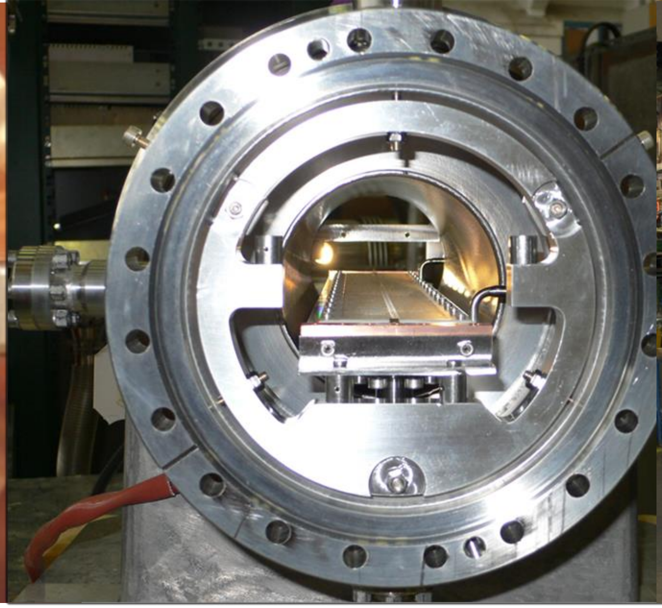
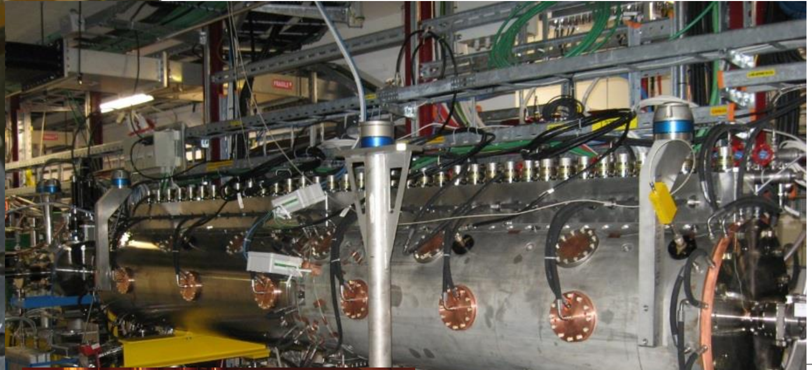
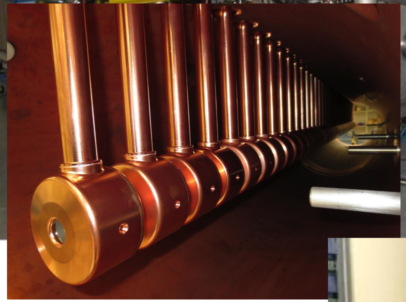
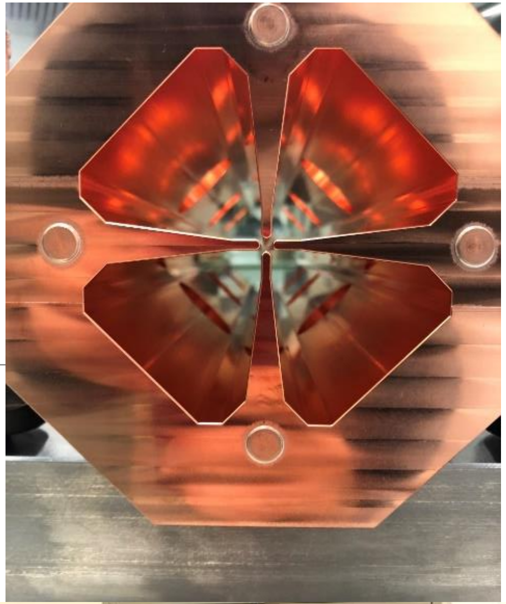
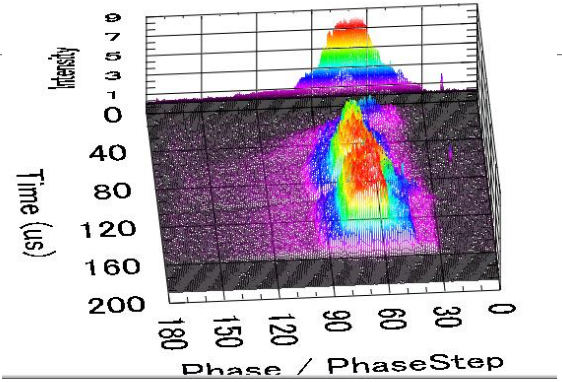
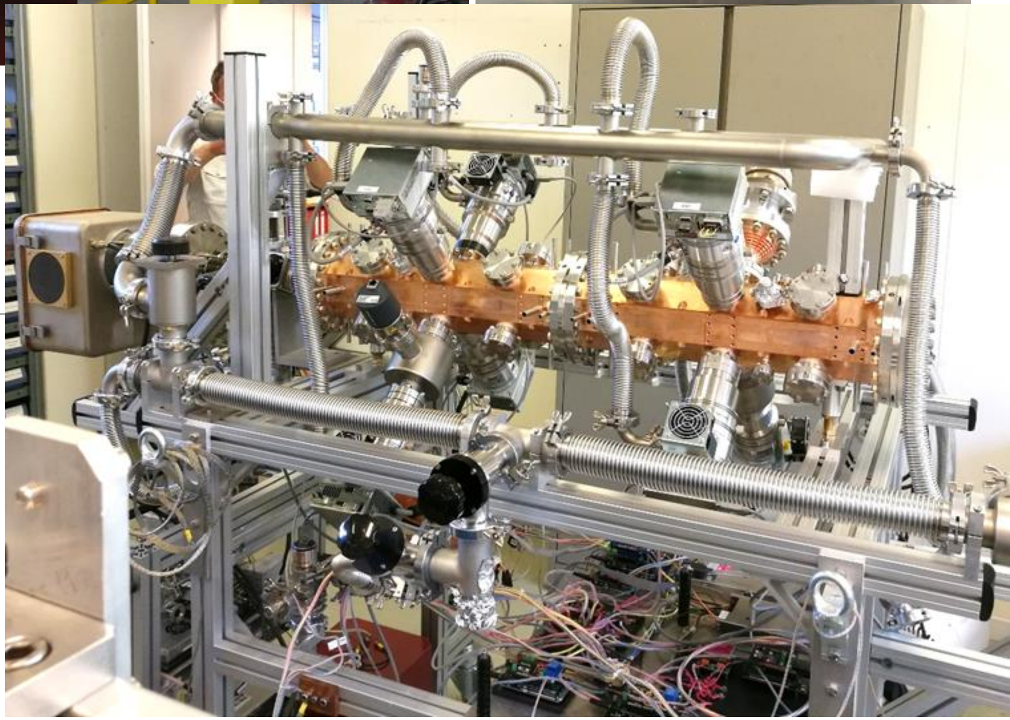






LINAC proton activities at CERN

Alessandra M Lombardi (BE-ABP-HSL)



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)

Name-to-be found : 750 MHZ RFQ for carbon ion (2020-under construction)

PS/RF/Note 96-27
25 October 1996

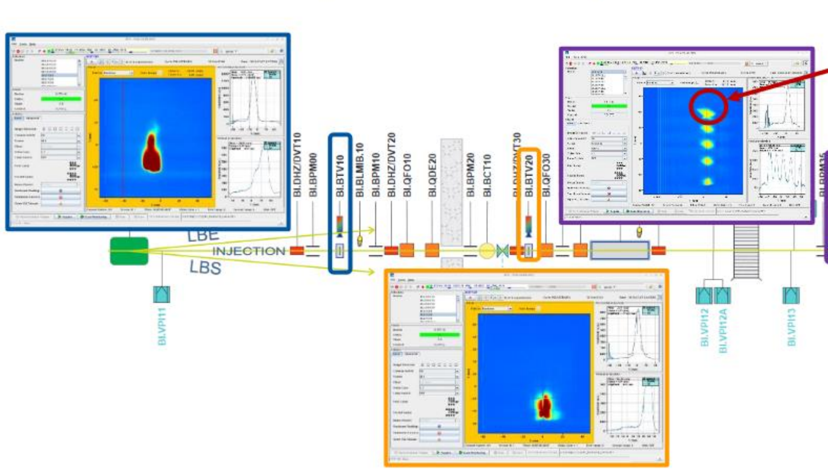
PROPOSAL FOR A 2 GEV LINAC INJECTOR
FOR THE CERN PS

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

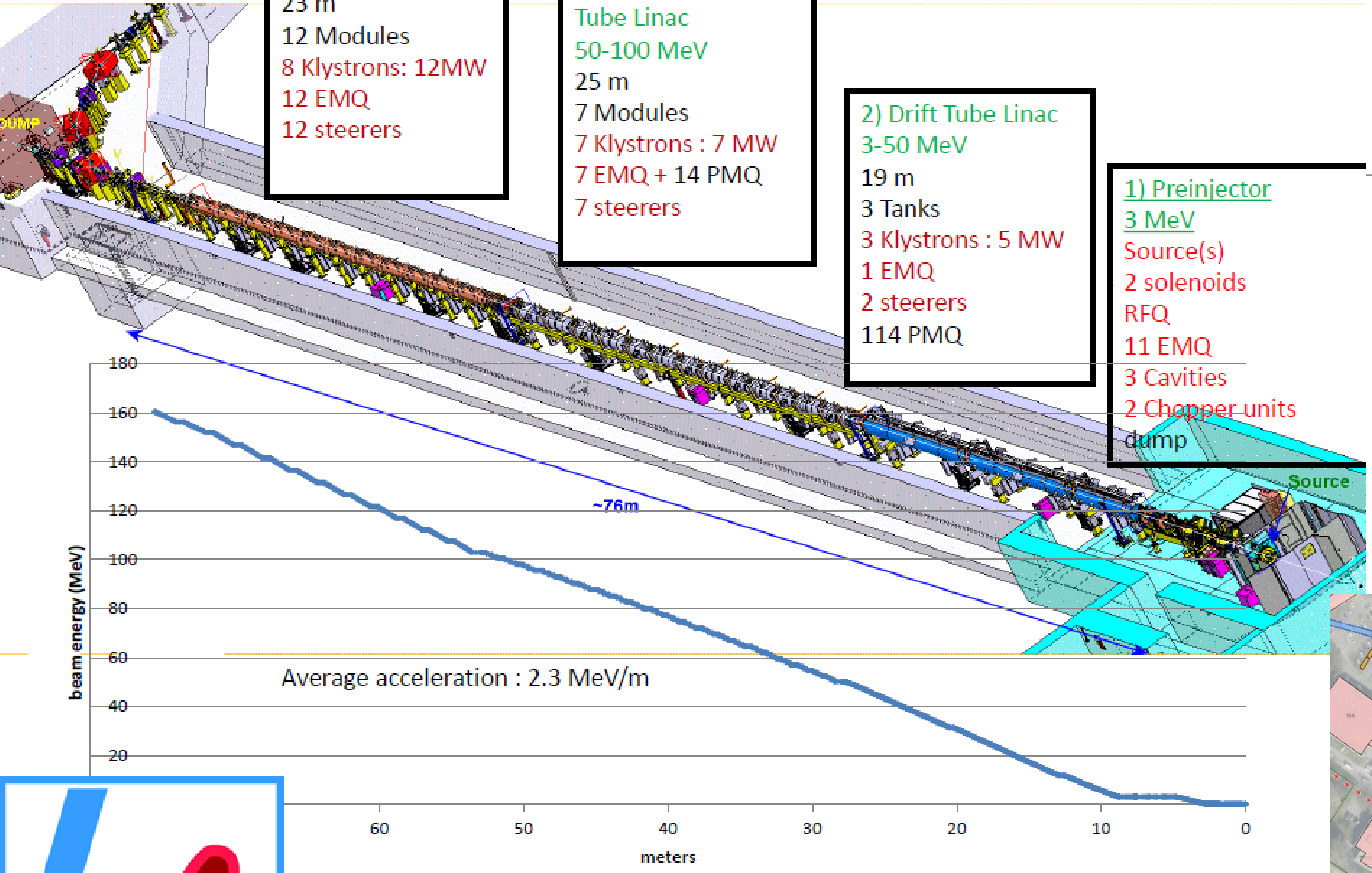
In its June 2007 session the CERN Council has approved the White Paper "Scientific Activities and Budget Estimates for 2007 and Provisional Projections for the Years 2008-2010 and Perspectives for Long-Term", which includes construction of a 160 MeV H- linear accelerator called LINAC4, and the study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

