nBLM: General Overview

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Outline

- ESS BLM: detector technologies

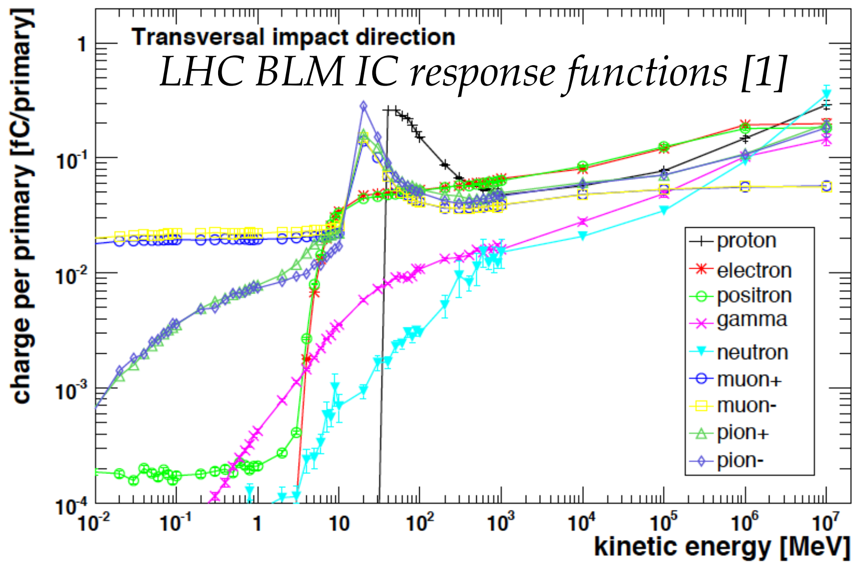
- nBLM project overview
- nBLM project schedule
- nBLM project status
- Scope of the review

- nBLM system architecture
  – Detector count, locations
  – Electronics layout

ESS BLM: detector technologies (1)

1. ESS SCL – icBLM

- Ionization chambers (ICs) developed for LCH BLM – primary BLMs in SCL
  - Beam loss information based on ionisation current measurement of secondaries
  - "cut off" at transversal photon and electron incidence ~2MeV (~30MeV for p and n) [1].



- Photon background due to the RF cavities
  - Bckg. mainly due to el. field Emission from cavity walls, resulting in bremsstrahlung photons created on cavity/beam pipe material [2].
  - Levels are difficult to predict numerically – depend on the quality of cavities, operation conditions and time.
  - Energy spectra estimation [3]: photons with energies up to tens of MeV in the high energy parts expected.

ESS BLM: detector technologies (2)

2. ESS SCL - 2^{nd} detector type: cBLM

- Future plans: design of 2^{nd} detector type in SCL which would be blind to background photons due to the RF.
- Currently considering to design Cherenkov radiation sensitive detectors – cBLM (Cherenkov based BLM)
- 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)

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

- BLM detectors needed 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 a viable solution.
- Micromegas detectors chosen for these parts of the linac
- The idea was to have a micromegas detector sensitive to fast neutrons and not to thermal n, X- and γ-rays based on signal height discrimination.
- Details about the micromegas detectors in general and the nBLM detector design "*nBLM detector design*", L. Segui.

nBLM project overview (1)

3 different external teams contributing to the nBLM project

1. **CEA Saclay Detector Team – TA#1** (T. Papaevangelou, DEDIP, IRFU)
   - IKC (AIK 7.9/CEA 1.11), contract with ESS BI (ESS-0052571).
   - T0 in June 2016, signed in July 2017
   - In collaboration with ESS BI:
     - Design and produce micromegas detectors
     - Design and production/procurement of Front End Electronics (FEE), provide specs for HV, LV PS, cable type, connectors,…
     - Design and production/procurement of the Gas system
     - Provide support during nBLM installation and commissioning.

2. **CEA Saclay Control SW Team –TA#2** (F. Gougnaud, DIS, IRFU)
   - IKC, contract with ESS ICS.
   - In collaboration with ESS BI:
     - Develop nBLM prototype control system to support the nBLM tests.
     - Provide specifications for the FPGA FW development.
     - Support during SW integration/deployment and nBLM system commissioning.

nBLM project overview (2)

3. Lodz Univ. of Technology – TA#3

- IKC (IK14.4.3#1), contract with ESS ICS
- Start in January 2018.
- SoW: contribute to the FPGA FW development for the nBLM.

- **Role of the BLM system lead (ESS BI)**
  - Responsible for the system as a whole (performance, schedule, budget)
  - All activities related to the nBLM project must be performed in collaboration with the system lead.
  - Design choices must be approved by the system lead.
  - System lead must be informed about any project changes (schedule or scope wise).

- **Regular bi-weekly** meetings to discuss current activities and open questions
  - Ongoing with the Saclay Detector Team (T. Papaevangelou, L. Segui)
  - Saclay Control SW team (F. Gougnaud) also started to participate recently
  - Lodz team will be invited to participate once they start working on the project.
- Using wiki and JIRA for documentation and activity tracking.

nBLM project schedule

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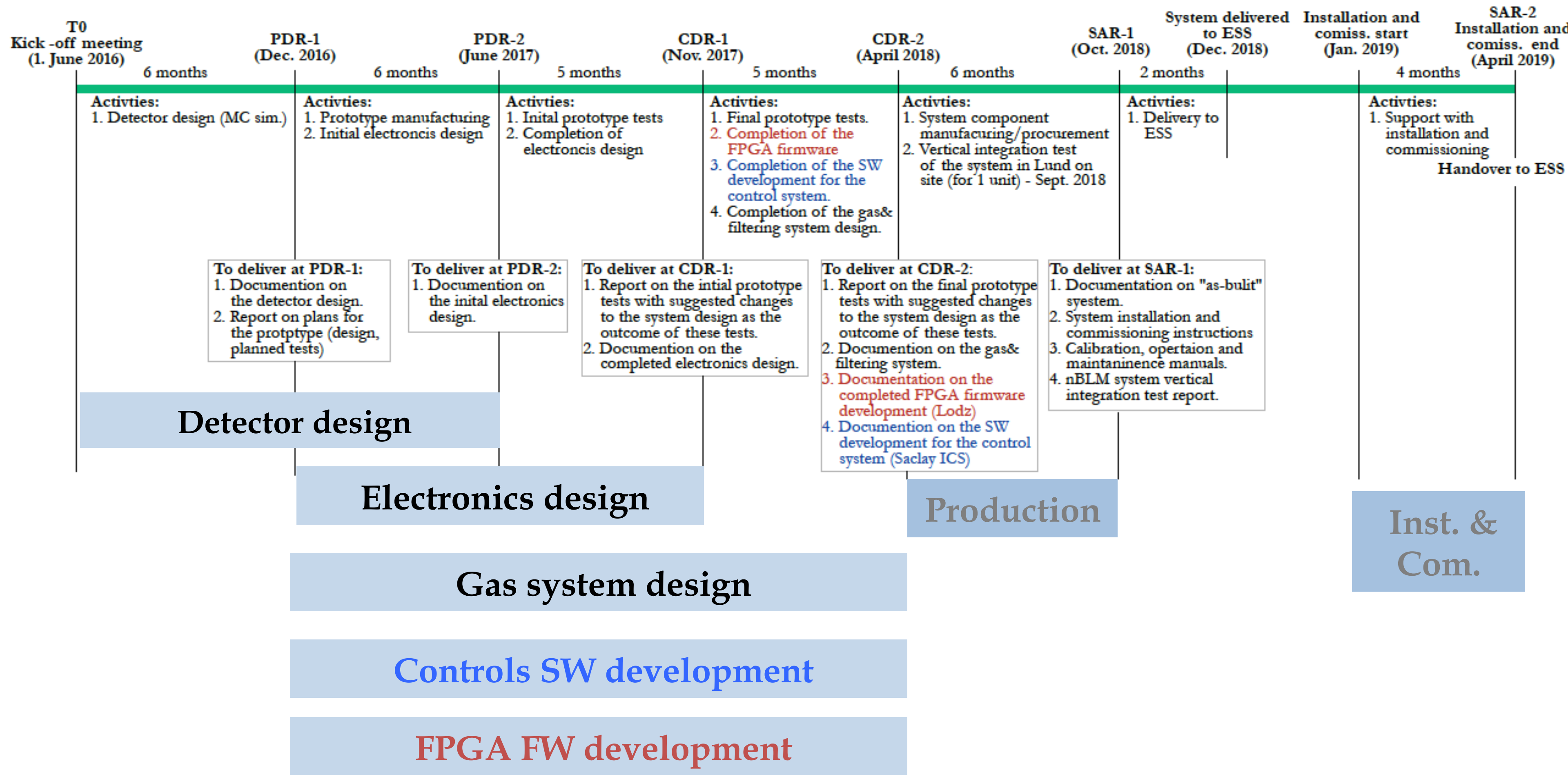
Time line for the **TA#1** (in blue TA#2 and in red TA#3 contributions)



