Simulations and detector technologies for the Beam Loss Monitoring system at the ESS linac

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Outline

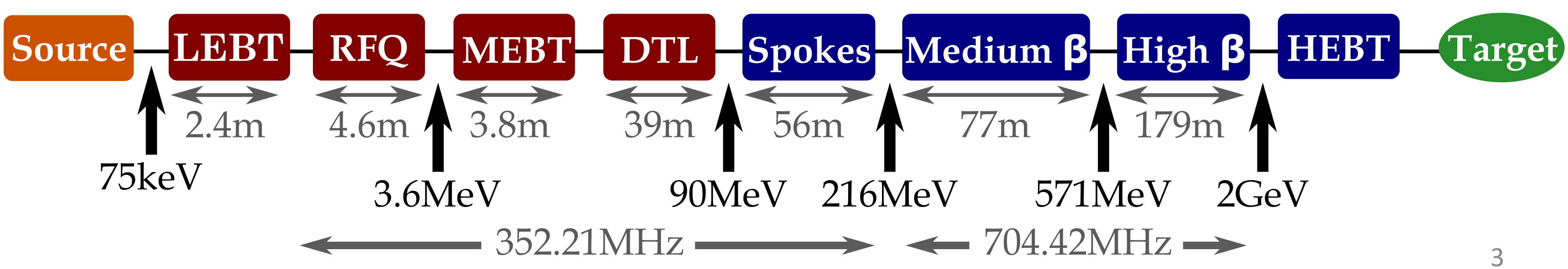
- The ESS linac
- The ESS BLM system: detector technologies
- Monte Carlo (MC) simulations for the ESS BLM
  - Tasks
  - Part of the simulation task in more details.

  ***Note**: The focus is on the MC simulations for tracking of the lost protons outside the beam pipe in contrast to the beam dynamics simulations for beam optics optimization (the lost protons from those are inputs the MC simulations under discussion)*

- Summary

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 (1.1109 p/bunch)
  - Beam pulse = 2.86ms
  - Repetition rate = 14Hz
- Normal conduction linac (NCL):
  LEBT, RFQ, MEBT, DTL (5 tanks).
- Superconducting linac (SCL):
  Spoke, Elliptical and HEBT sections.

