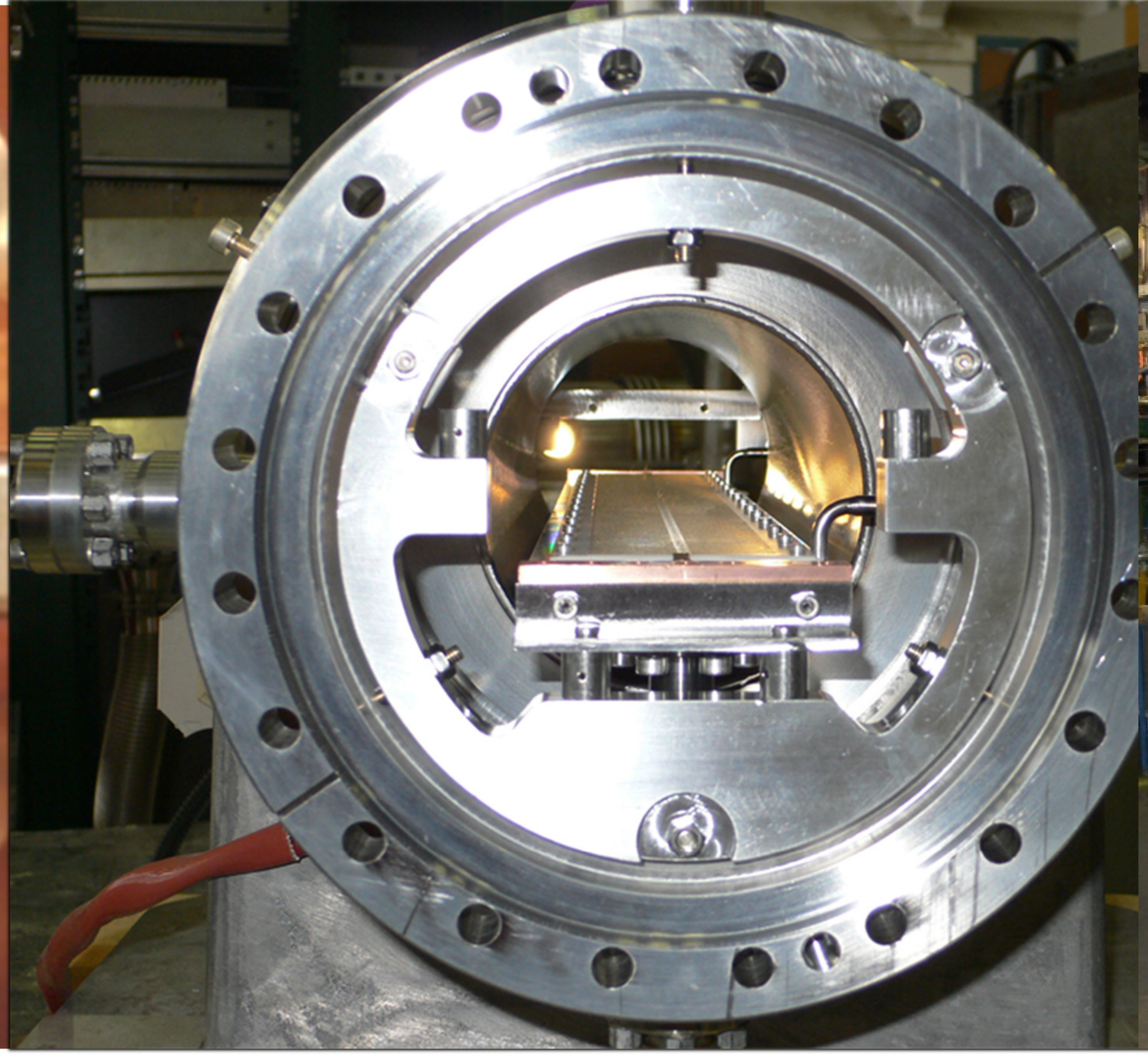
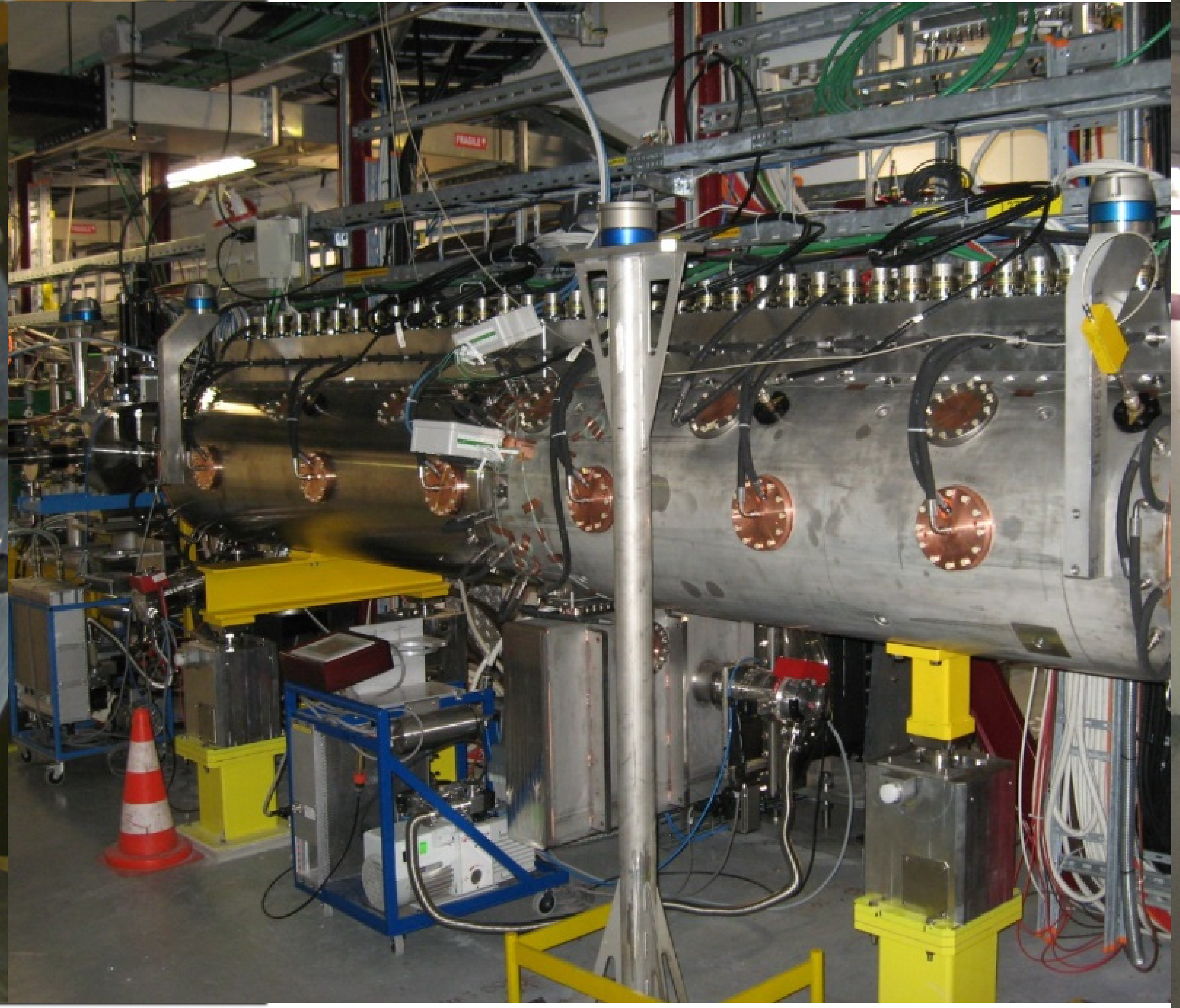
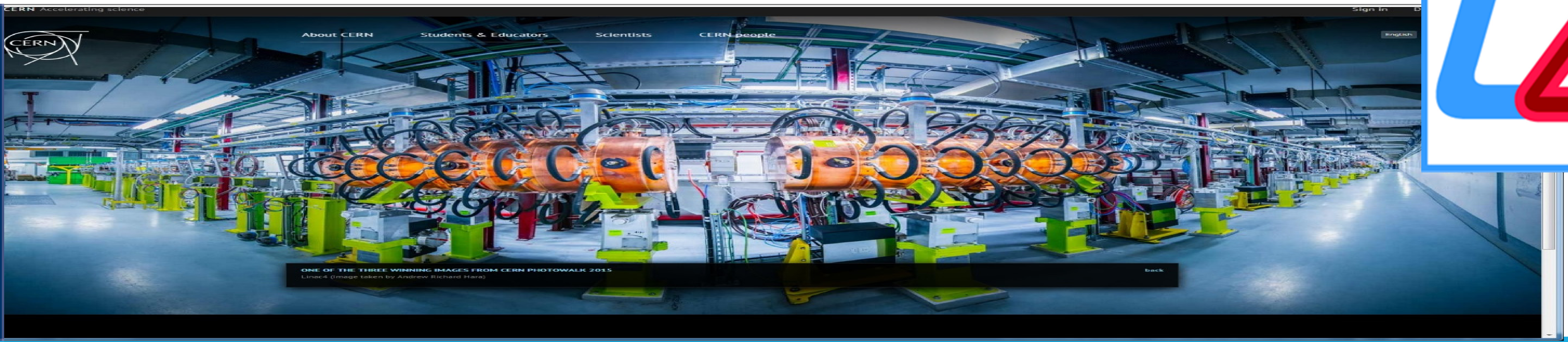


Linac4: From Initial Design to Final Commissioning

Alessandra M Lombardi for the LINAC4 Team



Budker Institute of Nuclear Physics

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK
JRC collaboration partner

Oliver.Abevrle,Davide.Aguglia,Luca.Arnaudon,Philippe.Baudrenghien, Giulia.Bellodi Caterina.Bertone,Yannic.Body,Jan.Borburgh,Enrico.Bravin,Olivier.Brunner,Jean-Paul.Burnet,Marco.Buzio,Christian.Carli,Etienne.Carlier,Miguel.Cerqueira.Bastos,julie.coupard,Jean-Marc.Cravero,Pierre.Dahlen,Benoit.Daudin,Jurgen.de.Jonghe,Nuno.Dos.Santos,L.Ducimetiere,Tony.Fowler,jean-frederic.fuchs,Delphine.Gerard,Frank.Gerigk,jean-michel.giguet,Silvia.Grau,Jean-Claude.Guillaume,Louis.Hammouti,Klaus.Hanke,Michael.Hourican,Mark.Jones,Quentin.King,Ioan.Kozsar,Jean-Baptiste.Lallement,Gilles.Le.Godec,Franco.Lenardon,Alessandra.Lombardi,Luz.Lopez-Hernandez,Serge.Mathot,Stefano.Moccia,Eric.Montesinos,Antony.Newborough,David.Nisbet,Mauro.Paoluzzi,Aurelie.Pascal,Daniel.Perrin,Jerome.Pierlot,Serge.Pittet,Bruno.Puccio,Uli.Raich,Suitbert.Ramberger,Carlo.Rossi,Richard.Scrivens,Lars.Soby,Jocelyn.Tan,Hugues.Thiesen,Pierre.Alexandre.Thonet,Giovanna.Vandoni,Maurizio.Vretenar,Wim.Weterings,Christos.Zamantzas,Thomas.Zickler, Elena.Benedetto,Alessandro.Bertarelli,Etienne.Carlier,Jean-Pierre.Corso,julie.coupard,Yves.Cuvet,Alessandro.Dallocchio,L.Ducimetiere,Gilles.Favre,Alan.Findlay,Jan.Hansen,Lars.Jensen,Rhodri.Jones,Detlef.Kuchler,Jean-Michel.Lacroix,Bettina.Mikulec,Dominique.Missiaen,john.molendijk,Benoit.Riffaud,Federico.Roncarolo,Carlo.Rossi,Jose-Luis.Sanchez.Alvarez,Andrzej.Siemko,Marco.Silari,Lars.Soby,Didier.Steyaert,Jocelyn.Tan,Pierre.Alexandre.Thonet,joachim.vollaire,Rolf.Wegner,Sylvain.Weisz, Michel.Arnaud,Luca.Arnaudon,Sonia.Bartolome,Cedric.Baud,cyrille.patrick.bedel,aurelio.berjillos,christian.marc.bernard,Ana-Paula.Bernardes,Alessandro.Bertarelli,Sebastien.Bertolo,thomas.william.birtwistle,Jan.Blaha,Sebastien.Blanchard,Yannic.Body,philippe.boisseaux-bourgeois,robert.borner,Olivier.Brunner,pawel.andrzej.burdelski,Didier.Chapuis,Ahmed.Cherif,Laurent.Colly,Fabio.Corsanego,Jean-Pierre.Corso,julie.coupard,Christophe.Coupat,Jean-Marc.Cravero,Olivier.Crettiez,Maryse.Da.Costa,Alessandro.Dallocchio,jose.delagama,gian.piero.di.giovanni,Tobias.Dobers,Gerald.Dumont,John.Etheridge,Gilles.Favre,ja.ferreira,Ramon.Folch,Katy.Foraz,Robert.Froeschl,jean-frederic.fuchs,Anne.Funken,javier.galindo,georgi.minchev.georgiev,Frank.Gerigk,jean-michel.giguet,Gael.Girardot,David.Glenat,Paulo.Gomes,Marine.Pace,Silvia.Grau,Jean-Louis.Grenard,Damien.Grenier,Serge.Grillot,jean-francois.gruber,Roberto.Guida,greta.guidoboni,Jean-Claude.Guillaume,abel.gutierrez,Louis.Hammouti,Jan.Hansen,Steve.Hutchins,Stephane.Joffe,Mark.Jones,Ioan.Kozsar,Jean-Michel.Lacroix, David.Landre,raphael.langlois,jean.marc.lassauce,patrick.lelong,Jacques.Lettry,Yann.Lupkins,Jose.Marques,Christophe.Martin,alex.martinez,Pablo.Martinez.Yanez, Albert.Masson,Christian.Mastrostefano,Simon.Mataguez,Serge.Mathot,Bettina.Mikulec,Stefano.Moccia,Richard.Mompo,Boris.Morand,richard.francis.morton,Antony.Newborough,Christophe.Nicou,Pierre.Ninin,David.Nisbet,Remy.Noulibos,Miguel.Ojeda-Sandonis, Francesco.di.Lorenzo, Micheal.o.Neil, Chiara Bracco, Federico Roncarolo

PS/RF/Note 96-27
25 October 1996

PROPOSAL FOR A 2 GEV LINAC INJECTOR FOR THE CERN PS

R. Garoby, M. Vretenar

CERN/PS 99-064 (RF)

STATUS OF THE PROPOSAL FOR A SUPERCONDUCTING PROTON LINAC AT CERN

R. Garoby, M. Vretenar

CERN–AB–2006–084 ABP/RF

Linac4 Technical Design Report

1-Proposals from 1996 to 2006

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).

2-Decision in 2007 **R. Aymar director general**

3-Ground Breaking ceremony : 16 October 2008

4-Inauguration : 9 May 2017

The big picture : LHC Luminosity

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

N_b	number of particles per bunch
n_b	number of bunches
f_r	revolution frequency
ε_n	normalised emittance
β^*	beta value at Ip
F	reduction factor due to crossing angle

From optics at Interaction point

From machine design and limitations (e cloud)

Brightness from Injectors : defined at low energy

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

See K. Hanke WEPVA036

Baseline beam parameters

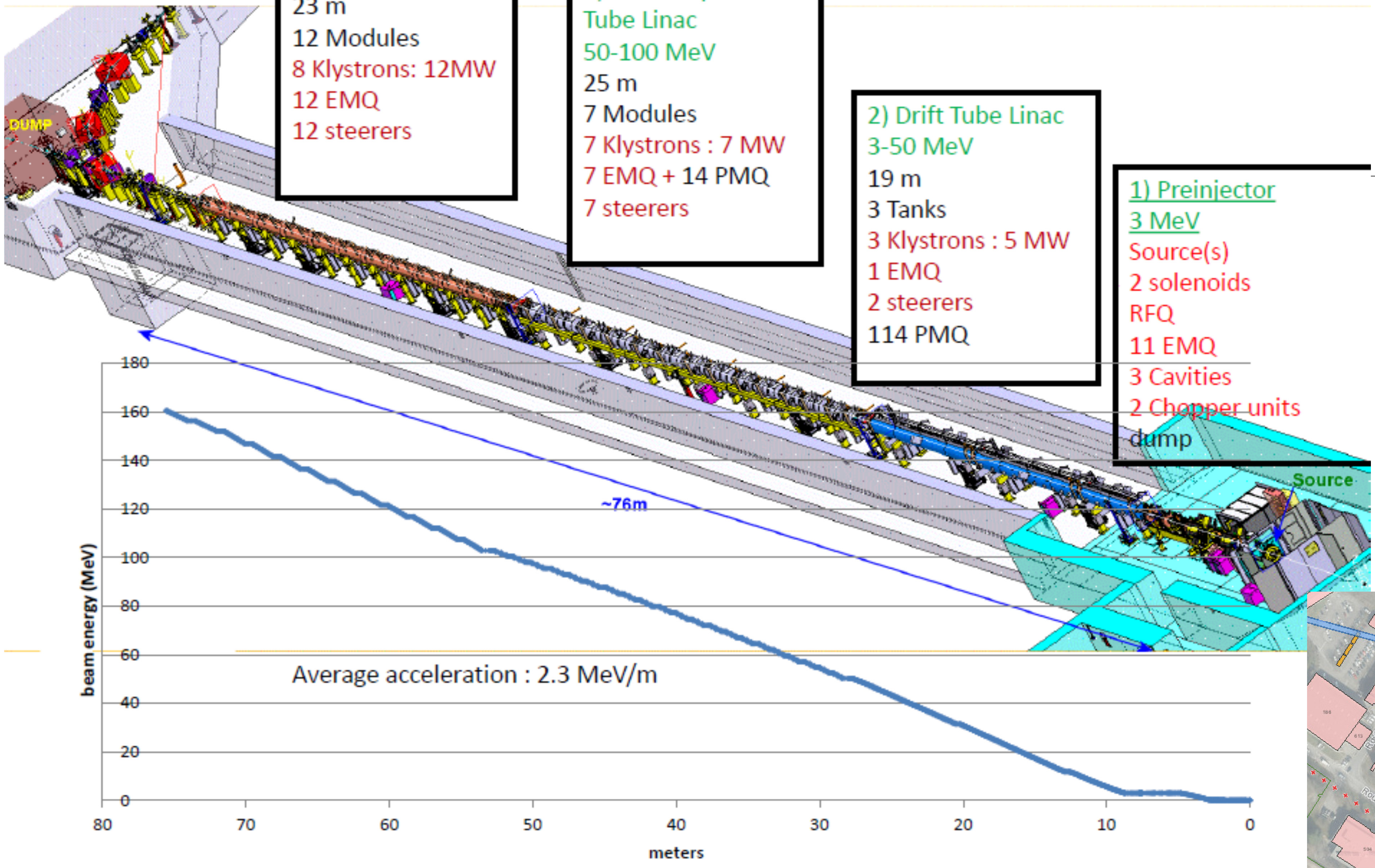
	LINAC4 – CDR -2006	LINAC4 – achieved (2016)	
*	H-	Stripping and more tested in Half Sector Test	
	70mA peak at the source 65 ma peak at 3 MeV 40 mA after chopping	50mA peak (in twice the acceptance of the RFQ) 30 mA peak at 3 MeV (record) 20 mA after chopping	Peak current from the source Average beam 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 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	