nBLM project status (1)

CEA Saclay Detector Team contribution (TA#1)

- Summary of completed past activates and plans together with work performed since the PDR-2 is presented in "*nBLM status and plans*" by T. Papaevangelou.
- Contract ends with end of nBLM system installation and commissioning - estimated to April 2019 at the time of the contract preparation.

Current ESS schedule [4]

- Installation of nBLM electronics in the racks in the racks:
  - The installation window opens mid Jan. 2018.
  - Anticipate beginning in fall 2018 as coordinate by BI installation manager (S. Grishin).
- nBLM detector installation and commissioning:
  - MEBT and DTL tunnel installation: Oct. 2018 – May 2019.
  - Warm linac beam commissioning: Aug. 2019 – June 2020.
  - Beam through DTL – Q3 2020.
- Needs for extension of the TA#1 contract in order get the expert support during installation and commissioning which was foreseen by the current contract.

nBLM project status (2)

nBLM BEE and SW timeline

- July 2016: kick-off meeting
  - Plan to use IOxOS board with ~GSa/s FMC, anticipated **Nov. 2016, latest Jan 2017**
  - **Nov. 2016** (before PDR-1): back up BEE platform demonstrated at Saclay..
- **April 2017**:
  - Agreed to lower sample rate FMC (250MSa/s)
  - Anticipated to be demonstrated with IOxOS board (and timing board) and neutron detector at Saclay in **May 2017** (in time for July 2017 PDR-2).
- **End Nov. 2017**: low event rate IOxOS based scope application demonstrated at Saclay
  - Controls SW development can now commence
  - More effort form ESS ICS needed to support planned nBLM system tests.
  - To support the near future tests (focus on the system as whole) we plan to use the back up BEE (Struck 8300ku) until the IOxOS based BEE system is ready.

- **Dec 2017** – this CDR
  - nBLM Controls system design document with specs for the FPGA FW development and python script simulating FPGA functionality (originally expected in Oct. 2017) – not final
  - Details about the nBLM Control system design with status in "*nBLM Control System design*" by Y. Marriette.

nBLM project status (3)

TA#3 schedule (FPGA FW development by Lodz team):

Milestone	date
Start date	T0 (Jan. 2018)
Conceptual design	T0+6m (July2018)
Prototype version	T0+8m (Sept. 2018)
PDR	T0+9m (Oct. 2018)
CDR	T0+12m (Jan.2019)
SAR & prod. FW delivery	T0+17m (May 2019)
Final report	T0+18m (June 2019)

Note:

- The prototype version expected later than the nBLM CDR-2 (April 2018) and later than expected by the Saclay Control SW (June 2017).
- Crafted fast to get the contract in place.
- Intend to negotiate some intermediate deliverables.

Scope of the CDR-1

- **Past activities and reviews**
  - Past: PDR-1 with focus (Dec. 2016)
    - Initial detector design
    - Demo of the backup BEE platform
  - Past: PDR-2 with focus (June 2016)
    - Completion of the detector conceptual design.
    - Initial electronics design.
- **Today: CDR-1 with focus**
  - Completion of the nBLM electronics design as a whole (FEE, BEE, selection of cables, HV,LV PS..).
  - Results of the detector and electronics prototype tests.
  - New detector design.
  - Also presented: final detector locations
  - Additional activities in order to fit the project schedule to the ESS installation plan:
    - Partial completion of the gas system design.
    - Electronics layout (detector connections to the racks/crates/cards).
- **Future: CDR-2 with focus**
  - Completion of the FPGA FW and controls SW development.
  - Completion of the full gas system design
  - Final prototype tests (focused on the system as a whole).
  - System verification plan, safety hazards assessment,…

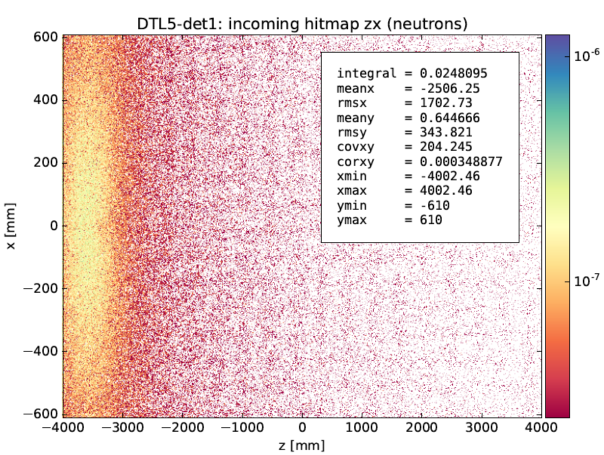
nBLM detector count

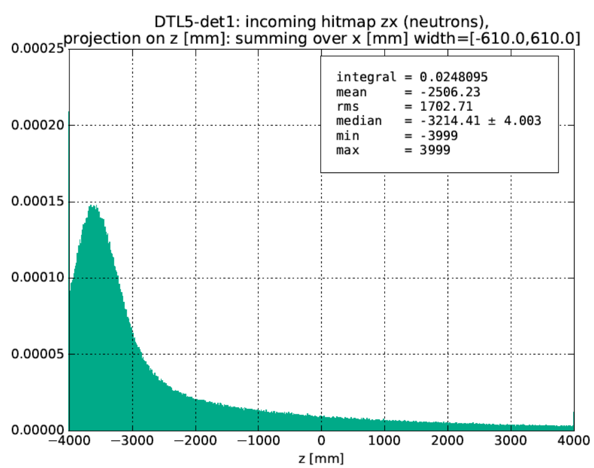
- TA#1: 42 detector units will be delivered
  - Each unit (FS) consists of 2 detectors: F (fast) and S (slow)
  - Each of the detectors equipped with it needs to function (FEE as well as BEE, HV, LV and gas pipes,..).
- Detector locations have been fixed and put in the ESS model (ESS-0191514, also attached to the agenda).
- Locations will be included in the next lattice update.
- In total: 2 x 41=82 detectors placed (41 F, 41 S)

nBLM detector locations (1)

Geant4 simulations of localised losses in the DTL:

- Performed by ESS BI to support nBLM detector development.
- Observed neutron hit maps on phantom detectors surrounding the DTL tanks (10cm away) exhibit a peak
- Correlation between loss location and hit map peak position observed.
- Hit map RMS ranging between 0.9m to 3.6m depending on the proton energy (larger RMS for higher energies)





Neutron hit map and projection (normalized to the number of primaries) for sim2-0 (pencil beam at 5mrad hitting aperture at the beginning of DTL5)

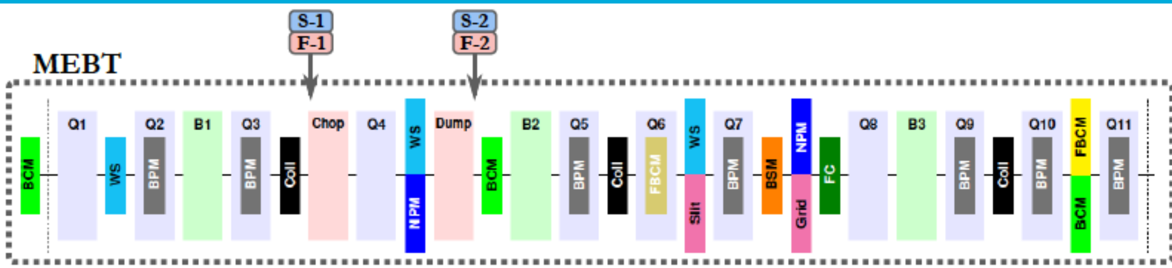
nBLM detector locations (2)

- Most of detectors placed in DTL and Spoke regions.

