Optimisation for pre-injectors for hadron therapy

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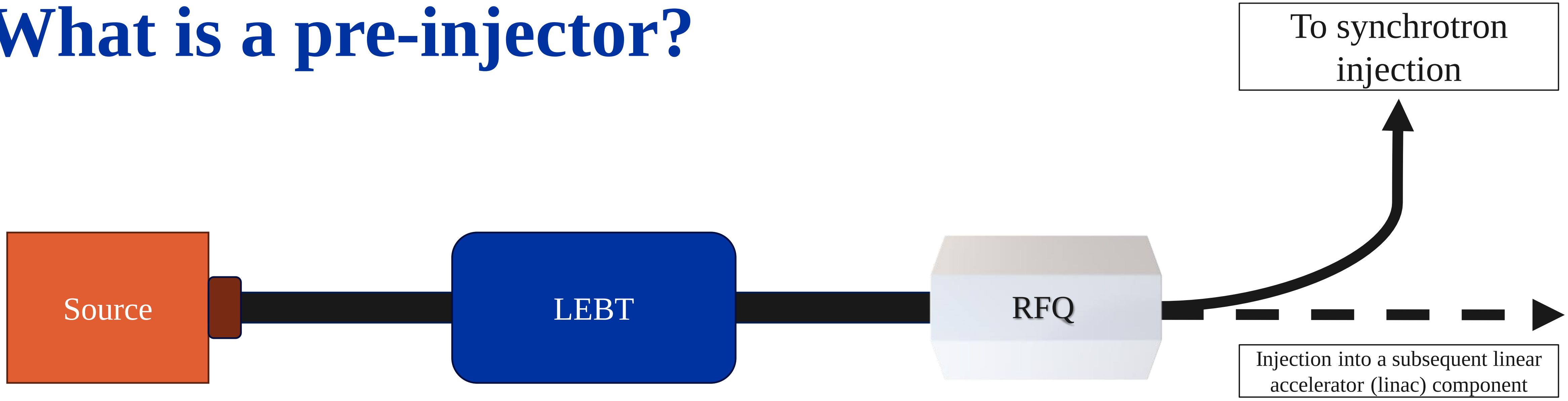
Hadron Therapy Workshop: status and perspectives, plans for next generation facilities

Outlook

- Definition of a pre-injector
- Pre-injectors in medical facilities
- CERN Linac 4
- Medical applications within ABP-HSL
- Study outline
- AM01:
  - Design
  - Beam optics
- Next steps

What is a pre-injector?

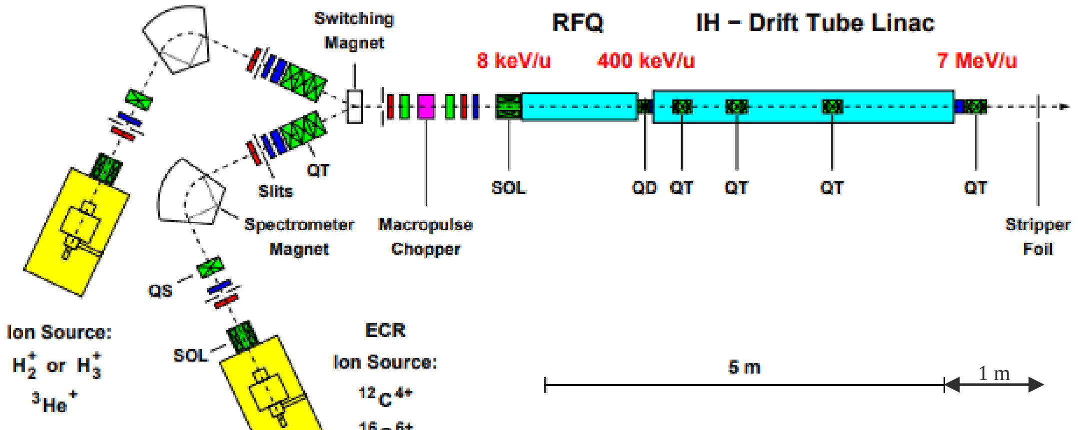


<u>Role</u>:

- Ions are generated in the pre-injector's ion source(s)
- The pre-injector ensures the ion beam has the correct energy, intensity, and stability for efficient downstream acceleration
- A precise ion beam in hadron therapy minimizes damage to surrounding healthy tissues
- Pre-injector optimization enhances **collimation**, reduces **energy spread**, and improves **energy deposition** at the *Bragg peak*, minimizing early-stage beam losses
- Reducing energy losses and improving system efficiency significantly **reduce operational costs** in hadron therapy facilities

