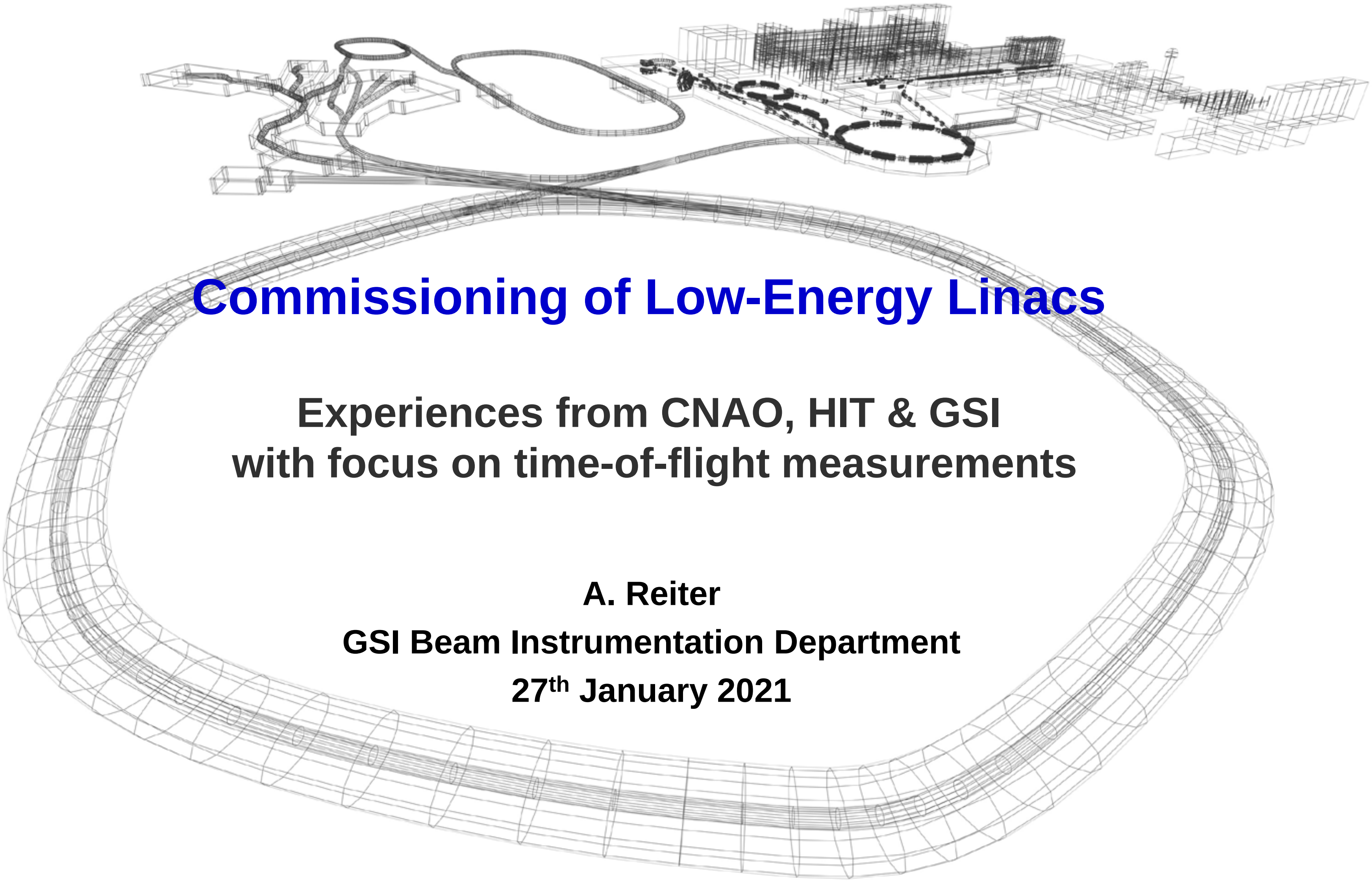


Commissioning of Low-Energy Linacs

Experiences from CNAO, HIT & GSI with focus on time-of-flight measurements

A. Reiter

GSI Beam Instrumentation Department

27th January 2021

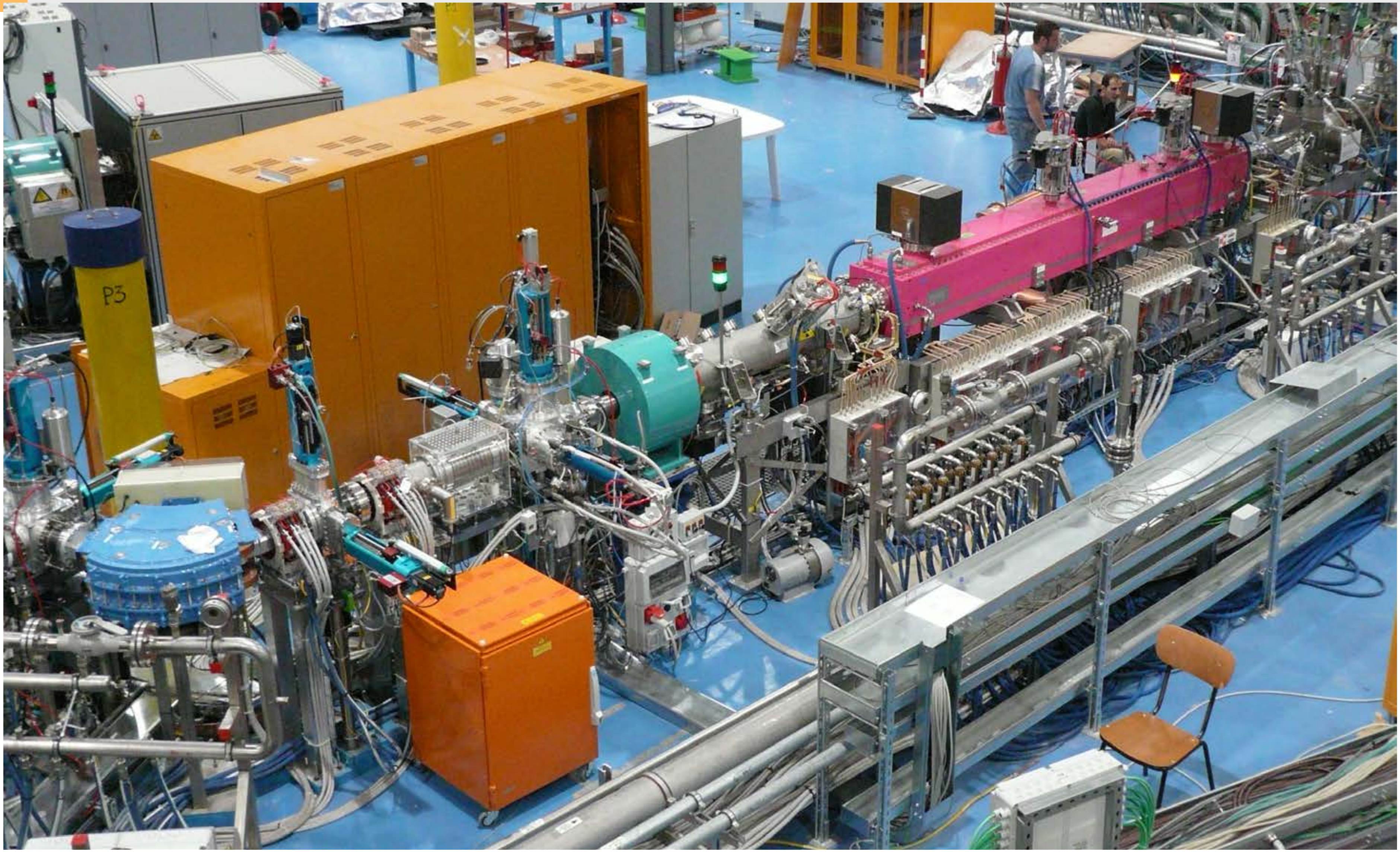
Outline

- **CNAO & HIT Injector Linacs**
  - Overview of test bench
  - Phase probes, i.e. capacitive ring pickups

- **Measurements**
  - RFQ Inter-tank phase probe calibration
    Beam energy and time focus
  - IH-DTL Beam energy
    Stripping efficiency and energy loss in Carbon foils
    Dispersion estimate
  - Energy ambiguity during operation

- **Summary**
  - Results
  - General remarks

CNAO Therapy Facility
Overview of 216.8 MHz Injector Linac



Commissioning Stages
Test Benches at CNAO

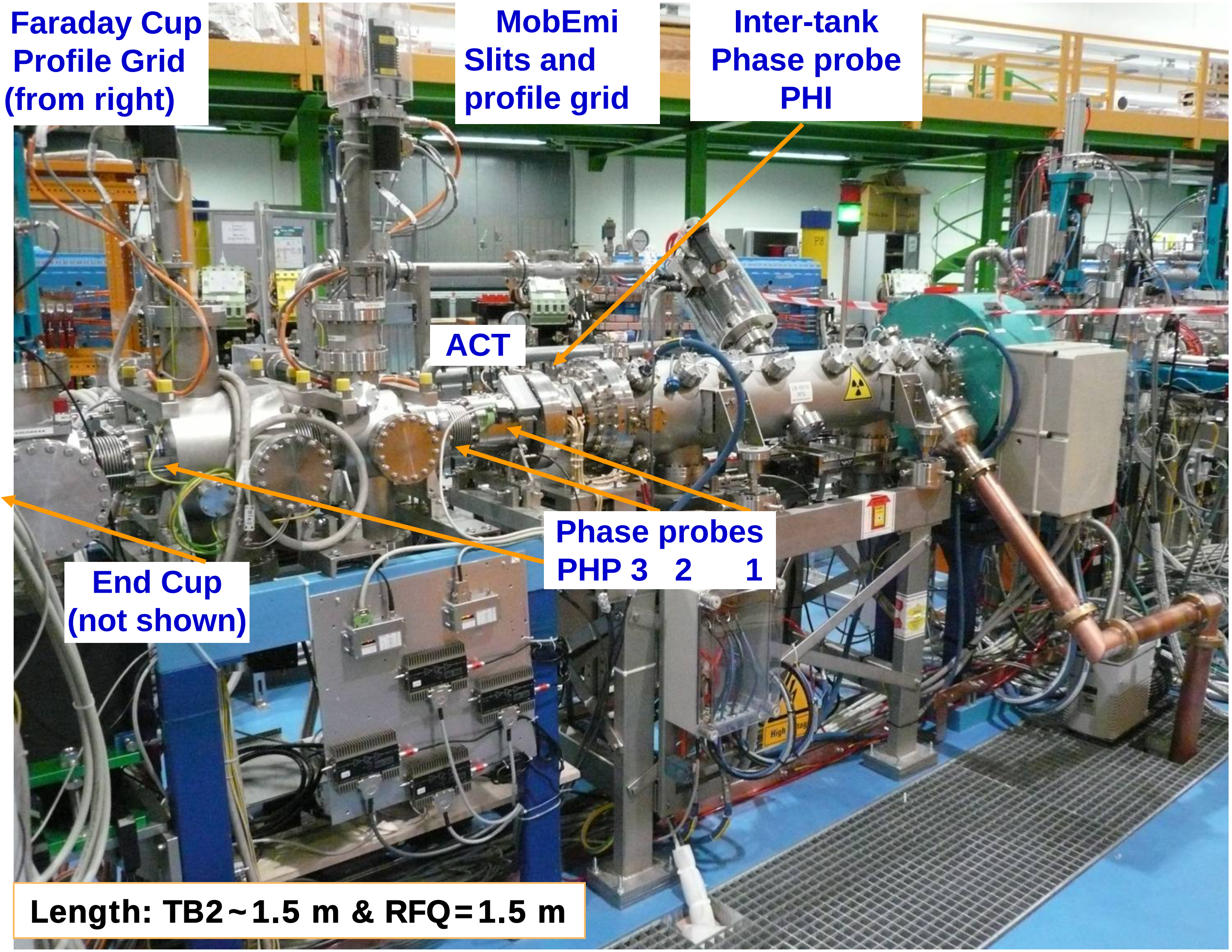
- **GSI Test Bench**
  - Commissioning of RFQ and rebuncher setup

- **Low-energy Branch Test Bench Zero (TB0)**
  - Low energy beam lines: Beam Steering & Solenoid Focussing Properties into RFQ
  - Transverse Emittance at RFQ injection position

- **RFQ Test Bench 2 (TB2) 3 weeks of beam time**
  - Full and “probe” beam
  - Beam Steering
  - Transmission
  - Transverse Emittance
  - Phase probe calibration
  - Beam energy
  - Time focus at IH-DTL injection

- **IH-DTL Test Bench 3 (TB3) 5 weeks of beam time**
  - ....
  - Stripping efficiency
  - Energy loss in stripper foils
  - Dispersion estimate

CNAO Setup of Test Bench TB2
Commissioning of 400 keV/u RFQ



Instrumentation:

Current: AC transformer, Faraday & End Cup

Profile: SEM grid (X+Y), 1.2 mm wire spacing

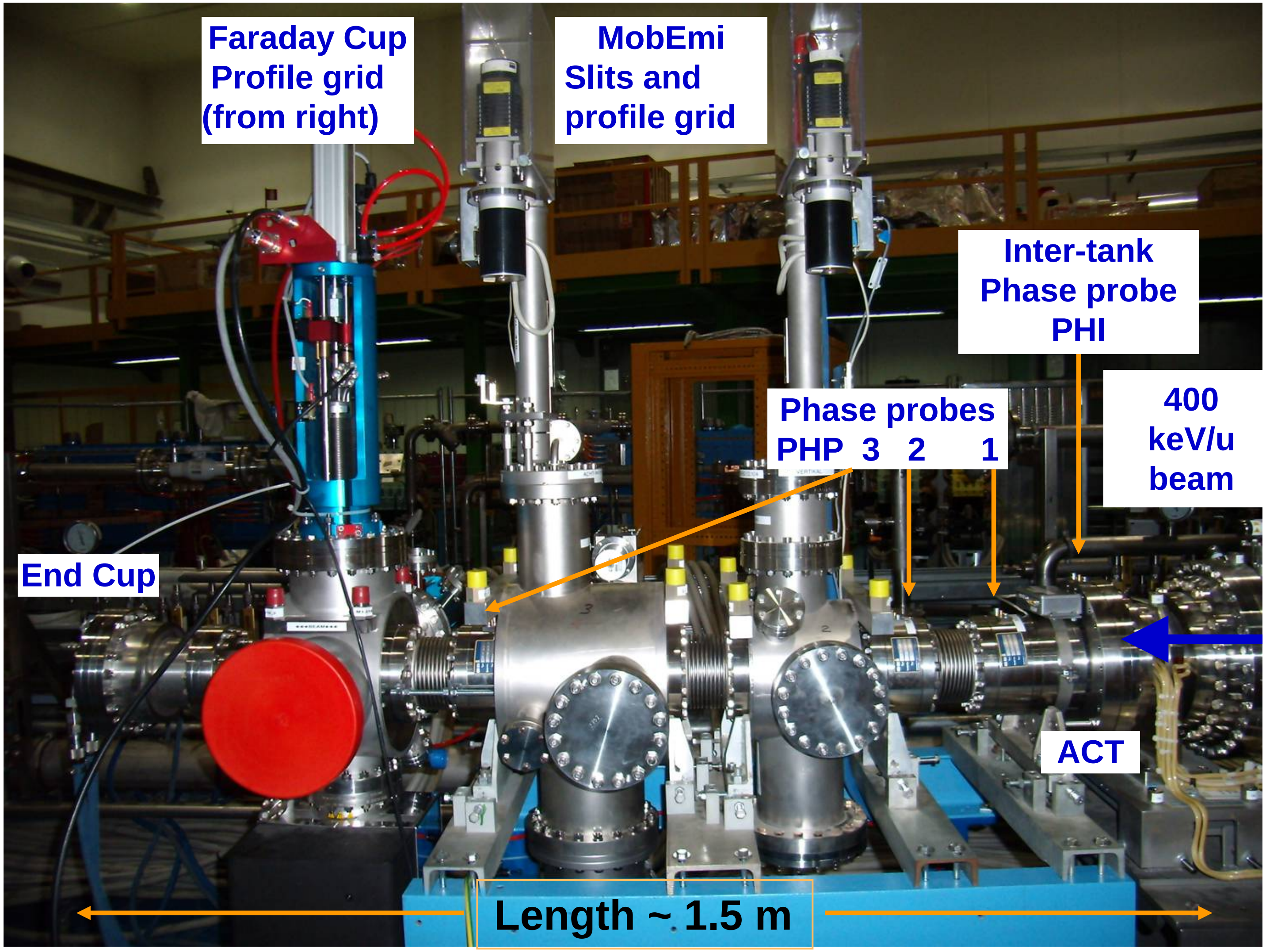
Energy: phase probe & RFQ tank signal

Transverse emittance:
Slit–Grid system with 0.1 mm slits and SEM grids (X or Y), 1 mm spacing, on stepper motors.

Optional sub-steps of SEM grid for improved resolution.

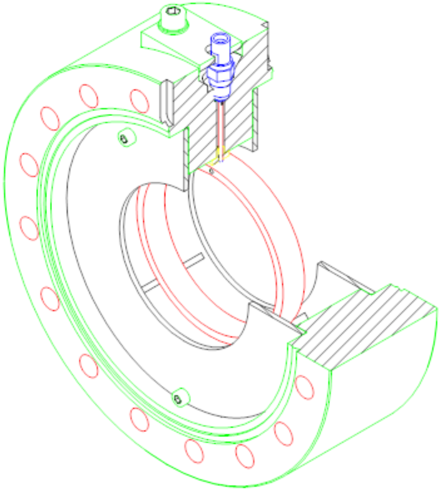
Details on the hardware can be found in the appendix.

CNAO Setup of Test Bench TB2 Commissioning of 400 keV/u RFQ



Inter-tank probe PHI:

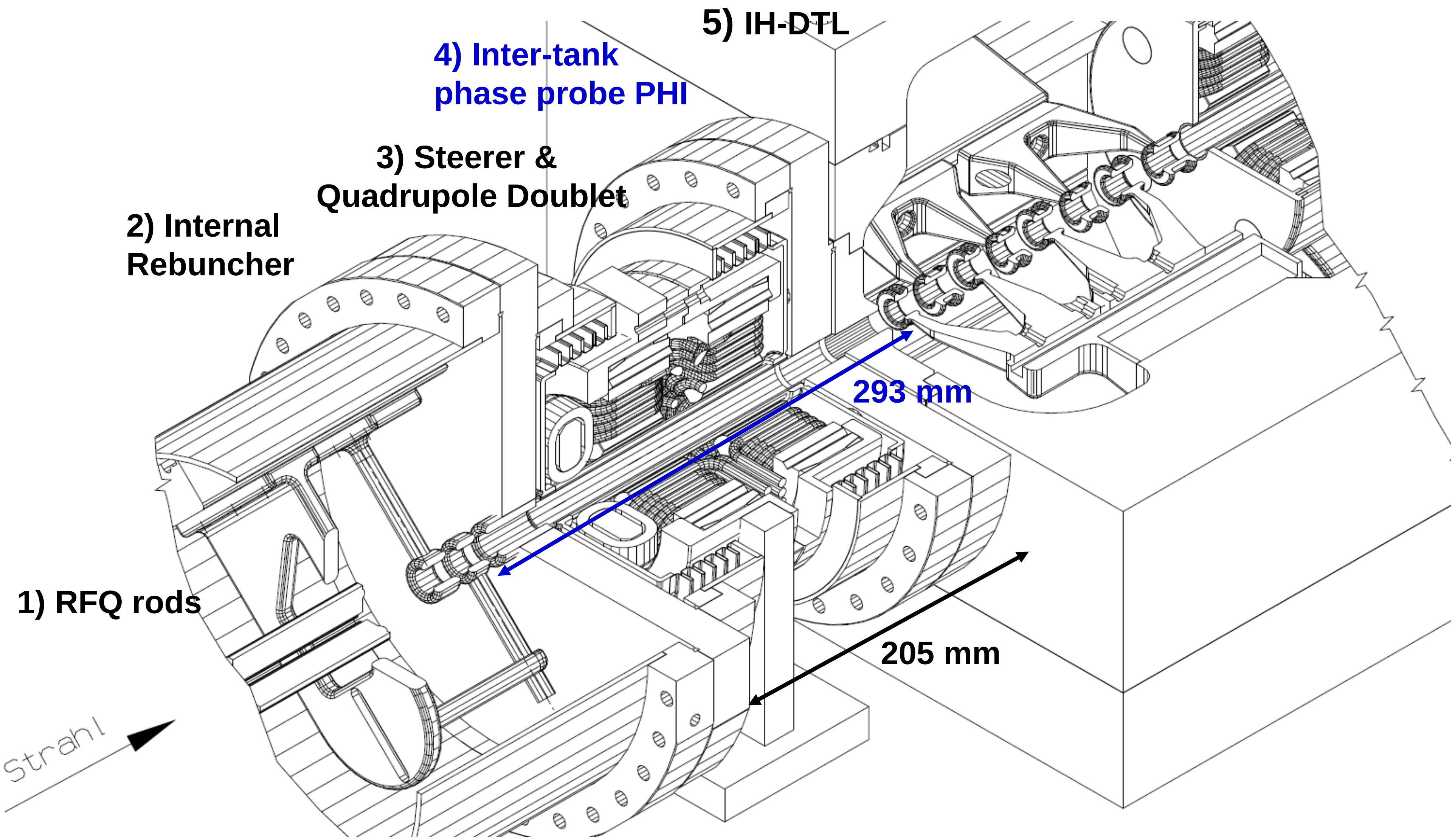
- 50 Ω geometry
- 1 cm ring radius
- 1 cm ring length
- Protective plate
- Length 20 mm



Phase probe PHP:

- 50 Ω geometry
- 3 cm ring radius
- 1 cm ring length
- Protective plate
- Length 50 mm

RFQ Structure with Internal Rebuncher, Inter-tank Section and IH-DTL entrance



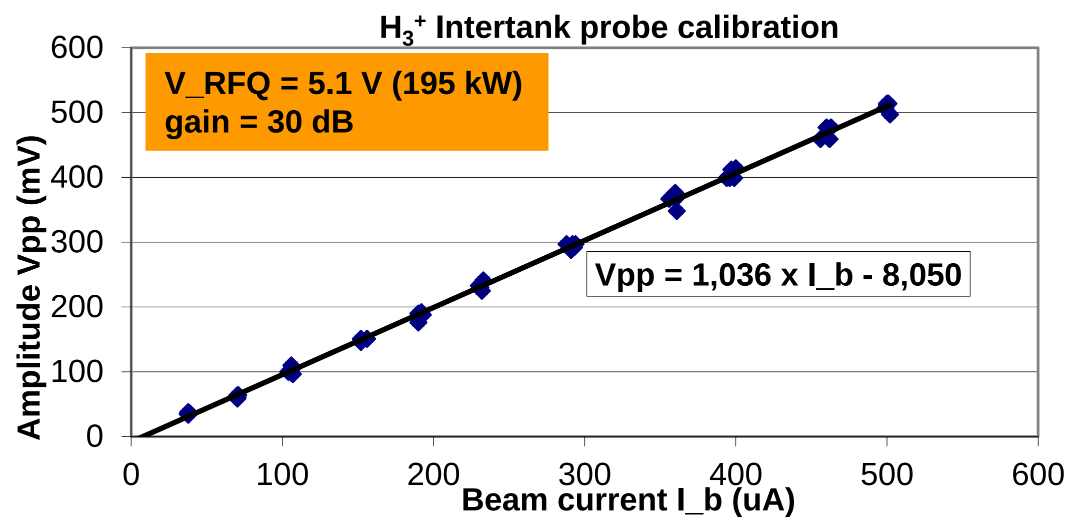
Calibration of Inter-tank probe PHI
“Emergency” AC current transformer

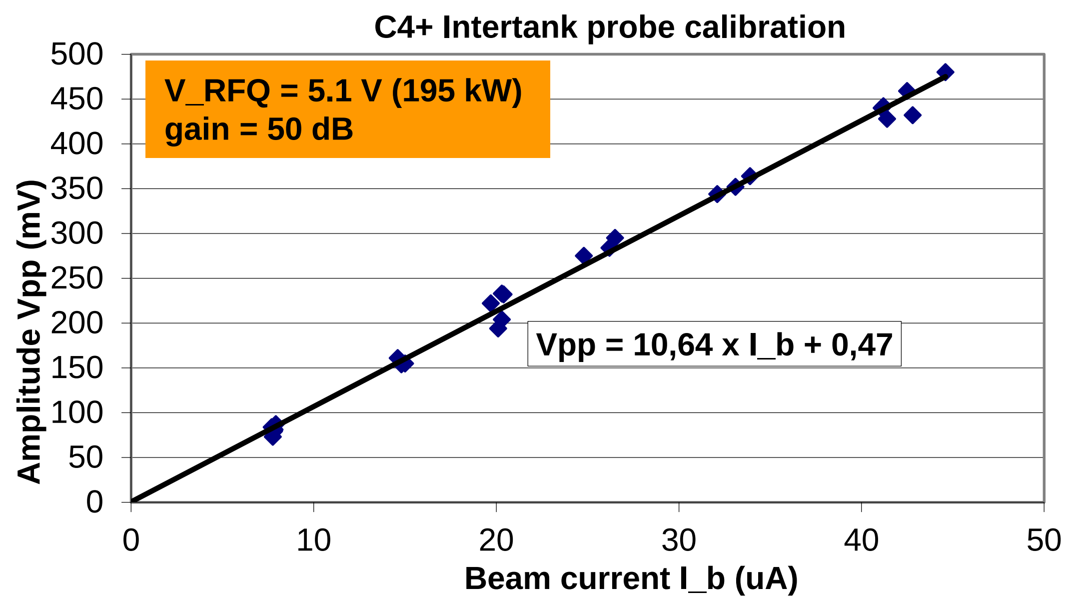
Use case (better fear!):
The planned ACT had to be dropped due to space restrictions. Trouble shooting during later operation in case the overall transmission through injector linac is too low.

Measurement:
Thanks to reliable results of TB0 commissioning for ion source beam and RFQ injection parameters, we attempted a probe calibration recording PHI amplitude Vpp vs. current I_b in TB2 for both reference beams at nominal RFQ settings.