- To enhance the coverage in the DTL and Spoke:
  - The detector units are separated.
  - Detectors placed in alternating sequence of F (fast) and S (slow) type detectors.
  - Typical distance between successive F and S detectors:
    - DTL: ~1m.
    - Spoke: ~2m

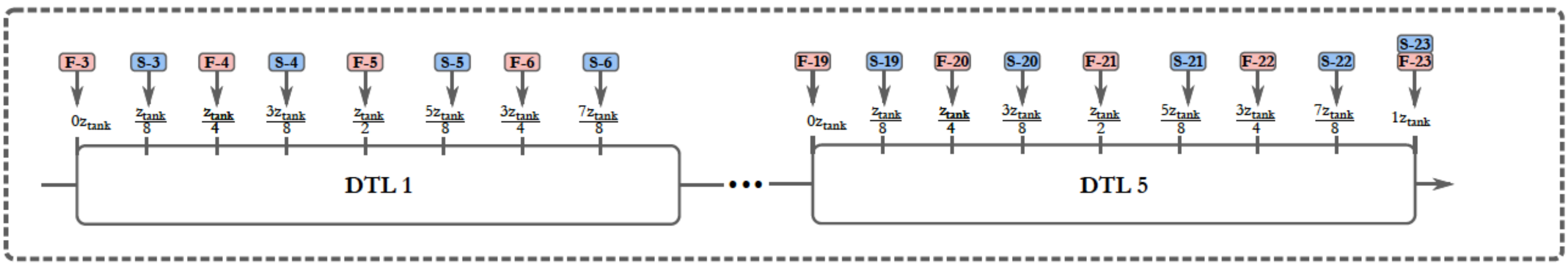
- Other sections: detectors not separated (FS type)

nBLM detector locations (3): MEBT & DTL



MEBT:

- 2x2=4 detectors
- FS before chopper and after dump

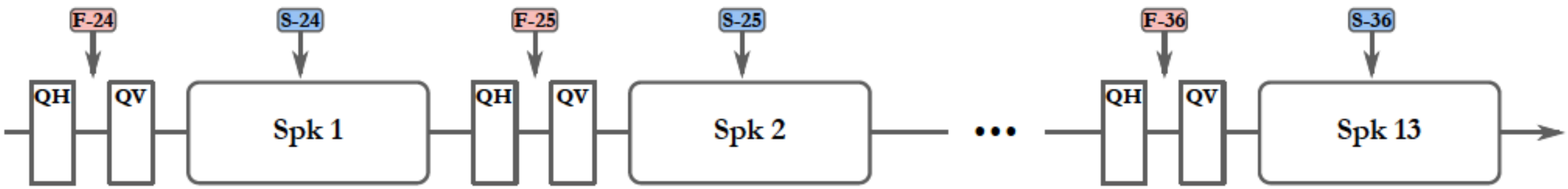


DTL:

- 8 detectors (4F, 4S) per tank,
- Extra FS at the end of tank 5
- Distance between successive detectors = 1/8 tank
- 5x8+2=42 detectors

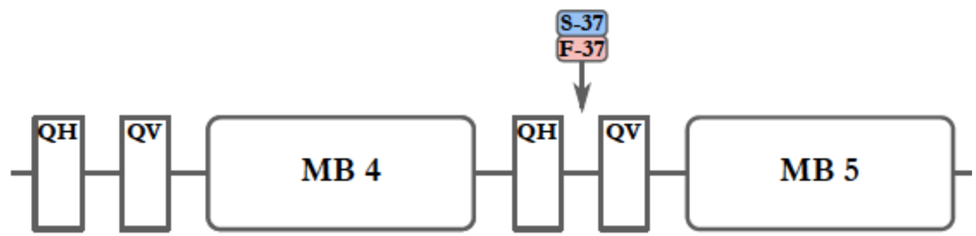
nBLM detector locations (4): Spoke – A2T

Spoke:
- 1F per quad pair, 1S per cryo
- 13x2=26 detectors

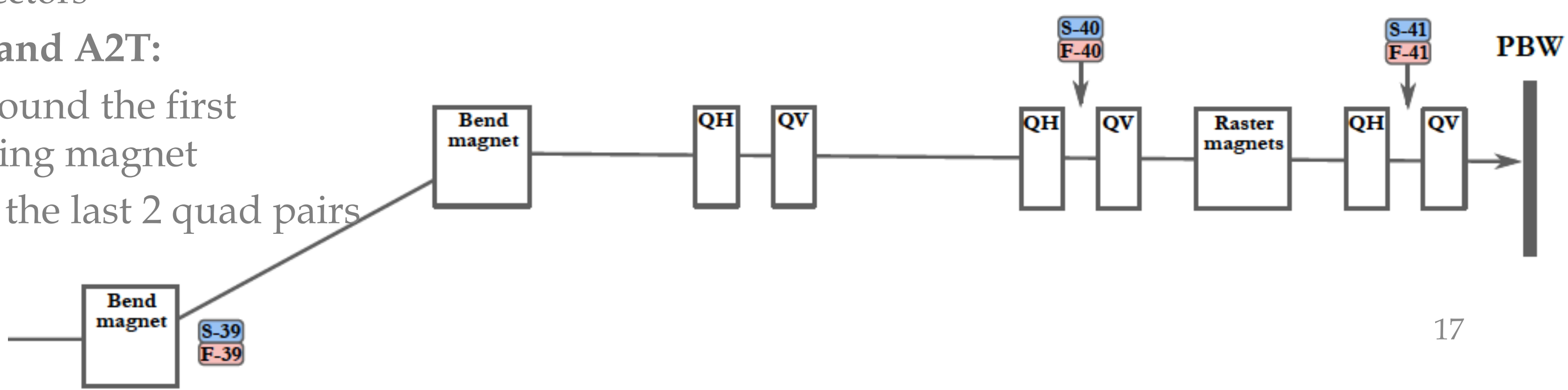


MB:
- FS in the MB LWU5
- 2 detectors

HB:
- FS in the HB LWU11
- 2 detectors



HEBT and A2T:
- FS around the first bending magnet
- FS at the last 2 quad pairs



nBLM electronics layout

- Details about the nBLM electronics layout available in supporting documentation as well as in ESS-006336.

- BE, LV and HV cards can support several detectors.
  - BE cards: maximum 8 detectors
  - HV card: maximum 48 detectors
  - LV card:
    - 8 channels,
    - Each channel can feed a group of detectors – assumed to feed maximum of 8 detectors (needs to be re-checked).
  - HV and LV cards placed in the same crate, 2 crates available

- Cable count
  - Each detector (F or S): 2 HV cables (1 for mesh and 1 for drift)
  - Each LV detector group: 1 LV cable with 3 lines, +/-5V, Gnd
  - Each detector (F or S): 1 signal cable.

nBLM electronics layout: signal

Signal connections

- A card/crate/rack malfunction represents danger to have no info on the beam loss over several subsections of the linac, if a sequence of successive detectors connected to the same card/crate/rack, malfunction.

