# LINAC4 $H^-$ source studies and future developments

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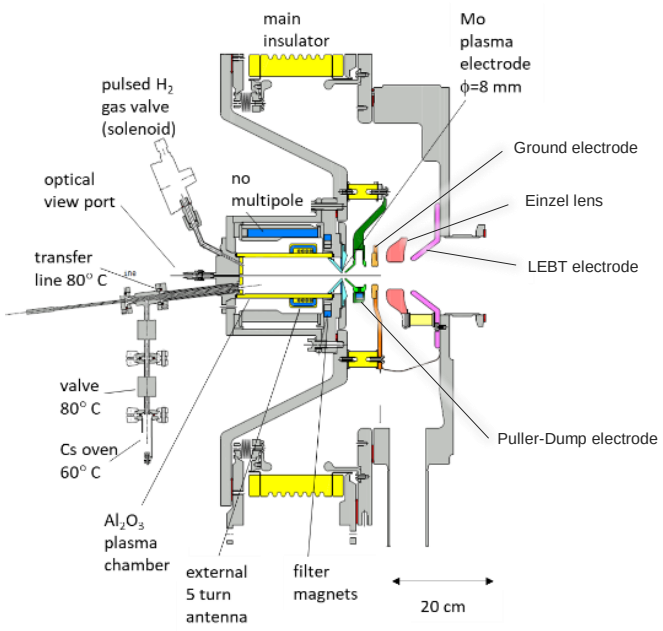
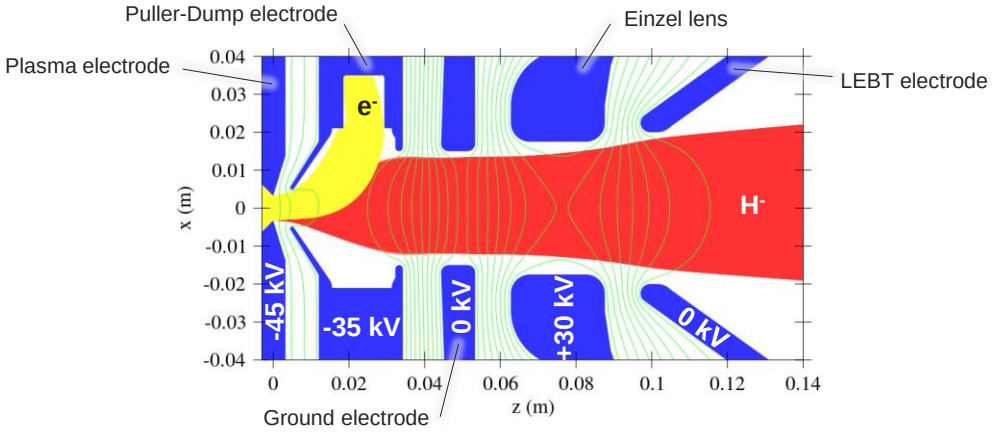
# Outline

- New source extraction system
- Measurements at the test stand
- Measurements at LINAC4
- High intensity MDs
- Future plans

# LINAC4 operational source (IS03) until 2023



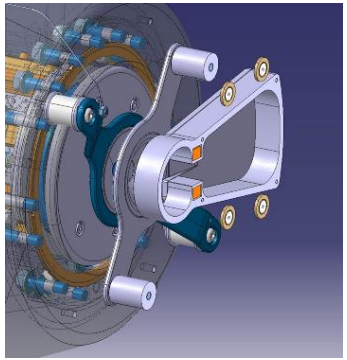



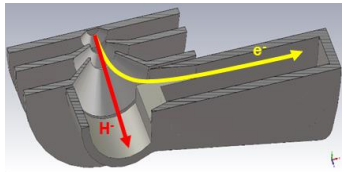

- 2 MHz RF $H^-$ ion source with continuous cesiation
- Volume and surface $H^-$ production at 45 keV energy
- Pulsed gas injection
- Beam pulse length from source 850 µs, 600 µs after the RFQ, 0.83 Hz rep. rate
- Pulse-to-pulse beam current stability <1% (1 sigma)
- Current LINAC4 operation: 35 mA from source, 27 mA after the RFQ
- Autopilot software for beam stability by regulating the RF power

