Aspects of THz FELs

A.F.G. van der Meer

FELIX facility

FOM-Rijnhuizen, Nieuwegein /

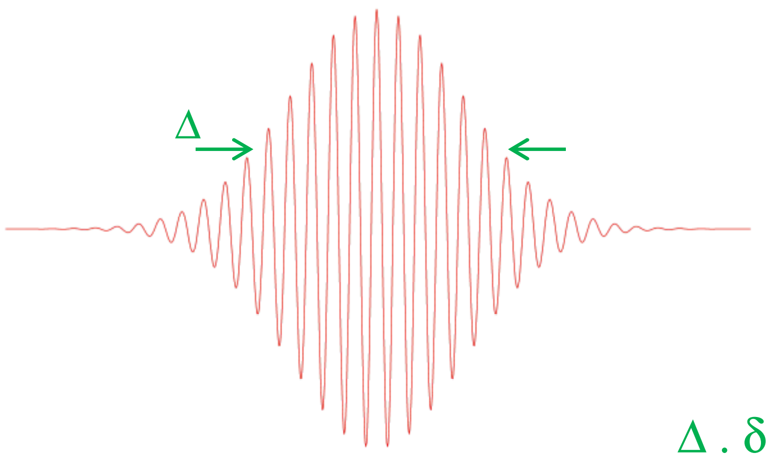
Radboud university, Nijmegen

Outline

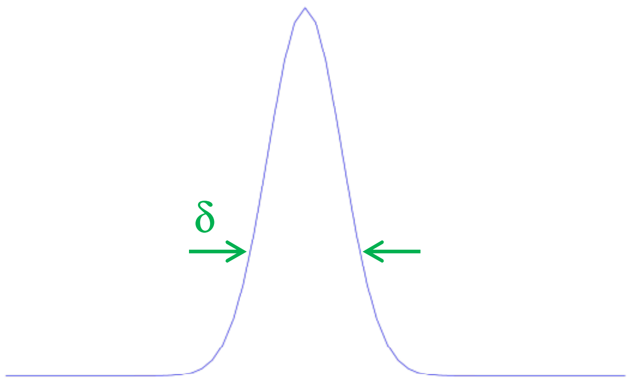
- Radiation bandwidth
- Slippage effects
- Resonator issues
- THz FEL facilities

Radiation bandwidth: Fourier transform

pulse shape



spectrum



$\Delta \, . \, \delta \; \varepsilon$ constant

'transform limited' : no frequency / phase fluctuations of the carrier

Radiation bandwidth: long pulse

For μs pulses, sub-MHz bandwidth in principle possible

However:

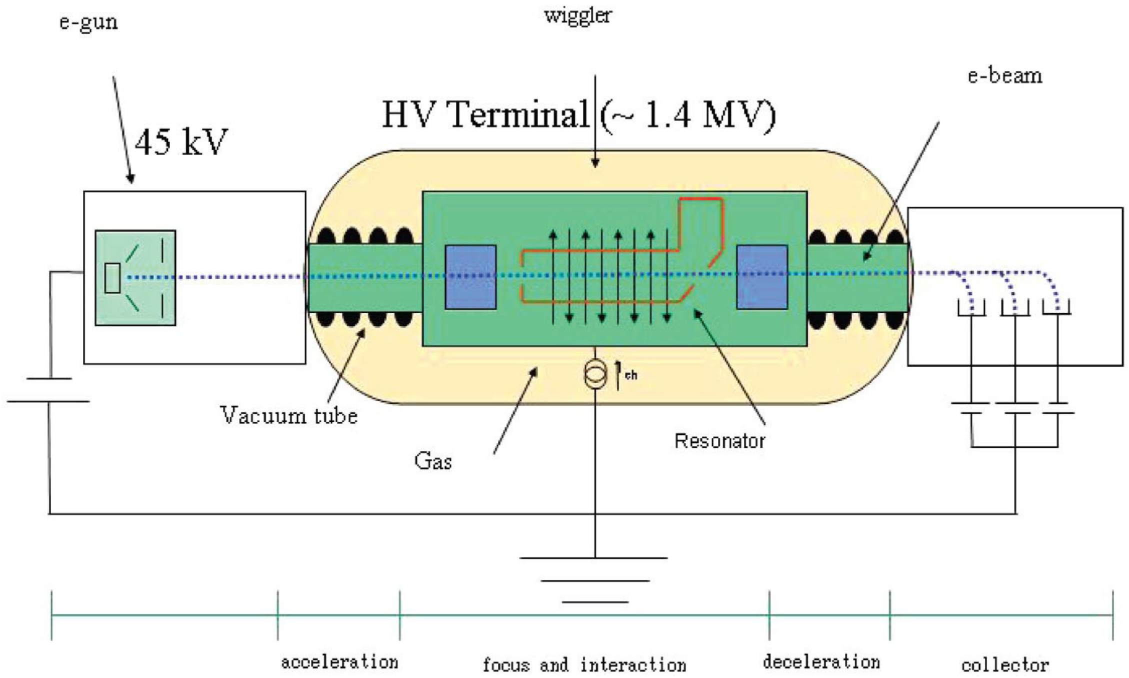
- Start-up from noise
- During one roundtrip no communication between parts of the optical pulse that are further than $N_u \,.\, \lambda$ apart
- Mode competition can be slow:

$$\Delta\omega/\omega \approx (t / \tau_c)^{1/2} / (2 \,.\, N_u)$$, with τ_c the cavity decay time

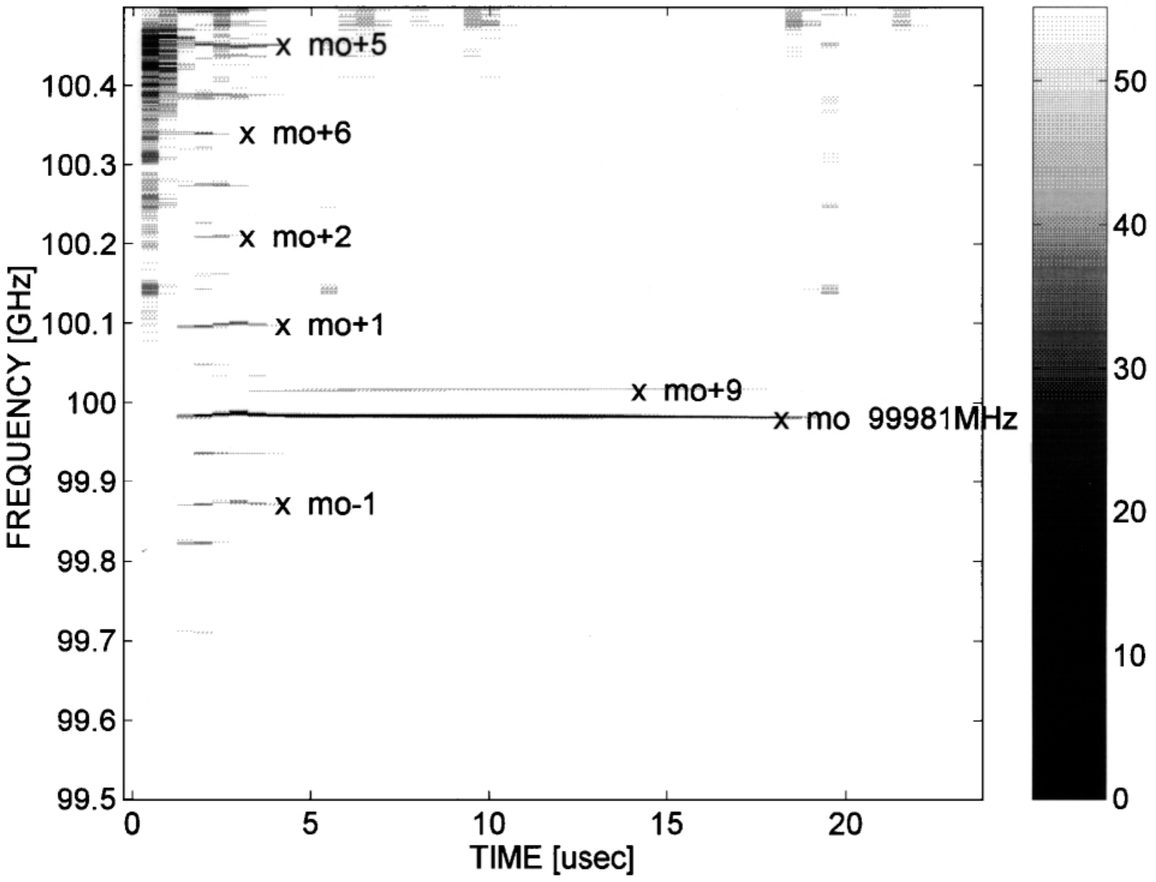
T.M. Antonsen et al. PRL 62 (1989) 1488

Radiation bandwidth: mm-wave

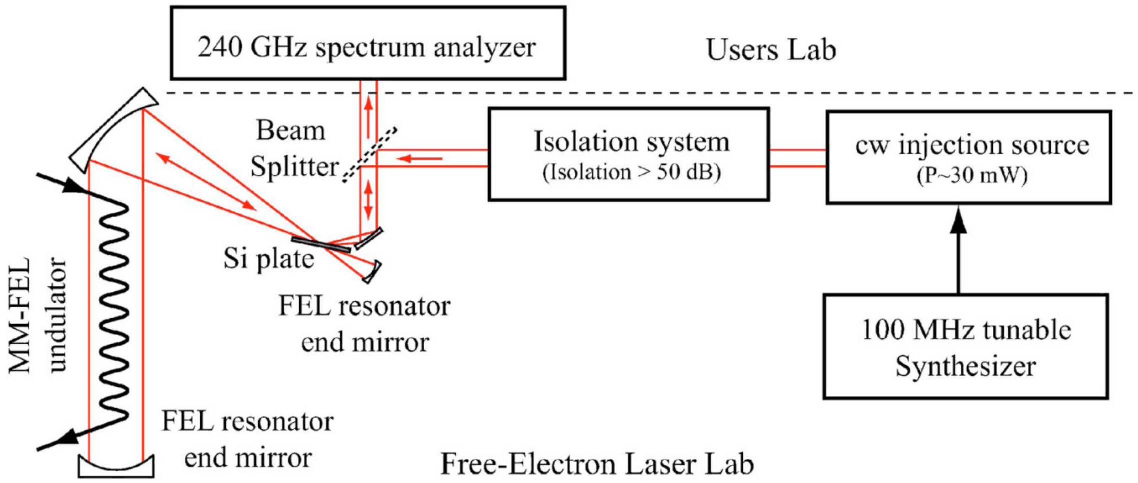
EA-FEL

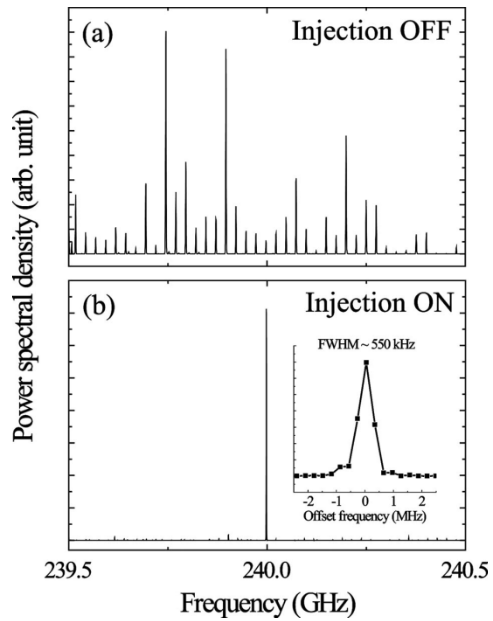


Radiation bandwidth: EA-FEL single mode



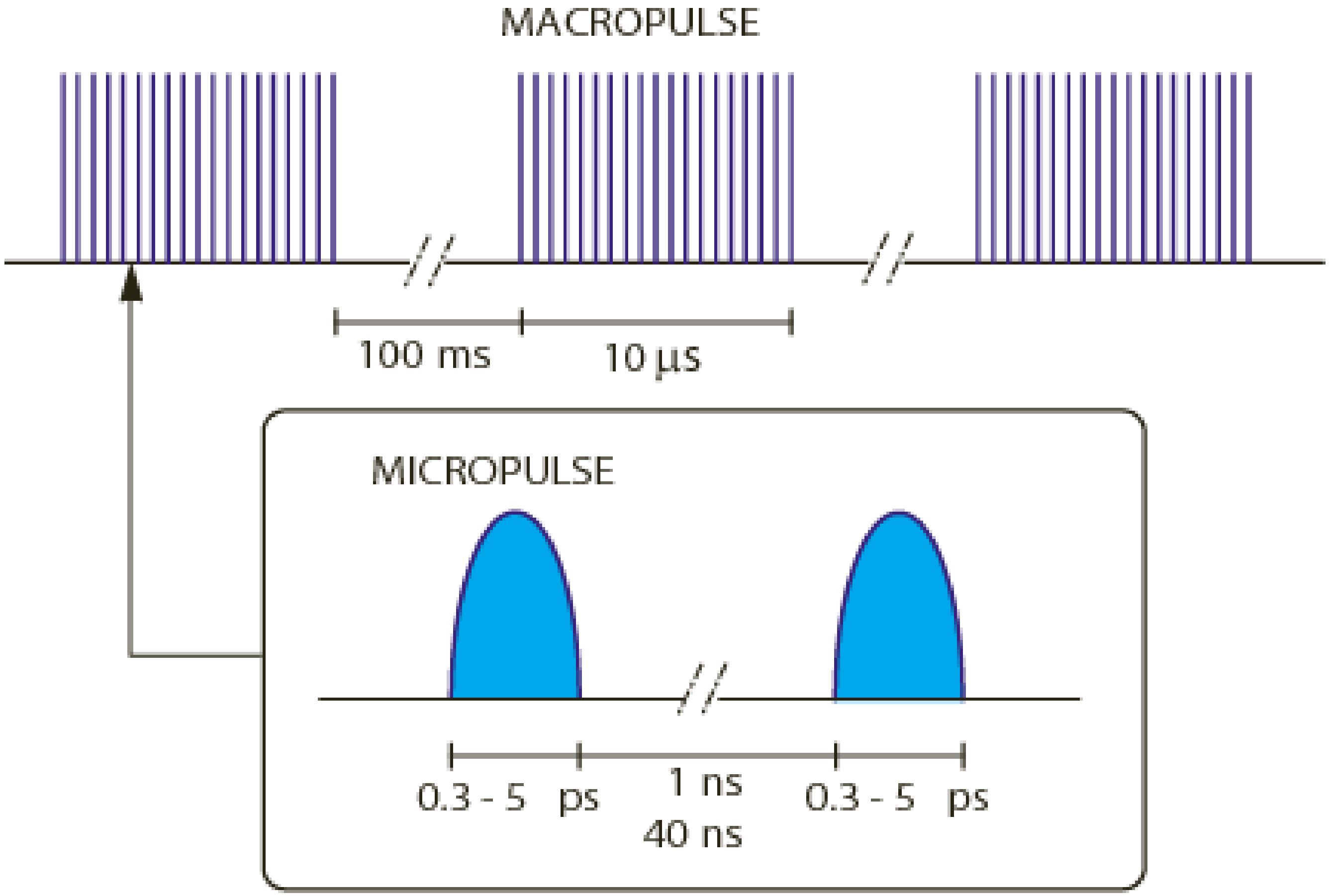
Radiation bandwidth: injection locking UCSB





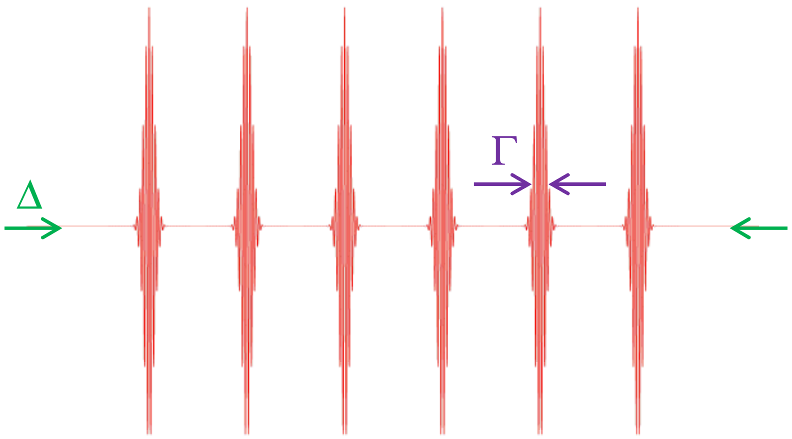
S. Takahashi et al. PRL 91 (2007) 174102

