Radiation stability and hyperfine mode structure of the terahertz NovoFEL

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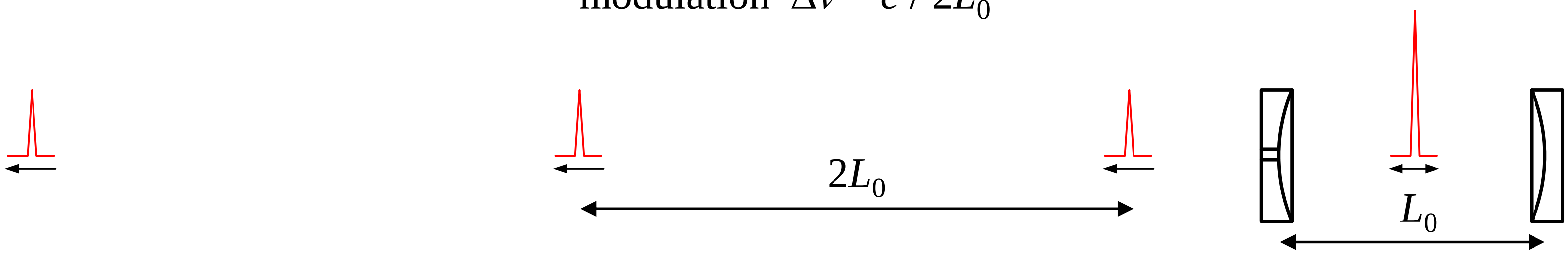
Three types of coherency and spectral structure in FELs

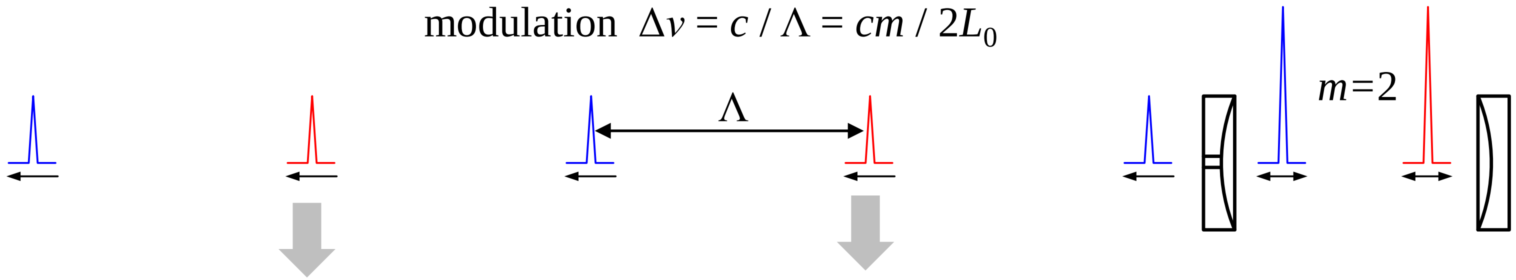
1) Hyperfine coherency – coherency between pulses radiated by one intra-cavity pulse:

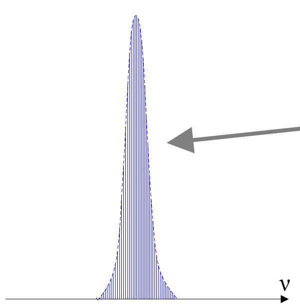
modulation $\Delta\nu = c / 2L_0$

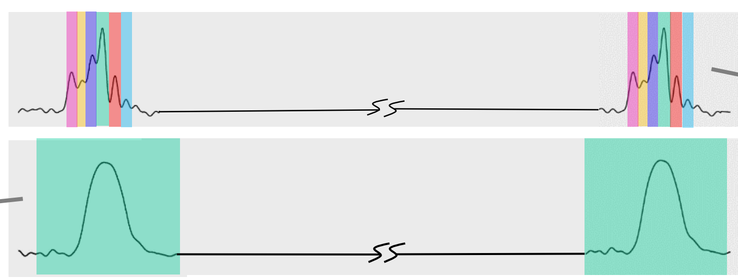


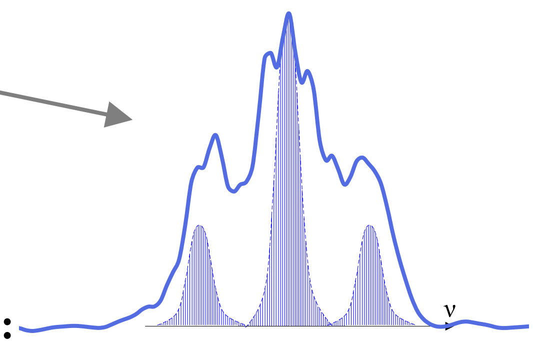
2) Fine coherency – coherency between different intracavity pulses:

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









3) Intra-pulse coherency – coherency inside pulse:

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

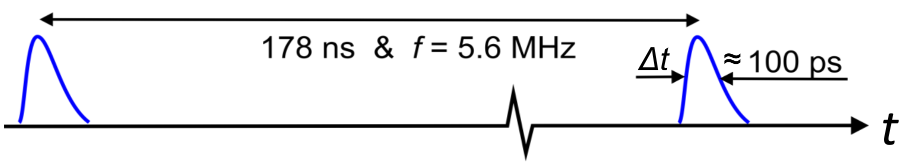
line width $\Delta\nu = c / L_{pulse} = 1/\Delta t$, stable regime, Fourier-transform limit

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

Radiation parameters of the NovoFEL

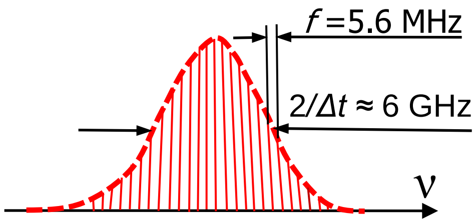
Laser	Terahertz	Far-Infrared	Infrared
Status	In operation since 2003	In operation since 2009	In operation since 2015
Wavelength, μm	90 – 240	37 – 80	8 – 11 (7–30)
Relative spectral width (FWHM), %	0.2 – 2	0.2 – 2	0.1 – 1
Monochromaticity	$2 \cdot 10^{-8}$		
Maximum average power, kW	0.5	0.5	0.1 (1)
Maximum 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:



