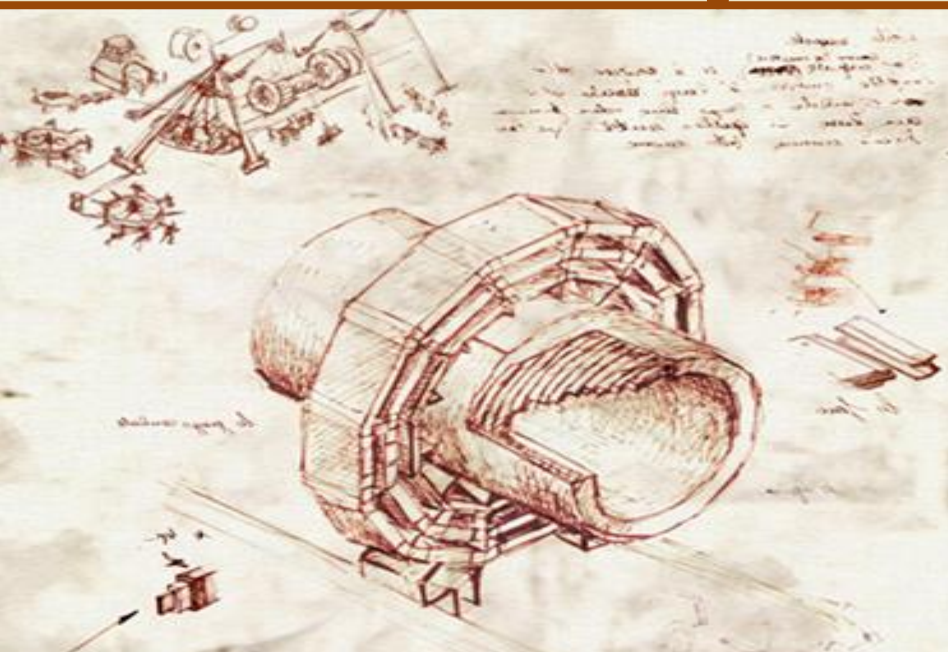
John Adams Institute for Accelerator Science

Imperial College London

Royal Holloway University of London

University of Oxford

Unifying physics of accelerators, lasers and plasma



LHC sketches by Sergio Cittolin (CERN) – used with permission

Prof. Andrei A. Seryi

John Adams Institute

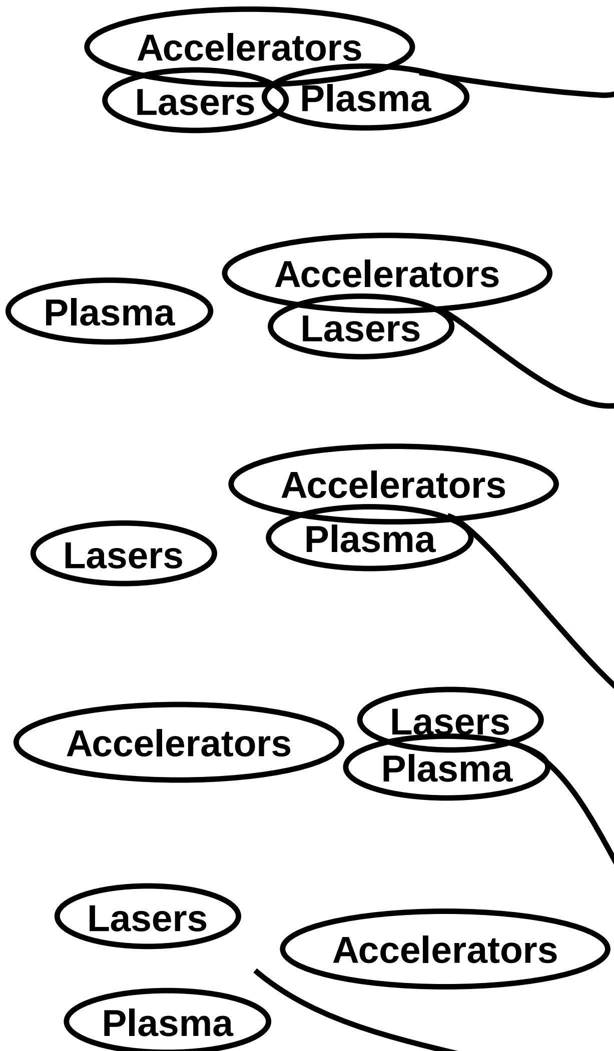
Lecture 4: Synergies between accelerators, lasers and plasma

USPAS16

June 2016

Accelerators-Lasers-Plasma

Degree of synergy & topics



- Beam sources, laser beam generation
- Wave propagation (in structures, in plasma)
- Laser propagation in plasma (critical density)
- Plasma acceleration
- Radiation (synchrotron, betatron)
- Free Electron Lasers

- Focusing (chromaticity, aberrations, beam quality)
- Cavities (RF and optical)
- Laser-beam interaction (ponderomotive force, laser imprints on e- beam in wigglers)
- Cooling (e-, stochastic, optical stochastic, laser)
- Compton x-ray sources
- Chirped Pulse Amplification
- Bunch or pulse compression

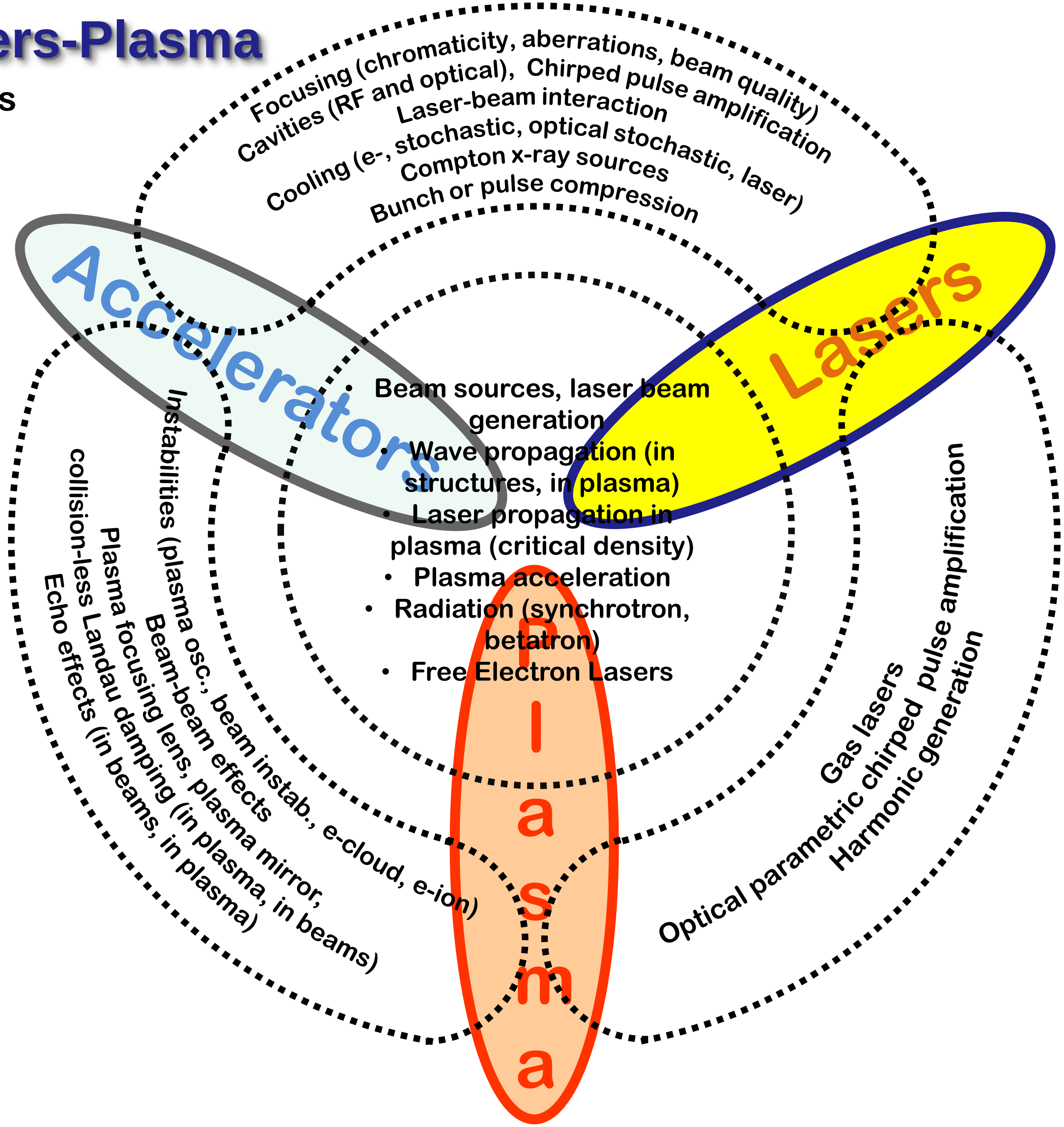
- Instabilities (plasma osc., beam instab., e- cloud, e-ion)
- Beam-beam effects
- Plasma focusing lens, plasma mirror
- collision-less Landau damping (in plasma, in beams)
- Echo effects (in beams, in plasma)

- Gas lasers
- OPCPA
- Harmonic generation

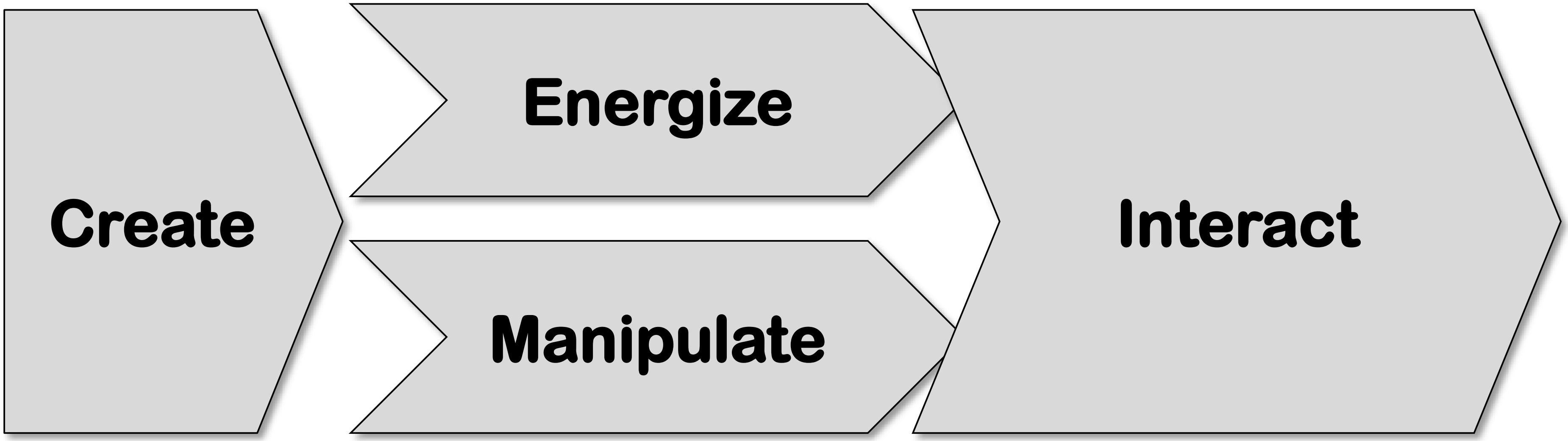
- Are there any topics we want to discuss?

