Linac4 source and low energy experience and challenges

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- **Measurements at the test stand**
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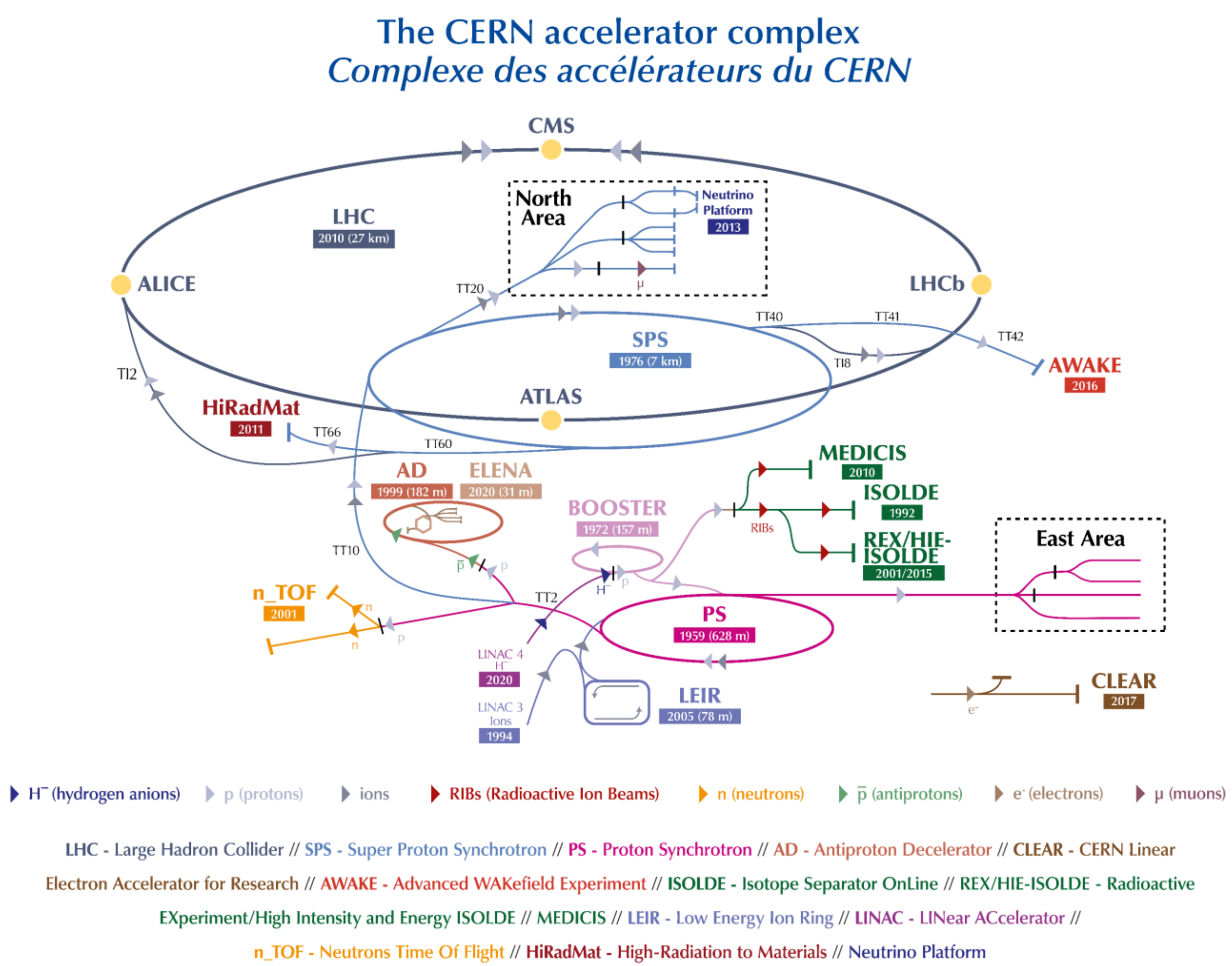
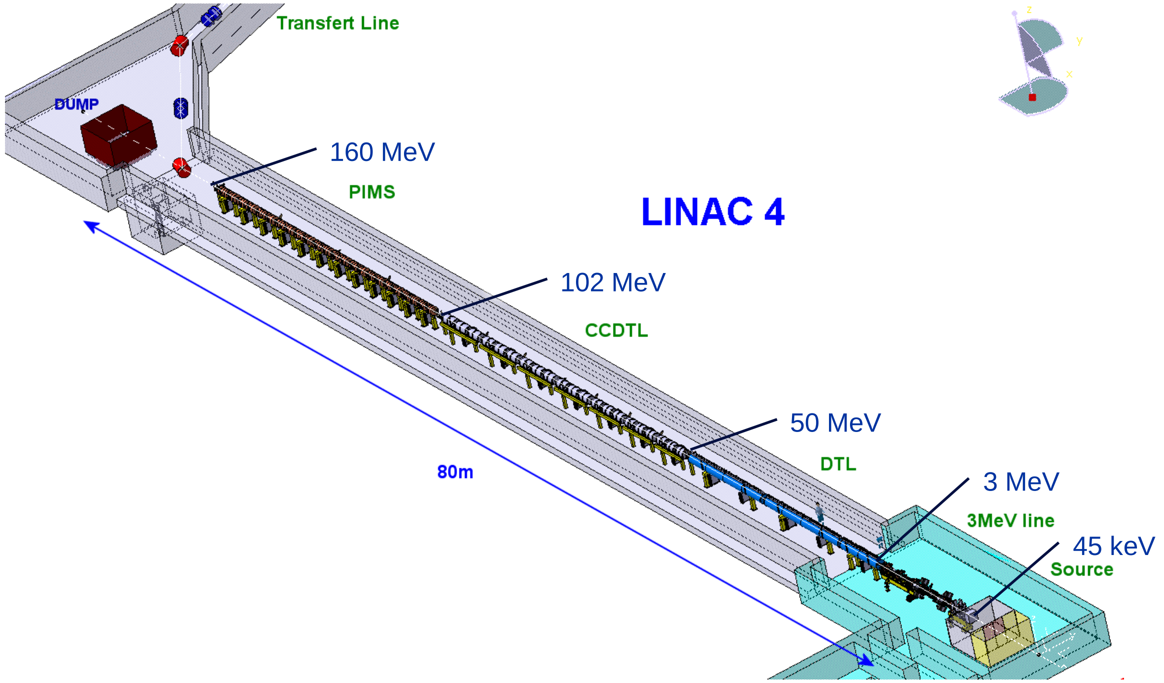
Introduction

