MAX IV

First Results of a Pulse Wire Measurement System for ID Characterization at MAX IV

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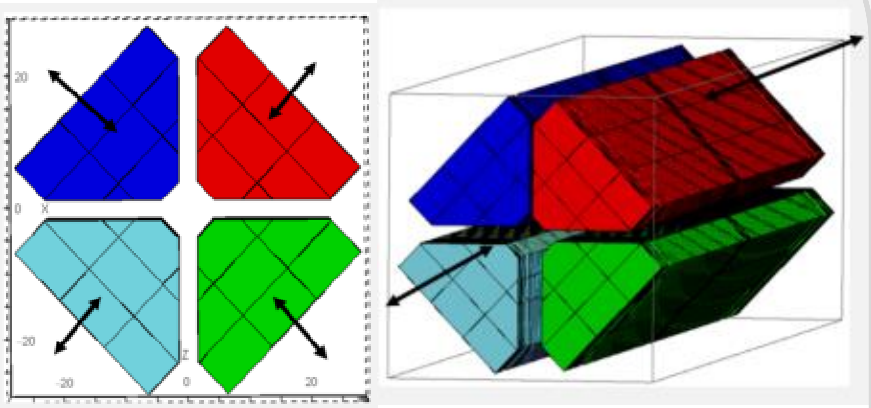
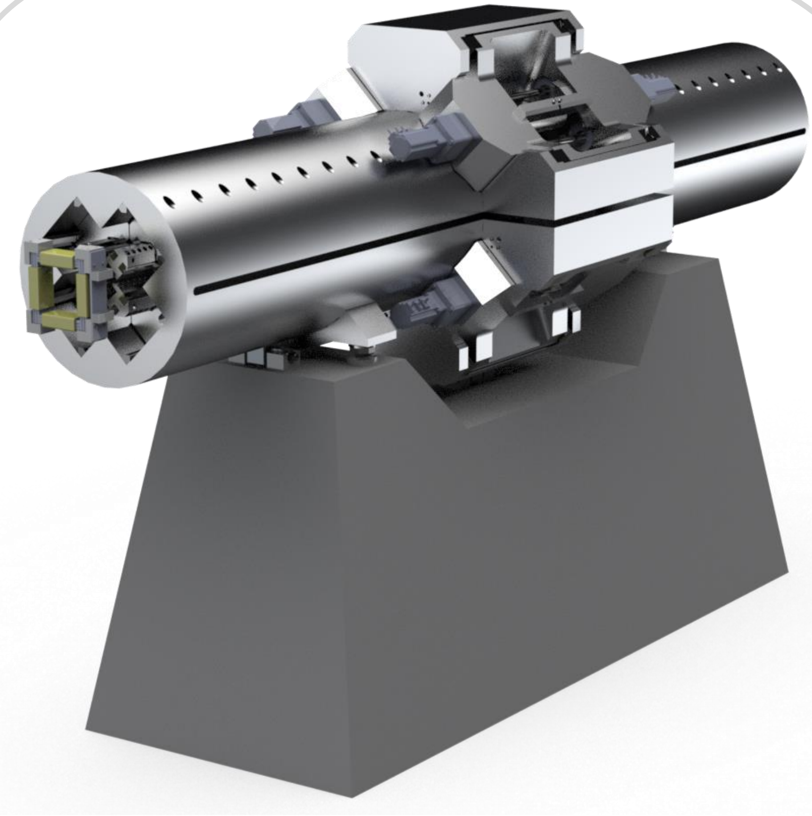
Outline

- ☐ Status of MAX-IV ID project
- ☐ Presentation of the PWM method
- ☐ Numerical simulations
- ☐ PWM bench implementation
- ☐ Measurements results
- ☐ Conclusion

SXL FEL Undulator development



Magnet type	SmCo (B_r=1.1 T)
Period Length	40 mm
Photon energy range	0.25 – 1 keV
Magnetic gap range	8.0 – 17.3 mm
Effective K range	3.9 – 1.51
Max. gap / min. eff. K	28 mm / 0.55
Undulator magnetic length	3 m

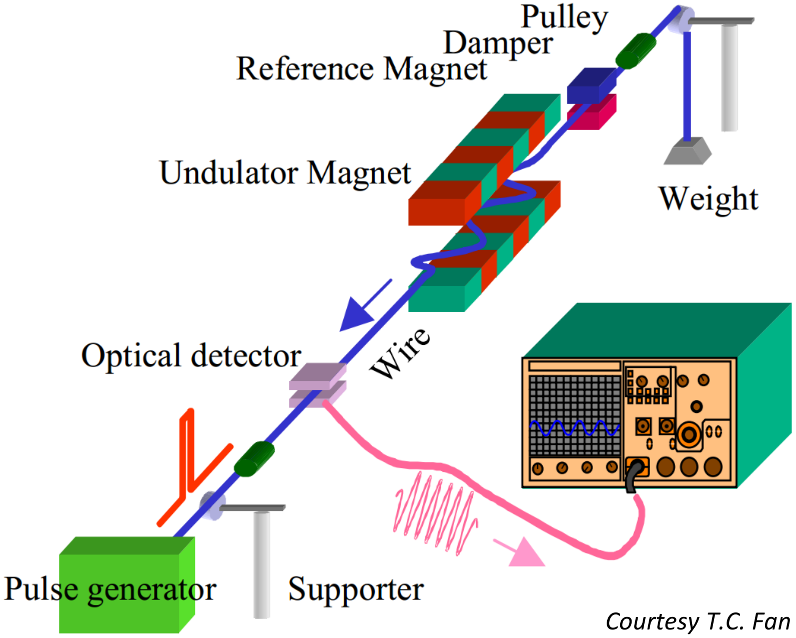


- Due to limited accessibility a functioning **pulsed wire system is needed.**

- Horizontal slit can be incorporated if necessary for Hall-probe access.

Presentation of the PWM method

Pulsed wire system layout



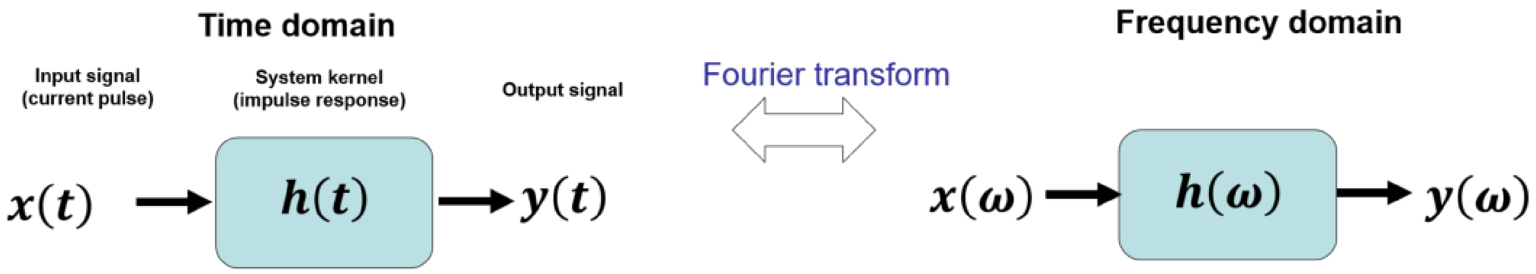
Courtesy T.C. Fan

- ➢ Local field measurement (Similar to Hall probe)
- ➢ First and second Field integral measurements
- ➢ Magnet alignement (magnetic center)
- ➢ Fast measurement (<50 ms !)

