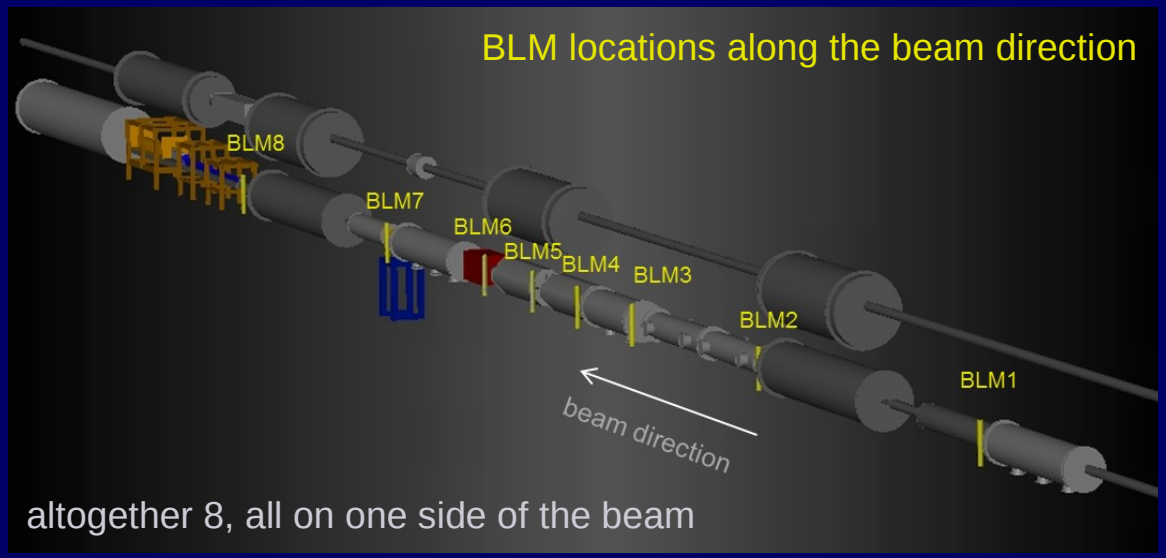
Tracking of the interacting particles through the two radiation hard QPs (D. Ondreka)



cross section of the beam pipe through the warm QPs

Optional positions of Beam Loss Monitors (BLMs) along the SIS100 Extraction Straight Section

select different locations along Extraction Straight Section to study the longitudinal dependence of the BLM signals (to be used for optimization of the BLM positions)



BLM1 – downstream of Kicker S5.1

BLM2 – downstream of Cryog.QD S5.1

BLM3 – downstream of Electrostatic Septum

BLM4 – downstream of Kicker S5.2

BLM5 – downstream of warmQP1

BLM6 – downstream of warmQP2

BLM7 – downstream of Kicker S5.3

BLM8 – downstream of CryoQD S5.3

Analysis Procedure

Two different methods to extract the response of the LHC-IC type BLMs in terms of current

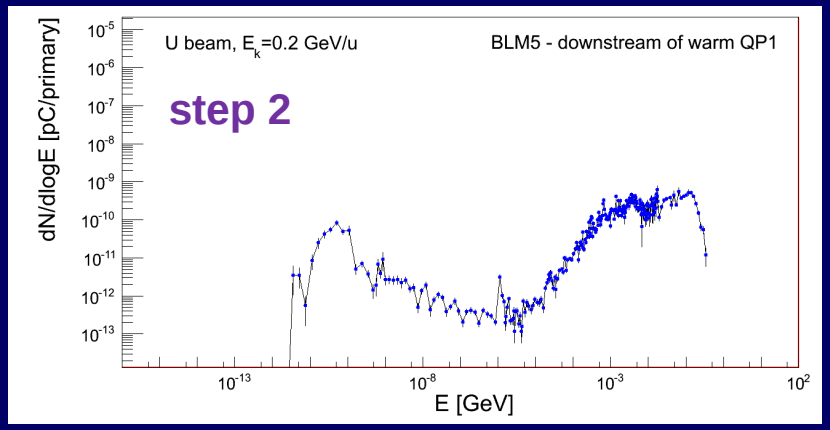
Method I :

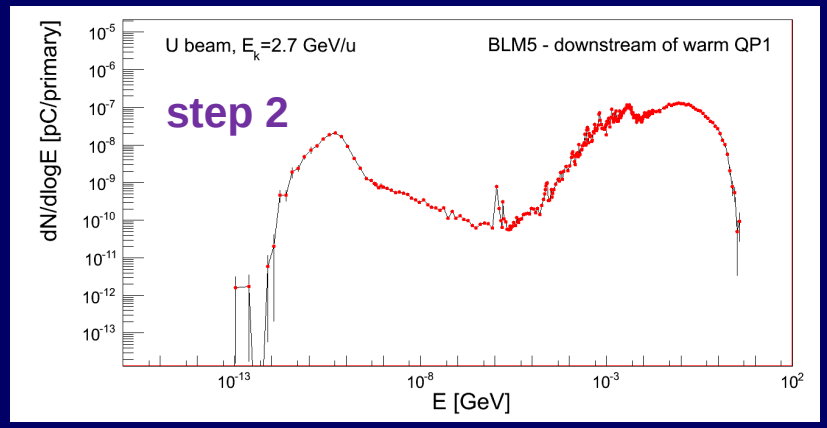
- Simulate fluence spectra of all particles within the active volume of the BLMs (1)
- Fold spectra with a specific response function (2) and integrate over energy (3) to get charge/primary

LHC-NOTE 422 (2008)

CERN-EN-NOTE-2010-001

two examples of folded fluence spectra



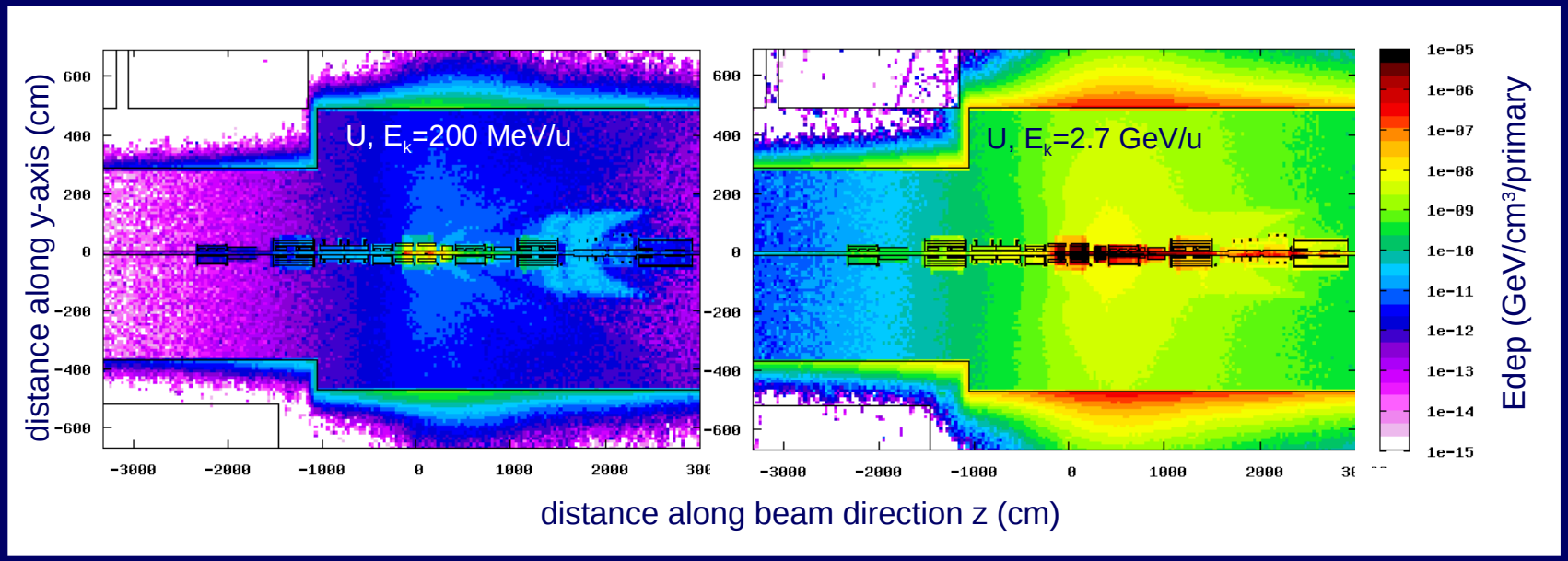


- Multiply with beam loss intensity to obtain current in the BLMs (4)

Analysis Procedure

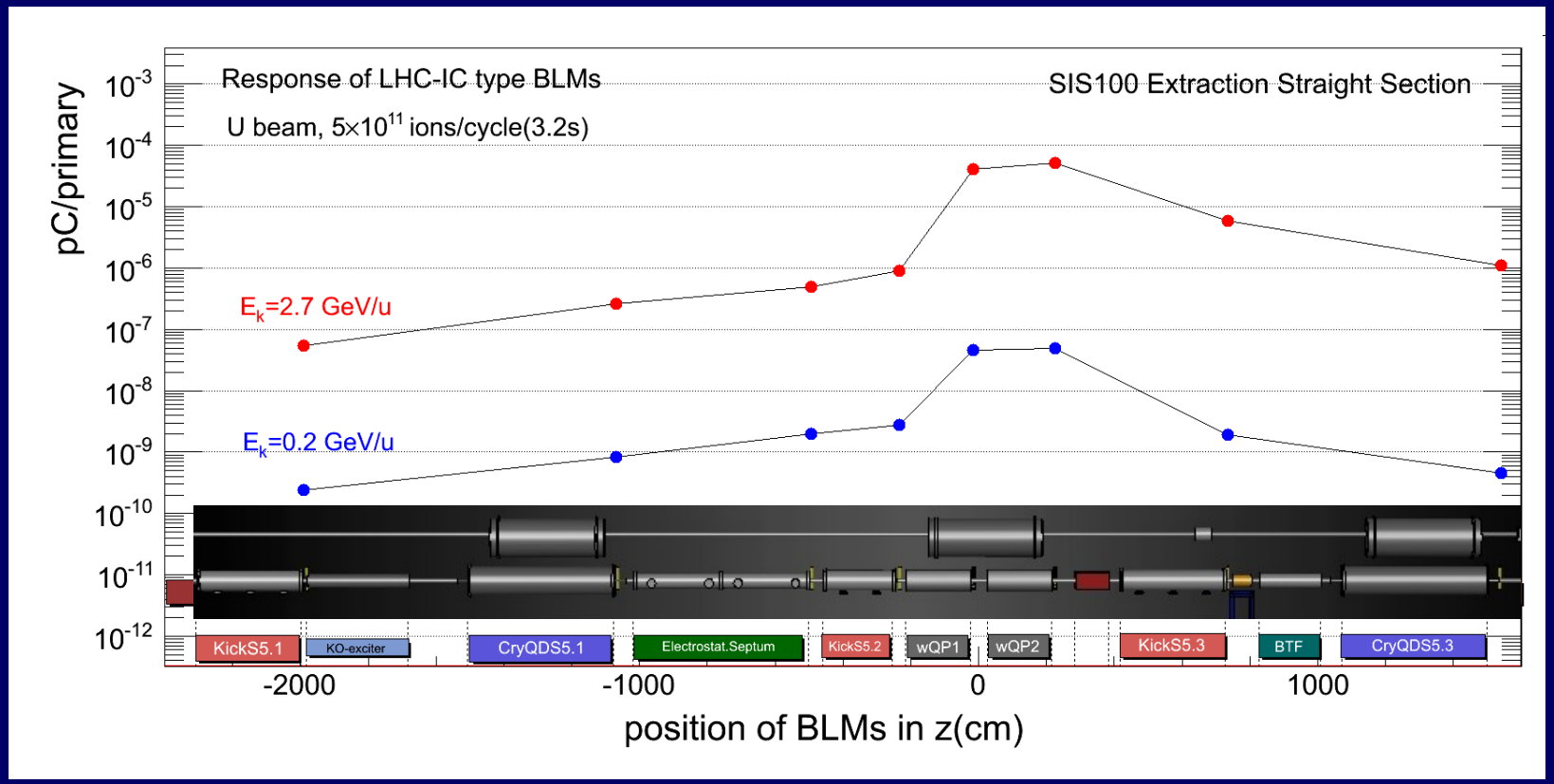
Method II :

