Beam Physics Requirements

Based on the presentation by Y. Levinsen for PDR
(https://indico.esss.lu.se/event/650)

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CDR of BPM Electronics
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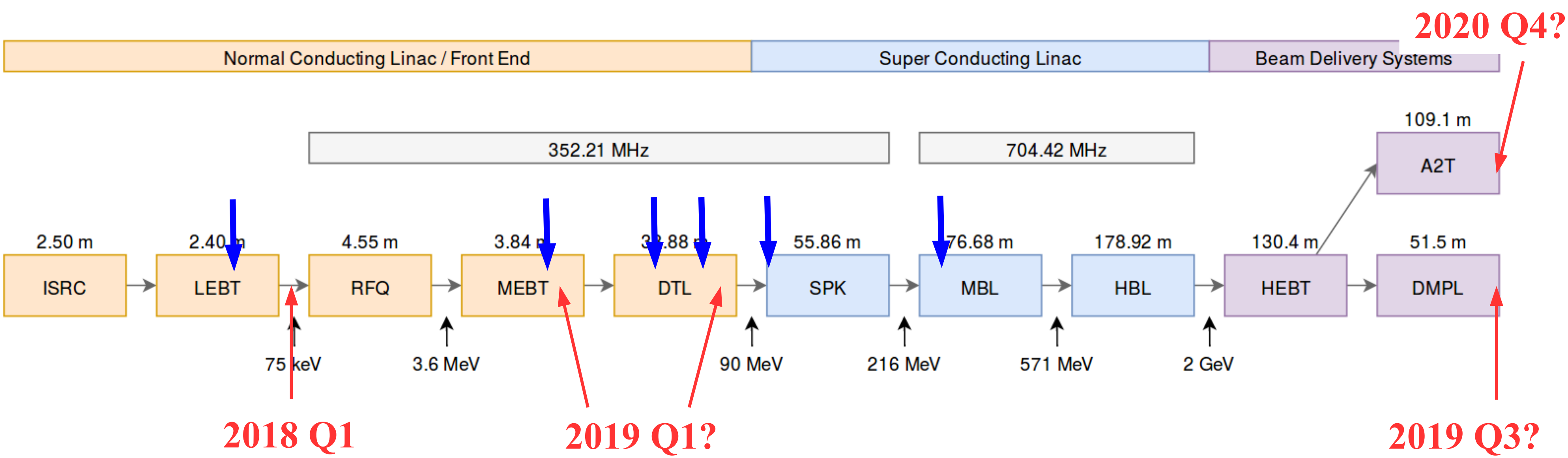
Disclaimers

- This presentation is a modification of what Y. Levinsen presented for the PDR on Oct 13, 2016 (https://indico.esss.lu.se/event/650/) .
  - I appended some aspects from the beam commissioning and scheduling.
  - Instead, I removed some contents such as the basic info of what we use BPMs for and how and the analysis of the requirement system itself. (If some necessary information is missing, we can pull back Yngve's presentation.)
- Comments on the steering
  - In most parts of our linac, the steerers and BPMs have one-to-one relation. (Exceptions are the MEBT, DTL1, and A2T.) In such a case, unless there is a failure BPM, the solution is mathematically unique and independent of the solving algorithm. Namely, the one-by-one threading should work.
  - In reality, we could have a failure so we'd like to have the linear least square (SVD) method ready from day 1.
- Comments on the phase scan
  - Unlike SNS, the interfaces of the SC sections are smoothly matched and some of the SC cavities are not at the max strength. This means that we determine both the phase and amplitude with the phase scan for the SC cavities as well.

ESS commissioning timeline



- **The re-planning is ongoing based on realistic delivery dates!**
- Beam commissioning of RFQ, MEBT, and DTL are in parallel to the installation of the SC lianc components. During this period, the beam parameters are quite limited, especially for DTL: {62.5 mA, 50 us, **0.1 Hz**}.
- HBL (a part of it up to ~1.3 GeV?) will be installed in 2020.
- The tuning dump is limited to certain beam modes and within 12.5 kW.
- The target will be ready for the beam in late 2020?

Beam modes (standard sets of beam parameters)

Section/type	Current [mA]	Pulse length [us]	Rep rate [Hz]	Main usages
IS, LEBT	6 - 90.0	≤ 6000	≤ 1	
RFQ, MEBT	6 - 62.5	≤ 50	≤ 1	
DTL1-4	6 - 62.5	≤ 50	≤ 1?	
Probe	6	≤ 5	≤ 1	- Initial check - Beam threading
Fast tuning	6 - 62.5	≤ 5	≤ 14	- RF setting
Slow tuning	6 - 62.5	≤ 50	≤ 1	- Invasive measurement - LLRF setting
Long pulse verification	6 - 62.5	≤ 2860	≤ 1/30	- Beam loss check - Lorentz detuning check

NCL commissioning

Standard

- All the beam stops can take the fast tuning and slow tuning modes. (But, there are lower limits for the energy.)
- The tuning dump has a 12.5 kW limitation for the shielding.