- ❖ Signal distorsion (dispersion, resonance, pertubations, …)
- ❖ Low signal to noise ratio
- ❖ Wave damping
- ❖ Wire Sag

Presentation of the PWM method

Analytical modelisation



$$y(t) = x(t) * h(t) = \int_0^t x(\tau)\cdot h(t-\tau)d\tau$$

(Convolution product)

$$y(\omega) = h(\omega)\cdot x(\omega)$$

(Product)

Pulse wire system impulse response Fourier transform ⇨

$$h(\omega) = \frac{-1}{2\underbrace{\mu}_{\text{Wire mass density}}}\left(\underbrace{\frac{1}{i\cdot\omega}}_{\text{Integrator Fourier transform}}\cdot\frac{1}{c_0}\cdot\underbrace{\bar{B}(k)}_{\text{Magnetic field Fourier transform}}\right)$$

$$\underbrace{k}_{\text{Wave number [rad/m]}} = \frac{2\pi}{\underbrace{\lambda}_{\text{Wave length [m]}}}$$

$$\underbrace{c_0}_{\text{Wave speed [m/s]}} = \sqrt{\underbrace{T}_{\text{Wire tension [N]}}/\mu}$$

$$\omega = k\cdot c_0\ [\text{rad/s}]$$

Presentation of the PWM method

Analytical modelisation

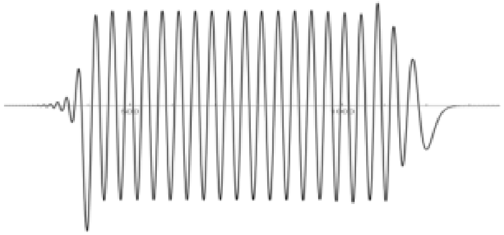
Dispersion Origin and effects

❑ **Different speed of each frequency component of the wave signal**

$$\begin{cases} c_0 \Rightarrow c(k) \\ \omega = k\cdot c(k) \end{cases}$$

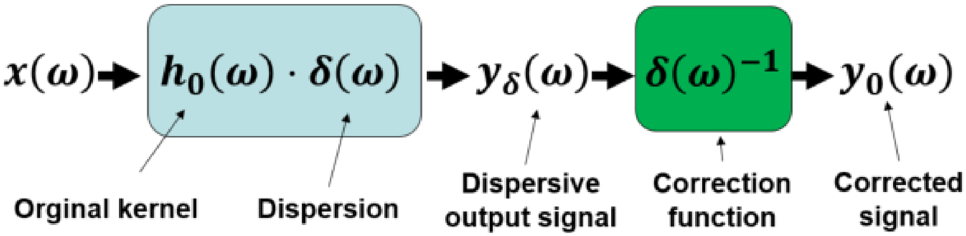
$$h(\omega) = \frac{-1}{2\mu}\left(\underbrace{\frac{1}{i\cdot k\cdot c(k)}}_{\text{corrupted integrator}}\cdot\frac{1}{\underbrace{\left(c(k)+\frac{dc(k)}{dk}\right)}_{\text{Non constant wave speed}}}\cdot\bar{B}(\omega)\right)$$

$$k \rightarrow k(\omega)$$



Simulation of dispersive wave

Correction strategy



$$\delta(\omega)^{-1}$$

$$\delta(\omega)^{-1} = \left(\frac{c(k)}{c_0}\right)\left(\frac{c(k)+k\,\frac{dc(k)}{dk}}{c_0}\right)\frac{i\cdot k\cdot c(k)\Delta t}{e^{i\cdot k\cdot c(k)\Delta t}-1}$$

+

Measurement of wave speed function $c(k)$

D. Arbelaez et al.

Numerical simulations

Simulations goals

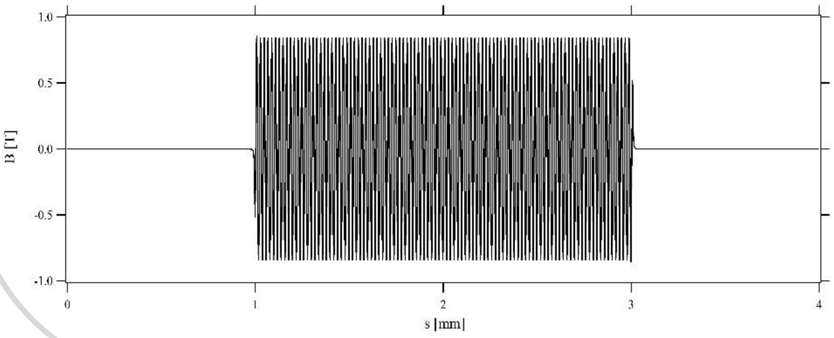
- ✓ **Signal dispersion**
- ✓ **Test of the wave speed identification**
- ✓ **Test the efficiency of the correction method**
- ✓ **Test the sensitivity of the correction result**

Simulations Parameters

parameter	variable	value	Unit
Undulator period	λ_u	20	mm
Undulator Length	L_u	2	m
Wire tension	T	5	N
Wire flexural rigidity	Ei_w	$6.4\cdot10^{-7}$	Nm^2
Wire mass per unit length	μ	$6.9\cdot10^{-5}$	kg/m
Current pulse amplitude	I_{pulse}	2	A

- Copper-Nickel-Silicon wire
- 100 µm diameter
- $C_0 = 269\ \mathrm{m/s}$

Undulator model magnetic field



Wire displacement expression

$$V_s(t) = \frac{I_{\mathrm{pulse}}}{2\mu}\int_{-\infty}^{\infty}\frac{e^{i\omega\Delta t}-1}{\omega^2}\bar{B}(k)e^{-i\omega t}\mathrm{d}k$$ (short and long current pulse)

$$V_s(t)' = \frac{I_{\mathrm{pulse}}}{2\mu}\int_{-\infty}^{\infty}\frac{\left(e^{i\omega\Delta t}-1\right)\left(1-e^{i\omega\Delta t}\right)}{\omega^2}\bar{B}(k)e^{-i\omega t}\mathrm{d}k$$ (positive+negative current pulse)

Discrete version for simulation

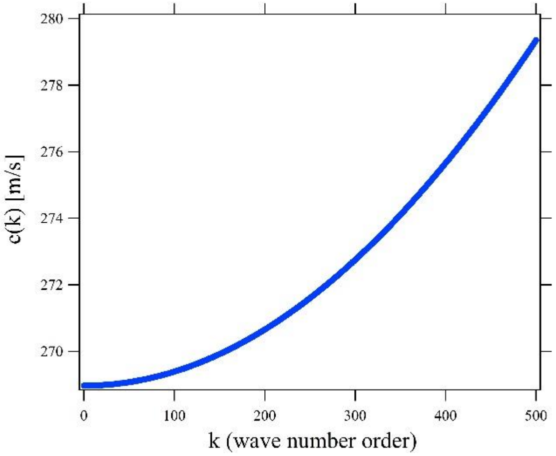
$$V_{sD}(t) = 2\Re e\left(\frac{I_{\mathrm{pulse}}}{2\mu}\sum_{k=1}^{(N_{\mathrm{Sample}}/2)-1}\frac{\left(e^{i\cdot k\cdot k_{\mathrm{f}}\cdot c(k)\Delta t}-1\right)}{\left(k\cdot k_{\mathrm{f}}\cdot c(k)\right)^2}\bar{B}(k)e^{-i\cdot k\cdot k_{\mathrm{f}}\cdot c(k)\cdot t}\right)$$

$$k_{\mathrm{f}} = \frac{2\pi}{\Delta s\cdot N_{\mathrm{sample}}}$$

first order Wave number

Sampling step [mm]