- Calculate directly the energy deposited in the active volume of the BLMs in terms of GeV per primary
- Extract the charge by using the W conversion factor, i.e. the average energy required to produce an electron-ion pair; W=34.8±0.2 eV for the case of nitrogen



Although the two methods give the same result, the folding method has several advantages, e.g. much less CPU time required to achieve good statistics (the results to follow based on the folding method)

Response of the IC-type BLMs in pC/(lost primary) to beam losses during slow extraction (lost particles intercepted by warm QPs) for E_k=0.2 and 2.7 GeV/u



Values at injection energy E_k=0.2 GeV/u smaller by about 3 orders of magnitude compared to the values at extraction energy E_k=2.7 GeV/u

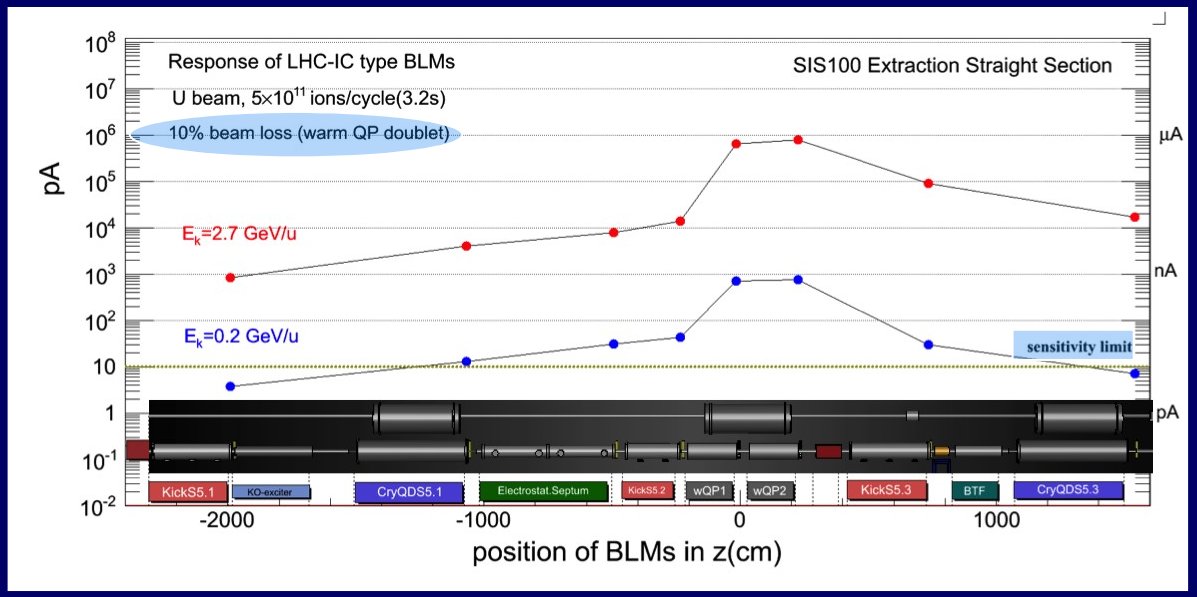
The two BLMs downstream of the warm quadrupoles with the highest signal (closest to the source) sensitive to losses of 0.1% at the lowest and 0.0001% at the highest energy

Conclusions I

- Great sensitivity of the LHC-IC type BLMs to the beam losses within the radiation-hard warm quadrupoles (slow extraction, halo collimation)

- Instantaneous radiation caused by 0.1% beam losses at the lowest- and 0.0001% at the highest energy detectable by these monitors, providing a sensitivity to beam loss rates of >1.5×10^8 and >1.5×10^5 ions/s, resp.

Response of the IC-type BLMs in pA to 10% beam losses



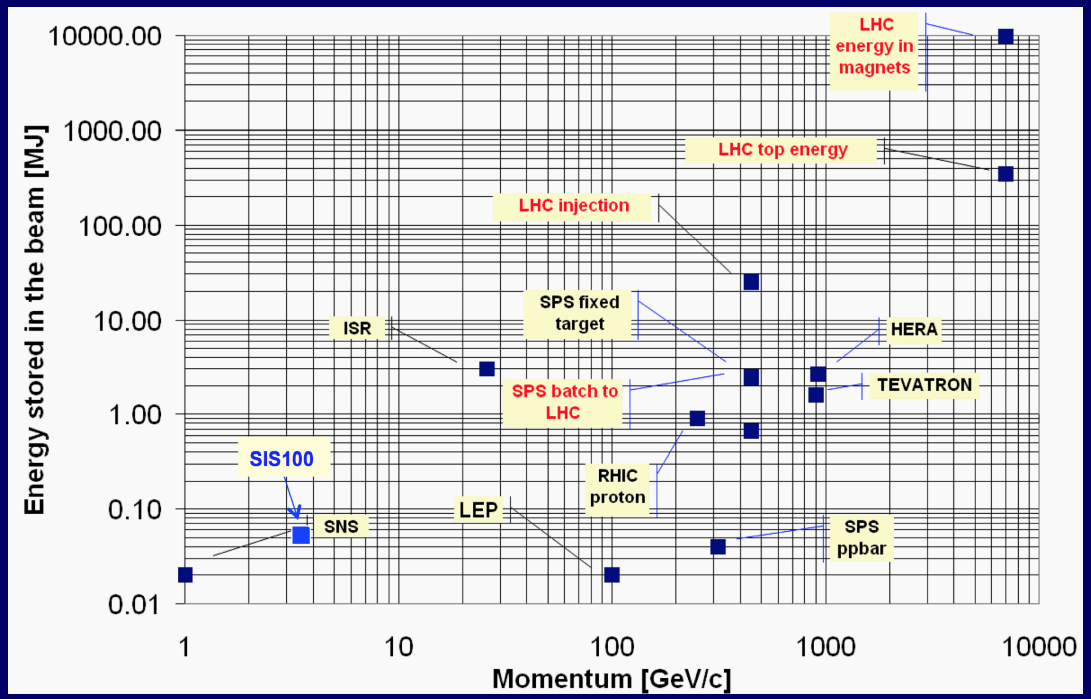
Simulations to be redone once more details have become available (exact beam loss probability distribution along the two warm QPs, exact position of the planned collimator in between...)

Quench prevention of the SIS100 Quadrupole Modules by a BLM system?

In lack of a systematic input of all important sources of failures, i.e. uncontrolled beam losses at SIS100, the steady-state losses due to charge exchange of ions in the rest gas are taken as a representative example to investigate the usefulness of a BLM system for quench prevention

Machine protection

source R. Assmann ?



Stored beam energy for various accelerators

To ensure safe operation (without damage), a safe disposal of all energy required

Compared to other accelerators the total energy of the SIS100 ion beam is very low, i.e. a factor of 7000 lower than at the LHC

While the overall damage potential at SIS100 seems much lower, this does not mean that the protection of the machine has to be less strict

In certain accidental scenarios involving e.g. the beam pipe, the damage problem can also be severe at SIS100, due to the Z^2 dependence of the initial energy deposition

Machine protection

To ensure a safe operation (without damage), a safe disposal of all the energy required

LHC p @ 7 TeV
2808 bunches with 1.15×10^{11} p each;
beam size $\sigma_{x/y}$=0.3 mm

SIS100 U @ 2.7 GeV/u
5×10^{11} ions per spill;
beam size $\sigma_{x/y}$=3 mm

total beam energy 362 MJ **total beam energy 0.05 MJ**

> 7000 higher value at LHC

Consider the beam hitting a thin (1 mm) wall of a vacuum chamber

peak Energy density depos. 20 kJ/g **peak Energy density depos. 2 kJ/g**

a factor of 10 higher value at LHC

both values above the critical energy density of 1.1 kJ/g to melt steel!

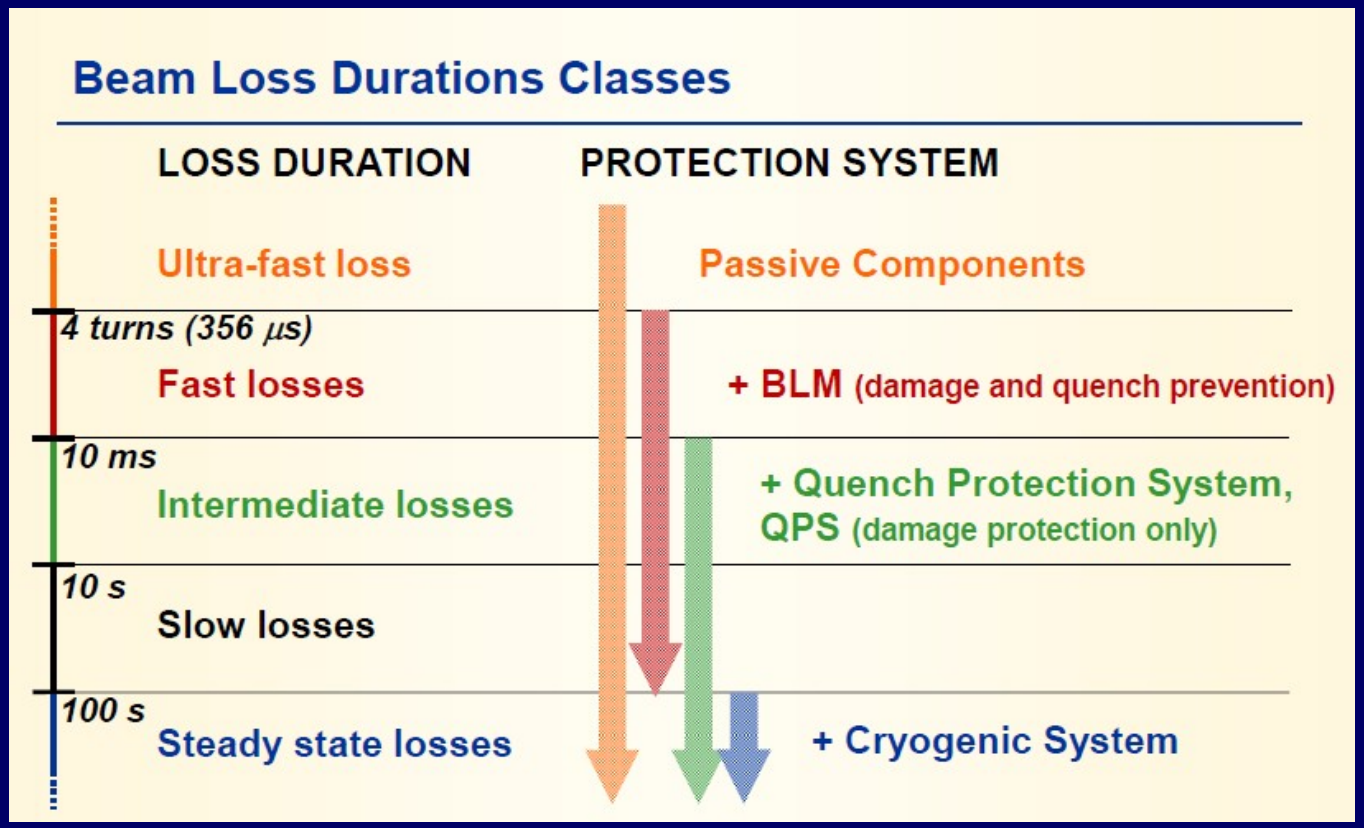
total Energy deposited 100 J/mm **total Energy deposited 760 J/mm**

a factor of 8 higher value at SIS100 !