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

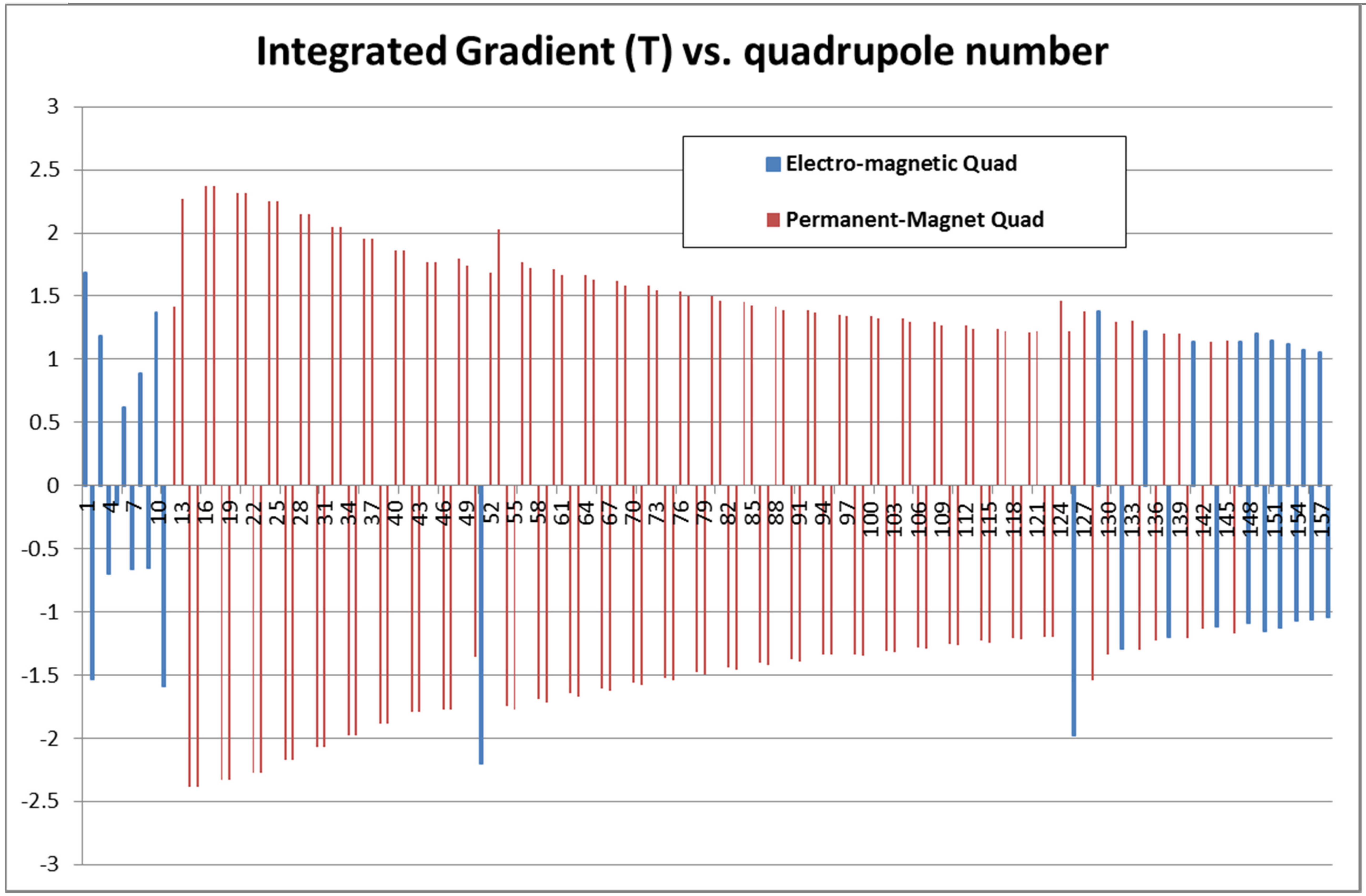
1) Preinjector
3 MeV
Source(s)
2 solenoids
RFQ
11 EMQ
3 Cavities
2 Chopper units
dump



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

Located 12m underground

Quadrupoles :mostly PMQ (127/158)

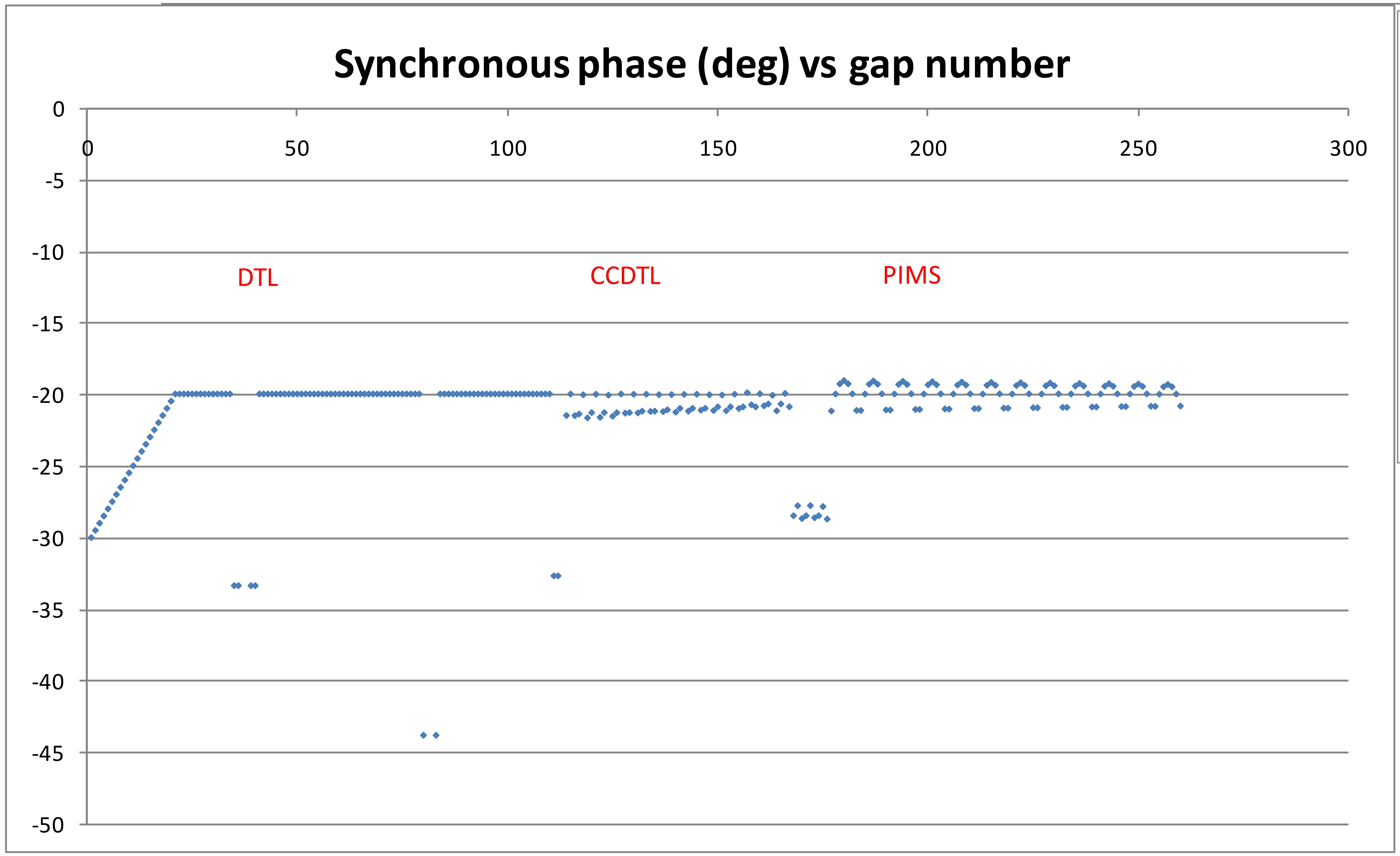


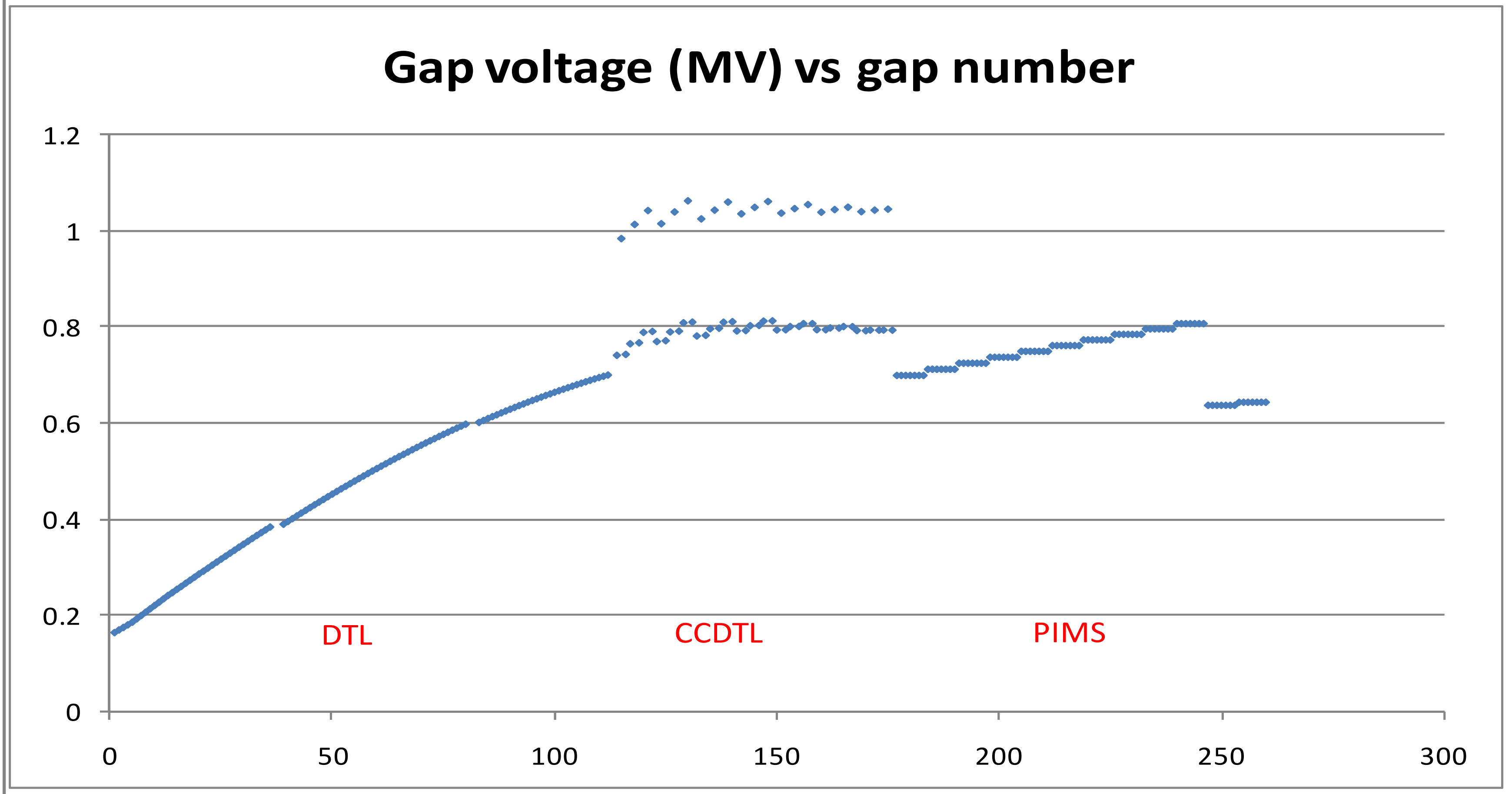
-Flexibility in matching and chopping 0-80 mA currents from the pre-injector.

-Flexibility in bringing beams with energy from 50 MeV onwards to the PSB.

PMQ for tank2 , 60 mm in diameter and 80 mm in length

Accelerating Gaps (262) voltage and phase

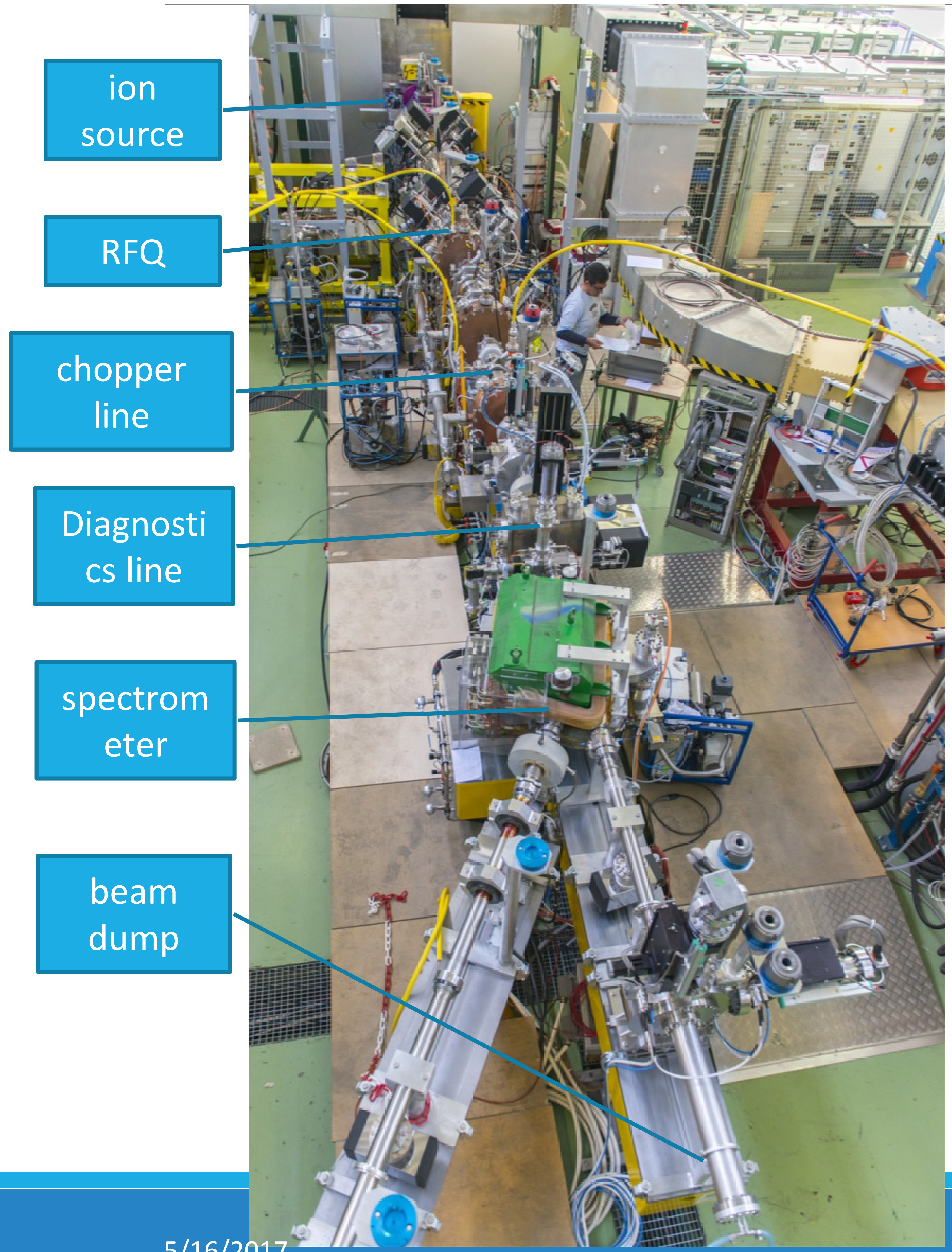




Quasi-synchronous structures with external focusing from 50MeV

Sequence of 3 identical gaps from 50 to 100MeV and 7 identical gaps from 100 to 160MeV

