FINE AND HYPERFINE STRUCTURE OF FEL EMISSION SPECTRA

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Motivation

- **Characterization of the FELs radiation**
- **Important for user experiments in the field of high-resolution THz spectroscopy**

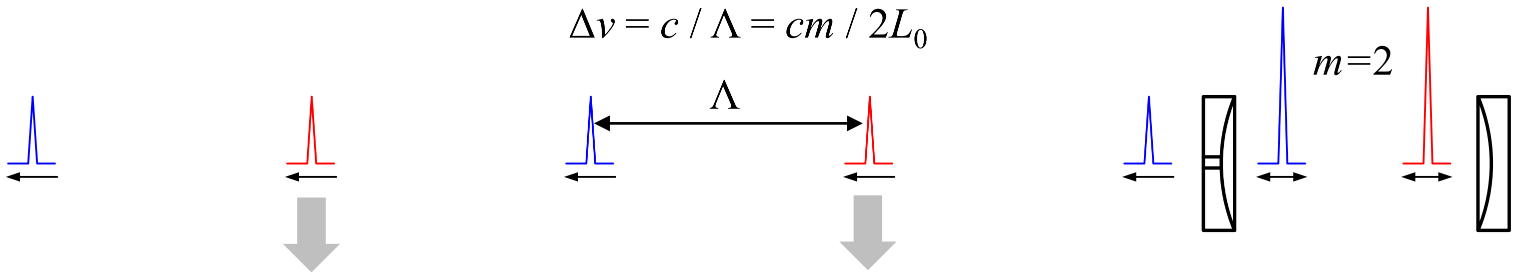
Three types of coherency and spectral structure in FELs

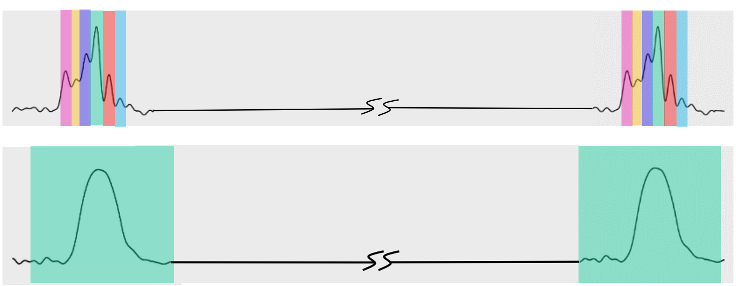
1) Hyperfine coherency – coherency between pulses radiated by one intra-cavity pulse:

$$\Delta \nu = c / 2L_0$$

2) Fine coherency – coherency between all radiated pulses:

$$\Delta \nu = c / \Lambda = cm / 2L_0$$





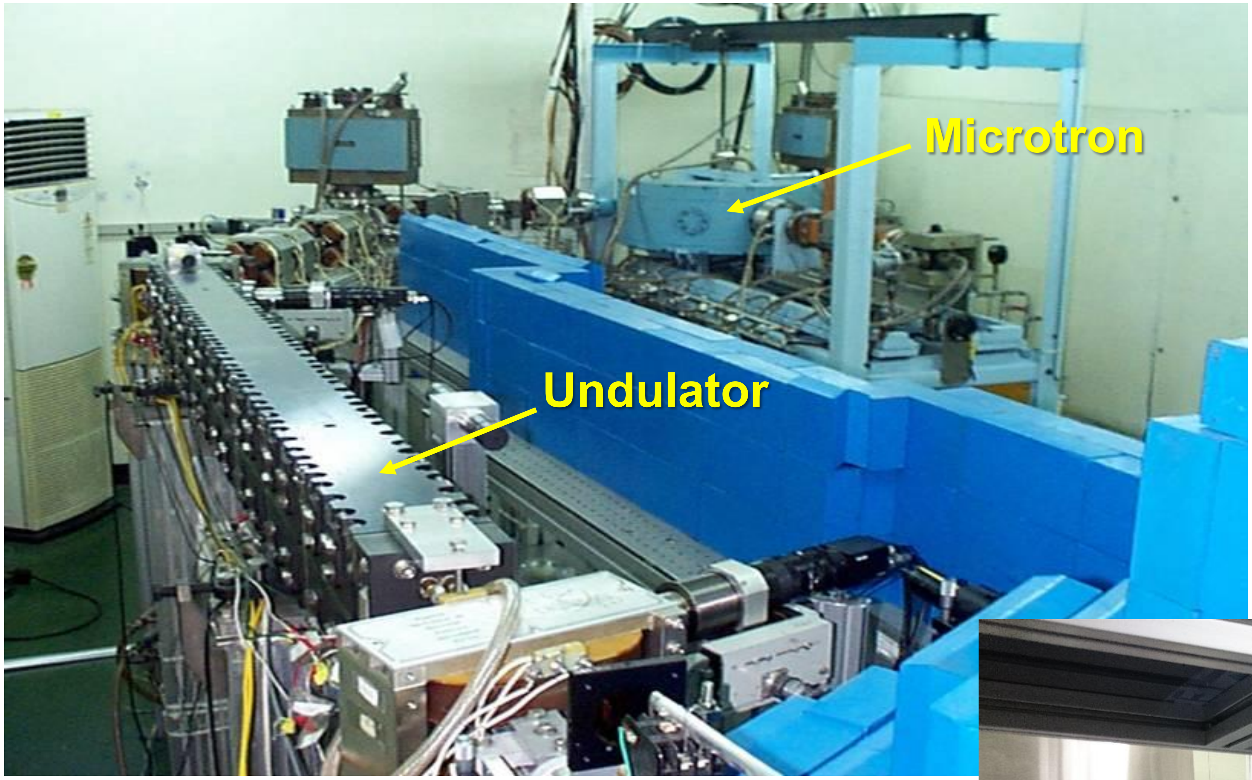
3) Intra-pulse coherency – coherency inside pulse:

$\Delta \nu = c / L_{slippage} = c / \lambda N$, unstable regime, side-band instability on trapped electrons

$\Delta \nu = c / L_{pulse} = 1/\Delta t$, stable regime, Fourier-transform limit

