Beam transfer and splitting improvements

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With thanks to M. Fraser, Y. Dutheil, F. Velotti, V. Bencini, P. Arrutia, E. Johnson, D. Gamba, K. Li and many others

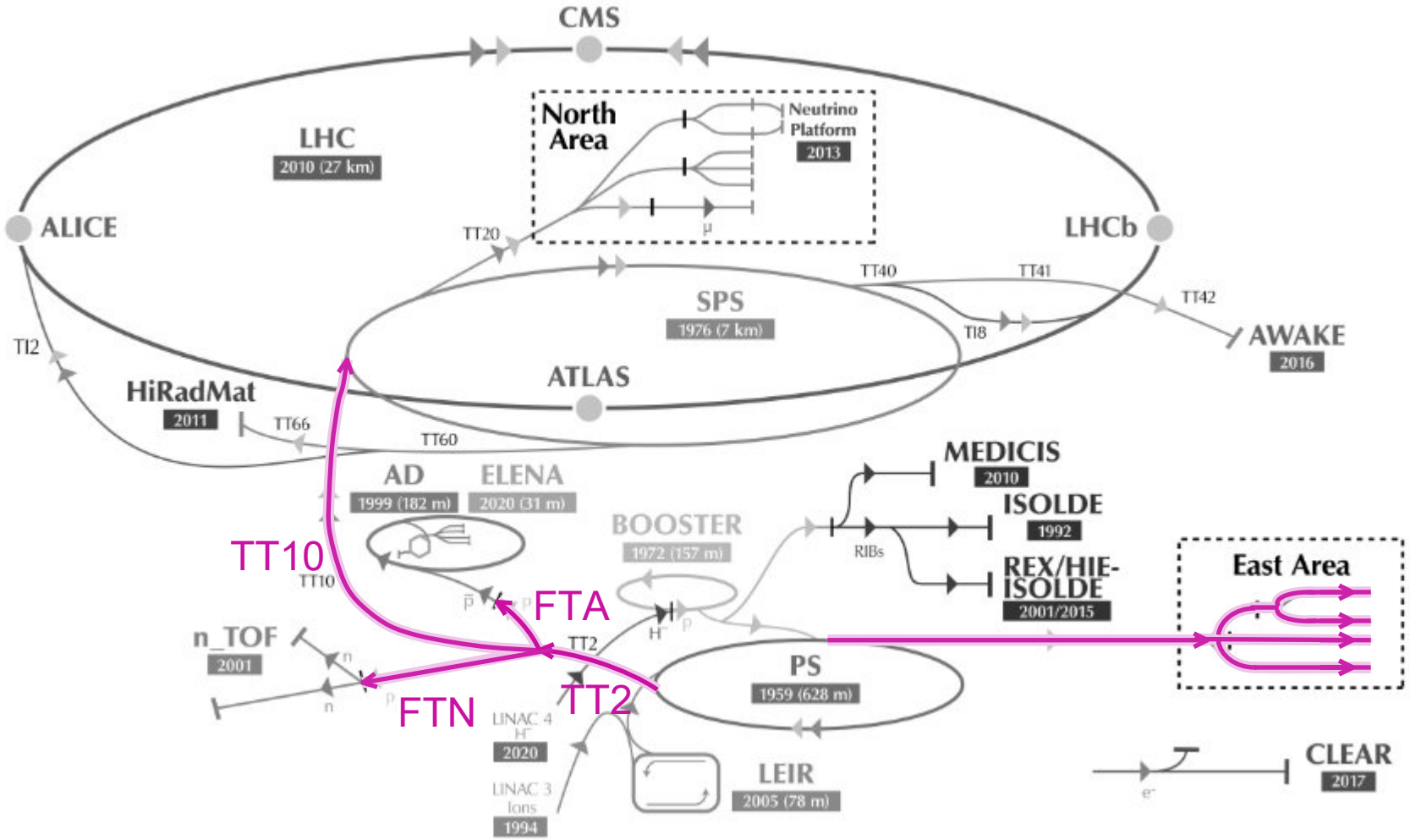
Joint Accelerator Performance Workshop 2022

Wednesday 7th December 2022

Outline

- **Transfer line (TL) optics investigations and optimisation:**
  - **FTA, FTN:** beam losses and need for instrumentation.
  - **East area:** exploitation of BTVs for successful reconstruction of initial beam parameters.
  - **TT2, TT10:** measured dispersion mismatch.
  - **LEIR TLs**: discrepancies seen in kick response measurements.
  - **AWAKE TLs:** tools for beam steering and tomographic measurements.
  - **TT20 TLs:** large deviation observed between optics model and measurements.
- **TT20 beam splitting improvements:**
  - MD measurements of splitting efficiency.
  - TT20 splitter activation (TCSC/MSSB).
  - Reducing beam loss at the splitter magnets with crystal shadowing.

Transfer lines following the PS



FTA transfer line

2021

Inferred beam size on target was larger than design (1 mm)

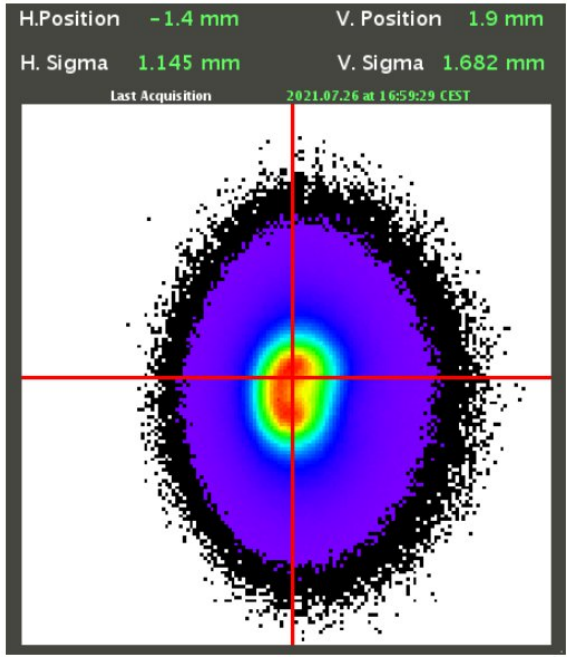
- *OTR measurements.*
- *Reduced AD $\bar{p}$-capture.*

22/07/2021

New optics:

- *Reduced beam size on target.*
- *No gain in $\bar{p}$-yield.*

Chromox in-air target screen, with fast degradation in the center



***2021 optics:** beam size on BTV9064 was reduced by 37% horizontally and 13% vertically.*

FTA transfer line

2021 — *Inferred beam size on target was larger than design (1 mm)*

22/07/2021 — New optics.