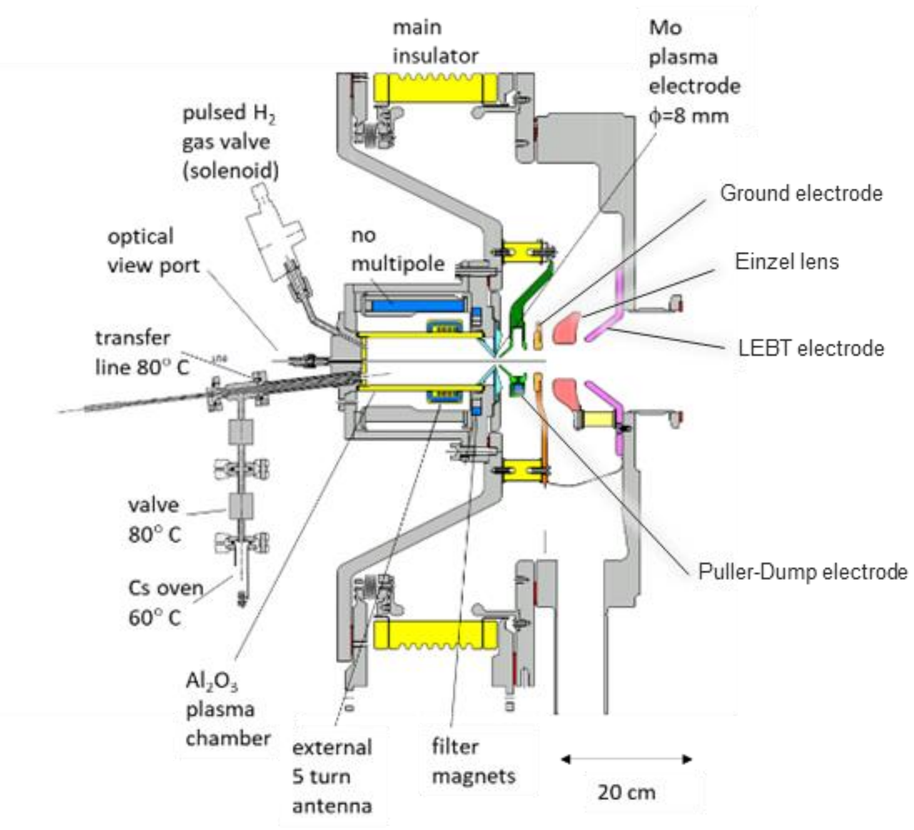


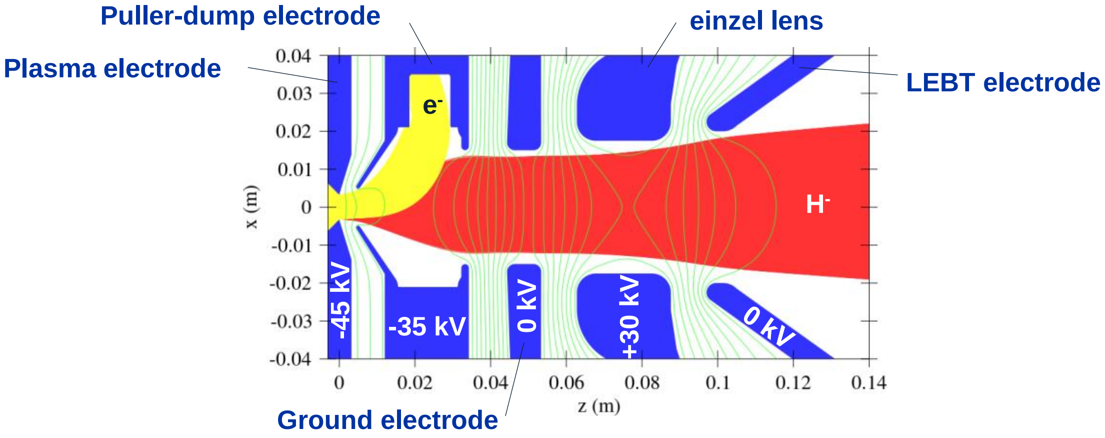


From 2020, Linac4 is the new injector of CERN's proton accelerator complex.

The low-energy part of Linac4 consists of a 45 keV H^- ion source, a low-energy beam transport (LEBT), and a radio-frequency quadrupole (RFQ) that accelerates the beam to 3 MeV.

