Beam energy measurement on the SPIRAL2 accelerator

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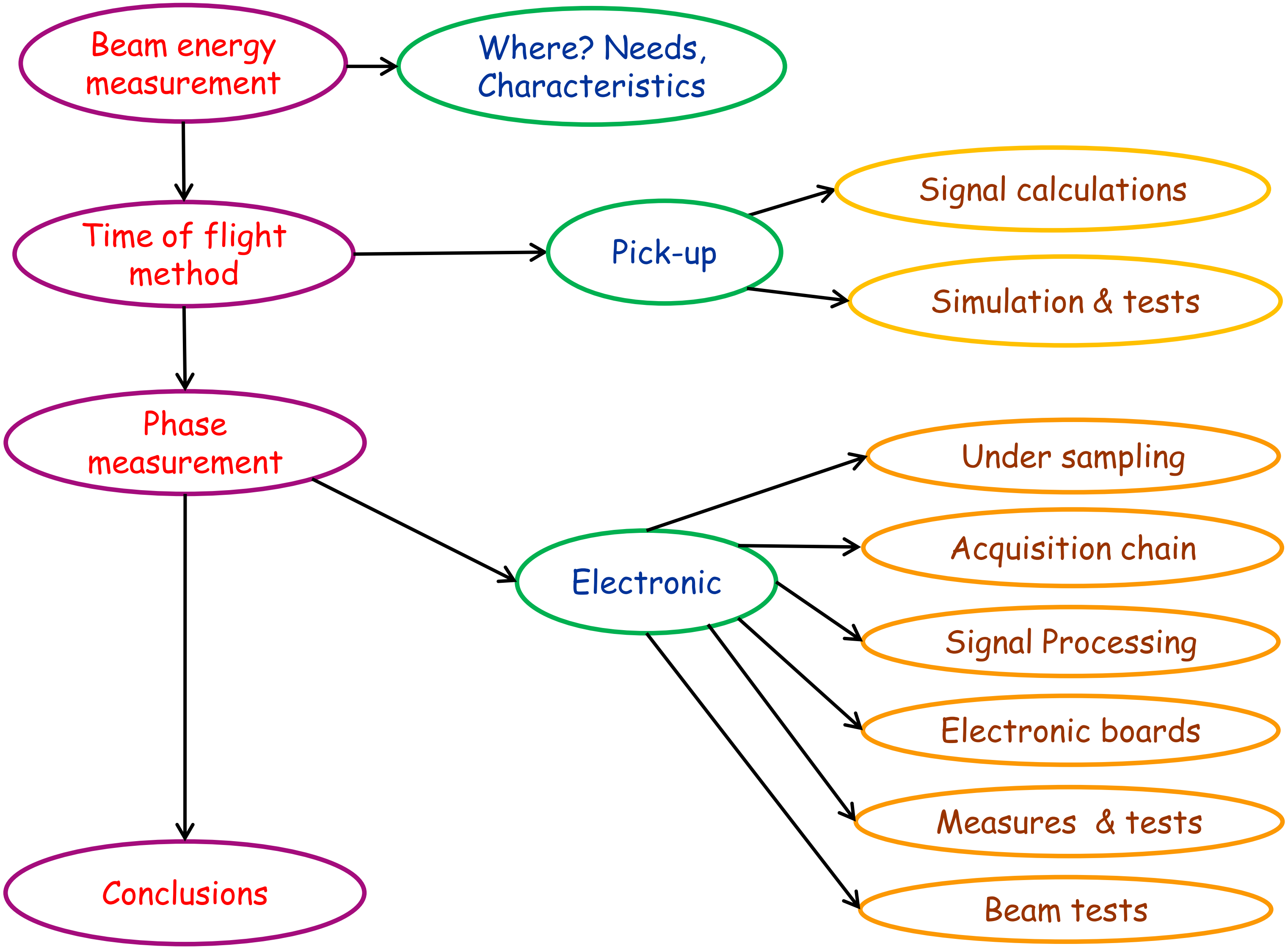
SPIRAL: Linearly Accelerated Radioactive Ion Production System

Outline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Where? Needs, Characteristics
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Pick-up
Signal calculations
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Phase measurement
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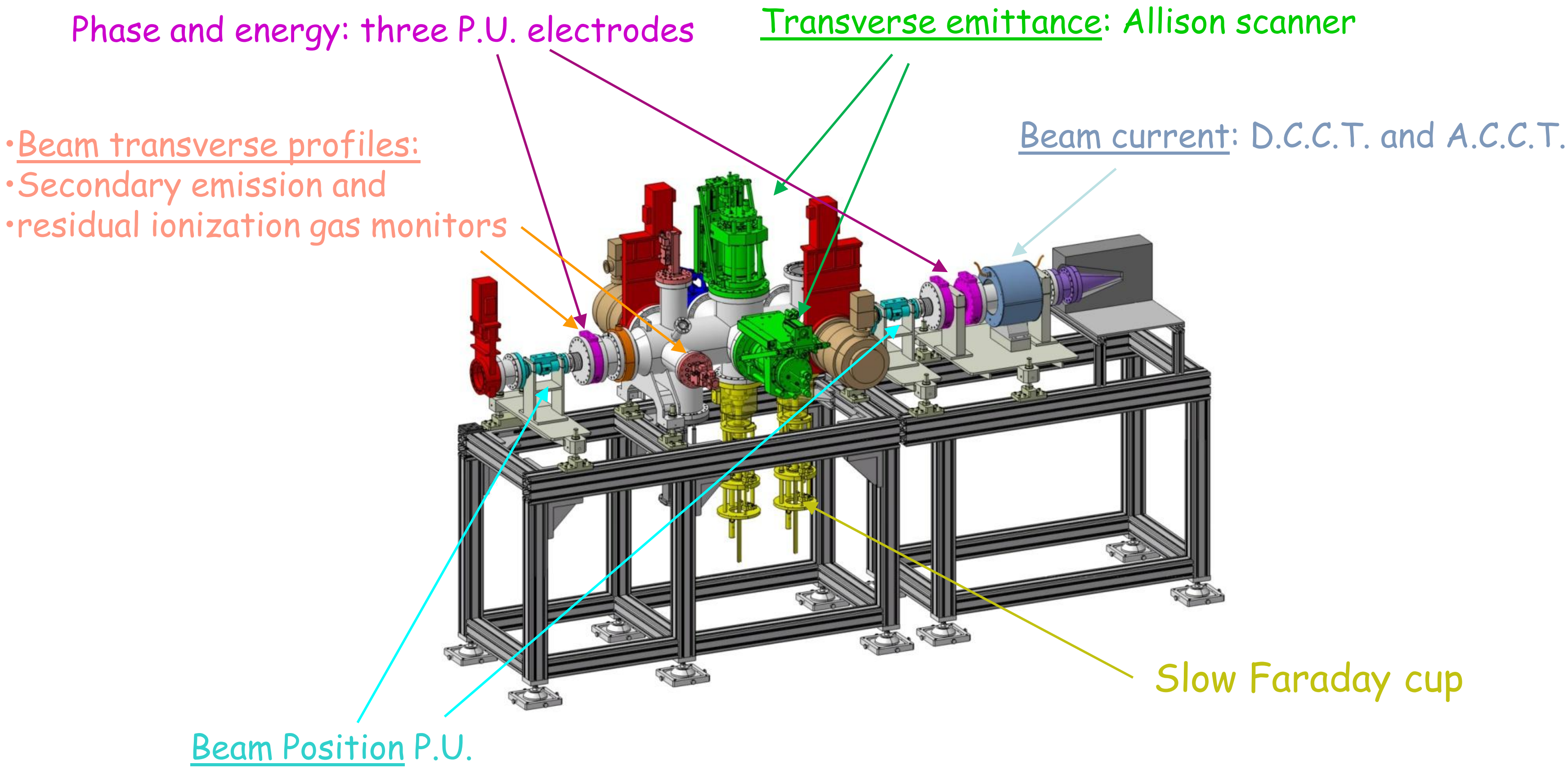
Under sampling
Acquisition chain
Signal Processing
Electronic boards
Measures & tests
Beam tests
Conclusions

MEBT beam energy measurement

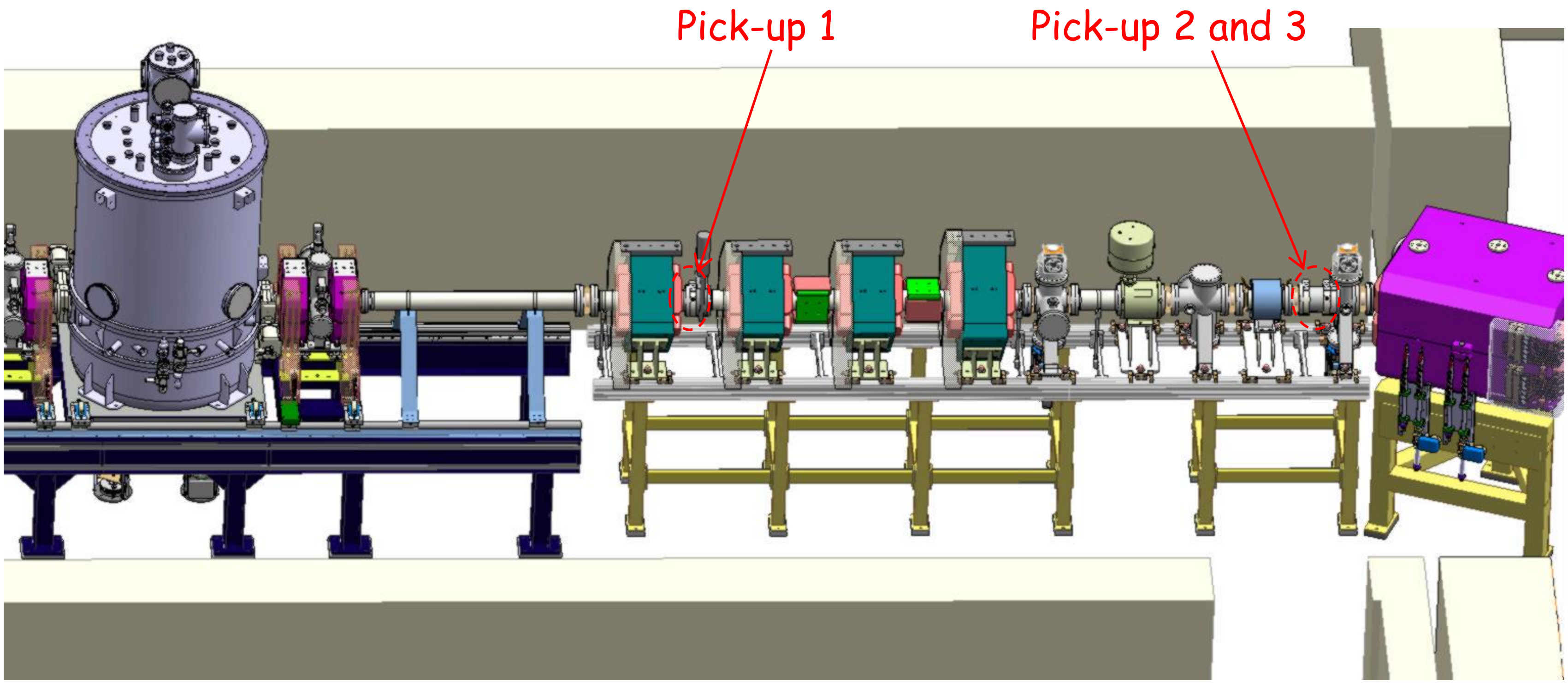
Two beam energy measurements are planned on the SPIRAL2 accelerator.
The first device will be installed on the Intermediate Test Bench (ITB) downstream the RFQ and the re-buncher 1.
The ITB will be used to qualify the beam at the exit of the RFQ (*).



* See the Ditanet presentation of P. Ausset on the SPIRAL 2 accelerator diagnostics , the 26th September 2011

HEBT beam energy measurement

A second measure of energy by time of flight will be done at the exit of the linac in the HEBT line.



The length between Pick-up1 and 2 is around 3,9 m.