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What we need when? (1)

- NC linac commissioning, from 2019 Q1 (?)
  - The pulse length is limited to 50 us.
  - The priority is on the accuracy of the phase measurement with {6 mA, 5 us}.
    - The steering can be repeated and improved later with a higher intensity beam. Whereas, the phase scan is always performed with {6 mA, 5 us} beam to avoid the beam loading
    - Beam loading issue for {62.5 mA, 5 us}?
  - The first thing to do for a DTL tank is setting the RF phase and amplitude.
    - The steering with no power is no longer valid after the tank is powered.
    - Checking the polarities before setting the RF is still possible. (But, not for DTL1.)

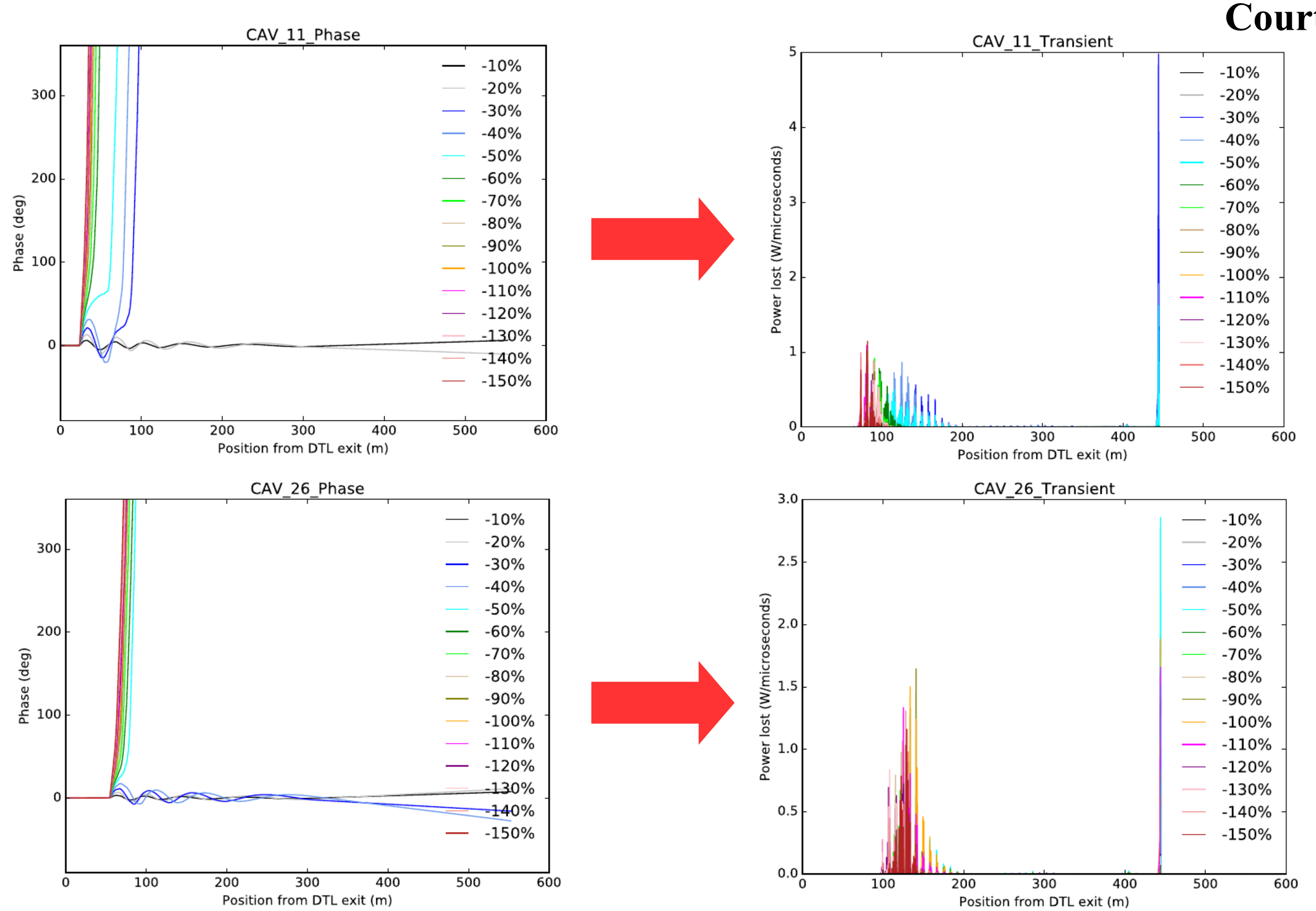
What we need when? (2)