Result:
1. Two consistent calibrations with an estimated accuracy of (10–15) %

2. Small dependency of calibration factor on RFQ power (V_RFQ): 3% change for voltage change of 0.1 Volt (4% RF power)


H_3^+ Intertank probe calibration


C4+ Intertank probe calibration

PHP signals: measurement and expectation
Line charge model & response function

Simple analytical model:

1. Calculate signal induced in ring electrode by a point charge (dashes black lines)
2. Fold with line charge
3. Fold with transfer function H(ω) of phase probe modelled as RC circuit
4. For long transmission: cable dispersion
5. Overlap adjacent signals to calculate expected signal shape (black line)

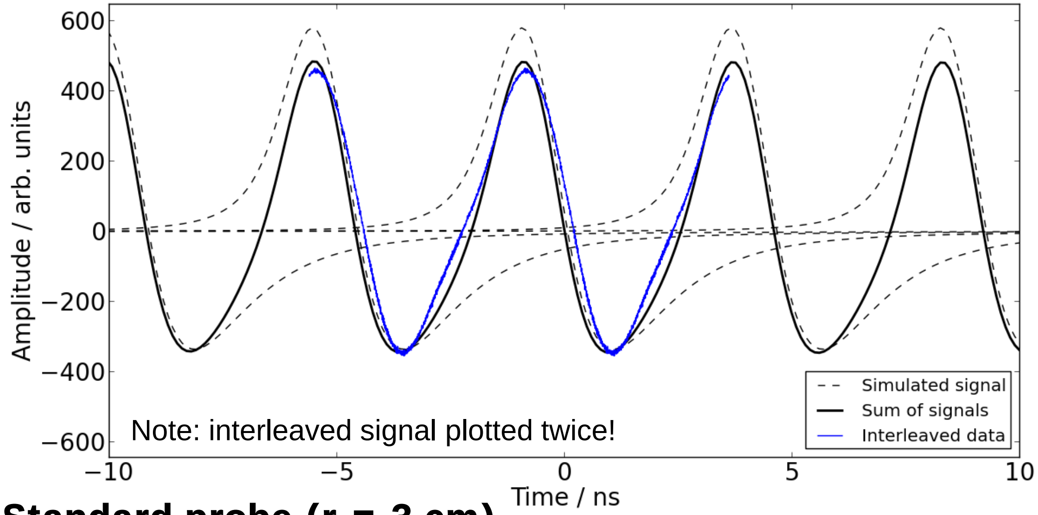
Result:

At small energies, the overlap at 216.8 MHz modifies the expected signal shape significantly:

Signal amplitude is reduced.
Inter-tank probe: „saw-tooth“/triangular signal
Standard probe: „sine-wave“ signal

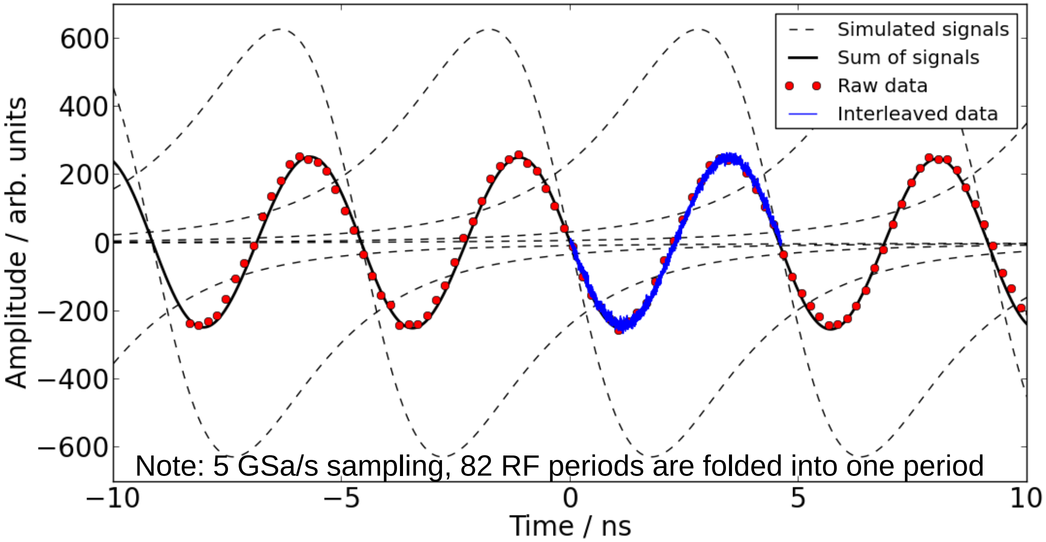
Despite the obvious model shortcomings – electric field distribution without boundary conditions, no protective plate – the model was very valuable in several occasions, especially together with data of ion optics simulations.

Inter-tank probe (r = 1 cm)



Note: interleaved signal plotted twice!

Standard probe (r = 3 cm)



Note: 5 GSa/s sampling, 82 RF periods are folded into one period

RFQ beam energy
Stability measurement – time-of-flight and energy

Measurement:

- Operate RFQ linac at 5 Hz (beam & stability pulse)
- Save energy measurement every 30 s
- 5 GSa/s acquisition (multiples of 82 RF periods)
- Acquire three ring pickups and one RFQ tank signal

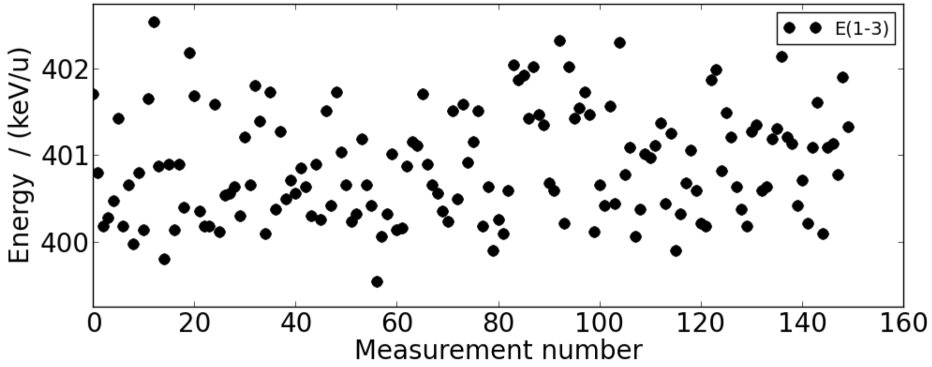
Result:

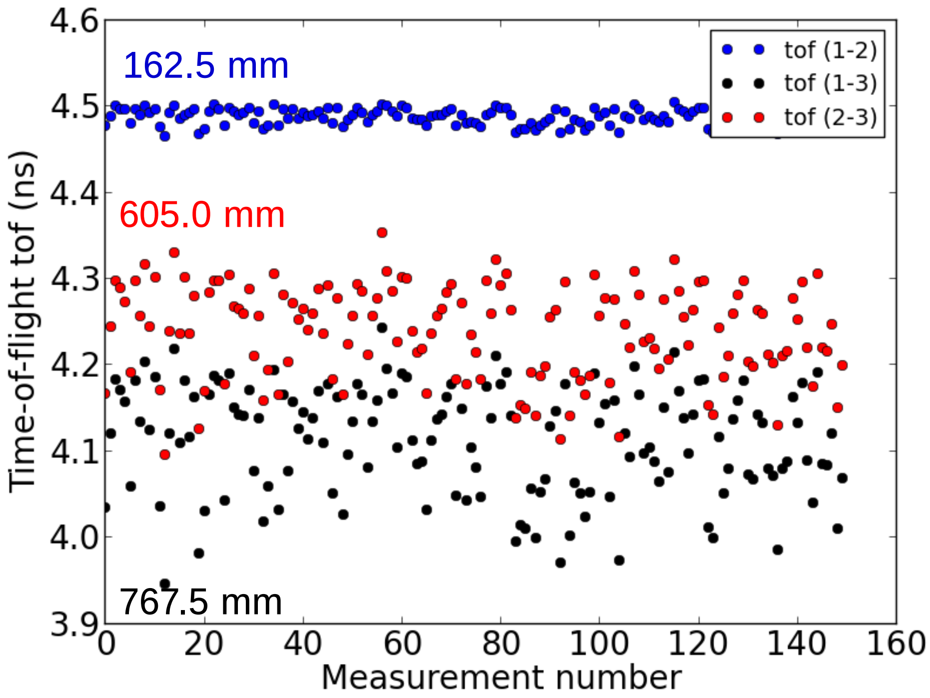
1. Data of 150 measurements show energies in range [399 , 403] keV/u or 1% of nominal energy and within specification.

2. time-of-flight = N x t_rf + TOF, where TOF is derived from maximum position of cross correlation between interleaved PHP signals, N is the bunch number, t_rf is the RF period.

3. Mean value E(RFQ) = (400.88 ± 0.63) keV/u
   Resolution σ(E)/E = 1.6x10^{-3}

4. TOF distributions scatter increasingly for longer flight paths in a range of 30 to 250 ps. This should be resolvable with the analysis: Δt(theor.) ~ 2.6 ps
   => Attempt to plot data vs. RFQ tank signal





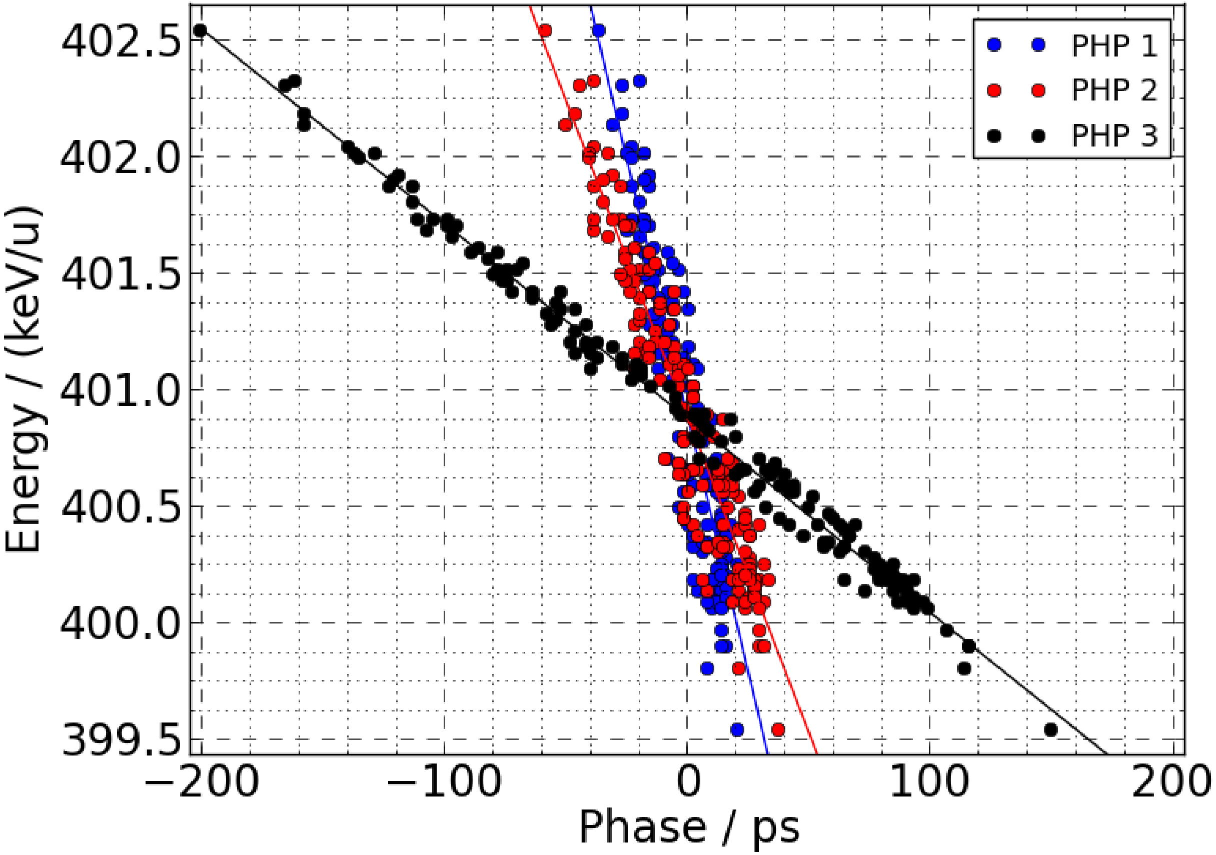
RFQ beam energy
Stability measurement – “phase space”

2D analysis:

1. Construct “arrival times” (arbitrary phase) at probes PHP 1, PHP 2 and PHP 3 as TOF time between RFQ tank reference and PHP signals: tof(1–RFQ),..., tof(3-RFQ)
2. Calculate E(1-2), E(2-3), E(1-3)
3. Fill scatter plots wrt. to mean values: tof(1-RFQ) vs. E(1-2),...,

Result:

1. All three distributions are clearly correlated. Their main axis represent something like the orientation of the phase space ellipse.
2. The plots determine the effective resolutions of t(eff) ~10 ps
3. Residuals from straight-line of PHP 3 data: ΔE(rms)=0.06 keV/u (Δt ~6.7 ps)