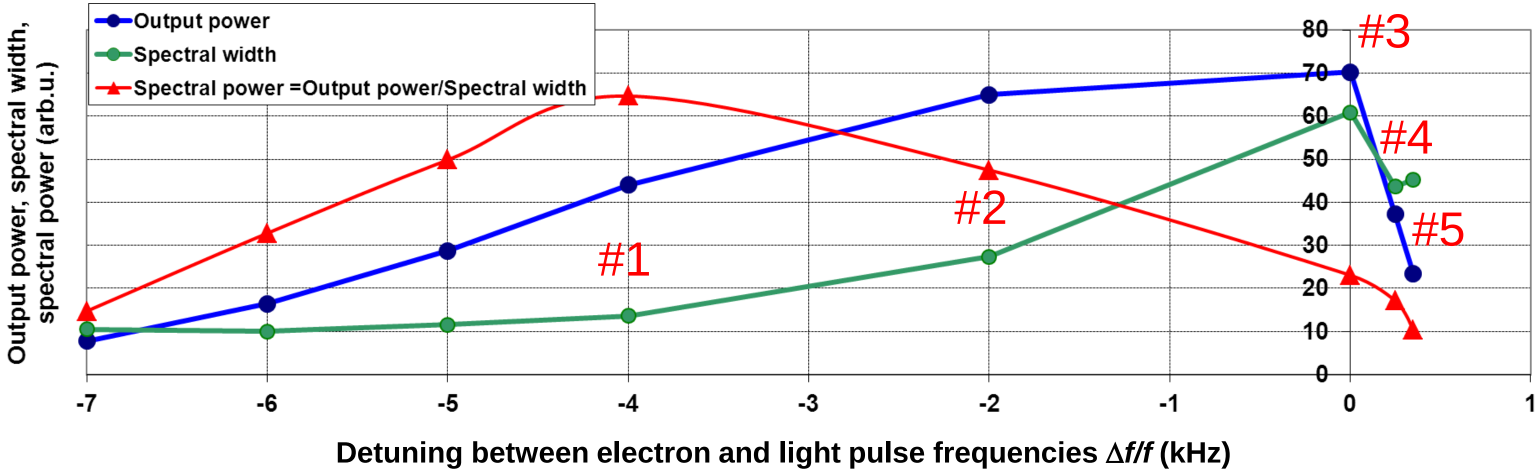
Fourier transform of coherent laser pulses:

Hyperfine mode structure with
$\Delta\nu = f = c/2L_0$ = 5.6 MHz

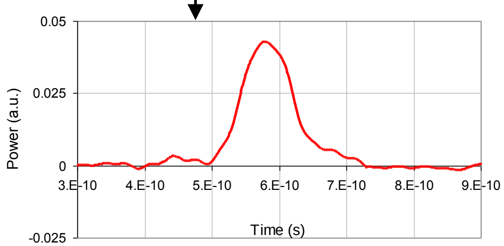


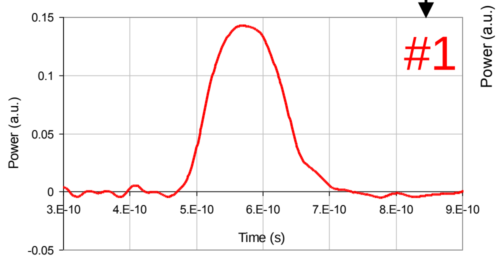
Number of intracavity pulses: m = 1 ; 2 ; 4
5.6 MHz ; 11.2 MHz ; 22.4 MHz

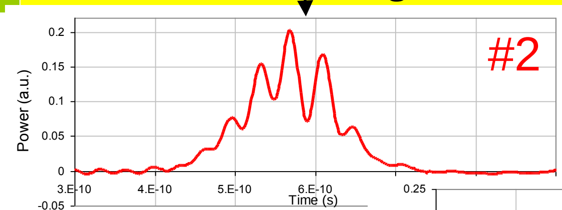
Three operating regimes of THz NovoFEL. Intra-pulse coherency

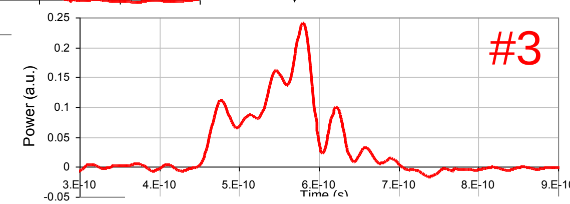


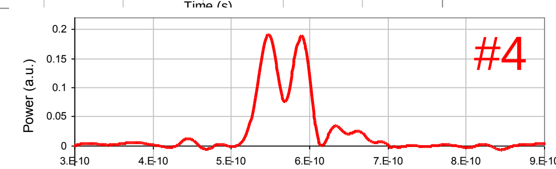
Stable regime | **Multimode regime** | **Unstable regime**