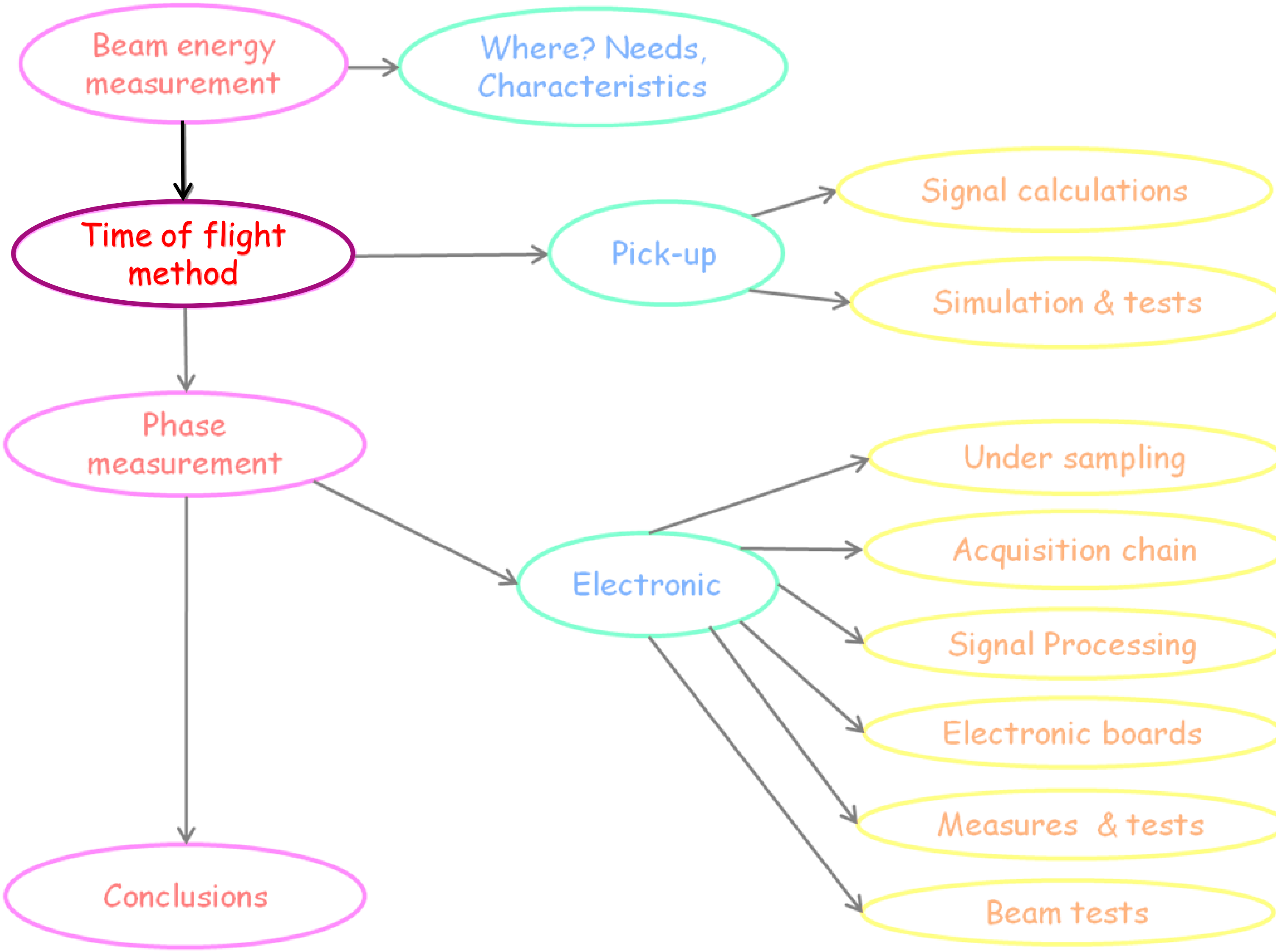
MEBT and HEBT Beam characteristics

The SPIRAL2 accelerator is designed to accelerate ions (q/A=1/3), deuterons and protons.

	MEBT	HEBT
Energy E (MeV/A)	0,75	2 to 20 *
Velocity β=v/c	0,04	0,065 to 0,2
Frequency Facc(MHz)	88,05	88,05
Period (ns)	11,35	11,35
Length Lacc (cm)	13,6	22 to 68
Length L12 (m)	1,5	3,9
Bunch Number	11	5 to 17
Pick-up diameter (mm)	80	120

* HEBT energy: min: 2MeV (proton) max: 20 MeV/A (deuteron)

Time of Flight method

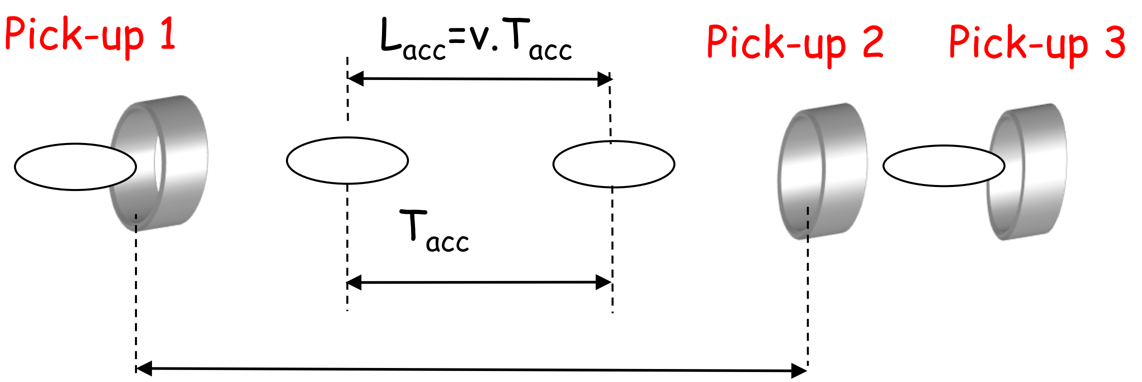


Time of Flight method

The Time of Flight Method consists in measuring the time difference between signals produce by bunches on two pick-ups. If the length between pick-ups is well known, the velocity is given by:

$$V = \frac{Lenght}{Time}$$

The Time can be calculated from the pick-up phase. $t = Tacc * \frac{\varphi}{360}$



$$T_{12} = N.T_{acc} + \delta t_{12} = T_{acc}\,(N + \delta\varphi_{12}/360)$$

$$T_{12} = T_{acc}\,(N + \frac{\delta\varphi_{12}}{360})$$

But we have to take account the number of bunches included between the first two pick-ups. The third pick-up is used to determine this number N of bunches.

Energy calculation with Phase measurements

The distance between the pick-up 2 and 3 is chosen to have :

$$L_{23} < L_{acc} \qquad \frac{\varphi_{23}}{360} = \frac{L_{23}}{L_{acc}} \qquad L_{acc} = L_{23} * \frac{360}{\varphi_{23}}$$

Steps to calculate the beam energy:

1 Number of bunches

$$N = \text{integer}\left(\frac{L_{12}}{L_{acc}}\right) = \text{integer}\left(\frac{L_{12}}{L_{23}} . \frac{360}{\varphi_{23}}\right)$$

2 Time between Pick-up 1 and 2

$$T_{12} = T_{acc}\,(N + \frac{\delta\varphi_{12}}{360})$$

3 Velocity

$$v = \frac{L_{12}}{T_{12}} = \frac{L_{12}}{T_{acc}(N + \frac{\varphi_{12}}{360})} = 360 . \frac{L_{12}}{360 . N + \varphi_{12}} . F_{acc}$$

4 Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

5 Beam Energy per nucleon

$$\left(\frac{E}{A}\right)_{MeV} = \frac{ion\_masse}{A} Em_u(\gamma - 1)$$

[2] Lecture Notes on Beam Instrumentation and Diagnostics - Peter Fork (GSI) – JUAS 01-03-2006
[3] Beam Instrumentation and Diagnostics – Peter Strehl – Editeur Springer Berlin 2006

Accuracy

The accuracy is given by the formula:

$$E \approx \frac{1}{2}mv^2 = \frac{1}{2}m(\frac{L}{T})^2 \qquad \left|\frac{\Delta E}{E}\right| = 2\sqrt{(\frac{\Delta L}{L})^2 + (\frac{\Delta T}{T})^2} = 2\sqrt{(\frac{\Delta L}{L})^2 + (\frac{\Delta(\delta\varphi)}{360N + \Delta(\delta\varphi)})^2}$$

For SPIRAL2, the required accuracy of the energy is 0,2 percent.

$$\sqrt{(\frac{\Delta L}{L})^2 + (\frac{\Delta(\delta\varphi)}{360N + \Delta(\delta\varphi)})^2} = \frac{1}{1000}$$

$$(\frac{\Delta L}{L})^2 + (\frac{\Delta(\delta\varphi)}{360N + \Delta(\delta\varphi)})^2 = 10^{-6}$$

ITB accuracy

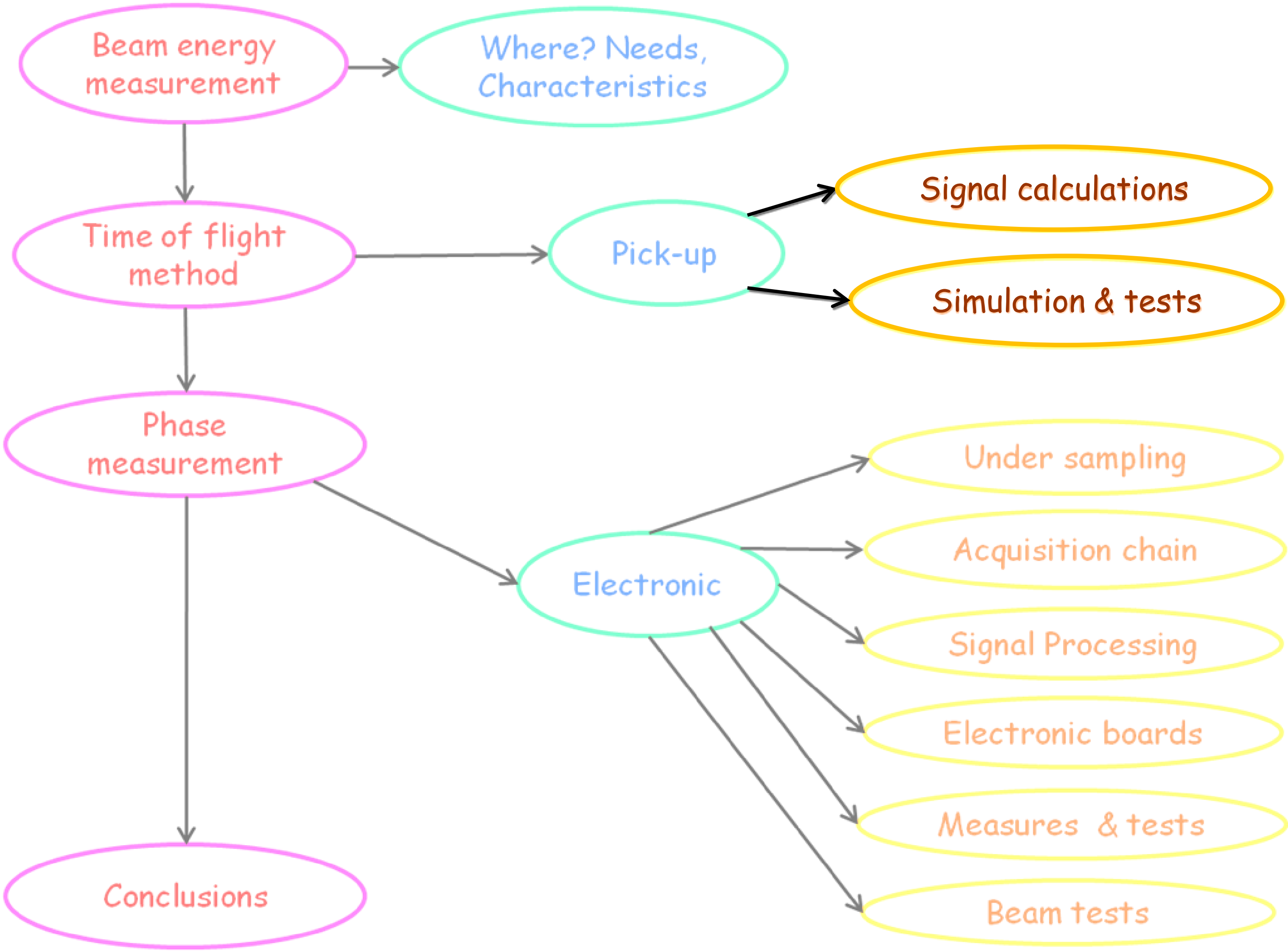
$$L = 1{,}5m \qquad (\frac{\Delta L}{L})^2 = 0{,}5.10^{-6} \qquad \Delta L \approx 1mm$$

$$(\frac{\Delta(\delta\varphi)}{360N + \Delta(\delta\varphi)})^2 = 0{,}5.10^{-6} \qquad \Delta(\delta\varphi) \approx \sqrt{0{,}5.10^{-6}}.360.N$$

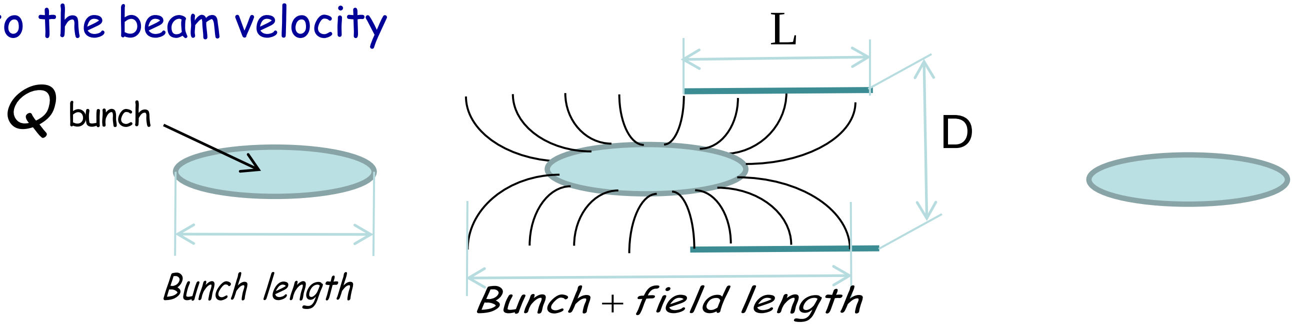
$$N \approx \frac{1{,}5}{13{,}6.10^{-2}} \approx 11 \qquad \Delta(\delta\varphi) \approx \sqrt{0{,}5.10^{-6}}.360.11 = 2{,}8^\circ$$

For the ITB, the distance has to be known with an accuracy better than 1 mm and a phase better than 2,8°.