Sample number

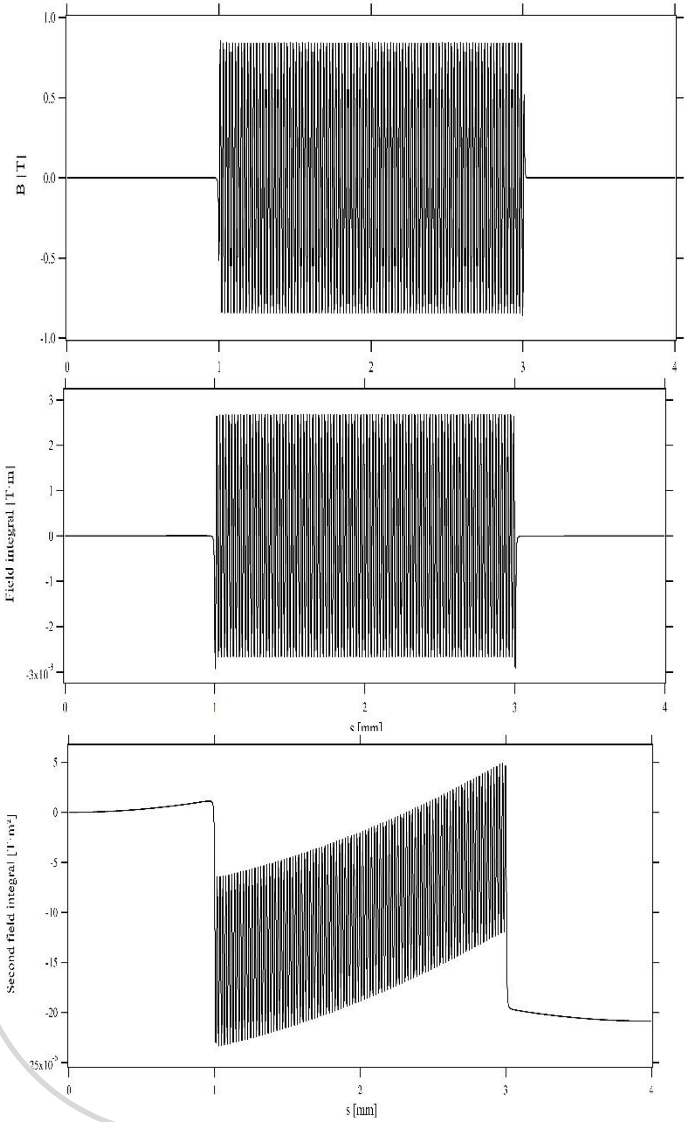


$$c(k) = c_0\sqrt{1+\frac{Ei_w}{T}k^2}$$

(generation of a discrete Table of wave speed function)

Numerical simulations

Undulator magnetic field (model)

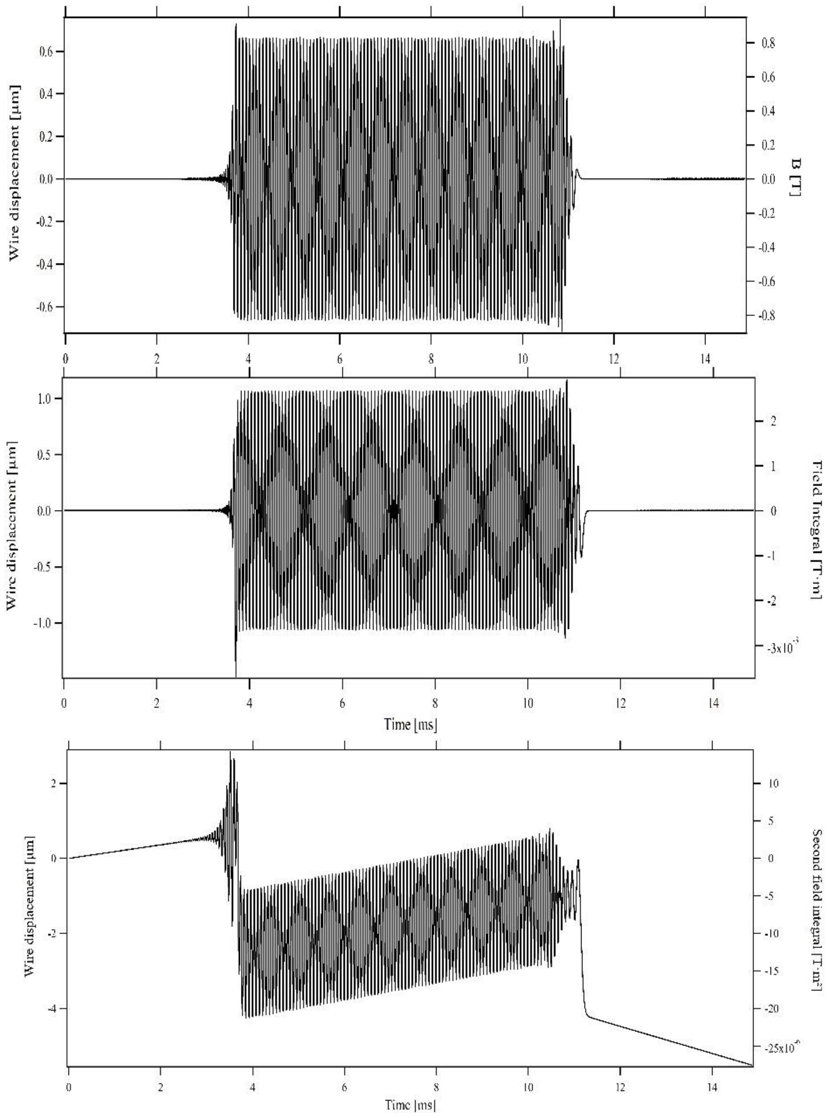


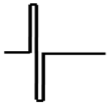
Field

1^{st} Field integral

2^{nd} Field integral

Pulsed wire measurement (Simulation)





$\Delta t \ll \frac{\lambda_u}{c_0}$

$\Delta t \ll \frac{\lambda_u}{c_0}$

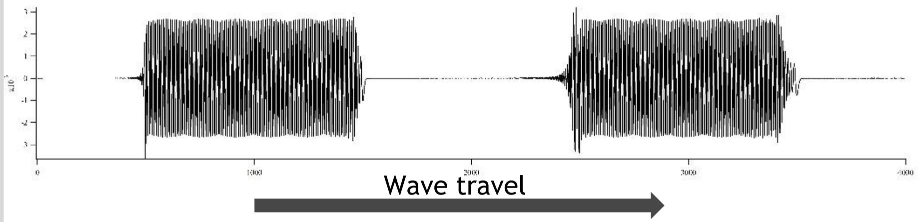
$\Delta t \geq \frac{L_u}{c_0}$

Numerical simulations

Dispersion correction

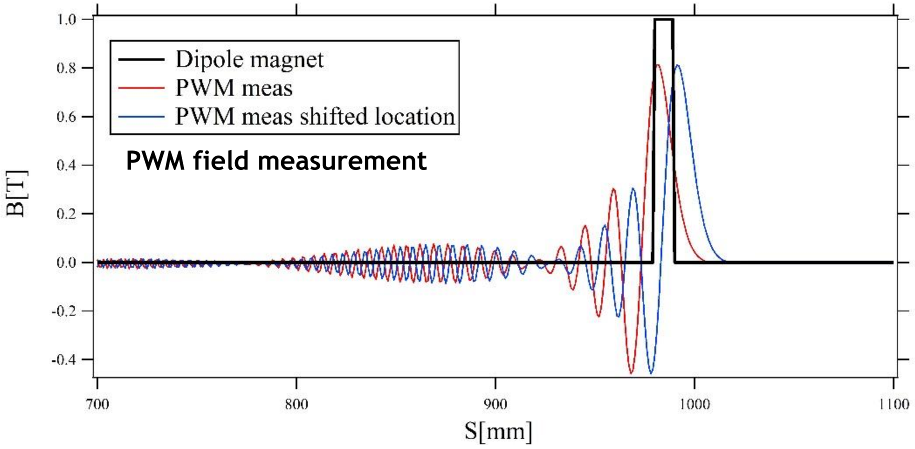
- Wave speed measurement $(c(k))$
- Identification of the parameter (Ei_w)