Later stages of the energy deposition, including secondaries:
as little as 1 mJ/g deposited energy quenches a magnet, and 15 J/g (?)
causes magnet damage protection of SIS100 should also be very strict

Uniqueness of the BLM system for Quench Prevention

The LHC-IC type BLMs were designed with the goal to be very fast (integration time between 40µs and 84s), to be radiation hard, to have a high realibility and a large dynamic range (from pA to mA)



BI group, CERN

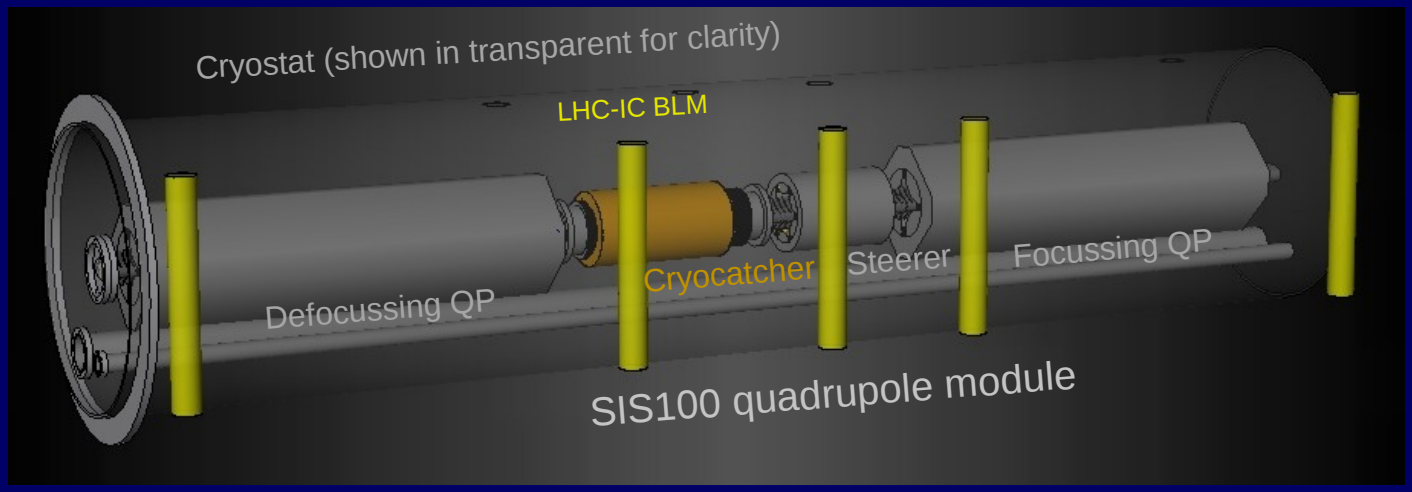
BLMs only system for quench prevention

BLMs only active system for magnet protection between 100 µs and 10 ms

Principal Aim of the Studies

Use FLUKA simulations to evaluate the correlation between the energy deposition inside the superconducting coils and the signals in BLMs outside the cryostat (as done for the LHC magnets)

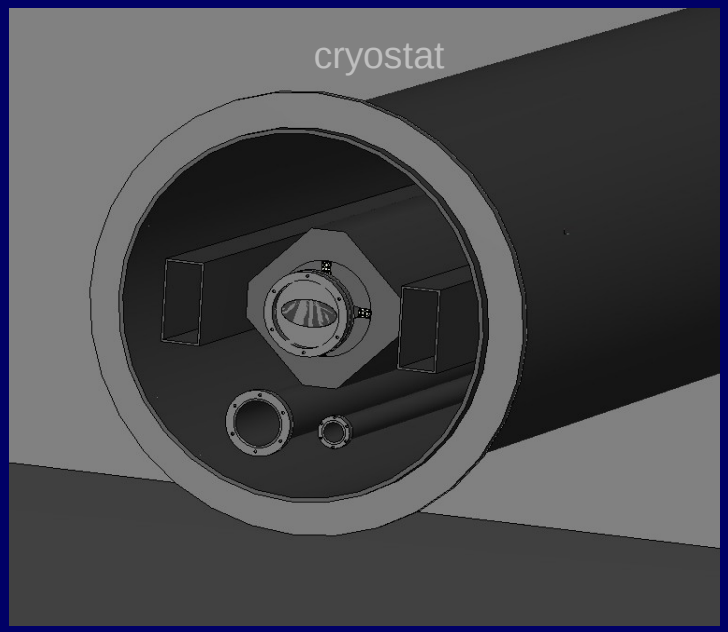
Find out whether the LHC-IC type BLMs (lower threshold of ~10pA) are sensitive to the 'quench-prevention threshold'

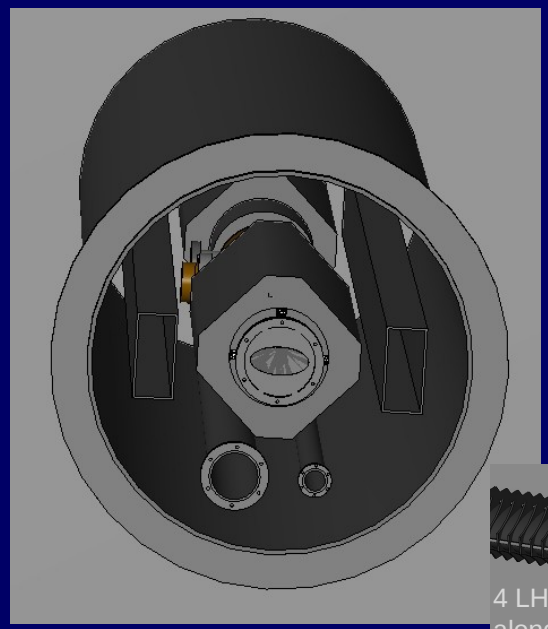


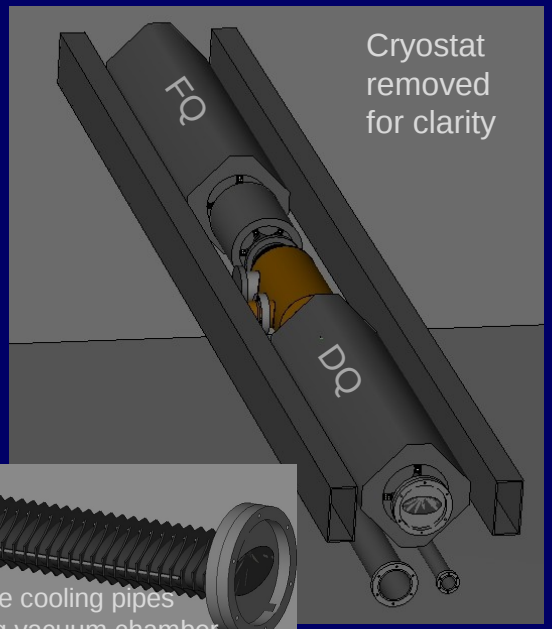
The BLM threshold depends on beam energy, type of losses, loss location, loss duration

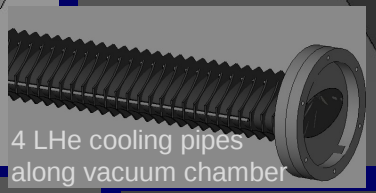
Example for an important mechanism for ion beam losses at the SIS100: charge exchange between the ion beams and the rest gas (steady–state source)

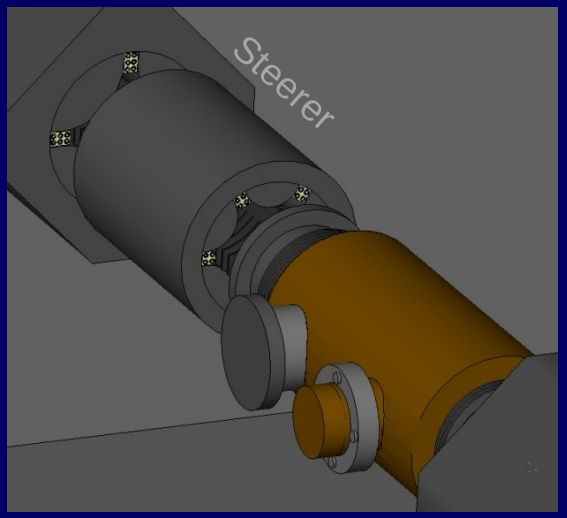
FLUKA geometry of a SIS100 Quadrupole Module

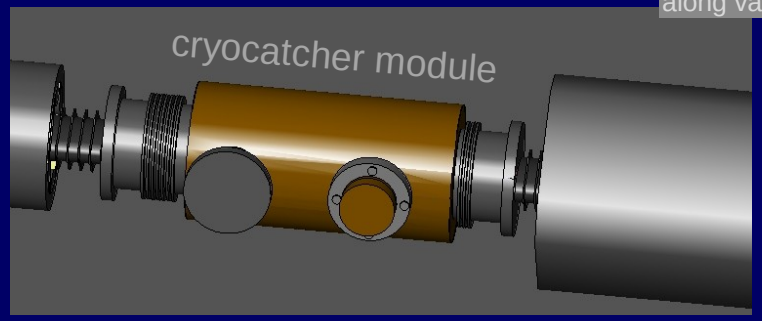


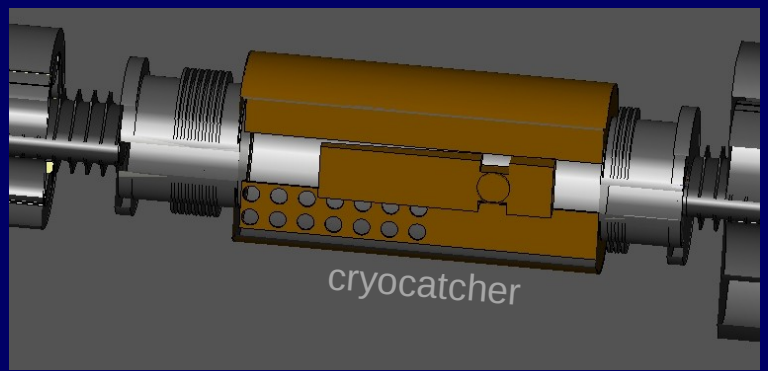


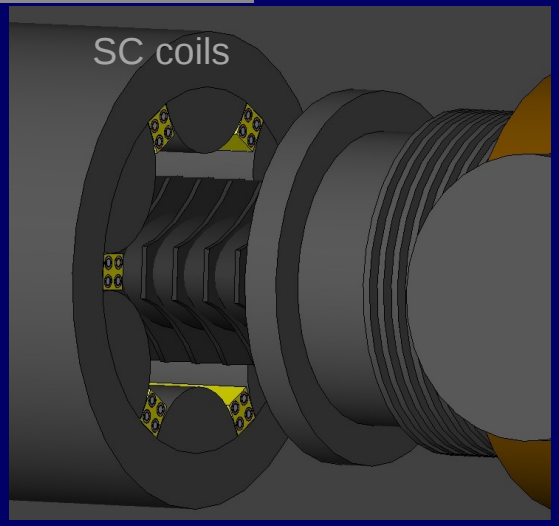










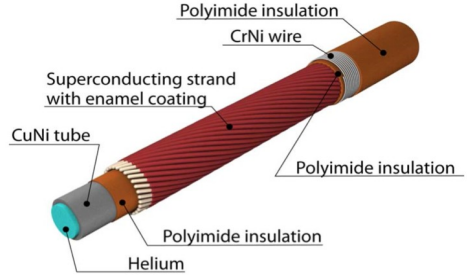


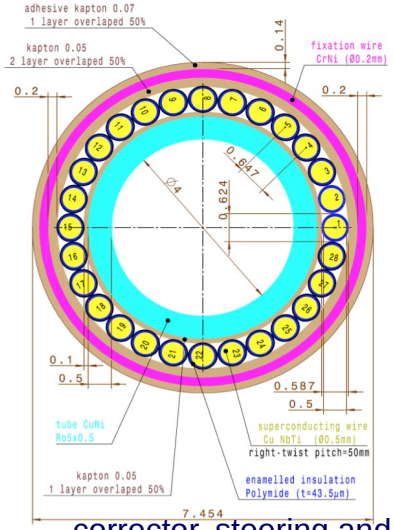
copper stainless steel epoxy

SC cables:
Kapton, NiCr, Cu/NbTi CuNi
LHe

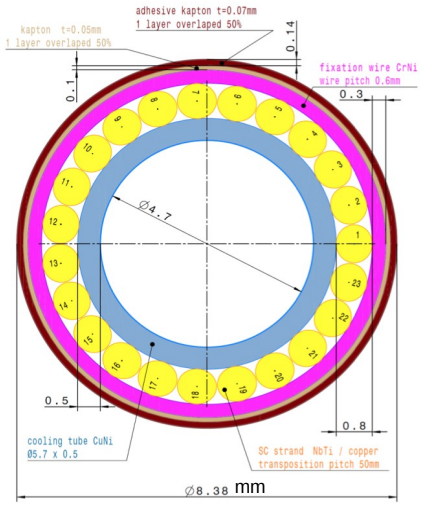
Nuclotron-type SC Cables: composition and dimensions

