BEAM COMMISSIONING OF LINAC4 at CERN

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Outline

- LINAC4 layout and choices
- Commissioning results
- Reliability and beam quality run
- Conclusions and outlook

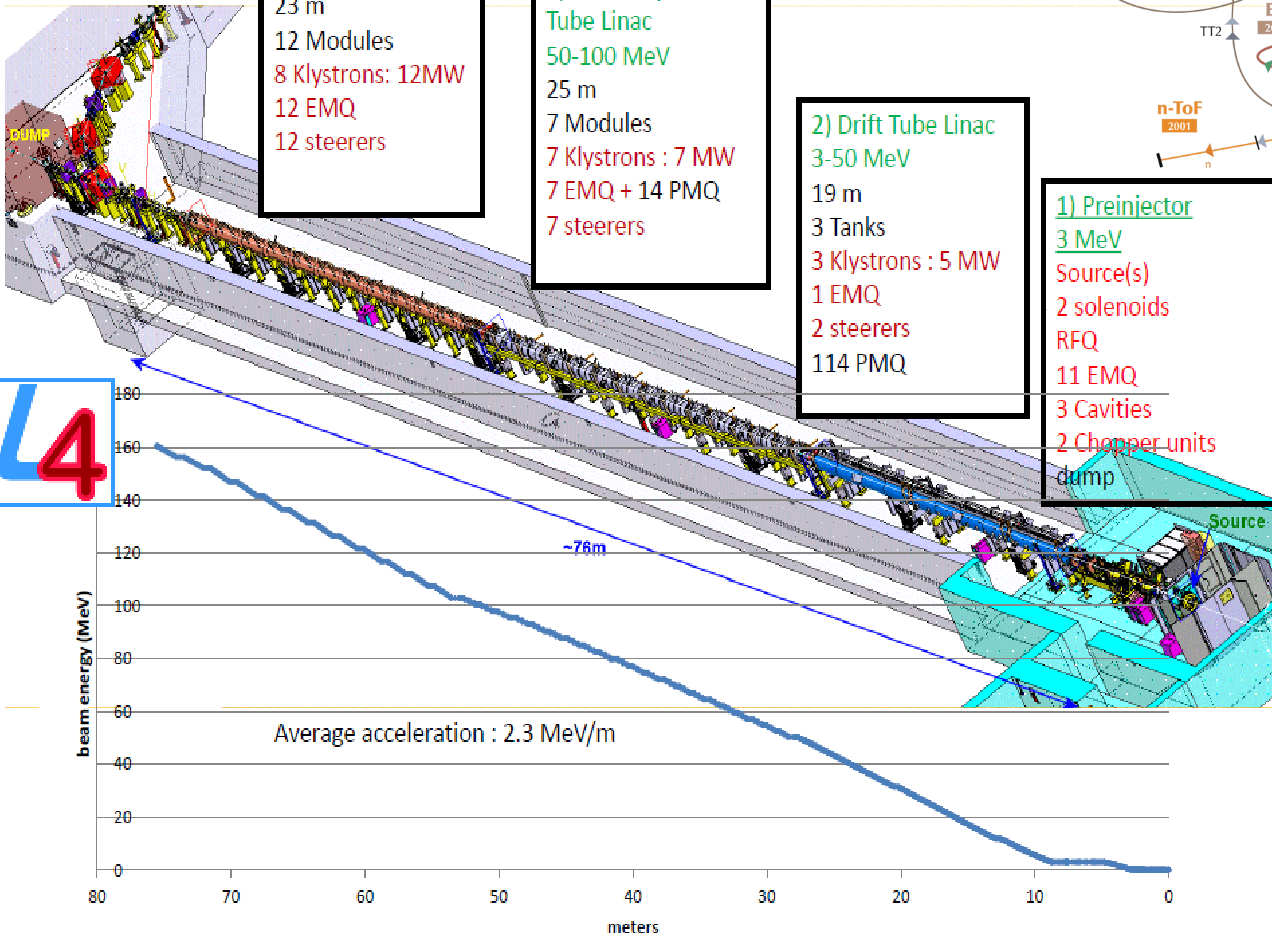
LINAC4

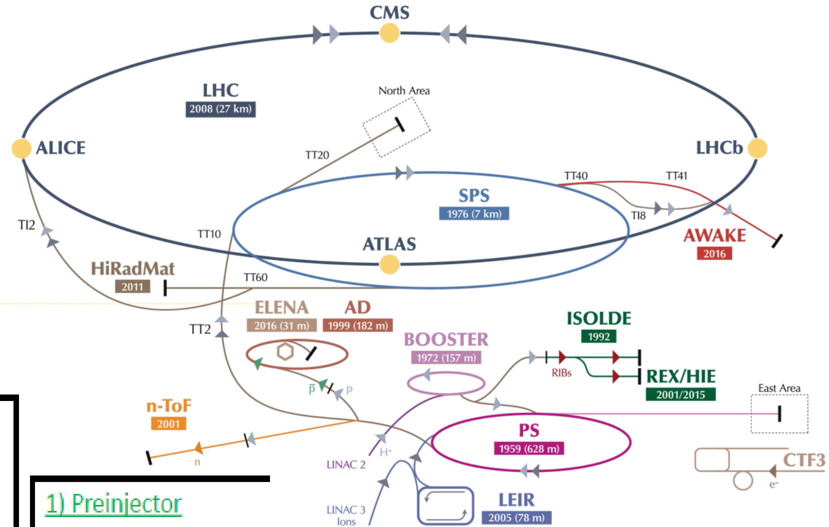
4) Π-mode Structure
100-160 MeV
23 m
12 Modules
8 Klystrons: 12MW
12 EMQ
12 steerers

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

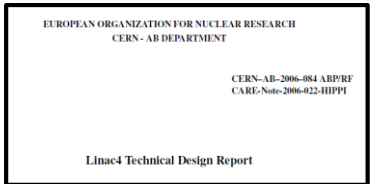




Frequency : 352 MHz
Duty cycle for PSB : 0.06 %
Max duty cycle : 5%

Located 12m underground

LINAC4 from 2000's to 2020


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - AB DEPARTMENT

CERN–AB–2006–084 ABP/RF
CARE-Note-2006-022-HIPPI

Linac4 Technical Design Report

2006

2010

2013 - 3MeV

2015 - 50 MeV

2016 -160 MeV

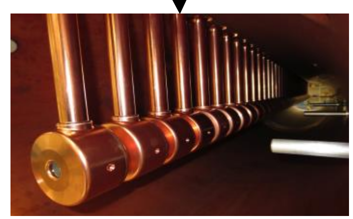
Pre-studies | Construction | Installation Beam commissioning | Connection Operation

2008

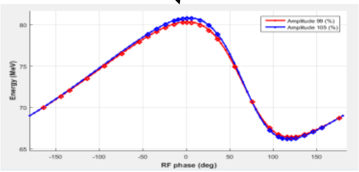
Project approved

2012

2014 - 12 MeV



2016 -107 MeV



Staged commissioning

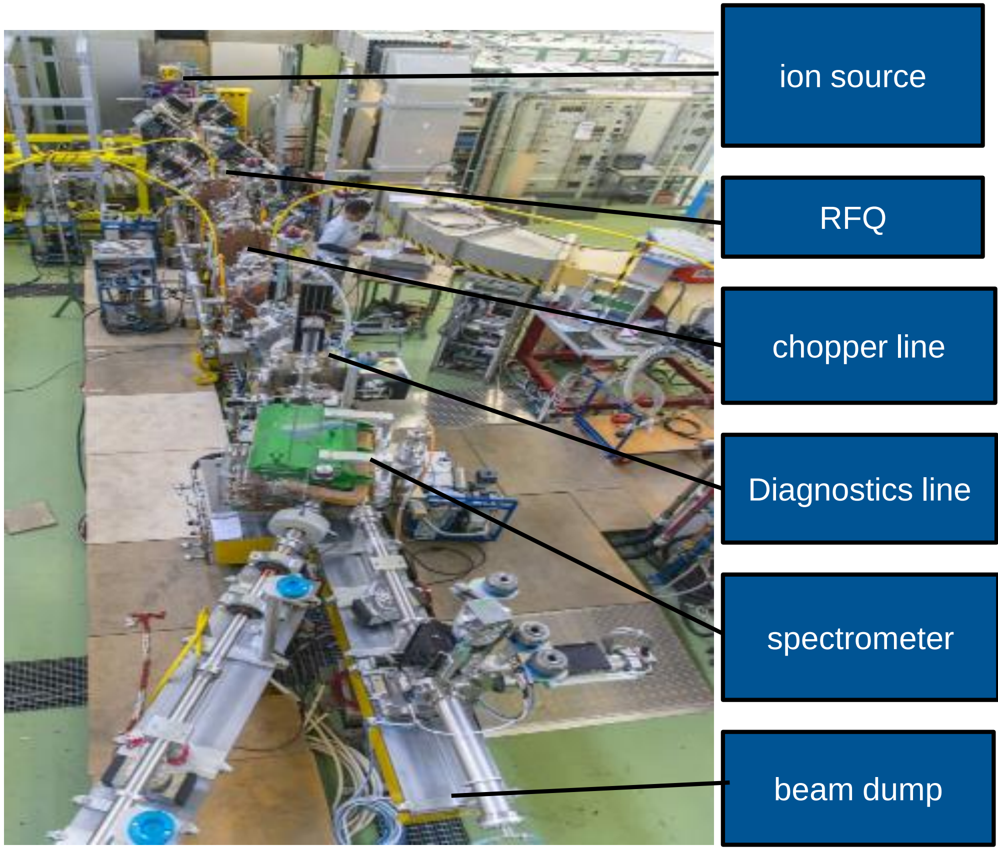
Low energy test bench at 3 MeV and 12 MeV
Direct measurements