Accelerators-Lasers-Plasma

Degree of synergy & topics



Create – Energize – Manipulate – Interact

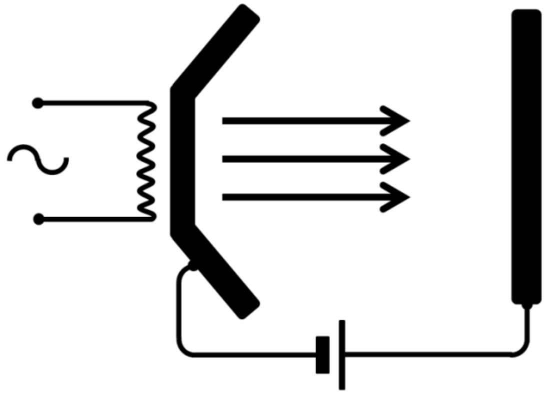


- Let's discuss beams, laser and plasma following the natural sequence
  - creating them
  - preparing for use
    - Energizing (accelerating, amplifying, exciting waves in plasma)
    - Manipulating (focusing, compressing, stretching, etc.)
  - and using them

Create – Energize – Manipulate – Interact

- Create
  - Beams of particles
    - e- (photo cathode laser driven)
    - Ion (plasma, laser driven)
  - Laser beams
    - Types, examples
  - Plasma
    - Discharge
- Energize
- Manipulate
- Interact

Beam sources



Thermal cathode e- gun

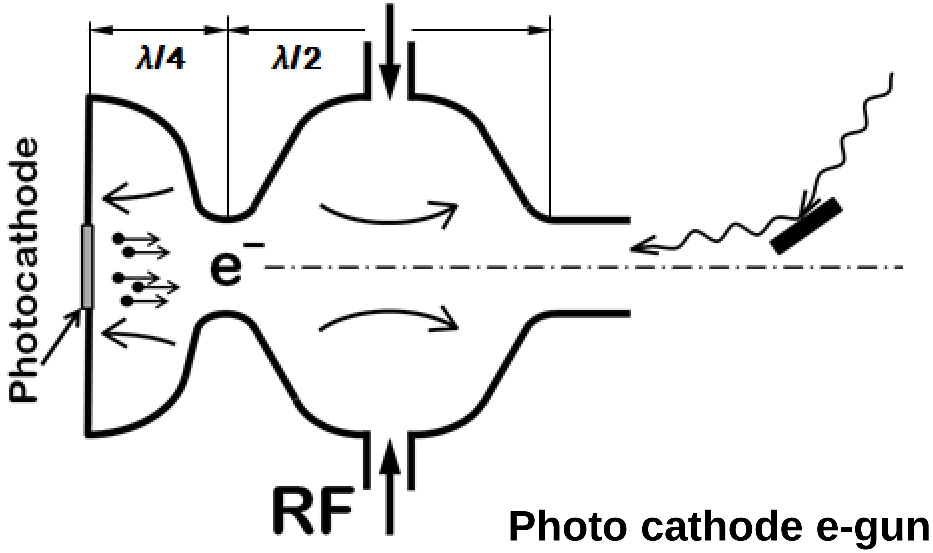
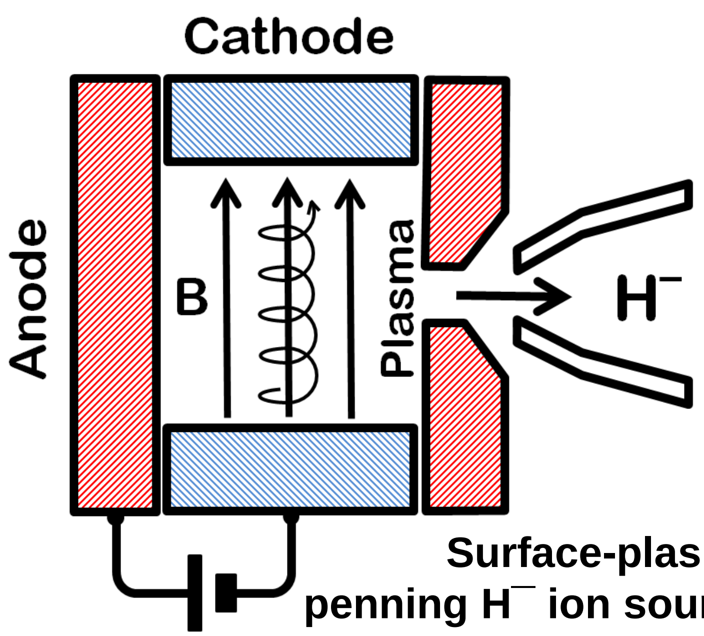


Photo cathode e-gun

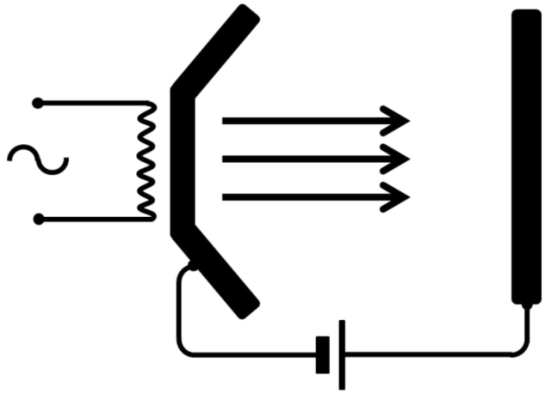


Surface-plasma penning H^- ion source

As you can guess, laser ion sources are also possible

Laser ion source

Beam sources



Thermal cathode e- gun

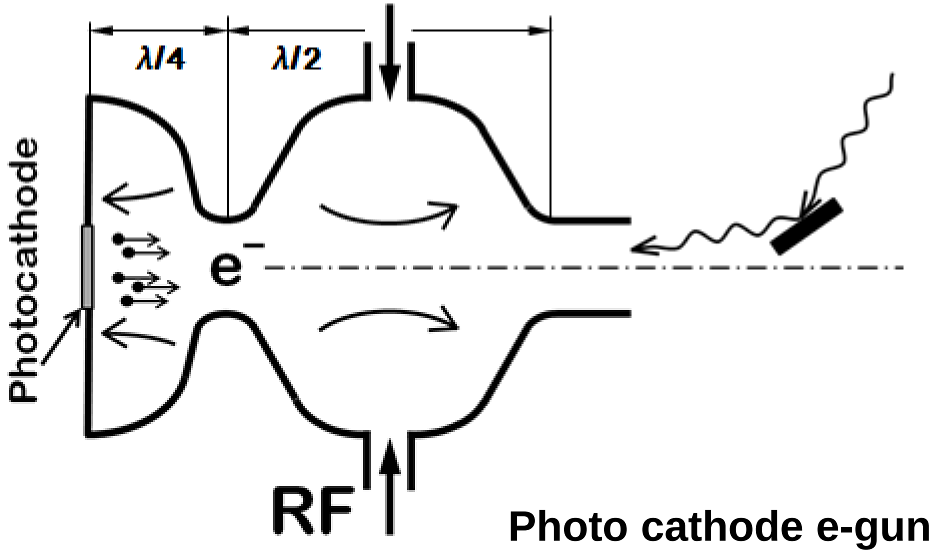
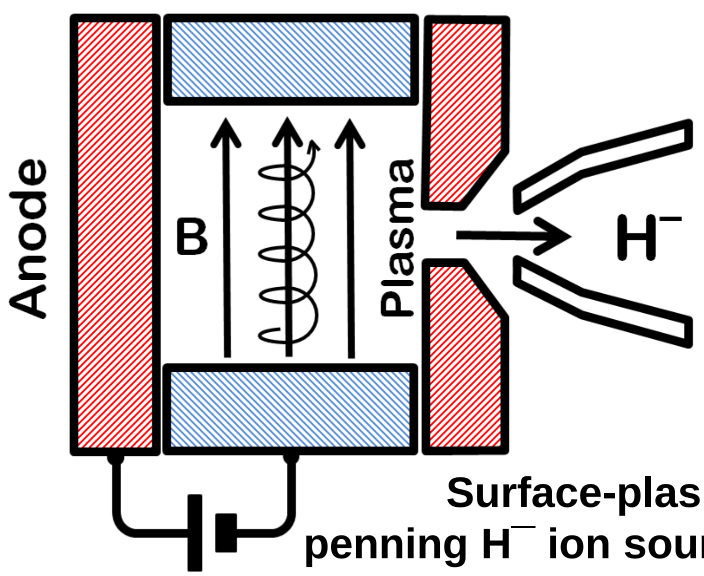
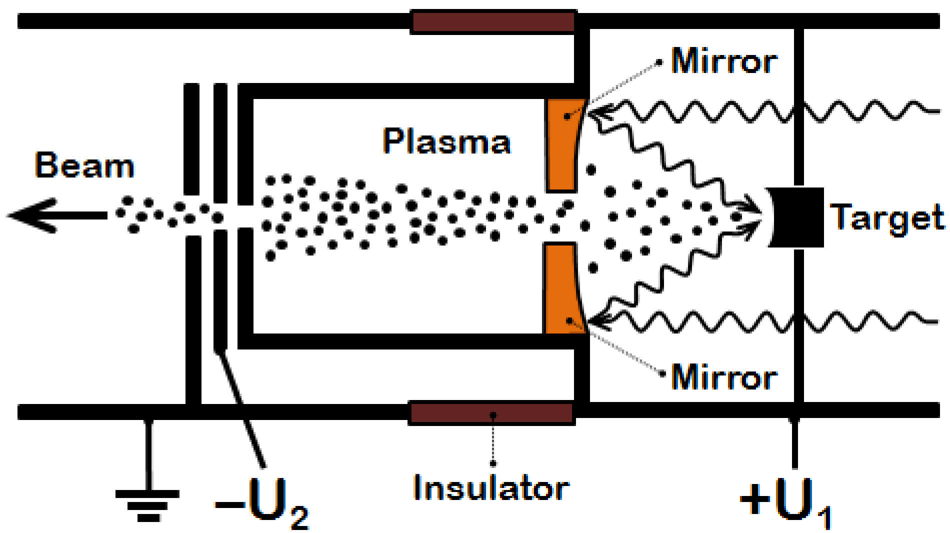


Photo cathode e-gun



Surface-plasma penning H⁻ ion source



Laser ion source (CERN)

Photocathode guns

Electrons are generated with a laser field by photoelectric effect

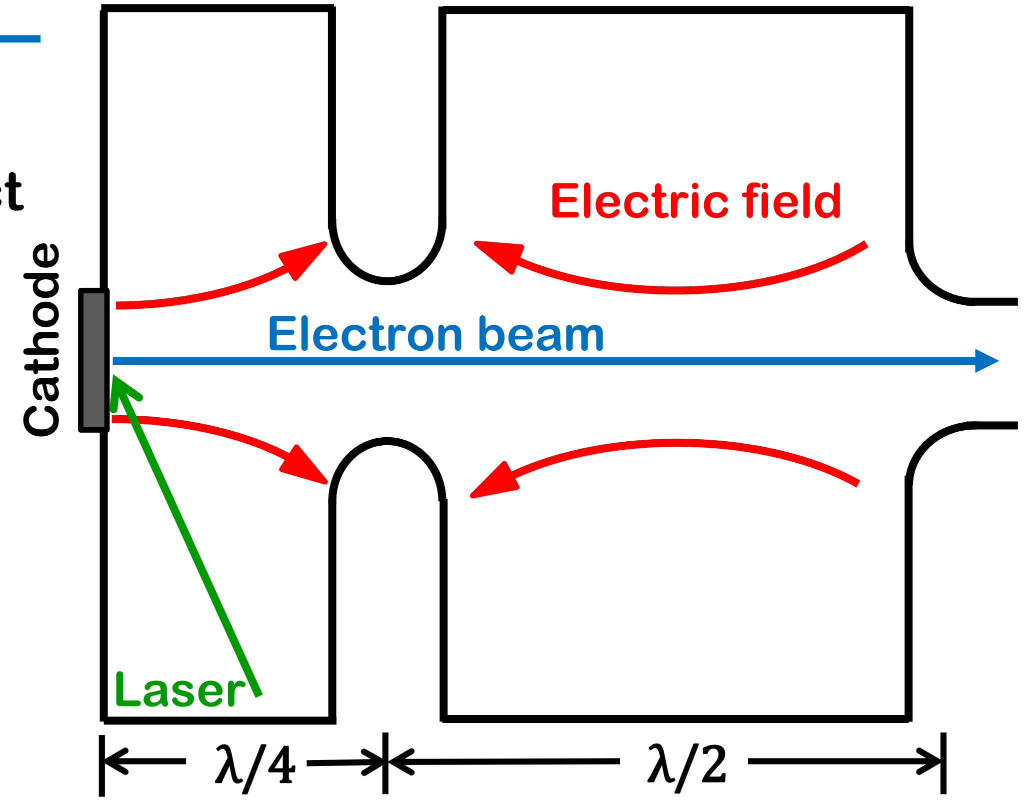
High voltage at the cathode is delivered by the RF structure