Pre-injector –source to 3 MeV (Oct 13)



Critical part was tested in a dedicated test stand equipped with a diagnostics line including :

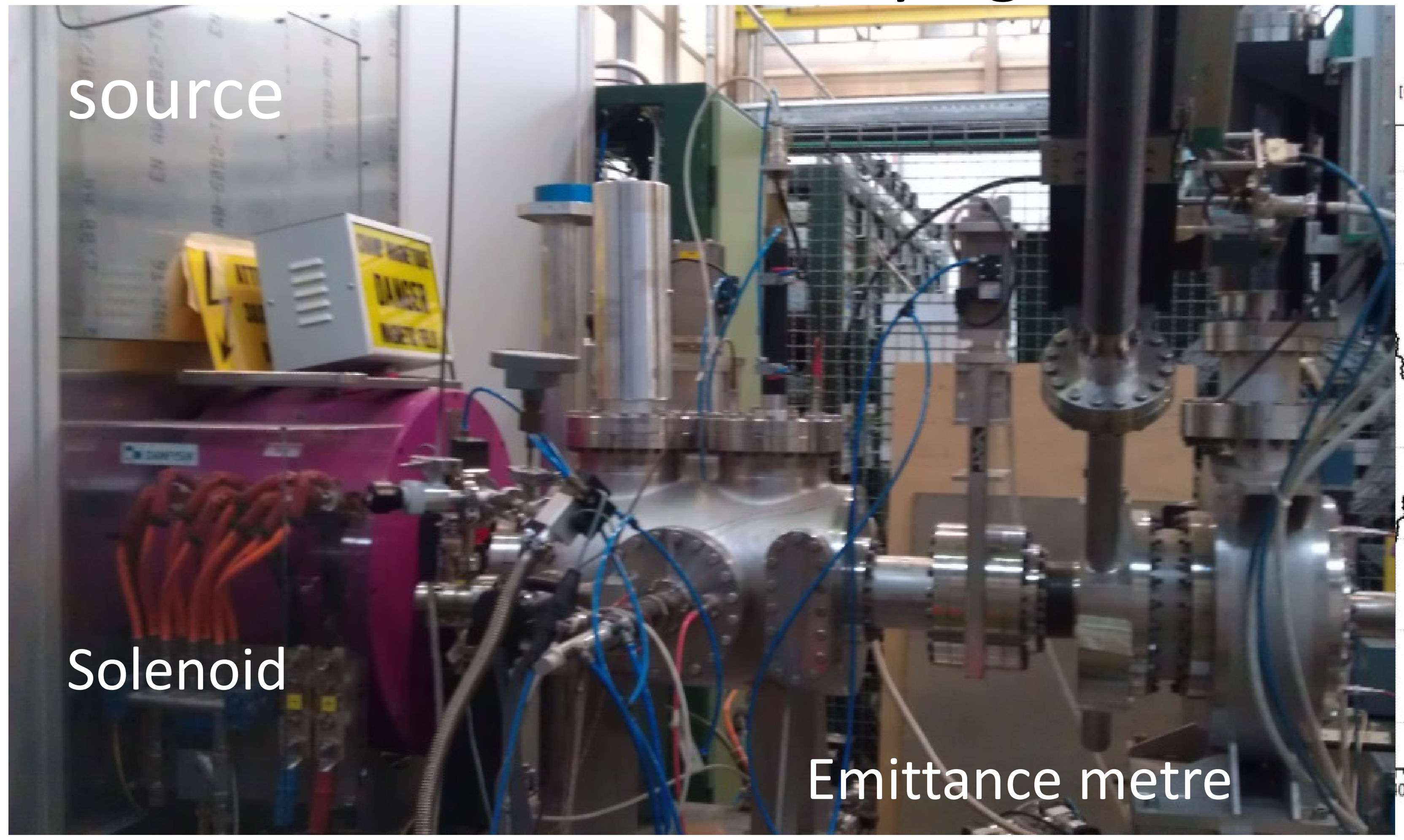
1)direct emittance measurement

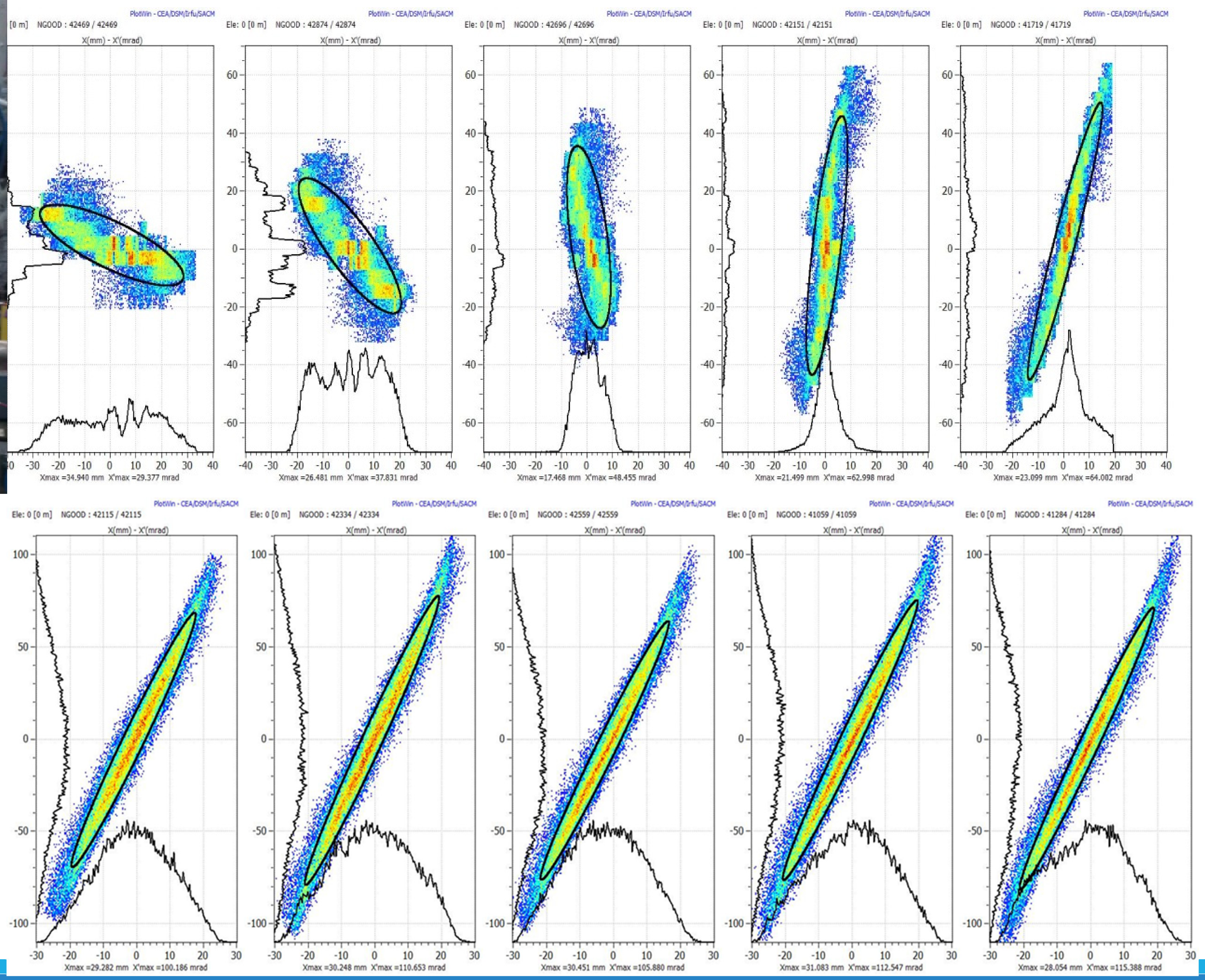
2) bending spectrometer magnet

3) time-of-flight

Extensive measurements at 45 keV

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

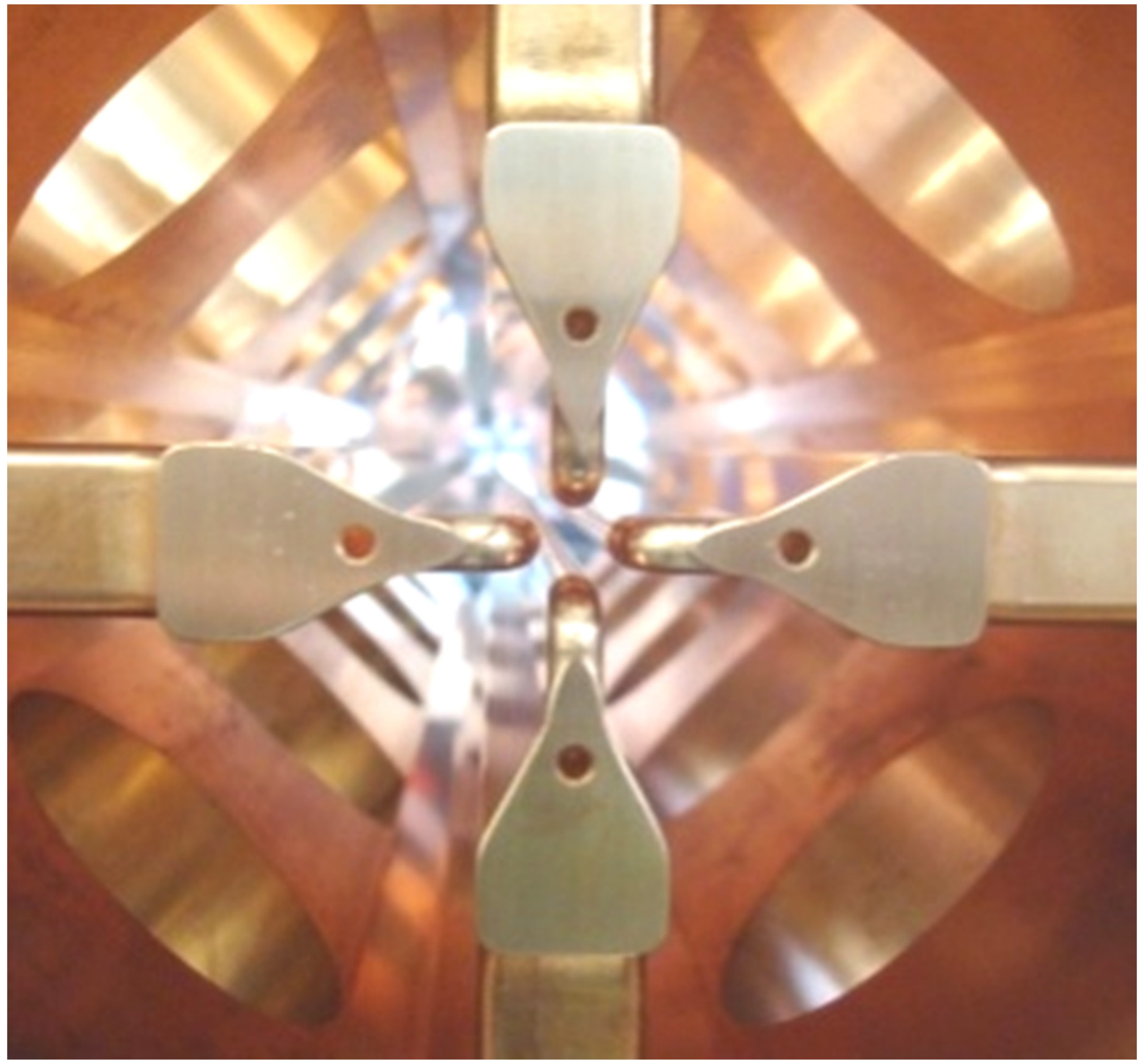




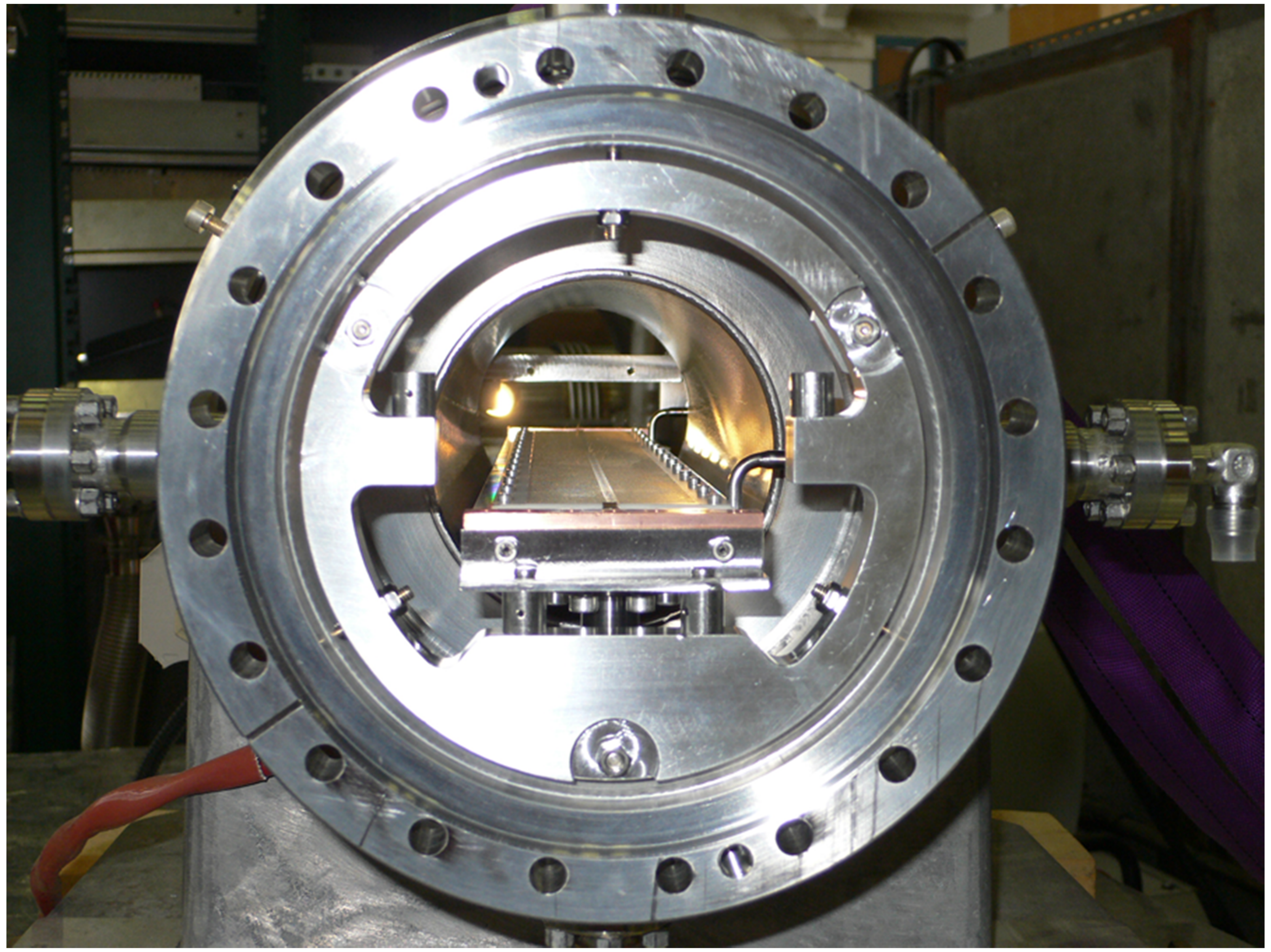
2 – back-trace to source out

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

Pre-injector



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



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

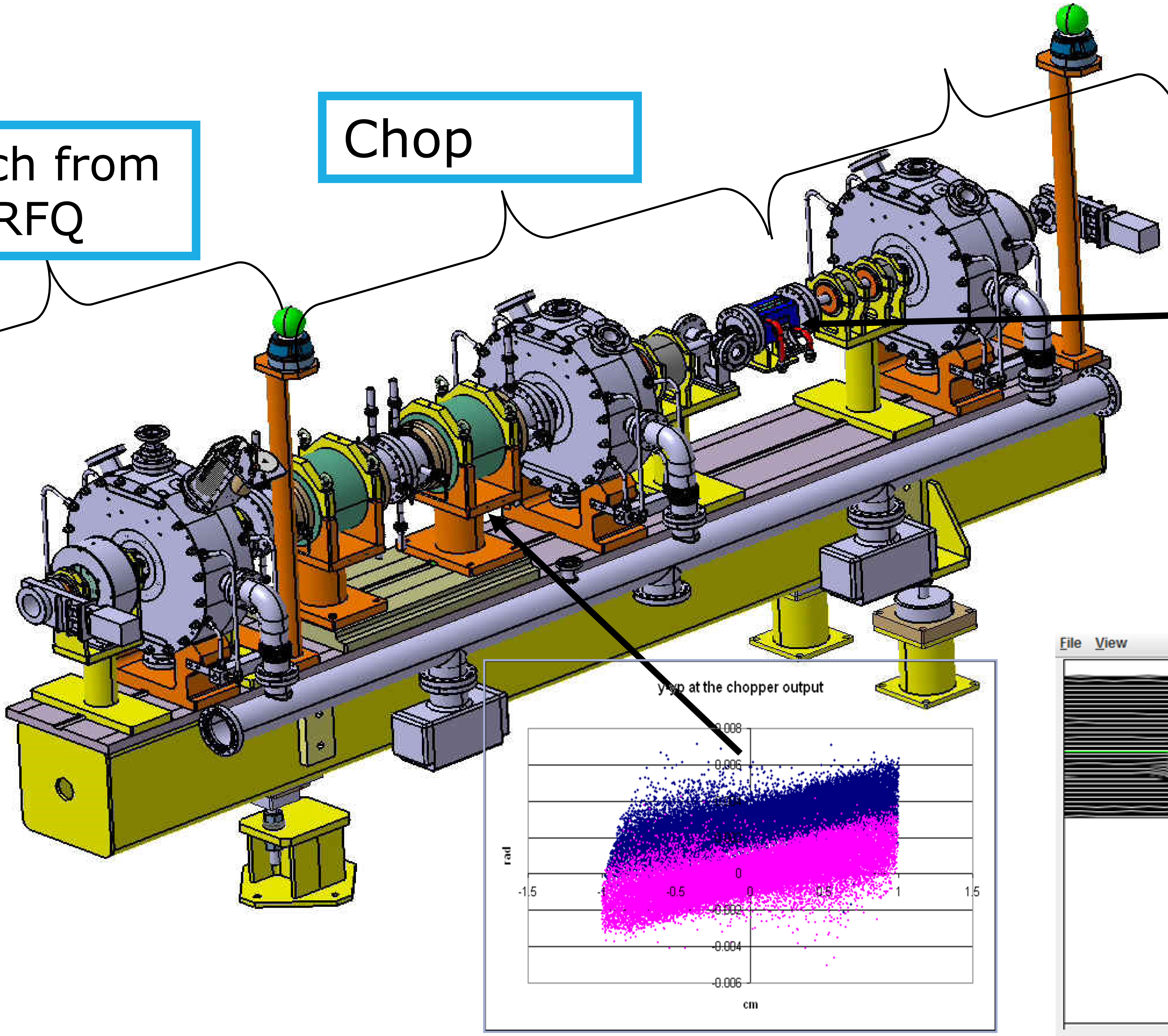
CHOPPING at 3 MeV

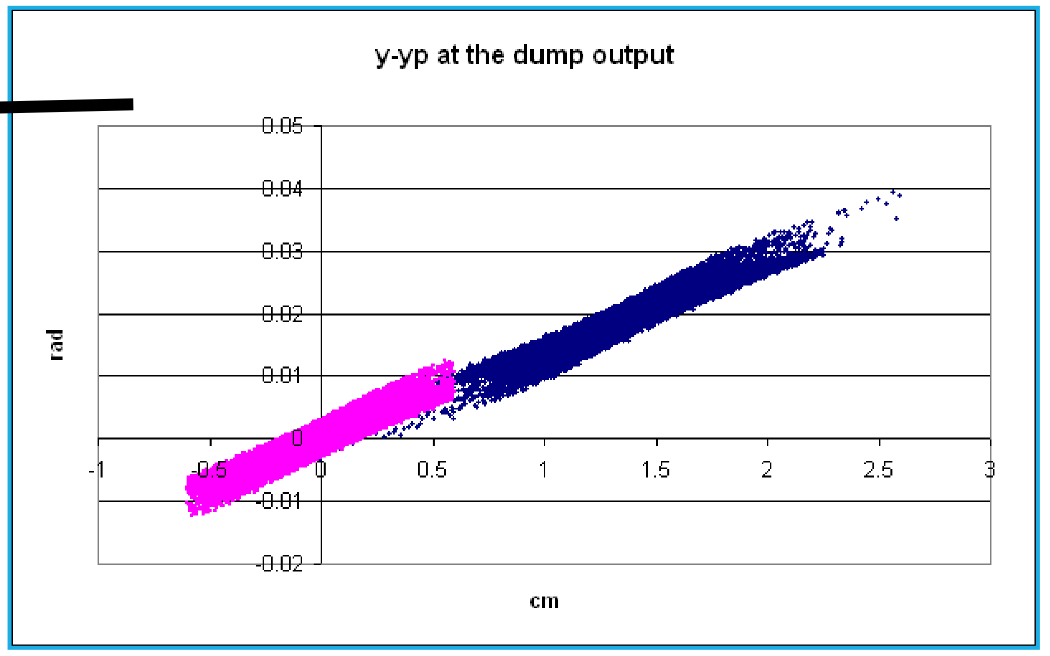
emoving microbunches (150/352) to adapt the 352MHz linac bunches to the 1 MHz booster frequency