Radiation bandwidth: linac pulse structure

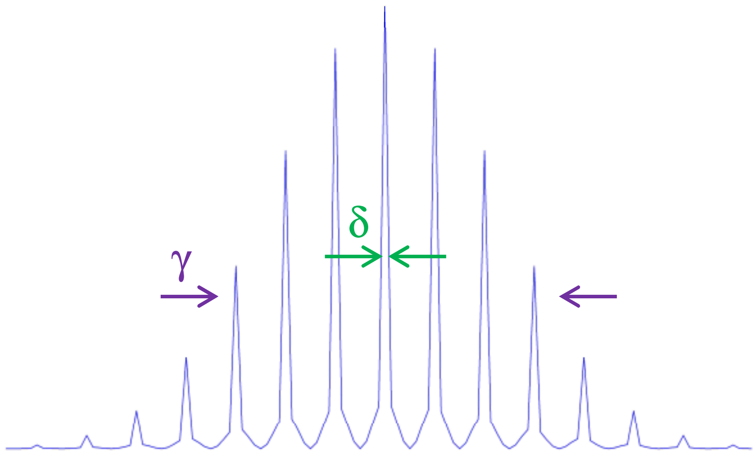


Radiation bandwidth: Fourier transform

multiple pulses



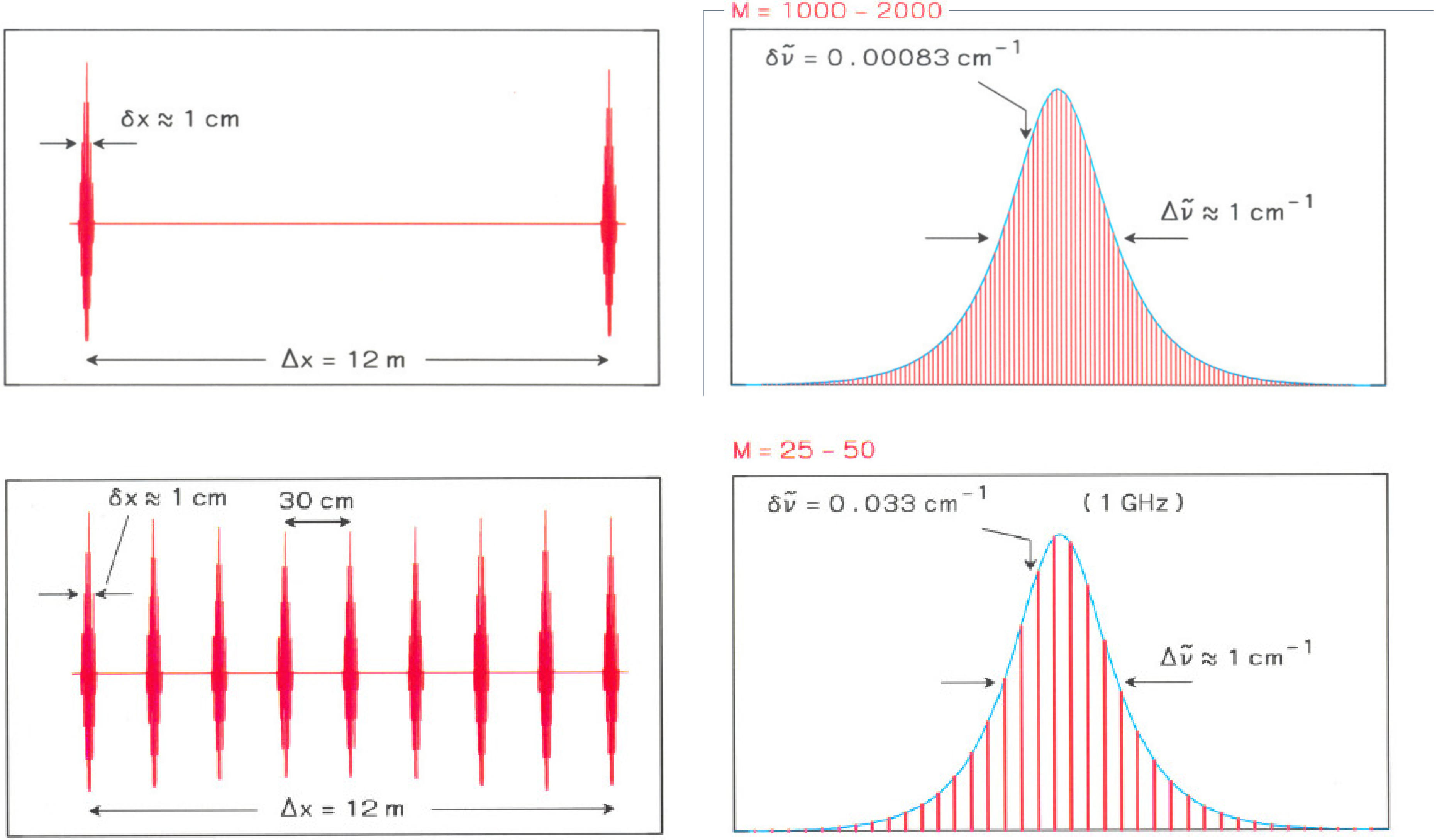
multiple spikes



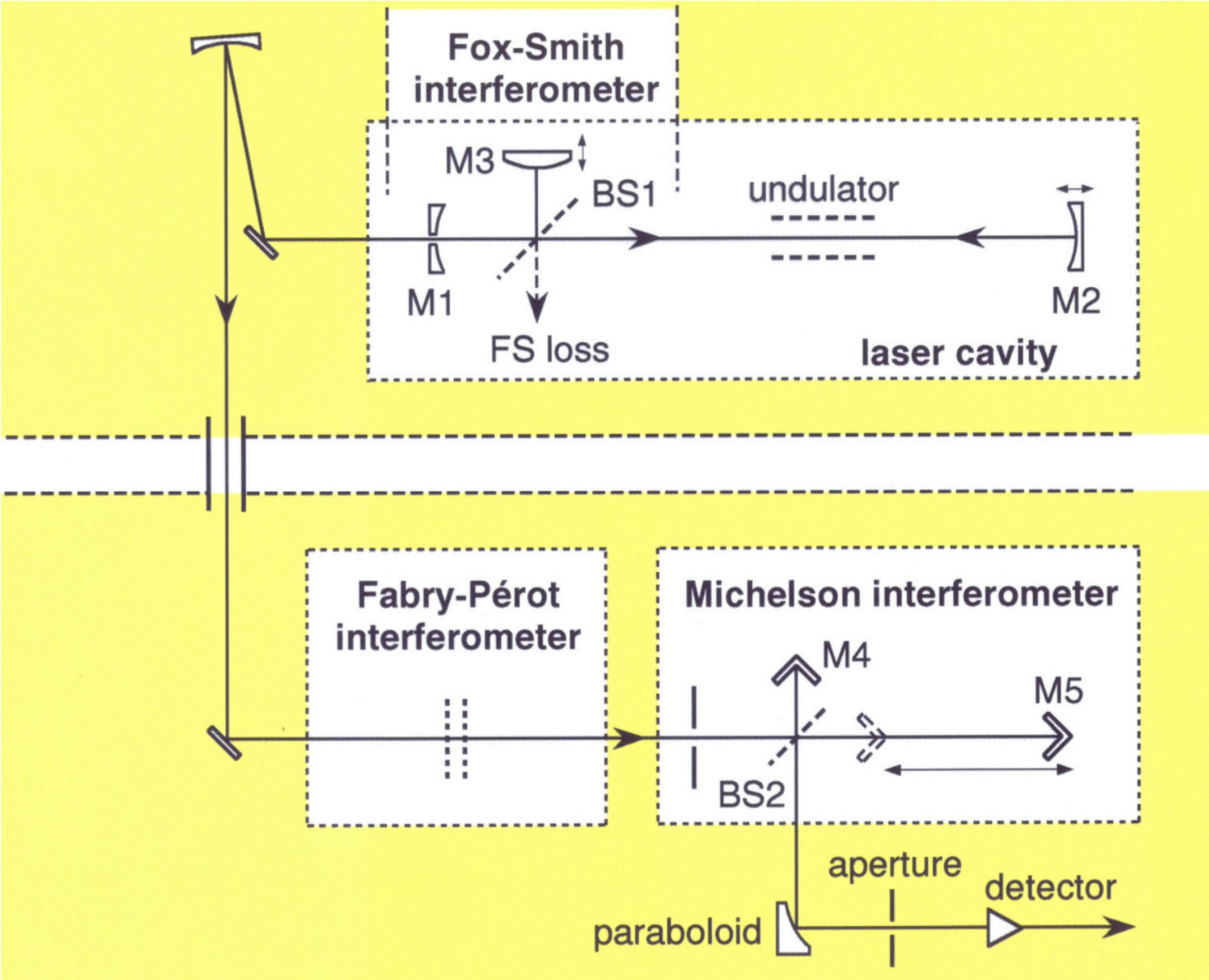
$$\Gamma \,.\, \gamma = O(1)$$

$$\Delta \,.\, \delta = O(1)$$

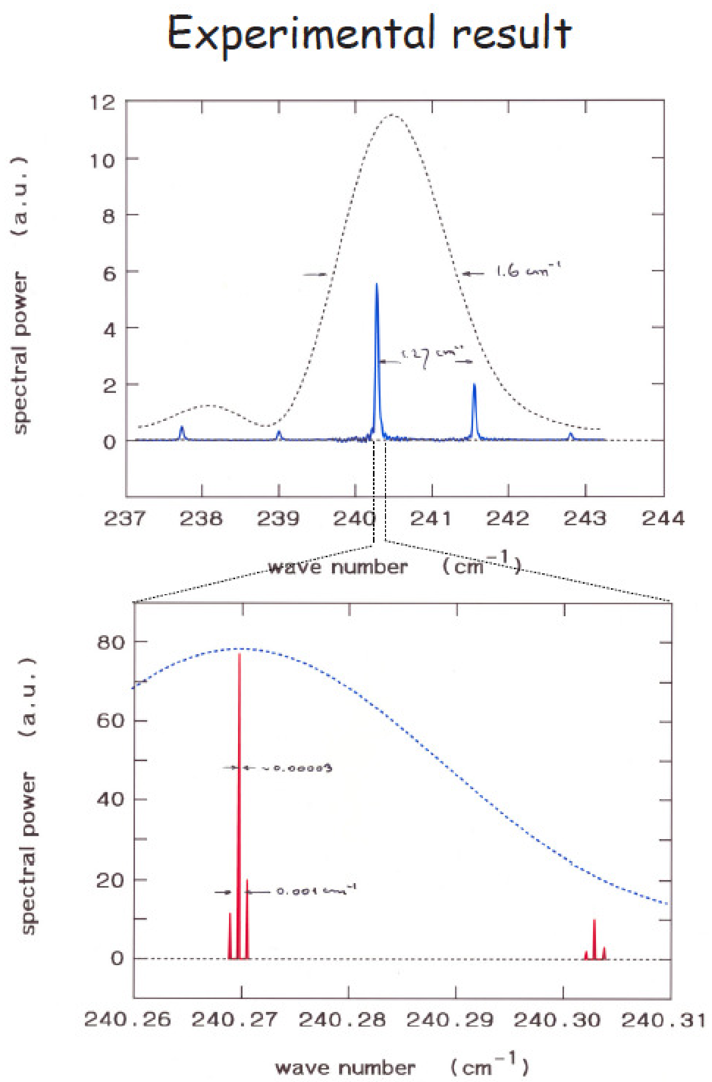
Radiation bandwidth: phase locking



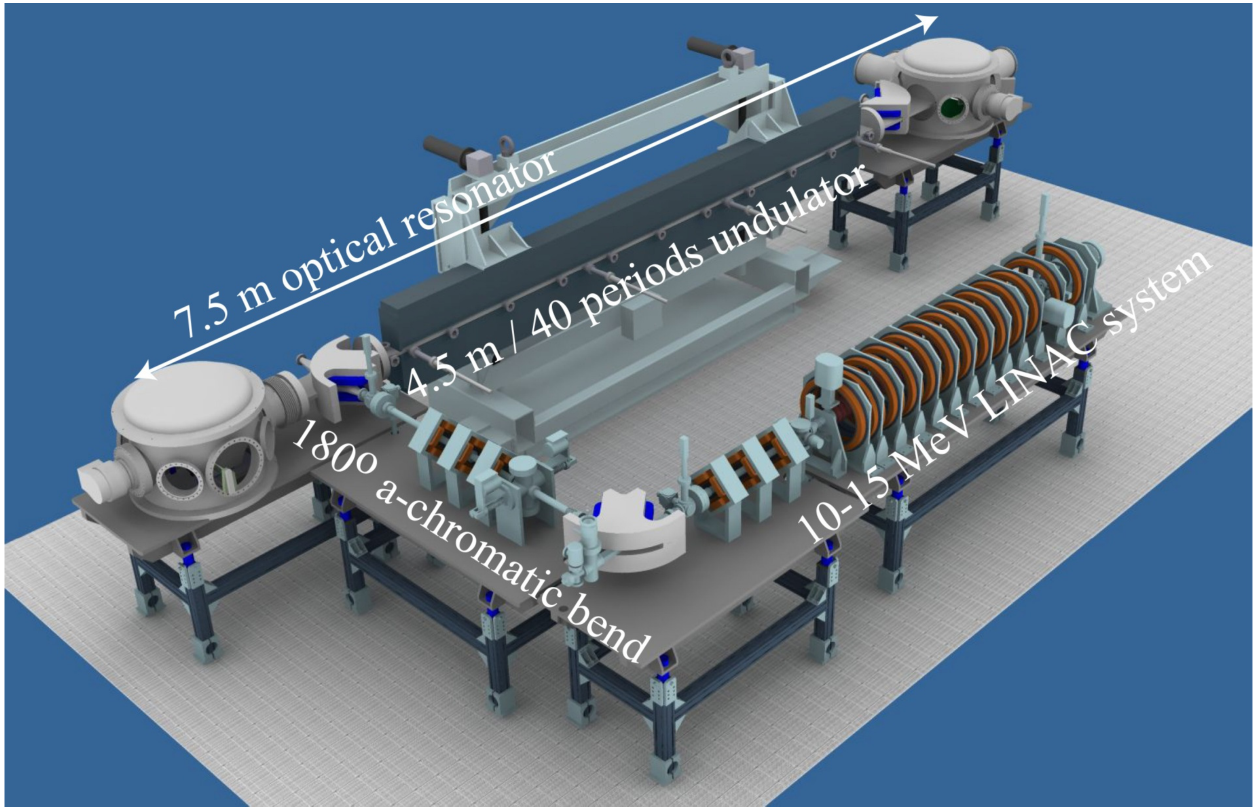
Phase locking & single mode selection



Phase locking & single mode selection



Emerging facility: 'FLARE' in Nijmegen



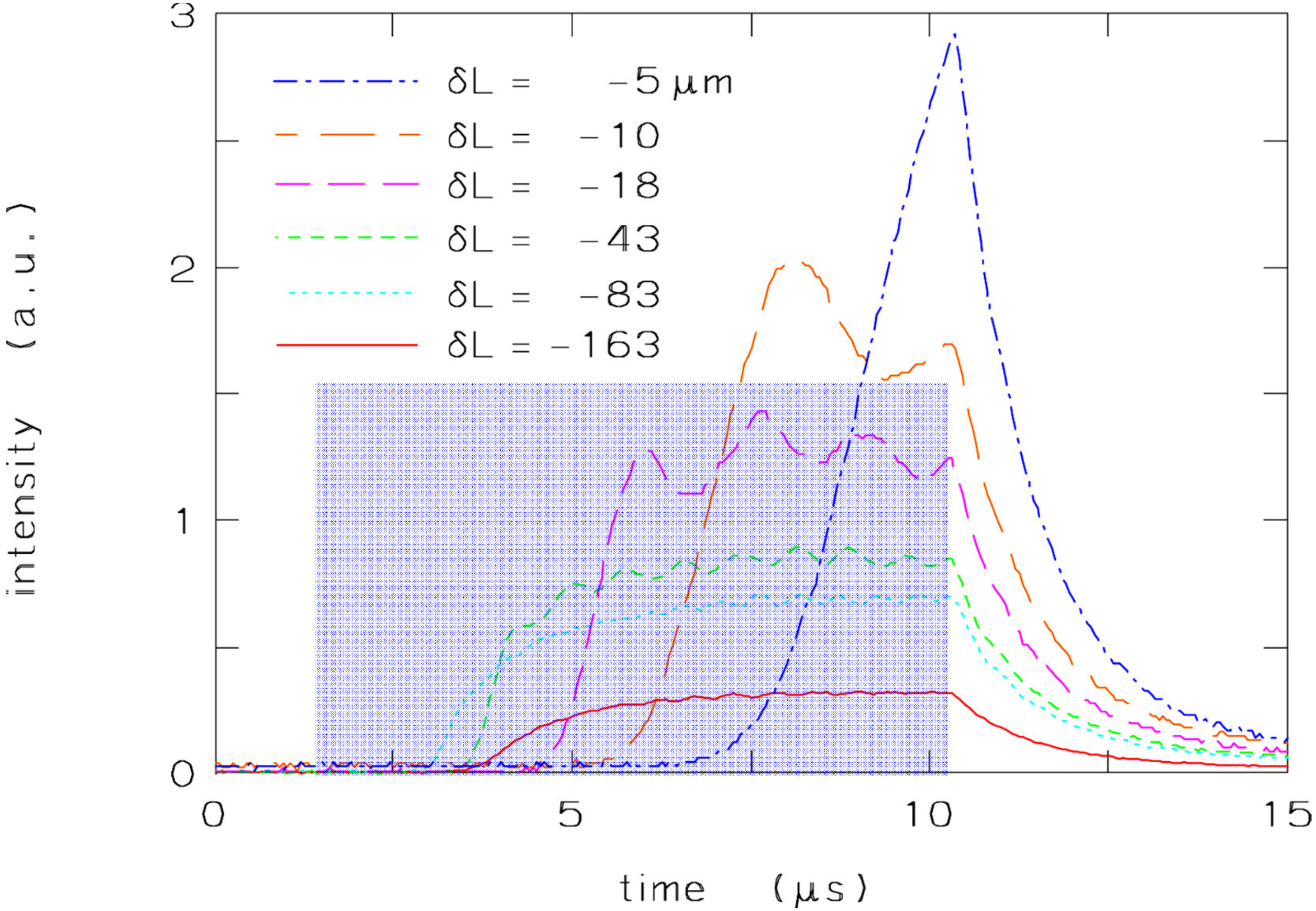
e-beam: 10-15 MeV, 3 GHz, 10 μs, 10 Hz
wavelength range: 100 – 1500 μm
special feature: narrow-band mode