50-60 MV/m in L-band
100-140 MV/m in S-band

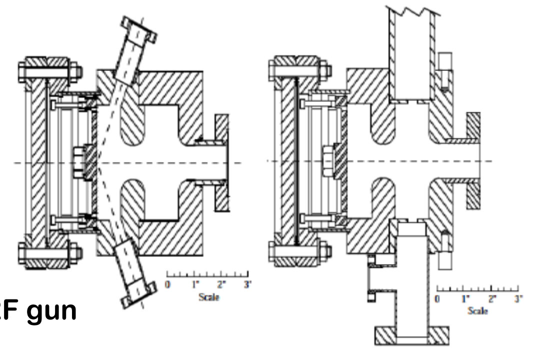
Higher gradients are useful to accelerate the particle fast and reduce the effect of space charge (scales as $1/E^2$)

Electron pulses can be made short (as the laser pulse - few ps)

One and half cell RF photocathode gun

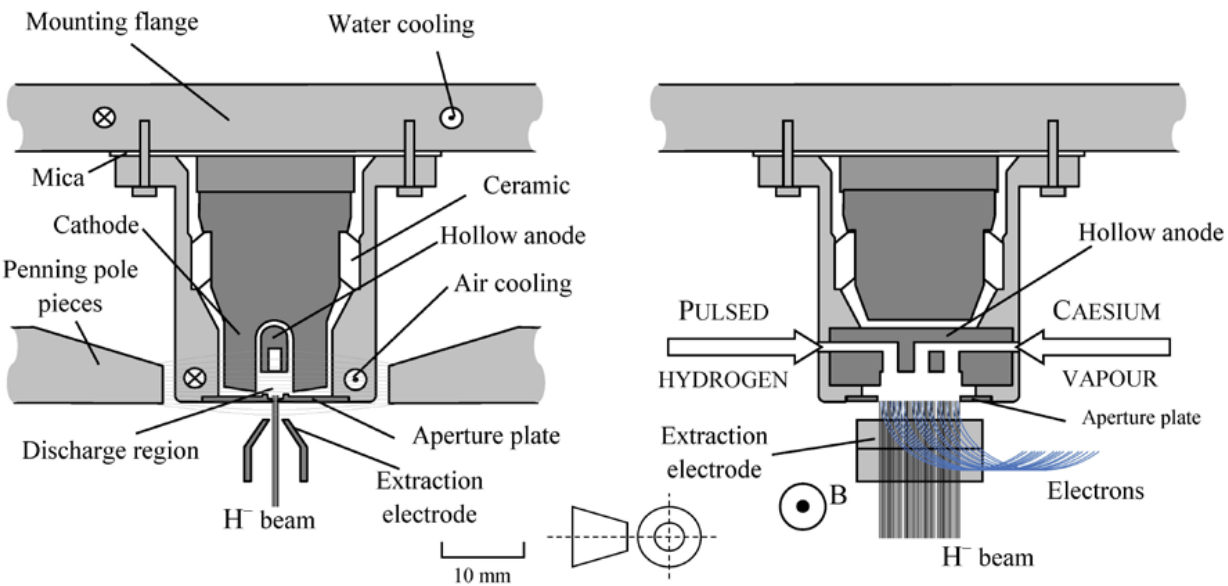


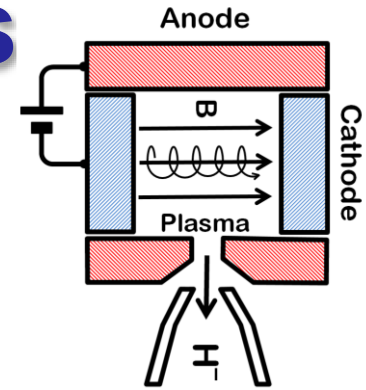
RF Cavity

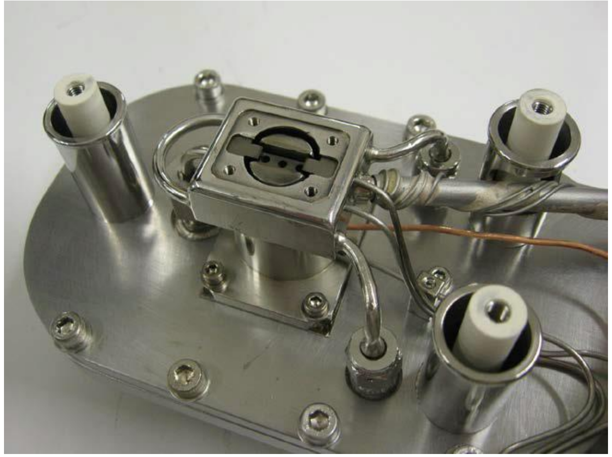


BNL /SLAC/UCLA RF gun

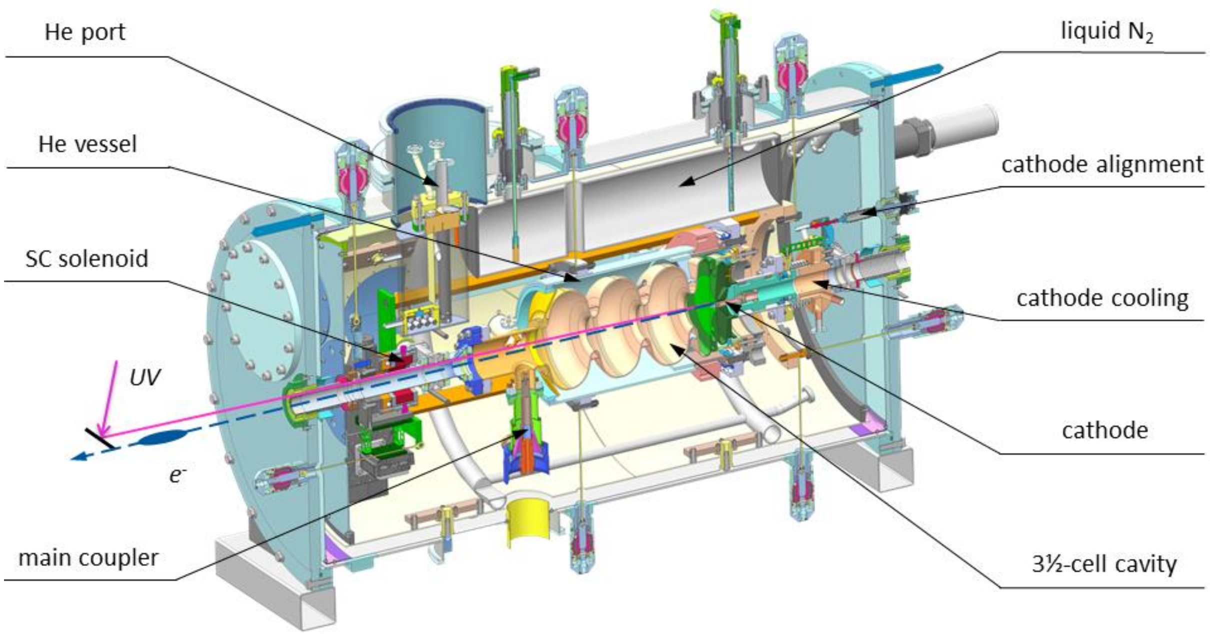
Beam sources – more details





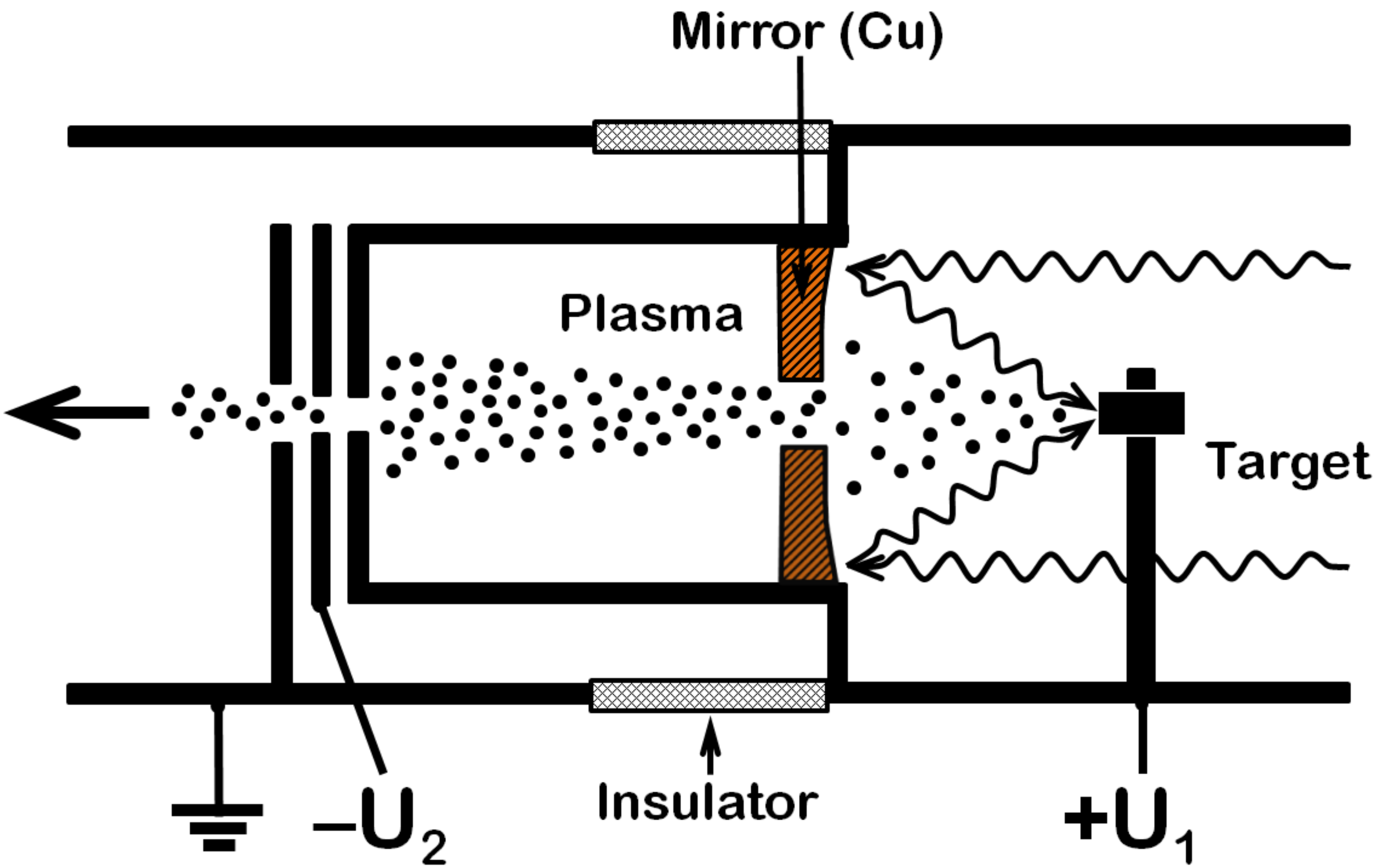


RAL Penning H– ion source with the anode cover plate and extract electrode removed



ELBE SRF Gun II – aiming to high average current (1 mA) and low emittance (1 mm mrad @ 77 pC) for the ELBE LINAC (Germany)