The all coherency are independent. Hyperfine coherency is present *a priory*

KAERI FEL facility



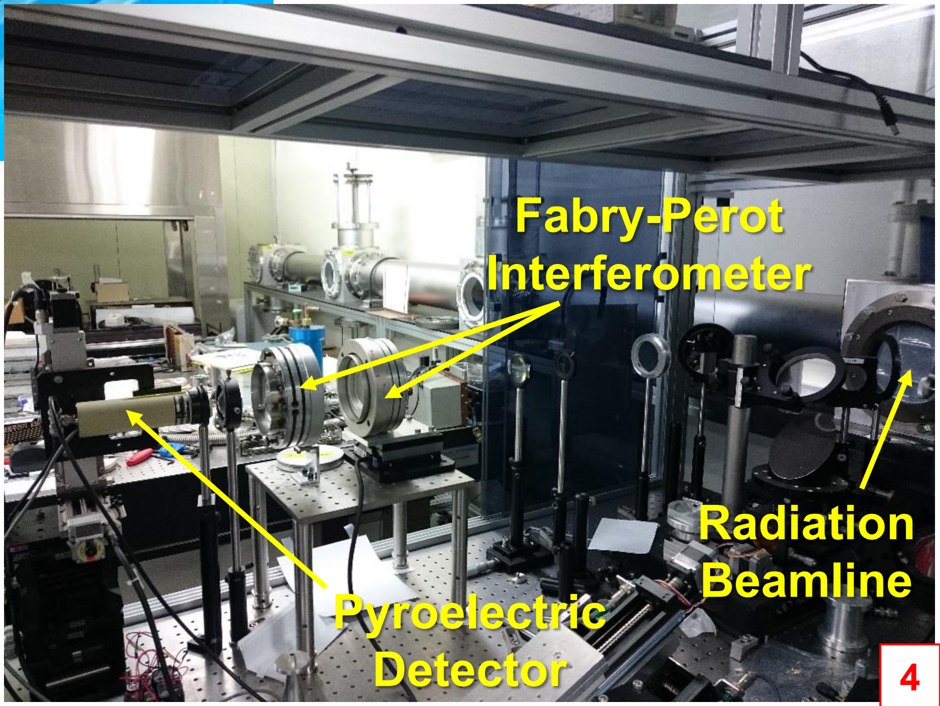
$E = 6\text{-}7$ MeV
$I = 40\text{-}50$ mA
$\lambda = 110\text{-}160$ μm
$P_{macro} = 40\text{-}50$ W
$P_{micro} = 0.5\text{-}1$ kW

Macropulse: $\Delta t_{mac} = 5\text{-}6$ μs; $f_{mac} = 1$Hz

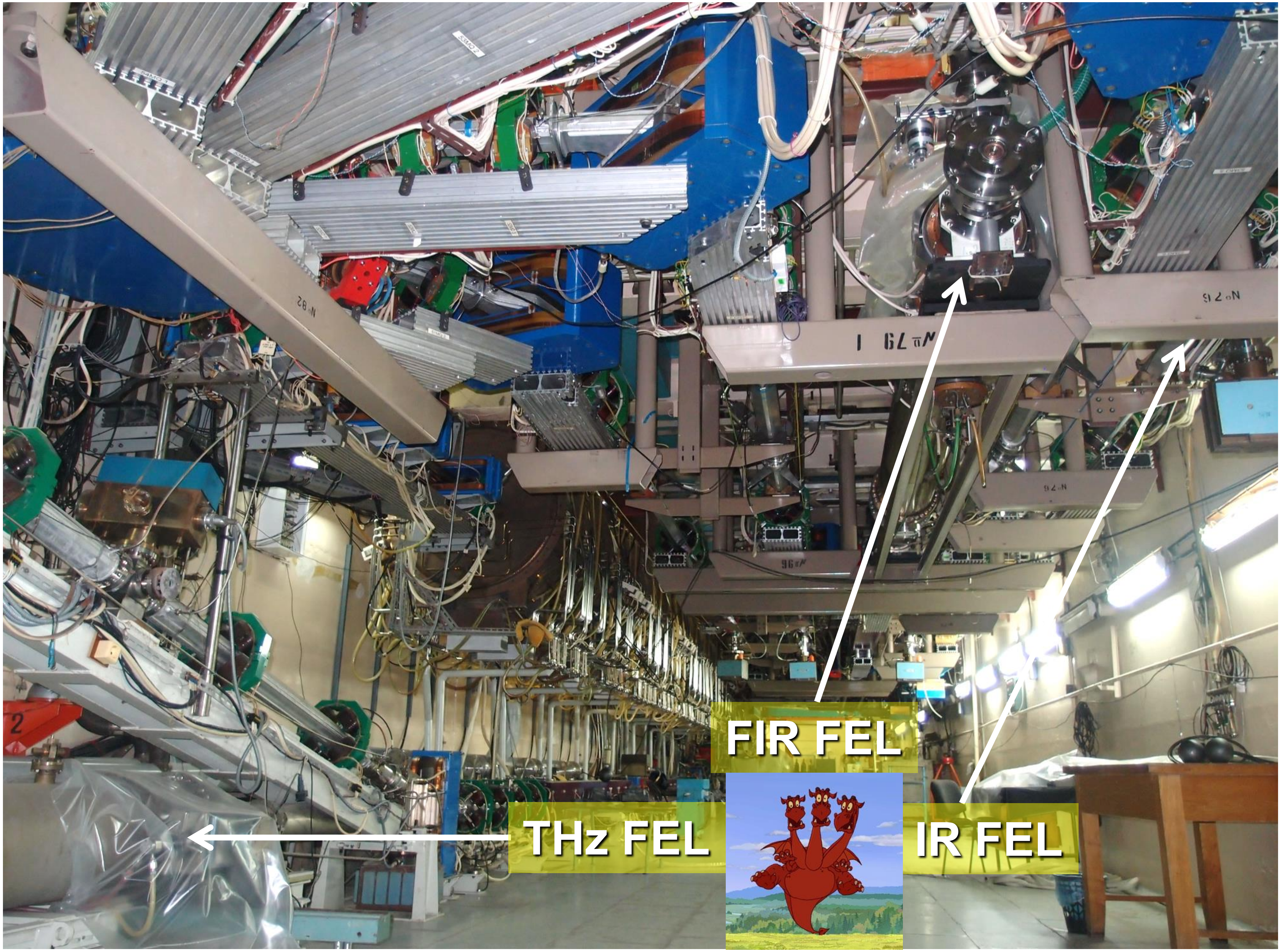
Micropulse: $\Delta t_{mic} \approx 30$ ps; $f_{mic} = 2.8$ GHz
(space period $\Lambda = 107$ mm)

Optical Resonator: $L = 2781$ mm;
$f_{OR} = c/2L = 54$ MHz

Number of intracavity pulses: $2L/\Lambda = 52$



NovoFEL facility



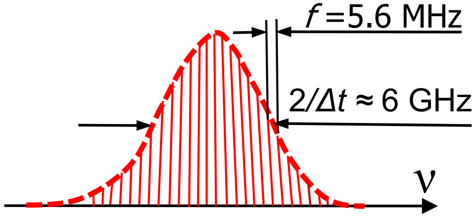
Radiation parameters of the NovoFEL

Laser	Terahertz	Far-Infrared	Infrared
Status	In operation since 2003	In operation since 2009	In operation since 2015
Wavelength, μm	90 – 240	37 – 80	8 – 11 (7–30)
Relative spectral width (FWHM), %	0.2 – 2	0.2 – 2	0.1 – 1
Monochromaticity	$2 \cdot 10^{-8}$		
Maximum average power, kW	0.5	0.5	0.1 (1)
Maximum peak power, MW	0.9	2.0	10
Pulse duration, ps	70 – 120	20 – 40	10 – 20
Pulse repetition rate, MHz	5.6; 11.2; 22.4	7.4	3.7
Polarization	Linear, > 99.6 %		
Beams	Gaussian beams with diffraction divergence		