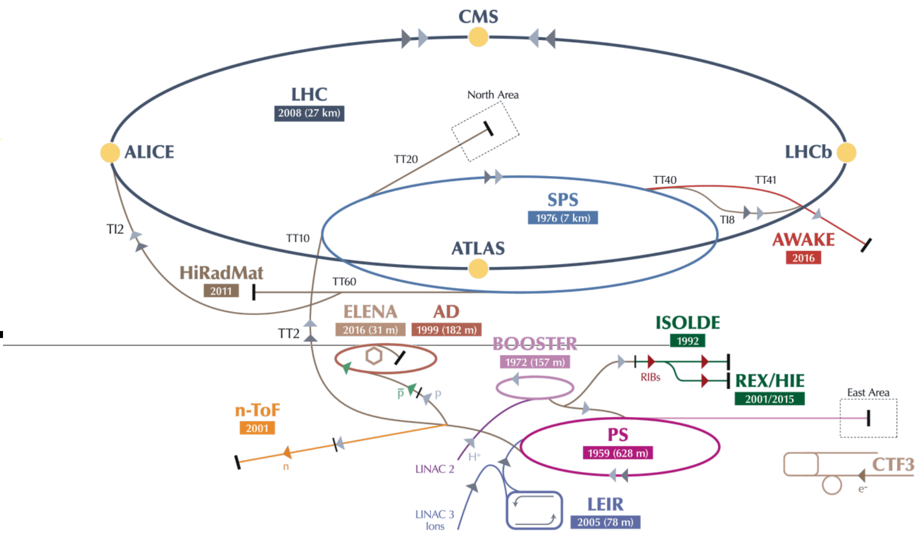
4) Π-mode Structure
100-160 MeV
23 m
12 Modules
8 Klystrons: 12MW
12 EMQ
12 steerers

3) Cell-Coupled Drift Tube Linac
50-100 MeV
25 m
7 Modules
7 Klystrons : 7 MW
7 EMQ + 14 PMQ
7 steerers

2) Drift Tube Linac
3-50 MeV
19 m
3 Tanks
3 Klystrons : 5 MW
1 EMQ
2 steerers
114 PMQ

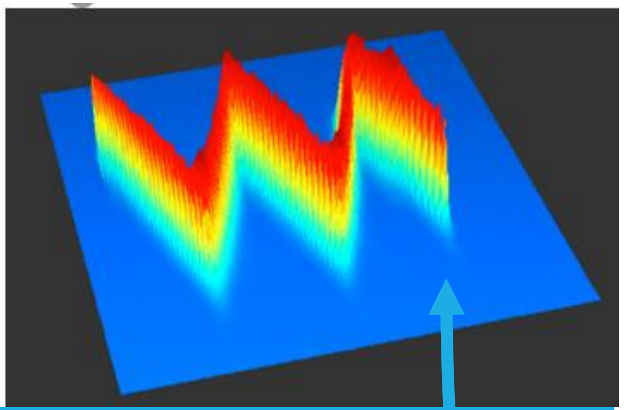
1) Preinjector
3 MeV
Source(s)
2 solenoids
RFQ
11 EMQ
3 Cavities
2 Chopper units
dump





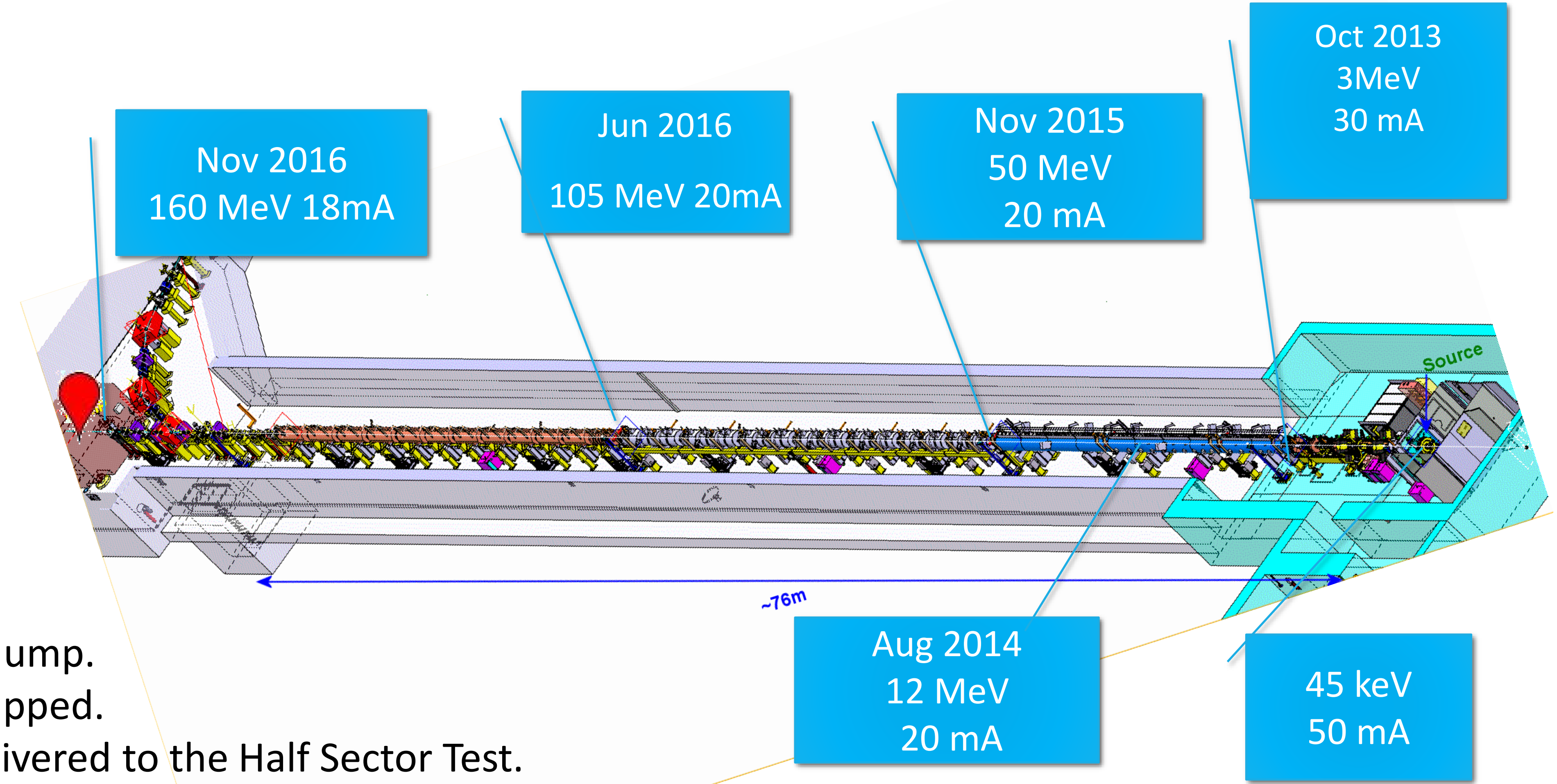
Frequency : 352 MHz
Duty cycle for PSB : 0.06 %
Max duty cycle : 5%
Located 12m underground

Baseline beam parameters



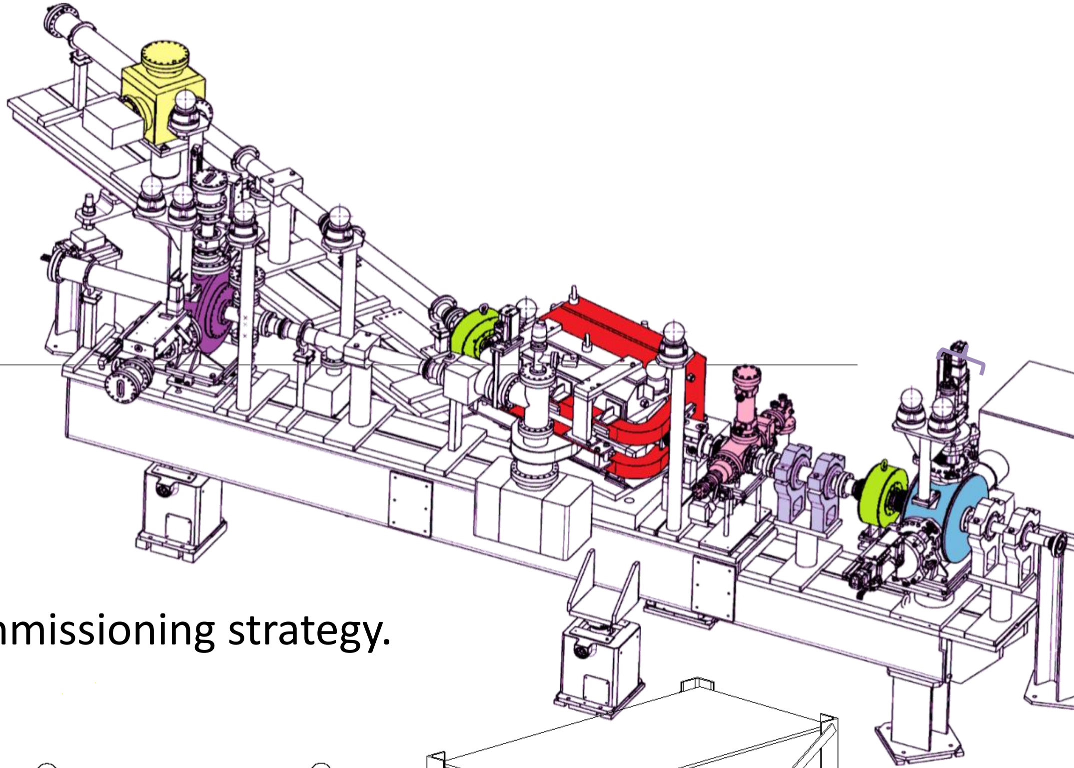
LINAC4 – CDR -2006	LINAC4 – achieved (2016) and perfected 2016-2019	
H-	Stripping and more tested in Half Sector Test	
70mA peak at the source 65 ma peak at 3 MeV 40 mA after chopping	50mA peak (in twice the acceptance of the RFQ) 30 mA peak at 3 MeV (record) 20 mA after chopping	Peak current from the source Average beam current after chopping (LEBT and RFQ transmission and chopping factor)
160 MeV	160.48 MeV	All RF structures performing to specs
0.4 π mm mrad	0.3 π mm mrad (at 160MeV)	Smaller emittance , allows for more turns injected
400 µsec 1Hz (4 rings)	Up to 600 µsec 1Hz	Longer injection in the PSB (100-150turns)
Fast Chopping at 3 MeV	Demonstrated , including transmitted beam quality	Unprecedented flexibility: Beam from 1µsec to 150µsec
Energy painting with the last accelerating modules	proof of principle of energy painting	Measured phase variation for 100 µs long pulse when a energy variation is programmed along the pulse –

Commissioning in stages of increased energy



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

Temporary measurement benches

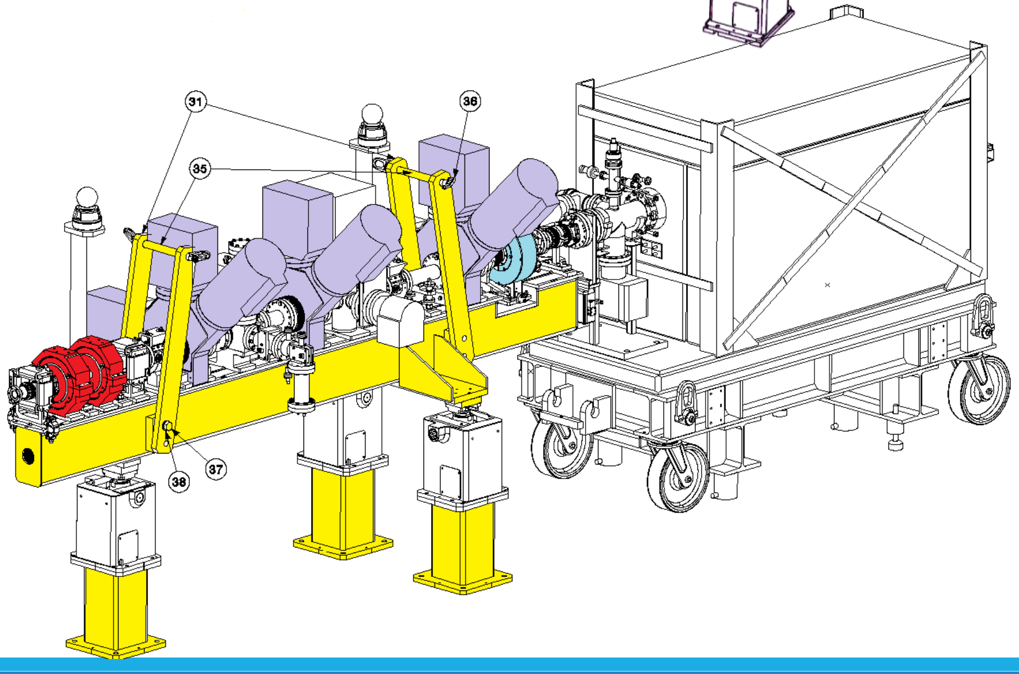


Low energy test bench at 3 and 12 MeV
Direct measurements:
- Transverse emittance with slit-grid.
- Energy – Energy spread with a spectrometer.

Taking data for preparing and gaining confidence in higher energies commissioning strategy.

High energy test bench at 50 and 107 MeV
Indirect measurements:
- Transverse emittance with 3 profile monitors.
- Longitudinal emittance with bunch shape monitor.

Energy with Time of Flight.

