Laser physics for materials scientists

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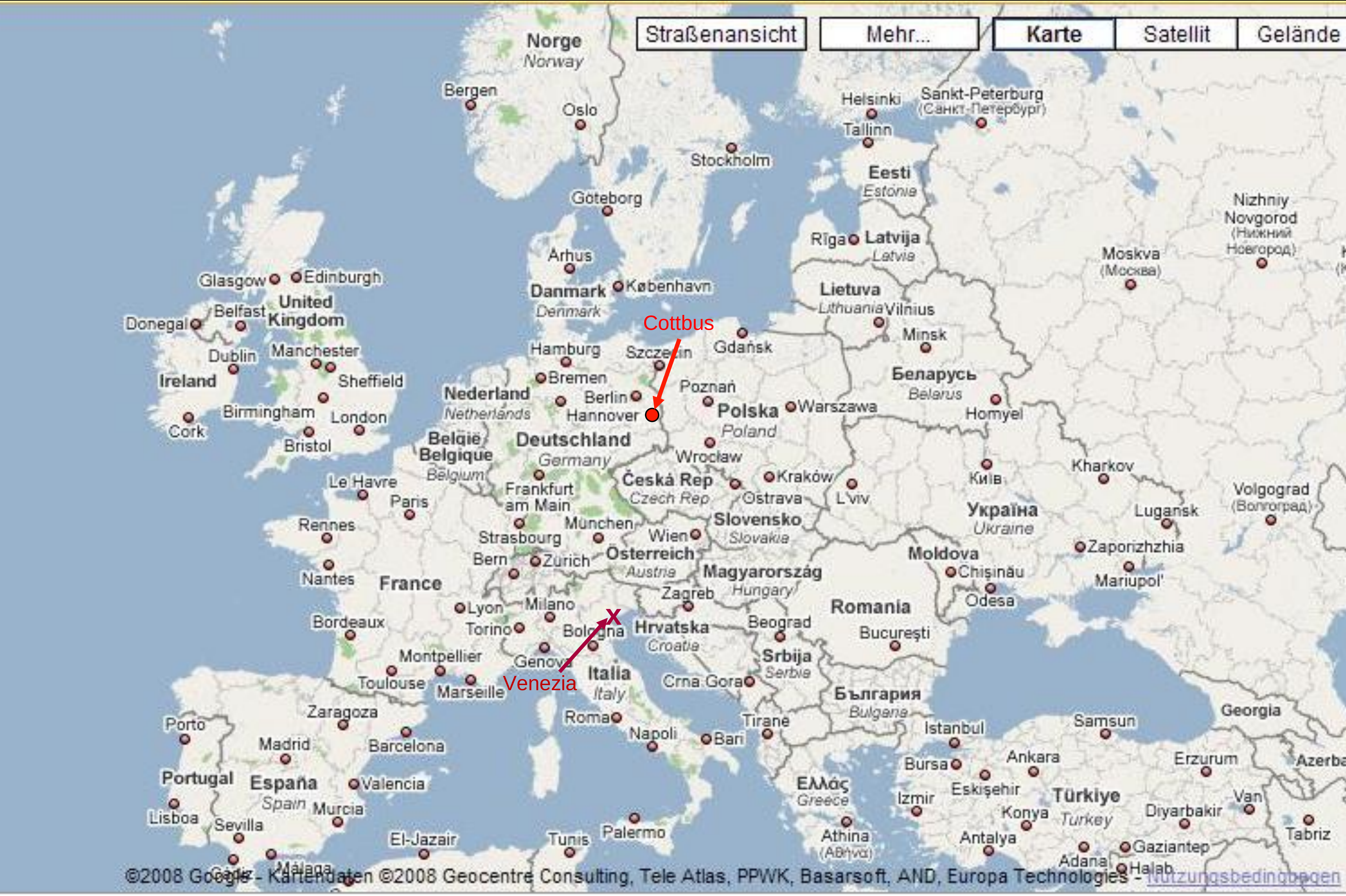
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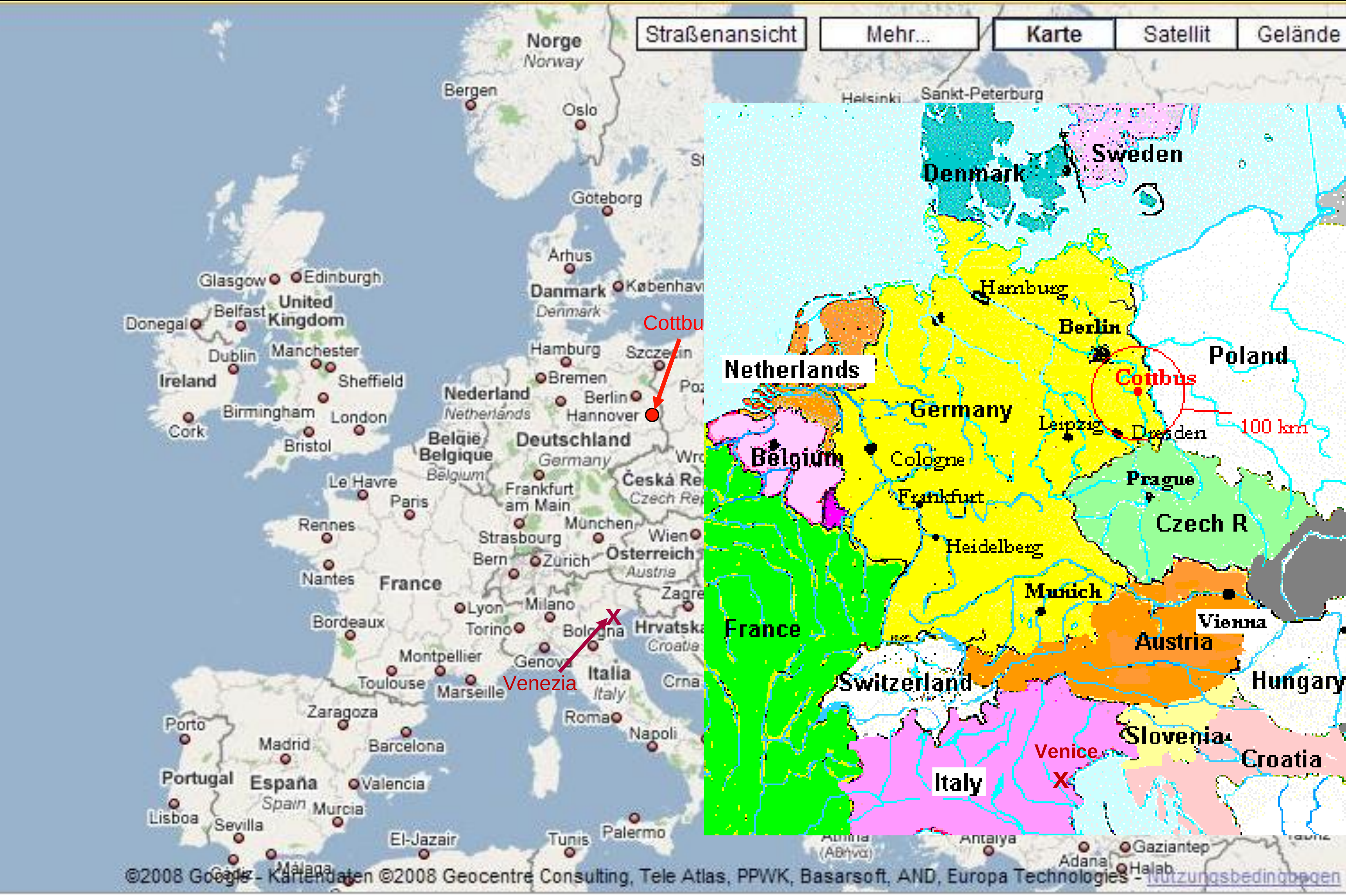
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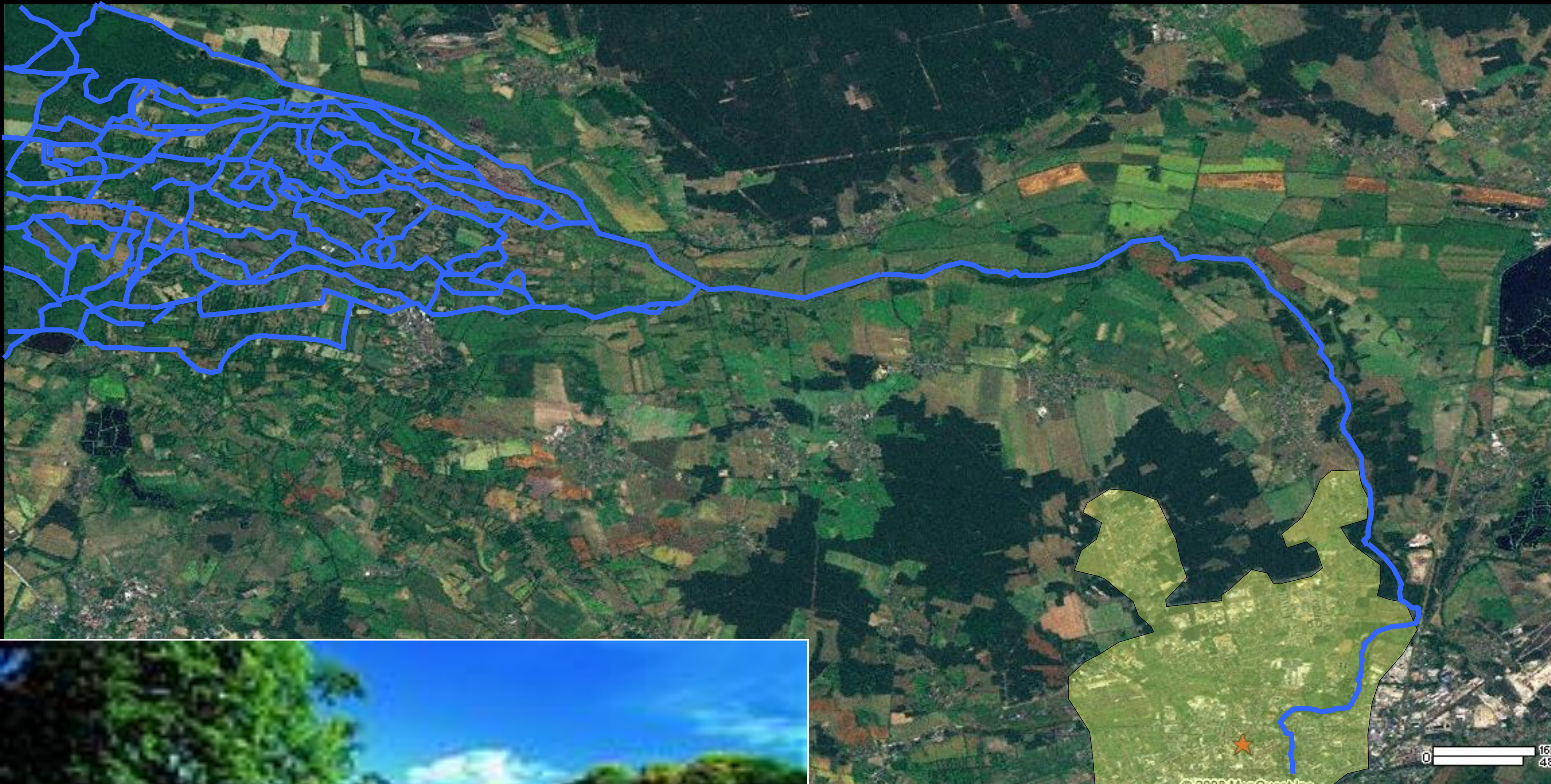
Italy