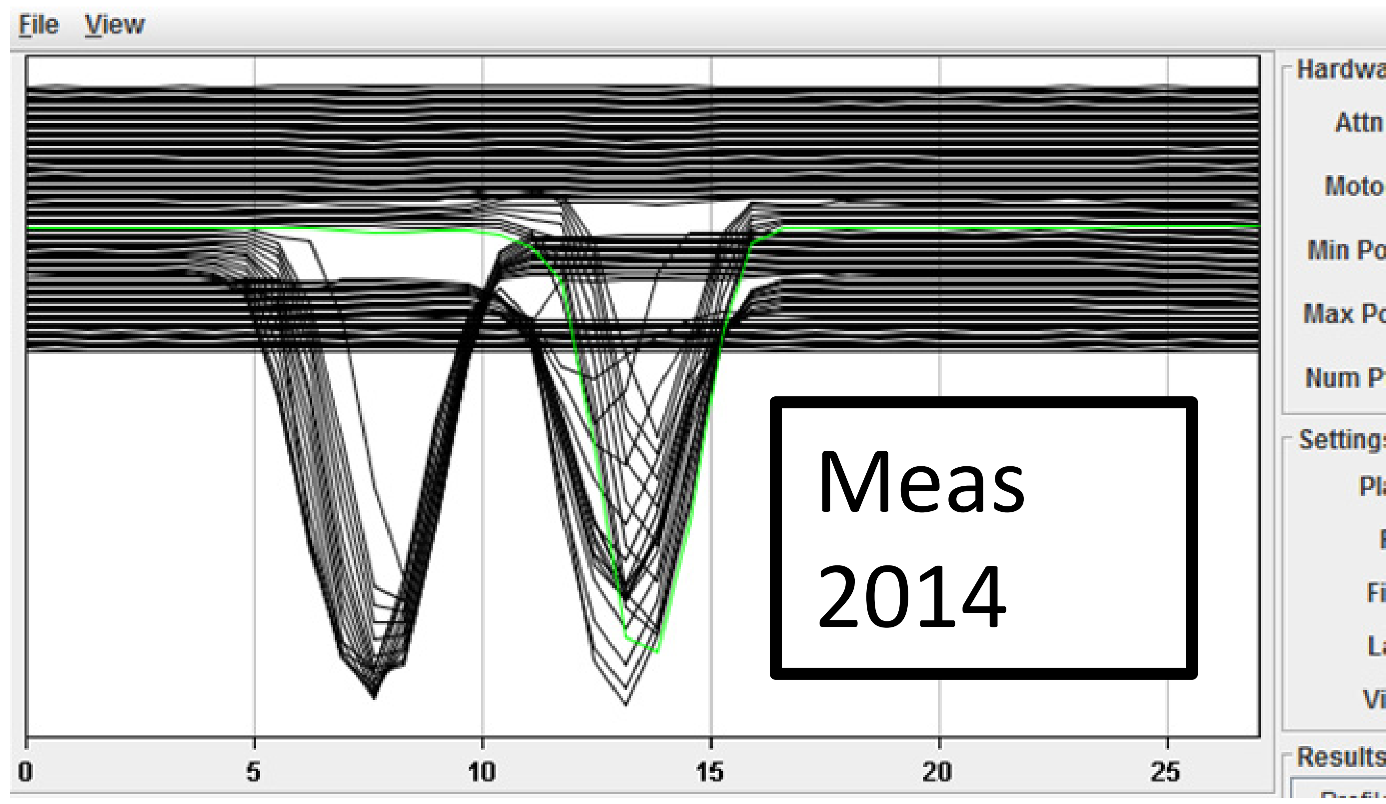
Match from the RFQ

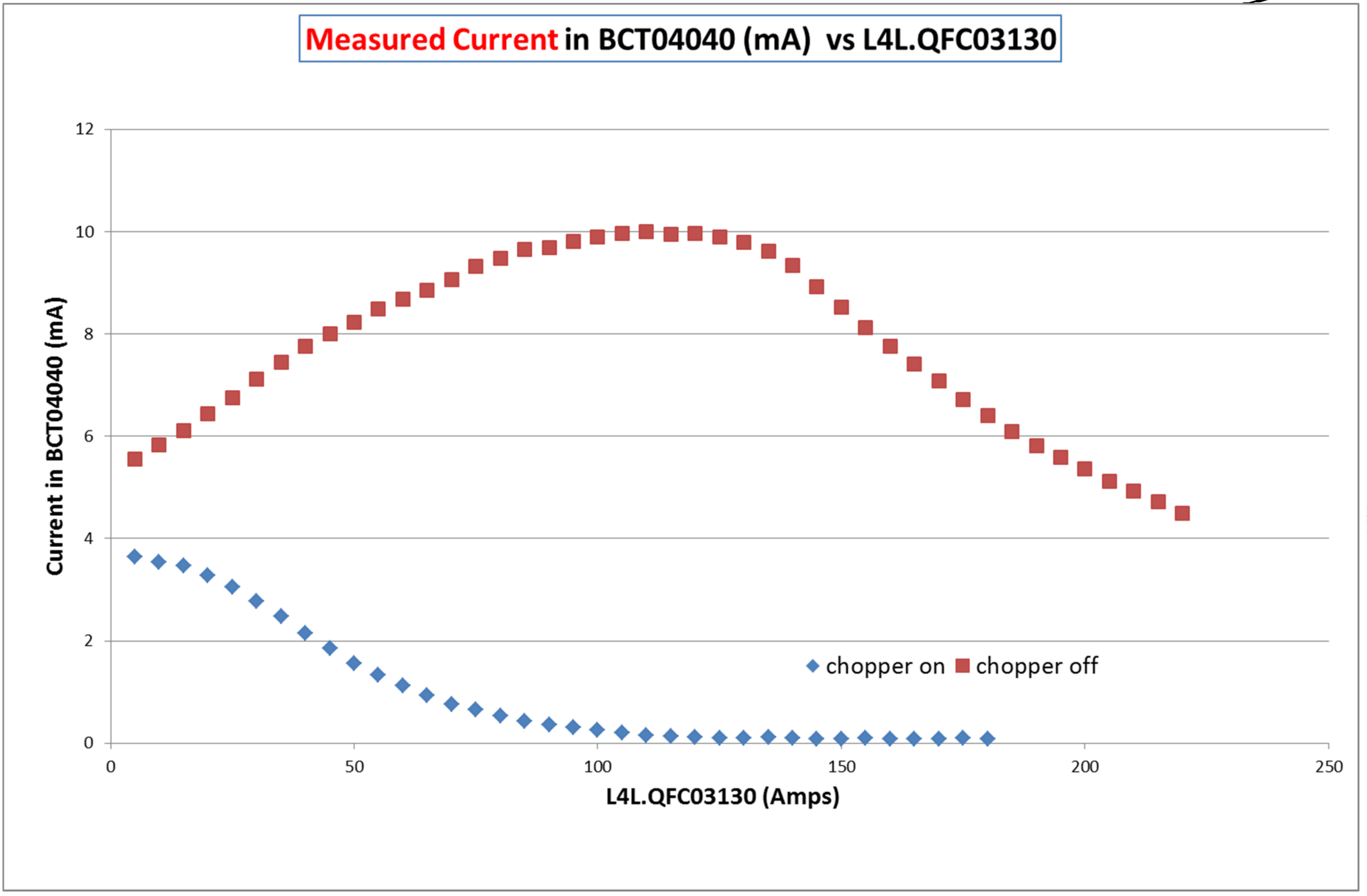
Chop

Match to the DTL





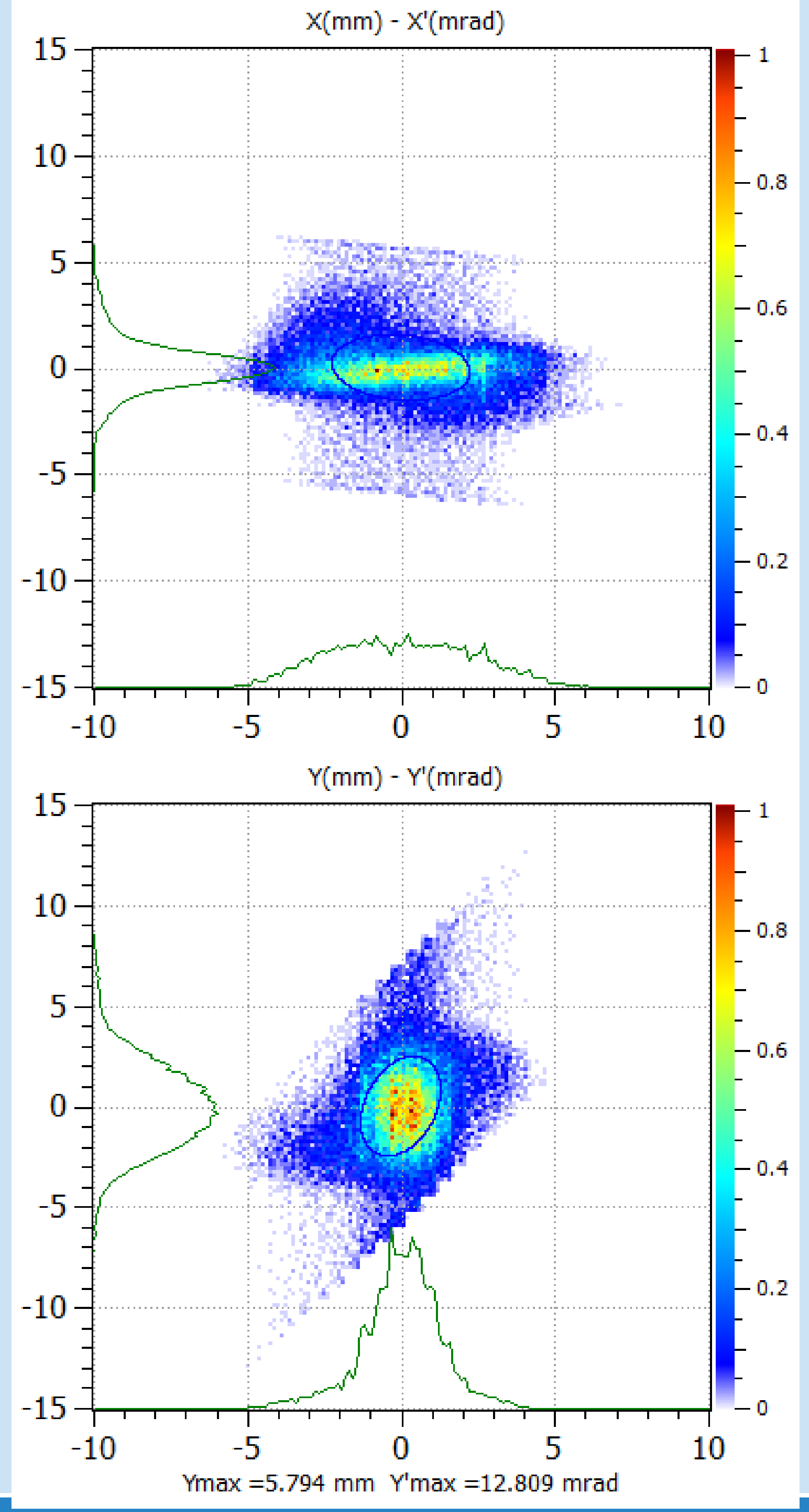




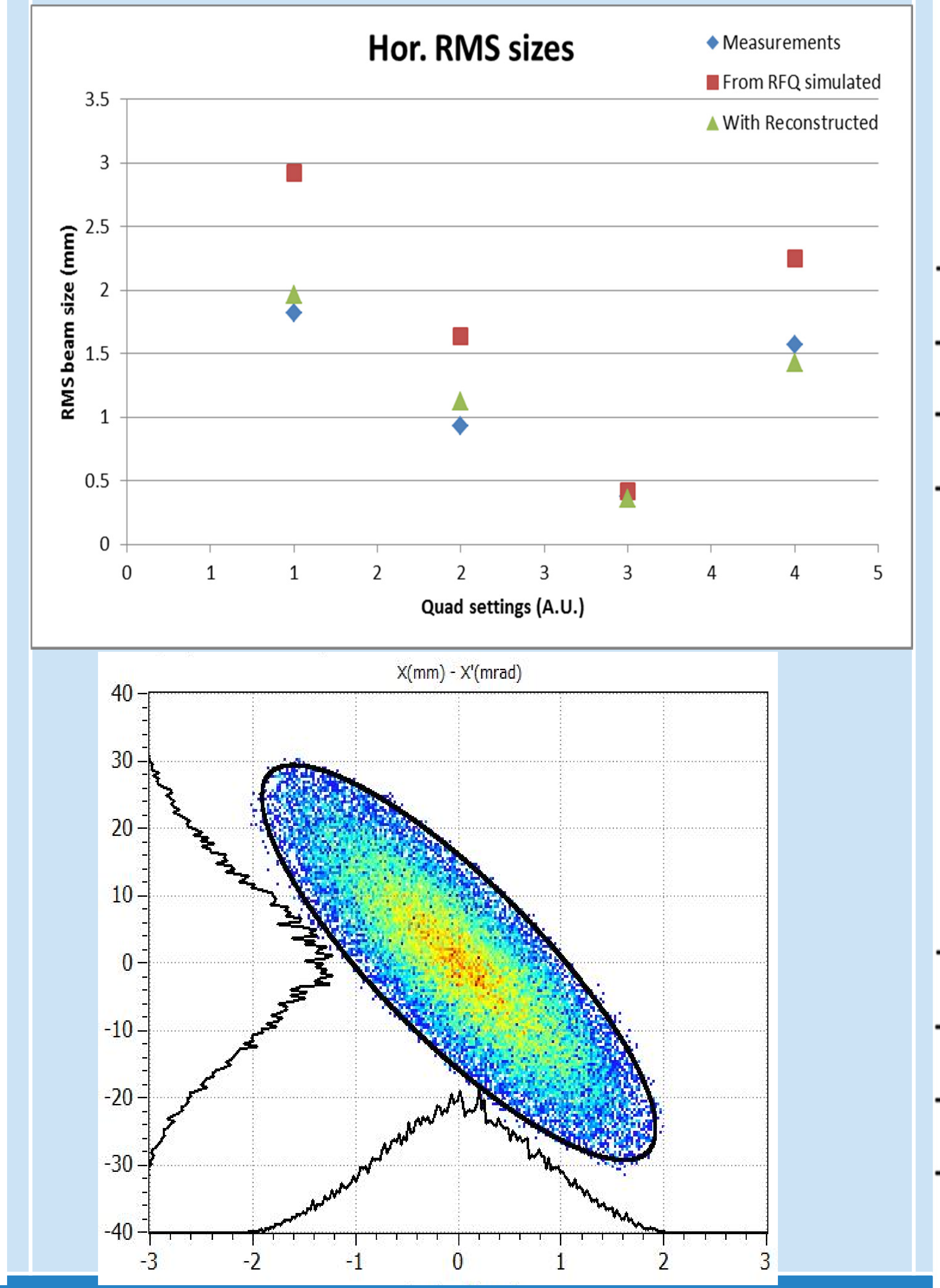
Beam current downstream the dump

Pre-injector : validation of diagnostics

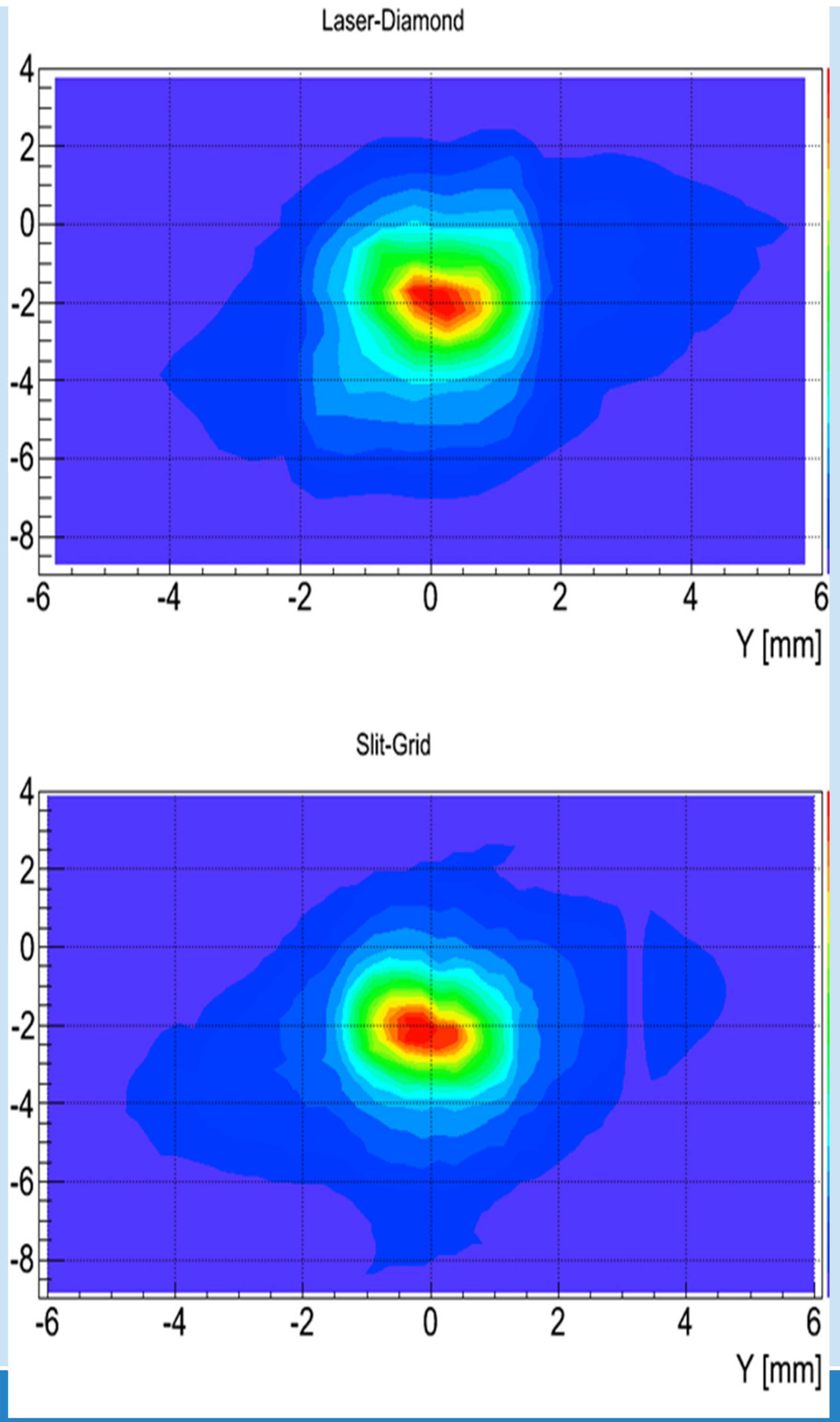