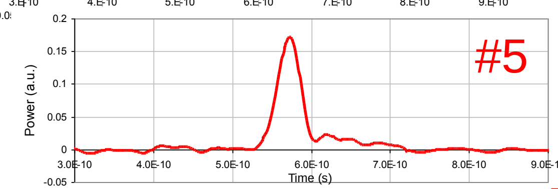












Resonance (unstable) and stabilized regimes of the NovoFEL

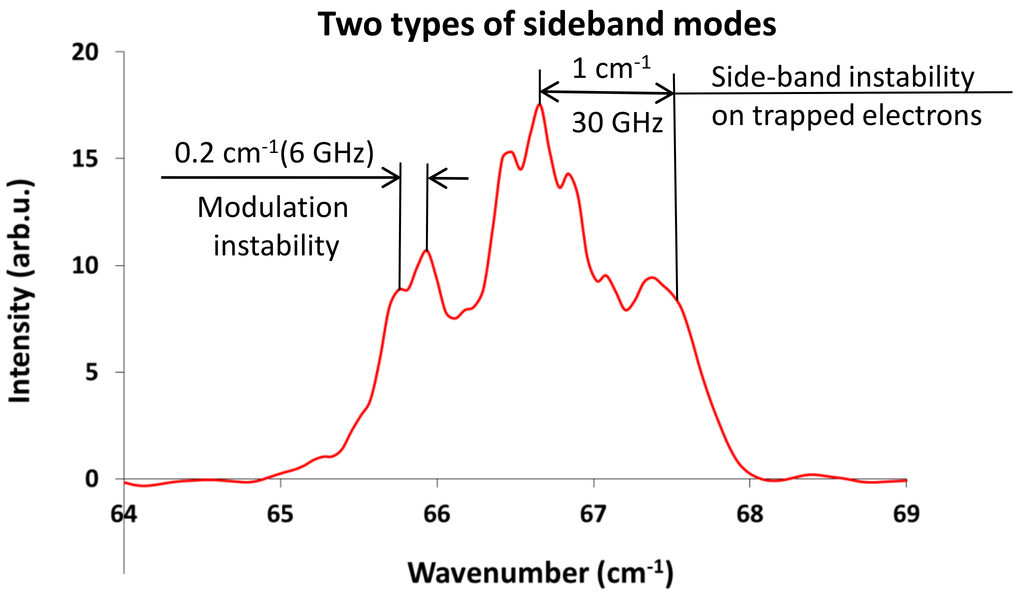
Resonance (unstable) regime:

Detuning of electron and light pulse repetition frequencies $\Delta f/f = 0$

P= Max

Two types of side-band (modulation) instabilities

Coherency length < pulse length



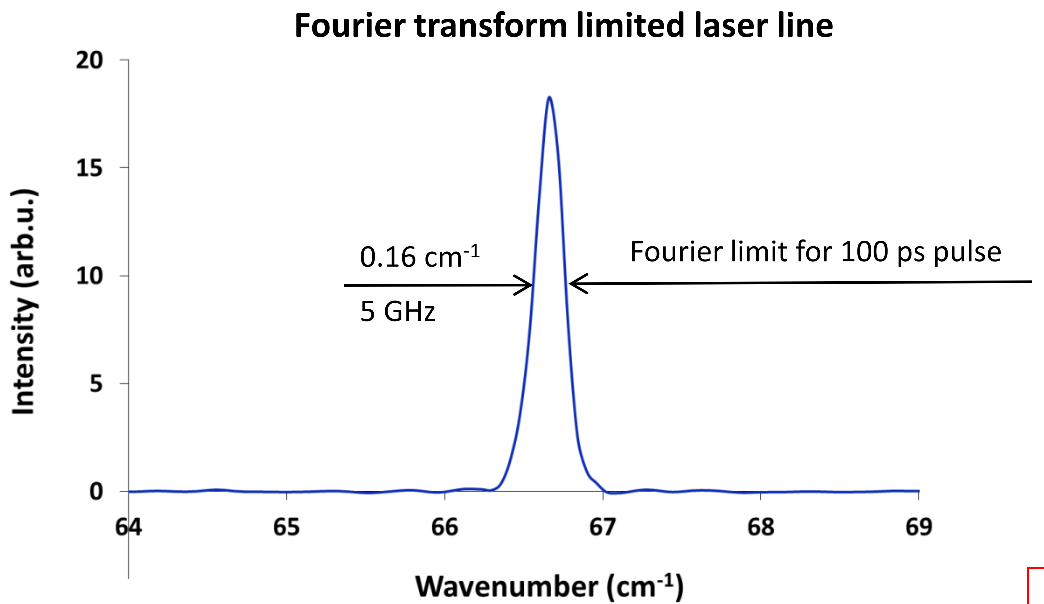
Stabilized regime:

Detuning of electron and light pulse repetition frequencies $\Delta f/f \approx 2.5 \cdot 10^{-5}$

P ≈ Max/2

Side-band (modulation) instabilities are fully suppressed

Coherency length > pulse length



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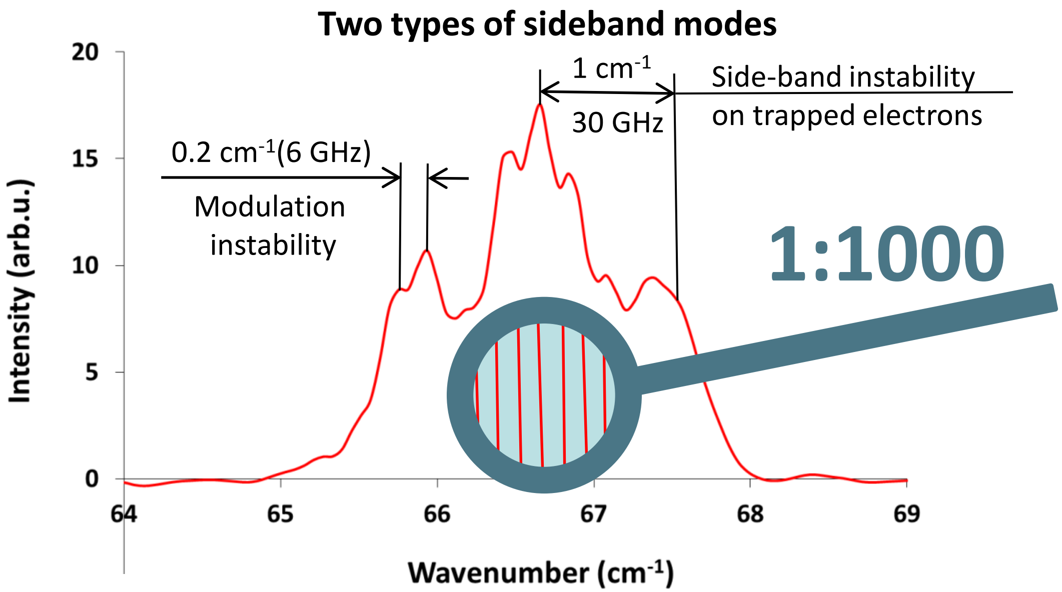