- To increase the availability successive pairs of F and S connected to different card/crate/rack forming 2 groups of detectors.
  - The separation done to the rack level.
  - This grouping applied to detectors in the DTL and Spoke sections where FS detectors are separated in to F and S (and in MEBT where 2 non-separated units FS are placed).

- In other section, with sparse placement of a detector units (FS), the cables are connected to to closest rack (3rd group of detectors).

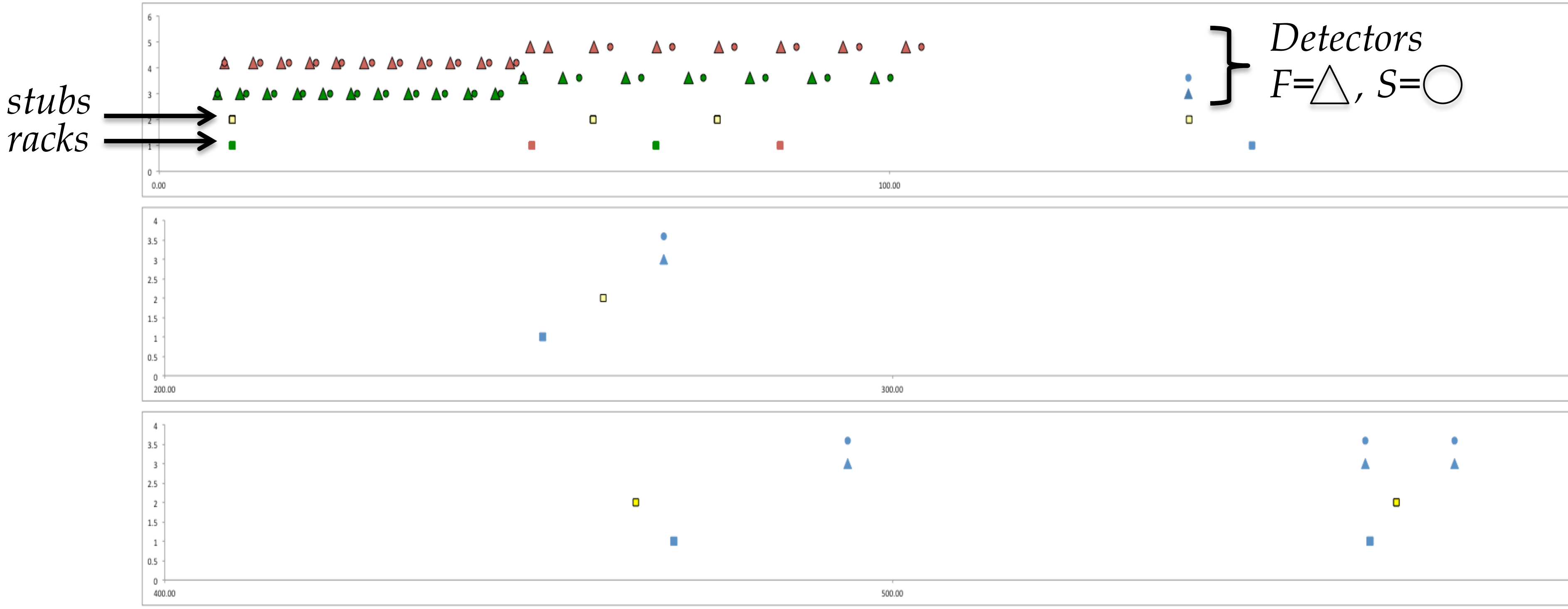
nBLM electronics layout: signal

Signal connections:

- Group1 or Group2:
  - 6 – 4 detectors per BEE card,
  - 4 – 3 cards per each rack/crate.
- Group3:
  - 2 or 4 detectors per BE card,
  - 1 card per crate

Plot legend

- *x-axis runs along the linac*
- *Bottom line of markers – racks, color mark which detector gorup connects to them*
- *Middle line of markers – subs*
- *Top band of markers: F and S detectors, y axis value and color mark which rack they connect to*



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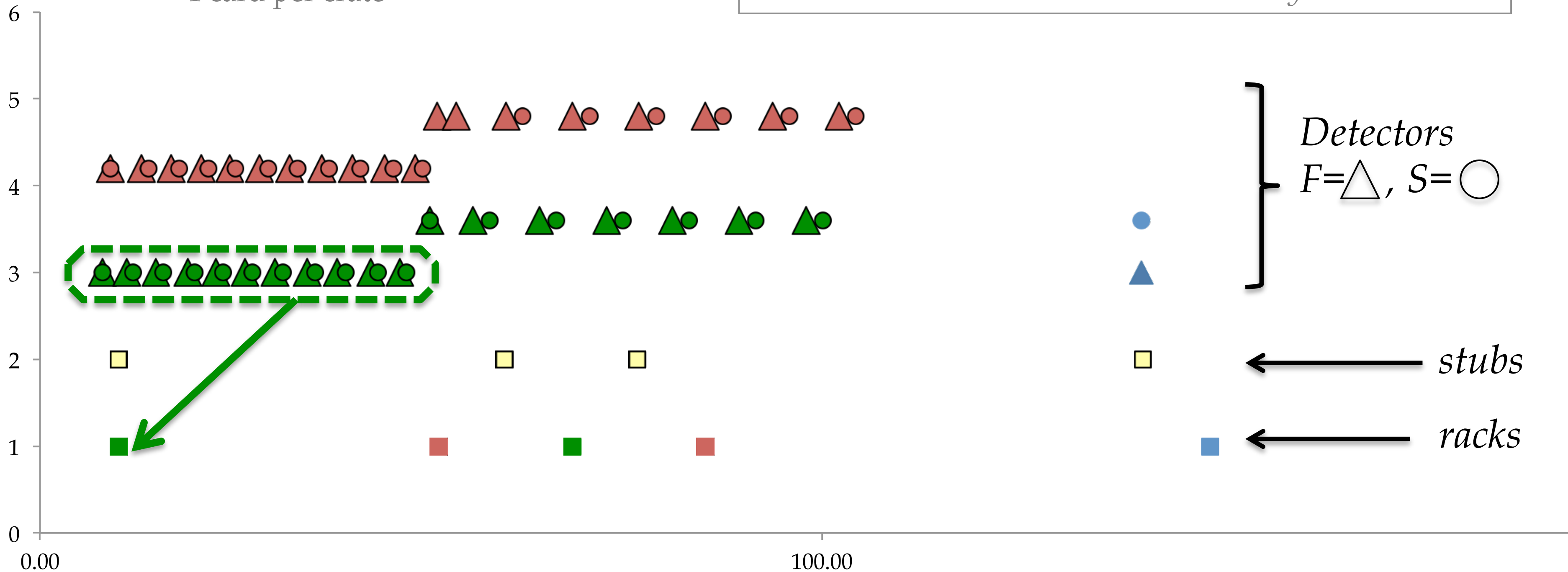