Laser ion source

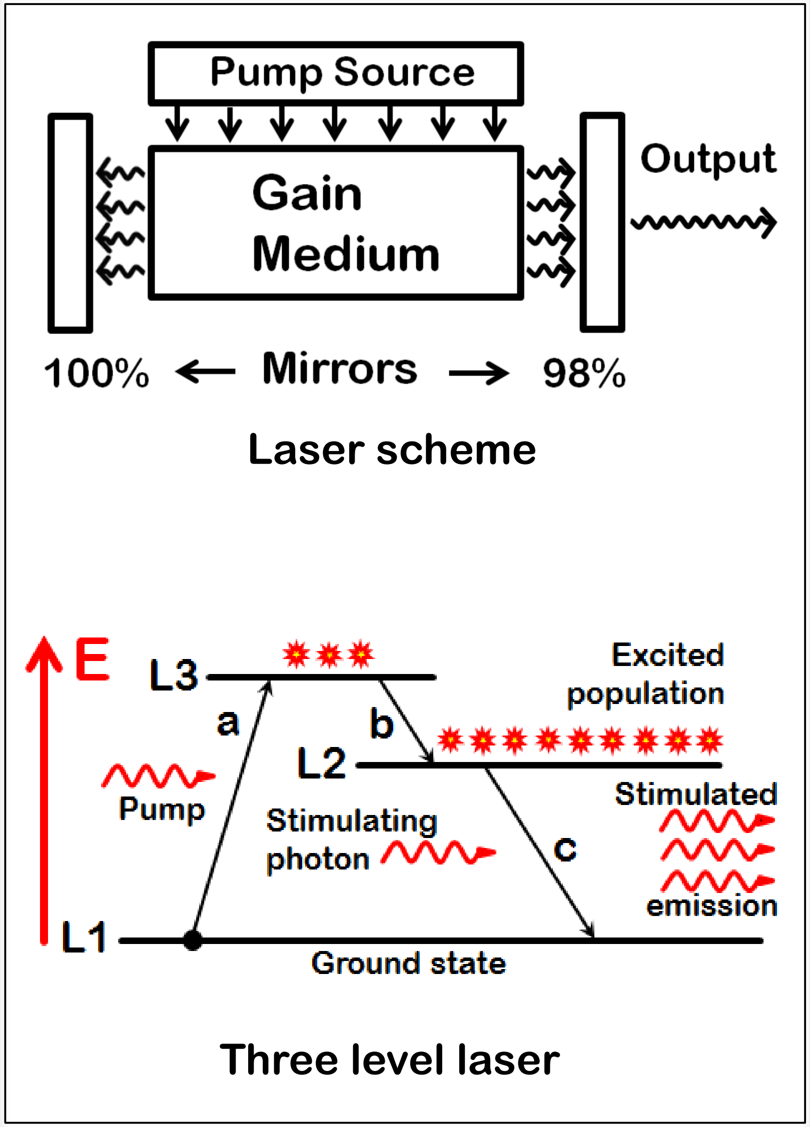


Laser ion source (CERN)

Laser ion source

Richard Scrivens, CERN, http://scrivens.web.cern.ch/scrivens/lis/home.html

Lasers – scheme & transitions in 3 level laser



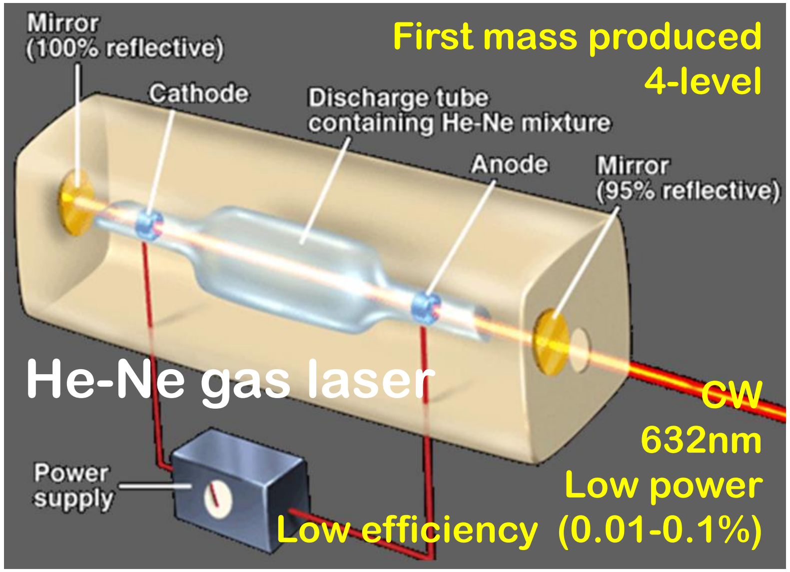
- Laser components
  - Gain Medium (amplifies the light)
  - Resonator (gives optical feedback)
  - Pump Source (makes population inversion)

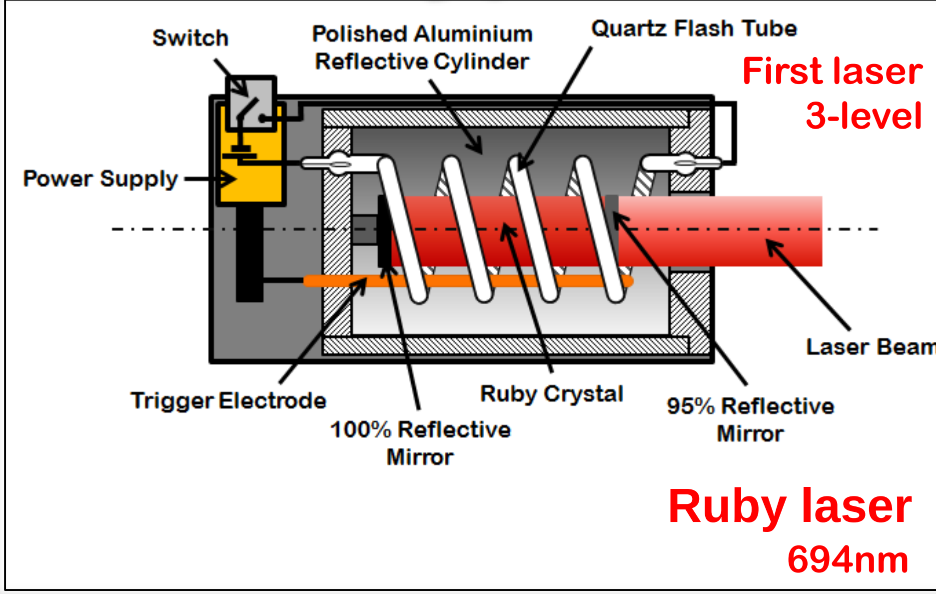
a. The pump gets population from ground state L1 to the higher energy level L3

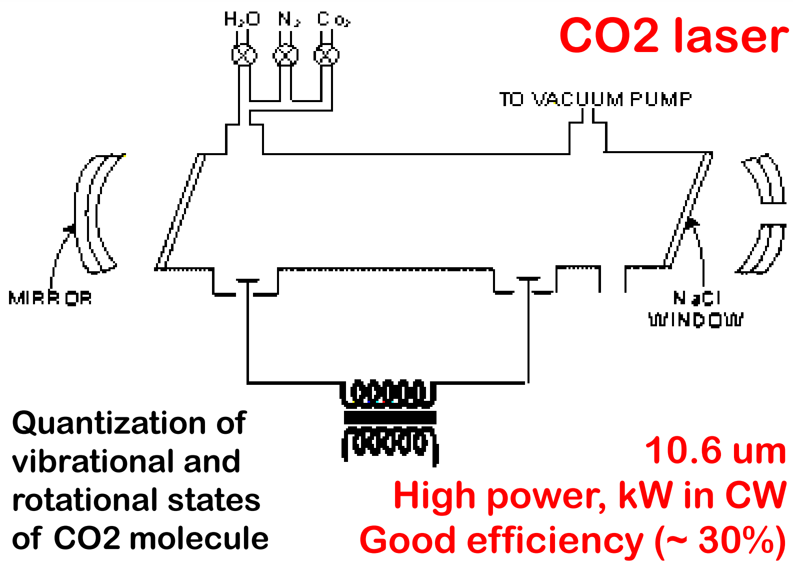
b. The excited population gets from L3 to L2 through non radiative decay
   - The lifetime of L3 is very short and all the population in state L3 decays to state L2

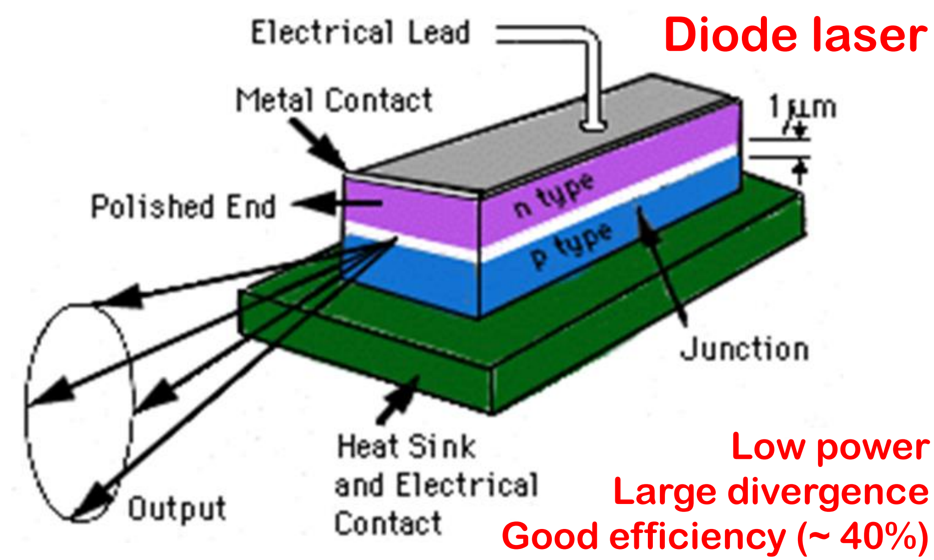
c. Stimulated emission from L2 to state L1
   - Lifetime of energy state L2 is long => population inversion occurs with respect to state L1
   - Once the population inversion is obtained, stimulated emission will give optical gain