Typical radiation regime of THz NovoFEL with 1 pulse in optical resonator is continuous 5.6-MHz train of 100 ps pulses:

Fourier transform of coherent laser pulses:

Hyperfine mode structure with
$\Delta\nu = f = c/2L = 5.6$ MHz



Number of pulses inside optical resonator: **1 ; 2 ; 4**

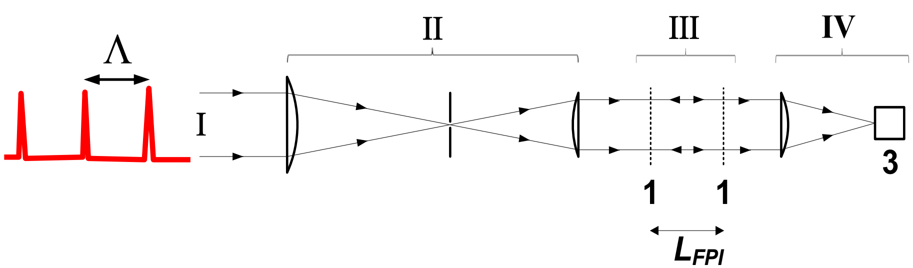
5.6 MHz 11.2 MHz 22.4 MHz

Instruments and Methods. Resonance Fabry-Perot Interferometer

I – radiated FEL pulses (beams)
II – lens beam compressors and wavefront correctors
III – mesh resonance Fabry-Perot interferometers
IV – detector systems

1 – electroformed metallic meshes
2 – hollow dielectric waveguide (glass tube)
3 – different detectors

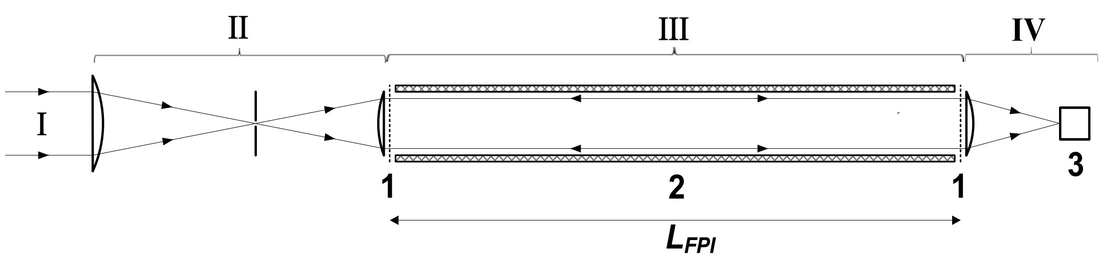
a) KAERI FEL:



Λ = 107.2 mm
$L_{FPI\text{-}1}$ = 53.6 mm (m=1)
$L_{FPI\text{-}2}$ = 107.2 mm (m=2)
} fine

$L_{FPI\text{-}3}$ = 536 mm (m=10)
dense 20-μm meshes
} hyperfine

b) NovoFEL:



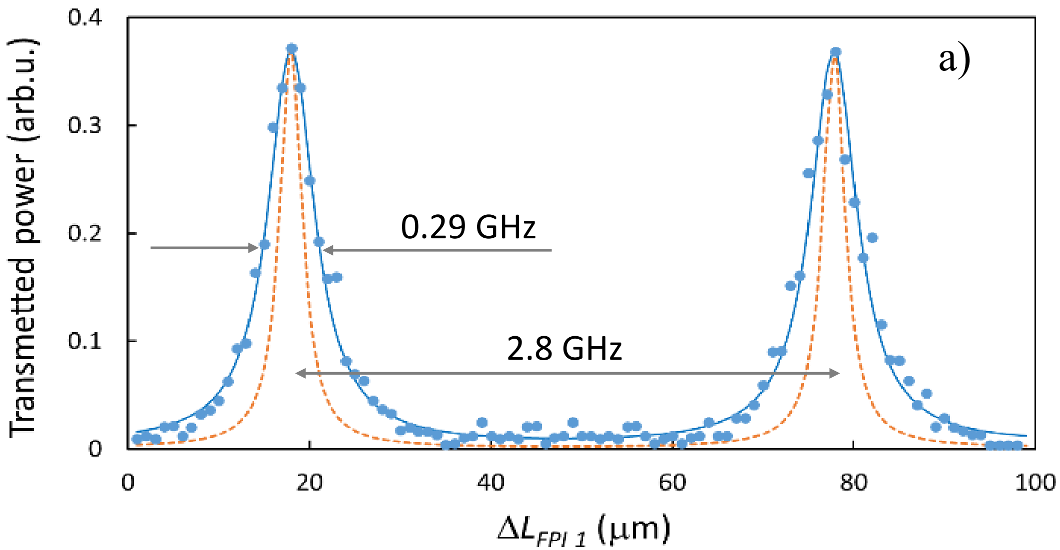
Λ = 26589 mm
L_{FPI} = 2658.9 mm (n=5)
} fine

Λ = 53178 mm
L_{FPI} = 2658.9 mm (n=10)
} hyperfine

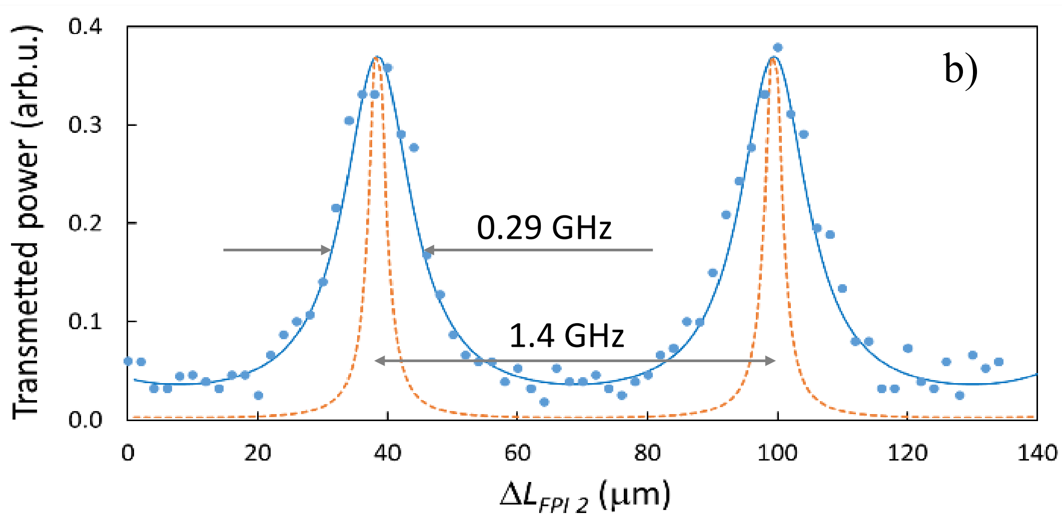
Resonance Fabry-Perot Interferometer (FPI):
$L_{FPI} = \Lambda/(2n)$ or $L_{FPI} = (\Lambda/2)\cdot m$, where Λ is the distance between pulses and n and m are integers.