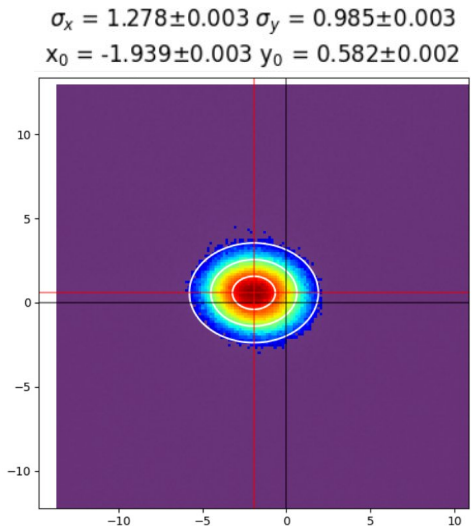
end 2021 — *Hotspot at FTA branching.*

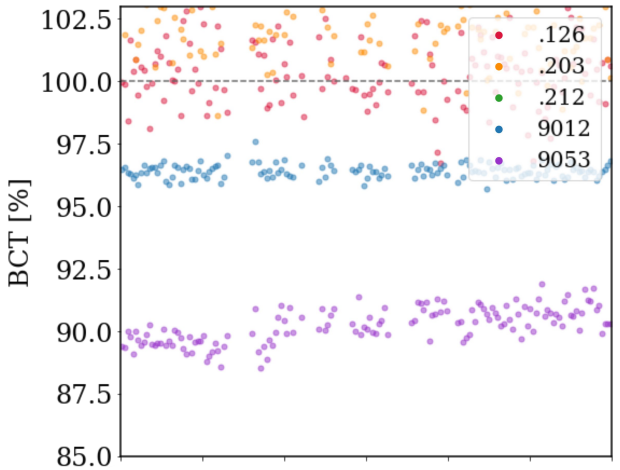
03/2022 — *Optics reversed to pre-2021.*

04/2022 — *Optics optimisation*

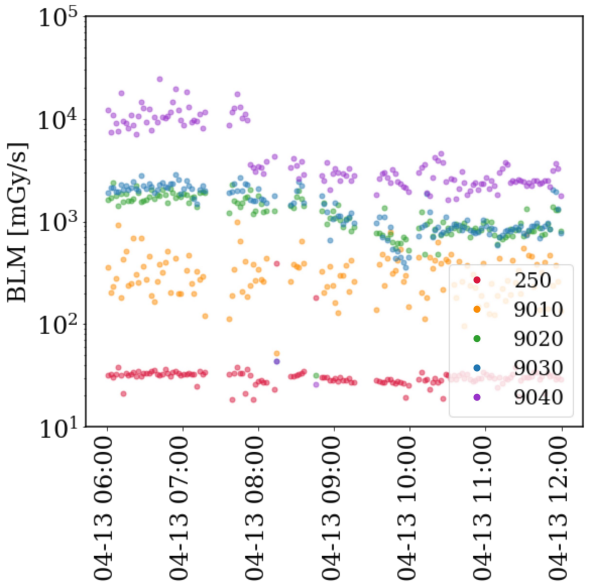
- *Beam size on BTV9064 1.3 mm×1.0 mm*
- *Reduced losses*
- *Small increase in transmission*

Much better beam size estimates since TS2 (see talk by D. Gamba).



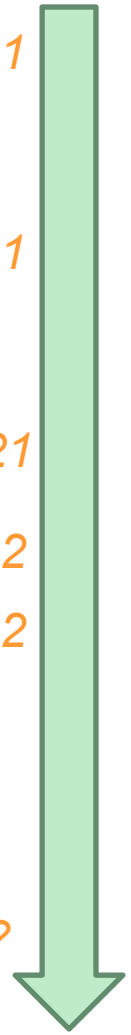


Normalised to a ring BCT.



BCT and BLM data during empirical optics optimisation and steering using BLMs (04/2022).

FTA transfer line



2021 — *Inferred beam size on target was larger than design (1 mm)*

22/07/2021 — *New optics:*

end 2021 — *Hotspot at FTA branching.*

03/2022 — *Optics reversed to pre-2021.*

04/2022 — *Optics optimisation*

future? — **Future steps**

Future steps

- Further beam measurements to improve transmission during 2023 commissioning.
- Steering using BLMs but **transmission remains at 90%** despite investigation.
- Careful review of the model apertures during YETS.

Desiderata

- **Request for BPMs**, due to difficulty maintaining the beam trajectory and the alignment on target. BPMs would also aid with improving losses/transmission.
- **Beam time** for optics investigations during the 2023 restart before AD takes beam.

FTN transfer line

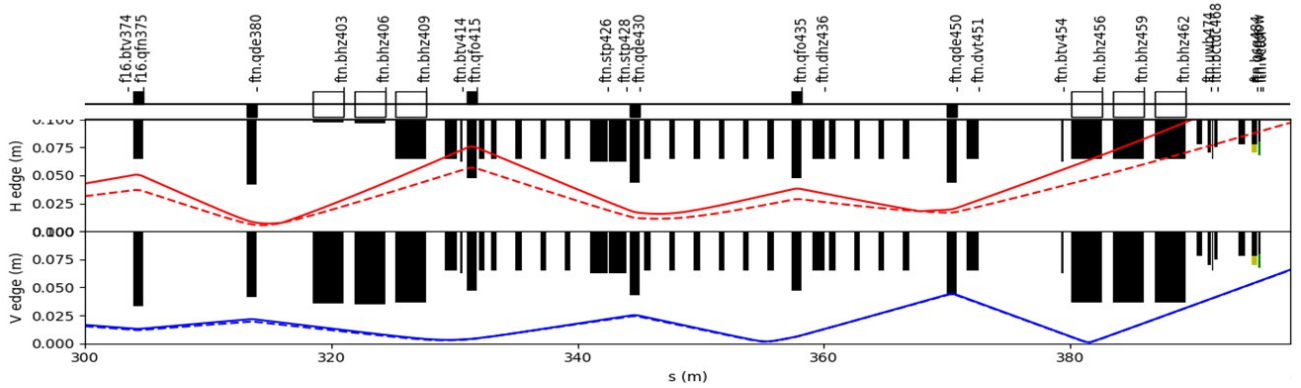
- The current optics are a **compromise** between maximising beam size on target while minimising beam losses.
  - Still several **aperture-limited** regions. The issue has been followed by a dedicated TF since the restart post-LS2 [1].
  - Quadrupoles 465 and 480 were removed and replaced by large aperture chambers (YETS21/22).
- **Resources needed to adapt old transfer lines are often under-estimated, for future projects the optics modelling and its consolidation must be considered as an integral part of projects** (see talk by Y. Dutheil).

Future steps:

- Set up golden reference in F16 during commissioning (using BPMs) so as to correct any drifts upstream of FTN.
  - Opens the possibility for automatic beam position monitoring in F16 and possibly automatic correction too, if needed.
- Review of the FTN reference position with possible realignment during the YETS.

Desiderata: FTN would benefit from BPMs as aperture limitations throughout the line make the trajectory critical.

New optics with reduced beam losses [2].



