Report regarding the MC simulations for the BLM - focus on the nBLM

Irena Dolenc Kittelmann
(ESS)

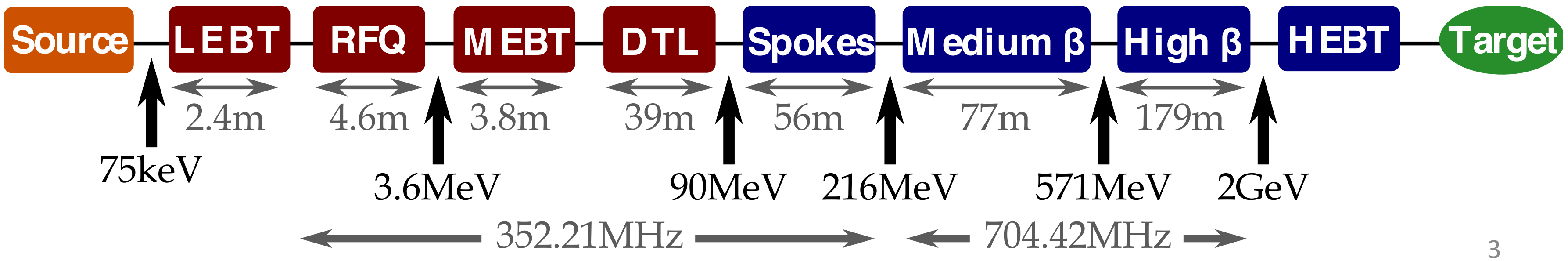
12. August 2016

Outline

- The ESS linac
- The ESS BLM system: detector technologies
- The ESS BLM detector count
- The ESS BLM simulations (tasks, inputs, SW, geometry)
- nBLM system specifications
- Response time
- Detector locations
- nBLM: threshold energy for slow/fast neutron discrimination
- nBLM: neutron hit map mean and RMS for the localised losses in the DTL
- Dynamic range

ESS linac

- ESS – neutron source based on a proton linac:
  - Nominal average beam power = 5MW
  - Proton energy at the target = 2GeV
  - Beam current = 62.5mA (1.1×10^9 p/bunch)
  - Beam pulse = 2.86ms
  - Repetition rate = 14Hz
- Normal conduction linac (NCL) - "warm linac":
  LEBT, RFQ, MEBT, DTL (5 tanks).
- Superconducting linac (SCL) – "cold linac":
  Spoke, Elliptical and HEBT sections.



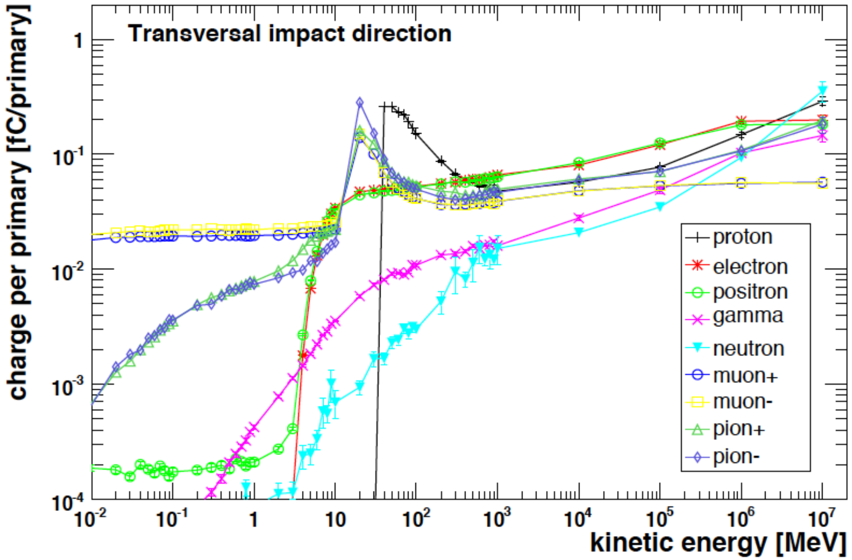
ESS BLM: 3 detector technologies

1. ESS SCL – ICBLM

- Ionization chambers (ICs) developed for LCH BLM – primary BLMs in SCL
- Photon background due to the RF cavities must be taken into account when using ICs a linac
  - Bckg. mainly due to el. field emission from cavity walls, resulting in bremsstrahlung photons created on cavities/beam pipe materials [3].
  - Levels are difficult to predict numerically – they depend on the quality of cavities, operation conditions and time.
  - Energy spectra estimation [4]: photons with energies up to tens of MeV can be expected.
  - Plan to asses this experimentally as well.

- LHC IC sensitivity to photons:
  "cut off" at transversal photon and electron Incidence ~2MeV (~30MeV for p and n) [1]
- Background sampling and subtraction in the signal processing necessary.

LHC BLM IC response functions [1]



2. ESS SCL - 2nd detector type: - cBLM (Cherenkov based BLM)

- Currently considering to design Cherenkov radiation sensitive detectors.
- To be used as an addition to the ICs, which are the primary BLM detectors in the SC parts.
- Cherenkov radiation based detector offer inherent rejection of the RF cavity background..

ESS BLM: 3 detector technologies

EUROPEAN SPALLATION SOURCE

3. ESS NC linac: nBLM (neutron sensitive BLM)

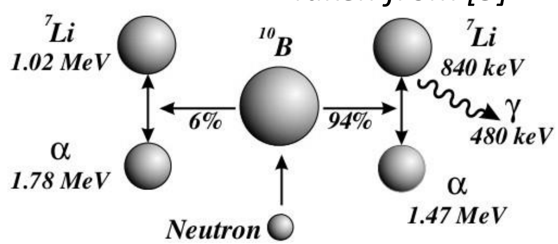
- Plane to place BLM detectors in the MEBT and DTL sections.
- Particle fields outside the beam pipe and tanks in this area expected to be dominated by neutrons and photons.
- RF cavity background still a possible source of photons in these areas – neutron sensitive detectors should be considered.
- Micromegas detectors chosen for these parts of the linac – IKC annex AIK 7.9/CEA 1.11
- The idea is to design a micromegas detector sensitive to fast neutrons and not to thermal n, X- and γ-rays based on signal discrimination [5].

ESS nBLM

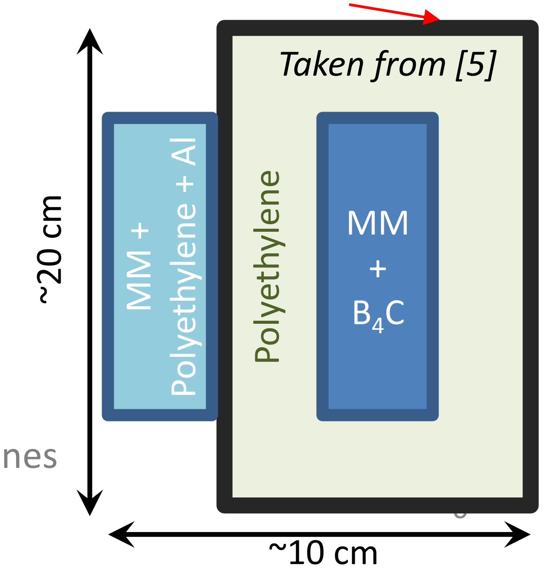
nBLM – the neutron sensitive BLM

- Micromegas detectors will be used in these parts of the linac.
- Detector in development by the micromegas experts from CEA Saclay
- The idea is to design a micromegas detector sensitive to fast neutrons and "blind" to thermal n, X- and γ-rays based on signal discrimination [5].

Taken from [5]



- **Current proposal:** assembly of 2 modules [5].
  - **1st module (slow losses)**
    - Capable of monitoring low fluxes (~few n $cm^{-2}s^{-1}$).
    - Polyethylene: moderator to thermalize the incoming fast n.
    - B_4C layer(s) to capture thermalized n.
    - Cd (~mm) to eliminate background thermal n.
  - **2nd module (fast losses)**
    - appropriate for high fluxes of fast n, coming from the front.
    - Polyethylene for n conversion to p recoils (~ few mm) through n elastic scattering on H atoms.
    - Al foil or deposition (~50nm) on the polyethylene (thickness defines the neutron energy threshold), followed by a micromegas.



ESS BLM detector count

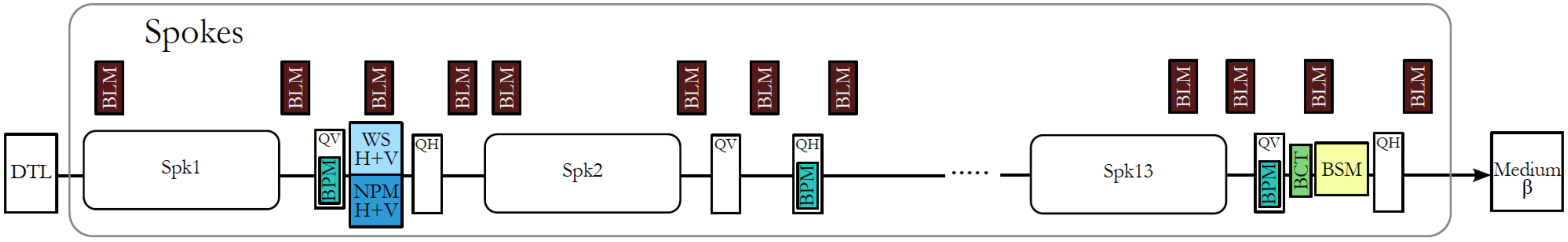
NC linac – nBLMs

- Original count when writing the technical annex:
  - MEBT: 1 per collimator or chopper dump
  - DTL: at least 1/tank, 1 between the tanks, 1 at start or end of the DTL

SC linac - ICBLMs

- 3-4 devices per doublet lattice cell: 4 where there is a cryomodule and 3 in the transport section.

Linac section	Num. of devices ICBLM	nBLM
MEBT	/	4+1=5
DTL	(1/tank) 5	>=11=5+6
Σ	5	16
Spokes	13×4=52	13+1=14?
Medium β	9×4=36	4?
High β	21×4=84	
HEBT	(3/q-pair) 15×3=45	1
dog leg	(3/q-pair) 7×3=21	/
	(1/dipol) 2	/
A2T	15	/
Dump line	6	/
Σ	261	0-19
ΣΣ	266	35
ΣΣΣ		301



ESS BLM simulations

MC simulations for tracking the lost protons needed to determine:

1. System response time limit (MC simulation in combination with the thermo-mechanical simulations needed only for complicated shapes and/or more precise estimation)
2. Detector locations.
3. Dynamic range of the system.
4. Initial MPS threshold settings at the startup and later adjustments to those - not discussed here.
5. Anticipated response of the system during fault studies (to verify the system response) – not discussed here.

ESS BLM simulations

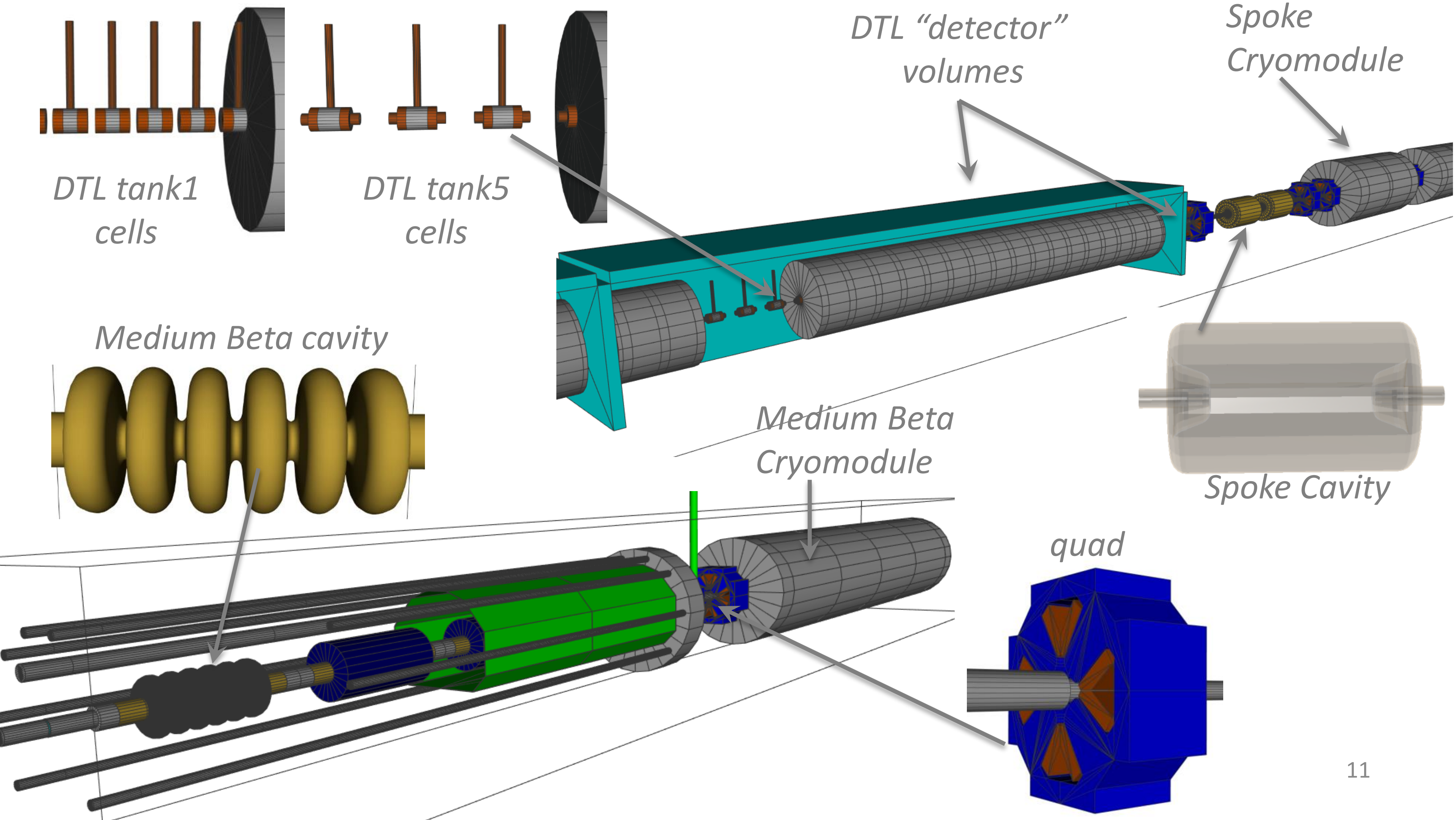
Required inputs:

- Ideally one would have
  - Expected loss maps during normal operation when lowest signal expected.
  - A list of accidental beam loss scenarios with loss maps and time constants together with the elements that must be protected with their damage levels.
  - Some form of a preliminary list of the accidental beam losses exists (not finalized)
    - This list is the outcome of the beam loss discussions I started, which Enric transformed into “Hazard workshop”
    - See https://ess-ics.atlassian.net/wiki/display/ARAMI/Beam+induced+damage+workshops
- Large number of possible accidental scenarios in a linac. No filtered list (according to relevance for (n)BLM and likelihood of occurrence) of accidental loss scenarios (with time dependent loss maps), available at the time when simulations were started. Thus simplifications/assumptions are/were needed (discussed later).