Wave speed measurement



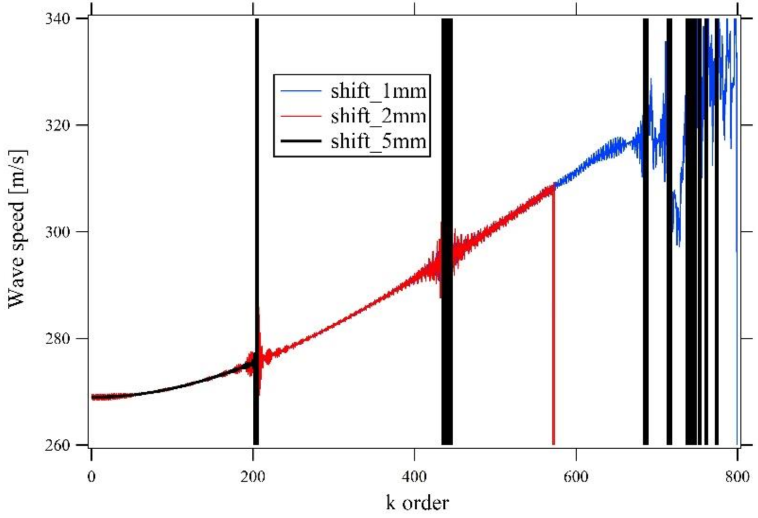
- Measurement at two location
- Use of undulator field or thin dipole magnet

Thin dipole 10mm length

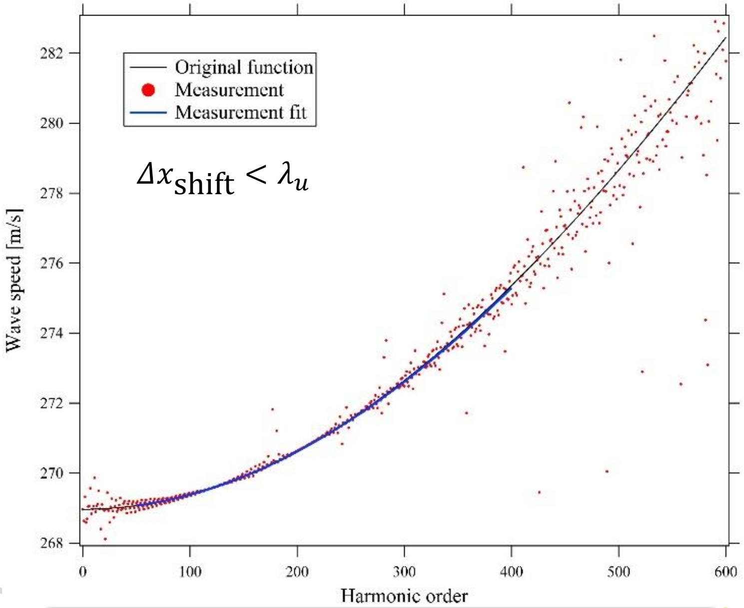


$$c(\omega)=\frac{\omega\Delta x}{\mathrm{Arg}\left(\bar{V}_{sD}^{*}(\omega)\cdot\bar{V}_{sD}'(\omega)\right)}\longrightarrow\boxed{Ei_w}$$

Wave speed measurement with thin dipole 10 mm lenght



Wave speed measurement with undulator



Numerical simulations

Dispersion correction

$$V_{sD_0}(t) = 2\Re e\left(\sum_{\omega=1}^{\omega=\left(N_{\text{sample/2}}\right)-1} \bar{V}_{sD}(\omega)\cdot \bar{F}_C\left(k\left(\omega\cdot\omega_{\text{f}}\right)\right)e^{-i\cdot c_0\cdot k\left(\omega\cdot\omega_{\text{f}}\right)\cdot t}\right)$$

Corrected signal

Dispersed signal FFT

Correction function

$$\boxed{\bar{F}_{C_{\text{B}}}(k) = \frac{\Delta t^2}{c_0}\frac{\left(k\cdot c(k)\right)^2 c_0}{\left(e^{i\cdot k\cdot c(k)\Delta t}-1\right)\left(1-e^{i\cdot k\cdot c(k)\Delta t}\right)}}$$

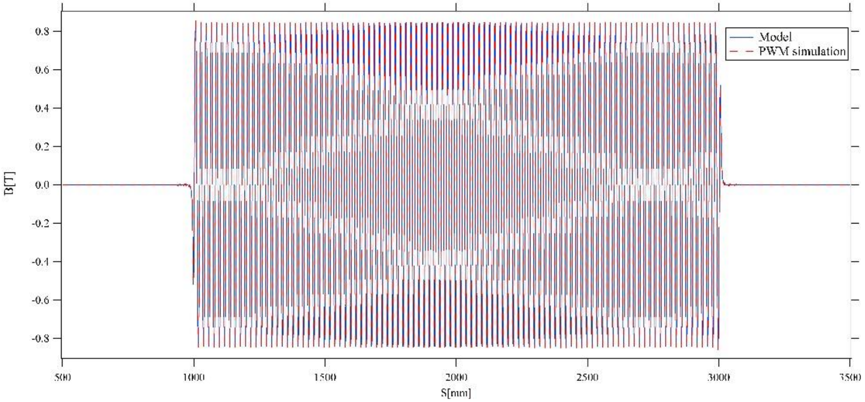
Field correction function

$$\boxed{k(\omega) = \sqrt{-\frac{T}{Ei_w}+\frac{\sqrt{T}\sqrt{c_0{}^2T+4Ei_w\omega^2}}{c_0Ei_\omega}}/\sqrt{2}}$$

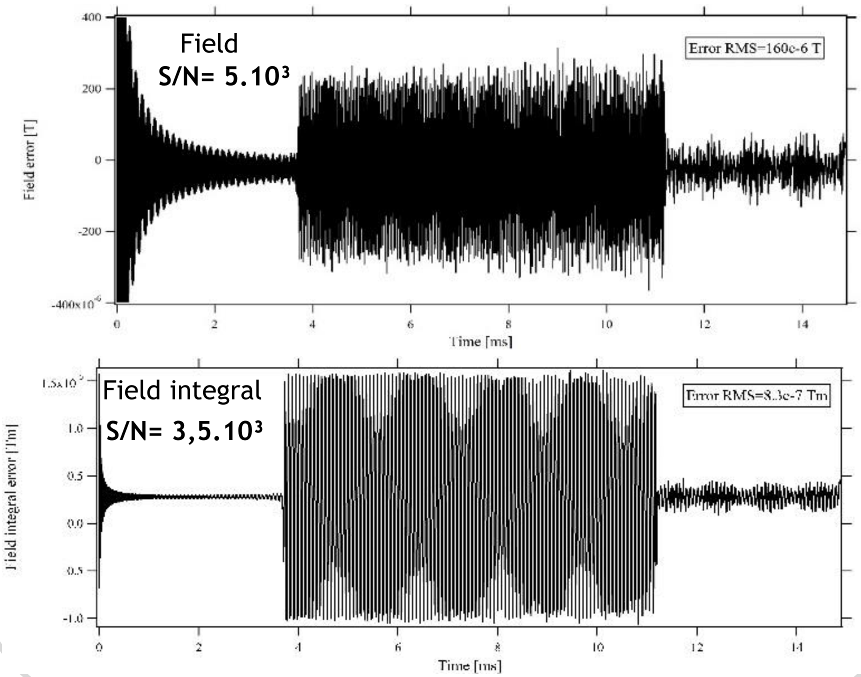
Frequency to wave number transfert function