- <u>SC linac (bar HBL) commissioning, from 2019 Q3 (?)</u>
  - The priority is again on the accuracy of the phase measurement with {6 mA, 5 us}.
    - The primary task of this period is to find the right RF setting for all 62 SC cavities.
  - Nearly debunched beam must be steered to one of beam stops.
    - We will check for the SC linac too, whether we should do a proper steering before setting the RF.
  - It is likely that we mostly use the fast and slow tuning modes during this time. But, we don't need to exclude the chance to try longer pulses.
  - For checking the Lorentz detuning compensation, we may want to “sample” the full 2.86 ms with 50 us slices. Is our diagnostics capable of such a measurement?
- <u>HBL, dogleg, and A2T commissioning, from 2020 Q4 (?)</u>
  - The accuracy of the phase measurement with {6 mA, 5 us} is still important.
    - We're likely to repeat the RF setting after the long shut-down.
  - We try to extend the pulse length before trying to increase the current.
    - Otherwise, we can't commission the raster system.
    - The long pulse capability is the ESS scope.

What we need when? (3)

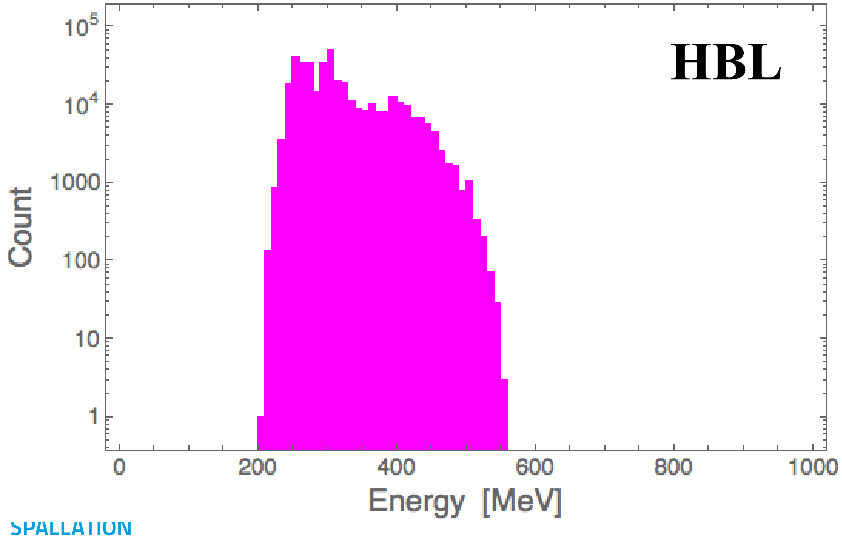
- <u>Advanced "features" which could be useful in future</u>
  - Direct energy measurement based on ToF. How reliable could it be?
  - SNS proposed the longitudinal Twiss measurements with the sum signal.
  - Beam loss "signature" detection, aka "beam loss minority report".