Examples of laser types

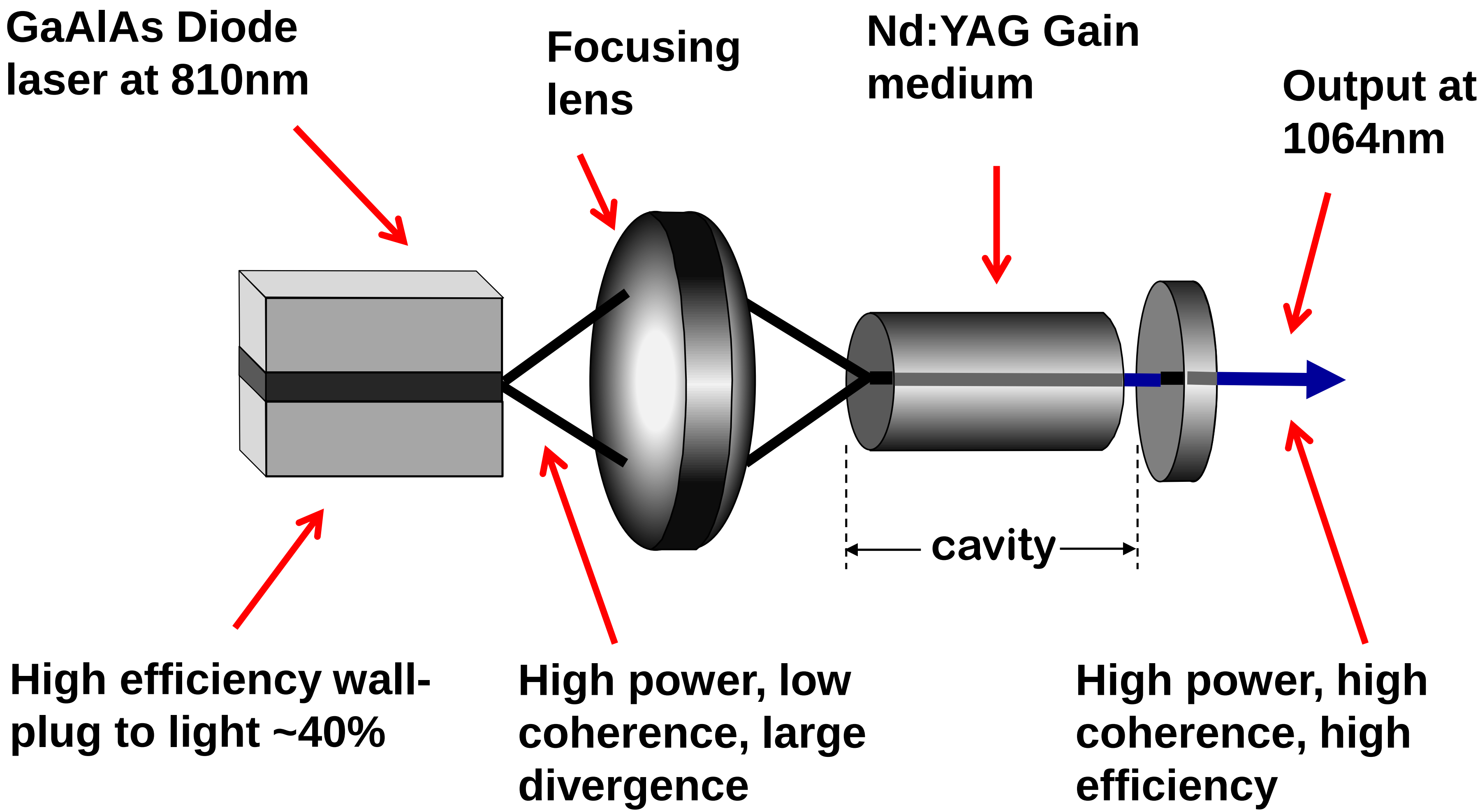






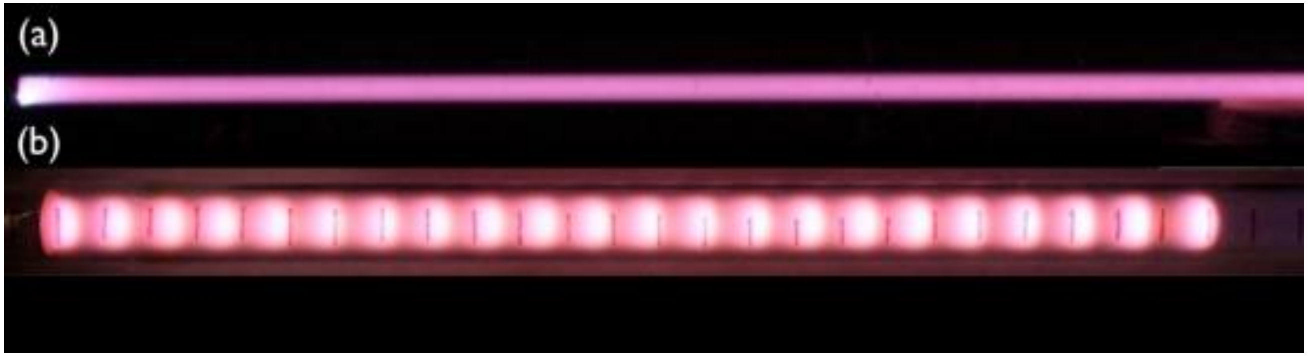


Diode laser – ideal for pumping



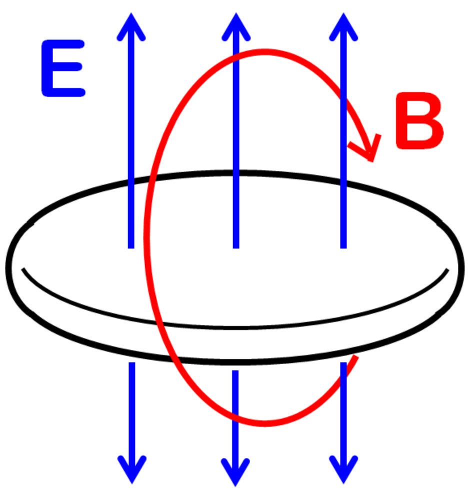
Nd:YAG neodymium-doped yttrium aluminium garnet; Nd:Y3Al5O12
Yb:YAG ytterbium-doped …

Plasma generation



Imperial/JAI: (a) Metre long plasma flash ionised by microsecond 30 kV pulsed discharge at pressure ~0.01 mbar; (b) dc plasma discharge produced by 3 kV supply at ~ 0.3 mbar showing strong striations, as well as dark spaces.

Discharge



Gas or target instantaneously ionized if

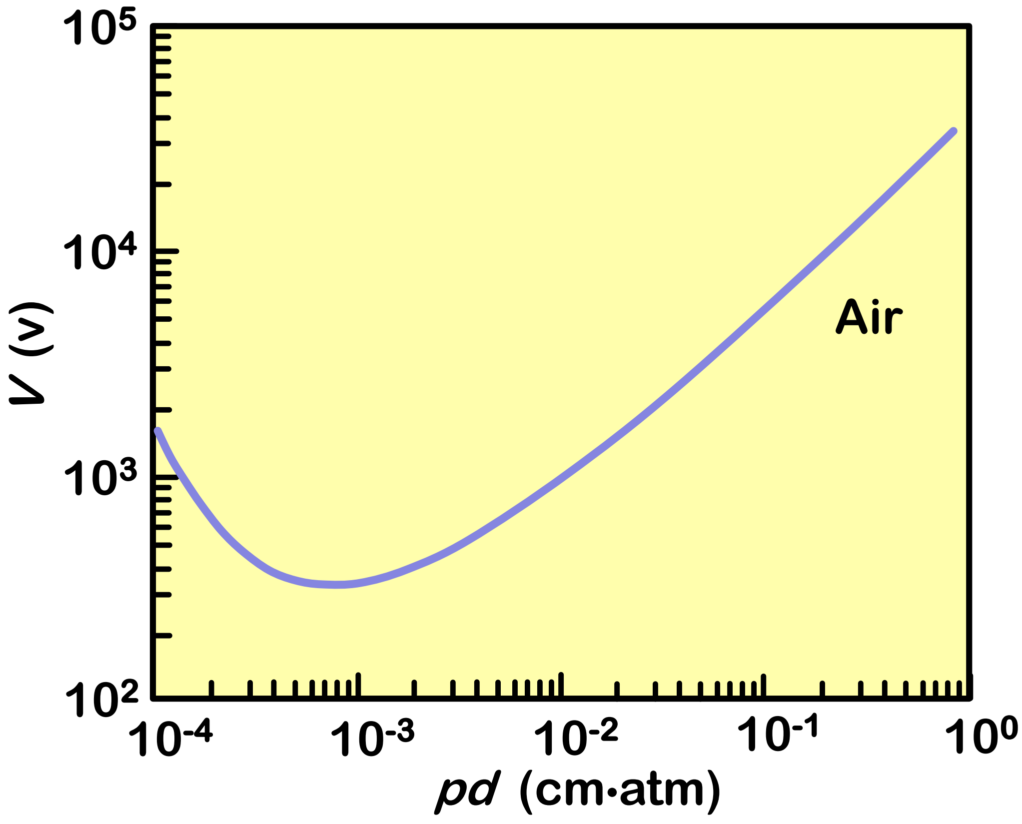
$$E_{beam} >> E_{atomic}$$

or

$$E_{laser} >> E_{atomic}$$

Field ionization - beam or laser ionization

Plasma generation

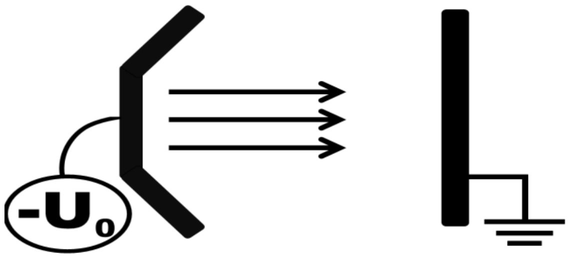


Paschen discharge curve for air

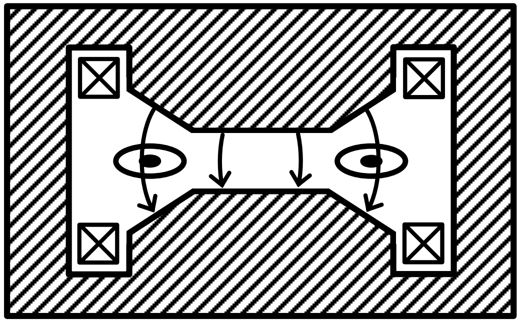
Create – Energize – Manipulate – Interact

- **Create**
- **Energize**
  - **Beam**
    - **Electrostatic acceleration**
    - **Betatron acceleration**
    - **RF cavities and structures**
    - **Plasma acceleration**
  - **Laser**
    - **Amplifiers**
    - **Fiber and Dipole technology**
    - **CPA**
    - **OPCPA**
  - **Plasma**
    - **Waves in plasma**
    - **Laser penetration to plasma, critical density and critical surface**
- **Manipulate**
- **Interact**

