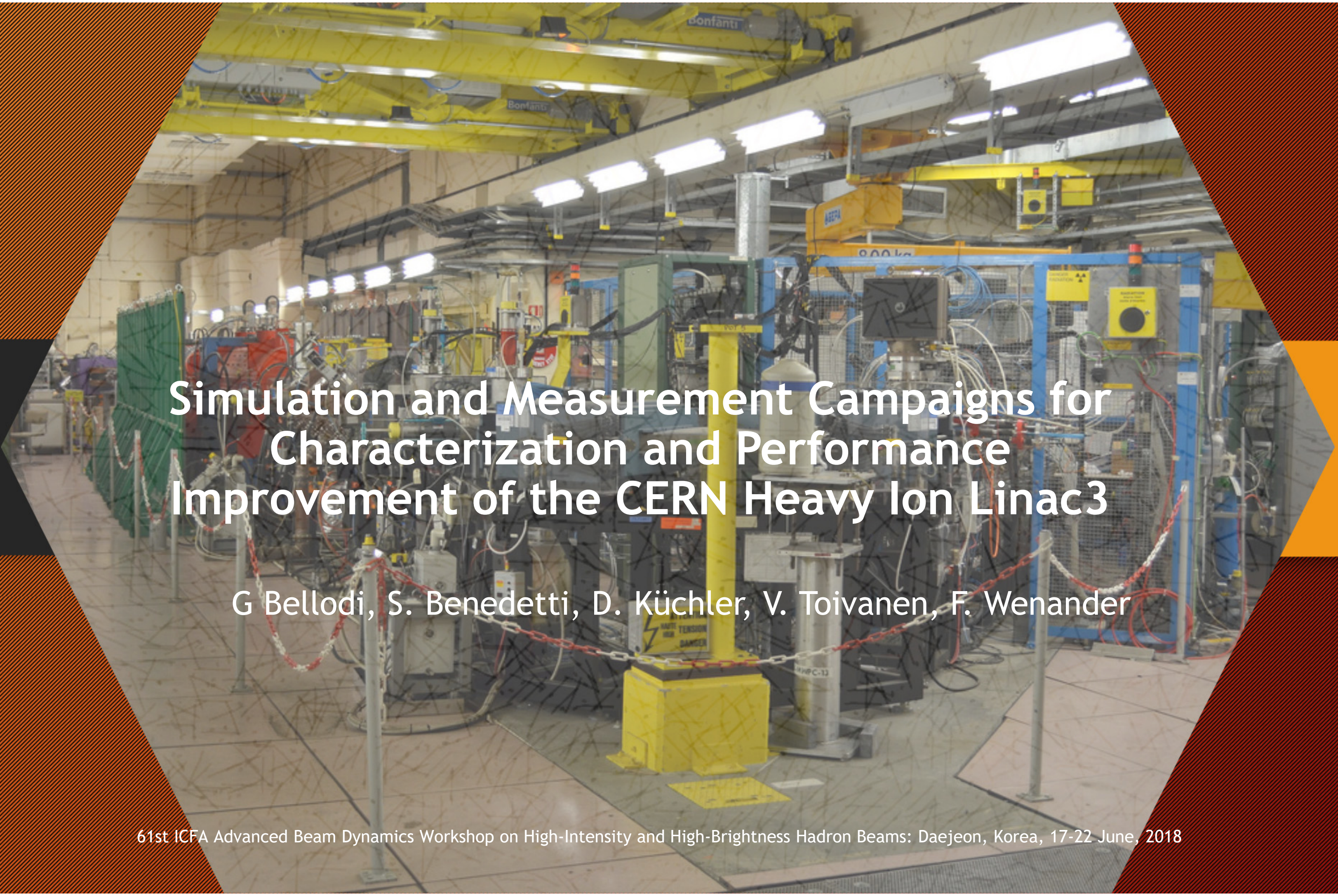
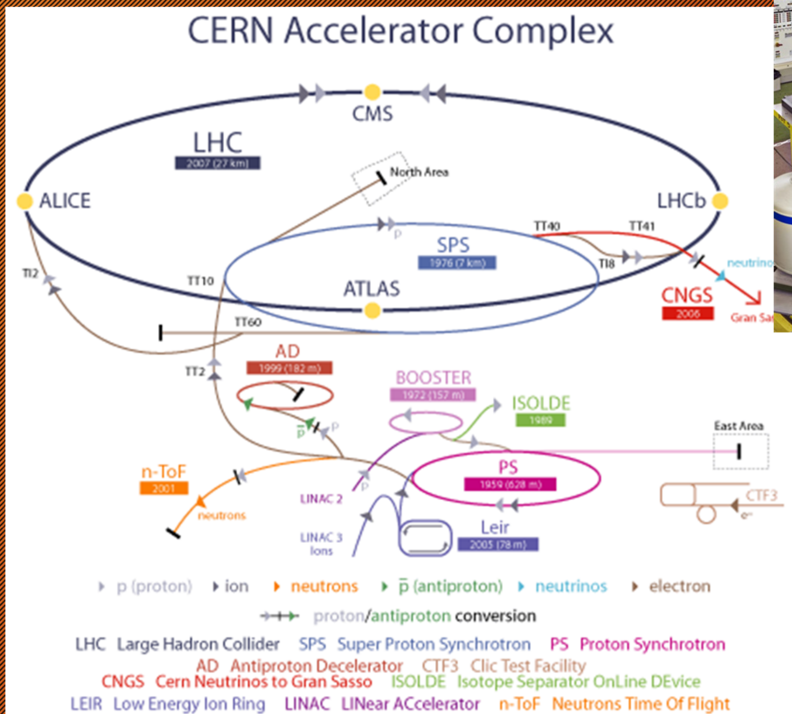


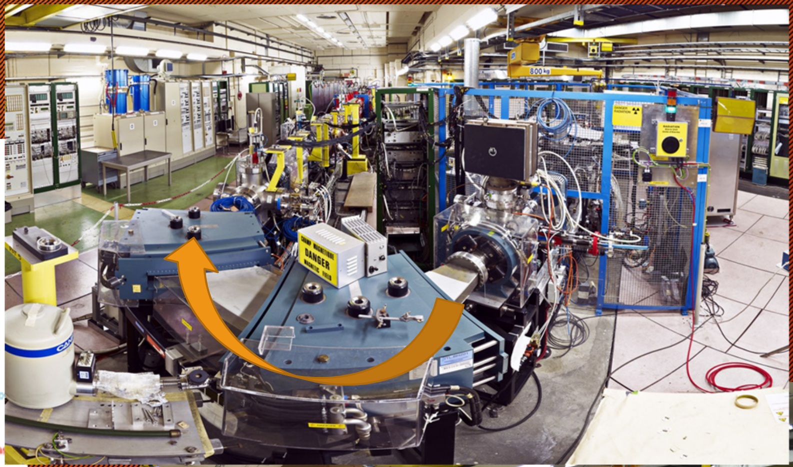
Simulation and Measurement Campaigns for Characterization and Performance Improvement of the CERN Heavy Ion Linac3

G Bellodi, S. Benedetti, D. Küchler, V. Toivanen, F. Wenander

61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams: Daejeon, Korea, 17-22 June, 2018

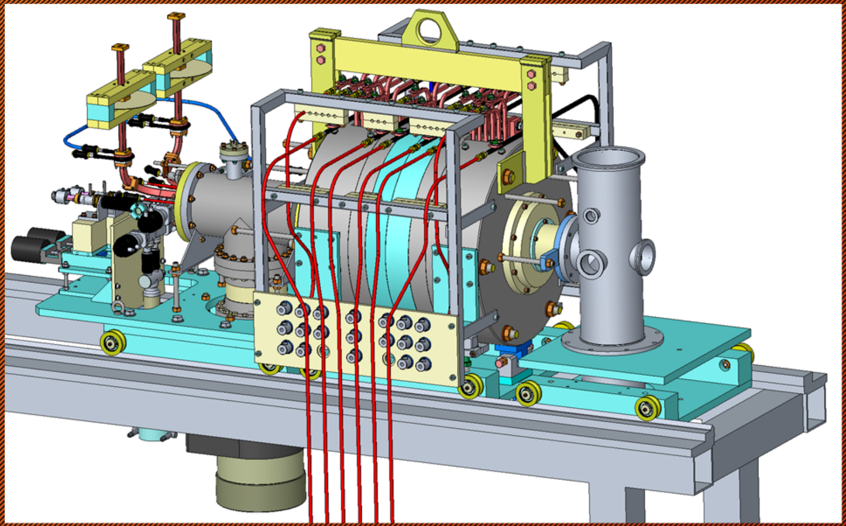
Linac3

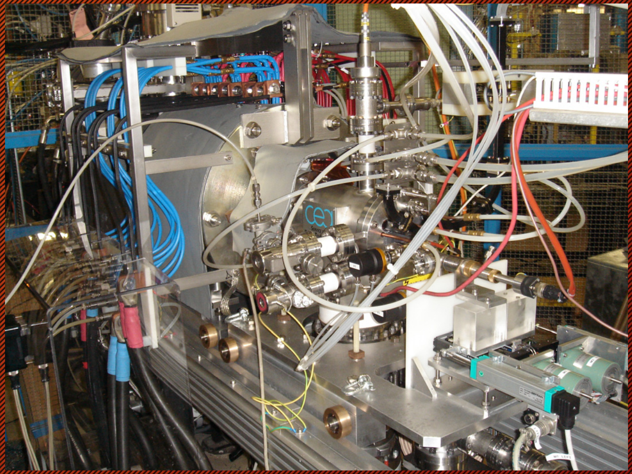

CERN Accelerator Complex
CMS
LHC
2007 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI2
TT10
ATLAS
TI8
neutrinos
CNGS
2006
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
neutrons
LINAC 2
LINAC 3
Ions
Leir
2005 (78 m)
p (proton) ion neutrons p̄ (antiproton) neutrinos electron
proton/antiproton conversion
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
AD Antiproton Decelerator CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight


DANGER

GTS-LHC ECR Ion Source

- 14.5 GHz room temperature ECR ion source based on Grenoble Test Source (GTS) by CEA, Grenoble
- Installed in 2005 to replace original ECR4 source
- Operated exclusively in afterglow mode (10 Hz, 50% duty cycle)
- Predominantly Pb^{29+} beams (Ar^{11+} in 2015, Xe^{22+} in 2017)





Linac3 in the LHC Injectors Upgrade programme

LHC performance targets post-LS2: x2 gain in peak luminosity requested by experiments to fulfil goal of 10 nb^{-1} Pb-Pb by 2035

Post-LS2 LHC SCHEME	50 ns bunch trains at LHC injection
Number of bunches (n_b)	1248
Ions/bunch (N)	$1.2 \cdot 10^8$
Normalised transverse emittance ($e_{x,y}$) [mm]	0.9
energy	7ZTeV
Peak lumi	7×10^{27} Hz/cm2

Linac3 in the LHC Injectors Upgrade programme

LHC performance targets post-LS2: x2 gain in peak luminosity requested by experiments to fulfil goal of 10 nb^{-1} Pb-Pb by 2035