Pre-injectors in medical facilities

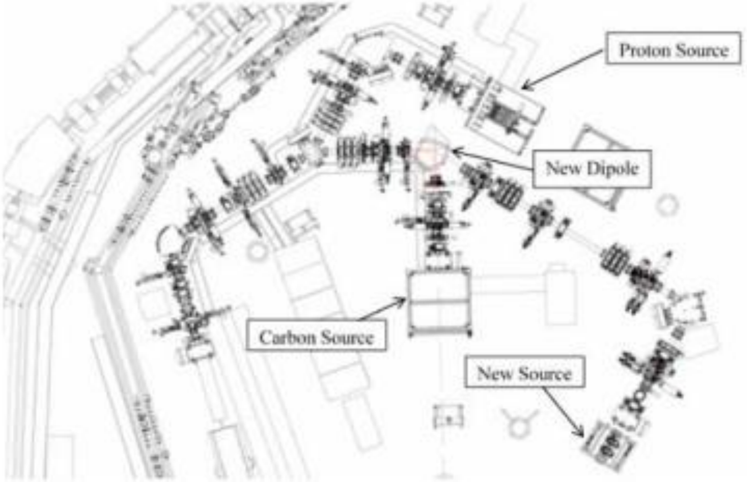
HIT*



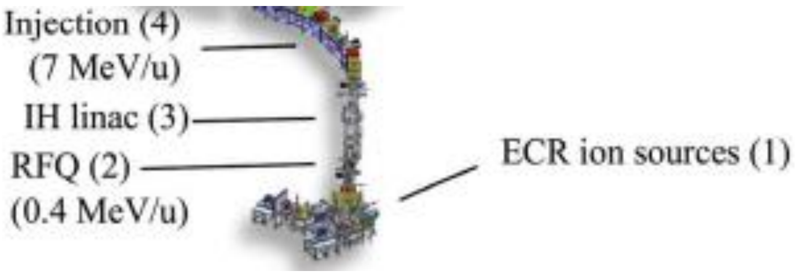
Total injector length ≈ 13 m (including sources, LEBT and stripper)

- Linac cavity size is inversely proportional to frequency; higher frequencies mean smaller cavities
- Typical operating frequency is 217 MHz; the aim is to shift to **higher frequencies** e.g., 750 MHz
- Smaller cavities reduce the pre-injector's footprint; essential in space-limited clinical settings
- Pre-injectors must adhere to strict safety and **reliability standards**, ensuring high uptime and minimal maintenance