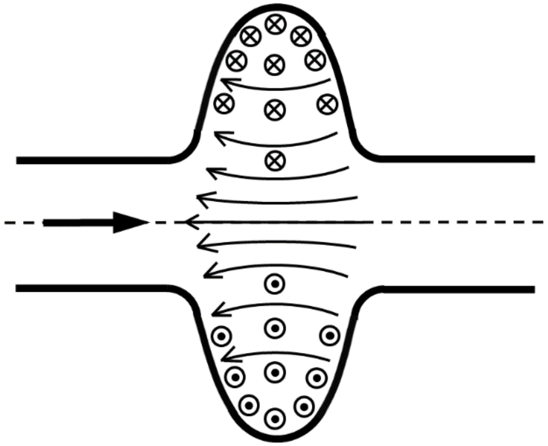
Beam acceleration



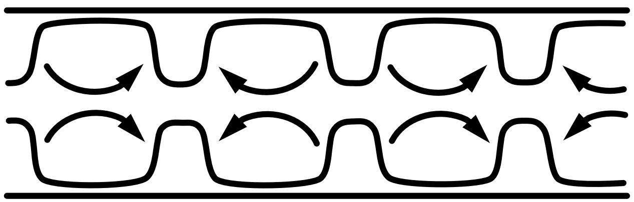
Electrostatic



Betatron

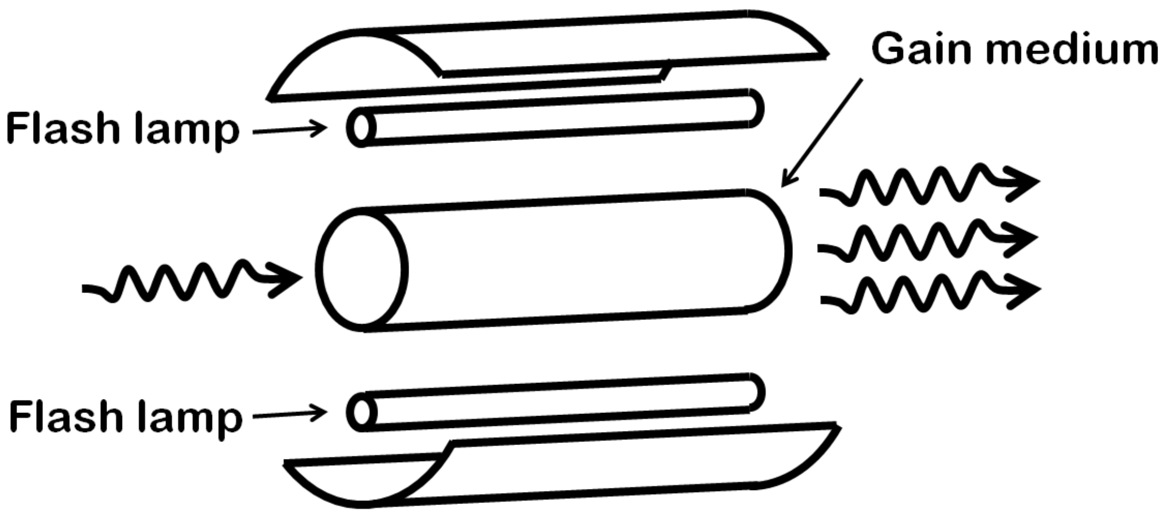


RF cavities



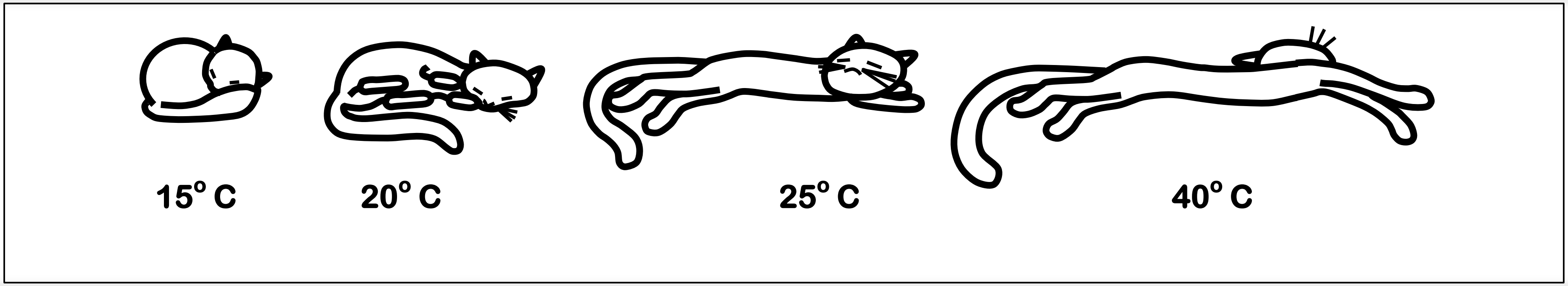
RF structures

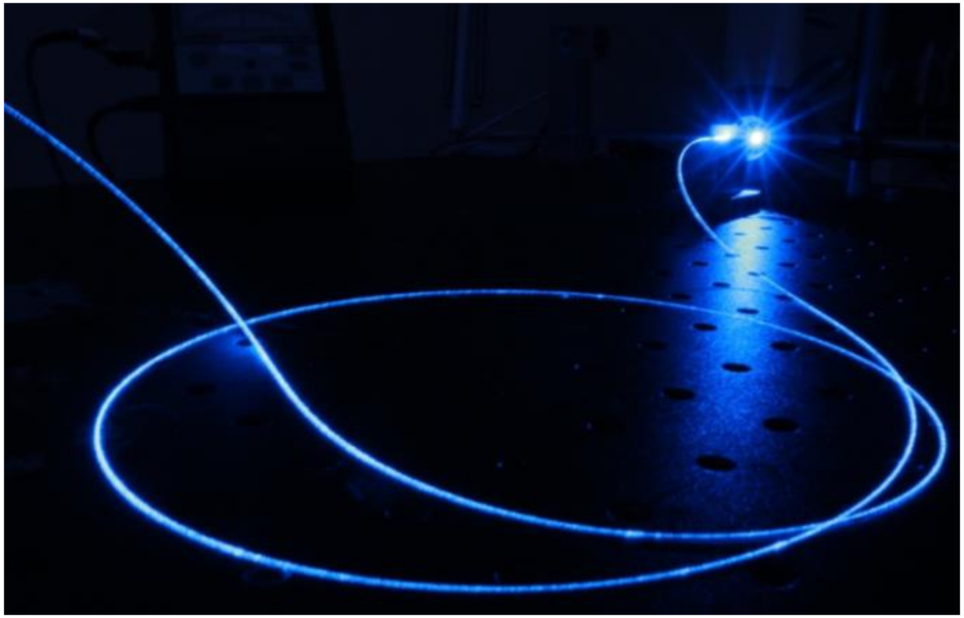
Laser amplifiers



Common principle: gain medium is pumped to produce gain for light at the wavelength of a laser made with the same material as its gain medium

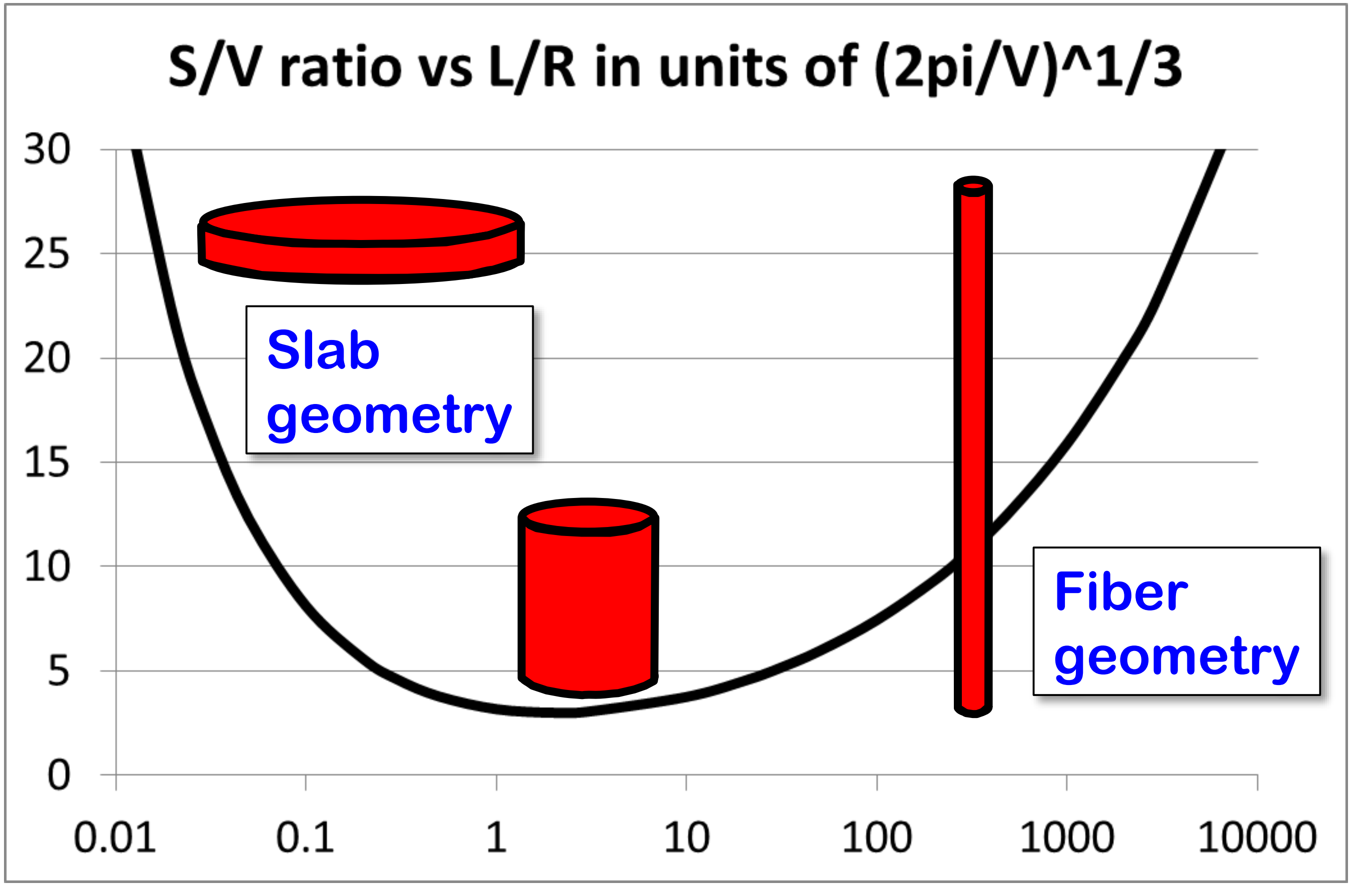
- Ultra-short and ultra high power – challenges:
  - Ultra short – nonlinear effect in the medium
  - High power – heating the amplifier medium
- These challenges limit rep rate, power and efficiency
  - Some of the most powerful lasers fire just once per few hours!
- A lot of inventions in the field of light amplification





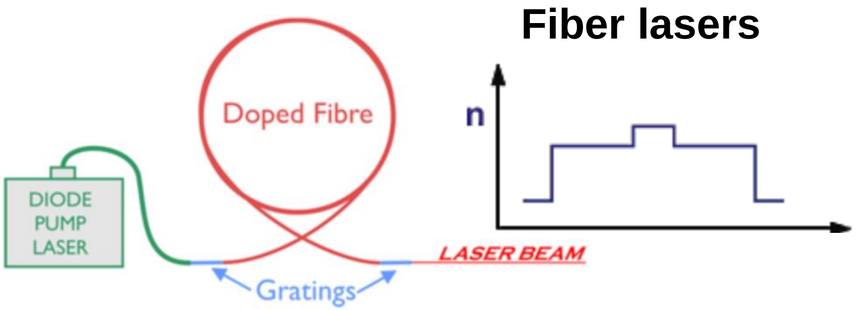
Is there a general inventive principle that connects cats and fiber lasers?

Fiber lasers and slab lasers

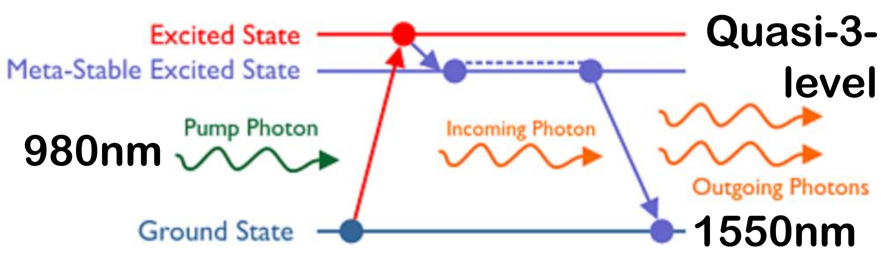


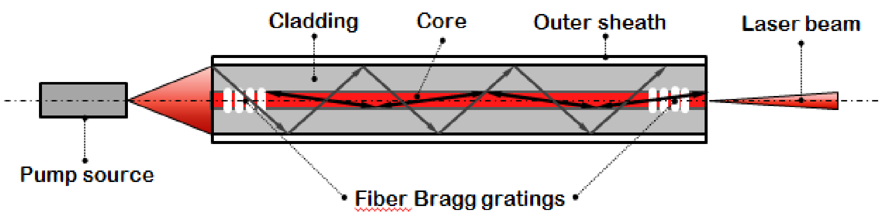
- **Fiber lasers and DiPOLE laser technology use the principle of larger surface to volume ratio**
  - **Possibility of high power, high rep rate, high efficiency**