Slippage effects

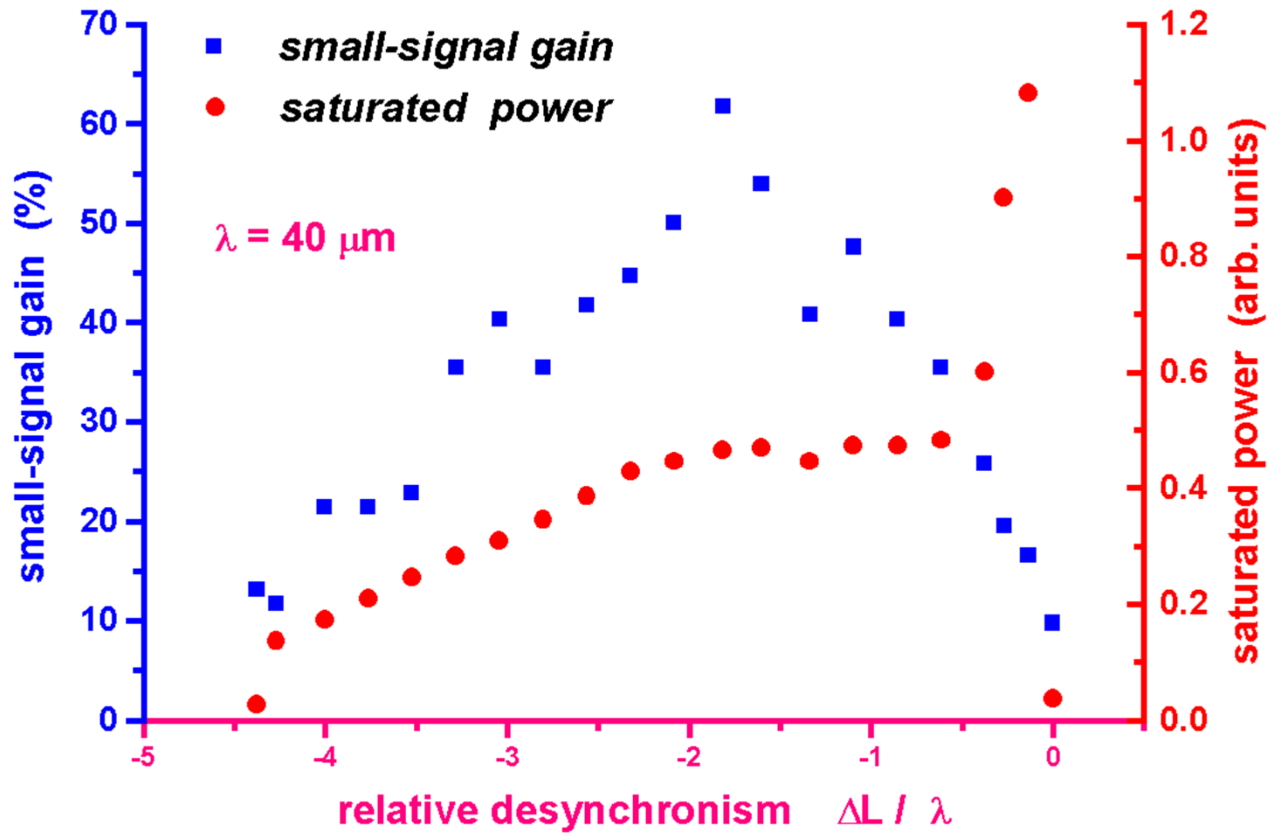
- Lethargy
- Efficiency enhancement
- Limit-cycles
- Bandwidth tuning

Slippage effects

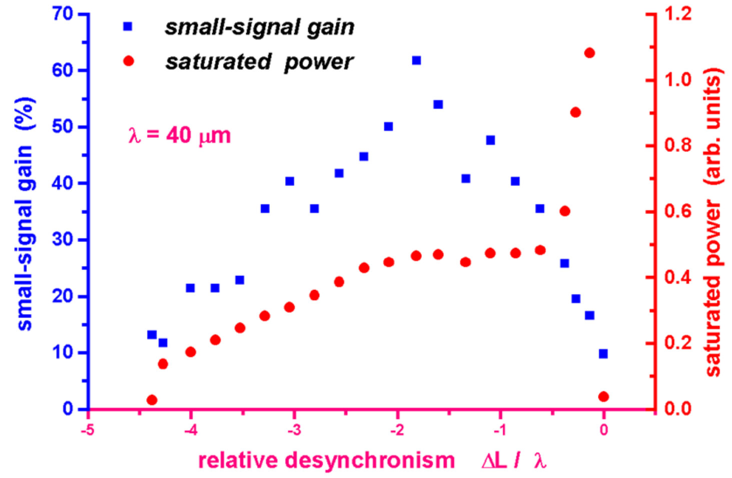
FELIX macropulse shape at λ = 40 μm



Slippage effects: gain and saturation



Slippage effects: gain and saturation

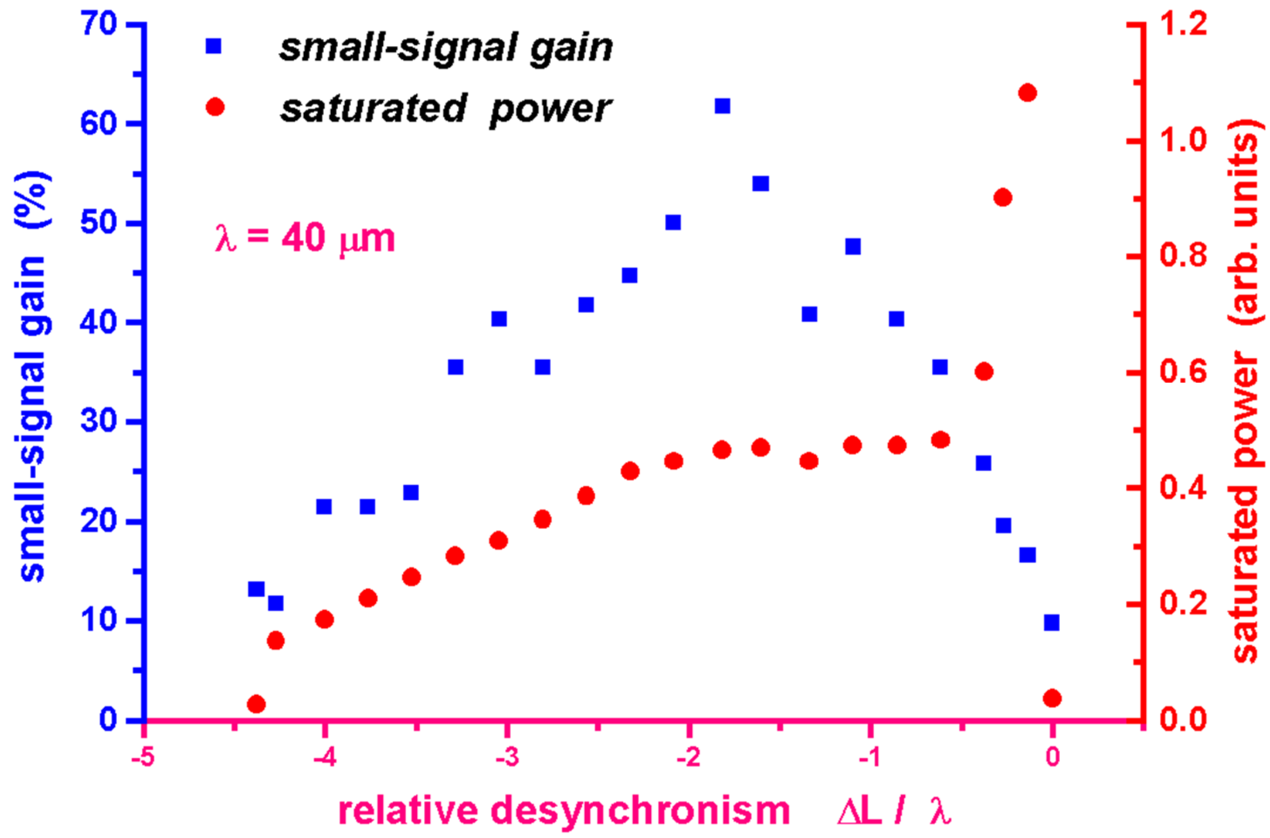


Slippage correction:

$$g_o \longrightarrow \text{Gain} \sim \frac{g_o}{\left(1+\frac{N_u\lambda}{3\sigma_z}\right)}$$

$$g_o \sim I \sim \frac{Q_b}{\sigma_z} \longrightarrow \text{Gain} \sim \frac{Q_b}{\left(\sigma_z+\frac{N_u\lambda}{3}\right)}$$

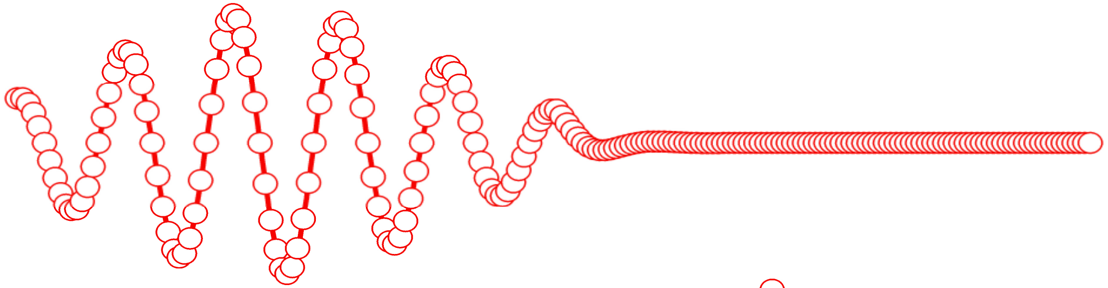
Slippage effects: gain and saturation



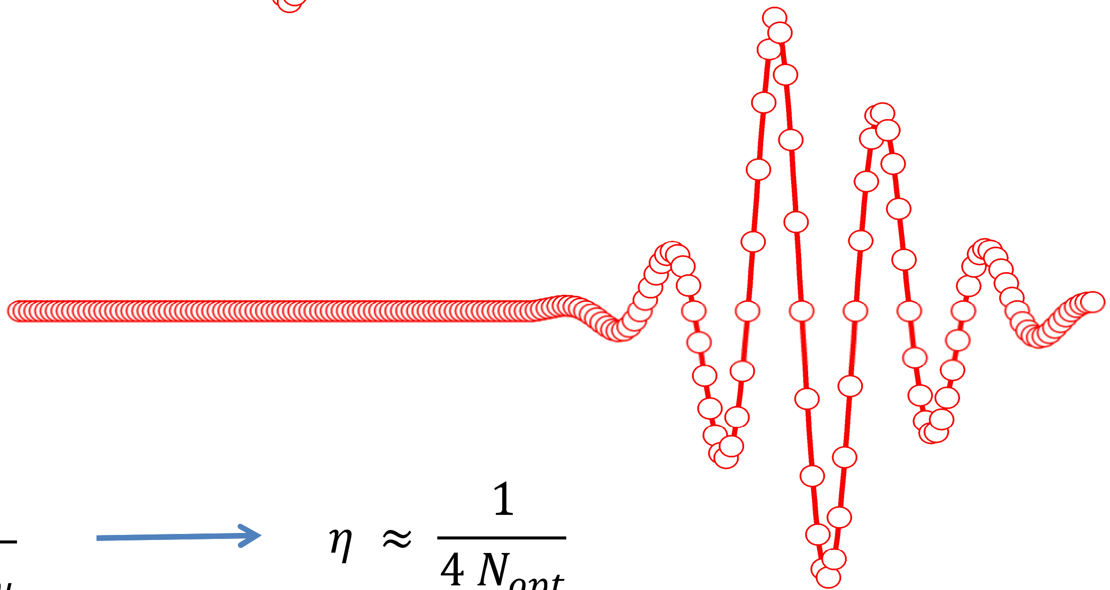
Slippage effects: efficiency enhancement