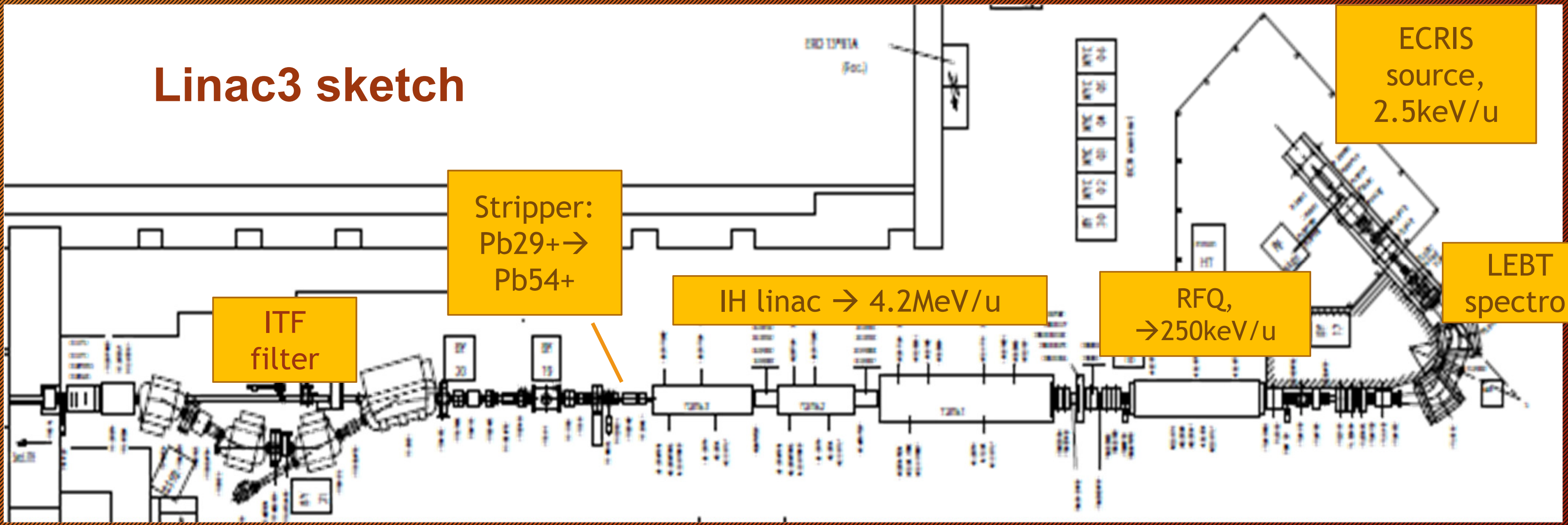
Post-LS2 LHC SCHEME	**50 ns bunch trains at LHC injection**
Number of bunches (n_b)	1248
Ions/bunch (N)	$1.2 \cdot 10^8$
Normalised transverse emittance ($e_{x,y}$) [mm]	0.9
energy	7ZTeV
Peak lumi	7×10^{27} Hz/cm2

Linac3 baseline studies

- ❑ Study of possible **beam intensity improvements** (source extraction geometry and LEBT optics modifications for better matching of the input beam to the low energy transport section).
  → Goal: increase the extracted Linac3 intensity by 20%.

- ❑ Improve and validate existing simulation models of Linac3, mostly incomplete.
  Gain in understanding of the beam dynamics for more reliable future operation.
  Source extraction simulations.

Linac3 sketch



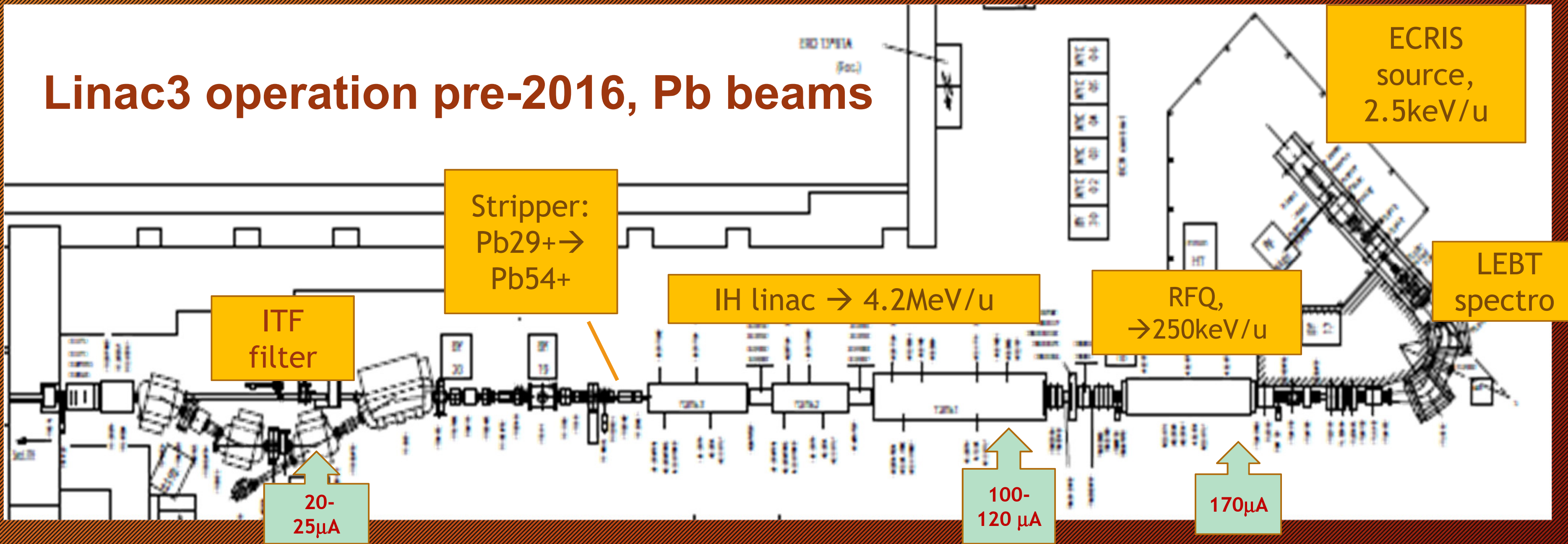
Routine operation:

GTS-LHC (ECRIS) source run in afterglow mode, 14.5GHz microwave plasma heating, 2.5 keV/u

Linac extraction: 200μs long beam pulse spaced by 200ms @ 4.2MeV/u

Linac3 extracted intensity ~ 5.8 x10^8 Pb54+ ions/per bunch

Linac3 operation pre-2016, Pb beams



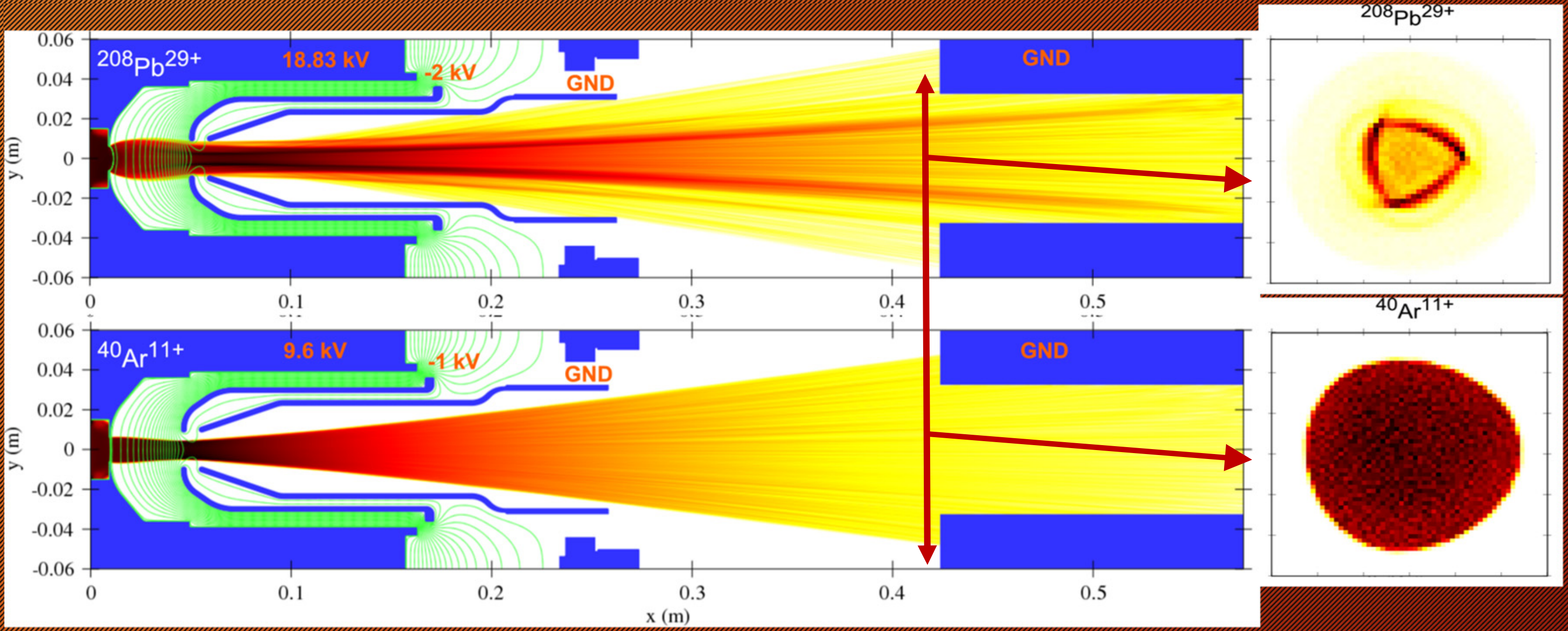
Routine operation pre-2016:
GTS-LHC (ECRIS) source run in afterglow mode, 14.5GHz microwave plasma heating, 2.5 keV/u
Linac extraction: 200μs long beam pulse spaced by 200ms @ 4.2MeV/u

Linac3 extracted intensity ~ 5.8 x10^8 Pb54+ ions/per bunch

Record values: 215 eμA of Pb27+ after charge state separation in the spectrometer and 31 eμA of Pb54+ at the end of the linac, NOT long-term and NOT at the same time!