ESS BLM simulations: SW and linac geometry

- **Simulation tool**:
  - Geant 4 (v10.00.03) simulation framework developed by the ESS neutron detector group [6]
  - Physics list: QGSP_BIC_HP
  - Cuts:
    - No tracking cuts set
    - Production cuts: for e-,e+ and photons set to 10µm; for p set to 0
- **Geant4 based ESS linac geometry created**
  - Certain element models (quads, Spoke and elliptical cavities, mid part of the elliptical cryomodules) adapted and changed where needed from existing ESS linac model made for the shielding calculations [13].
  - Magnetic field maps for the SCL quads outside the beam pipe included – important impact on the simulation results for detectors placed close to the quads [14]
  - Aperture along the linac follows the values in the 2015 baseline beam physics lattice of the ESS linac (2015.v1)
  - Tunnel walls included (important for neutron spectra)
  - Current simplifications:
    - Simplified quad geometry (yoke and coil extent, also the length the quads in the end parts of the linac has recently changed)
    - Simplified model of the DTL gaps (build with 1-2 cylindrical shapes on each side of a gap with fraction (gap distance)/(cell width) fixed for each tank)
    - Model for cavities in High Beta sections is calculated by scaling part of the Medium Beta cavity profile
    - Not included: postcouplers in DTL, Beam instrumentation, Correctors, supports, MEBT chopper and chopper dump , spoke cavity insertions

ESS BLM simulations: linac geometry

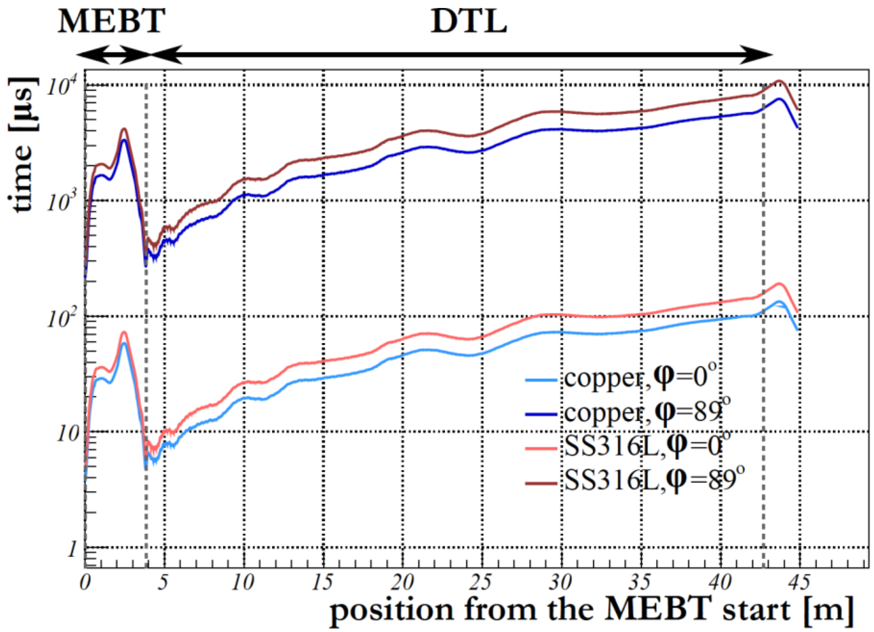


nBLM system specifications

- Agreed with CEA Saclay that ESS provides the following:
  1. Time response limit
  2. Detector size
  3. Dynamic range
  4. Particle fluxes and spectra for the relevant beam loss scenarios.
  5. Background particle fluxes and spectra
  6. Slow neutron energy limit for slow neutron.
- Point 6: can be extracted from point 4 by requiring for the neutron global time (time from lost proton generation) when entering the detector to satisfy the time response limit.
- Points 3-5
  - depend on detector location and size – detector locations and sizes selected to optimize these points.
  - Interconnected: dynamic range can be estimated as the particle flux for the the two extreme beam loss cases.
  - Point 5 extracted from 5 and 4 – for photons RF cavity background estimations needed as well
- Focus on:
  - Time response, detector locations (and size) and dynamic range – determined through Monte Carlo (MC) simulations of lost protons

Response time

- Required response time set in the past:
  - NC linac (MEBT-DTL): ~5 μs.
  - SC linac: ~10 μs.
  - Numbers based on a simplified melting time calculations, where a block of material (copper or stainless steel) is hit by a beam of protons with a uniform profile under perpendicular incidence angle, no cooling considered [7].
- Numbers recently re-checked with a Gaussian beam and update beam parameters:
  - **NC linac:** calculated melting time values of 3-4μs imply even stronger demands on the response time (confirmed with a MC simulation as well).
  - **SC linac**: the 10μs requirement for response time fits well with the results of this calculations.
    However: other damage mechanisms may mandate even shorter response time SCL (discussed further).



Response time

"Worst case" angle

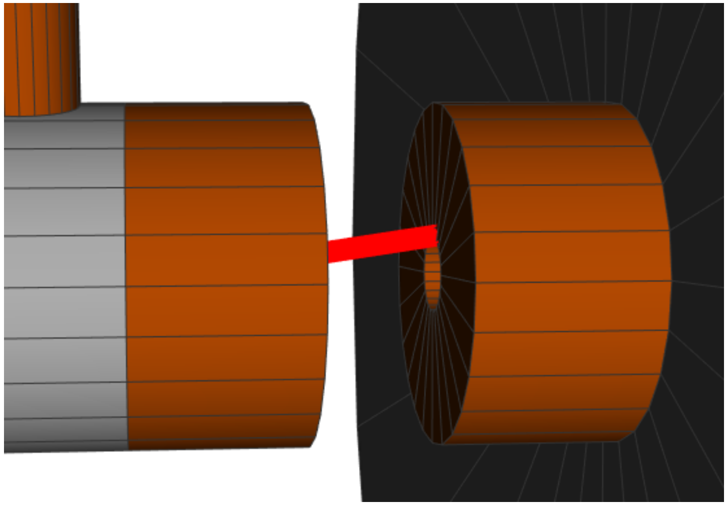
- Melting time depends on the incidence angle (~2 orders of magnitude difference between very shallow and perpendicular incidence). Is perpendicular incidence a good assumption?
- What is the least shallow incidence angle of the most focused beam that can be expected to hit the aperture?
  - Expected to occur for a particular case of incorrect settings for a set of corrector magnets – time consuming beam dynamics simulations required to asses this.
  - **Simplification (suggested by R. Miyamoto) :**
    - *Increase one of the initial coordinates x,x',y, or y' at the beginning of a section until the beam centroid starts touching the aperture.*
    - *Take the highest deflection along this section as the worst case angle.*
  - Assessment of this type performed for the DTL and HEBT (courtesy of R. Miyamoto):

ESS Linac section	Peak x' or y' [mrad]
DTL tank 1	50
DTL tank 2-3	15
DTL tank 4-5	10
HEBT	~20

Response time

Implications on the response time

- **NC linac**
  - Depending on the gap distance, an incidence close to perpendicular potentially possible in the DTL tank1 due to the almost flat surfaces between the gaps.
  - With the simplified DTL geometry for the BLM simulation: geometrically possible though highly improbable - requires an incidence angle larger than about 3 times the worst case one (for a Gaussian beam with typical RMS~1mm, where 3RMS of the beam core hits the gap surface).
  - Deserves further studies with more accurate DTL mechanical model.



- **SC linac**
  - Plan to check the beam pipe melting time with the beam under “worst case” angle.
  - However: degradation of cavities observed at SNS after loosing <15µs pulse of 26mA beam ~10/day [8].
  - Experience at the SNS motivates setting response time limit for ESS SC linac significantly lower than 15µs.

Response time - update

- Better model for the DTL: drift tube approximated with “cone(s)+tube”
  - Length of each varies with the DTL length
  - With the DTL length the gap surfaces get more and more conical, starting from almost flat (ie. no cone) in DTL1 – from this perspective the worst case angle expected at the end of the DTL.
  - From the energy deposition point of view the worst case expected at the beginning of the DTL.
  - Where to expect the most damaging condition?
  - I have a file with extensive info about the DTL which I received from Renato at the end of May. I contacted him to see if it contains also info about how to model the cone part (length or angle of the cone). As I didn’t receive an answer, the question above stays unanswered (together with the answer on the response time).

Response time - update

- Now there is "new working group" (Riccard Anderson, Enric, Mamad, Ryoichi, Aurelien, Annika?) that seems to be discussing beam losses
  - Seems like a continuation of the "hazard workshop" in a way
  - (now?) Focused exactly on the question I have been posing for a long time: "what is the least shallow angle with the most focused beam that we can expect?"
  - Currently they are discussing warm linac
  - I got aware of the discussions recently (though they met only twice before that) - I'm guessing they would like to have some MC simulations + report on the nBLM (irrelevant for the discussions I believe)
  - The document reporting their activities available at:https://ess-ics.atlassian.net/wiki/display/PS/Risk+Management
  - Meeting notes:

    https://ess-ics.atlassian.net/wiki/display/LG/20160804
- Suggestion regarding the detector design:
  - Ask this working group if they have a final number for us. If not, let's stick to the 5us.
  - Note also that the response time discussed before is a sum of all contributions from slide 22. Thomas and his team needs to have allocated some fraction of this, since now they are responsible for design only up to the BE (this means: "detection time" + time for the analogue signal shaping + signal propagation to the FPGA).
  - If we stick to the 5us for the total allocated for the nBLM, than we can maybe reserve 1us for the FPGA "processing time" (ask Maurizio), 1us for "particle time" (see slide 27) and 3us for Thomas' part ("detection" + FE analogue signal shaping + signal propagation to the FPGA)?

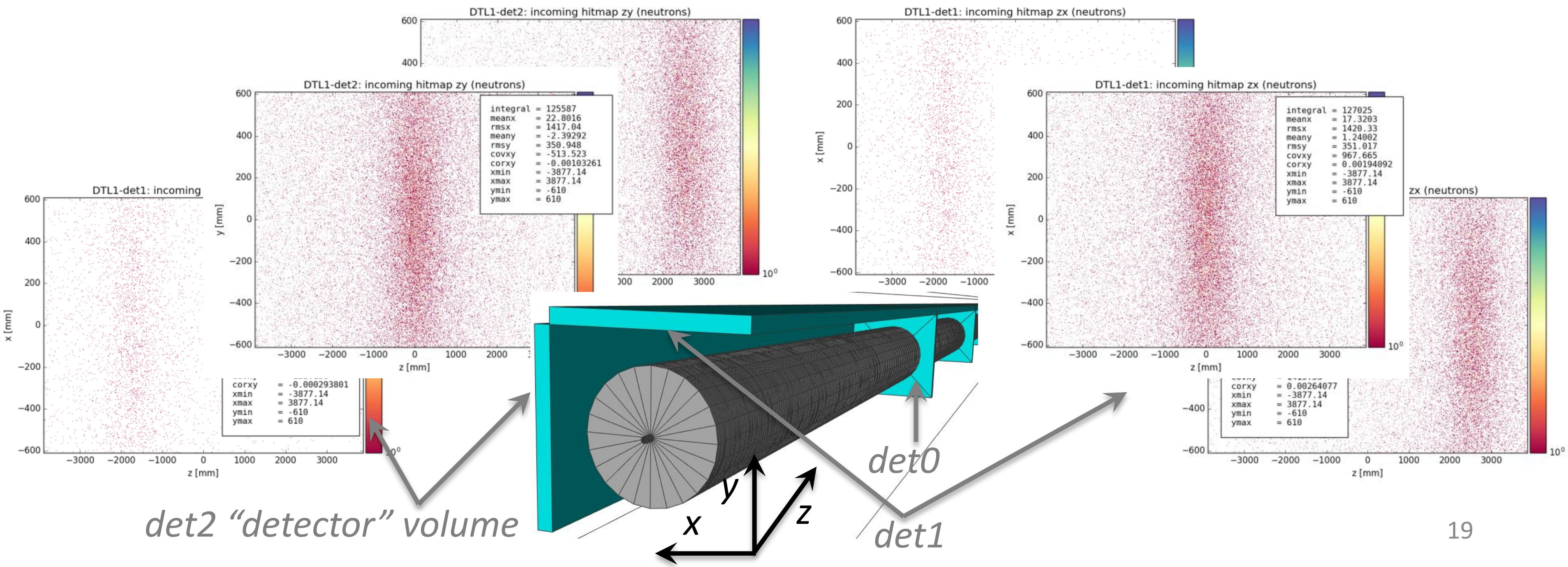
Detector locations

- Most suitable set of detector locations (together with the detector size and count): insures the system is not blind to any accidental loss.
- In the absence of complete list of accidental losses with, the following strategy is assumed in order to select detector locations:
  - *Select a set of localized loss scenarios with selected fixed beam energy, incidence angle and loss location along the linac section under investigation.*
  - *Incidence angle varies between the loss scenarios from ~2mrad up to the "worst case angle".*
  - *Energy of the lost protons varies from the lowest expected to the nominal value at the loss location. Planned to asses the lowest anticipated energy values in the near future.*
  - *Use phantom detector (vacuum) to surround the section and run a simulation for each of the loss scenarios in order to produce hit maps of incoming neutrons (for nBLM NCL) or all particles (for ICBLM in SCL).*
  - *Extract the hit map mean and RMS values along the section length and compare with the origin of the loss.*
  - *By comparing the results from all the simulation runs the best detector locations can be extracted.*
- **ICBLM in SCL**: similar strategy based on optimization methods combined with genetic algorithms for selecting the locations has been tried in the past –plan to augment this work with the above mentioned simplified strategy.
- **nBLM in NCL**: current focus here due to the need to develop specifications for this detector design.

Detector locations: DTL1 – preliminary results

DTL tank1 example (preliminary):

- Proton beam under 50mrad from the z-axis with Gaussian profile (RMS~1mm), energy set to the nominal values at the loss location.
- Incoming neutron hit maps for 3 different localized loss locations along the DTL tank1.
  - Det1 and det2: all hit maps exhibit a peak on the the axis that runs along the tank (z-axis), indicating possible correlation of the peak position with the loss location.
  - Det0: flat hit map distribution



Detector locations: DTL1 – preliminary results

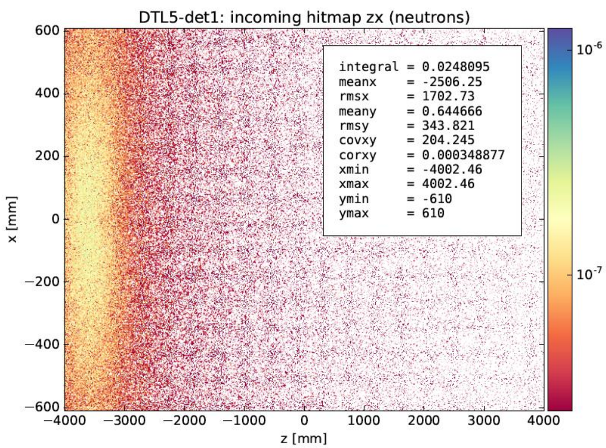
EUROPEAN SPALLATION SOURCE

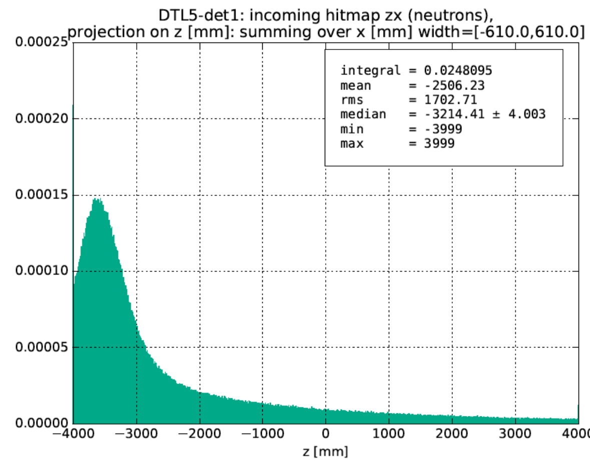
Observations regarding det1 and det2 neutron hitmaps in DTL1:

- Gaussian beam (RMS~1mm) at 50mrad from z-axis with azimuth angle 0^o (beam pointing up towards det1) – the case from the previous slide:
  - Mean z-values agree with the loss locations to ~0.02 - 0.8m depending on the loss location.
  - Note: loss location is assumed as the point at which the lost proton hits the aperture (10mm in DTL1)
  - RMS z-values ~1.4-1.5m
  - Same holds if det. volume placed below the tank (with lowest number of hits).
  - General note on azimuth angle and hit rates (looking at all simulation runs):
    - The highest hit rate is found on the detector placed in direction of the beam and the lowest hit rate on the detector on the opposite side
    - If I remember correctly, the difference between the hit rates on det1 and det2 (if beam pointing towards the top det1) changes along the DTL, the smallest being at the end of the DTL.
- Checked a few other cases: pencil beam and/or different incidence angle at fixed loss location – very preliminary observations:
  - For incidence angles 10-50mrad (pencil beam) the RMS and mean z-values do not change drastically
  - Number of hits seems to increase with increasing angle – case with 2mrad incidence (pencil beam) shows extremely low number of hits (?)
  - No dramatic change between pencil beam or beam with RMS 1mm (50mard beam)
  - Indication that physics and not geometry dictate the observed loss location (mean on z-axis)?
- Results look promising in the view of the BLM system capability to localize the loss origin– further simulations needed for more conclusive results.