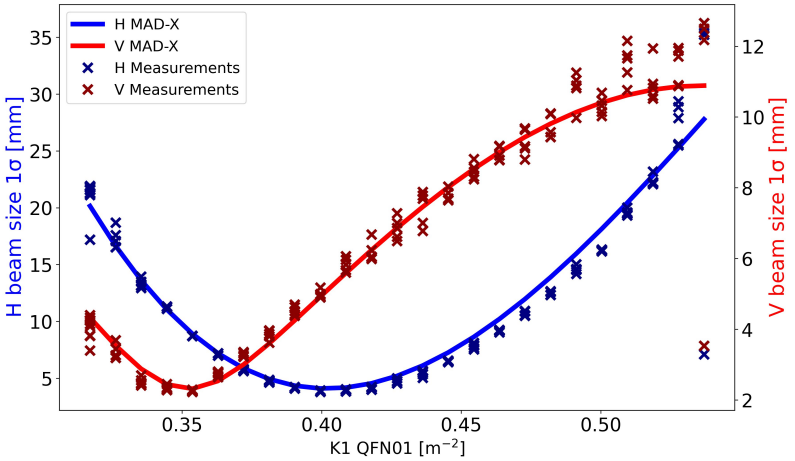
E. Johnson

East Area

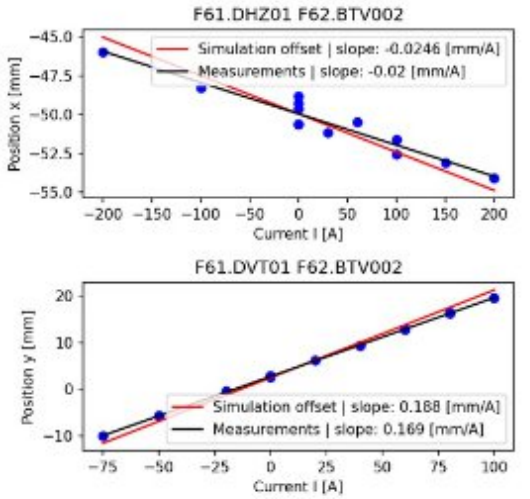
- **Initial beam parameters**, allowing for a good agreement with the optics model from the start of F61 to T08.
- BTVs used for profiling DC beams.
- New UCAP node publishes beam positions inferred from BPMs, BTVs and Wire Chamber.
- BTVs assimilated into YASP for steering (not tested due to limited beam time).

Key issues in 2022

- Areas without vacuum defocus the beam, especially the first bend in F61.
- BTV images in T08 show saturation or low signal.
  - BTV020 (saturated), BTV035 (saturated), BTV096 (low signal).
  - Filter wheels to be installed on remaining T08 BTVs.



Quad scan in F6D used to reconstruct initial parameters at the beginning of F61.



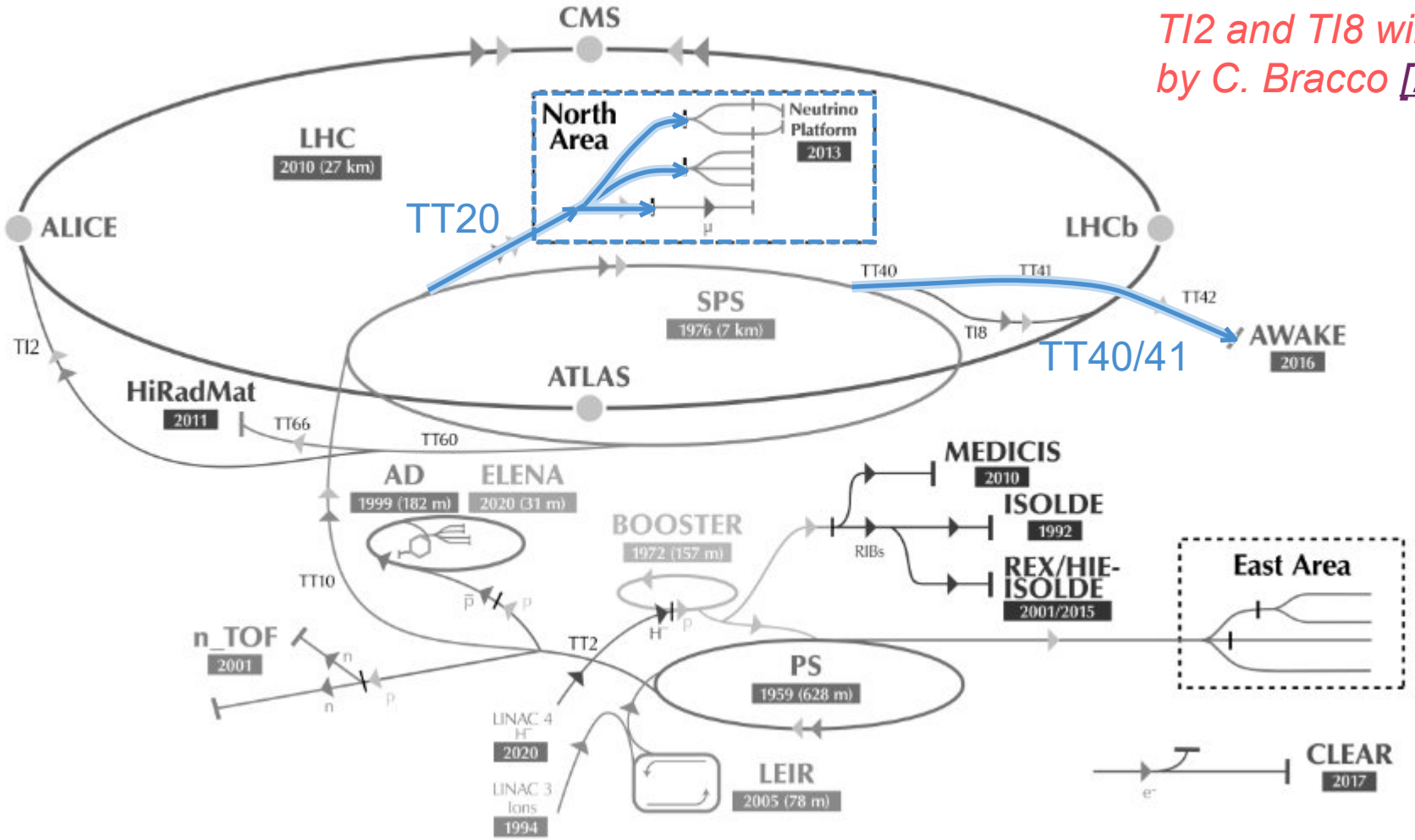
Kick response measurements in T8.