Spreewald (riparian forest at Spree-river inland delta)



Cottbus

Venice

Cottbus / Spreewald



Lignite (brown coal) Mining / Opencast Mines

b-tu Brandenburgische Technische Universität
Cottbus - Senftenberg

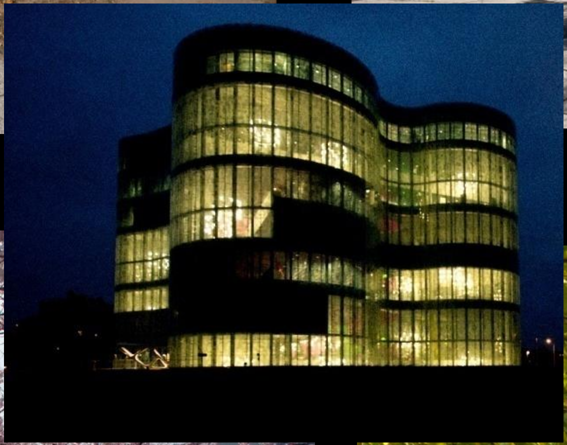
founded 1991/2013

≈ 7,000 Students
3,000 from abroad

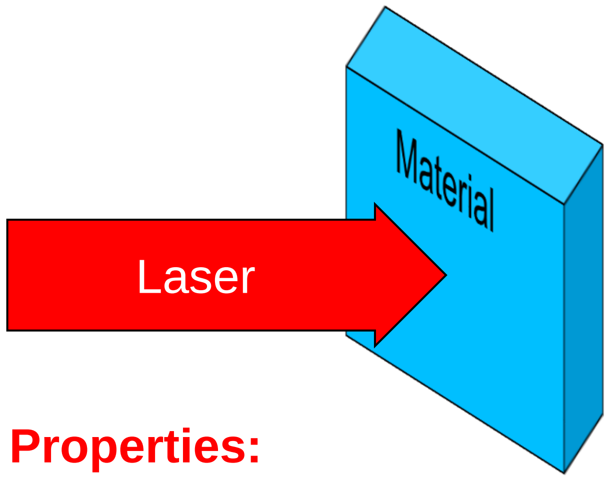
≈ 180 Professors

≈ 670 Staff (Faculty)



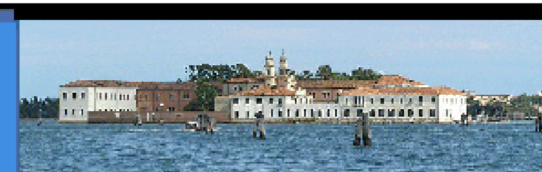


Lasers in Material Science



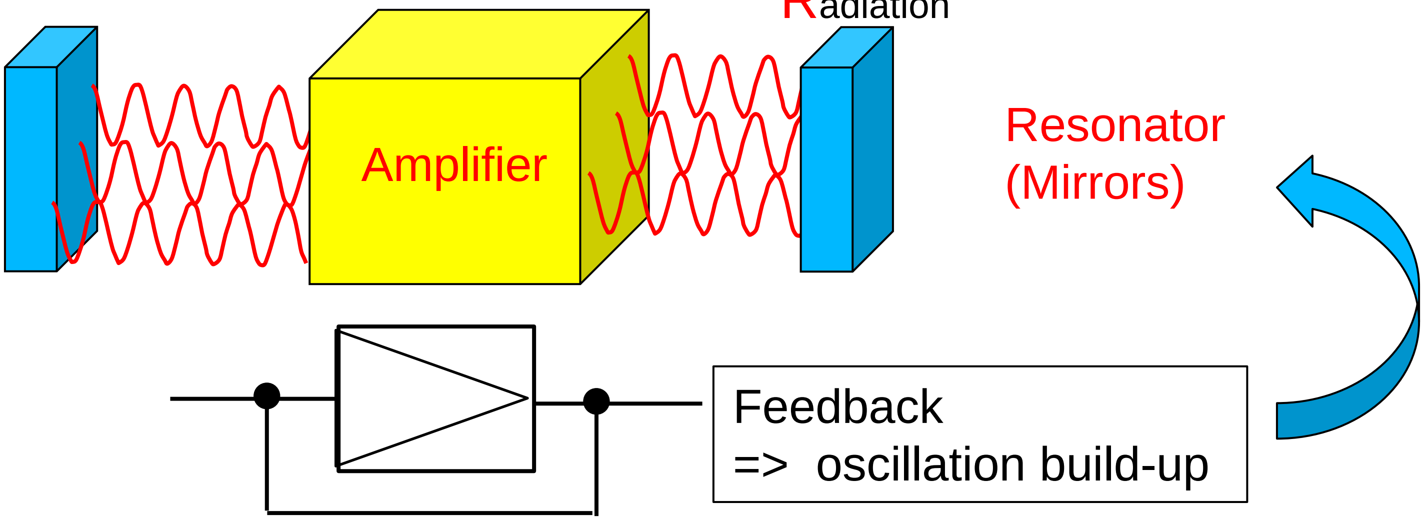
Properties:
- Energy / Fluence
- Focusing
- cw / Pulse
- Pulse Duration/Shape
- Wavelength

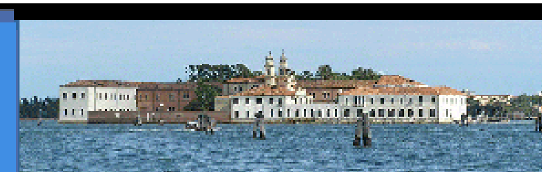
- Analysis
- Processing
- Modification
- Creation
- Manufacturing
- …



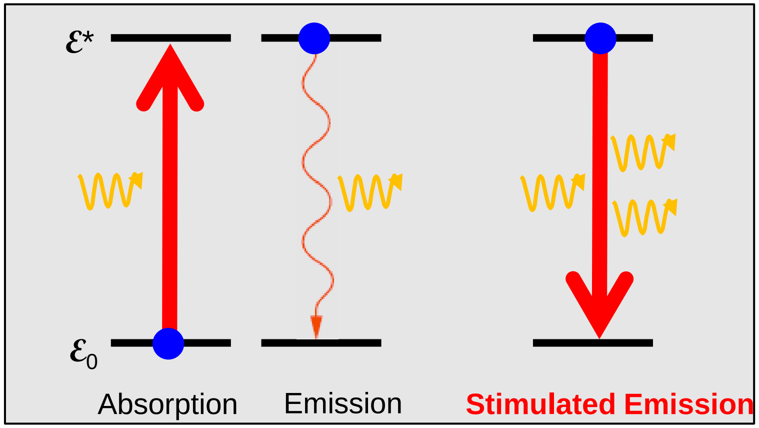
Lasers in Material Science

Light
Amplification
by
Stimulated
Emission
of
Radiation





Lasers in Material Science



Light
Amplification
by
Stimulated
Emission
of
Radiation

Rate Equations

$$\frac{dn^*}{dt} = B\rho n_0 - B\rho n^* - An^*$$

$$\frac{dn_0}{dt} = -B\rho n_0 + B\rho n^* + An_0$$

$$\frac{d\rho}{dt} = B\rho(n^* - n_0)$$

n_0, n^*: population of levels $\mathcal{E}_0$, $\mathcal{E}^*$

ρ : photon density (~ E^2)

$A \sim 1/\tau$: Einstein coefficient of *spontaneous* emission (τ: lifetime of state $\mathcal{E}_0$)

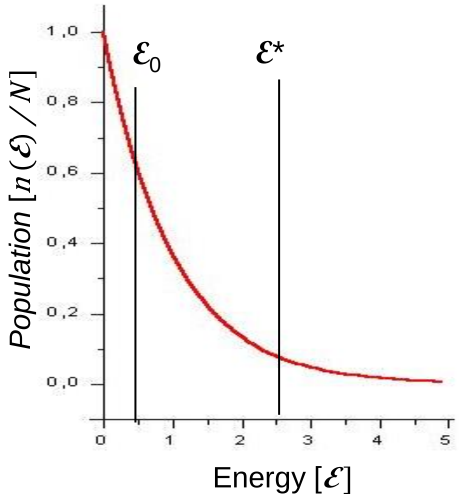
B : Einstein coefficient of *stimulated* emission

Amplification:

$\Delta n = (n^* - n_0) > 0$
Population Inversion

Boltzmann Distribution

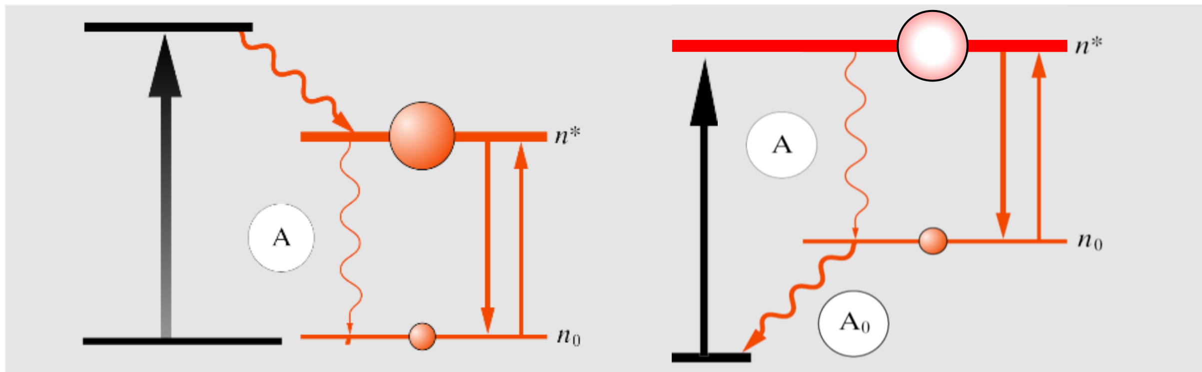
$$\frac{n(\mathcal{E})}{N} = exp\left\{-\frac{\mathcal{E}}{kT}\right\}$$



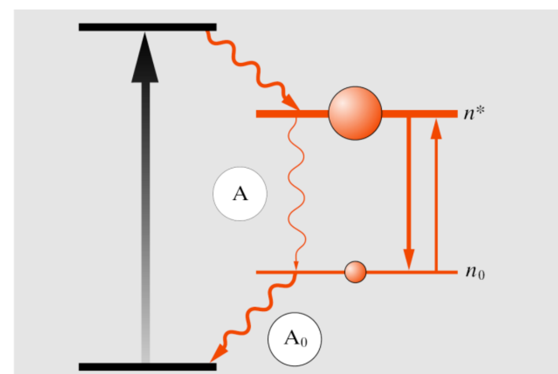
Lasers in Material Science

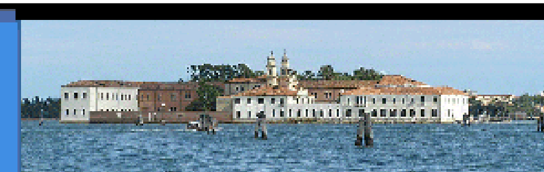
REAL laser gain media: **more** than two levels