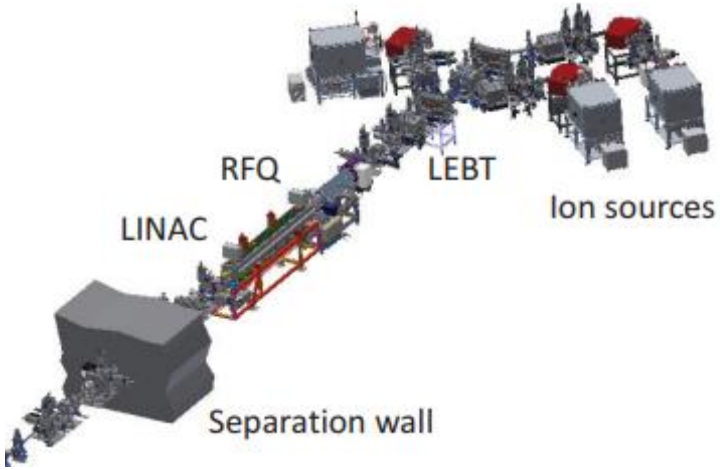
CNAO**



MIT***



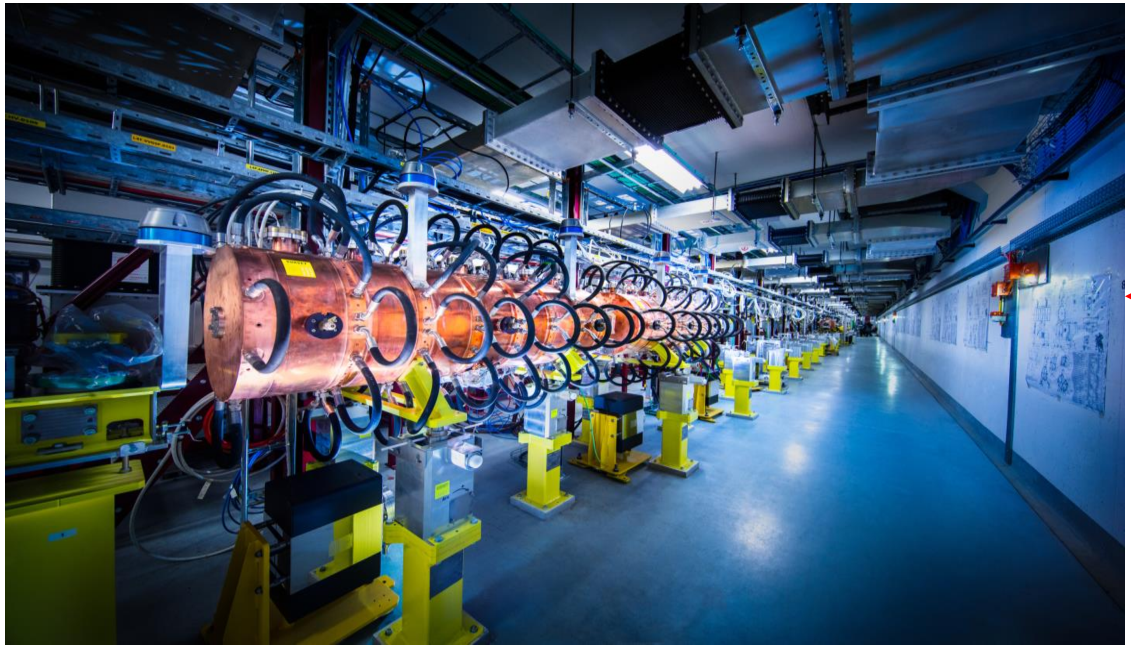
MedAustron****



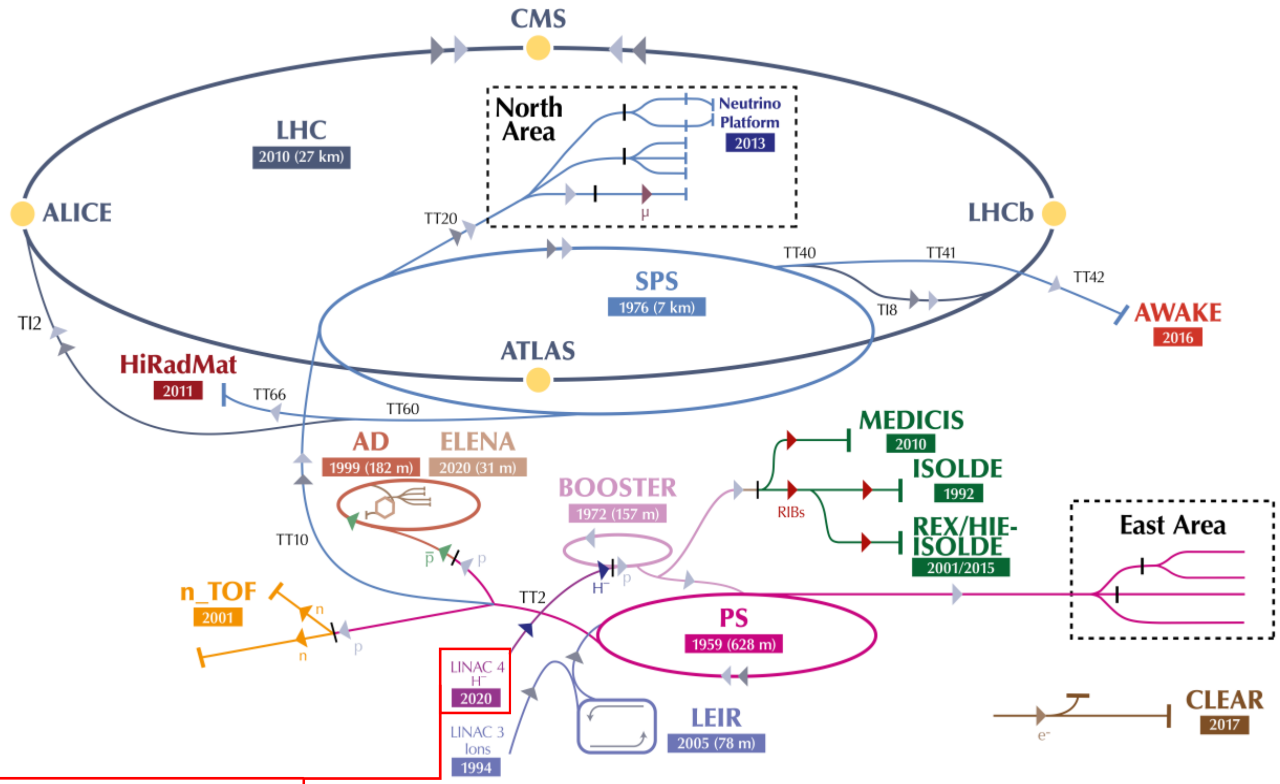
*https://accelconf.web.cern.ch/l00/papers/MOD10.pdf
**https://inspirehep.net/files/4d5e18d3c0e53566a4153231cff0aaeb
***https://inspirehep.net/files/4fc095b86d9620590d563cb034f9790d
****https://cds.cern.ch/record/2003190/files/thpme001.pdf

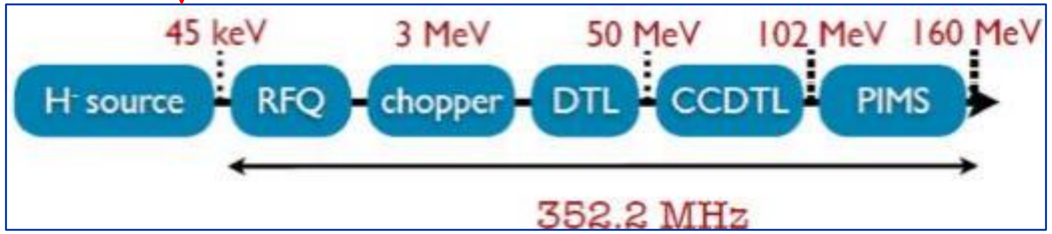
CERN Linac 4

- Linac4: 1st stage of the LHC injection chain
- Replacement for Linac2 during the 2019 – 2020 shutdown
- It became the source of proton beams for the LHC in 2020
- Negative hydrogen ions H^- (hydrogen atoms with an additional electron) accelerated to 160 MeV