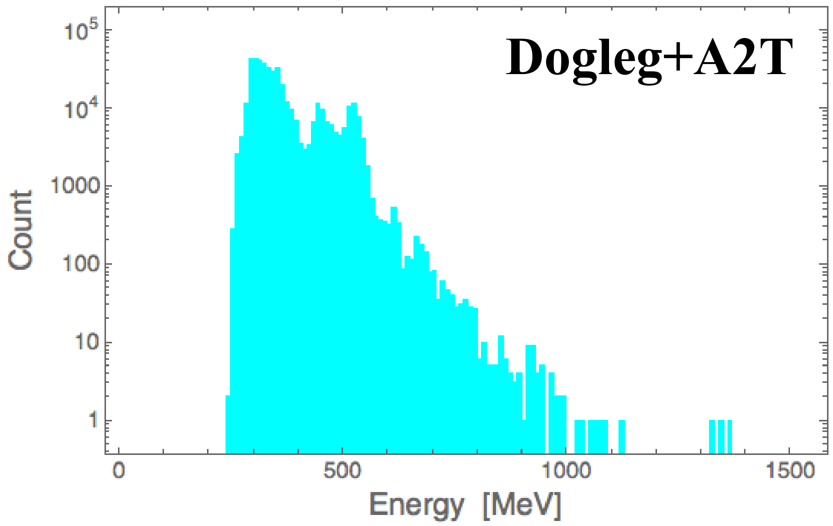
Courtesy of M. Eshraqi



A few things from the simulation

- The error sensitivity of the linac (62.5 mA) has been verified with
  - ±0.2 mm BPM accuracy (±0.1 mm for DTL)
  - ±1° and ±1% RF phase and amplitude set errors
- Beam loss situation
  - In the NC linac, if the longitudinal distribution out of the RFQ is “good”, the losses are primarily due to transverse issues, combined with the small aperture in MEBT and DTL.
  - In the SC linac, all the losses are primarily due to (affected by?) the longitudinal issues.
- The RF phase and amplitude are important throughout the linac. Whereas, the ±0.2 mm BPM accuracy MAY BE not an absolutely requirement. (Though, having a good trajectory inside a cavity is also good for the longitudinal dynamics.)





Courtesy of Y. Levinsen (Special study with stat: 4% and 4°, Dyn: 2% and 2°)

Requirements discussed in PDR

- **Nominal beam**
  - 62.5 mA
  - 2.86 ms
  - 14 Hz
- **Low current beam**
  - 6.3 mA
  - 5 us
  - 0.1-14 Hz
- **Debunched beam**
  - ≥ 6.3 mA
  - ≥ 5 us
  - 0.1-14 Hz
  - ~250 m to the target for 2 GeV
  - ~430 m to the target for 570 MeV
- **A2T**
  - 0.5 mm accuracy assumed.

- Low current phase most crucial.
- The response time for MPS.
- Resolution defined over what time scale? ~88 MHz?

Nominal beam

Error study

Phase resolution	0.2 deg
Phase accuracy	1 deg*
Position resolution	20 µm
Position accuracy	+- 200 µm**
Total response time to AMC	2 µs