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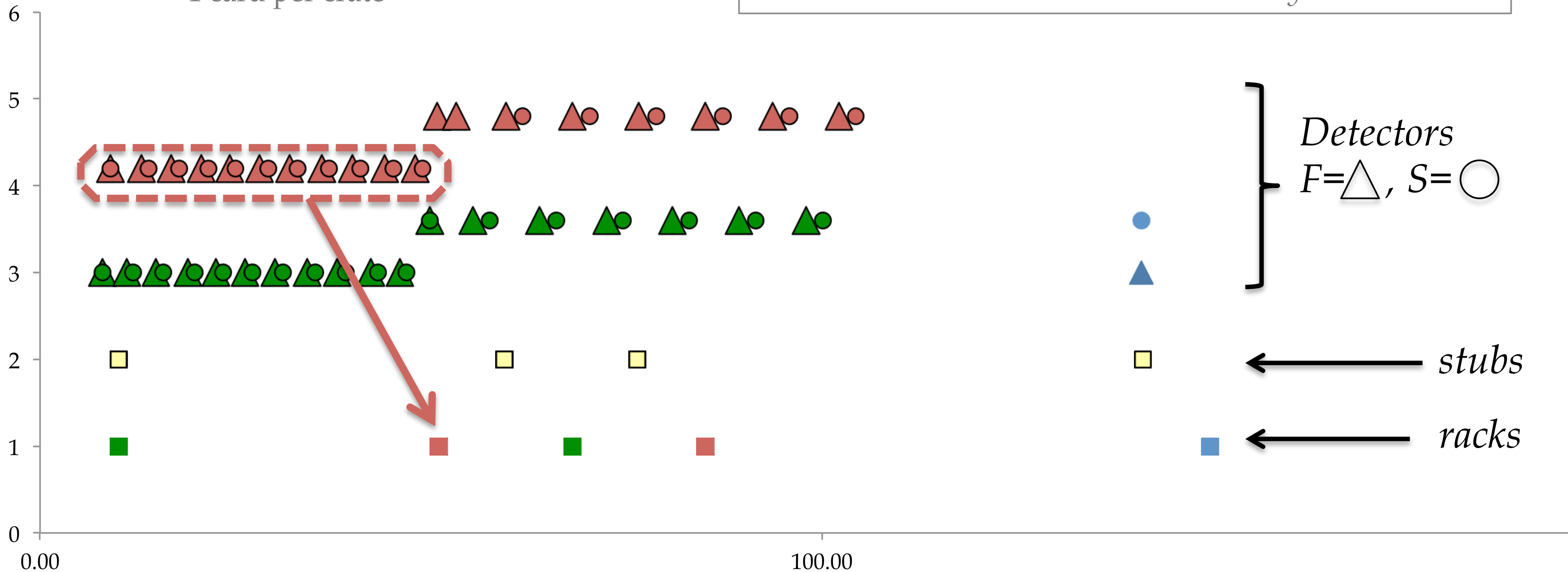

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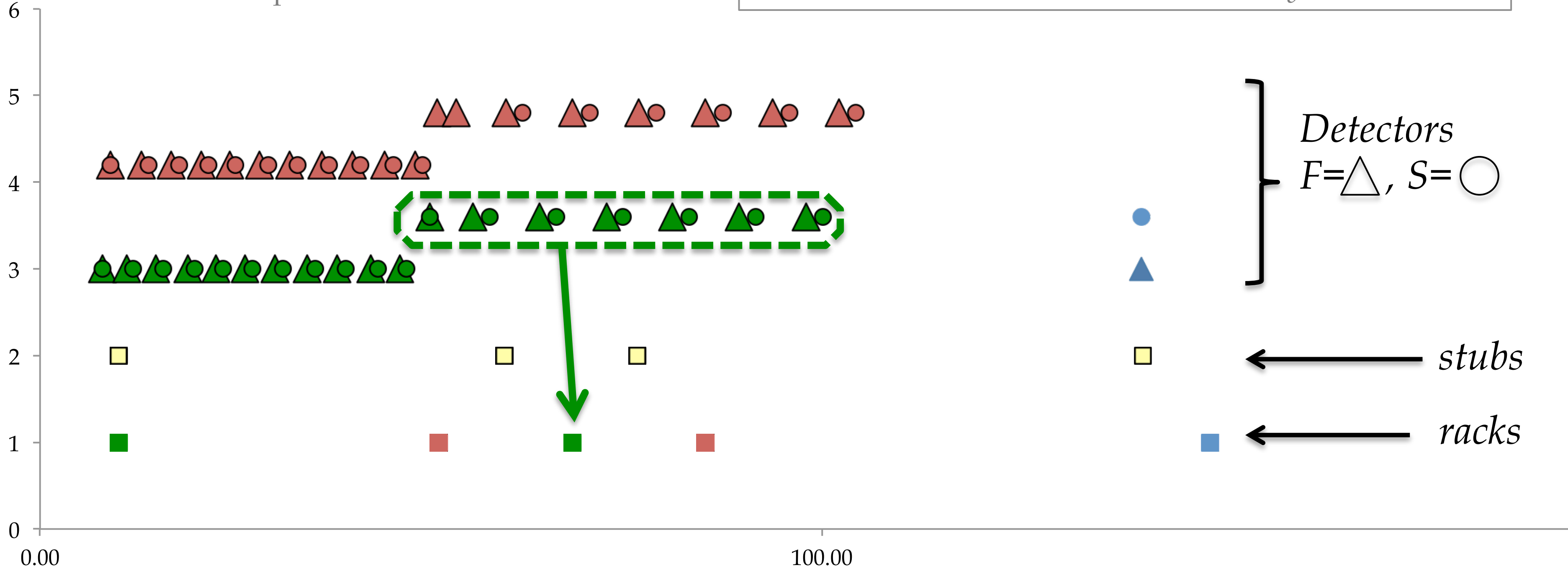

nBLM electronics layout: signal

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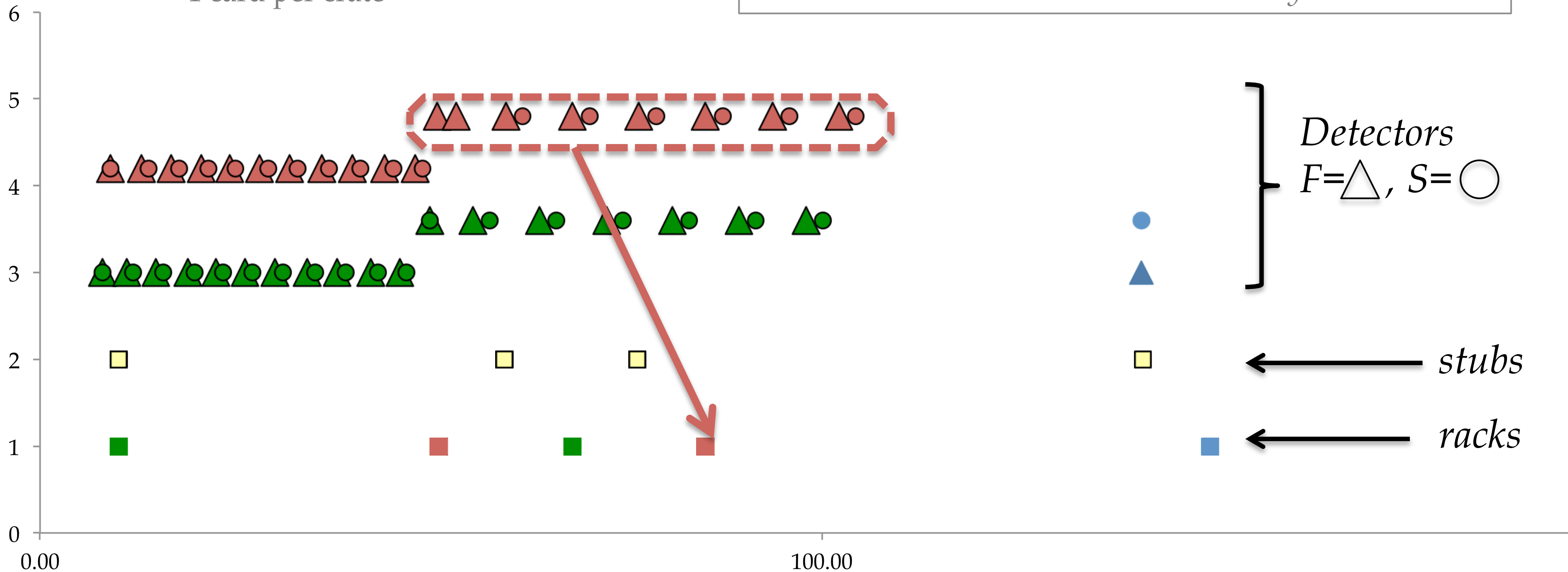