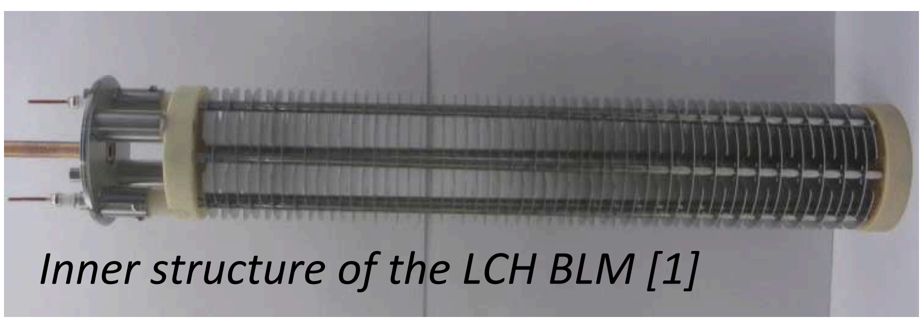


ESS BLM: detector technologies

Plan to use 3 types of detectors

1. **ESS SCL– 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

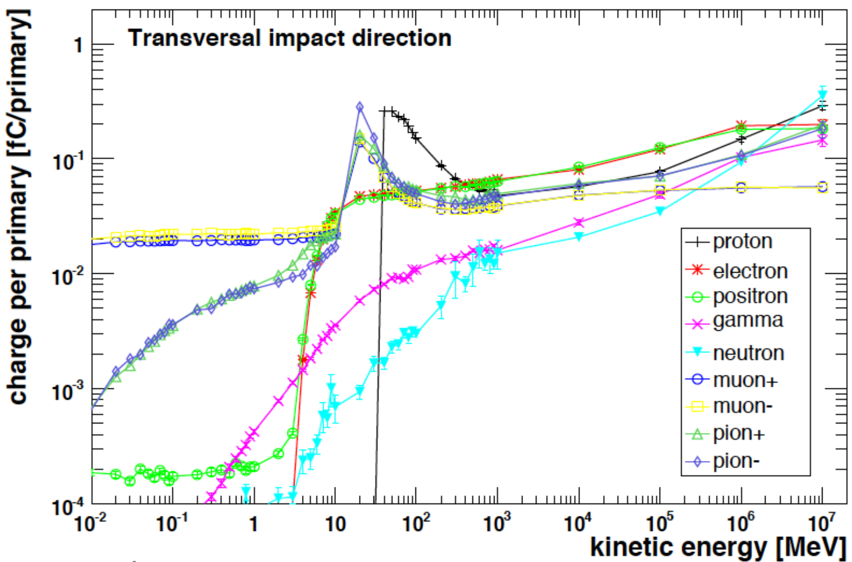
ESS BLM: detector technologies

1. ESS SCL - ICBLM (continued)

- 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: detector technologies

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

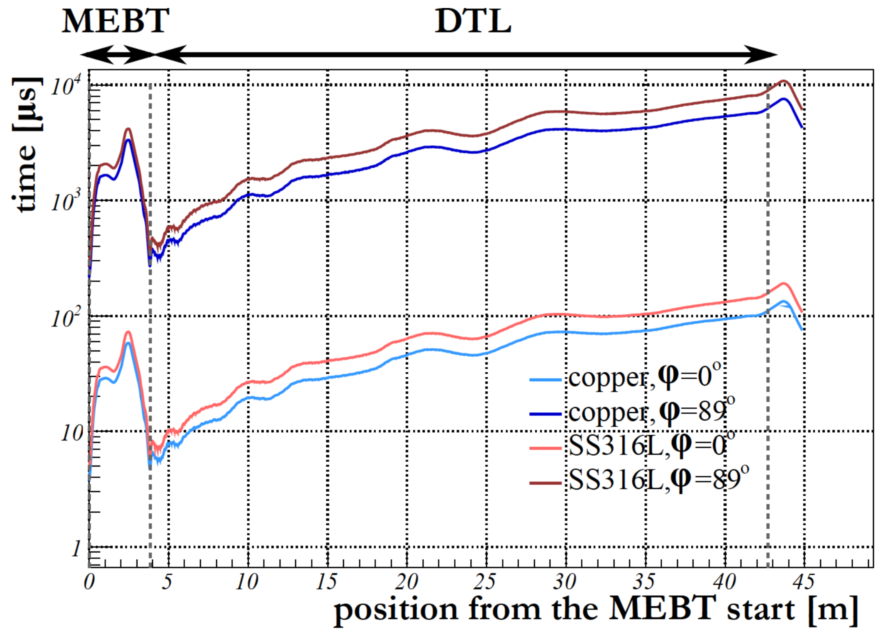
- Plane to place BLM detectors in the MEBT and DTL sections.
- Particle fields outside the beam pipe and tanks in this area expected to be dominated by neutrons and photons.
- RF cavity background still a possible source of photons in these areas – neutron sensitive detectors should be considered.
- Micromegas detectors will be used in these parts of the linac.
- Detector design currently in development by the micromegas experts from CEA Saclay.
- 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 BLM simulations: tasks

- **MC simulations for tracking the lost protons needed to determine:**
  1. System response time limit.
  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.
- **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 together with the elements that must be protected with their damage levels.
  - However, simplifications/assumptions are needed (discussed later), due to a large number of possible accidental scenarios in a linac.
- **Simulation tool:**
  - Geant4 simulation framework developed by the ESS neutron detector group [6].
  - Geant4 based ESS linac geometry created (summary of assumptions and simplifications in the back-up material)

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.*

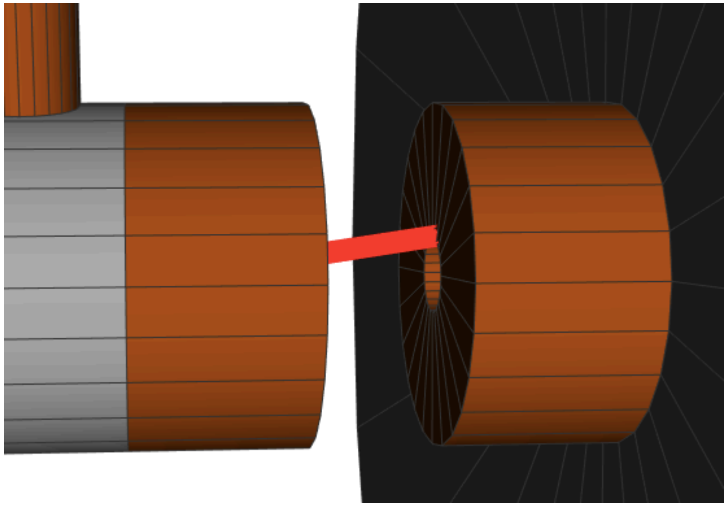
  - Assessment of this type performed for the DTL and HEBT (courtesy of R. Miyamoto):

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.
  - 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.