RFQ beam energy
Stability measurement – time focus

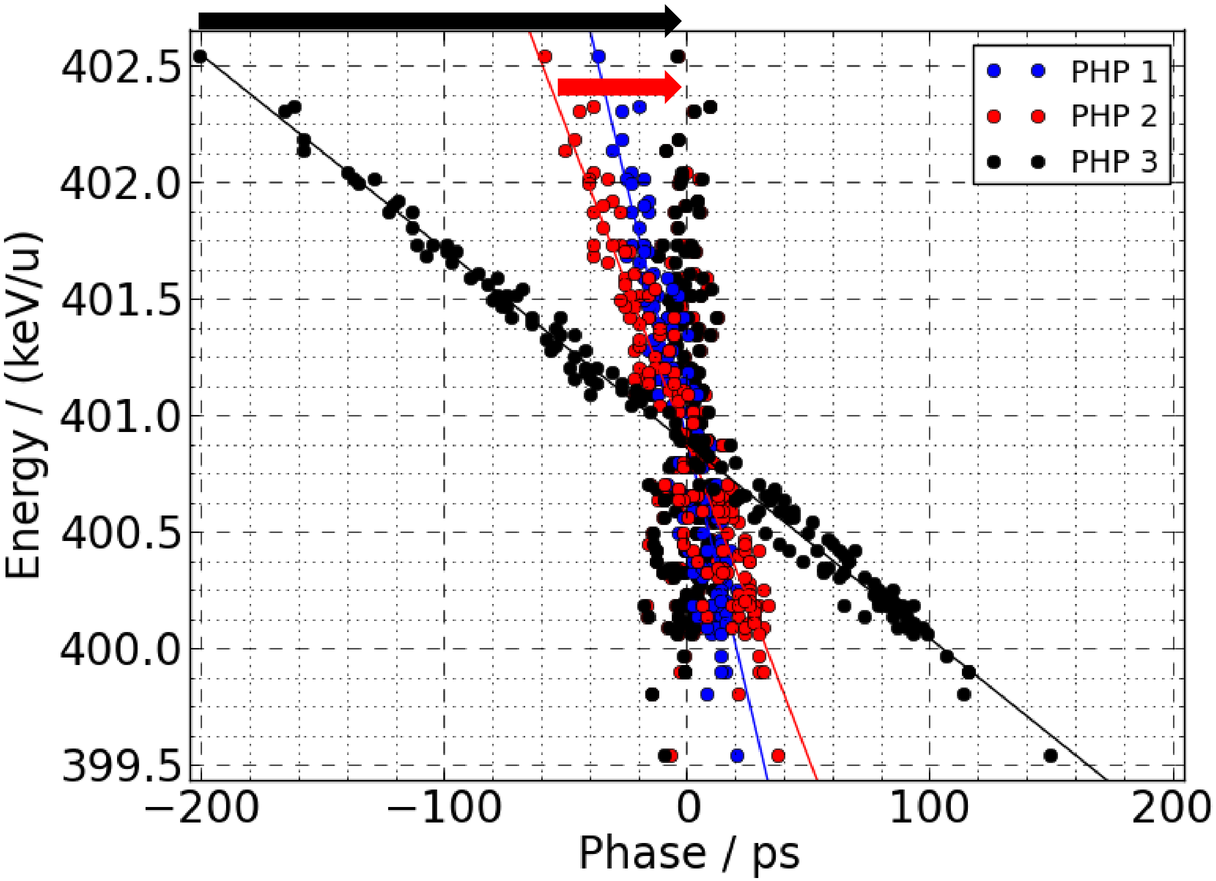
Calculation:
Back tracking of distributions using known phase probe distances until correlation vanishes.

Result:

1. The back-tracked distributions for PHP 2 and PHP 3 are shown for a drift space of 287.8 mm.
2. The result is in agreement with the mechanical distance of 293.0 mm between last gap in RFQ and 1st gap of IH-DTL.

=> Confidence that internal rebuncher voltage was setup quite well during initial RFQ commissioning at GSI.

Note: this analysis was carried out long after the commissioning campaign of the injector linac!



CNAO Setup of Test Bench TB3 Commissioning of 7 MeV/u IH-DTL

Test bench TB3
RFQ & IH-DTL
7 MeV/u H_3^+/C^{4+}

same hardware in "stretched" setup

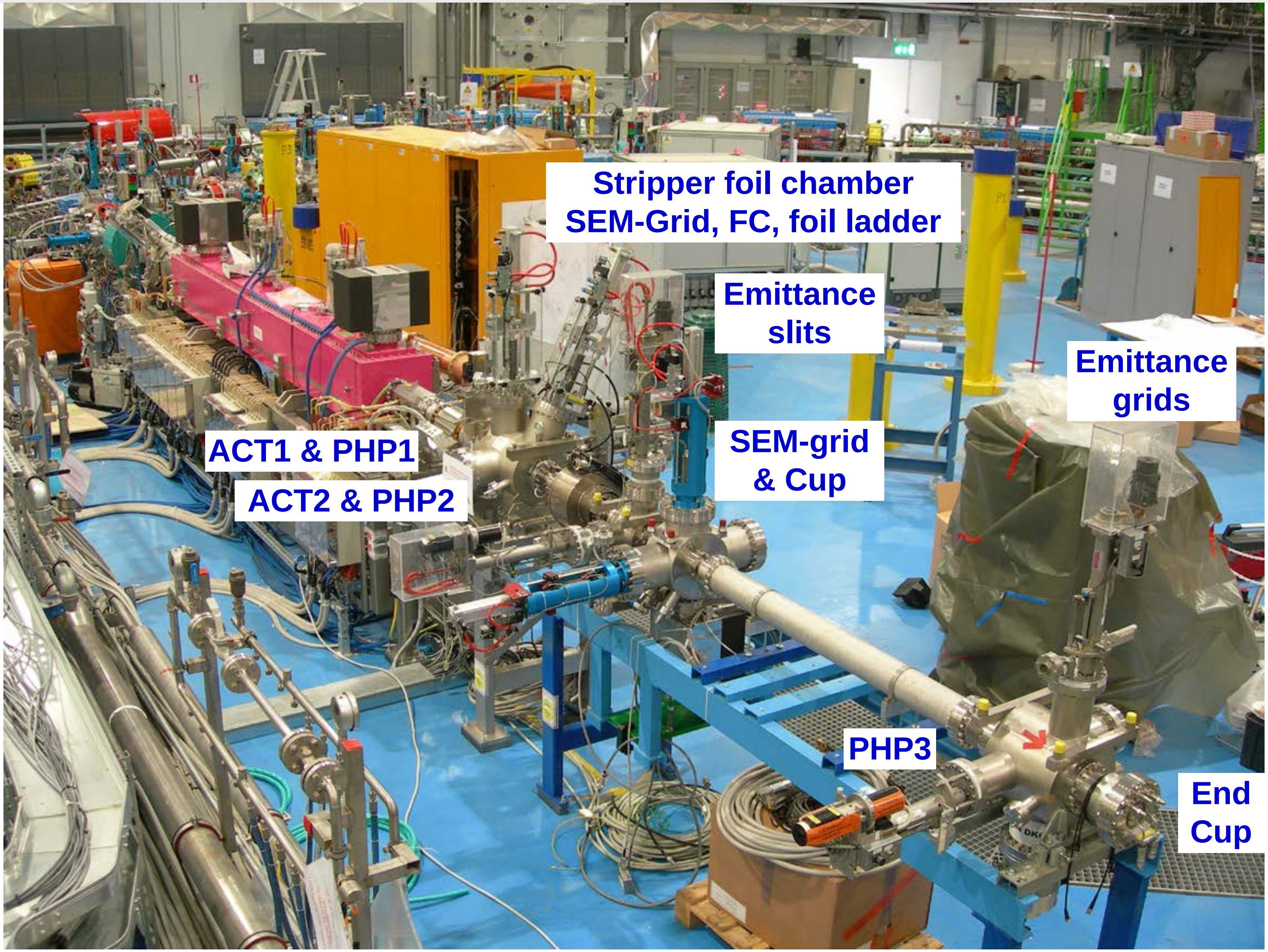
IH-PHP1:	380.0 mm
PHP 1-2:	1147.5 mm
PHP 2-3:	2650.0 mm
PHP 1-3:	3797.4 mm

Carbon foil stripper

$t = 100\ \mu g/cm^2$

$H_3^+ \longrightarrow 3\ p$

$C^{4+} \longrightarrow C^{6+}$



IH-DTL beam energy (HIT)
Stability measurement

Measurement:

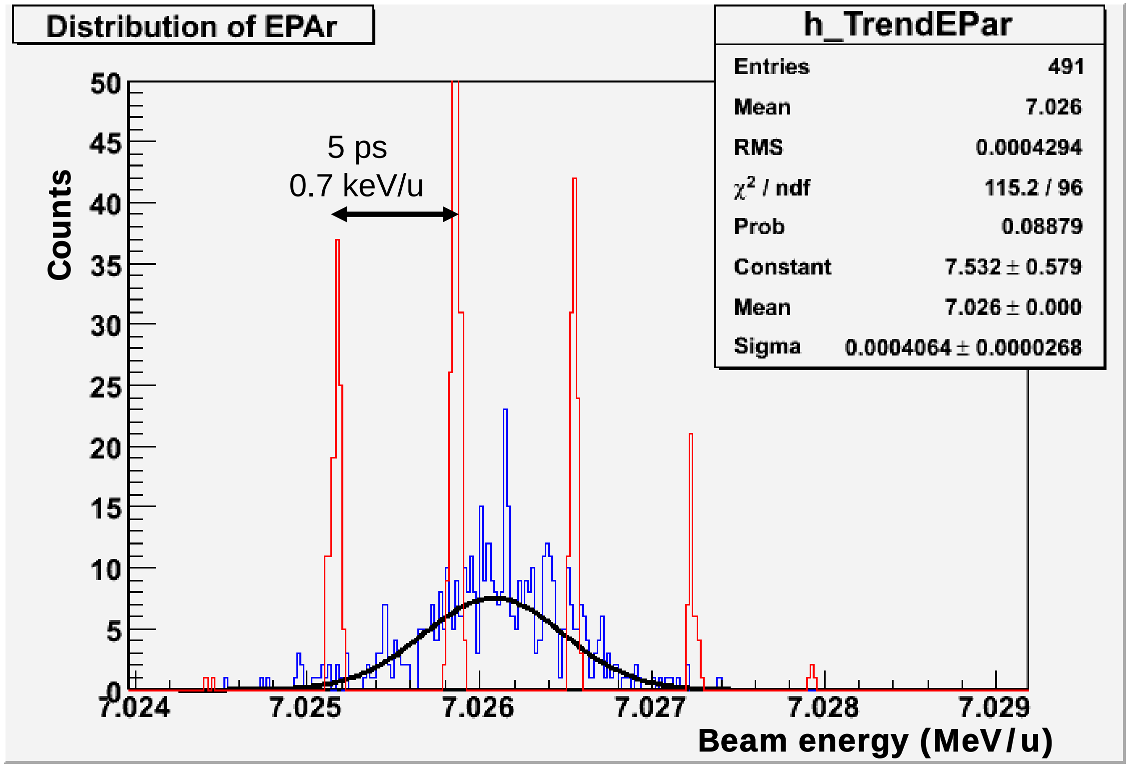
- Operate RFQ & IH-DTL linacs at < 5 Hz
- 4 GSa/s acquisition (multiples of 41 RF periods)
- Short-term measurement of 491 samples with Carbon beam (few minutes)

Result:

1. Red histogram: Resolution of 5 ps (or 0.7 keV/u) visible at this energy, if maximum position of cross correlation is used for TOF calculation.

2. Blue histogram: P2 fit around maximum of cross correlation to increase TOF resolution. The distribution can be described with a Gaussian (black line):
   E = 7.026 MeV/u ; σ(E) = 0.4 keV/u or "short-term" resolution σ(E)/E = 6x10^{-5}

3. Beam energy depends on cooling water temperature:
   ΔE/ΔT ~ 15 keV/u / 1°C at CNAO



Conclusion:
Operation of linacs with complex ion optics may require monitoring beyond "classic" variables and may need to include the "wider" accelerator environment in the control system.

IH-DTL beam energy (CNAO)
Stripping efficiency

Measurement:

- Foil material: 100 $\mu g/cm_2$ Carbon
- Stripping effect: H_3^+ => 3 p
  C^{4+} => C^{6+}
- Efficiency: ratio of currents with/without foil

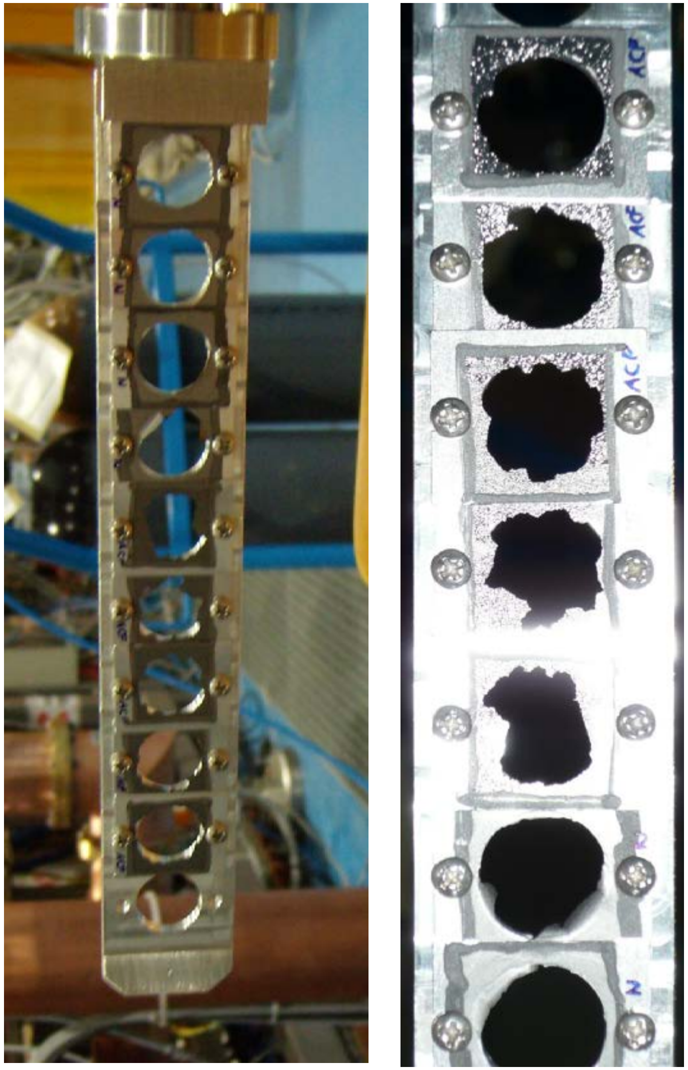
Result:

- 1st attempt was a complete failure.
- We saw no stripping effect and no energy loss in the foil.
- Dismount foil stripper from vacuum chamber to find that all foils were blown!
- 2nd attempt produced the desired efficiency values, but we had some electron background in the AC transformer.