nBLM electronics layout: signal

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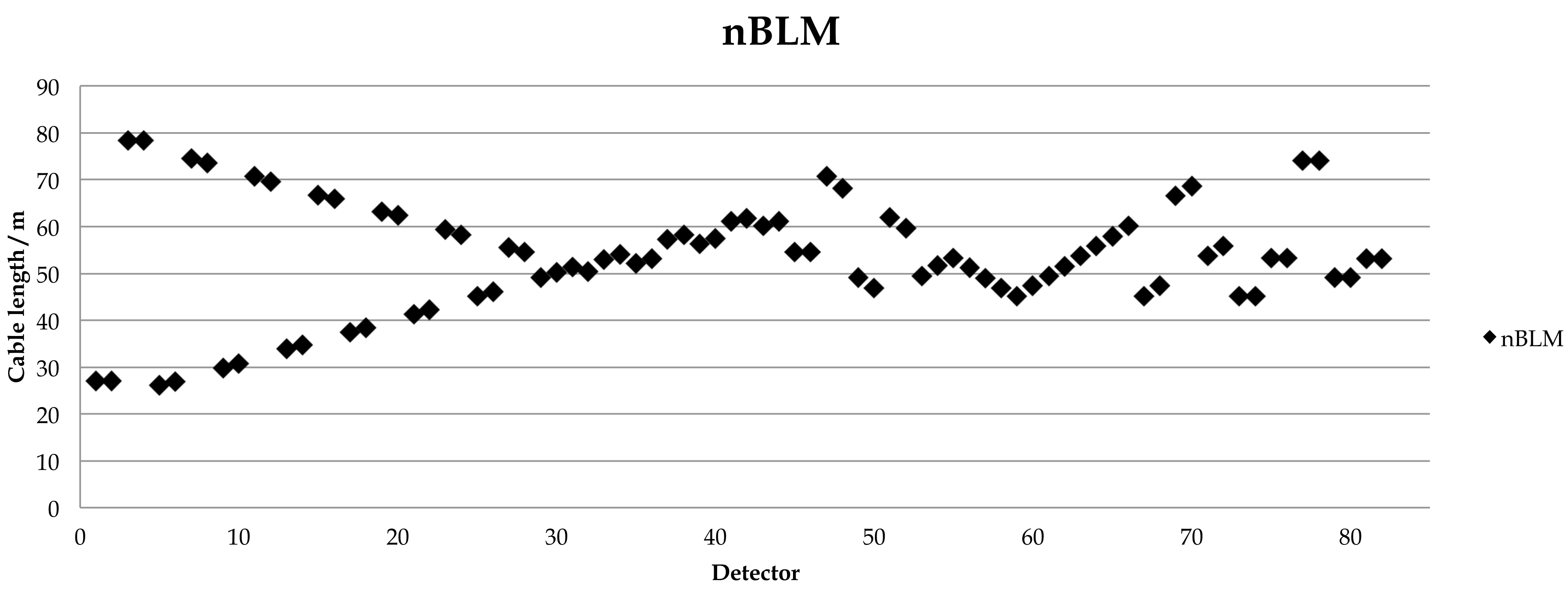
Signal cable length < 80m



nBLM electronics layout: HV

HV connections

- 2 crates housing both LV and HV cards
- Group1 and Group2 separation possible only down to the card level without unreasonable increase in cable length.
- Crates placed in the 2 different racks occupied with nBLM BEE
- Selected pair of racks which give second to minimum total cable length.
  - 1st crate placed in the 1st track
    - feeds first 74 detectors
    - Group1 (+1FS unit from Group3) and Group2 connected to different cards
  - 2nd crate placed in next to last rack
    - Feeds last 8 detectors (4 FS units, Group3)
    - All connected to 1 card
  - Total cable length per one HV connection ~ 6km (~200m more than the minimum)

nBLM electronics layout: LV

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LV connections

- Follow the same scheme as with HV connections.
  - Detectors on the same HV card, also on the same LV card (LV detector group) – both LV and HV card are in the same crate.
- Group1 and Group2:
  - Each LV channel feeds 8 – 6 detectors.
  - Each LV card feeds either Group1 (+1FS unit from Group3) or Group2 detectors.
  - 2 LV cards, both located in the first rack.
- Group3:
  - 1FS unit (2 det.) on the same card as Group2.
  - Other FS units connected separate channels on 1 card.

References

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

[2] 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)

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

[4] https://indico.esss.lu.se/event/905/contribution/10/material/slides/0.pptx

[5] T. Shea, "*Overview of beam loss diagnostics*", nBLM PDR-2, https://indico.esss.lu.se/event/835/

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

[7] T. Papaevangelou, Micromegas detector applications for beam diagnostics" CERN BI seminar, CERN, Geneva, Switzerland (2016), http://indico.cern.ch/event/540799/

[8] 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)

[9] 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

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

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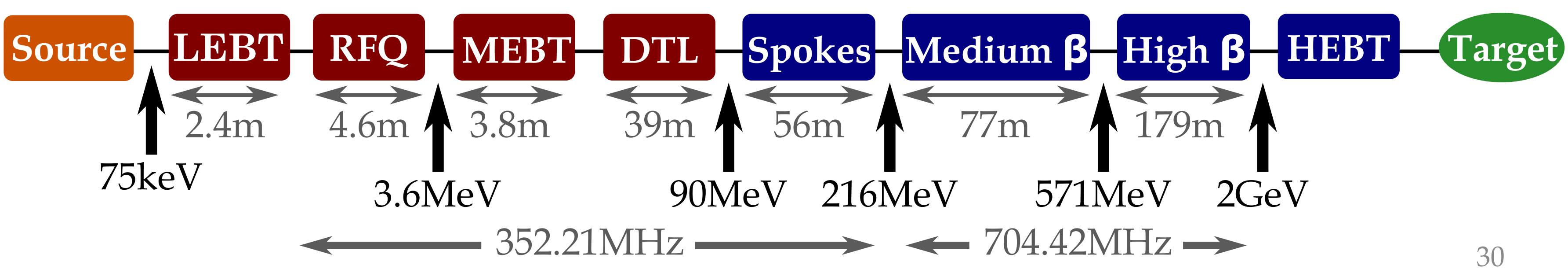
Back up material

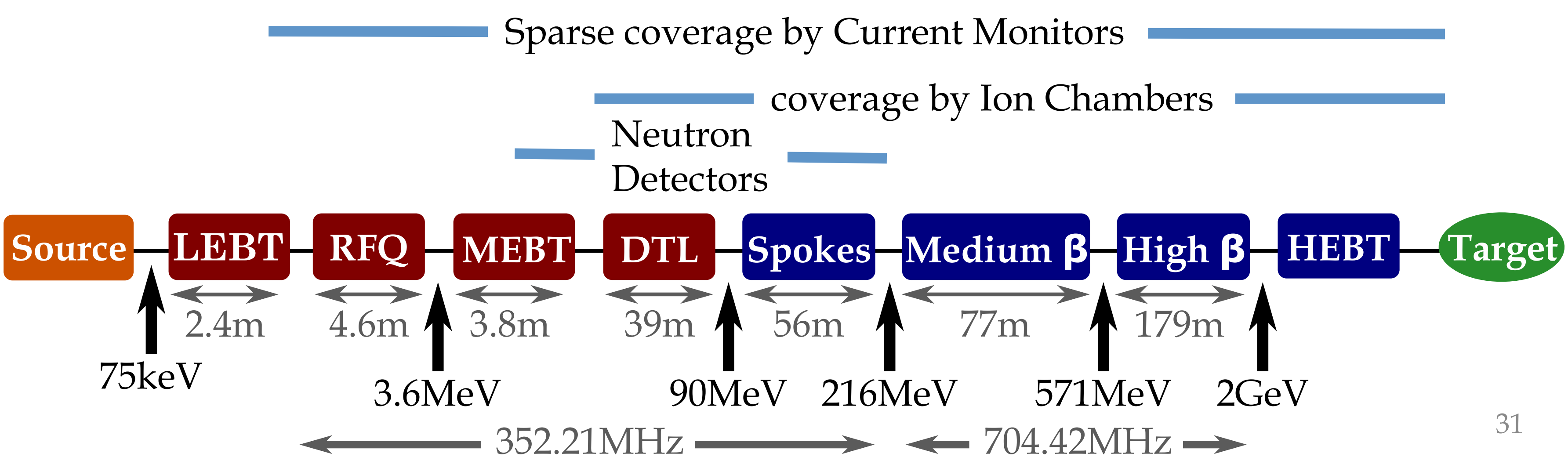
ESS linac

- 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 Beam Loss diagnostic tools
(from T. Shea)

