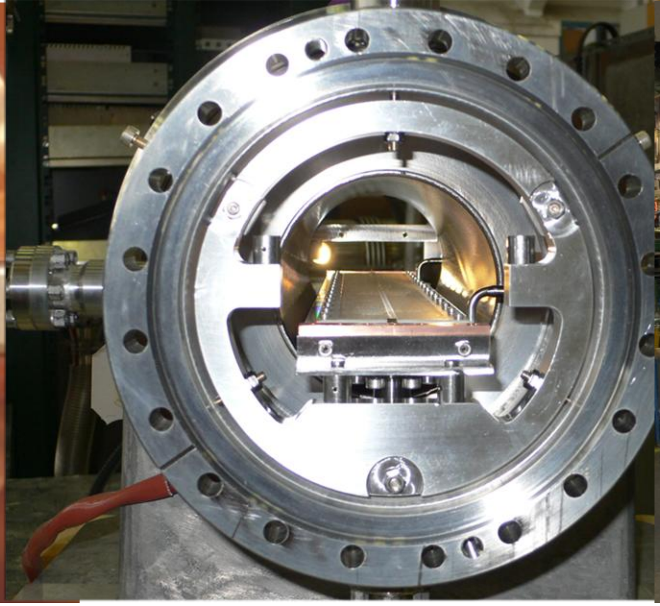
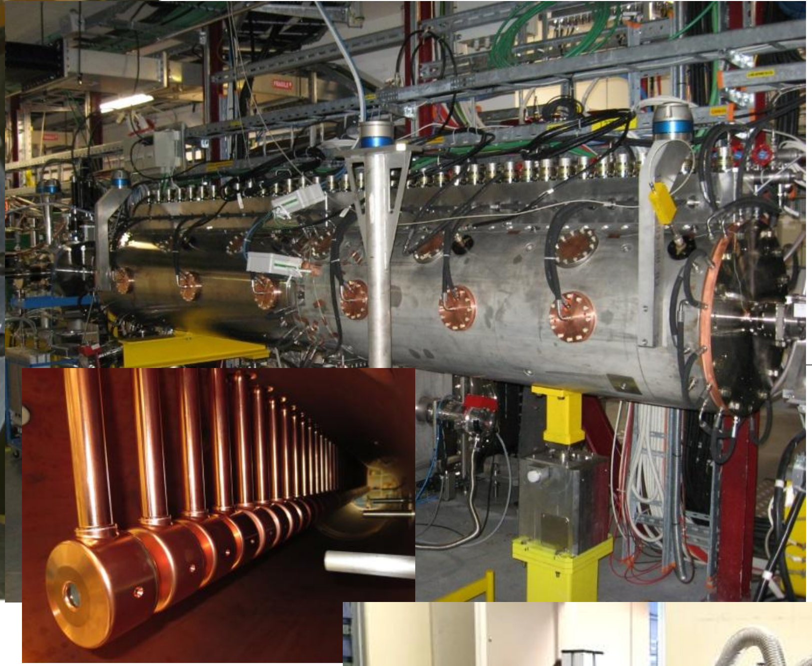
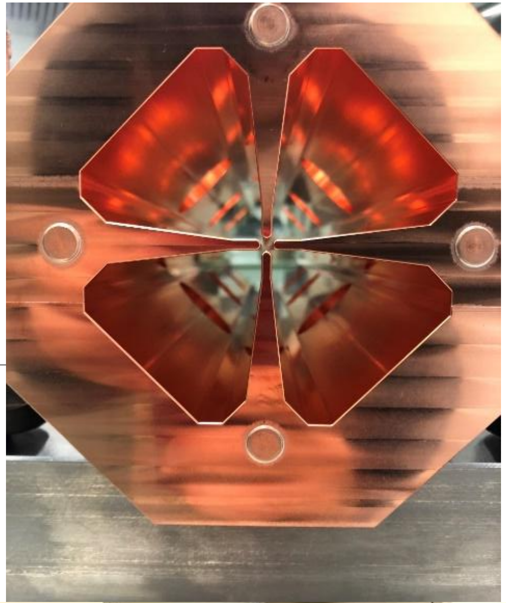
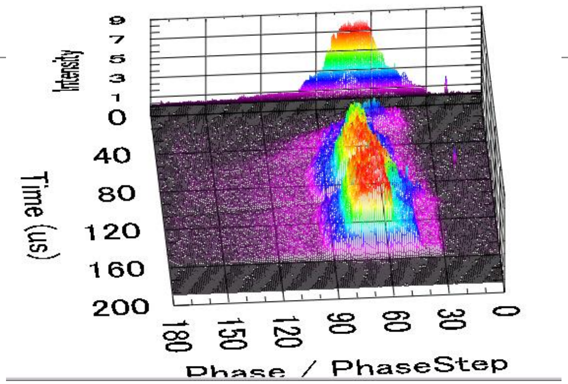





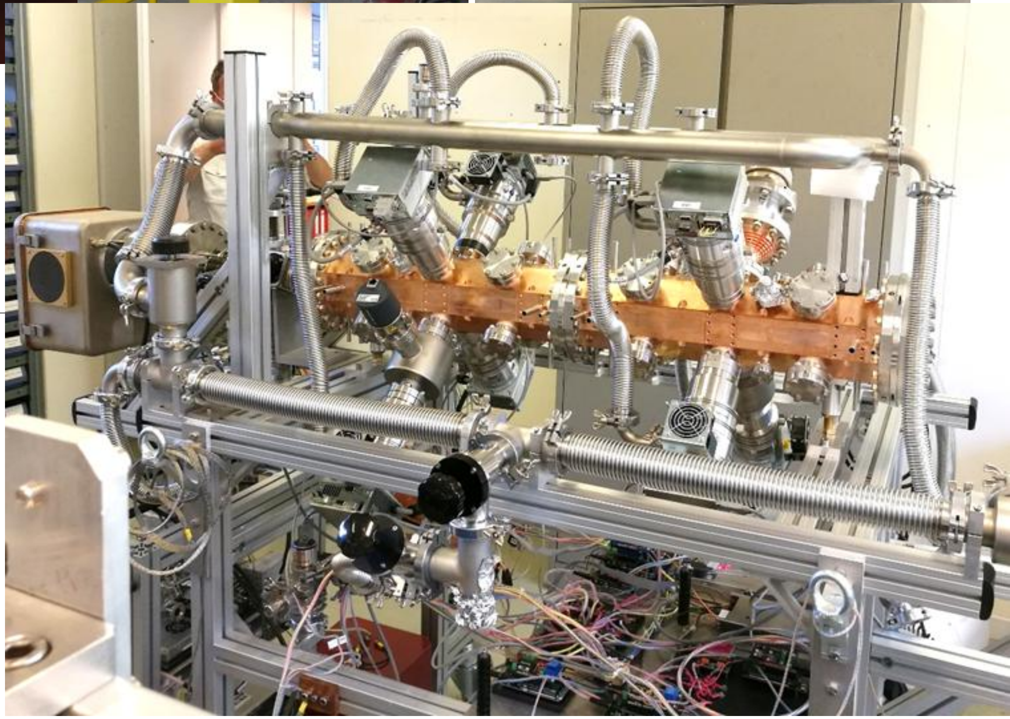
# High-frequency linear accelerators for societal and medical applications

Alessandra M Lombardi (BE-ABP-HSL)

MED GUN

CERN



# Outline

Highlight of Linac 4 (2006-2020)

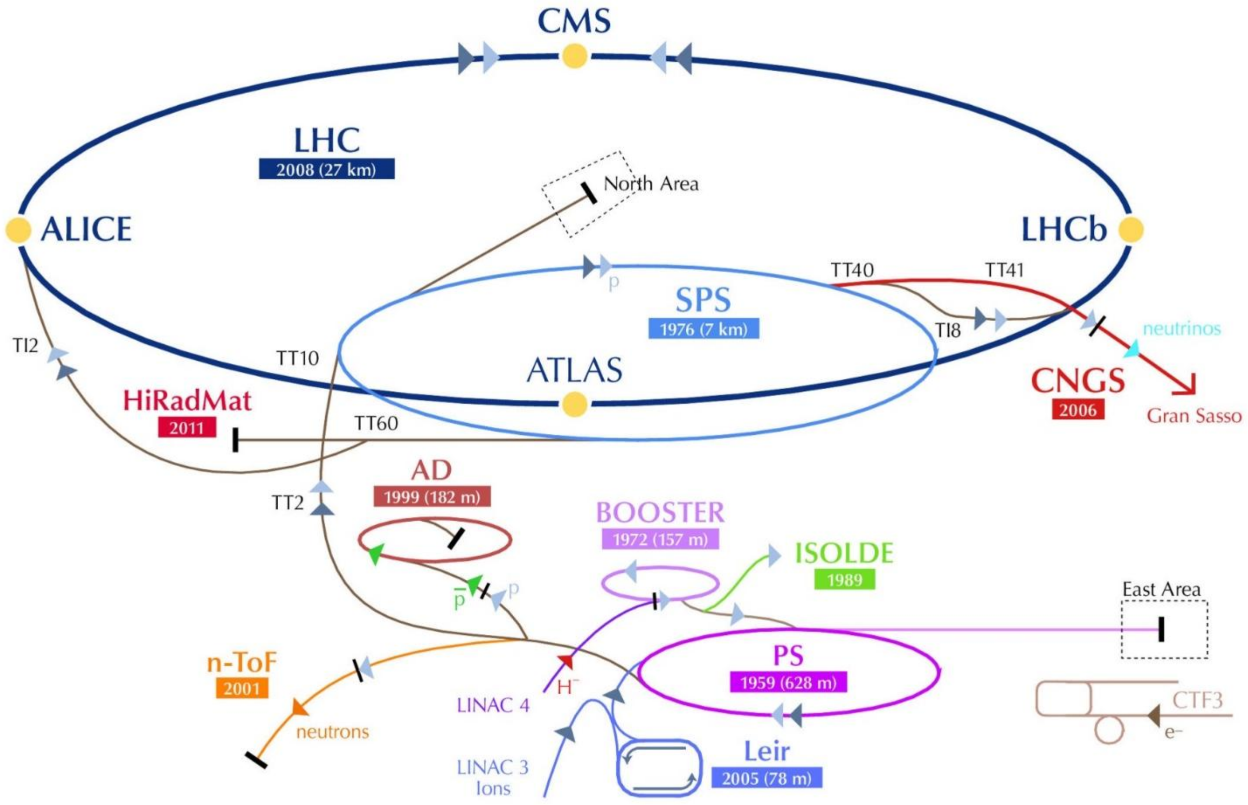
R&D on LINAC4 was applied in medical and societal projects

LIGHT : 750MHz RFQ for medical protons (2015-2017)

ELISA-MACHINA : 750 MHZ RFQ for societal use (2017-2022)

HELIUM and Fully stripped Carbon: 750 MHZ RFQ for carbon ion (about to be tested)

# CERN ACCELERATOR COMPLEX



# The big picture : LHC Luminosity

$$\mathcal{L} = \frac{\gamma}{4\pi} \times f_r \times \frac{F}{\beta^*} \times n_b \times N_b \frac{N_b}{\varepsilon_n}$$

From optics at Interaction point

From machine design and limitations (e cloud)

Brightness from Injectors : defined at low energy

| | |
|---|---|
| $N_b$ | number of particles per bunch |
| $n_b$ | number of bunches |
| $f_r$ | revolution frequency |
| $\varepsilon_n$ | normalised emittance |
| $\beta^*$ | beta value at Ip |
| F | reduction factor due to crossing angle |

***LHC INJECTOR CHAIN :***

***Linac2 (50 MeV) 1978 length 40 m***
***160mA , 100 μsec , 1 Hz***
Max Space Charge Tune Shift reached
↓
***PS Booster (1.4 GeV) 1972 – radius 25 m***
***4 rings stacked***
***Output energy already upgraded twice***
↓
***PS (25 GeV) 1959 – radius 100 m***

↓
***SPS (450 GeV) - 1976 radius 1100 m***

PS/RF/Note 96-27
25 October 1996

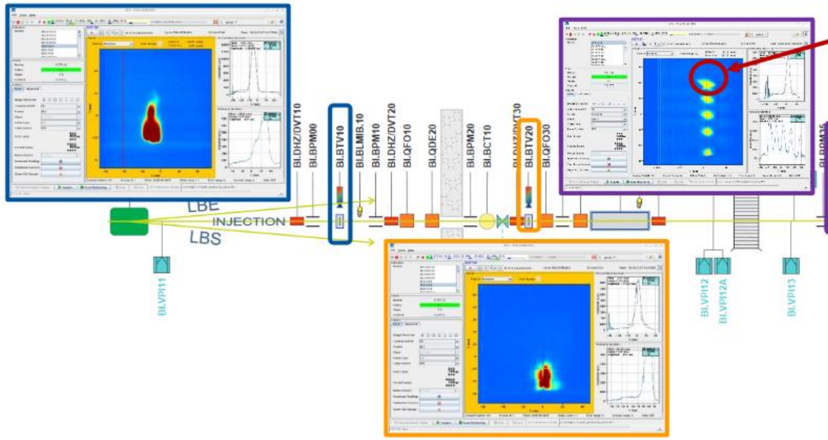
PROPOSAL FOR A 2 GEV LINAC INJECTOR
FOR THE CERN PS

R. Garoby, M. Vretenar

CERN–AB–2006–084 ABP/RF

Linac4 Technical Design Report

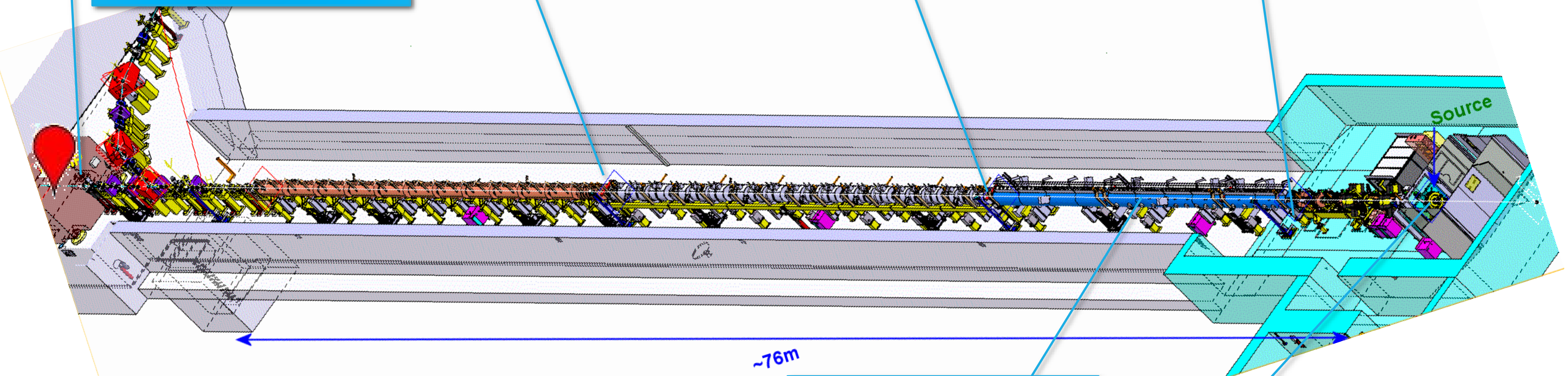
• At 13h00 first beam crossing LTB.BHZ40 and threading to the first BTV, BI.BT