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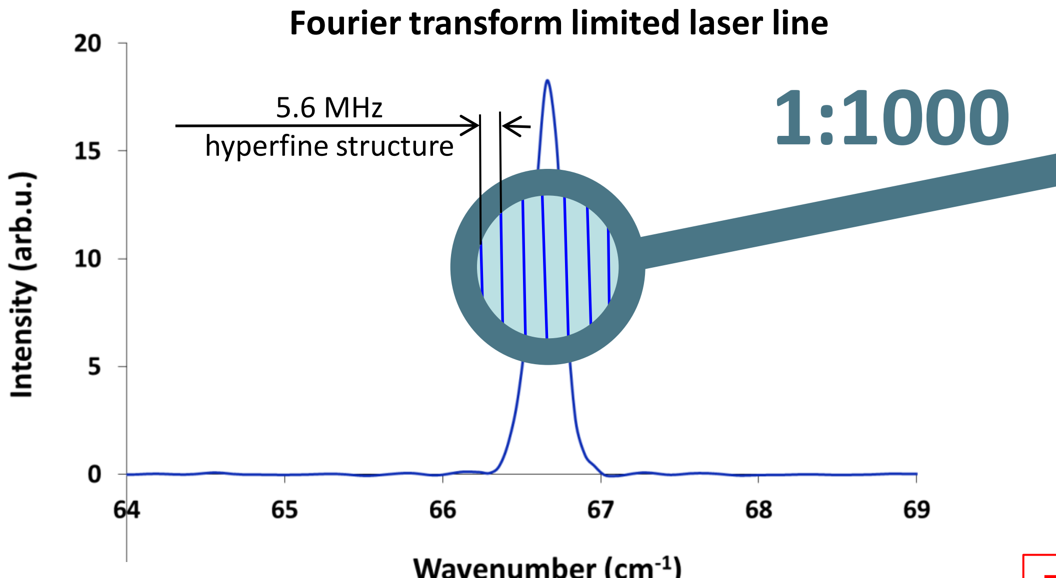

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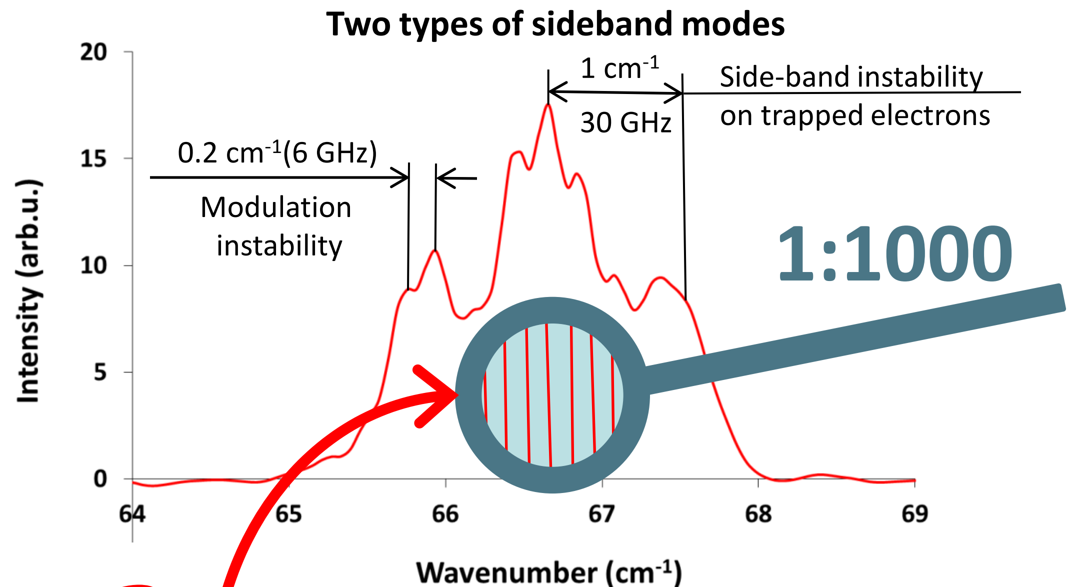

there is a difference ?

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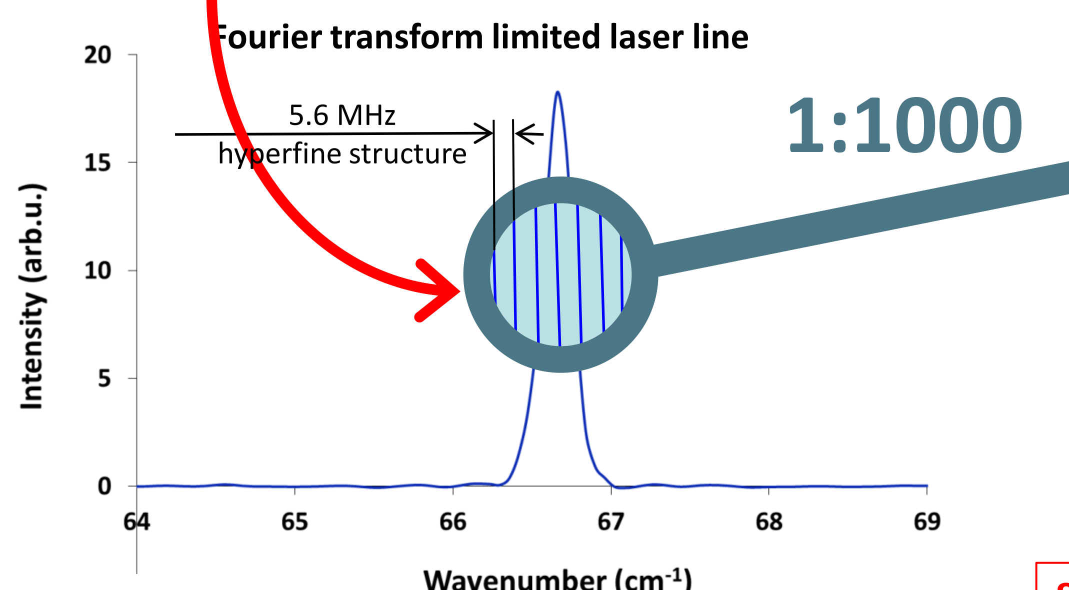
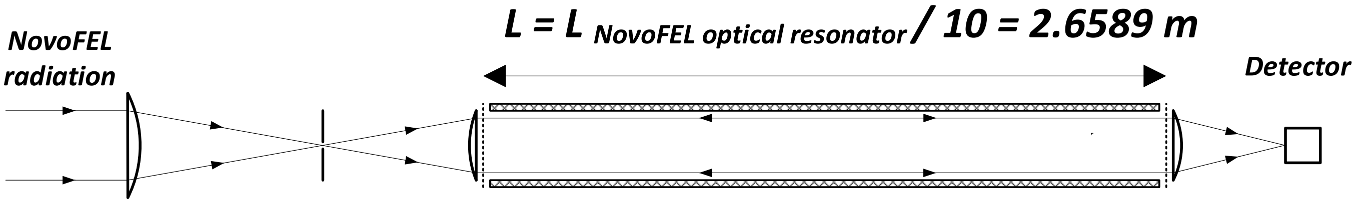