F. Velotti

TT2, TT10 transfer lines (PS-->SPS)

- TT10 **dispersion mismatch** measured during the commissioning post-LS2.
  - Dispersion measurements made for all optics and kick response (KR) measurements in TT10.
  - TT10 KR identified discrepancies for MAL.1001 for all optics, suggesting a localised issue.
  - Issues found with quadrupole settings in TT2 which improved mismatch by 30%.
  - As no emittance blow up measured so far for LHC beams this is a low priority.
- **Frequently need re-steering** due to PS extraction.
  - Helped by having a new stitched optics model from TT2 to SPS.
  - **Automation:**
    - Proposal for continuous automatic steering with with SVD or MICADO algorithms.
    - Aim to combine it with local steering, loss reduction and transmission optimisation.
    - Automatic steering tested in TT2/10 could then be deployed to other transfer lines.

Transfer lines following the SPS



TI2 and TI8 will be covered by C. Bracco [2].

AWAKE transfer lines

TT43 (e^--transfer-line) ongoing issues

- Cannot use YASP due to hysteresis in correctors.
- Discrepancies between model and measurements, line is highly sensitive to input parameters.
- Limited reproducibility of beam from RF gun.

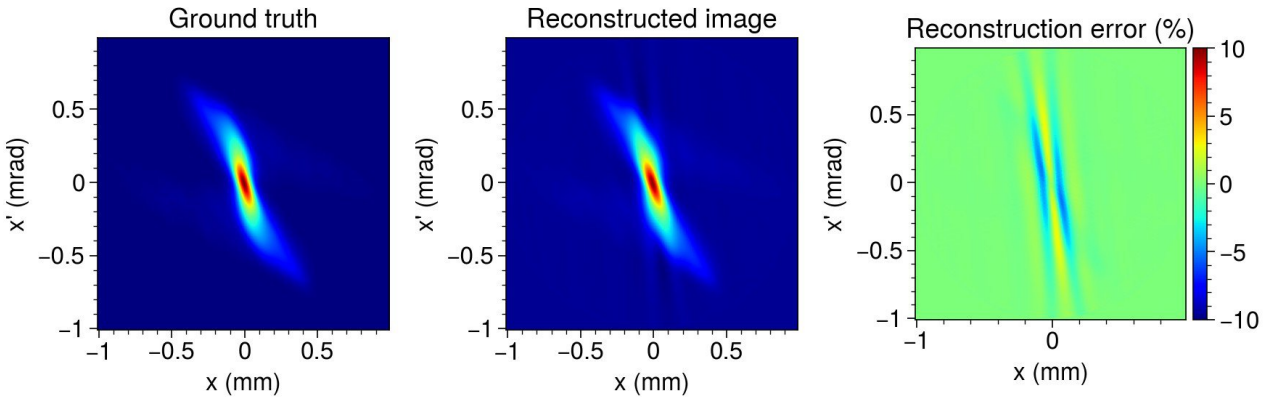
Tools under development

- **Tomographic-reconstruction** tool, using two or three quadrupoles to cover wide phase range—to be extended to higher dimensions.
- **Orthogonal-steering** tool with degaussing at every step.

TT40/TT41 (p^+-transfer-line) future considerations

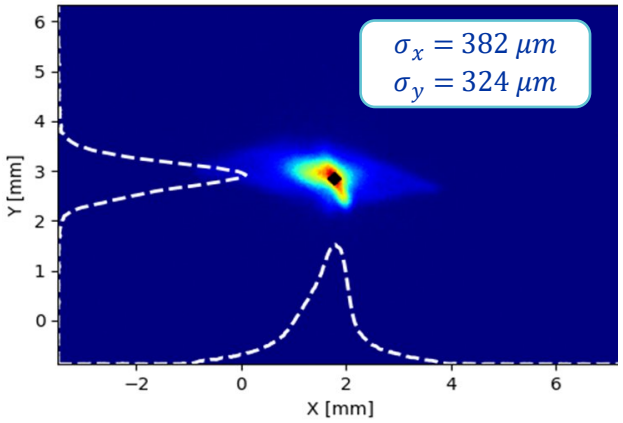
- Power converter noise in TT40/41 is a **limiting factor** in achieving the beam alignment and pointing precision required for AWAKE Run2c.
- Noise is uncorrelated between PCs and not predictable cycle-to-cycle.