The CERN accelerator complex
Complexe des accélérateurs du CERN





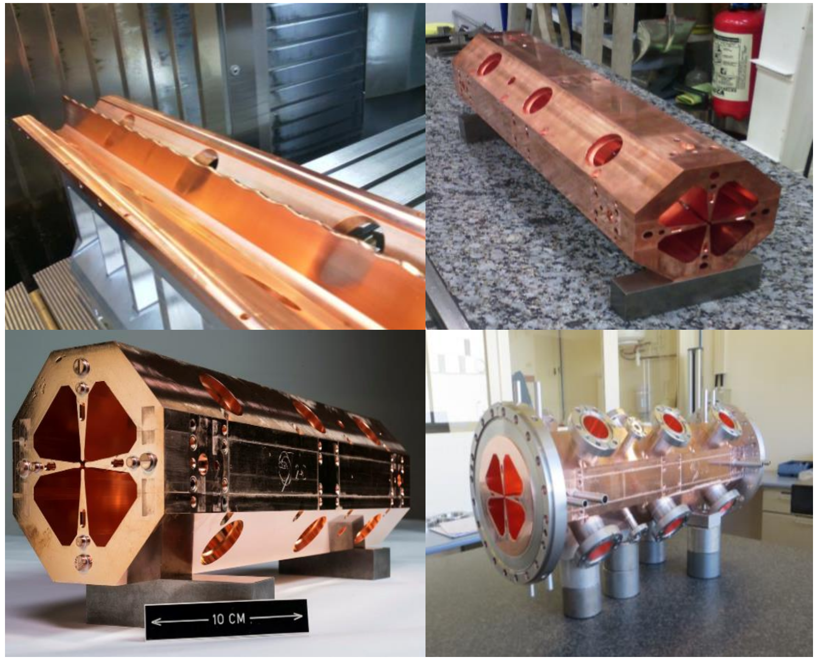
https://home.cern/science/accelerators/linear-accelerator-4

Medical Applications within ABP-HSL

LiGHT – Linac for Image Guided Hadron Therapy

Foundation for:

- LINAC-based hadron-therapy facility:
  - compact 750 MHz RFQ design based on Linac 4 expertise
  - use: injector to bunch, focus and accelerate the beam up to 5 MeV within 2 m
  - peak RF power: 400 kW

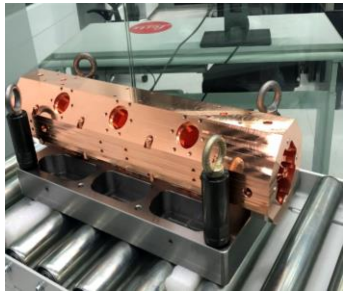


Copy for medical facility:

- Built in Italian industry
- First beam July 2021

Redesigned for portability:

- MACHINA (Florence)
- IBA, PIXE, PIGE, XRF..

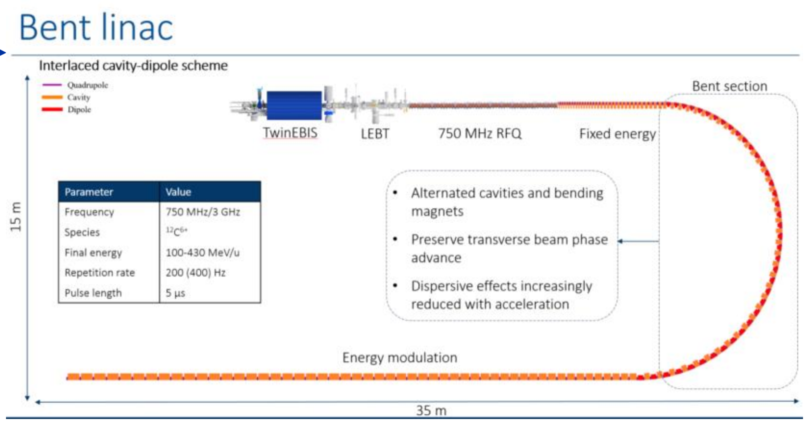


Redesigned for $^{12}C^{6+}$:

- Built in Spanish industry
- Collaboration agreement with CIEMAT 2022

Redesigned for portability:

- ELISA
- Science Gateway 2023



Carbon Linac for Medical Applications

- A/q = 2 (Protons, Helium and stripped Carbon ions)
- Pencil beam treatment

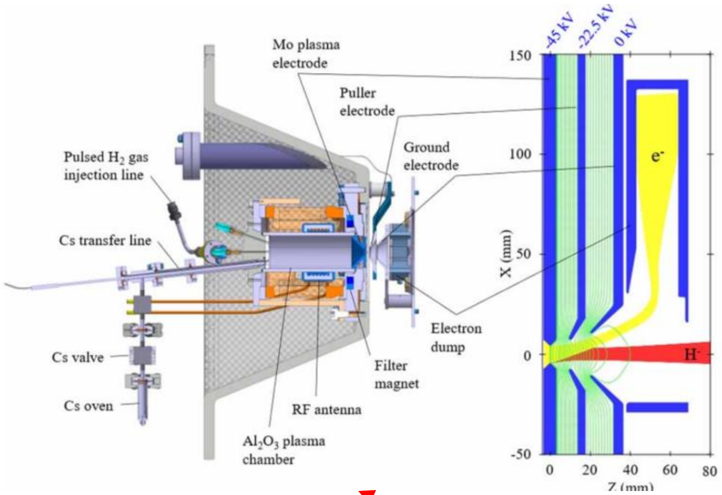
- Novel source extraction system:
  - Low Current (e.g., 100 µA) → Injector needs (conventional part. treatment..)
  - High Current (e.g., 10 mA) → FLASH, BNCT, Radioisotope Production..