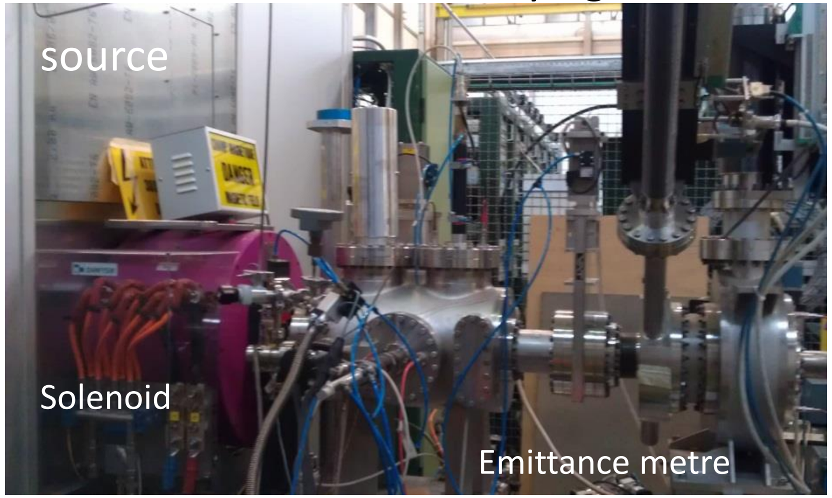


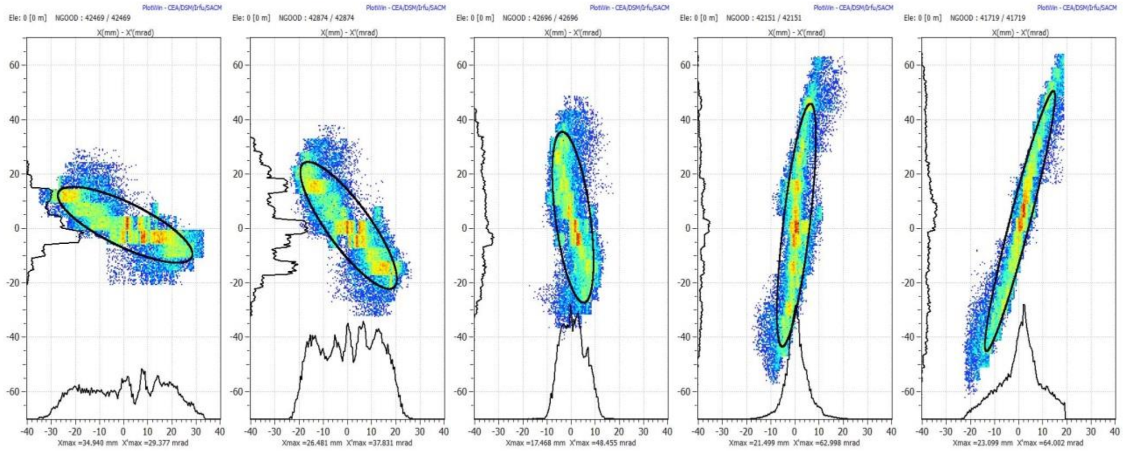
Permanent measurement line in the transfer line for 160 MeV
4 profile monitors, beam current transformer and BPMs.

This turned out to be a CRUCIAL STEP-see next slide

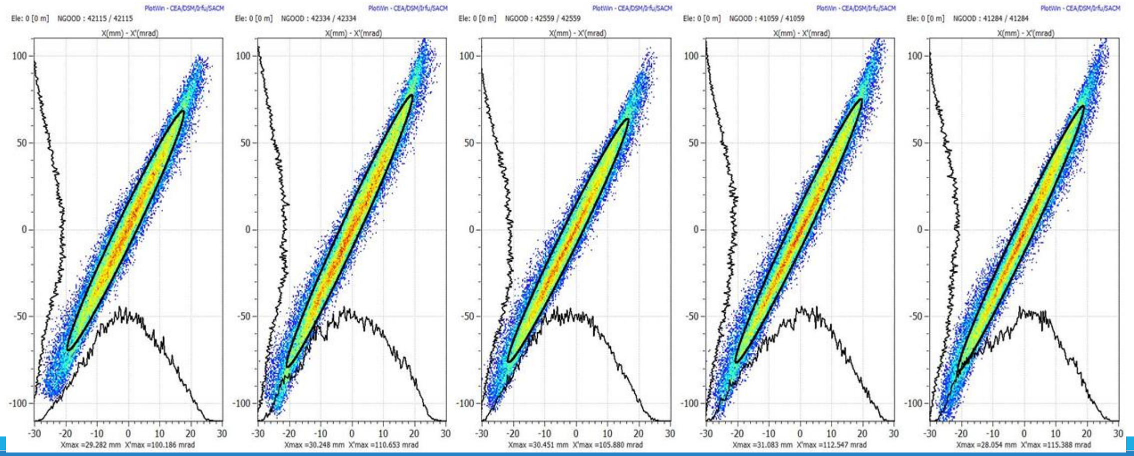
Extensive measurements at 45 keV

1- take measurements varying solenoidal field and generate in tracking code





2 – back-trace to source out



3 - Result : we have an empirical input beam distribution that very well represents the dynamics in the LEBT and the rest of the accelerator.

Transverse emittance at higher energies

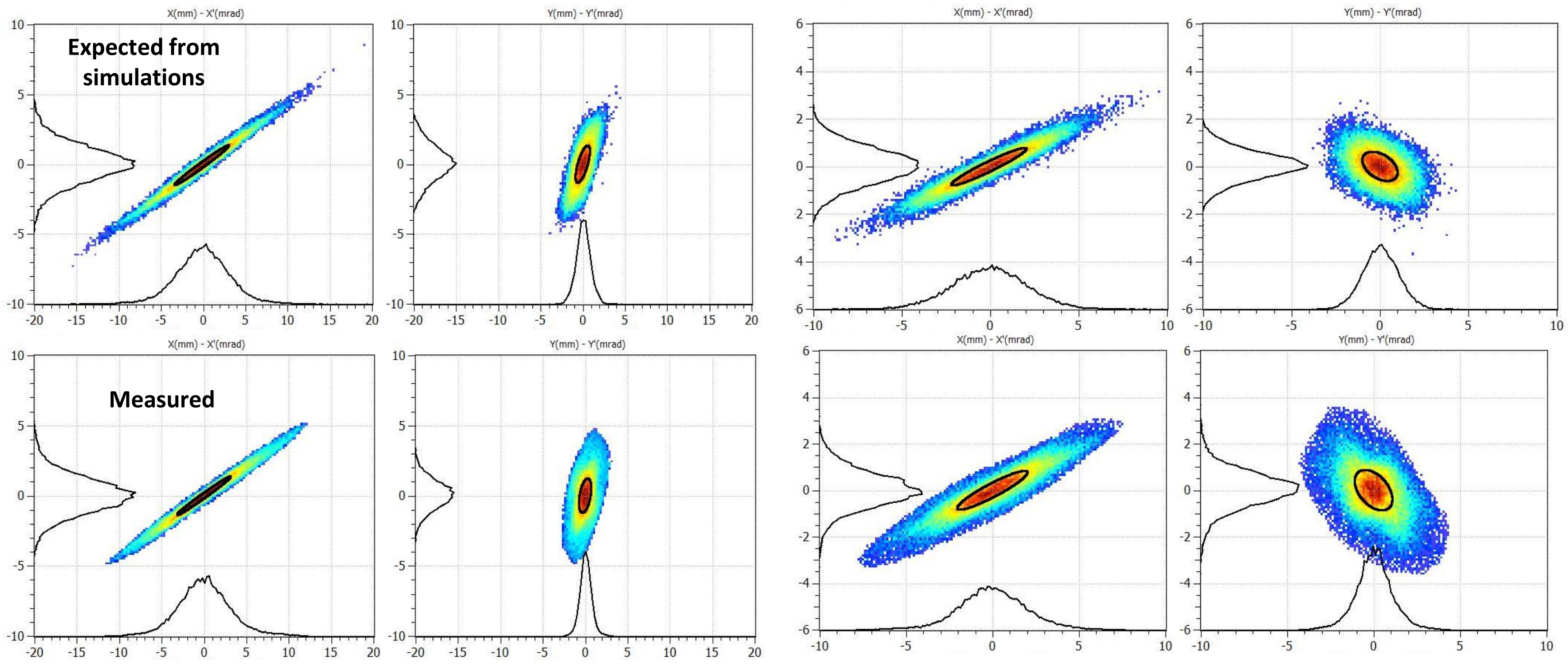
Transverse emittances were indirectly measured with:

- the “**Forward method**”
- the “**Hybrid Tomographic method**”

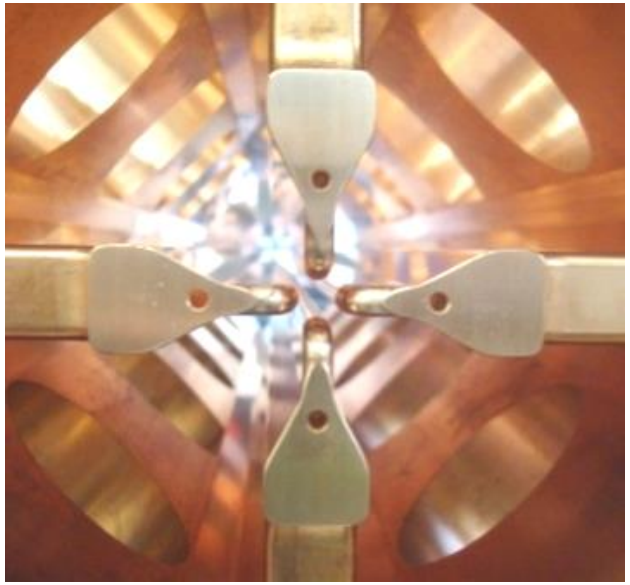
Both based on: The 3 profiles method – Including the space charge forces with multi-particle simulation codes.