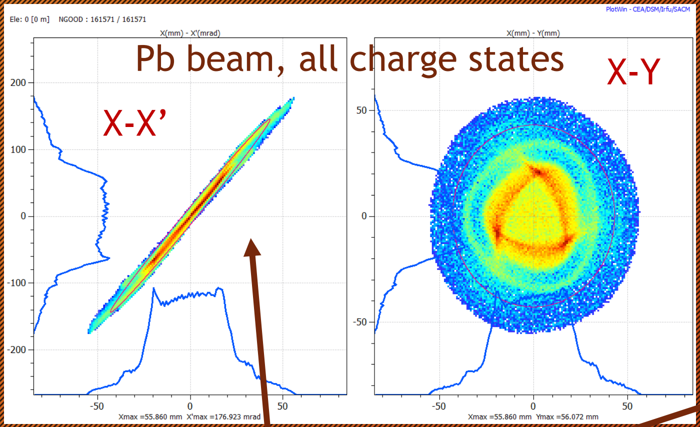
Max source intensity ≠ max linac transmission

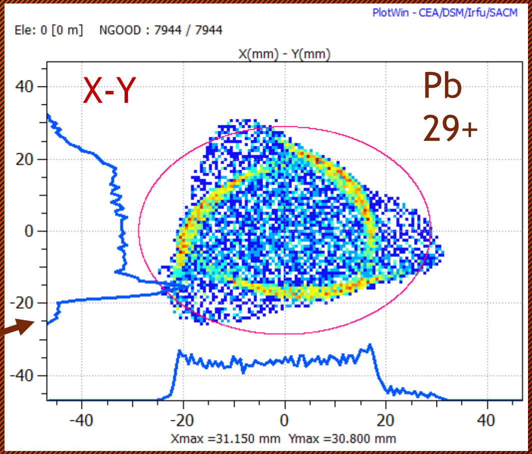
Source extraction studies, Pb and Ar beams



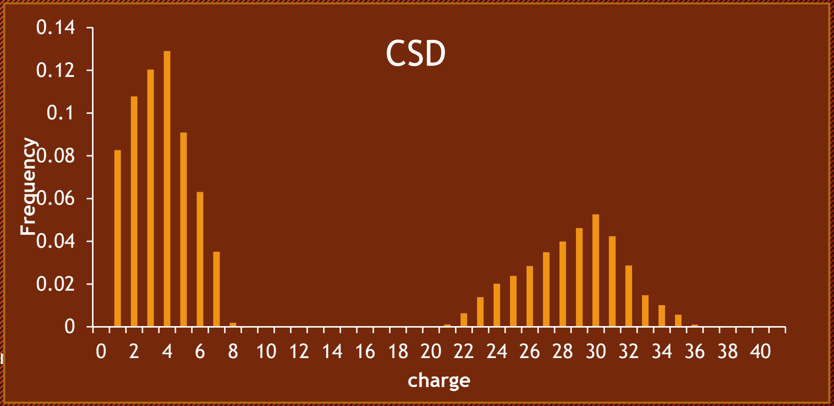
IBSimu ion optical code, 3D magnetic field maps and electrode geometry, full space charge
Initial ion species defined on the basis of Charge State Distribution measurements
Afterglow discharge modelled by higher plasma potential and cold electron population

Pb beam at source extraction

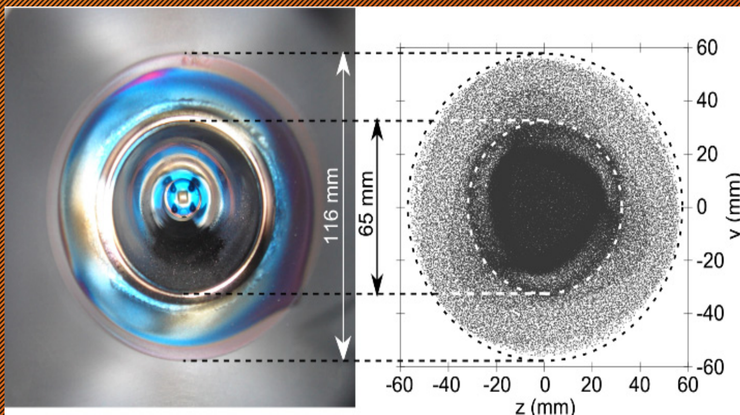


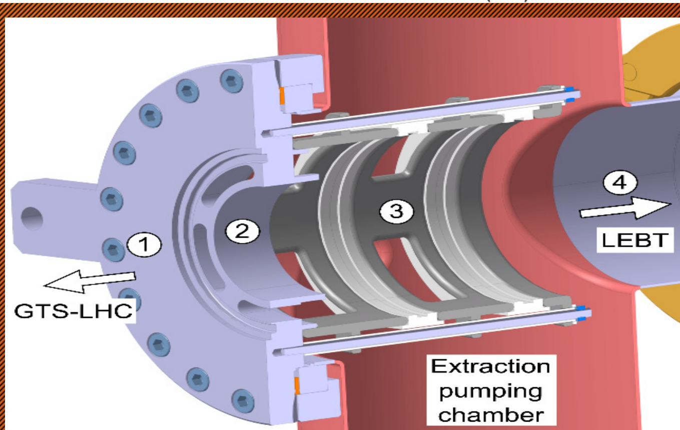


Highly divergent beams and typical ECR 3-lobes structure



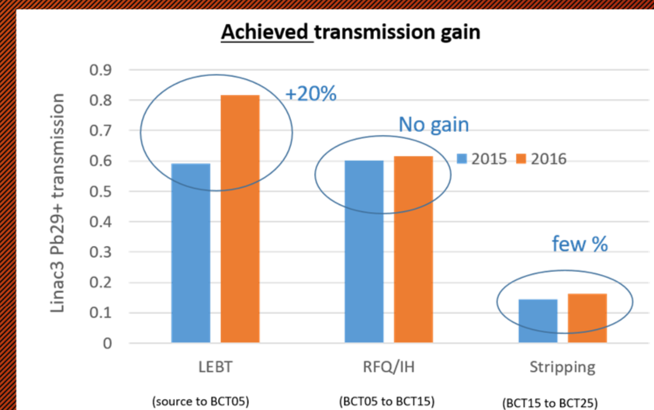
Beam collimation footprints





Prompted re-design of beam extraction region to reduce losses (end 2015):

1) Beam pipe diameter increased from 65mm to 100mm
2) Einzel lens installed to provide additional focusing (but not so beneficial…)

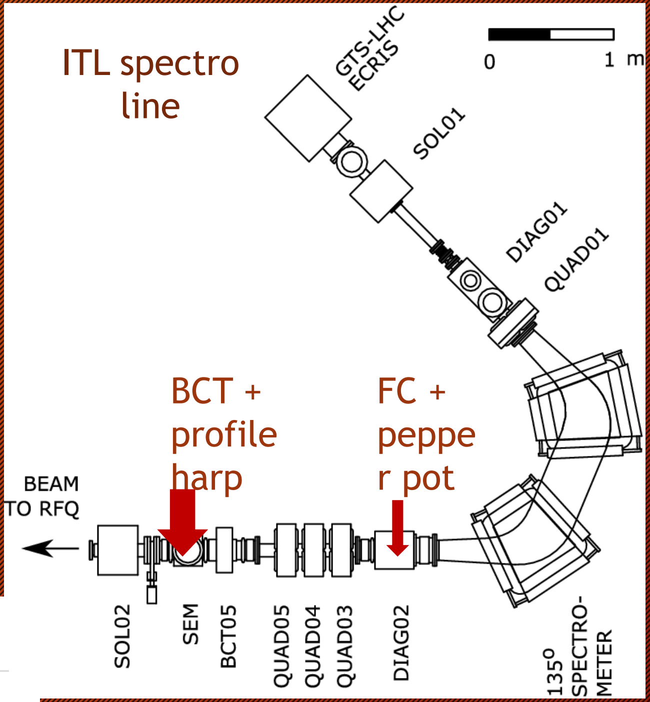


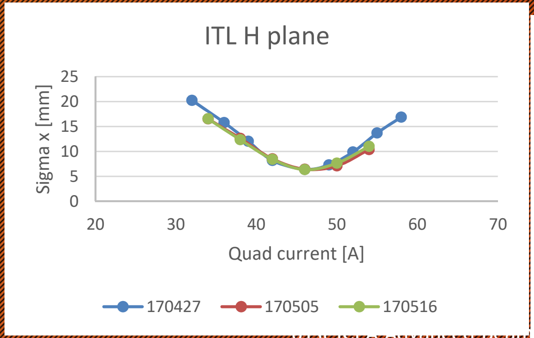
Pb^{29+}	*2015 run*	*after upgrade*	*gain*
ion source exit	170 μA	210 μA	24 %
Linac3 exit	25 μA	35 μA	40 %

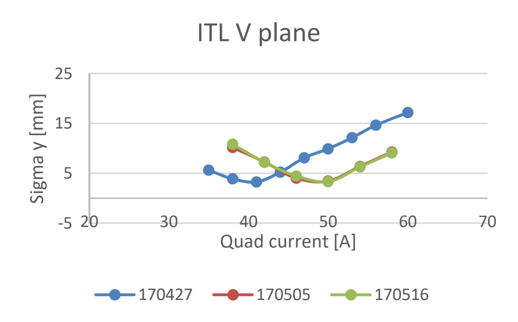
Beam characterization campaign

No diagnostics until after the bend , very difficult to validate beam extraction simulations!

First available location for emittance/phase space measurement is after the bending magnets. Indirect measurements via quadrupole scans technique



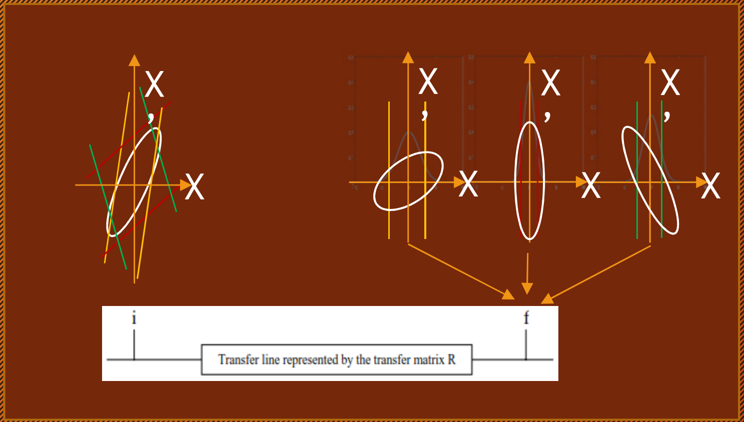




Two methods applied:

Two methods applied:

Forward method



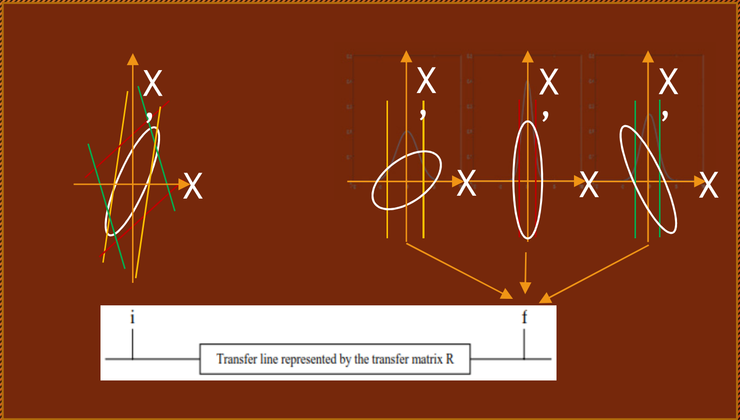
Assumptions:

- Beam is uncoupled (no skew quads, solenoids…)
- The are no losses in the line
- **Beam is centered and symmetric**

Comparison of measured and simulated RMS beam sizes (→some loss of information with non-Gaussian beams)

Two methods applied:

Forward method

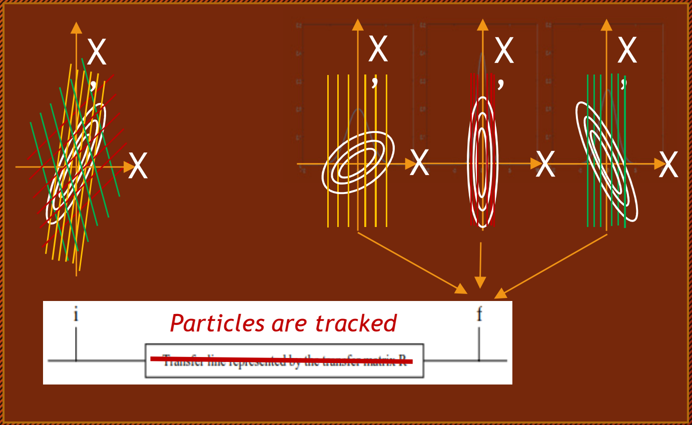


Assumptions:

- Beam is uncoupled (no skew quads, solenoids…)
- The are no losses in the line
- **Beam is centered and symmetric**

Comparison of measured and simulated RMS beam sizes (→some loss of information with non-Gaussian beams)

Tomography



Linear mapping of the measured beam profiles onto the initial phase space for comparison and iterative modification of the initial distribution until convergence is reached.