Conclusion:

- Some days are less successful than others.
- An optical view port on the chamber could have helped.
- Make sure to prepare spares for „critical“ items!

Luckily, we had another two foil ladders brought to Italy.
Sparking in RFQ destroyed the input stage of the PHI inter-tank pickup amplifier several times during commissioning, a problem that we had not encountered at HIT.



IH-DTL beam energy (CNAO)
Energy loss in 100 µg/cm$_2$ Carbon foils

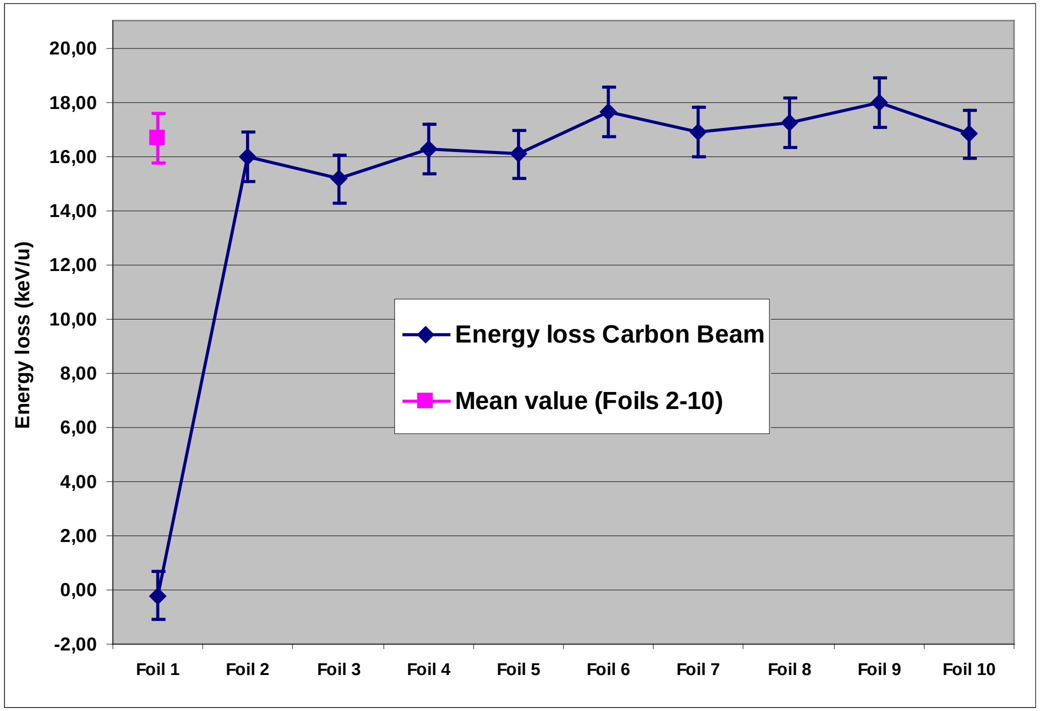
Date:	**15.07.2009**		**Beam:**	**C6+**	**Names :**	**Silvia & Piero**			**RUN-143**	
	Foil 1	**Foil 2**	**Foil 3**	**Foil 4**	**Foil 5**	**Foil 6**	**Foil 7**	**Foil 8**	**Foil 9**	**Foil 10**
Average (No foil)	7188,55	7188,55	7188,55	7188,55	7188,55	7188,55	7188,55	7188,55	7188,55	7188,55
Average (With foil)	7188,75	7172,56	7173,39	7172,27	7172,48	7170,91	7171,65	7171,32	7170,58	7171,74
Energy loss	**-0,21**	**15,98**	**15,16**	**16,27**	**16,07**	**17,64**	**16,89**	**17,22**	**17,97**	**16,81**

Stripping foil ageing:

- Monitor foil thickness in-situ via energy loss.
- Use Carbon beam because of larger energy loss 16 keV/u vs. 5 keV/u for protons
- To minimise external factors, we need a fast measurement with and without foil.

Measurement:

- Average over 10 pulses
- Foil 1 = empty frame
- Mean energy loss (16.67 ± 0.89) keV/u
- Atima prediction 16.2 keV/u



Result:

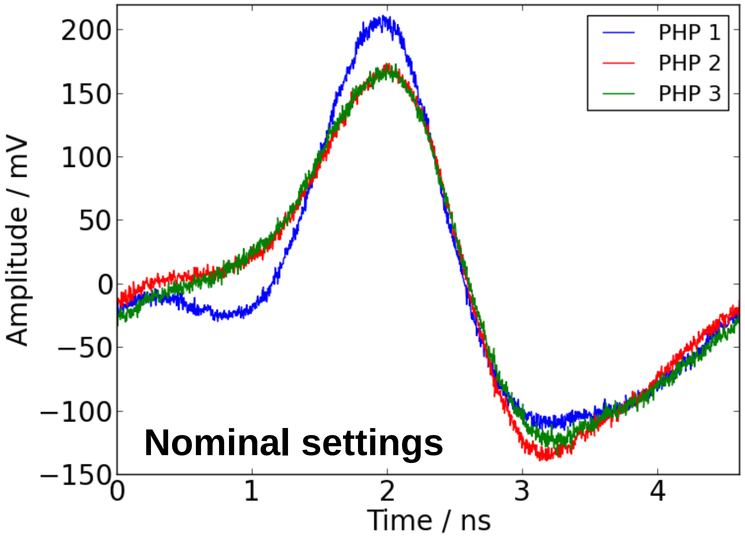
- Uniformity of foils is quite good.
- Energy ratio is sensitive enough to detect ~15% variation in foil thickness quickly.
- Many years later, we know that the foils last much longer than ever expected!

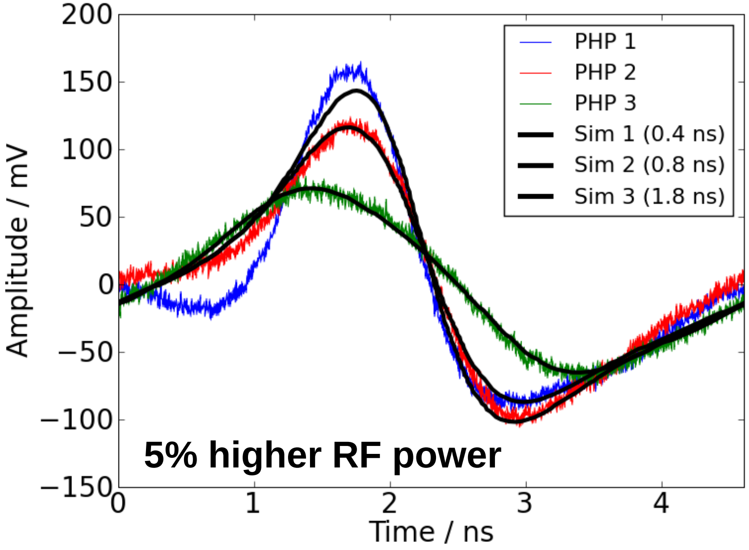
IH-DTL beam
Rough estimate of dispersion

Measurement:
- Lacking the capacity of bunch shape measurements, only a rough attempt was possible. At nominal settings signals of PHP 2 and PHP 3 do not vary much.
- When the linac was operated at higher RF power, dispersion became evident in the phase probe signals at distances of 380 mm, 1527 mm and 4177 mm.

Result:
1. The signals were approximated by line charges of given width at all three positions
2. Extrapolation to zero (IH-DTL exit) yields a width of 0.25 ns (or 20° at 216.8 MHz)
3. Assuming a momentum dispersion of Δp/p = ±1.5% the signals could be reproduced.
4. For nominal operation we estimated an upper limit for the dispersion Δp/p = ±0.2 % in agreement with the design value.

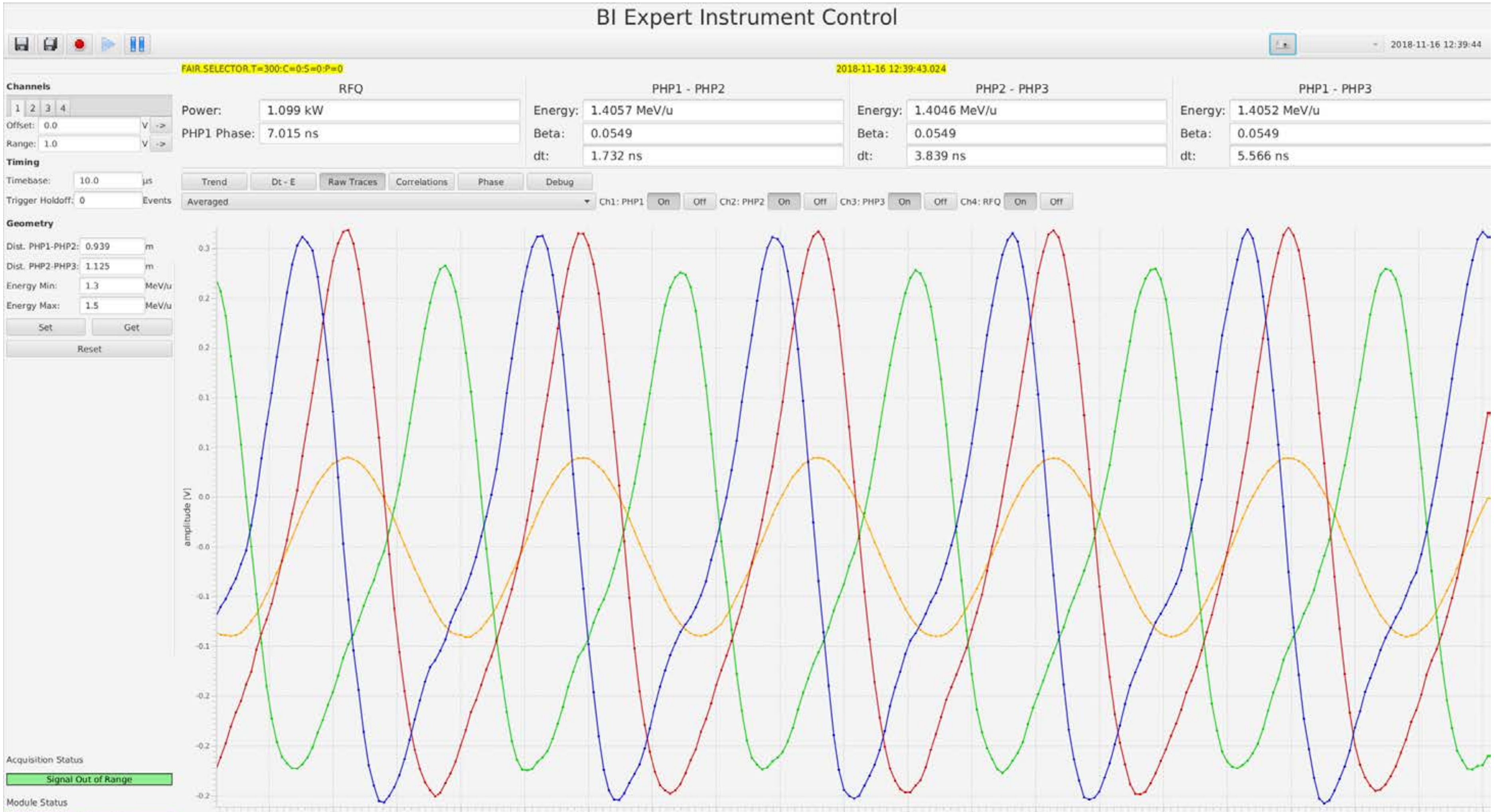
Conclusion:
Although we got reasonable results, the analysis is intrinsically rather weak and unreliable. A dedicated monitor (fast Faraday cup, bunch shape monitor,...) would have been helpful.