Linac4 operational source until 2023: IS03



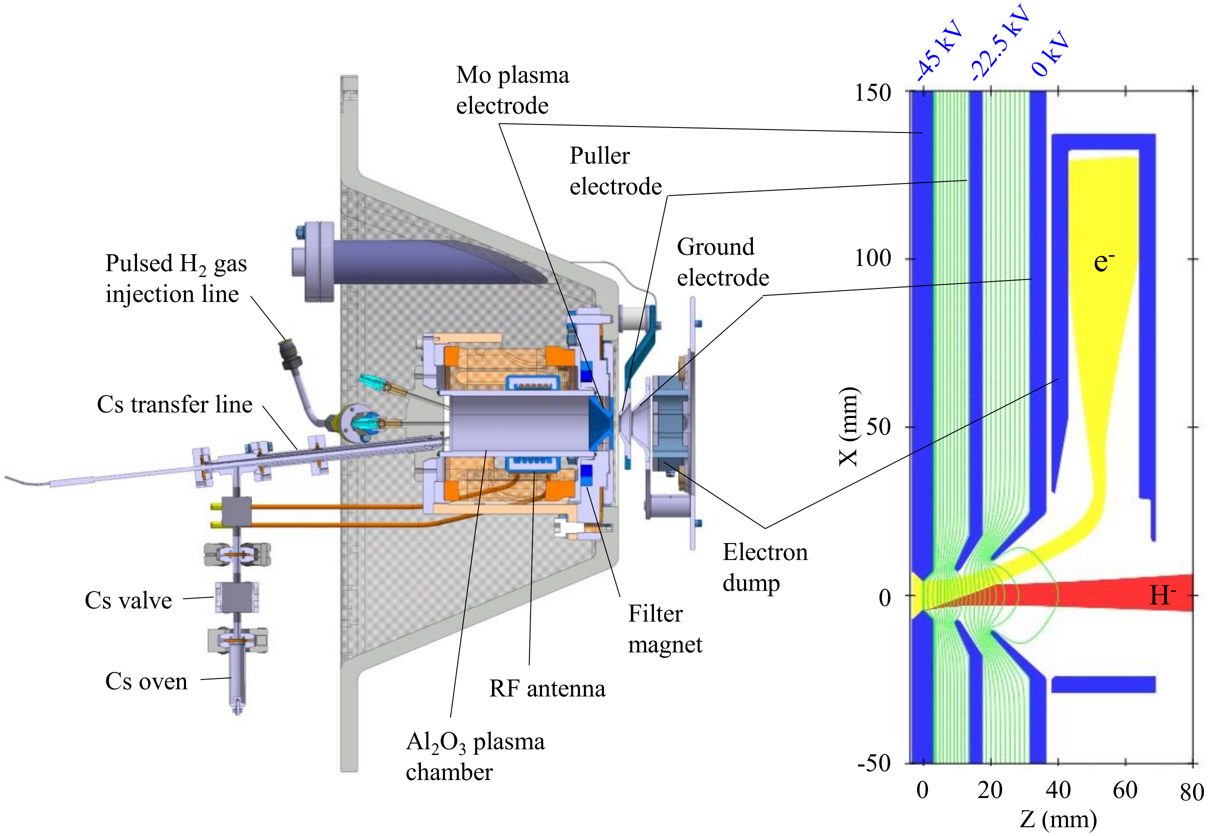


- 2 MHz RF H^- ion source with continuous caesiation.
- Volume and surface H^- production at 45 keV energy.
- Pulsed gas injection.
- Beam pulse length from source 850 µs, 600 µs after the RFQ, repetition rate 0.83 Hz.
- Pulse-to-pulse beam current stability <1% (1 rms).
- Current Linac4 operation: 35 mA from source, 27 mA after the RFQ.
- Autopilot software for beam stability by regulating the RF power.
- **Main limitation: extracted beam emittance exceeding the acceptance of the RFQ, resulting in low beam transmission.**

Ref.: D. Noll, J.-B. Lallement, and A. Lombardi, “Beam characterization of Linac4’s IS03”, CERN, Geneva, Switzerland, Rep. CERN-ACC-Note-2019-014, 2019.

New source extraction system: IS04

Source review in 2020 with an objective to reach 45 mA beam reliably out of the RFQ in 2023, after demonstration at the Linac4 source test stand in 2022.



- IS04 has the **same plasma generator** as IS03: plasma chamber, RF system (amplifier and antenna), gas injection system, and caesiation system.
- IS04 has a **different extraction and electron dumping scheme**:
  - **Simplified design** with only plasma, puller, and ground electrodes.
  - **Eliminated puller-dump and einzel lens**, causing emittance growth. Einzel lens was also the source of HV breakdowns causing downtime. **One less power** supply improving the reliability and the availability.
  - **Shorter** extraction system by 6 cm.
  - **Co-extracted 45 keV electrons** onto a dedicated dump.
- IS04 extraction system **design is optimized for 50 mA** H^- beam.

Ref.: G. Bellodi, H. J. De Grandsaignes D'Hauterives and D. Noll, "Linac4 source extraction re-design for higher current operation", CERN, Geneva, Switzerland, Rep. CERN-ACC-Note-2021-0009, 2021.

Simulations of extraction in IBSimu: IS03 case

IBSimu simulates plasma extraction, electron dumping, and space-charge dominated ion transport.

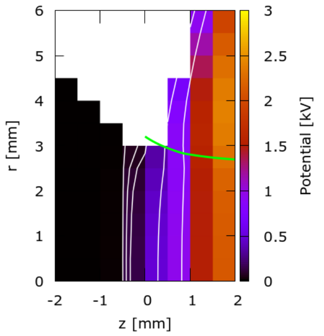
At the plasma meniscus, charge density changes on the scale of Debye length.

- ➢ Mesh resolution in this region (around plasma electrode aperture) should be in the order of λ_D
  - ➢ 10 µm rz mesh around meniscus, 500 µm 3D mesh elsewhere.

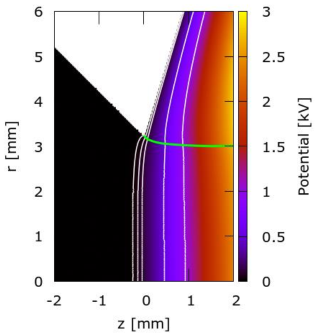
Approximations made in plasma extraction model, neglecting the magnetic field and collisional effects near the plasma sheath region.

- ➢ Underestimation of the charge density near the plasma sheath
  - ➢ Scale up the charge density by 30% to match simulated and measured emittances.

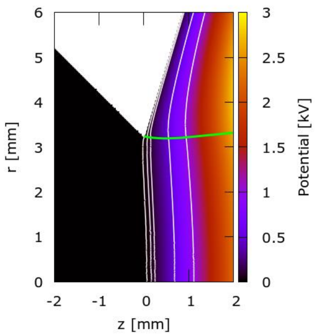
For IS04, despite having the same plasma generator as IS03, the same approach didn't lead to a good agreement between the measured and simulated emittances, which is 5-8 times smaller (~0.05 mm.mrad, rms, norm.).



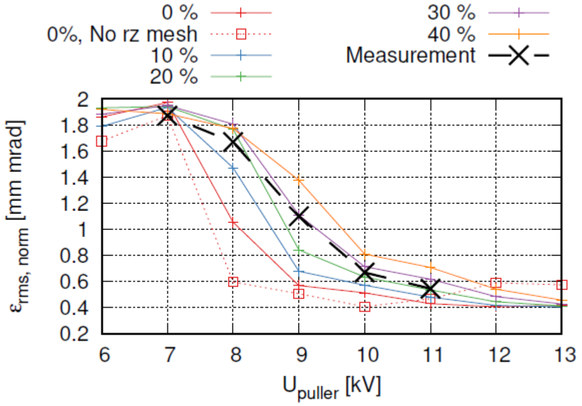
3D mesh 500 µm
w/o charge density scaling



rz mesh 10 µm
w/o charge density scaling



rz mesh 10 µm
30% charge density scaling



Ref.: D. Noll, J.-B. Lallement, and A. Lombardi, "Beam characterization of Linac4's IS03", CERN, Geneva, Switzerland, Rep. CERN-ACC-Note-2019-014, 2019.

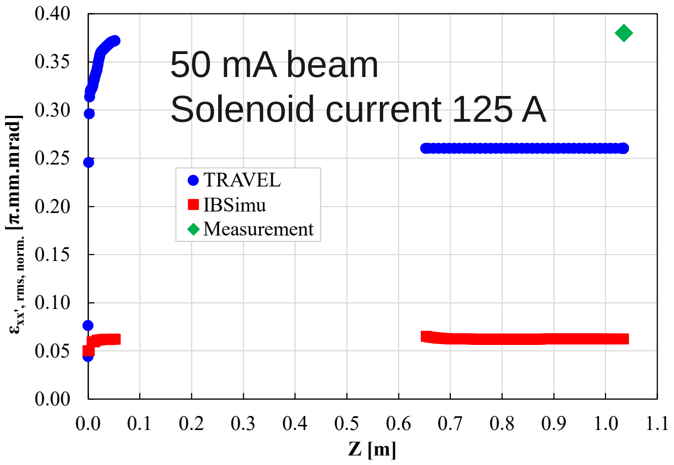
Ref.: T. Kalvas and J. Lettry, "Deviation of H- beam extraction simulation model", in Proc. AIP Conf., 2052 (2018) 050007, Contribution to NIBS 2018.