@ 50 MeV

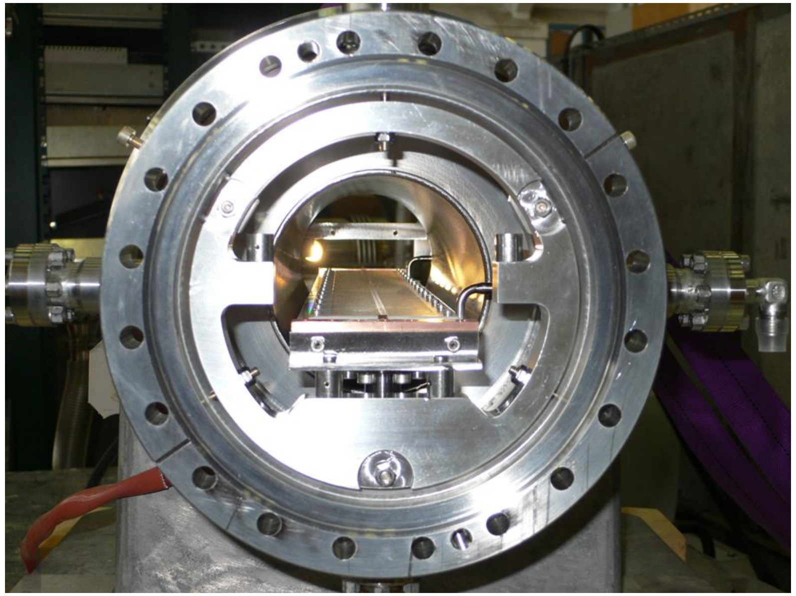
@ 107 MeV



Innovations in LINAC4



3 MeV/ 352 MHz/ 3 m long RFQ
Commissioned with beam 2013

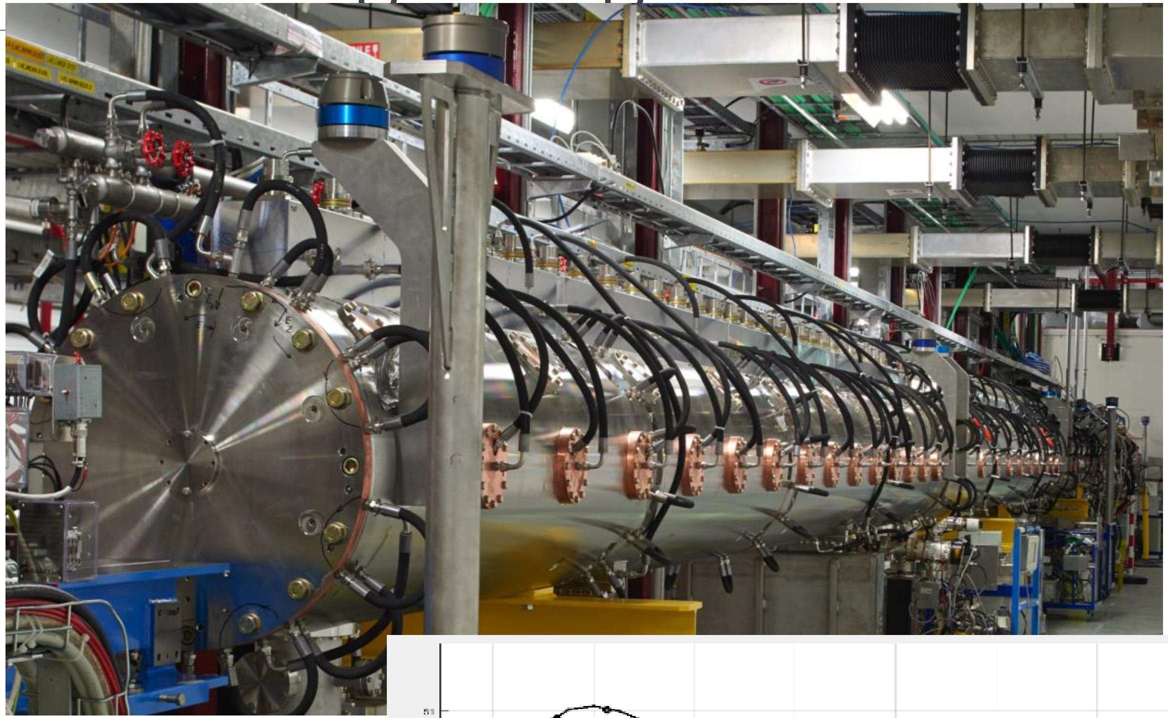


Fast chopper, validated 2013
Risetime<10nsec/ extinguish factor 100%

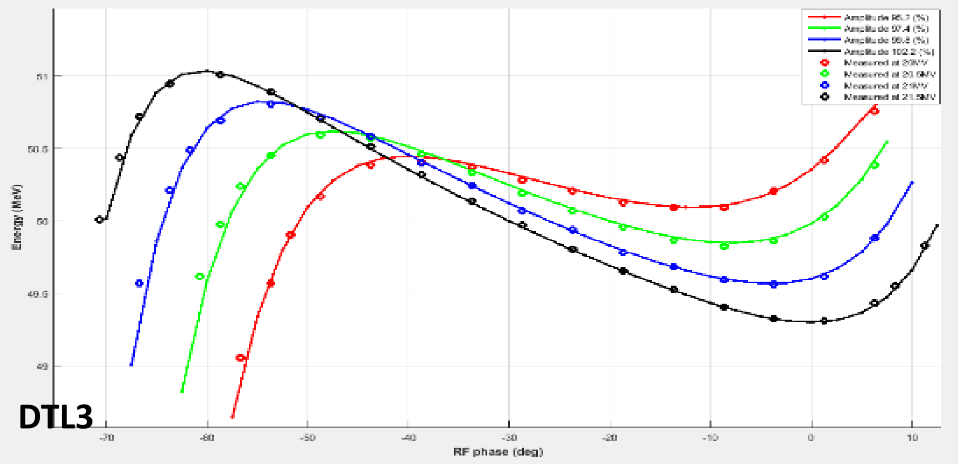
PMQ for tank2 , 60 mm in diameter and 80 mm in length
Produced in European industry for the first time

Drift Tube Linac : 3-50 MeV

(3-12-30-50 MeV, commissioned in 2 stages Aug 14 and Nov 15)

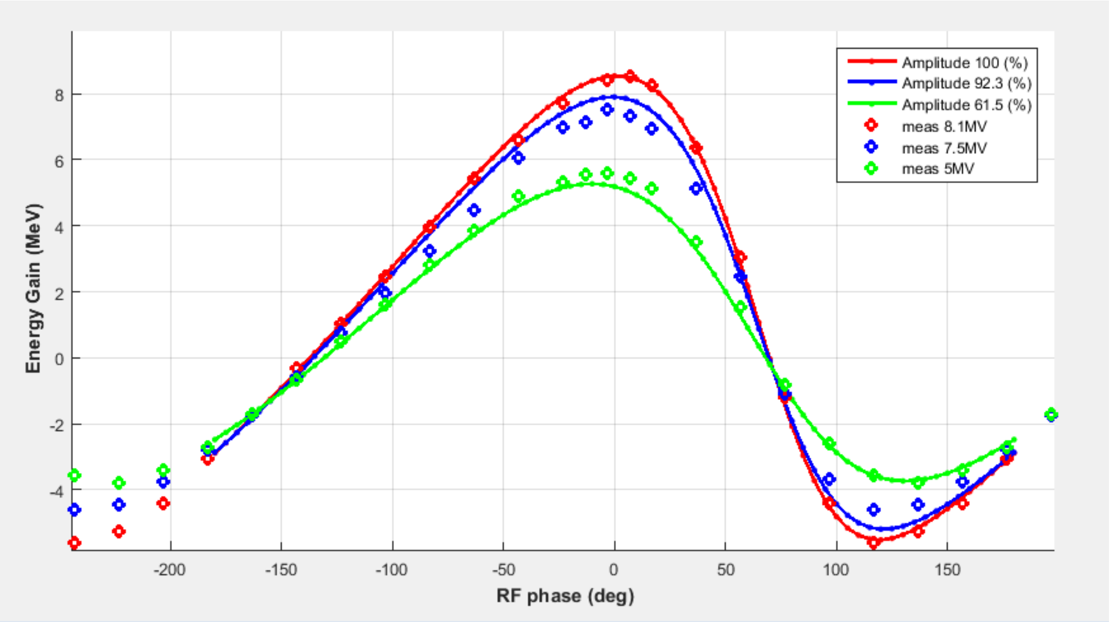


3 tanks



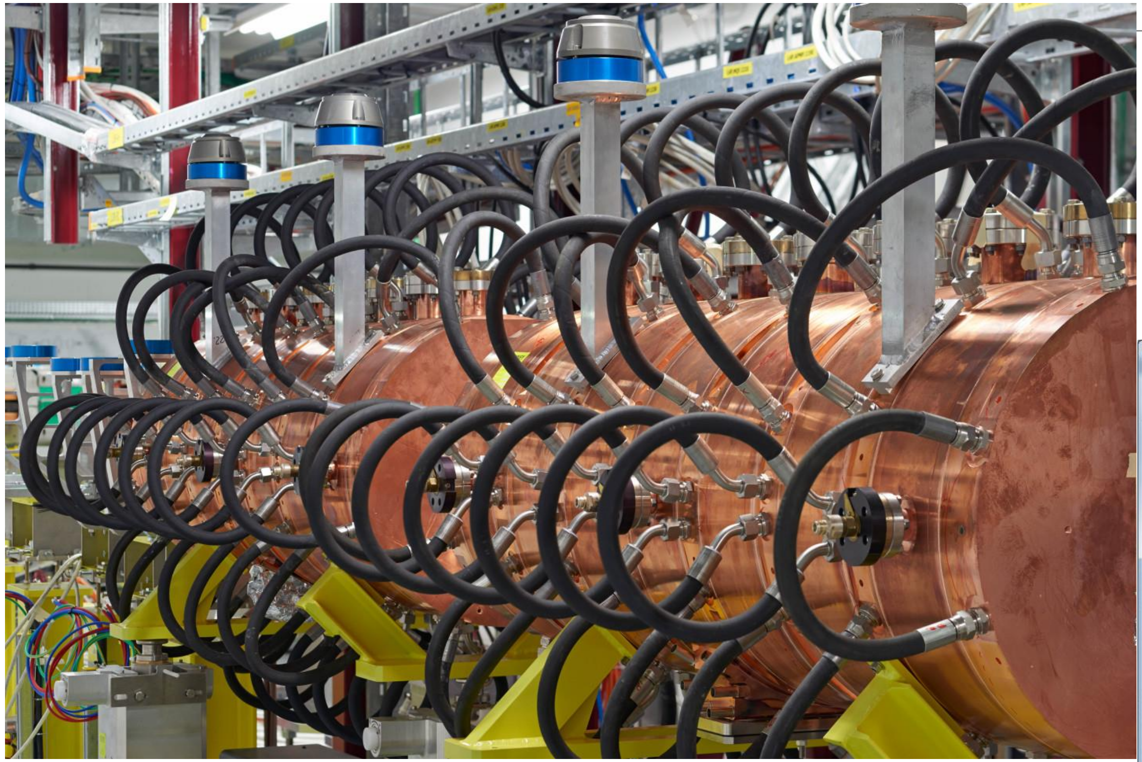
Cell Coupled Drift Tube LINAC : 50-100MeV (commissioned June 16)

- 7 modules of 3 accelerating cavities (3 gaps each) and 2 coupling cells,
- quadrupoles outside of RF structure,
- first-ever CCDTL in a working machine!

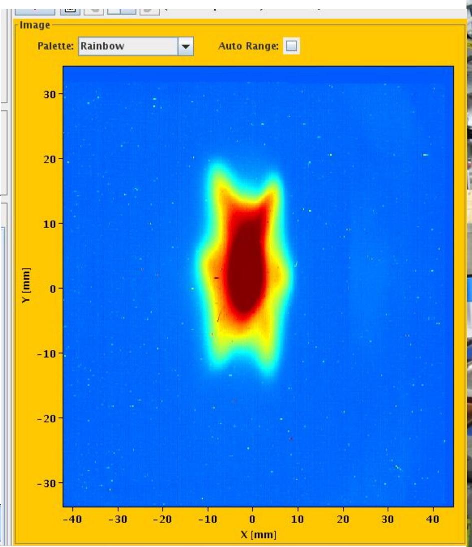


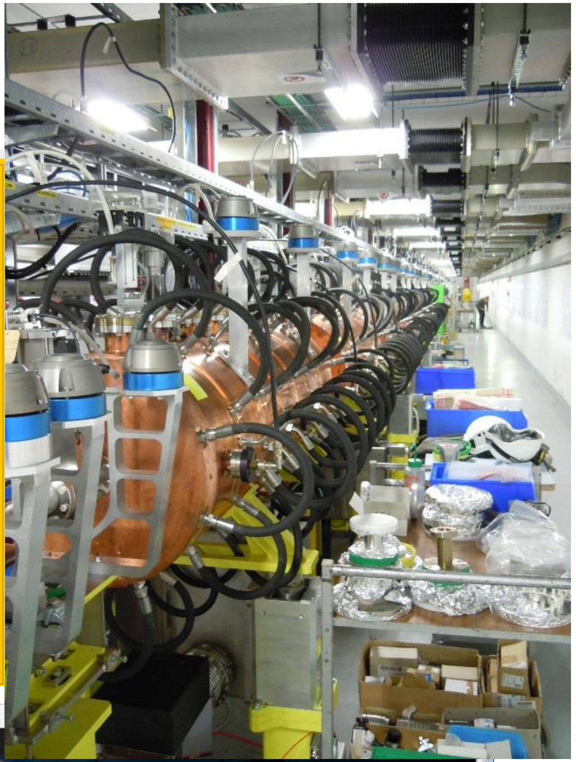
Average energy vs cavity phase for CCDTL module 3 measured June 2016 with Time-of-Flight

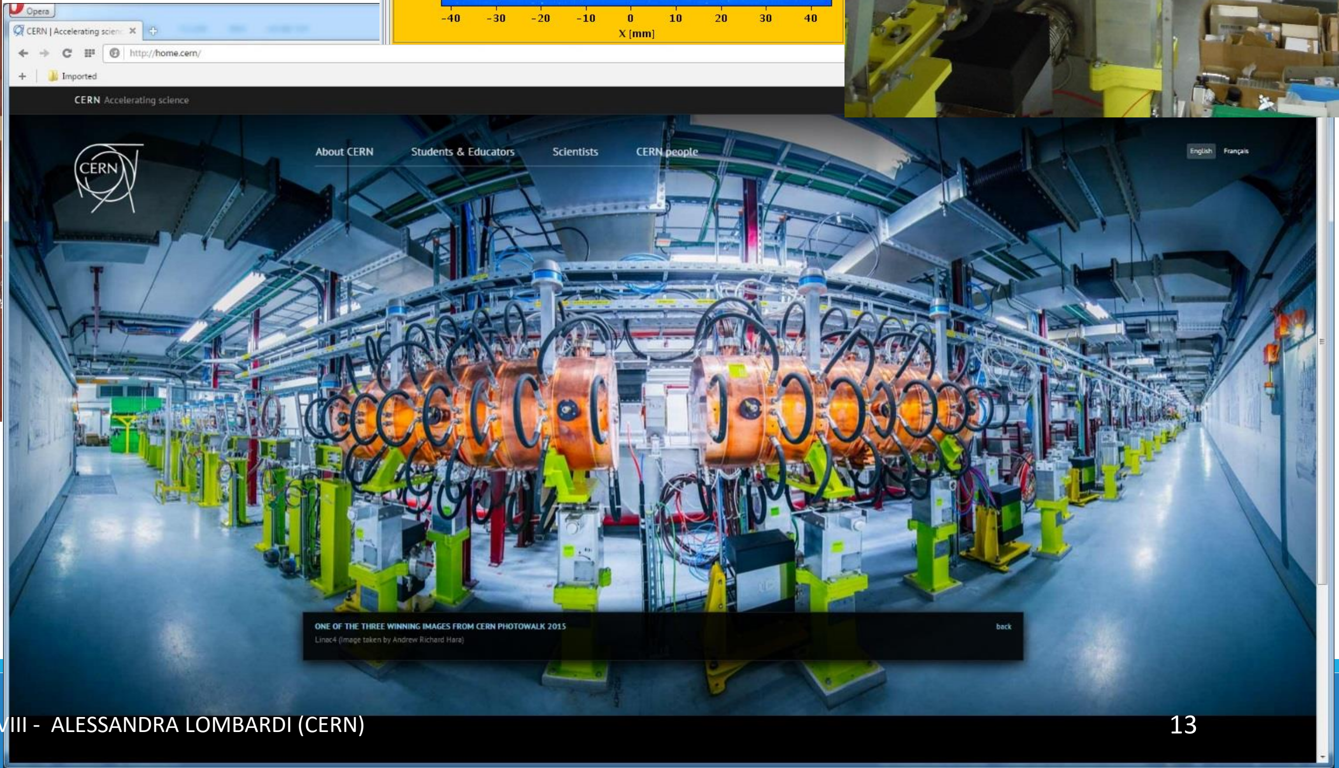
Pi-mode structure : 100-160 MeV (commissioned Oct 16)