Calculations, simulation & tests



Electromagnetic effect on the pick-up signal due to beam pipe diameter and to the beam velocity



Beam intensity

$$Ib(t) = \frac{Q_{bunch}.e^{\frac{-t^2}{2\sigma t^2}}}{\sigma_t\sqrt{2\pi}} \qquad \sigma t_{total} = \sqrt{\sigma t_{bunch}^{\;2} + \sigma t_{field}^{\;2}}$$

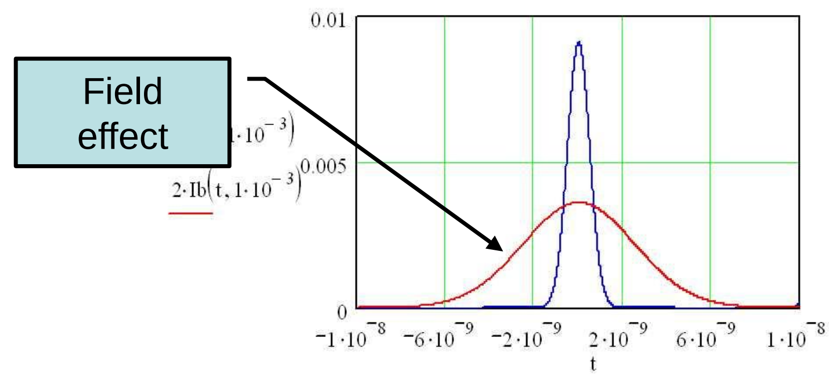
$$\sigma t_{\;field} = \frac{D}{2\sqrt{2}.\gamma.\beta.c}$$

On the ITB:

$$\sigma t_{\;bunch} = 0{,}5\;.10^{-9}\,s$$

$$D = 84mm \qquad \sigma t_{\;field} = 2{,}5\;.10^{-9}\,s$$

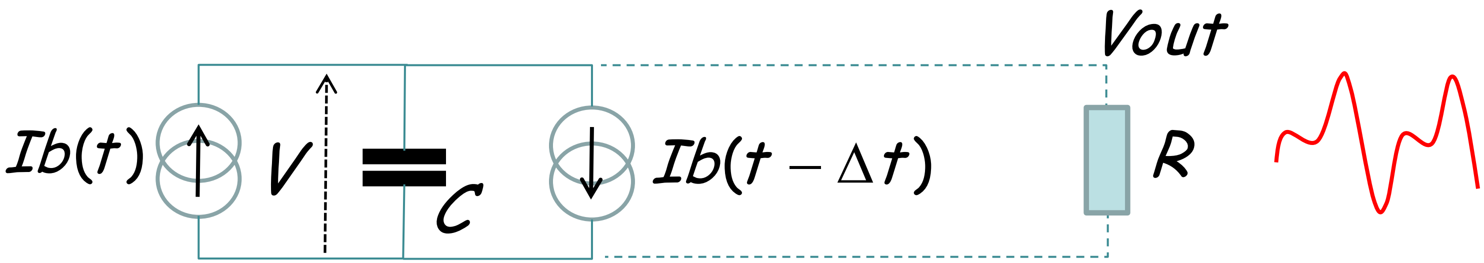
Simulation for 1emA beam



Pick-up Signals

The beam effect on the electrode can be described by two current sources, one for the beam entering and one for the beam leaving the electrode separated by a delay $\Delta t = L/v$

This gives the following electric equivalent scheme:



The expression of the voltage across the load R is:

$$Vout(t) = \frac{e^{\frac{-t}{RC}}}{C}\int_0^t [Ib(x) - Ib(x - \frac{L}{v})].e^{\frac{x}{RC}}\,dx$$

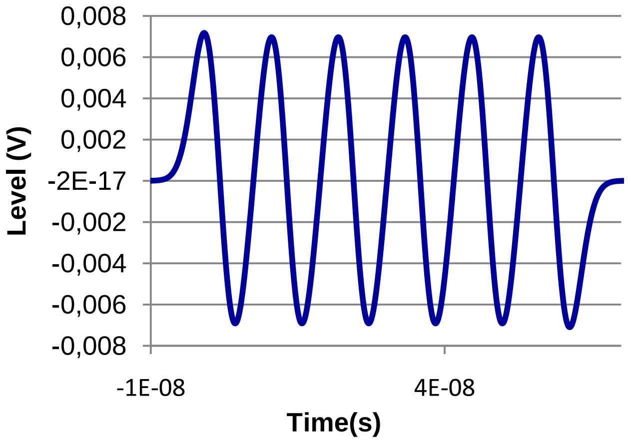
On the ITB:

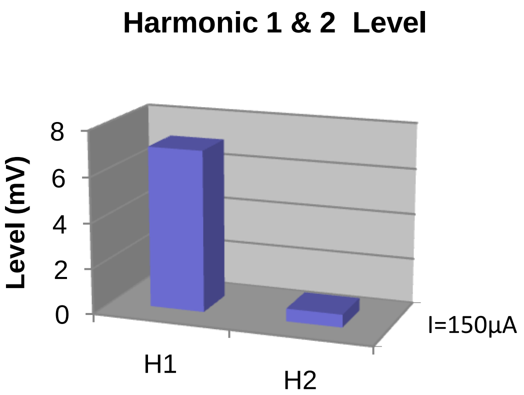
C ~ 8,8 pF RC ~ 0,44 10^{-9}s

[1] Beam Instrumentation, J.Bosser, CERN-PE-ED001-92 Revised nov.1994

Pick-up signal simulation with Ibeam=150µA

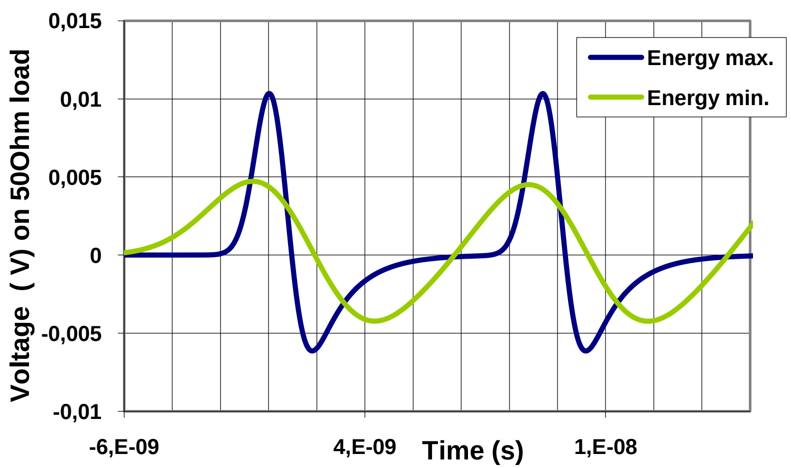
in MEBT Ø80mm

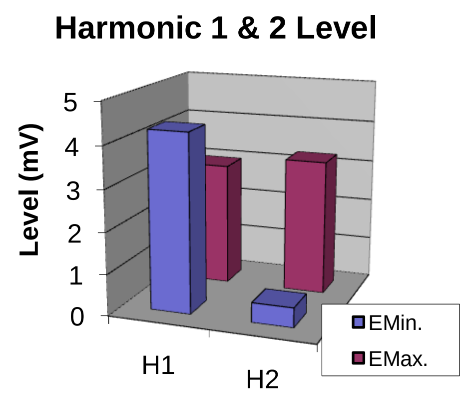




In MEBT, only H1 detection can be used.

in HEBT Ø120mm





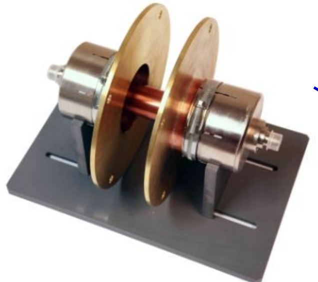
In HEBT, H1 or H2 detection can be used. To cover the whole Spiral2 energy range, H1 detection is the most suitable.

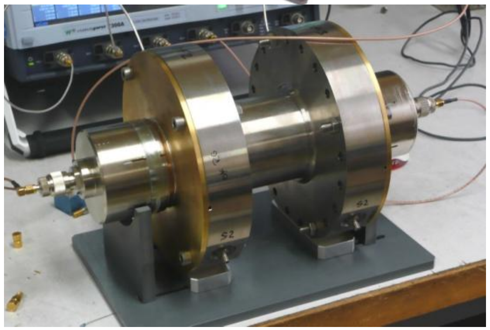
Pick-up: Simulations and Tests

Pick-up 1

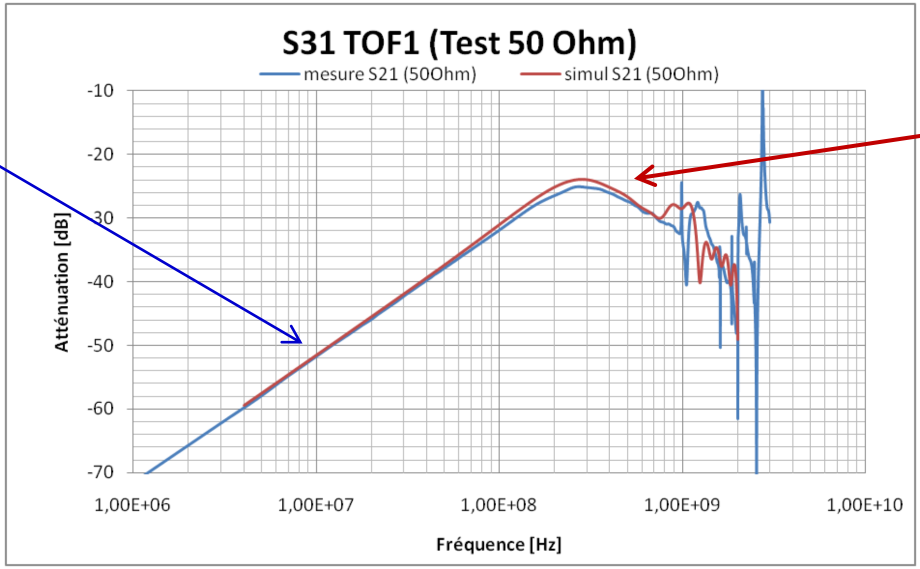
Pick-up 2 and 3

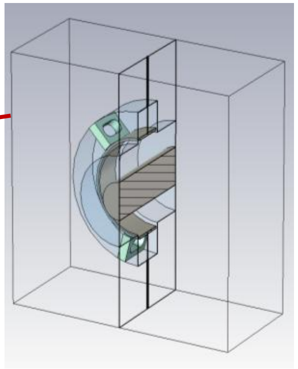
Test Bench





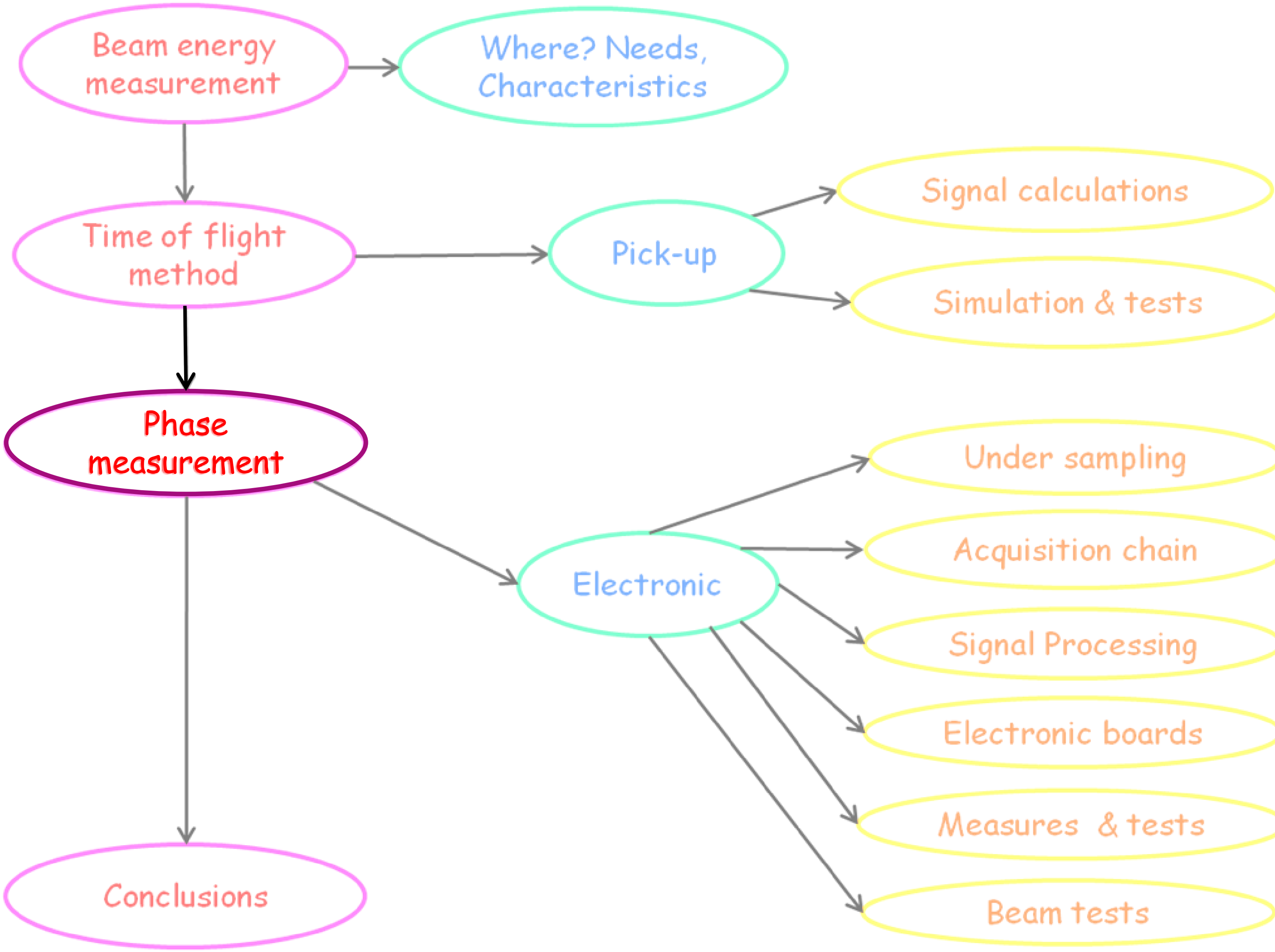
Simulation with CST µwaves Studio





The test bench is a coaxial line witch allows to send a RF signal in the middle of the pick-ups. The simulated curve (in red) is very close to the measured curve (in blue).