- Transverse emittance with slit-grid
- Energy spread with a bending spectrometer

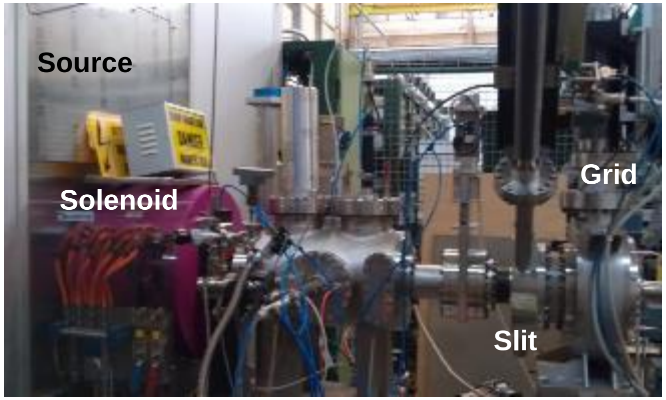
High energy test bench at 50 and 107 MeV
Indirect measurements

- 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

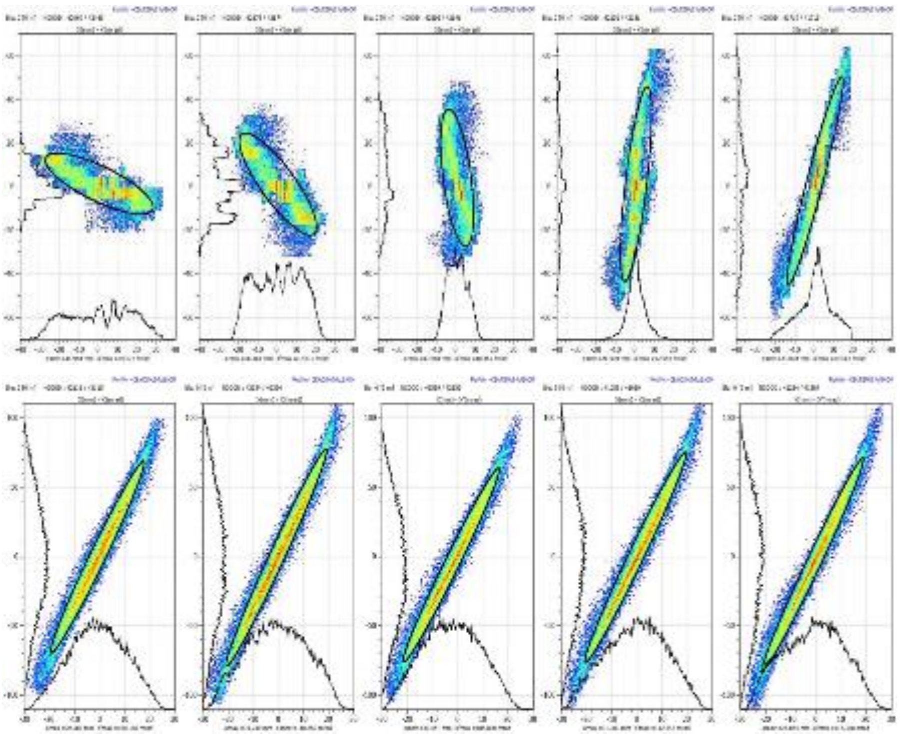


Extensive measurements at 45 keV



Measurements varying solenoidal field & generate beam distributions

Back-track to the source output



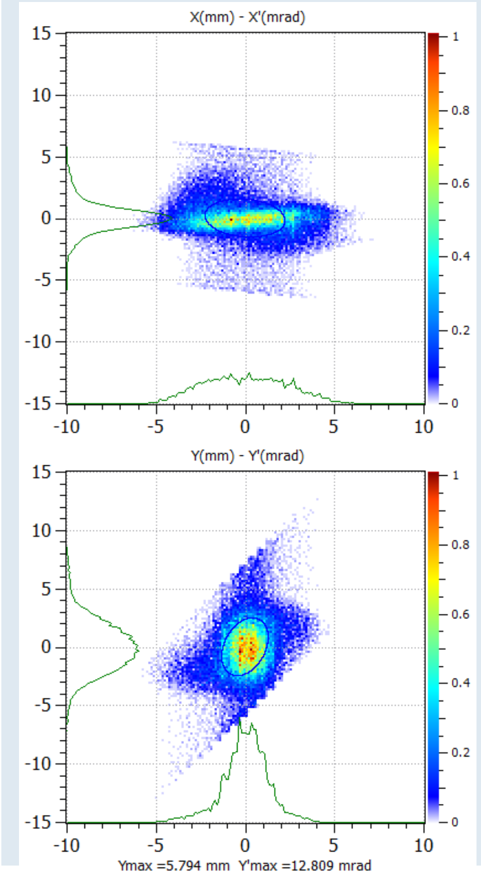
We have an **empirical input beam distribution** that very well represents the dynamics in the LEBT and the rest of the accelerator

Pre-injector: validation of diagnostics

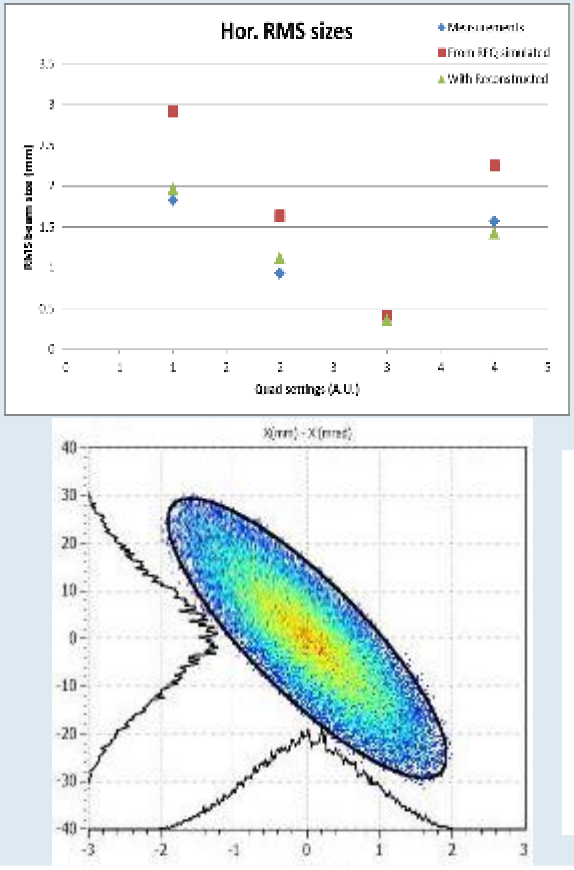
rms normalised transverse emittance @ 3 MeV measured by 3 independent systems:

<u>0.3 pi mm mrad</u>

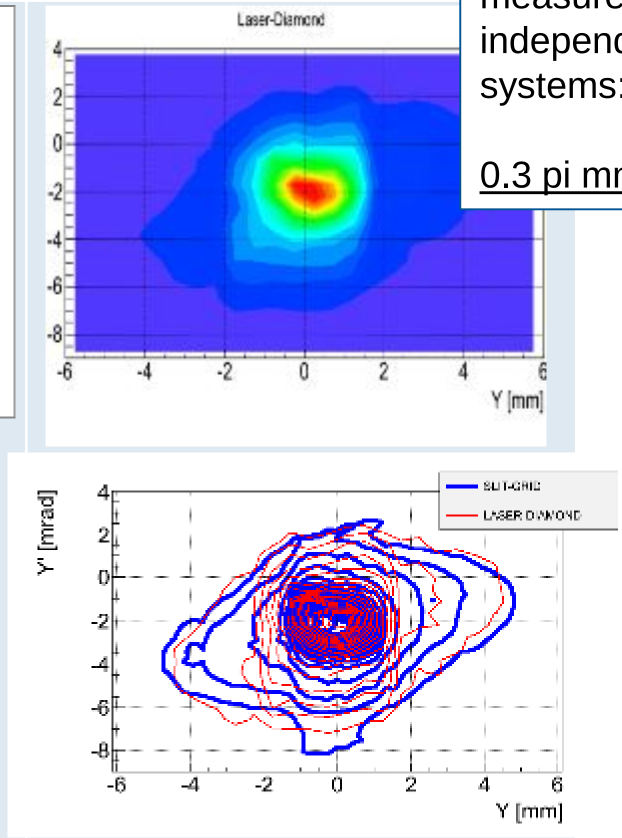
Slit-and-grid



From profile measurement



Laser + diamond



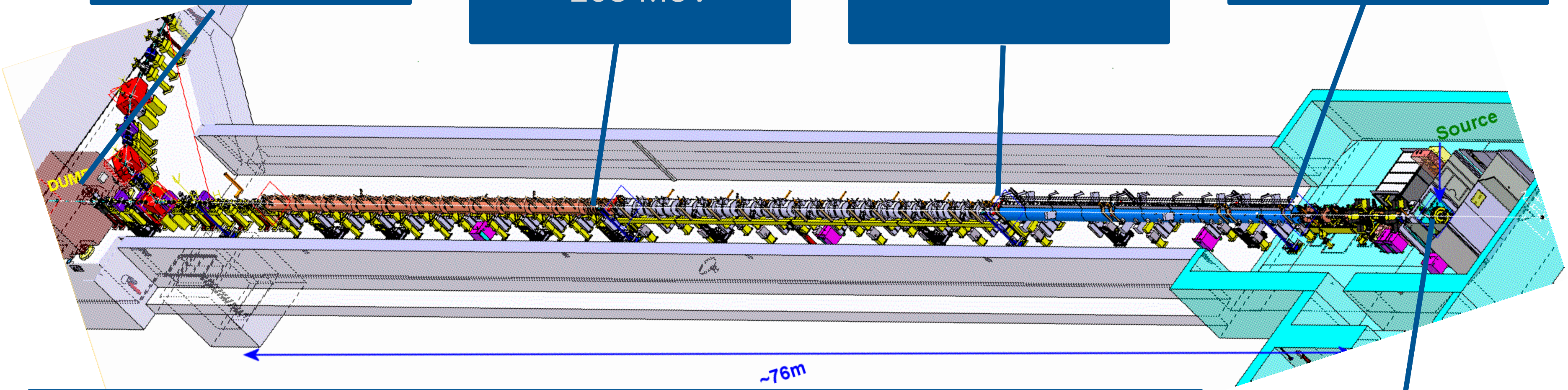
November 2016: the final energy is reached!