More powerful method. No assumptions on symmetry and/or beam position.

RMS normalized emittances, 2017 measurements with xenon beams

		εx π mm mrad	εy π mm mrad	αx	αy	βx m/rad	βy m/rad
ITL	*Analytical reconstruction*	0.13	0.15	-3.90	-1.59	1.32	0.57
		0.14	0.18	-3.49	-2.50	1.15	0.72
		0.13	0.18	-3.37	-2.77	1.08	0.83
		0.11	0.18	-3.39	-2.67	0.96	1.11
	Tomographic reconstruction	0.11	0.14	-4.68	-1.73	1.65	0.97
		0.11	0.15	-3.98	-2.57	1.37	0.88
		0.12	0.16	-4.02	-2.54	1.41	0.89
		0.09	0.17	-3.55	-2.47	1.07	1.22
ITM	*Analytical reconstruction*	0.08	0.21	0.05	3.63	0.06	0.79
		0.07	0.20	0.18	4.87	0.10	1.07
	Tomographic reconstruction	0.08	0.29	0.07	2.38	0.06	0.63
		0.08	0.36	0.25	3.04	0.09	0.80
ITF	*Analytical reconstruction*	0.13	0.16	-2.76	-1.75	6.17	1.56
		0.12	0.13	-1.82	-1.25	4.87	1.07
	Tomographic reconstruction	0.14	0.17	-2.38	-1.81	5.17	1.58
		0.12	0.15	-2.09	-1.60	5.04	1.30

Good agreement between the two methods (~15%)

Good reproducibility of results over time

Insufficient resolution of profile harp and short distance between quadrupole and harp

RMS normalized emittances, 2017 measurements with xenon beams

		εx π mm mrad	εy π mm mrad	αx	αy	βx m/rad	βy m/rad
ITL	*Analytical reconstruction*	0.13	0.15	-3.90	-1.59	1.32	0.57
		0.14	0.18	-3.49	-2.50	1.15	0.72
		0.13	0.18	-3.37	-2.77	1.08	0.83
		0.11	0.18	-3.39	-2.67	0.96	1.11
	Tomographic reconstruction	0.11	0.14	-4.68	-1.73	1.65	0.97
		0.11	0.15	-3.98	-2.57	1.37	0.88
		0.12	0.16	-4.02	-2.54	1.41	0.89
		0.09	0.17	-3.55	-2.47	1.07	1.22
ITM	*Analytical reconstruction*	0.08	0.21	0.05	3.63	0.06	0.79
		0.07	0.20	0.18	4.87	0.10	1.07
	Tomographic reconstruction	0.08	0.29	0.07	2.38	0.06	0.63
		0.08	0.36	0.25	3.04	0.09	0.80
ITF	*Analytical reconstruction*	0.13	0.16	-2.76	-1.75	6.17	1.56
		0.12	0.13	-1.82	-1.25	4.87	1.07
	Tomographic reconstruction	0.14	0.17	-2.38	-1.81	5.17	1.58
		0.12	0.15	-2.09	-1.60	5.04	1.30

Good agreement between the two methods (~15%)

Good reproducibility of results over time

Insufficient resolution of profile harp and short distance between quadrupole and harp

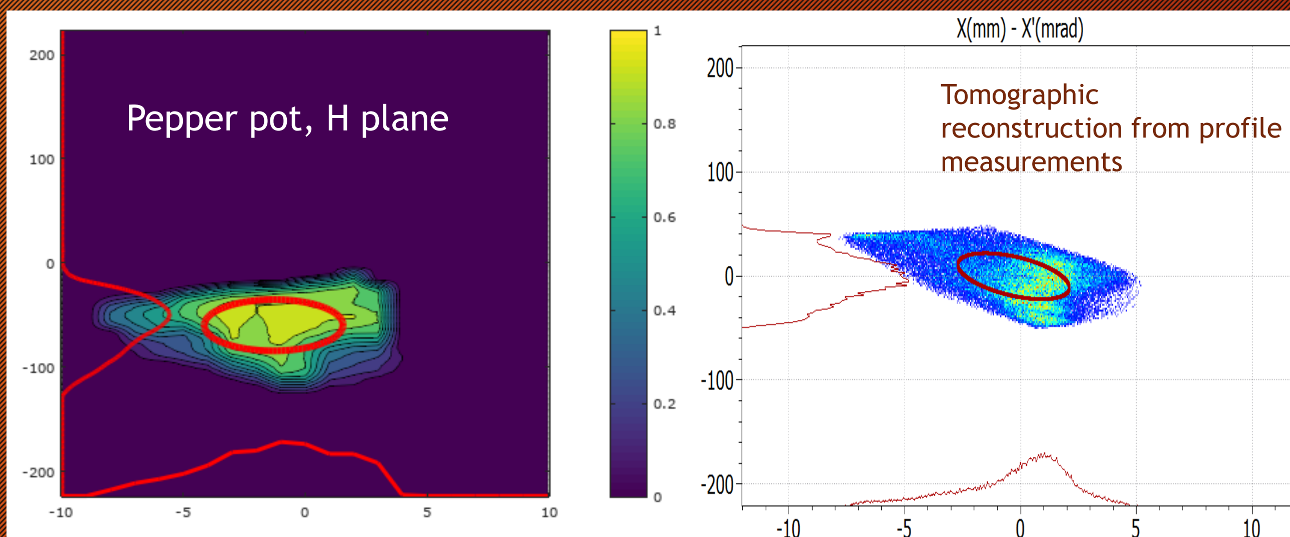
Pepper pot

H plane measurement	Pepper Pot	Reconstruction
Alpha	-0.007	0.583
Beta [m/rad]	0.116	0.126
Emitt_norm RMS [mm.mrad]	0.168	0.110

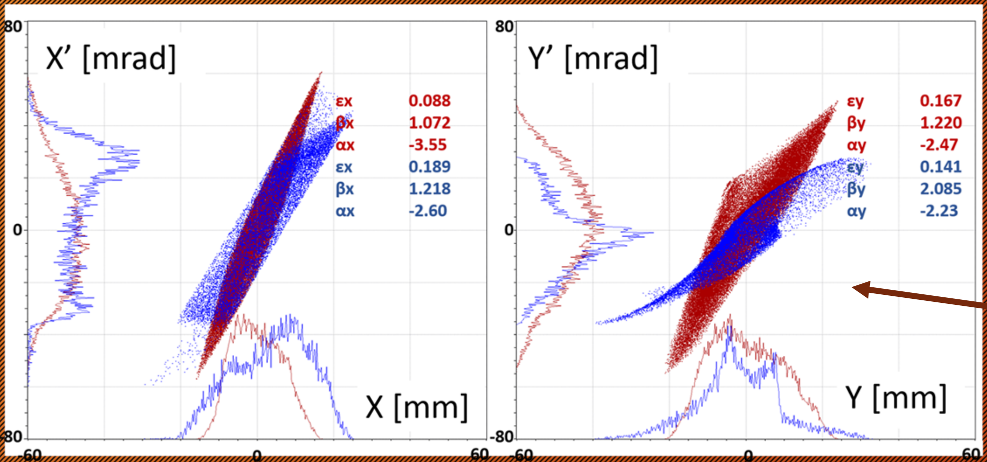
Installed after the bend but never reached operational status

Good agreement of measurements in the H plane with tomographic technique.

Impossible to get a measurement in the V plane due to beamlets' overlapping effect (beam characteristics not being optimal for measurement at the device location)



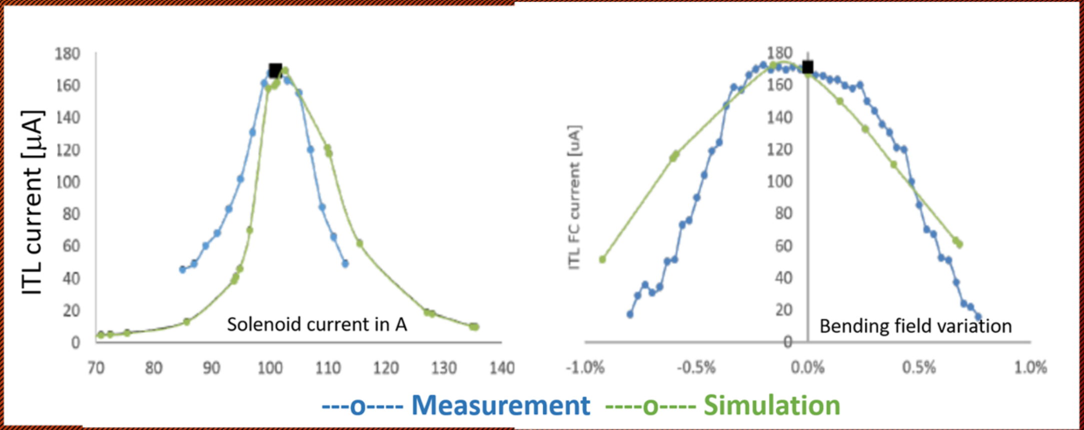
ITL measurements vs simulations



Mismatch between beam phase space tomographic reconstruction (red dots) and simulation results, tracking the IBSimu extracted beam (blue dots). Beam at the exit of the spectrometer bend.

Transmitted beam intensity vs solenoid/bending magnet current. Fair agreement only possible after parameter rescaling exercise.