CW Demonstrator Commissioning (1.4 MeV/u => 1.9 MeV/u)
Raw Traces at 1.4 MeV/u

Raw Traces (Averaged)



Offset: 0.0 V
Range: 1.0 V
Timebase: 10.0 µs
Trigger Holdoff: 0 Events
Dist. PHP1-PHP2: 0.939 m
Dist. PHP2-PHP3: 1.125 m
Energy Min: 1.3 MeV/u
Energy Max: 1.5 MeV/u

RFQ
Power: 1.099 kW
PHP1 Phase: 7.015 ns

PHP1 - PHP2
Energy: 1.4057 MeV/u
Beta: 0.0549
dt: 1.732 ns

PHP2 - PHP3
Energy: 1.4046 MeV/u
Beta: 0.0549
dt: 3.839 ns

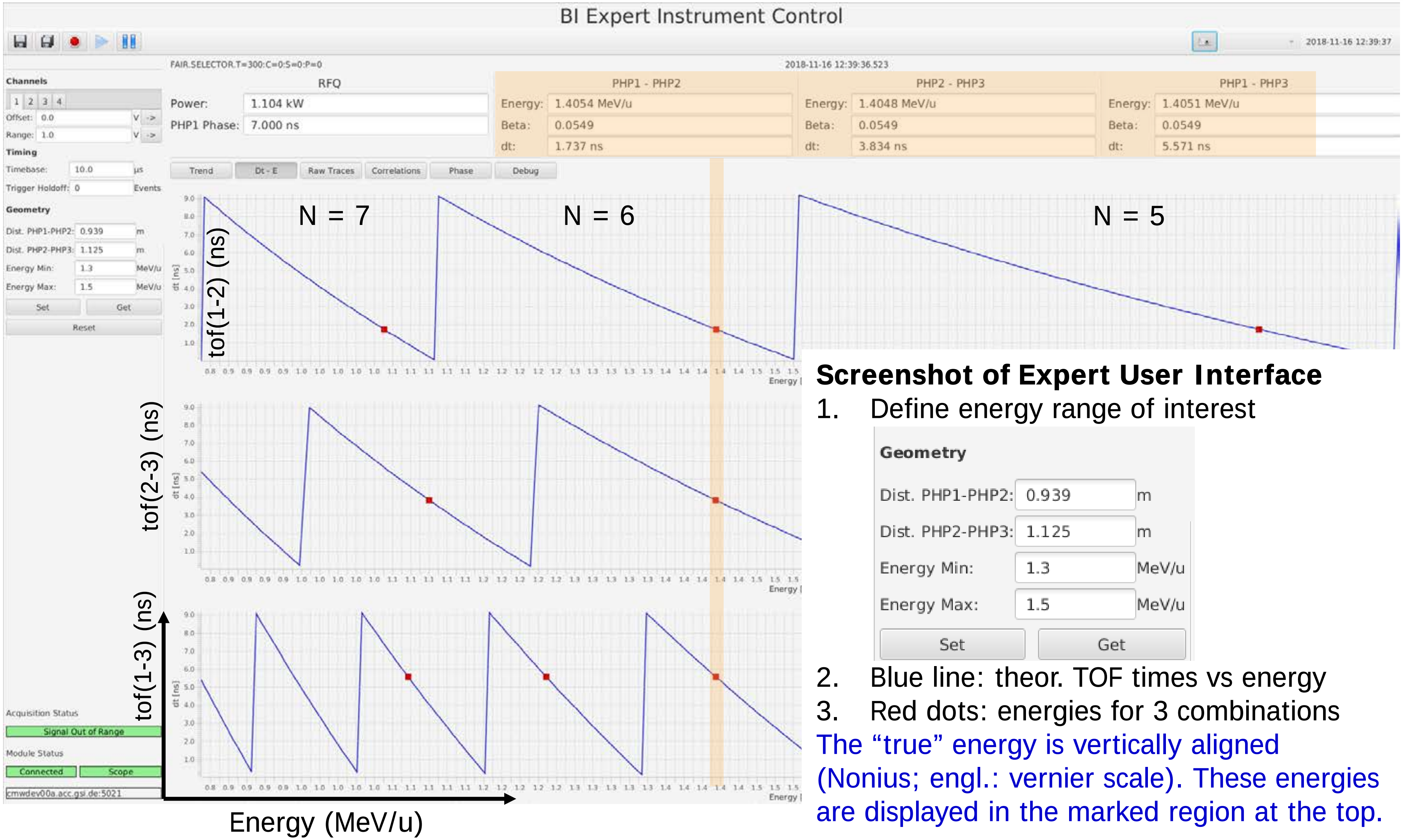
PHP1 - PHP3
Energy: 1.4052 MeV/u
Beta: 0.0549
dt: 5.566 ns

Averaged

Energy calculation relies on correct bunch number N. When the linac energy changes, this number needs to be updated, ideally automatically.

CW Demonstrator Commissioning (E = 1.4 – 2.0 MeV/u) Variable energy / bunch number N – “Nonius” plot

TOF – E plot (1.3 – 1.5) MeV/u



BI Expert Instrument Control

2018-11-16 12:39:37

FAIR.SELECTOR.T=300:C=0:S=0:P=0

2018-11-16 12:39:36.523

Channels 1 2 3 4

Offset: 0.0 V

Range: 1.0 V

Timing

Timebase: 10.0 µs

Trigger Holdoff: 0 Events

Geometry

Dist. PHP1-PHP2: 0.939 m

Dist. PHP2-PHP3: 1.125 m

Energy Min: 1.3 MeV/u

Energy Max: 1.5 MeV/u

Set Get

Reset

Acquisition Status

Signal Out of Range

Module Status

Connected Scope

cmwdev00a.acc.gsi.de:5021

RFQ

Power: 1.104 kW

PHP1 Phase: 7.000 ns

	PHP1 - PHP2	PHP2 - PHP3	PHP1 - PHP3
Energy:	1.4054 MeV/u	1.4048 MeV/u	1.4051 MeV/u
Beta:	0.0549	0.0549	0.0549
dt:	1.737 ns	3.834 ns	5.571 ns

Screenshot of Expert User Interface

1. Define energy range of interest

Geometry

Dist. PHP1-PHP2: 0.939 m

Dist. PHP2-PHP3: 1.125 m

Energy Min: 1.3 MeV/u

Energy Max: 1.5 MeV/u

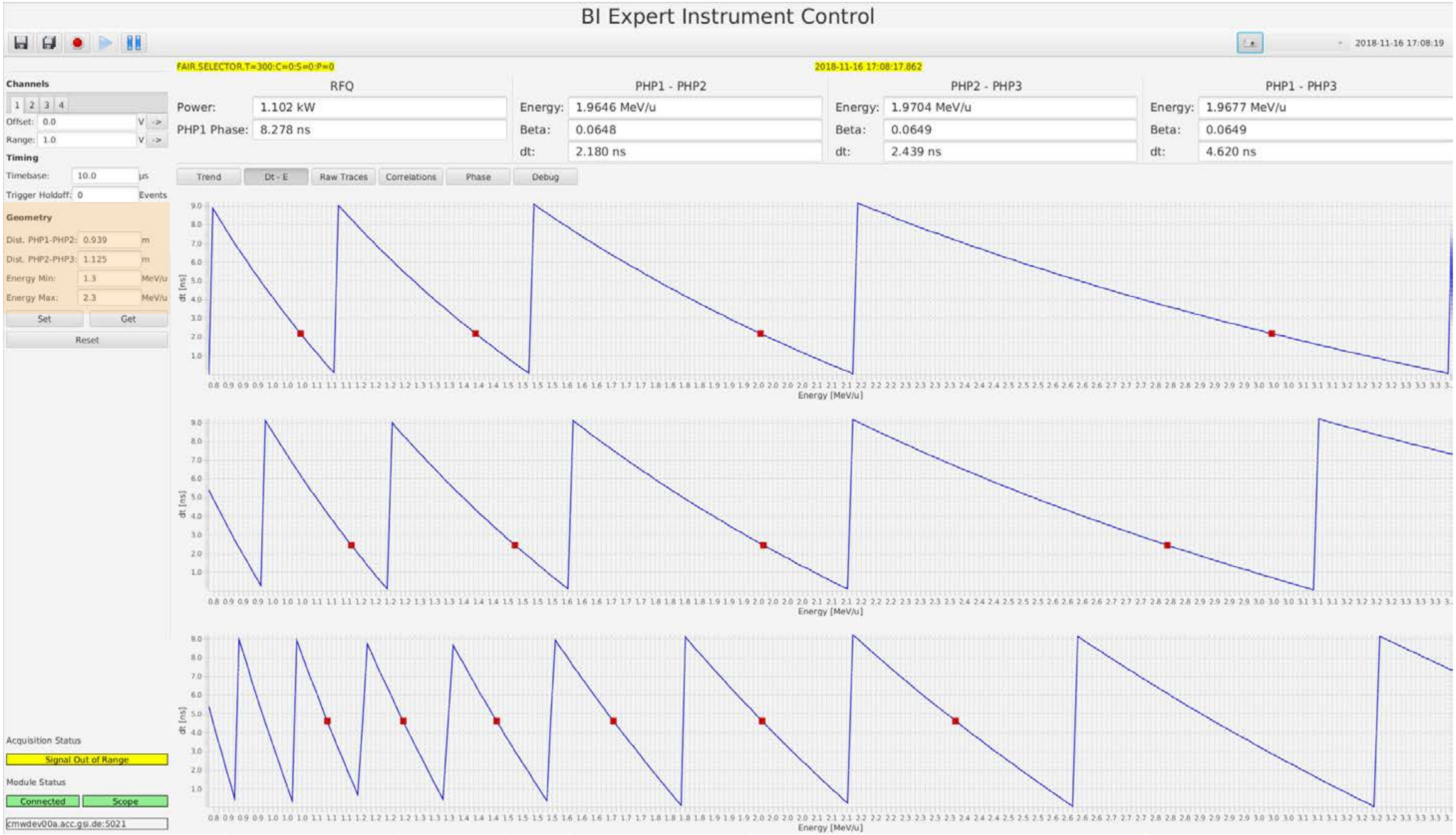
Set Get

2. Blue line: theor. TOF times vs energy
3. Red dots: energies for 3 combinations

The “true” energy is vertically aligned (Nonius; engl.: vernier scale). These energies are displayed in the marked region at the top.

CW Demonstrator Commissioning (E = 1.4 – 2.0 MeV/u)
Variable energy / bunch number N – “Nonius” plot

Same plot as before, now for range (1.3 – 2.3) MeV/u



2018-11-16 17:08:19

FAIR.SELECTOR.T=300:C=0:S=0:P=0

2018-11-16 17:08:17.862

Channels

1 2 3 4

Offset: 0.0 V

Range: 1.0 V

Timing

Timebase: 10.0 µs

Trigger Holdoff: 0 Events

Geometry

Dist. PHP1-PHP2: 0.939 m

Dist. PHP2-PHP3: 1.125 m

Energy Min: 1.3 MeV/u

Energy Max: 2.3 MeV/u

RFQ

Power: 1.102 kW

PHP1 Phase: 8.278 ns

PHP1 - PHP2

Energy: 1.9646 MeV/u

Beta: 0.0648

dt: 2.180 ns

PHP2 - PHP3

Energy: 1.9704 MeV/u

Beta: 0.0649

dt: 2.439 ns

PHP1 - PHP3

Energy: 1.9677 MeV/u

Beta: 0.0649

dt: 4.620 ns

Acquisition Status

Signal Out of Range

Module Status

Connected Scope

cmwdev00a.acc.gsi.de:5021

The energy axis ticks still need to be optimised!

Summary
Commissioning Experience

- **Hardware**
  - For HIT & CNAO commissioning standard instrumentation of TB2 and TB3 was suited for its purpose.
  - For proper longitudinal phase space investigations, e.g. in larger multi-stage Linacs, dedicated bunch shape monitors seem mandatory: fast FC, Feschenko monitors, dipole spectrometer, etc.
  - Make sure to have spares and quick access to resources in case of problems.

- **Software & Analysis**
  - Time-domain analysis developed at HIT & CNAO now in use at GSI at several Linacs (HITRAP Decelerator, CW Demonstrator, CRYRING RFQ injector, UNILAC)
  - Further improvements in TOF measurement for 12 bit oscilloscopes can be expected (to be confirmed).
  - Access to ion optic simulations or results (data) to model response of instruments, especially for cases outside nominal parameters.
  - There is never enough software for online or offline analysis, so Python and alike are very helpful.

- **Commissioning**
  - Careful execution of TB0 commissioning was crucial and made RFQ commissioning easier.
  - The preparation phase before beam time is at least as important than the beam time itself.
  - Take time for simple things (verify expectations), especially steering investigations, signal distortions (e.g. by other components or beam-related background like electrons), etc.
  - Document a lot (success/problems/failures, procedures, good/bad results) during beam time.
  - Evaluate, summarise and distribute status and current knowledge after each commissioning campaign.

!!! Thank you for your kind attention !!!

Before commissioning

After commissioning

Special thanks to all colleagues who were involved in the commissioning and our friends from CNAO in Pavia and HIT in Heidelberg

!!! Many thanks to the organisers of this workshop !!!