short pulse propagation

entrance



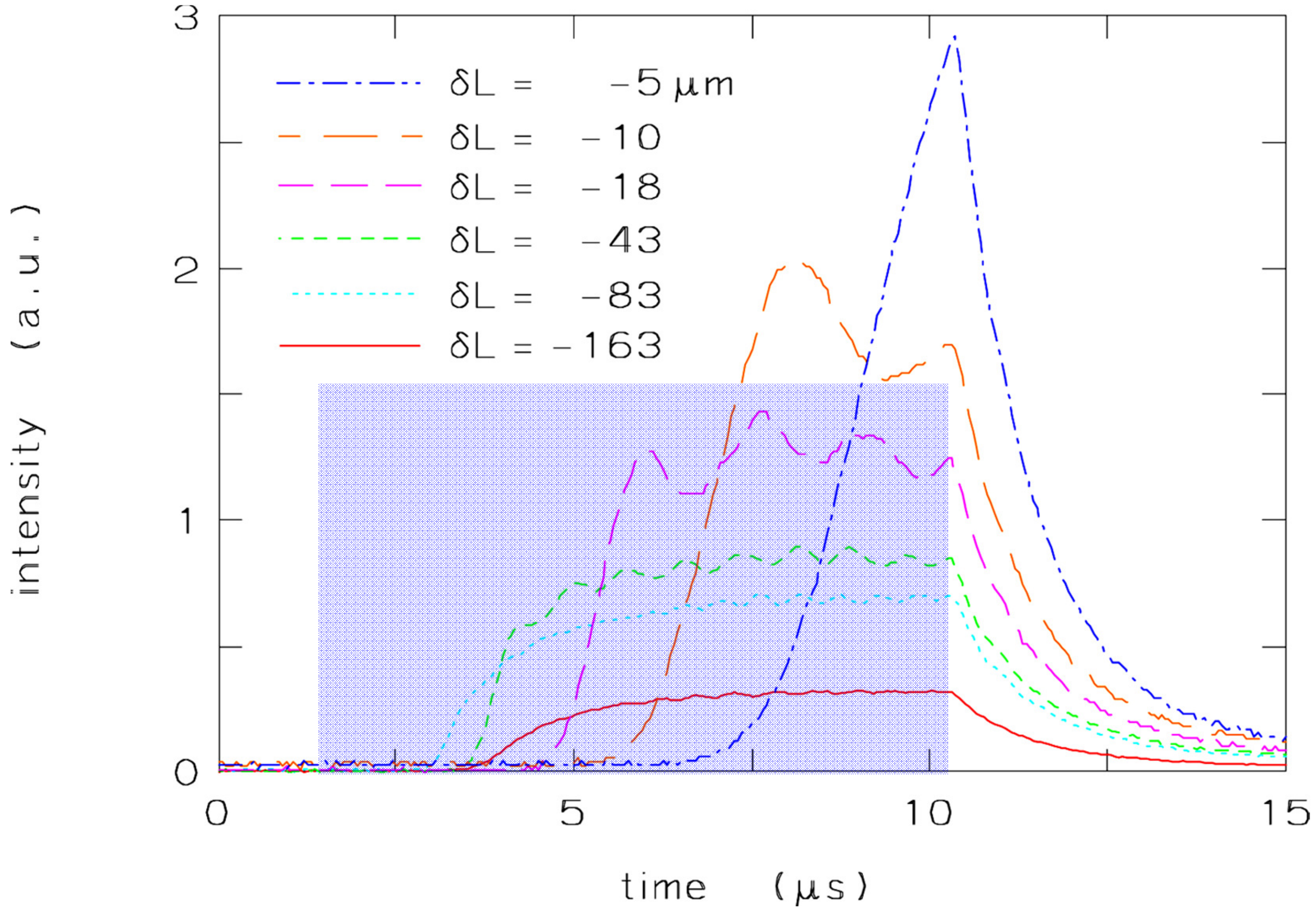
exit



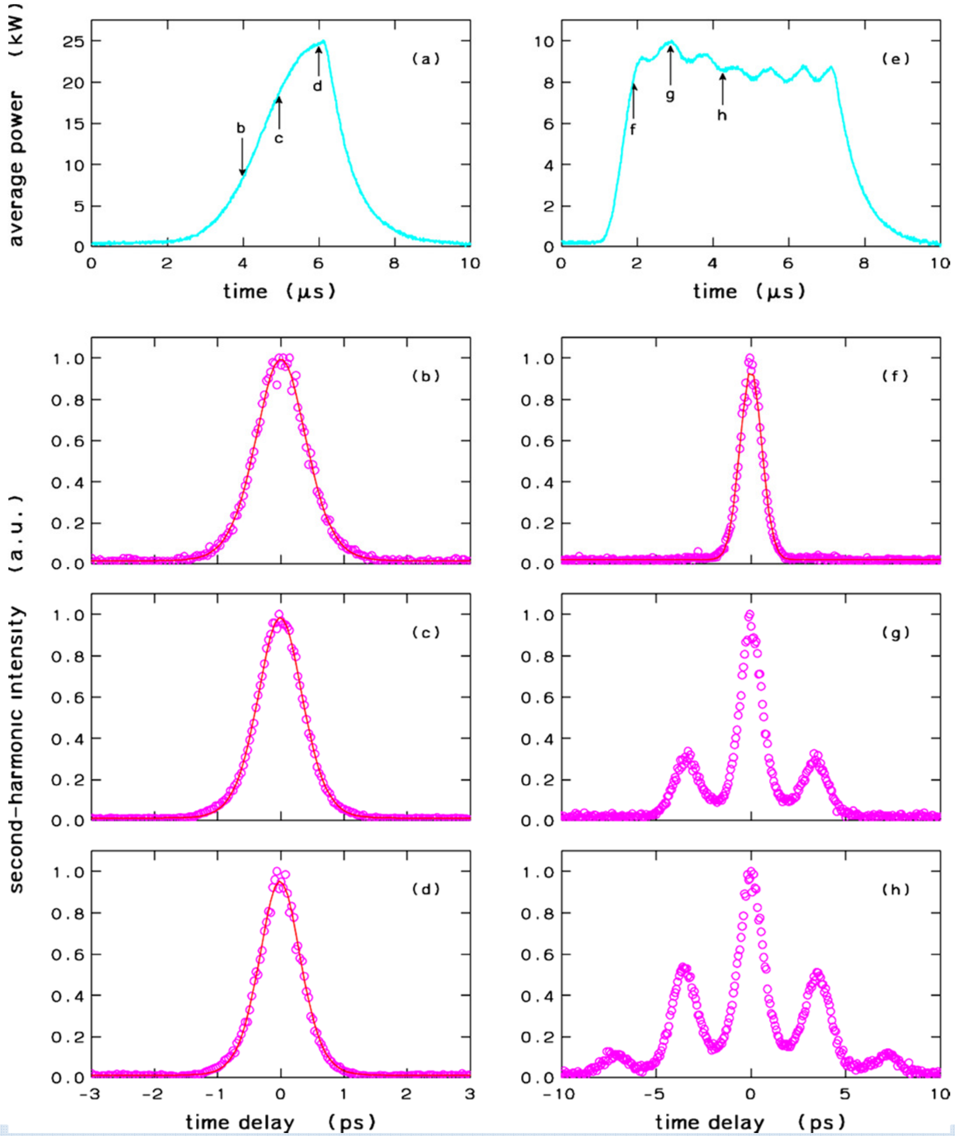
$$\eta \approx \frac{1}{4\,N_u} \longrightarrow \eta \approx \frac{1}{4\,N_{opt}}$$

Slippage effects

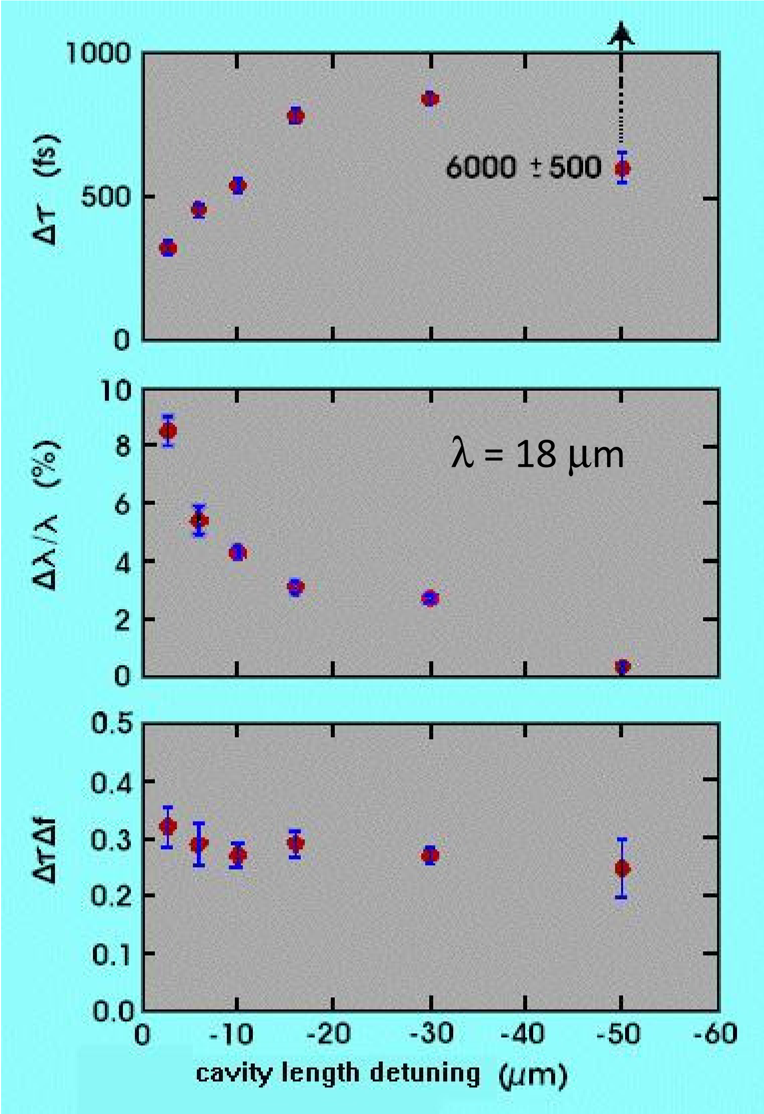
FELIX macropulse shape at λ = 40 μm



Slippage effects: limit cycles



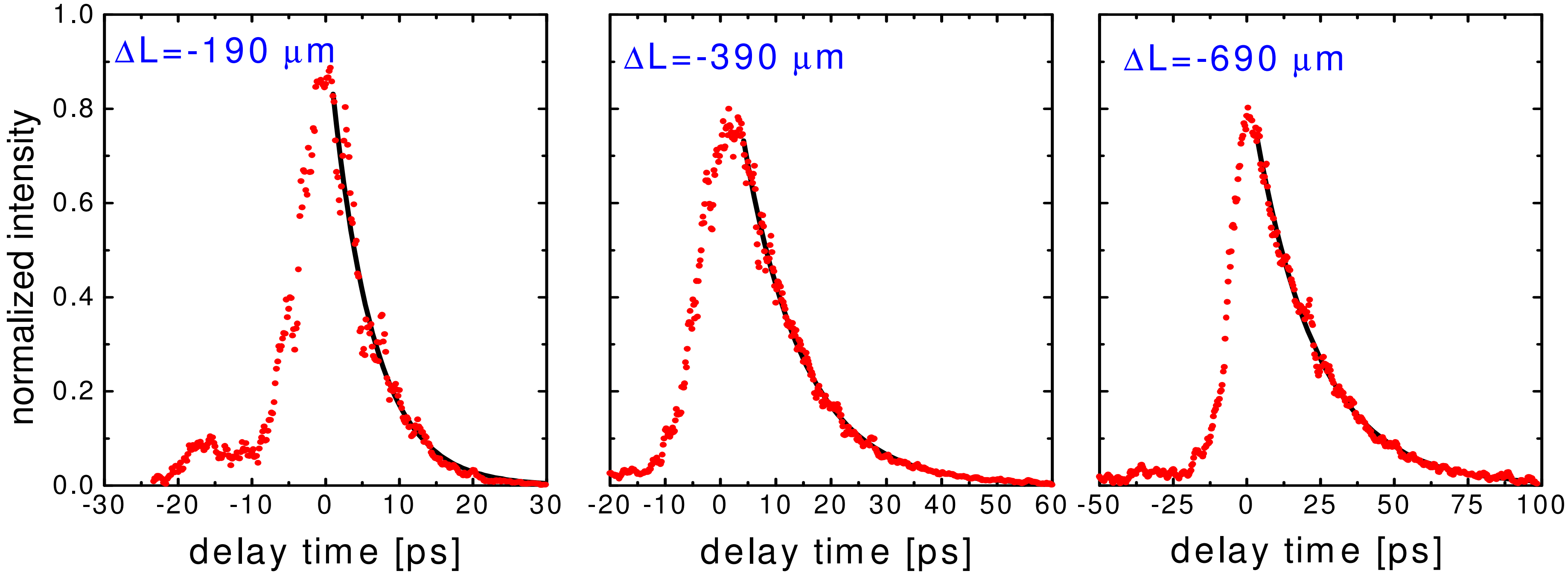
Slippage effects: bandwidth tunability



- bandwidth 0.4 - 6% [FWHM]
- near transform limited

Slippage effects: pulse length tunability

FELIX micro-pulse shape at λ = 150 mm
for different cavity detunings

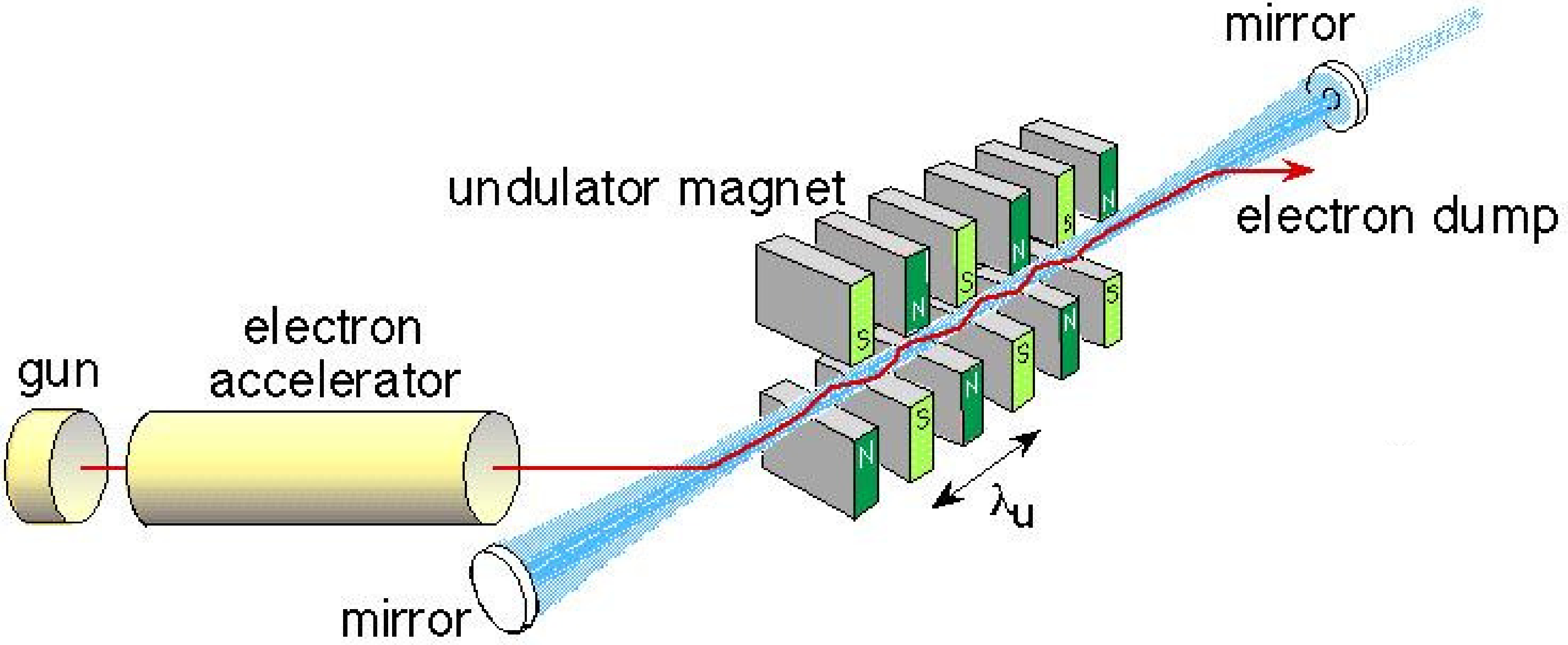


Exponential leading edge has a time constant:

$$\tau = \frac{2\Delta L}{\alpha c}$$

where α are the cavity losses and ΔL is the cavity detuning from synchronism

Resonator issues

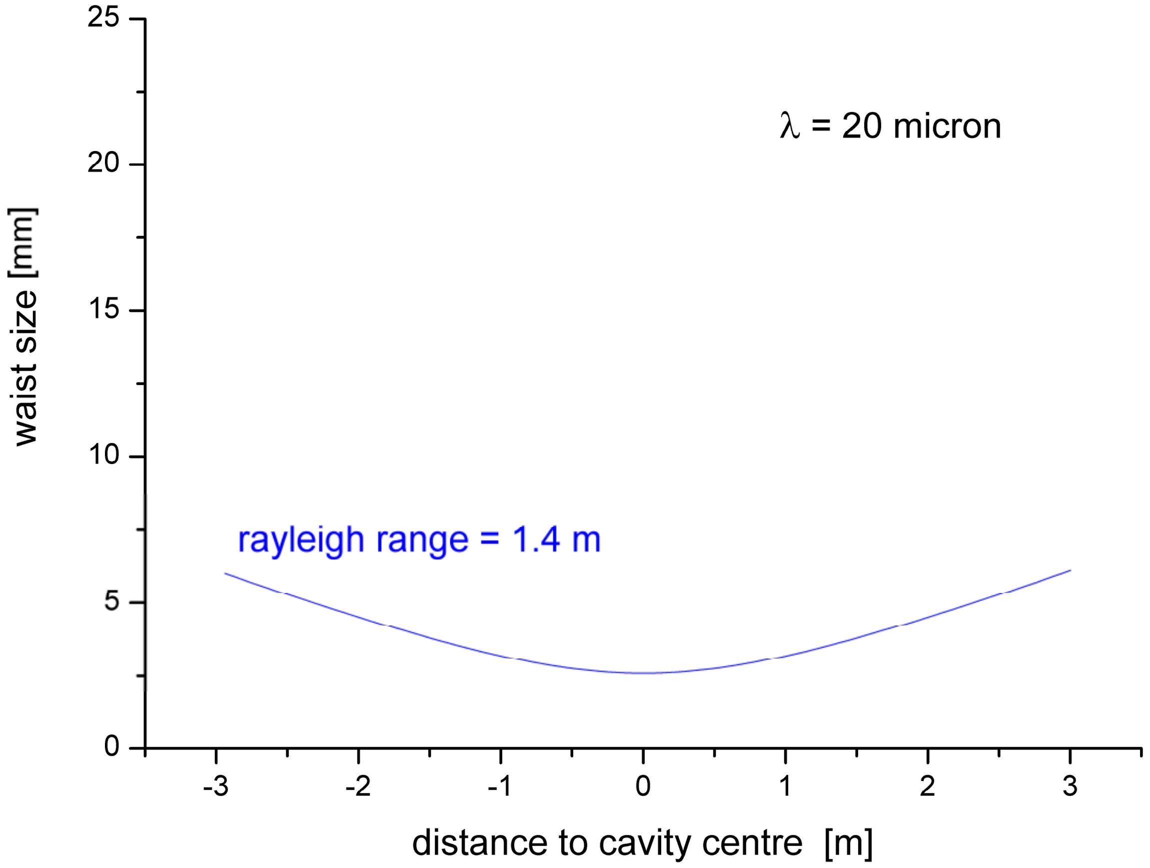


Resonator issues

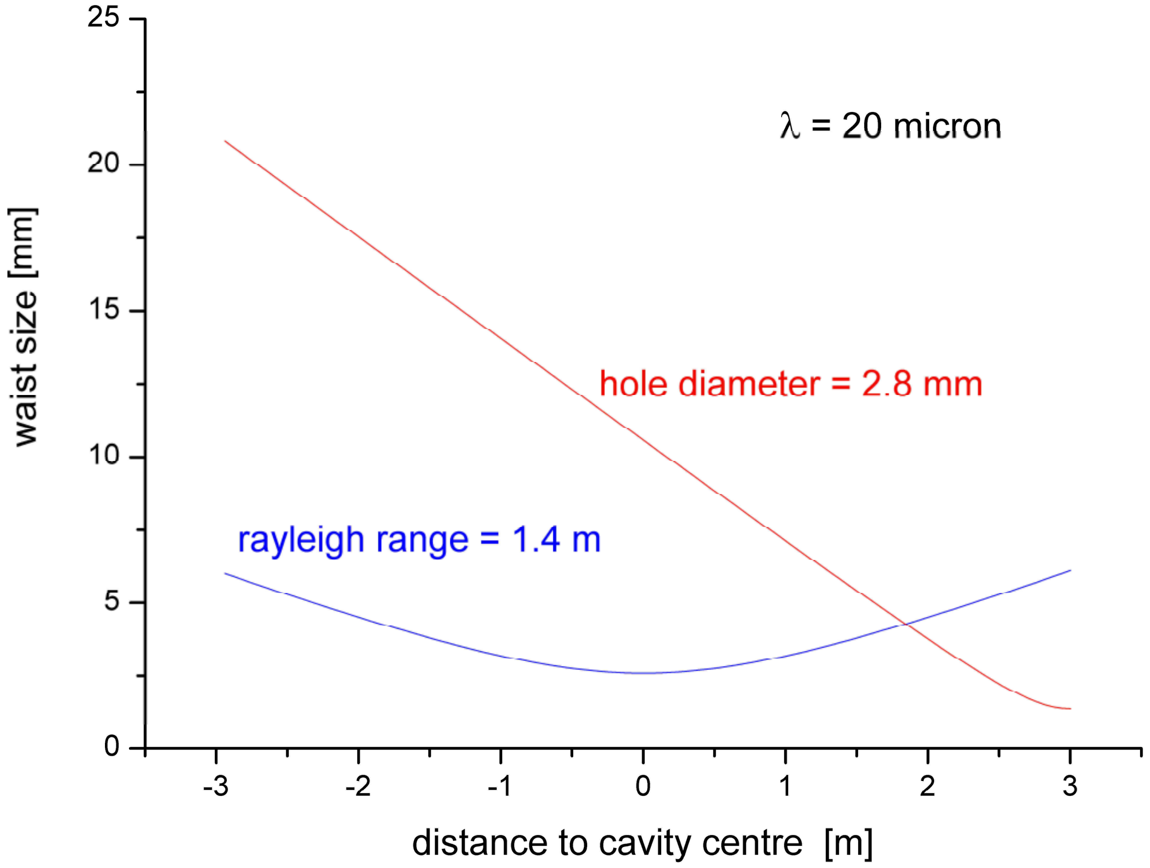
out-coupling schemes:

- 'semi-transparent' mirrors
- beam splitter
- hole coupling
- edge coupling

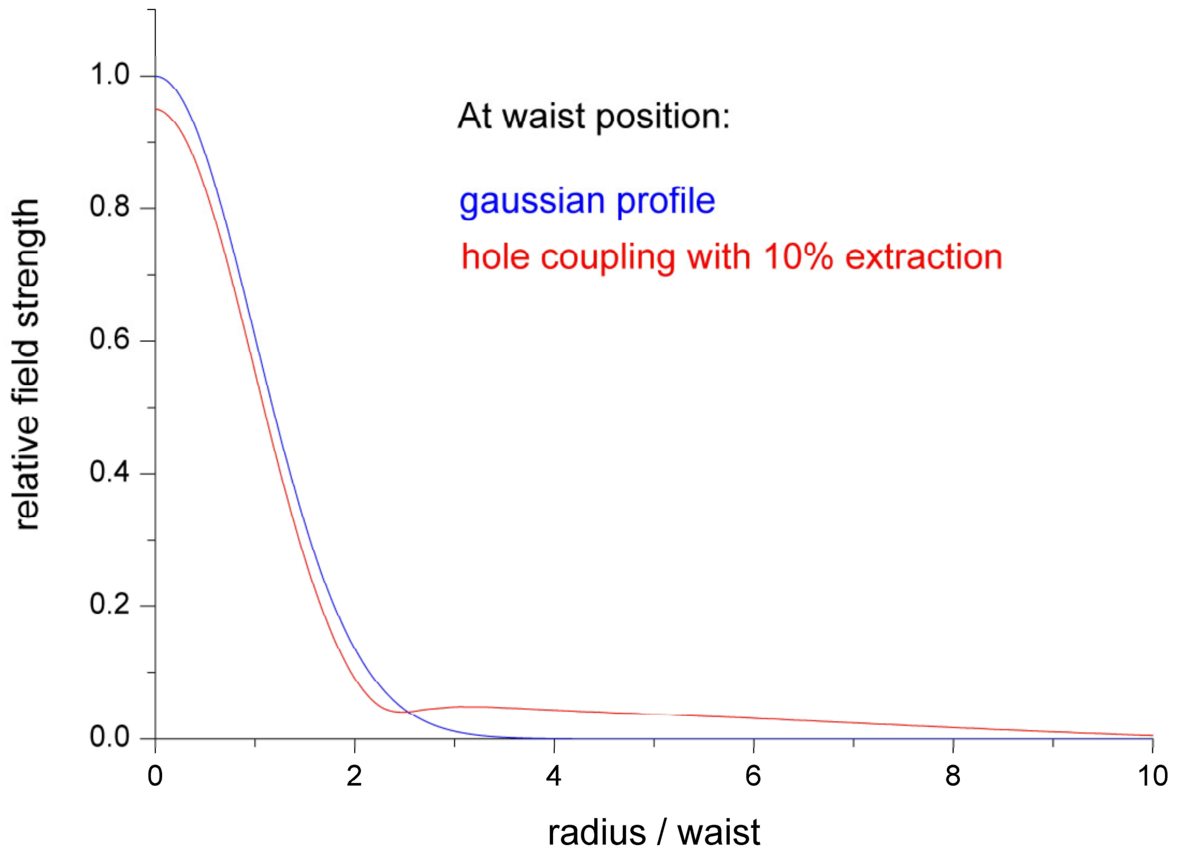
Resonator issues: on-axis hole coupling



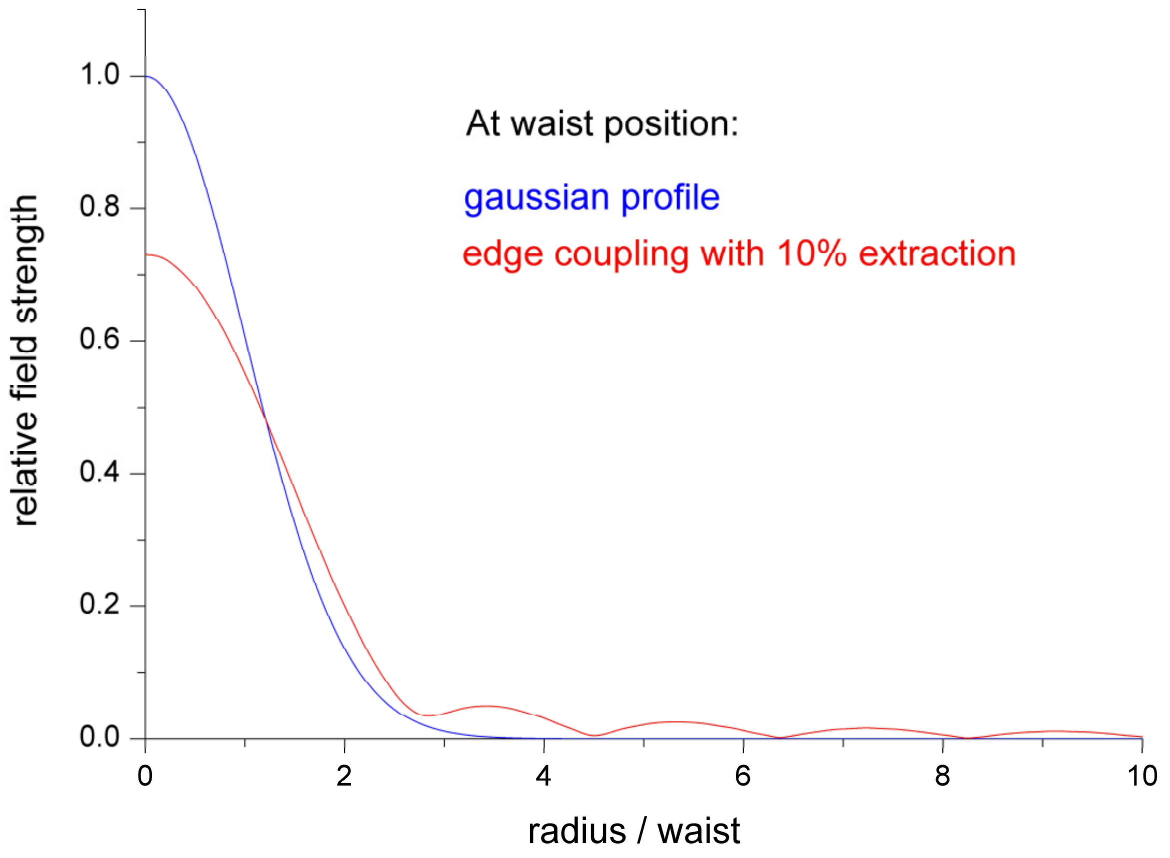
Resonator issues: on-axis hole coupling



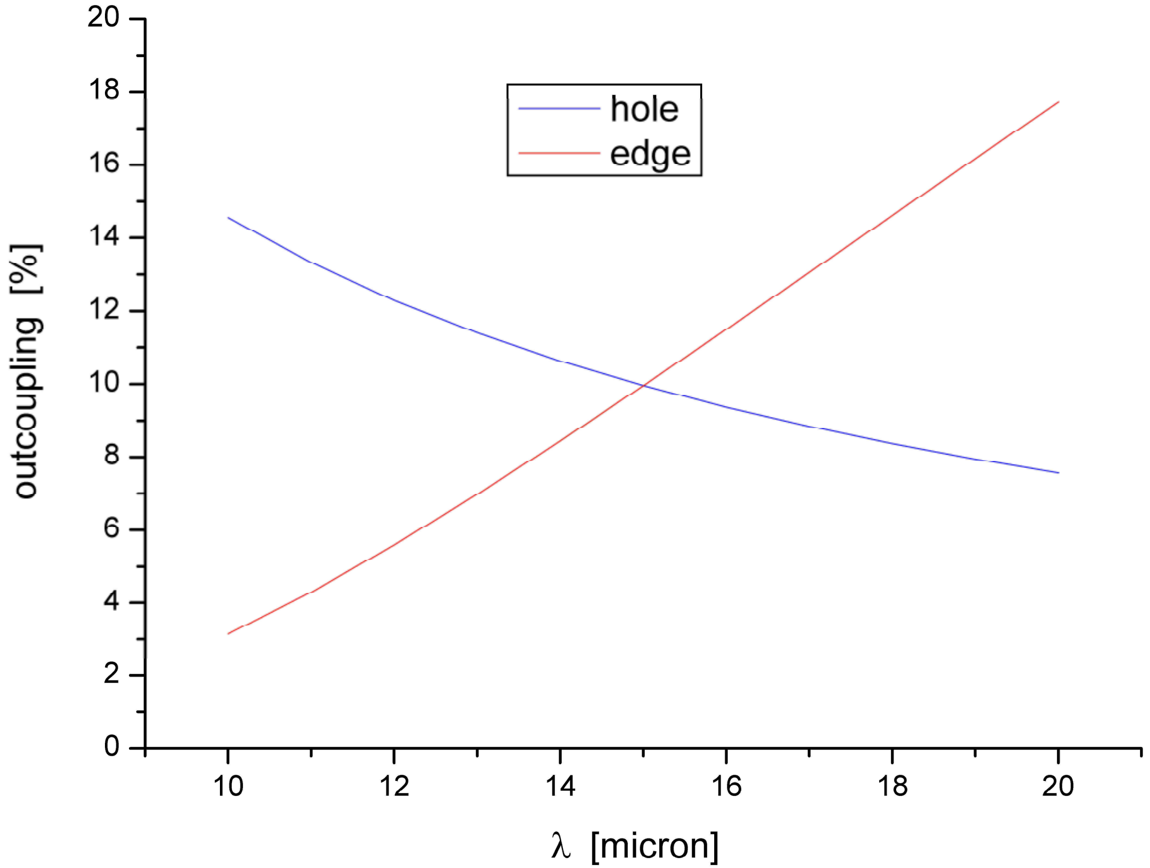
Resonator issues: on-axis hole coupling



Resonator issues: edge-coupling

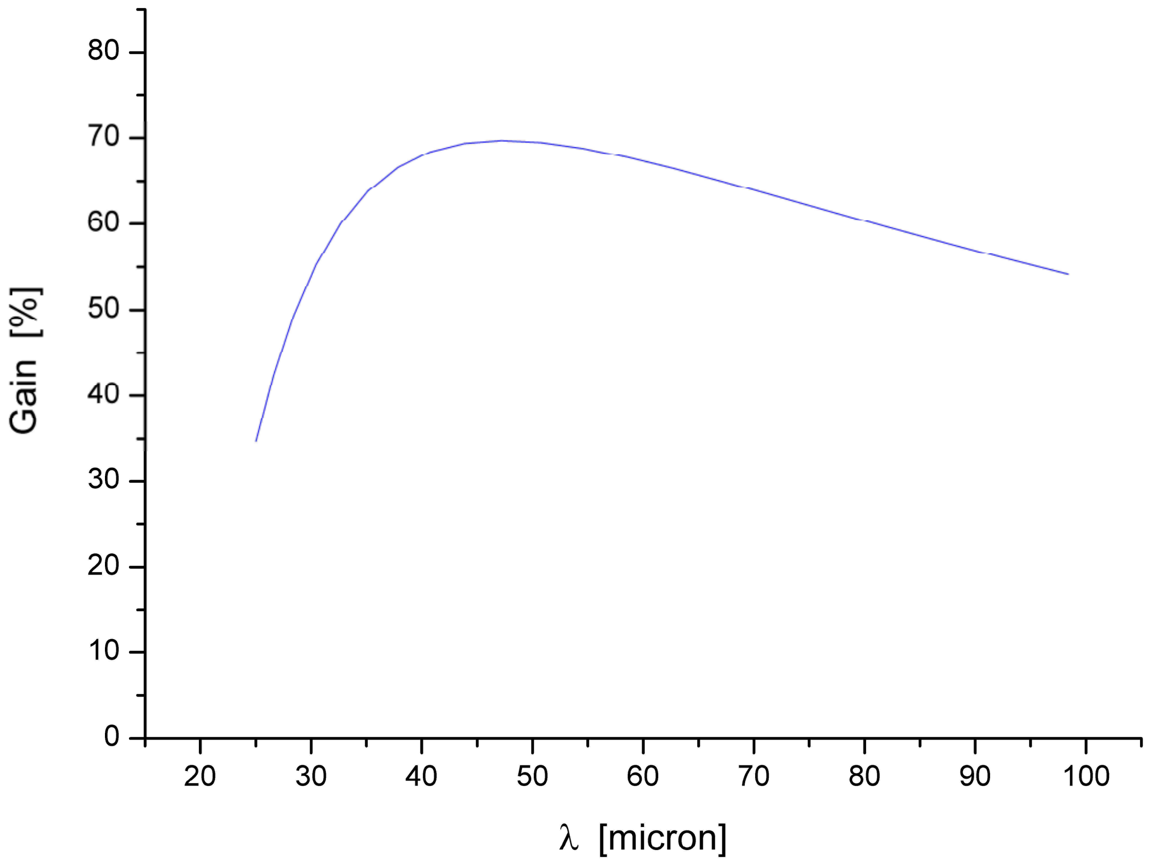


Hole vs edge coupling: λ - dependence

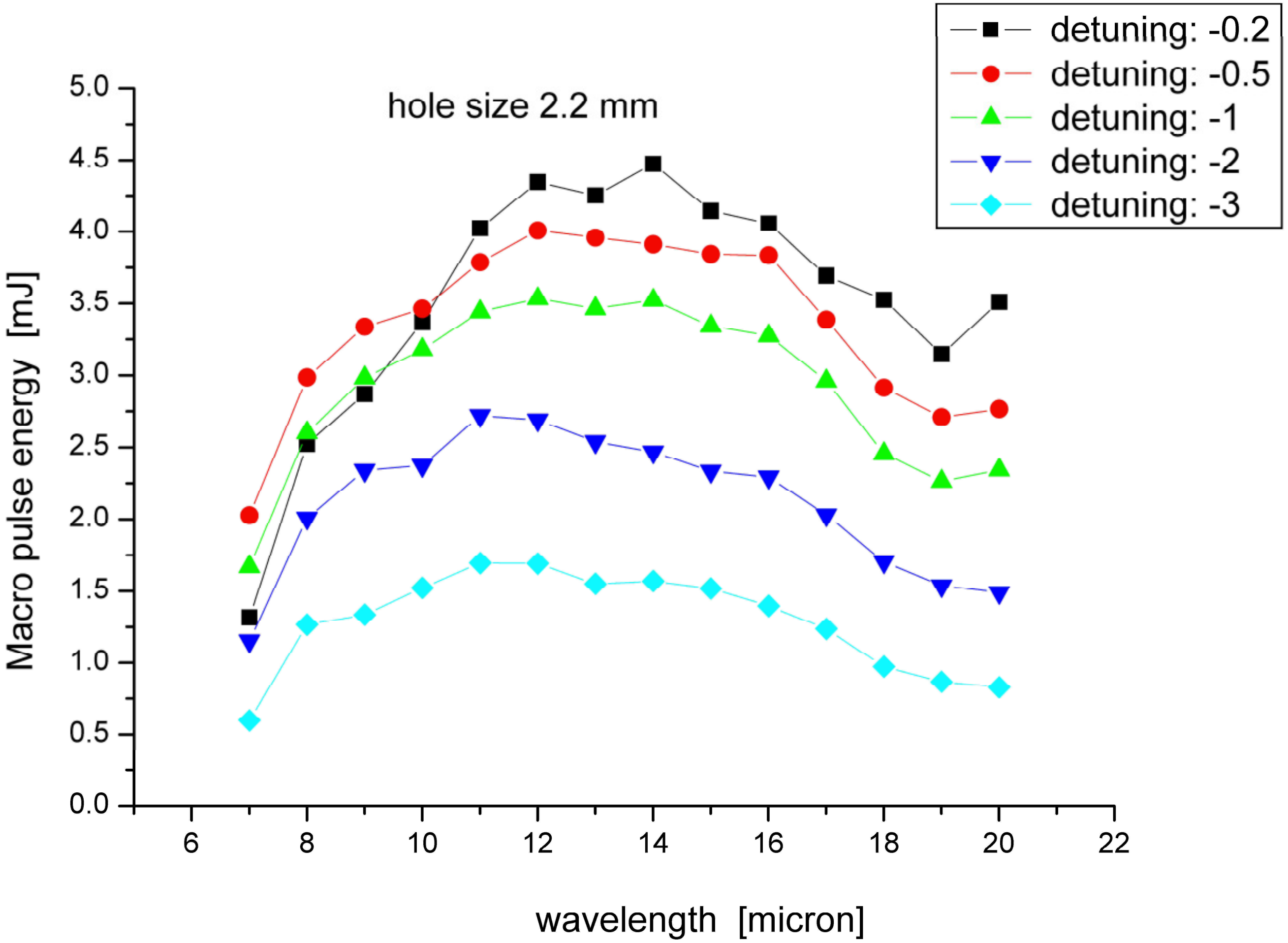


Hole vs edge coupling: λ - dependence

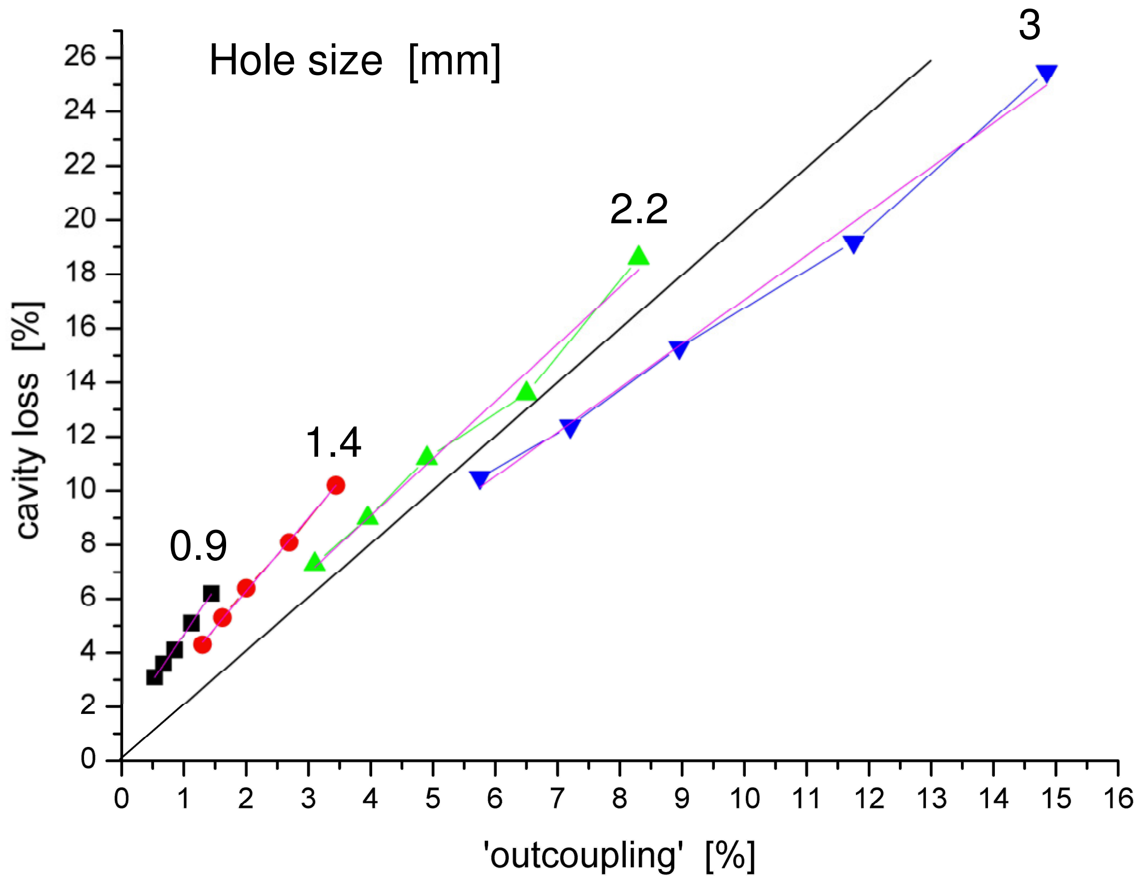
Typical gain curve



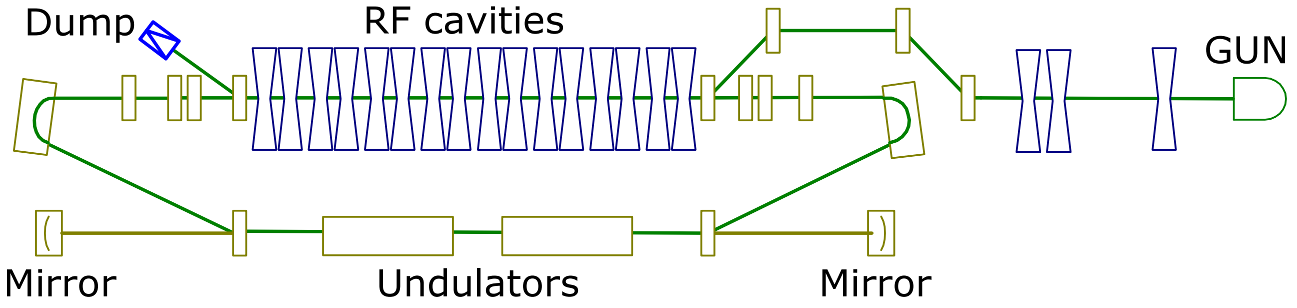
Hole coupling: tuning curves



Hole coupling: measured losses

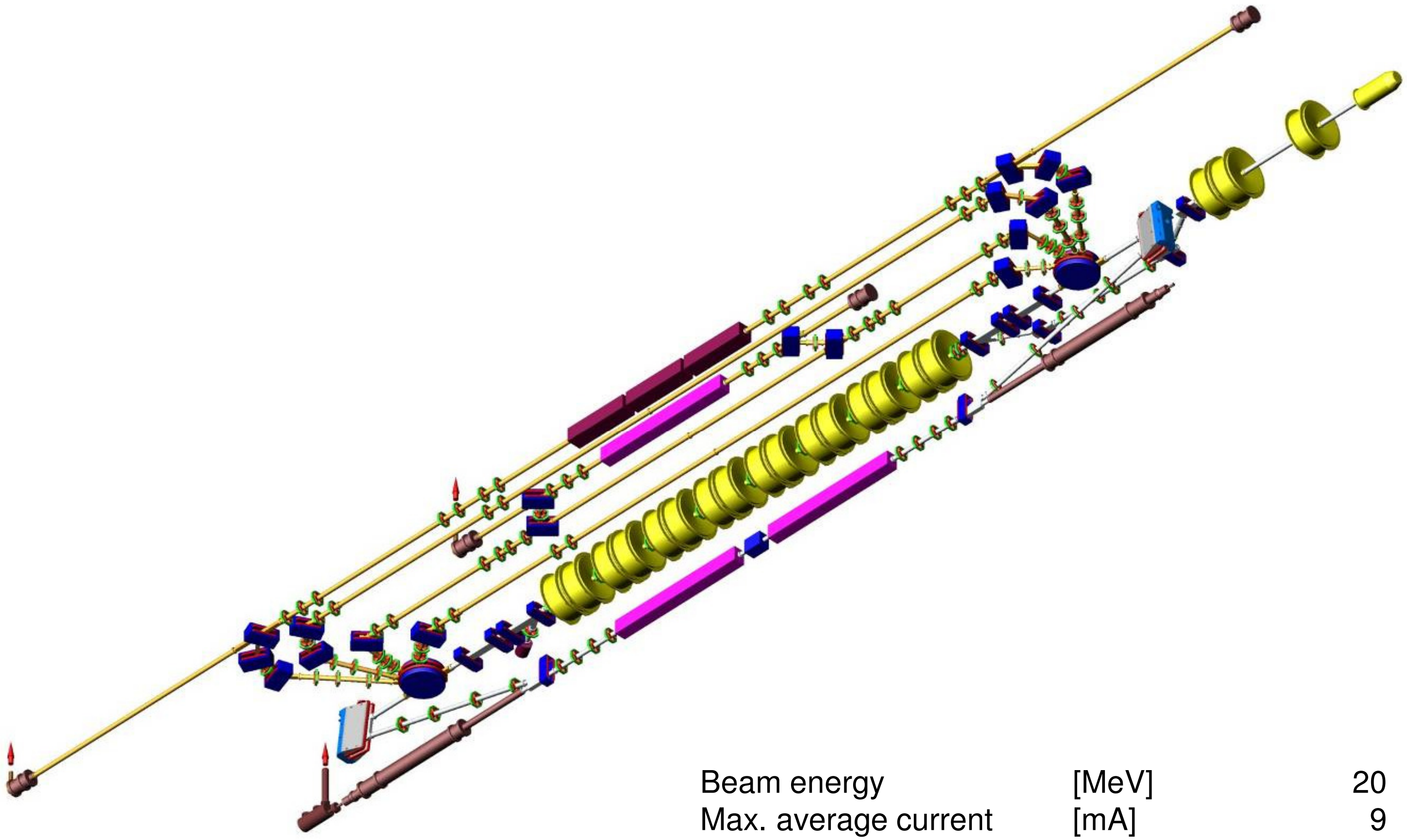


Emerging facilities: BINP in Novosibirsk



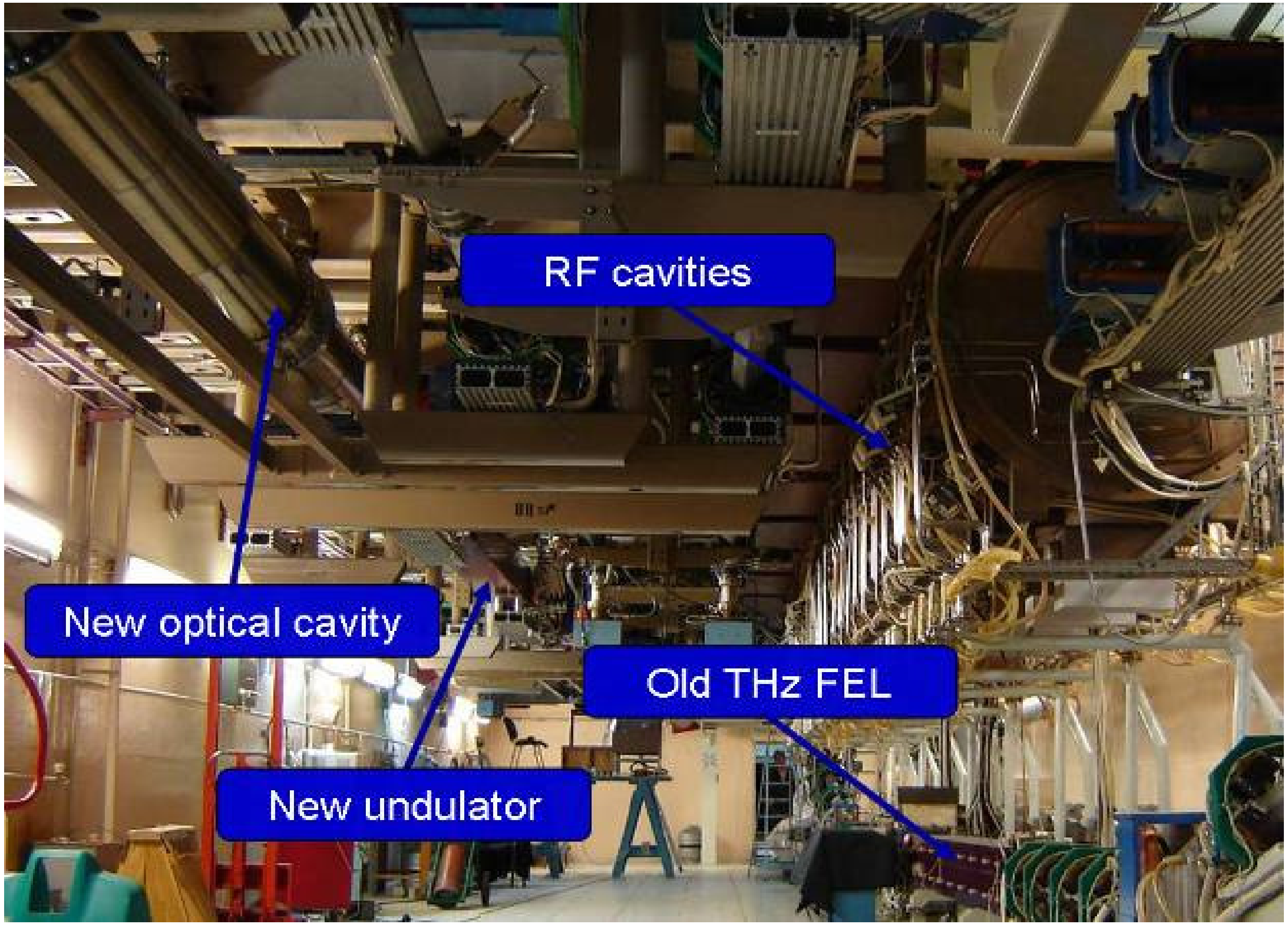
Beam energy	[MeV]	11
Max. average current	[mA]	30
Max. μ-bunch rep rate	[MHz]	22.5
μ-bunch charge	[nC]	1.5
Wavelength	[μm]	120-240
Max. average output	[W]	500