Beam transverse footprint – stripped – 160 MeV at BTV1077 , Mar 2017





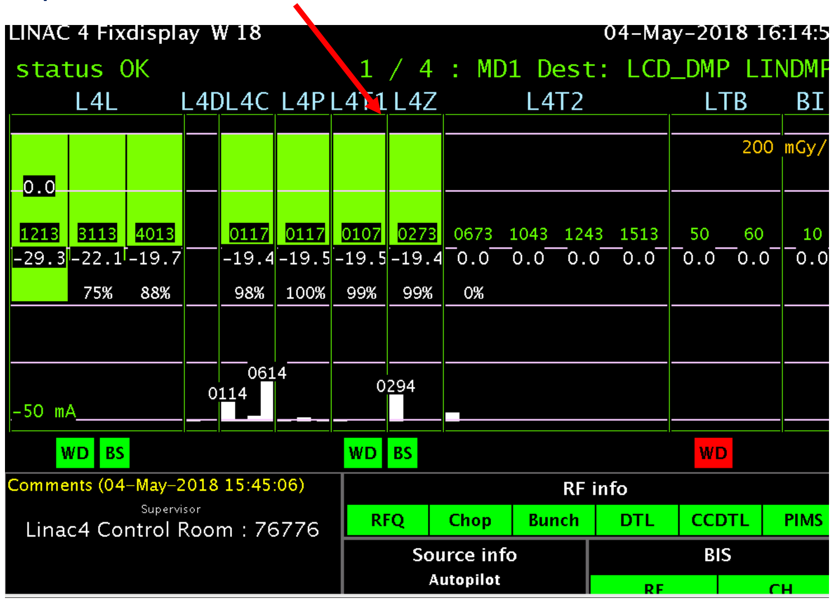


Reliability run

1. Insure a smooth transition from commissioning to operation: train operators, necessary software development, learn to deal with the increased flexibility.
2. Find any weak points and mend them in time for the connection
3. Achieve a *beam-availability* for the PSB as high as possible and possibly above 90% : importance of the fault tracking system

From 2016 it was all about intensity and reliability : 160 MeV on the dump

Criterium for LINAC4 availability: Current in BCT before the dump



LINAC4 run 24/7 in parallel to normal operation on **best-effort basis** with:

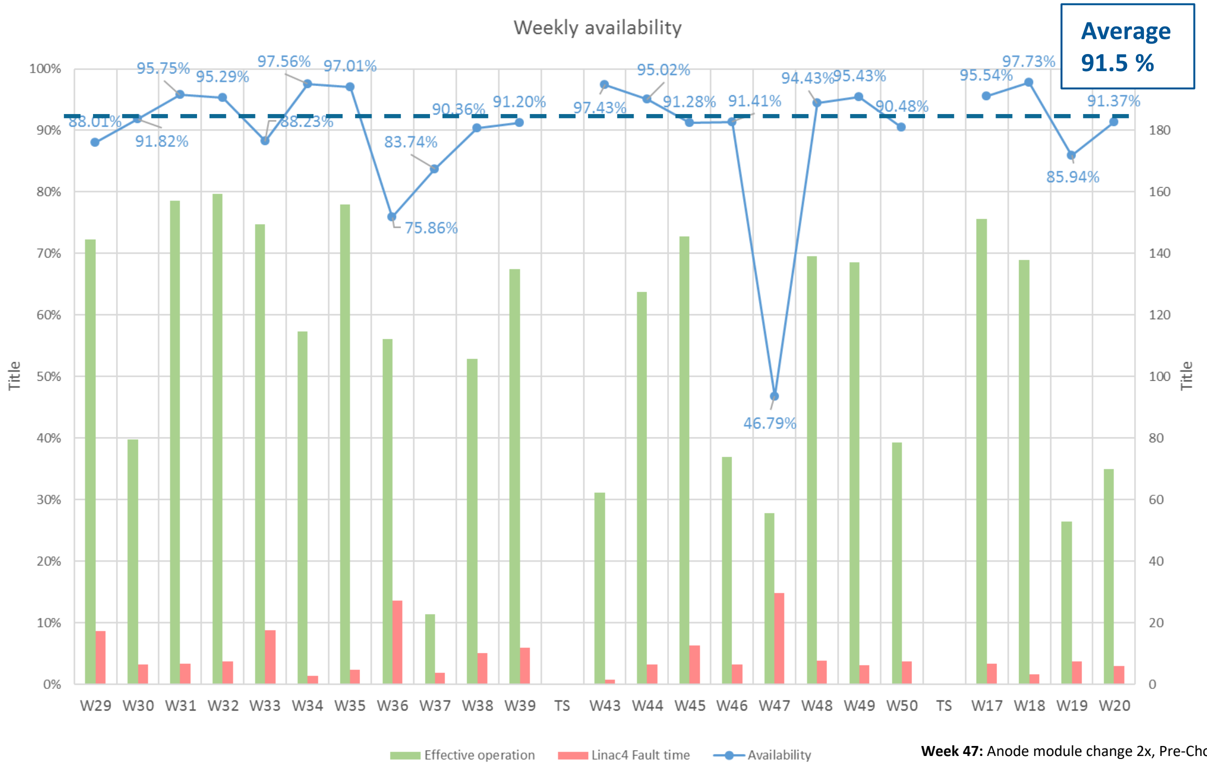
- Operators deal with issues where possible
- **Expert** availability and interventions **only during working hours**
- Faults are fully tracked (Accelerator Fault Tracker AFT)
- Stop AFT Clock during off-hours when fault needs expert intervention & during MDs

Thorough logbook verification w/ Timber/LASER information

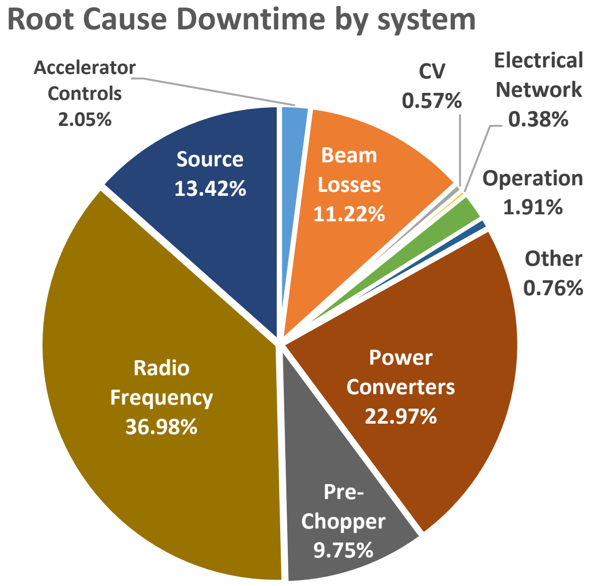
First availability run

Period: 13/07/2017 – 15/05/2018
Last update: 05/06/2018

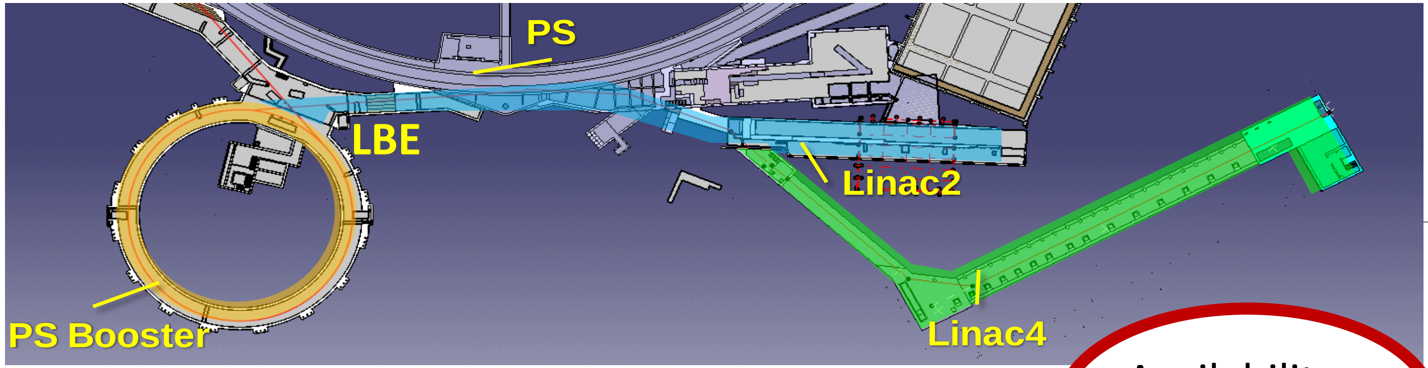
Availability	Fault Count	Operation	Suspended OP	Effective Operation	Fault Mean Time to Repair
91.5%	**449**	23 weeks	~ 8 weeks	~15 weeks	~29 min



Week 47: Anode module change 2x, Pre-Chopper connector to feedthrough to vacuum

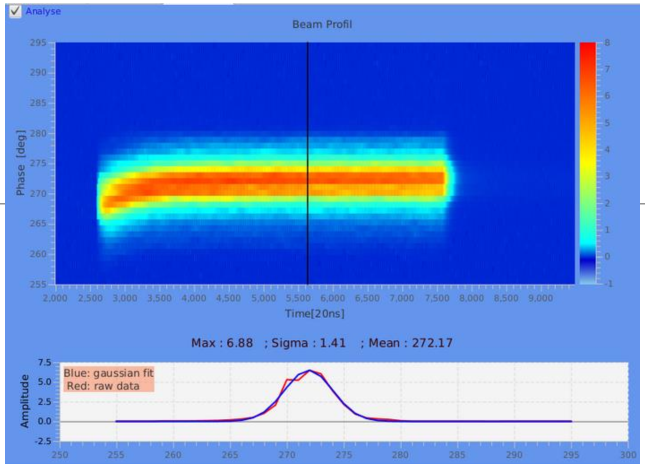


2019 : Beam to the LBE !

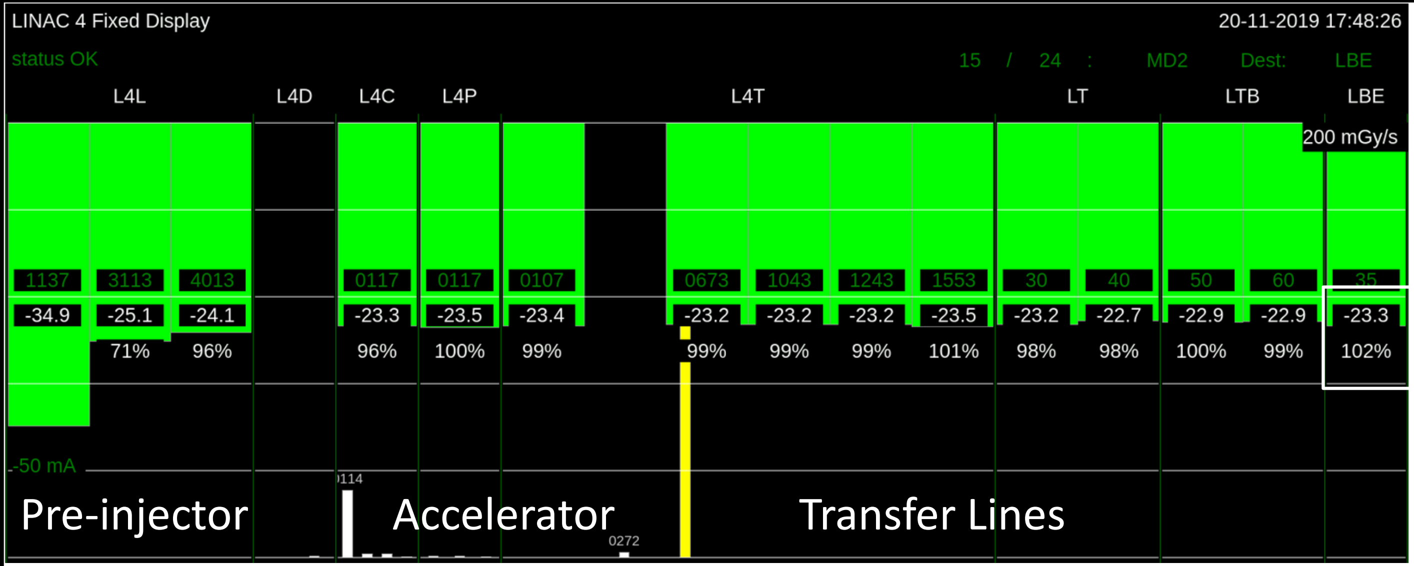


Availability
93.9%

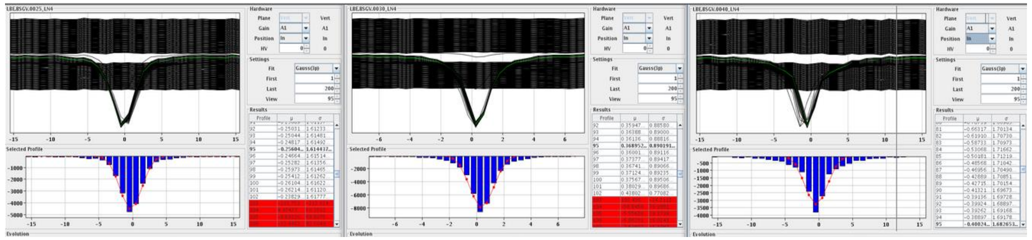
- Excellent transmission from 3 MeV to the LBE
- Routinely 23mA (un-chopped) that allows the production of all the pre-LS2 beams
- The devil is in the pre-injector



Beam phase spread at 160 MeV – in specs.