Simulations of IS04 extraction: TRAVEL vs IBSimu

A different approach:

- Particle distribution generated in IBSimu at the plasma electrode aperture and used as input in TRAVEL code.
- Particles tracked through electric field map of extraction electrodes and magnetic field map of the solenoid in TRAVEL.
- Simulations of a fully stabilized beam with full space-charge in the extraction and fully space-charge compensated beam in the LEBT after 200 μs transient.

Further study is ongoing to correctly assess if this difference comes from the boundary conditions used at the plasma meniscus and extraction bore region or if the space-charge has been correctly considered.

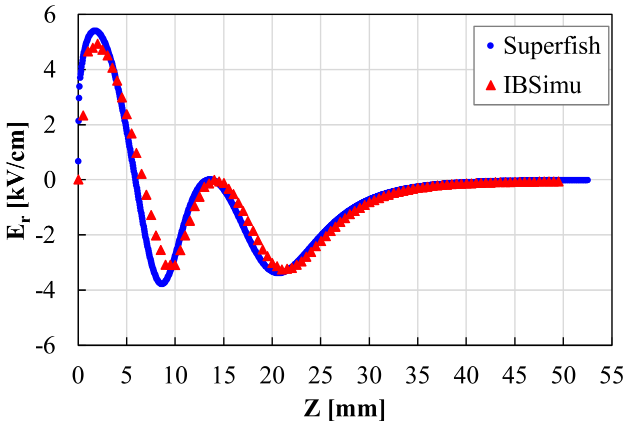


Emittance in TRAVEL much higher than in IBSimu but still 30% lower than measured.

Emittance evolution inside solenoid not shown.

Most of the emittance growth in TRAVEL happens in the first 10 mm of the extraction.

Differences in the radial electric field component between IBSimu and Superfish for the same geometry.

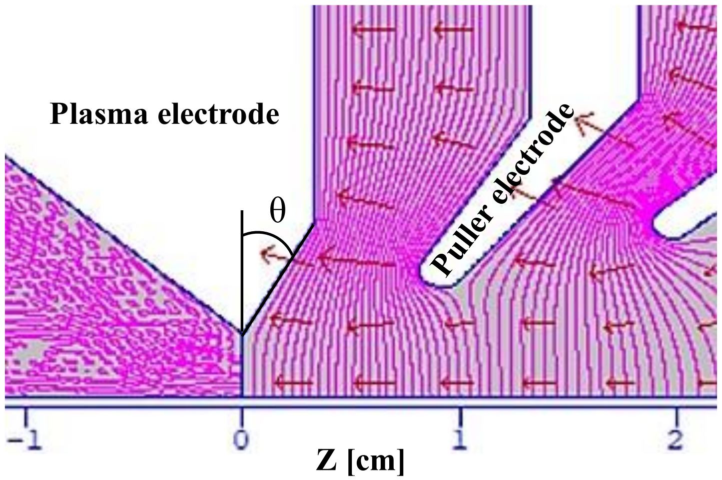


Simulations of IS04 plasma electrode angle and puller voltage effect on emittance

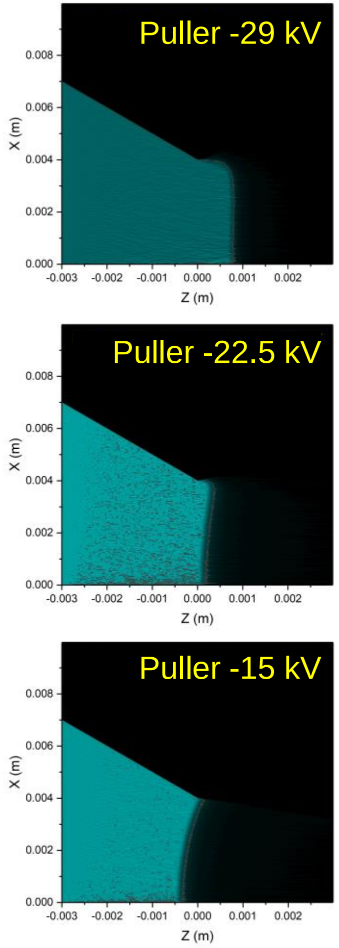
For a given puller voltage, plasma electrode angle affects the plasma meniscus shape and initial focalization of the beam.

Simulate and test 25° and 45° electrodes to compare with the nominal 35° electrode:

- Up to 20% lower emittance with 45° electrode; confirmed by measurements.
- 45° electrode retained for all further studies and tests.



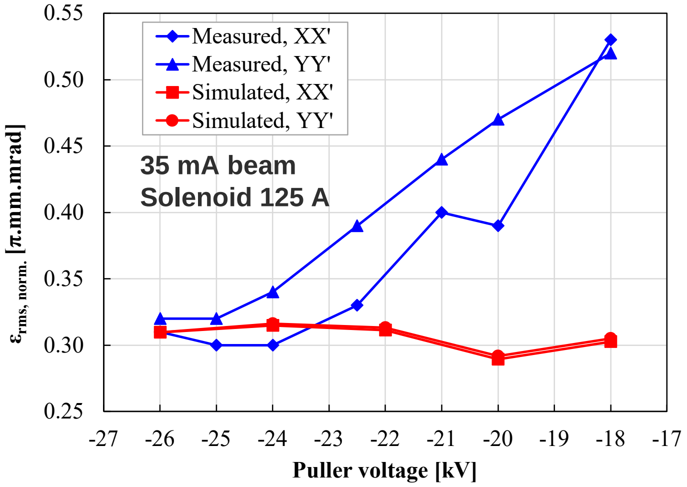
Meniscus vs puller voltage



For a given distance between plasma and puller electrodes, puller voltage affects the plasma meniscus shape and initial focalization of the beam.

Simulate and test puller voltage effect on emittance:

- Simulations show 7% lower emittance for -20 kV.
- Emittance measurements show smallest emittances between -26 kV and -24 kV.
- RFQ transmission was max for -24 kV.