Slit-and-grid



From profile meas



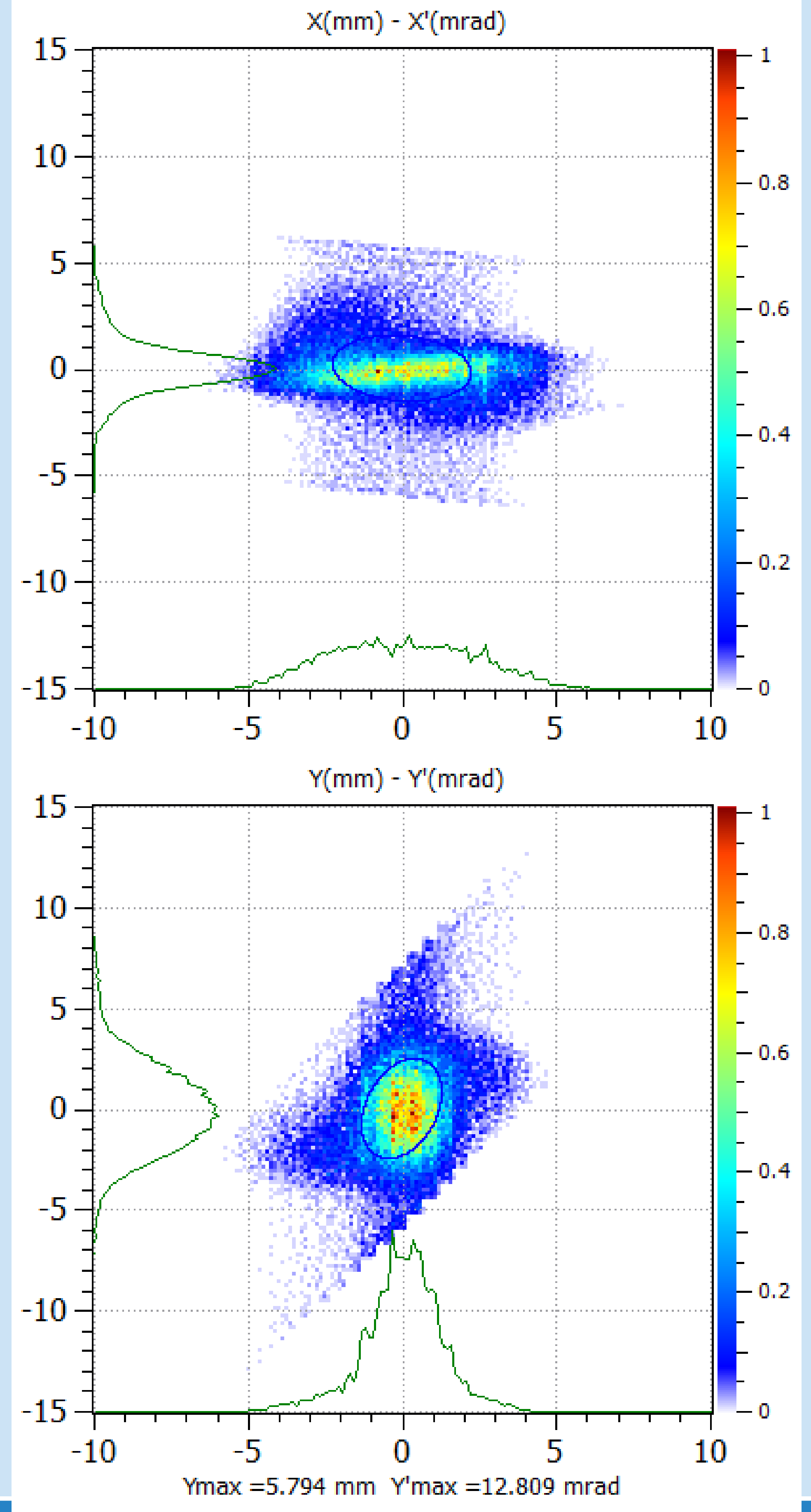
Laser + diamond



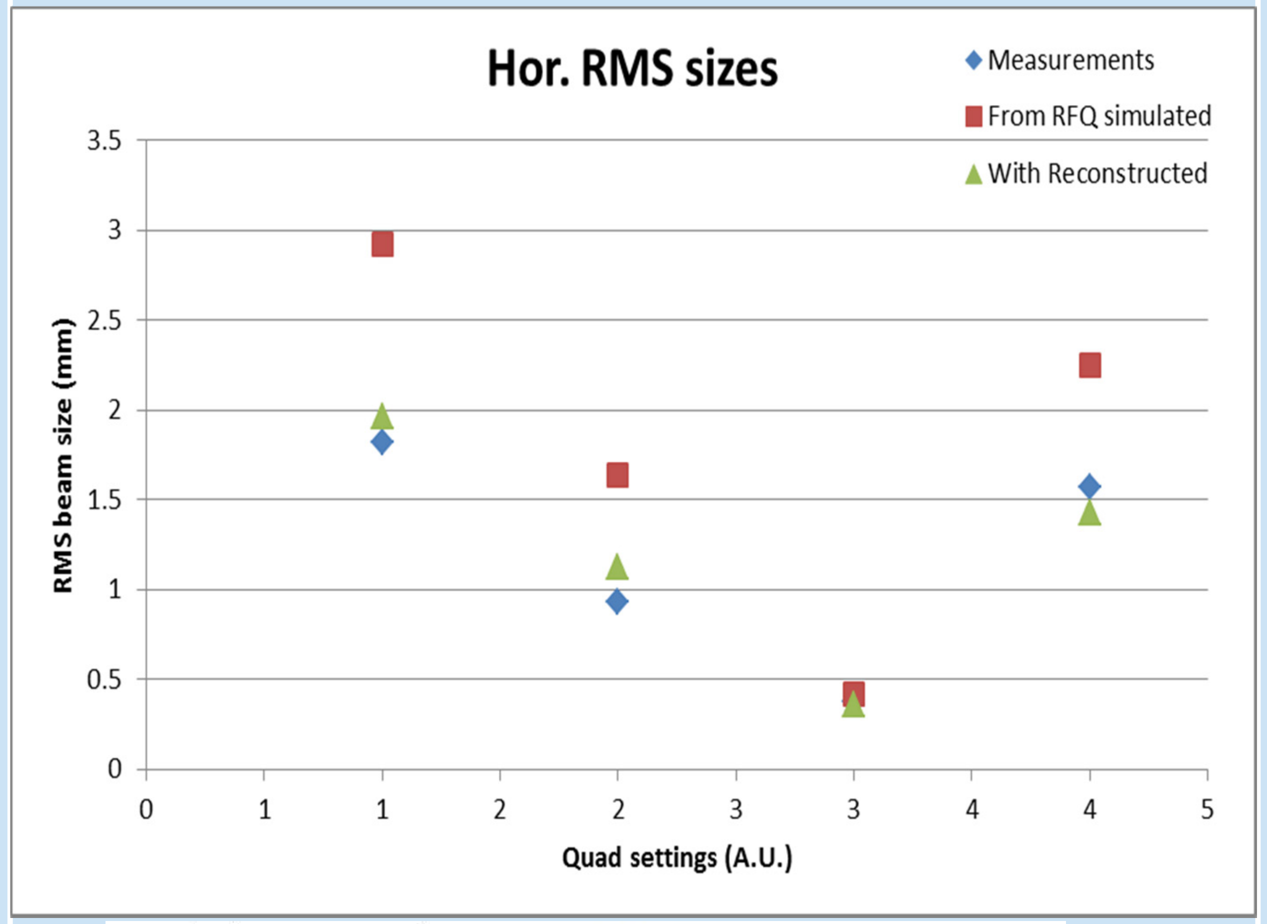
rms normalised Transverse emittance at 3 MeV measured by 3 independent systems is <u>0.3 pi mm mrad</u>

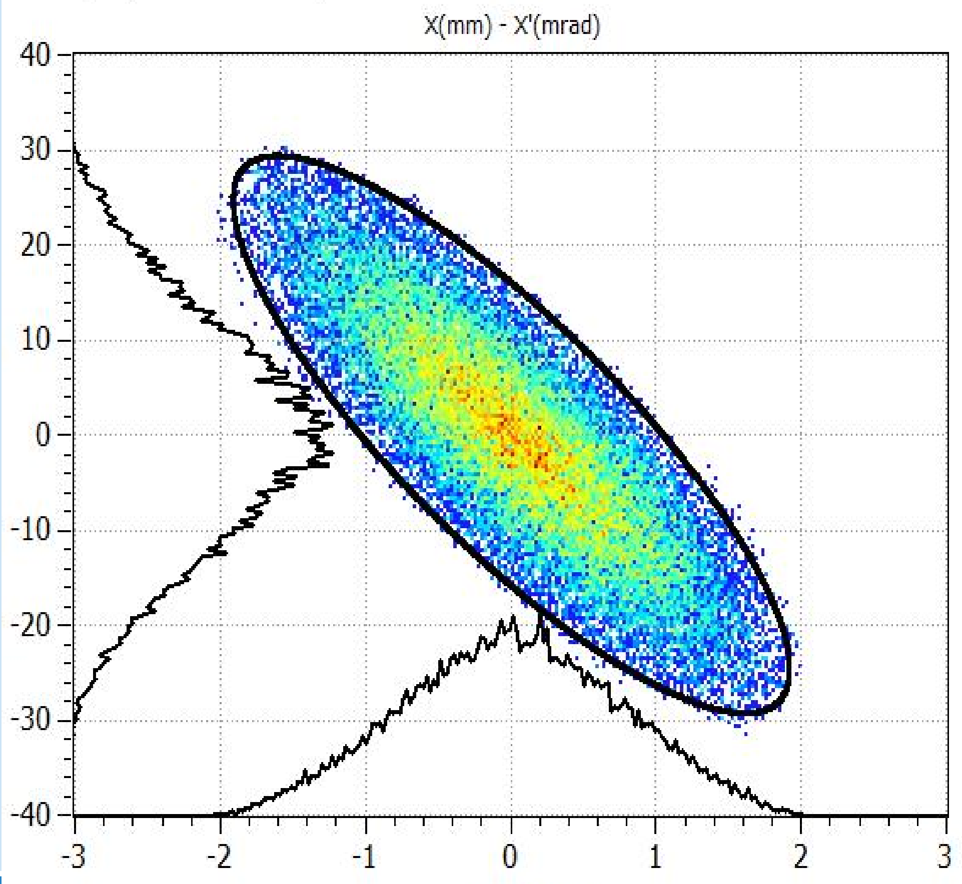
Pre-injector : validation of diagnostics