Appendix

Beam parameters
Overview

- Ion Source

Type:	2x ECR ion source, Pantechnik Supernanogan 14 GHz	
Ion species:	H_3^+	C^{4+}
Un-stripped current:	1100 µA	250 µA
Macropulse:	< 200 µs (typ. 35 µs for synchrotron injection)	
RF frequency f_{RF}:	216.816 MHz (τ_{RF} = 4.61 ns)	

- RFQ

length	1.5 m	
input energy	8.0 keV/u	
output energy	(400 ± 6) keV/u (±1.5%)	beta = 0.0293
transmission	≤ 60 %	
current	500 µA (H_3^+)	75 µA (C^{4+})
4x ε_{exp}(rms) hor/ver	19 /14 π mm mrad (H_3^+)	18 /12 π mm mrad (C^{4+})
ε_{sim} (95%)	24 π mm mrad	

- IH-DTL

length	4.0 m	
acceptance	50 π mm mrad	
input width	+/- 15° (0.4 ns)	
output energy	7.0 MeV/u ± 21 keV/u (±0.3%)	beta = 0.122
emittance	0.83 π mm mrad	
width at stripper	+/- 6° (0.15 ns)	

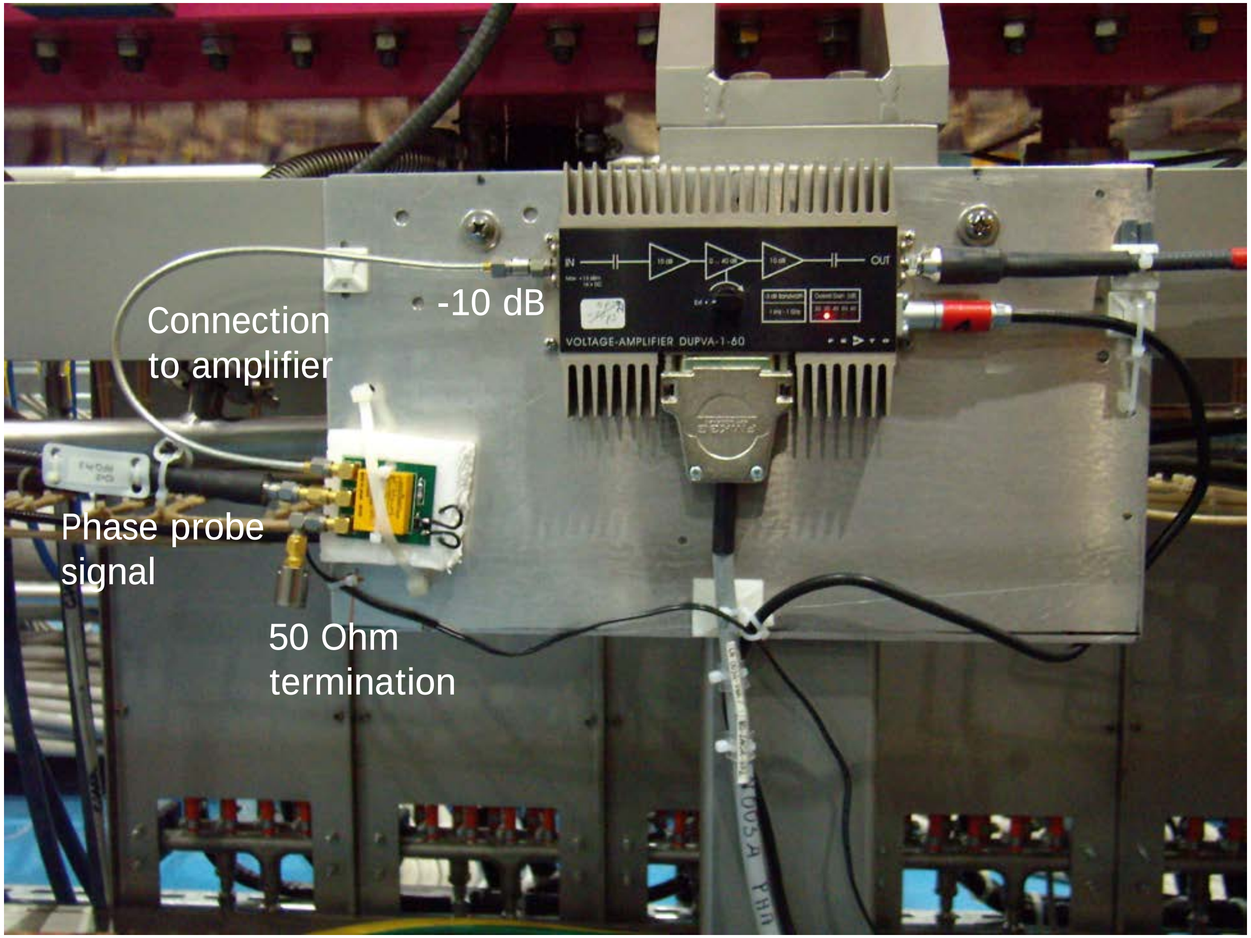
Setup of inter-tank probe PHI
One spark from damage

Problem:
Sparking damaged the input amplifier stage several times during commissioning.

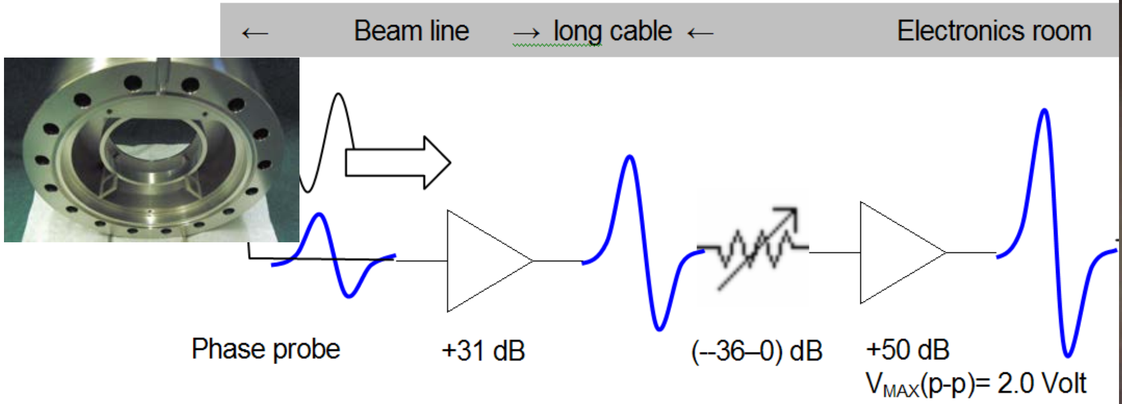
Solution:

1. RF relay to dump power in 50 Ω, if phase probe not in active use.
2. Add 10 dB attenuator at input

Picture shows mock-up amplifier protection installed during commissioning

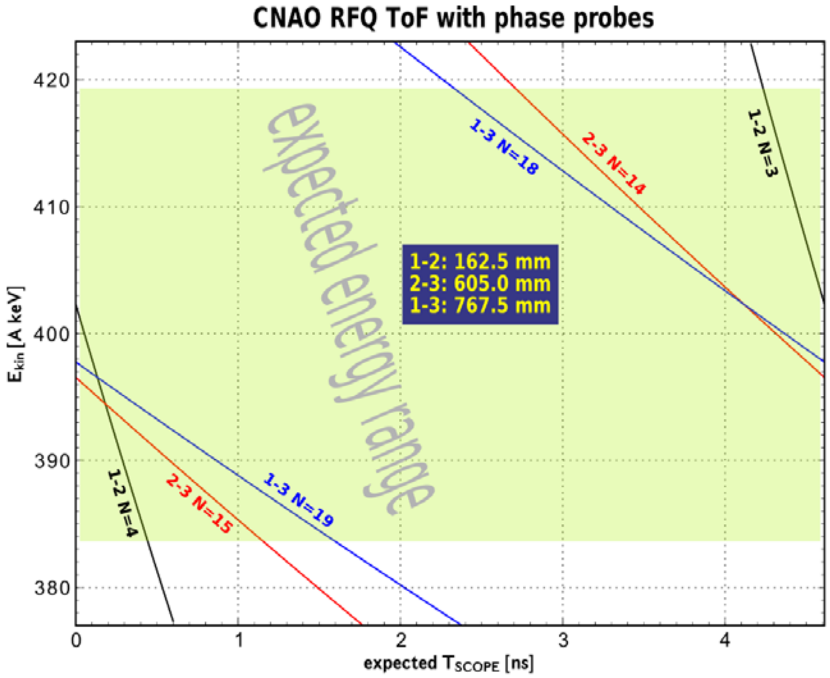


Time-of-flight (TOF) setup
Acquisition of three phase probes & tank signal



Tank signal: Attenuated RF power signal via out-coupling loop on RFQ tank

1. **Switchable pre-amplifiers (not tank signal)**
   - 1 stage [or 2 stages]
   - GSI type and/or commercial amplifiers (z.B. Femto DUPVA-1-60, Miteq AM-1641)
2. **Transmission via coaxial cable**
3. **Oscilloscope digitization**
   - sampling speed: (4 – 5) GSa/s
   - resolution: 8 bit (nominal)
   - bandwidth: 1 GHz
   - trigger: fixed to RF phase



Signal Analysis & TOF calculation
Exploit periodic nature of signals and sampling

New (for us!) Time-domain analysis:

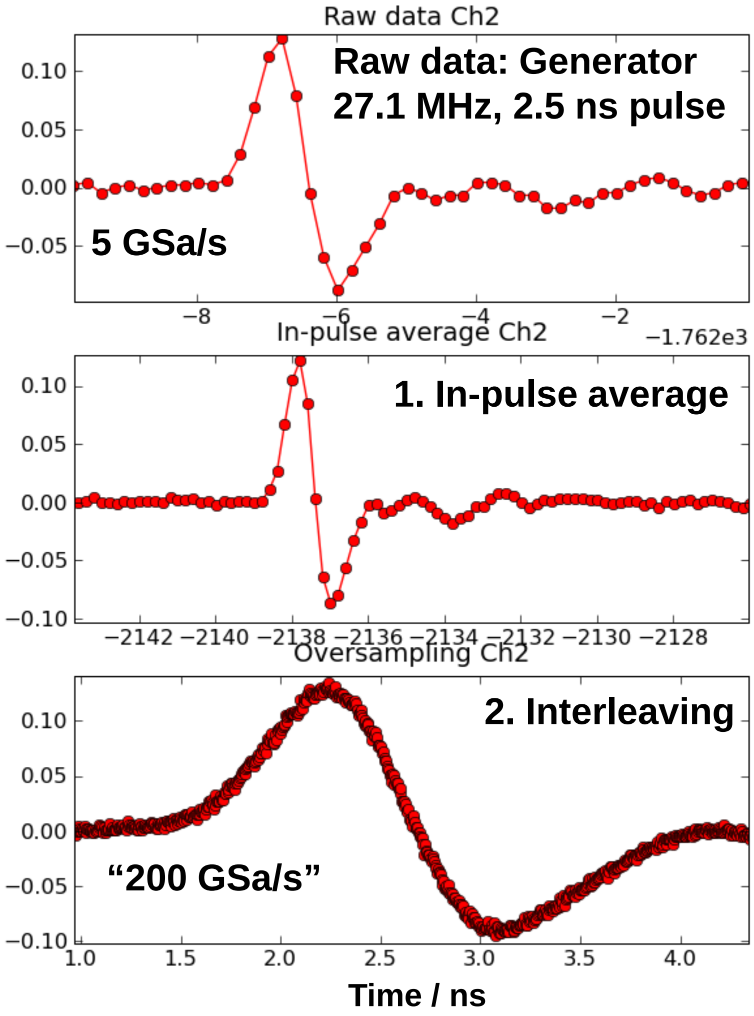
1. **In-pulse average to improve signal quality**:
   Mean of e.g. 6 blocks of 41 RF periods (~378 ns).
   Every 41 periods, RF signal and sampling frequency are in phase (apart from a small offset); length of block is determined by RF period and sampling interval.

2. **Interleaving to improve time resolution**:
   Map 41 consecutive RF periods into a single RF period.
   If the signal shape is assumed to be the constant, data for each of the 41 periods may be regarded as a single measurement of the same quantity (where the DAQ start is slightly shifted with respect to other data sets).

3. **Optional: smoothing of signal shape**:
   Apply filter running average or FFT, subtract background

4. **Cross correlation:** Calculation of time offset between signals, i.e. time-of-flight TOF via maximum position

5. **Energy calculation:** Calculation for given drift spaces, bunch numbers between phase probes and TOF times



Raw data: Generator 27.1 MHz, 2.5 ns pulse

5 GSa/s

1. In-pulse average

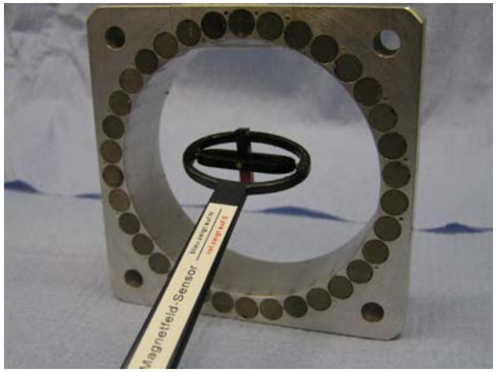
2. Interleaving

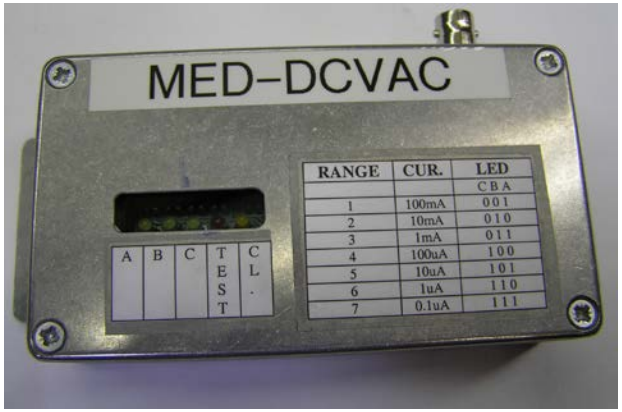
“200 GSa/s”

Faraday Cup

Mechanical data (with linear feedthrough)

Dimensions (L x W x H) [mm]	918 x 239 x 216
Space requirement (L x W) [mm]	1100 x 300
Diameter of Faraday cup [mm]	50
Weight [kg]	20.9
Vacuum flange	CF150
Electron suppression	Static dipole field and HV electrode