Two operation modes of the FPI:
a) Slow, Frequency-domain, $P_{\text{transmitted}} = P(L_{FPI})$; b) Fast, Time-domain, $P_{\text{transmitted}} = P(t, L_{FPI} = \text{const})$

Fine spectral structures of the KAERI FEL



$$N_c = \varepsilon_1 \cdot m = 10 \cdot 1 \approx 10$$

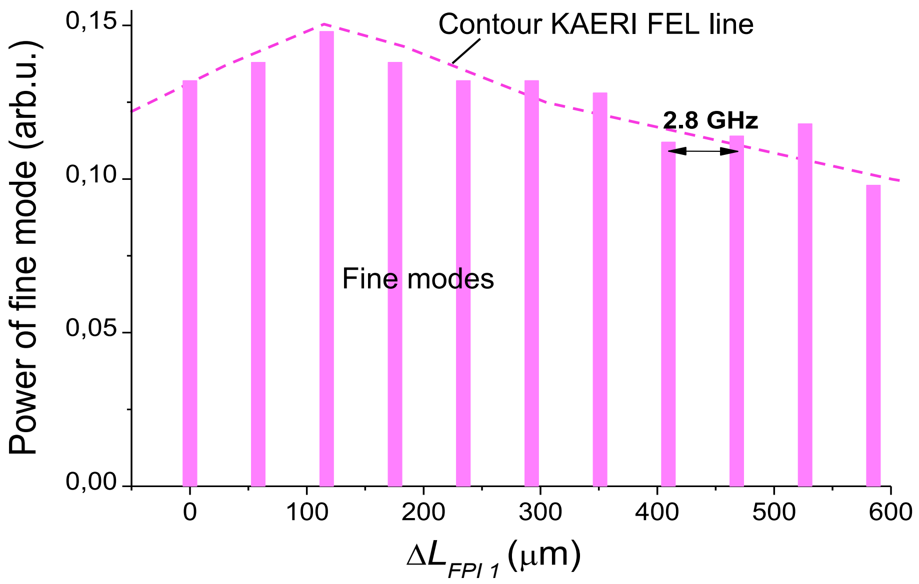


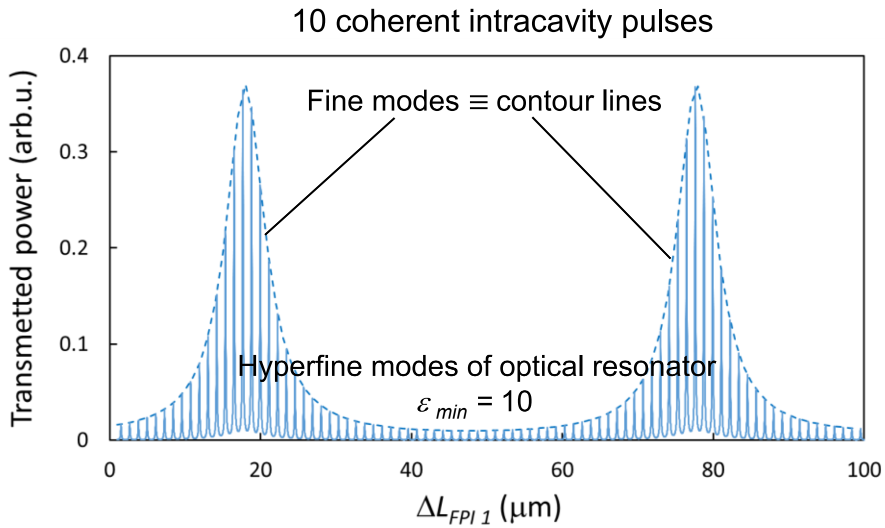
$$N_c = \varepsilon_2 \cdot m = 5 \cdot 2 \approx 10$$

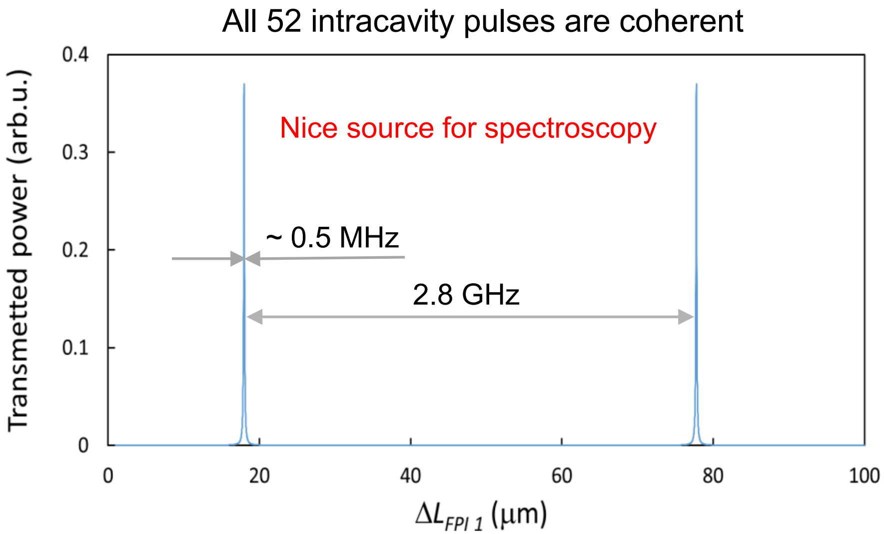
10 coherent pulses (1/5 part)
Monochromaticity = 0.29 GHz/2.9 THz=10^{-4}