Outline

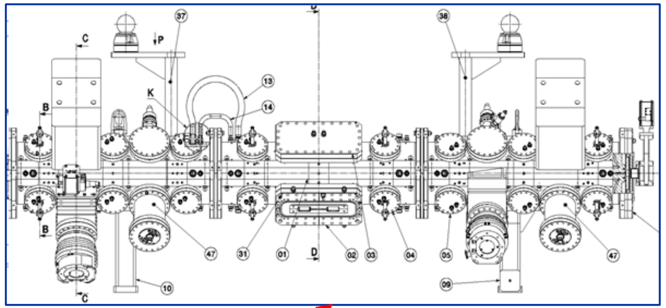
Scope

- Design of a novel/compact source extraction system **for reaching high currents**
- **High current** availability will increase the patient **treatment capacity** as well as the produced **radioisotope yield**
- Non availability of a dedicated high-current source for experimental testing rather than L4's **IS04 in proton mode**
- **Direct matching** from the source → L4 **RFQ** (*to allow for testing*) with the input beam conditions identical to IS04
- **Enhance** the **beam quality** delivered to the RFQ

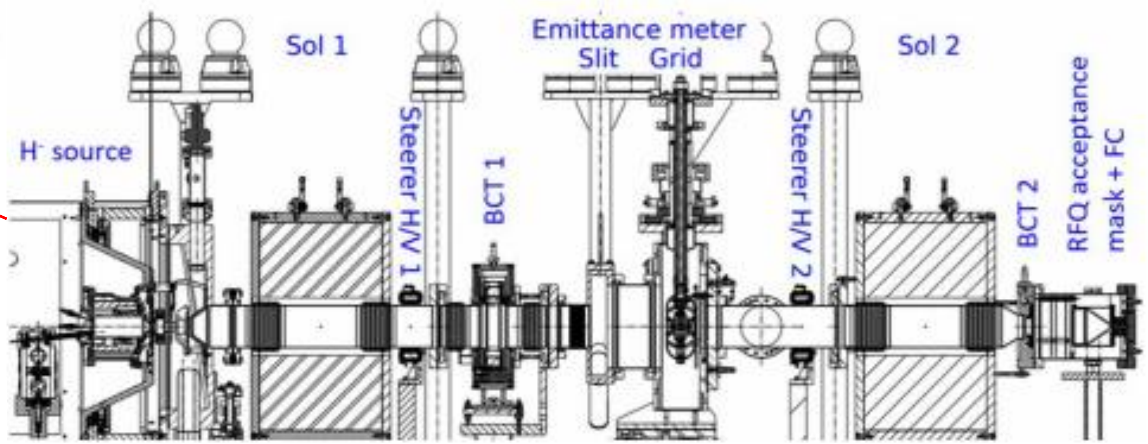
IS04 Source + Extraction System



L4 RFQ