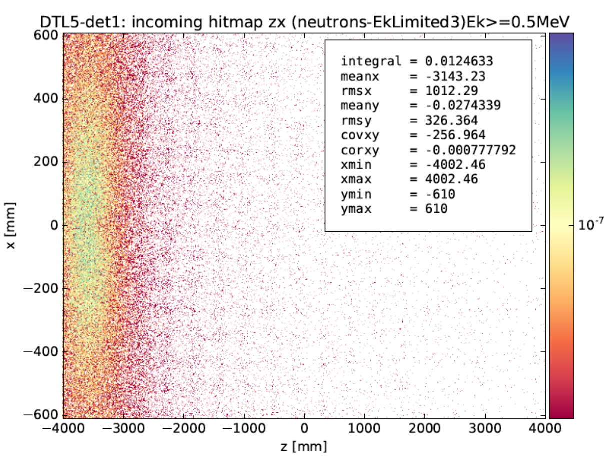
nBLM: threshold energy to discriminate slow/fast neutrons – $E_{n,Thr}$

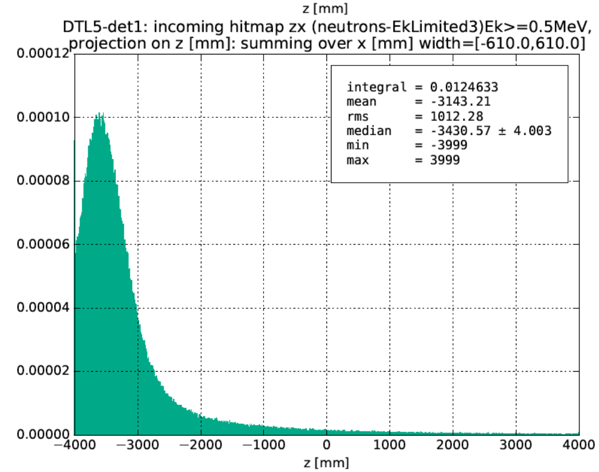
- The hit maps depend on the energy cut – with higher $E_{thr,n}$ the hitmaps get "cleaner"
- Detector DTL5-det1 plots from **sim2-10**: pencil beam under 5mrad, at the beginning of the DTL5:





Neutron hit map and projection (normalized to the number of primaries) – no cut





Neutron hit map and projection (normalized to the number of primaries) – E_k >0.5MeV

nBLM: threshold energy to discriminate slow/fast neutrons – $E_{n,Thr}$

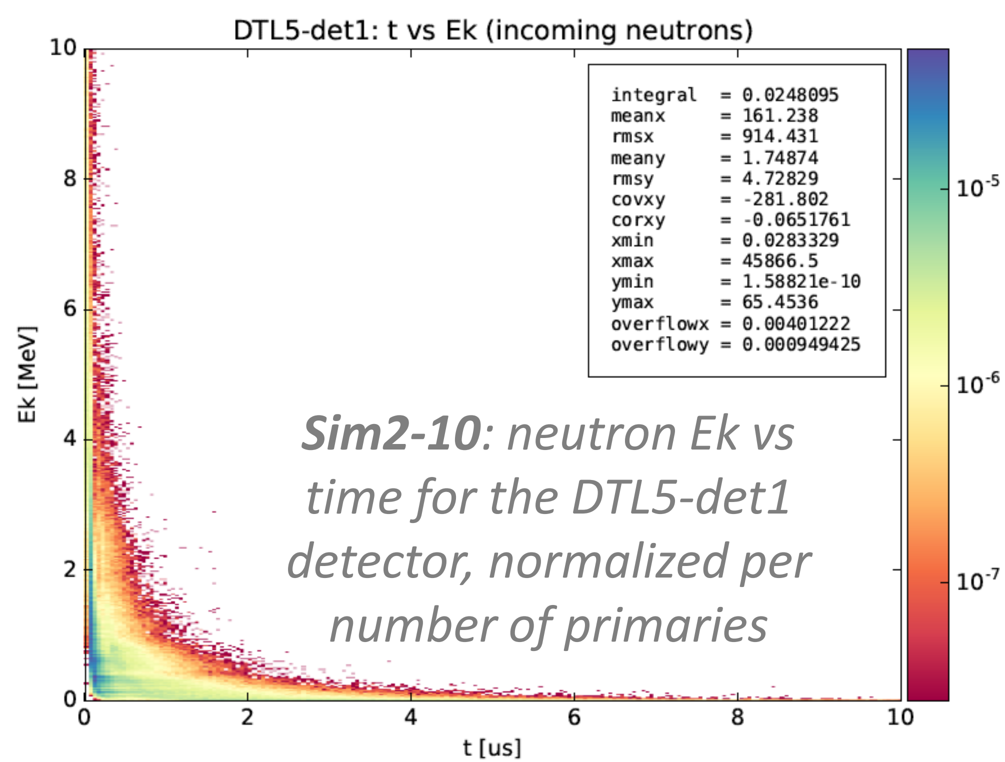
- The selection of E_{thr} affects:
  - The expected mean and RMS of the hitmaps (thus detector locations)
  - number of detector hits on detector (thus detector size)
- The response time of the BLM system is a sum of:
  - "Particle time" - PT: time between the onset of beam loss (the primary is lost) and the moment particle (primary or secondary) hits the detector.
  - Detection time: time needed for the detector signal to develop and to collect enough hits/current
  - Processing time: from the output of the detector to the BIS output on the FPGA
- My simulations: PT is scored, the current simulations assume "instant loss" – no time development of the loss (would need realistic loss scenarios with time development for that)

nBLM: threshold energy to discriminate slow/fast neutrons – $E_{n,Thr}$

EUROPEAN SPALLATION SOURCE

Method for determination of the “best” E_{thr}:

- Produce neutron E_k vs time (“PT”) 2d histos.
- Select the E_{thr} and project the hits with $Ek>E_{thr}$ on the “time” axis.
- Find the E_{thr} for which f_{lim} fraction of the hits in the projected histogram lie above the PT time limit t_{lim}
- Selected:
  - Limit1: t_{lim}=1μs, f_{lim1}=0.01
  - Limit2: t_{lim}=1μs, f_{lim2}=0.1



nBLM: threshold energy to discriminate slow/fast neutrons – $E_{n,Thr}$

Estimated the E_{thr} from simulations of various settings of localized losses in the DTL:

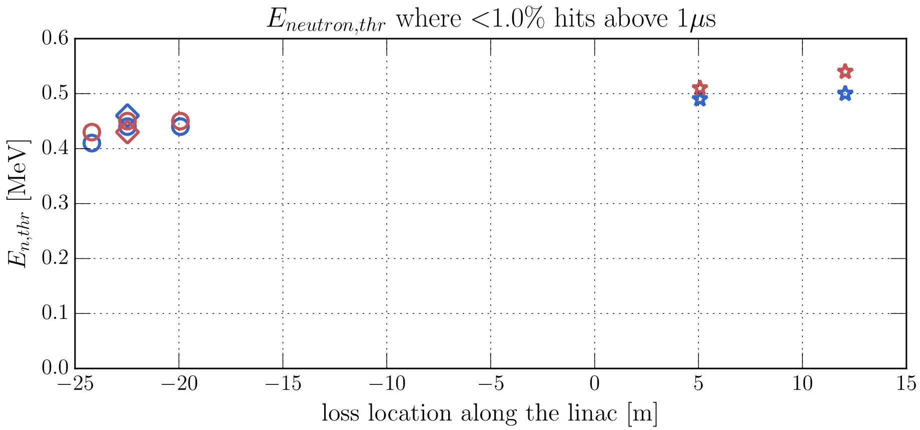
- **Beam size**: pencil beam or a Gaussian beam with typical dimension of σ_x, σ_y=1mm
- Loss location: beginning, mid and end of DTL1; beginning and end of DTL5
- **Energy**: set to the nominal value at the gun location, where the beam is tilted by a the angle θ from the z-axis (runs along the linac length) in order to hit the the desired **loss location** (location where the center of the beam hits the aperture).

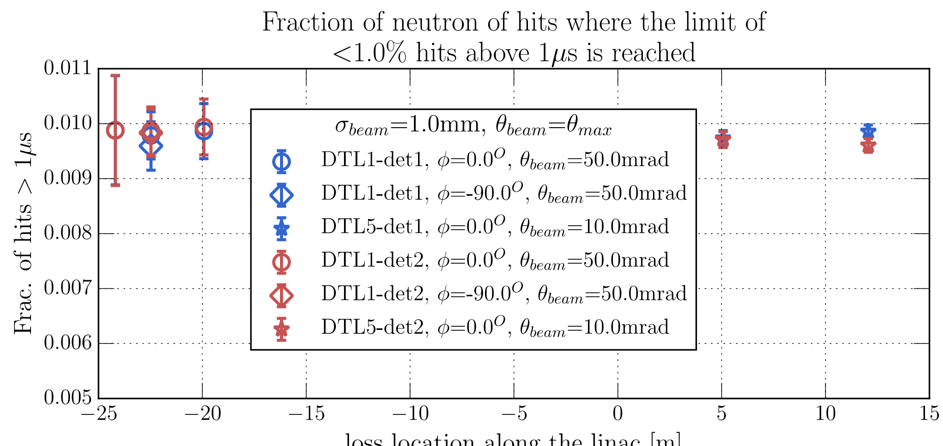
  In the simulations ran so far the energy ranged from 11.5MeV to 70MeV.
- **Beam angle polar θ**: set to ≤ maximum allowed ("worst case", see slide 14) in the section where the loss occurred.

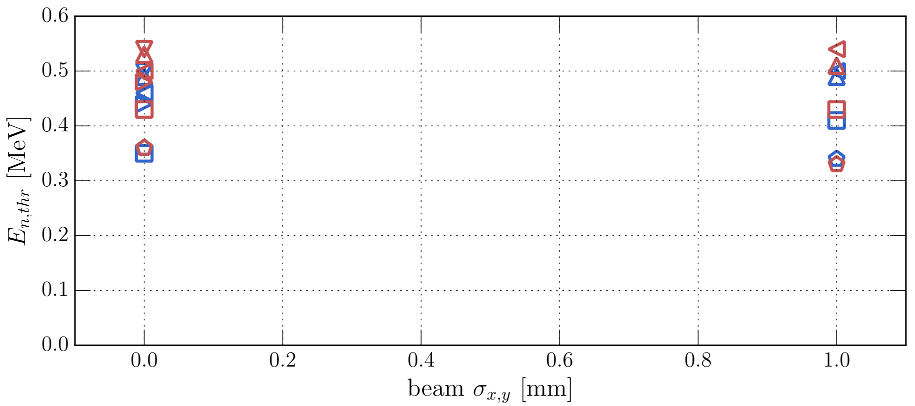
  In the simulations ran so far, θ ranged from 5mrad to 50mrad. Tried also with 2mrad at the beginning of DTL1 (the lowest possible – otherwise the gun position outside the MEBT), but to little hits observed with 700e6 primaries.
- **Beam azimuth angle ϕ**: set to 0° (beam directed up, towards det1) in all but one case, where -90° (directed away from det2, where no detector present) was considered.

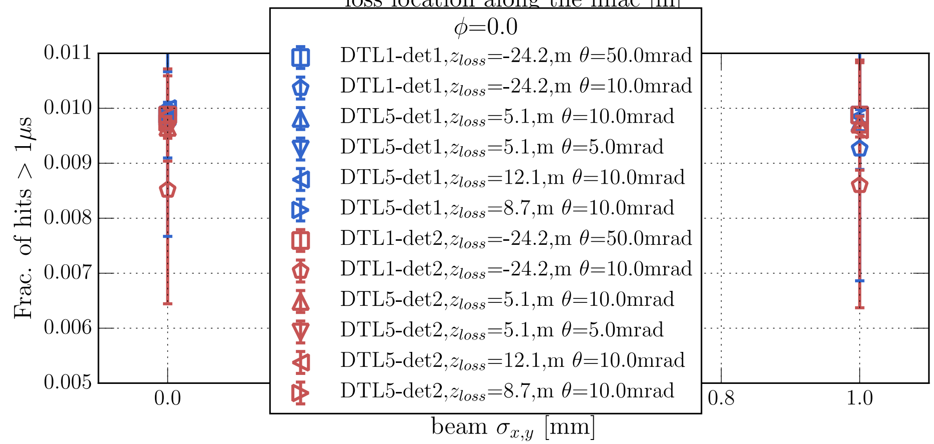
nBLM: threshold energy to discriminate slow/fast neutrons – $E_{n,Thr}$