Slit-and-grid

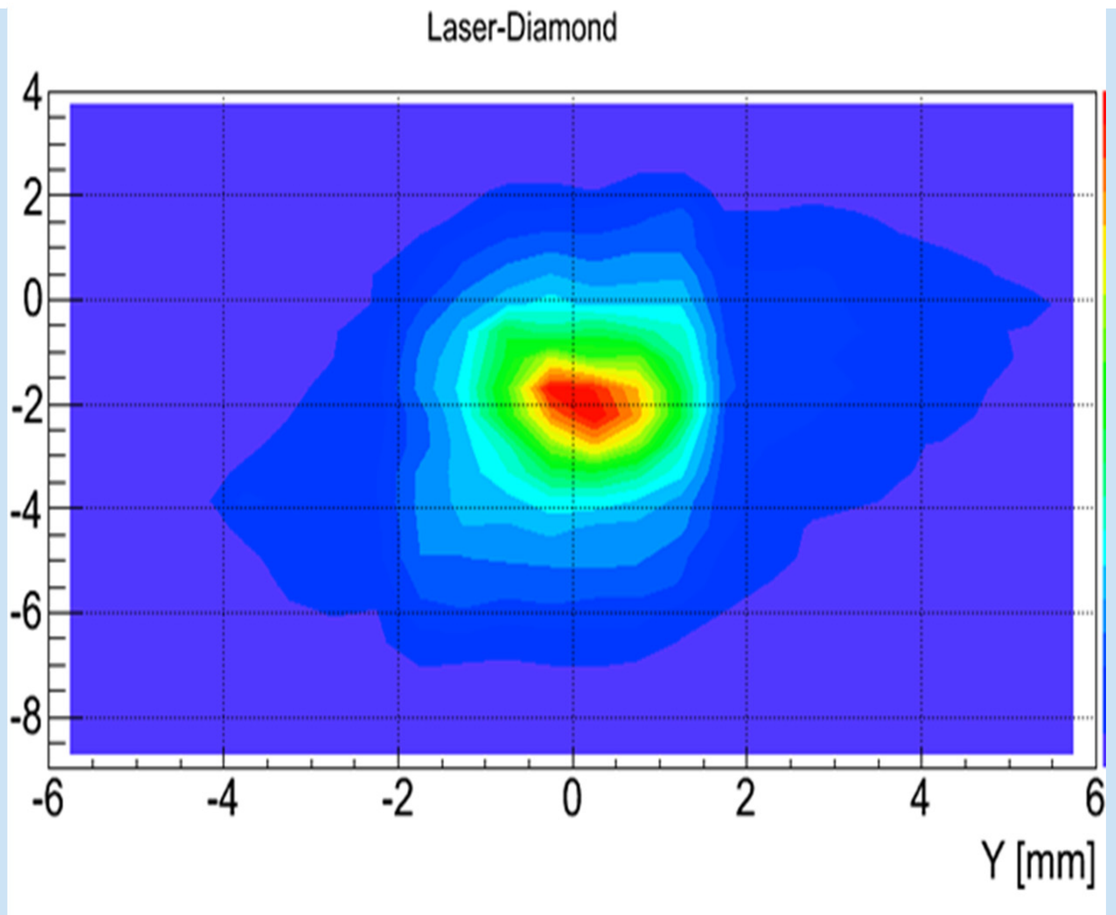


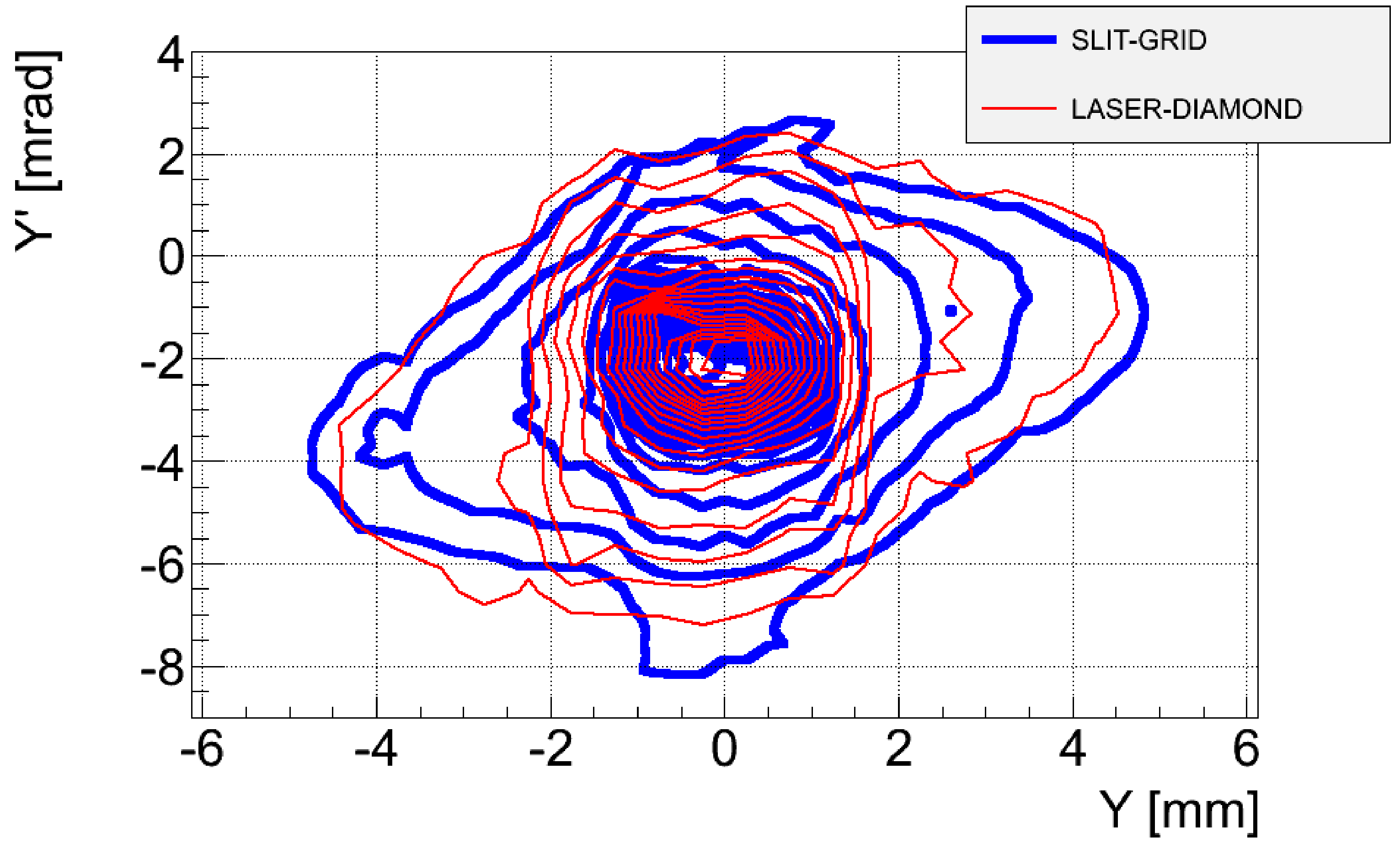
From profile meas





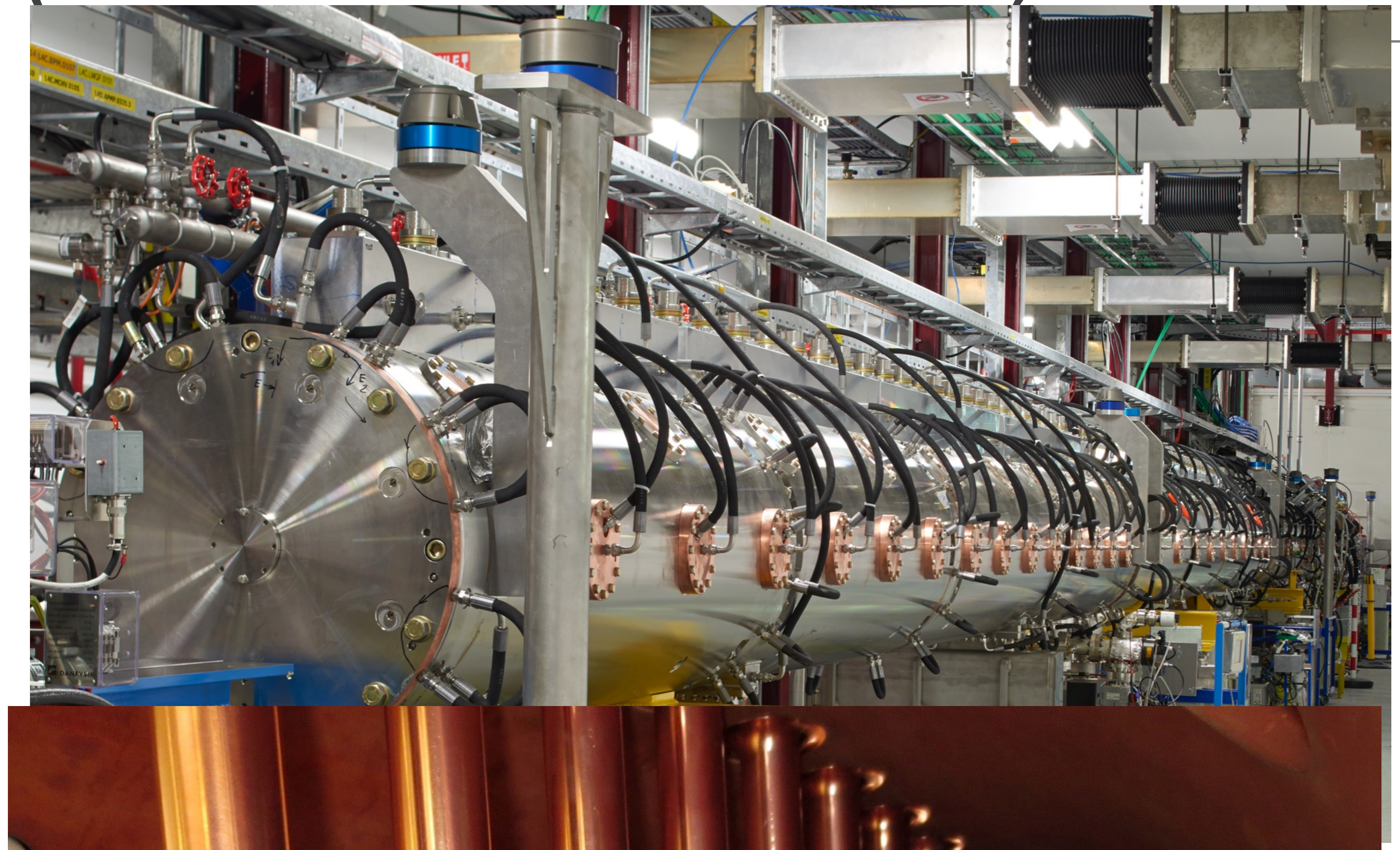
Laser + diamond





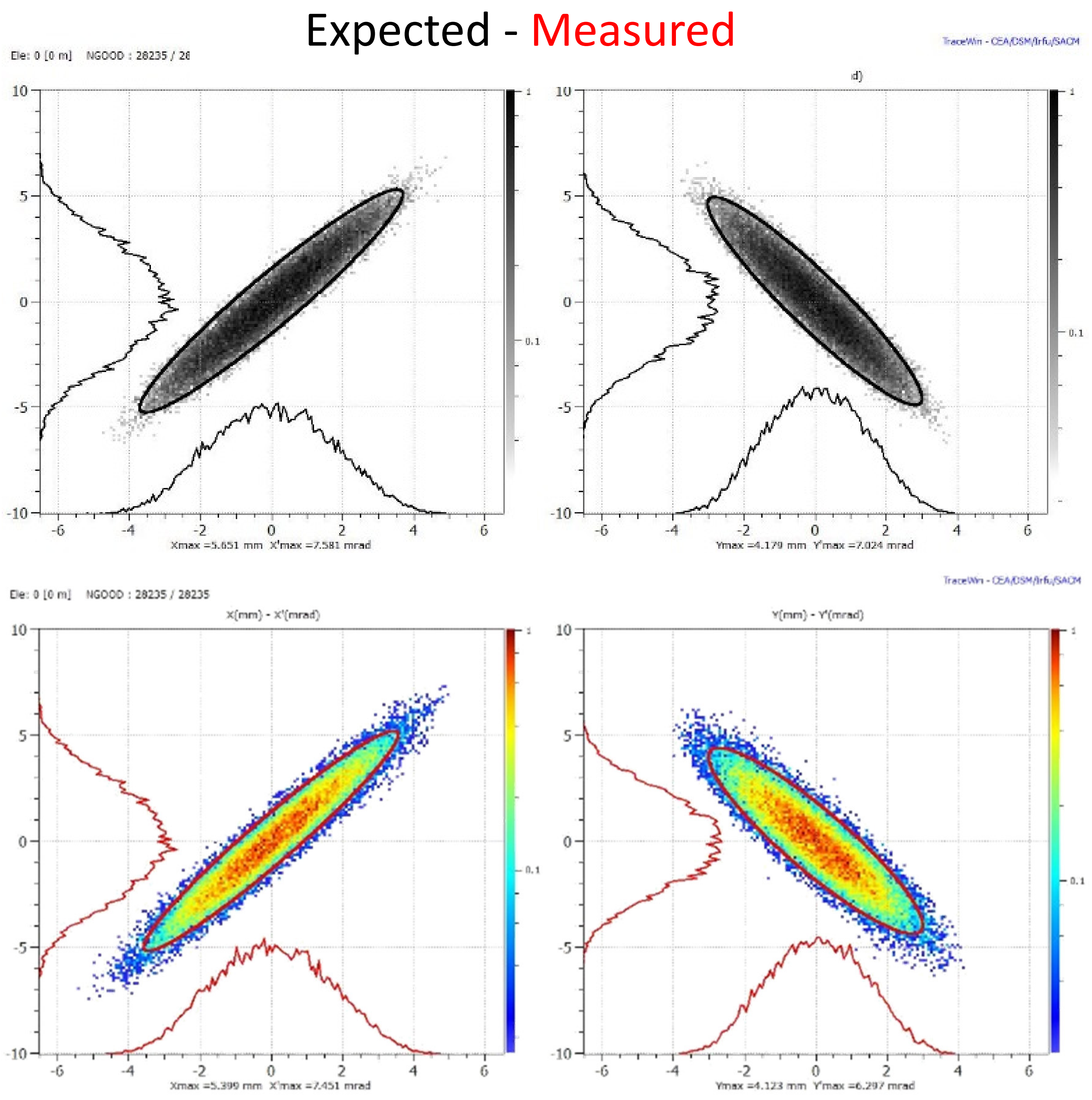
rms normalised Transverse emittance at 3 MeV measured by 3 independent systems is <u>0.3 pi mm mrad</u>

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

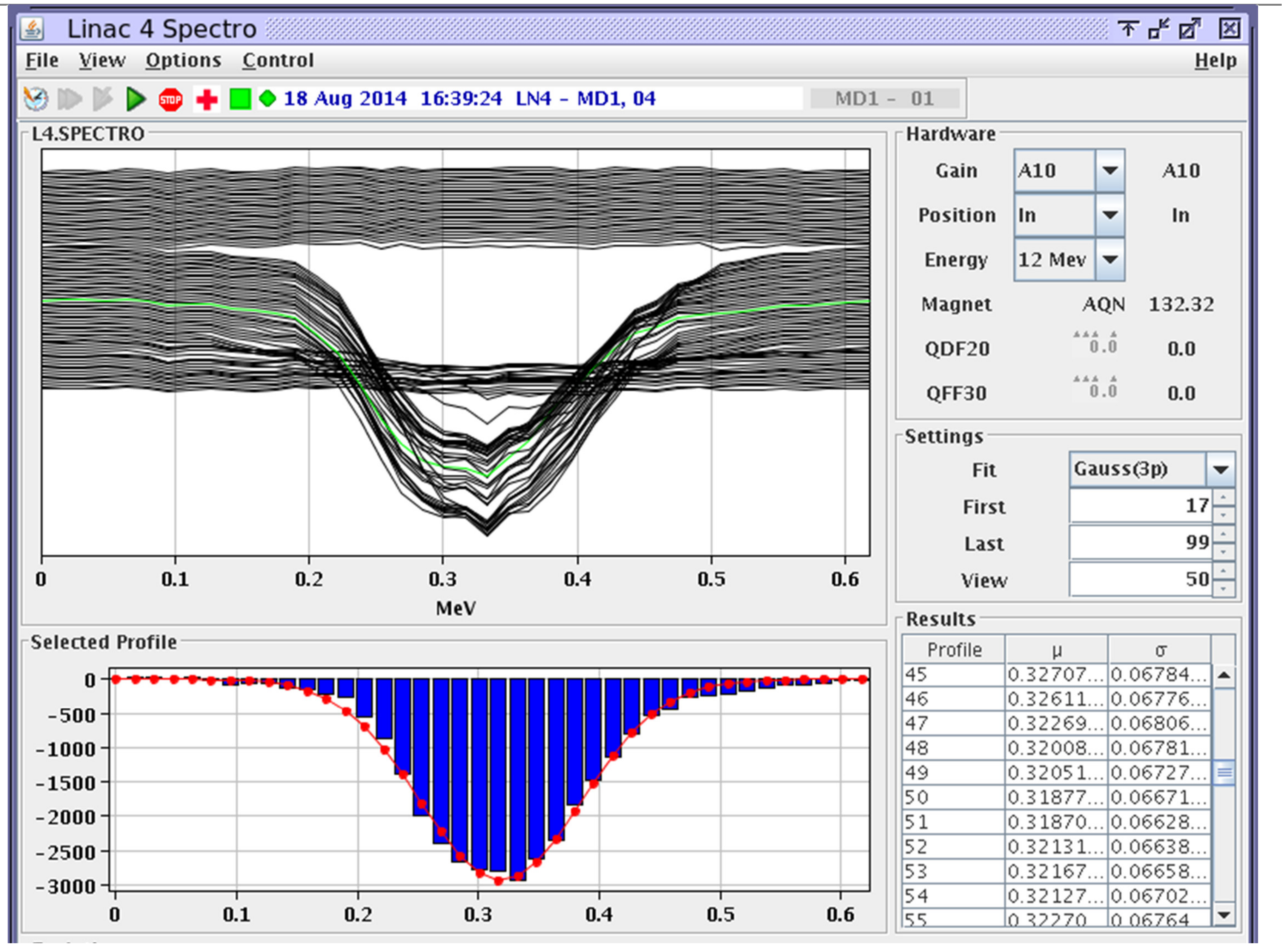


- Designed for ≥30 years of reliable operation with up to 10% duty cycle
- Rigid self supporting steel tanks assembled from <2m long segments
- Tank Design almost without welds, heat treated after rough machining
- PMQs in vacuum for streamlined drift tube assembly
- Adjust & Assemble: Tightly toleranced Al girders w/o adjustment mechanism
- Spring loaded metal gaskets for vacuum sealing and RF contacts
- Easy to use patented mounting mechanism
- Additional C-seal and temperature probe channel employed for leak testing
- Increased gap spacing in first cells of T1 to reduce breakdown in PMQ fields
- Cooled RF-port & vacuum grid in AISI 304L tank for 10% duty-cycle