Linac4 source test stand

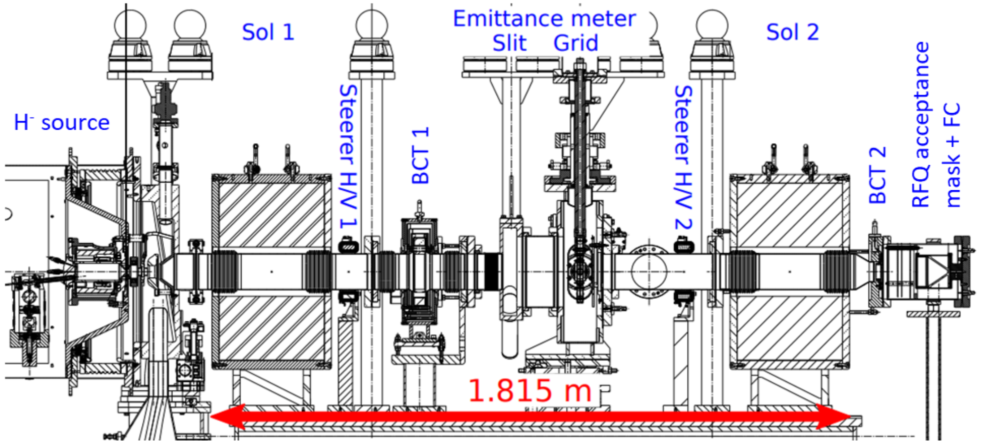
Purpose

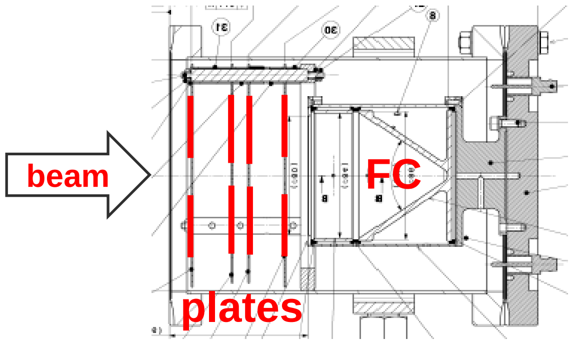
- H^- source development and tests.
- Validation of Linac4 spare source units.
- Low-energy material irradiation.
- Test of Linac4 spare RFQ in 2024.

Layout

- Similar to Linac4 source and LEBT, with two solenoids and two H&V steerers.
- RFQ acceptance mask* with integrated FC at the place of the RFQ.
- Slit-grid emittance meter.
- Two BCTs for beam current measurements.
- Gas injection in the LEBT for space charge neutralisation.

**Set of 4 plates with square hole, which define the transverse acceptance of the RFQ. Particles reaching the FC are within the transverse acceptance of the RFQ.*
RFQ acceptance mask only discriminates in transverse planes, therefore the beam transmission is higher compared to the transmission through the RFQ.





RFQ acceptance mask

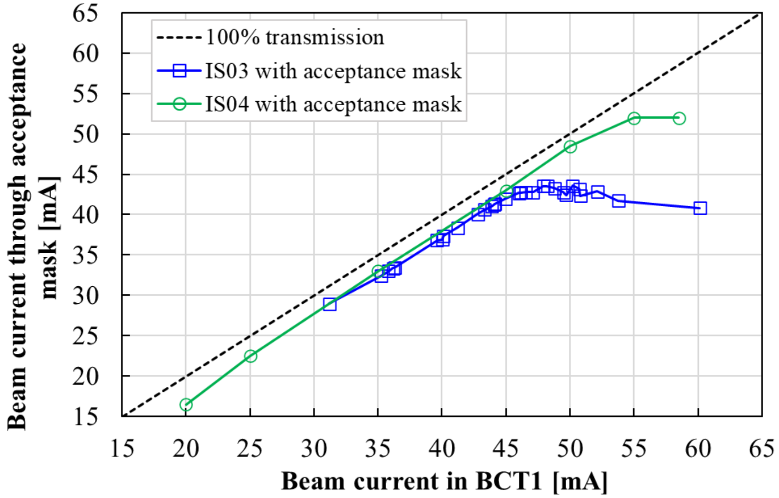
Measurements at the test stand with IS04

Source and extraction optimization

- Plasma electrode angle, puller voltage.
- RF antenna position.
- Gas injection timing.

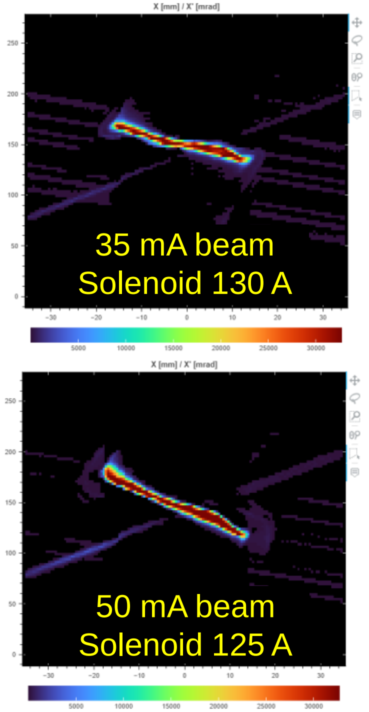
LEBT optimization

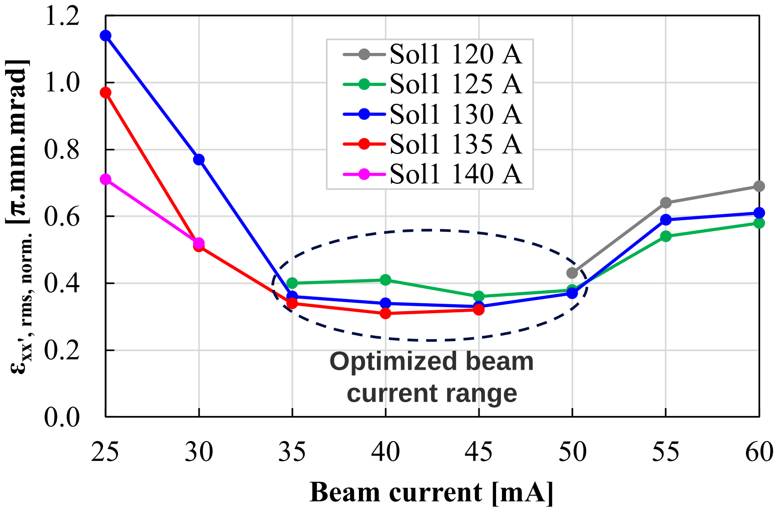
- Solenoid focusing and beam steering for max beam transmission through RFQ acceptance box (matching to the RFQ).



Emittance measurements

- Not possible for the matched optics as beam size larger than the slit range of ±35 mm.
  - ➢ Need stronger solenoid focusing
    - ➢ Emittances may not be fully representative of what enters the RFQ.





Measurements at Linac4 with IS04

Tests with the RFQ up to 3 MeV in Nov. 2021.