Numerical simulations

PWM signal correction simulation

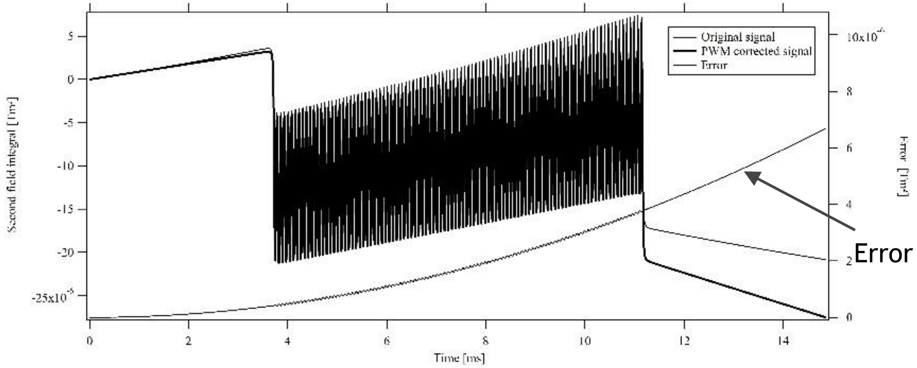


Error: Original field - corrected signal

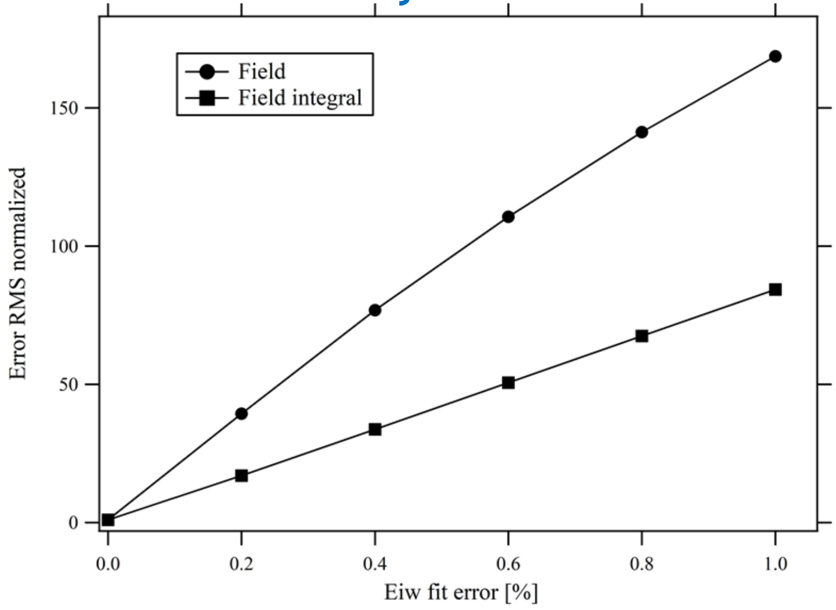


Dispersion correction

Second Field integral

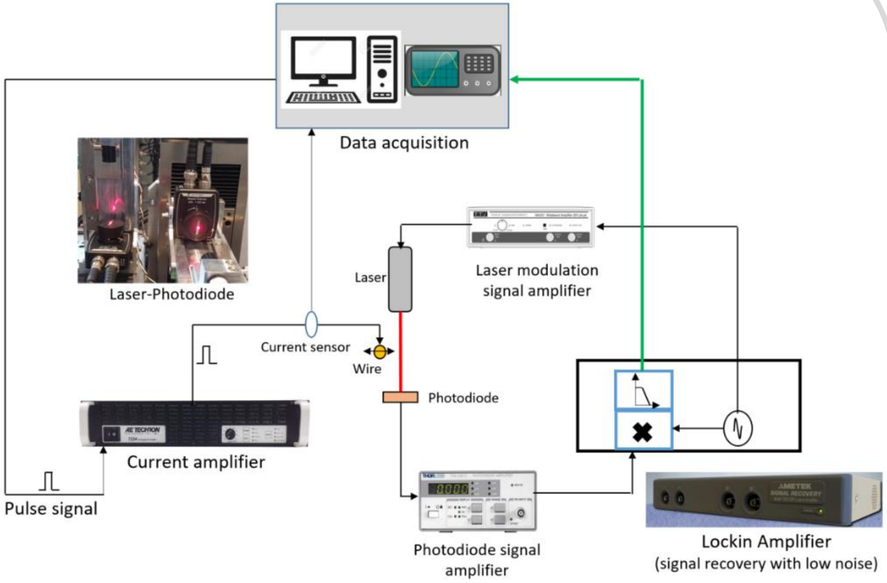


Sensitivity to Eiw error



PWM bench implementation

PWM Bench architecture



Data acquisition

Laser-Photodiode

Laser

Laser modulation signal amplifier

Current sensor

Wire

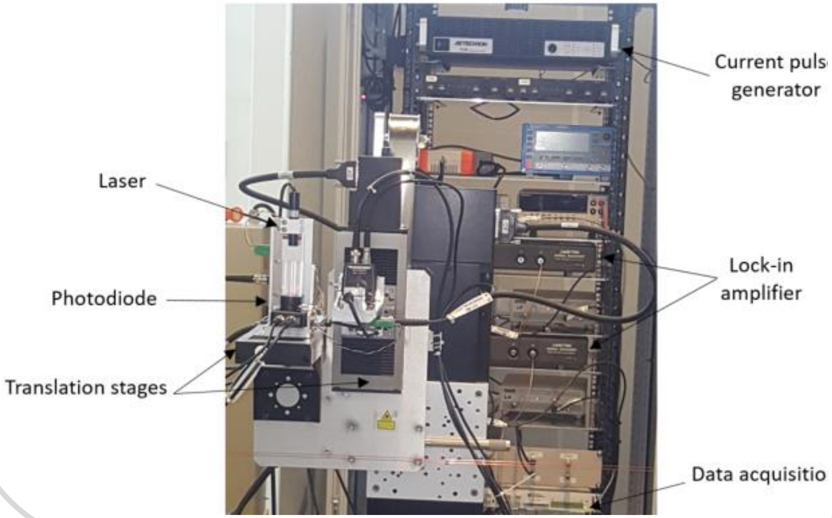
Photodiode

Current amplifier

Pulse signal

Photodiode signal amplifier

Lockin Amplifier
(signal recovery with low noise)