Results for Limit1 (t_{lim}=1μs, f_{lim1}=0.01), det1 and det2



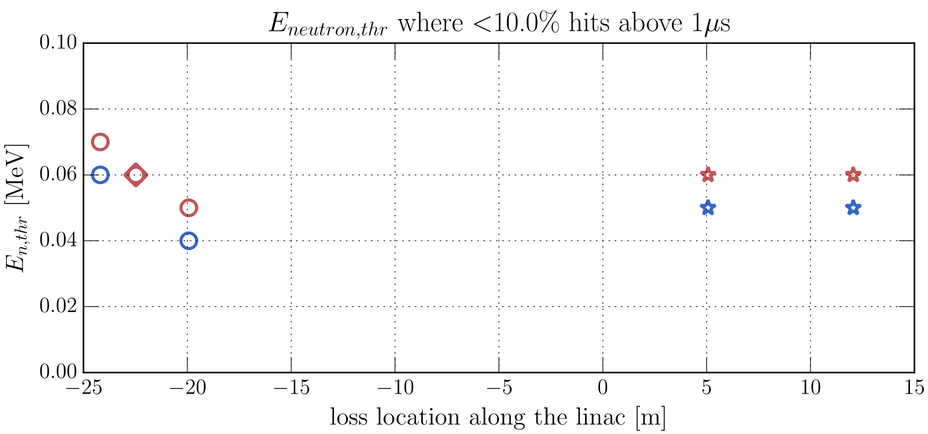


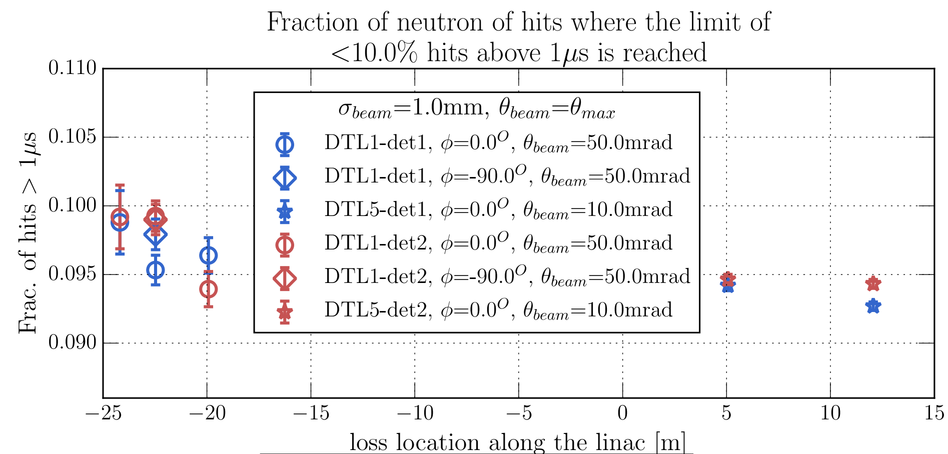


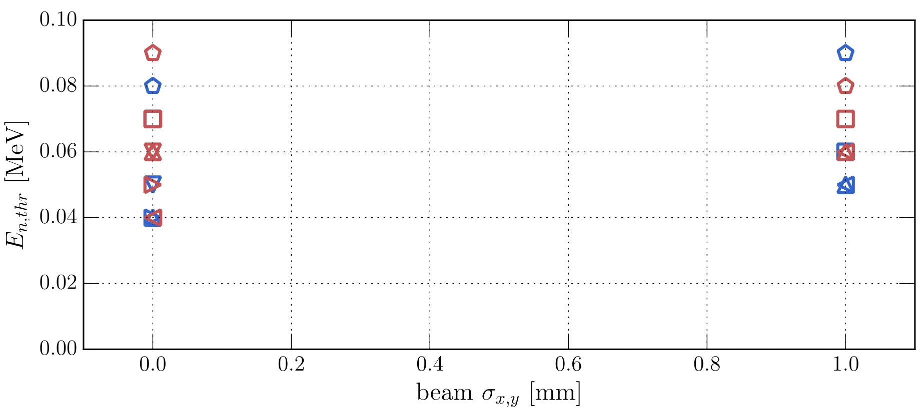


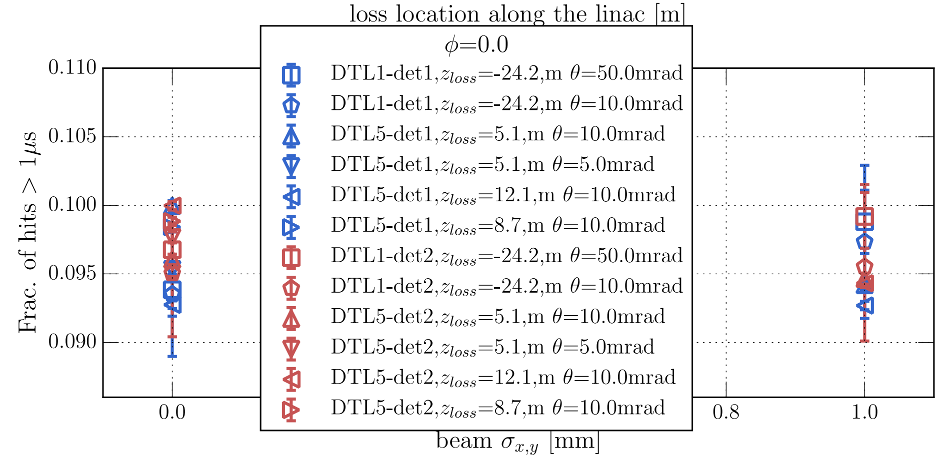
nBLM: threshold energy to discriminate slow/fast neutrons – $E_{n,Thr}$

Results for Limit2 (t_{lim}=1μs, f_{lim2}=0.1), det1 and det2









nBLM: threshold energy to discriminate slow/fast neutrons – $E_{n,Thr}$

EUROPEAN SPALLATION SOURCE

Comments

- No dramatic change in E_{thr} with loss location (thus energy), beam angles beam sizes and detector position (if det1 and det2 considered) visible in the data at hand
- Average E_{th} - averaged over all simulations runs reported in the plots on the previous slide:
  - limit1 (t_{lim}=1µs, f_{lim1}=0.01): (0.44 ± 0.06) MeV
  - limit2 (t_{lim}=1µs, f_{lim1}=0.1): (0.06 ± 0.01) MeV
  - Guidelines regarding the detector design:

    To insure the best impurity, assume the 0.5MeV limit for E_{thr}. If this turns out to be a bad choice for some reason (unacceptable detector dimensions or to too low count rates, once the detector sizes are fixed,…), go for E_{thr}= 0.05MeV

nBLM: neutron hitmap mean and RMS

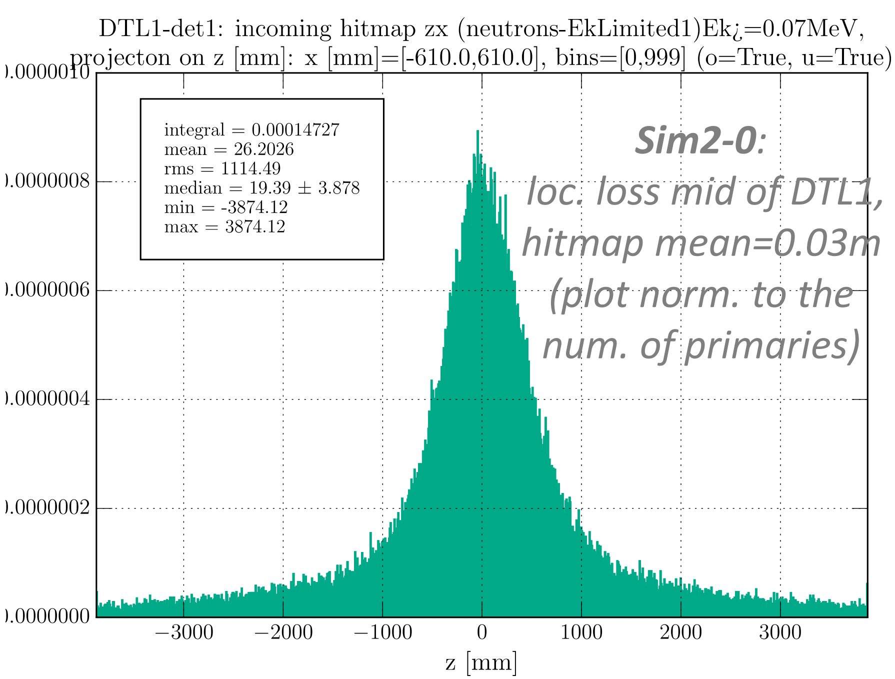
- Produced neutron hitmaps (for det1 and det2) from all available localized loss simulation runs (same as for best E_{thr} determination – simulation settings differ in beam size, loss location/energy in DTL and beam azimuth or polar angle)
- 3 different cuts used: E_k>0.04/0.07/0.4/0.5 MeV
- Focused now on the 0.5MeV and 0.07MeV – upper limit E_{thr} for the 2 time limits in E_{thr} determination

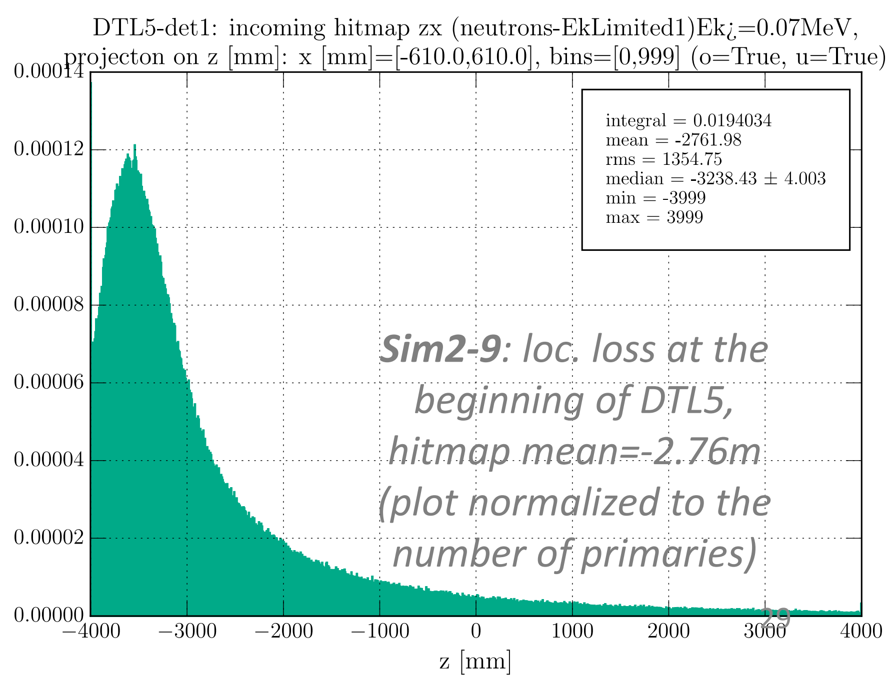
nBLM: neutron hitmap mean and RMS

EUROPEAN SPALLATION SOURCE

Observations:

- Mean extracted from the hitmap projections on the z-axis (runs along the beam line) gives a bad estimation of the visible peak – the sampled data represents a symmetric distribution, limited in z and not centered at 0 (except for the loss location in the middle of the tank).
- Same problem with RMS



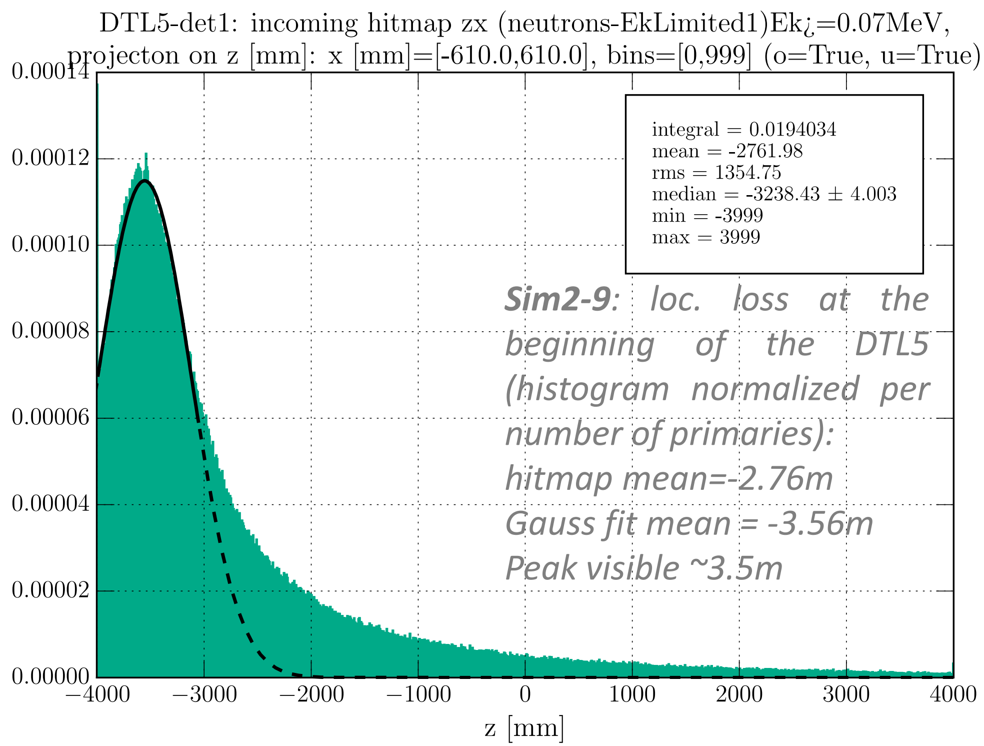


nBLM: neutron hitmap mean and RMS

EUROPEAN SPALLATION SOURCE

Observations:

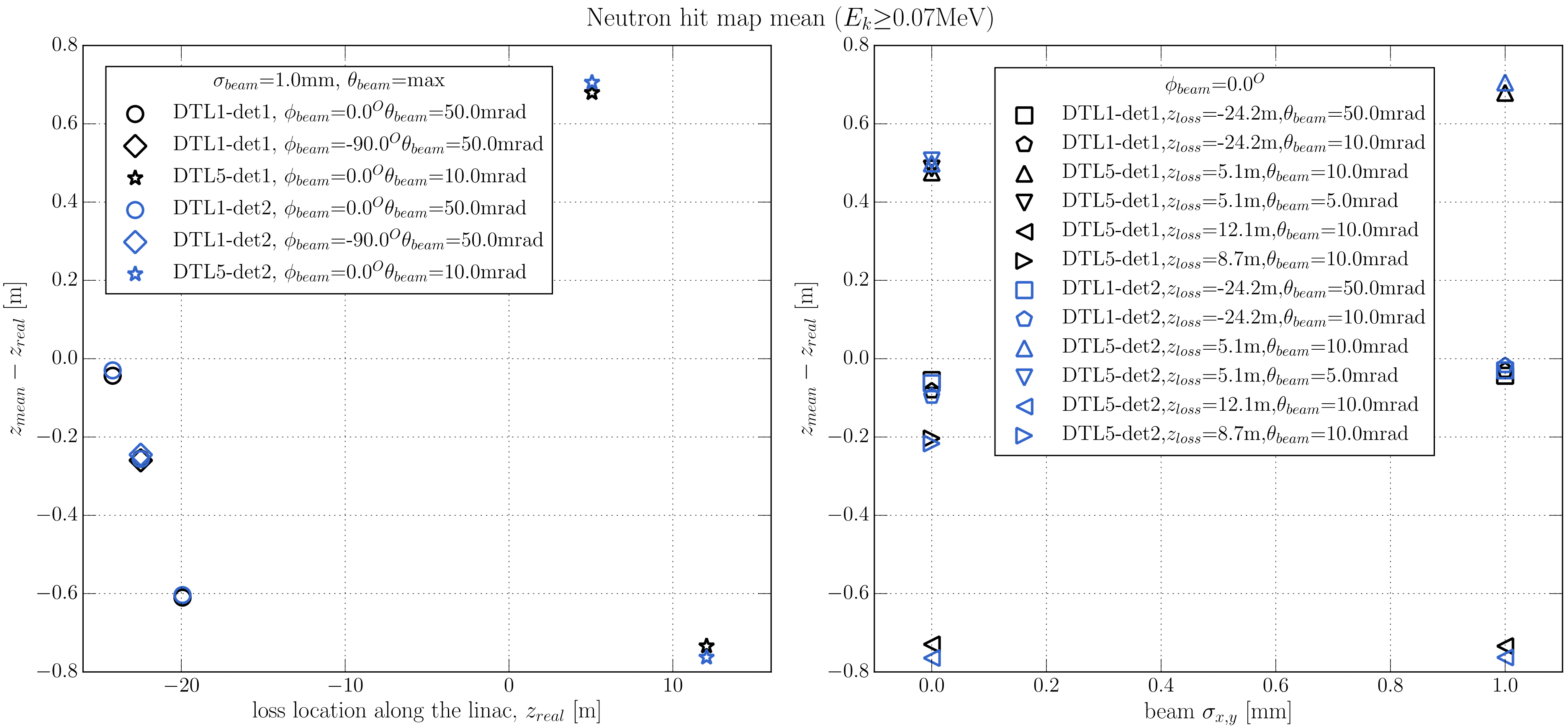
- Used a Gaussian fit around the peak of the distribution (fit range ± 0.5m) to extract the distribution mean and RMS
- The observed distributions do not follow the Gaussian shape – extracted Gaussian σ and hit map RMS underestimate the real RMS value
- Better way to determine the RMS:
  - Use the Gaussian mean instead hitmap mean and
  - Use the data on only one side of the peak
- Curves on the histo:
  - Solid line: gaussian fit to a selected range
  - Dotted line: fit function extension over the fit range



Sim2-9: loc. loss at the beginning of the DTL5 (histogram normalized per number of primaries): hitmap mean=-2.76m Gauss fit mean = -3.56m Peak visible ~3.5m