Proposals (1996-2006) → Decision in 2007 R. Aymar director general → Ground Breaking ceremony : 16 October 2008 → Inauguration : 9 May 2017 → Injection in PSB : 7 December2020

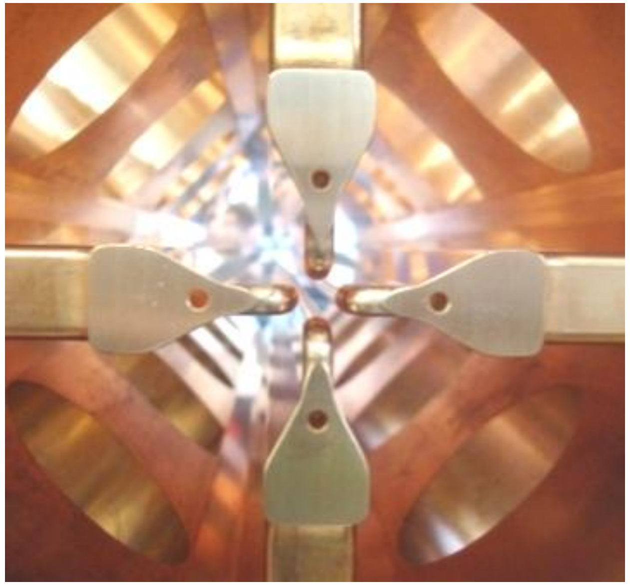
*In its June 2007 session the CERN Council has approved the White Paper "Scientific Activities and Budget Estimates for 2007 and Provisional Projections for the Years 2008-2010 and Perspectives for Long-Term", which includes construction of a 160 MeV H- linear accelerator called LINAC4, and the study of a 5GeV, high beam power, superconducting proton Linac (SPL).*

# Commissioning in stages of increased energy

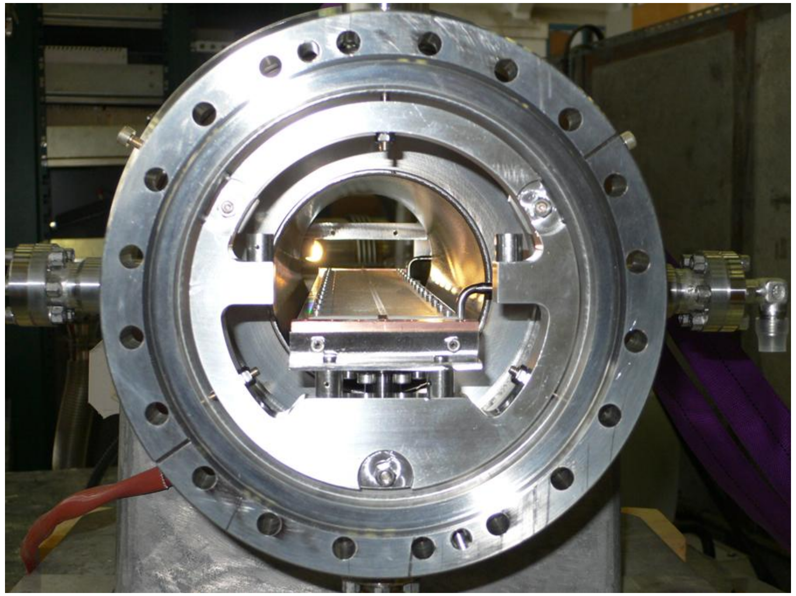



Safely on the dump.
It has been stripped.
It has been delivered to the Half Sector Test.

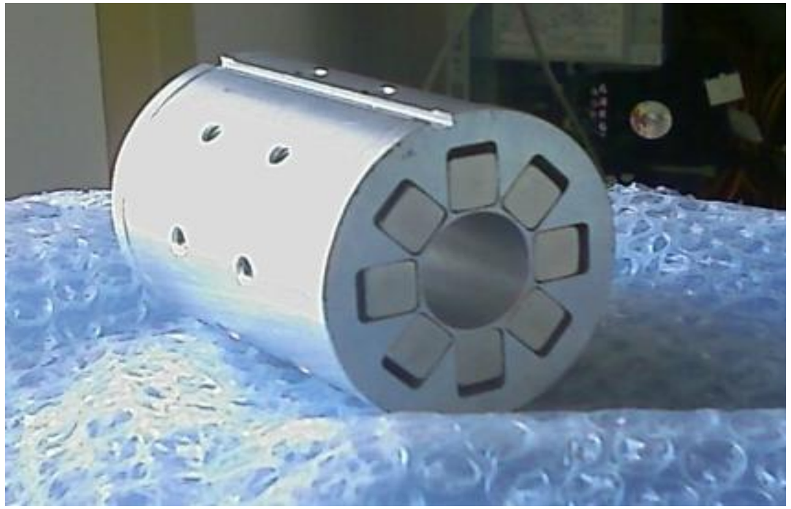
# Innovations in LINAC4



3 MeV/ 352 MHz/ 3 m long RFQ
Commissioned with beam 2013
**Experience used for design of equivalent Radio Frequency Quadrupole for medical and societal applications**



Fast chopper, validated 2013
Risetime<10nsec/ extinguish factor 100%



PMQ for tank2 , 60 mm in diameter and 80 mm in length
**Produced in European industry for the first time**

# LIGHT pre-injector

**2014**
- *S. Myers : head of office for medical applications*
- Study efficient accelerator in the energy range few keV to 5 MeV for a LINAC-based hadron-therapy facility (3GHz)

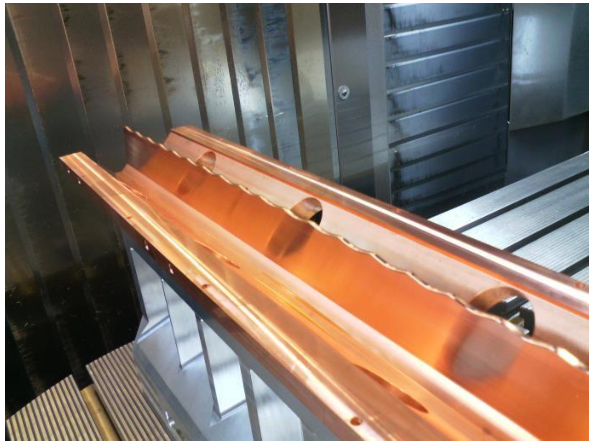
**2015-16**
- 2015 Construction and assembly at CERN
- 2016 installation at SA2 includes a commercial proton source

**2017**
- First beam in February
- Validation of the beam dynamics
- CERN was granted a patent

**2017 - 2023**
- Used by ADAM/AVO at CERN as a pre-injector for a hadron based facility (tests up to 70MeV)

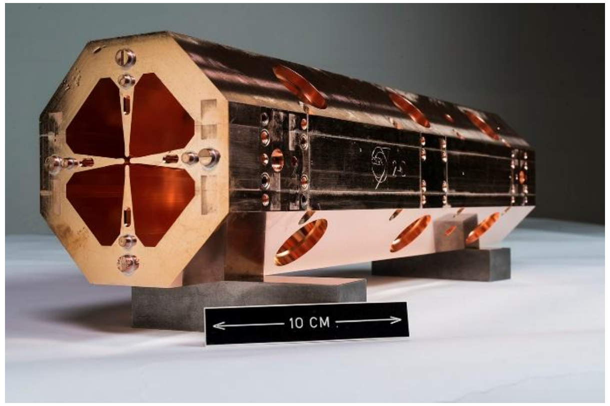
# 2015 - CONSTRUCTION

| Source and RFQ parameters | |
|---|---|
| RF Frequency | 750 MHz |
| Input | 40 keV |
| Output Energy | 5 MeV |
| Length | 2m |
| Vane voltage | 65kV |
| Peak RF power | 400kW |
| Duty cycle / max | 0.4% /(5%max) |
| Input/Output Pulse Current in 3GHz acceptance | 100/30 μA |
| Transv. emittance 90% | 0.1 pi mm mrad |
| Average aperture (r0) | 2mm |
| Maximum modulation | 3 |

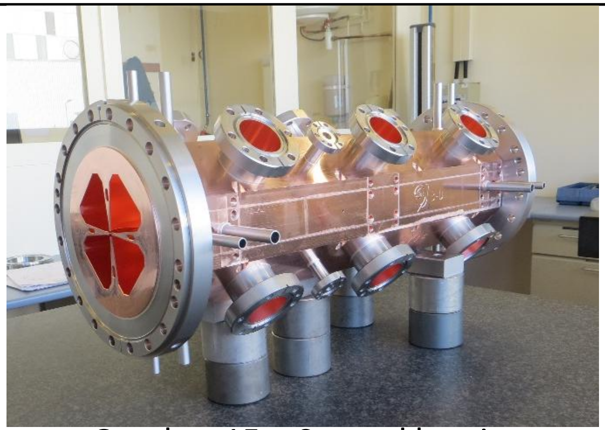


**March 15 -Machining (±10 μm)**

**May 15- Assembling (±15 μm )**



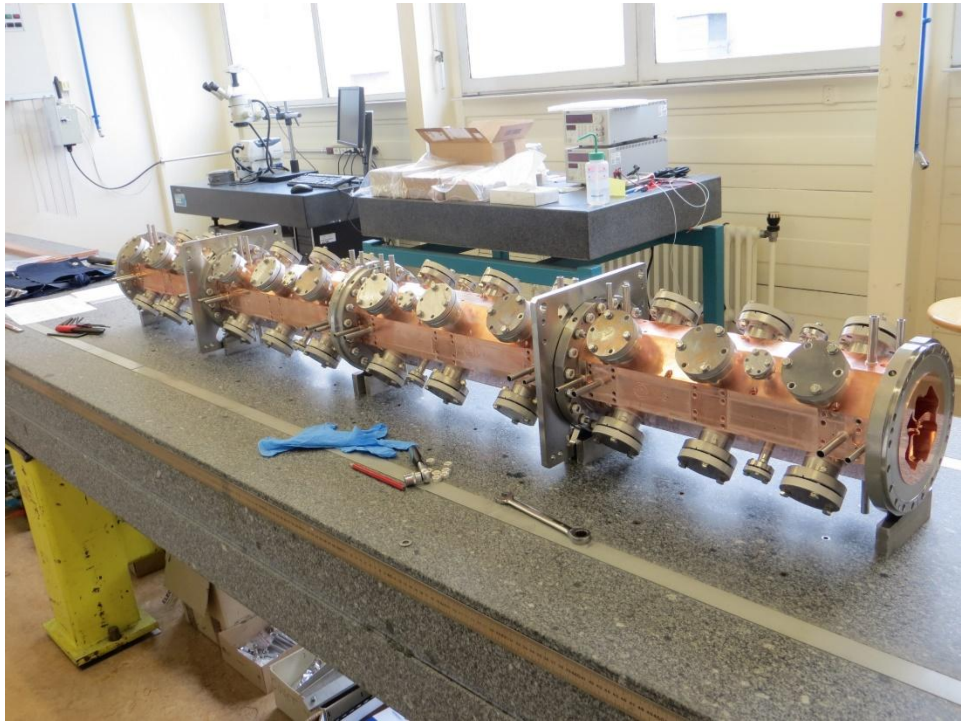

June 15 - First brazing



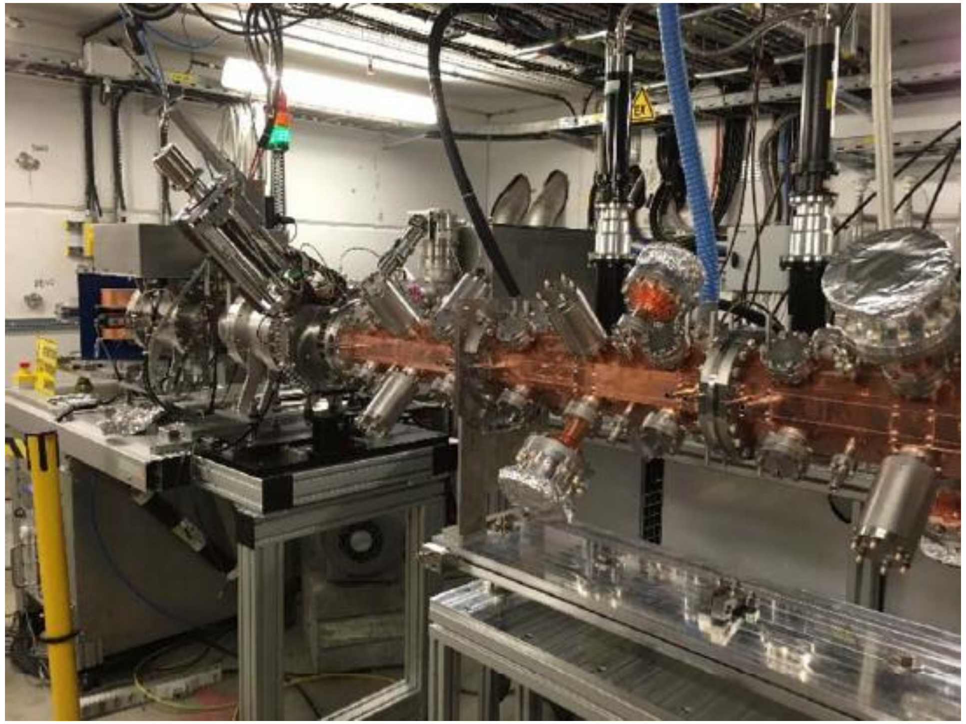
October 15 – Second brazing

ADVANCED ONCOTHERAPY ADAM an ADVANCED ONCOTHERAPY company LiGHT Linac for Image Guided Hadron Therapy