Emerging facilities: BINP in Novosibirsk

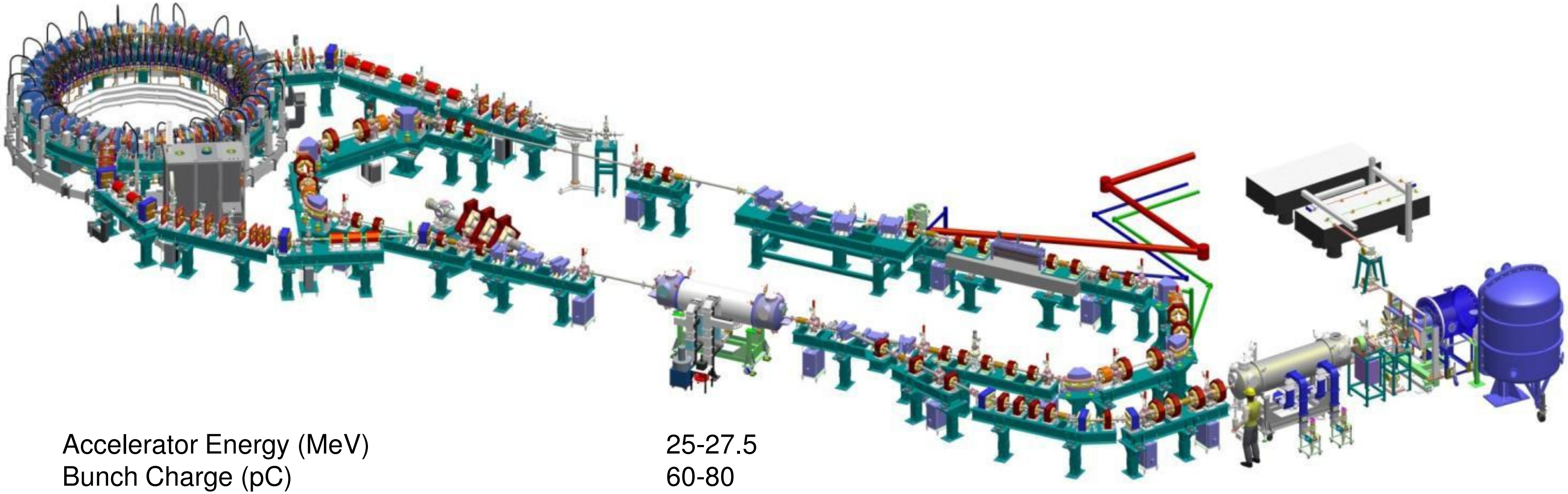


Beam energy	[MeV]	20
Max. average current	[mA]	9
Max. µ-bunch rep rate	[MHz]	7.5
µ-bunch charge	[nC]	1.2
Wavelength	[µm]	40-80
Max. average output	[W]	500

Emerging facilities: BINP in Novosibirsk



Emerging facilities: 'ALICE' in Daresbury

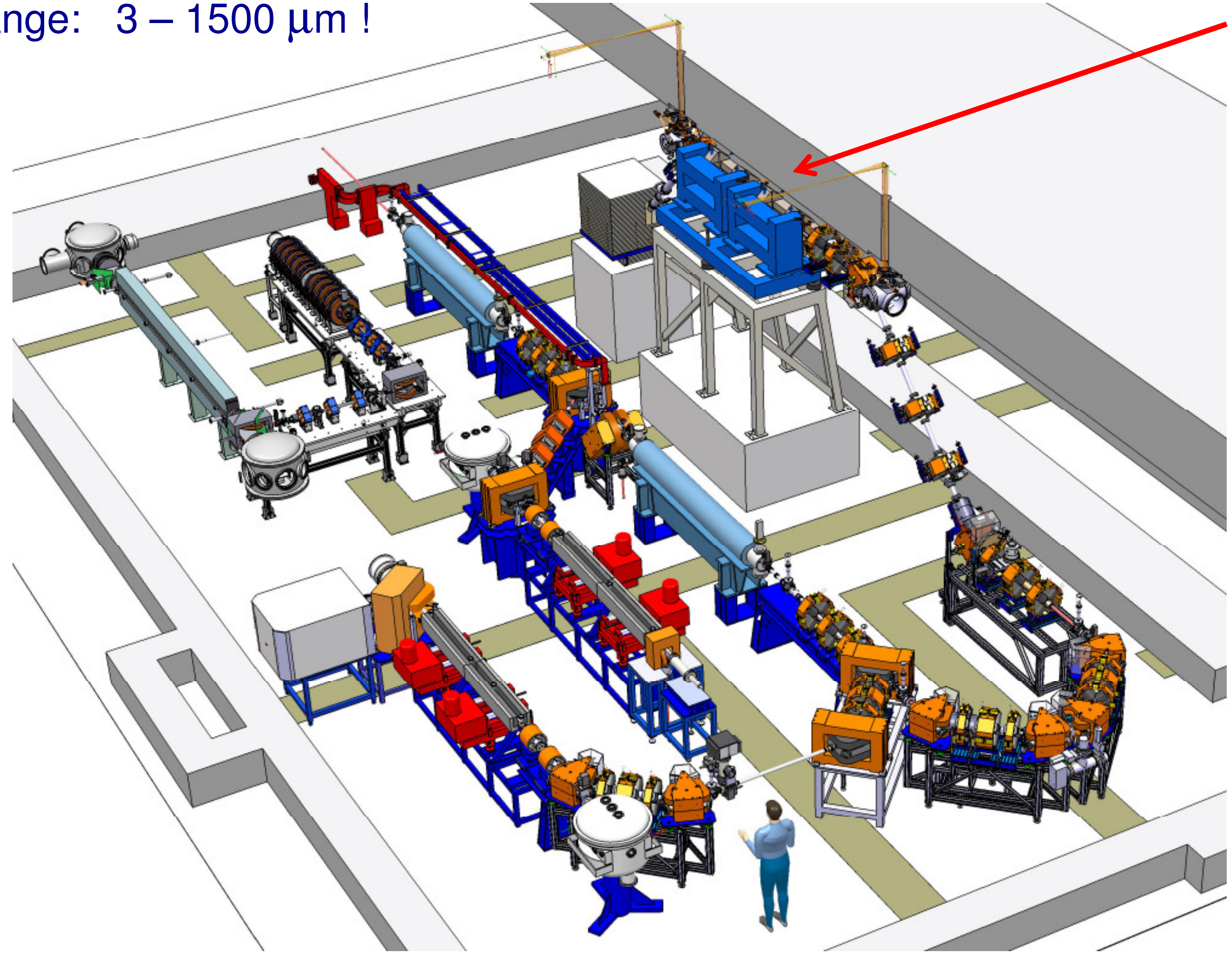


Accelerator Energy (MeV)	25-27.5
Bunch Charge (pC)	60-80
Micropulse repetition rate (MHz)	16.25
Macro pulse length (μs)†	≤85
Number of micropulses/macropulse	≤1380
Micropulse length (ps)	~1
Macropulse repetition rate (Hz)	10
Wavelength range demonstrated (μm)	5-9
Micropulse energy (μJ)	~1
Peak power (MW)	~1
Average power within macropulse (W)	~10
Average power (mW)	~10
Polarisation (linear)	>95%

Emerging facilities: 'FELIX' in Nijmegen

wavelength range: 3 – 1500 μm !

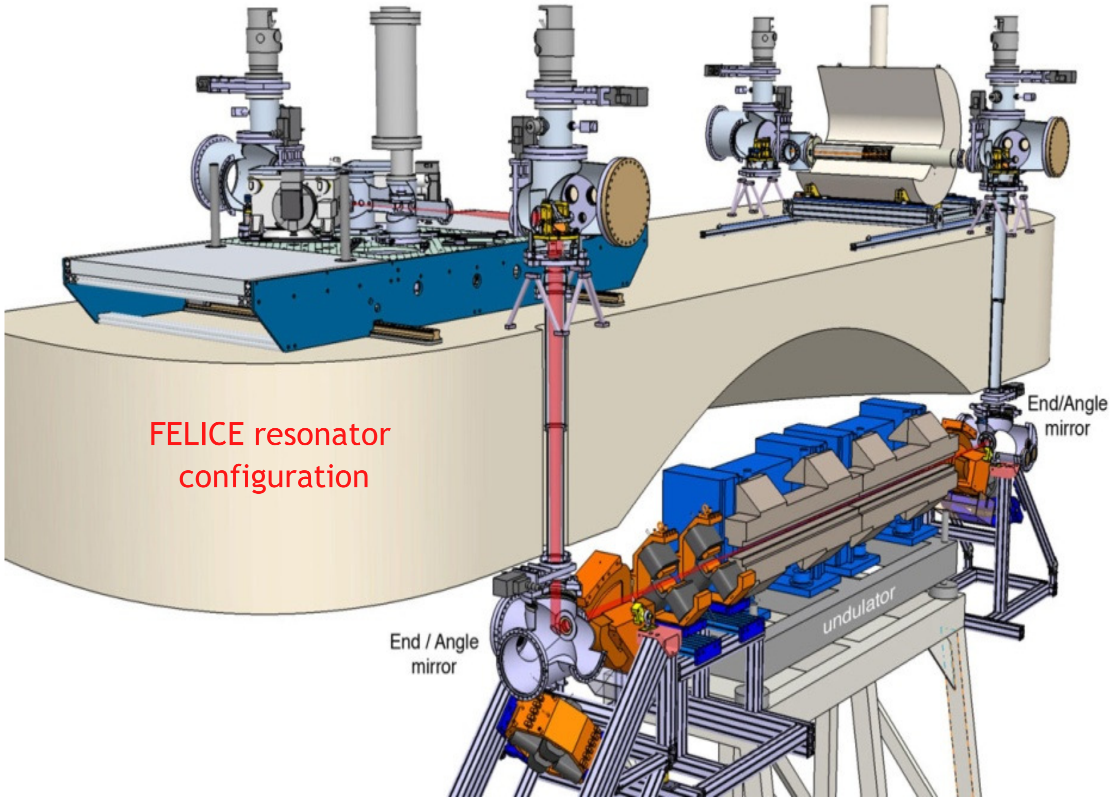
'FELICE'



The FELICE beam line

molecular beam experiment

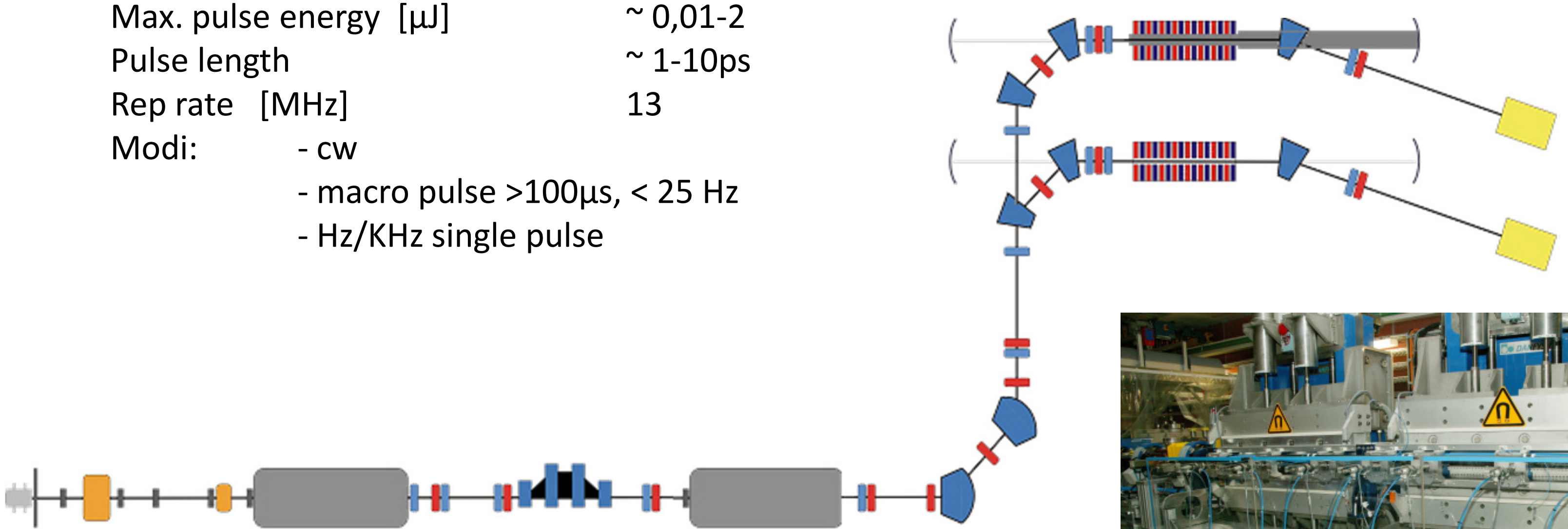
FTICR-MS experiment

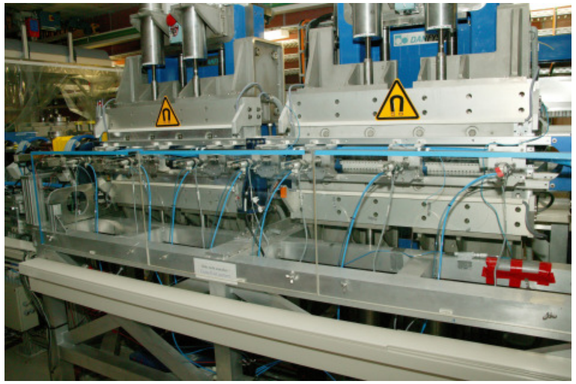


Existing facilities: 'FELBE' in Dresden

Undulator period [mm]	27.3
Number of periods	2 * 34
Undulator K	0,3 – 0,7
Undulator type [hybrid]	NdFeB
Wavelength [µm]	3-22
Max. power (out)	~ 25 W
Max. pulse energy [µJ]	~ 0,01-2
Pulse length	~ 1-10ps
Rep rate [MHz]	13

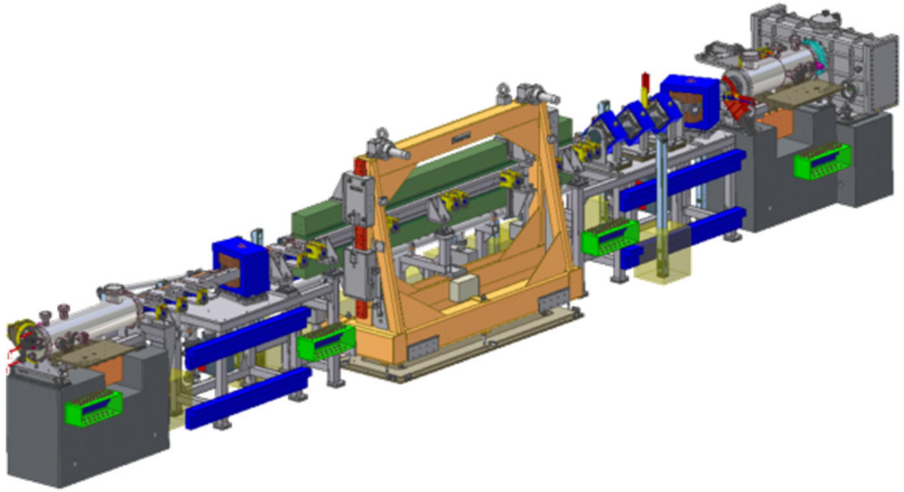
Modi:
- cw
- macro pulse >100µs, < 25 Hz
- Hz/KHz single pulse