E. Fischer at al., Proc. of RUPAC 2012, 141





corrector, steering and chromaticity sextupole



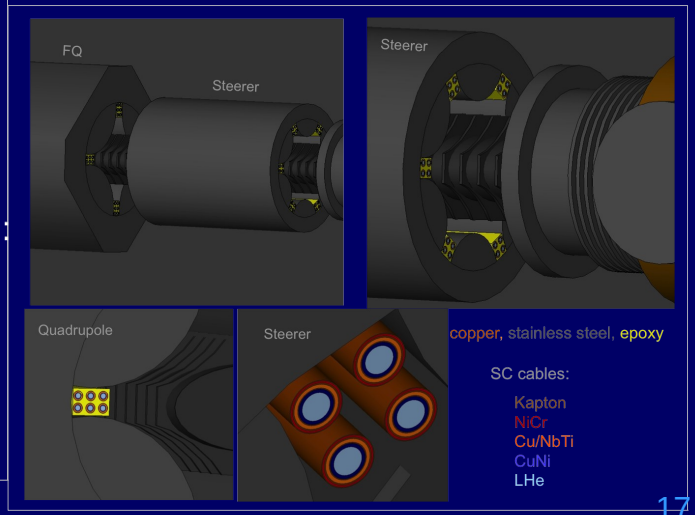
main magnets: dipoles and quadrupoles

schematic view of the hollow SC cables of the SIS100 magnets

two-phase He cooling

SC cables modeled as concentric tubes of Cu-Ni, Nb-Ti with Cu stabilizer, and the Ni-Cr fixation wires (Kapton part also included)

NiCr	50/50 %	cylinders; wall thicknesses 0.2/0.5 mm
Cu/NbTi	58/42%	approximated by cylinders; wall thickness of 0.5/0.8mm; fill factor of 80% for the superconducting strands → reduce density by 20% to conserve total amount of material
Cu/Ni	50/50%	cylinders; wall thicknesses 0.5 mm



Assumptions for the simulations

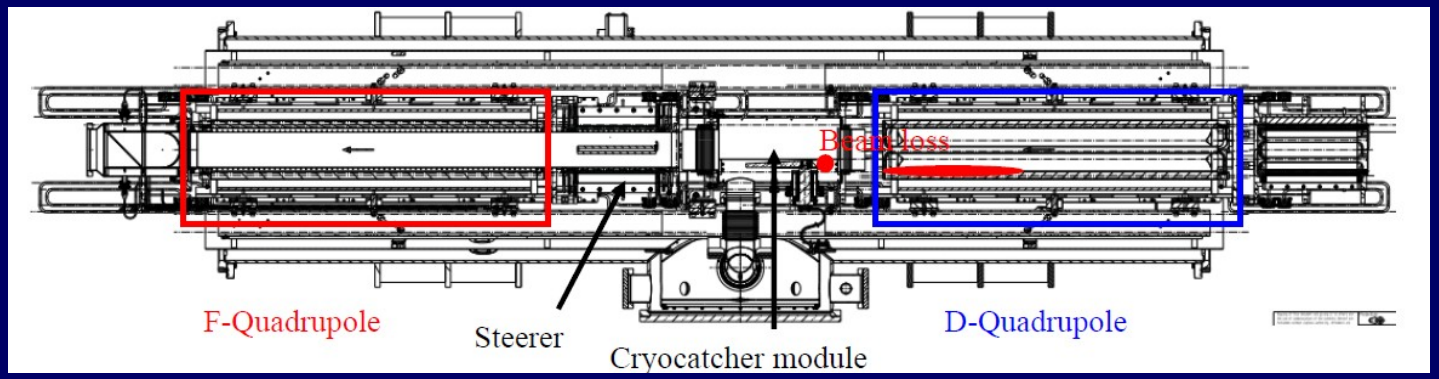
- U^{28+} beam of E_k=2.7 and E_k=0.2 GeV/u

input on beam trajectories based on tracking code StrahlSim (L.Bozyk)

- source I: Cryocatcher with distributed impact points

impact of charge-exchanged U^{29+} at the start of the Cryocatcher

Gaussian distribution in the vertical (x) and horizontal (y) direction with $\sigma_{x/y}$ =3 mm centered in the middle of the cryocatcher



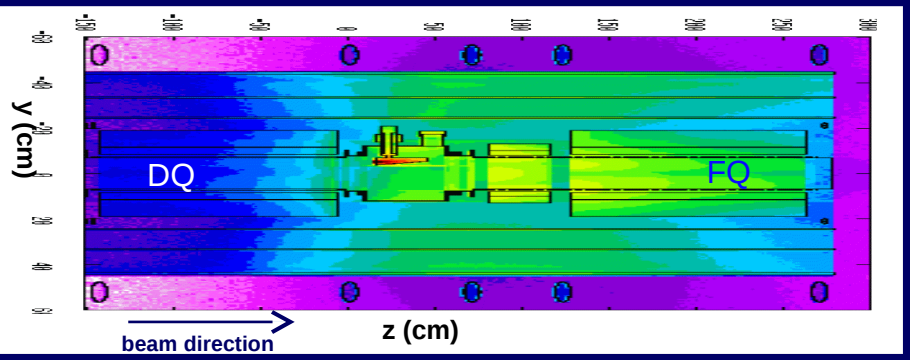
- source II: Defocussing Quadrupole Chamber wall with distributed impact points

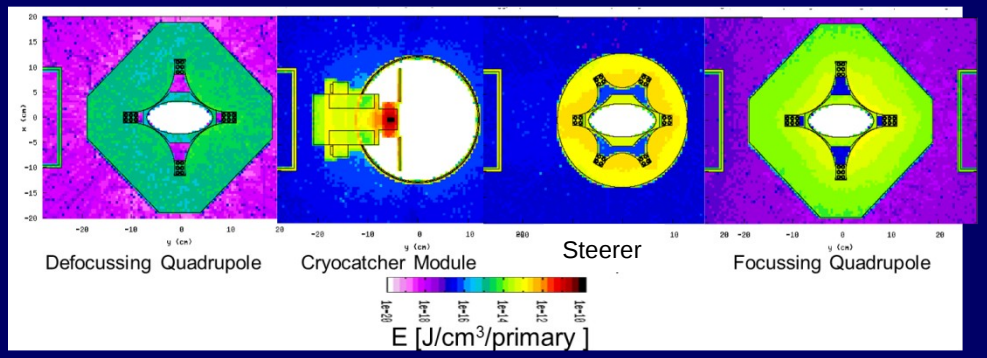
impacts of doubly charge-exchanged U^{30+} along the last 40% of quadrupole length with an angle θ=0.1°

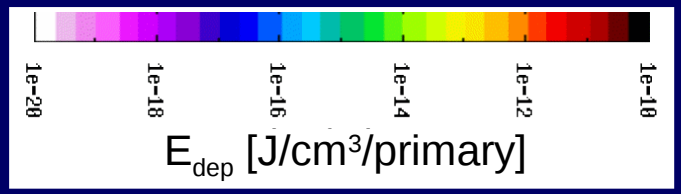
Gaussian distribution in the vertical direction with σ_x=3 mm

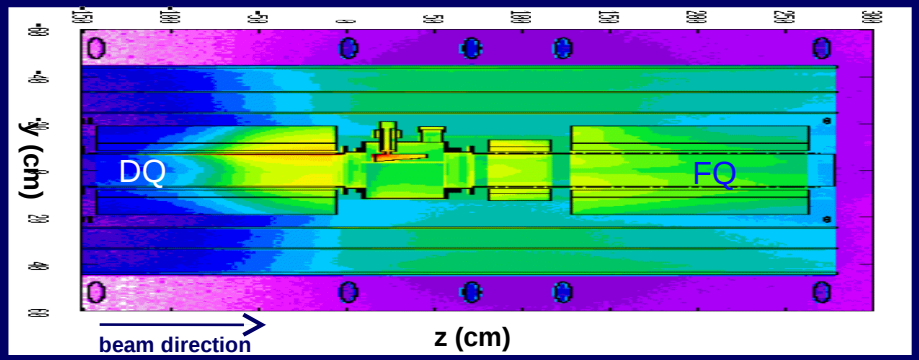
Energy Deposition in a QP Module – U beam, E_k=2.7 GeV/u

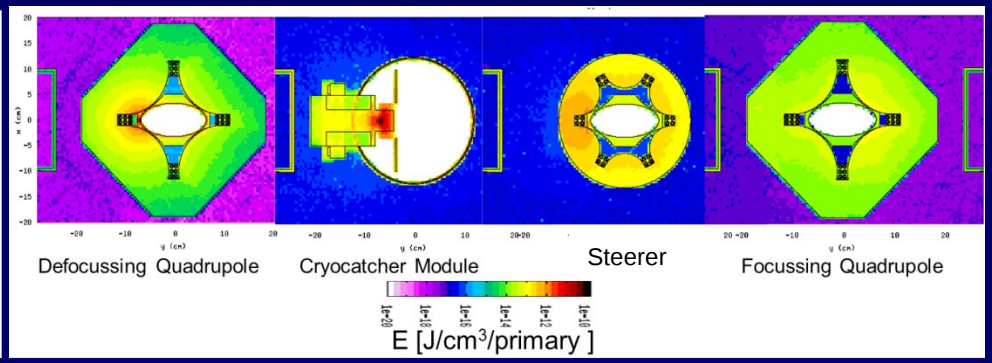
Source I – energy deposition from ions hitting the cryocatcher