3- or
4-level
systems



Pumping: Establishment of population inversion





Lasers in Material Science

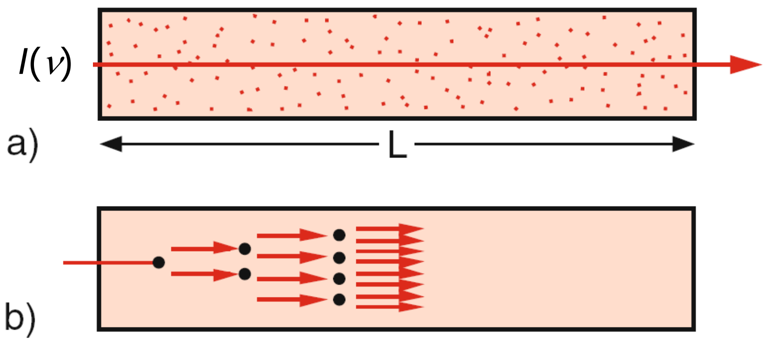
Combination of **gain-medium/pumping** and **resonator (cavity)**

=> Laser properties

- wavelength, monochromacity, bandwidth
- beam profile
- continuous wave (cw) / pulsed operation
  - power
  - pulse energy
  - repetition rate
  - pulse duration
    - pulsed pumping [ms, µs]
    - Q-switch (giant pulse) [ns]
    - mode-locking
      [very (ps) / ultra (fs) short pulses]

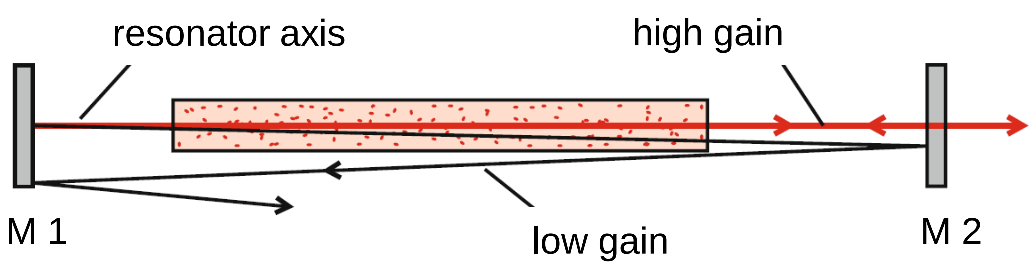
Lasers in Material Science

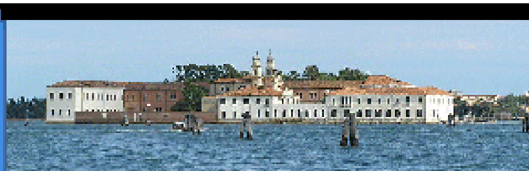
Resonators (cavities)



$I(L) = I_0 \, exp\,\{-\alpha(\nu)L\}$ (Beer's Law)

$I(L) = I_0 \, exp\,\{g(\nu)L\}$ (g : gain)





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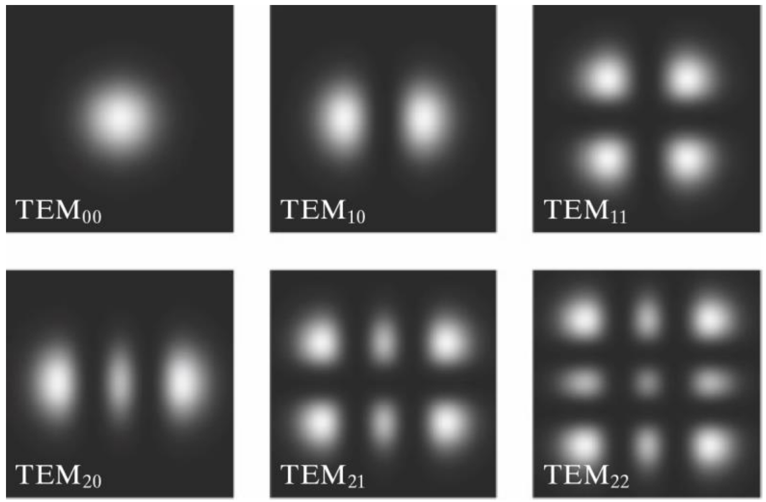
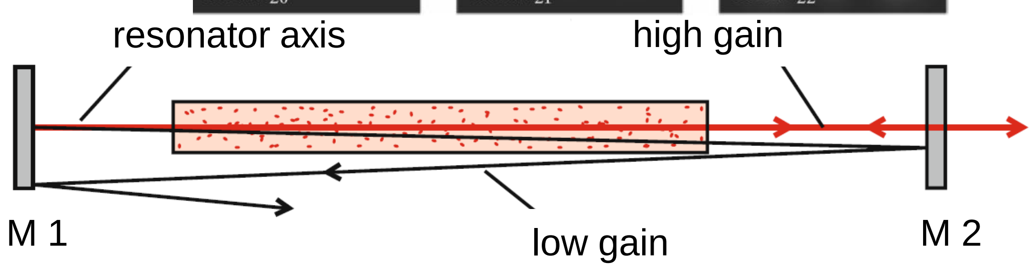
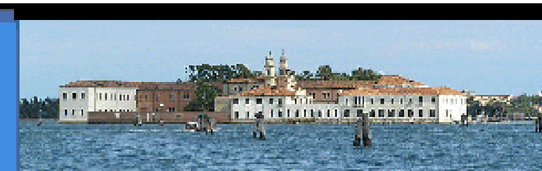
Resonators (cavities) : transverse modes (TEM)







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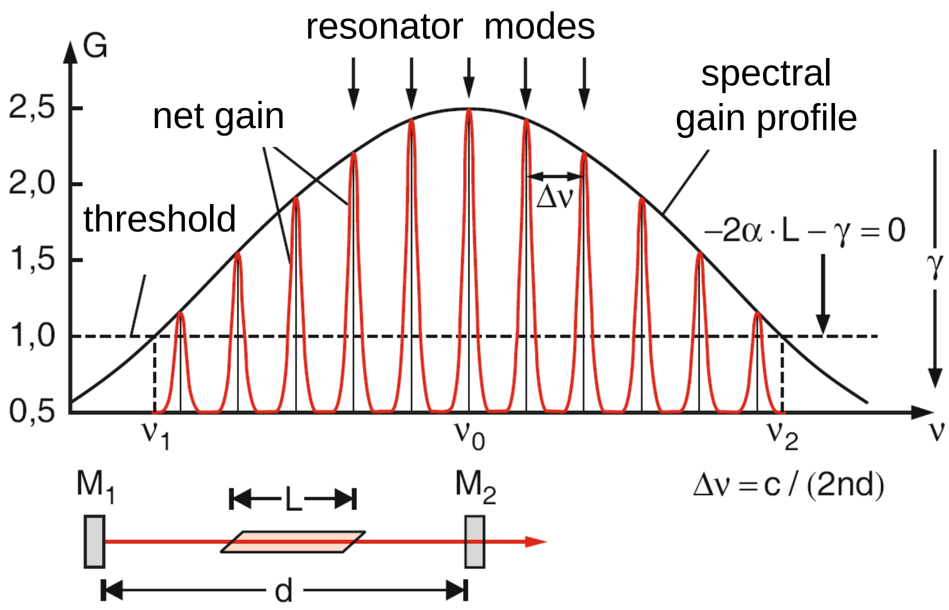
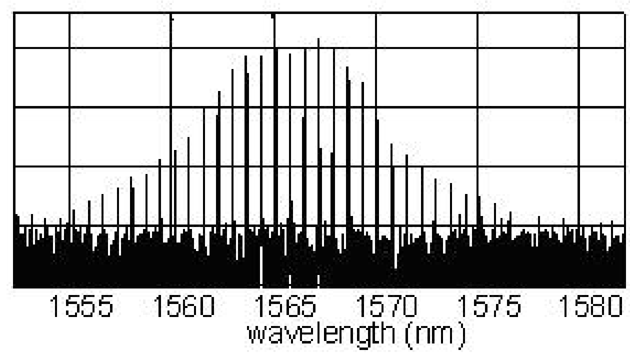
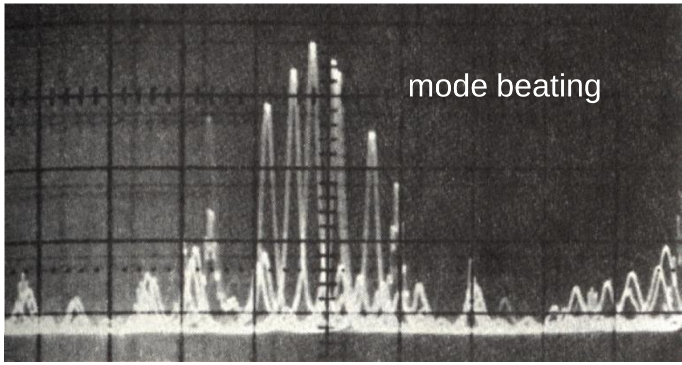
Resonators (cavities) : longitudinal modes