LEBT



Linac4 Test Stand ≈ 2 m

AM01 Design

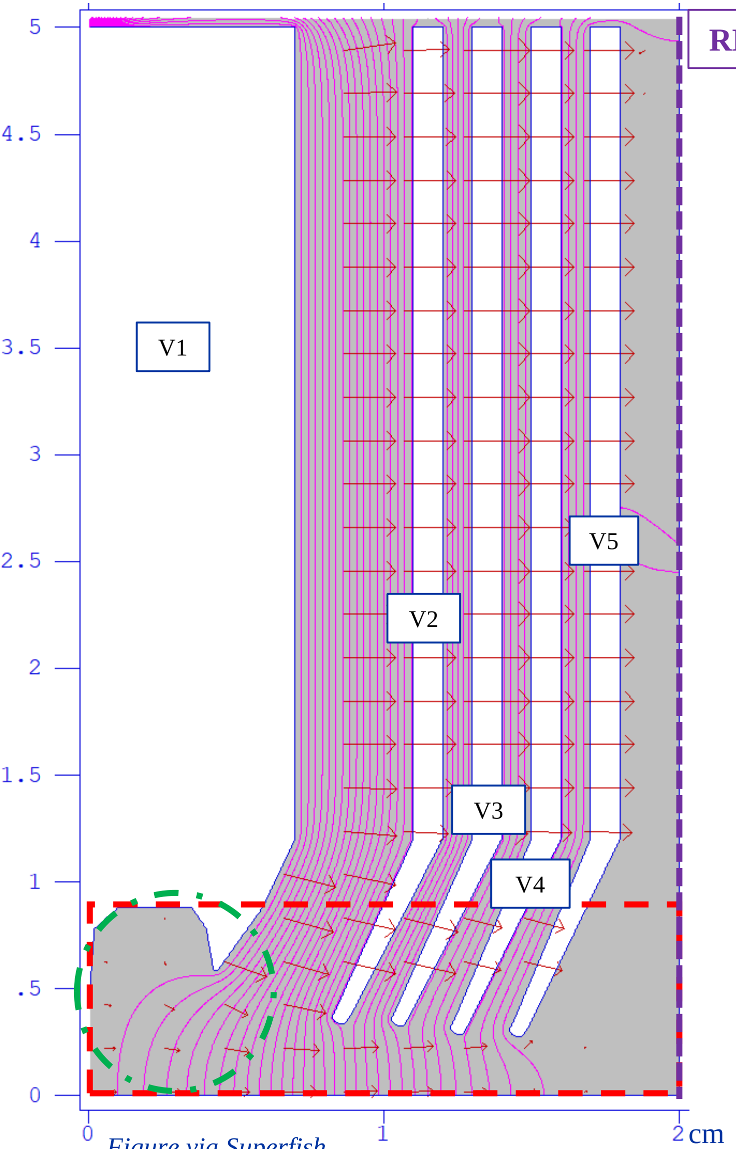
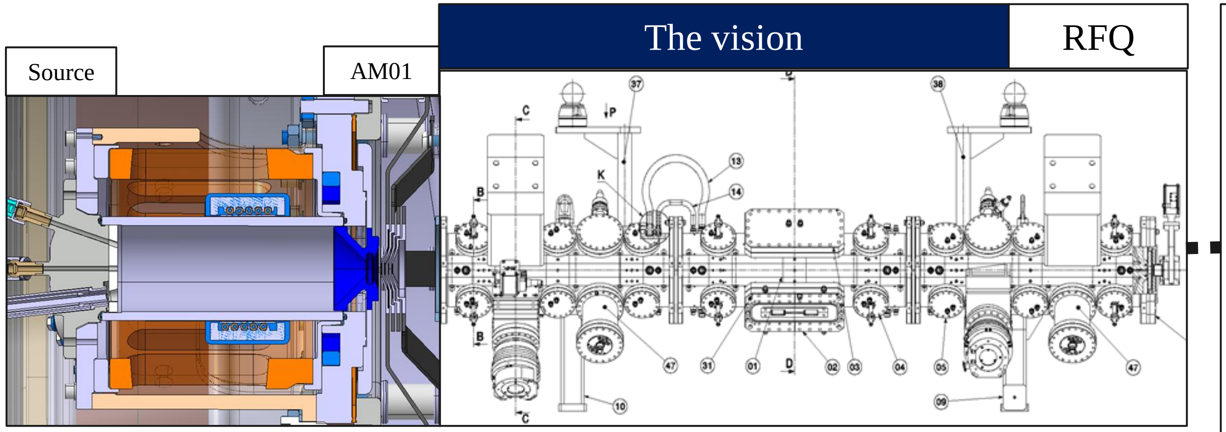


Figure via Superfish

… "Miniaturizing pre-injector linacs"



Note: Figure not on scale

Options:

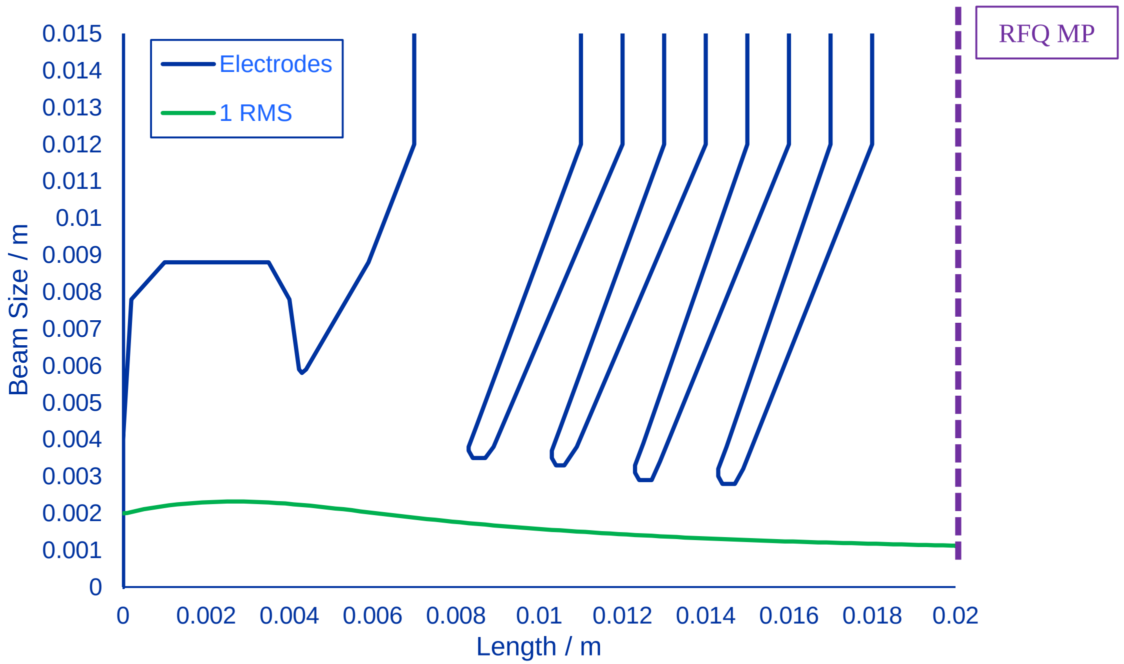
- RFQ-only ≥ 352 MHz with an E_{out} of 2-3 MeV/u for IBA, PIXE, PIGE, XRF ..
- RFQ-only ≥ 352 MHz with an E_{out} of 5 MeV/u to be used as an injector into a medical synchrotron for patient treatment
- RFQ ≥ 352 MHz with an E_{out} ≥ 3 MeV/u combined with a DTL-type structure (A/q ≥ 2) to increase E_{out} for a wide range of radioisotope production (theragnostics, conventional isotopes)