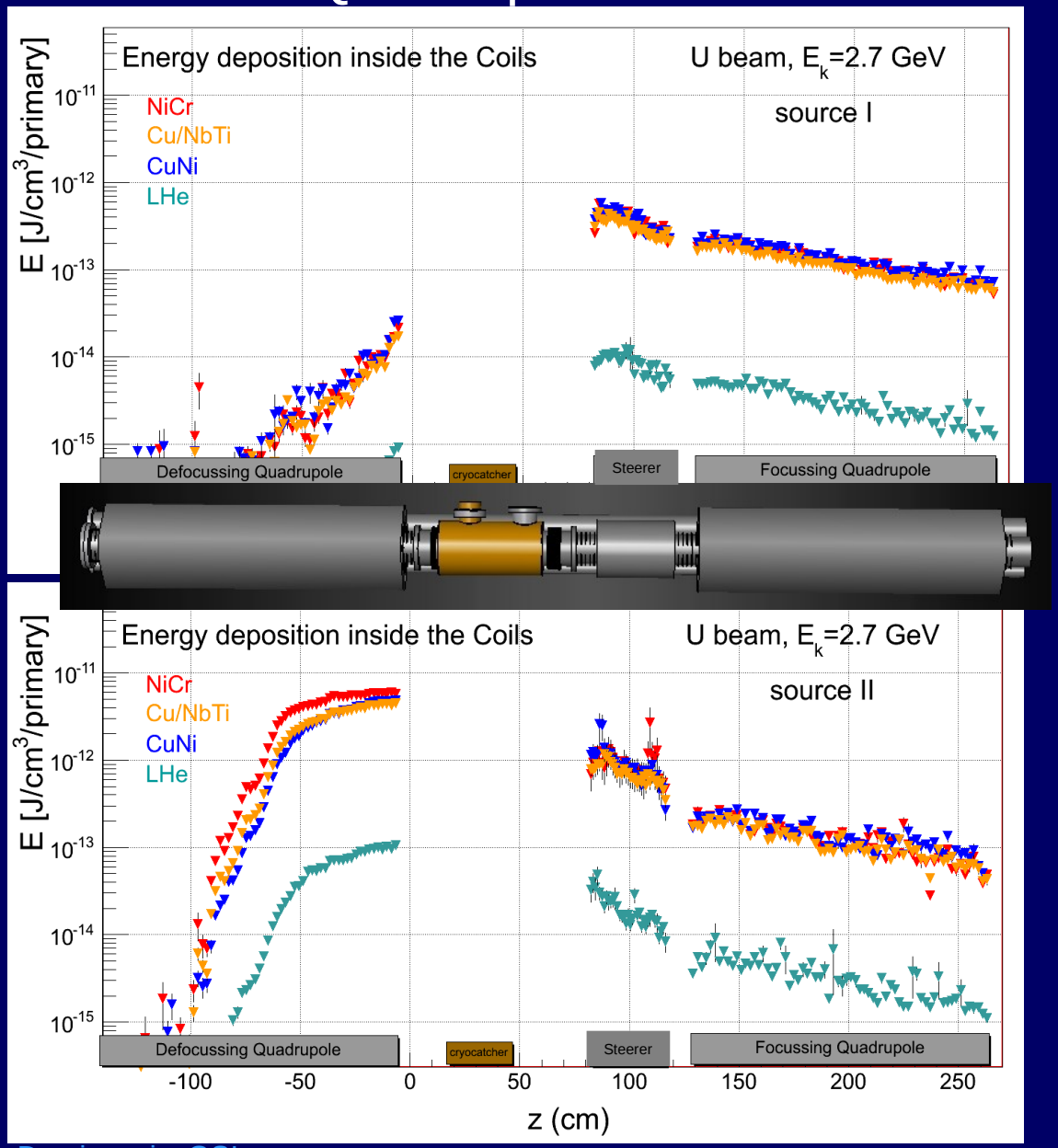






Source II – energy deposition from ions hitting the DQ chamber

Summary of Energy Deposition inside the Coils of the Quadrupole Module for the two sources



Source I

U^{29+} ions hitting Cryocatcher

Longitudinal profile of Maximum Energy Deposition located inside the two innermost coils on the left side of the beam (inner side of machine)

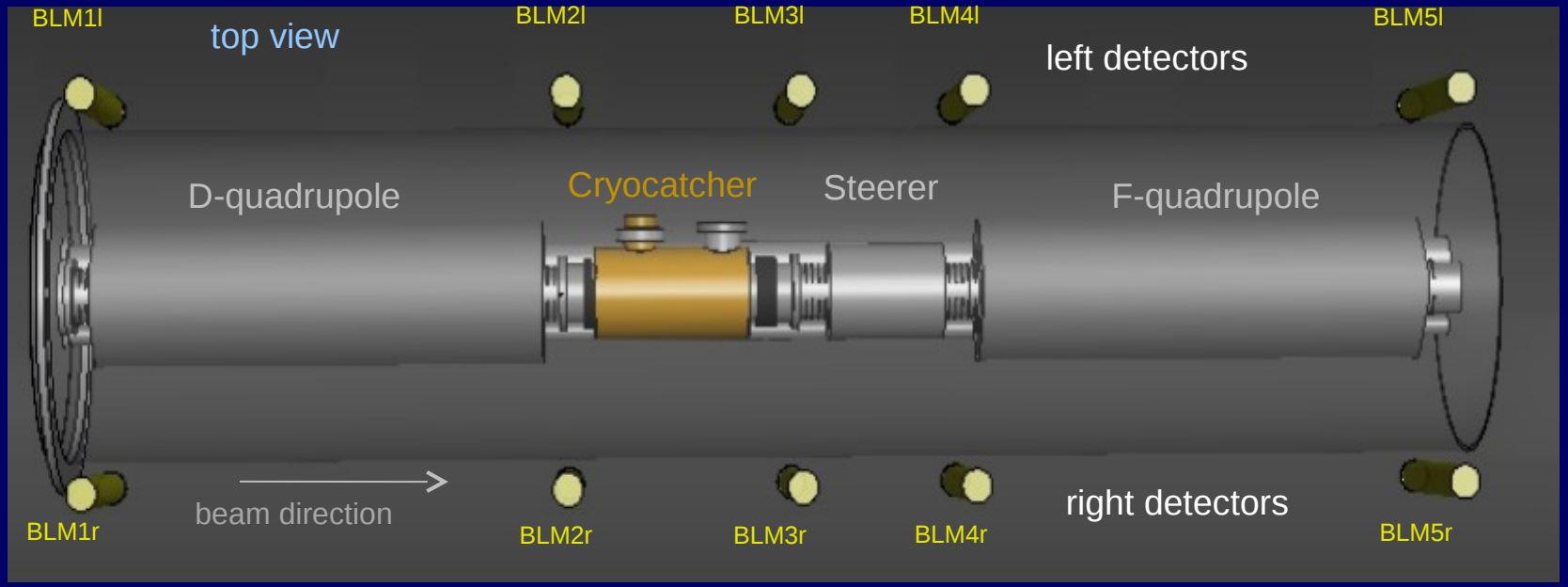
Source II

U^{30+} ions hitting vacuum chamber of DQ

Note: to extract the E_{dep} within the different layers of the SC coils very fine grids were used in radial and azimuth direction . Due to the steady-state loss case and due to the fact that the heat has time to locally spread, the bin size is matched to the volume of the cable layer considered to be in thermal equilibrium, Thus the 1-dim projections of E_{dep} are averaged over the cable layers transverse dimension

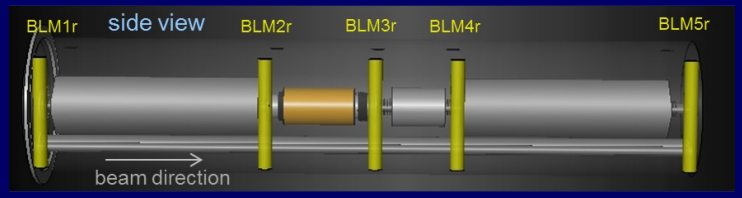
Optional locations of BLM monitors outside the cryostat

select different locations along a QP module to study the longitudinal dependence of the BLM signals (to be used for optimization of BLM positions)



Beam Loss Monitors – LHC type

altogether 5×2 positions studied on both sides of the beam



BLM1 l/r – upstream of Defocussing Quadrupole

BLM2 l/r – downstream of Defocussing Quadrupole

BLM3 l/r – downstream of Cryocatcher Module

BLM4 l/r – downstream of Steerer/Sextupole

BLM5 l/r – downstream of Focussing Quadrupole

indexes l/r refer to the left/right side of the beam

Simulation of BLM response - Analysis Procedure

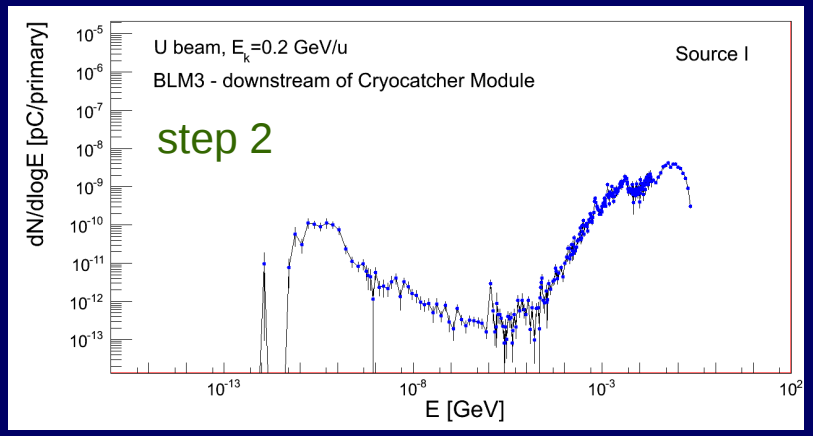
Two different methods to extract the response of the LHC-IC type BLMs in terms of current

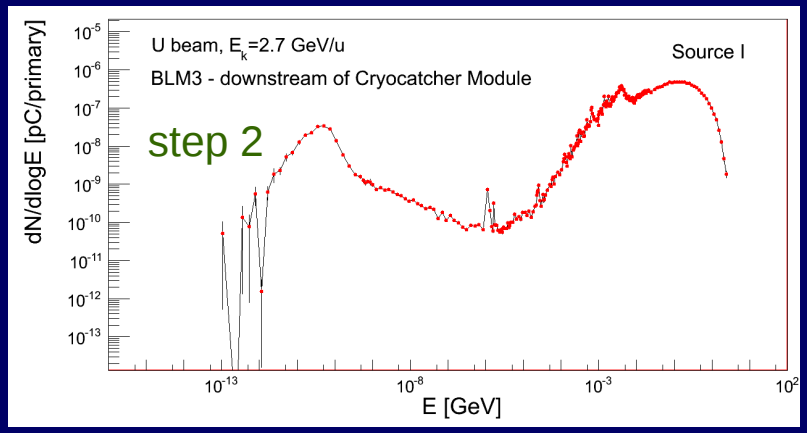
All results to follow based on folding Method I :

- Simulate fluence spectra of all particles within the active volume of the BLMs (1)
- Fold spectra with a specific response function (2) and integrate over energy (3) to get charge/primary

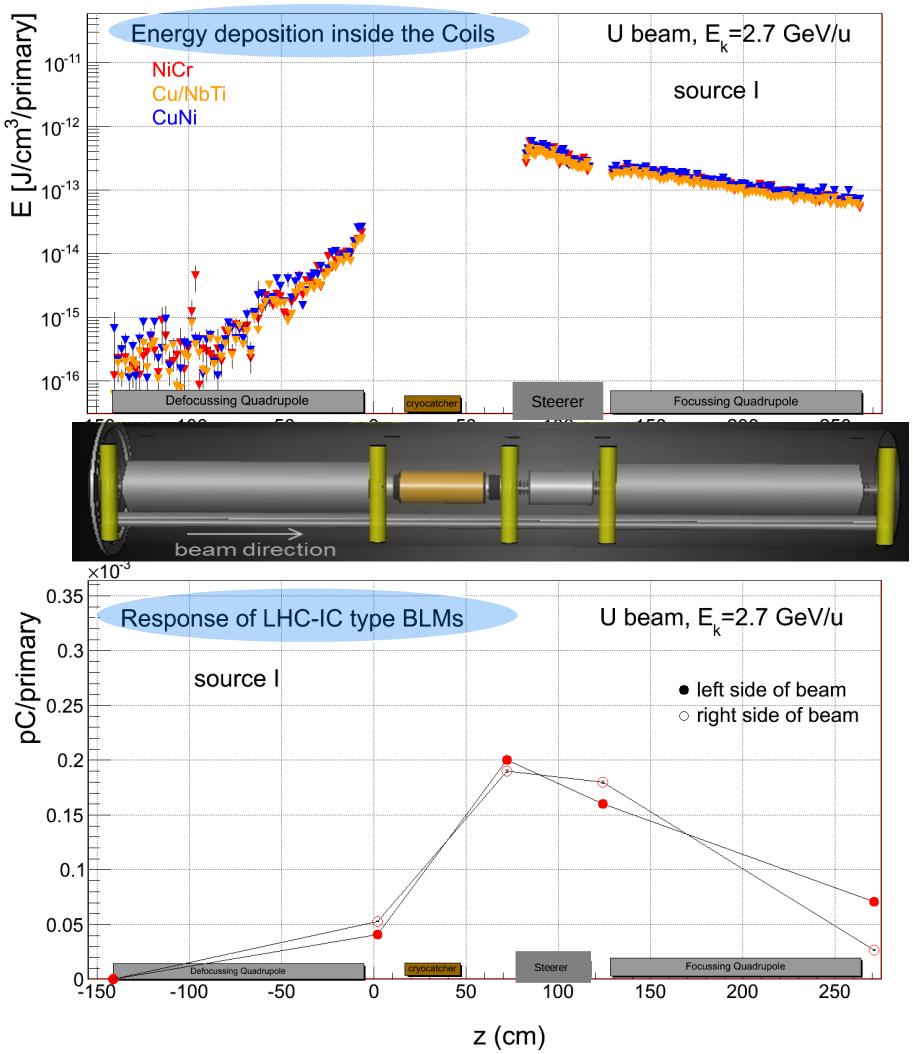
LHC-NOTE 422 (2008)
CERN-EN-NOTE-2010-001

two examples of folded fluence spectra - Source I





- Multiply with beam loss intensity to obtain current in the BLMs (4)