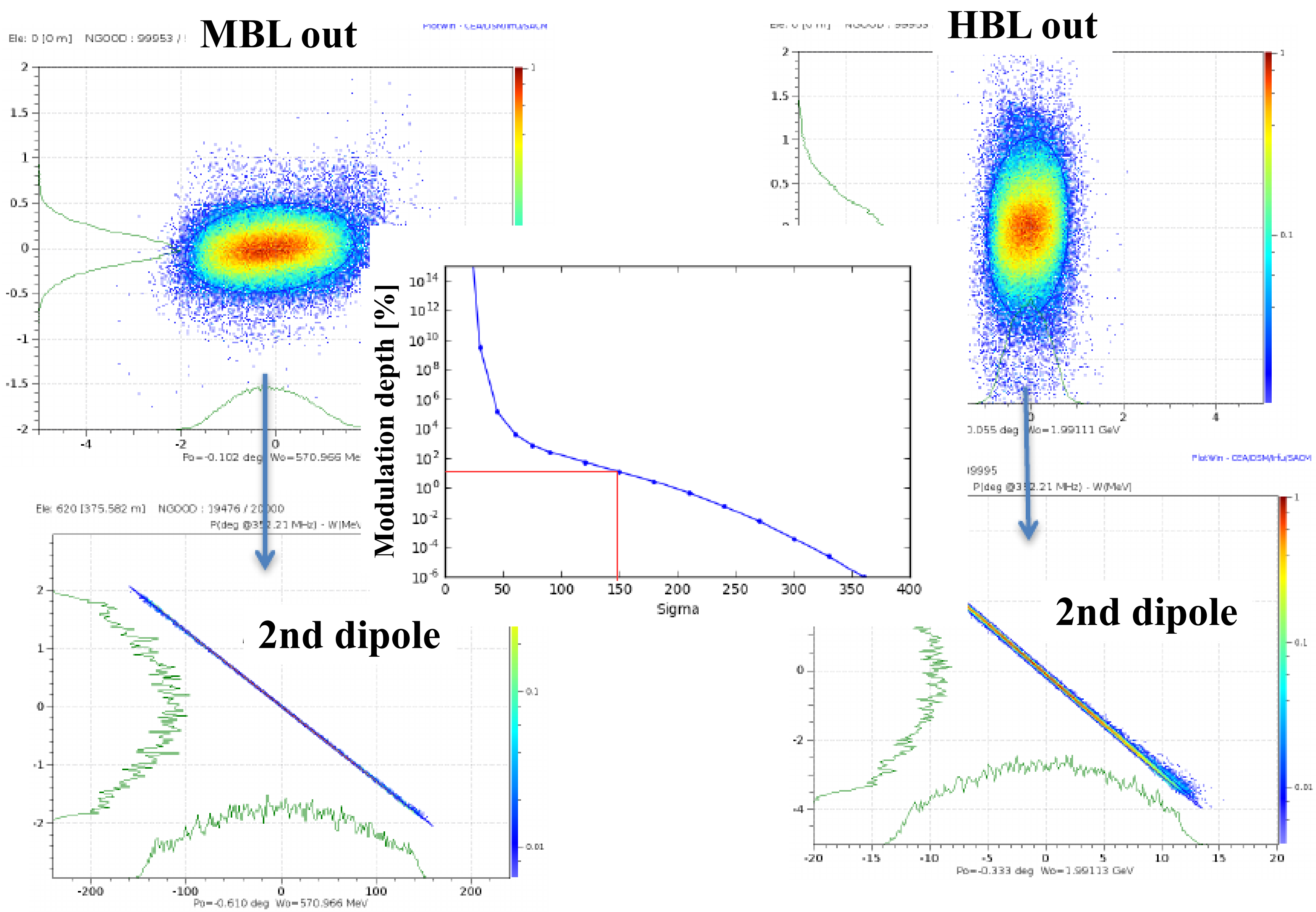
Low current beam

Phase resolution	**2 deg**
Phase accuracy	1 deg*
Position resolution	**200 µm**
Position accuracy	+- 400 um**
Total response time to AMC	2 µs

Debunched beam

Phase resolution	**-**
Phase accuracy	-
Position resolution	**2 mm**
Position accuracy	**+- 2 mm**
Total response time to AMC	2 us

Debunched beam examples



Courtesy of Y. Levinsen

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Comments on nonlinearity and monotonicity

- The nonlinearity shouldn't be a major issue since the trajectory correction can be performed iteratively.
- For the monotonicity, as long as it is maintained up to ~50% of the aperture, I see no issue. (If such a case happens, a rough correction should be obvious.)
- Nevertheless, we (beam physics) should prepare a scan application to check the responses of BPMs.

Expecting signals

- **Are there discussions/agreements among beam physics, diagnostics, and ICS??**
- Signal types
  - Beam (related) parameters
    - Reconstructed position. In meter? In millimeter? Is it easy to switch?
    - Phase with respect to the reference line. In degree.
    - Raw signals (sum, different, each pick-up) and wave-forms.
  - Device parameters (Do we prefer to the word “meta-data”?)
    - Offsets and calibration parameters (including cable lengths, temperature, …?)
- Averaging, sampling, and reporting for the beam (related) parameters
  - Averaging over a whole pulse
    - A single pulse could range from ~5 us to ~3 ms.
  - Sampling within a pulse
    - The desired sampling length could depend on the pulse length:
      - Sampling the 5 us pulse desired and possible?
      - 5-10 us for 50 us (for LLRF)
      - 50 us beyond 50 us (for the Lorentz detuning compensation)
  - Averaging over multiple pulses
    - For both case above, the capability of averaging over N pulses or T sec is required.
    - N or T specified at which level?
  - Reporting faster than 1 Hz useful?
  - Are we clear about the definition of the “resolution”? What I care is the standard deviation for the repetitive measurements with the {6 mA, 5 us} beam.

Closing remarks

- The requirements are based on the error sensitivity studies and haven't changed since the PDR.
- If matters, the most crucial and needed from the beginning is the phase measurement with the low intensity {6 mA, 5 us} beam.
- Beam physics should perform further detailed studies of the phase scan.