RFQ V=3.2 MV (operational reference value)

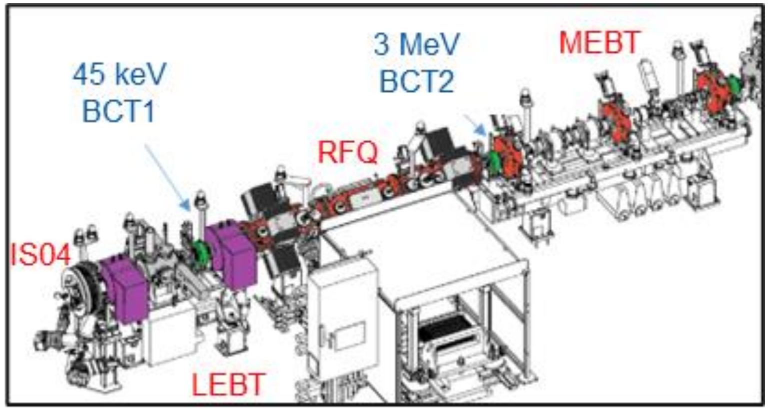
- Comparable performance for beam current <40 mA but considerably better above that
- Higher saturation current of ~50 mA with IS04 compared to ~40 mA with IS03.
- 38 mA out of the RFQ for 50 mA input.
- Solenoid polarity influences the beam transmission (up to 10%).

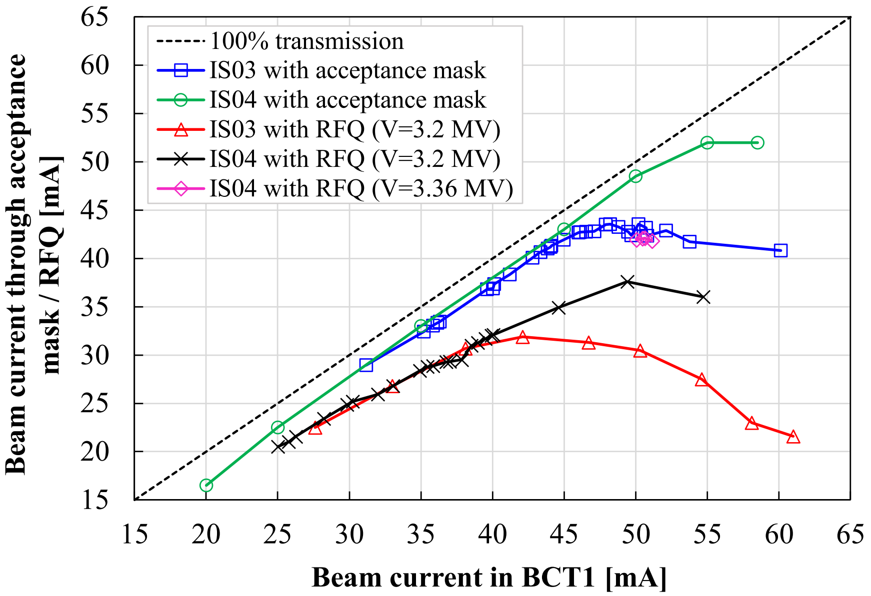
RFQ V=3.36 MV (5% increase)

- 42 mA out of the RFQ for 50.4 mA input (83% transmission).
- RFQ operational voltage not optimum for max beam transmission and limits both transverse and longitudinal acceptance.

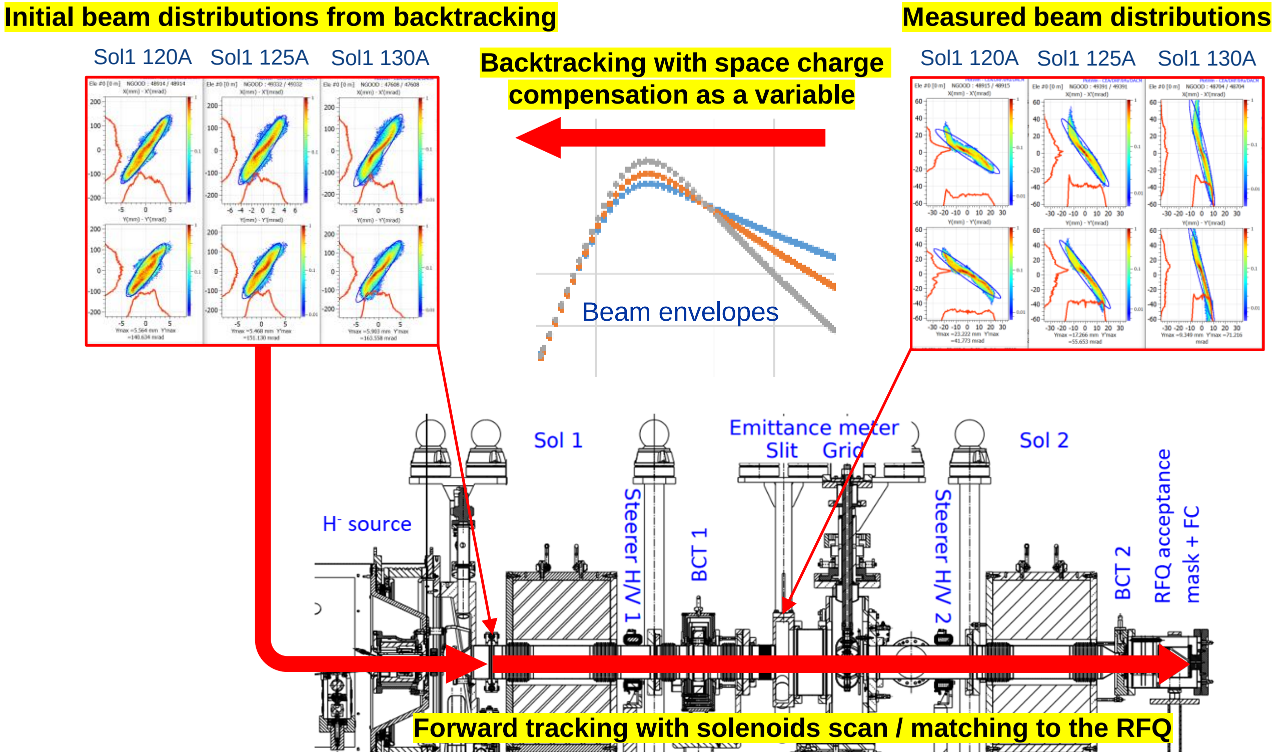
After a successful reliability run at the test stand in 2022, it has been decided to replace IS03 by IS04 as the operational source of Linac4 from January 2023.