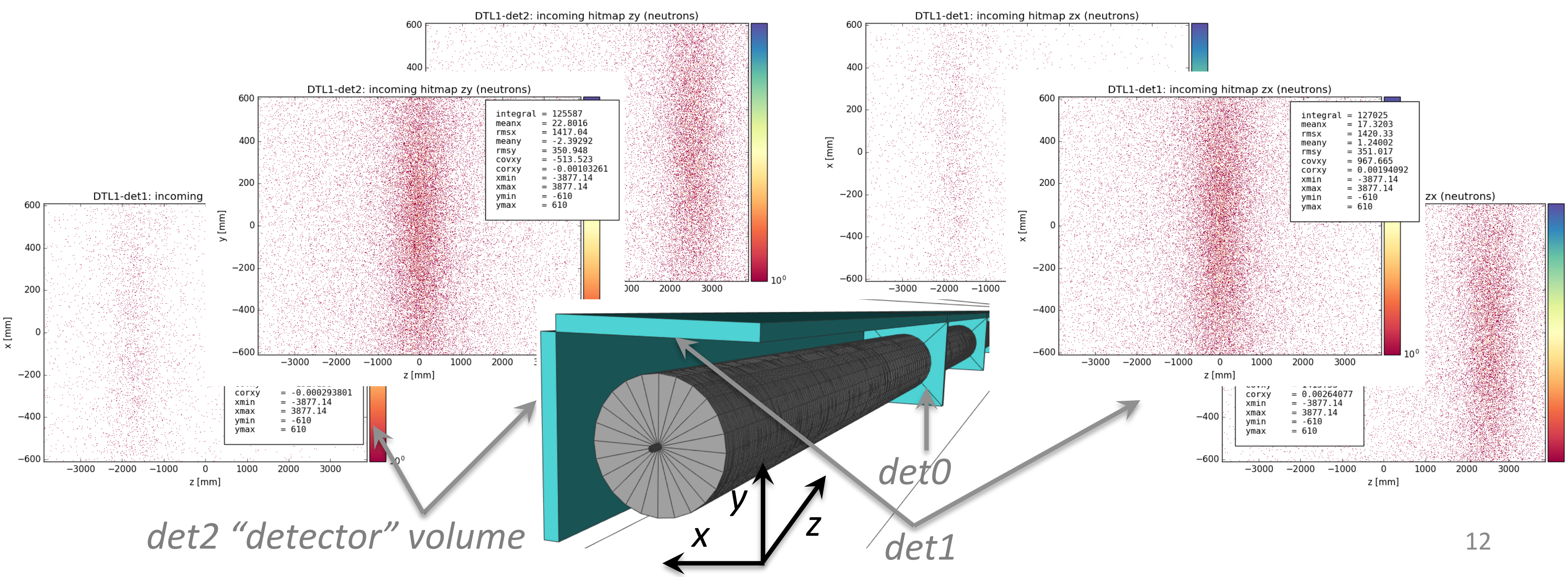
Detector locations

- Most suitable set of detector locations (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 varied between the loss scenarios from ~1mrad 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

DTL tank1 example (preliminary):

- Proton beam under 50mrad from the z-axis, energy set to the nominal values at the loss location.
- Incoming neutron hit maps for 3 different localized loss locations along the DTL tank1.
  - For both det1 and det2: peak in the hit map visible
    - Mean z values agree with the loss locations to ~0.02 - 0.8m depending on the loss location.
    - RMS z values ~1.4-1.5m (for both det1 and det2).
  - Same holds if det. volume placed below the tank (with lowest number of hits), but no correlation with loss origin for det0.
- Looks promising in the view of the BLM system capability to localize the loss origin– further simulations needed for more conclusive results.