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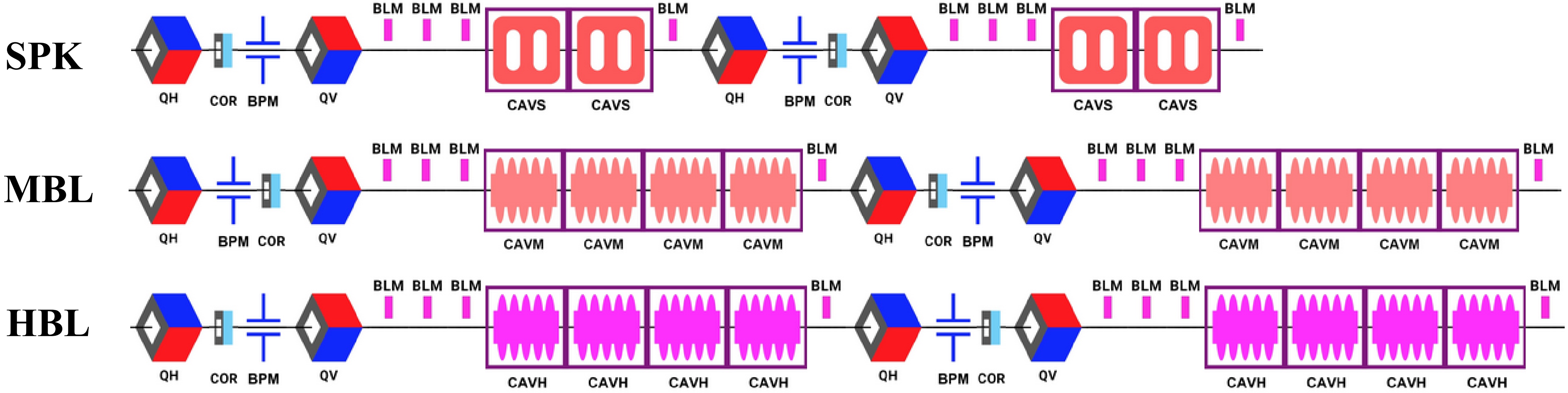
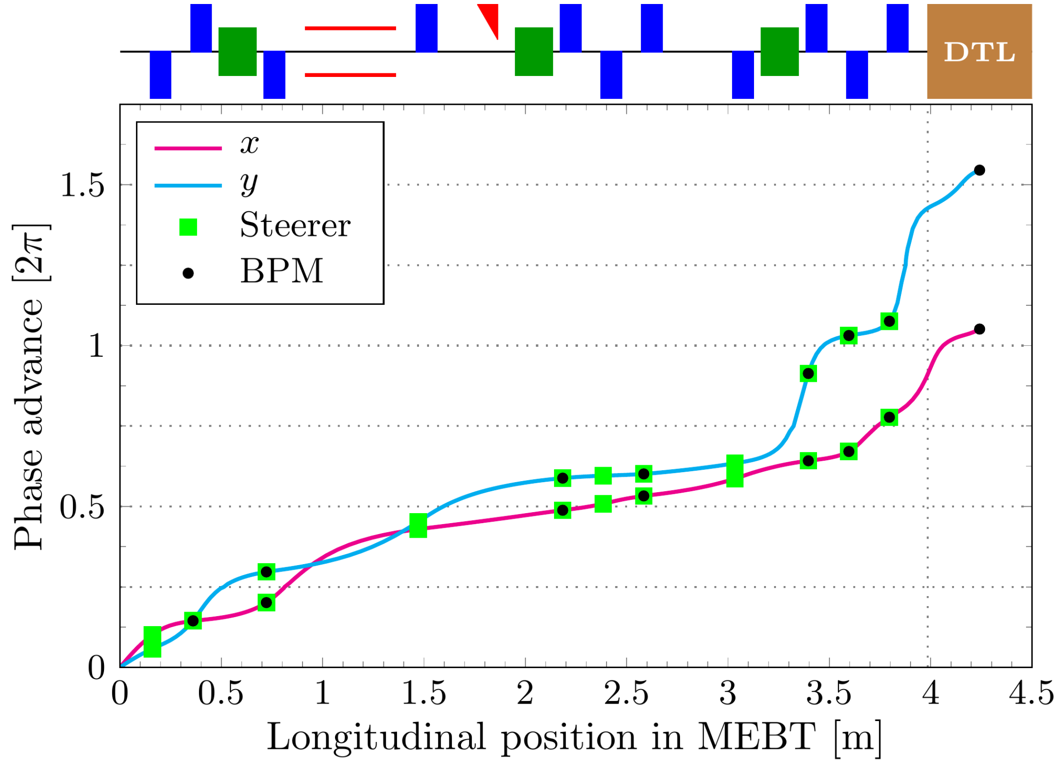
Backup slides: details on the layout