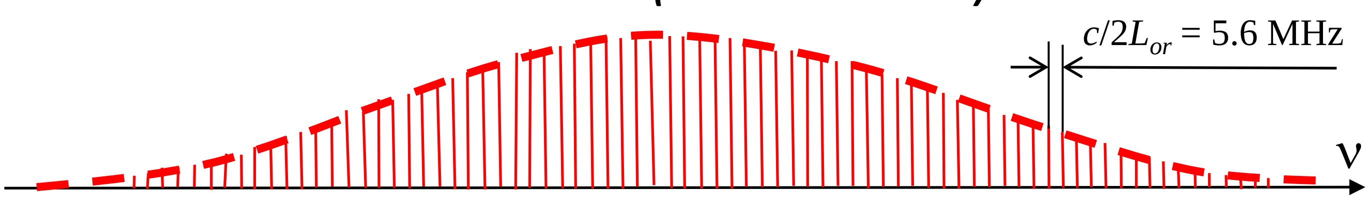
Ultra-long resonance waveguide vacuum Fabry-Perot interferometer (2017)

Modified optical resonator of universal gas laser

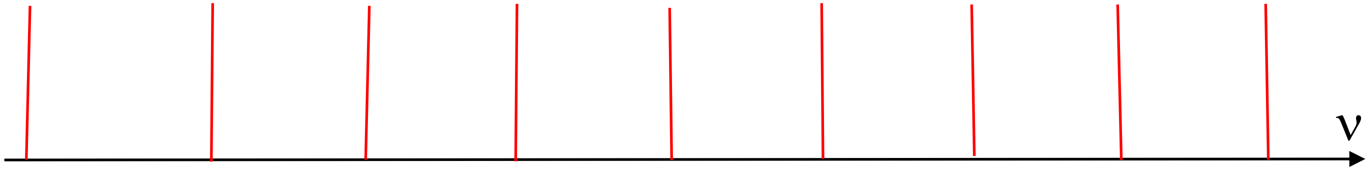
The universal gas laser in active mode will used for heterodyne measurement of line width in fine mode structure



NovoFEL lines (≈ 1000-2000 lines):

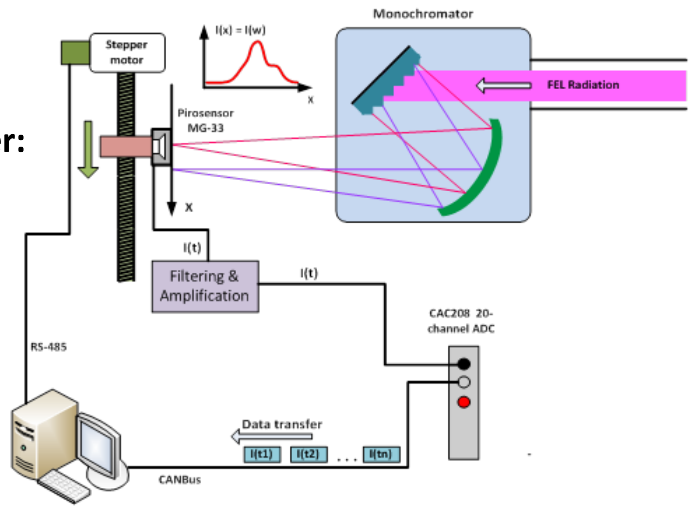


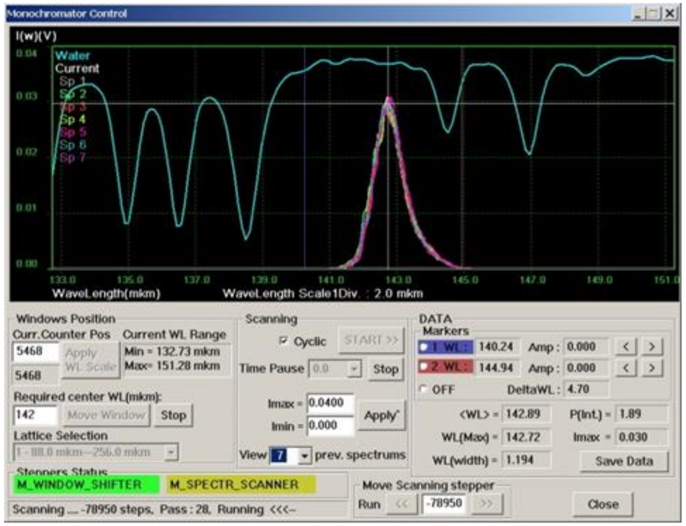
Fabry-Perot instrumental function (100-200 lines in NovoFEL radiation contour):



Hyperfine spectral structure of the NovoFEL

On-line grating spectrometer:

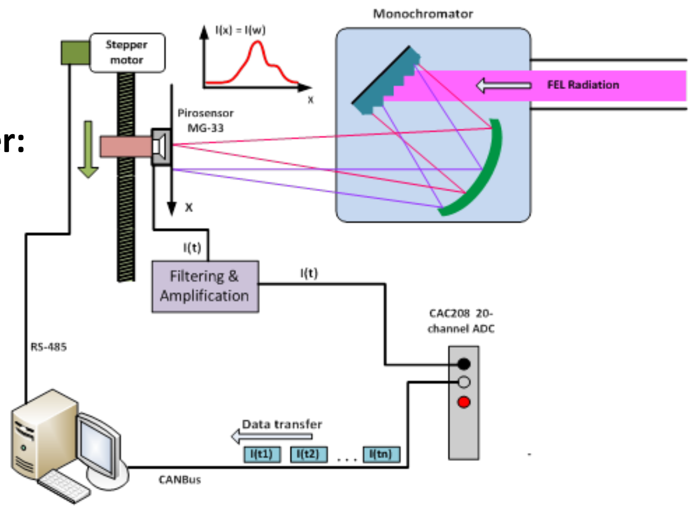


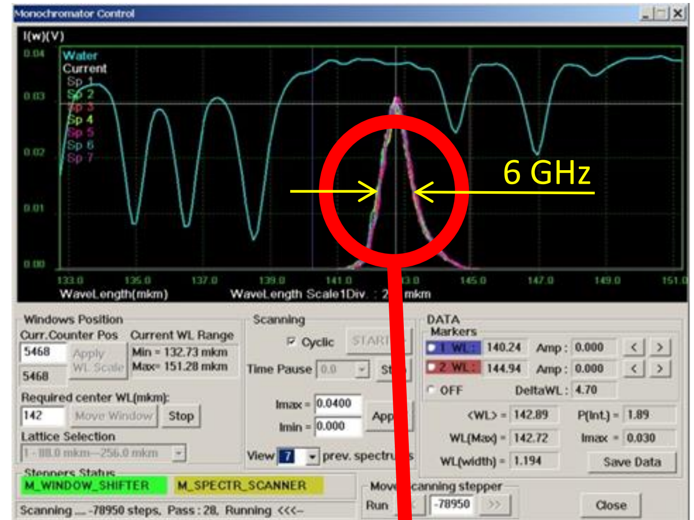


Typical regime of the NovoFEL: 1 pulse inside optical resonator

Hyperfine spectral structure of NovoFEL radiation

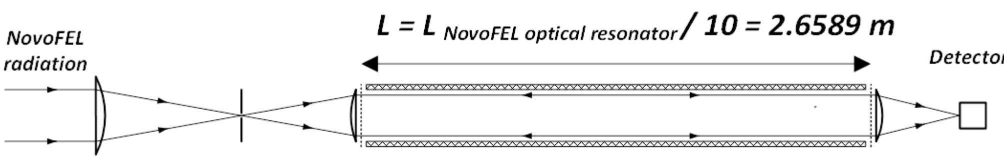
On-line grating spectrometer:

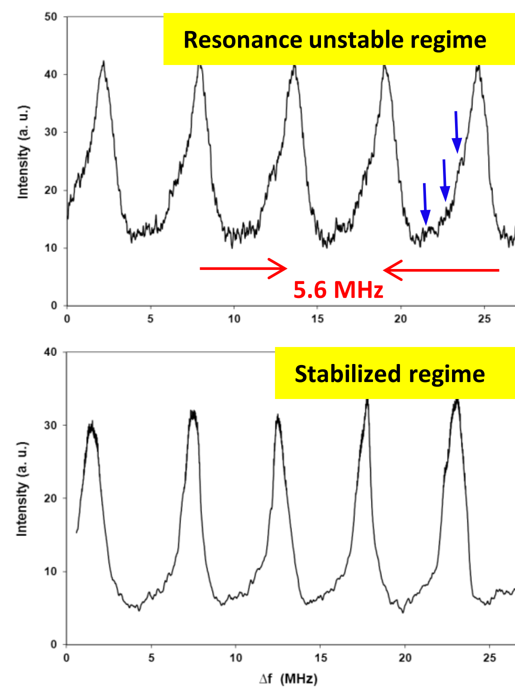




$\lambda_0 = 168\ \mu m$

Ultra-long resonance waveguide vacuum Fabry-Perot interferometer:

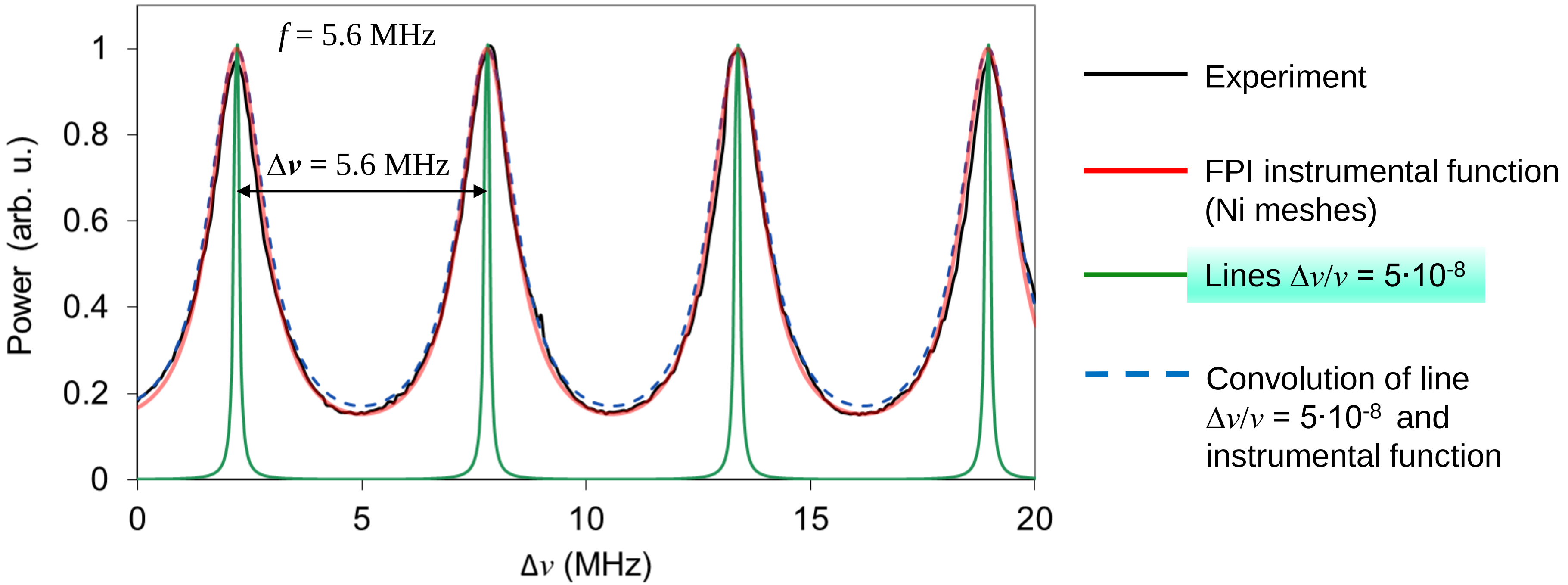




Week transverse modes

Small difference

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



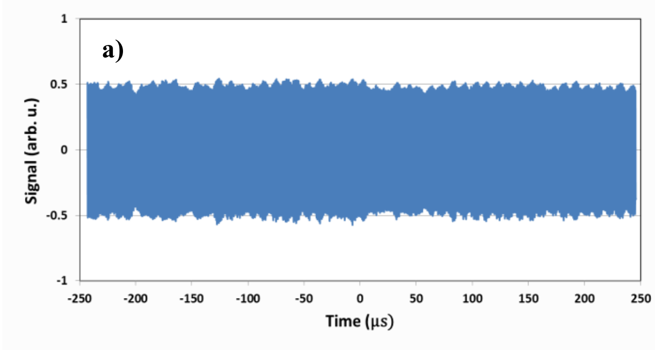
NovoFEL lines (longitudinal modes) $\Delta\nu/\nu \leq 5\cdot10^{-8}$ ($\Delta\nu \leq 100$ kHz) – upper estimate.

$(\Delta\nu/\nu)_{max}$ = λ / (Quality of passive optical resonator × 2 optical resonator length) = $\lambda / (Q \cdot 2L) = 2\cdot10^{-7}$
$(\Delta\nu/\nu)_{min}$ = Schawlow-Townes limit for lasers = $\lambda / (Q \cdot 2L \cdot N) = 2\cdot10^{-21}$; N – number of photons in optical resonator (10^{14})
$(\Delta\nu/\nu)_{min}$ = For free-electron lasers = $N_e / N_e^2 = 1 / N_e = 10^{-10}$; N_e – number of electrons in pulse (10^{10})

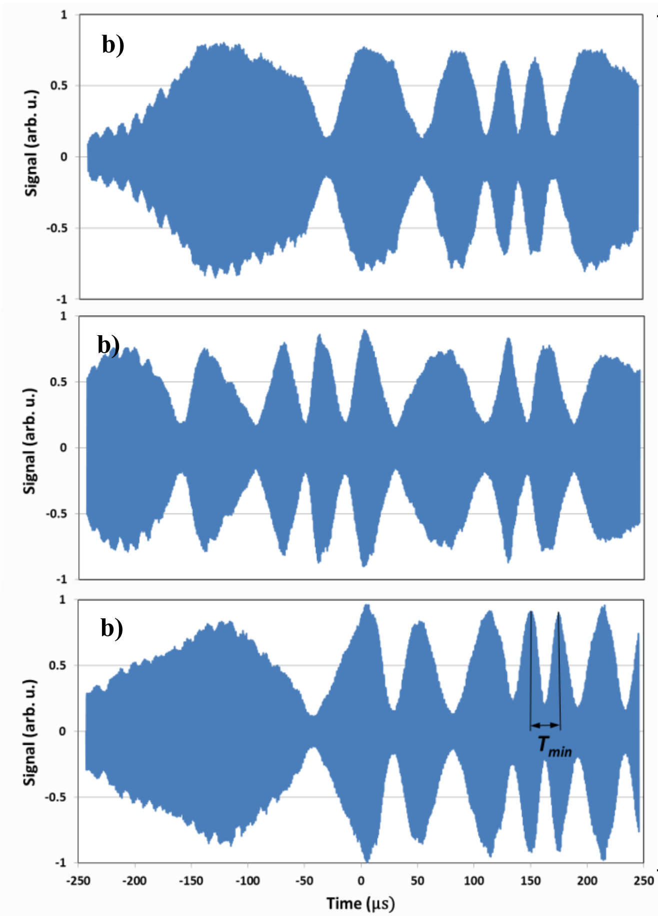
Main task here is measuring of real monochromaticity of the hyperfine lines.

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.

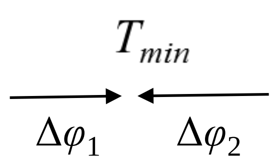
Real parameters of hyperfine spectral structure of the NovoFEL