Fiber laser and DiPOLE lasers



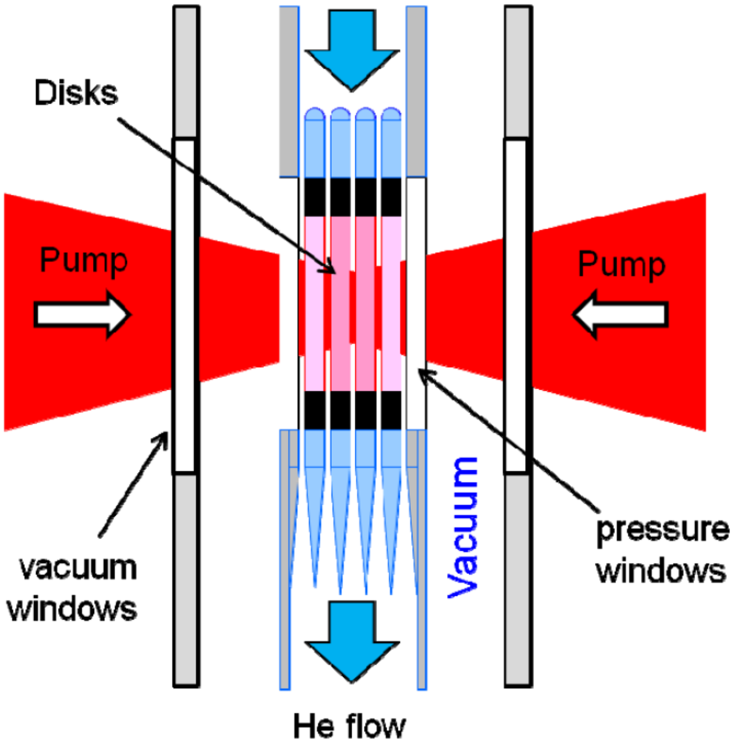
Diode pumped, Erbium-doped gain media





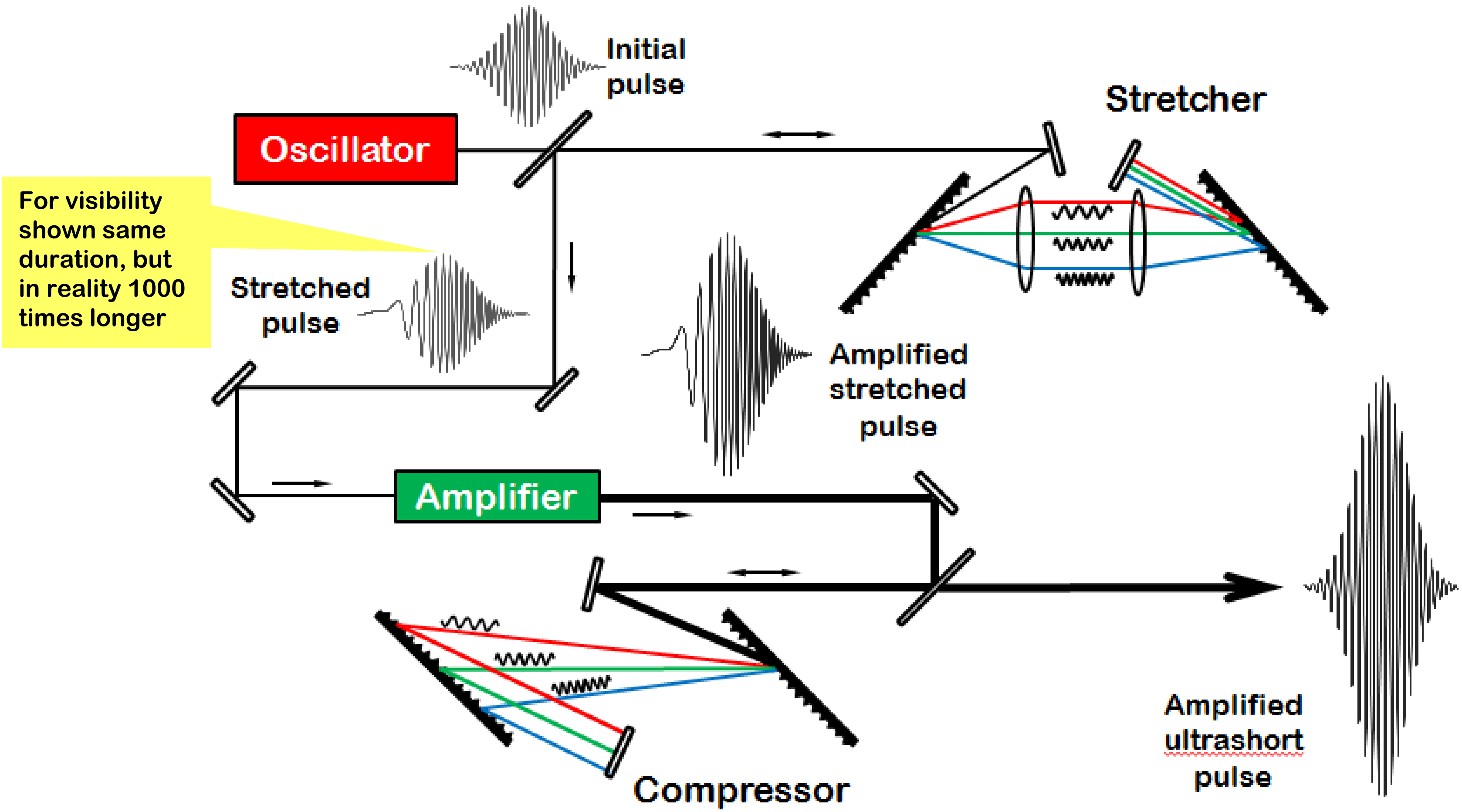
Bragg Gratings create reflections, acting as mirror
High efficiency, CW or sub-ps pulses
In CW mode – tens of kW
In pulsed mode – mJ in tens of kHz

DiPOLE = Diode Pumped Optical Laser Experiment – developed by CLF/RAL, UK



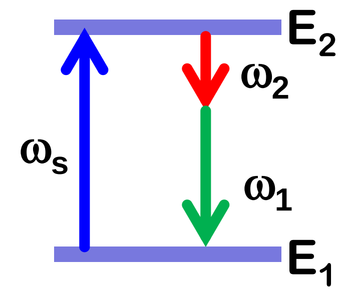
Cooled by cold He gas at 175K
Disks = Yb:YAG slabs
Aim to deliver kJ pulses at 10Hz
Pump at 939nm, radiate at 1030nm

CPA – Chirped Pulse Amplification



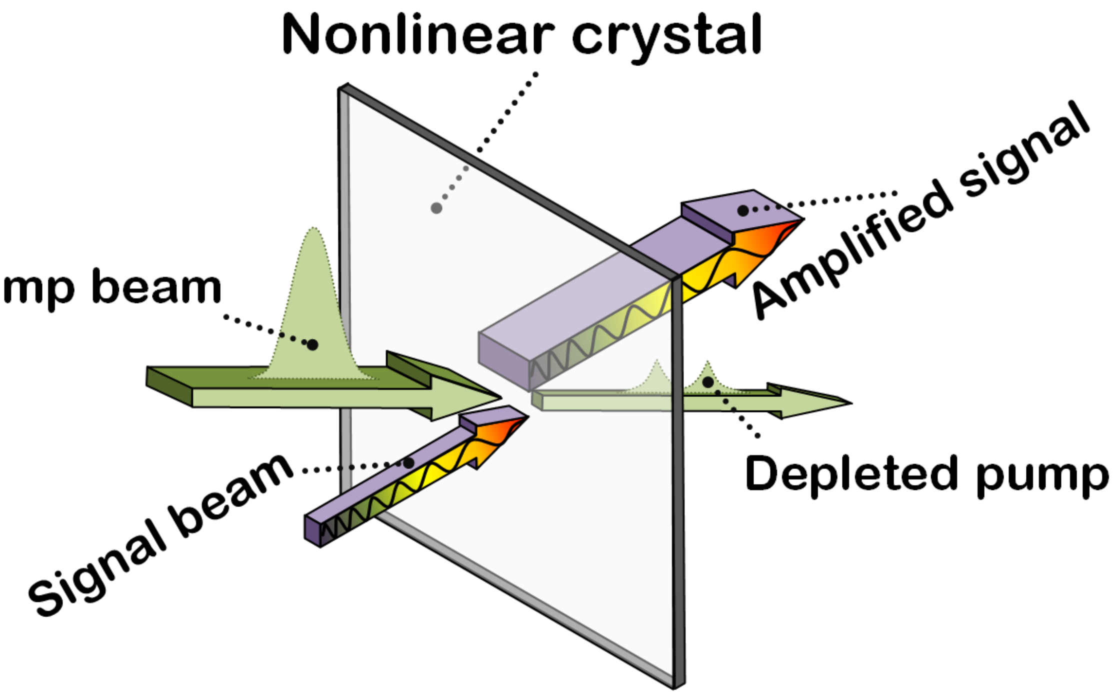
- **CPA: pulse stretching and compressing using time-energy correlation**

OPCPA – Optical Parametric CPA



Nonlinear crystal – optical parametric generation – input is ω_s, and output is ω_1 and ω_2, where $\omega_s = \omega_1 + \omega_2$

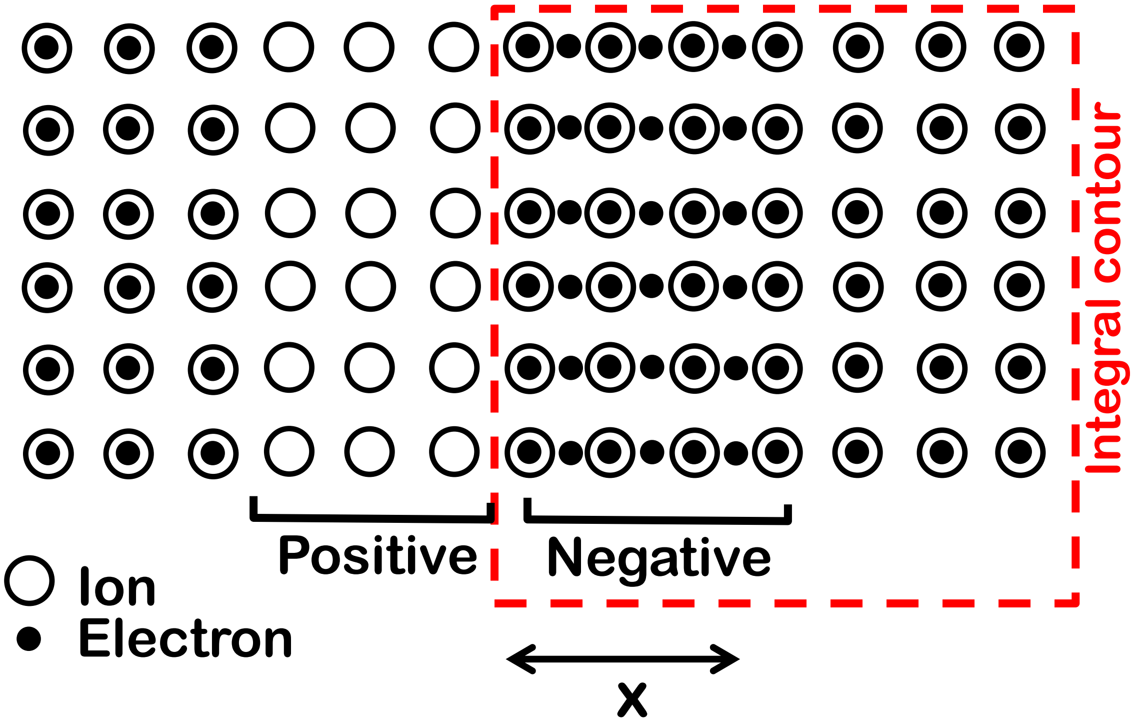
Optical parametric amplification – input is two beams, pump at ω_s and signal at ω_1. Output is amplified ω_1 beam and weakened ω_s beam, and additional idler beam at ω_2



OPCPA scheme amplifies a frequency stretched "signal" pulse when a pump beam and a signal beam are present in a nonlinear crystal

CW to femtosecond
UV to TeraHertz
mW→TW→PW

Plasma oscillations



Derive ω_p

$$\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega} \rho dV$$

$$E = \frac{nex}{\varepsilon_0}$$

$$F = m\frac{d^2x}{dt^2} = -eE = -\frac{ne^2x}{\varepsilon_0}$$

Oscillation frequency: $\omega_p^2 = \frac{ne^2}{\varepsilon_0 m}$

use: $r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}$ **to rewrite as:** $\omega_p^2 = 4\pi n c^2 r_e$

Useful formula $f_p \sim 9000\ n^{1/2}$ (n in cm^{-3})

Equations and units

SI

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \qquad \oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega} \rho\, dV$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oiint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_{\partial\Sigma} \mathbf{E}\cdot d\boldsymbol{\ell} = -\frac{d}{dt}\iint_{\Sigma} \mathbf{B}\cdot d\mathbf{S}$$

$$\nabla \times \mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right) \qquad \oint_{\partial\Sigma} \mathbf{B}\cdot d\boldsymbol{\ell} = \mu_0 \iint_{\Sigma} \mathbf{J}\cdot d\mathbf{S} + \mu_0\varepsilon_0 \frac{d}{dt}\iint_{\Sigma} \mathbf{E}\cdot d\mathbf{S}$$

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$$

Gauss-cgs

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi\mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}\right)$$

$$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)$$

Microscopic Maxwell equations and Lorentz force in SI and Gaussian-cgs units

The SI units are the standard, but Gaussian units are more natural for electromagnetism. Advice: deriving the formula, instead of writing for example *e* or *h*, express the end result via more natural quantities (m_ec^2, r_e, λ_e, α, etc.)