# 2016 : assembly, tuning and high power RF

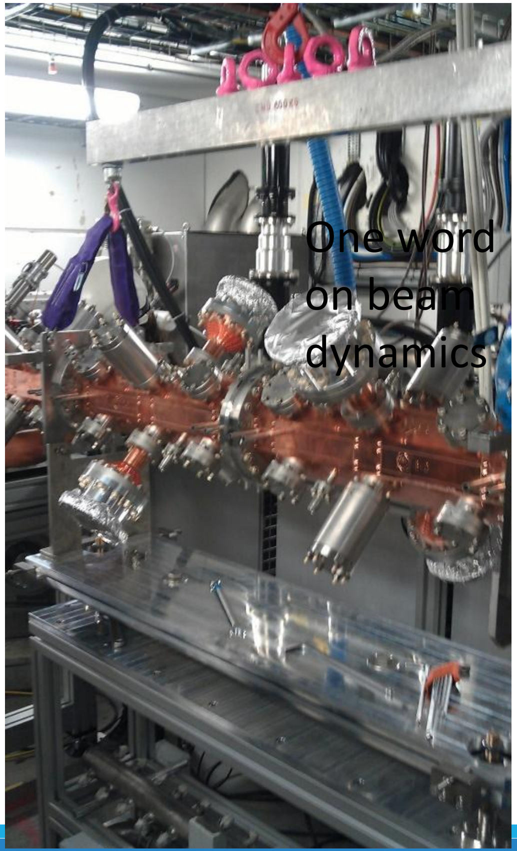


RF measurements



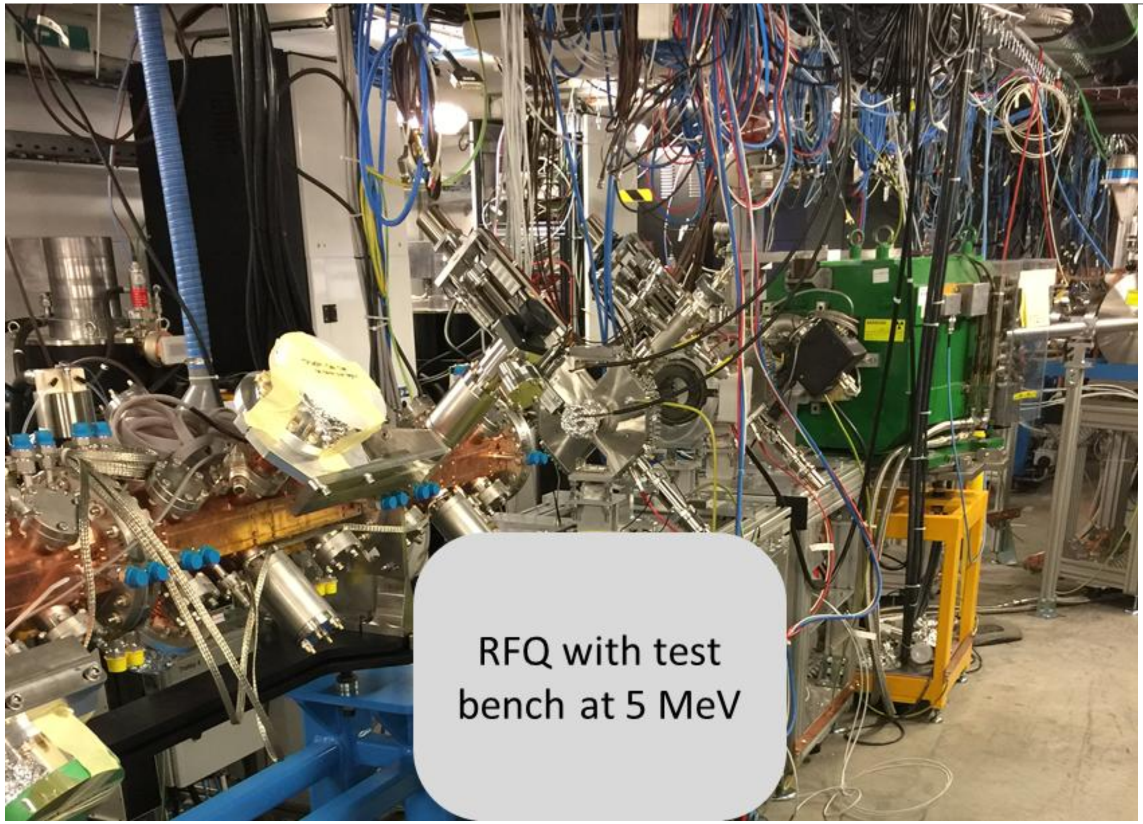
Ready for beam tests

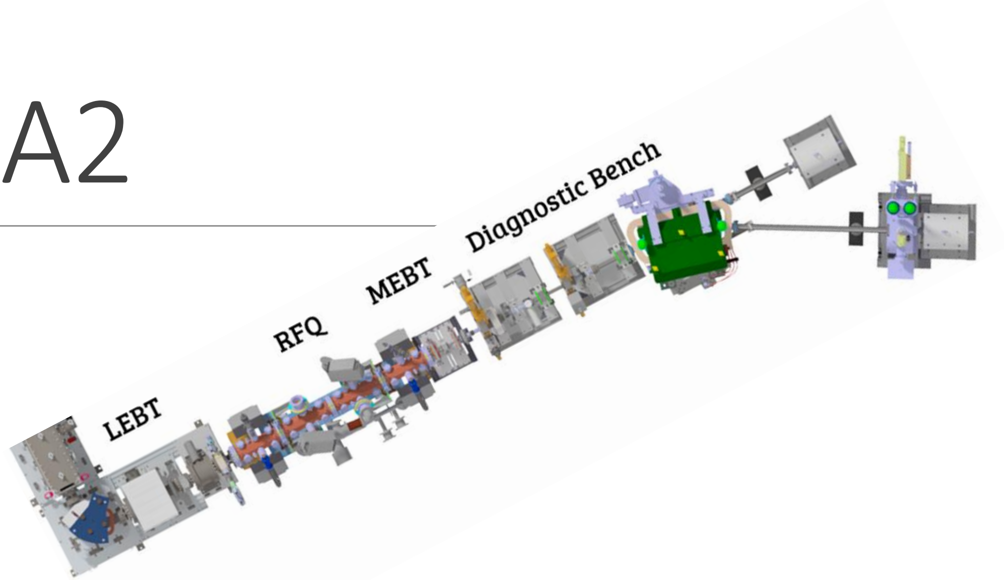
ADAM an ADVANCED ONCOTHERAPY company



One word on beam dynamics

# 2017 : proton beam at SA2



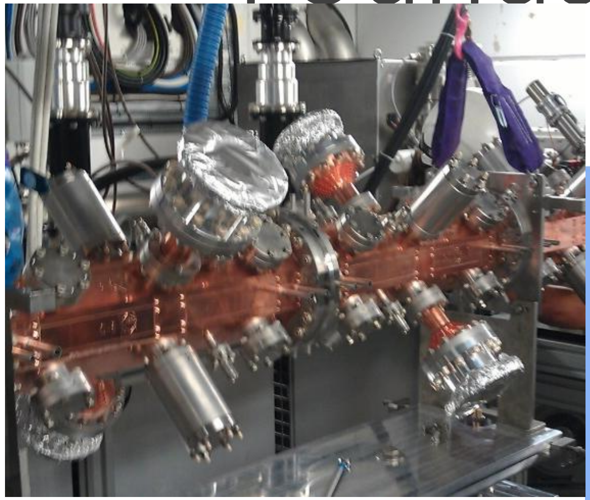

LOW ENERGY PRE-INJECTOR for ADAM/AVO test facility at SA2

*Radically new design from the beam dynamics point of view- validated by beam measurements. It build on the experience of the LINAC4 RFQ for RF design and mechanical design.*

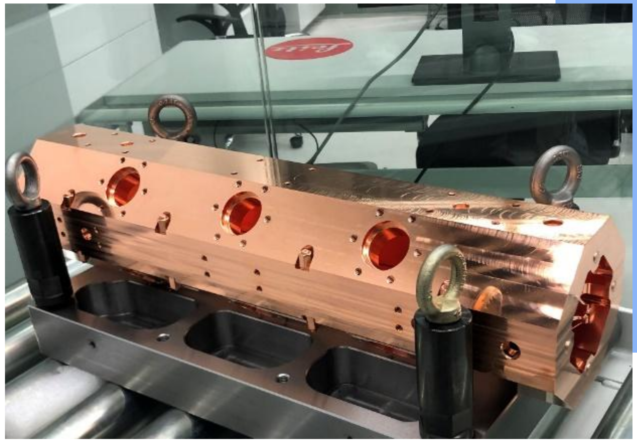
Built in the CERN workshop : less than 2 years from start of construction to installation, this included RF tuning.

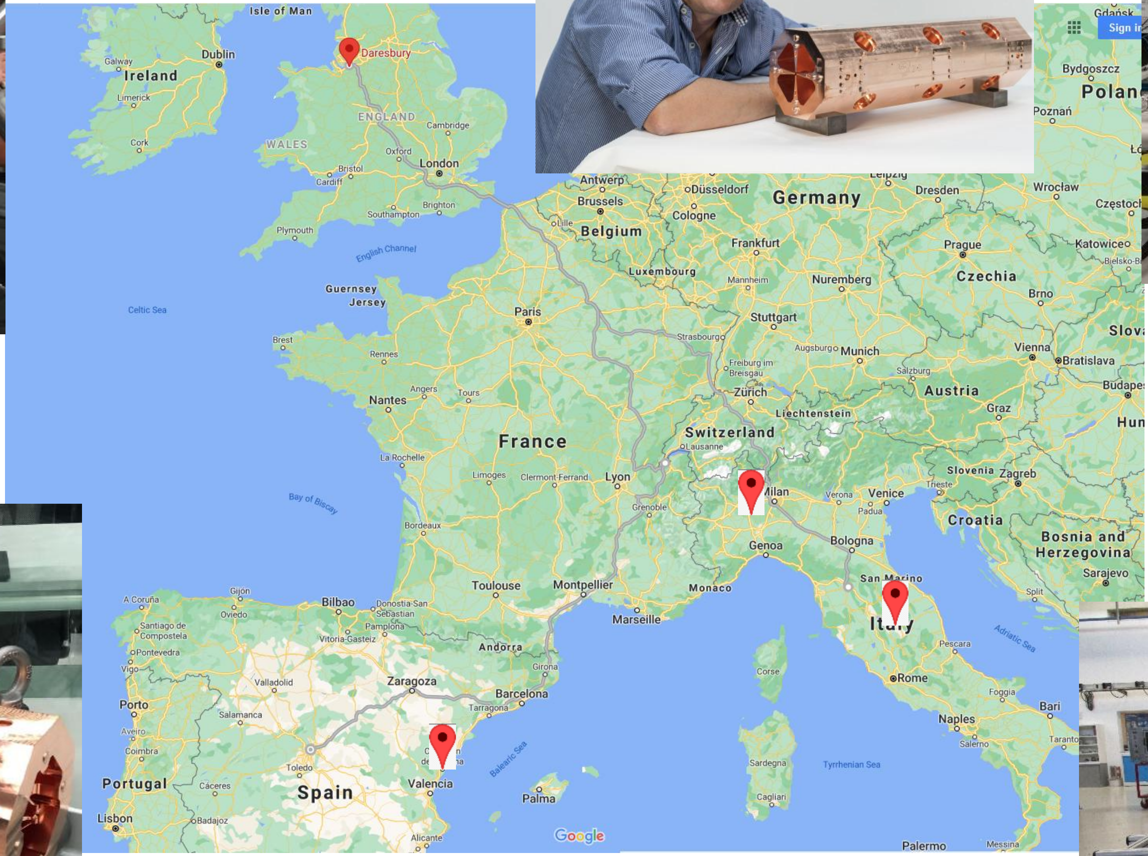
A copy is built in industry.

# Foundation for 4 other RFQs



**Copy for medical facility**:
Built in Italian industry,
First beam July21

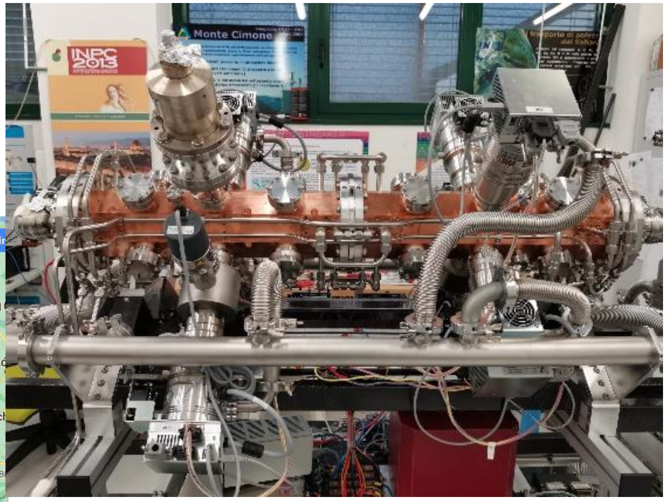





**Redesigned for portability** :

ELISA (2022 science gateway)

MACHINA (in Florence)




INFN
Istituto Nazionale di Fisica Nucleare
CERN
The MACHINA (PIXE-RFQ) Project
Technical Design Report
June 2018

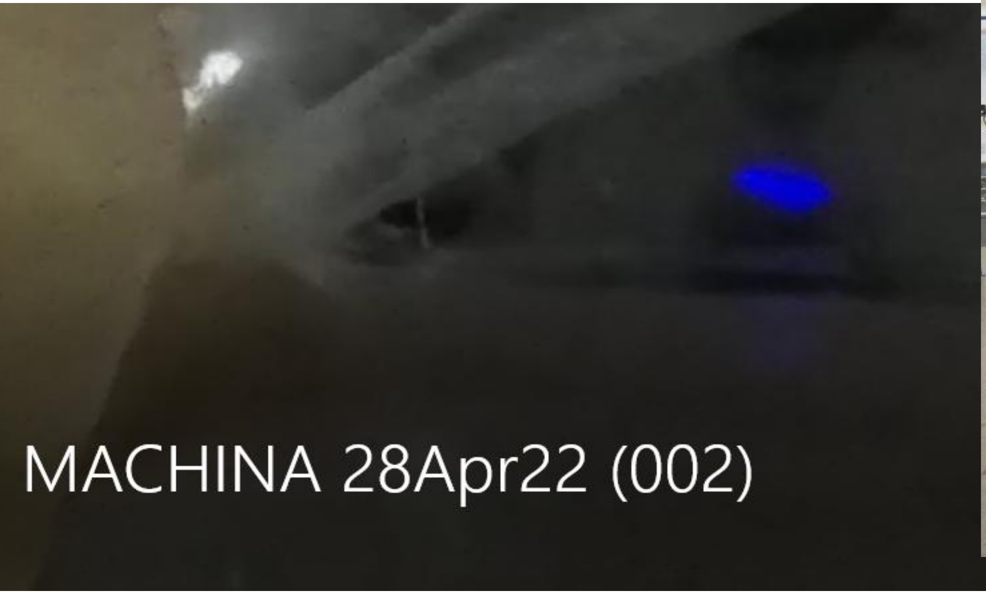
**Redesigned for Carbon6+ : in** collaboration with CIEMAT and Spanish industry, at the CERN medical test stand building