96% transmission from 3 MeV to the LBE – 23mA suitable for all pre-LS2 beams



Emittance measurements in LBE – as expected

LINAC4: measured beam characteristics

Parameter	Measurement
Peak intensity at 160 MeV	25 mA
Emittance rms normalized	0.3 π mm mrad
Max usable pulse length	600 μs
Stability shot-to-shot	2%
Pulse flatness	2% for 160μs pulse 5% fpr 600μs pulse
Beam position jitter along the pulse at the linac dump	+/- 1mm
Fast Chopping at 3 MeV	Rise time < 10ns Extinction factor close to 100% Unprecedented flexibility: beam 1-600 μs

AVALIABILTY 2021 : 99%

LIGHT pre-injector

Operation and beam commissioning of LIGHT proton accelerator — *Veliko Dimov*
Bodrum / Türkiye
Wednesday 09:45 - 10:10

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)

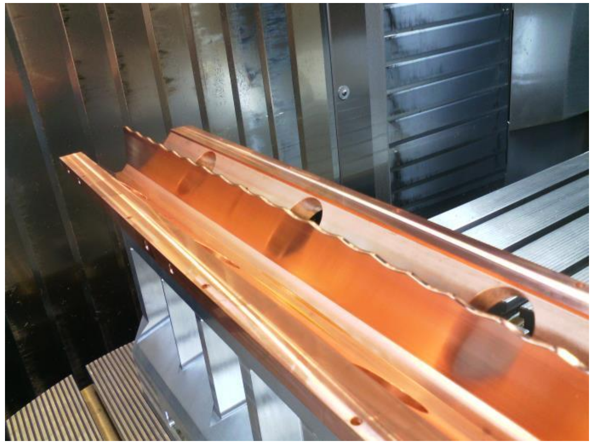
2015-16
- 2015 Construction and assembly at CERN
- 2016 installation at SA2 includes a commercial proton source

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

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

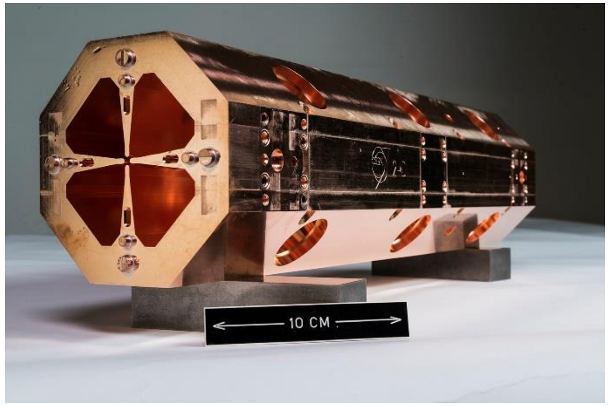
2015 - CONSTRUCTION

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

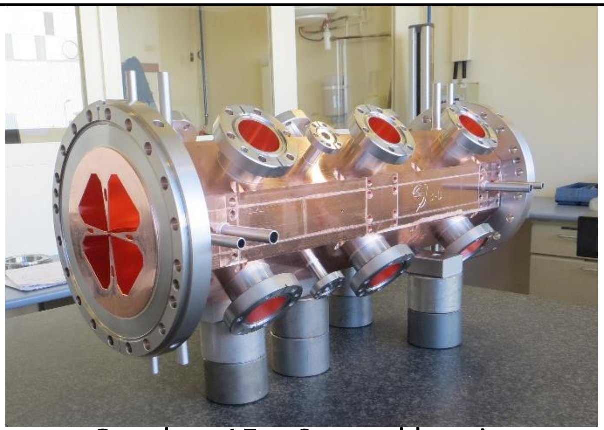


March 15 -Machining (±10 μm)

May 15- Assembling (±15 μm)