Drift tube LINAC – beam measurements



Transverse emittance at 50 MeV after the Drift Tube Linac, Nov 2015

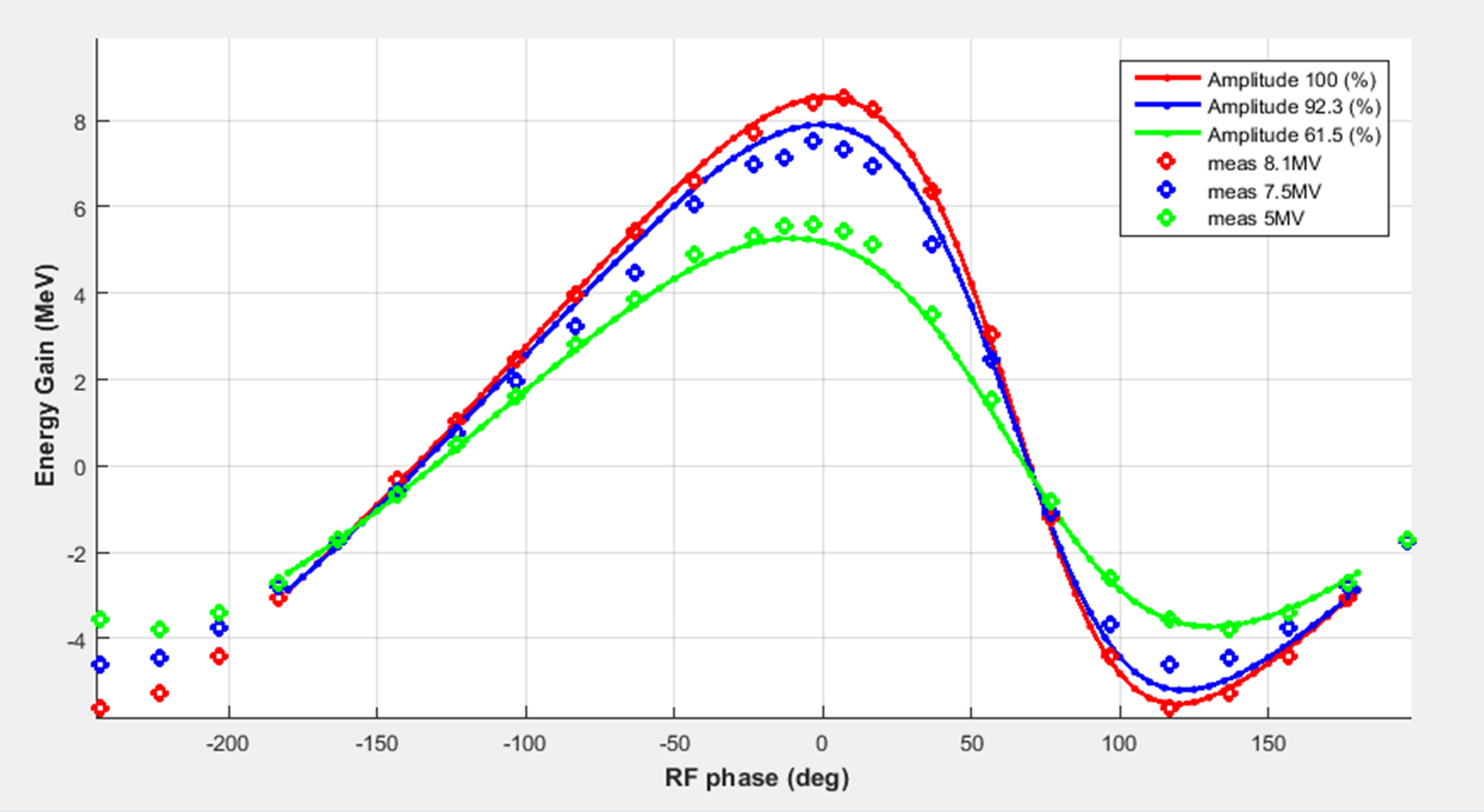


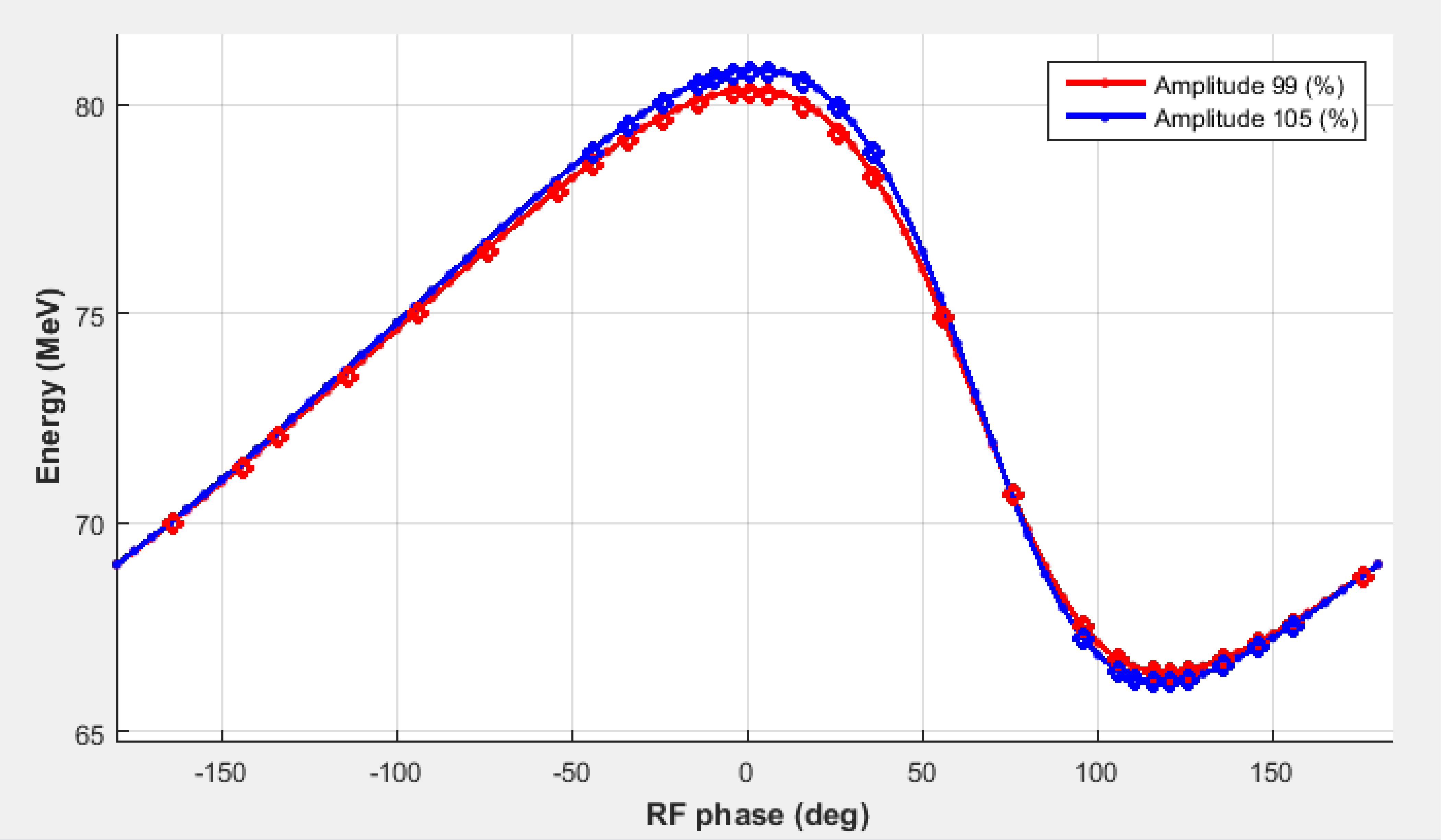
Spectrometer (bending + grid) measurements indicate an rms energy spread of 52.8 keV (vs 49.2 keV expected) after DTL tank1,12MeV, August 2014

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,
- copper plated stainless steel,
- time-consuming assembly because of high number of C-shaped metal seals, several attempts necessary to achieve vacuum tightness,
- around 1 month of conditioning needed to clean surfaces,
- non-trivial support mechanics because of 12 support points per module,
- all drift tube centres are aligned within ±0.1 mm
- first-ever CCDTL in a working machine!

CCDTL beam measurements

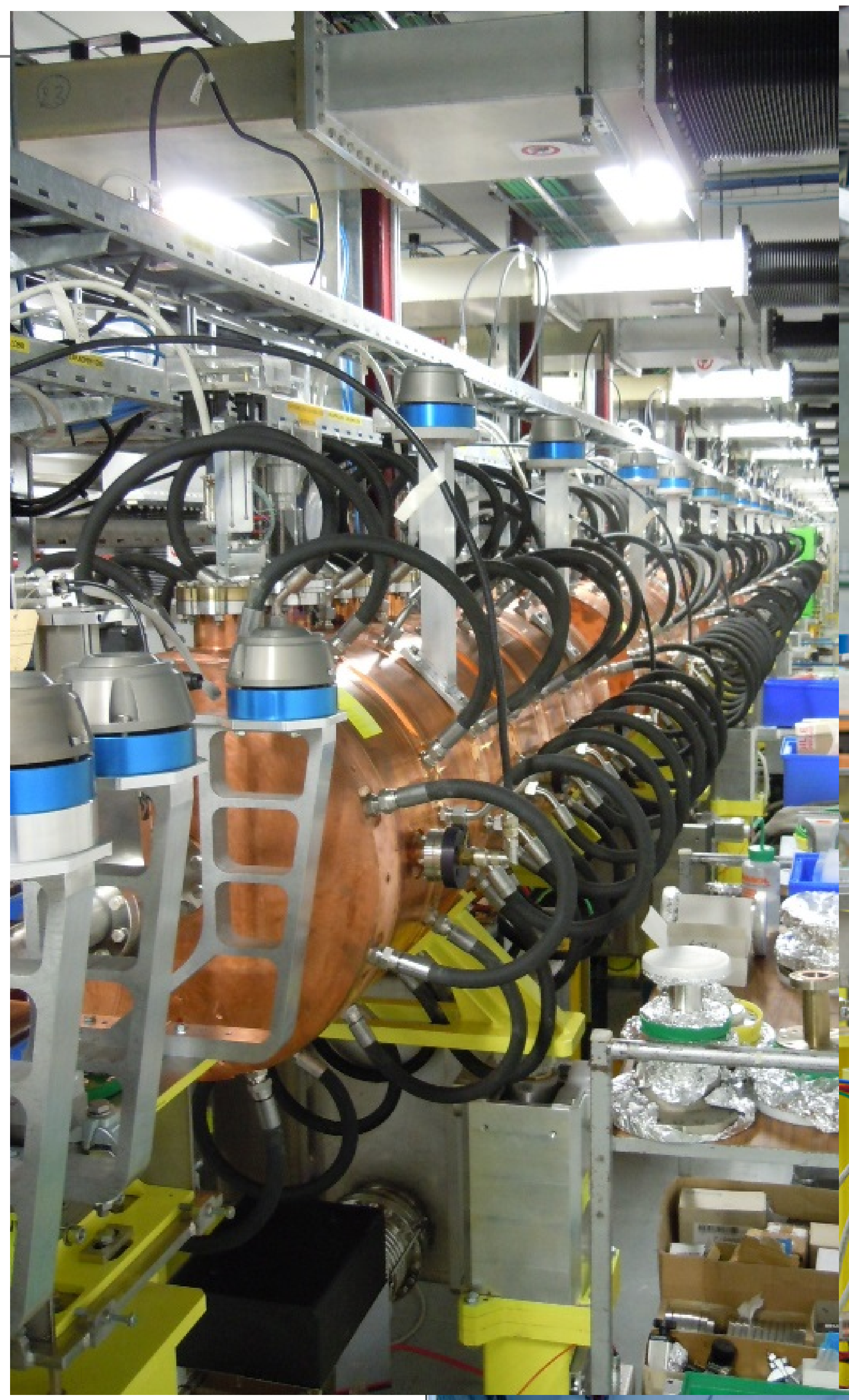


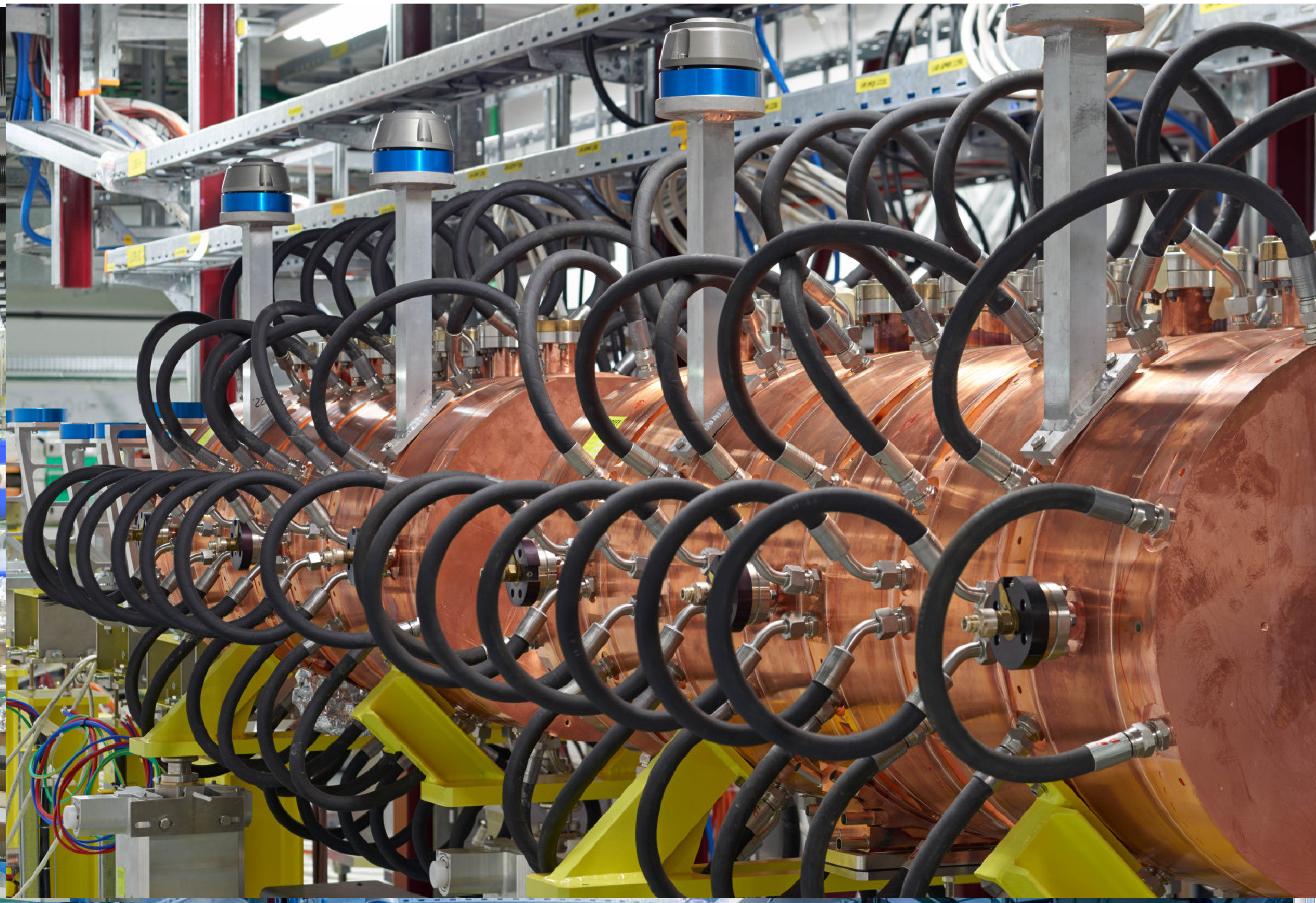


Average energy vs cavity phase for CCDTL module 3 and 4 measured June 2016 with Time-of-Flight

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

- Bulk copper, no RF seals, discs and rings are tuned and electron-beam welded at CERN
- Long qualification period for series production (~3 years), critical point was precision machine large pieces of copper (10 - 20 um on 500 mm diameter pieces)
- Conditioning time of prototype: 24 hours
- First low-beta pi-mode structure to go into operational machine





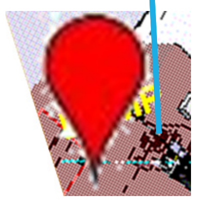
Made it to the final energy!