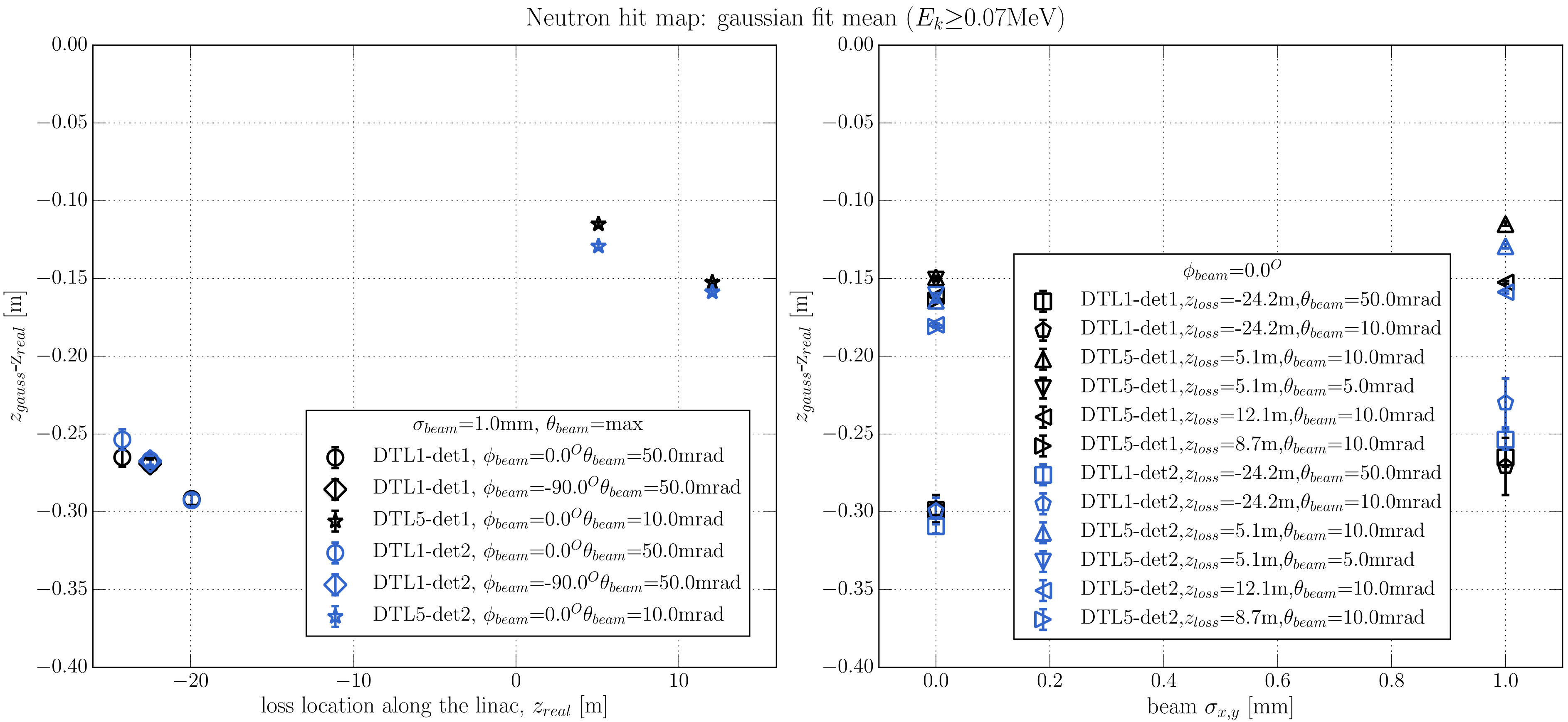
nBLM: neutron hitmap mean and RMS – E_k≥0.07 MeV cut

- Neutron hitmap with E_k>0.07 MeV cut: difference between the hitmap mean and the loss position



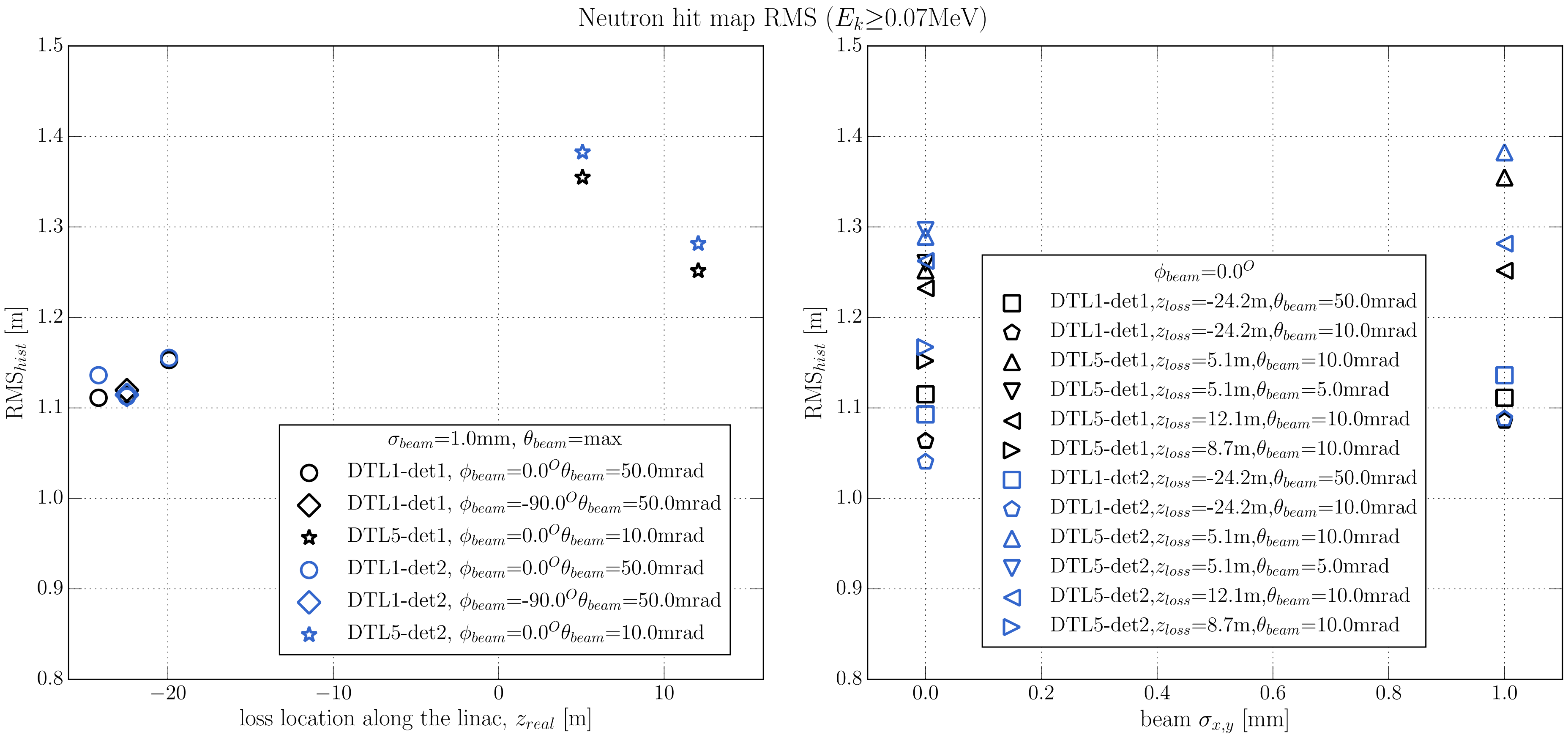
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.07$ MeV cut

- Neutron hitmap with $E_k > 0.07$ MeV cut: difference between the loss location and mean from the Gaussian fit to the hit map projection



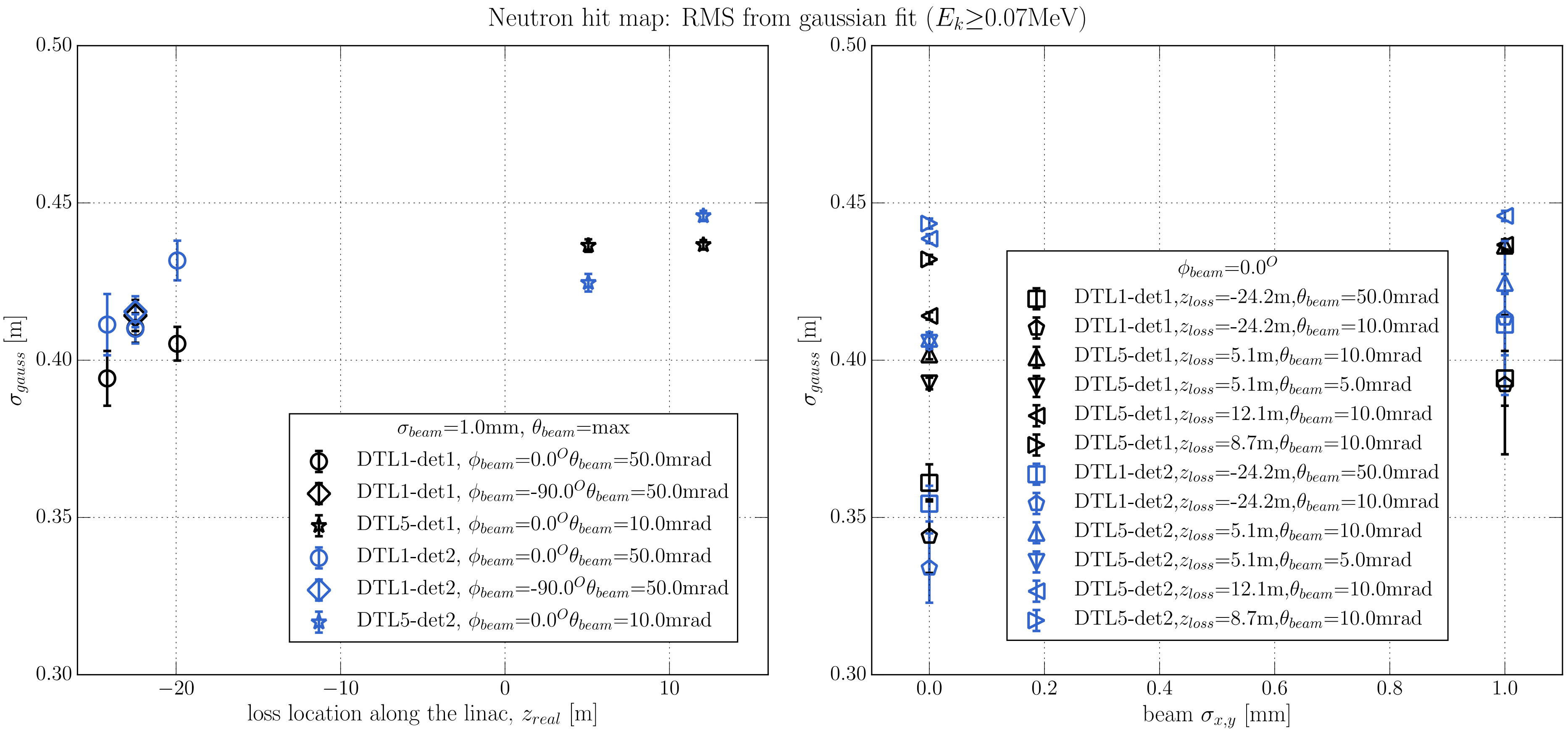
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.07$ MeV cut

- Neutron hitmap with $E_k > 0.07$ MeV cut: hitmap RMS



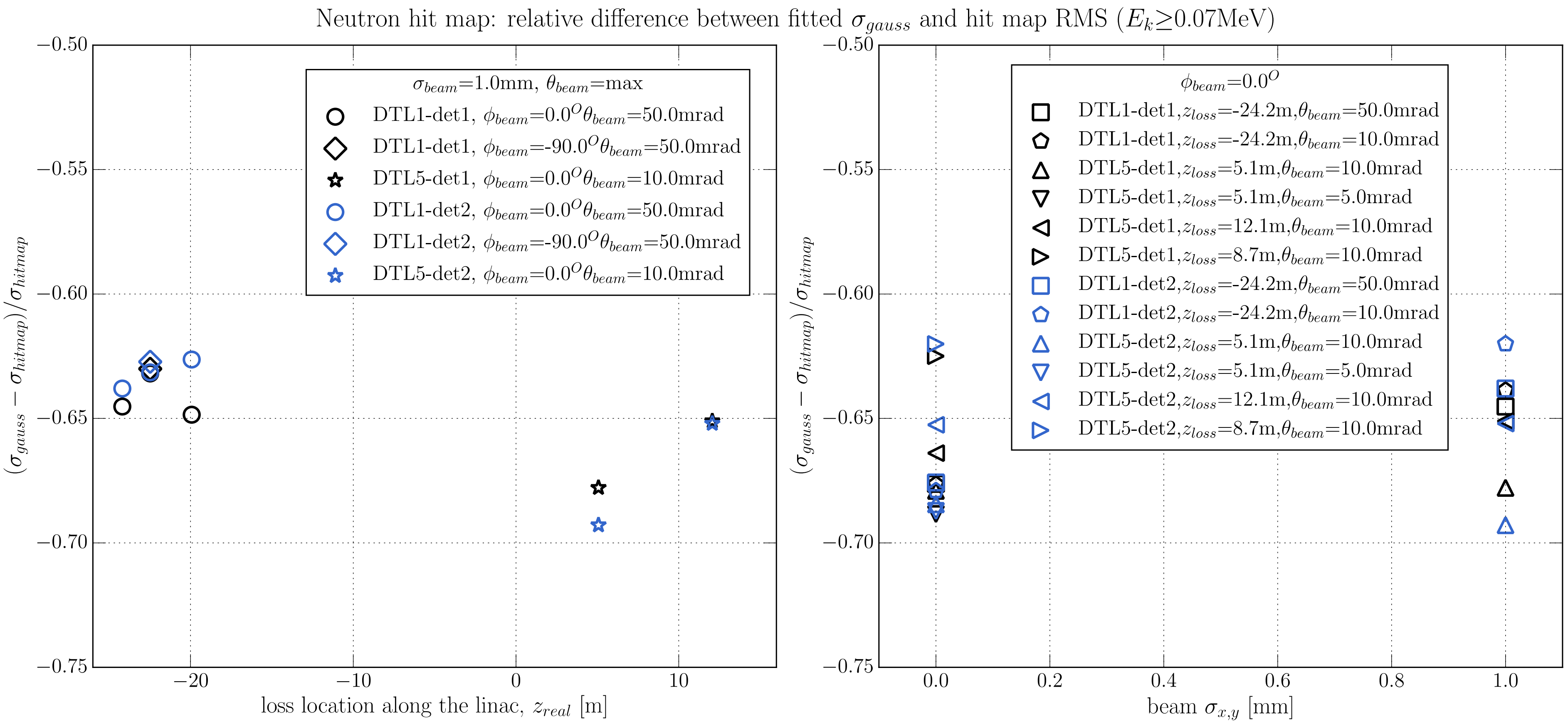
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.07$ MeV cut

- Neutron hitmap with $E_k > 0.07$ MeV cut: σ from the Gaussian fit to the hitmap projection



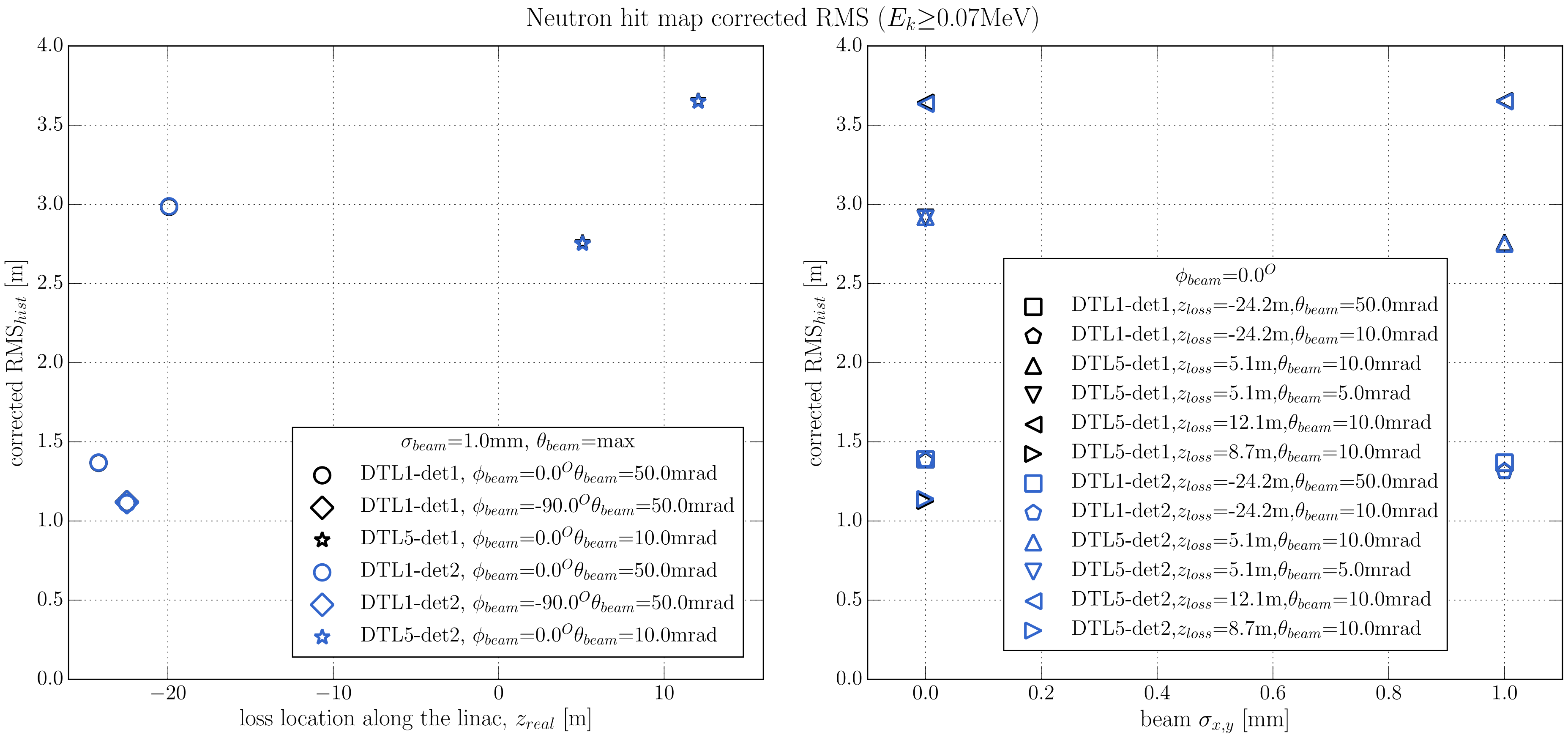
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.07$ MeV cut