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

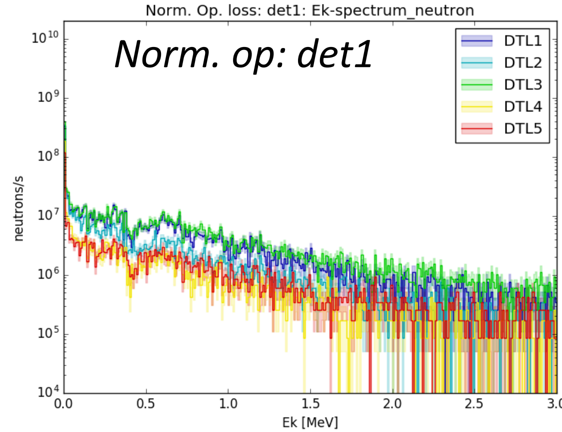
Norm. op. vs. 1W/m loss neutron spectra (neutrons/s hitting the det. volumes surrounding the DTL tanks) in NCL

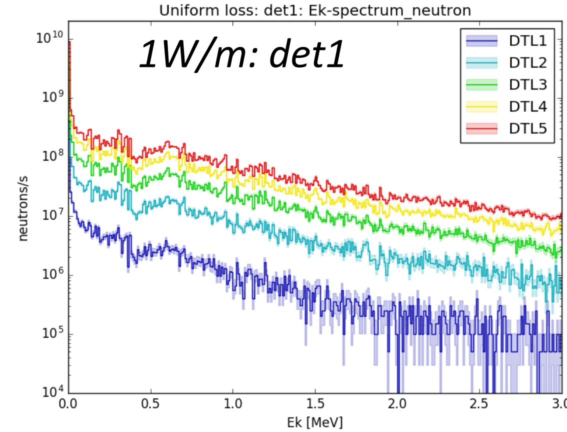
- ***Note:*** *Results of the beam dynamics error study [9,10] used as the inputs to BLM simulation and assumed to represent a realistic loss scenario of the ESS linac during normal operation.*

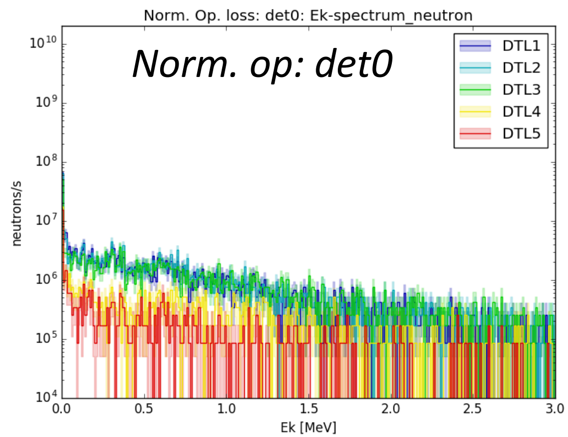
- **1W/m loss:**
  Increase in incoming neutrons with the tank number (neutron cross section increases with Ek).

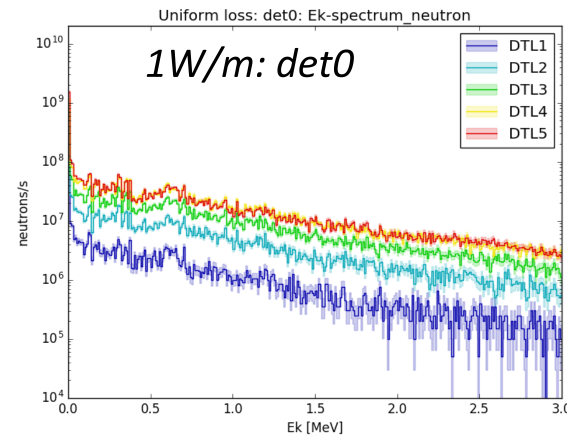
- **Normal operation loss:**
  Neutron flux lowest in the last two tanks (emittance decreases with Ek).

- **Norm. op. vs. 1W/m loss**
  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.) .









Dynamic range

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.

- **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.

Summary

- **ESS BLM detector technologies:**
  - Ionization chambers will be used as the primary detector in the SCL parts (ICBLM).
  - Future plans: explore an option to use Cherenkov radiation based detectors as a complementary monitor to the ICBLM in SCL. Advantage: inherent rejection of the RF cavity background.
  - Novel neutron sensitive micromegas detectors will be used as BLMs in the NCL parts – detector design in development by the micromegas team from CEA Saclay.
- **ESS BLM Monte Carlo simulations:**
  - All past efforts connected to simulations exclusively focused on the ICBLM.
  - Currently the focused turned to the nBLMs due to the need for the nBLM detector design specifications.
  - Strategies to determine the specifications needed for the design of the BLM system (response time, detector locations, dynamic range) were discussed.
  - Some preliminary results for the nBLMs were presented, together with the past results focused on the ICBLMs.