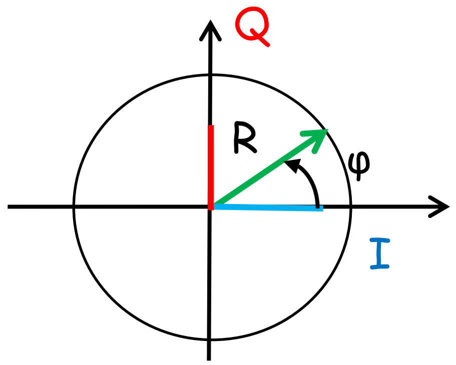
Phase measurement



Phase measurement

The phase measurement of a pick-up signal consists in measuring the phase of one signal harmonic and a reference. In our case, the harmonic 1 or 2 will be used to measure the phase.

Sinusoidal RF signal



$$r(t) = R\sin(\omega t + \varphi)$$

$$r(t) = \underbrace{R\cos(\varphi)}_{I}\sin(\omega t) + \underbrace{R\sin(\varphi)}_{Q}\cos(\omega t)$$

I : In phase component

Q : Quadrature phase component

$$I = R\cos(\varphi) \qquad Q = R\sin(\varphi)$$

$$r(t) = I\sin(\omega t) + Q\cos(\omega t) \qquad R = \sqrt{I^2 + Q^2} \qquad \varphi = \mathrm{atang}\left(\frac{Q}{I}\right)$$

Periodical signal = sum of harmonics

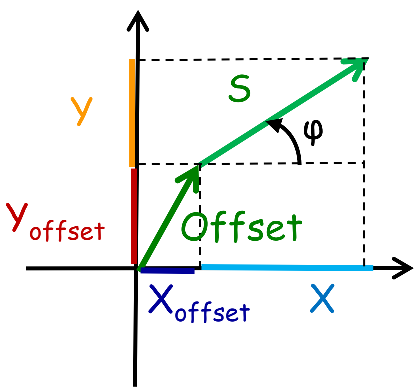
$$s(t) = \sum_{n=0}^{\infty} S_n \sin(n.\omega t + \varphi_n)$$

n: harmonic number

$$s(t) = \sum_{n=0}^{\infty}\left[I_n \sin(n.\omega t) + Q_n \cos(n.\omega t)\right] \qquad S_n = \sqrt{I_n^2 + Q_n^2} \qquad \varphi_n = \mathrm{atang}\left(\frac{Q_n}{I_n}\right)$$

Phase offset and noise

Phase measurements can be disturbed or limited by an offset and a noise.
An offset is a disturbance which is superposed on the signal to be measured.



Solution: The offset deduction is made by measuring X and Y with and without the beam.

$X_{beam\_off} = X_{offset}$ $Y_{beam\_off} = Y_{offset}$

$X_{beam\_on} = X + X_{offset}$ $Y_{beam\_on} = Y + Y_{offset}$

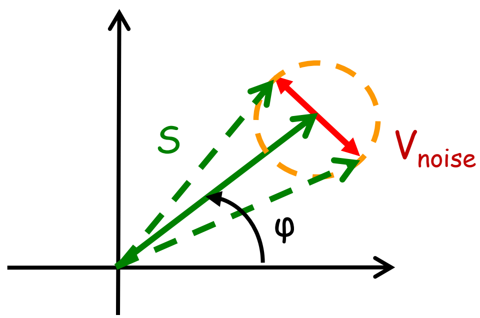
$$S = \sqrt{(X_{beam\_on} - X_{beam\_off})^2 + (Y_{beam\_on} - Y_{beam\_off})^2}$$

$$\varphi = a\tan\left(\frac{Y_{beam\_on} - Y_{beam\_off}}{X_{beam\_on} - X_{beam\_off}}\right)$$

A noise is a random signal defined by a standard deviation σ.
p(V): Amplitude Probability

$$p(V) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{V}{\sigma}\right)^2}$$

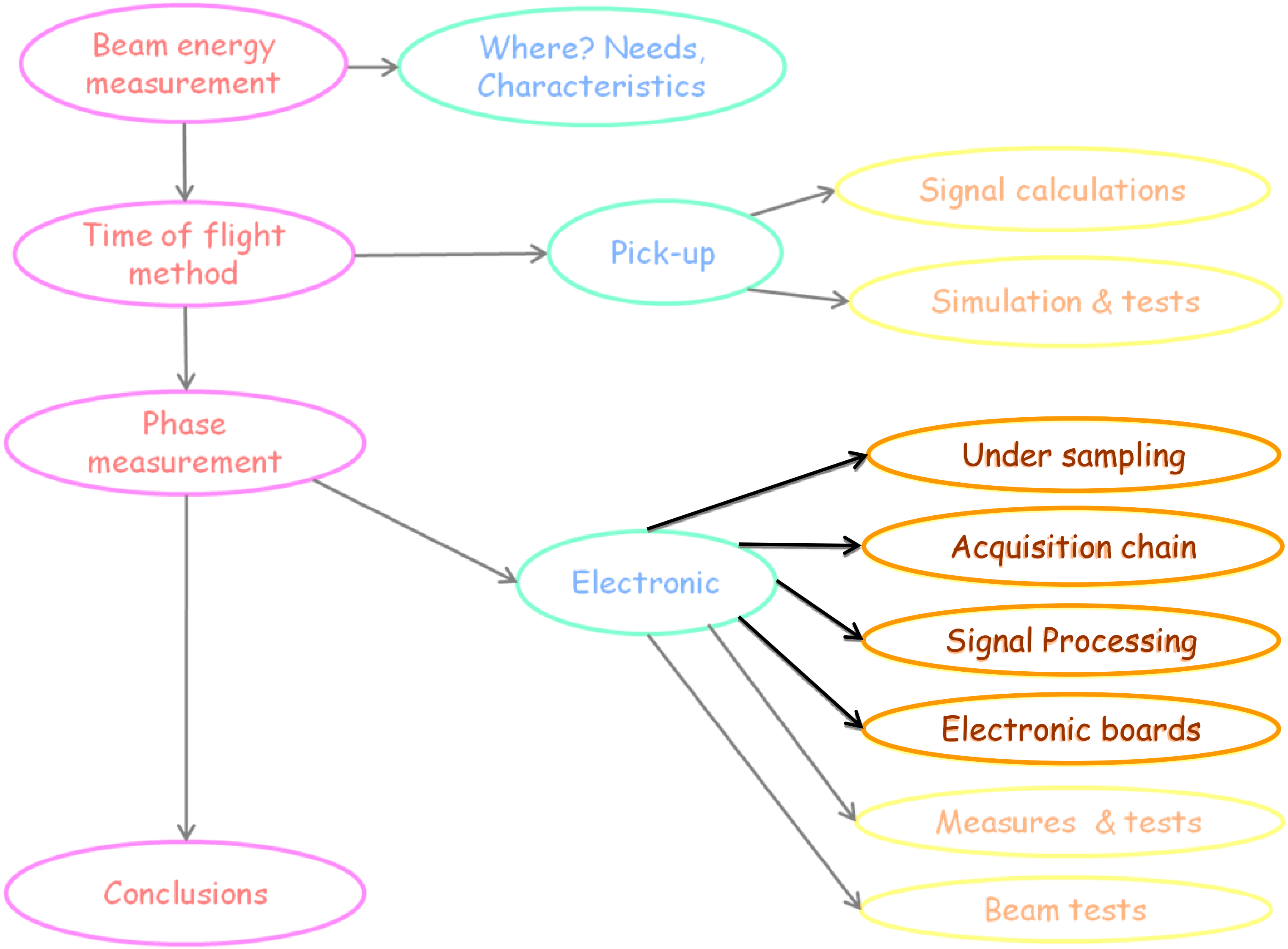
$$\varphi_{noise} \approx \frac{V_{noise}}{S}$$



Solution: Filter and/or average signals X and Y

$$\sigma_{average} = \frac{\sigma}{\sqrt{n_{average}}}$$

Electronic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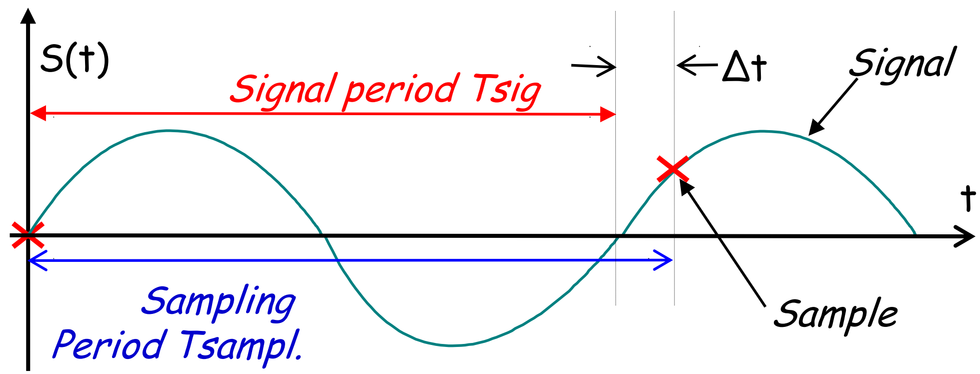
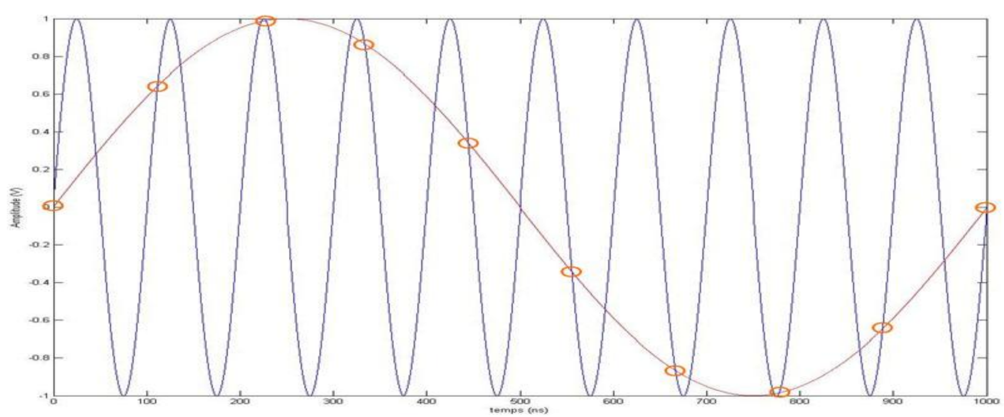
When the frequency of a periodical signal is well known, it is possible to use the undersampling technique to acquire the signal. In our case, one value per period is acquired with a slight shift in time.



Example of the signal transposed at a lower frequency



This method allows to have enough time for the data processing.

Undersampling

Undersampling in the frequency domain

$$\Delta t = T_{sampl.} - T_{sig.} \qquad \Delta f = F_{sig.} - F_{sampl.} = \frac{1}{T_{sig.}} - \frac{1}{T_{sampl.}}$$

Nb: Number of points used to reconstruct the signal

$$Nb = \frac{T_{sign.}}{\Delta t} = \frac{T_{sign.}}{T_{sampl.} - T_{sign.}} = \frac{F_{sampl.}}{F_{sign.} - F_{sampl.}} = \frac{F_{sampl.}}{\Delta F}$$

The sampling frequency is equal to: $F_{sampl.} = F_{sig.} \frac{Nb}{Nb+1}$

The equivalent frequency is: $F_{equi.} = F_{sig.} * Nb$

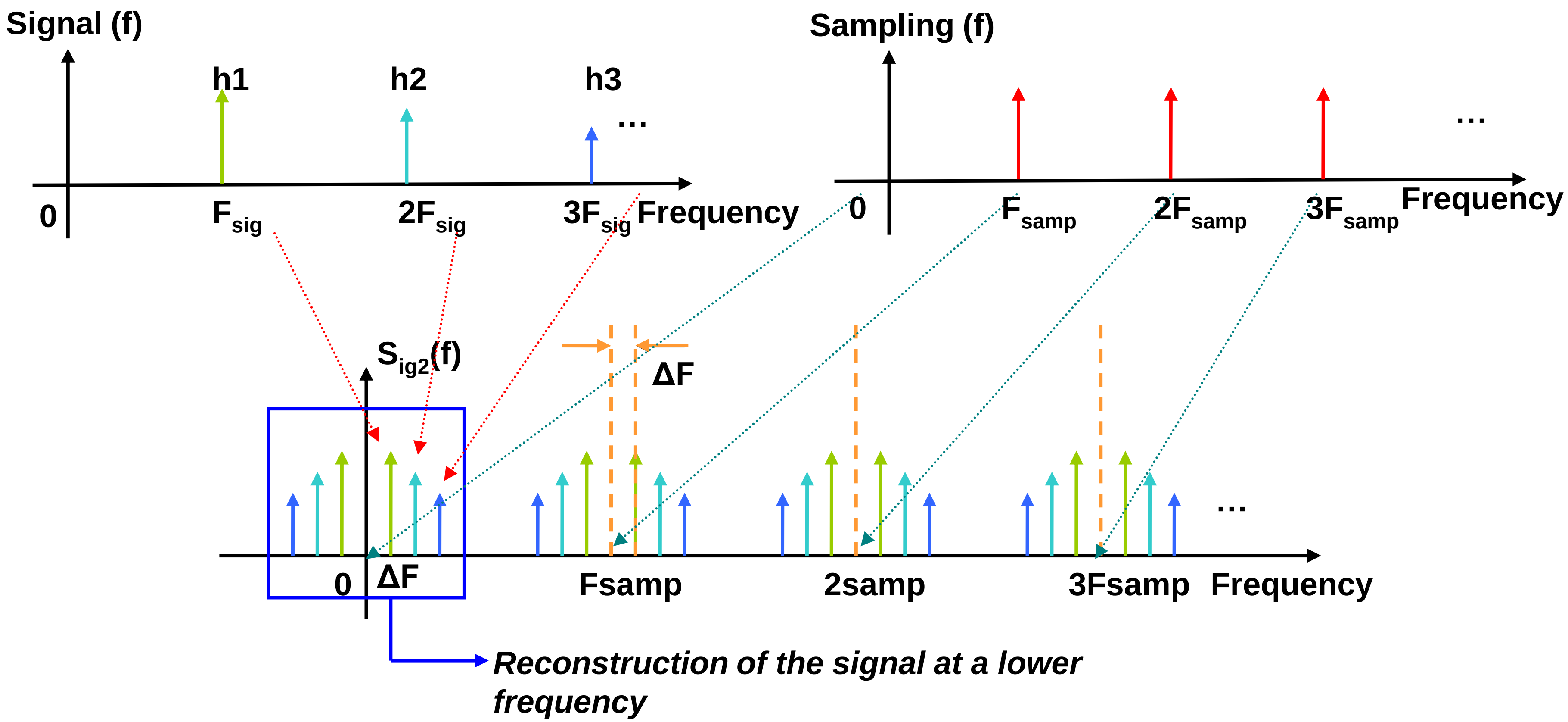
Example:

A 88 MHz signal is undersampled at a sampling frequency allowing reconstruct the signal by 256 points.

$$F_{sampl.} = F_{sig.} * \frac{256}{257} = 87{,}66 MHz$$

$$F_{equi.} = 88 * 256 = 22{,}5 GHz$$

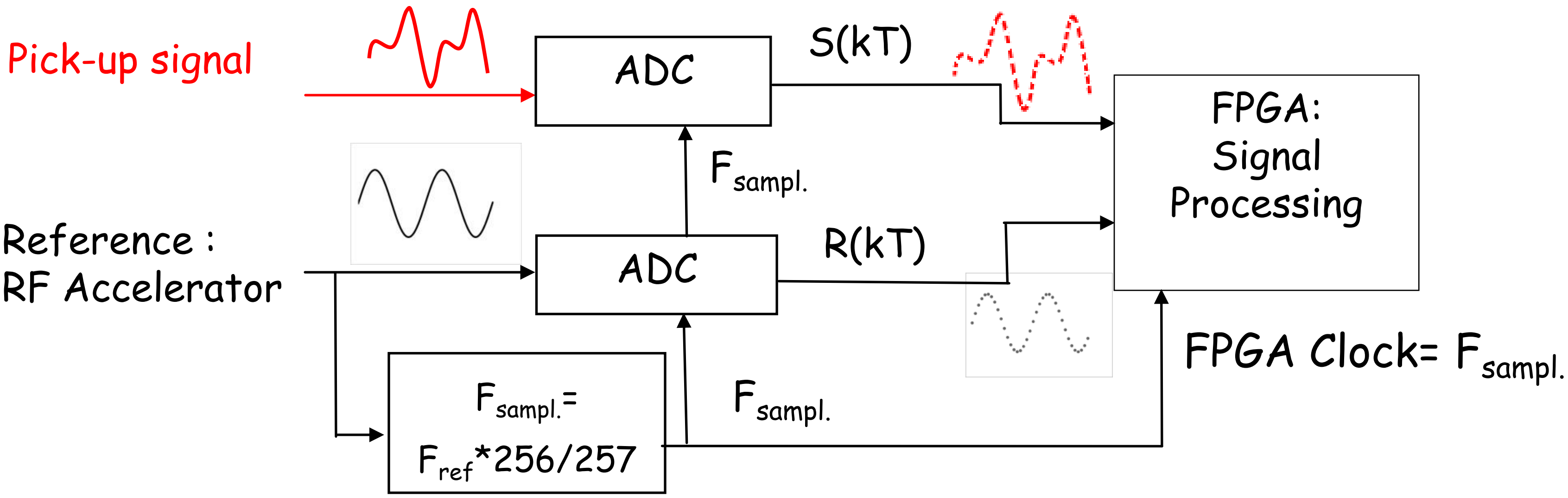
Undersampling in the frequency domain



The undersampling method allows to transpose at the lower frequencies the harmonics of the input signal.

Acquisition chain

Pick-up signals and the RF reference are sampled in the same time.



T: Sampling period $T = \frac{1}{F_{sample}}$

Fsampl. is calculated from the reference RF with a ratio which gives Nb=256 .
Nb is the number of samples necessary to reconstitute a signal period.

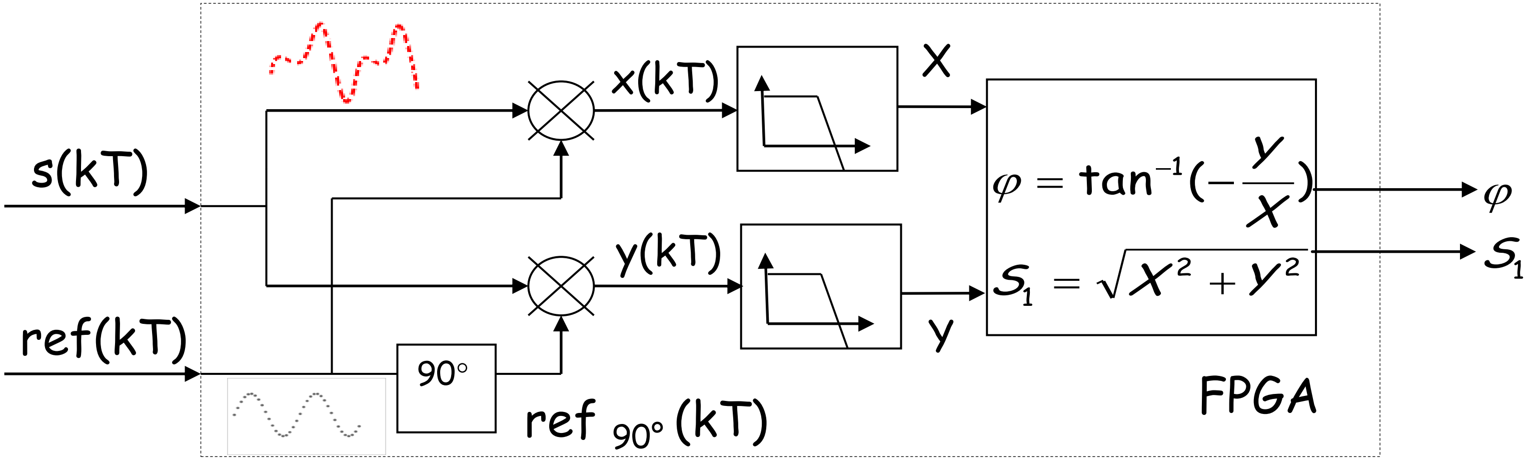
Reference RF SPIRAL2 = 88,05 MHz

$F_{sampl.}$ ~ 87,7 MHz

The sampling of signals and the reference at the same time allows not be sensitive to the sampling frequency jitter.

Signal processing

The signal processing consists in designing a lock-in amplifier function.



$$s(kT) = \sum_{n=0}^{\infty}\left[I_n \sin(n.\,\omega kT) + Q_n \cos(n.\,\omega kT)\right]$$

$$ref(kT) = R\sin(\omega kT) \qquad ref_{90^\circ}(kT) = R\sin(\omega kT + 90^\circ) = R\cos(\omega kT)$$

$$x(kT) = s(kT) * ref(kT) \qquad y(kT) = s(kT) * ref_{90^\circ}(kT)$$

The low pass filters (or average) take only the DC part of x(kT) and y(kT).

$$X = \frac{R\,I_1}{2} = \frac{R\,S_1 \cos\varphi}{2} \qquad y = \frac{R\,Q_1}{2} = \frac{R\,S_1 \sin\varphi}{2}$$

The low pass filter determines the detection bandwidth.

Signal processing

$$X = \frac{R\,I_1}{2} = \frac{R\,S_1 \cos\varphi}{2} \qquad Y = \frac{R\,Q_1}{2} = \frac{R\,S_1 \sin\varphi}{2}$$

From X and Y, we can calculate the harmonic1 modulus S_1 and the phase φ_1 .

$$I_1 = \frac{2X}{R} \qquad Q_1 = \frac{2Y}{R}$$

$$S_1 = \sqrt{I_1^2 + Q_1^2} = \sqrt{\left(\frac{2X}{R}\right)^2 + \left(\frac{2Y}{R}\right)^2}$$

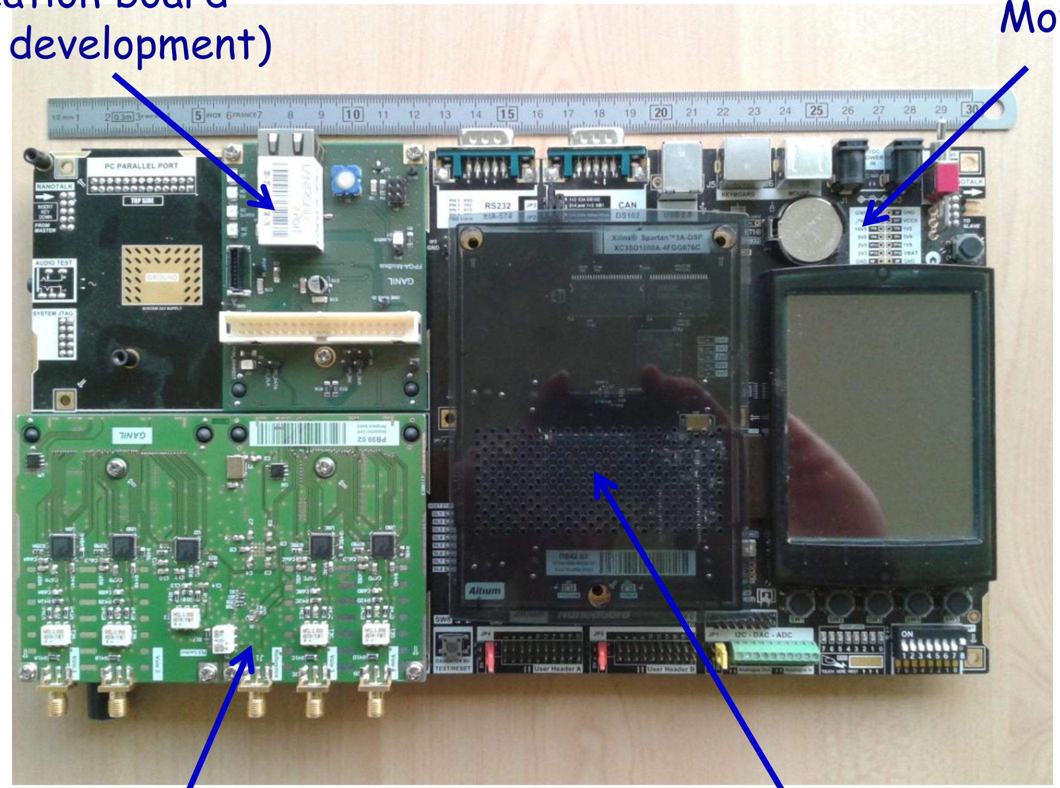
$$\varphi_1 = \mathrm{atang}\left(\frac{Q_1}{I_1}\right) = \mathrm{atang}\left(\frac{Y}{X}\right)$$

S_1: Module of the first harmonic of s(t)
φ_1: Phase of the first harmonic of s(t)

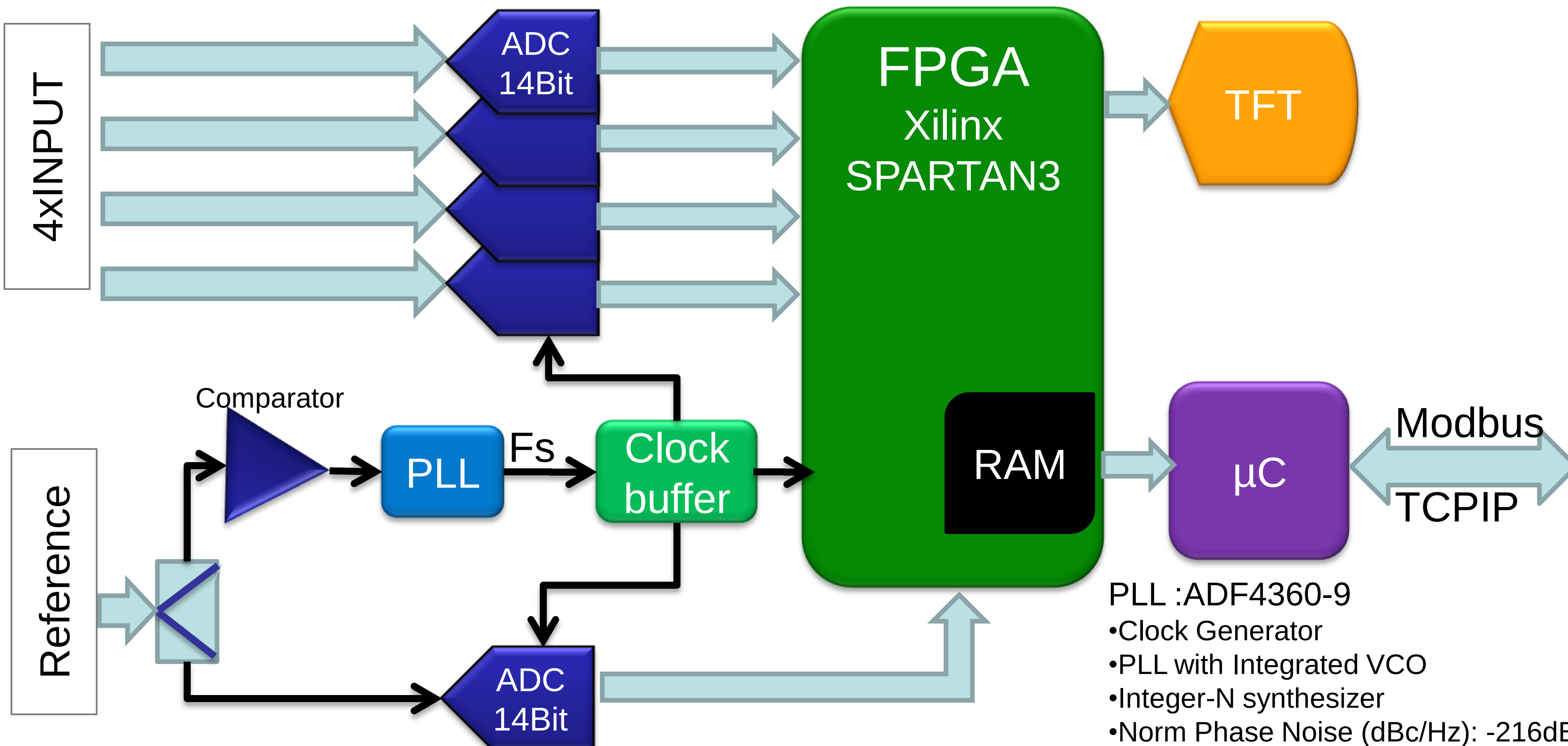
By changing the frequency of the reference (n.F), the coefficients Sn and φn can be calculated in the same way.