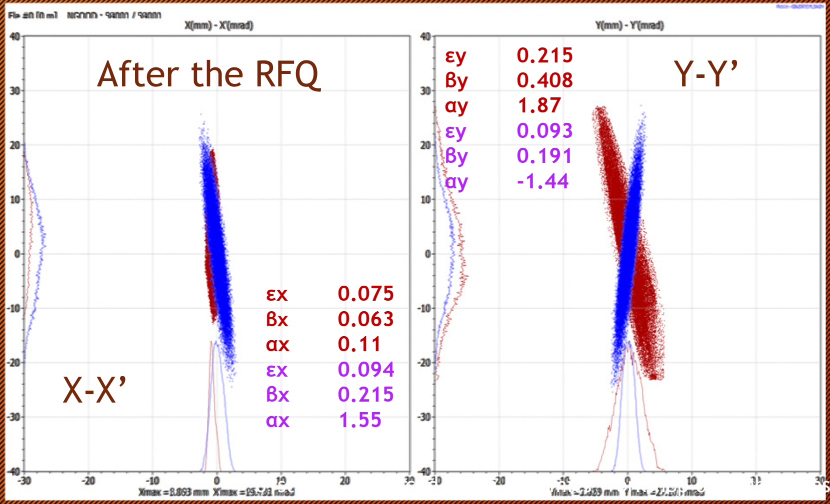
→ Evidence that some assumptions made in simulations are not correct!

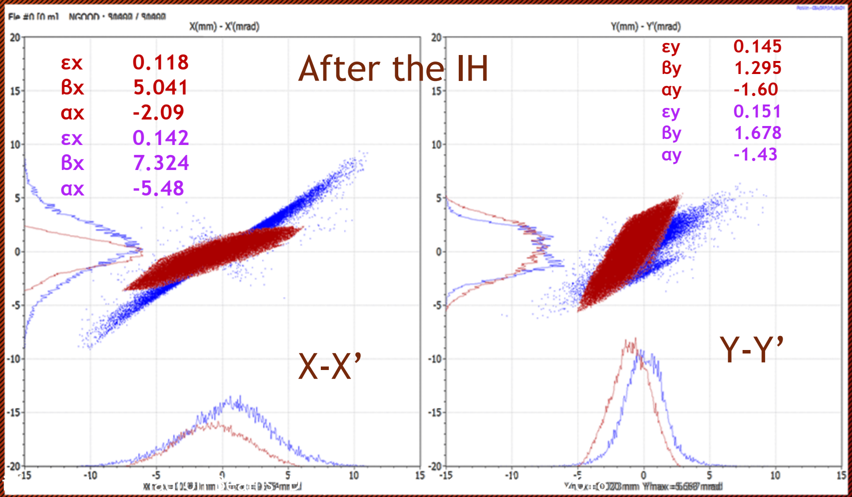


The reconstructed beam distribution after spectrometer bend was used as input for all downstream tracking with PATH (instead of the beam extracted using IBSimu).

~70% operational beam current transmission through the RFQ was confirmed in simulations (RFQ transverse acceptance limitation~ 200 mm mrad).

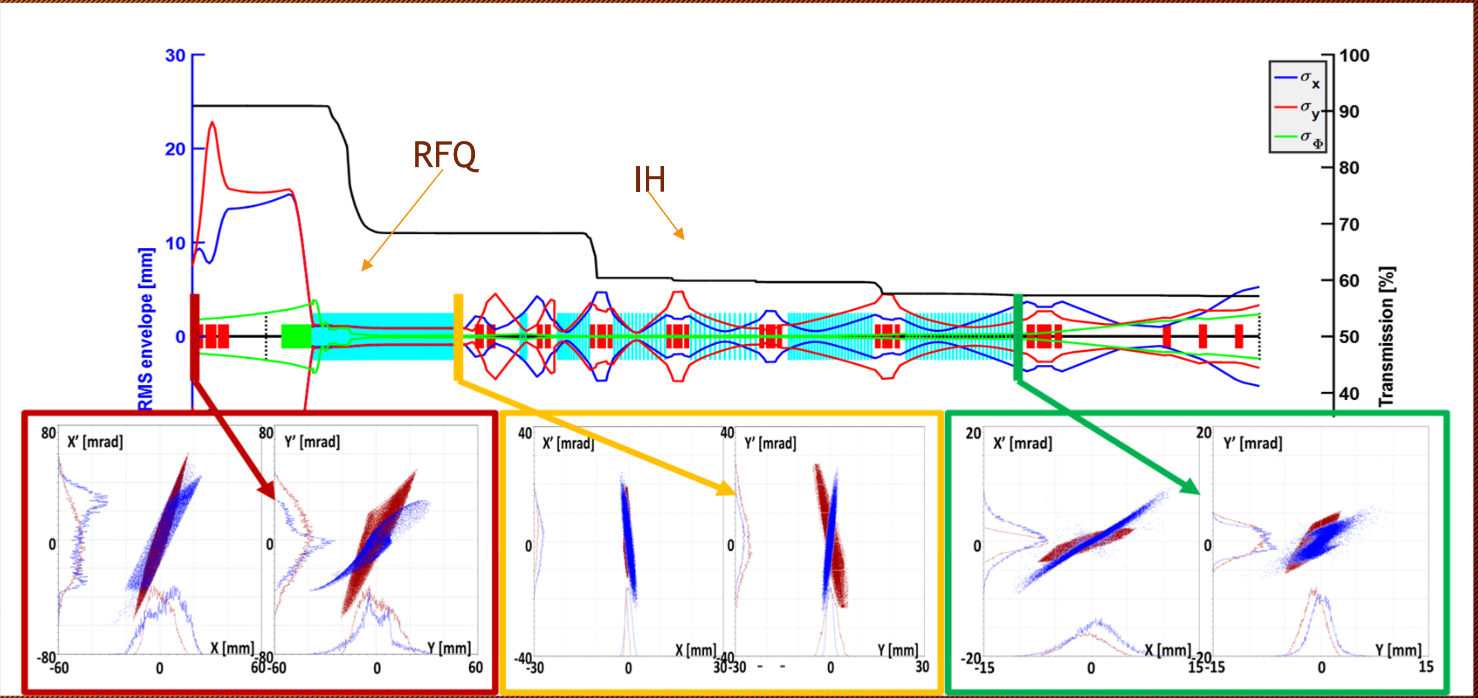
Comparison with beam phase space reconstruction from measurements at the RFQ exit is very good in the H plane. Vertical plane reconstruction suffers from insufficient resolution of the profile harp (affecting measurement precision).





Linac3 beam dynamics end-to-end (RFQ input to IH output)

- Dependence of beam transmission on several parameters (tank amplitudes and phases, IH quad gradients) was measured through variable scans and well reproduced in simulations.
- Operational transmission through RFQ (~70%) and IH (~80%) was confirmed by beam tracking.



Outcome of the studies

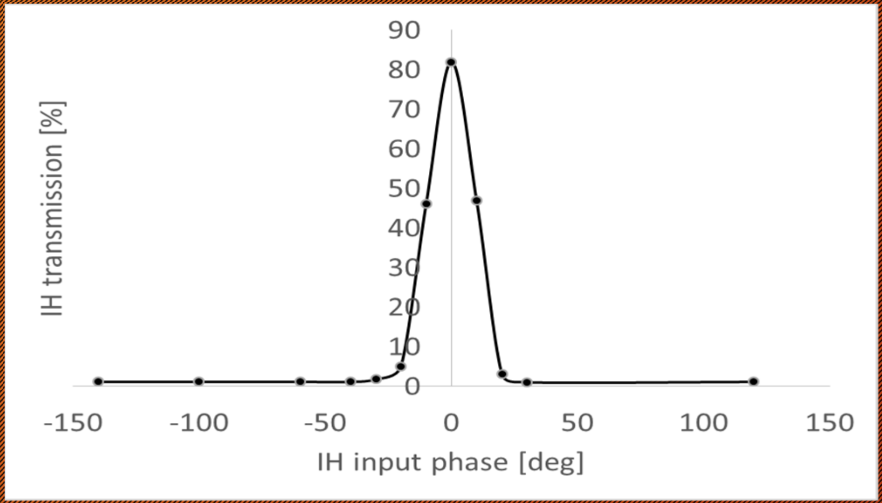
RFQ confirmed as main bottleneck for beam transmission (transverse acceptance=200 mm mrad =0.11 mm mrad RMS normalized lower than input beam transverse emittance)

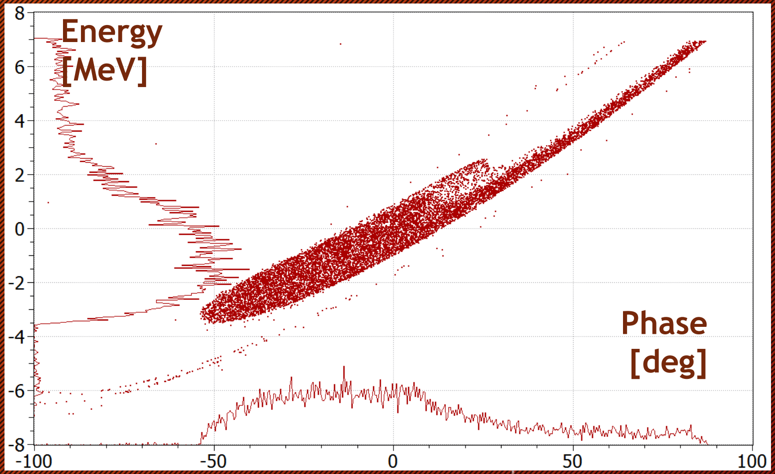
Prompted investigations towards a low-impact “light” re-design of the cavity , maintaining cavity length and field impact and yielding a comparable or lower output longitudinal emittance (to avoid transferring the problem downstream)

Redesign constraints

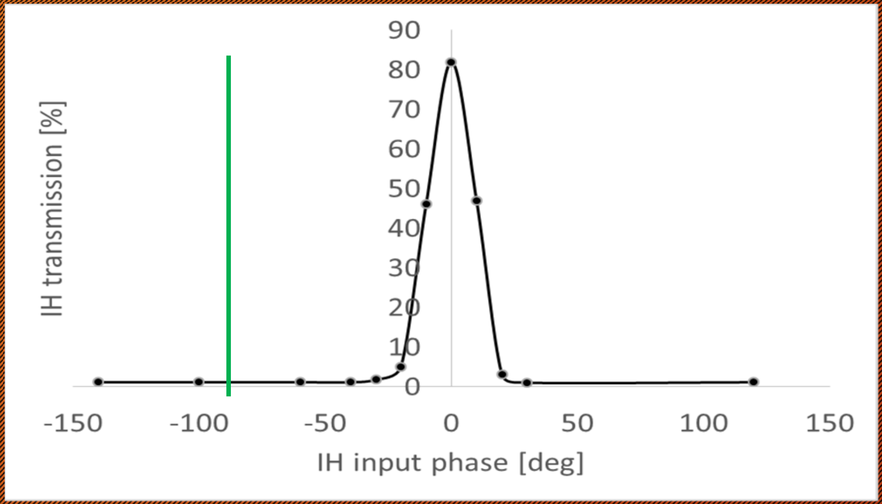
Parameter	Value
Input / Output energy	2.524 / 250 keV/u
Operating frequency	101.28 MHz
Length	2.5 m
Input transverse accept	> 0.8 pi.mm.mrad
Output longitudinal emit	< 40 pi.deg.keV/u
Max surface electric field	24 MV/m