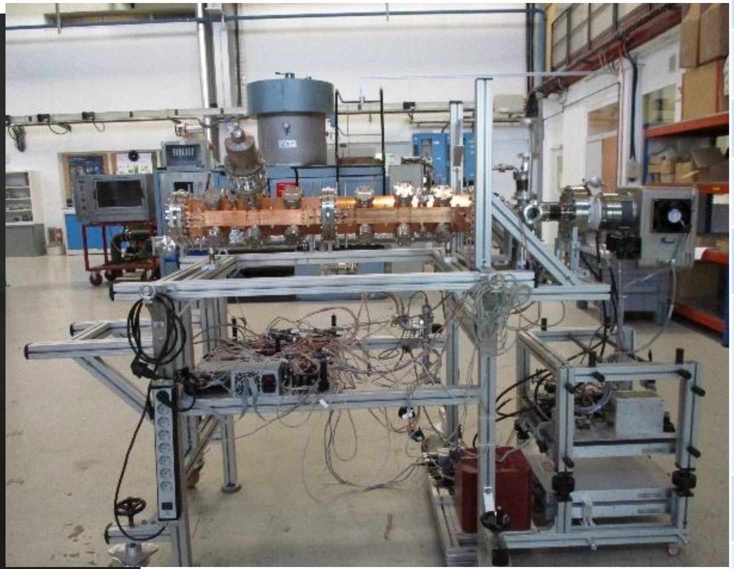
LABEC

Laboratorio di tecniche nucleari per l'Ambiente e i Beni Culturali
INFN e Dipartimento di Fisica e Astronomia dell'Università di Firenze


# MACHINA

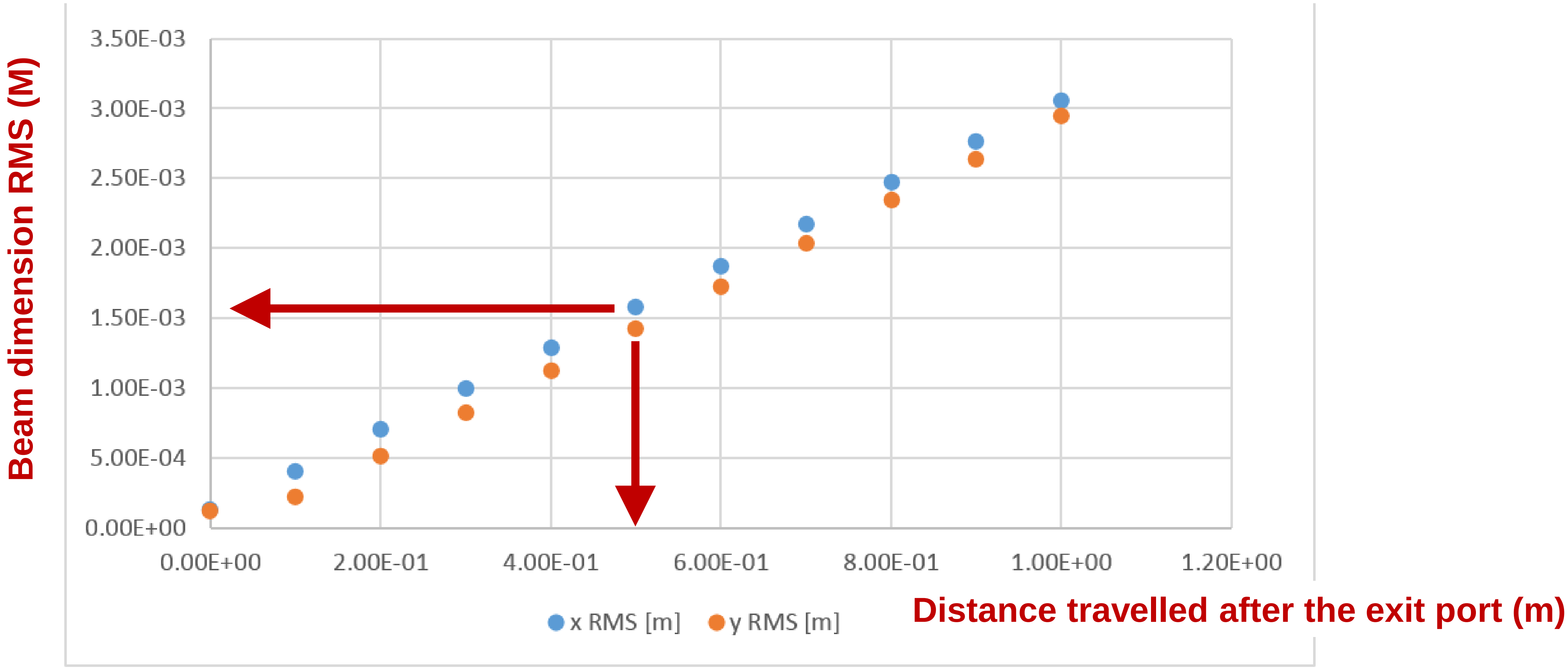
| Source and RFQ parameters | |
|---|---|
| RF Frequency | 750 MHz |
| Input | 20 keV |
| Output Energy | 2 MeV |
| Length | 1m |
| Vane voltage | 35kV |
| Peak RF power | 100kW |
| Duty cycle / max | 0.4% /(5%max) |
| Input/Output Pulse Current in 3GHz acceptance | 100/30 µA |
| Transv. emittance 90% | 0.1 pi mm mrad |
| Average aperture (r0) | 1.4 mm |
| Maximum modulation | 2.8 |



Light from the Bragg peak at 2 MeV (measured at CERN).