Nov 2016
160 MeV

Jun 2016
105 MeV

Nov 2015
50 MeV

Oct 2013
3 MeV
27 mA

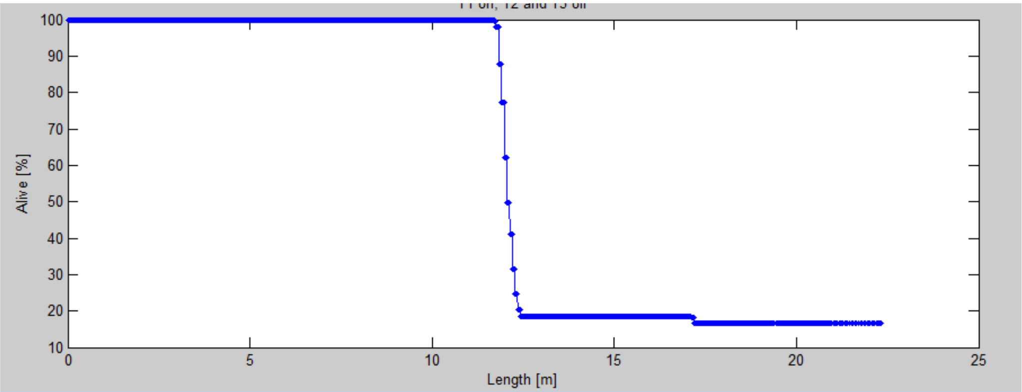


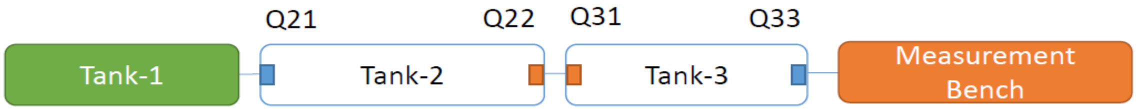
45 keV
50 mA

- Commissioning in stages is key to swift commissioning!
- Commissioning time ~3-4 weeks per stage >> HW-checkout + Beam commissioning!
- Good beam dynamics combined with good beam diagnostics is key
- Good understanding of beam characteristics at low energy essential

Commissioning lessons

Simulation tools are good guide dogs
Starting the 50 MeV commissioning stage -> low transmission





Advantage of staged commissioning:

- Everything up to DTL1 was commissioned
- Hot-point at DTL3 entrance (radiation measurement)
- Plus beam dynamics simulations

Allowed us to understood that last DTL2 PMQ and first DTL3 PMQ were accidentally inverted
Beam restarted after 3 days…

Reliability/Beam Quality Run (July 17 - May18)

Rationale & Goals

1. Ensure a smooth transition from commissioning to operation: train operators, necessary software development, learn to deal with the increased flexibility, *gain experience with the full system.*
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*

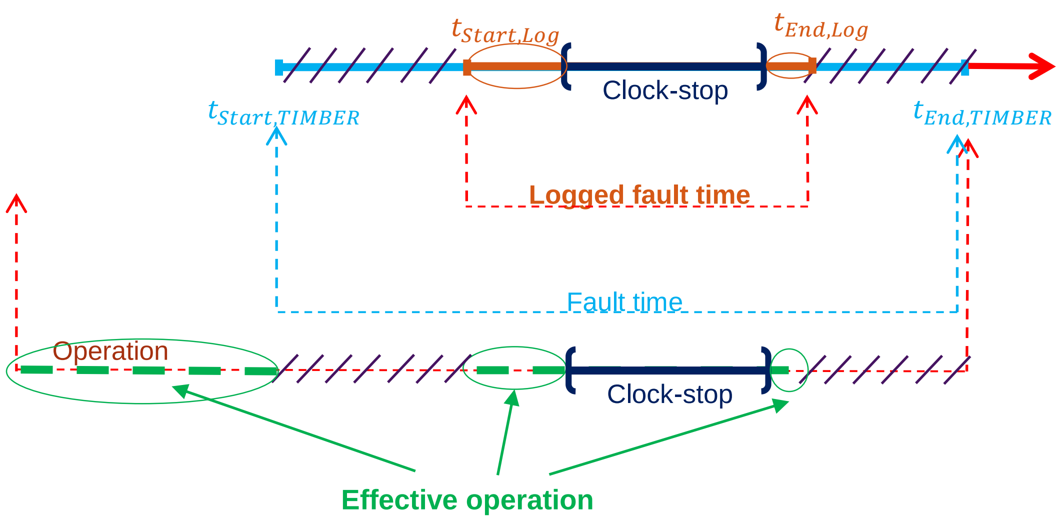
2017												2018											
1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Shut down	Half Sector Test		Debuncher installation		Reliability Run						Shut down		Spare for Reliabilty Run		interventions, repairs					Beam recommissioning			Shut down
EYETS											shutdown												LS2

Failure analysis

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

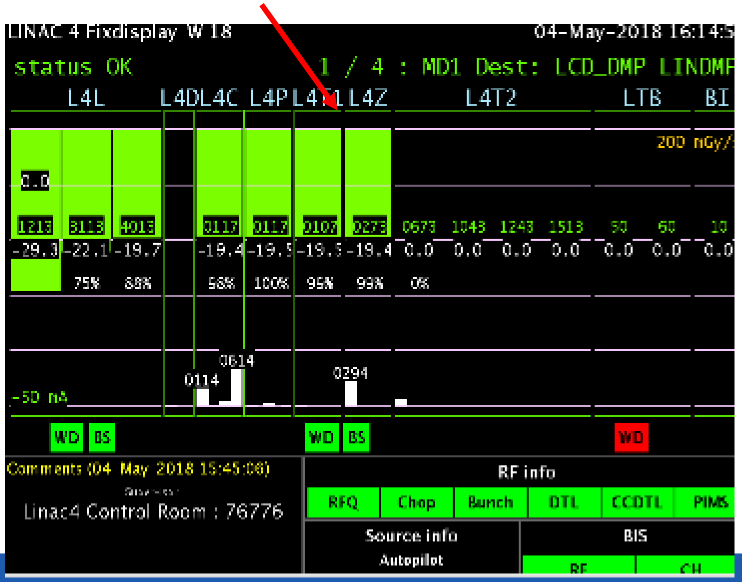
- Operators deal with issues where possible
- **Expert** availability and interventions **only during working hours**
- Faults are fully tracked (Accelerator Fault Tracker AFT)
- Stop AFT Clock during off-hours when fault needs expert intervention & during MDs

Thorough logbook verification w/ Timber/LASER information



$$Q = \frac{Logged\ fault\ time}{Effective\ Operation}$$

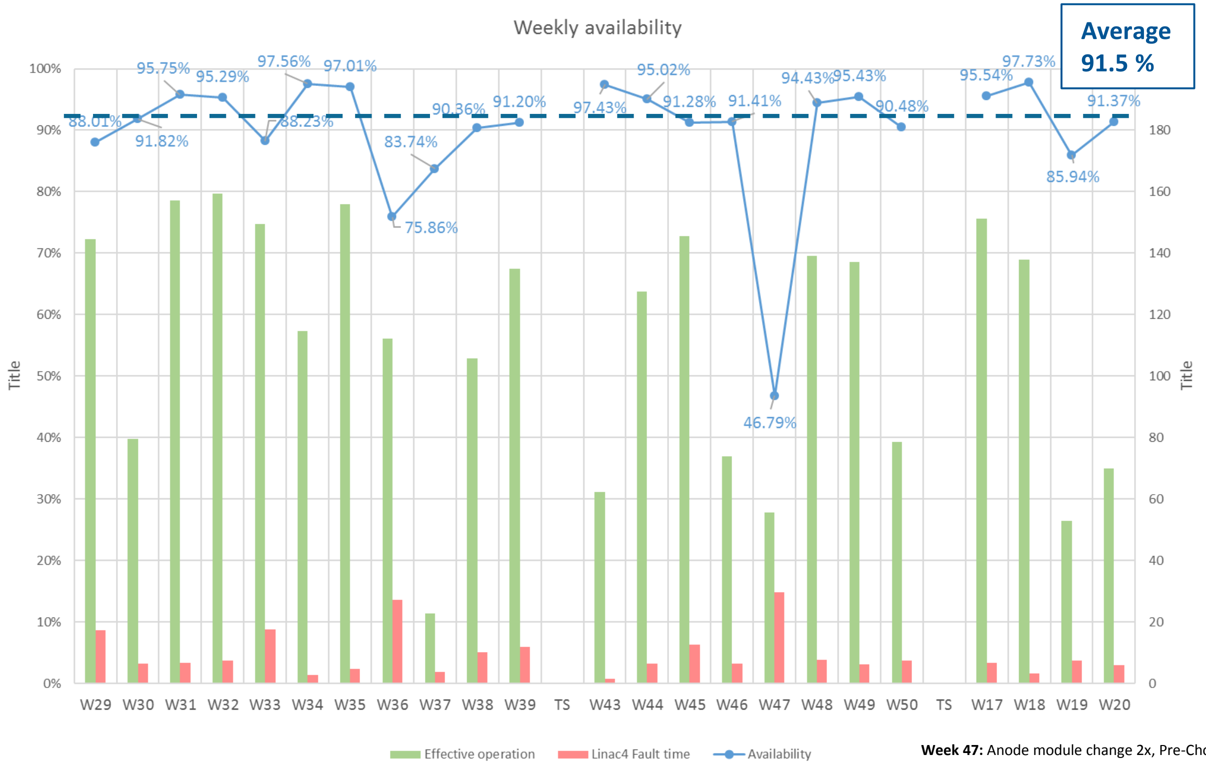
Criterium for LINAC4 availability: Current in BCT before the dump