- **Total beam loss**, microsecond measurement latency required for protection
  - BCM, icBLM (saturation, nBLM (current mode) ➔ Interlock; Threshold/derivative term for fast protection
- **> 1.6 milliamp lost for up to 200 µs**
  - BCM, icBLM, nBLM -> Interlock; Damage model for protection
- **~ µC lost over 200 µs to many seconds** (diffusion time)
  - icBLM, nBLM -> Interlock; Damage model for protection
- **~ "1 Watt/meter" radiation dose management**
  - icBLM, nBLM -> alarm based on dose/activation plan



ESS BLM requirements: L4

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Level 4 requirements relevant for BLM (★)

#	Type	Name	Description
1	Beam loss	XXX beam loss measurement	The beam loss shall be measured in the XXX section.
2	Beam loss	XXX beam loss measurement sensitivity	A beam current loss of 10mW/m shall be detected.
3	General	XXX PBI damaging beam detection mitigation	Beam conditions that are potentially damaging to machine components shall be detected by the instrumentation and reported fast enough so that the conditions can be mitigated before damage occurs.
4	General	XXX PBI peak current range	Proton beam instrumentation in the XXX section shall function over a peak beam current range of 3 mA to 65 mA
5	General	XXX PBI pulse length range	Proton beam instrumentation in the XXX section shall function over a proton beam pulse length range of 5µs to 2.980 ms.
6	General	XXX PBI pulse-by-pulse measurement update rate	Unless specifically stated, all instrumentation shall be able to perform the measurements and report the relevant PV data at a repetition rate of 14 Hz.

(★) Snapshot from the document collecting all L4 PBI requirements (by J. [illegible]) to be transferred to CHESS, search in CHESS not successful

ESS BLM requirements: system specific

BLM system specific requirements

- L4#1:
  - defines coverage (MEBT, DTL, Spoke, MB, HB, HEBT, A2T, DMP)
- L4#2:
  - Beam loss measurement sensitivity
  - Sets the lower limit of the dynamic range
- L4#3:
  - Sets the upper limit for the dynamic range.
  - Sets the limit on the response time.
  - Relates to thresholds for inhibiting the beam production.
- L5#4-#6:
  - Translates to requirement that the system shall be able to function for all beam modes.
- Additionally: the system is required to work standalone independent of the master clock in order to be able to monitor the rates during "shut downs".

Neutron production in MEBT
(from T. Shea [5])

- Potential sources of neutrons in MEBT
  - Collimator - TZM (99% Mo, 0.5% Ti, 0.08% Zr)
  - Buncher cavities and RFQ – copper

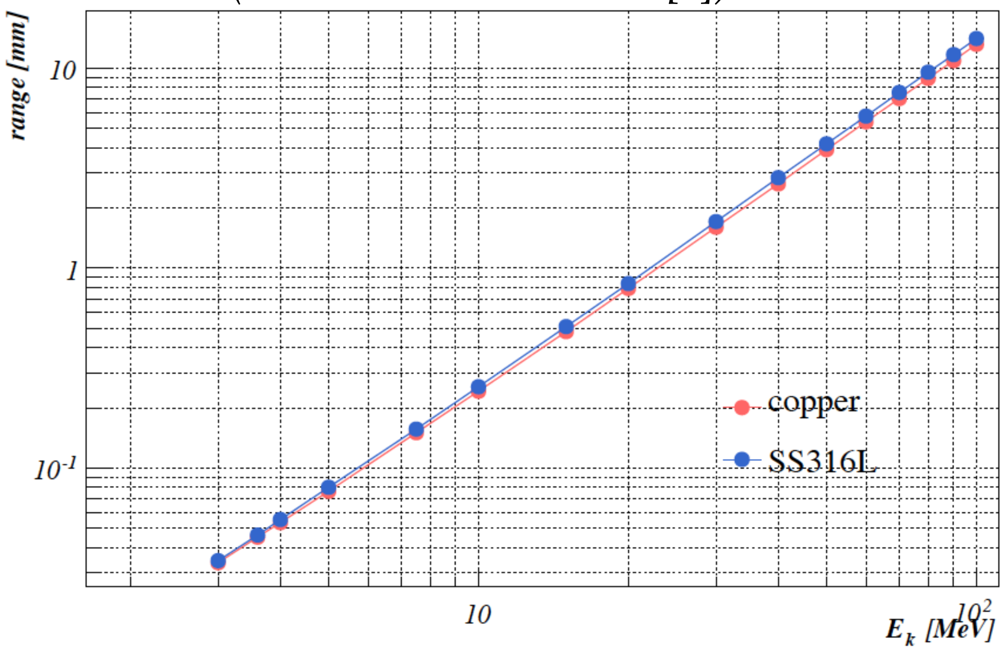
- Cross section
  - Only ^{65}Cu (30% of ^{nat}Cu) has threshold below the MEBT energy , σ =29 to 132 mb (3 to 4 MeV)
  - TZM is considered as pure Mo, 3 isotopes of Mo have a threshold energy for neutron production below the MEBT energy (3.6 MeV)
    - ^{95}Mo (15.92% of ^{nat}Mo), σ =0.6 to 8.8 mb (3 to 4 MeV)
    - ^{97}Mo (9.55% of ^{nat}Mo), σ =6e^{-3} to 9 mb (2 to 4 MeV)
    - ^{98}Mo (24.13% of ^{nat}Mo), σ =0.6 to 9.8 mb (3 to 4 MeV)

- Analytical estimation of the neutron flux per proton
  - Reaction can occurs only in the first 20 um of material (energy loss ~ 1 MeV)
  - Use average cross section to calculate the flux
    - Copper: ~10^{-6} n per proton
    - TZM: ~10^{-7} n per protons, assuming that each jaw is absorbing 0.25% of the total beam power, the flux generated by the collimators in the MEBT is ~ **10^{9} n.s^{-1}**

ESS NCL: particle fields

- DTL: protons (3.6-90MeV) stopped in the 3 – 5 cm 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 [6])



ESS nBLM

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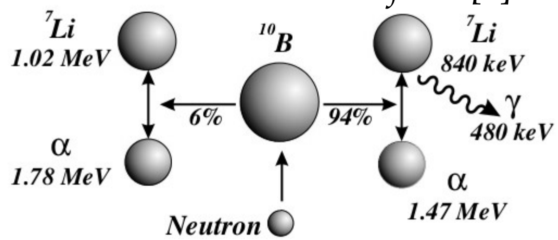
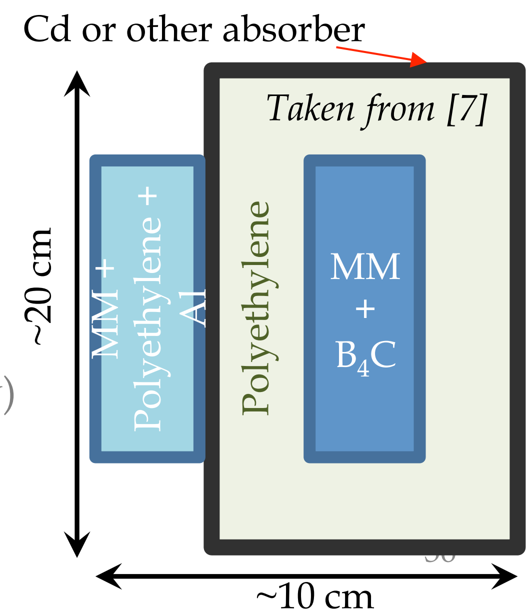
nBLM – the neutron sensitive BLM

- 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 -ra based on signal discrimination.