# The 2 MeV proton beam downstream of the RFQ exit port




**0.5 m Desired HE Beamline lenght**

## From simulations :

75 cm beamline after the RFQ + 2 PMQ 40 T/m

⇒ Beam spot size on sample ~ 400 μm

40 cm beamline after the RFQ + 2 PMQ 80 T/m

⇒ Beam spot size on sample ~ 400μm

## Where can we go?

with 2 PMQ 80 T/m, we could have a

⇒ beam spot size on sample of ~35 μm

with 2 PMQ 90 T/m, we could have a

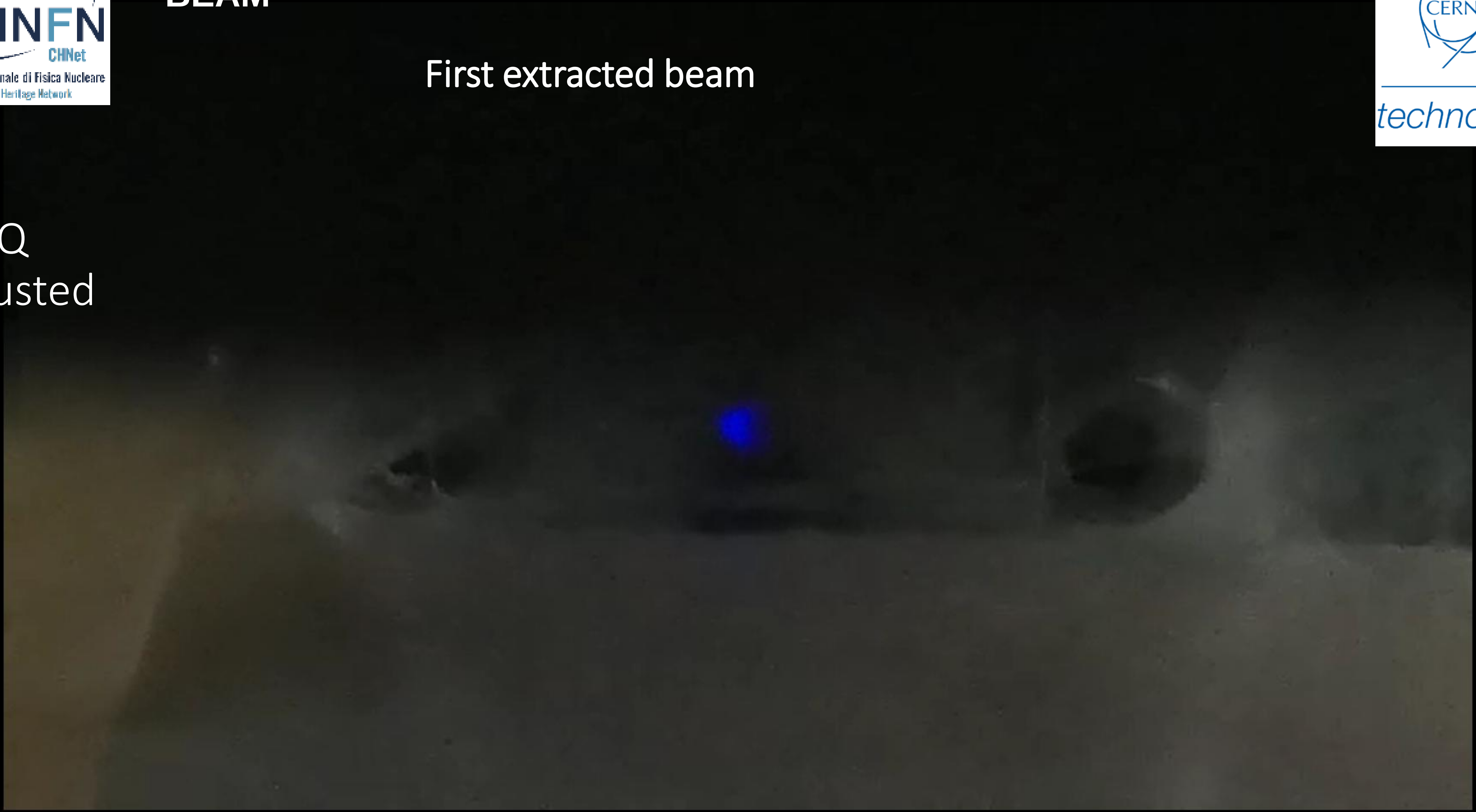
⇒ beam spot size on sample of ~20 μm



⇒⇒

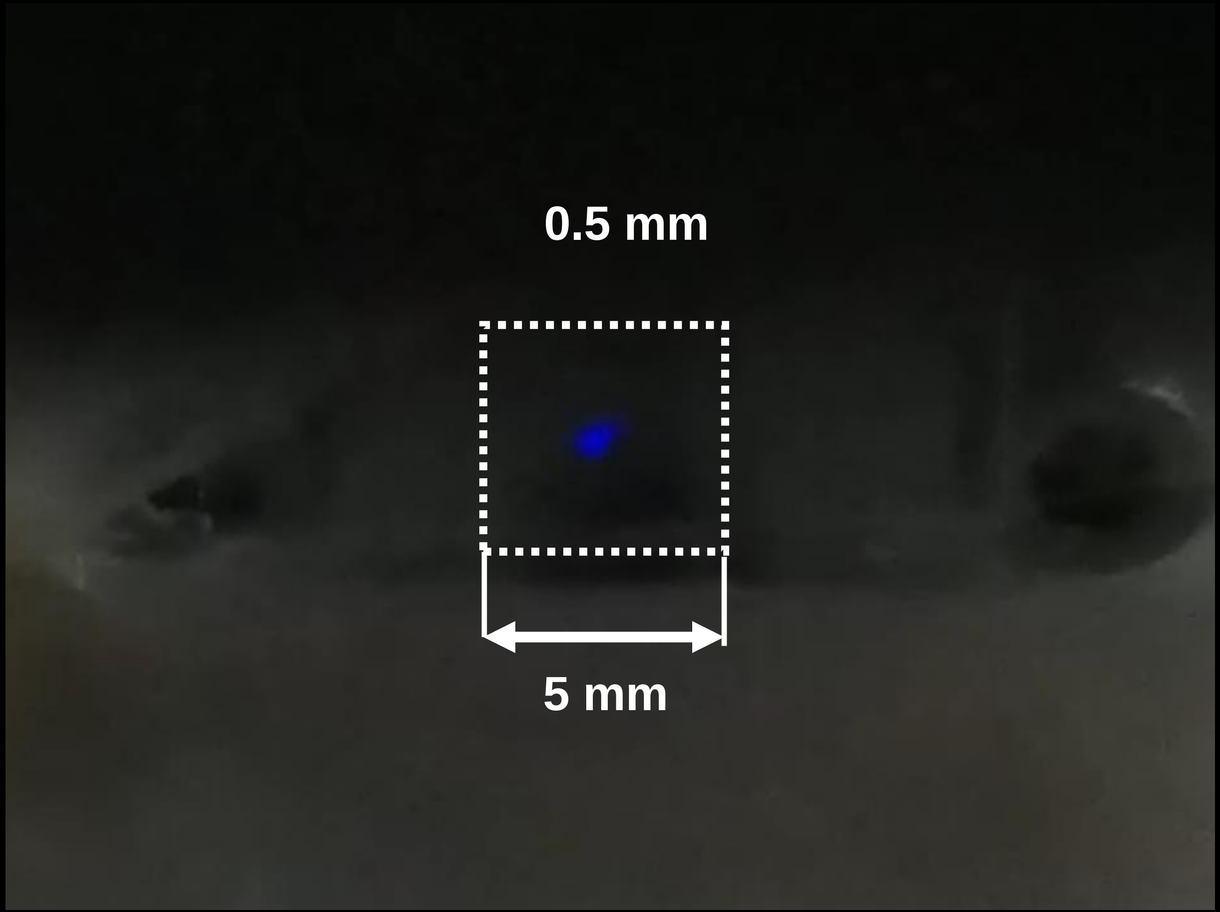
# First extracted beam

PMQ
adjusted



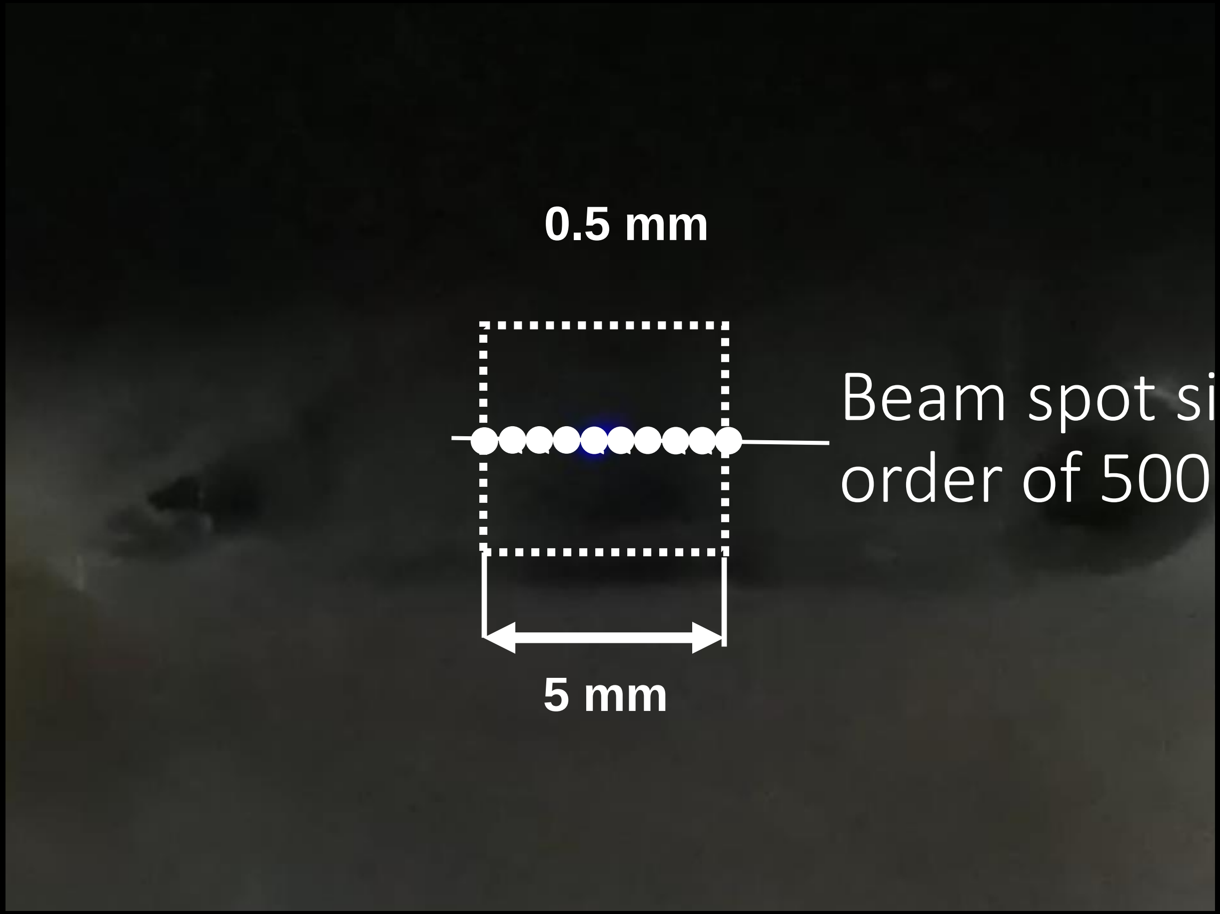
# First extracted beam

PMQ roughly optimised



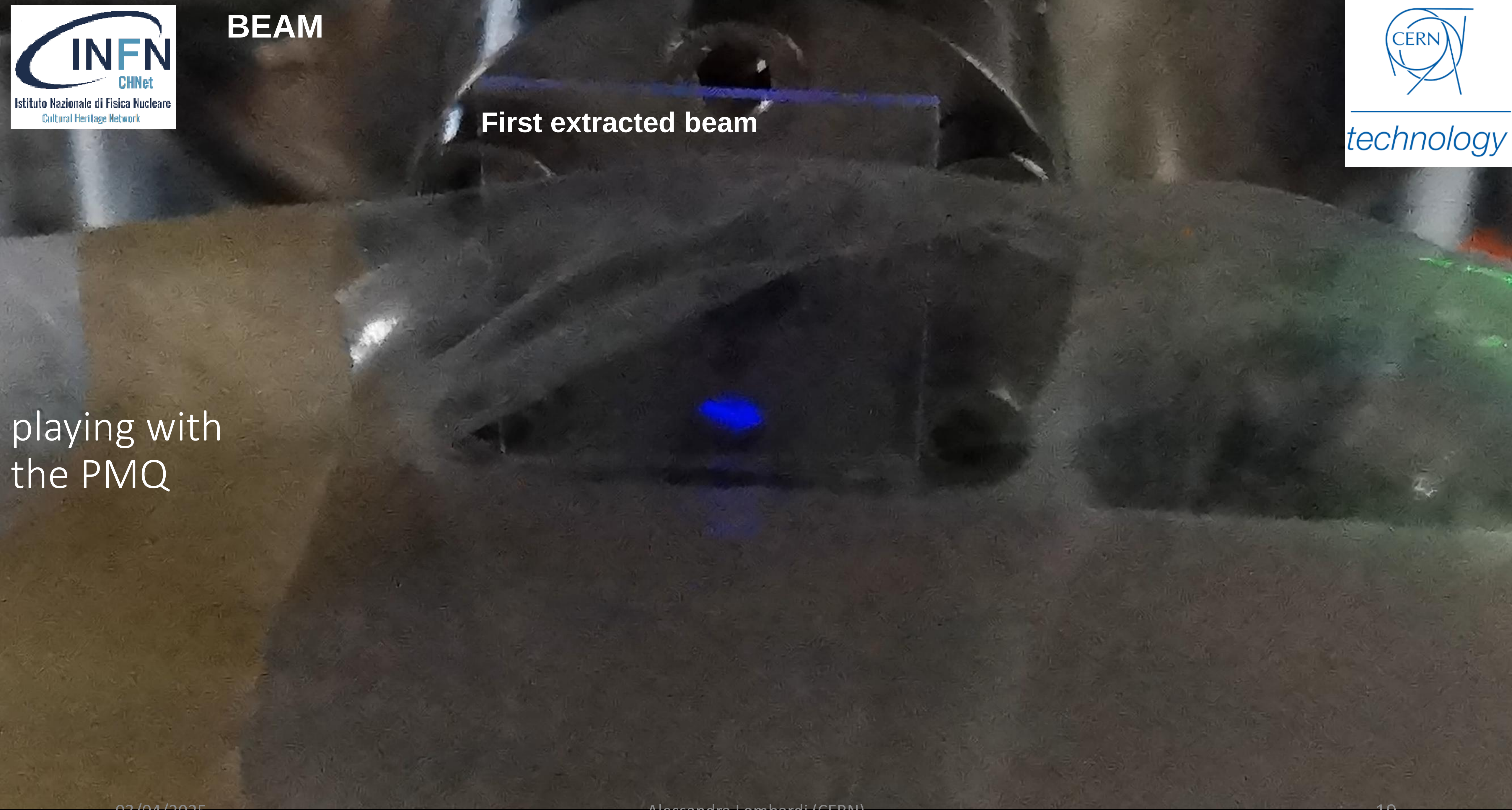
## First extracted beam

PMQ roughly optimised




Beam spot size of the order of 500 μm

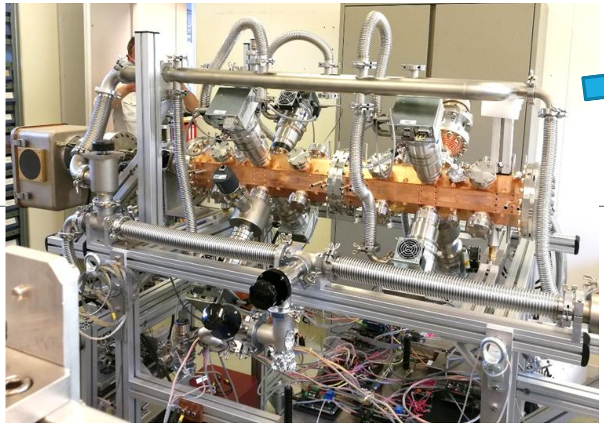
# BEAM

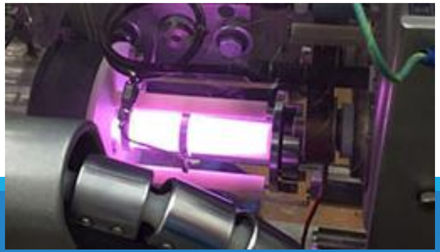


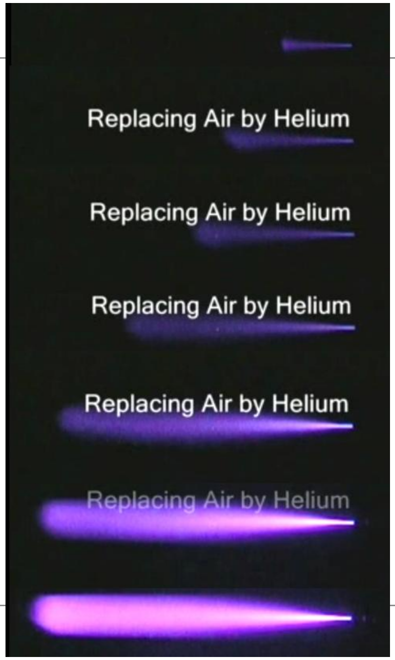
# ELISA

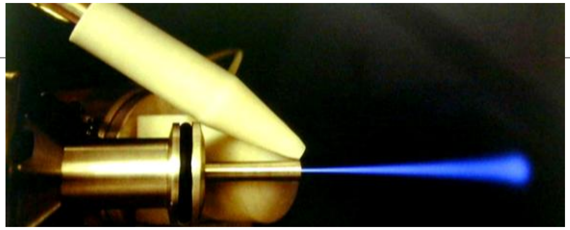
## Experimental Linac for Surface Analysis

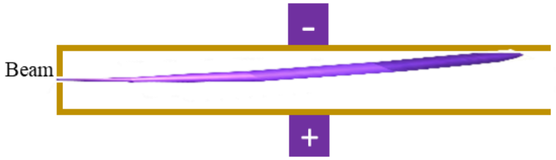
A miniature proton accelerator for Science Gateway

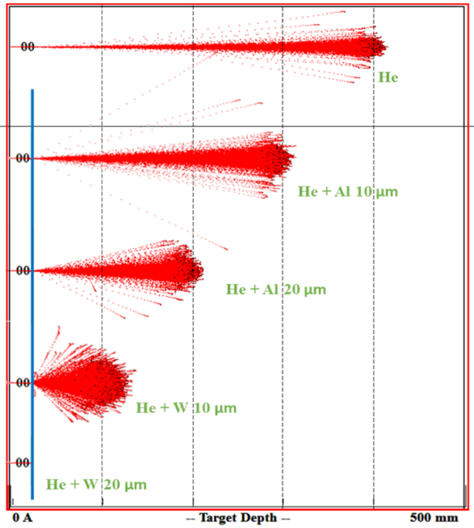






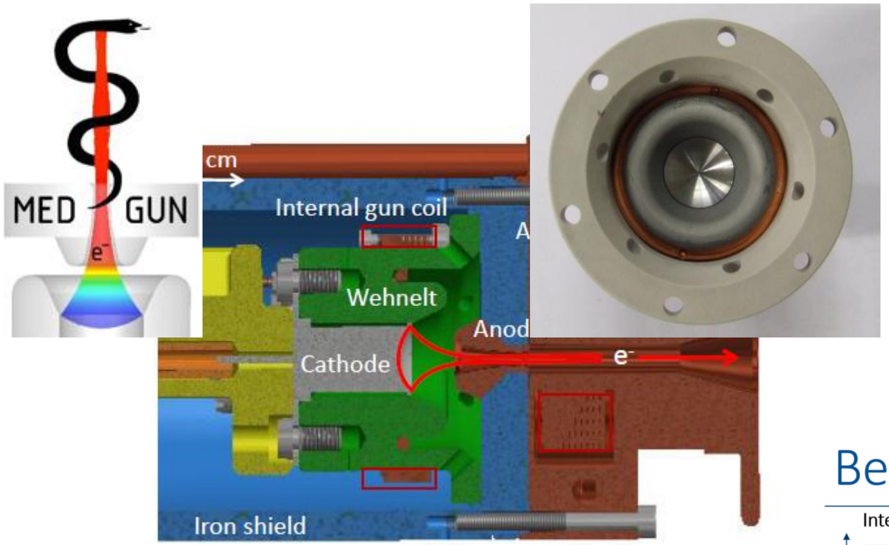


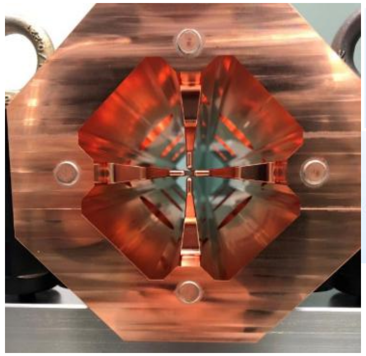

Demonstration / Experience to the public with the beam

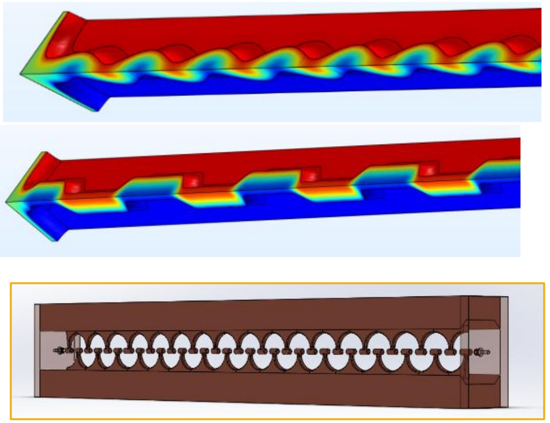
# NEXT challenge : accelerate Carbon in a LINAC

1- Source of fully stripped carbon ion with sufficient quality for use in a medical facility




*MEDeGUN mechanical design*

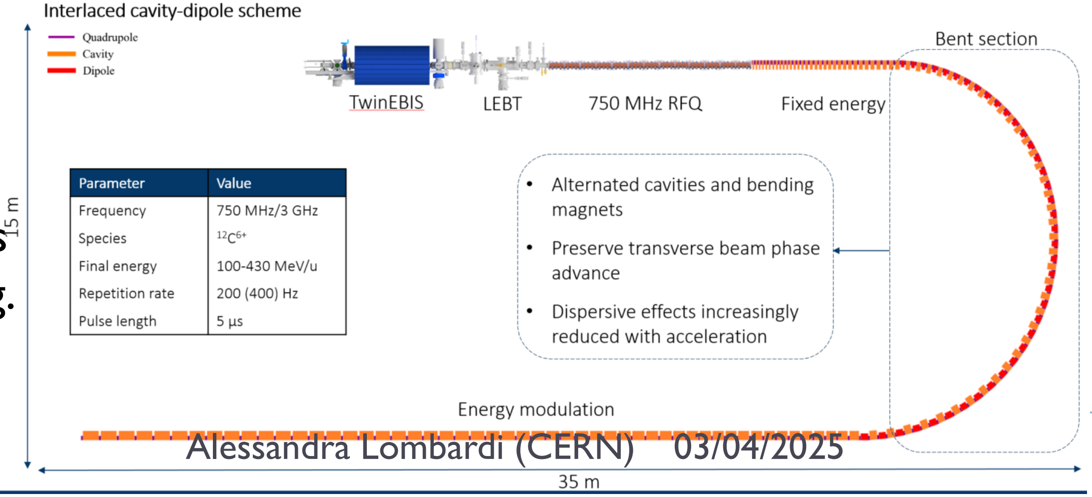




RFQ and IH

2- An efficient and easy to use pre-injector

## Bent linac

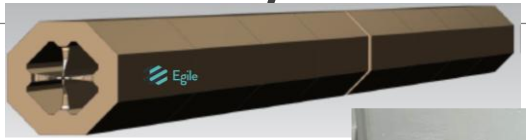



| Parameter | Value |
|---|---|
| Frequency | 750 MHz/3 GHz |
| Species | $^{12}C^{6+}$ |
| Final energy | 100-430 MeV/u |
| Repetition rate | 200 (400) Hz |
| Pulse length | 5 µs |

3- LINAC with a "hospital-friendly" footprint , adaptable to existing buildings and allowing intermediate station for e.g. Radioisotope production