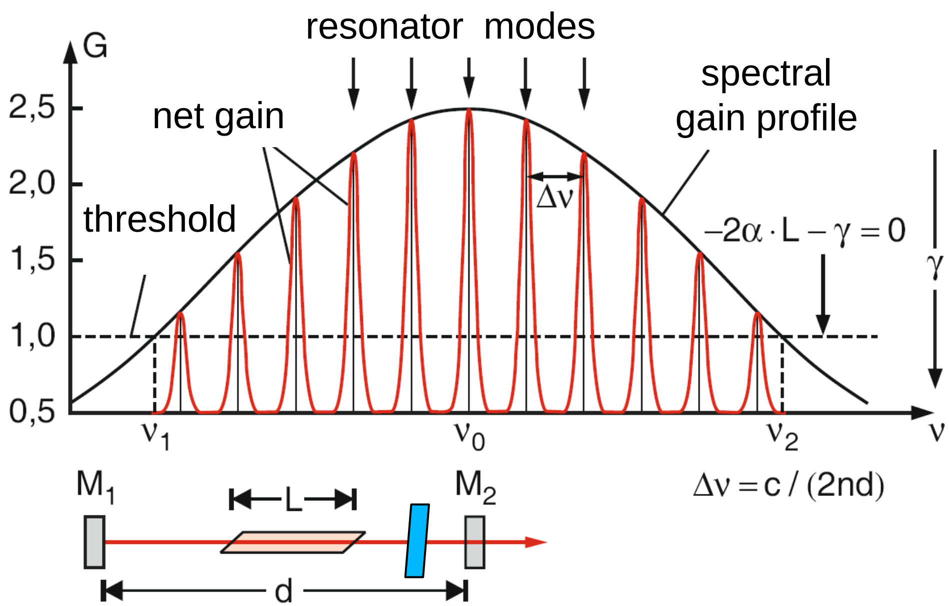


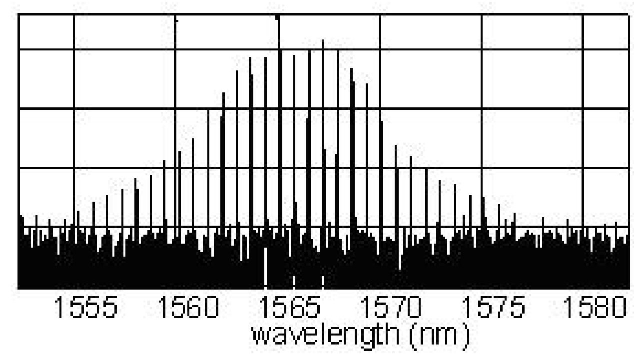


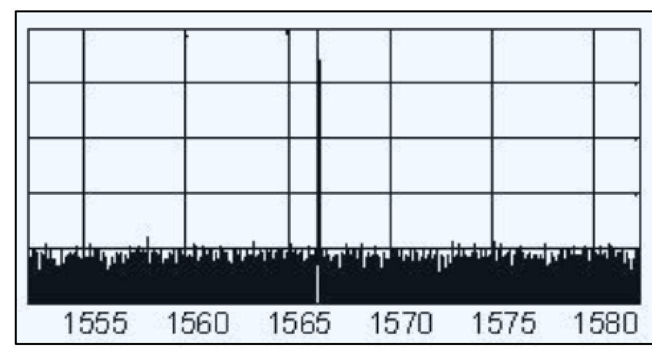
time

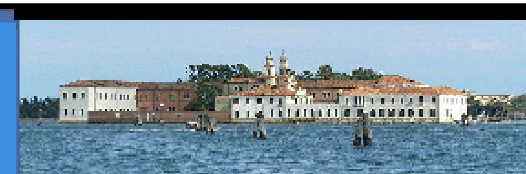
Lasers in Material Science

Resonators (cavities) : longitudinal modes





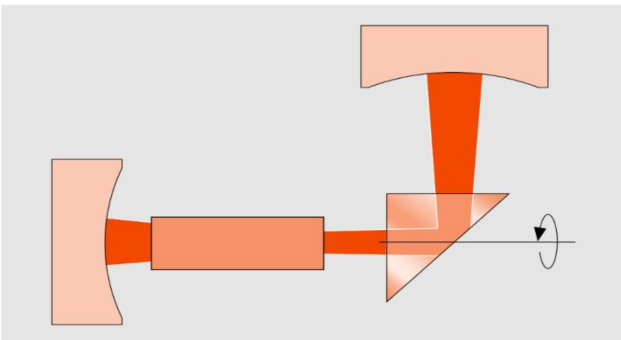


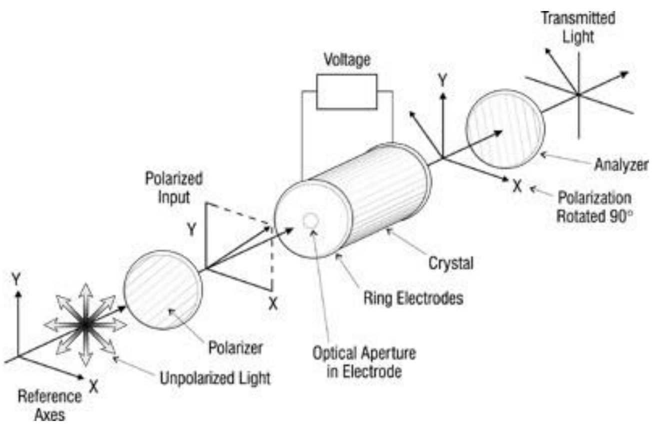


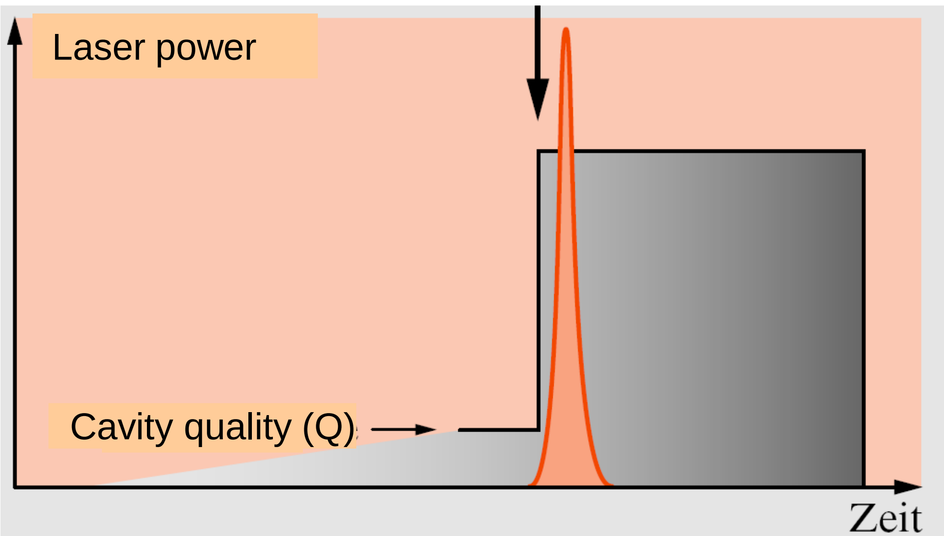
Lasers in Material Science

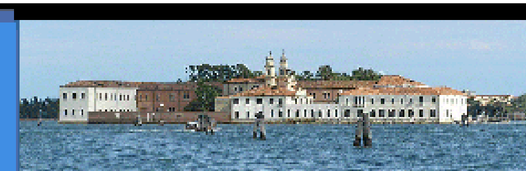
Resonators (cavities) : short pulses

Q-switch
(10 ns)





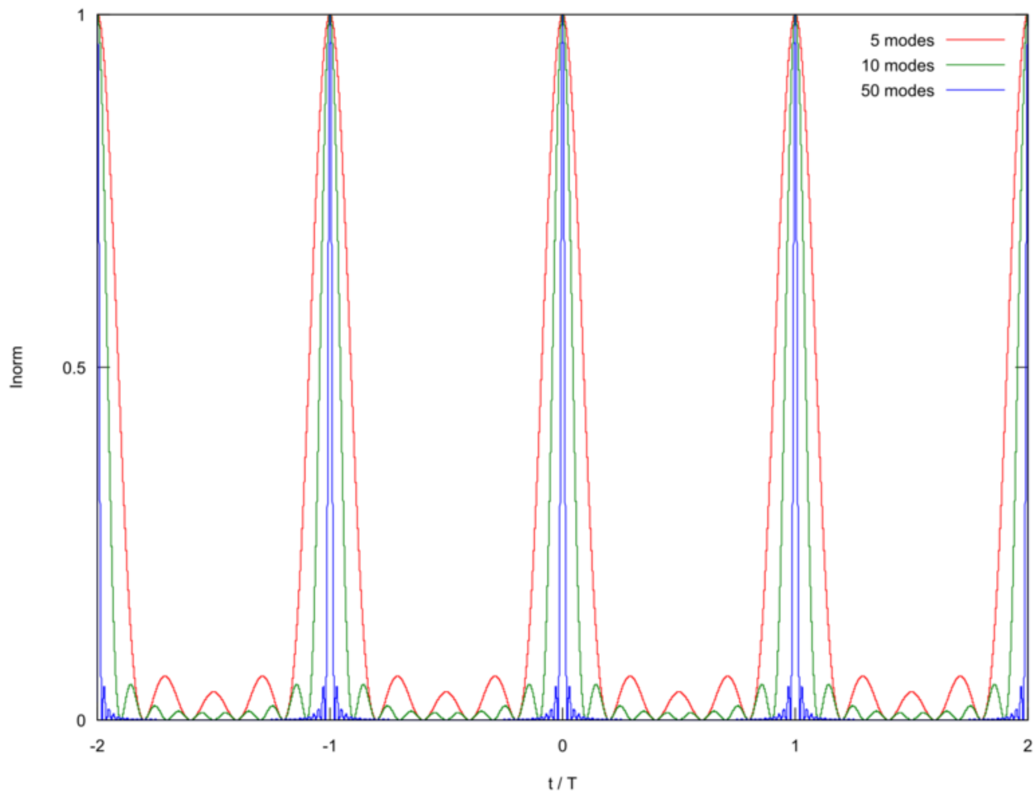


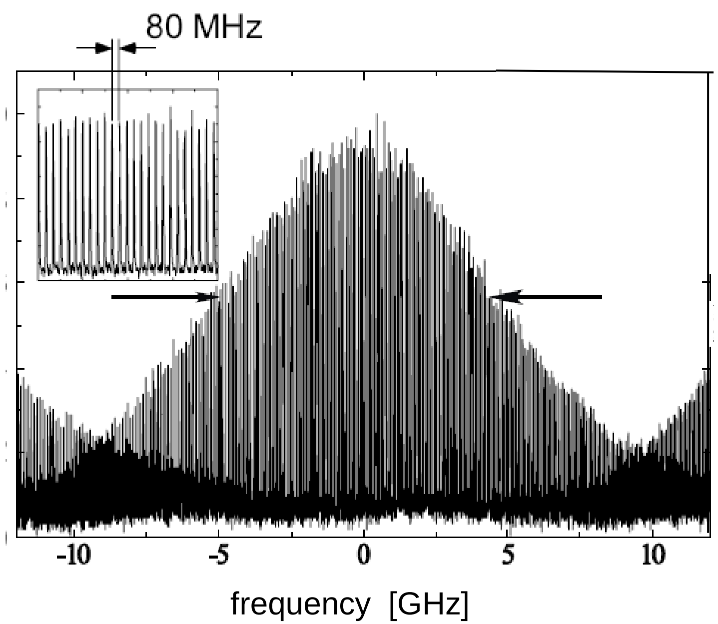


Lasers in Material Science

Resonators (cavities) : short pulses

mode locking
(5 fs … 100 ps)