TT43: Tomographic reconstruction, simulated performance

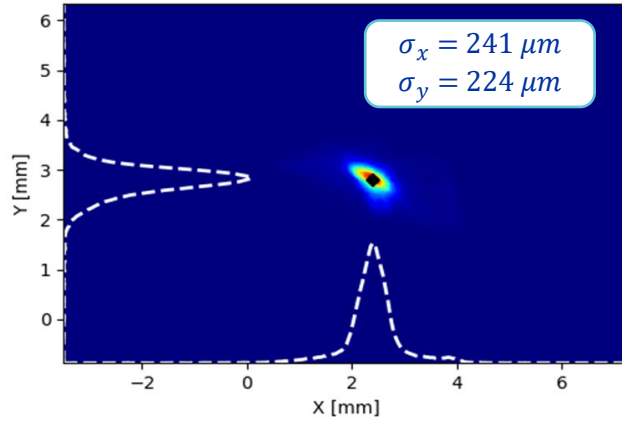


TT43: optimisation of beam size and distribution at injection point

Before optimisation

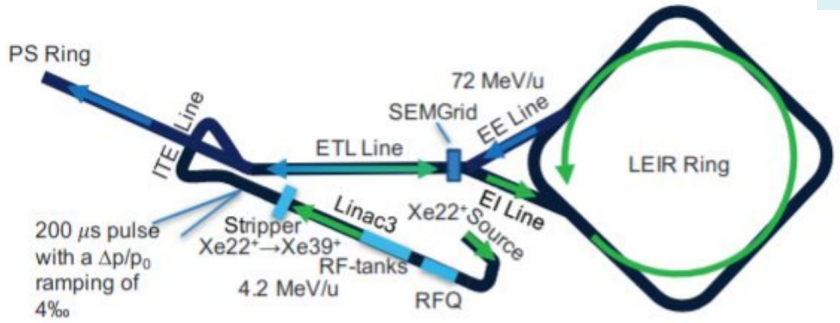


After optimisation



F. Velotti

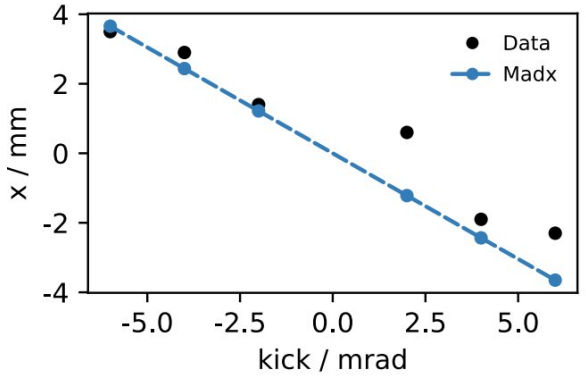
LEIR transfer lines



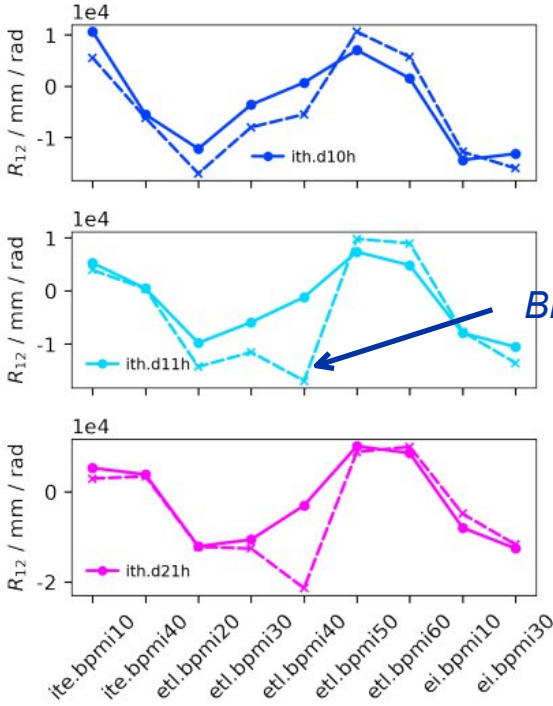
Optics measurements in transfer lines (12-15th July 2022):

- Inconsistent settings found in LSA for quadrupoles in ITH and ITE.
- ITH and horizontal ITE correctors needed scaling by factor of 2.
- Vertical correctors in ETL needed a change of sign.
- Insensitive responses from BPMI.40, possible dispersion or cross-coupling.
- Non-linear kick response scans which could suggest non-linear BPM response.
- Very good agreement in EI.

Kick response: BHN03 with BPMI40



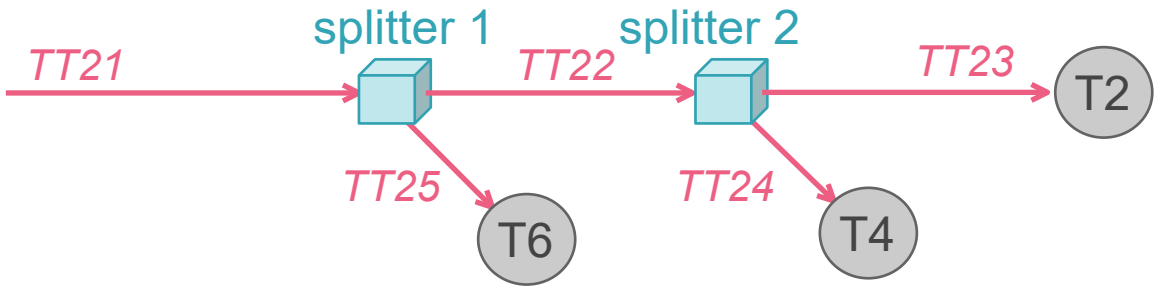
R_{12} measurement: ITH



[3]

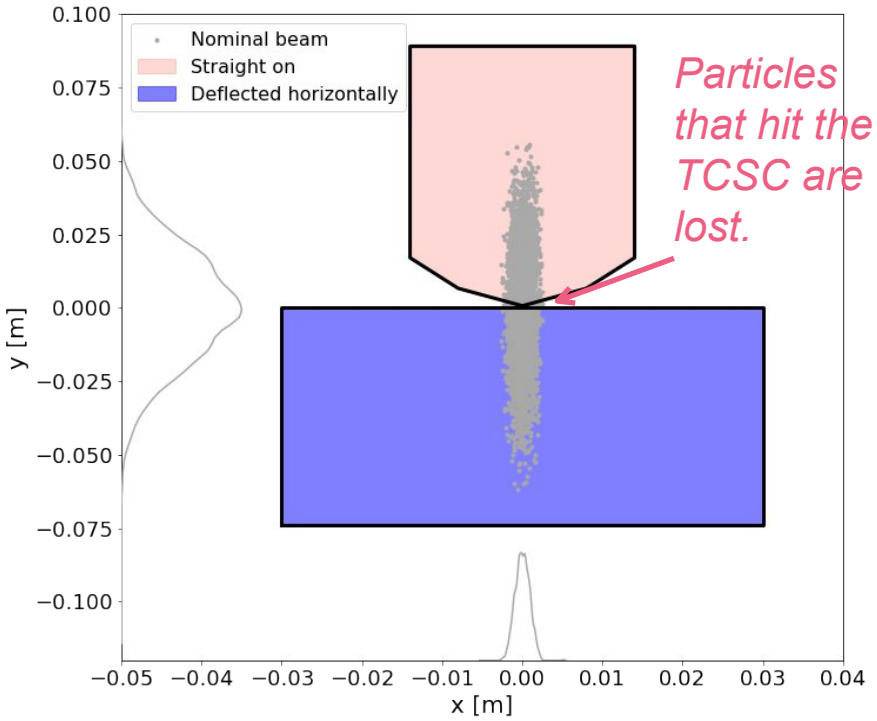
TT20 beam splitting

- Two splitters, consisting of three 5-m-long Lambertson septa (**MSSBs**) each.
- Allows beam to be sent to three primary-production targets simultaneously.
- A mask (**TCSC**) shields each splitter, with an effective thickness of 3 mm.



- From simulation, with optimal alignment there are **3% losses** during splitting for the worst-case 50:50 splitting ratio.

TCSC front-face



[4]