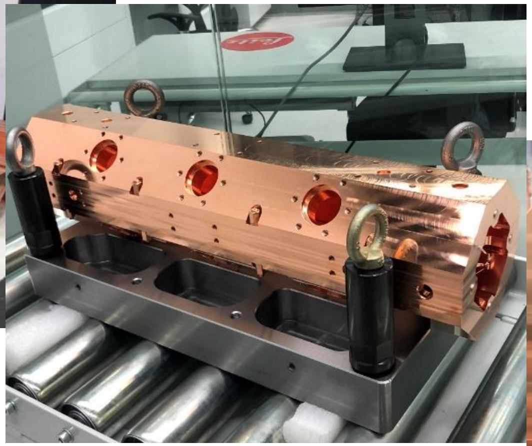
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CERN

# Collaboration CERN-CIEMAT-CDTI-Spanish Industry – RadioFrequencyQuadrupole

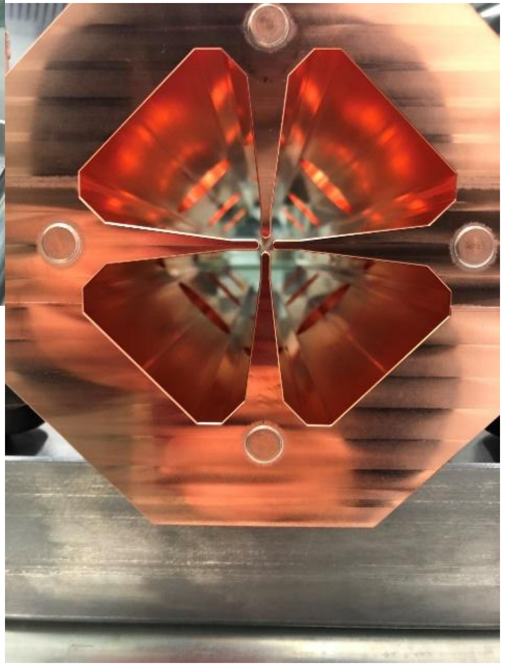



1-Drawings


2-Precision machings



3-Assembly and brazing

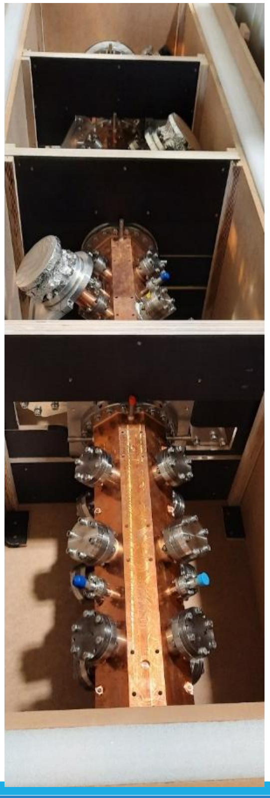


4-First (of 4) section completed

Egile

2.5 m long
750 MHz
Will deliver Carbon (or Helium) at 10 MeV (total energy)
Designed at CERN  built in Spanish Industry

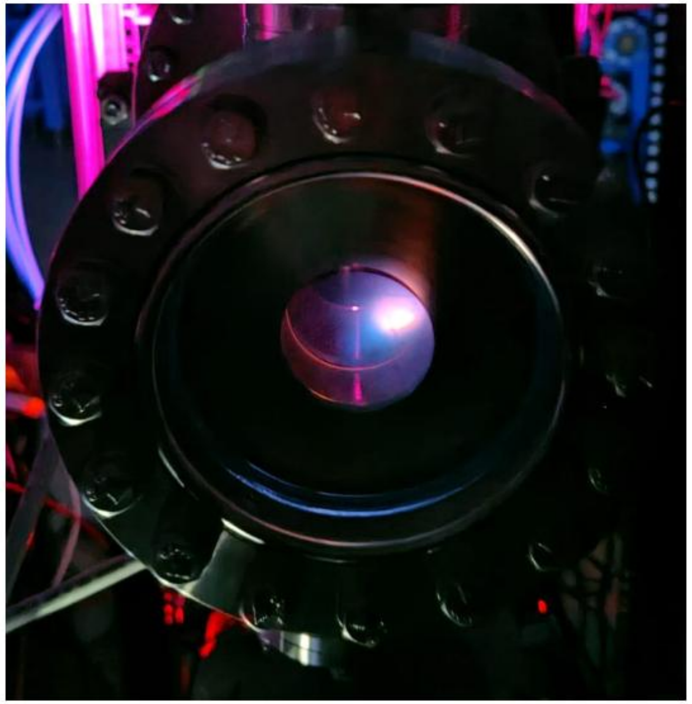
# RFQ – 2.5 m – Helium from 0.015 to 2.5 MeV/u

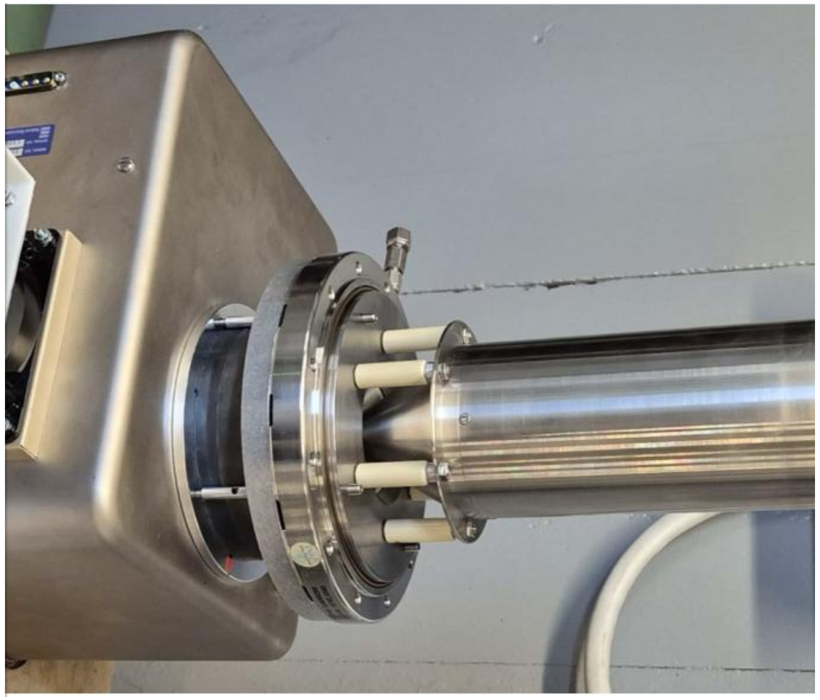




# Source 1 – NEC –low intensity protons

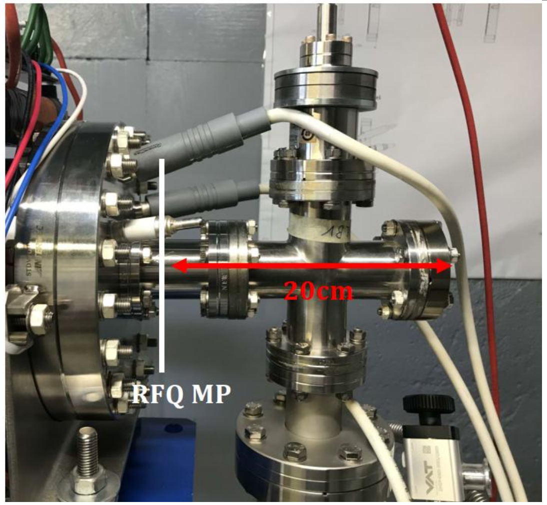
- Two innovative extractions:
  - “Extract and match”
  - “fast extraction and gridded lens”

Commercial source – probe extraction-
with company-furnished extraction, the nominal current is around 20μA





# Details on the two extractions and expectations 1/2




- 3 power supplies and 26 cm from the source plasma chamber to the RFQ matching plane
- Limited flexibility in matching (source needs to be commissioned in standalone mode)
- Guaranteed best beam quality as limit the manipulations on a low-energy beam. This is extended to high intensity.
- ……..still some teething problems with alignment and spot size…

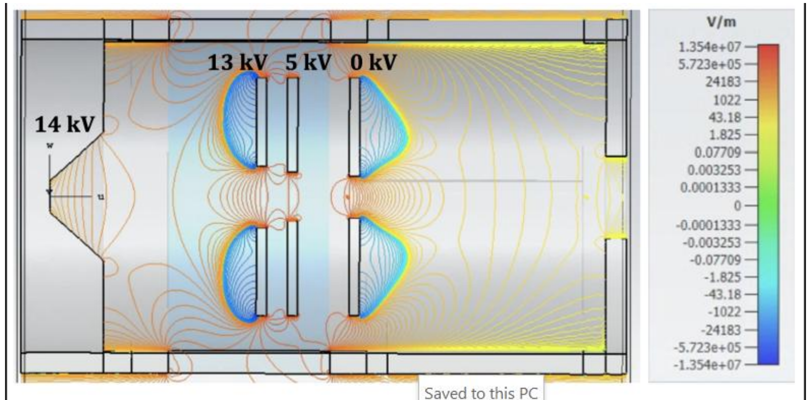
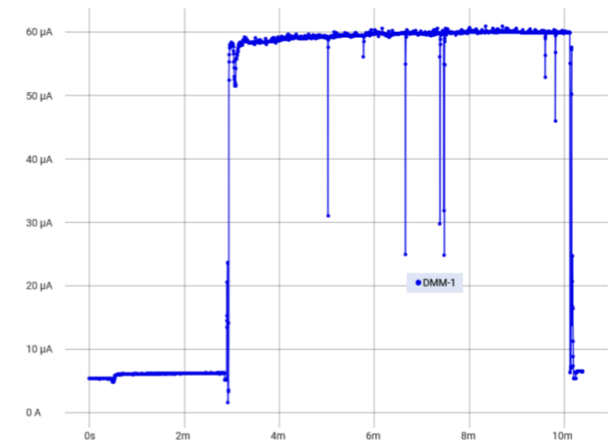
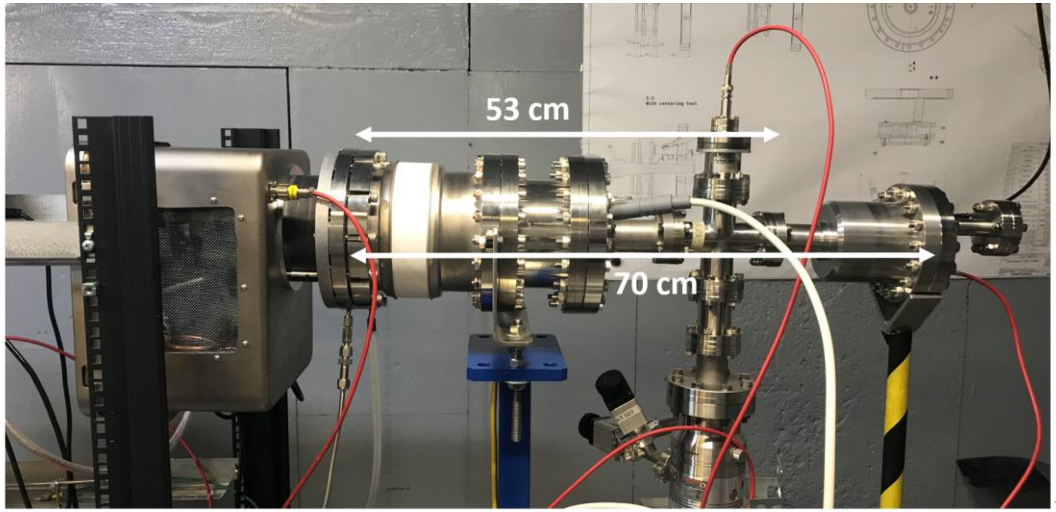



**Figure 6.23:** Equipotential lines and electric field values for 3D model of the extraction system geometry.

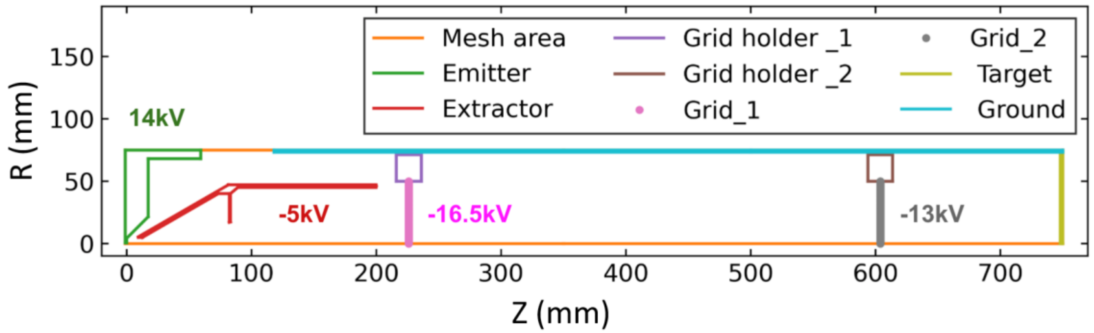
Probe: 2.5 kV

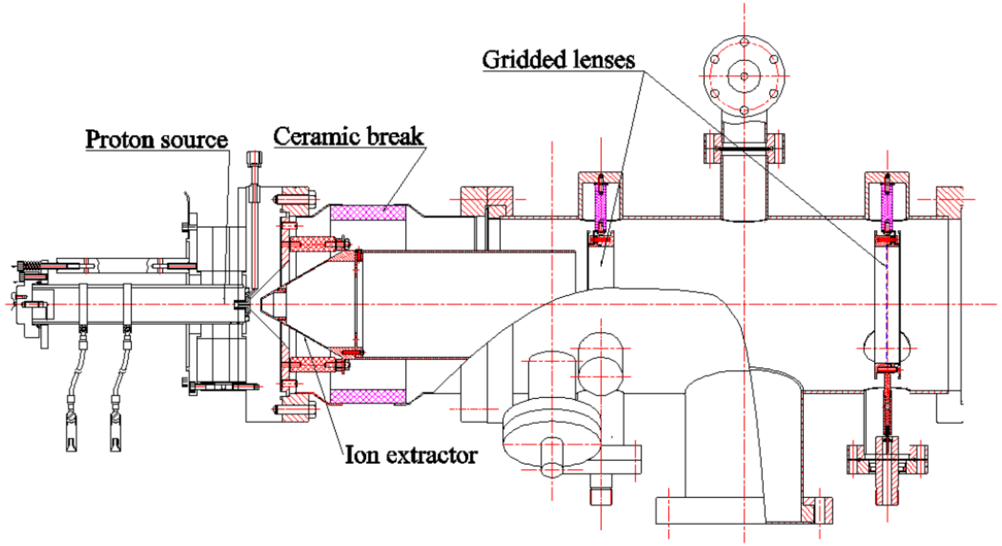



# Details on the two extractions and expectations 2/2



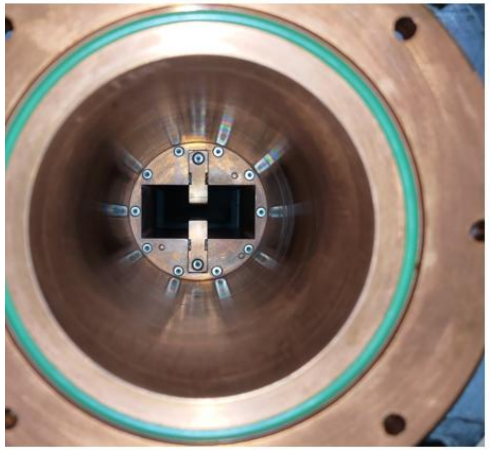

- 4 power supplies and 70 cm from the source plasma chamber to the RFQ matching plane
- Full flexibility in matching
- Possible emittance growth in the Einzel lens for higher intensity