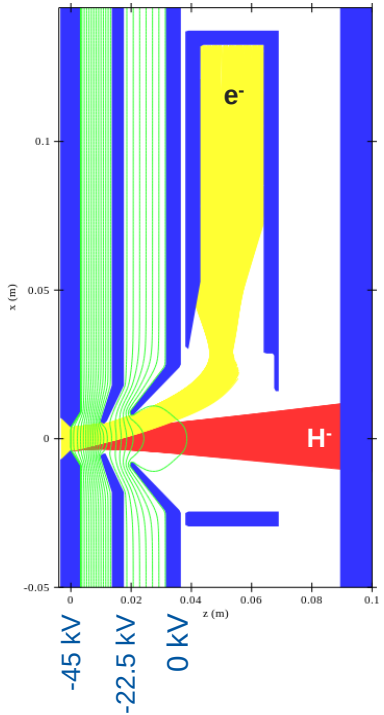
# New source extraction system (IS04)

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

- IS03 and IS04 have identical plasma generators: plasma chamber, RF system (amplifier and antenna), gas injection system, and cesiation system.
- IS04 has a different extraction and electron dumping scheme:
  - Simplified design with only plasma, puller, and ground electrodes.
  - Eliminated puller 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.
  - Coextracted 45 keV electrons onto a dedicated dump.
- IS04 extraction system design is optimized for 50 mA.

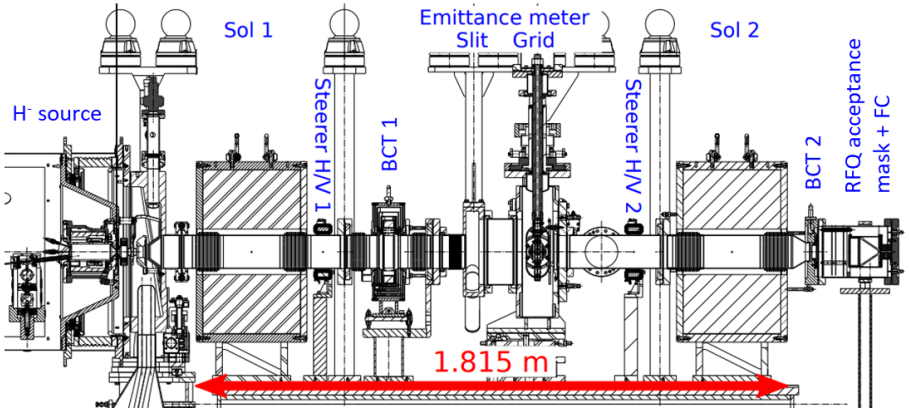


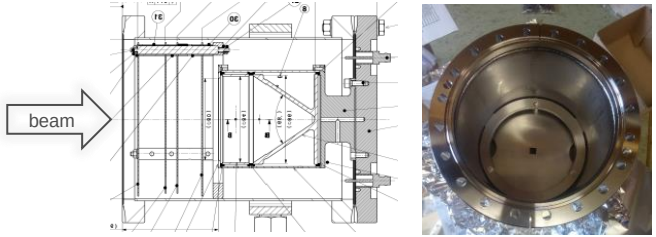


# LINAC4 source test stand

- Purpose
  - $H^-$ source development and tests
  - Validation of LINAC4 spare source units
  - Material irradiation
- 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