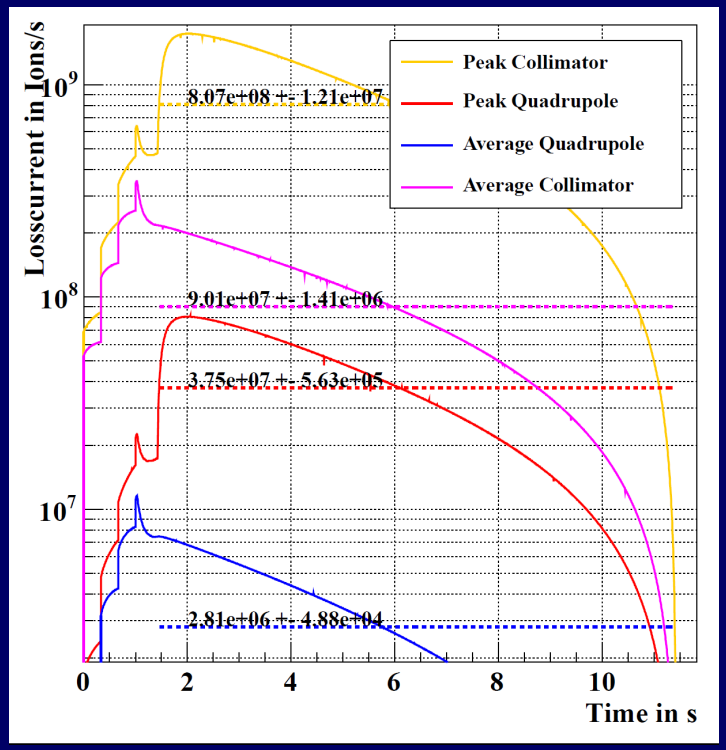


source I

max E_{dep} [J/cm³/primary]	BLM signal [pC/primary]				
	BLM1	BLM2	BLM3	BLM4	BLM5
4.5×10^{-13}	2×10^{-6}	4×10^{-5}	2×10^{-4}	1.6×10^{-4}	7×10^{-5}

largest signal downstream of the cryocatcher module, at the position of BLM3

Beam Loss Rates for the two Sources



StrahlSim results, Lars Bozyk 01/2013

For each of the sources two different cases considered:

Peak Loss Case – beam loss with highest load onto the collimator and the vacuum chamber wall

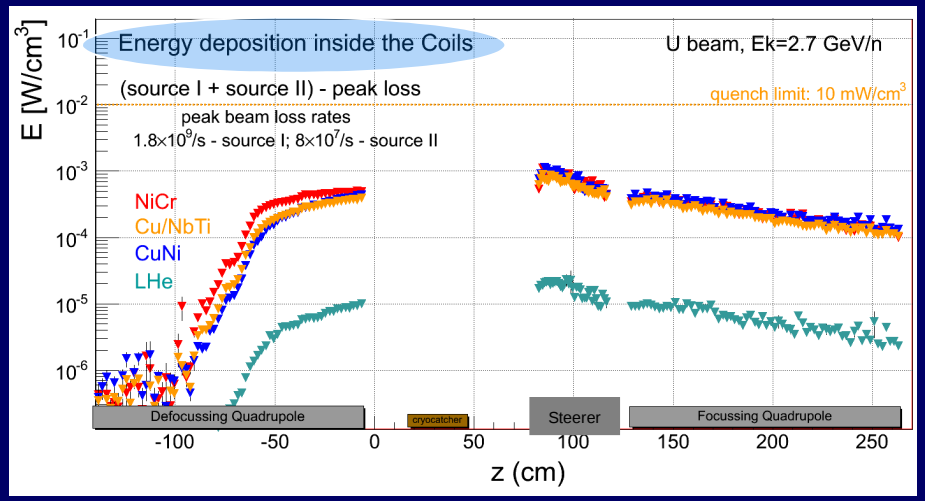
Average Loss Case – beam loss onto an "average" collimator and appendant quadrupole (depicted as "average collimator" and "average quadrupole")

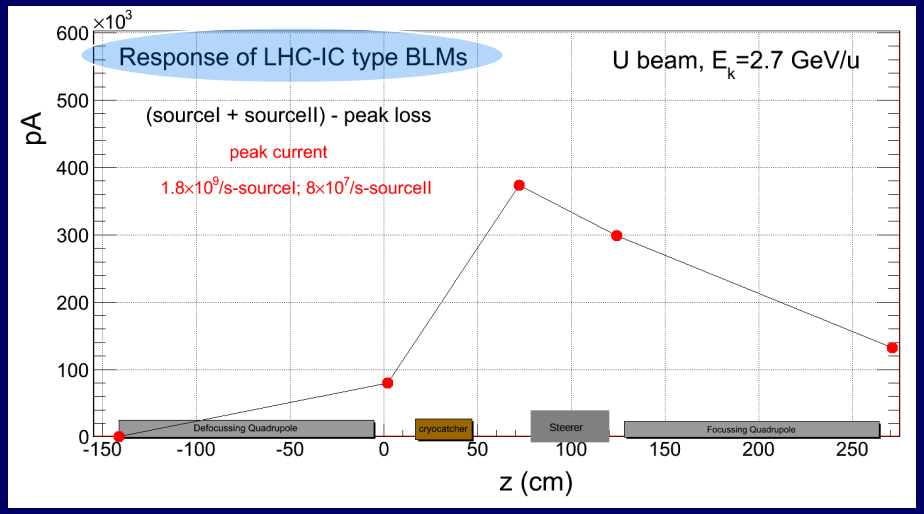
For each of the two cases the peak and the average loss current values are considered

to extract the Power deposition in W/cm³, the following currents have been used:

E_k=2.7 GeV/u	Loss Current [ions/s] - Source I		Loss Current [ions/s] - Source II	
	Peak value	Average value	Peak value	Average value
Peak loss case	1.8×10^9/s (1%)	8×10^8/s (0.5%)	8×10^7/s (0.05%)	3.8×10^7/s (0.02%)
Average loss case	2.2×10^8/s (0.1%)	9×10^7/s (0.05%)	7.4×10^6/s (0.005%)	2.8×10^6/s (0.002%)

Correlation of Power Deposition in the Coils in W/cm³ and the BLM signals in pA for the sum of the two sources at E_k=2.7 GeV/u





normalization to peak values for the 'Peak Loss Case' □ source I + source II

maximum power deposition P_d^{max}=1×10⁻³ W/cm³

max P_{dep} [W/cm³]	BLM signal [pA]				
	BLM1	BLM2	BLM3	BLM4	BLM5
1×10⁻³	3900	8×10⁴	3.7×10⁵	3×10⁵	1.3×10⁵

all currents measurable by LHC-IC type BLMs, peak current downstream of cryocatcher module

Rescaling of the present values for the other beam loss cases

Same signals for horizontal orientation of the BLMs (not shown)

Estimate of Quench-prevention thresholds

Definition of Quench-prevention threshold – signal measured by the BLMs corresponding to the energy deposition in the coils equal to the quenching limit of the superconducting cables

$$Q_{BLM}^{th}[\text{nA}] = \frac{P_{dep}^{quench}\left[\frac{W}{cm^3}\right]}{E_{dep}^{cable}\left[\frac{J}{cm^3 \times lost\ primary}\right]} \times Q_{BLM}[\text{nC/lost primary}]$$

Accurate estimation of threshold requires more input for the SC cables (margin spectra, cooling power vs. loss duration)

Results for the thresholds:

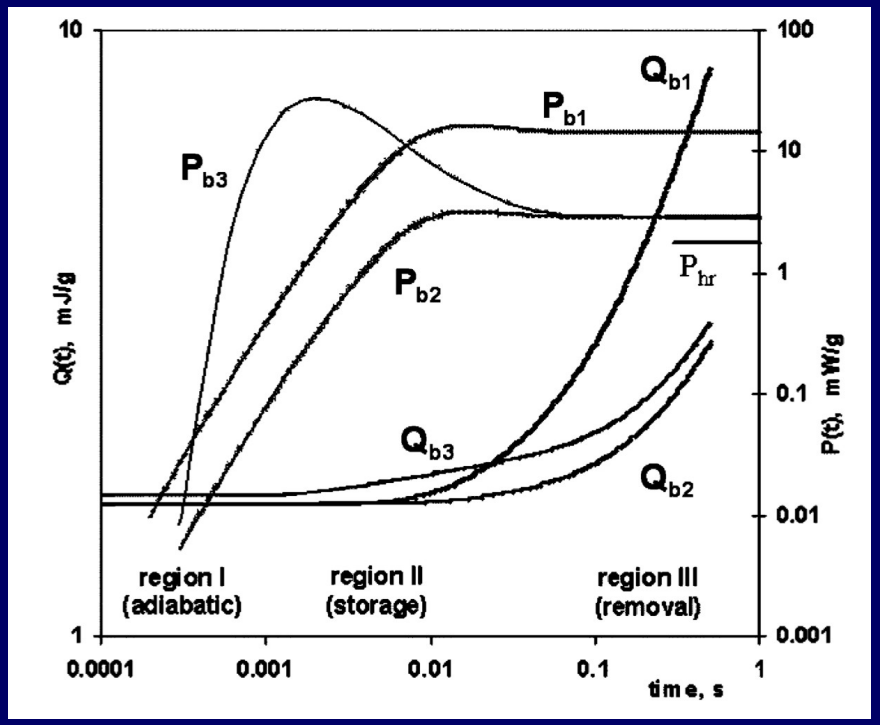
Quench limit [W/cm³]	Threshold [nA]					Threshold [mGy/s]				
	BLM1	BLM2	BLM3	BLM4	BLM5	BLM1	BLM2	BLM3	BLM4	BLM5
0.01	40	800	3700	3000	1300	0.7	15	70	55	25

conversion factor from Gray to charge deposited in the BLM

$$C_{Gy}^{C} = 5.4 \cdot 10^{-5}\ C/Gy$$

Note: thresholds independent of beam loss rate

Quench margin spectra for the Nuclotron-type cables



Quench margin spectra for Nuclotron-type cables (Cu/NbTi) vs. beam loss duration from:

H.G. Khodzhibagiyan, A.D.Kovalenko and E. Fischer, Some Aspects of cable design for fast cycling superconducting synchrotron magnets, IEEE Transaction and Applied Superconductivity, VOL. 14, No. 2, June 2004

Quench limits for the option (b3):

steady-state limit 3mW/g (20 mW/cm^3)
adiabatic limit 1.6 mJ/g

Steady-state limit of 10 mW/cm^3 (1.4 mW/g) for Cu/NbTi coils based on *Review of Quench Limits, N. Mokhov, Fermilab 2012* (was used instead)