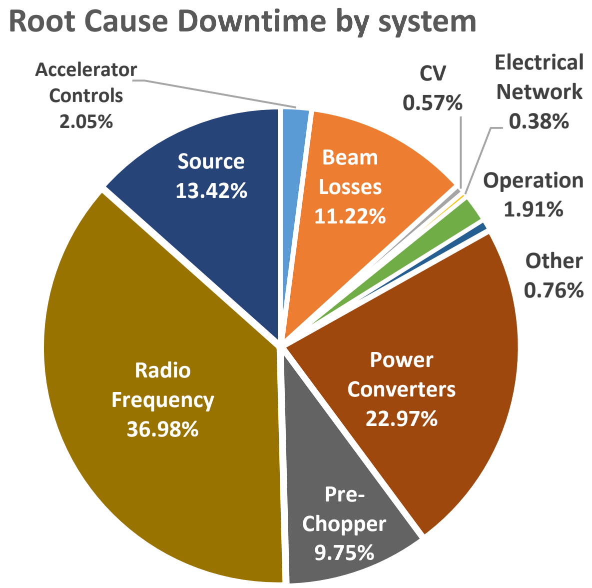
Availability data

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



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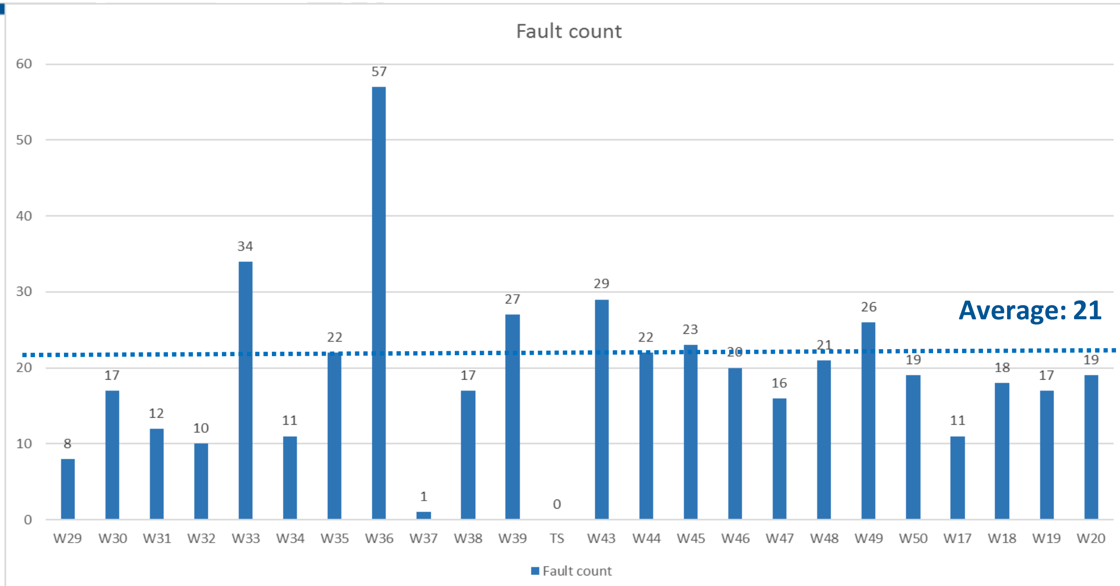
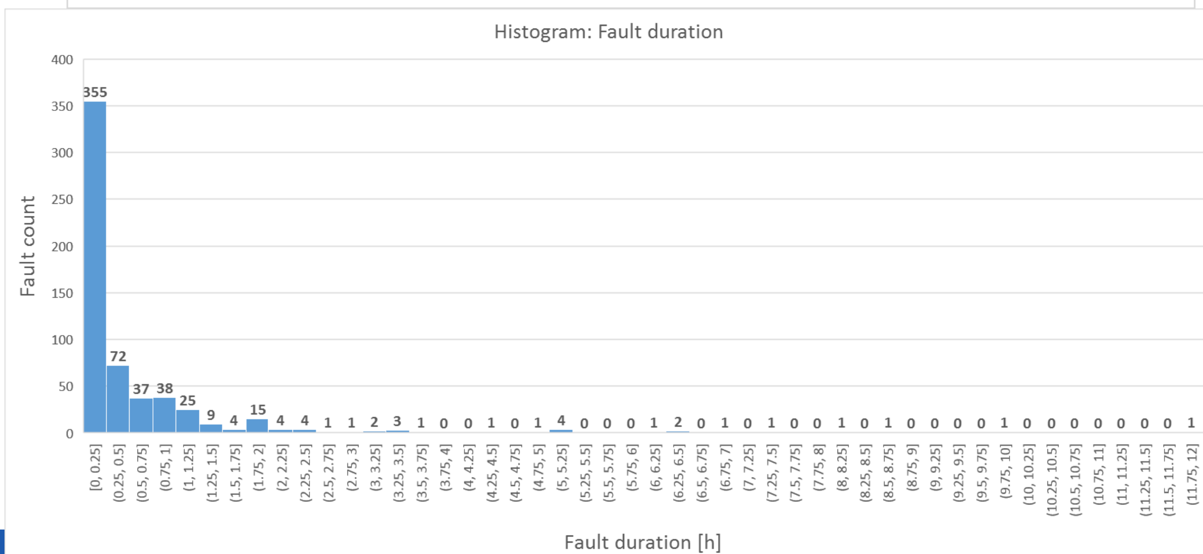


Fault counts / week
(not including parallel faults)

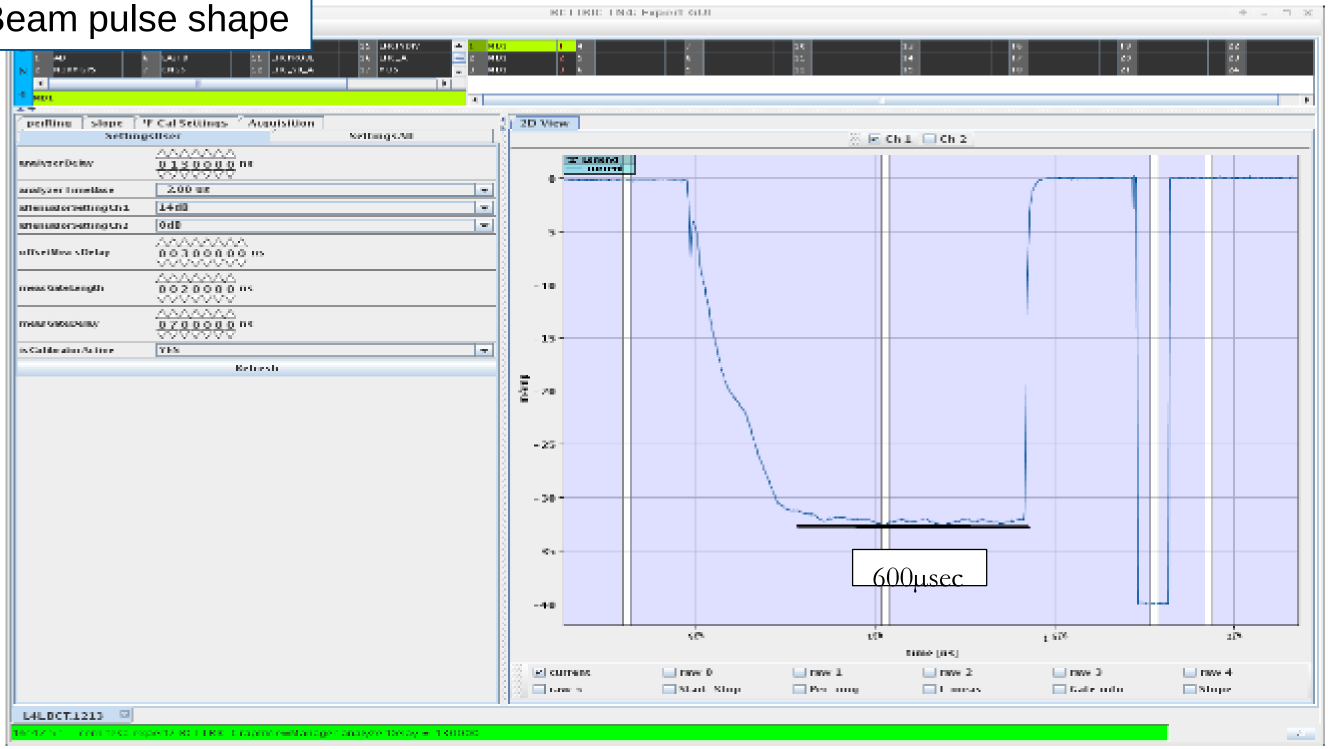


Mostly short faults < 15’

Beam quality run 2018

- 12 weeks of beam quality run spring 2018
  - Extensive HW checkout, RF setup and beam re-commissioning after YETS activities
  - Measurements of beam quality & characteristics

Beam pulse shape



RF setup 2018

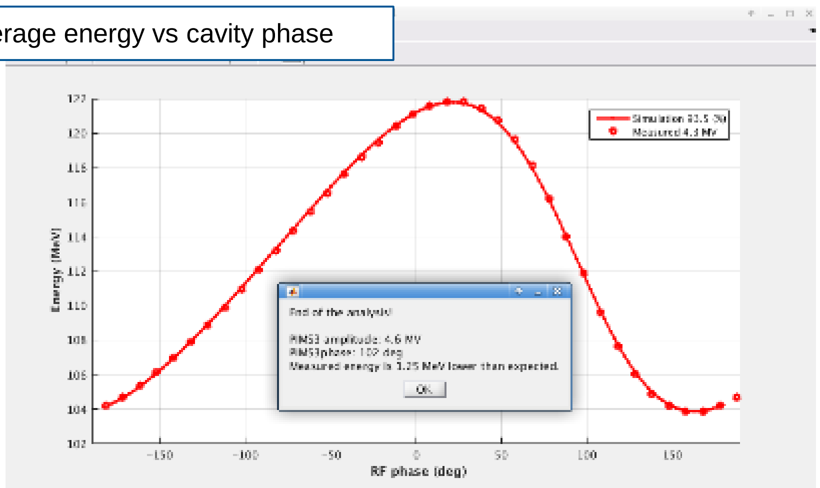
Via beam-loading measurements:

Initial setup: automatic phase scan of each cavities with beam loading measurement. Offline analysis to fit the data.