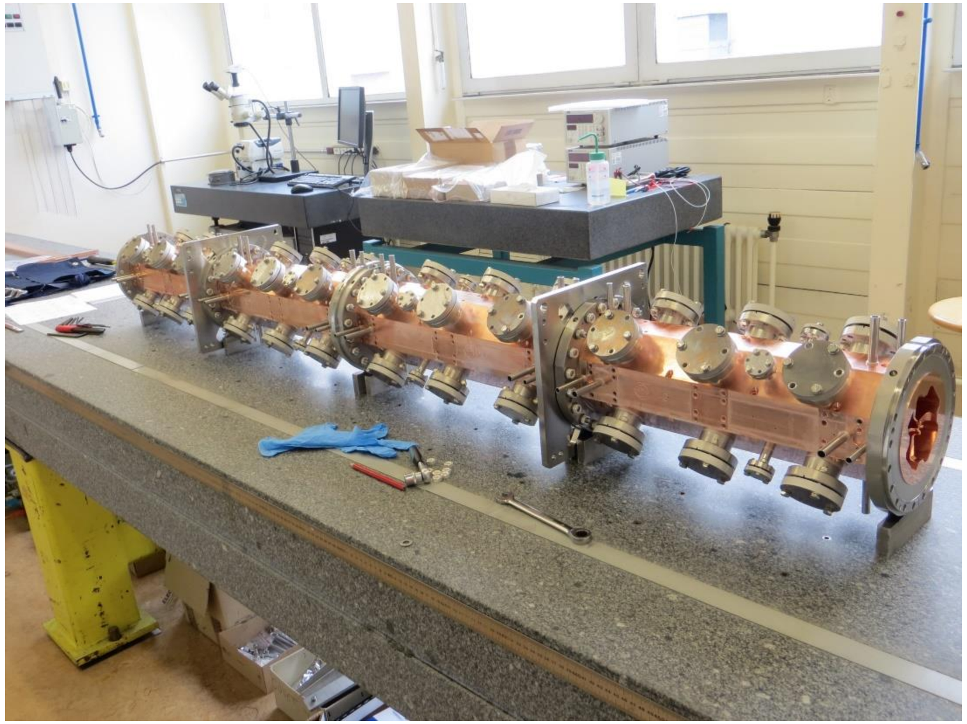


June 15 - First brazing

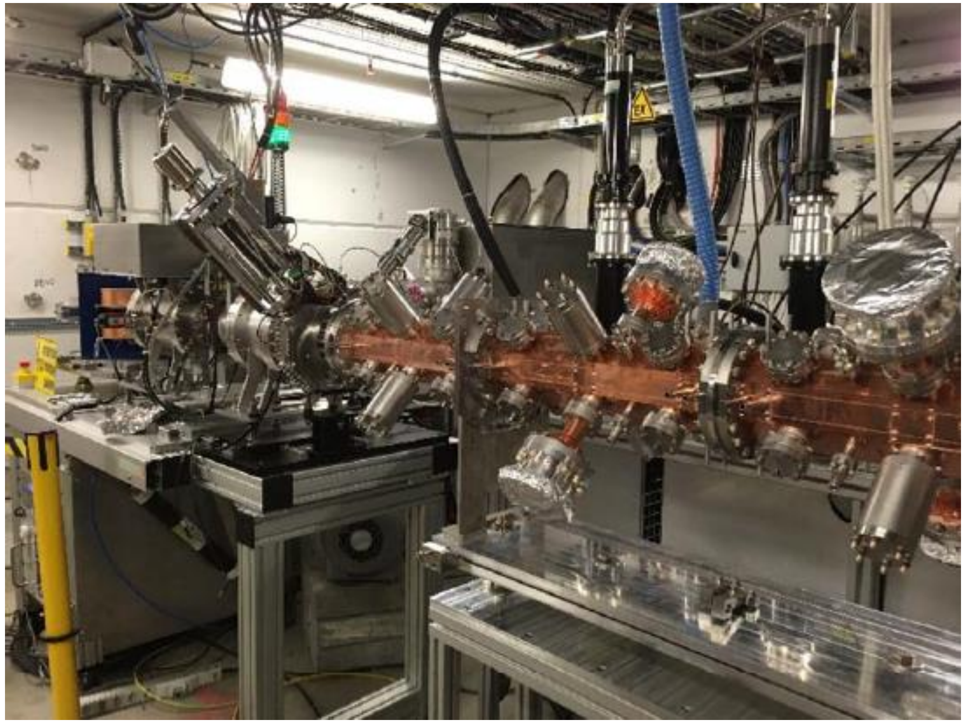


October 15 – Second brazing

2016 : assembly, tuning and high power RF

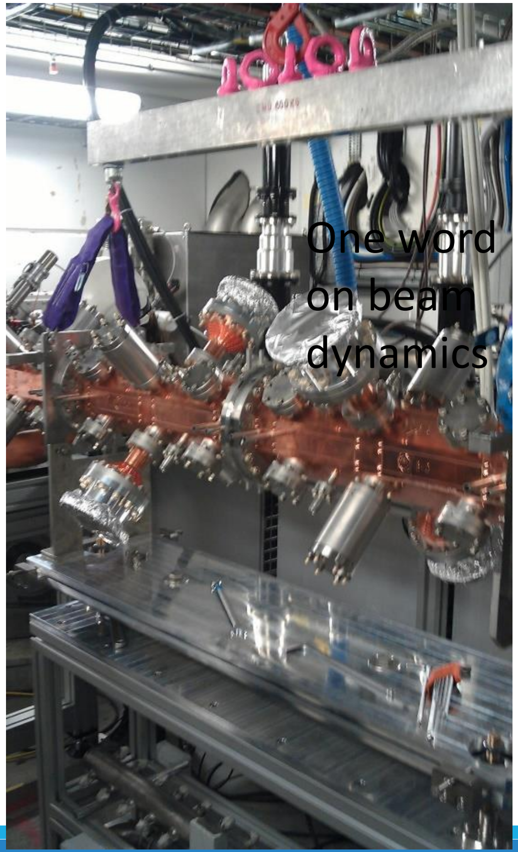


RF measurements

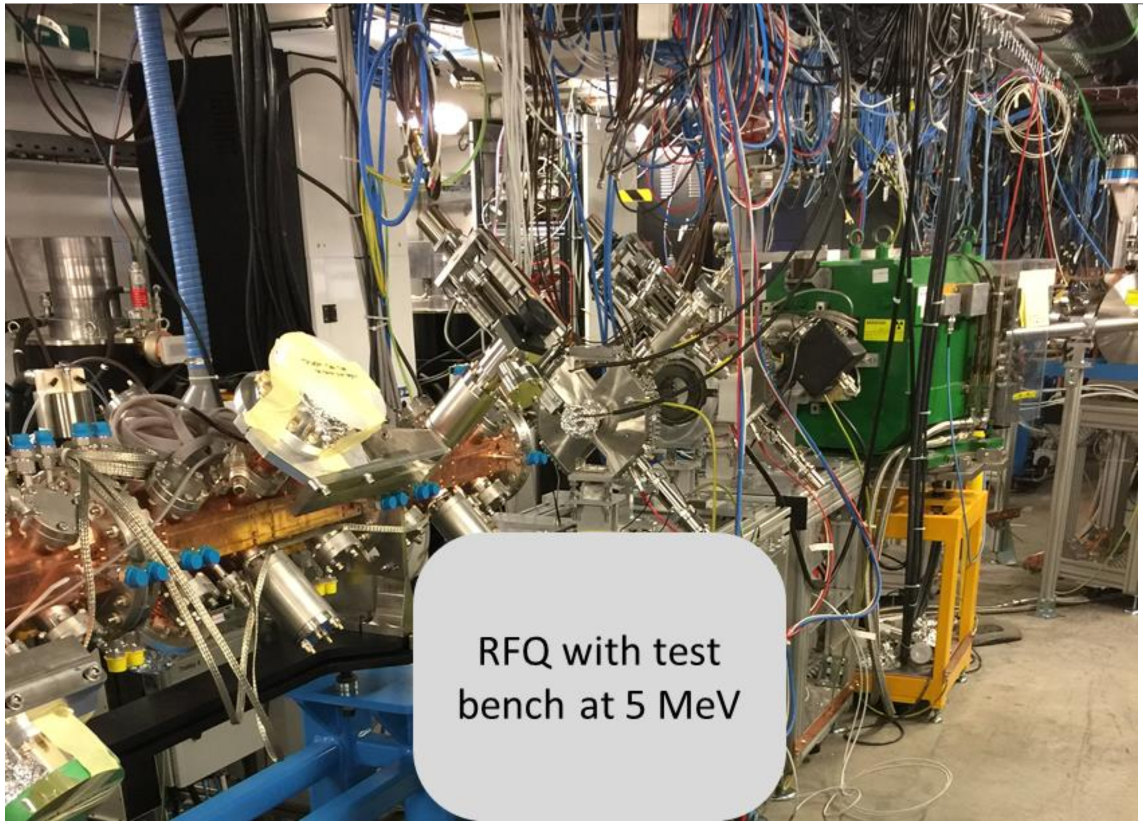


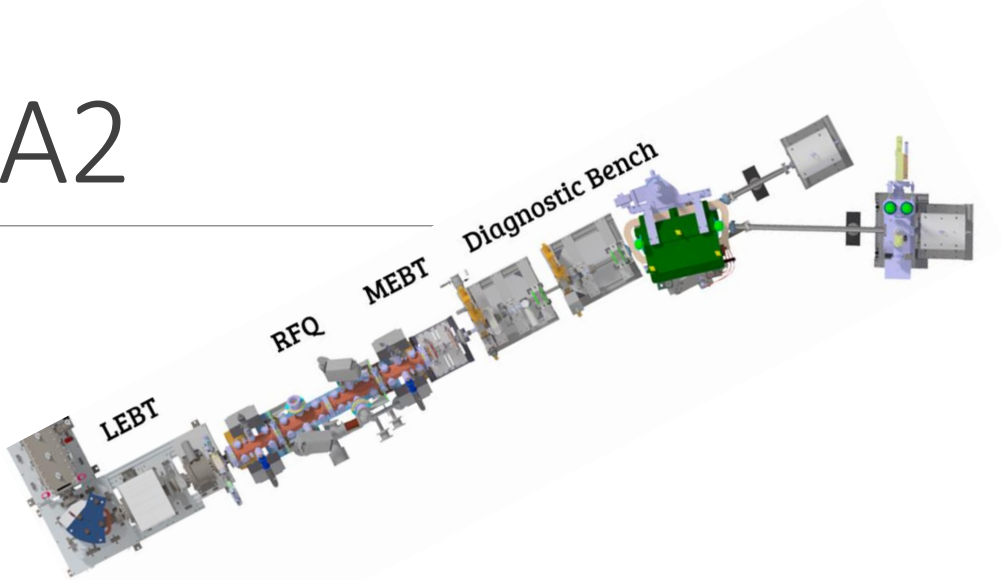
Ready for beam tests

ADAM
an ADVANCED ONCOTHERAPY company



2017 : proton beam at SA2





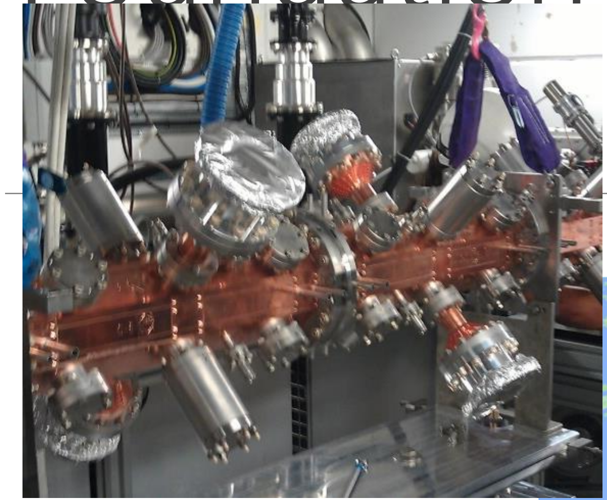
LOW ENERGY PRE-INJECTOR for ADAM/AVO test facility at SA2

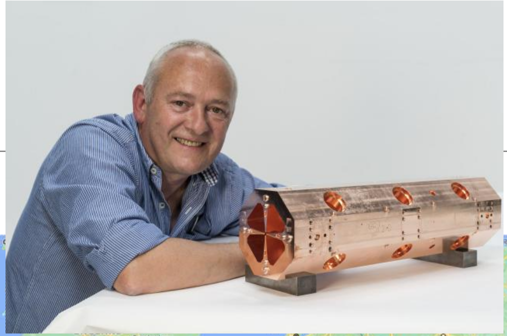
Radically new design from the beam dynamics point of view- validated by beam measurements. It build on the experience of the LINAC4 RFQ for RF design and mechanical design.

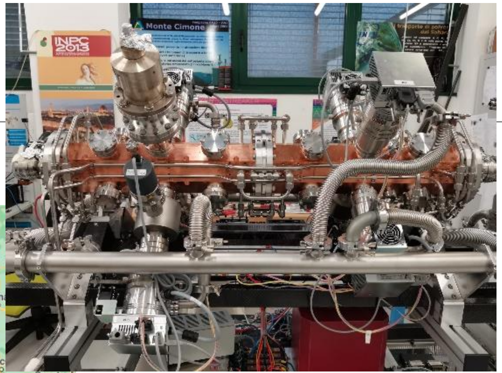
Built in the CERN workshop : less than 2 years from start of construction to installation, this included RF tuning.

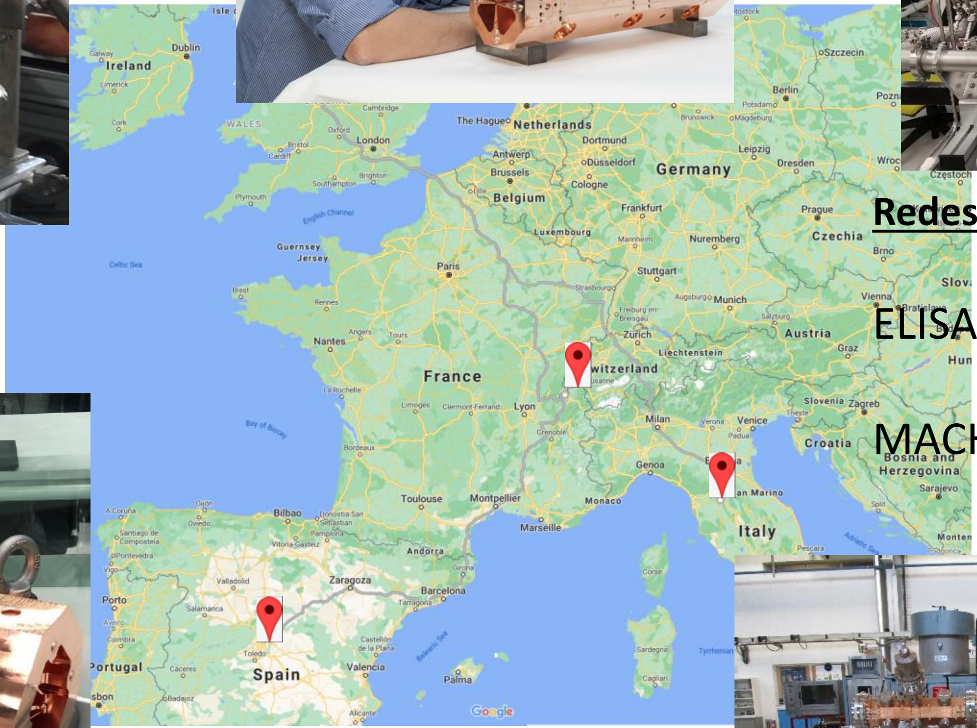
A copy is built in industry.

Foundation for 4 other RFQs







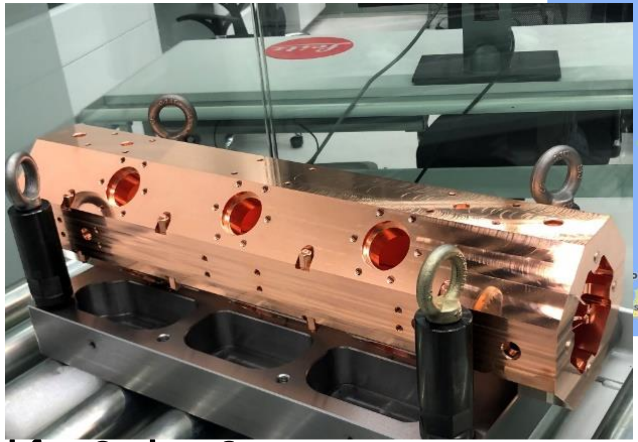


<u>Copy for medical facility</u>:
Built in Italian industry,
First beam July21

<u>Redesigned for portability</u> :

ELISA (2022 science gateway)

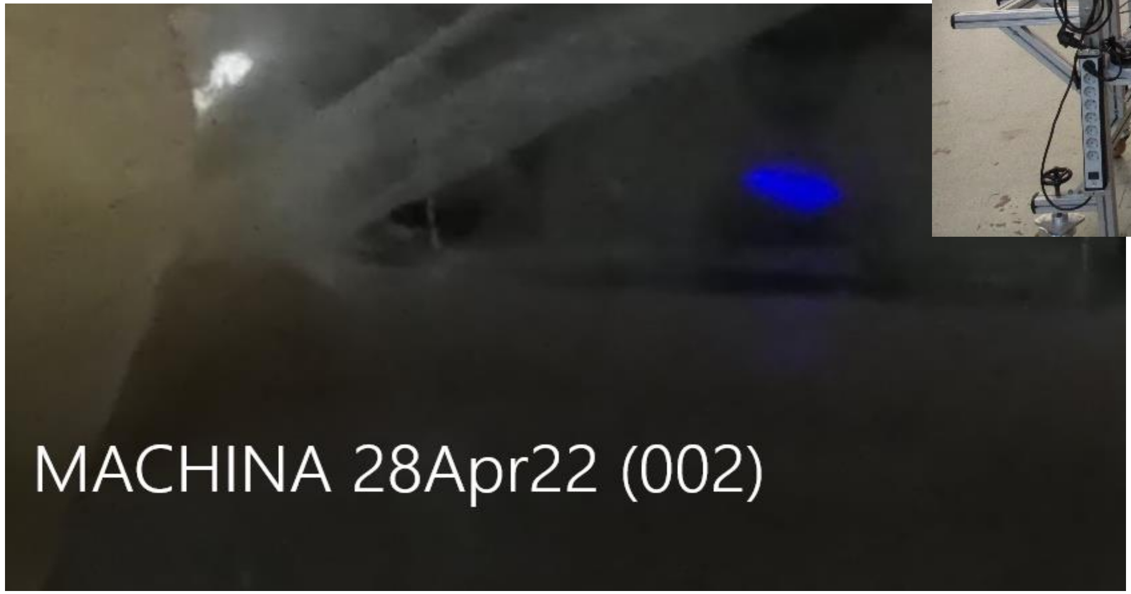
MACHINA (in Florence)




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

<u>Redesigned for Carbon6+</u> :
Built (1 out of 4 modules) in Spanish industry
collaboration agreement with CIEMAT, due in 2022
Test at CERN ideally in SA2

MACHINA



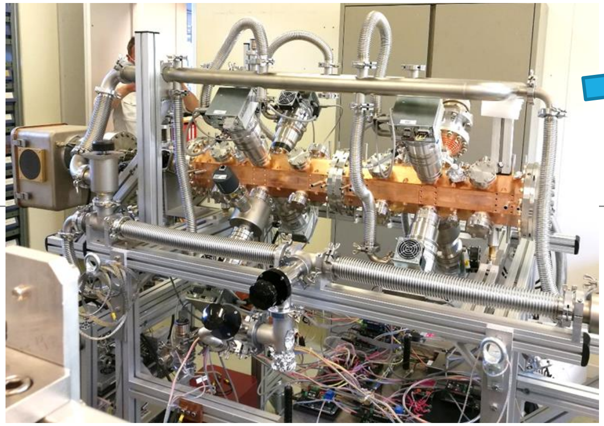
Light from the Bragg peak at 2 MeV.