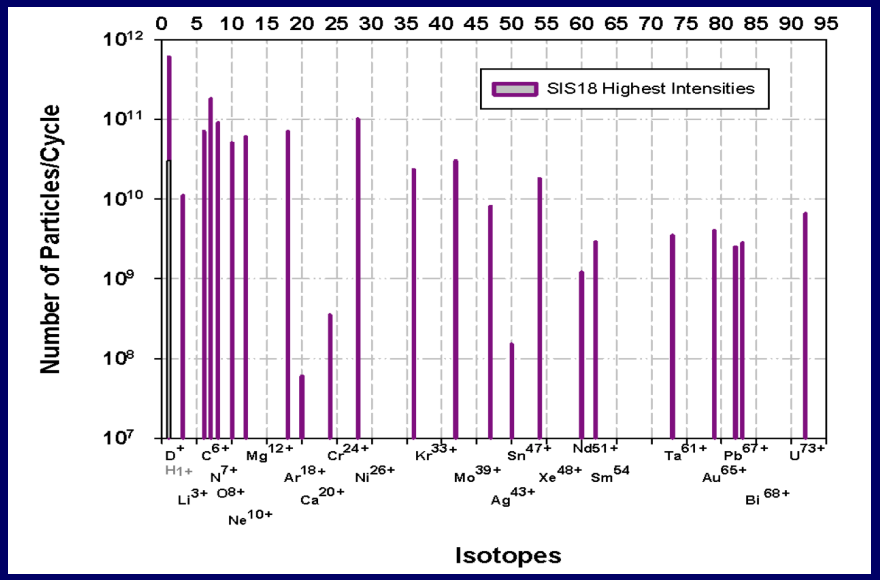
Although the margin spectra for the final design of the SIS100 SC coils should be recalculated, the following conclusions will remain:
all the threshold values will be measureable with the LHC-IC type BLMs

Side remark: the max power deposition within SC coils due to ionization losses will be at least one order of magnitude below the quench limit no quenches during normal operation

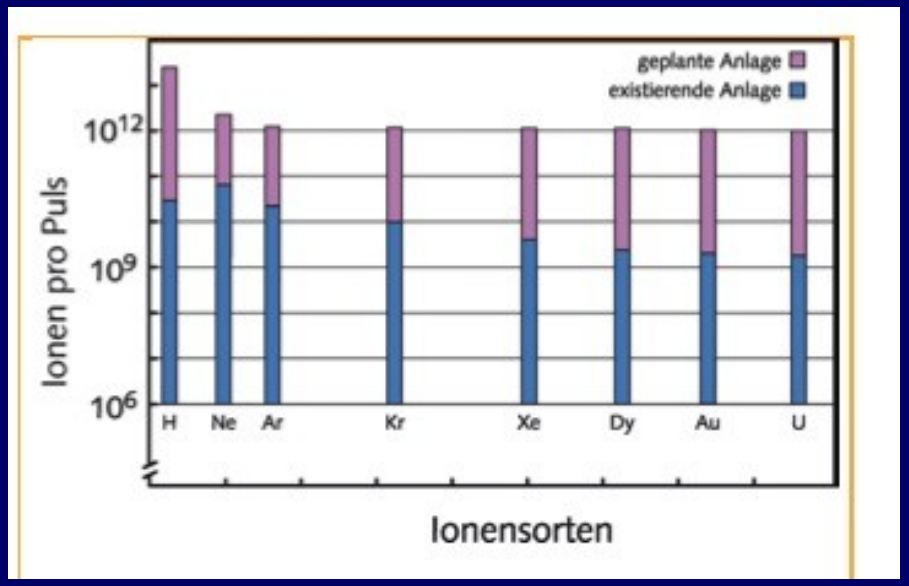
Quench-prevention thresholds for different ion beams and energies

Full spectrum of heavy-ions at GSI/FAIR: present and future

present (SIS18)



future (SIS100)



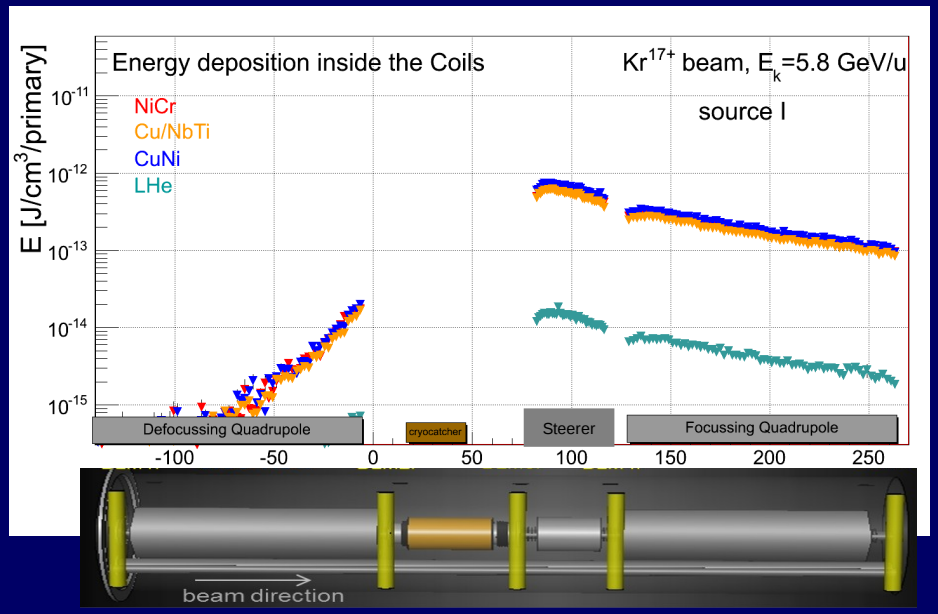
Many different (partially and fully stripped) ion beams will be accelerated with the SIS100

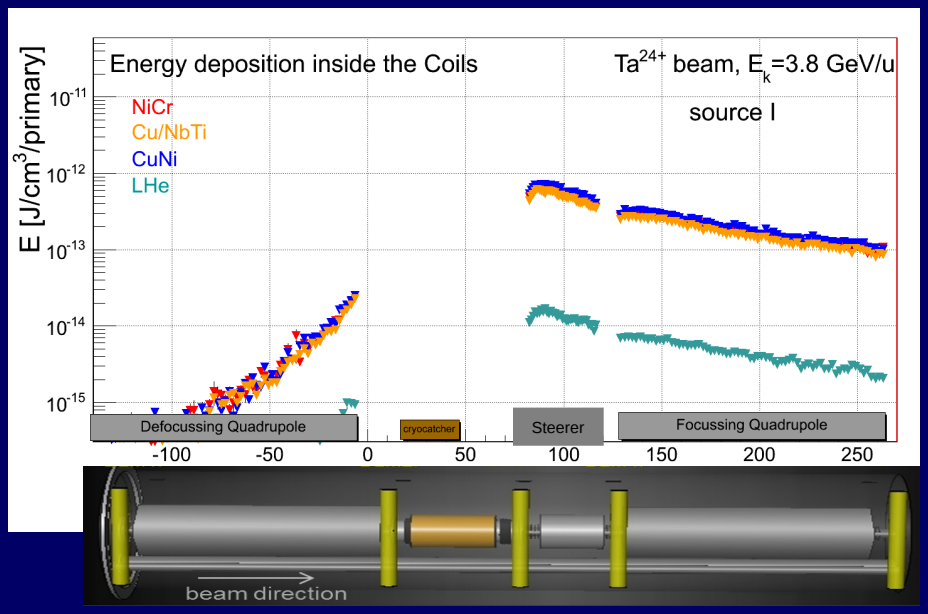
Different BLM settings (thresholds) for each ion species?

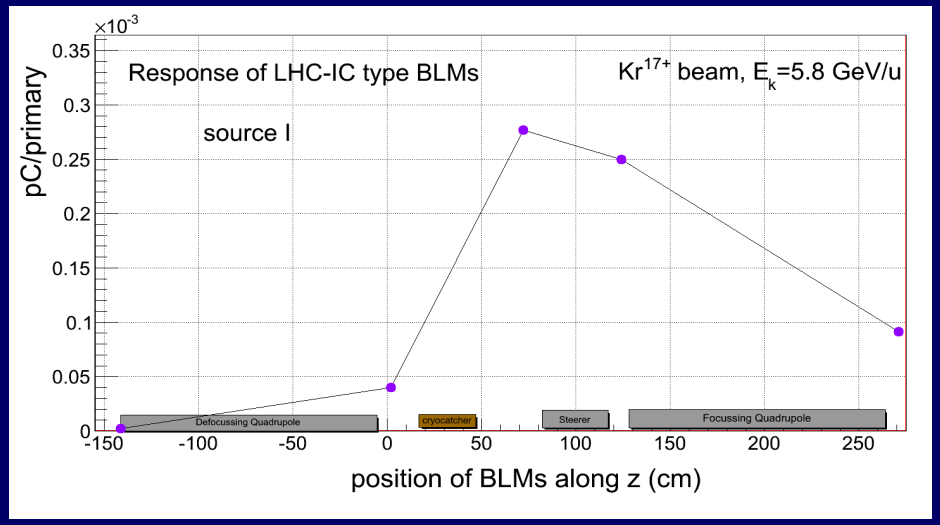
Consider partially stripped ions U^{28+}, Ta^{24+}, Xe^{22+}, Kr^{17+} and full-energy ions Ar^{18+} and Xe^{54+} to cover a large range of different energies and ions (charge exchange irrelevant for the two latter)

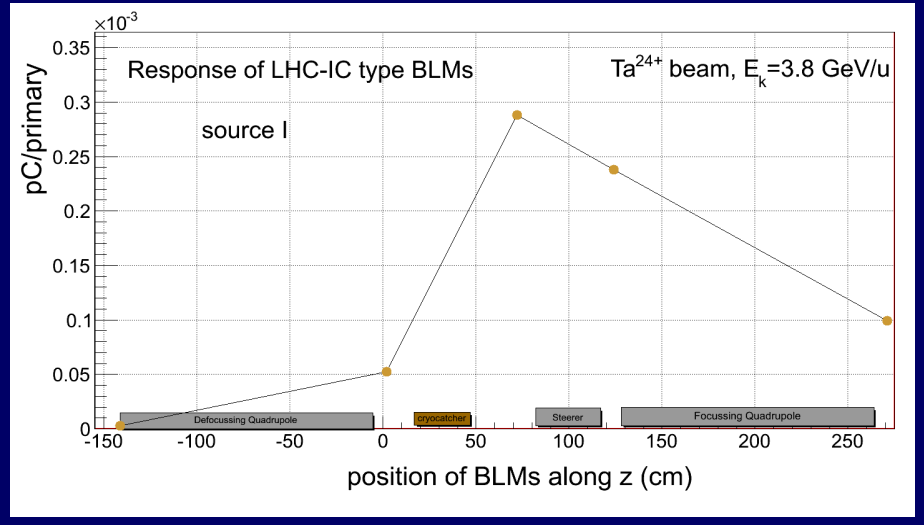
Correlation of Energy Deposition in the Coils in [J/cm³/lost primary] and the BLM signals in [pC/ lost primary]