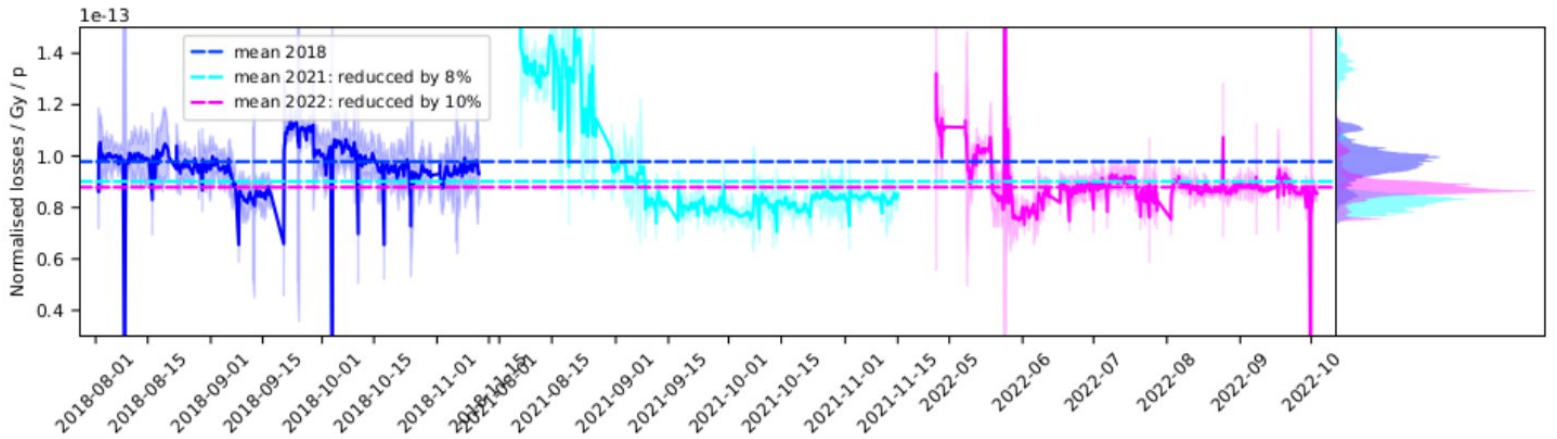
TT20 TCSC activation

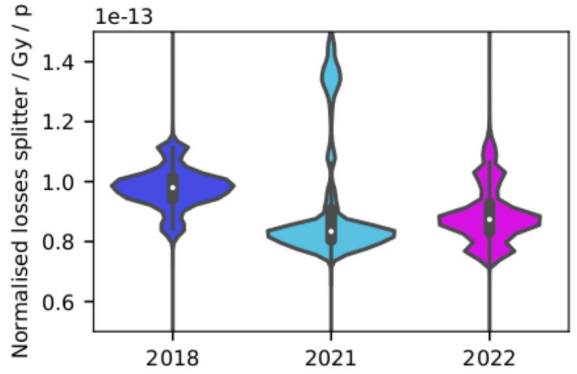
Beam losses and TCSC activation

- Unprecedented 2022 intensity meant **3 times the TT20 activation** observed in 2022 vs. 2021 (see talk by K. Li).
- 10% lower beam losses (normalised) at TCSC because of alignment and optimisation.
- Measured dose rate at the TCSC of **80 mSv/h** at approximately 40 cm distance, after 30 hours cool down [5].

Future considerations

- Further investigation needed into the impact of high radiation levels in TCC2.
  - Quantify potential downtime for a TCSC/MSSB intervention.
  - Establish RP constraints for TCSC intervention, for example consider the 2022 TCSC exchange.





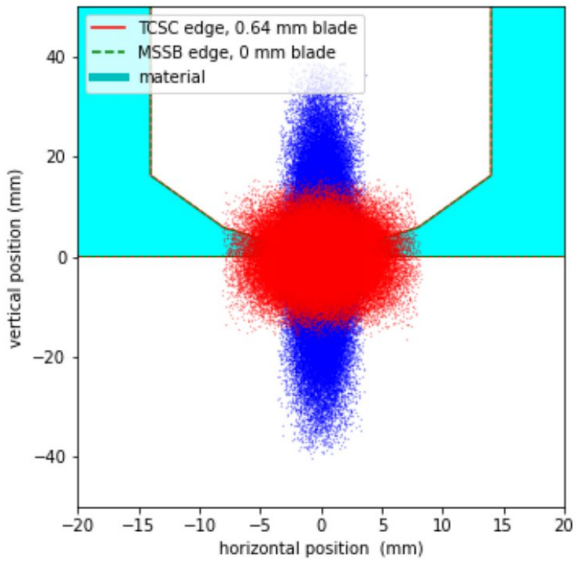
[6]

Y. Dutheil

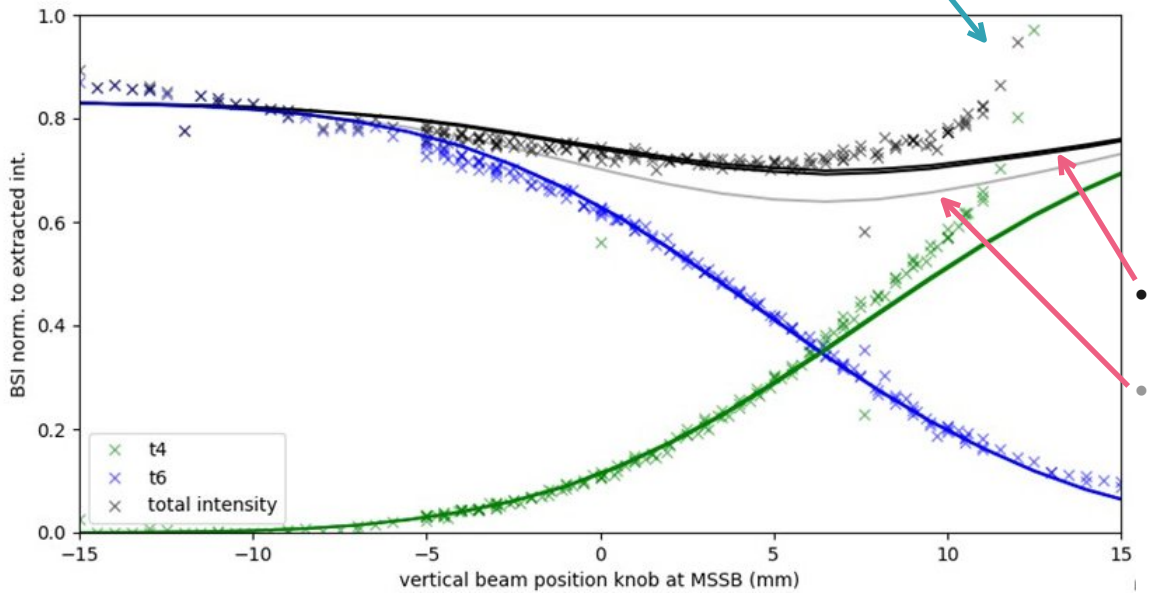
Splitting efficiency measurements

- MD to measure the splitting efficiency by scanning the beam across splitter blade and measuring losses.
- Using a smaller vertical beam size to increase proportional losses from 3% to 6%.
- Successfully demonstrated we are close to optimum, agreeing with the alignment survey at the end of LS2.
- Limited control over the beam trajectory led to losses near the BSI which were reported as signal.

Increase proportional losses with beam distribution.



Summer 2022 - splitter efficiency MD



- *Black line shows perfect case (6% losses).*
- *Grey line shows poor alignment (10% losses).*

Crystal shadowing

P. Arrutia

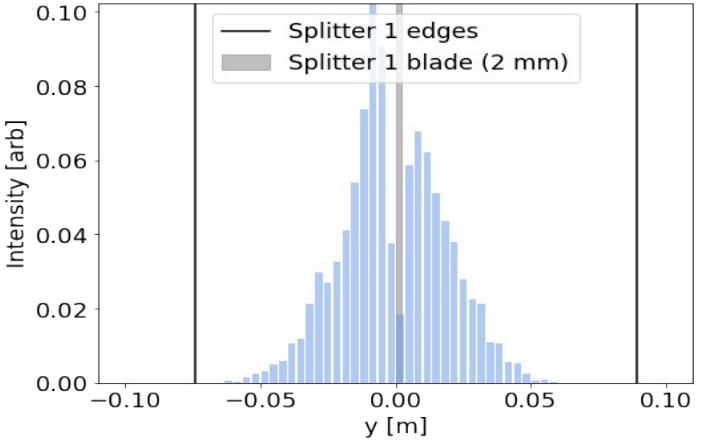
- **Aim:** reduce beam density at the TT20 splitter blade to reduce beam losses.
- **Proposed method:** install a **thin, bent crystal** in TT20 to deflect a portion of the beam which would hit the TCSC.
- Bent crystals can be used to deflect high-energy and high-intensity beams. Technology is applicable also for reducing losses at the ZS septum (see talk by F. Velotti).