- Neutron hitmap with $E_k > 0.07$ MeV cut: relative difference between the hit map RMS and σ from the Gaussian fit to the hitmap projection



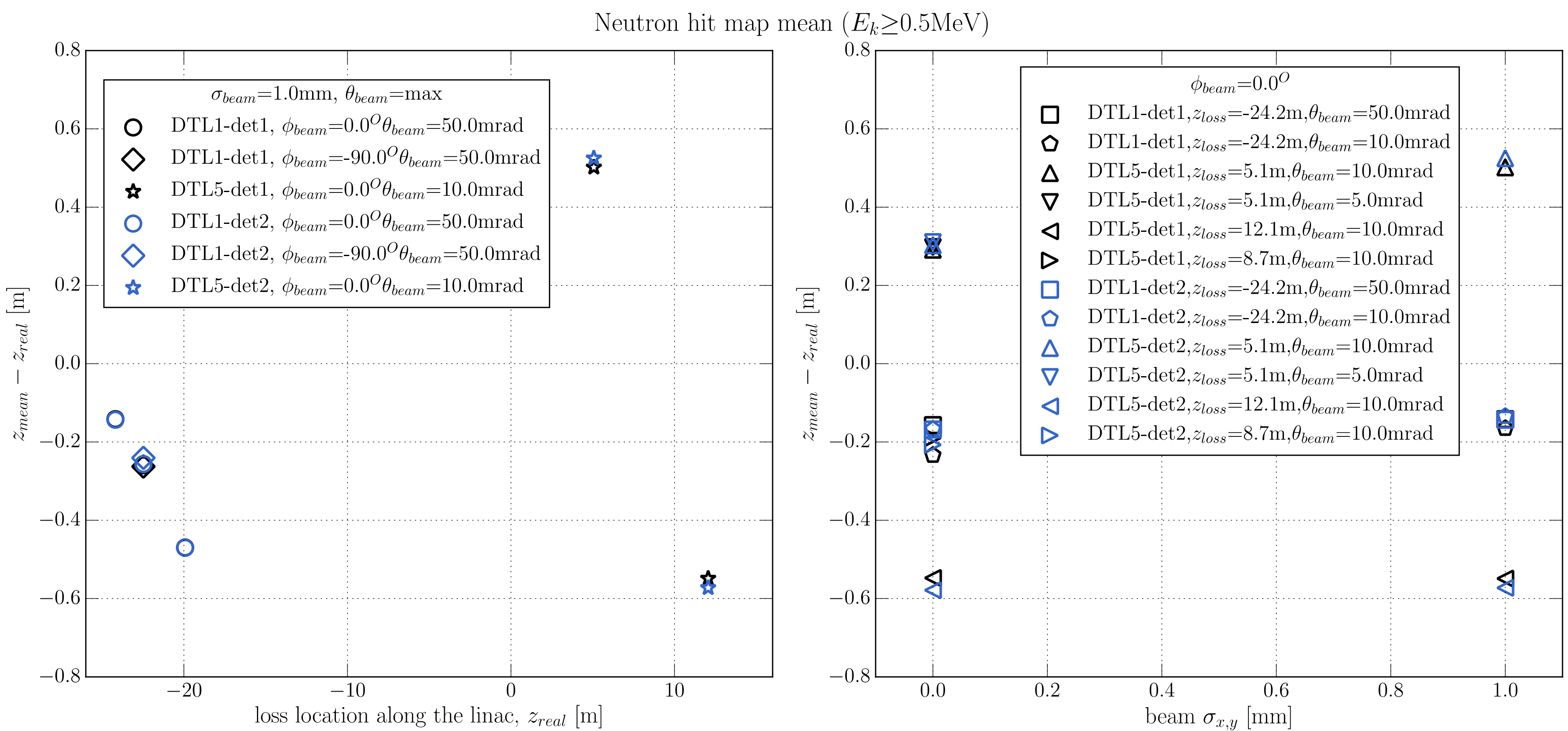
nBLM: neutron hitmap mean and RMS – E_k≥0.07 MeV cut

- Neutron hitmap with E_k>0.07 MeV cut: corrected hit map RMS



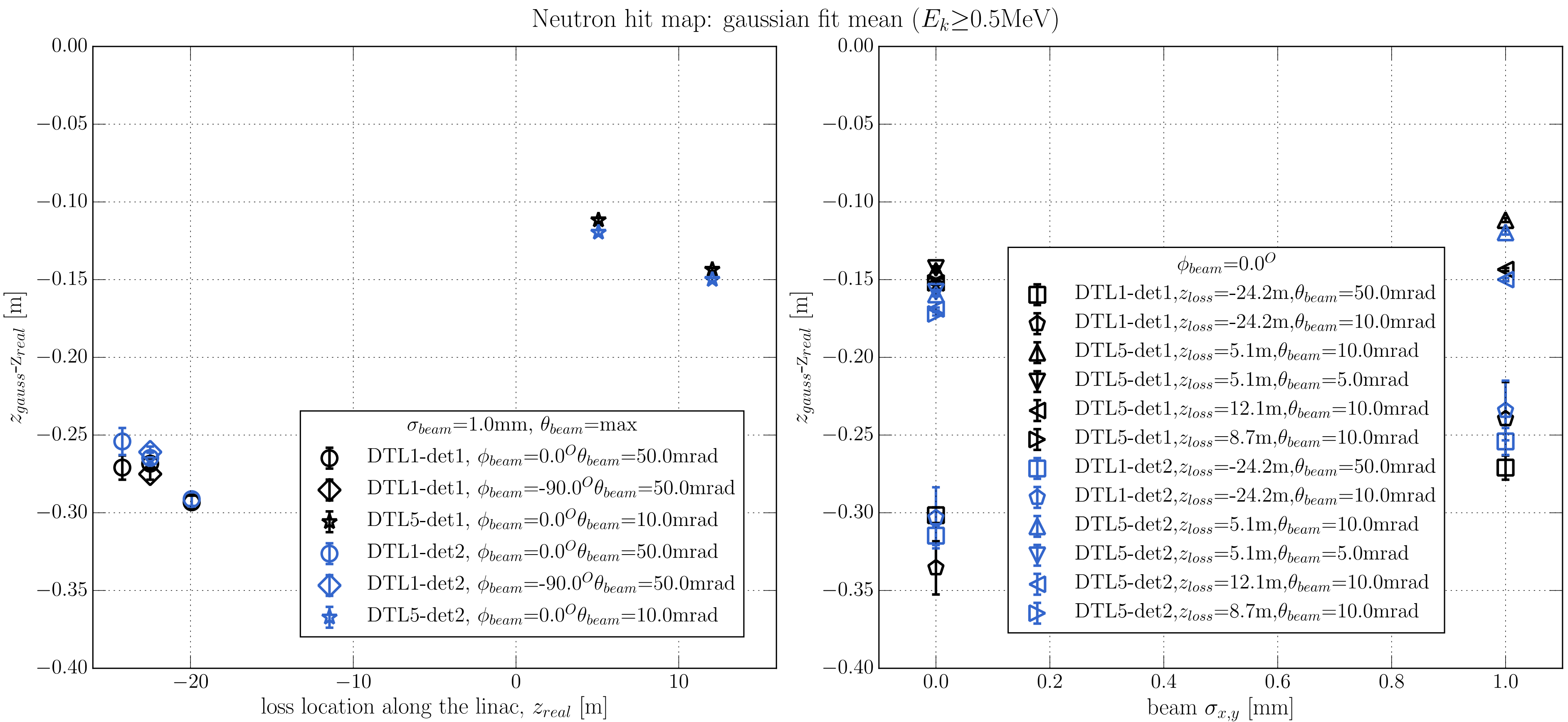
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.5$ MeV cut

- Neutron hitmaps with $E_k>0.5$ MeV cut: difference between the hitmap mean and the loss position



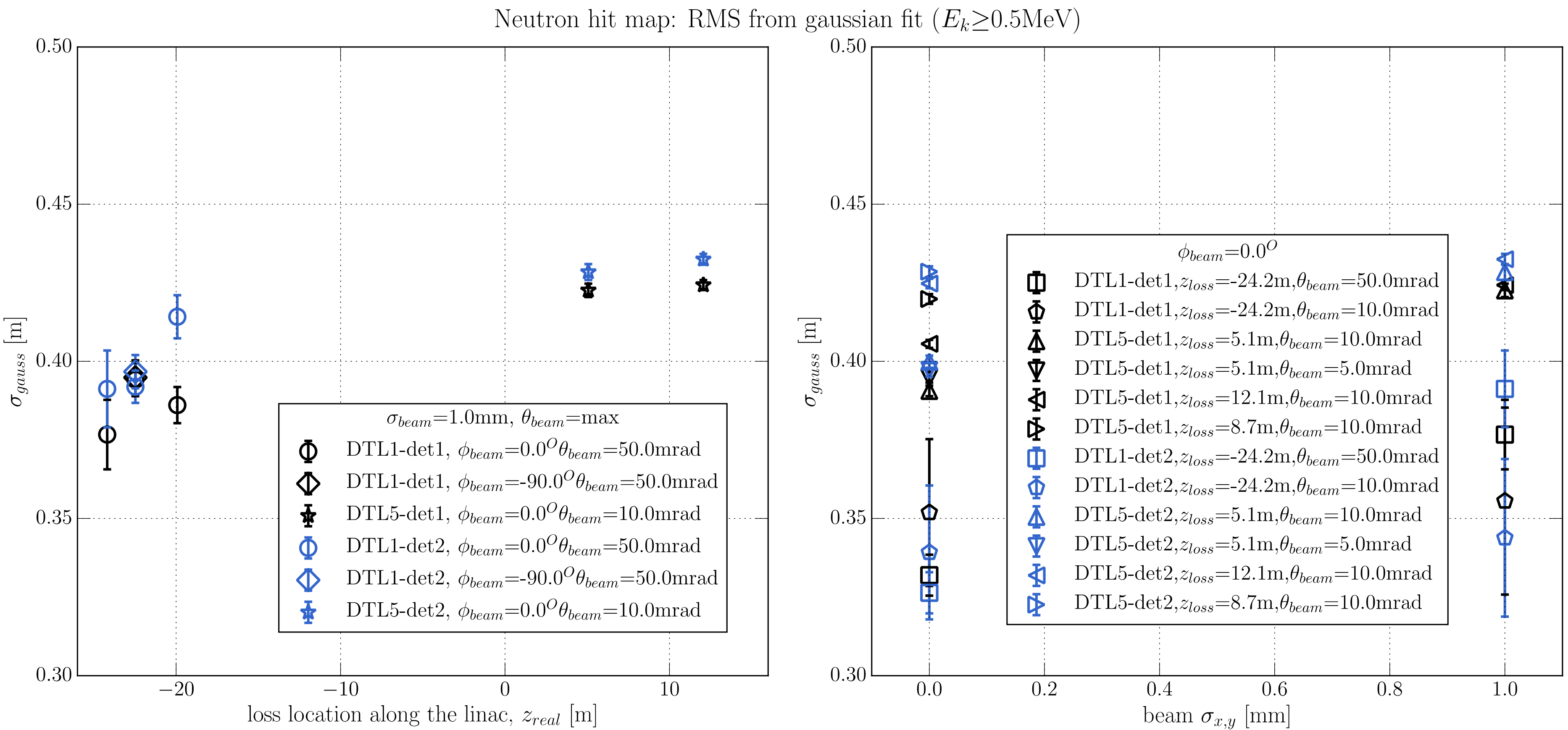
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.5$ MeV cut

- Neutron hitmaps with $E_k > 0.5$ MeV cut: difference between the loss location and mean from the Gaussian fit to the hit map projection



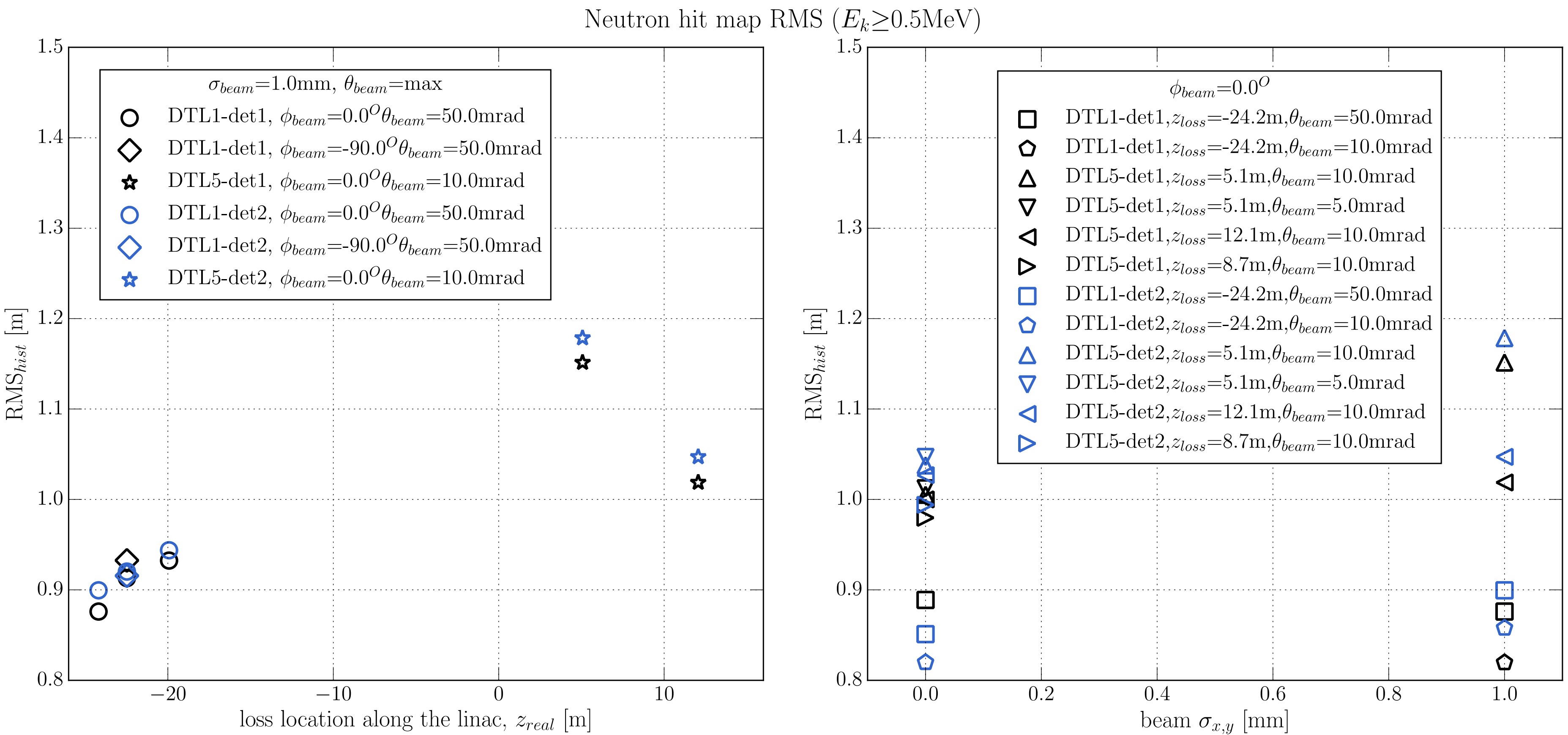
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.5$ MeV cut