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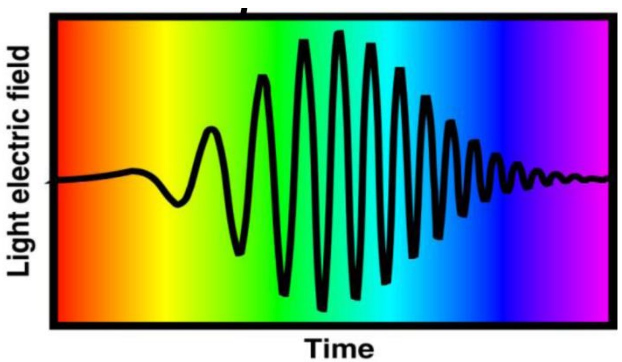
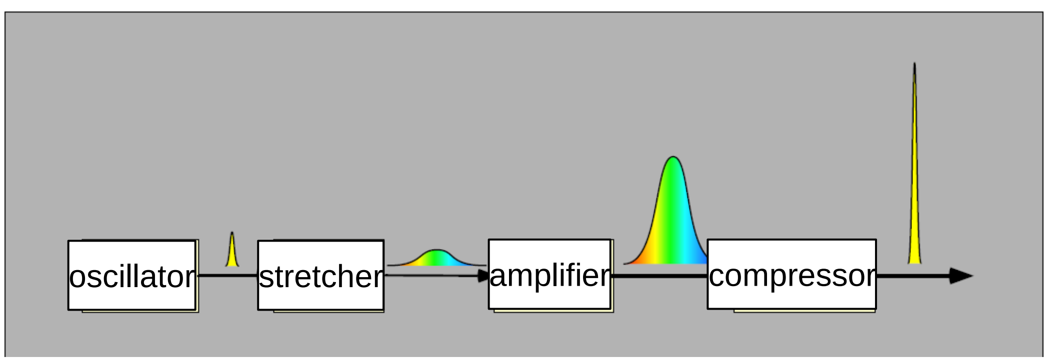
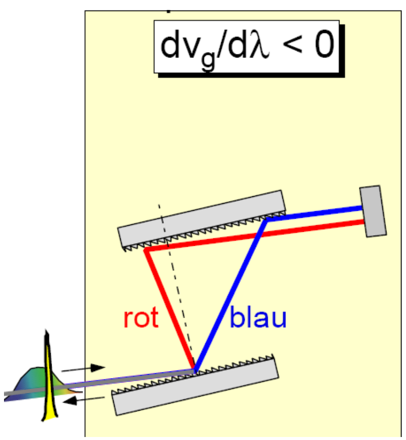
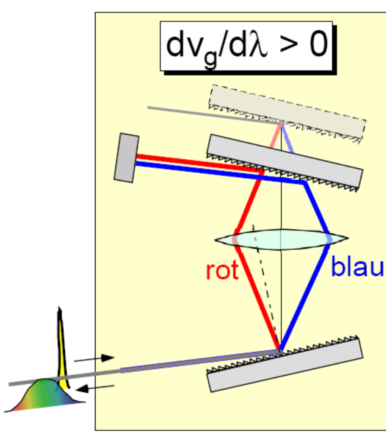
Resonators (cavities) : short pulses

mode locking
(5 fs … 100 ps)
chirped pulse amplification







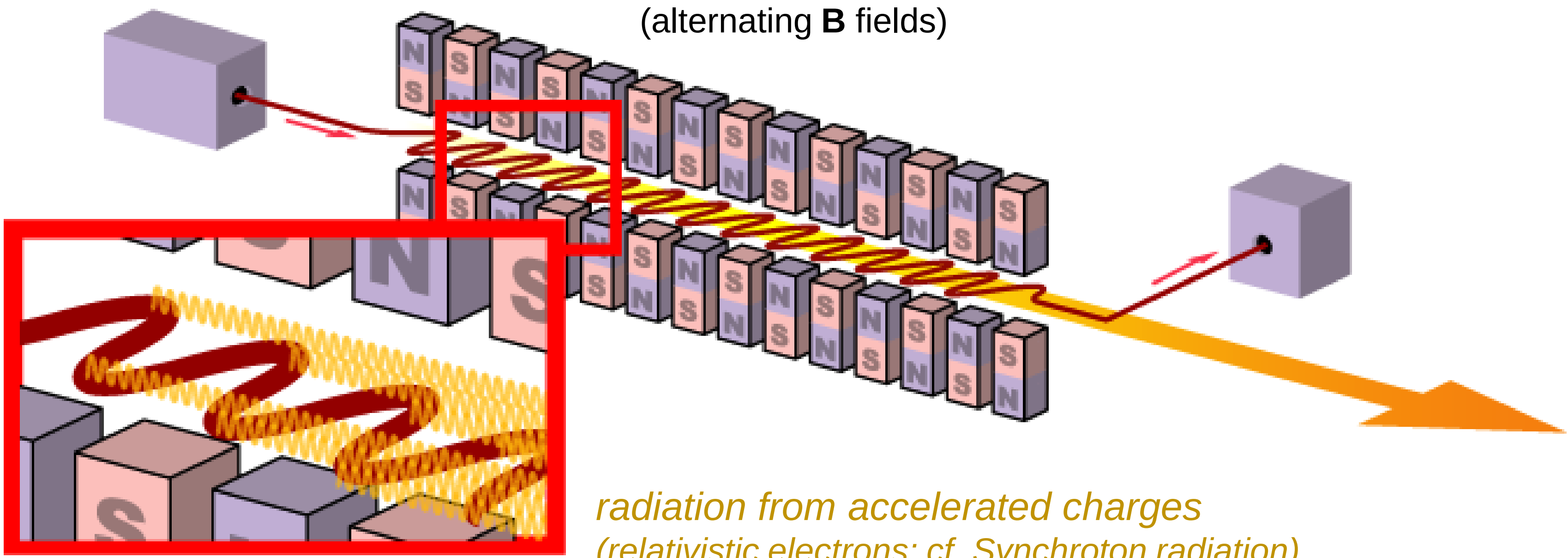


Lasers in Material Science

Free electron laser (FEL)

accelerator
(relativistic electrons)

undulator
(alternating **B** fields)

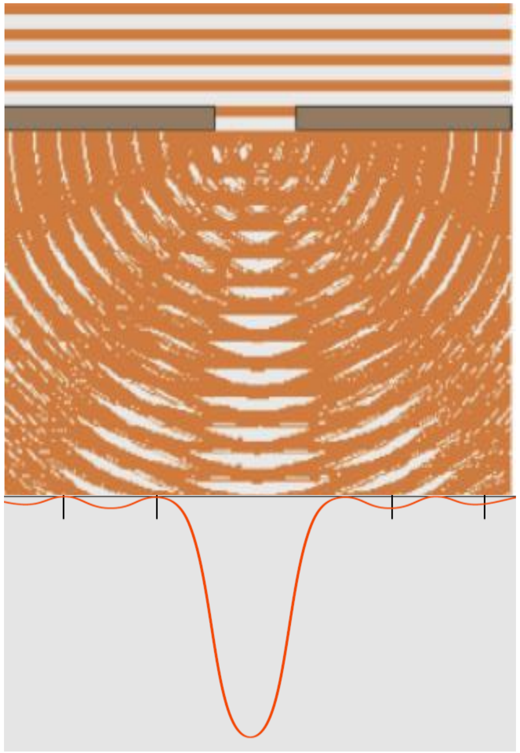


radiation from accelerated charges
(relativistic electrons; cf. Synchroton radiation)

Lasers in Material Science

Beam Propagation

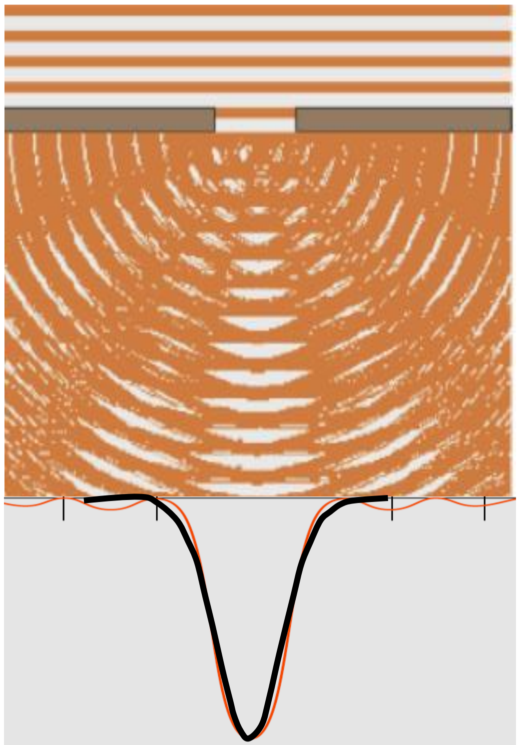
Diffraction



Lasers in Material Science

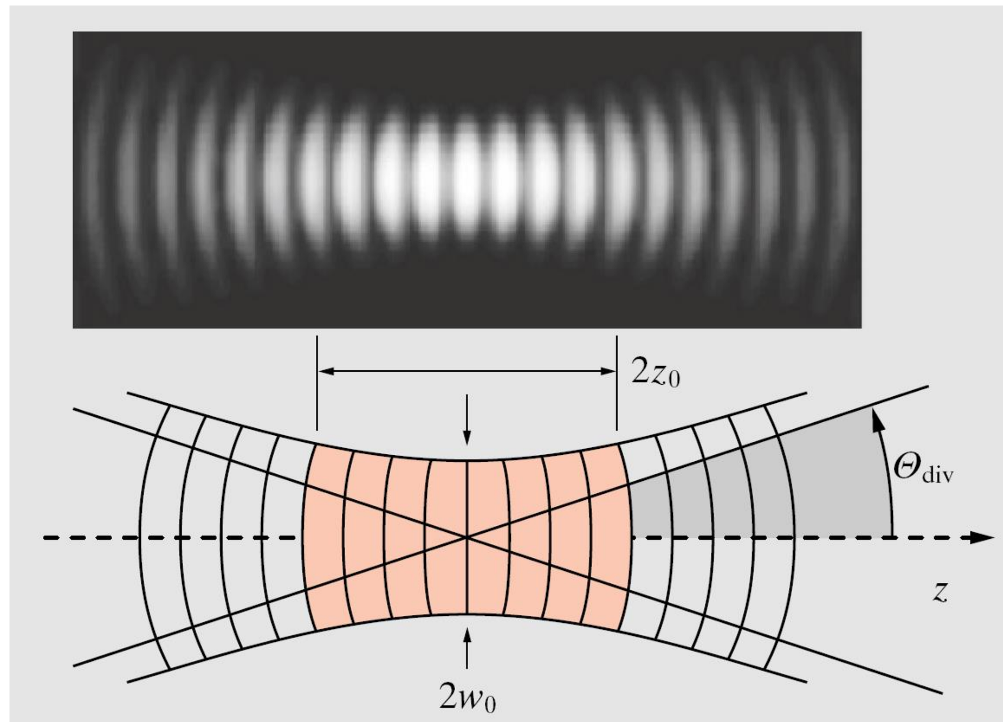
Beam Propagation

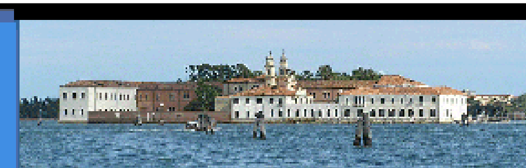
Diffraction



Gaussian Profile (M² = 1)

Gaussian Beam TEM_{00}
(diffraction limited)