Amplifier data

Power supply	+ 15 V DC, approx. 3 VA
Measuring range 1	100 mA full scale
Measuring range 2	10 mA full scale
Measuring range 3	1 mA full scale
Measuring range 4	100 µA full scale
Measuring range 5	10 µA full scale
Measuring range 6	1 µA full scale
Measuring range 7	100 nA full scale
Signal output	Current loop 20 mA full scale
Signal amplitude error	≤ 1 % of full scale
Signal resolution	≤ 2 nA pp over 1 ms pulse length in measuring range 1 µA; ≤ 1% of full scale in other ranges
Threshold time, low level control	≤ 2 µs
Threshold time, full modulation	≤ 4 µs
Test current	50 ± 7 nA

Now, we also use a commercial transimpedance amplifier, type Femto DHPCA-100

AC Current Transformer

Amplifier data

Power supply	± 15 V DC, approx. 3 VA
Measuring range 1	10 mA full scale
Measuring range 2	1 mA full scale
Measuring range 3	100 µA full scale
Measuring range 4	10 µA full scale
Signal output	Current loop 20 mA full scale
Specified load resistance	50 Ω / 0.1 % tolerance for 1V full scale
Signal amplitude error	≤ 0.5 % of full scale
Signal resolution	≤ 500 nA pp over 1 ms pulse length in measuring range 10 µA; ≤ 1% of full scale in other ranges
Rise time 10 – 90%, full output	< 0.5 µs in measuring range 1 and 2 < 1 µs in measuring range 3 and 4
Test current	80 µA ± 100 nA

Type of remote control	Static, CMOS level, common return line
Inputs	Measuring range, clamping pulse, test active
Outputs	Analog current output, cable OK
Type of control cable	0.14 mm², twisted pair, flame retardant
Max. length of control cable	100 m

Mechanical data

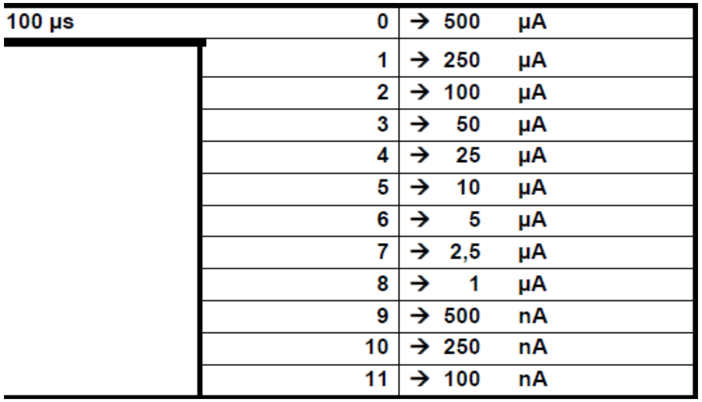
Vacuum flanges	2 x DN100CF, metal sealing
Aperture diameter	77 mm
Installation length	58 mm
Beam tube interruption / inner vacuum seal	O-Ring of NBR elastomer
Housing	Ferritic stainless steel, rust-free, soft magnetic
Vacuum leak rate	≤ 1 * 10^{-9} mbar * l/s
Dimensions (H*W*D)	190 * 205 * 65 mm
Weight (kg)	approx. 3.25

SEM-Grid Electronics

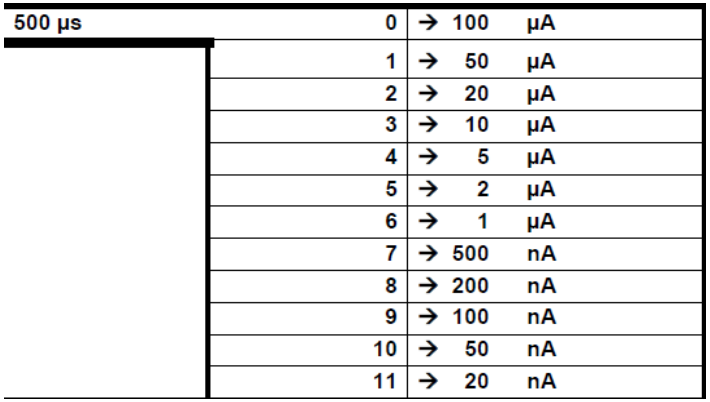
1. **Controller IBT-PGS-8**
   - Control unit for up to 8 SEM-grids
2. **Amplifier IBT-PGA-64**
   - 64-channel amplifier
   - operating principle:
     - current-to-voltage conversion
     - followed by integrator
       (100 or 500 µs at CNAO, others available)

This hardware was used for beam-line SEM-grid and emittance measurements at CNAO.

12 available ranges with sensitivity depending on integration time



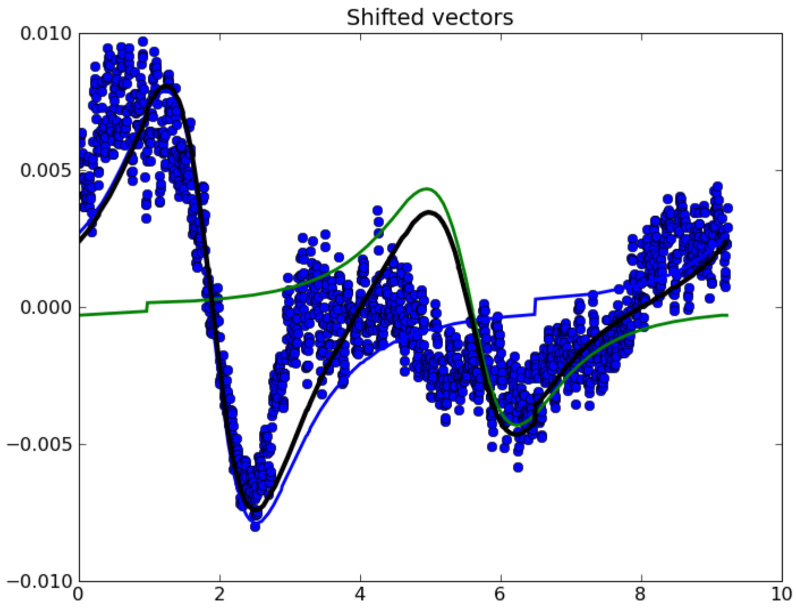
100 µs	0	→	500	µA
	1	→	250	µA
	2	→	100	µA
	3	→	50	µA
	4	→	25	µA
	5	→	10	µA
	6	→	5	µA
	7	→	2,5	µA
	8	→	1	µA
	9	→	500	nA
	10	→	250	nA
	11	→	100	nA



500 µs	0	→	100	µA
	1	→	50	µA
	2	→	20	µA
	3	→	10	µA
	4	→	5	µA
	5	→	2	µA
	6	→	1	µA
	7	→	500	nA
	8	→	200	nA
	9	→	100	nA
	10	→	50	nA
	11	→	20	nA

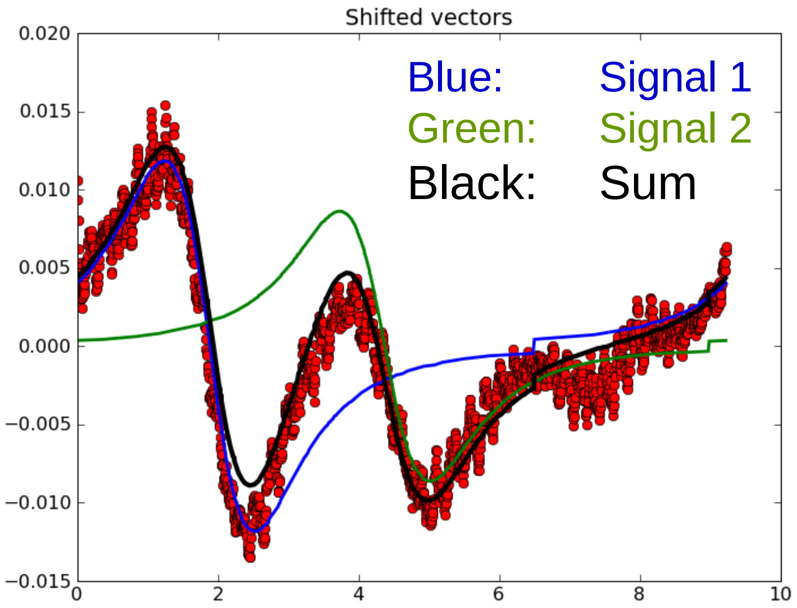
HITRAP Decelerator IH-DTL 4 MeV/u => 500 keV/u
Buncher scan after IH-DTL, beam current < 500 nA

Signal DP3



Time / ns

Signal DP4

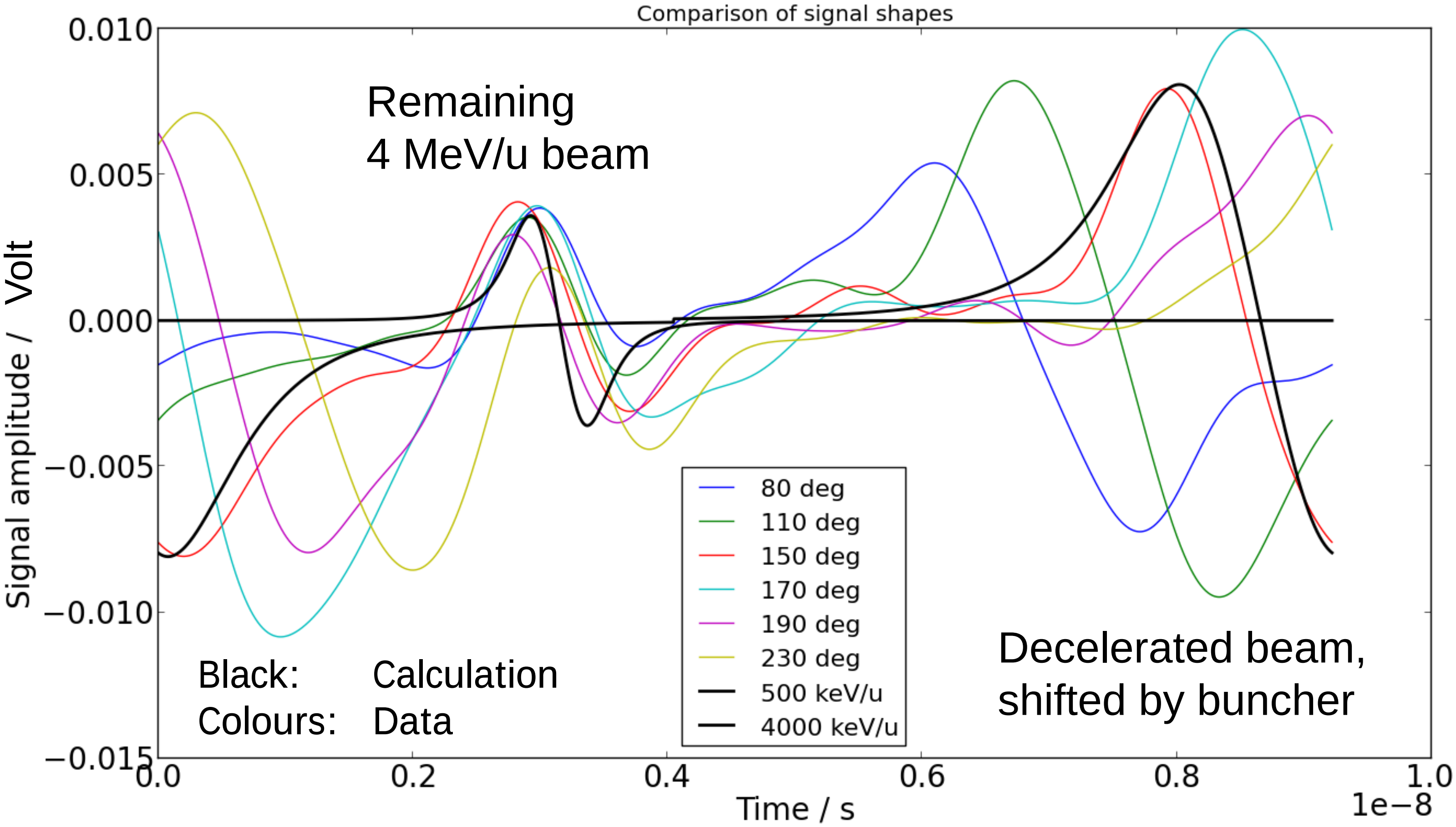


Time / ns

DP3 and DP4 pickup signals can be approximated as sum (black trace) of two phase probe signals (blue and green traces) of similar amplitude, shifted by ~2.5 ns.

The suspected double-bunch was generated by a fault (changed Q-value) in the second buncher. The time structure was confirmed by LORASR simulations.

HITRAP Decelerator IH-DTL 4 MeV/u => 500 keV/u
Buncher scan after IH-DTL, beam current < 500 nA



Remaining
4 MeV/u beam

Black: Calculation
Colours: Data

Decelerated beam,
shifted by buncher

Pickup signals were recorded during a scan of the buncher phase.
A fraction of the main beam passes through the decelerator and is not affected by the buncher.
The decelerated 500 keV/u component is shifted.

HITRAP Decelerator IH-DTL 4 MeV/u => 500 keV/u
Comparison of Energy Shift to Energy Analyzer

Observed time shifts of pickup signals were transformed into energy shifts.

Comparison to data of Energy Analyzer (EA), i.e. a dipole spectrometer with MCP imaging system, was very good.

Note: Energy axis inverted