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)

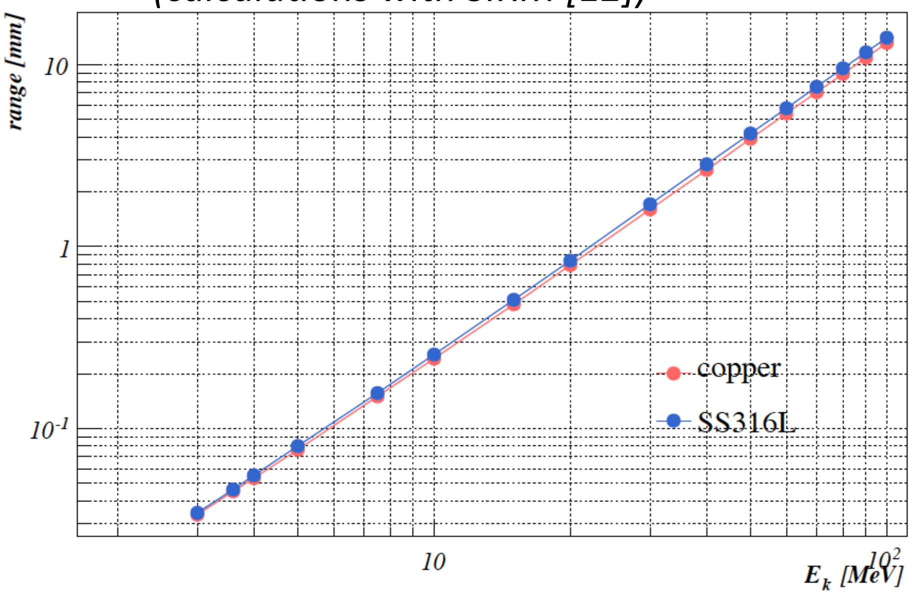
[14] ESS reports ESS-0040133, ESS-0052477

Back up material

ESS 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

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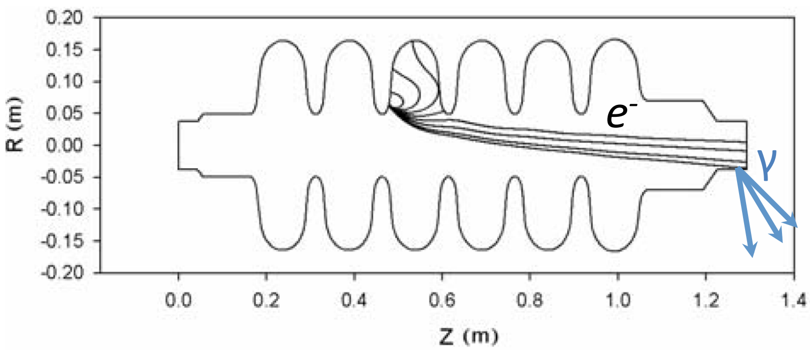
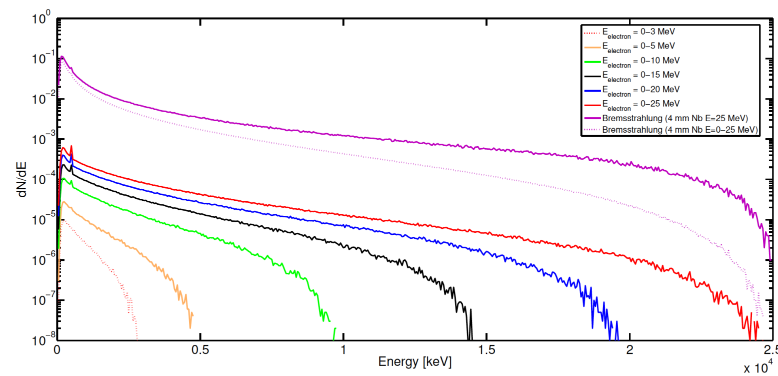
- Photon background due to the RF cavities mainly due to field emission from electrons from cavity walls, resulting in bremsstrahlung photons created in the field of nuclei of cavity/beam pipe materials [3].