Two examples: Kr^{17+} Ta^{24+}

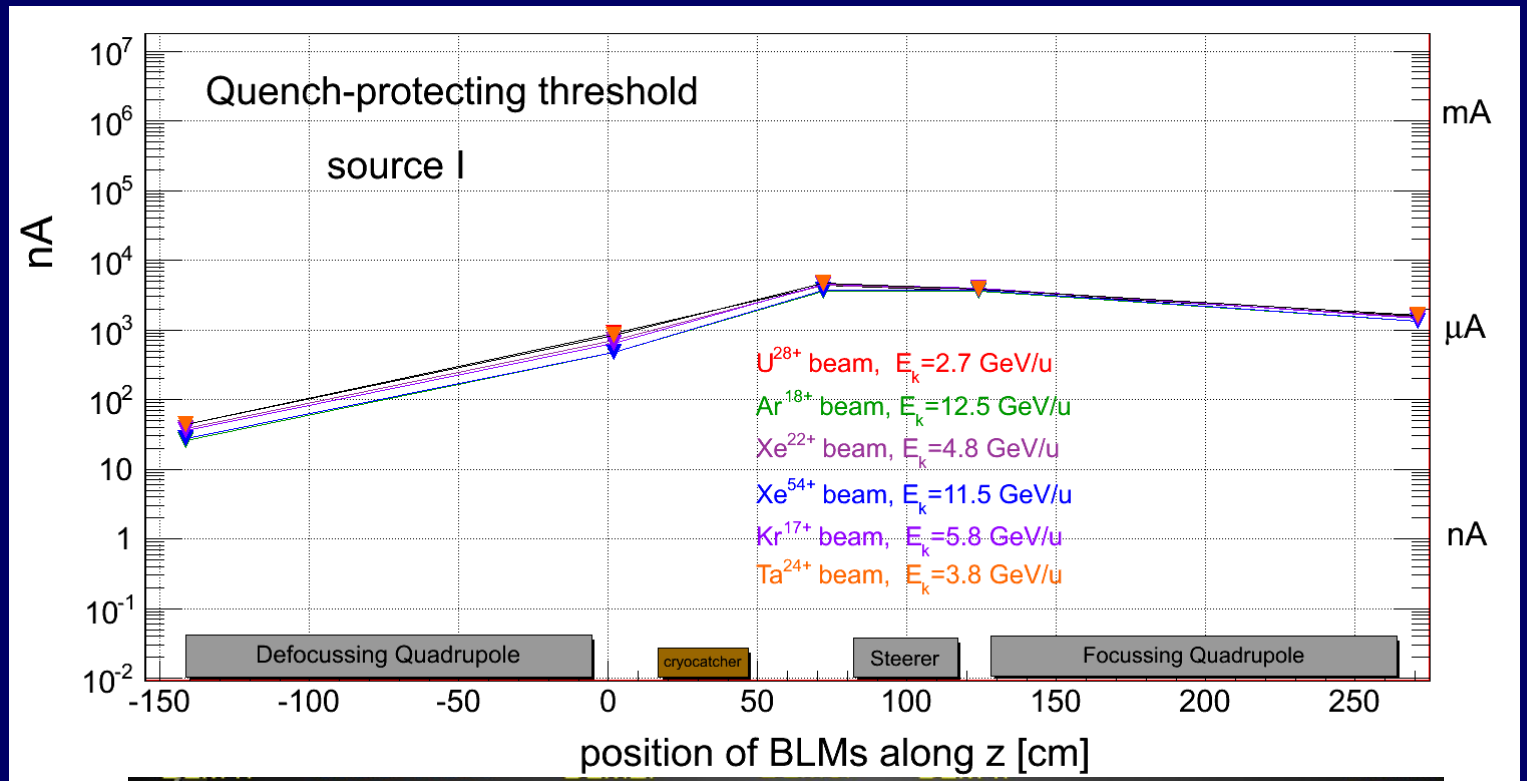


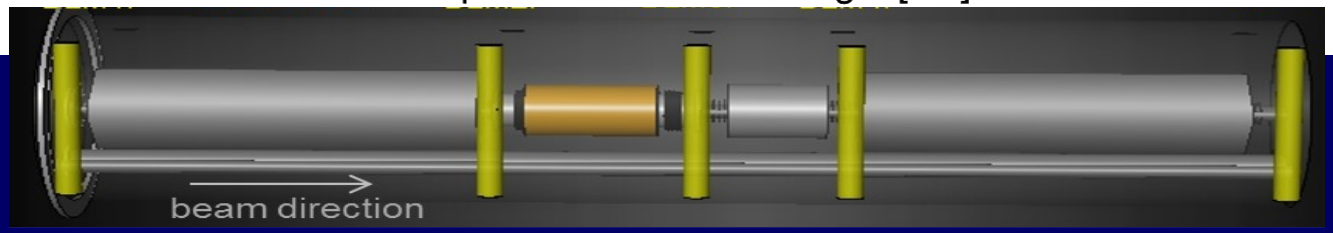






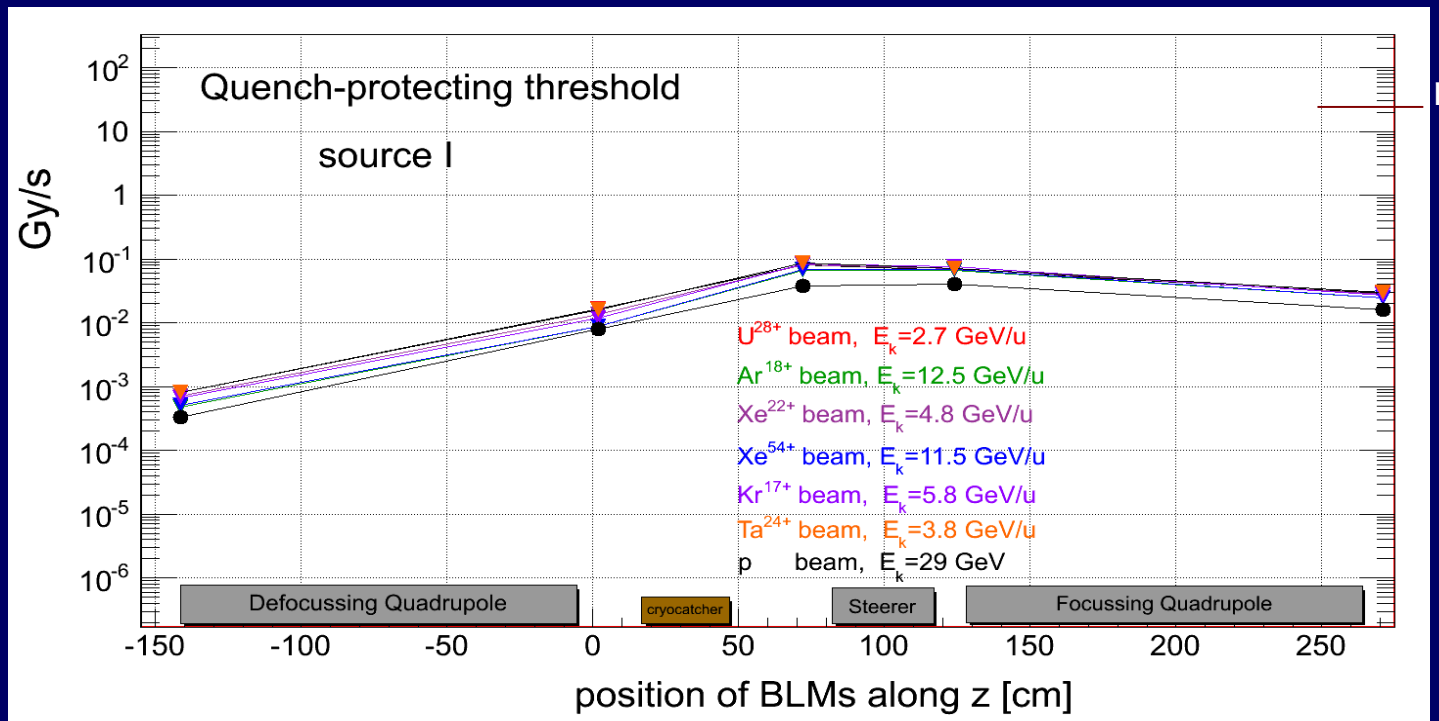
Quench-prevention thresholds in nA for different ion beams and energies



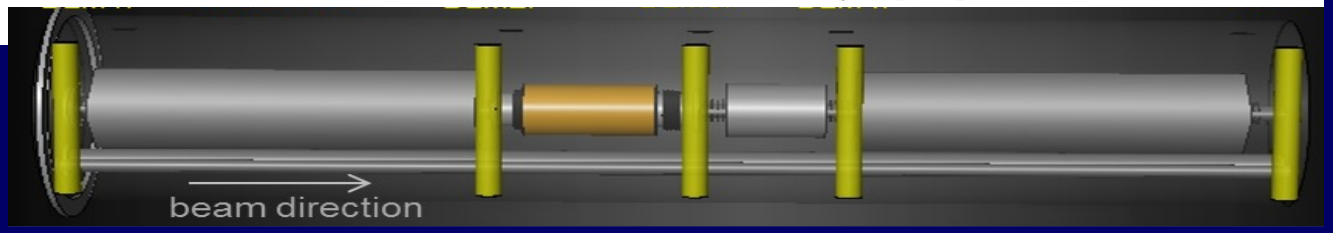


Quench-prevention thresholds the same for all ions/energies considered

Quench-prevention thresholds in Gy/s for proton and ion beams of different energies



max 23 Gy/s



Considering the same loss location, the quench-prevention thresholds the same to within a factor of 2 for proton and ion beams of different energies

Quench-prevention thresholds for different ion beams and energies

Ion beam	max [J/cm³/ lost primary]	Quench limit [W/cm³]	ions to quench /s	Threshold [nA]				
				BLM1	BLM2	BLM3	BLM4	BLM5
U^{28+}, E_k=2.7 GeV/u	4.5×10^{-13}	0.01	$2.2\times10^{+10}$	40	890	4440	3550	1560
Ta^{24+} E_k=3.8 GeV/u	6.1×10^{-13}	0.01	$1.6\times10^{+10}$	44	850	4680	3870	1620
Xe^{22+} E_k=4.8 GeV/u	7.2×10^{-13}	0.01	$1.4\times10^{+10}$	39	720	4444	3890	1500
Kr^{17+} E_k=5.8 GeV/u	6.2×10^{-13}	0.01	$1.6\times10^{+10}$	36	645	4470	4030	1475
Xe^{54+} E_k=11.5 GeV/u	2.2×10^{-12}	0.01	$4.5\times10^{+9}$	28	470	3690	3720	1330
Ar^{18+} E_k=12.5	8.3×10^{-13}	0.01	$1.2\times10^{+10}$	26	480	3620	3615	1325
p, E_k=29 GeV	7.7×10^{-14}	0.01	$1.3\times10^{+11}$	18	430	2050	2200	870

Quench-prevention thresholds for different ion beams and energies

Ion beam	max [J/cm³/ lost primary]	Quench limit [W/cm³]	ions to quench /s	Threshold [mGy/s]				
				BLM1	BLM2	BLM3	BLM4	BLM5
U^{28+}, E_k=2.7 GeV/u	4.5×10^{-13}	0.01	$2.2\times10^{+10}$	0.8	17	80	65	30
Ta^{24+} E_k=3.8 GeV/u	6.1×10^{-13}	0.01	$1.6\times10^{+10}$	0.8	16	87	72	30
Xe^{22+} E_k=4.8 GeV/u	7.2×10^{-13}	0.01	$1.4\times10^{+10}$	0.7	13	82	72	28
Kr^{17+} E_k=5.8 GeV/u	6.2×10^{-13}	0.01	$1.6\times10^{+10}$	0.7	12	83	75	27
Xe^{54+} E_k=11.5 GeV/u	2.2×10^{-12}	0.01	$4.5\times10^{+9}$	0.5	9	68	69	25
Ar^{18+} E_k=12.5	8.3×10^{-13}	0.01	$1.2\times10^{+10}$	0.5	9	67	67	25
p, E_k=29 GeV	7.7×10^{-14}	0.01	$1.3\times10^{+11}$	0.3	8	40	41	16

Conclusions II

- LHC-IC type BLMs very sensitive to the beam losses expected from charge exchange of U^{28+} beams
- Quench-prevention thresholds almost identical for all ion species and beam energies considered
- For the same beam loss location, similar thresholds for proton and ion beams (same at LHC)
- Quench-prevention thresholds independent of beam loss rates
- Different longitudinal positions of the 2 BLMs foreseen per QP module (could distinguish charge-exchange from other beam losses based on topology)

For details of the studies see Technical Note published on EDMS-GSI: FAIR-1SBDX-ER-0001 https://edms.cern.ch/document/1473055/1

BKP

Quotations from other talks

‘Quench = Physical Transition from Luminosity to Unproductivity State (with frustration)’

A. Siemko, 14th Chamonix Workshop, January 2005

‘All machines: Tevatron, HERA, RHIC, LHC demonstrated that beam induced quenching happens’

A. Siemko, 14th Chamonix Workshop, January 2005

‘General design philosophy at LHC – to ensure that there should always be at least 2 different systems to protect against a given failure type’

R. Schmidt et al., New Journal of Physics 8 (2006) 290

LHC Bending Magnet Quench Levels

LHC Project Report 44