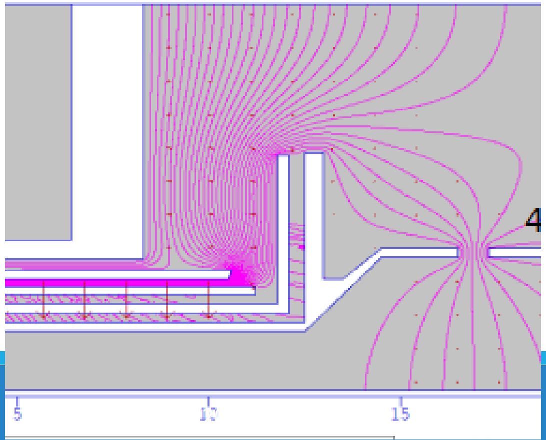



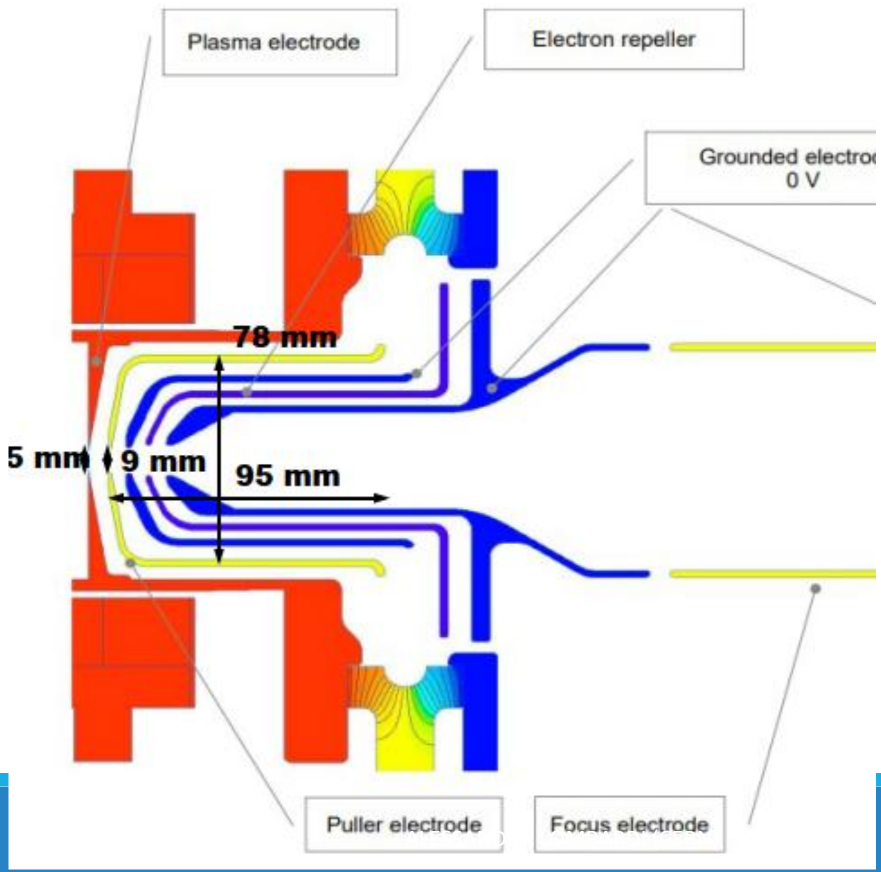
# Source 2 - Mono1000 ECR

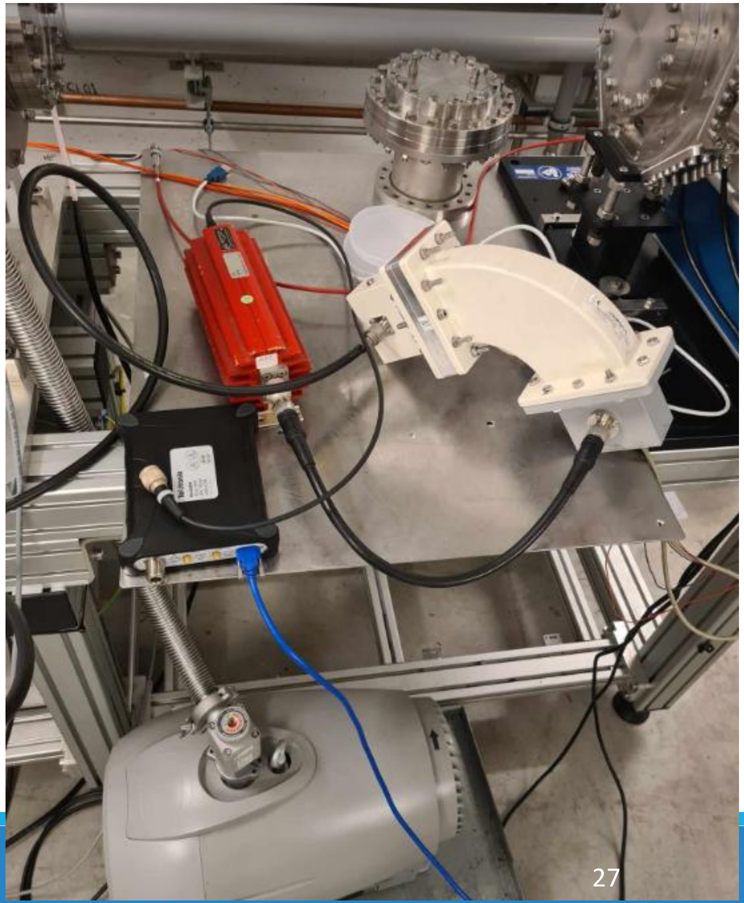
- Simulation of the present extraction
- Revamping the source used with the ADAM RFQ



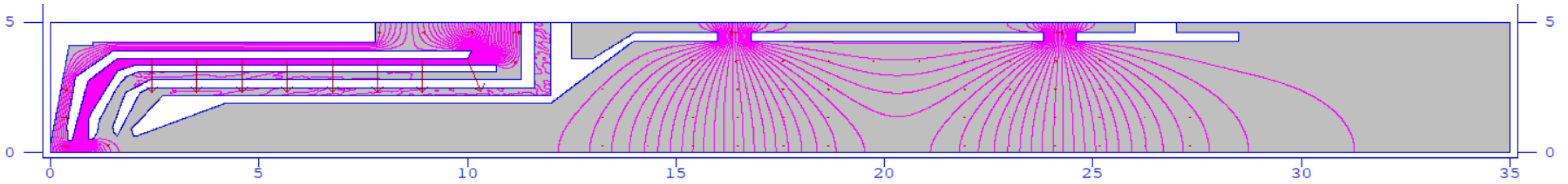
After

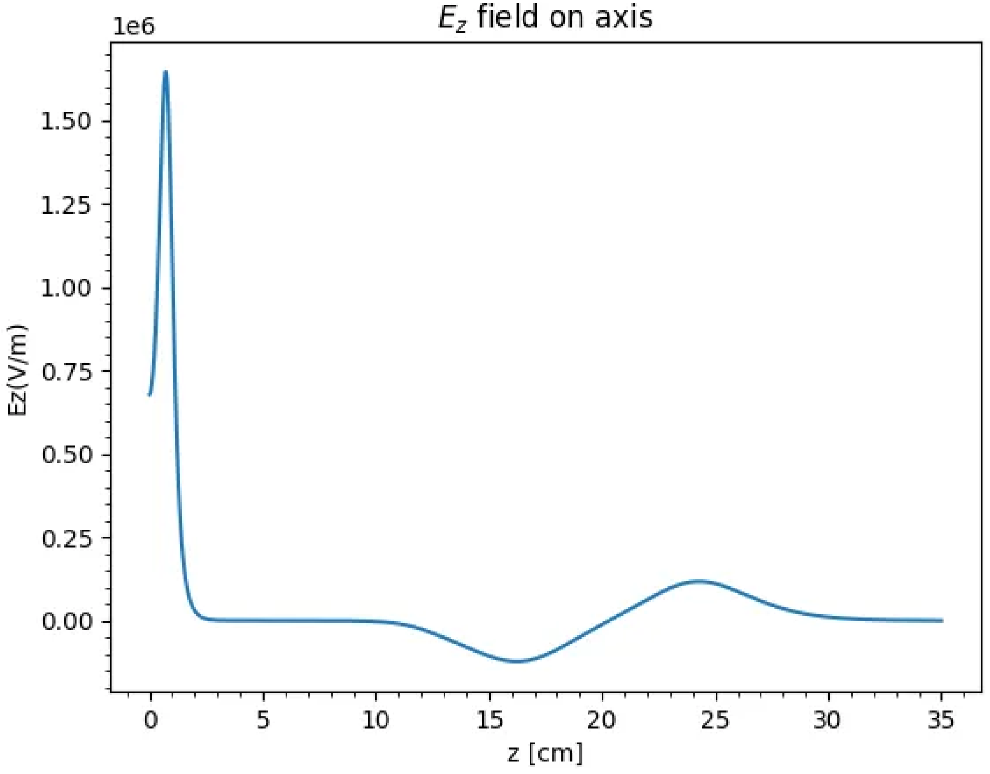


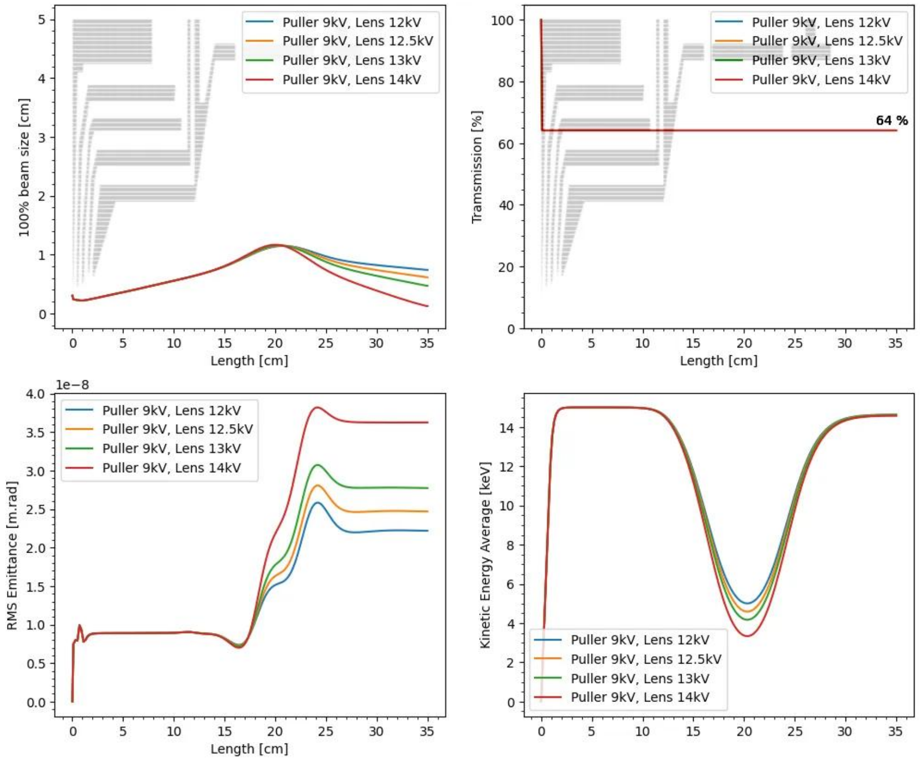


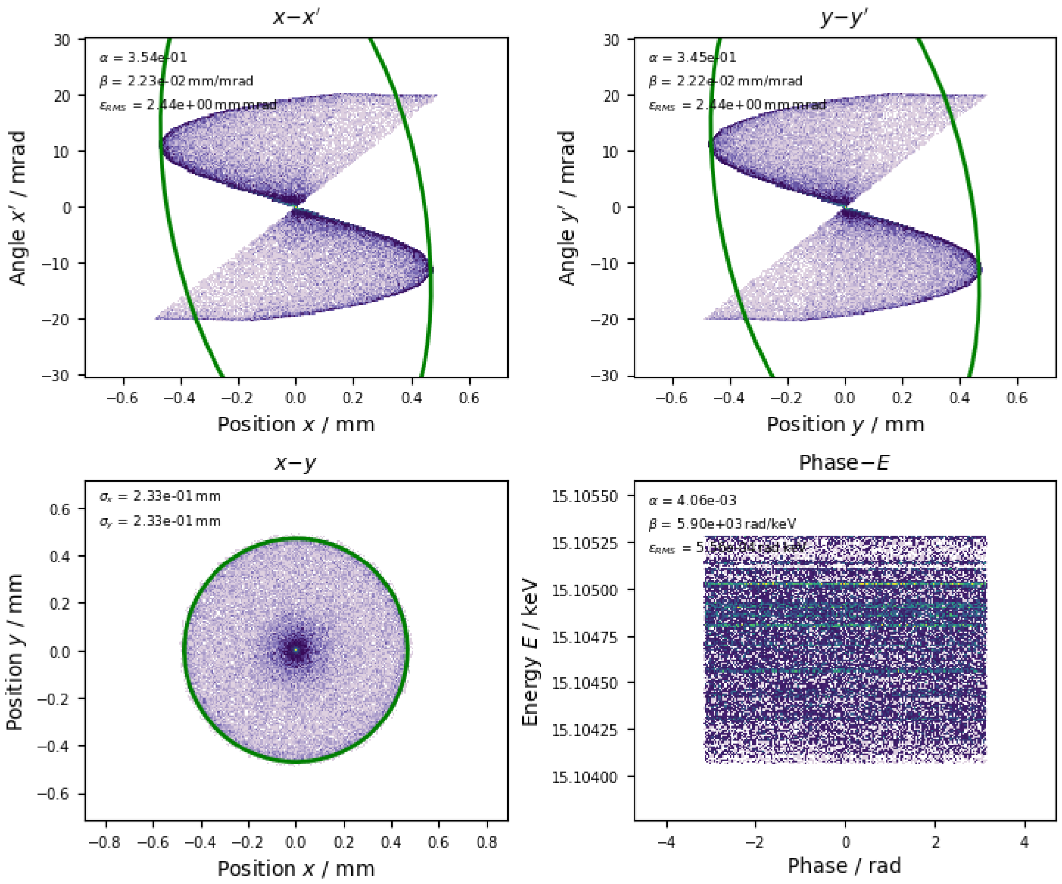
# source simulations-electrostatic field calculations