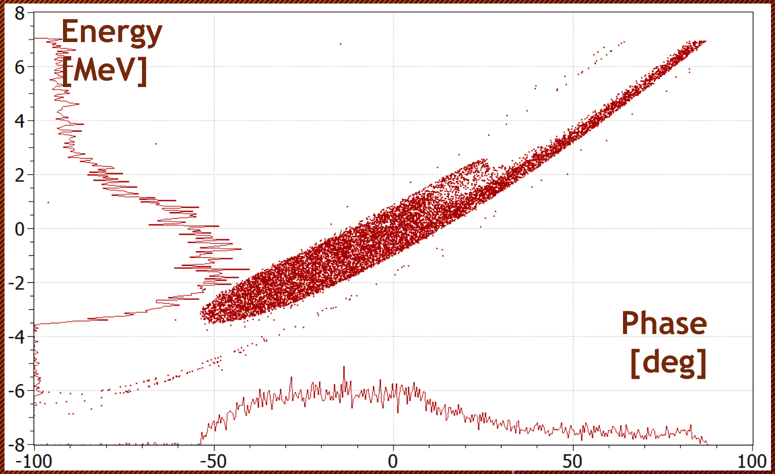
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



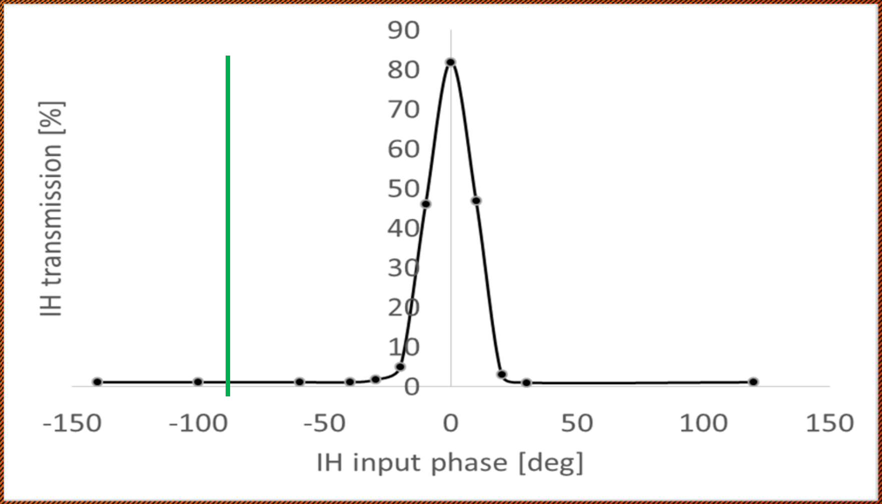


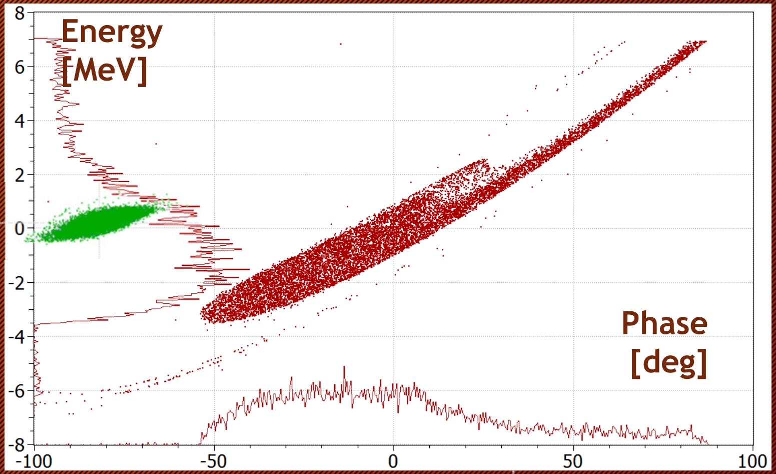
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



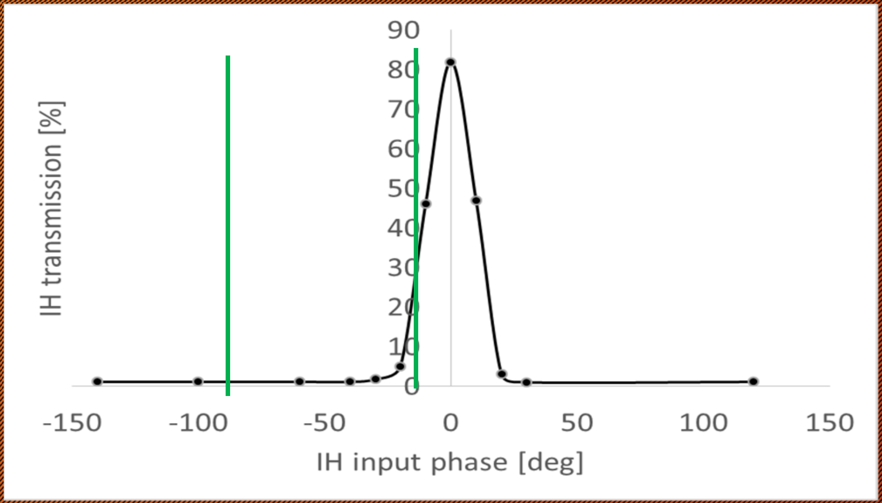


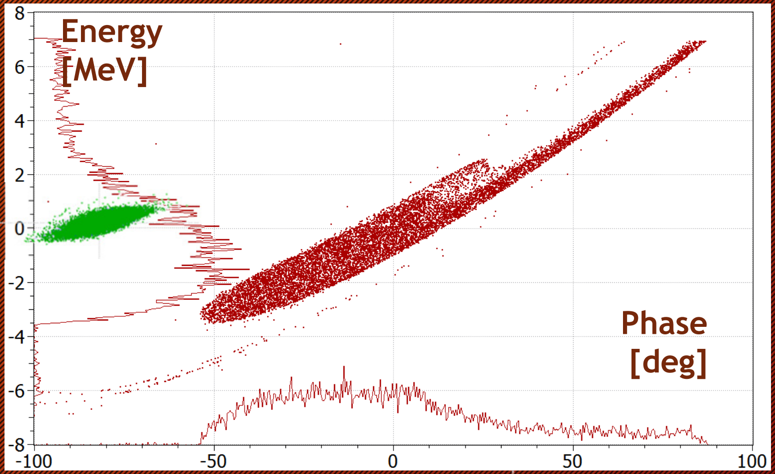
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



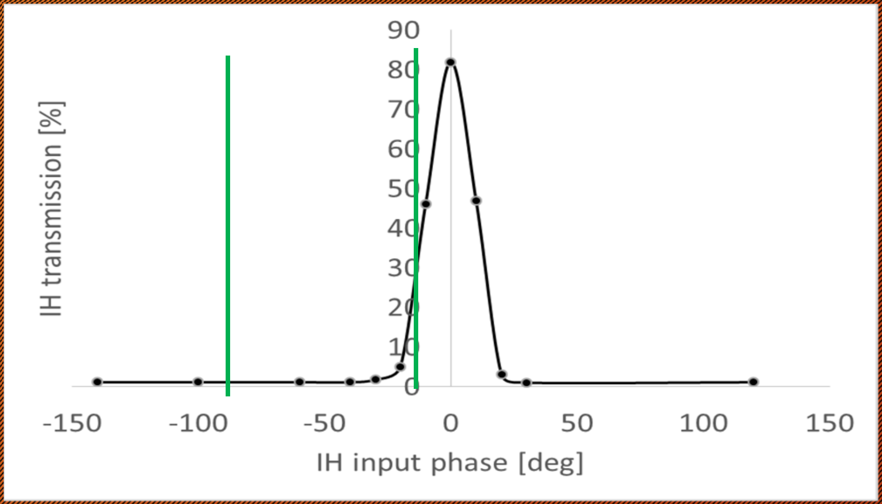


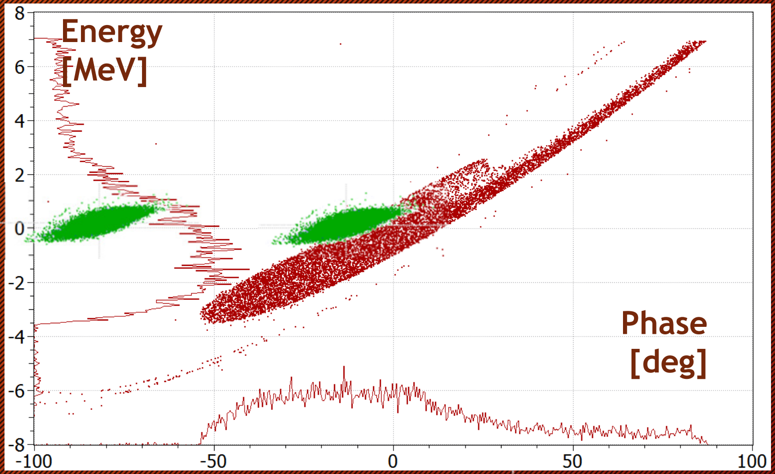
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



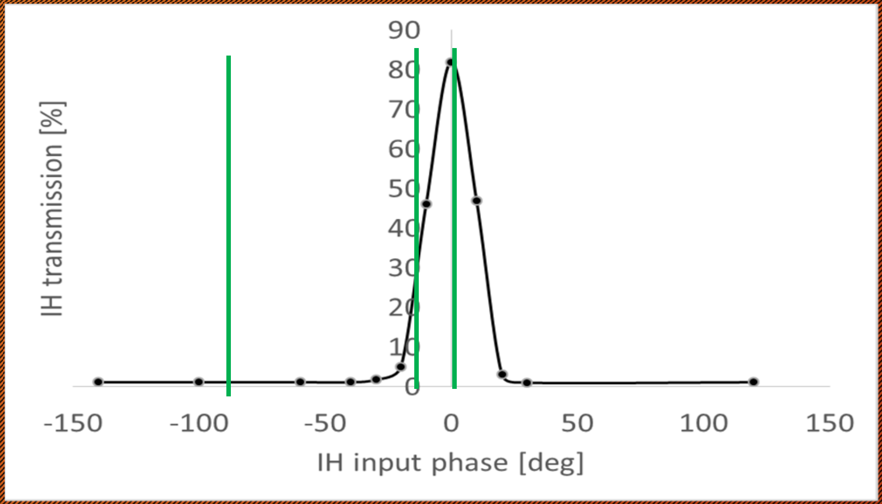


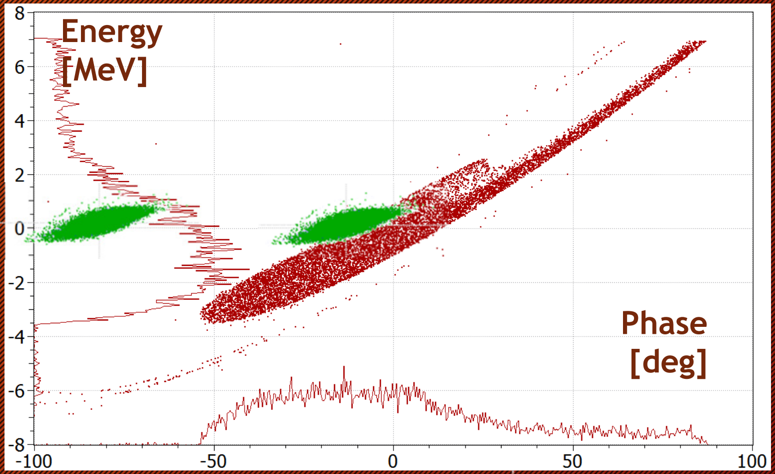
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