Via energy measurements (ToF technique):

Fine tuning of the setting points.
TOF application validated, human discernment needed for correct data interpretation + offline analysis / fits.

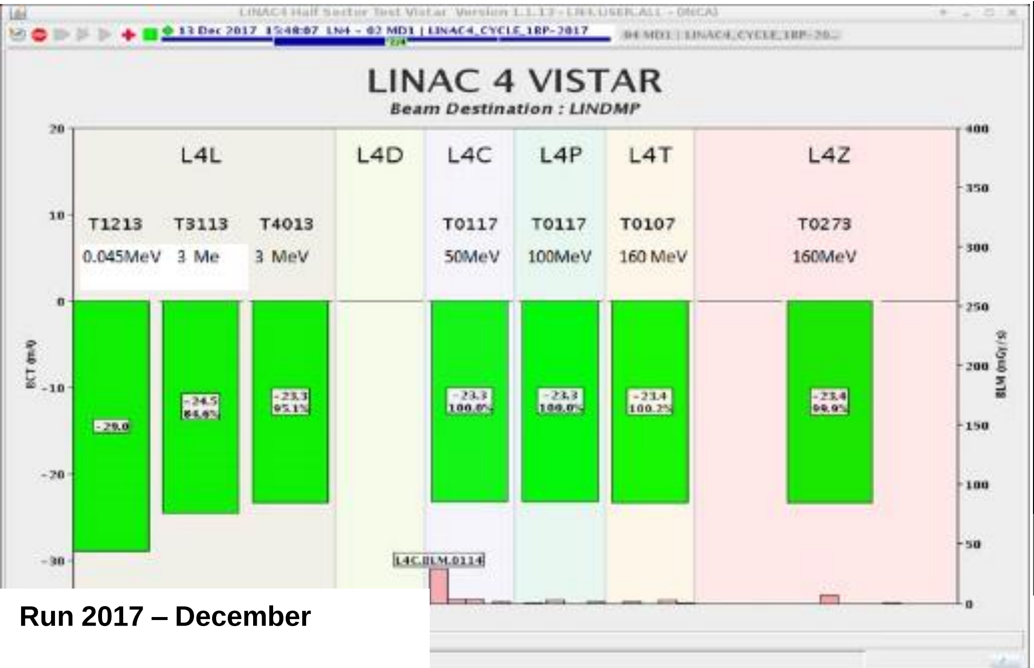
Average energy vs cavity phase



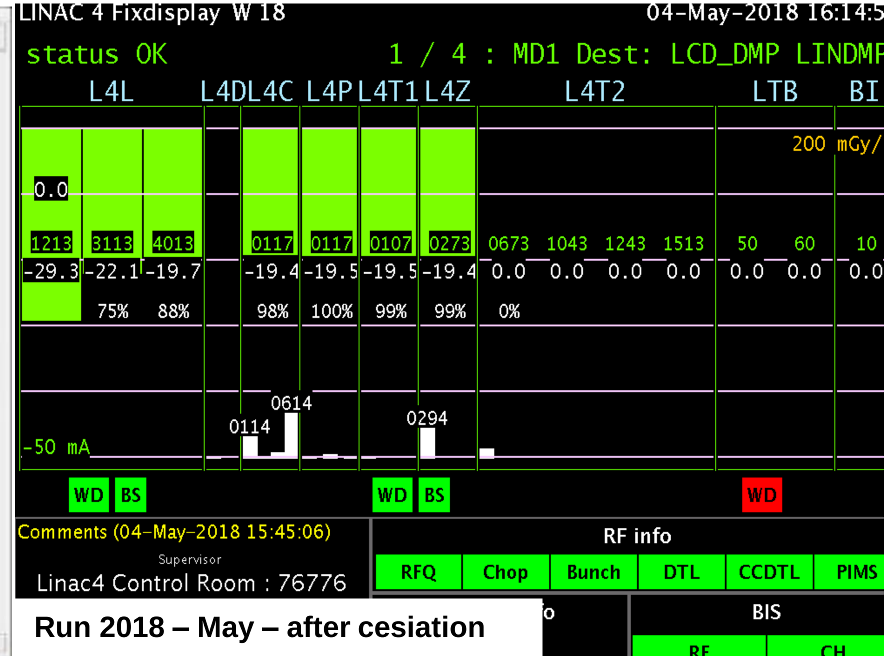
ToF sufficiently precise to allow setting each RF cavity to:

± 0.5 % in amplitude
± 0.5° for the phase

Beam quality measurements - current



Run 2017 – December



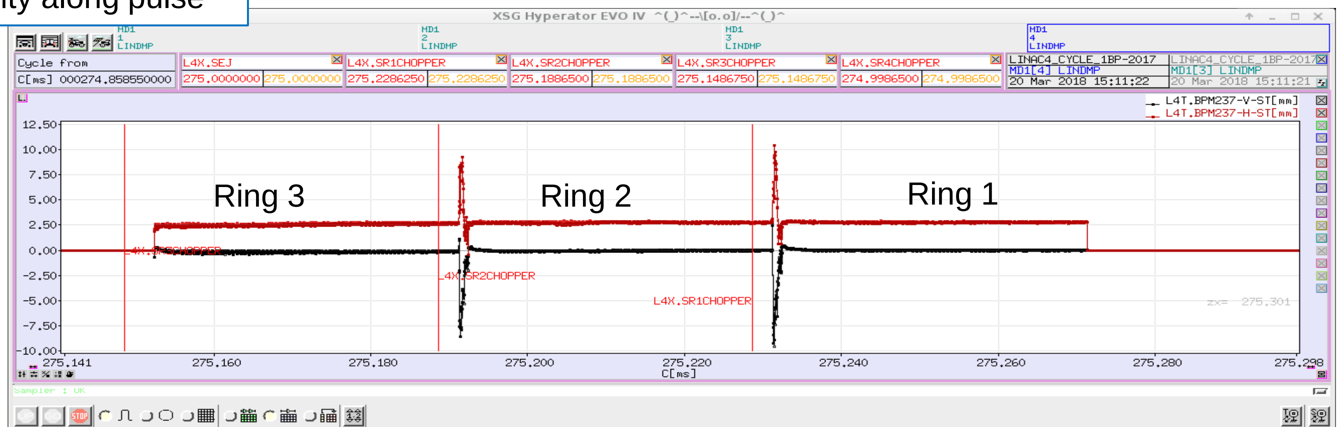
Run 2018 – May – after cesiation

Beam quality measurements – stability at 160 MeV

Current/position stability along pulse

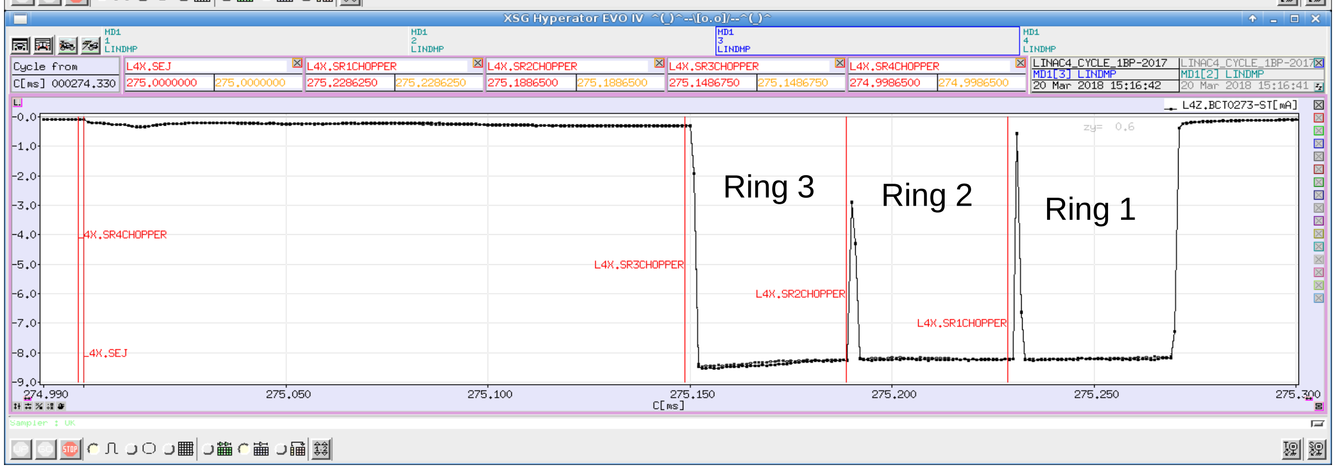
H/V position on L4T pick-up

✓ **< +-1mm**

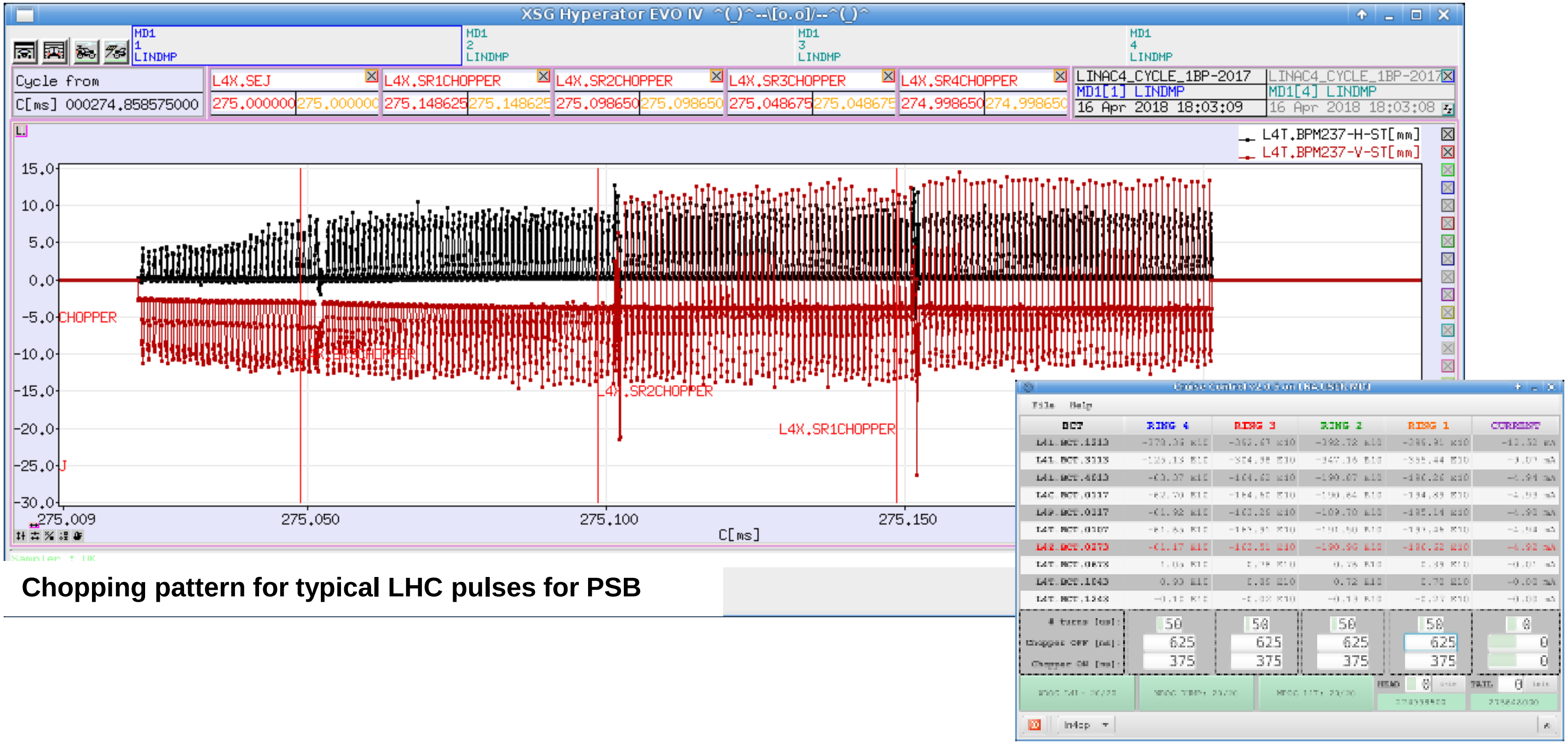


Beam intensity on L4Z BCT (3 rings)

✓ **< +-2%**



Beam quality measurements - chopping

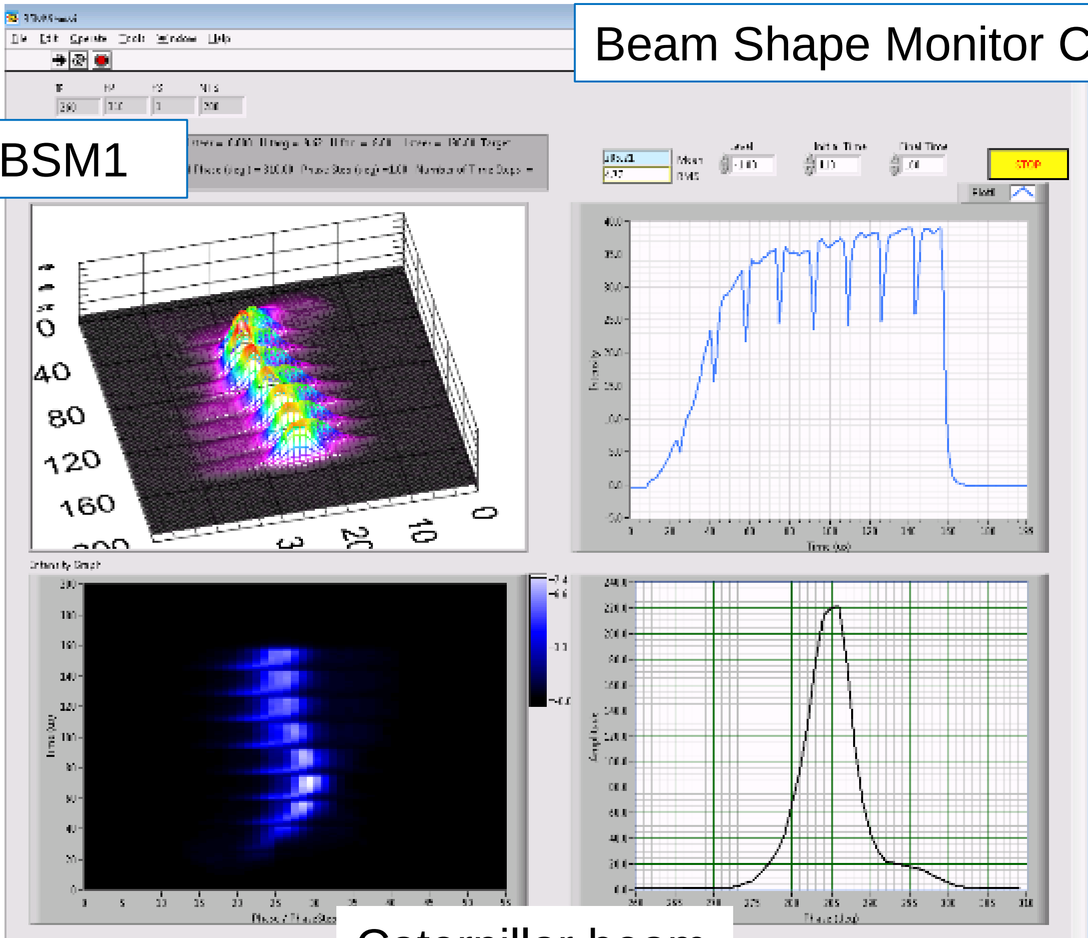


Chopping pattern for typical LHC pulses for PSB

Beam quality measurements – longitudinal shape

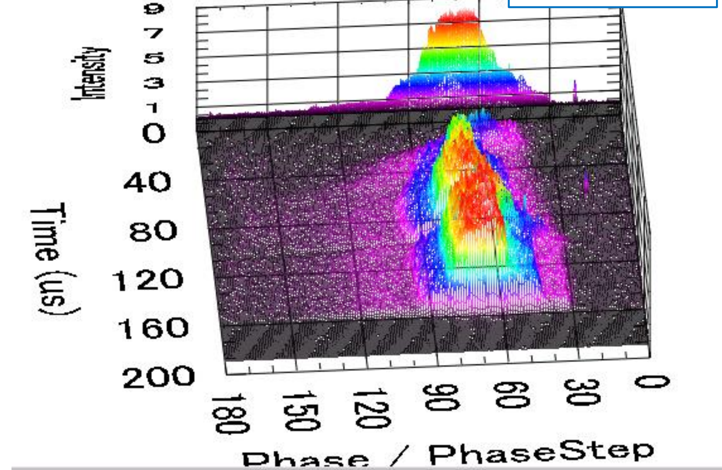
Beam Shape Monitor Commissioning

BSM1



Caterpillar beam

BSM2



LINAC4: measured beam characteristics

Parameter	Measurement
Peak intensity at 160 MeV	25 mA
Emittance rms normalized	0.3 p mm mrad
Max usable pulse length	600 ms
Stability shot-to-shot	2%
Pulse flatness	2% for 160ms pulse 5% fpr 600ms 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 ms

Conclusions and outlook

- Reliability run proved very useful experience allowing to identify issues beyond the possibilities during pure commissioning
  - Number of teething problems identified, strategies for mitigation for implementation in 2018
  - Gain further experience with a complex system
  - Run time used to measure and improve performance
  - Identification of areas that need strengthening
- Demonstrated reliable operation of the LINAC4 line to the dump
  - Most of LINAC4 beam requirements demonstrated (stability, flatness, chopper specifications etc)
  - Confidence in running LINAC4 after LS2 strenghtened
- Transition from Commissioning to Operation ongoing
- More general
  - Importance of a teststand that includes the full pre-injector and staged commissioning
  - Importance of a validated machine model and accuracy of particle tracking codes
- Outlook
  - 2018: 3 months re-commissioning after scheduled RF upgrade and maintenance activity
  - 2019: 3 months running with LBE line (emittance measurement)
  - After LS2: LINAC4 sole provider of protons for the whole CERN complex