BPM layout in SC linac



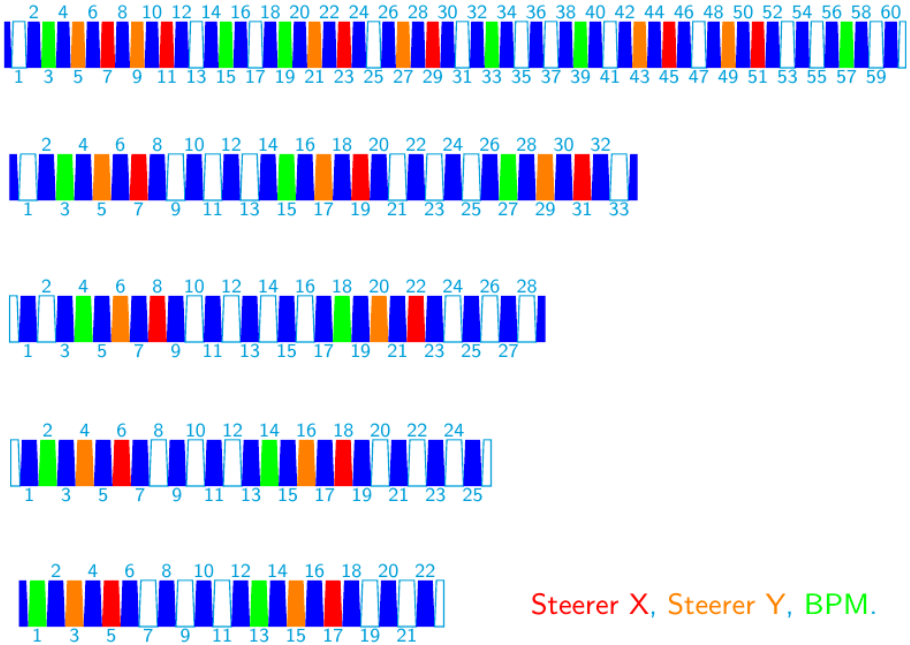
- One lattice period consists of one quad doublet and one cryomodule. Between the doublet, there is one BPM and one dual plane steerer.
- This applies to all SC sections as well as the HEBT and dogleg.
- The trajectory correction shouldn't be too crucial or difficult either for the SC linac. Even a missing BPM shouldn't be a big issue. Whereas the RF phase and amplitude errors, especially at the frequency jump, are crucial and the major source of the beam loss.

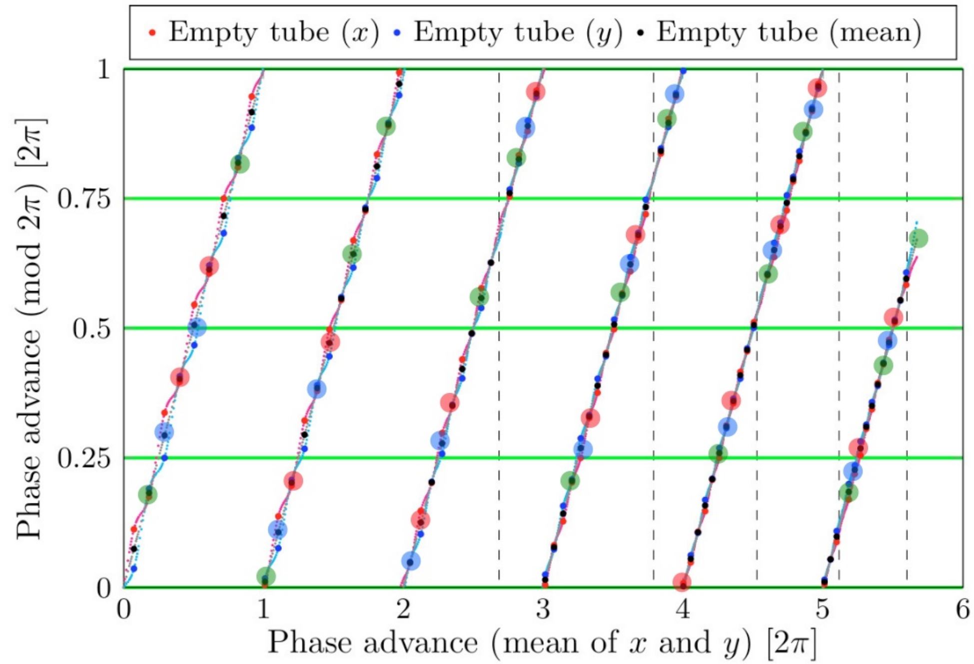
BPM layout in MEBT



- 7 BPMs (11 steerers). 2 before the chopper and 3 after the last buncher, for correction the injection and extraction.
- RMS vs aperture ratio is tightest so steering is important. On the other hand, a BPM inside a quad allows a simple beam-based alignment. This isn't the case for the rest of the linac.
- Additional BPM in Q4 might have been useful for monitoring the chopping and the buncher #1 phase scan. But, the total number limited by the old agreement.
- The 1st BPM in DTL very far, almost ~180 deg for the vertical plane. (Because we gave up to have one in the first empty tank due to the space issue.)