Current puls
generator

Laser

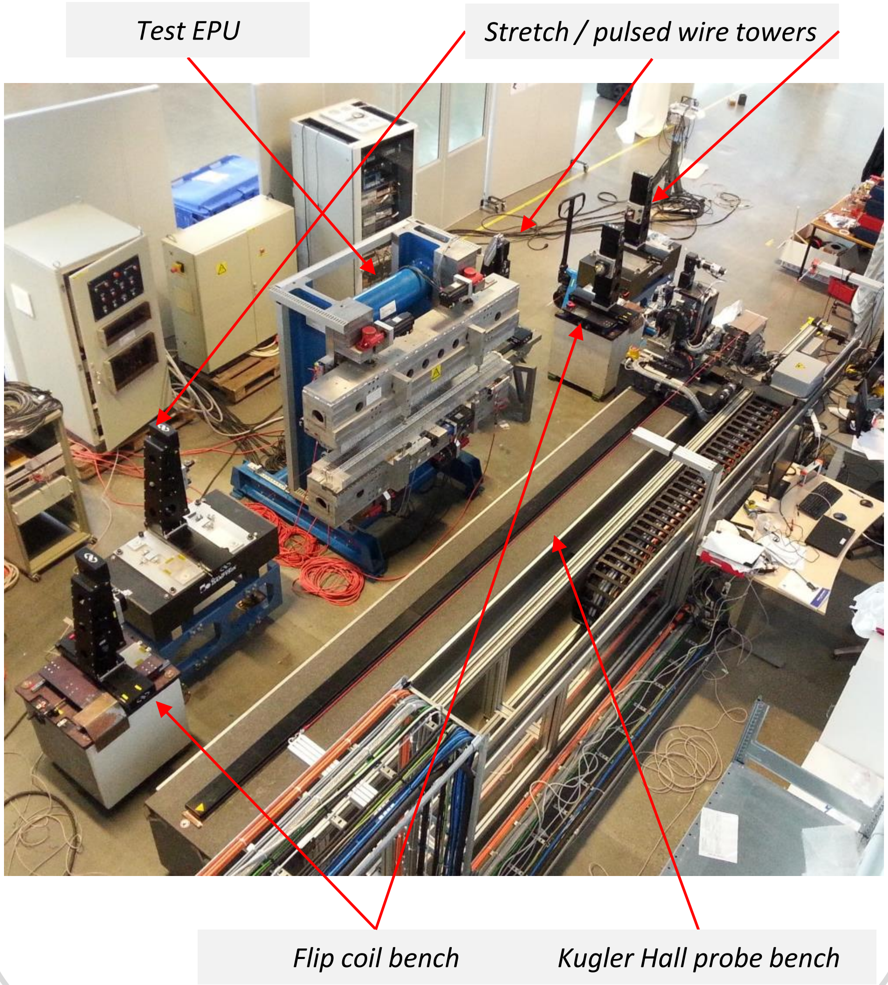
Lock-in
amplifier

Photodiode

Translation stages

Data acquisitio

Overview of the pulsed wire test setup



Test EPU

Stretch / pulsed wire towers

Flip coil bench

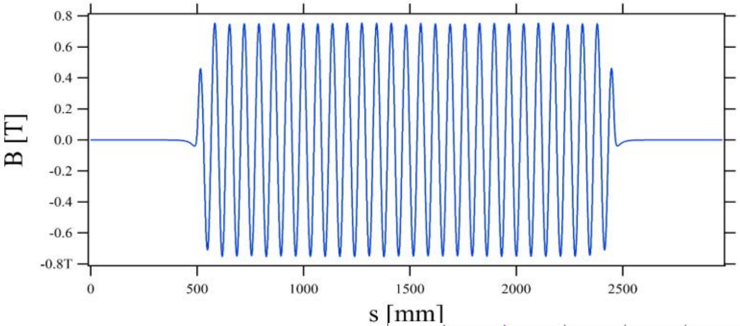
Kugler Hall probe bench

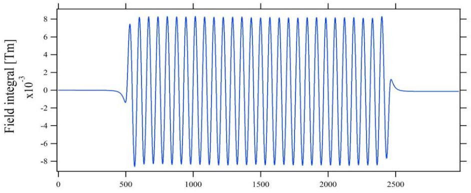
First measurements results

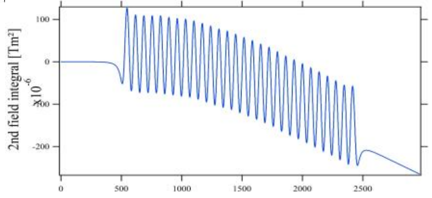
Hall probe measurements

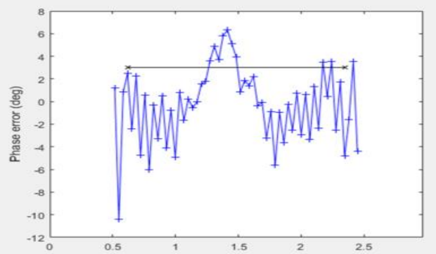
Kugler flat stone Hall probe measurement system is used a reference for the wire system, i.e. local field value and phase error.