Channelling

- Particles with small transverse momentum w.r.t to the crystallographic planes can propagate oscillating in potential well between planes.

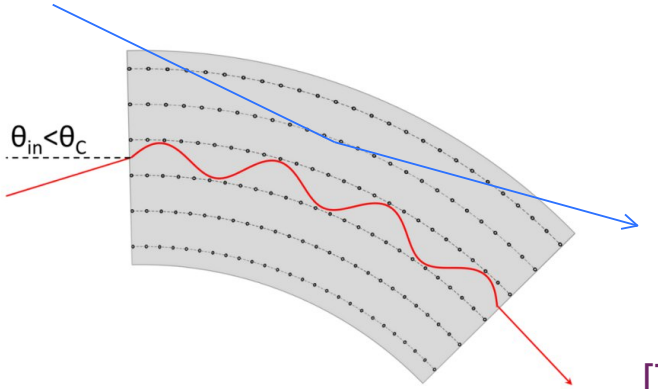
Volume reflection

- Particles are deflected by the potential well in the opposite direction to the channelling.



Reduced beam density at the splitter blade.

Channeling, volume reflection.



[7]

Splitting efficiency improvements

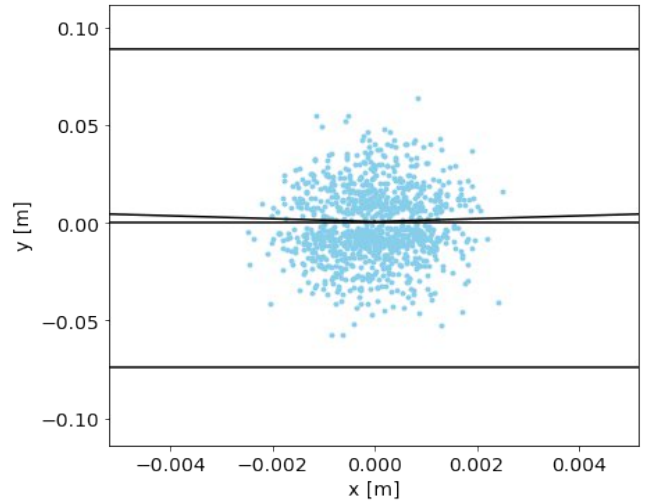
Crystal shadowing

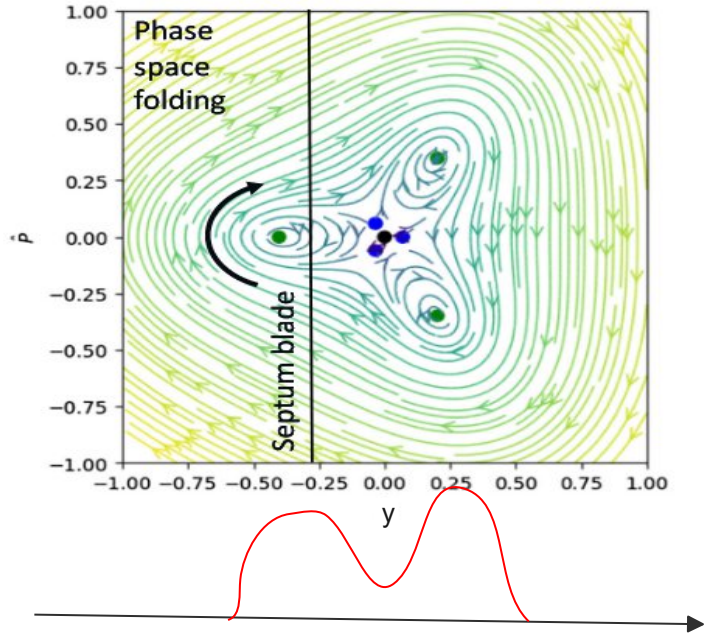
- Simulations in MADX suggest that a **5-crystal array** (1.8-mm-thick crystals) aligned in volume reflection may offer **5.5 times loss reduction**, but technology not available in near term.
- One 0.8-mm-thick crystal in channeling (currently available), would have larger deflection (165 μrad) but a decreased angular acceptance (20 μrad) and efficiency (70%).
- Simulations by the end of the year to characterise loss reduction with a 1.8-mm-thick crystal.

Phase space folding (longer-term prospect)

- Manipulate the vertical phase space inside the SPS ring with non-linear magnets to flatten the beam distribution.
- Vertical distribution ideally preserved during extraction which is in the horizontal plane.

TCSC front-face





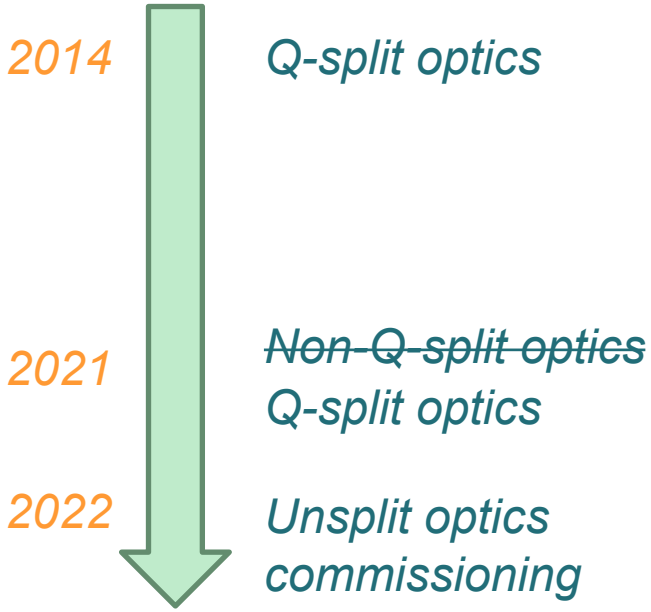
[8]

TT20 transfer line optics

Q-split optics: designed for SPS double extraction **(current operational)**.
Non-Q-split optics: matched for only LSS2 extraction to NA.
Unsplit optics: propagates beam “unsplit” through the splitters.

History

- Q-split optics loaded in 2014 — unknown why as only NA extraction.
- During 2021 start-up, the non-Q-split optics were implemented, resulting in a 20% reduction in transmission through P42.
- Therefore, reverted to Q-split optics.