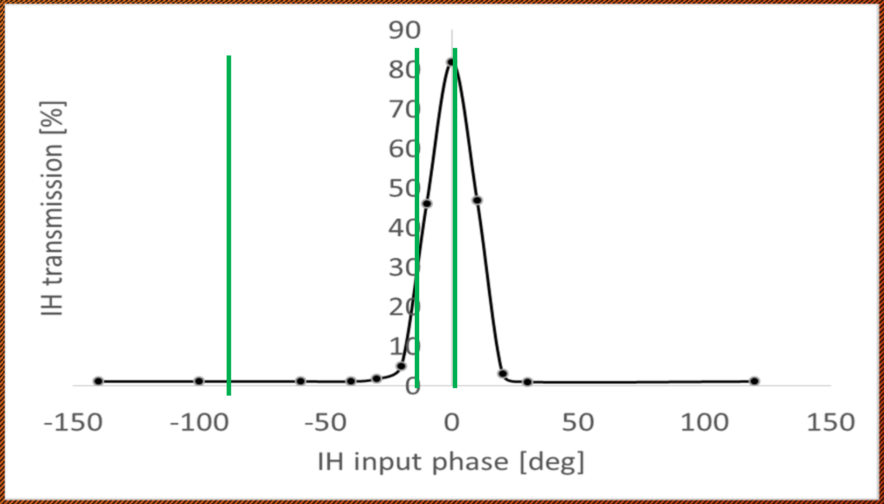


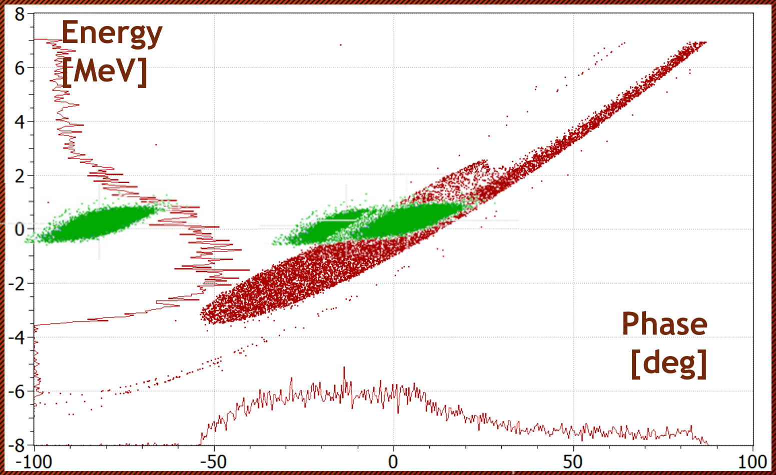
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



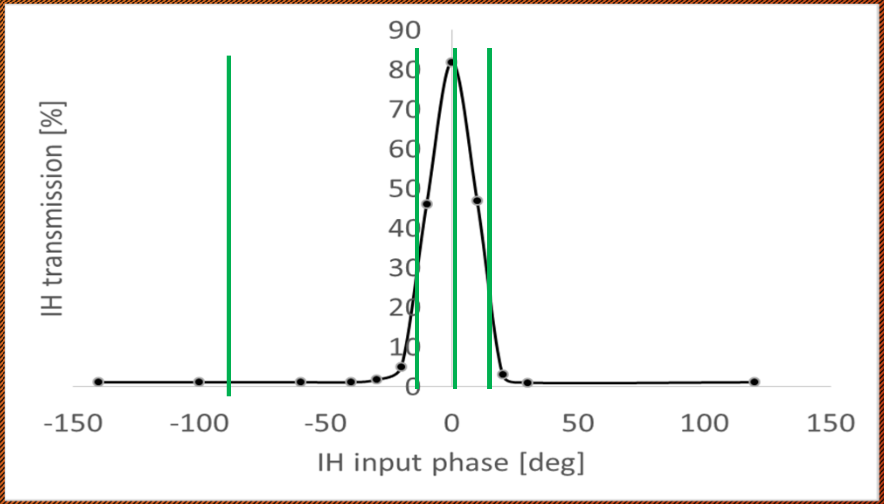


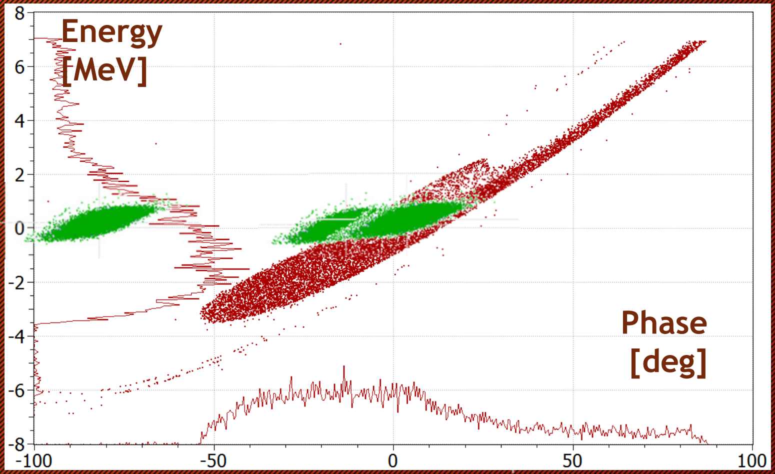
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



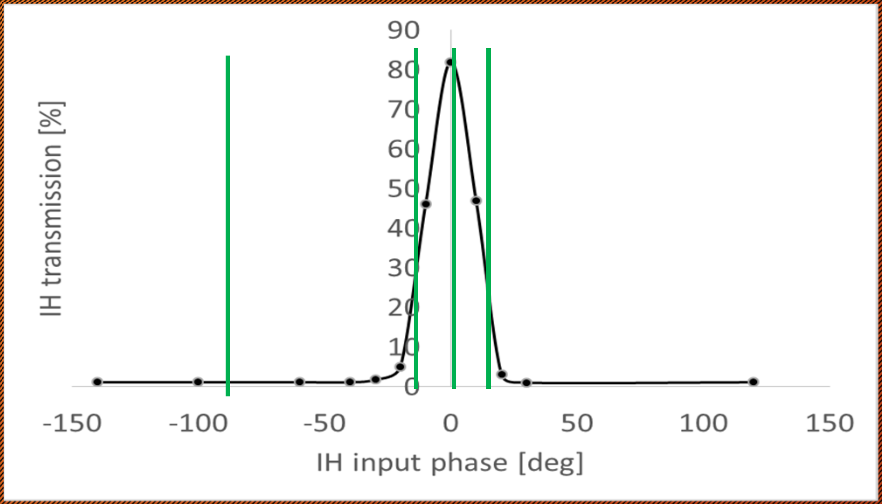


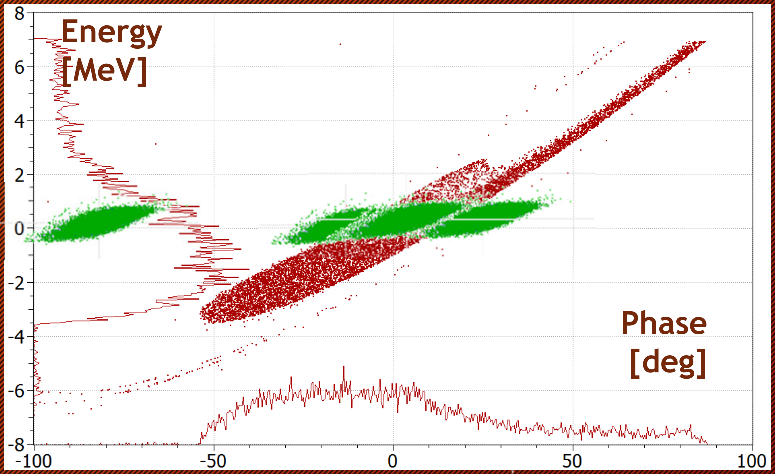
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



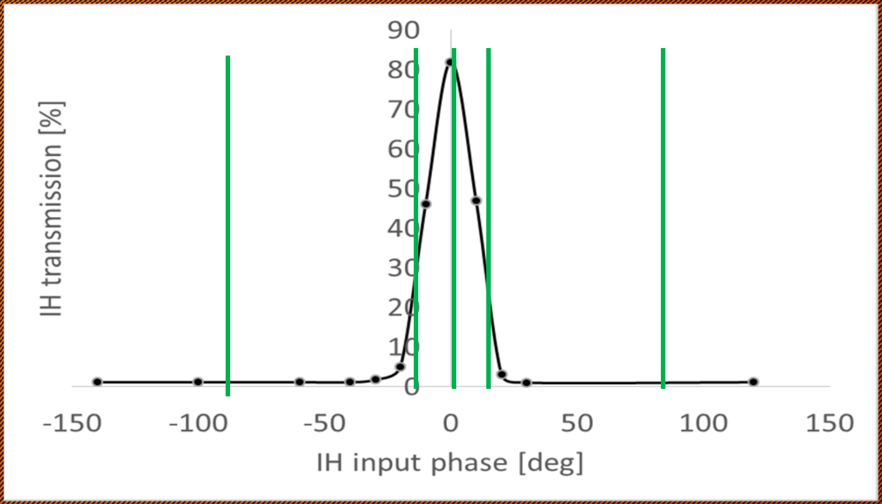


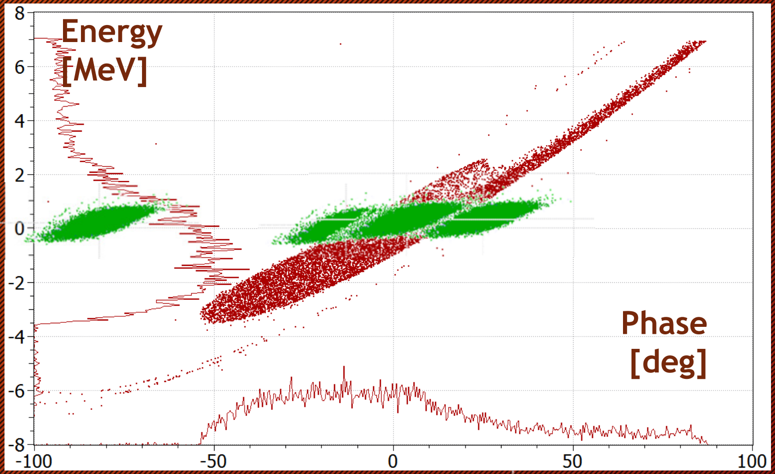
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