- ☐ 68mm period undulator
- ☐ 2m Length
- ☐ 20mm Gap





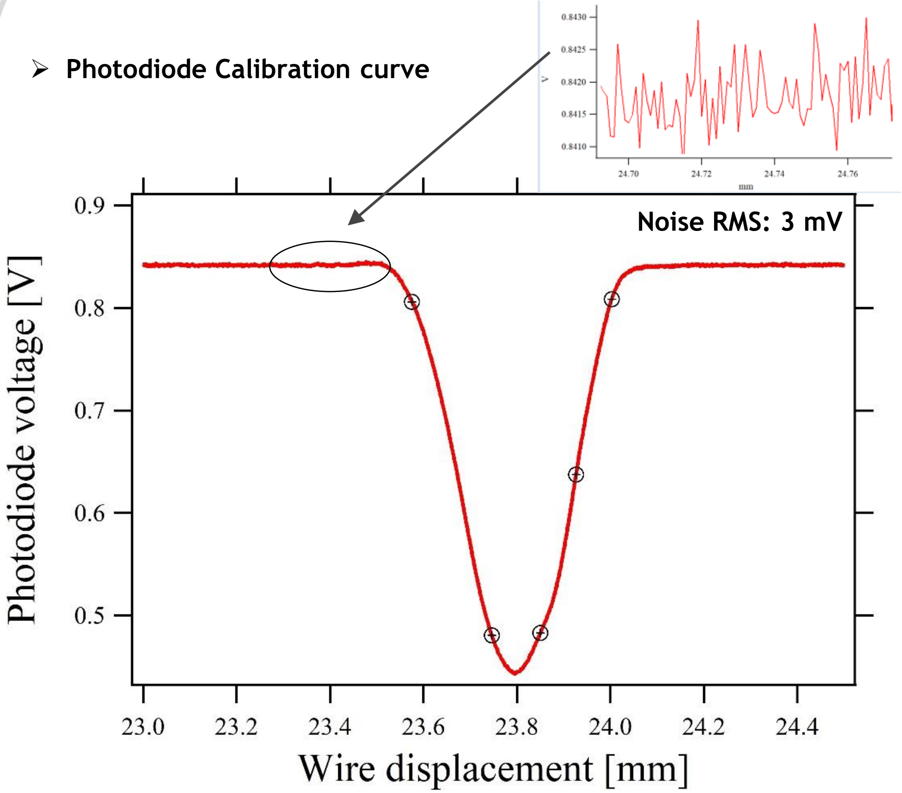




Phase error: 3°

PWM calibration and parameters

- ➢ **Photodiode Calibration curve**

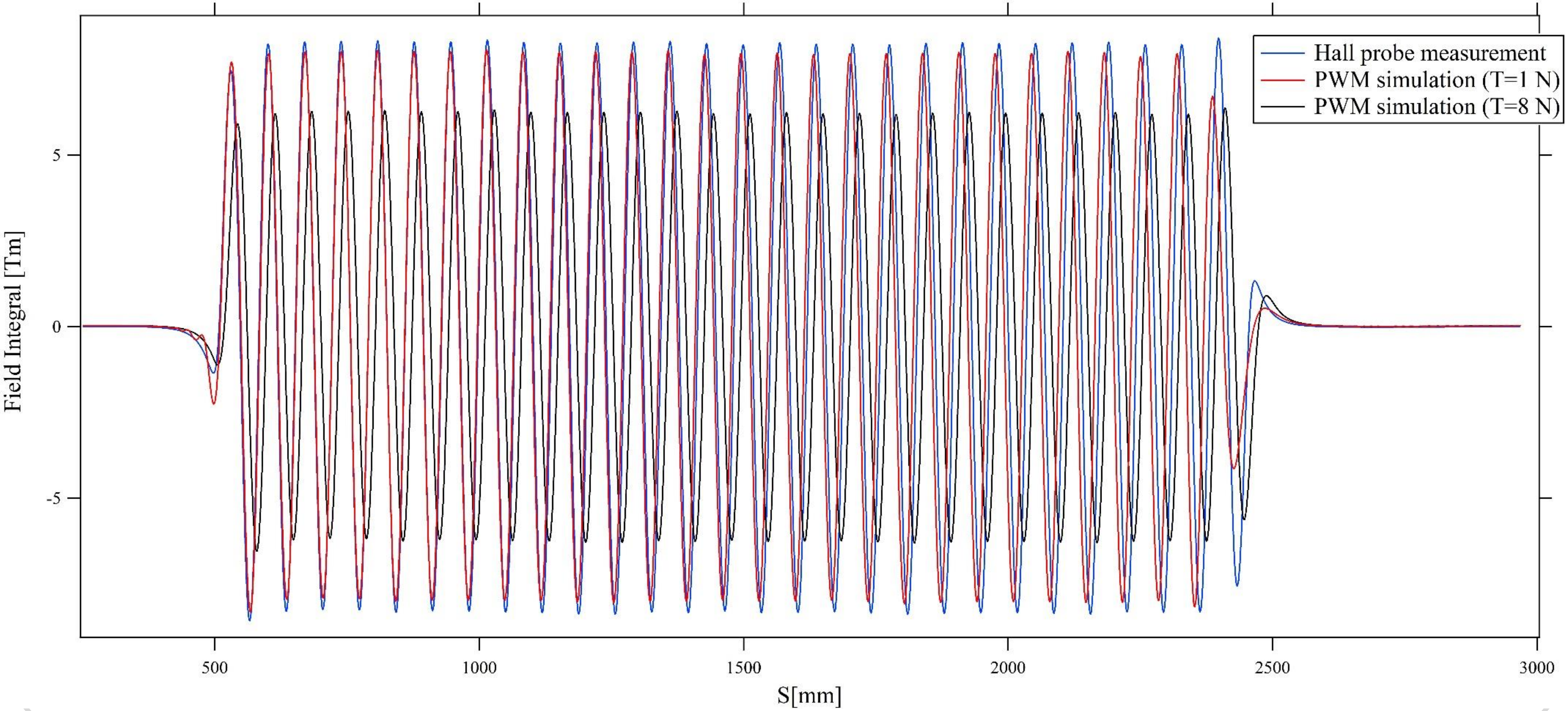


- ➢ **First measurement at different wire tension**
- ➢ **Copper-beryllium wire (CuBe) available**
- ➢ **Current pulse 4A, 100 µs**
- ➢ **Wire Diameter 125 µm**
- ➢ **Wire length 5.5 m**
- ➢ **C0=279 m/s**
- ➢ **Low Eiw parameter (wire inertia x young modulus)**
- ➢ **Low Dispersive effects**

First measurements results

Forseen of the PWM measurement with Hall probe data

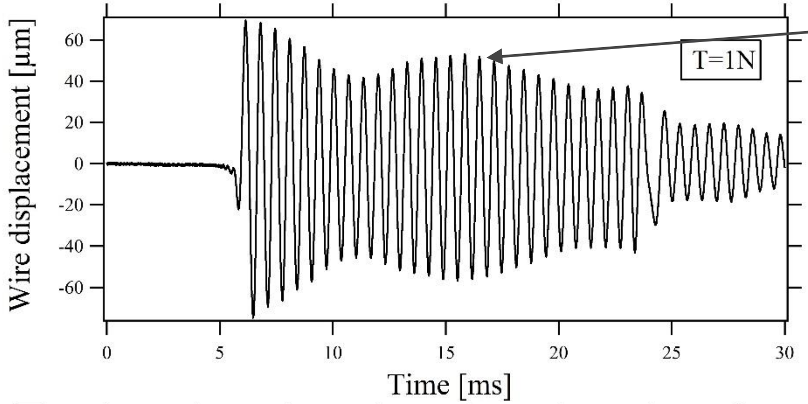
- Copper-beryllium wire (CuBe)
- Current pulse 4A, 100 µs
- Wire Diameter 125 µm

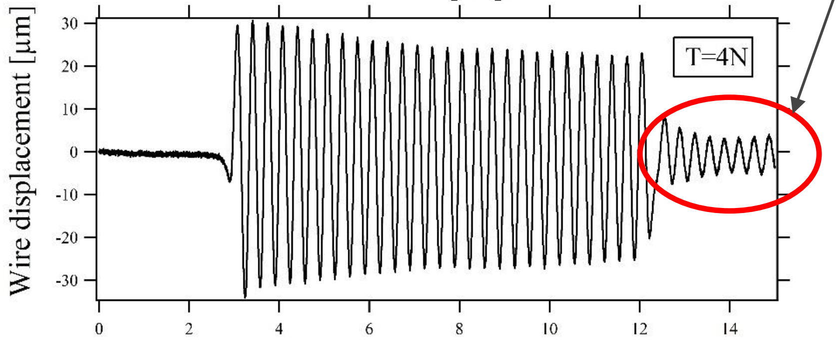


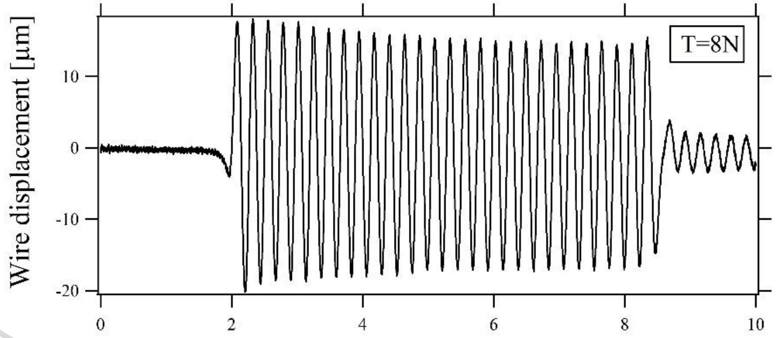
First measurements results

PWM measurements

- ➢ Effect of wire tension





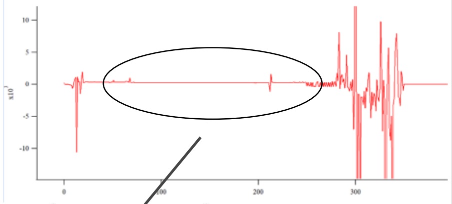


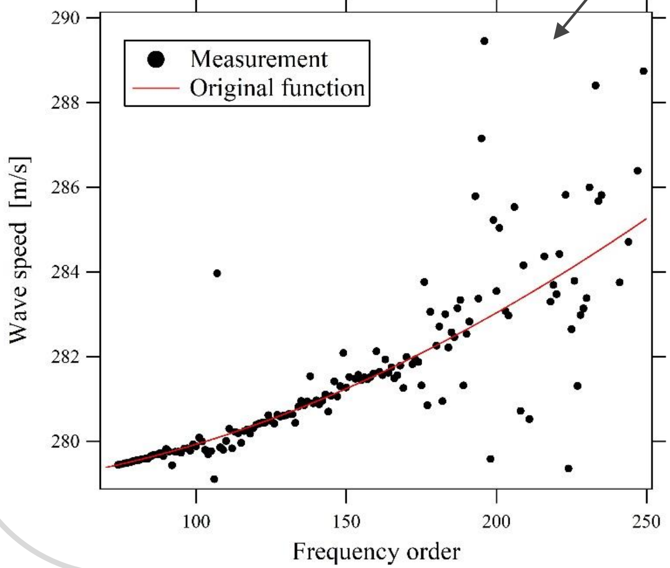
PWM measurements

- ➢ Measurements analysis
  - ❑ Signal shape modulation (wire resonance mode ?)
  - ❑ Signal Damping
  - ❑ Ghost Tail signal
  - ❑ Noise @ 0.5µm (measurements without Lock-in amplifier)
  - ❑ Good repetability of the measurements