f = 5.6 MHz,
1 intracavity pulse



f = 11.2 MHz,
2 intracavity pulses

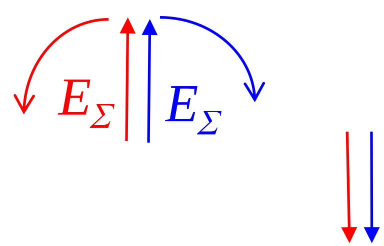


Hyperfine coherency time: T_{min} = 25 μs

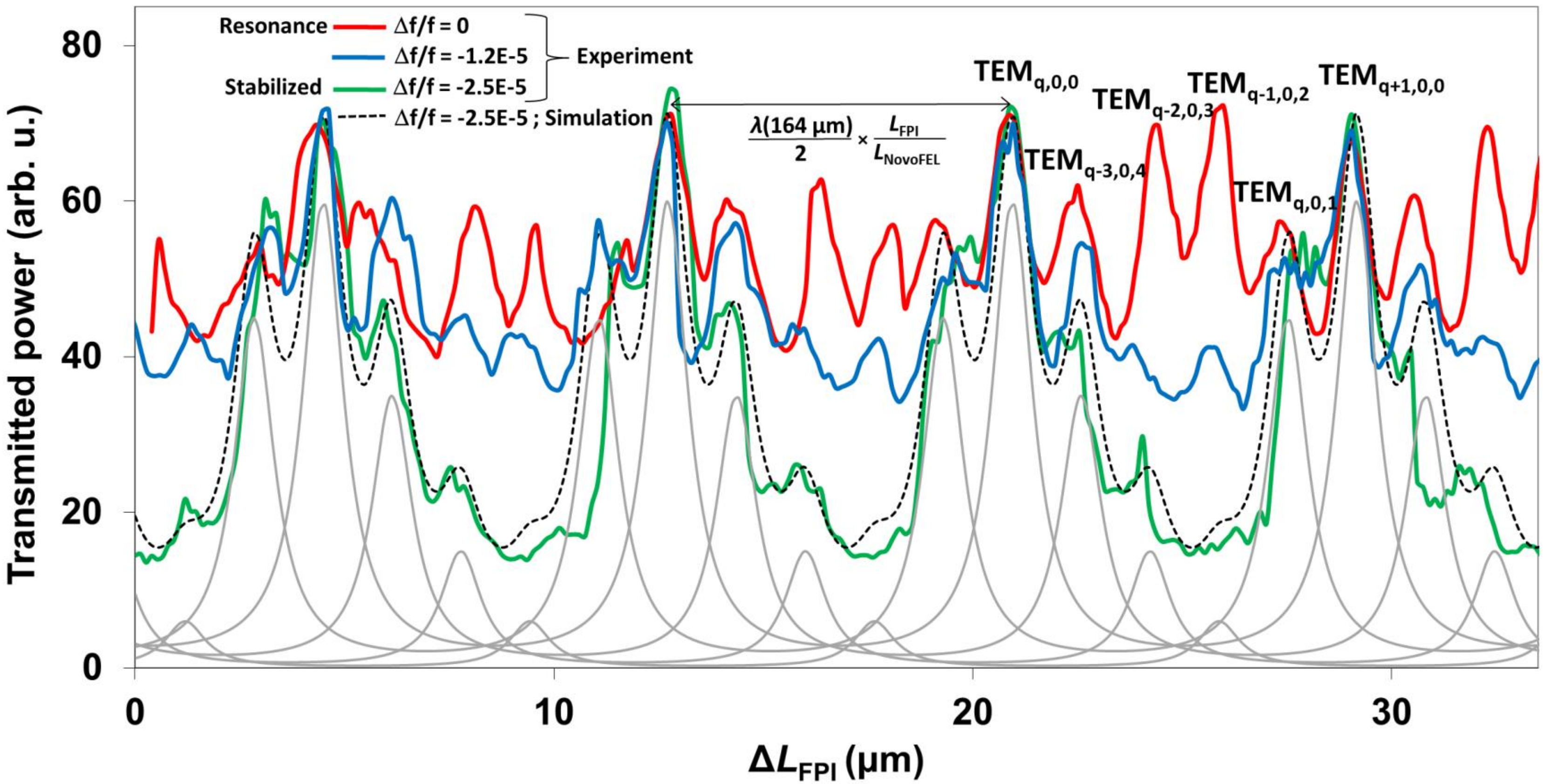
Average number of coherent output pulses in one-pulse 5.6-MHz regime: 140

Coherency length: 7 km

Monochromaticity of hyperfine comb-structure: $2.2 \cdot 10^{-8}$ (40 kHz)



Hyperfine spectral structure of NovoFEL radiation in regimes with imperfect electron beam



Transverse modes are much more intense in the resonance regime compared with the stabilized one

Phase of TEM*qnm* - mode:	$\Phi(n,m,z)=(n+m+1)\cdot\mathrm{atan}(z/L_R)$
Transverse mode indexes:	n – horizontal, m – vertical
	L_R – Rayleigh length

The reasons: 1) Low-energy tail in electron beam → Turning magnet → Vertical angles → Excitation of vertical transverse modes

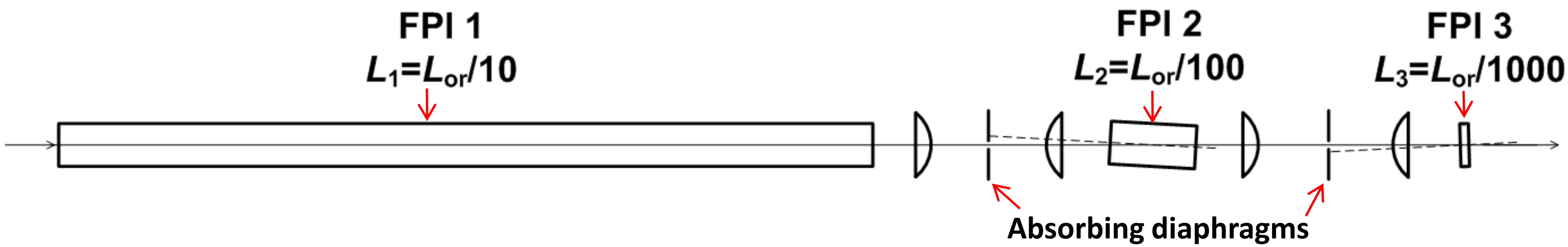
2) Non-axial input of electron beam in undulator → Vertical betatron oscillation of electron → Excitation of vertical transverse modes

Conclusion

- The hyperfine structure of the NovoFEL with a line monochromaticity of $2.2 \cdot 10^{-8}$ was measured (coherency length is 7 km, number of coherent output pulses is 140)
- There is no fine mode structure or coherency between different pulses inside the optical resonator of the NovoFEL
- Hyperfine structure is practically single-mode and the same in resonance and stabilized regime for perfect electron beam
- Hyperfine structure has intense transverse modes for imperfect electron beam. The power of the transverse modes increases significantly in resonance regime.

Thank you for your attention !

One-mode selection by three resonance Fabry-Perot interferometers



For P_{NovoFEL} = 200 W

$P_{\text{one selected mode}}$ = 50 mW

ν = 1.5 – 3.3 THz

Δν ≈ 40 kHz