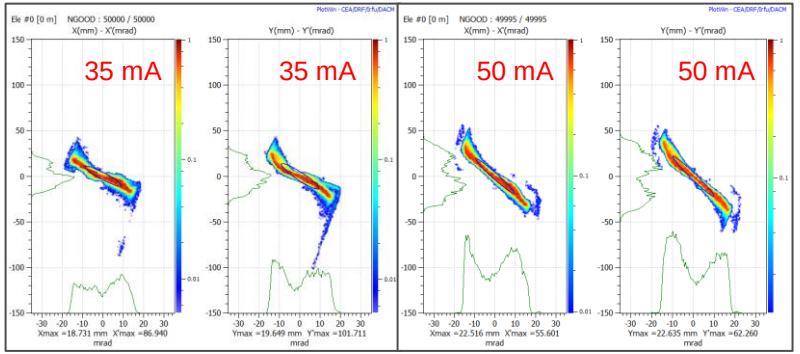



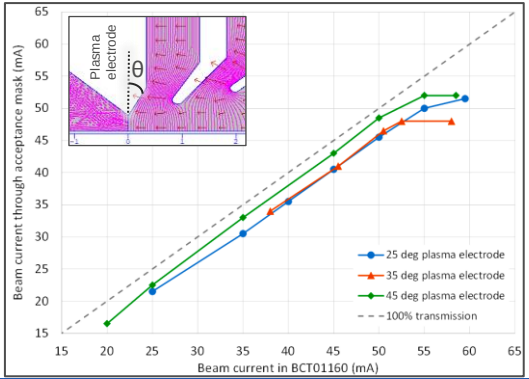

RFQ acceptance mask

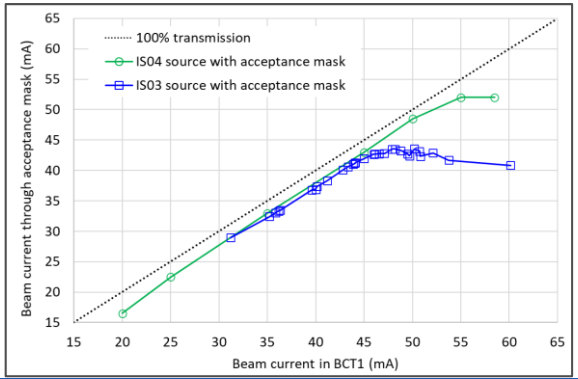
**Set of 4 plates with square hole, which define the transverse acceptance of the RFQ. Particles reaching the FC are within the transverse acceptance of the RFQ.*

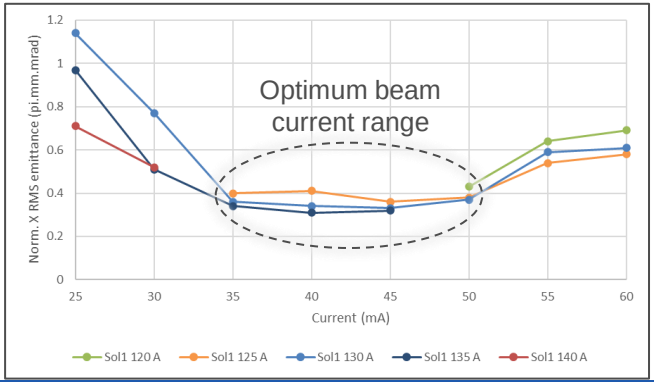
# Measurements at the test stand with IS04

- Plasma electrode angles
- RF antenna position
- Puller voltage
- Gas injection start timing and duration
- Emittance measurements for beam currents 25-55 mA
- LEBT optimization (magnets and space charge compensation) for max beam transmission through the RFQ acceptance mask



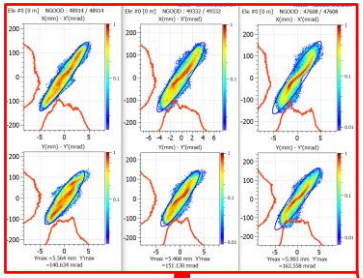



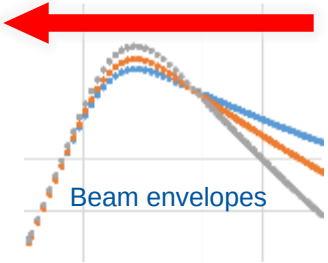
# Backtracking of measured beam

Initial beam distributions from backtracking

Sol1 120A Sol1 125A Sol1 130A

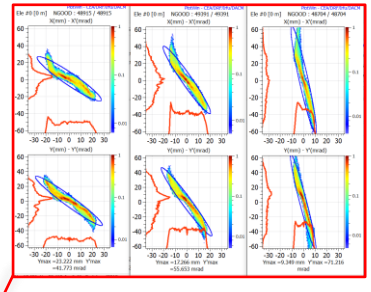


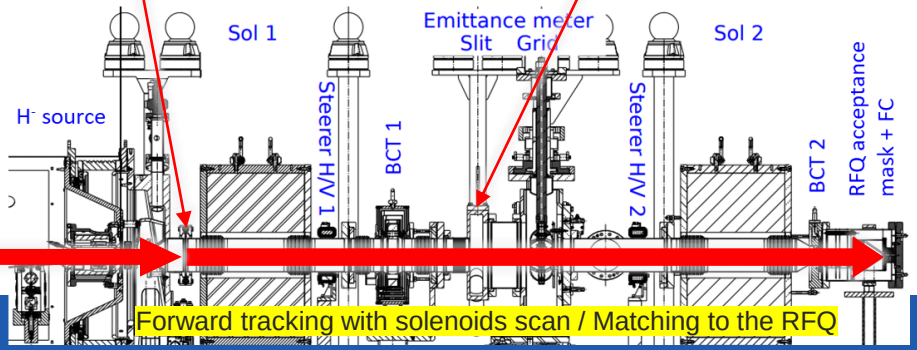
Backtracking with space charge compensation as a variable