- Neutron hitmaps with $E_k > 0.5$ MeV cut: σ from the Gaussian fit to the hitmap projection



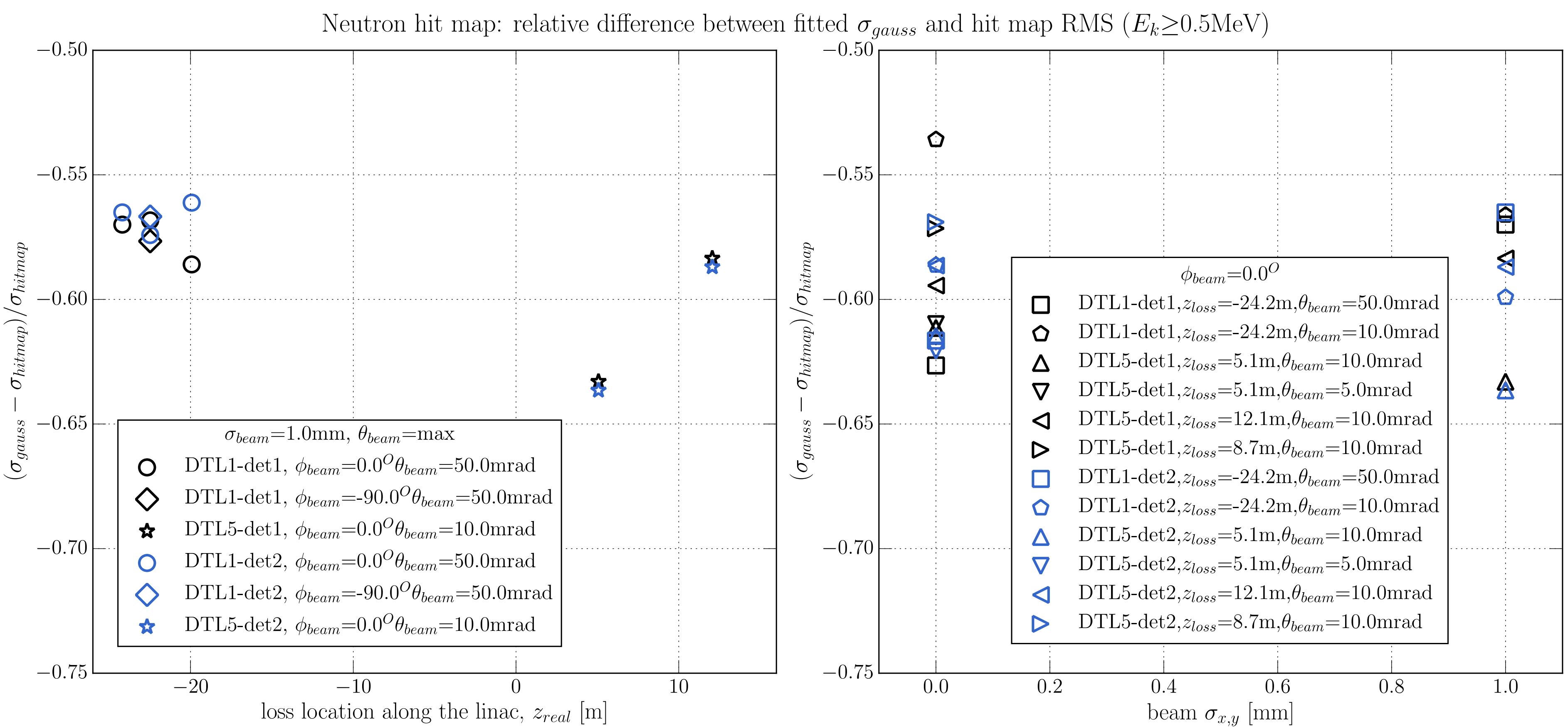
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.5$ MeV cut

- Neutron hitmaps with $E_k > 0.5$ MeV cut: hit map RMS



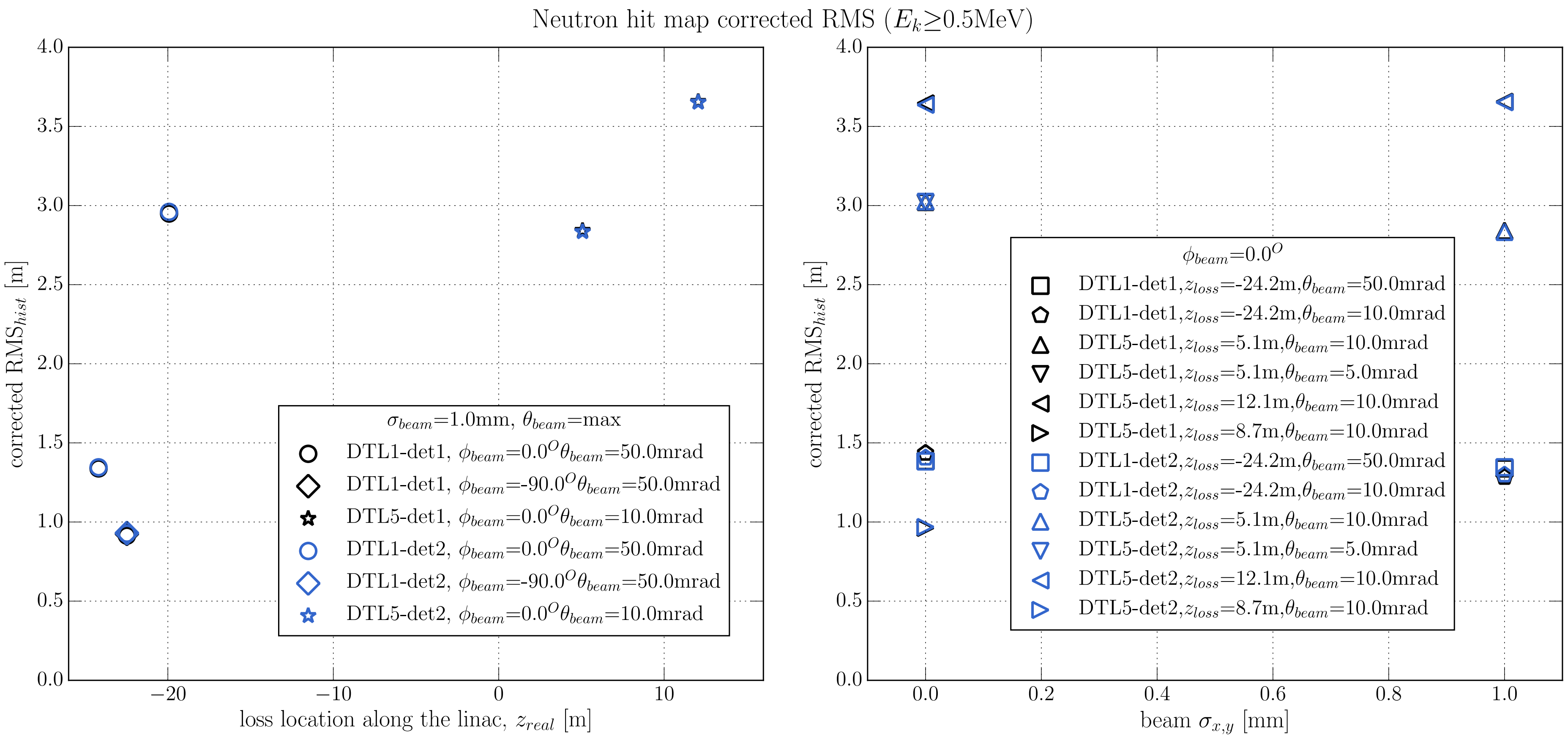
nBLM: neutron hitmap mean and RMS – $E_k \geq 0.5$ MeV cut

- Neutron hitmaps with $E_k > 0.5$ MeV cut: relative difference between hit map RMS and σ from the Gaussian fitted to the hitmap projection



nBLM: neutron hitmap mean and RMS – $E_k \geq 0.5$ MeV cut

- Neutron hitmaps with $E_k > 0.5$ MeV cut: corrected hit map RMS



nBLM: neutron hitmap mean and RMS – conclusions

Hitmap peak position:

- The peak of the projected distributions is best estimated with the mean from a Gaussian fit in a limited range around the peak (μ_{gauss})
- The difference between μ_{gauss} and the loss position z_{real}:
  - Does not show significant dependence on the detector position (det1 and det2 considered), beam size (up to considered 1mm size), beam polar or azimuth angle.
  - It does seem to depend on the loss location:
    - In the DTL1: ($\mu_{gauss}-z_{real}$) between ~ −0.25m and −0.35m
    - In the DTL5: ($\mu_{gauss}-z_{real}$) between ~ −0.18m and −0.1m
- Possible reasons for the loss location dependence:
  - Energy dependence and/or
  - Geometry dependence (gap size increases along the DTL, loss hit location fixed to the middle of the gap)
- Unclear why the difference is negative, need to score and check the tracks around the loss location to see what is happening. The difference can't be explained with non-zero beam size (here beam tail hits the aperture before the center does) since the simulation runs with pencil beam exhibit the negative difference as well.

nBLM: neutron hitmap mean and RMS – conclusions

Hitmap RMS:

- The RMS of the projected distributions is best estimated by calculating the RMS from the estimated σ_{gauss} on one side of the peak (the with larger amount of data)
- Observed σ_{gauss} :
  - Does not show significant dependence on the detector position (det1 and det2 considered), beam size (up to considered 1mm size), beam polar or azimuth angle.
  - No significant difference between the two different E_{thr} limits used – the lowest of the limits cuts the "background" efficient enough?
  - It does seem to depend on the loss location, ranging from 0.9 to 3.6m. With one exception (for the loss located a the end of DTL1), higher values observed in DTL5
- Possible reasons for the loss location dependence:
  - Same as before (energy and/or geometry dependence) – less likely
  - More tail available for the RMS calculation in case of the losses generated at the edge of the tanks

If the latter is the cause, expect an increase in calculated RMS for these cases, as it is observed in the data at hand.

nBLM: neutron hitmap mean and RMS – conclusions

EUROPEAN SPALLATION SOURCE

Detector locations and size

Following the discussion from the previous slides:

- The average corrected RMS ≈ 2±1m implies placing the nBLM detectors with max 3m distance.
- With typical dimension of a DTL tank ~8m in mind:
  - 4 detectors per tank (at 0, 1/4,1/2 and 3/4 length of the tank) + 1 in the end = 21 detectors
- Detector size should be adapted to the expected number of detected hits (detection efficiency*number of neutron hits over the time=response time)
- Hard to give a limit of acceptable number of detected hits as it should be inspected together with the detection impurity (depends on E_{thr} and background levels).
- Suggestions regarding the detector design:
  - Consider 4 detectors per tank (with spacing of ~2m)
  - Adapt the detector sizes (together with E_{thr}/detection efficiency and impurity) to give a reasonable dynamic range
  - Note: localized beam loss can occur at any azimuth angle (0-360^o). Lowest hit rate expected when the detector is placed at location opposite to the beam loss direction (see slide 20) .

    Use det1 from simulation sim2-3 (beam azimuth angle at −90^o, pointing away from detector DTL1- det1) and sim2-0 (beam loss towards DTL1-det2) to give an estimate on the difference between the lowest and highest hit rate estimation for the case of localized beam loss.

Dynamic range

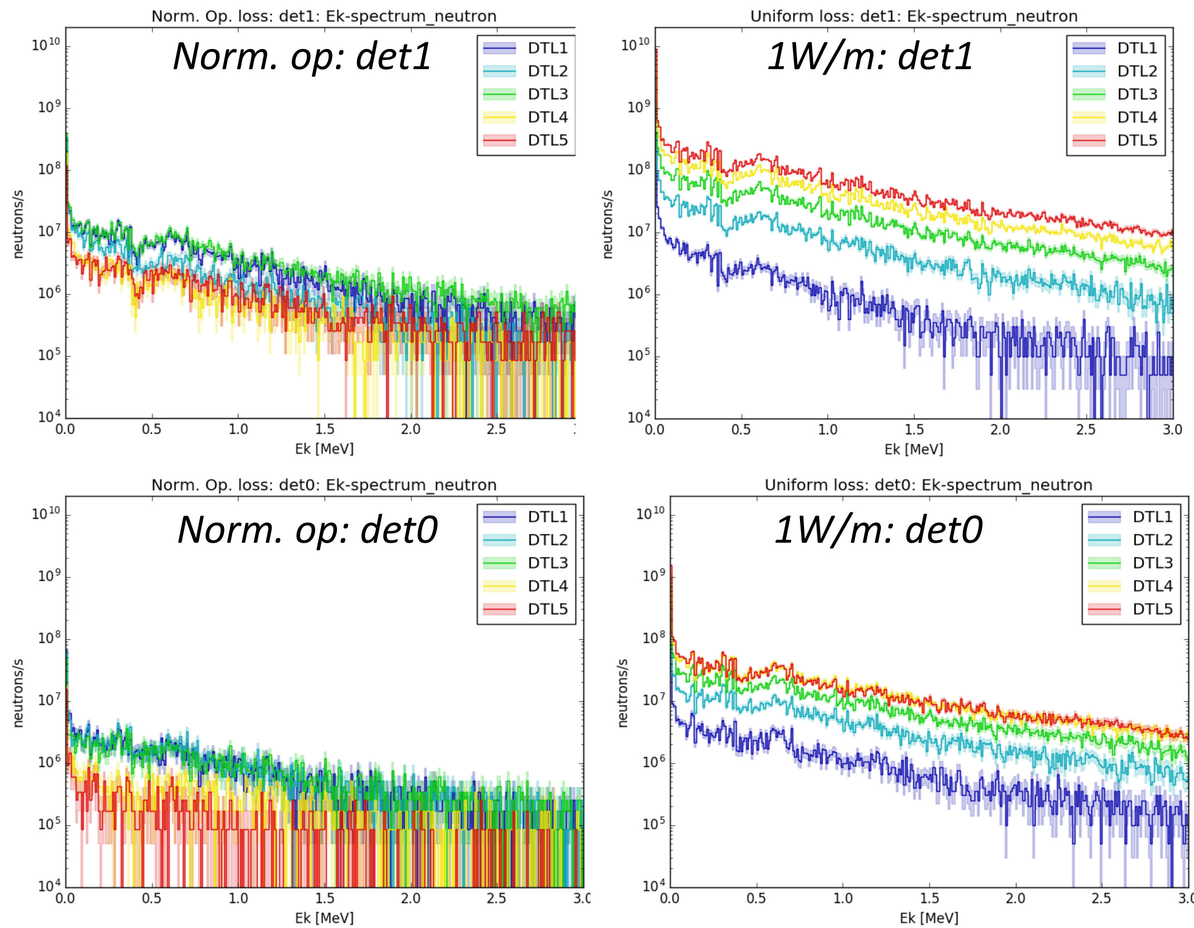
Dynamic range can be determined once the detector locations are know by inspecting 2 extreme cases:

- **Highest expected hit rate**
  - Marks the "worst case" accidental loss (most focused beam under least shallow angle hitting a detector).
  - Strategy: *assume the "worst case angles" and use the simulated hit rates to the estimated the upper limit for the dynamic range.*
- **Lowest expected hit rate**
  - Lower limit of the dynamic range typically set to a fraction of a 1W/m loss - coming from a limit for hands-on maintenance.
  - However, to support tuning and optimization it is useful asses scenarios where certain areas may have loss levels well below the activation limit.
  - The lower limit of dynamic range can than be set to a fraction of this signal.