Thank you for your attention

CERN

Transverse emittance at higher energies

Transverse emittances were indirectly measured with:

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

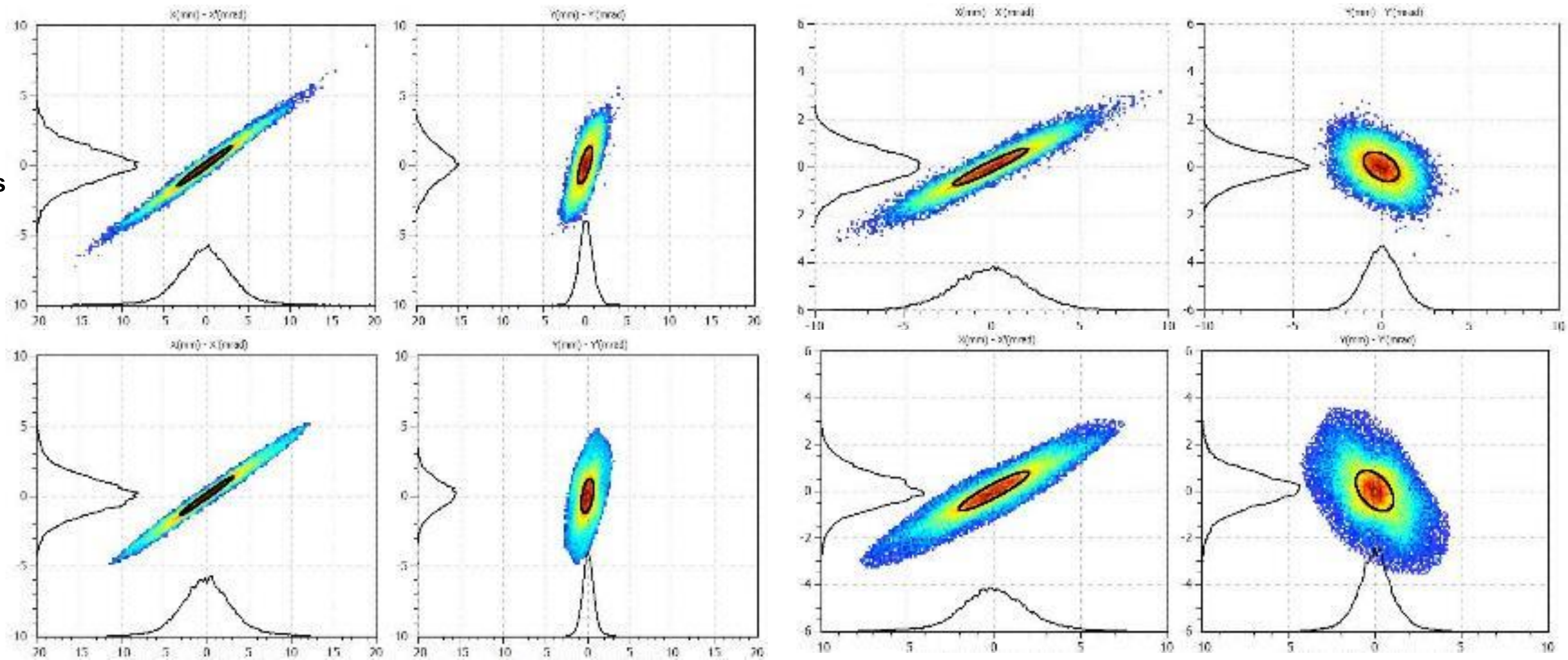
Both based on: The 3 profiles method – Including the space charge forces with multi-particle simulation codes.

@ 50 MeV

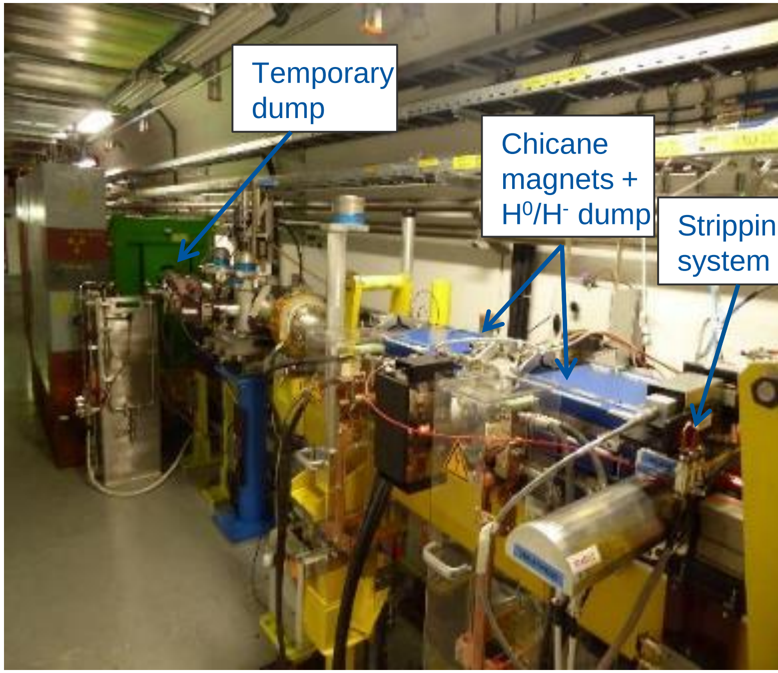
@ 107 MeV

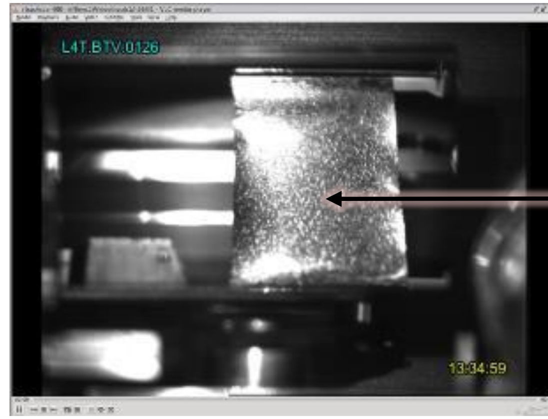
Expected from simulations

Measured



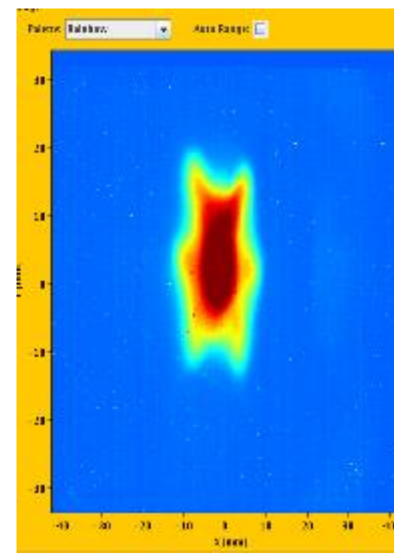
Half Sector Test (Nov ’16 – March ‘17)





1 µm thick carbon foil (24x68mm)

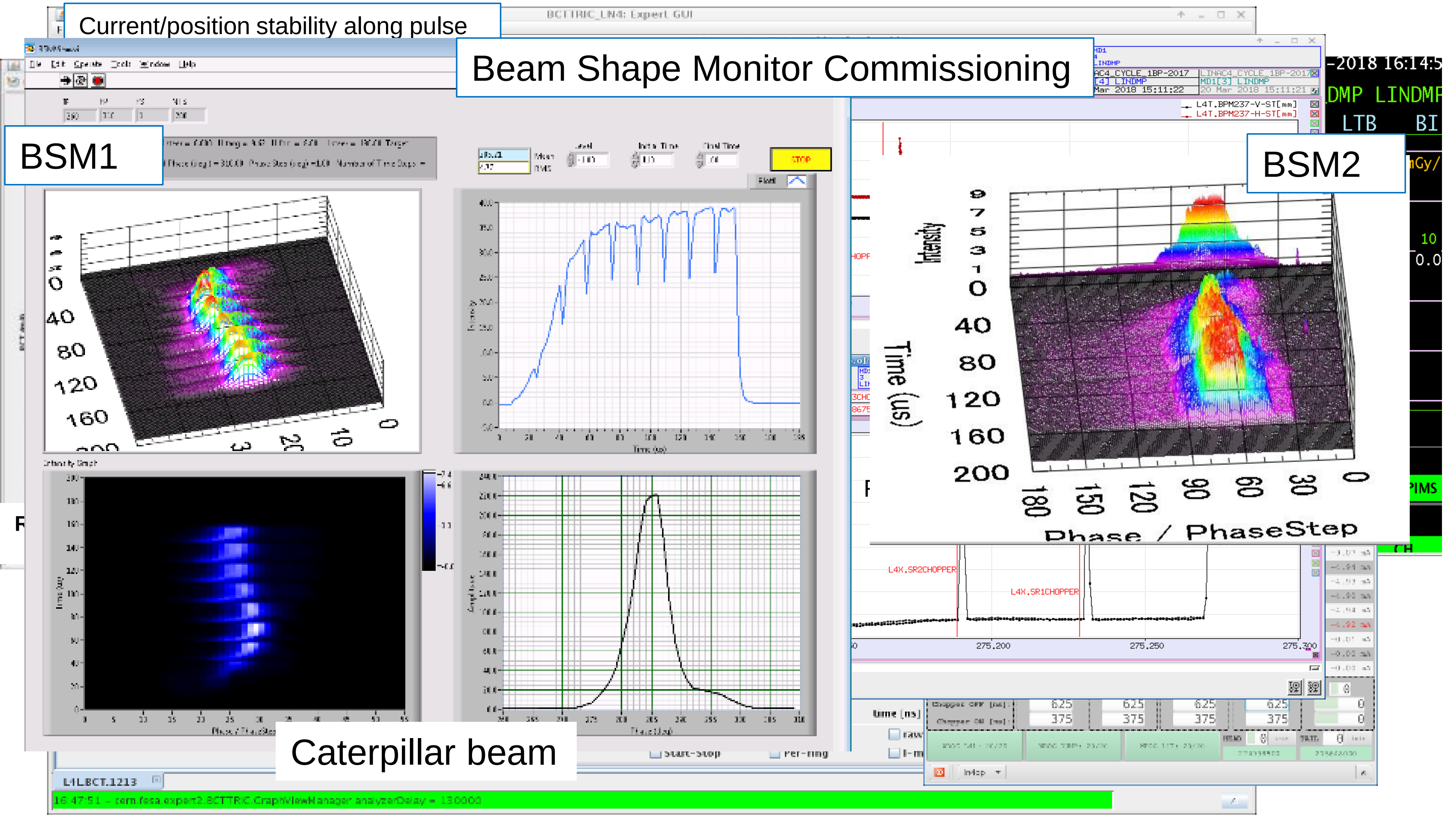
Beam transverse footprint – stripped – 160 MeV at BTV1077 , March ’17