Low-energy front-end in the Linac4 tunnel

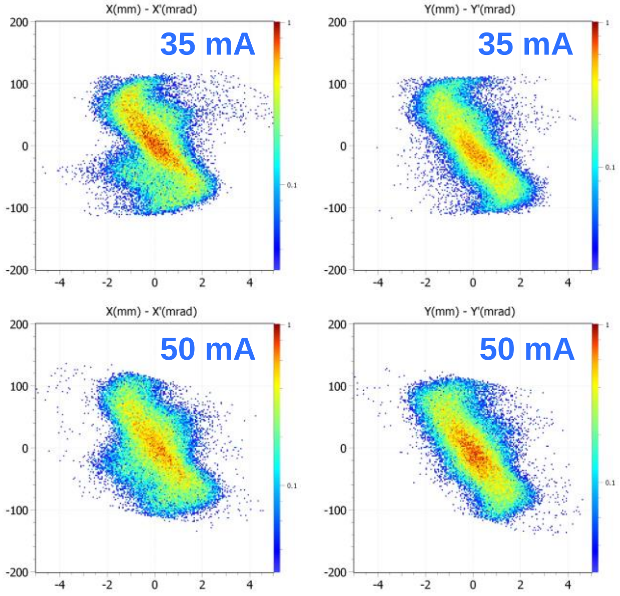




Backtracking of measured beam distributions



- For a given beam current, the minimum mismatch factor was found for very different SCC degrees in the H and V planes (98/85%), which is not what is expected.
- 4D emittance difference was minimised instead
  - SCC of 85% for 35 mA beam
  - SCC of 97% for 50 mA beam.



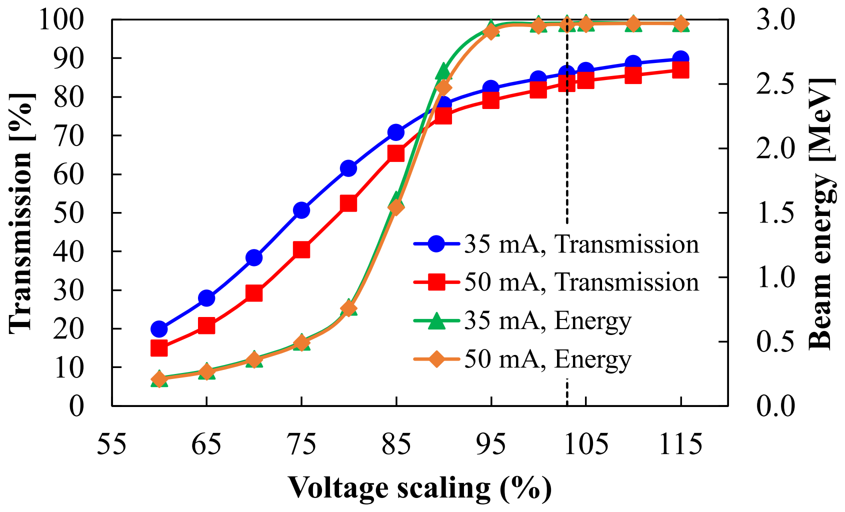
Matched transverse beam distributions at the RFQ matching plane

- With present emittance meter not possible to measure the beam distribution directly after the source.
- Beam distributions measured in the LEBT are backtracked to the entrance of the first solenoid field map, while varying the space-charge compensation degree (SCC) and minimising the differences between the three measured distributions.

Simulations of the RFQ

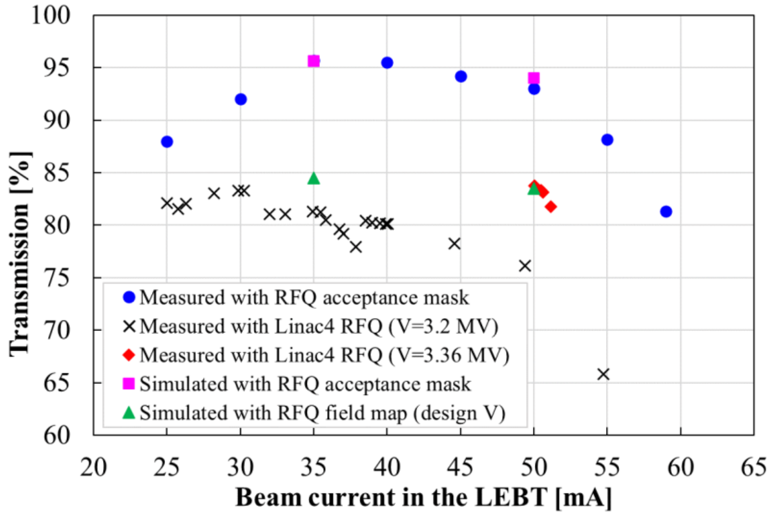
Backtracked beam distributions are used to simulate the beam transport through the LEBT, matching to the RFQ, and tracking through the RFQ field map.

Simulated beam transmission and mean energy at the RFQ exit as a function of the RFQ vane voltage.



The dashed line corresponds to the design inter-vane voltage of 79 kV.

Simulated and measured beam transmission through RFQ acceptance mask and Linac4 RFQ.



Simulated transmission with acceptance mask for 35/50 mA beam matches the corresponding measurements, while the simulation with 50 mA beam through the RFQ at the design voltage matches the measurement with the RFQ voltage 5% higher than the operational reference 3.2 MV.

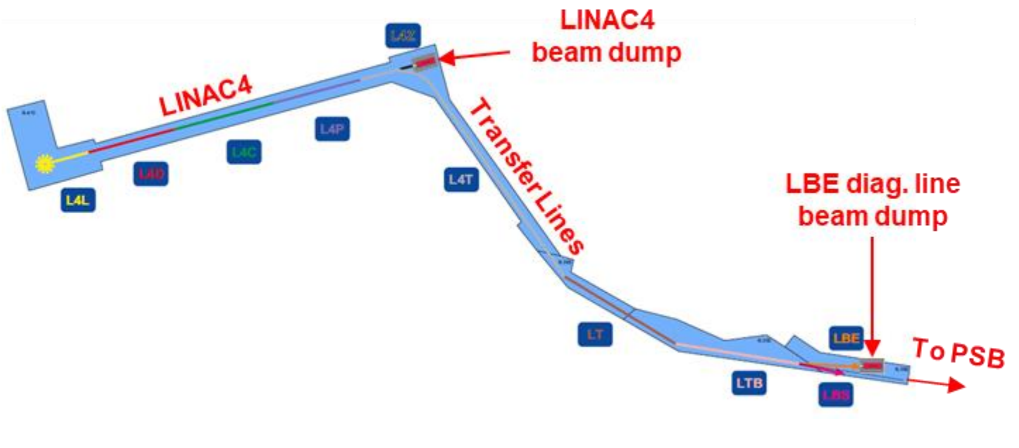
The vane voltage of the RFQ at Linac4 was carefully RF calibrated during tuning and commissioning, but a lower than expected amplitude would explain the differences in beam transmission.