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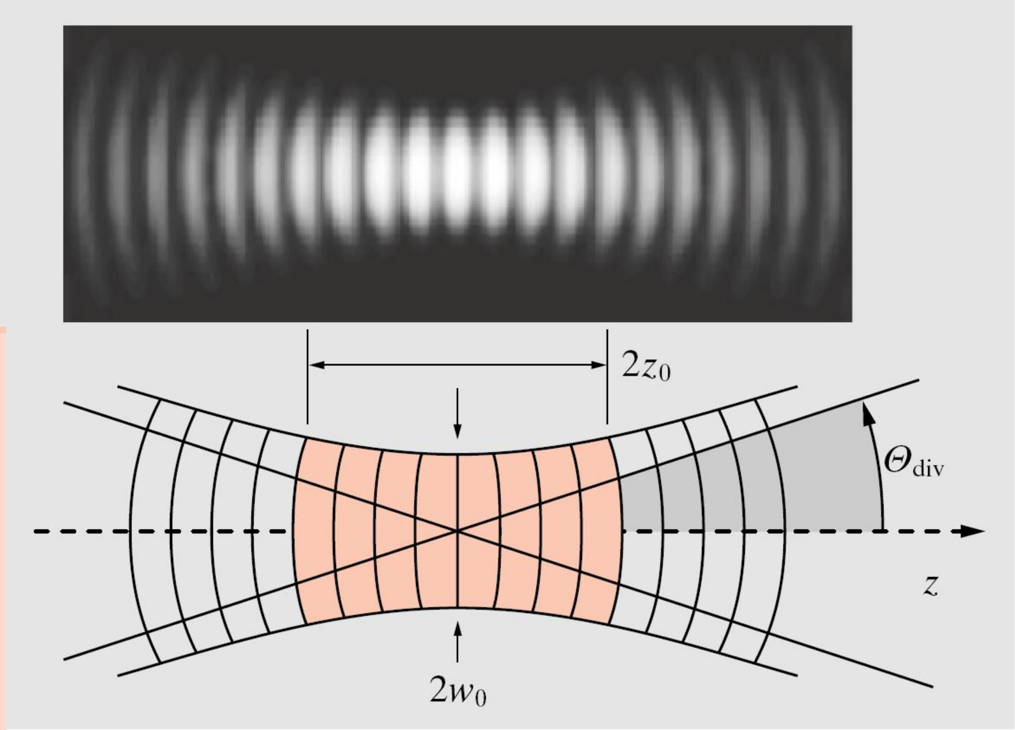
Beam Propagation

Gaussian Beam TEM_{00}



beam diameter $w(z) = w_0[1 + (z/z_0)^2]^{1/2}$

beam waist $w_0^2 = \lambda z_0/\pi$

divergence $\Theta_{div} = w_0/z_0$

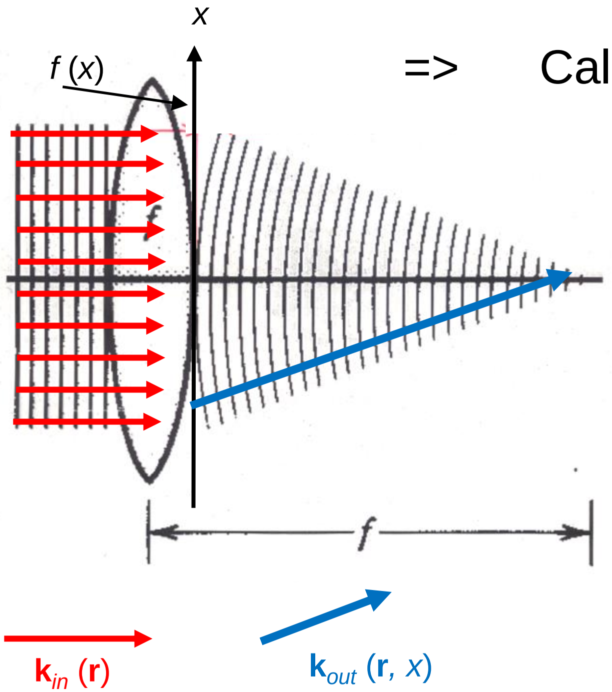
wavefront radius $R(z) = z[1 + (z_0/z)^2]$

Lasers in Material Science

Beam Propagation

Influencing beam propagation by optical elements (lenses, diaphragms, …)

=> Calculate effect by Fourier Transform



$$\mathbf{k}_{out}\,(\mathbf{r}, x) = \mathrm{FT}\,\{\underbrace{f(x)\otimes\mathbf{k}_{in}(\mathbf{r})}_{\text{field distribution at the exit of optical element}}\}$$

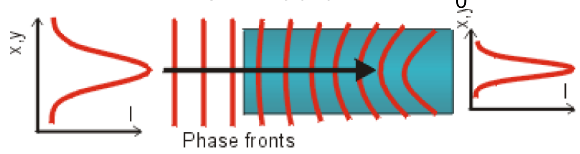
Lasers in Material Science

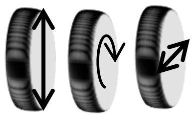
Beam Propagation

some problems/difficulties

- Focusing
  - tightest focus for diffraction limited beams (TEM_{00}; $M^2 = 1$)
  - all other beams have wider focus (incoherent, higher TEM modes …)
- Attenuation
  - attenuation by reduced pump power or grey filters results in changing beam divergence (thermal lenses, Kerr lenses)
  - better: *passive* attenuation, polarization optics

Kerr Medium: $n = n_0 + n' I$

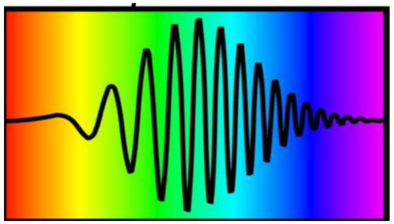




λ/2-plate

- Short pulses

  diffraction (glass) induces chirp
  - larger pulse duration
  - Reduced beam quality



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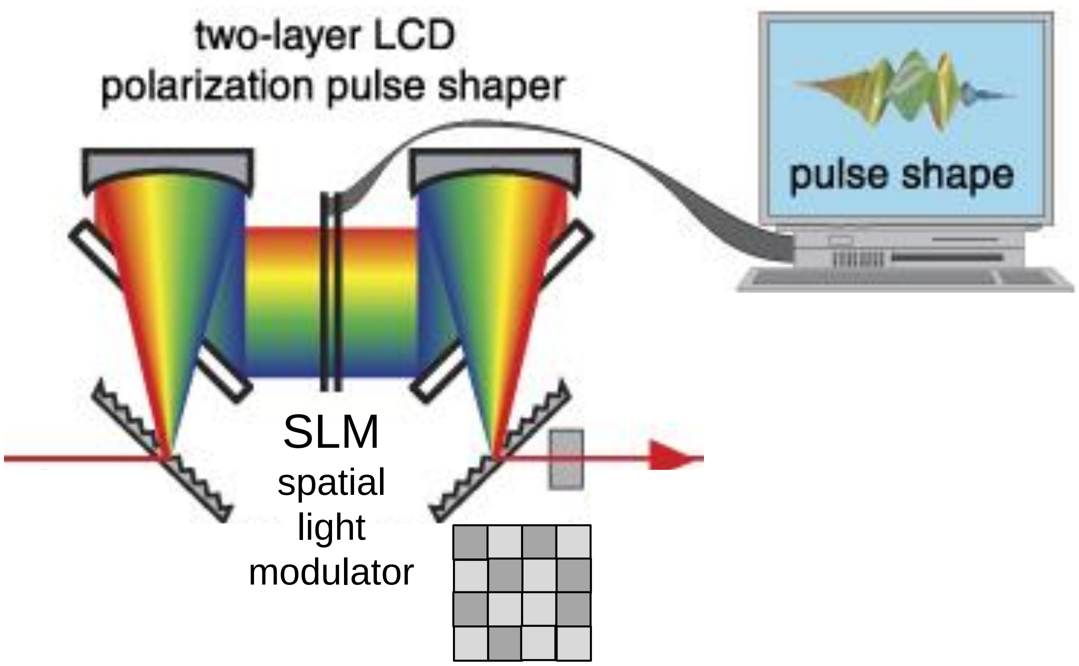
Beam Shaping
(spatio-temporal)



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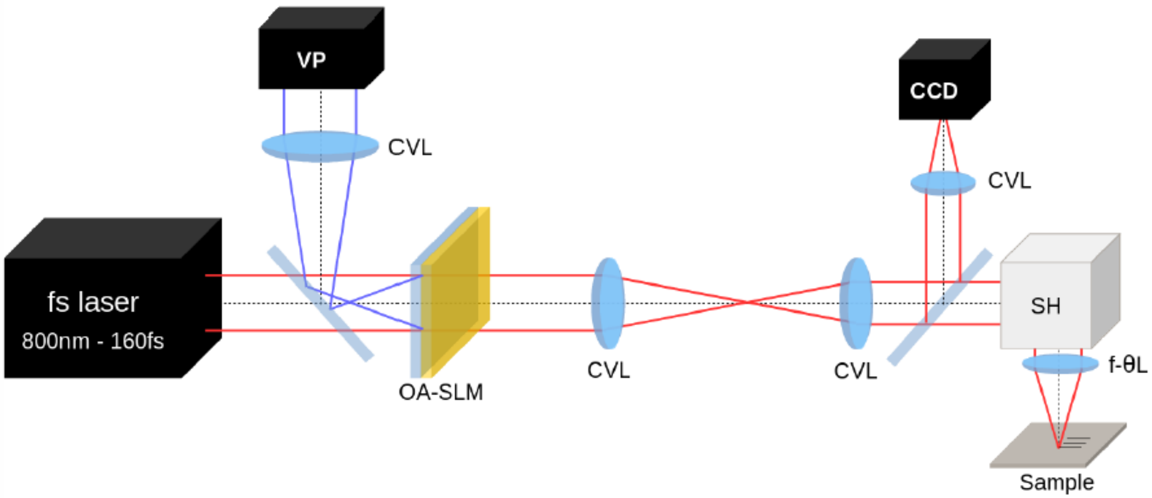
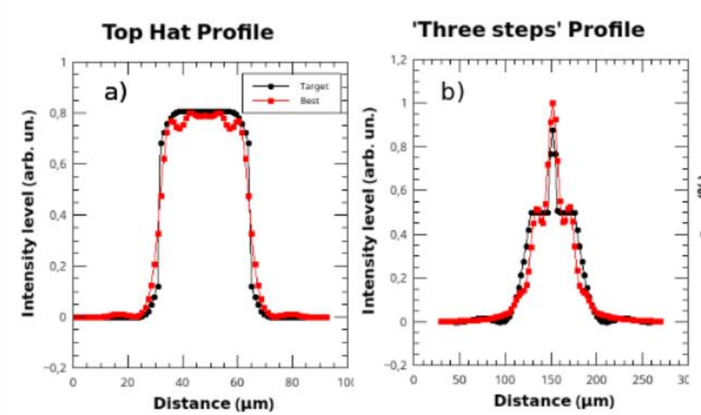
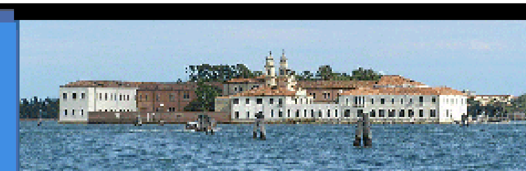
Beam Shaping
(spatio-temporal)