$$\delta f/f = \pm 250 \text{ kHz}/2.8 \text{ GHz} \approx \pm 10^{-4}$$

Fine and hyperfine structures of the KAERI FEL

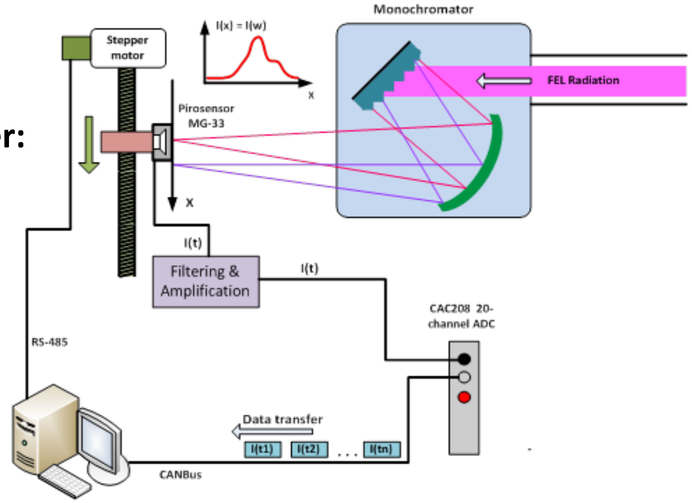


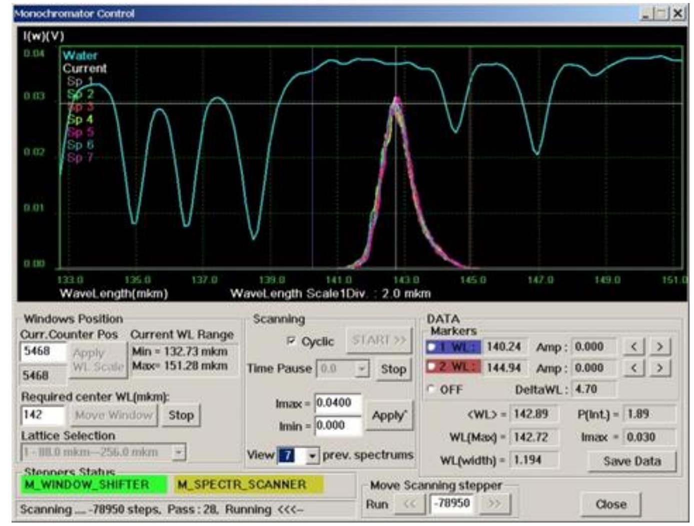




Hyperfine spectral structure of the NovoFEL

On-line grating spectrometer:

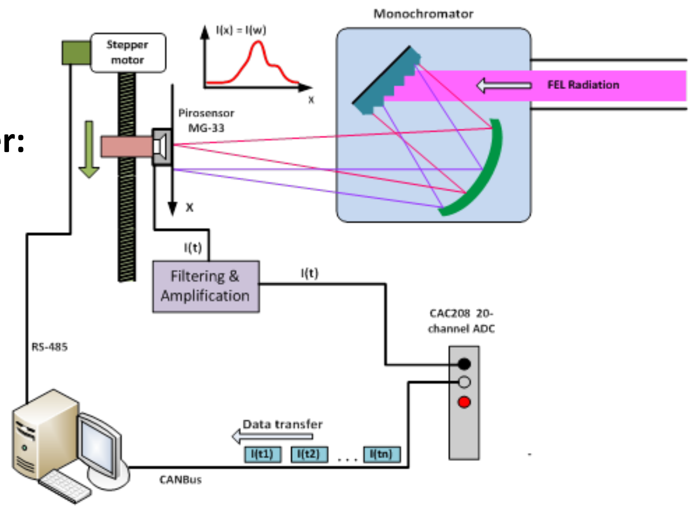


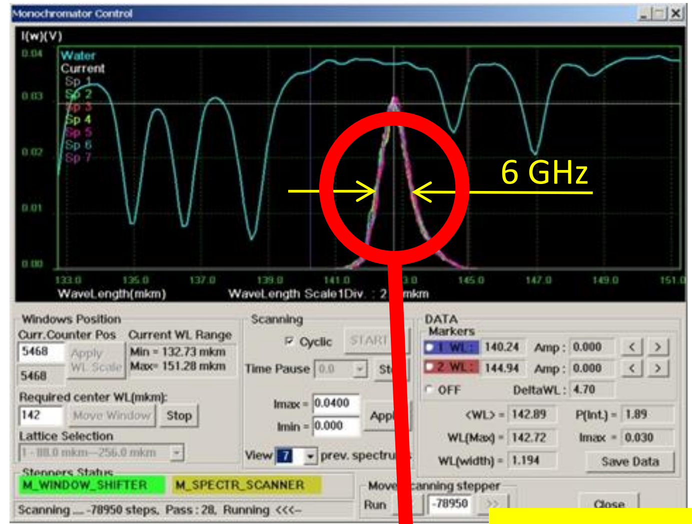


Typical regime of the NovoFEL: 1 pulse inside optical resonator

Hyperfine spectral structure of the NovoFEL

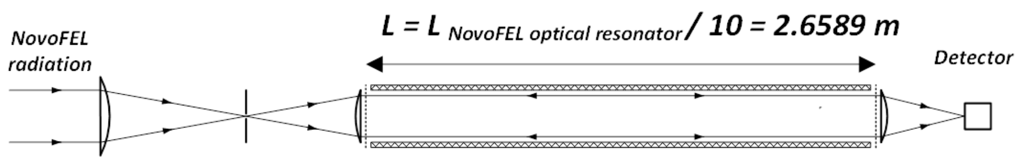
On-line grating spectrometer:



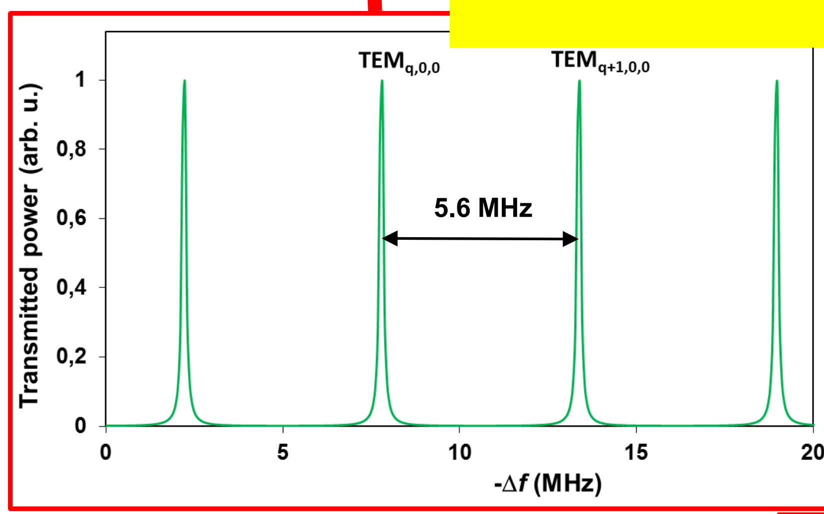


Hyperfine spectral structure of NovoFEL radiation

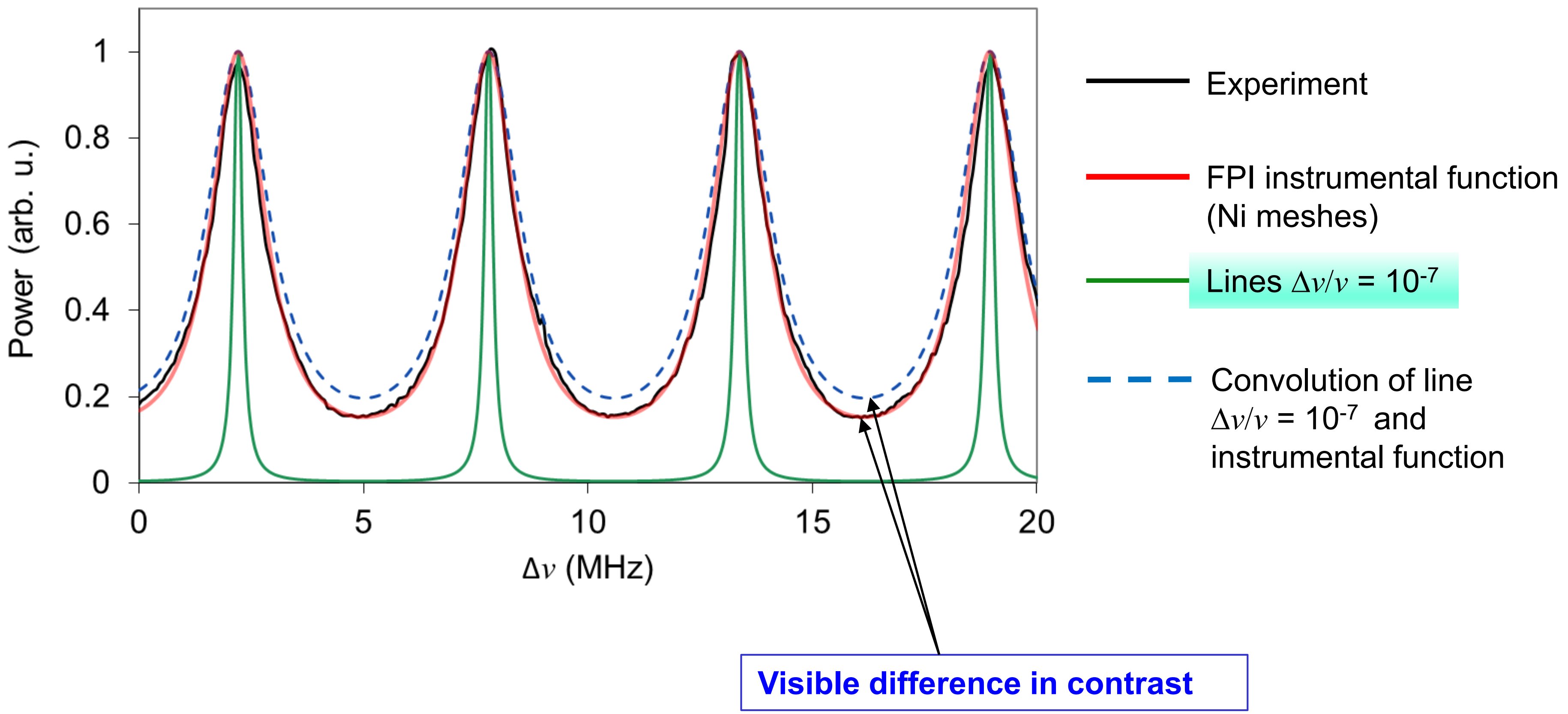
Ultra-long resonance waveguide vacuum Fabry-Perot interferometer:



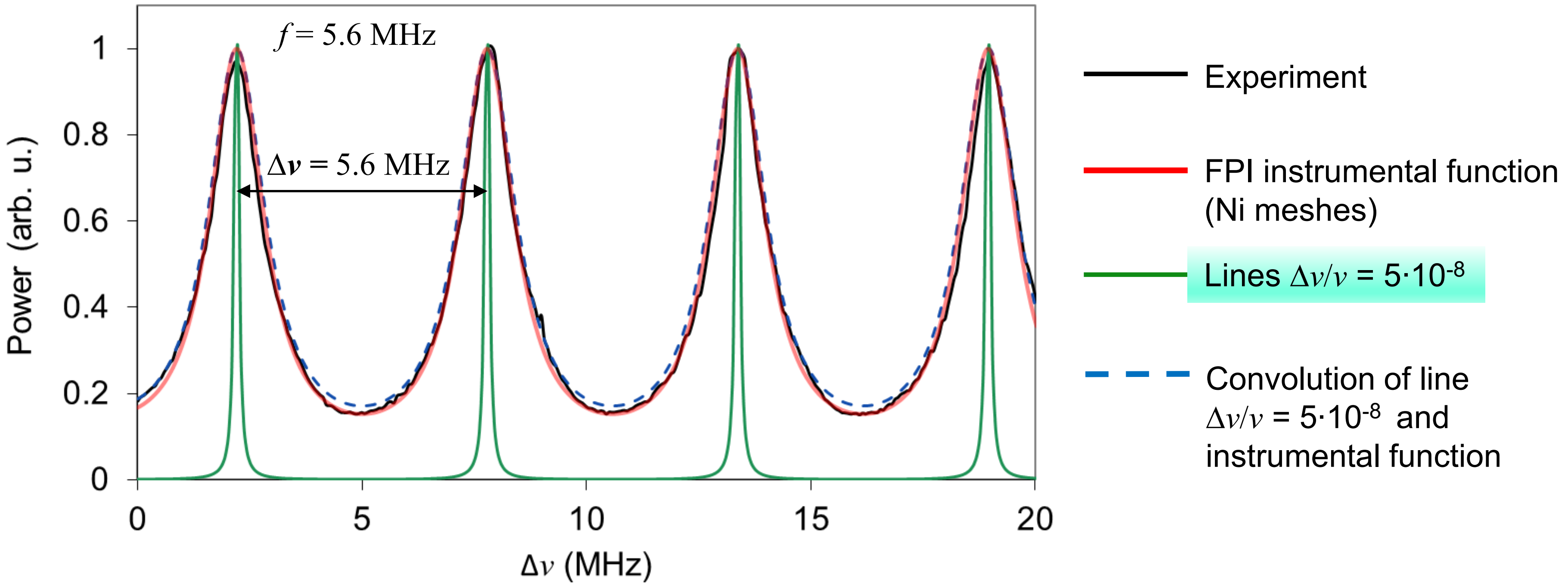
$\lambda_0 = 168$ μm



Hyperfine spectral structure of the NovoFEL: Pure TEM_{q00}-modes



Hyperfine spectral structure of the NovoFEL: Pure TEM_{q00}-modes



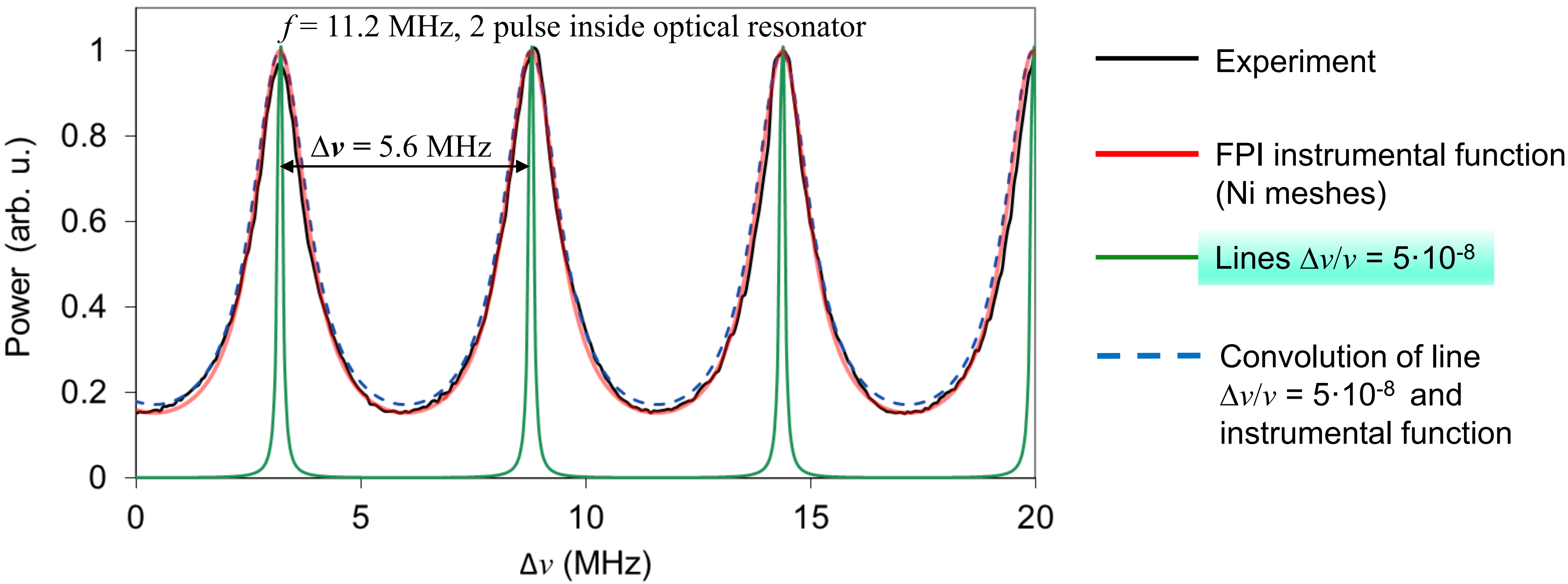
NovoFEL lines (longitudinal modes) $\Delta\nu/\nu \le 5\cdot10^{-8}$ ($\Delta\nu \le$ 100 kHz) – upper estimate:

$(\Delta\nu/\nu)_{max}$ = λ / (Quality of passive optical resonator × 2 optical resonator length) = $\lambda / (Q \cdot 2L) = 2\cdot10^{-7}$
$(\Delta\nu/\nu)_{min}$ = Schawlow-Townes limit = $\lambda / (Q \cdot 2L \cdot N)$; N – number of photons in optical resonator (10^{10})

Main task here is measuring of real monochromaticity of the hyperfine lines.

Gold meshes with maximal density can increase FPI resolution (fineness) in 4 times only compare to present nickel meshes. We need to go from frequency-domain to time-domain.

Fine and hyperfine spectral structure of the NovoFEL

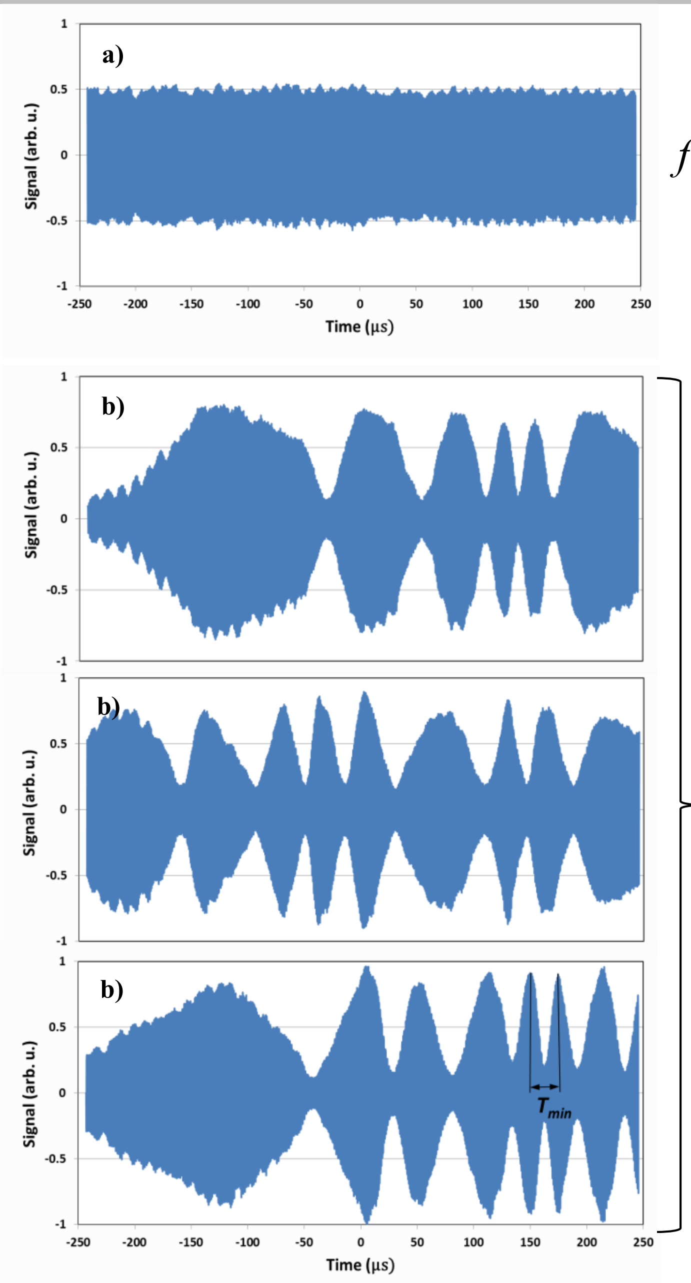


Spectra for *f* = 5.6 MHz (1 pulse) and *f* = 11.2 MHz (2 pulses) are identical.
Full absence of coherency between 2 pulses in optical resonator of the NovoFEL

Reason: Jitter $\delta f/f >> \lambda/2\Lambda = \lambda m/2L_0 = 5\cdot 10^{-6}$

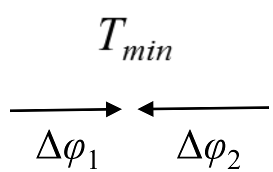
Very useful properties for time-domain experiment