Electronic boards

To simplify electronic developments, a commercial board is used to carry out the signal processing. (Nanobard NB2 of the Altium Compagny). Its flexibility and its tight integration with the Altium Designer software improve and simplify the system design.



Electronic synoptic



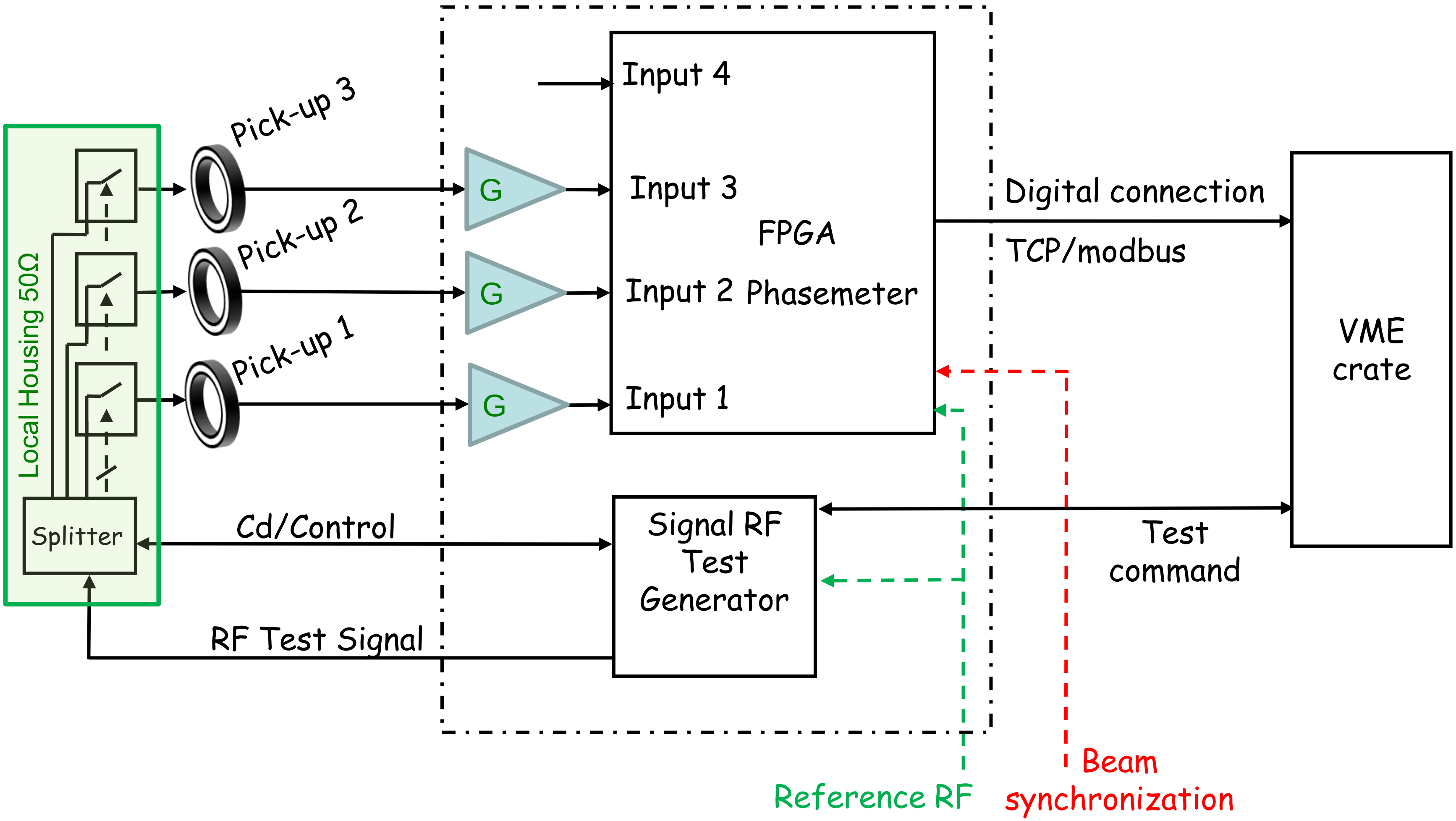
PLL :ADF4360-9
- Clock Generator
- PLL with Integrated VCO
- Integer-N synthesizer
- Norm Phase Noise (dBc/Hz): -216dBc

ADC : AD9246
- 14-Bit, 125 MSPS
- 1.8 V Analog-to-Digital Converter
- Low power: 395 mW @ 125 MSPS
- Differential input with 650 MHz bandwidth
- SNR = 71.7 dBc

Clock BUFFER: IDT5T93GL06
- 2.5V LVDS 1:6 GLITCHLESS
- Guaranteed Low Skew < 25ps (max)
- RMS Additive Phase Jitter 0.159 ps

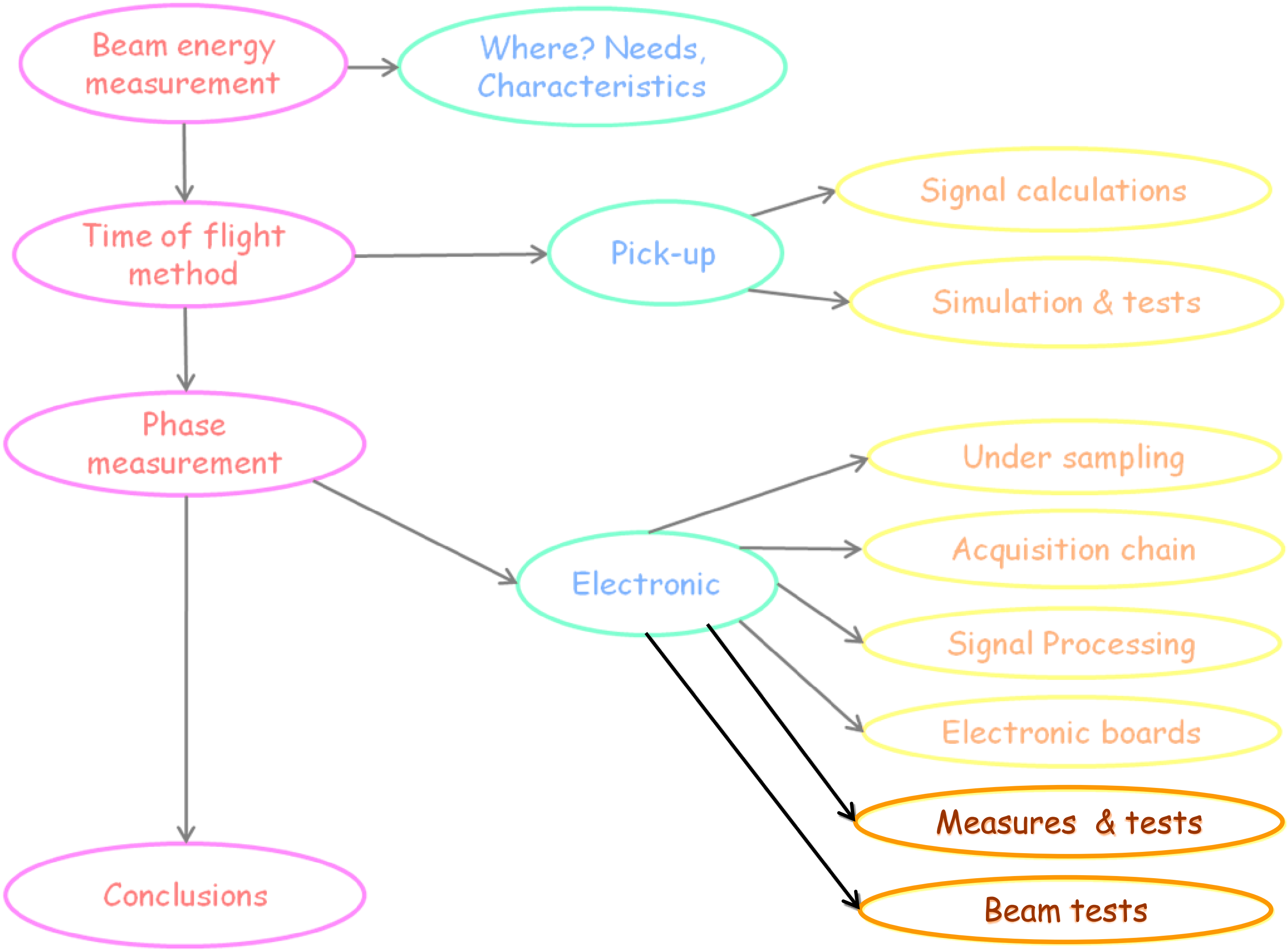
Comparators:ADCMP604
- Rail-to-Rail
- Very Fast, 2.5 V
- Propagation Delay Skew 70pS