- **Equipotential lines closer to circular shape** near the source electrode → Emittance shape
- Rounded corners, no flat surfaces in short electrode distances
- **Region of interest** (*beam axis*) for the simulations
- E-field with safety factor ~1.6
- Max. E-field @ Surface: 9.5 kV/mm (Current IS04 Extr. System 9.1 kV/mm, no sparking observed)

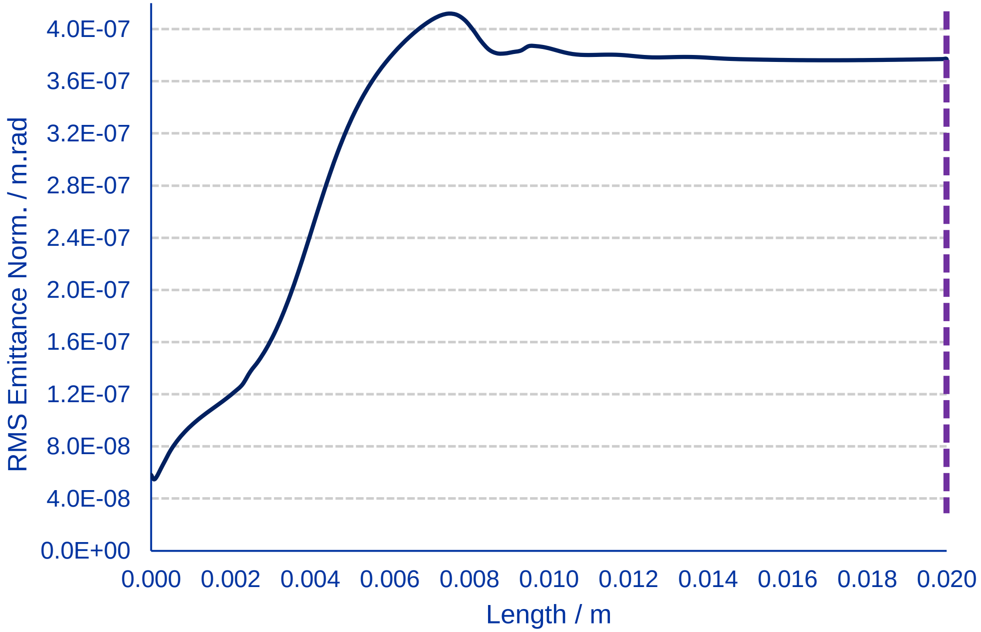
AM01 Beam Optics

- Computed using Travel:
  - for p, E_{out} = 45 keV, I = 40 mA

- Plasma source conditions same as IS04



Results computed with Travel



Next Steps

- ❑ **Finalize the AM01 3D design and proceed to manufacturing**

- ❑ **Preparations for experimental testing:**
  - Stabilize source gas
  - Ensure vacuum conditions
  - Conduct voltage conditioning

- ❑ **Conduct experimental testing in proton mode on the Linac4 test stand**
  - Implement beam diagnostics to measure the beam properties post-extraction

Thank you!

CERN

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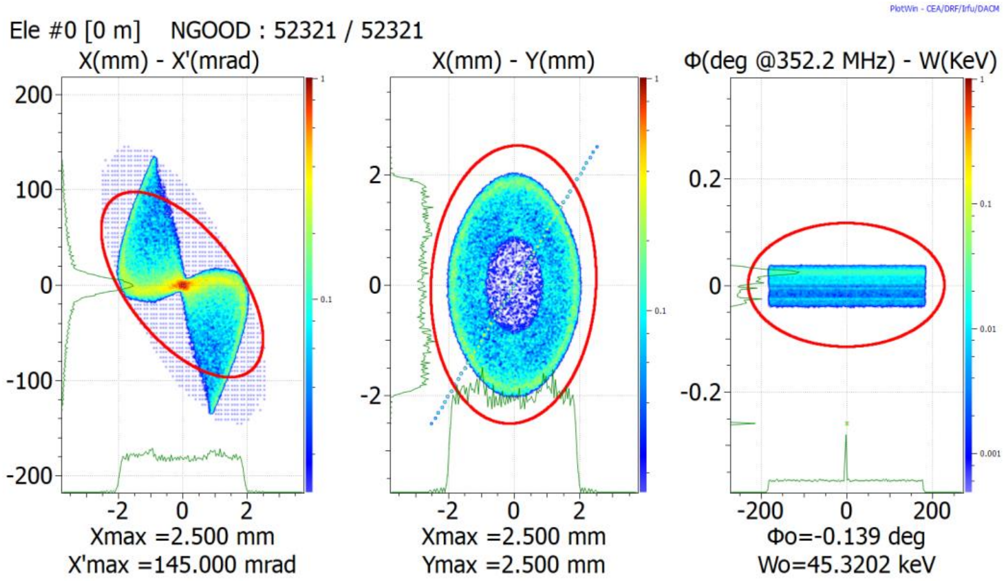
Backup Slides