Nov 2016
160 MeV 18mA

Jun 2016
105 MeV 20mA

Nov 2015
50 MeV
20 mA

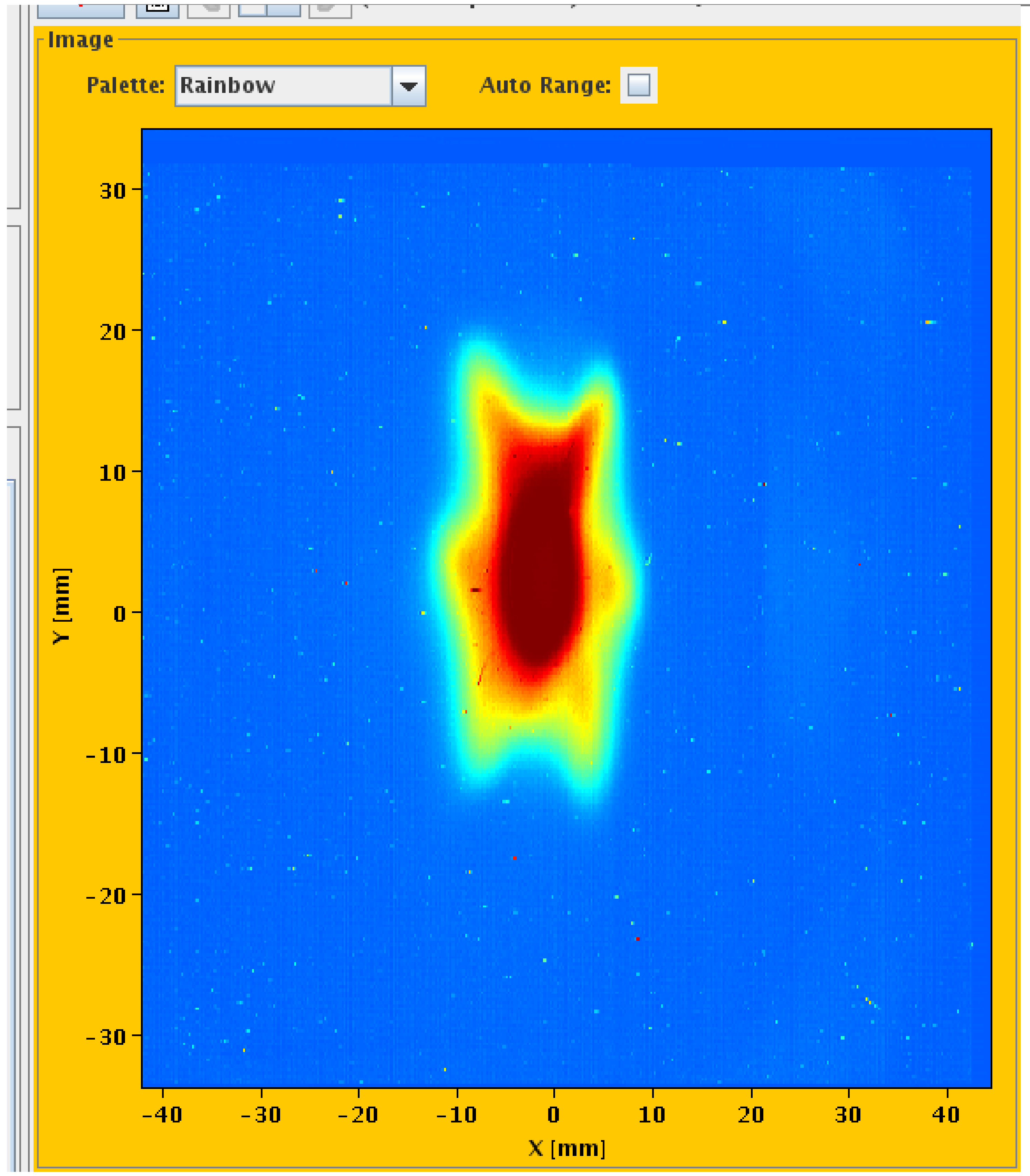
Oct 2013
3MeV
30 mA



45 keV
50 mA

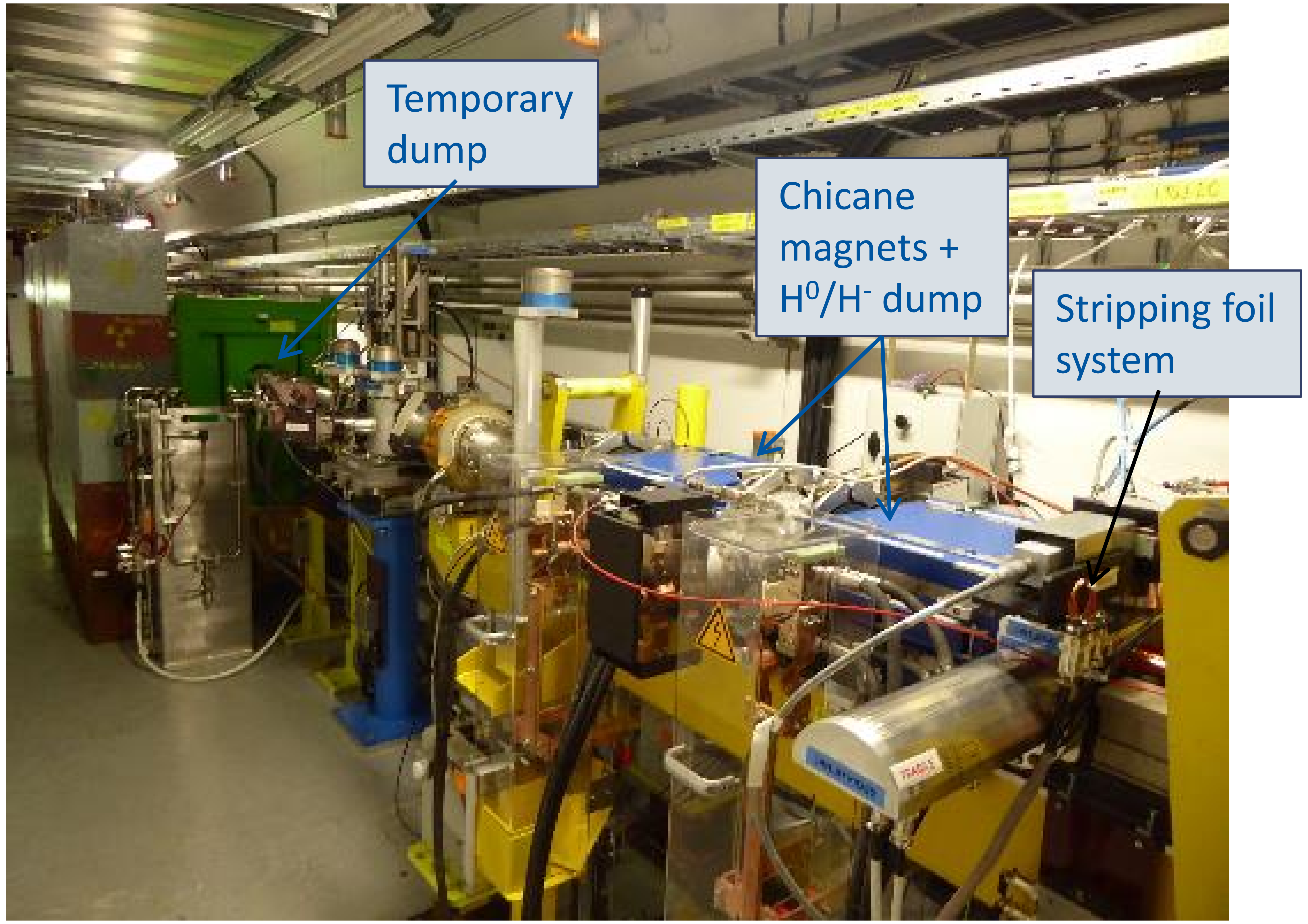
Safely on the dump.
It has been stripped.
It has been delivered to the Half Sector Test.

Half Sector Test (Oct 2016-mar2017)



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

Run the beam through half the injection chicane with aim of mitigating risks for Future PSB H^- Injection Section



Refer to MOPIK047, MOPAB120, MOPIK041

What next?

- demonstrate long term reliability

“non availability of the injectors is the main cause of down time for the LHC”

MOYAA1 Approaching the Nominal Performance at the LHC, Jorg Wenninger (CERN)

-connect to the PSB

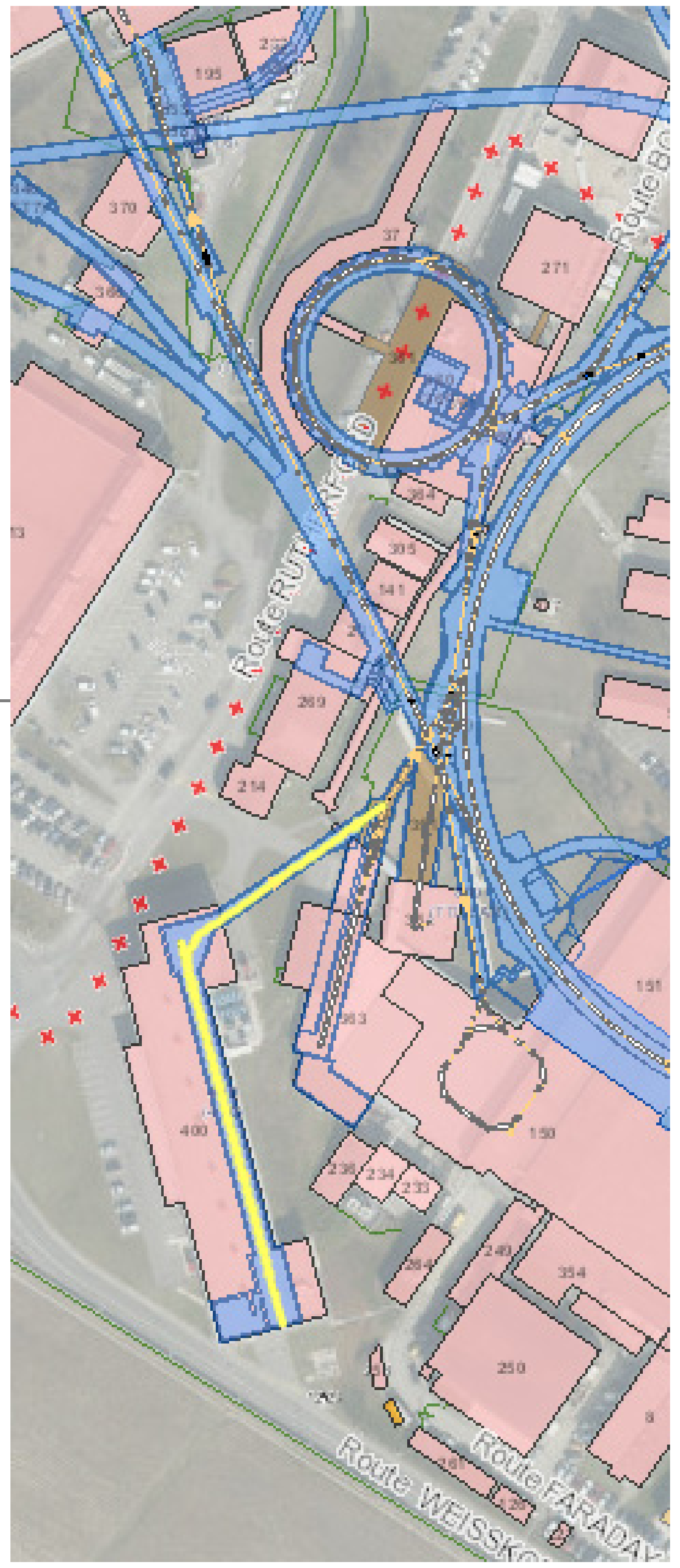
-achieve the nominal and possibly the ultimate current

Reliability run (June17-Mar18)

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

<table>
<tr><th colspan="12">2017</th><th colspan="12">2018</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td></tr>
<tr><td>Shut down</td><td colspan="2">Half Sector Test</td><td colspan="2">Debuncher installation</td><td colspan="6">Reliability Run</td><td colspan="2">Shut down</td><td colspan="2">Spare for Reliabilty Run</td><td colspan="5">interventions, repairs</td><td colspan="3">Beam recommissioning</td><td>Shut down</td></tr>
<tr><td colspan="4">EYETS</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">shutdown</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>LS2</td></tr>
</table>

To complete the transfer lines and connect to the PSB



160 MEV H- AS PLANNED

During LS2 for 6 months

- Install new BHZ20 and build the shielding around that area
- Renew the LBE line (emittance measurement)
- Install the H- injection equipment in the PSB

After LS2

- inject via charge-stripping up to 3 10^{12} protons per ring at 160 MeV (e.g. an average current of 25 mA along the pulse before chopping, injection over 40 turns of 40 µsec)
- The beam injected into each ring can be tailored to durations from 1 to 150 µsec,
- Average energy can be dynamically varied by ±1.2 MeV over 40 µsec
- the rms energy spread varied from 85 to 450 keV rms

50 MEV PROTONS IN EMERGENCY

During two weeks :

- Close the line (blank pipes available)
- Reposition the BHZ20
- Switch the source to proton

With 50MeV protons from LINAC4 the PSB would be able to deliver 75% of the present performance for the LHC beam. (**CERN-ATS-Note-2012-047 PERF**. – 2012)

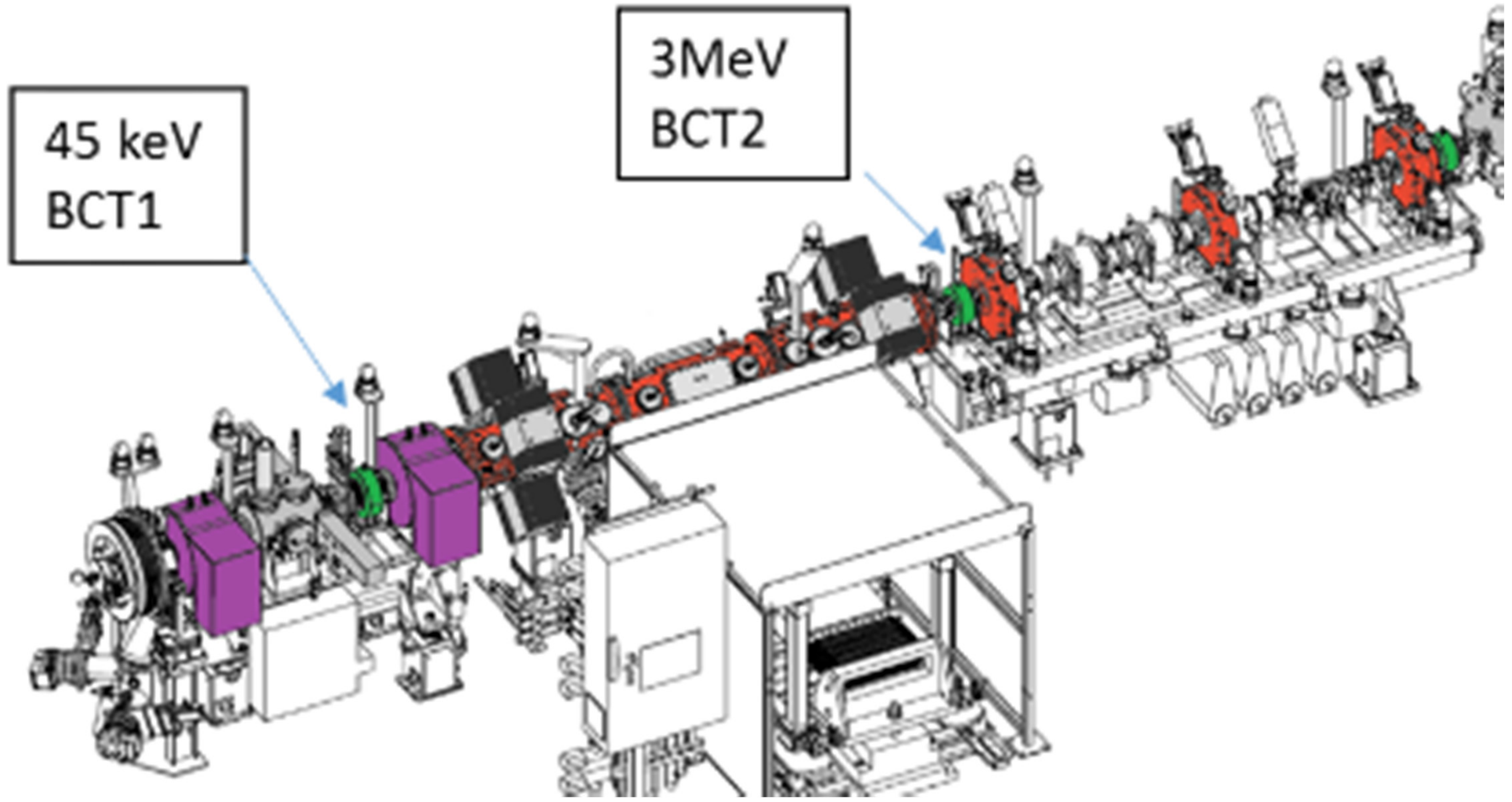
A word on the source

Many improvement since march 2015

1) Intensity
2) Stability
3) Auto-Pilot (automatic regulation of critical source parameters for increased stability)
4) Caesiation with autopilot , time needed went from half day w/o beam to few hours in degraded beam conditions

Parallel program at the test stand

1) Control of the emittance
2) Optimised electrode shape
3) Matching into the LEBT
4) Mastering neutralisation?



Current at 3 MeV before chopping	
Today's LINAC4	20 mA
Record LINAC4	30 mA
Nominal LHC Inj. Upgrade	40 mA
Ultimate LINAC4	60 mA
The gap to the nominal LIU can be compensated with twice the injected number of turns in the PSB.	

Final remarks

LINAC4 :

- All the hardware *except the source* in its final configuration
- There is an enormous flexibility built into LINAC4 to be exploited by the PSB and this will require time and trials
- Linac4 is upgradeable
  - in terms of duty-cycle (factor 5) and peak current (factor 3) without any modification to the hardware
  - In terms of duty cycle (factor 50) and final energy with substantial hardware modification

More general :

- The importance of a test stand which includes the full pre-injector
- The importance of validated machine model and accuracy of particle tracking codes
- Also for a relatively small quantity (about 150 Permanent Magnet Quadrupoles pieces) the procurement of the linac4 quadrupoles was an occasion to transfer knowledge to the European industry.