Electronic chain



RF Amplifier: HD24503 from HD Communication Corp. G=42dB

Electronic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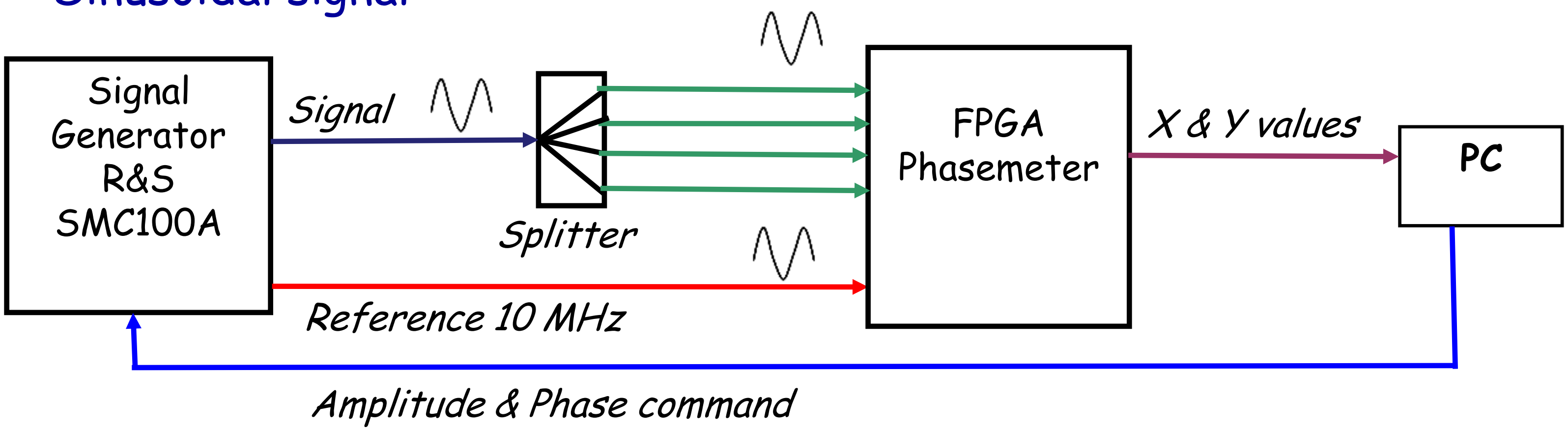
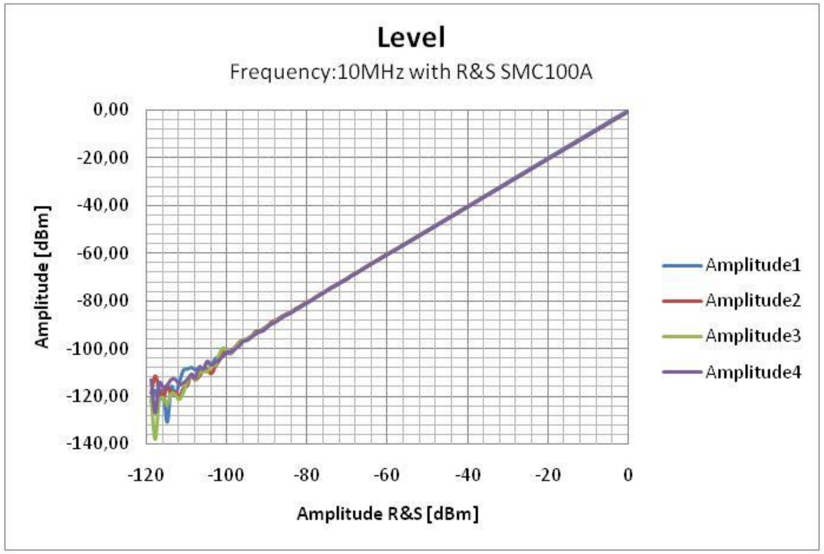
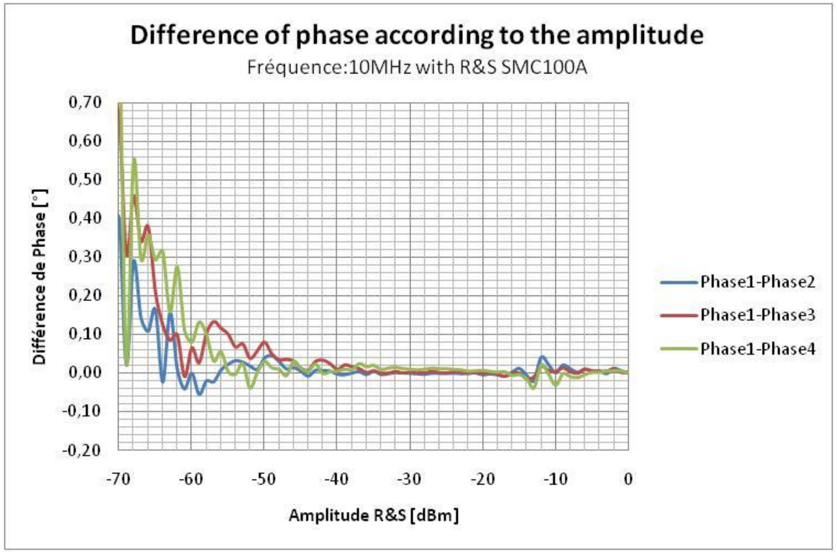
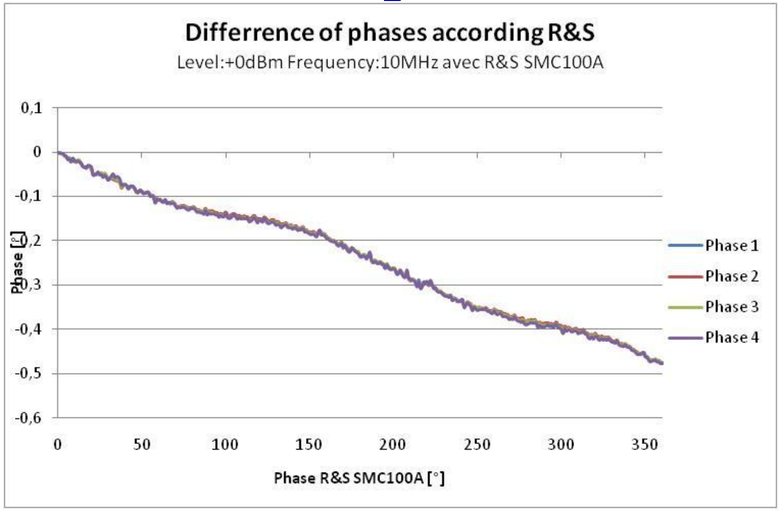
Sinusoidal signal

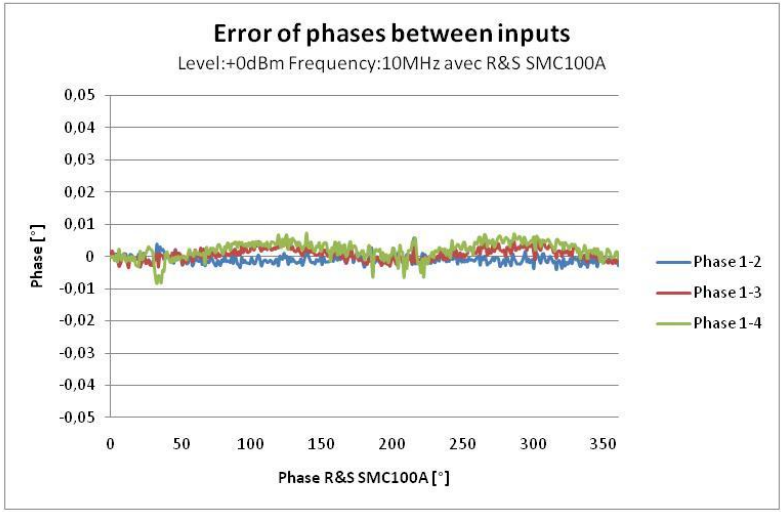


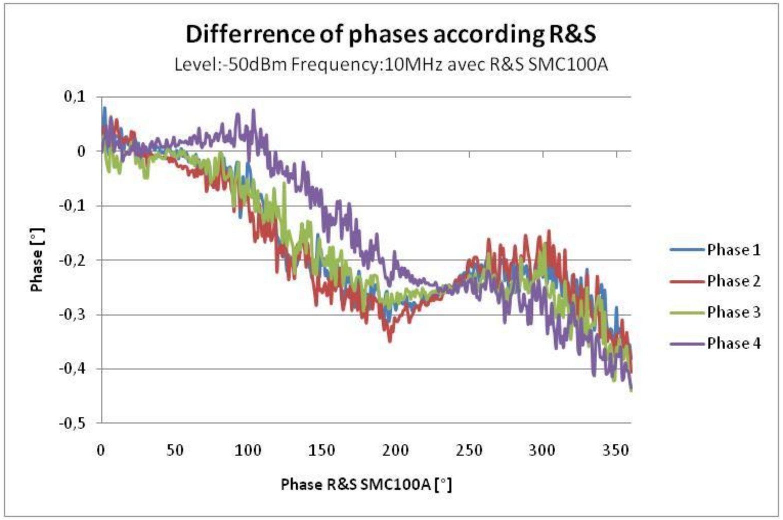


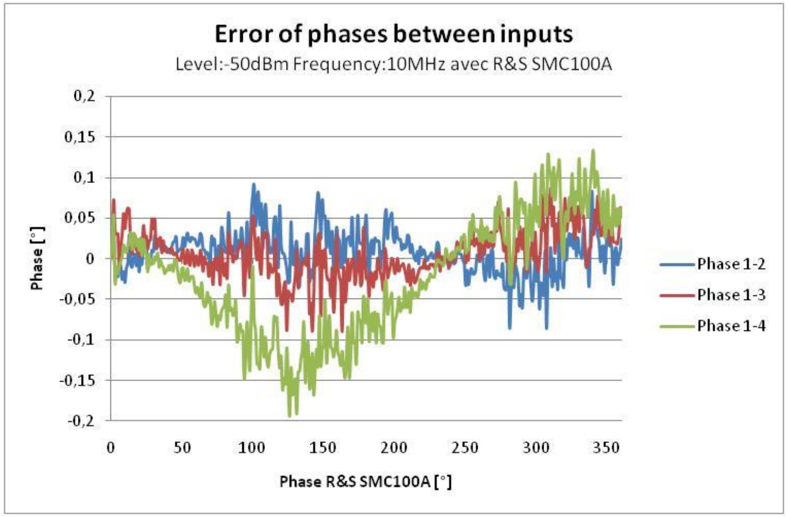


Sinusoidal signal



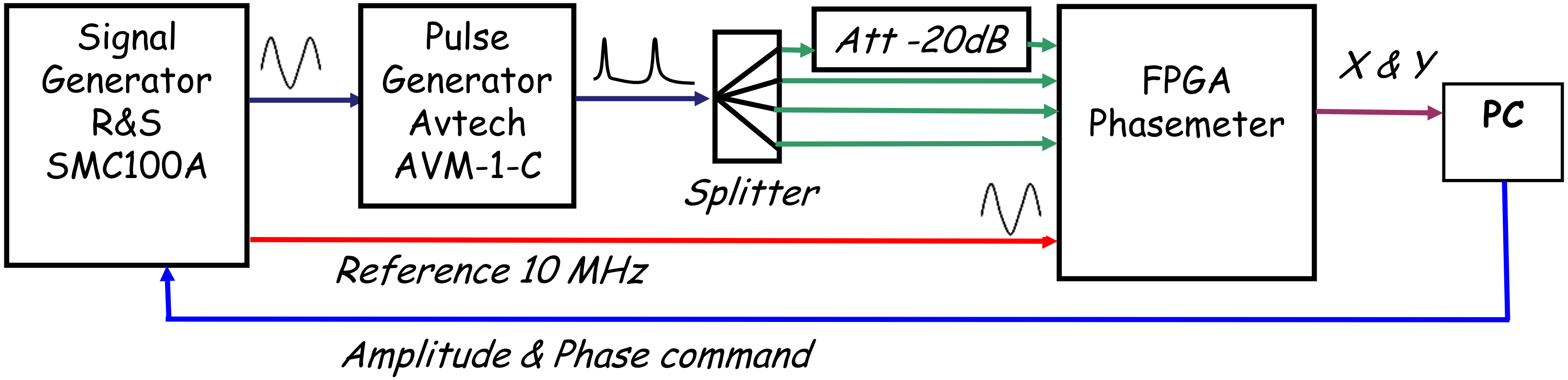


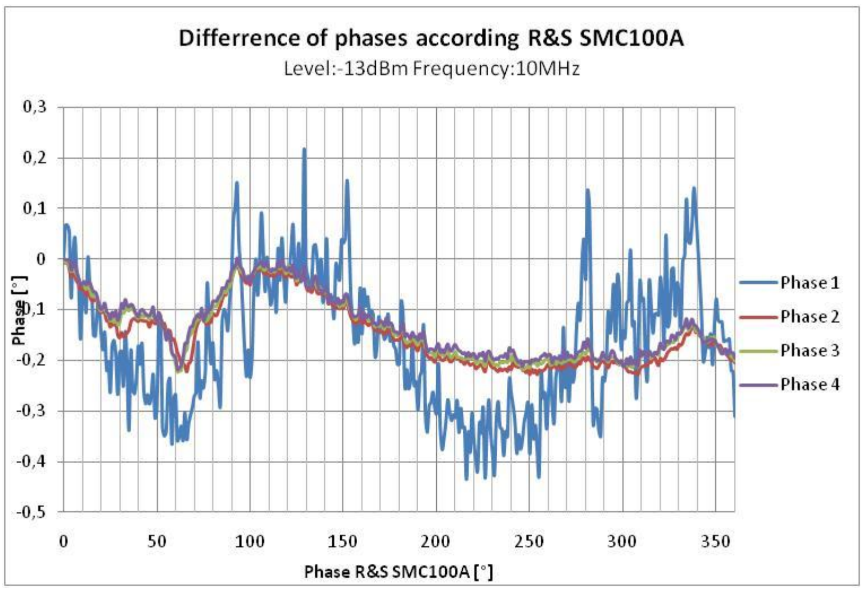


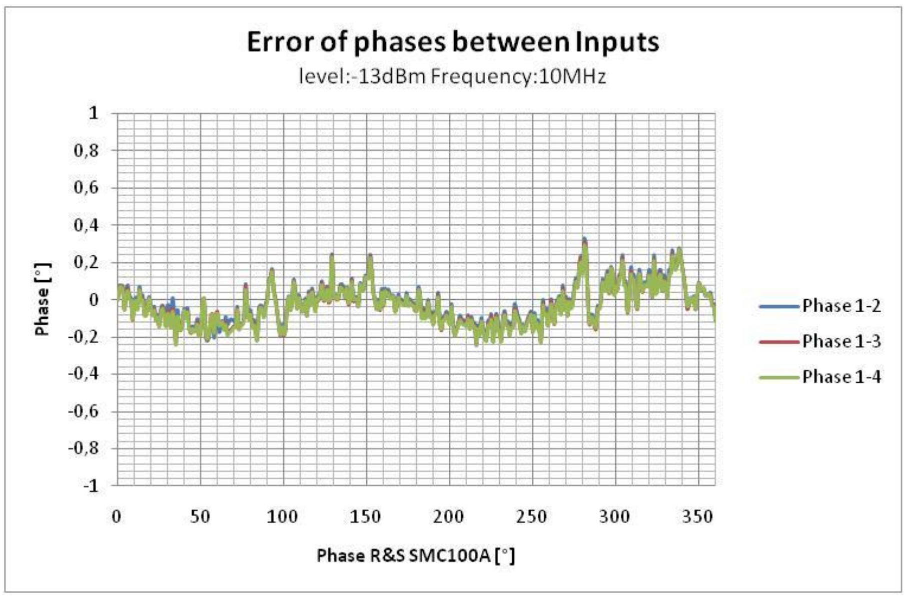


Test bench

Pulse signal

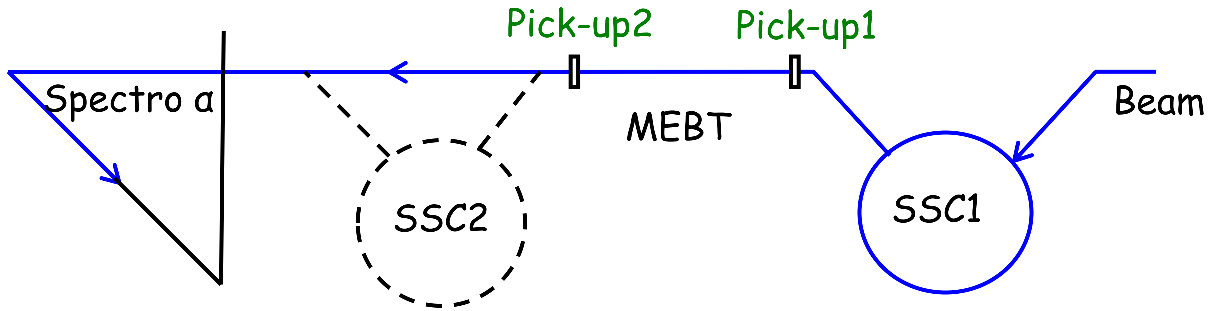






Beam Tests

Beam Tests on the GANIL accelerator were planned to compare beam energy measurements by time of flight with the FPGA phasemeter and the spectrometer method.