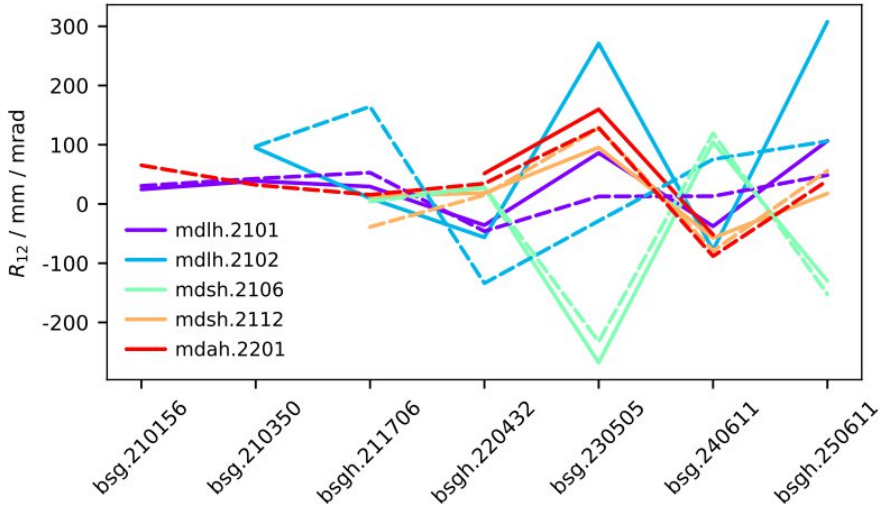
F. Velotti

TT20 optics model discrepancies

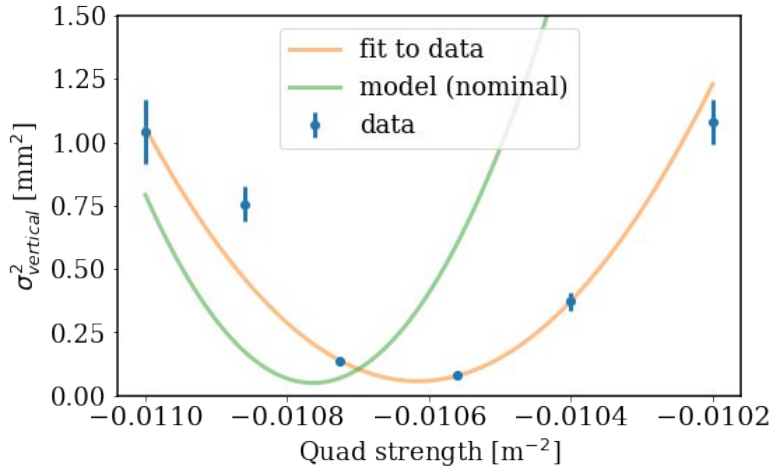
- During 2022, there was a campaign of measurements into the discrepancies between the optics model and measurements.

Observed discrepancies

- Q-split optics give **better P42 transmission** than non-Q-split, although, model predicts they should be similar.
- The optics model doesn't match well to **kick response** R_{12}-measurements for all optics.
- Quad scan results show an **incorrect focus** at the T4 target both horizontally and vertically.



Operational optics: *kick response shows poor agreement with model.*



Unsplit optics: *offset of beam focus at T4 target.*

TT20 transfer functions

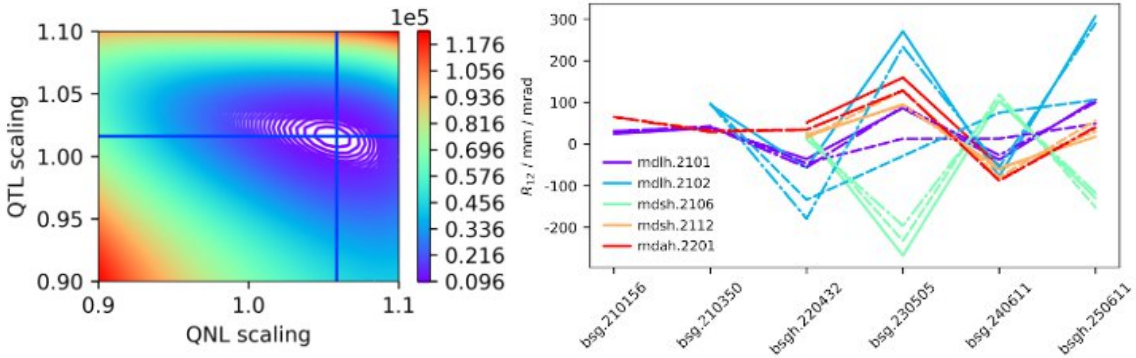
Transfer functions

- Incorrect QNL transfer function (TF) in LSA, instead using QTL TF with up to 3% error.
- QTL TF is from a 1987 sketch and doesn't match the one in LSA—unknown where the LSA TF is from.
- Few percent error on TFs propagate to large changes of R_{12} in TL.

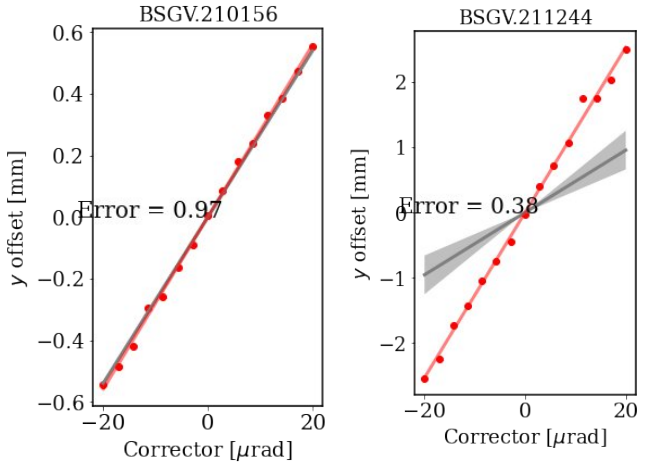
Magnetic measurements

- Measurements of suspected QNLD.2105 during ITS2—no deviations found.
- A one-year magnetic measurement campaign is planned in the framework of NA-CONS.
  - Priority for QNL, QTL, MBN and MSN magnets.
  - To measure TF and dynamic behaviour (field lag, stabilisation time).

Using data to fit for the QTL and QNL TFs.



Effect of 3% QNL TF error on kick response (grey shaded) compared with measurement (red)



Conclusions

Identifying common themes

- Use of instrumentation for optics investigations and steering:
  - Exploiting the existing instrumentation, e.g. using BLMs for steering and rematching in FTA.
  - Need for additional **instrumentation**, e.g. BPMs in FTN, FTA.
- Difficulties with using old transfer lines for new projects.
  - Time and resources invested in improving our understanding of old lines, e.g. TT20.
  - As well as the consolidation of hardware, we need **consolidation of optics-understanding**.
- Investing in **automation**:
  - Successes in testing optimisation in TLs, e.g to reconstruct F61 initial conditions in the East Area.
  - Automation proved useful particularly in lines where YASP was unsuccessful, e.g LEIR, extend to SPS-to-LHC TLs, fully automated TCDI alignment.
  - Proposals for further automation cases, e.g continuous feedback on steering, losses or transmission in the PS-to-SPS TLs.

Thank you for your attention