Goals:

- Run the beam through half the injection chicane with the aim of mitigating risks for future PSB H^- Injection Section – as connection schedule is very tight.
- Improve handling and procedures/ gather operational experience
- Debugging and improvement of beam instrumentation/ Sensitivity measurements
- Stripping efficiency measurements with BCTs & H0/H- monitor

Beam quality measurements



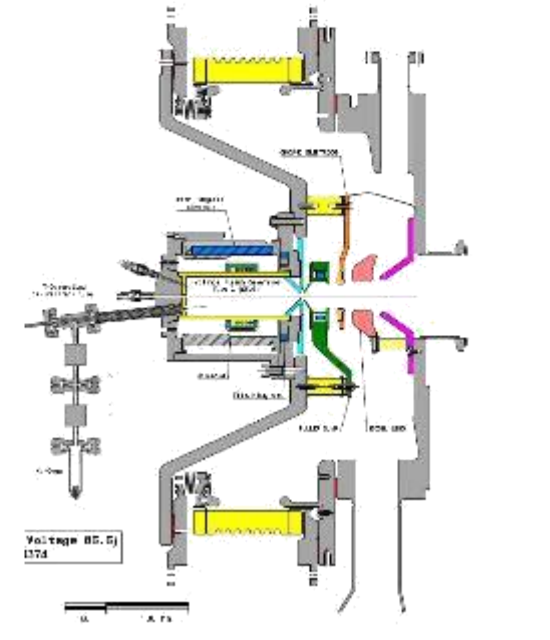
LINAC4: A new injector for the CERN proton complex

LINAC2	LINAC4 – CDR -2006	LINAC4 – achieved (2017)	
protons	H-	Stripping and more tested in Half Sector Test	
160 mA	70mA peak at the source 65 mA peak at 3 MeV 40 mA after chopping	50mA peak (in twice the acceptance of the RFQ) 27 mA peak at 3 MeV 20 mA after chopping	Peak current from the source Average beam current after chopping (LEBT and RFQ transmission and chopping factor)
50 MeV	160 MeV	160.48 MeV	All RF structures performing to specs
1 π mm mrad	0.4 π mm mrad	0.3 π mm mrad (at 160MeV)	Smaller emittance , allows for more turns injected
100 μsec 1Hz	400 μsec 1Hz (4 rings)	Up to 600 μsec 1Hz	Longer injection in the PSB (100-150turns)
200 MHz/ 40 m	352 MHz / 80 m		RF frequency that is not widespread anymore. No components “off the shelf”
-	Fast Chopping at 3 MeV 2μsec inj kicker rise-time	Demonstrated , including transmitted beam quality	Unprecedented flexibility, to be exploited Beam from 1μsec to 150μsec
-	Energy painting with the last accelerating modules	Not yet tested	

CERN

The 3 MeV pre-injector

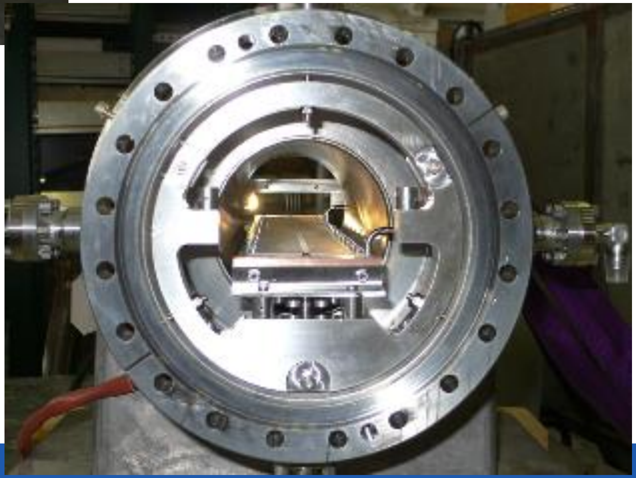
45 keV H- ion source – Cesiated
Delivering stably a 50 mA beam (27 mA within RFQ acceptance).
Further optimisation on-going in a dedicated test stand.



352.2 MHz RFQ
3 m long structure.
Designed and manufactured at CERN.
Reliable operation since 2013.

MEBT with fast beam chopper
3.5 m long matching line from RFQ to DTL
Fast and efficient beam chopping:

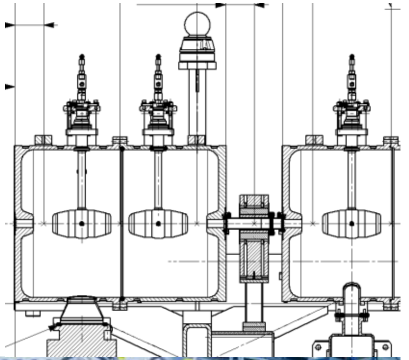
- Risetime < 10ns
- Extinguish factor 100%



The accelerating structures

Drift Tube Linac – 3 - 50 MeV
PMQs in vacuum – FFDD focusing scheme
Designed for > 30 years reliable operation at 10% duty cycle
Adjust and Assemble philosophy: Tight tolerance aluminium girder

Cell-Coupled DTL – 50 - 102 MeV
Construction by BINP and VNIITF in Russia.
7 modules x 3 cavities x 3 gaps.
PMQs located in between cavities.
First-ever CCDTL in a working machine !



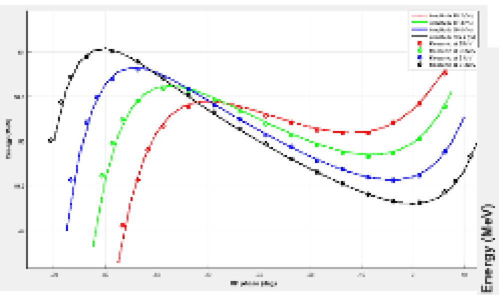
Π Mode Structure – 102 - 160 MeV
Collaboration with NCBJ and FZ-Jülich.
Discs and rings were tuned and electron-beam welded at CERN.
Long qualification period for series production:10-20 µm on 500 mm diameter pieces
First low-beta PIMS on an operational machine.

Setting the RF cavities: time-of-flight

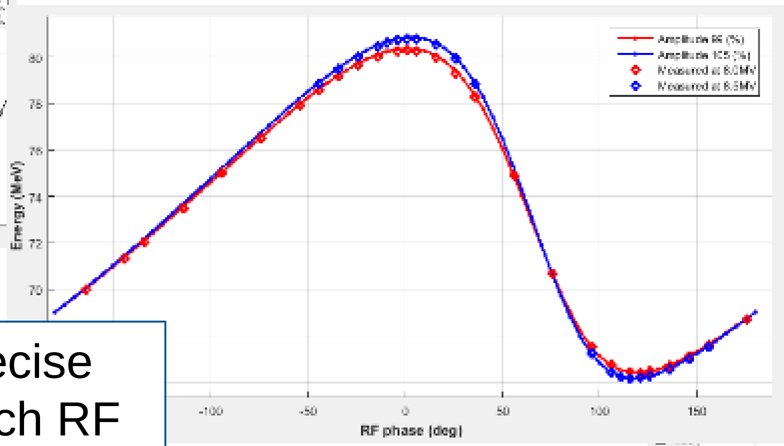
Most of the RF cavities settings are found with Time of Flight

- 17 Beam position monitors from 12 to 160 MeV (for 22 cavities)

DTL tank 3

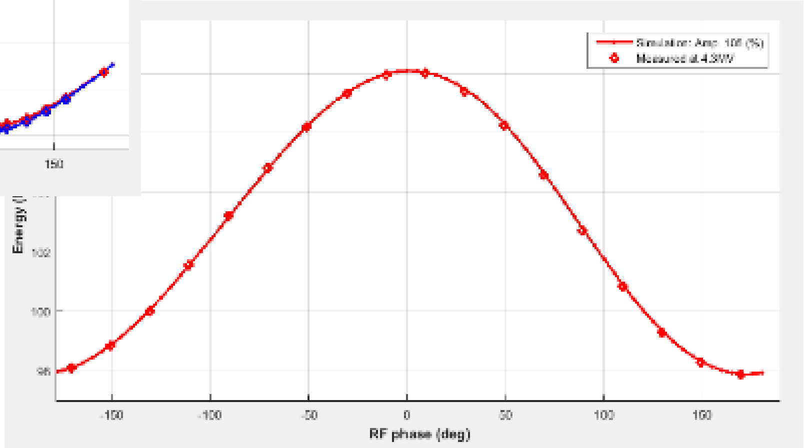


Average energy vs cavity phase



CCDTL module4

PIMS cavity 1



ToF sufficiently precise to allow setting each RF cavity to:

± 0.5 % in amplitude
± 0.5° for the phase

Increasing β & Decreasing number of gaps per cavity