- ➢ Wave speed measurement with undulator field
  - ❑ Fit around the undulator order

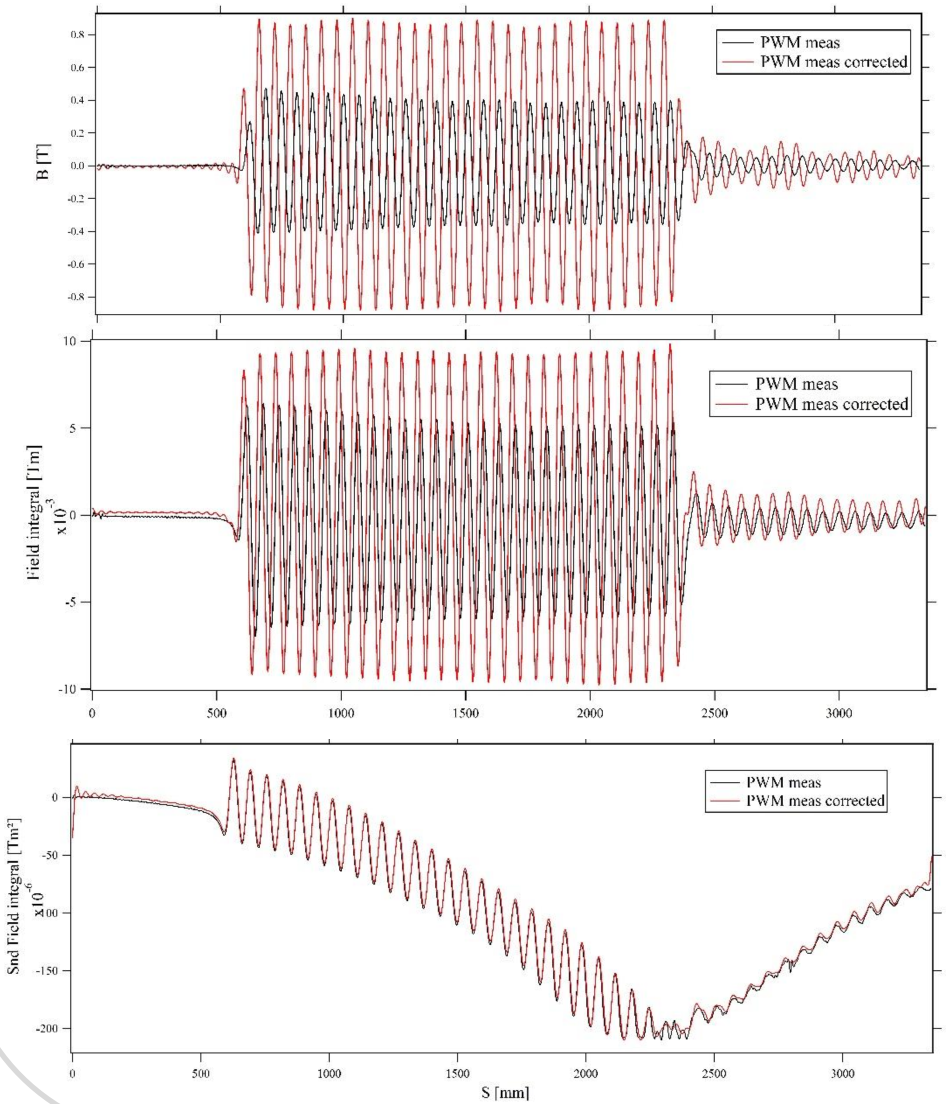
$$\Delta X_{shift} = 6mm$$



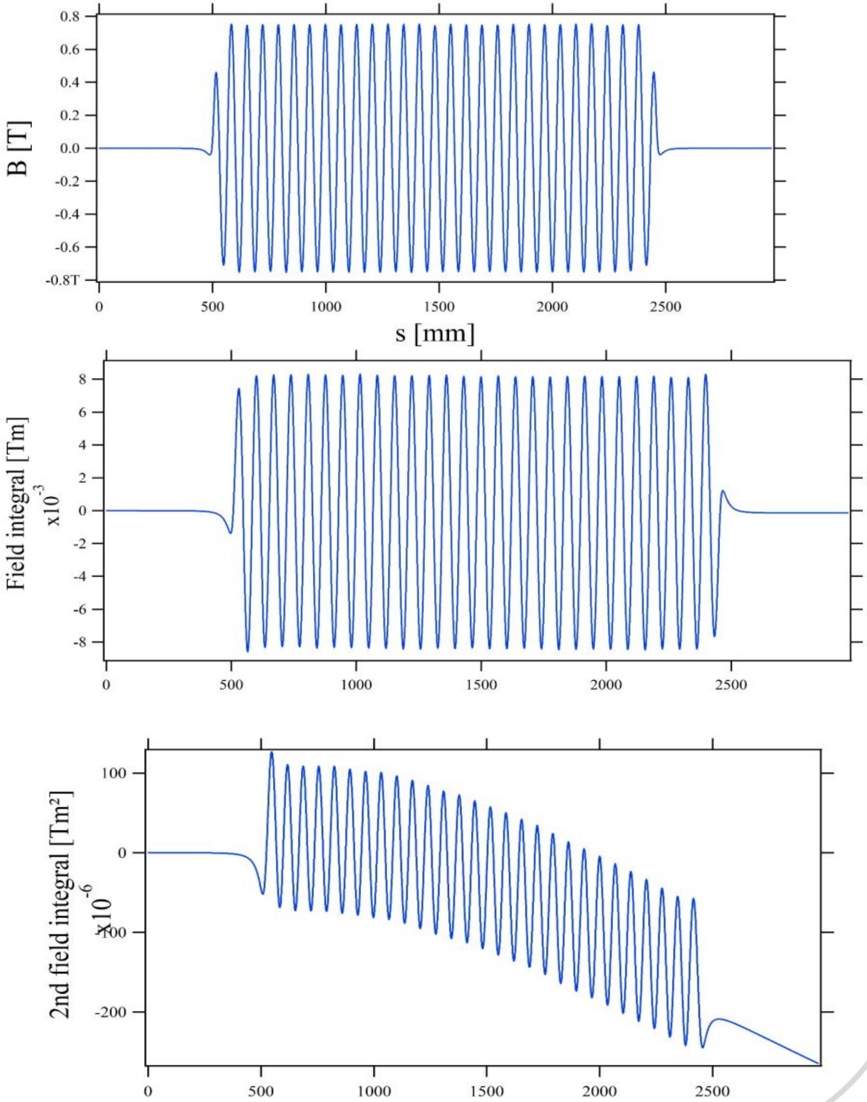


First measurements results

PWM measurements T=8N



Hall probe measurements



Conclusion

- ☐ PWM system is operationnal
- ☐ First results encouraging
- ☐ Good agreement between simulation and measurements
- ☐ Dispersion correction code effective
- ☐ Improvement of the PWM model (remove the wire resonance mode)
- ☐ Reduction of the signal noise with the Lock-in amplifier

Thank for your attention

References

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