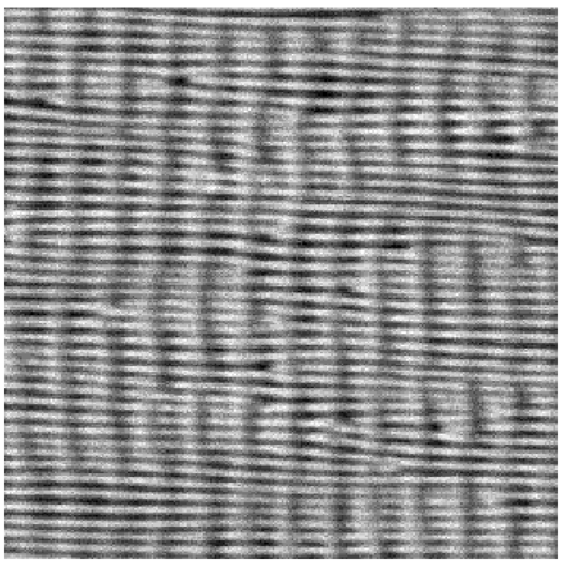
J. Houzet, N. Faure, M. Larochette, A.-C. Brulez, S. Benayoun, C. Mauclair; Opt. Express **24**, #257603 (2016)

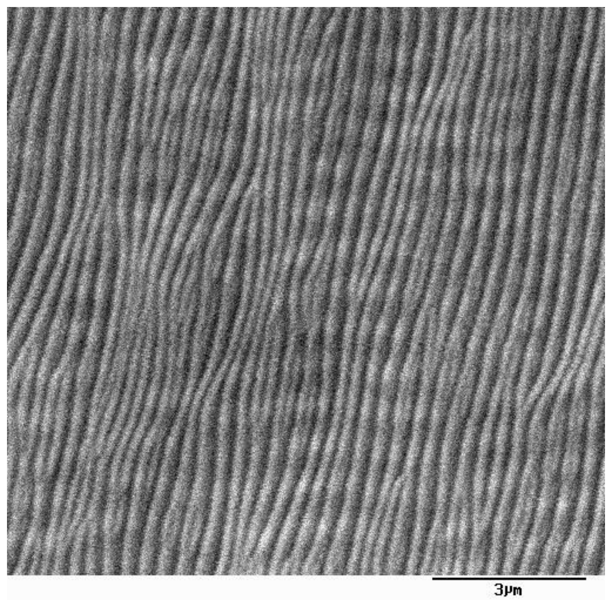


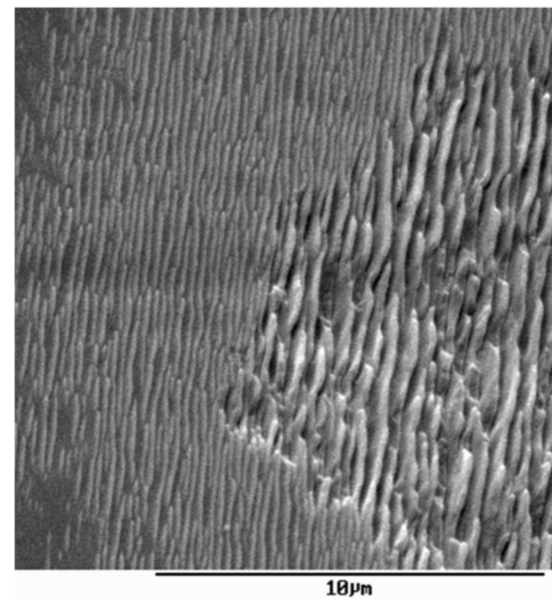
Lasers in Material Science

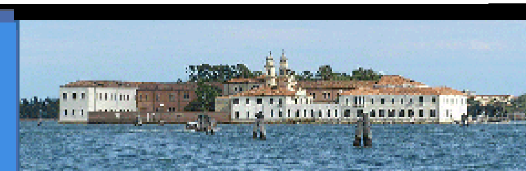
Special Application:

Laser Induced Periodic Surface Structures (LIPSS, ripples)







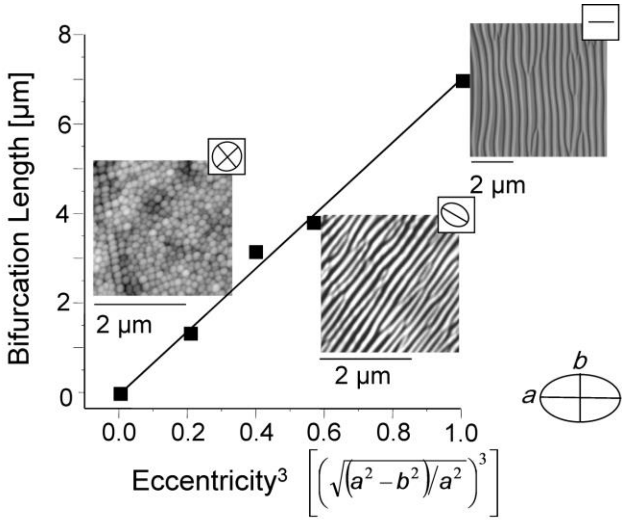


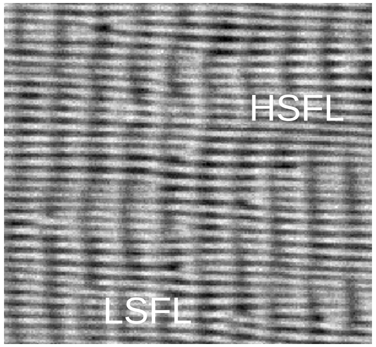
Lasers in Material Science

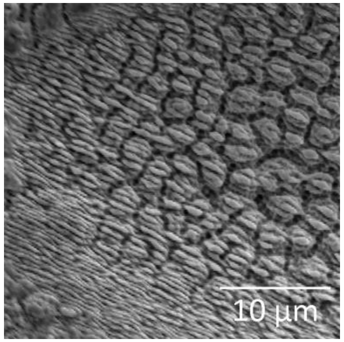
Special Application:

Laser Induced Periodic Surface Structures (LIPSS, ripples)

- Orientation strongly polarization dependent
- Different feature size:
  sub-Laser wavelength (HSFL; high spatial frequency LIPSS)
  about Laser wavelength (LSFL; low spatial frequency LIPSS)
  much larger than Laser wavelength (grooves, cones)





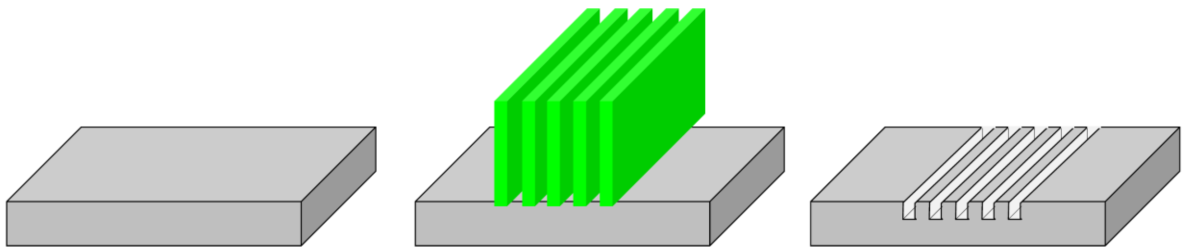


Laser Induced Periodic Surface Structures (LIPSS)

Two substantially different models for structure formation:

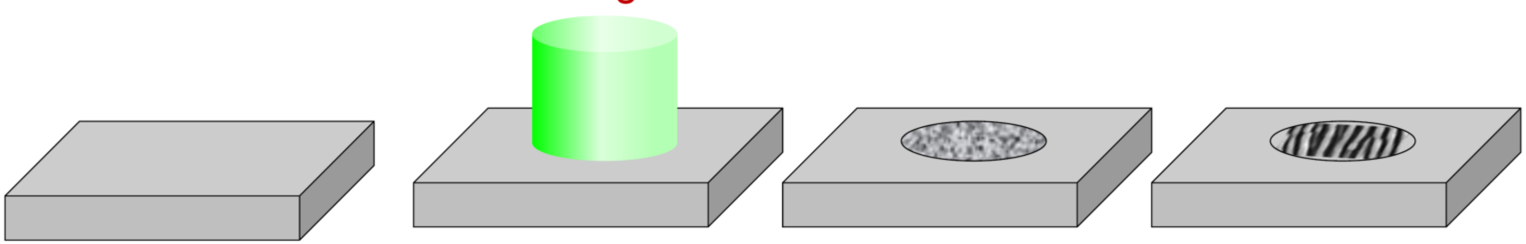
1) "STATIC" model:

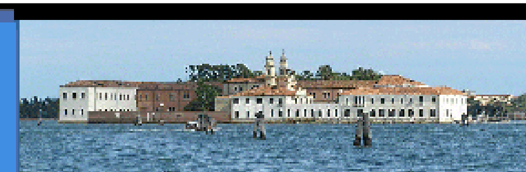
modulated energy input ⇒ modulated ablation ⇒ surface corrugation



2) "DYNAMIC" model:

"averaged" energy input ⇒ instability in irradiated region ⇒ dynamic evolution ⇒ self-organization





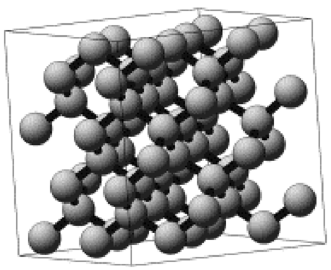
Lasers in Material Science   Laser Induced Periodic Surface Structures (LIPSS)

(surface) instability   =>   fast relaxation

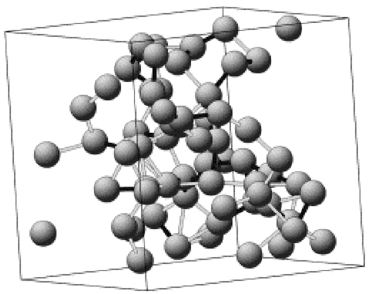
new pathways: nonlinear dynamics

↓

self-organized structure formation



t = −40 fs



t = 500 fs

H.O. Jeschke *et al.*,

Appl. Surf. Sci. **197-198**, p. 839, 2002.