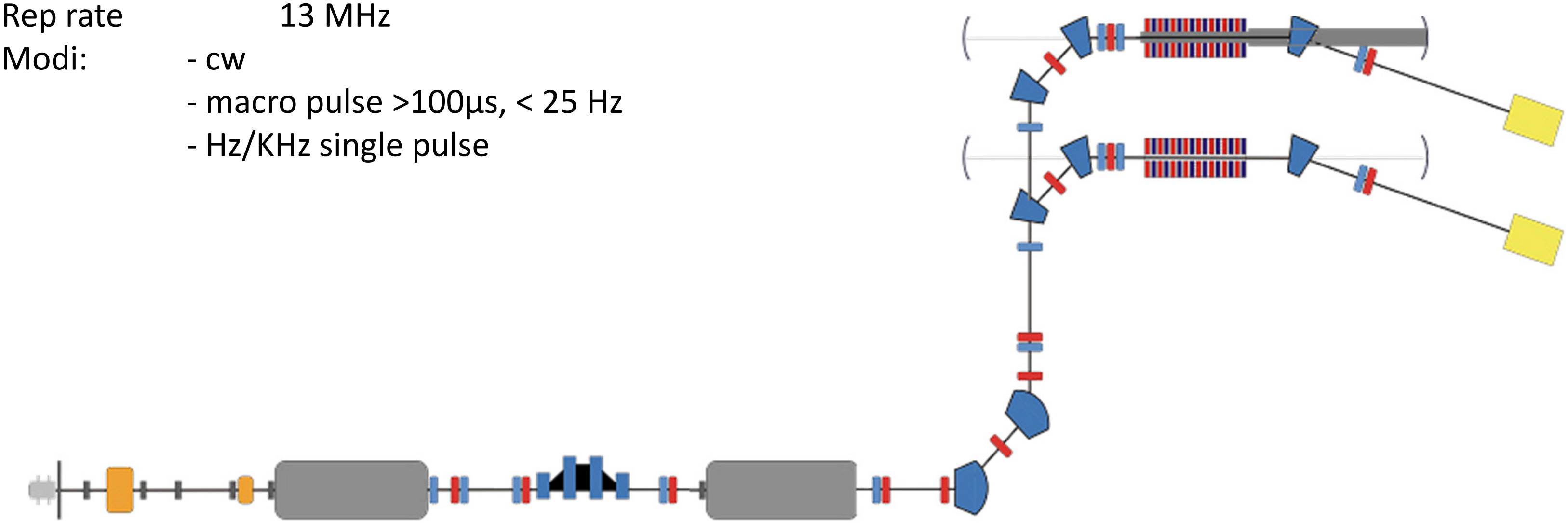


Existing facilities: 'FELBE' in Dresden

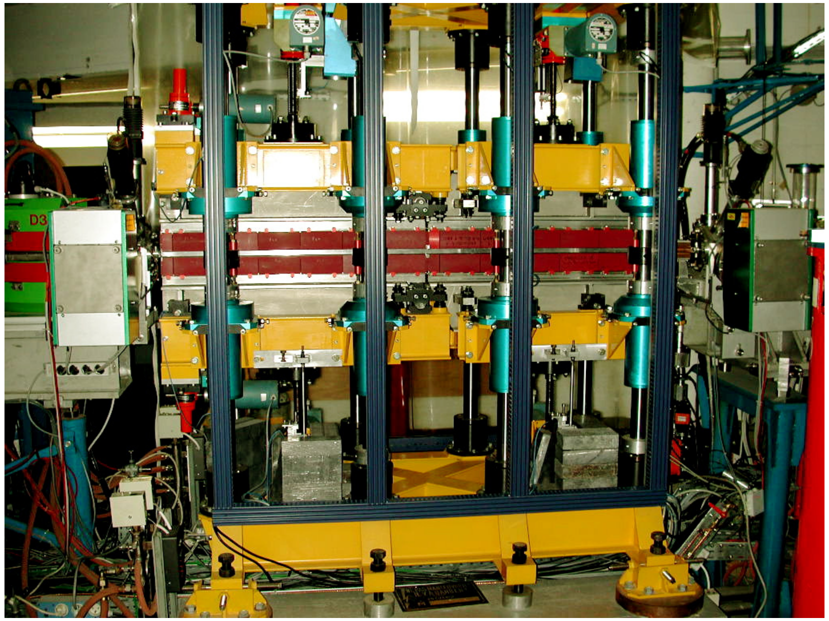
Undulator period 100 mm
Number of periods 38
Undulator K 0.3 - 2.7
Undulator type hybrid SmCo

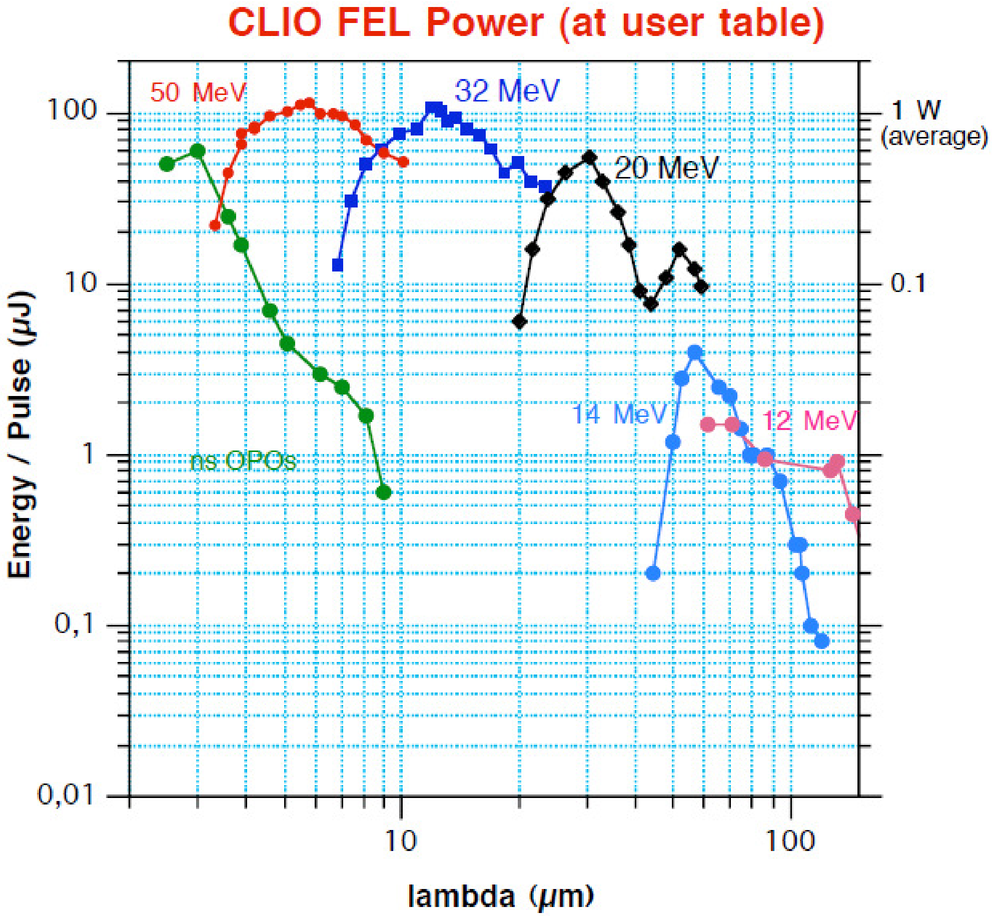


Wavelength 18 - 250 µm
Max. power (out) >10 W
Max. pulse energy >0,01-2 µJ
Pulse length ~ 1-25ps
Rep rate 13 MHz
Modi: - cw
- macro pulse >100µs, < 25 Hz
- Hz/KHz single pulse



Existing facilities: 'CLIO' in Paris



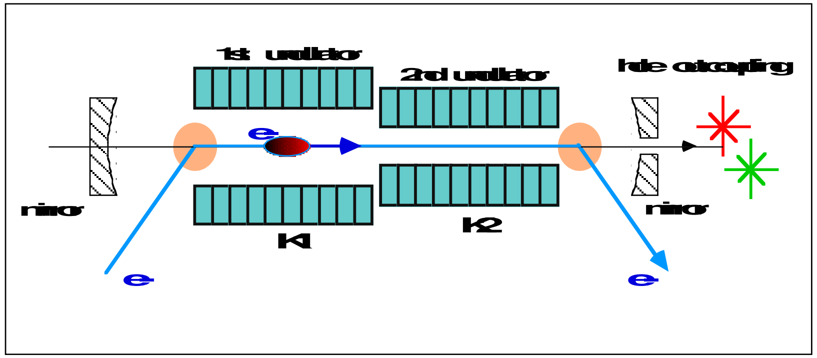


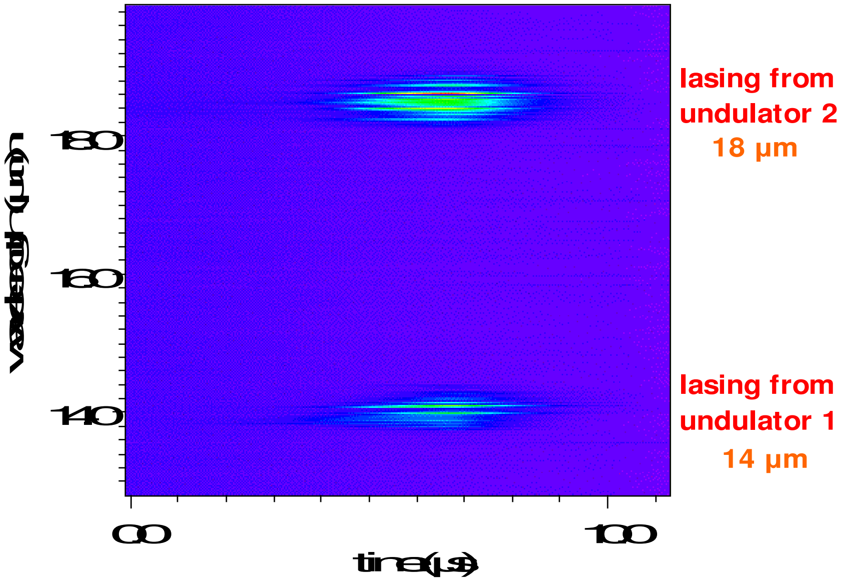
wavelength range: 3.5 – 150 μm
rep. rate: 65 MHz, 25 Hz
special feature: two-color operation

Existing facilities: 'CLIO' in Paris

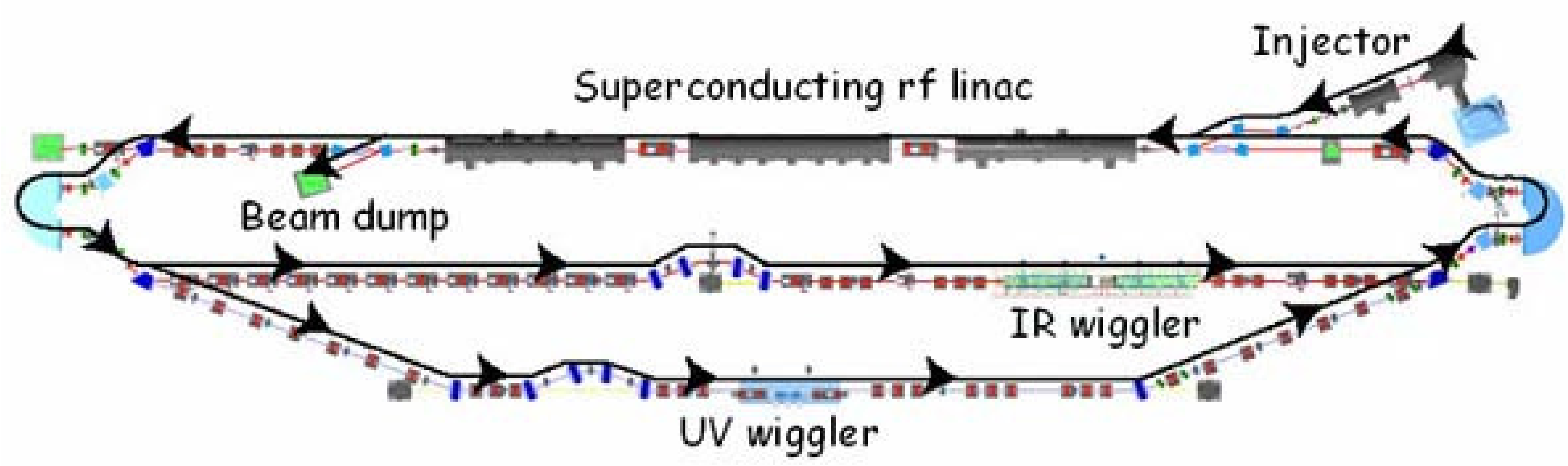
THE TWO COLOUR FREE- ELECTRON LASER

C L I O



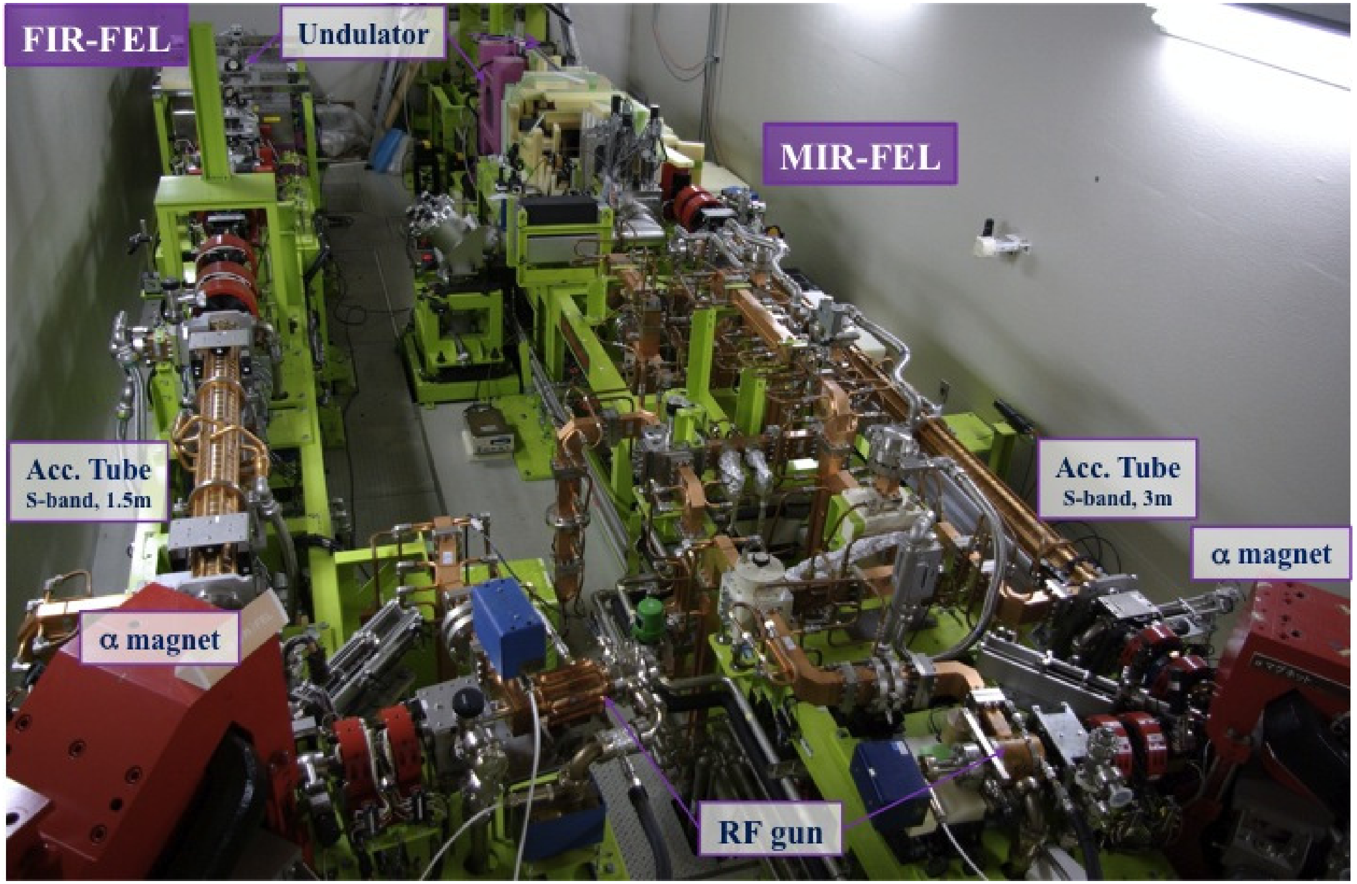


Existing facilities: JLab 10 kW FEL



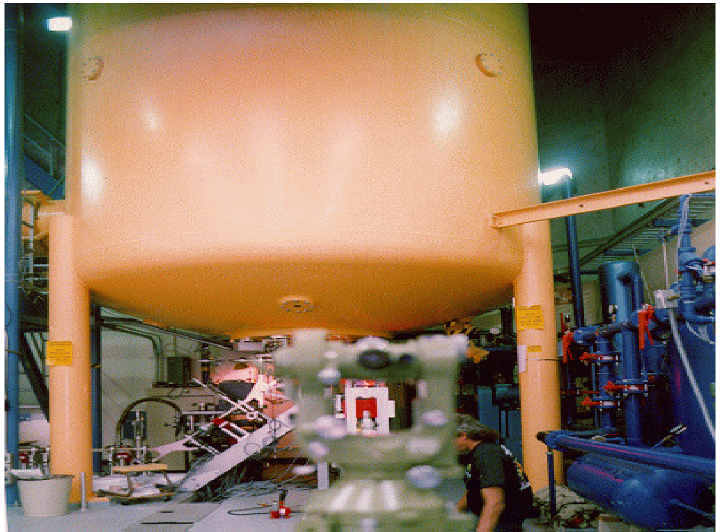
λ	0.25 – 14 μm
micro-pulse	1 ps, 75 MHz, CW
power (average!)	up to 10 kW
efficiency	up to 10%

Existing facilities: FEL-TUS in Tokyo



MIR-FEL: tuning range: 4.5 - 11 μm
rep. rate: 2856 MHz (micro-pulse), 5 Hz (macro-pulse)
pulse length, ≈ 2 ps (micro-pulse), ≈ 1 μs (macro-pulse)
micro-pulse energy: up to 15 μJ/pulse
macro-pulse energy: up to 50 mJ/pulse

Existing facilities: UCSB FEL



λ	0.1 – 2.5 mm
pulse	few μs, 5 Hz
Power	several kW peak