Operation and high-intensity tests at Linac4

Operation

IS04 source can reliably produce up to 50 mA of H^- beam. However, the **operational beam current from the source remains 35 mA (27 mA out of the RFQ)**, as this covers the present beam intensity needs.

The pulse-to-pulse beam stability from the source is typically in the order of 0.5-0.7% (rms) and the **source availability so far this year is 99.9%**.



Beyond operation

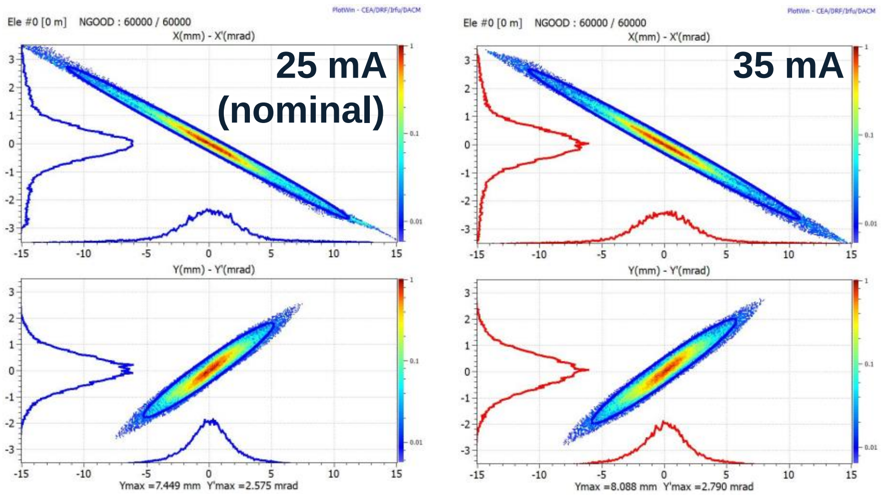
There is an interest from Physics Beyond Colliders Working Group at CERN to explore the capabilities of the injector complex, particularly in terms of higher beam intensity for future needs (e.g., ISOLDE, experiments) and flexibility in beam production scheme.

Dedicated high-intensity tests in 2023

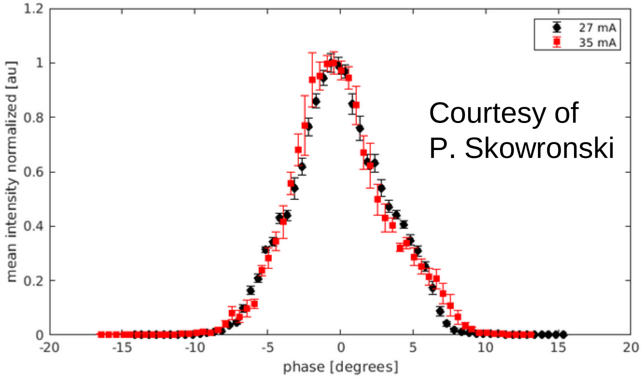
- Reproduced the performances obtained in 2021.
- Sent 40 mA beam to the end of the linac at 160 MeV and measured its characteristics.
- Sent 40 mA beam to the diagnostics line close to the PS Booster (PSB) injection and measured its characteristics.
- Prepared for injecting higher peak current into the PSB.

Results from high-intensity tests at Linac4

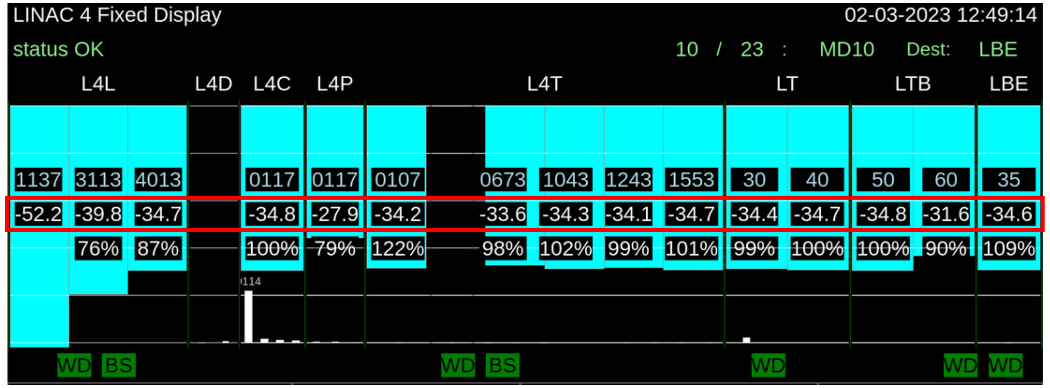
- 52 mA from source, 40 mA from the RFQ (operational voltage), and 35 mA in the rest of the linac and transfer lines.
- Higher RFQ voltage would improve the beam transmission.
- RF power of the cavities is on the limit; chopping is needed at 3 MeV.
- Bunch length like the one with the nominal beam current.
- 35 mA beam emittances measured at the LBE diag. line:
  - $\varepsilon_{xx'}$=0.27 mm.mrad (rms, norm.), $\varepsilon_{yy'}$=0.26 mm.mrad (rms, norm.).



Beam distributions measured in LBE



352 MHz bunch length measured at the end of the linac



Summary and outlook

Beam current of 35 mA from the source and 27 mA from the RFQ is sufficient for present needs.
IS04 can provide 50 mA, which is sufficient margin for possible near- / mid-term intensity needs, which would first require some hardware upgrade, e.g., RF klystrons.

The focus for the source development is now mostly on the operation needs.

- Improve stability and reliability, which is mainly dictated by the gas injection system and the pulsed valve stability.
- Considering flexible pulsing of the source with a variable cycle period (900 ms – 2.5 s) in view of increasing beam availability and accelerator complex flexibility/efficiency for different users.
  - Challenging for the source stability → considering continuous gas injection.
    - Would also be beneficial for source availability in view of its potential use for a muon collider with a high repetition rate of 50 Hz.

In parallel, continue studies of beam extraction and transport to further reduce the emittance and increase intensity.

- Ongoing effort to improve IBSimu extraction simulation model.
- Considering other codes (e.g., NINJA-BFX) capable of simulating plasma conditions and providing more realistic beam distribution as an input to TRAVEL simulations.
- Study effect of the solenoid polarity on the emittance and beam transmission through the RFQ.
- Study space-charge compensation along the LEBT and close to the RFQ injection.

Simulations and measurements have shown that the RFQ vane voltage may not be the optimum and that the typical beam transmission plateau above the nominal voltage has not been reached.

- Possibility to further analyse at the test stand with the spare Linac4 RFQ.
- After the Linac4 spare RFQ is tested and validated at the test stand, we will possibly have opportunities to test new source developments directly with the RFQ.

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