Dynamic range

Norm. op. vs. 1W/m loss neutron spectra (neutrons/s hitting the det. volumes surrounding the DTL tanks) in NC linac

- ***Note:*** *Results of the beam dynamics error study [9,10] used as the inputs to BLM simulation and assumed to represent a realistic loss scenario of the ESS linac during normal operation.*
- **1W/m loss:**
  Increase in incoming neutrons with the tank number (neutron cross section increases with Ek).
- **Normal operation loss:**
  Neutron flux lowest in the last two tanks (emittance decreases with Ek).
- **Norm. op. vs. 1W/m loss**
  Shape of the spectra the same for both loss scenarios.
  All spectra for the 1W/m above the corresponding ones for norm. op. loss (except for DTL1, det0, where 1W/m loss same or slightly below nor. op. one).
  The difference increases with tank number (~0 to ~1.5 order of mag.) .



Norm. op. vs. 1W/m loss in NCL

EUROPEAN SPALLATION SOURCE

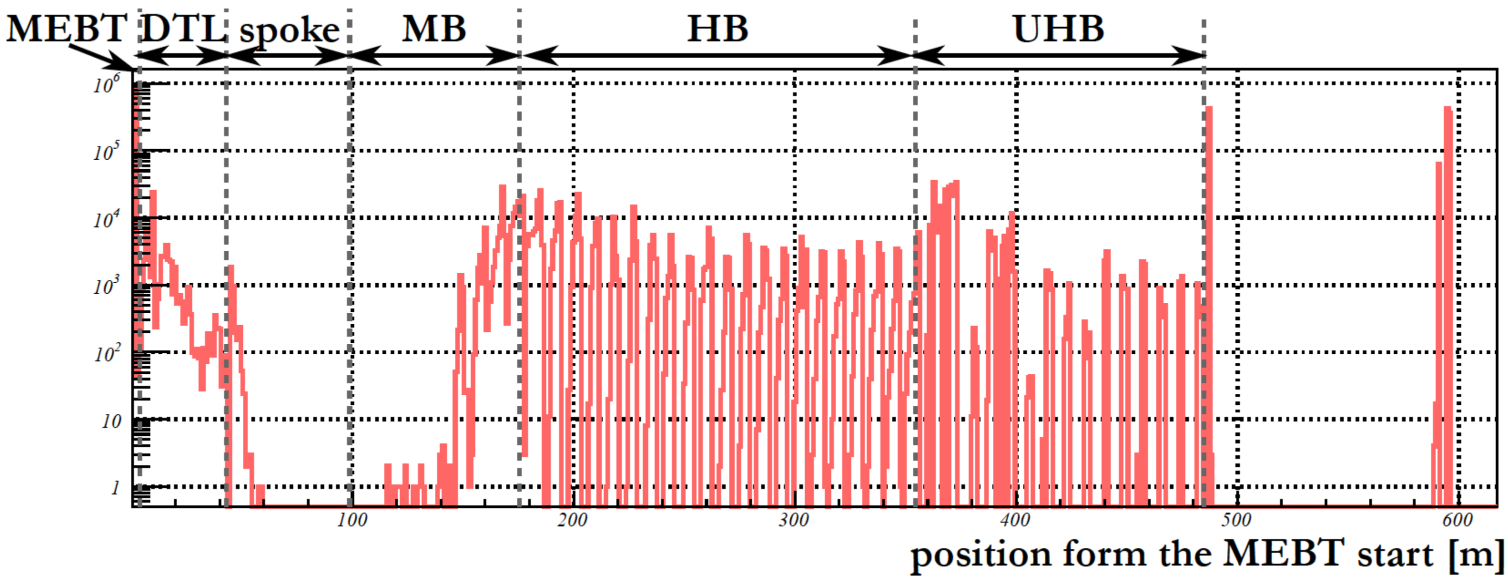
Simulation settings:

- **Normal operation**:
  - A beam dynamics error study performed [9,10].
  - Results of the error study used as the input to the BLM MC simulations of lost protons and assumed to represent a realistic loss scenario of the ESS linac during normal operation.
  - Lost protons in the BLM MC simulation were sampled from the lost particle distribution (direction azimuth and polar angle, position azimuth angle, energy) obtained from the previously mentioned beam dynamics error study.
    - No limitation on the statistic of the BLM simulation.
    - No assumptions on the lost particle distributions.
    - Correlation observed (and used in sampling) between the azimuth angles for lost proton position and momentum direction
- **1W/m loss:**
  - Uniform distribution of lost protons assumed along the linac.
  - Proton momentum direction polar angle form the beam axis fixed to 1mrad.
  - Proton position azimuth angle (vertical plane) sampled uniformly around the aperture.
  - Energy set to the nominal value at the lost proton location.
- **Geometry:**
  - Included sections: MEBT, DTL1-5, 4 first cryomodules of the Spoke section
  - Phantom detectors (vacuum) placed around the tanks (see p13 and p8)

ESS linac normal operation

Expected loss map during normal operation [9,10]:

- A beam dynamics error study performed (on the 2015 baseline beam physics lattice of the ESS linac – 2015.v1).
- Errors applied to 10k machines (600k macroparticles each).
- Error tolerance set to 100% of the nominal value – apart for dynamic error (RF jitter), where error tolerance increased to 200%.
- Results of these study used as the input to the BLM MC simulations of lost protons and assumed to represent a realistic scenario of the ESS linac during normal operation loss.



Dynamic range

EUROPEAN SPALLATION SOURCE

ESS BLM dynamic range specifications

- **nBLMs:**

  Once detector locations and dimensions are fixed:
  - Upper limit: can be set by assuming total beam loss with a focused beam under "worst case" incidence angle.
  - Lower limit: can be set to a fraction of the neutron flux expected during the normal operation.
  - Suggestion for the detector development regarding the lower limit:
    - Check the expected flux at normal operation at detector location with lowest expected flux. Select 1-10% of this flux for the lowest limit, the exact number depends on the detector size and should be adapted to give a reasonable dynamic range
- **ICBLMs**:
  - Preliminary values set in the past [11]:
    - "BLM is required to be able to measure at least 1% of 1W/m loss during normal. operation and up to 1% of the total beam loss".
    - Gave estimation on the ICLBM current range: ~800nA – few mA.
  - Plan to re-assess that once the ICBLM detector locations are fixed.
  - However for now assume the preliminary values when talking to William regarding the input currents for the BLEDP and time constant tuning.

References

[1] M. Stockner et al., "*Classification of the LCH BLM ionizations chamber*", WEPC09, DIPAC 2007, Venice, Italy (2007)

[2] M. Hodgson, *"Beam loss monitor design investigations for particle accelerators"*, PhD thesis (2005)

[3] E. Donoghue et al., *"Studies of electron activities in SNS-type SC RF cavities"*, Proc. Of 12th Int. Workshop on RF Superconductivity, Cornell Univ., USA (2005)

[4] B. Cheymol, *"ESS wire scanner conceptual design"*, ESS-0020237 (2016)

[5] T. Papaevangelou, Micromegas detector applications for beam diagnostics''

CERN BI seminar, CERN, Geneva, Switzerland (2016), http://indico.cern.ch/event/540799/

[6] T. Kittelmann et al., "*Geant4 Based Simulations for Novel Neutron Detector Development"* 20th International Conference on Computing in High Energy and Nuclear Physics (CHEP) (2013)

[7] L. Tchelidze, "*How Long the ESS Beam Pulse Would Start Melting Steel/Copper Accelerating Components?"* ESS/AD/0031, http://docdb01.esss.lu.se/DocDB/0001/000168/001/Time_Response_Requirements_BLM.pdf

[8] W. Blokland et al, " *A new differential and errant beam current monitor for the SNS accelerator*", IBIC 2013 (THAL2), Oxford, UK. (2013)

[9] Y.I. Levinsen, *"ESS 2015 Baseline Lattice Error Study",* ESS-0049433 (2016)

[10] Y.I. Levinsen, "*Challenges in the ESS linac*", HB 2016 (TUAM3Y01), Malmö, Sweden (2016)

[11] L. Tchelidze et al., *"Beam Loss Monitoring at the European Spallation Source"*, IBIC 2013 (WEPC45), Oxford, UK (2013)

[12] http://www.srim.org/

[13] N. Mokhov et al., "*ESS accelerator prompt radiation shielding design assessment*", ESS-0052477 (2016)

[14] ESS reports ESS-0040133, ESS-0052477

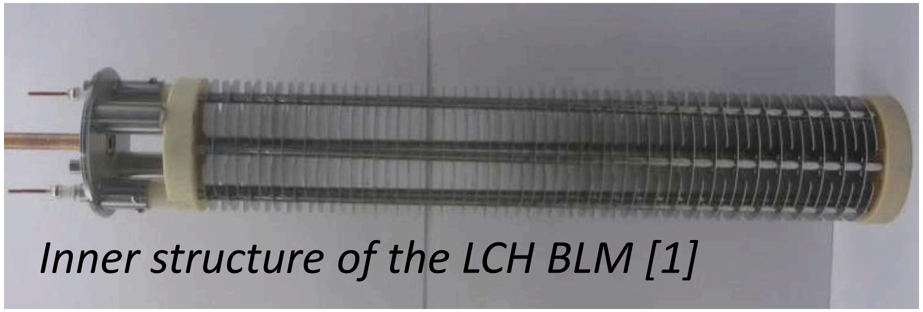
Back up material

ESS BLM: ICBLM

EUROPEAN SPALLATION SOURCE

ICBLM (Ionization Chamber based BLM)

- Showers of secondary particles (charged and neutral) are expected in the SC linac.
- Parallel plate gas Ionization Chambers (ICs) developed for the LHC BLM system will be used – chosen due to their fast response.
- ICs ordered in Summer 2014 (production line setup in Russia, to replenish spares for LHC and make prod. series for ESS and FAIR).


Inner structure of the LCH BLM [1]

Data from [1], [2]

Detector property property	Value
detector gas	N_2
pressure	1.1 bar
diameter	9 cm
length	50 cm
sensitive volume length	38 cm
num. of electrodes	61
electrode spacing	5.75 mm
electrode thickness	0.5 cm
electrode diamater	75 mm
bias	1.5 kV
max e^- drift time	300 ns
max ion drift time	83 μs
<energy> to create ion-e^- pair in N_2	35 eV
wall thickness:	
tube	2mm
bottom plate (facing el.box)	4mm
top plate	5mm

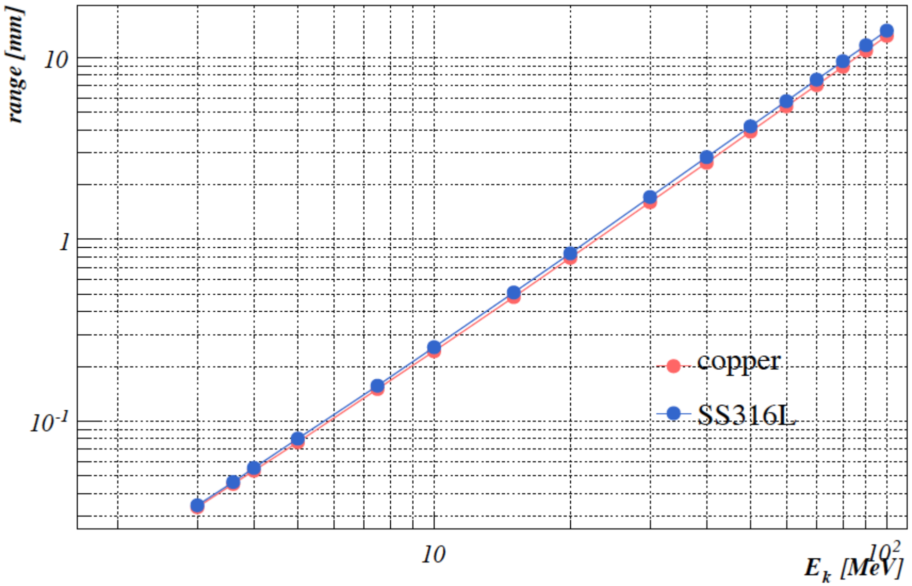
ESS NCL: particle fields

- DTL: protons (3.6-90MeV) stopped in the 3-5cm stainless steel walls.

- Expected particle fields outside of the DTL tanks dominated by neutrons and photons.

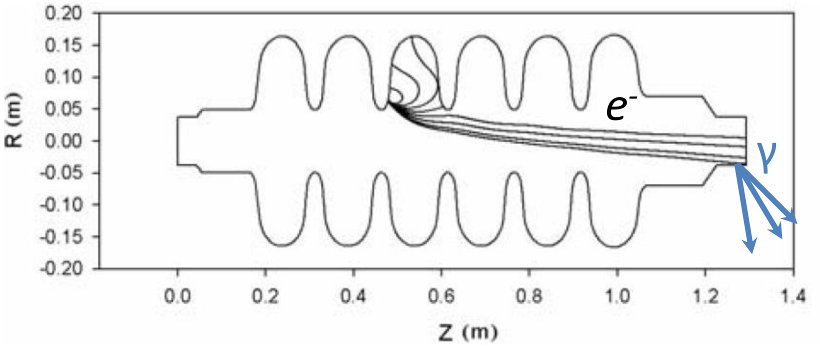
- Same conclusion holds for MEBT (3.6MeV).

Range of protons in copper and SS316L (calculations with SIRM [12])

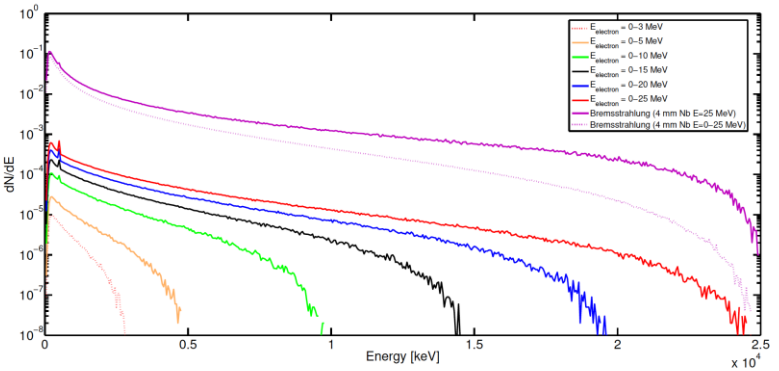


Background photons due to RF cavities

- Photon background due to the RF cavities mainly due to field emission from electrons from cavity walls, resulting in bremsstrahlung photons created in the field of nuclei of cavity/beam pipe materials [3].



- Energy spectra estimations show that photons up to few tens of MeV can be expected [4]:
  - A MC code (FLUKA) was used for these estimations where a pencil electron beam is impacting a 4mm niobium foil.
  - Purple curves on the plot on the left show expected energy spectra for the photons produced at the exit of the foil:
    - Solid line – for the monochromatic beam of electrons with energy of 25MeV
    - Dotted line – for the beam of electrons with uniform energy distribution from 0 to 25MeV.
    - Spectra are normalized per number of primaries.
  - Note: maximum acc. Gradient expected at ESS ~25MeV/m, cavity size ~1m.



Response time

- Required response time set in the past:
  - In NC linac (MEBT-DTL): ~5 µs.
  - In SC linac: ~10 µs.
  - Numbers based on a simplified melting time calculations, where a block of material (copper or stainless steel) is hit by a beam of protons with a uniform profile under perpendicular incidence angle, no cooling considered [7].
- Numbers recently rechecked with update parameters and Gaussian beam profile
  - SRIM [12] calculations used to extract the highest dE/dx (at the Bragg peak), where highest temperature is reached. This serves as an input to calculated the time needed to reach the melting temperature under constant irradiation.
  - For the NC linac recheck with a MC calculation for the worst case (most focused 3.6MeV beam under perpendicular incidence) – melting time values agree (3-4µs)
  - **NC linac:** the calculations imply that we should be even faster than 5µs
  - **SC linac**: the 10µs requirement for response time fits well with these calculations