Real parameters of hyperfine spectral structure of the NovoFEL



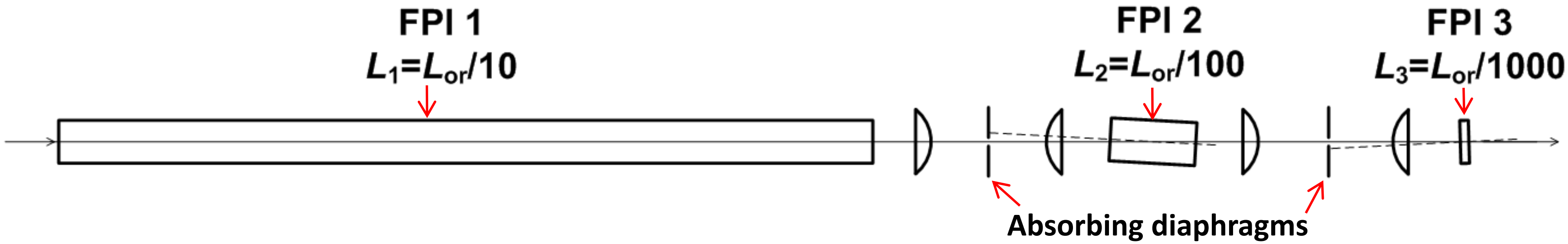
$f = 5.6$ MHz

$f = 11.2$ MHz



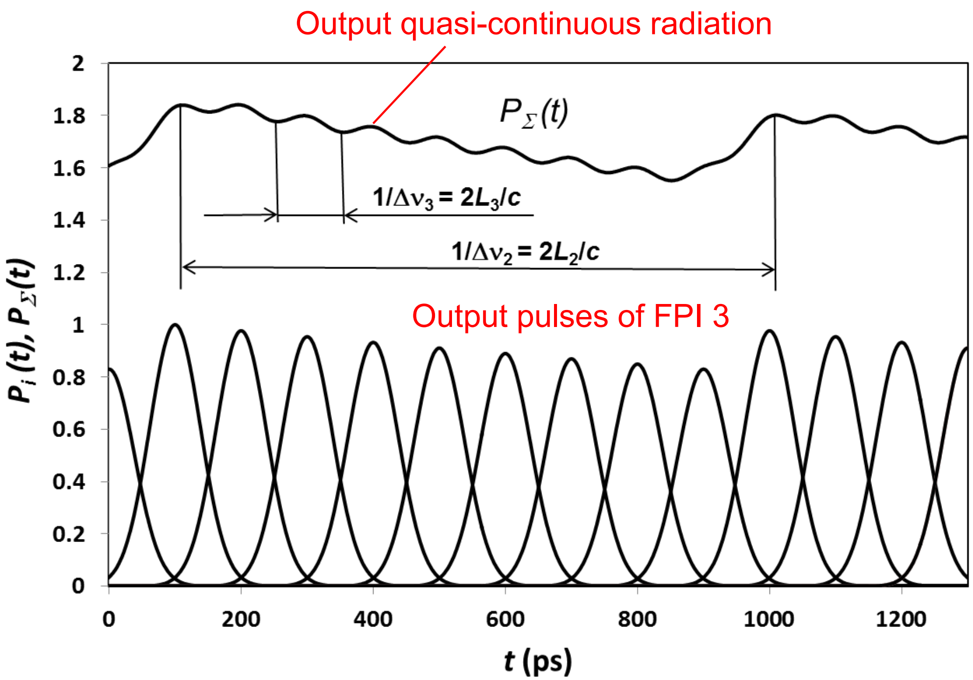
Hyperfine coherency time:	$T_{min} = 25$ μs
Average number of coherent output pulses in one-pulse 5.6-MHz regime:	140
Coherency length:	7 km
Monochromaticity of hyperfine comb-structure:	$2.2 \cdot 10^{-8}$ (40 kHz)

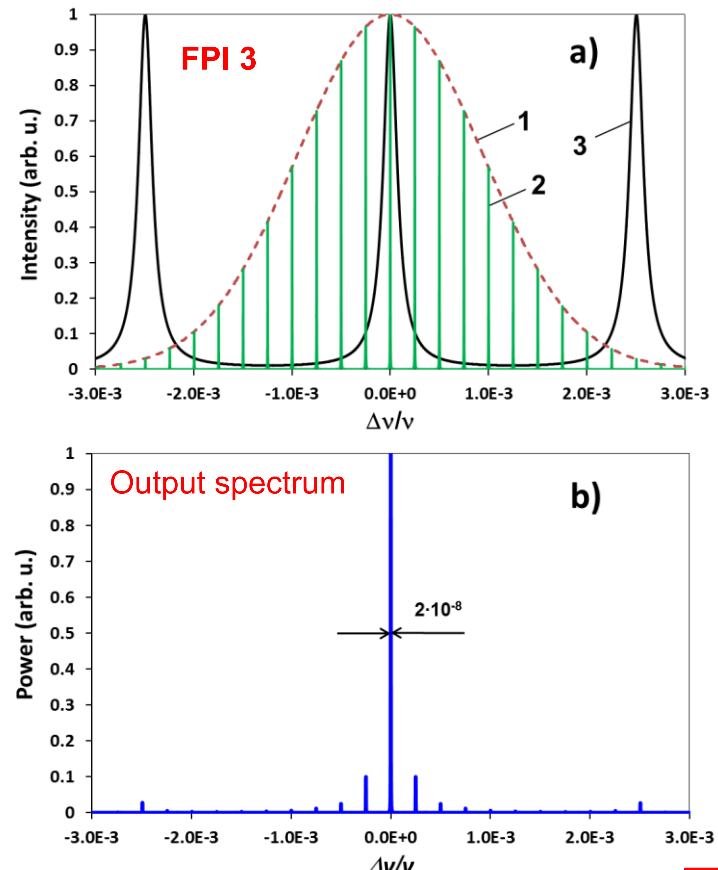
One-mode selection by three resonance Fabry-Perot interferometers



For $P_{\text{NovoFEL}} = 200$ W

$P_{\text{one selected mode}} = 50$ mW
$\nu = 1.5 – 3.3$ THz
$\Delta\nu \approx 40$ kHz





Conclusion

- The fine mode structure of the KAERI FEL radiation with a line monochromaticity of 10^{-4} was found (10 coherent intracavity pulses, 1/5 part)
- The hyperfine structure of the NovoFEL with a line monochromaticity of $2.2 \cdot 10^{-8}$ was measured (coherency length is 7 km). There is no fine mode structure or coherency between different pulses inside the optical resonator
- Knowledge of the real structure of the FEL's radiation is important both for their characterization and for different user spectroscopic methods developed on the facilities

Thank you for your attention !