- 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.

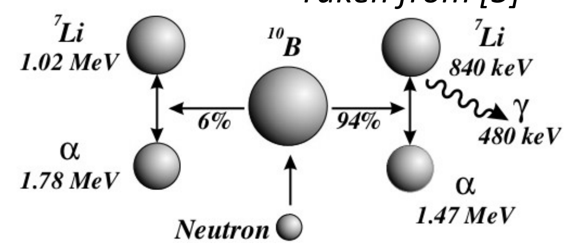


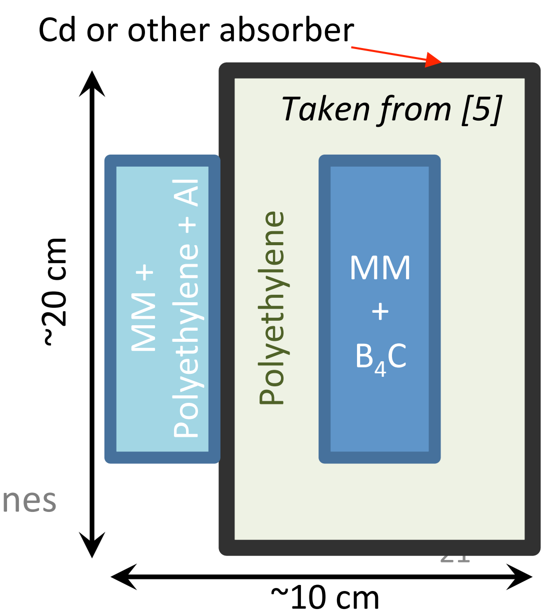
ESS nBLM

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].
- **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.

Taken from [5]