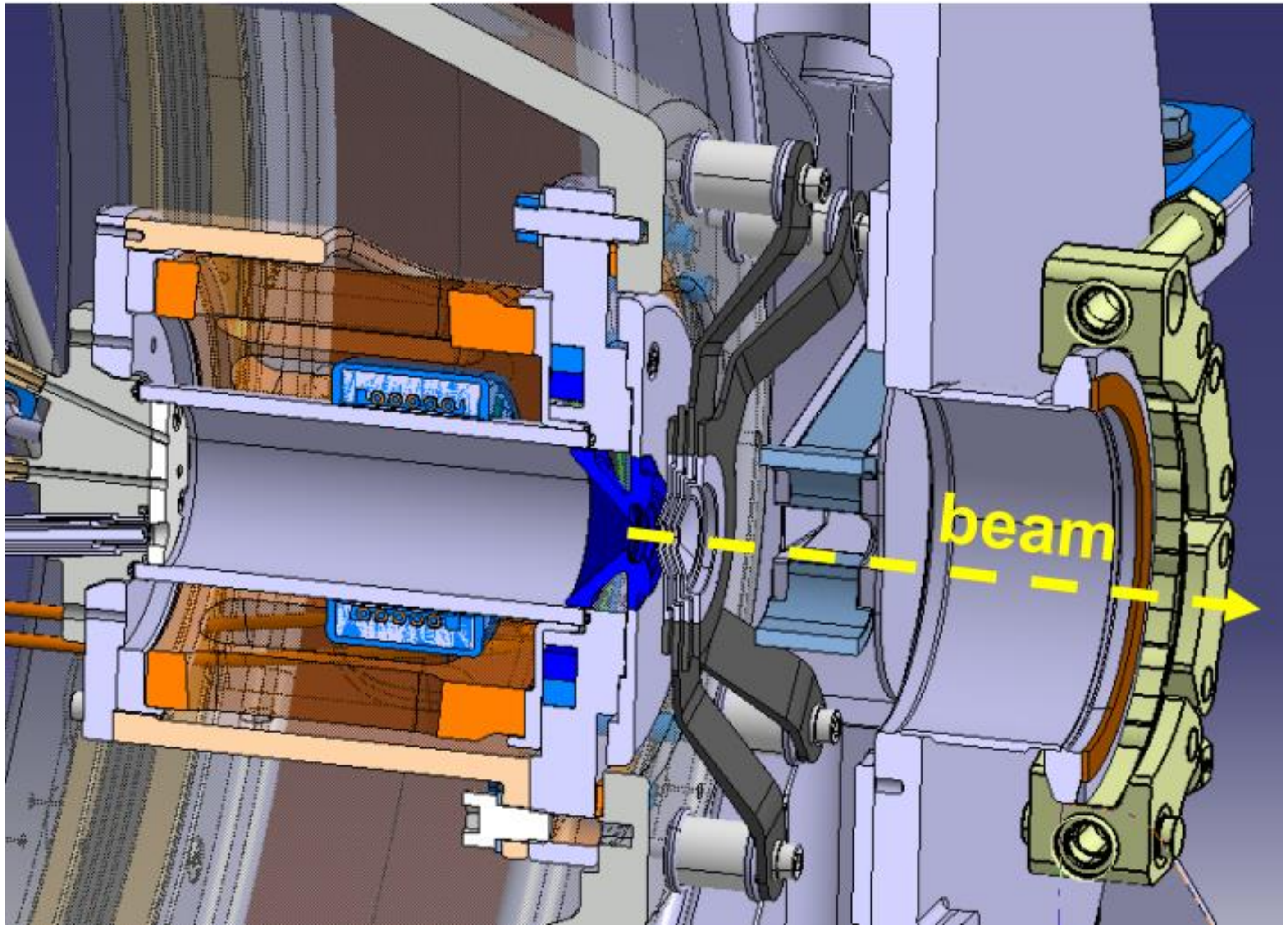
Input Beam Specifications	
Particle Type	H^+
X, Y / mm	± 4
X', Y' / mrad	± 800
Kin. E / eV	10
$\frac{\Delta E}{E}$ / %	0.1
I / mA	40

L4 RFQ Matching Criteria	
$Alpha_{x,y}$	0.88
$Beta_{x,y}$ (Twiss) / m/rad	0.02
RMS Emittance, Norm. / mm.mrad	0.35
Design Current / mA	40
Energy / keV	45

Output Beam Specifications	
Particle Type	H^+
X, Y / mm	± 1.9
X', Y' / mrad	± 134
Kin. E / eV	45×10^3
RMS Beam Size / mm	1.12
RMS Emittance, Norm. / mm.mrad	0.38
Alpha	0.73
Beta (Twiss) / m/rad	0.033
Transmission @ RFQ MP/ %	100



- Large Ellipse = RFQ Acceptance
- Red ellipse contains 93.68% of the beam ($5*\varepsilon_{RMS,\ norm}$)


beam