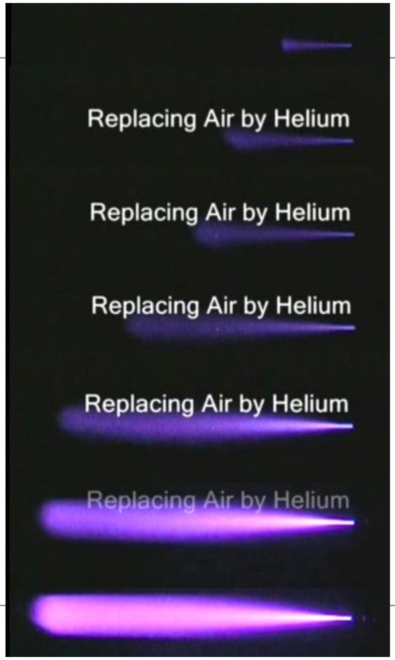
Source and RFQ parameters	
RF Frequency	750 MHz
Input	20 keV
Output Energy	2 MeV
Length	1m
Vane voltage	35kV
Peak RF power	100kW
Duty cycle / max	0.4% /(5%max)
Input/Output Pulse Current in 3GHz acceptance	100/30 μA
Transv. emittance 90%	0.1 pi mm mrad
Average aperture (r0)	1.4 mm
Maximum modulation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

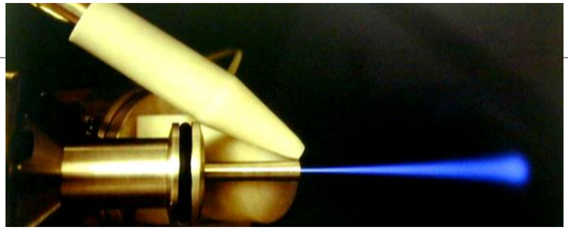
ELISA

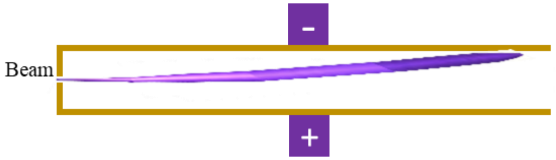
Experimental Linac for Surface Analysis

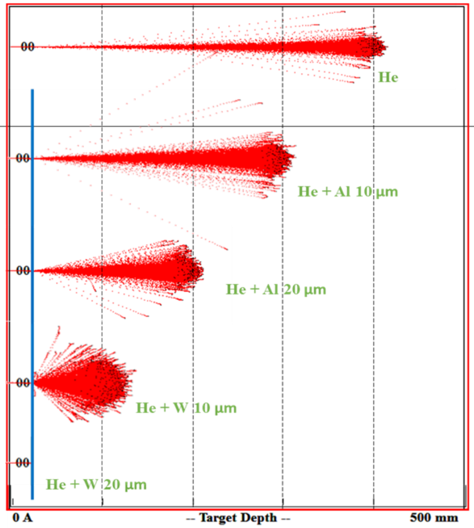
A miniature proton accelerator for Science Gateway



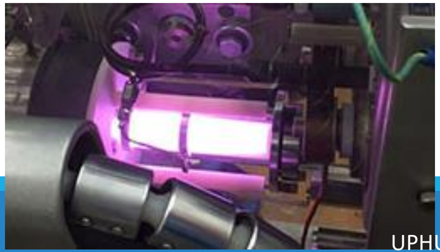


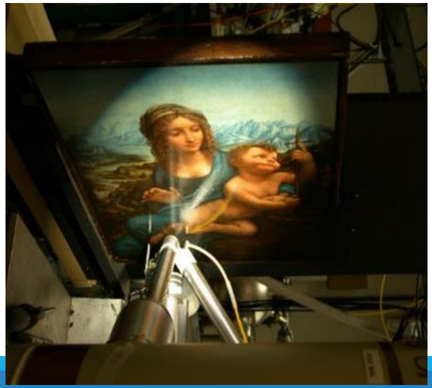






READY DOR PUBLIC OPENING June2023

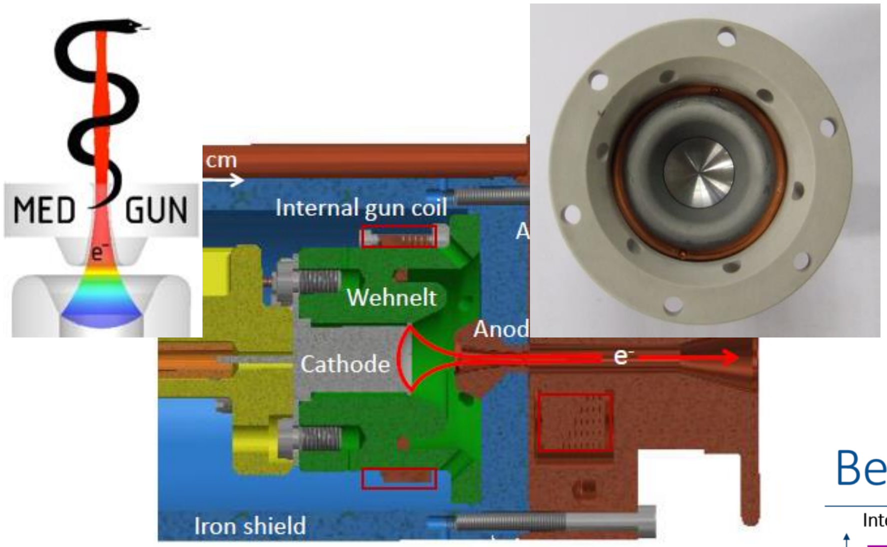




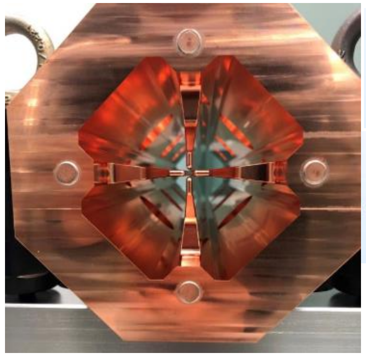
Demonstration / Experience in public with the beam

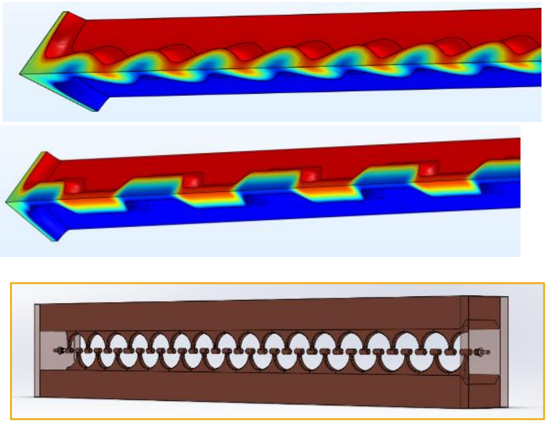
NEXT challenge : accelerate Carbon in a LINAC

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



MEDeGUN mechanical design

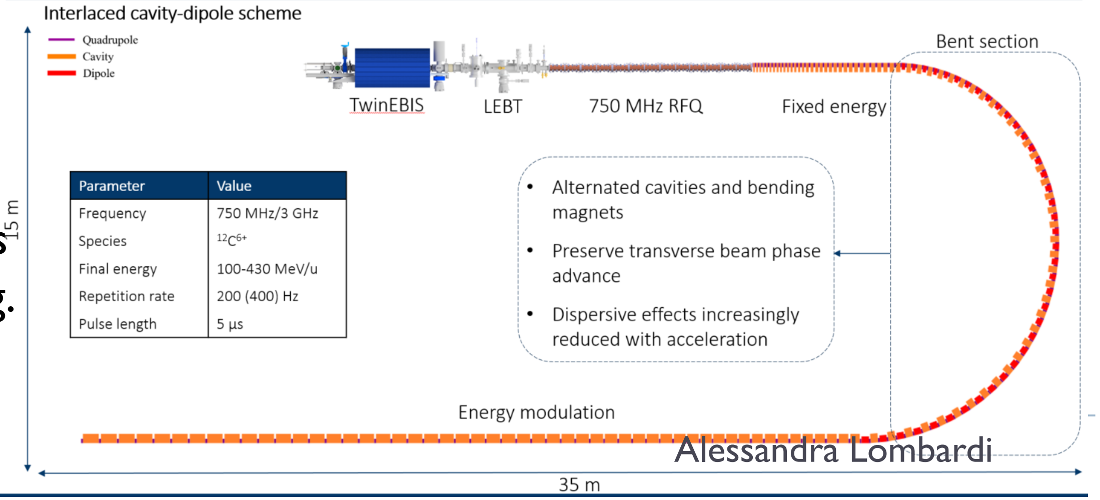




RFQ and IH

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

Sources

LINAC is designed for q/m =1/2

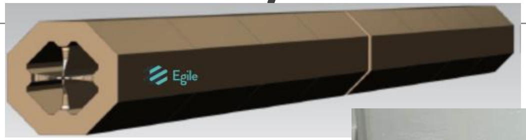
- Helium and fully stripped carbon ions
- Works for protons by reducing Magnetic and Electric field to ½

Ultimate source is a EBIS (tests ongoing at MedEGUN) delivering Carbon ions – not yet up to specs

A Helium source allows to validate all the aspects of the pre-injector (mechanics, RF and beam dynamics) without compromise : Helium source (destined to Sarajevo University) shall be ordered within 2022 , ready to use end 2023

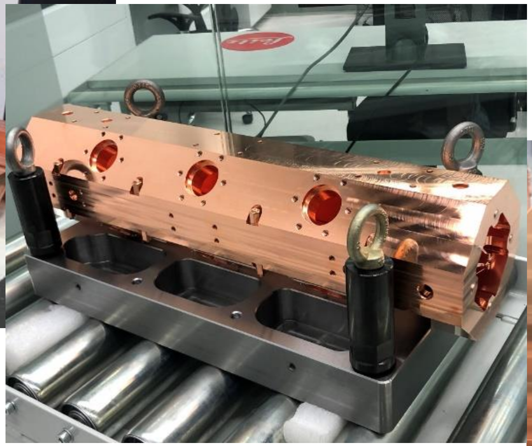
A proton source allows to validate beam dynamics but not RF (voltage holding capabilities, stability at high field etc) : proton source ELISA-like with the extraction designed in ABP is ordered with the aim of extracting protons as early as June 2023

Collaboration CERN-CIEMAT-CDTI-Spanish Industry – RadioFrequencyQuadrupole

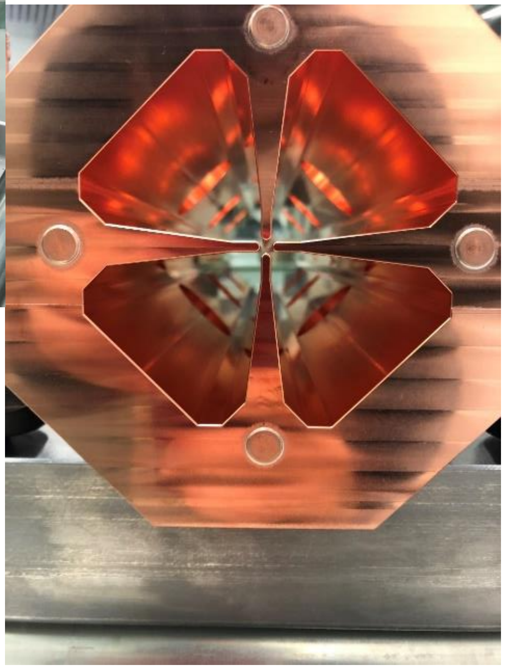


1-Drawings

2-Precision machings



3-Assembly and brazing



4-First (of 4) section completed

2.0 m long
750 MHz
Will deliver Carbon (or Helium) at 5 MeV (total energy)
Designed at CERN built in Spanish Industry
2/4 section completed – complete delivery june 2023

Somehow during 2023 we will have

A proton source designed to inject DIRECTLY into the RFQ – very little room for regulation

A helium source + a Low Energy Beam Transport designed to match a helium beam to the RFQ acceptance

A 750 MHz RFQ designed to accelerate from 15keV/ to 2.5 MeV/u particles with q/m =1/2

Plans 2023 and beyond

2022 : beam at 2 MeV from ELISA RFQ

2023 : spare of the LINAC4 RFQ ready

Characterize the proton and helium sources for use with the Carbon RFQ (2023)

Accelerate the beam through the Carbon RFQ (2023-2024)

Validate (hopefully) the 750 MHz RFQ design and proceed to the construction of the second RFQ to bring the beam to 5MeV/u

Test direct injection from the source into an RFQ (and feed back to LINAC4?)

Milestones in the development of RFQ at CERN.

1990	2007	2014	2019	2020
RFQ2	LINAC4 RFQ	HF RFQ	MACHINA / ELISA	Name_to_ be_ found
200 MHz	352 MHz	750MHz	750MHz	750MHz
0.5 MeV /m	1MeV/m	2.5MeV/m	2.0MeV/m	1.0MeV/m (q/m=1/2)
Power/m 244kW/m	Power/m 133 kW/m	Power/m 200kW/m	Power/ m 80kW/m	Power/ m 100kW/m
P/MeV 670kW/MeV	P/MeV 135kW/MeV	P/MeV 80 kW/MeV	P/MeV 40kW/MeV	P/MeV 80 kW/MeV
Weight :1200kg/m	Weight : 400kg/m	Weight : 100 kg/m	Weight : 100 kg/m	Weight : 100 kg/m
Ext. diametre : ~45 cm	Ext. diametre : 29 cm	Ext. diametre : 13 cm	Ext. diametre : 13 cm	Ext. diametre : 13 cm
200mA proton	40 mA H-	0.1 mA proton	0.1 mA proton	0.1 mA carbon ions
			Portable