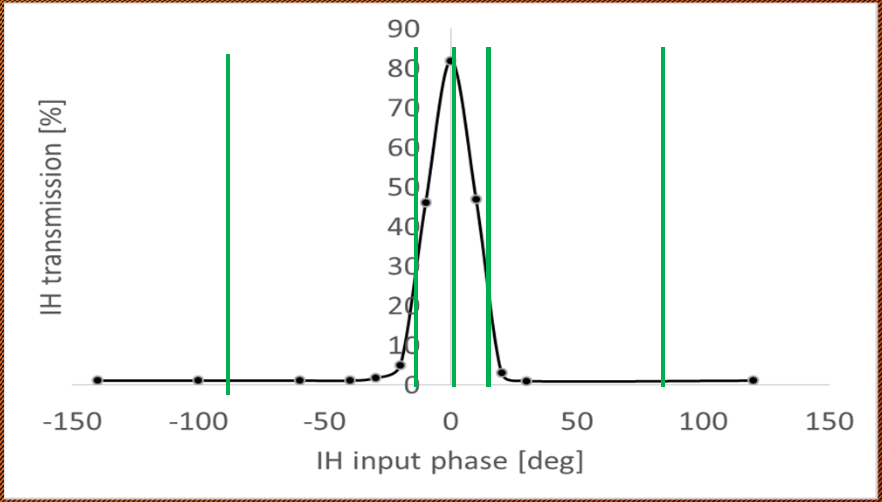


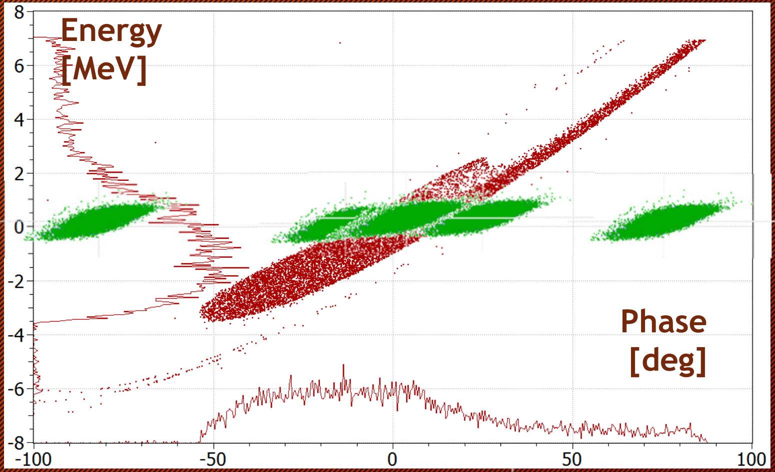
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)



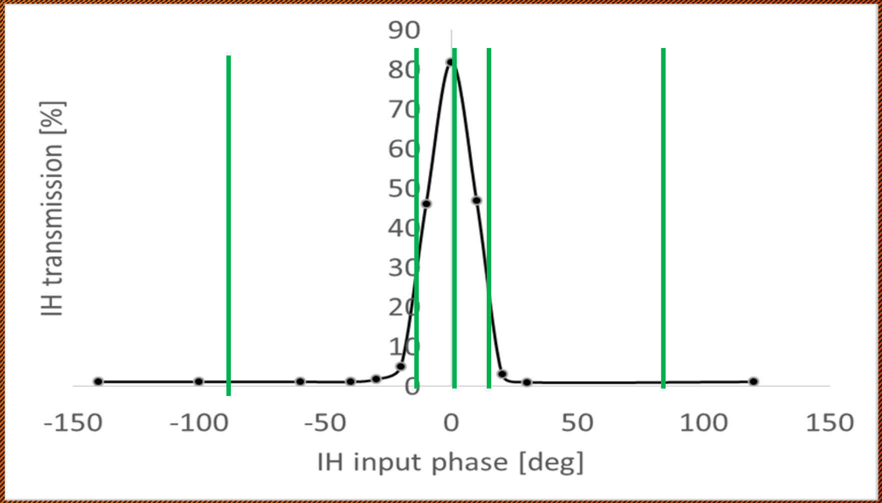


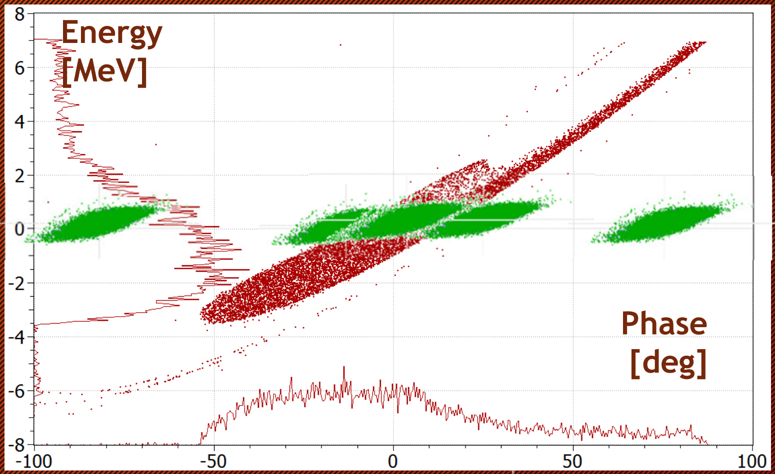
A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)





A solution was found on paper to increase the transmission by 20% with new rods design fitting in the same footprint (and slightly lower output longitudinal emittance)





RFQ output longitudinal emittance is tightly contained in the IH acceptance

Conclusions

Conclusions

Highlights of the beam dynamics restudy in Linac3 :

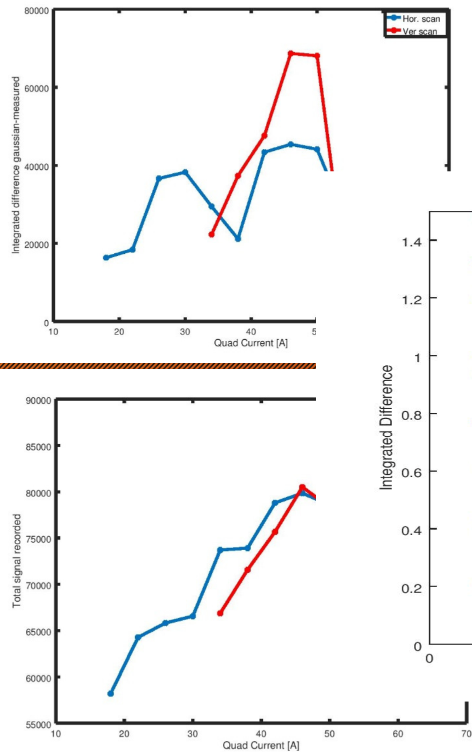
- First time simulations of beam extraction from the source using IBSimu (though results are not validated for lack of suitable instrumentation)
- Emittance measurement techniques successfully borrowed from Linac4 commissioning. Beam phase space distributions have been reconstructed from profile measurements using a tomographic method and used as input for further tracking downstream.

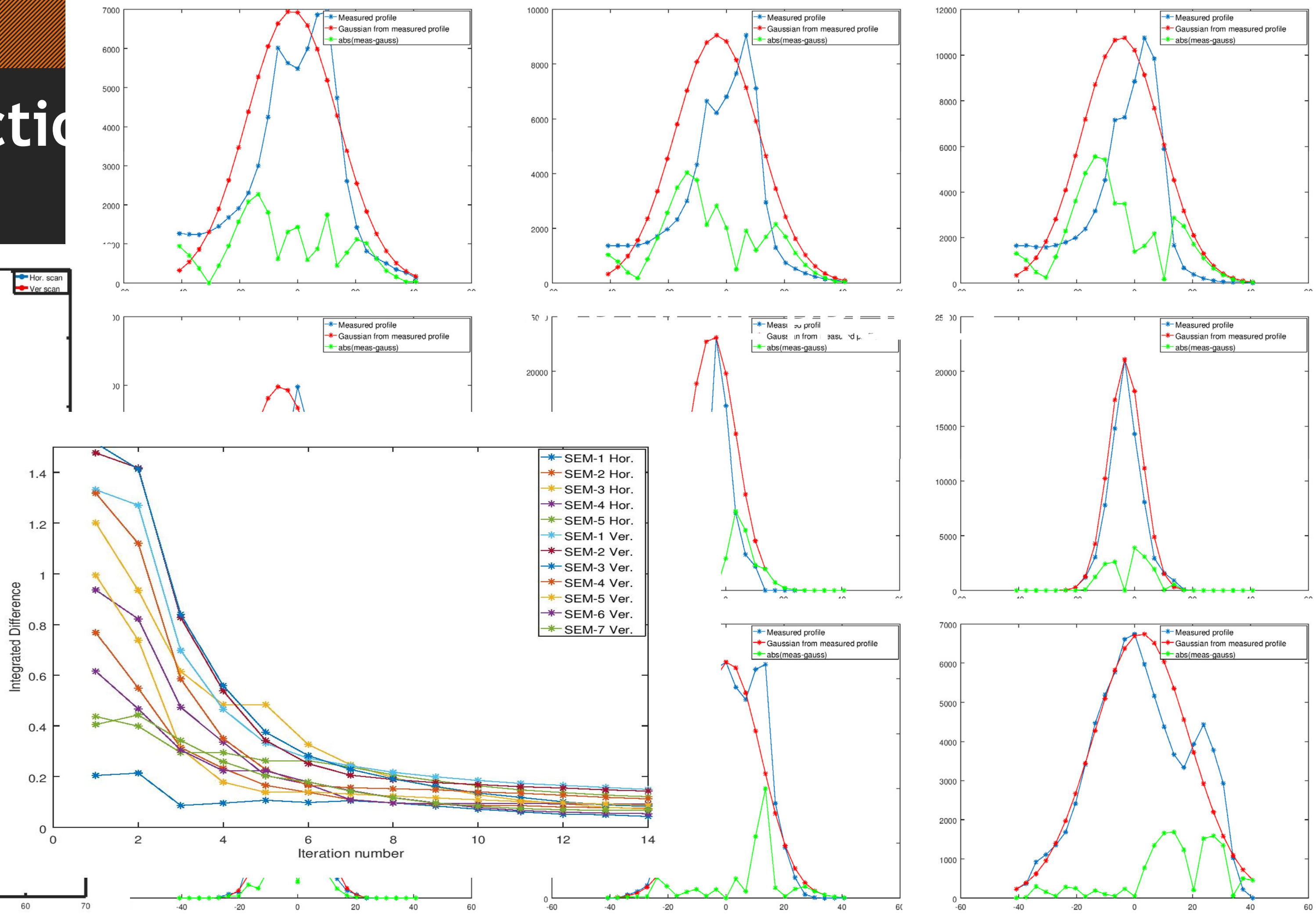
- Simulations have confirmed:
  1. aperture restriction in source extraction beam pipe (reduced after installation of larger chamber)
  2. measured beam distributions at selected locations
  3. observed beam transmission from RFQ input to IH output
  4. A RFQ re-design (on paper) has demonstrated the possibility to gain 20% in beam transmission with a new rods design.

Thank you for your attention

관심을 가져 주셔서 감사합니다.

Emittance Reconstructio 170516 Q5





$$\sigma = \sqrt{\frac{\sum(signal * (position - \mu)^2)}{\sum signal}}$$

$$\sigma = \sqrt{\frac{\sum(signal * |position - \mu|)}{\sum signal}}$$

$$\sigma = \sqrt{\frac{\sum(signal * (position - \mu)^2)}{\sum signal}}$$

If signals<0.025*$\sum signal$, then signal=0