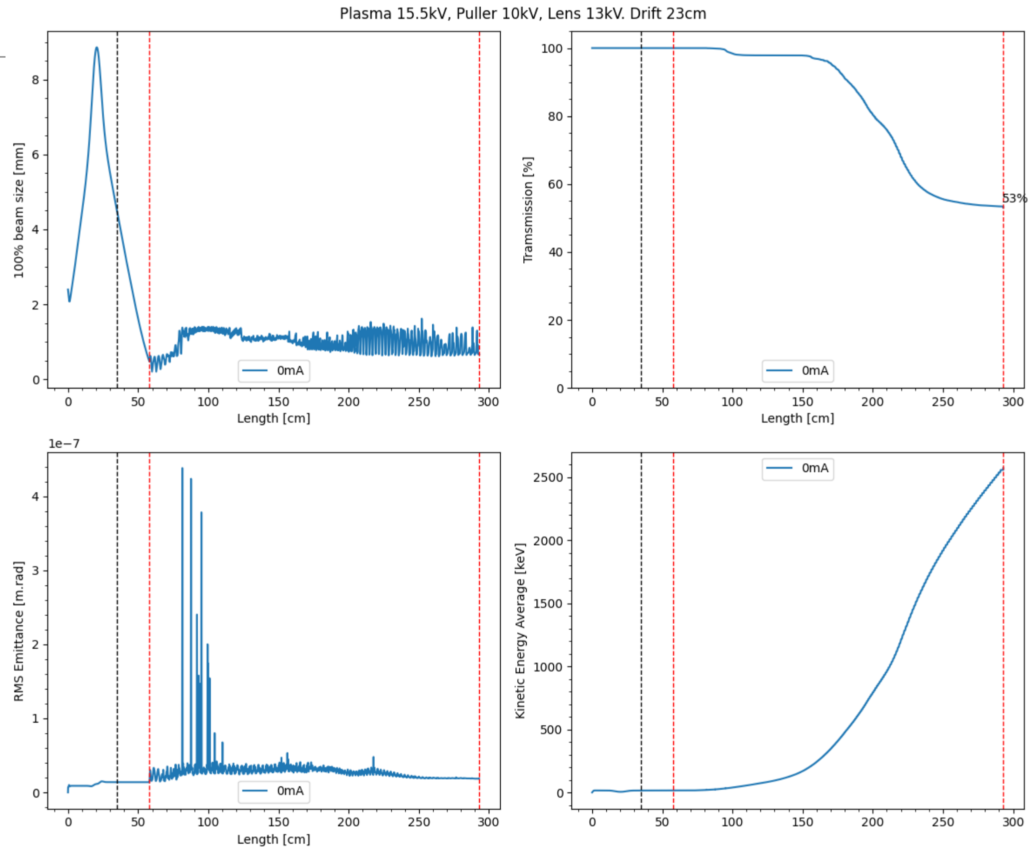


# Matching source beam to the RFQ




RFQ input beam
Green - acceptance




Transmission 53%

# Measurement

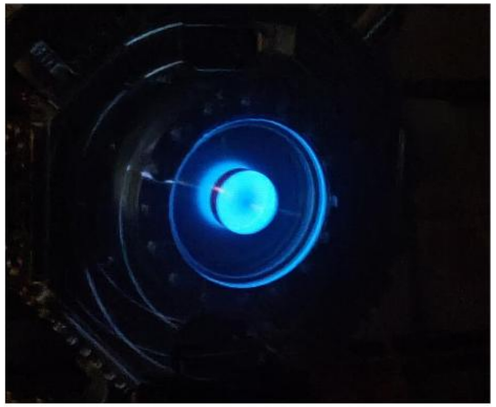
Source standalone

Proton energy 15KeV

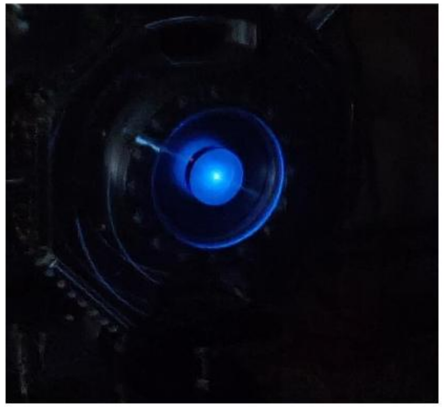
Intensity 100µA

Can go to 1mA

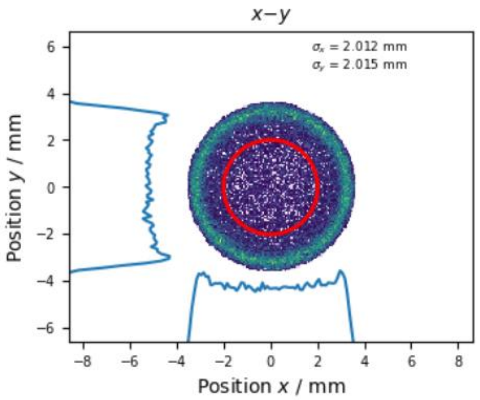
Lens <10kV



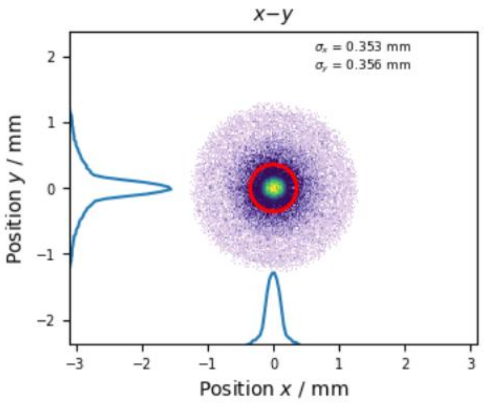
Lens 11kV



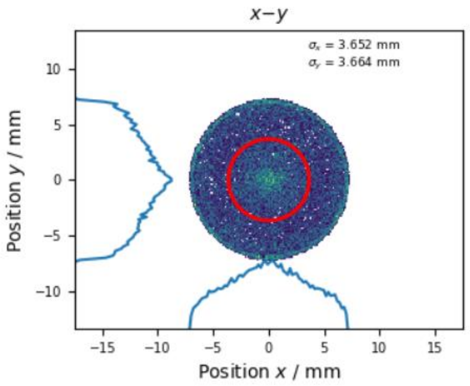
Big beam
Lens >12kV




Lens <12kV




Lens 13kV



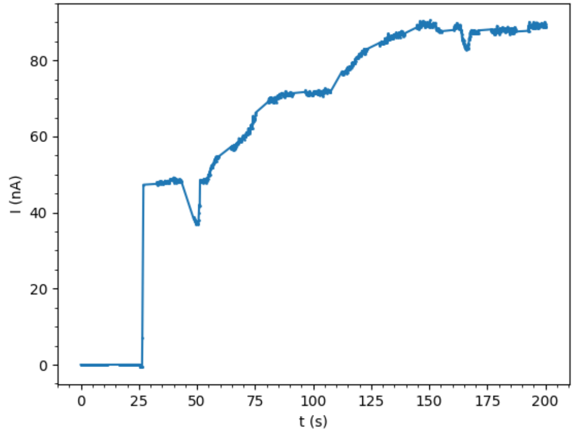

Lens 14kV

# Source 2 - Mono1000 ECR

- Assembled with the RFQ
- Faraday CUP at the entrance and at the exit of the RFQ
- 110uA for 10W in the source /90nA at the output of the RFQ unpowered
- 300uA for 20W in the source
- Beam went through the RFQ unpowered and was stereed

Low energy
Faraday cup
110uA/10W

High energy
Faraday cup
90nA/10W

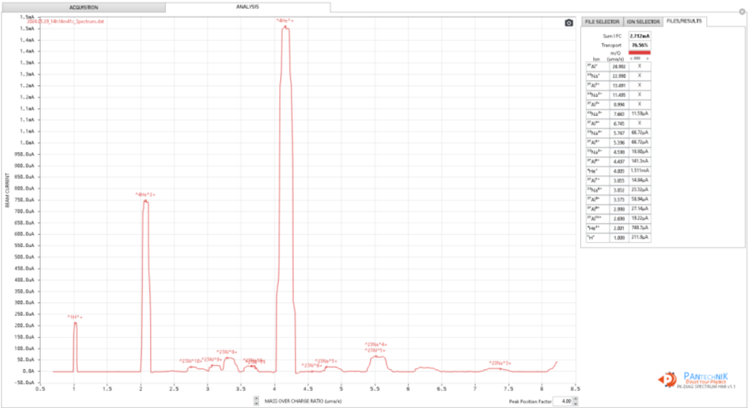


# Source 3 : Pantechnik supernanogun for UNSA– being assembled

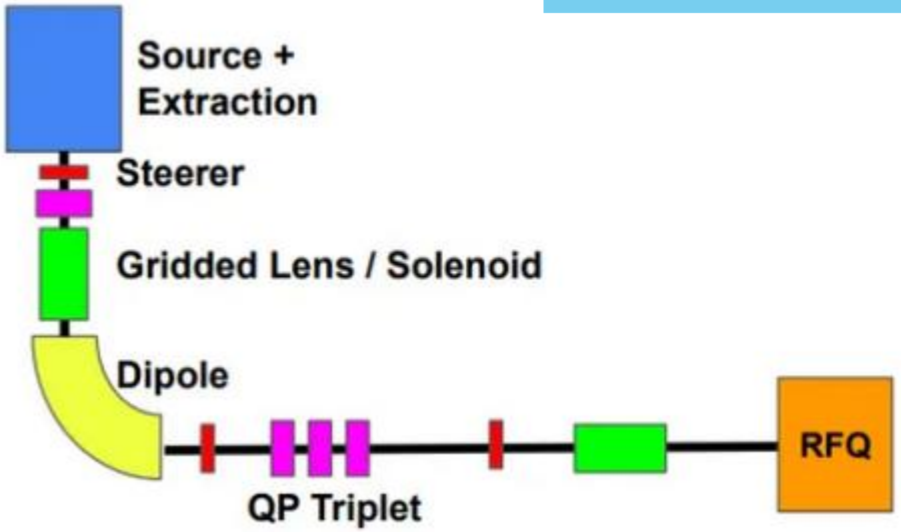
See
BOSNIAN HUB

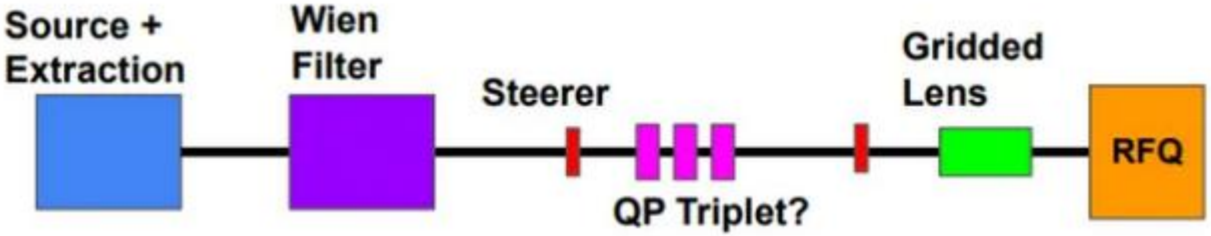
| Ions/Q | 1+ | 2+ | 4+ | 6+ | 8+ | 9+ | 11+ | 14+ | 20+ | 23+ | 25+ | 26+ | 27+ | 30+ | 31+ | 32+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | 2000 | | | | | | | | | | | | | | | |
| $H_2$ | 1000 | | | | | | | | | | | | | | | |
| $H_3$ | 700 | | | | | | | | | | | | | | | |
| He | 2000 | 1000 | | | | | | | | | | | | | | |
| C | 500 | 350 | 200 | 3 | | | | | | | | | | | | |
| N | 1000 | 300 | 100 | 10 | | | | | | | | | | | | |
| O | 1000 | 400 | 300 | 200 | | | | | | | | | | | | |
| Ne | 1000 | 300 | 200 | 160 | 25 | | | | | | | | | | | |
| Ar | 1000 | 350 | 250 | 200 | 200 | 90 | 30 | 1 | | | | | | | | |
| Kr | 1000 | | | | | | 25 | 15 | | | | | | | | |
| Ag | | | 250 | 250 | 200 | 90 | 30 | | 4 | | | | | | | |
| Xe | 500 | | | | 220 | | | | 15 | 14 | 10 | 5 | | | | |
| Ta | | | | | | | | | 4 | 0.8 | | | | | | |
| Au | | | | | | | | | | | | 10 | 6 | 1 | 0.7 | 0.2 |
| Pb | | | | | | | | | 10 | | 5 | 3 | 1 | | | |

- $^4He^+$ = 1500 eμA
- $^4He^{2+}$ = 750 eμA



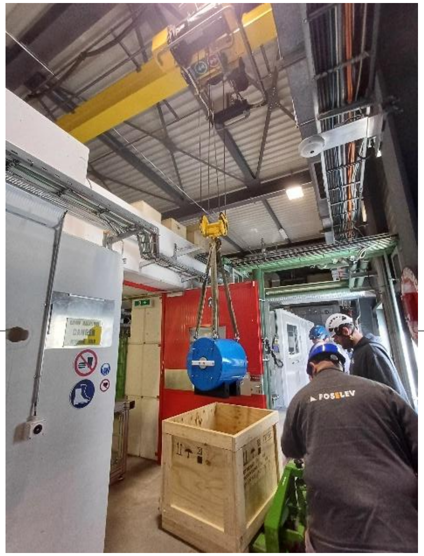
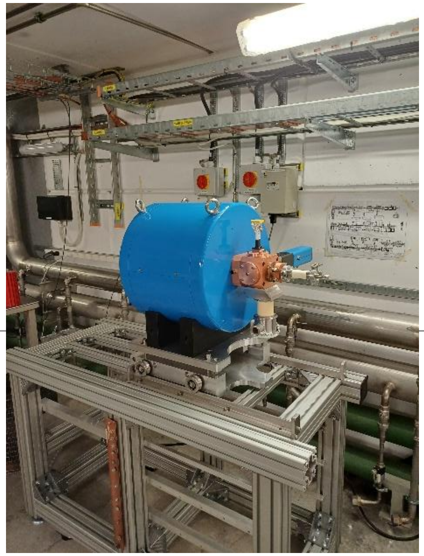
7 / 8 Modèle PK22-0103-AC01 PK24-3402-AC01_FAT Report.docm



# Source 3 – supernanogun

- Assembled in building 2250
- All power supplies tested with cosylab controls, rf amplifier next



# Future plans

We have in the test area

- A proton source designed to inject DIRECTLY into the RFQ –
- A helium source + a Low Energy Beam Transport designed to match a helium beam to the RFQ acceptance
- 750 MHz RFQ designed to accelerate from 15keV/ to 2.5 MeV/u particles with q/m =1/2

We will then

- Characterize the proton and helium sources for use with the RFQ and accelerate the beam through the Carbon RFQ
- Validate (hopefully ) the 750 MHz RFQ design and proceed to the construction of the second RFQ to bring the beam to 5MeV/u

Test stand at building 2250

- Ideal test bed for small accelerators for societal applications
- Proton therapy and art diagnostics is demonstrated, next challenges are helium/carbon ions and radioisotope productions, in line with IFIGENIA