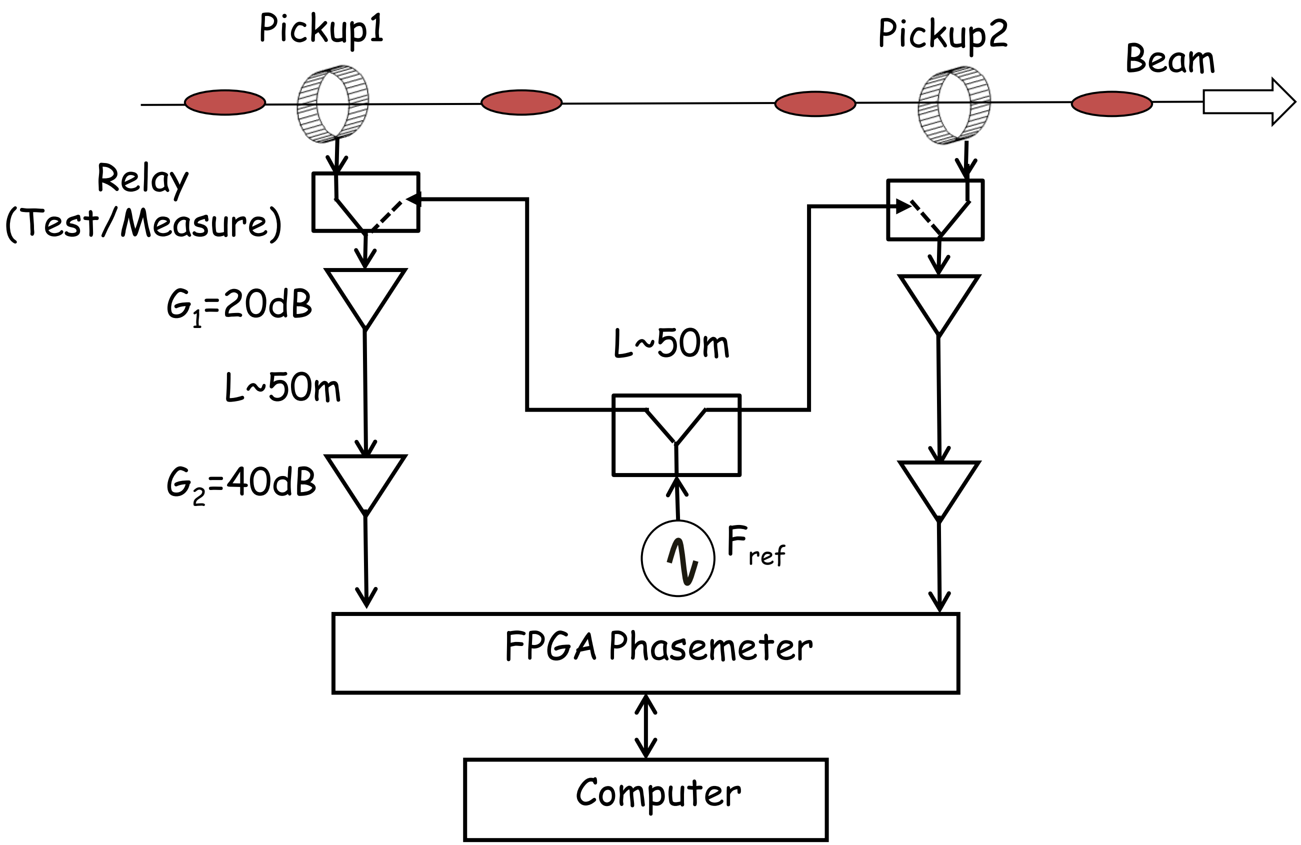


Scheme of the GANIL's Accelerator

SSC : Separated Sector Cyclotron

	MEBT
Energy E (MeV/A)	11
Velocity β=v/c	~ 0,15
Frequency Facc(MHz)	7,5 to 14
Length Lacc (m)	3,77
Length L12 (m)	9,1222
Bunch Number	2

System diagram

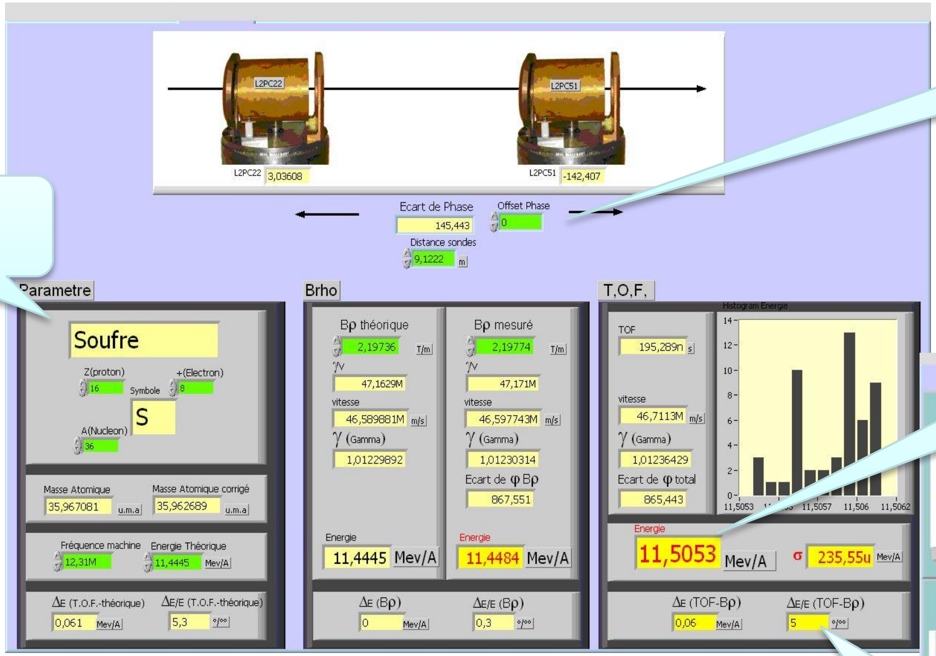


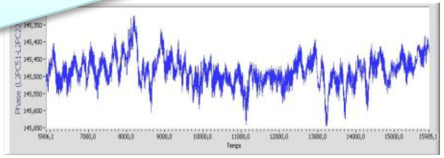
Relays can be switched to inject a test signal. This calibration signal gives the possibility to measure the phase difference between the two chains.

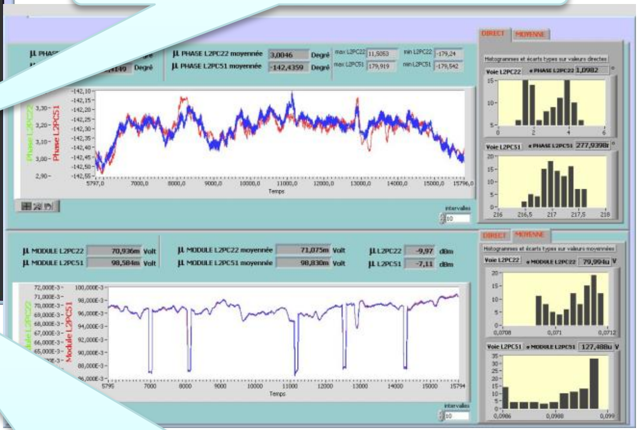
Beam Tests

A Labview program manages the following:

- Communication with the FPGA phasemeter
- Graphical User Interface (GUI)
- A phase difference calculation with an offset correction
- A TOF energy calculation
- An energy difference calculation between the two energy measurements







Beam parameters

Phase difference calculation with offset correction

TOF energy calculation

Energy difference calculation between the two energy measurement method

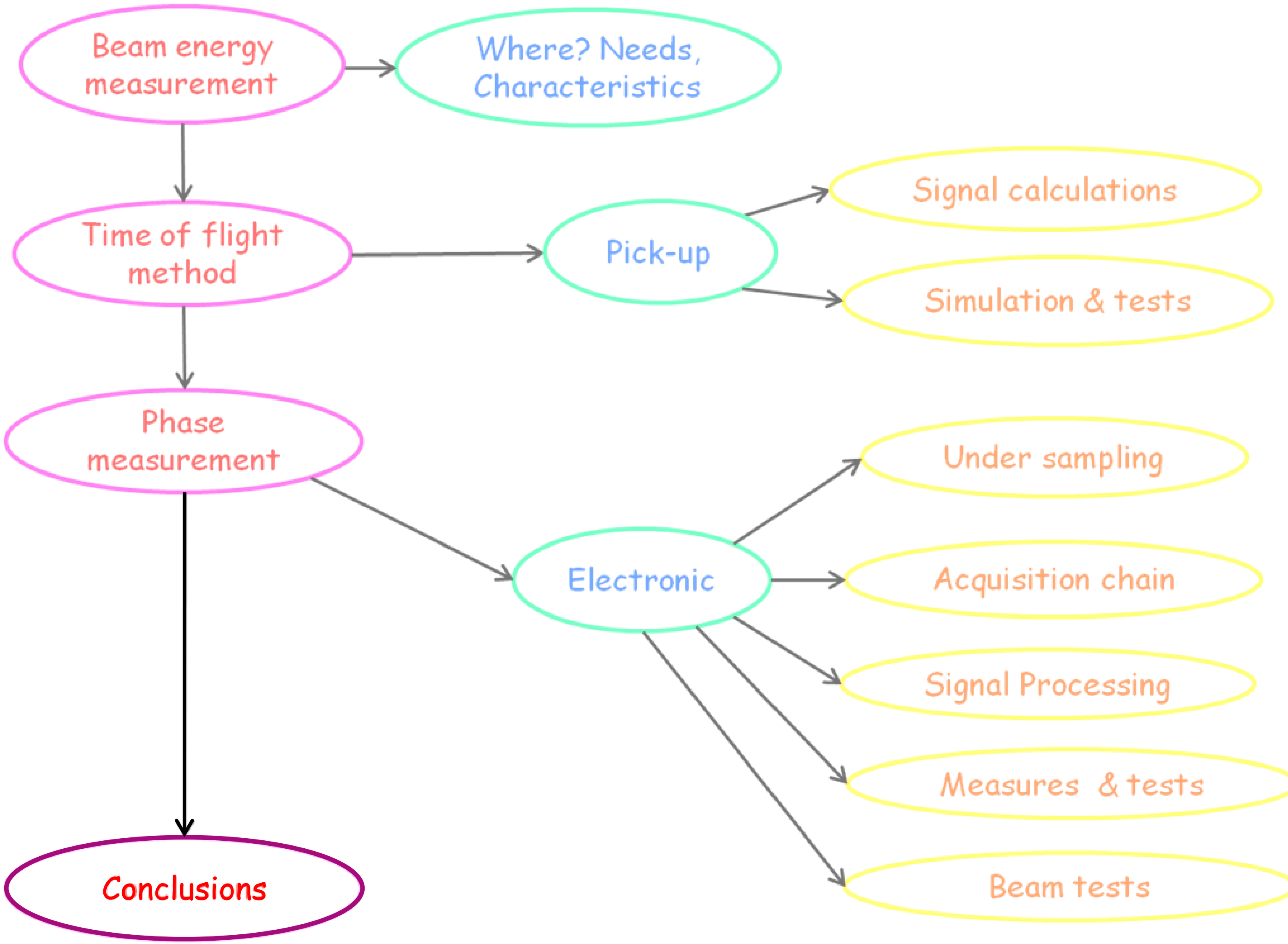
Beam Tests

Date: 21/06/2011
Beam Parameters: ^{36}Sulfur $^{8+}$
Energy: 11,4445 MeV/A
Beam Intensity: 3µAe

Energy measured by the spectrometer: 11,4484 MeV/A

Measure number	phase difference	total phase difference	total phase difference with offset compensation	**Energy calculated from phase measurements**	**Energy gap between TOF and spectrometer method (°/°°)**
1	145,56	865,56	868,26	11,4308	-1,54
2	145,44	865,44	868,14	11,4339	-1,27
3	145,39	865,39	868,09	11,4353	-1,15
4	145,31	865,31	868,01	11,4376	-0,95
5	145,31	865,31	868,01	11,4374	-0,96

Conclusions



Conclusions

The accurate phase measurement requires
-The necessity to subtract the offset
-The necessity to calibrate the phase difference between each channel

-The undersampling acquisition gives the possibility to calculate the phase of several harmonics in the same time.
-The direct sampling of the signal works well for large pulses. In the case of narrow pulses, it is necessary to filter the signal upstream.
-The sampling of signals and the reference at the same time allows not be sensitive to the sampling frequency jitter.

Next Steps:
- Use a FPGA with DSP functions to increase the computing power
- Add the measurement of the harmonic2 phase
- Integrate electronics in a crate
- Change the reference frequency (10 MHz to 88,05 MHz)
- Develop and validate the TCP/modbus communication
- Develop the Command/control interface in EPICS (Control system)
- Update the FPGA program to integrate safety functions (beam energy surveillance at the LINAC exit)

References

Thank You for your attention !

[1] Beam Instrumentation,J.Bosser, CERN-PE-ED001-92 Revised nov.1994
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[5] C. Jamet et al., Phase and amplitude measurement for the SPIRAL2 Accelerator, DIPAC09, Basel, Switzerland
[6] W. Le Coz, SPIRAL2 Beam Energy Measurement, DIPAC11, Hamburg, Germany