Measured beam distributions

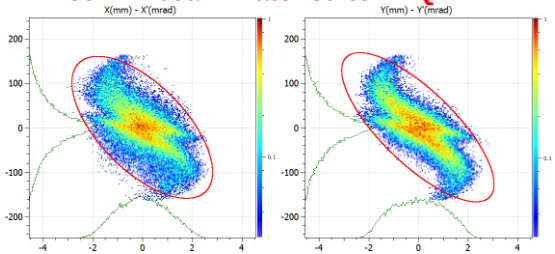
Sol1 120A Sol1 125A Sol1 130A





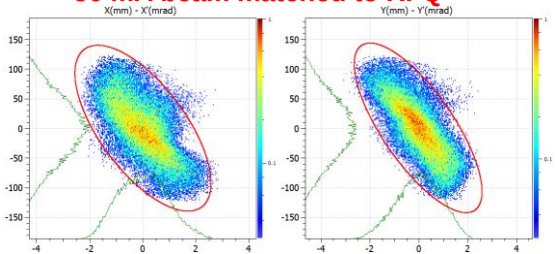

Forward tracking with solenoids scan / Matching to the RFQ

**35 mA beam matched to RFQ**




$\varepsilon_{xx'}$ = 0.39 π.mm.mrad (rms, norm.)
$\varepsilon_{yy'}$ = 0.34 π.mm.mrad (rms, norm.)
Transmission through RFQ 84.2%

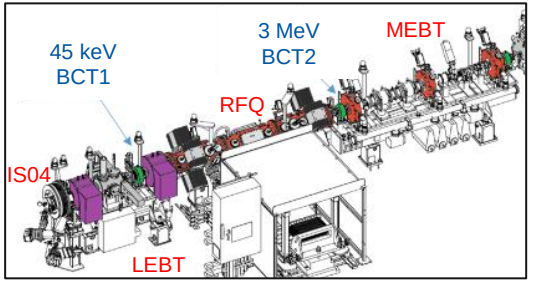
**50 mA beam matched to RFQ**

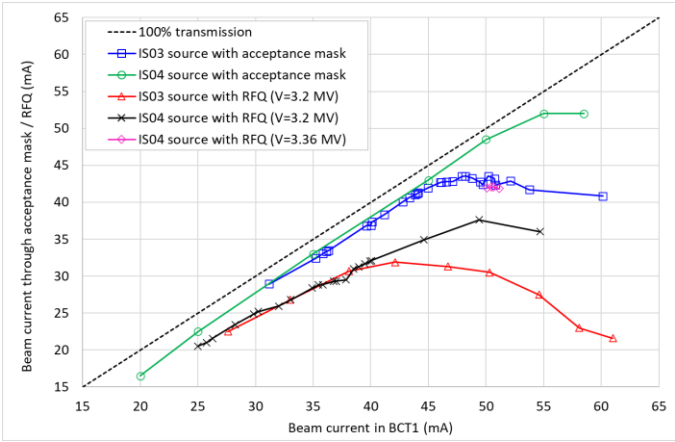



$\varepsilon_{xx'}$ = 0.31 π.mm.mrad (rms, norm.)
$\varepsilon_{yy'}$ = 0.27 π.mm.mrad (rms, norm.)
Transmission through RFQ 89.8%