Taken from [7]

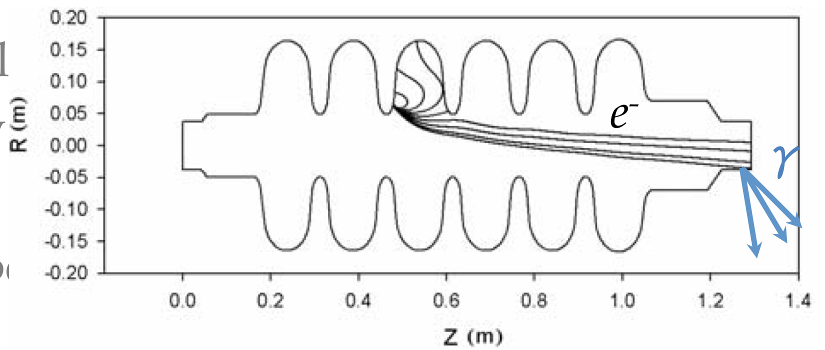


- **nBLM detector units:** assembly of 2 modules.
  - **1st module (slow losses)**
    - Capable of monitoring low fluxes (~few n $cm^{-2}s^{-1}$).
    - Polyethylene: moderator to thermalize the incoming fast n.
    - B_4C layer(s) to capture thermalized n.
    - Cd (~mm) to eliminate background thermal n.
  - **2nd module (fast losses)**
    - appropriate for high fluxes of fast n, coming from the front.
    - Polypropylene (deposited on Al foil at the entrance window) for n conversion to p recoils (~ few mm) through n elastic scattering on H atoms.
    - Threshold in cross-section for polypropylene ~0.5MeV.

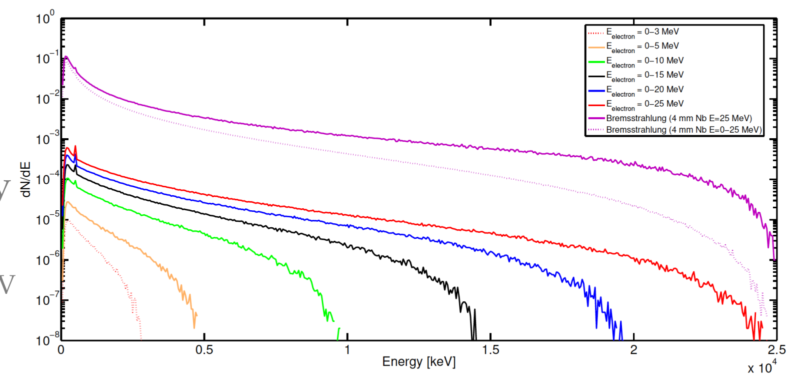


Background photons due to RF cavities

- Photon background due to the RF cavities mainl due to field emission from electrons from cavity walls, resulting in bremsstrahlung photons created in the field of nuclei of cavity/beam pip materials [8].



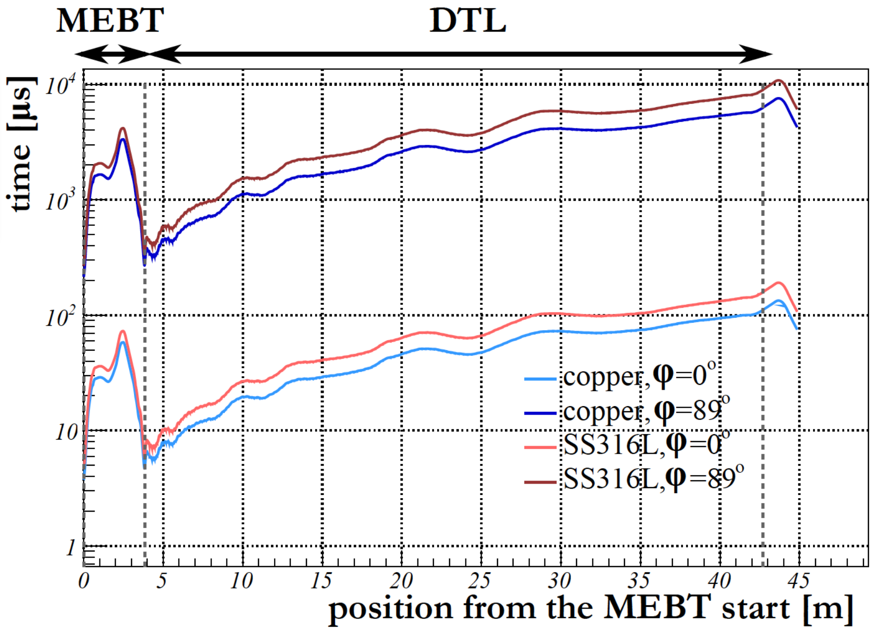
- Energy spectra estimations show that photons up to few tens of MeV can be expected [3]:
  - A MC code (FLUKA) was used for these estimations where a pencil electron beam is impacting a 4mm niobium foil.
  - Purple curves on the plot on the left show expected energy spectra for the photons produced 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:
  - 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 [9].
- Numbers recently re-checked with a Gaussian beam and update beam parameters:
  - **NC linac:** calculated melting time values of 3-4 μs imply even stronger demands on the response time (confirmed with a MC simulation as well).
  - **SC linac**: the 10 μs requirement for response time fits well with the results of this calculations.

    However: other damage mechanisms ma 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?

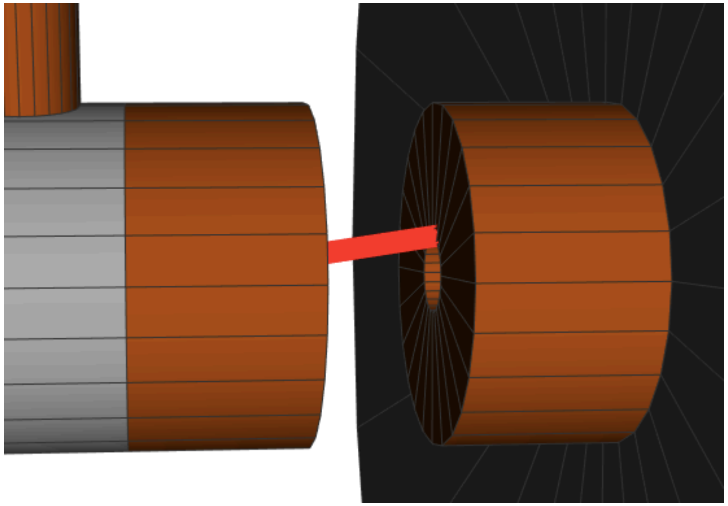
- What is the least shallow incidence angle of the most focused beam that can be expected to hit the aperture?
  - Expected to occur for a particular case of incorrect settings for a set of corrector magnets – time consuming beam dynamics simulations required to asses this.
  - **Simplification (suggested 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 <15 μ s pulse of 26mA beam ~10/day [10].
  - Experience at the SNS motivates setting response time limit for ESS SC linac significantly lower than 15 μ s.