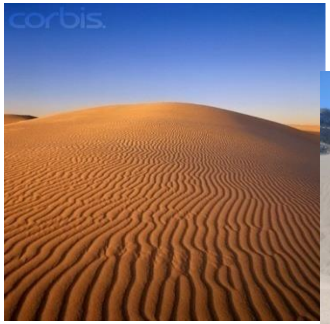
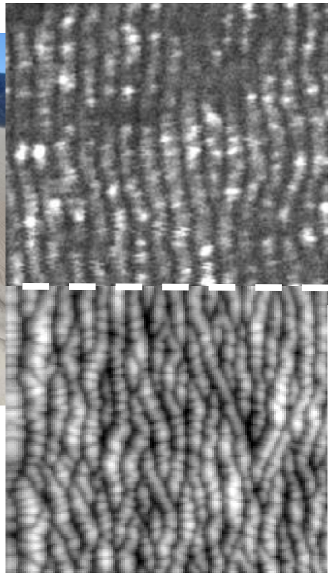


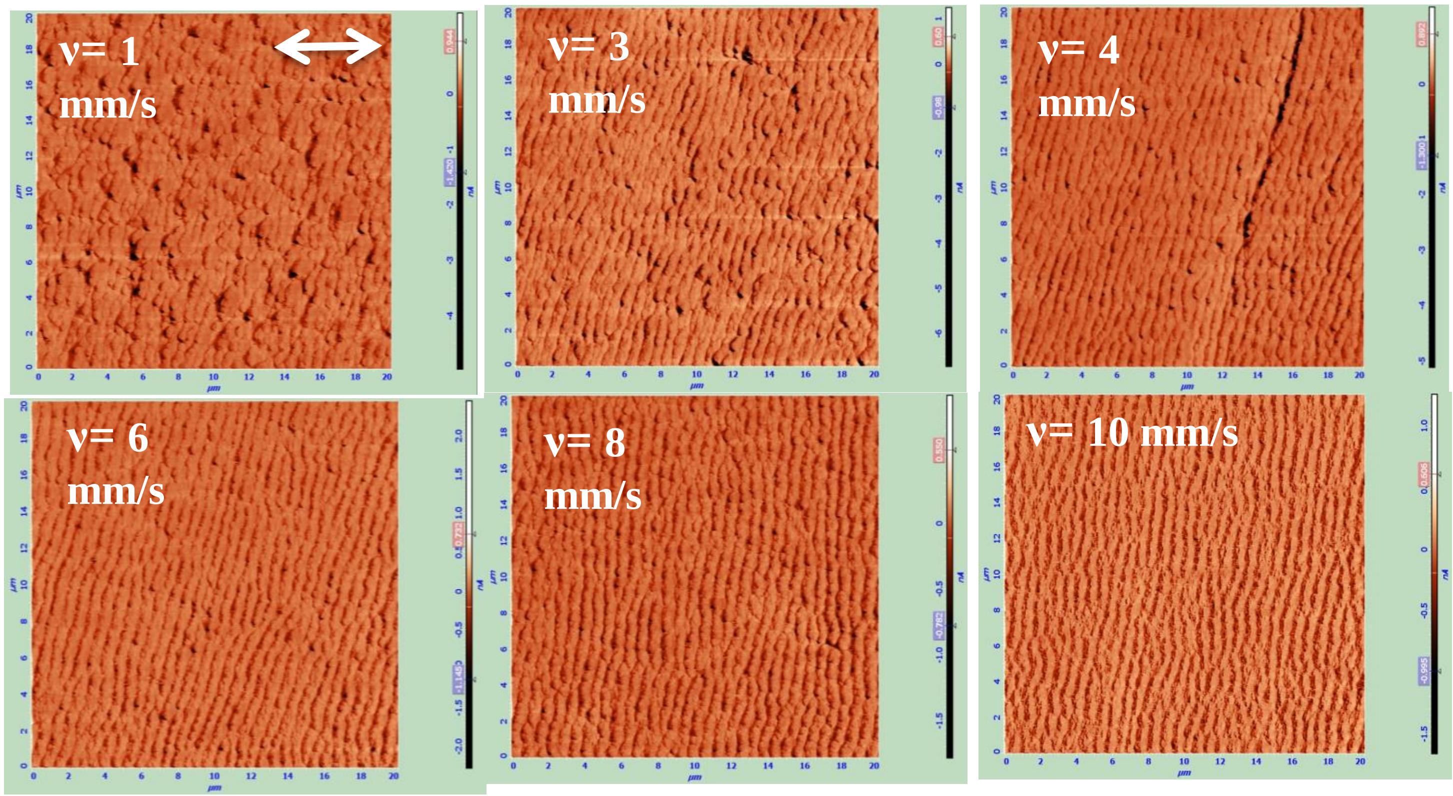
Photo: Gediminas Raciukaitis

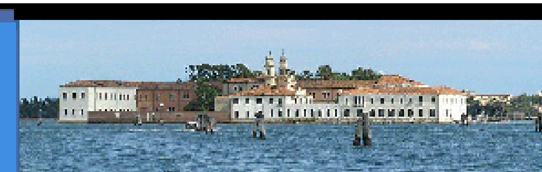


Lasers in Material Science Laser Induced Periodic Surface Structures (LIPSS)

Large area coverage (line scans) => very regular structure (esp. on metals)

stainless steel

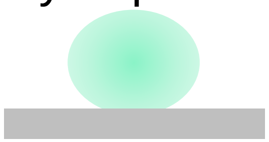


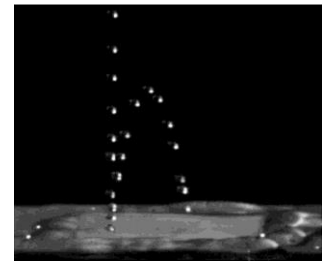


Lasers in Material Science   Laser Induced Periodic Surface Structures (LIPSS)

Large area coverage => modification of wettability

Hydrophobic

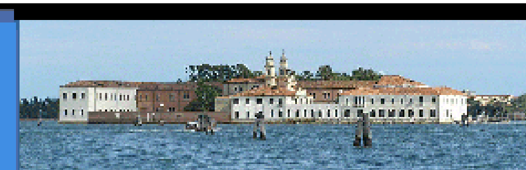




M.N.W. Groenendijk, Twente
[*The LPM**2006** Outstanding Student Paper Award (Oral)*]

Hydrophilic

cf.:
A.Y. Vorobyev, Chunlei Guo,
Laser Photonics Rev. **7**, 385–407 (2013)

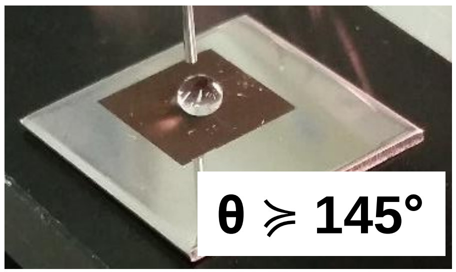


Lasers in Material Science Laser Induced Periodic Surface Structures (LIPSS)

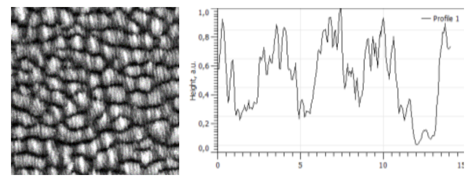
Large area coverage => modification of wettability

Comparison
Silicon vs.
Steel

- **Stainless steel (aged)**



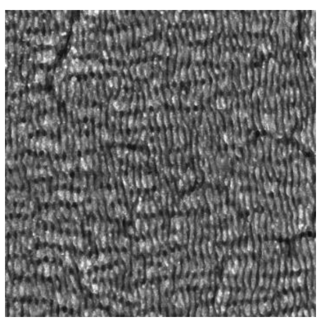
hierarchical patterns ⇒
Super-Hydrophobic



Aging or Topography?

- **Stainless steel**

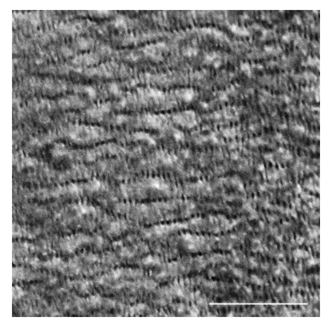
Hydrophobic (θ ≈ 125°)



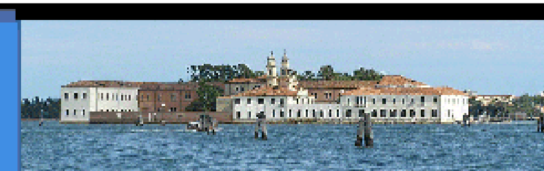
$\lambda_{fine} \approx 550$ nm
$\Lambda_{coarse} \approx 2$ µm

- **Silicon**

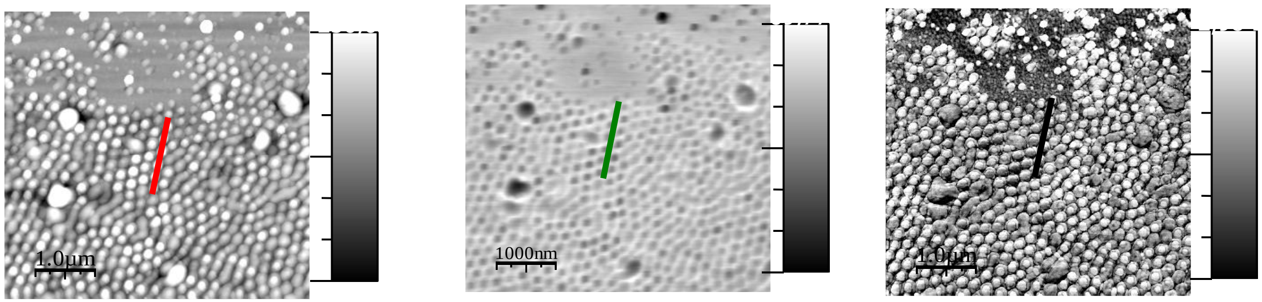
Hydrophilic (θ ≈ 13°)

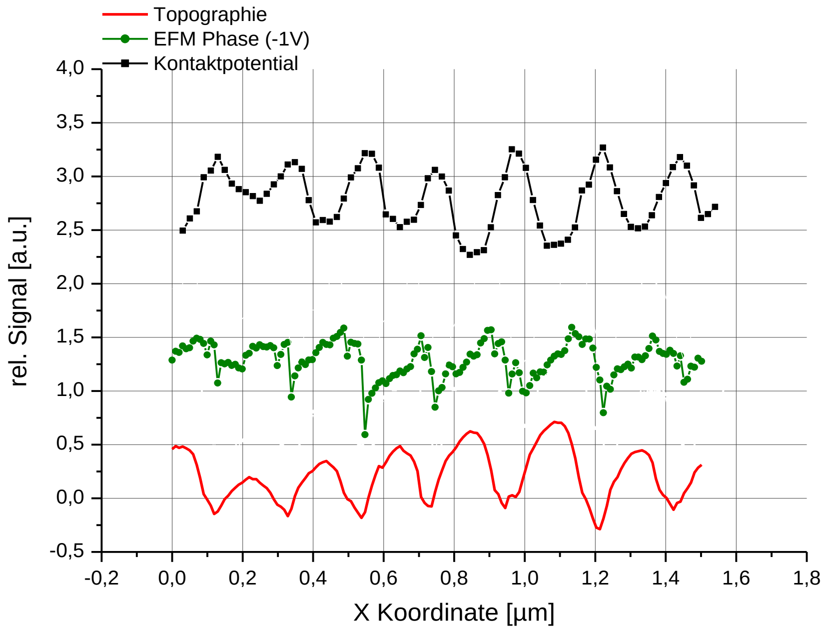


$\lambda_{fine} \approx 650$ nm
$\Lambda_{coarse} \approx 2$ µm

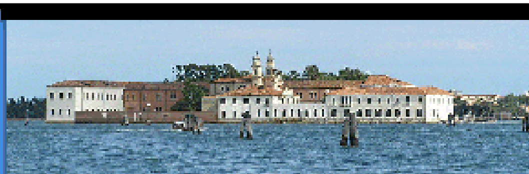


Lasers in Material Science Laser Induced Periodic Surface Structures (LIPSS)





Surface potential



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