# IS04 measurements at LINAC4

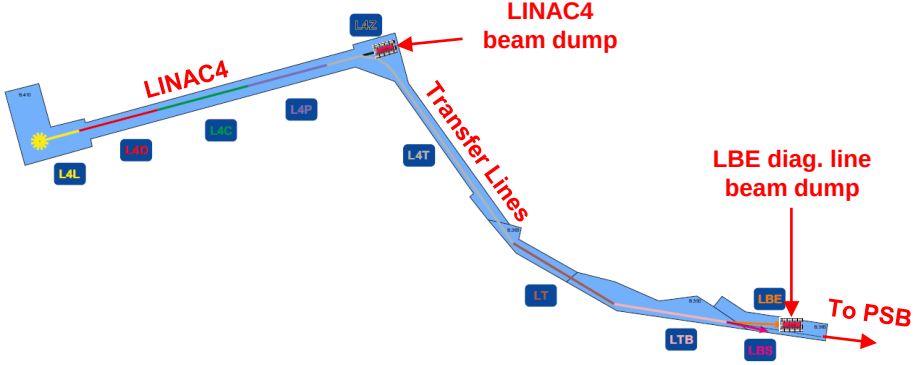
- Measurements with the RFQ up to 3 MeV in Nov. 2021
- RFQ V=3.2 MV (operational value)
  - Comparable performance for beam current <40 mA but considerably better above that
  - Higher saturation current (~50 mA) compared to IS03 (~40 mA). 38 mA out of the RFQ for 50 mA input.
- RFQ V=3.36 MV (5% increase)
  - 42 mA out of the RFQ for 50.4 mA input (83% transmission)
  - RFQ operational voltage not optimum for max beam transmission (known) 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 LINAC4 operational source from Jan. 2023.



# High intensity MDs with IS04 at LINAC4

- IS04 source can reliably produce up to 50 mA $H^-$ 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.
- Nevertheless, there is an interest from Physics Beyond Colliders Working Group at CERN to explore the capabilities of the injector complex, in particular in terms of higher beam intensity for future needs (e.g., ISOLDE, experiments) and flexibility in beam production scheme.

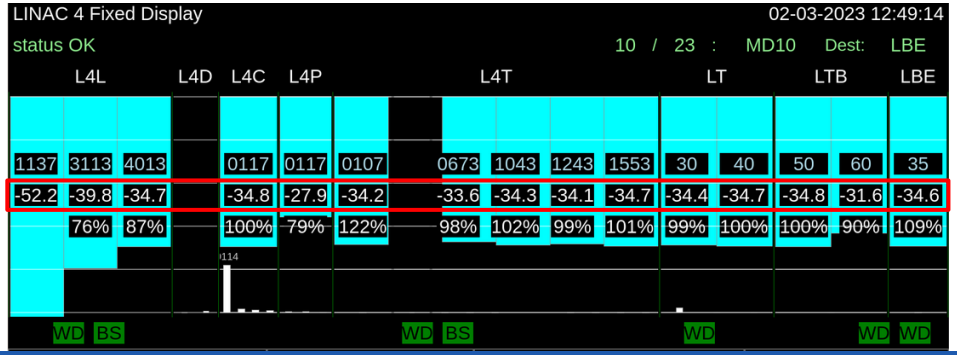


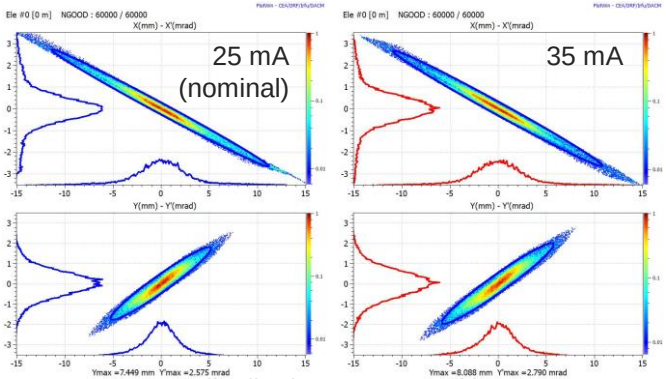

**Dedicated high intensity MDs in Feb., Mar., and May 2023:**

- 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.

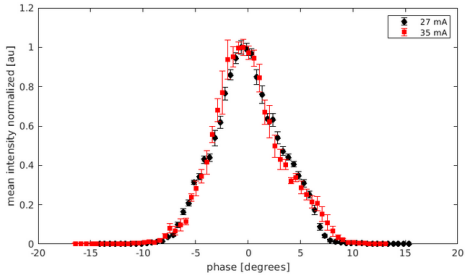
# Results from high intensity MDs

- 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
- 352 MHz 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.)
  - Well within PSB acceptance



Beam distributions measured in LBE



Bunch length measured in LBE

# Future plans

- Beam current of 35 mA from source and 27 mA from 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 – gas injection system/valve is the main contributor.
  - Considering flexible pulsing of the source with a variable cycle period (900 ms – 2.5 s) in view of increasing beam availability and accelerator flexibility/efficiency for different users – challenging for the source stability.
- In parallel, continue studies of beam extraction and transport to further reduce the emittance and increase intensity.
- 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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