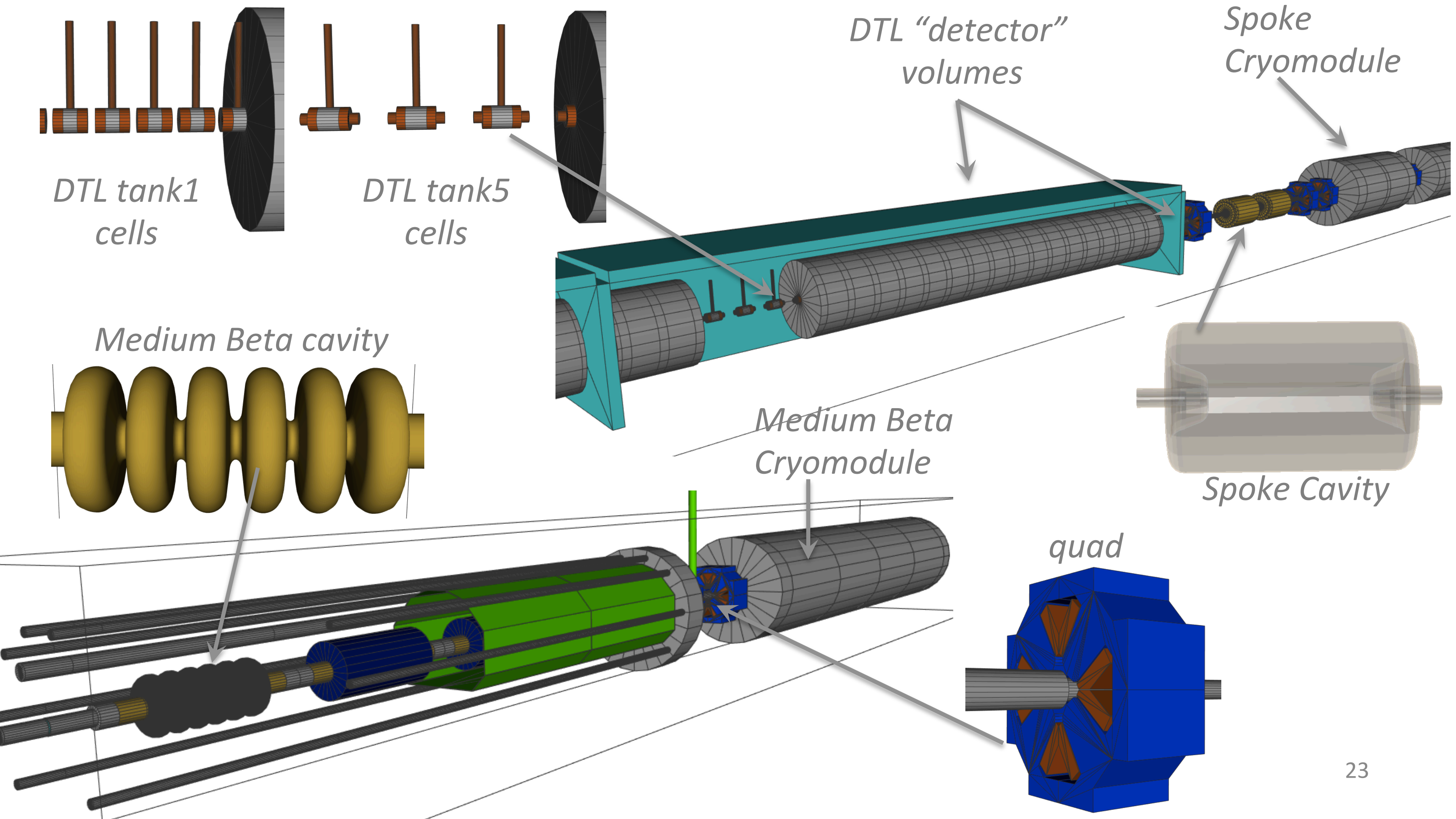




BLM ESS simulations: SW and linac geometry

- **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 10m; 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



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

ESS linac normal operation

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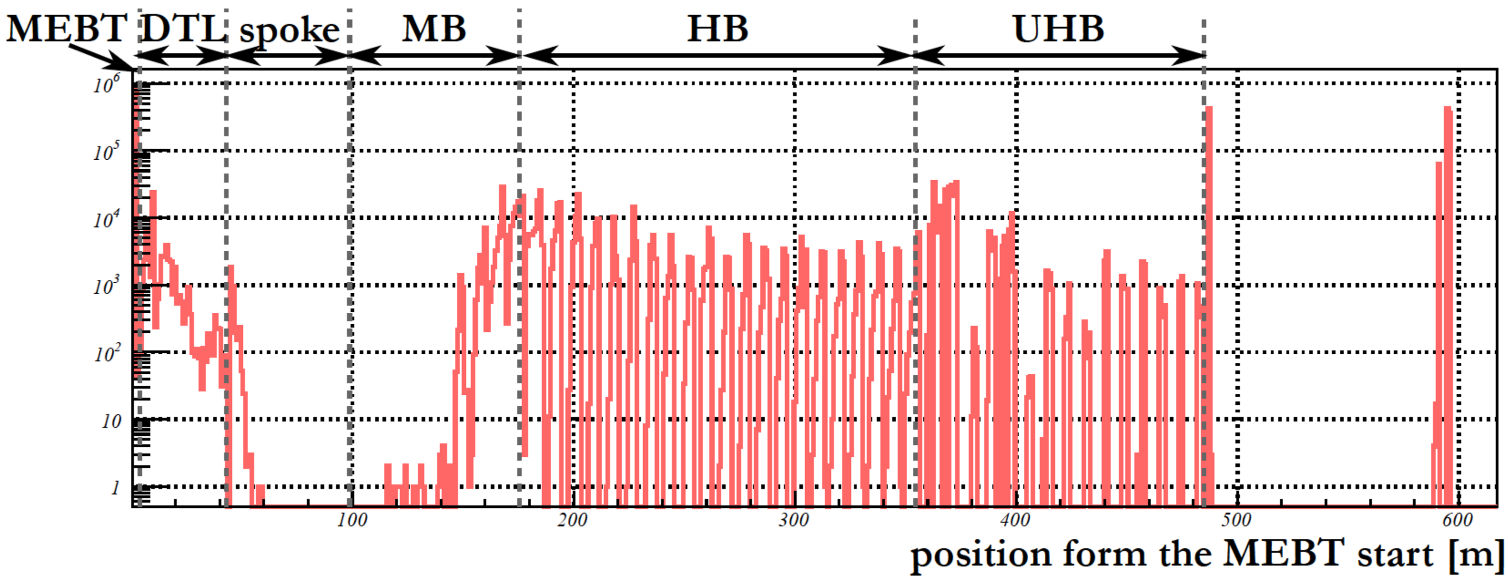
Expected loss map during normal operation [9,10]:

- 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.



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

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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)