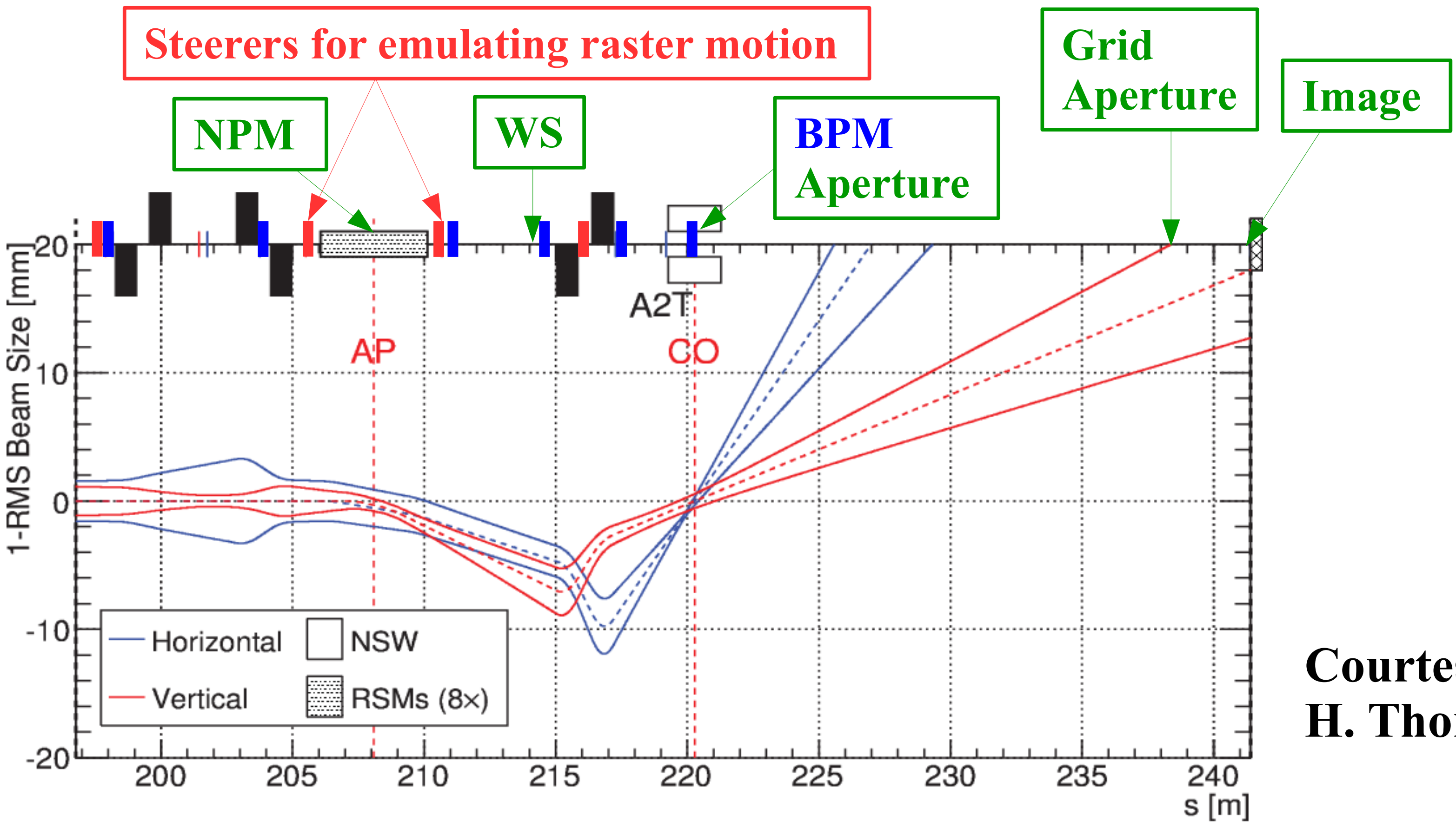
BPM layout, DTL





- 15 BPMs and steerer pairs (6, 3, 2, 2, 2).
- The distribution based on the phase advance but the total number limited by the agreement.
- Trajectory correction useless prior to setting the RF phase and amplitude.
- 6 BPMs and steerers are still not enough for the DTL1 with ~3 betatron periods. The trajectory is by far worst in DTL1 (~0.5 mm RMS in a typical error study) and a BPM failure could make the situation even worse.
- A BPM failure in DTL3-5 is still better than the normal situation of DTL1.

BPM layout in A2T



Courtesy of H. Thomsen

- 6 BPMs (plus 1 grid and 1 target imaging) and 4 steerers.
- The aperture is "closer" in A2T.
- The BPM at the shield wall extremely important for the raster optics adjustment but no backup.