SI

$$r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_ec^2}$$

$$\alpha = \frac{e^2}{(4\pi\varepsilon_0)\hbar c}$$

$$r_e \approx 2.82\cdot 10^{-15}\, m$$

$$\alpha \approx 1/137$$

$$\lambda\!\!\!^{-}_e = r_e/\alpha \approx 3.86\cdot 10^{-13}\,\mathrm{m}$$

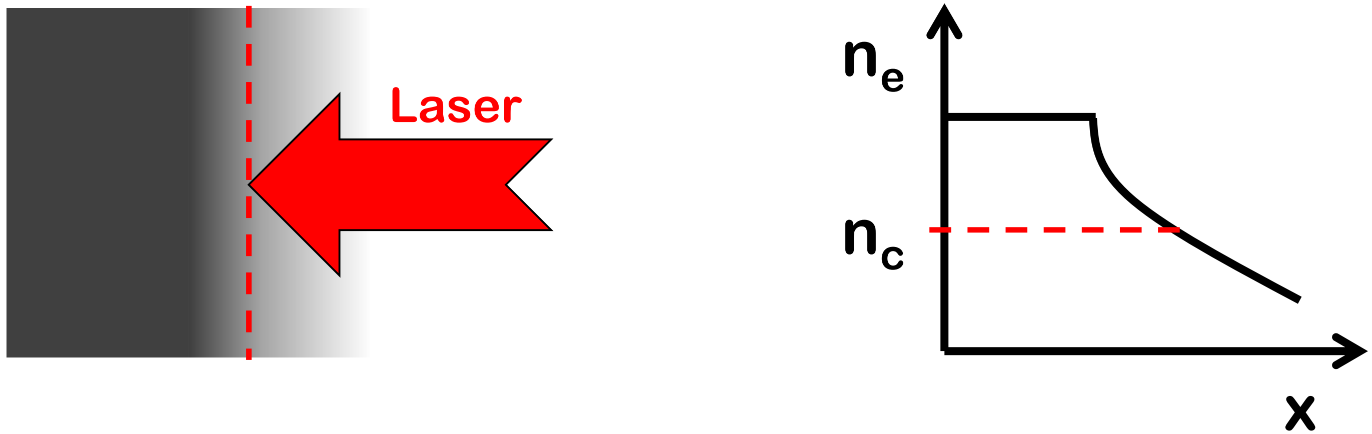
Gauss

$$r_e = \frac{e^2}{m_ec^2}$$

$$\alpha = \frac{e^2}{\hbar c}$$

Lasers and plasma - critical density and surface

When laser hits a target its surface is heated, and plasma is formed
Plasma expands into the vacuum, and its density drops



If ω_p is larger than laser frequency ω, then the plasma electrons can move fast enough to screen the laser

Therefore, laser penetrates only to the point where $\omega_p < \omega$

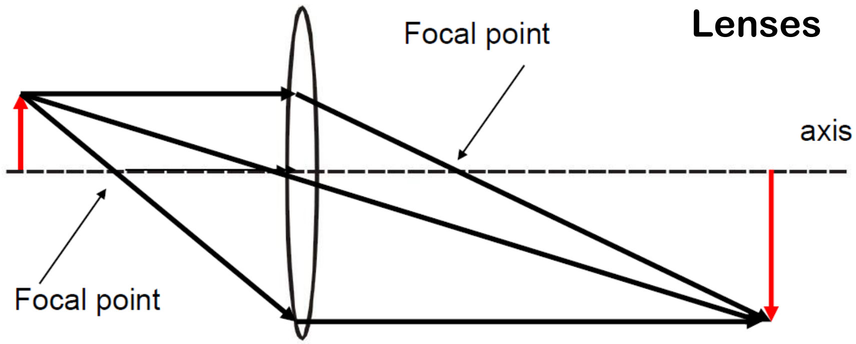
The critical density is thus $n_c = \omega^2 / (4\pi c^2 r_e)$

Create – Energize – Manipulate – Interact

- Create
- Energize
- Manipulate
  - Beam
    - Focusing (weak, strong, chromaticity, aberrations)
    - Compressing
    - Cooling (e-, stochastic, optical stochastic, laser)
    - Phase plane exchange
    - Transverse stability
  - Laser
    - Focusing
    - Compression
    - Phase locking
    - Harmonic generation
  - Plasma
    - Plasma focusing lens
    - Landau damping
    - Self focusing of laser in plasma channel
- Interact

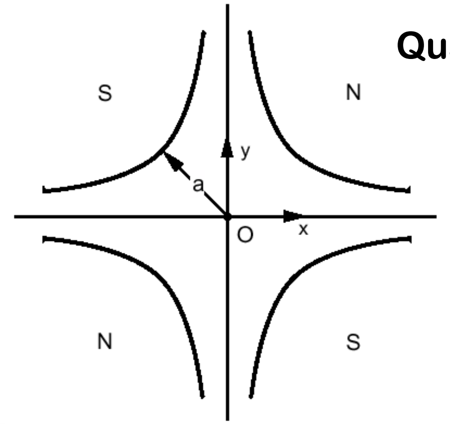
Beam and laser focusing

Lenses



Focus in both planes

Quadrupole magnet

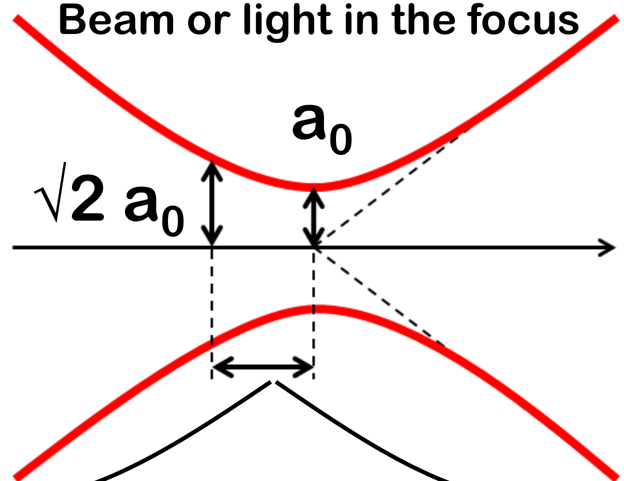


Focus in one plane, defocus in another:

$x' = x' + G\,x$

$y' = y' - G\,y$

Beam or light in the focus



Z_R

Rayleigh length

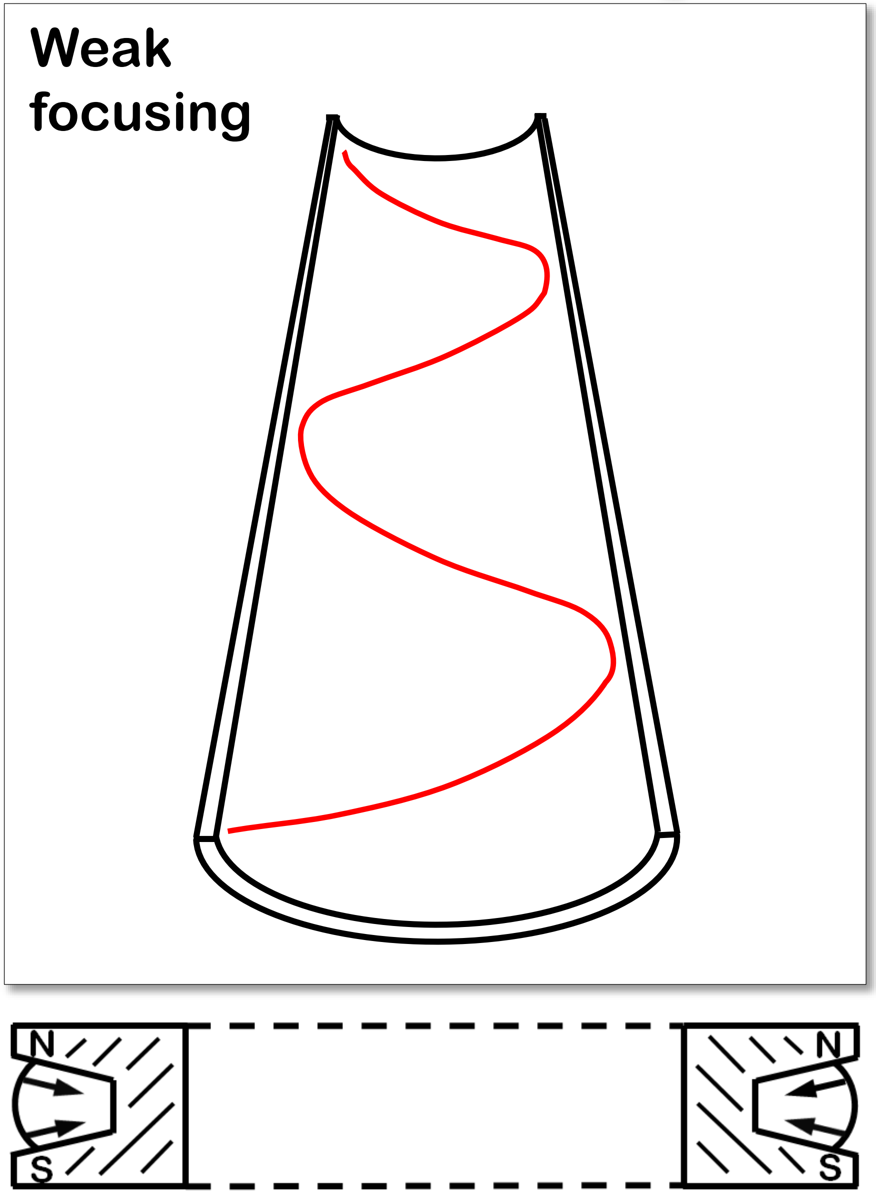
β_0

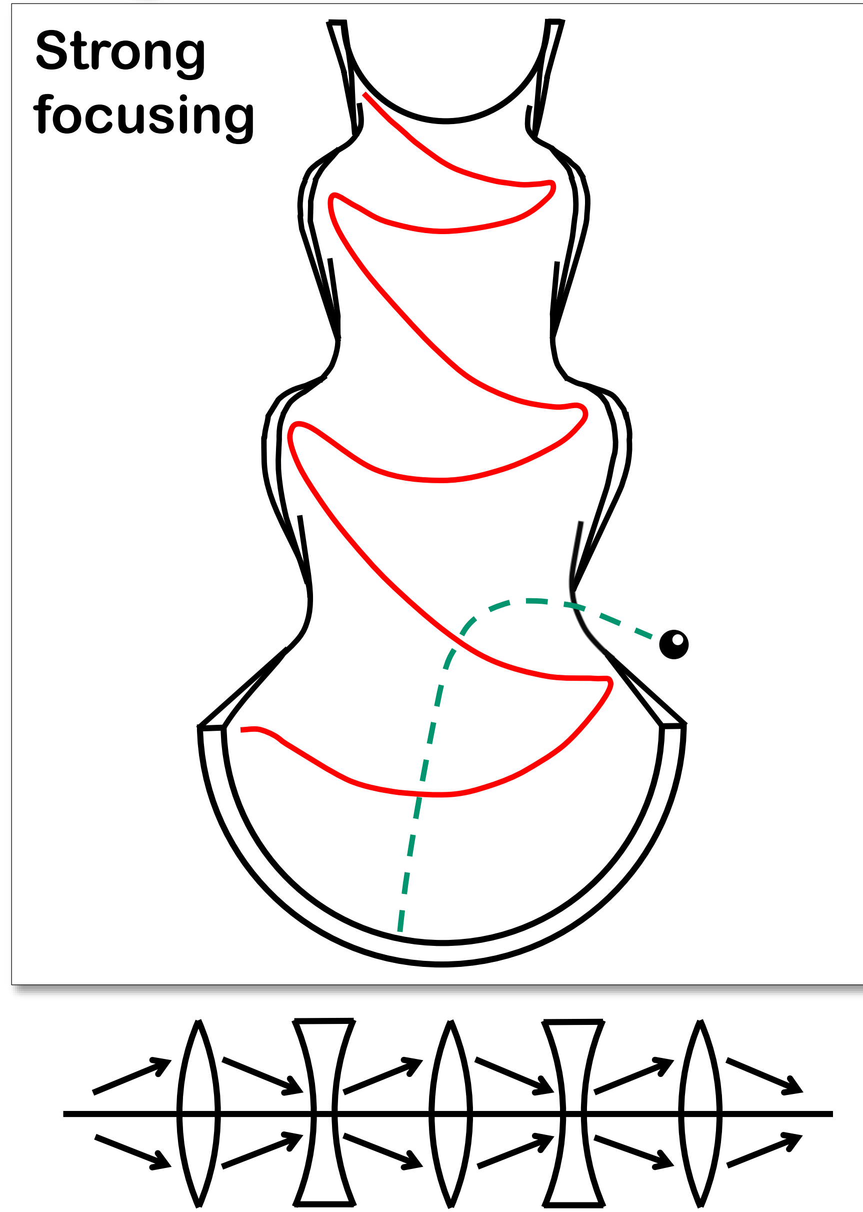
Twiss (beta) function in the focal point

Light focusing lenses or mirrors

Beam focusing w magnets

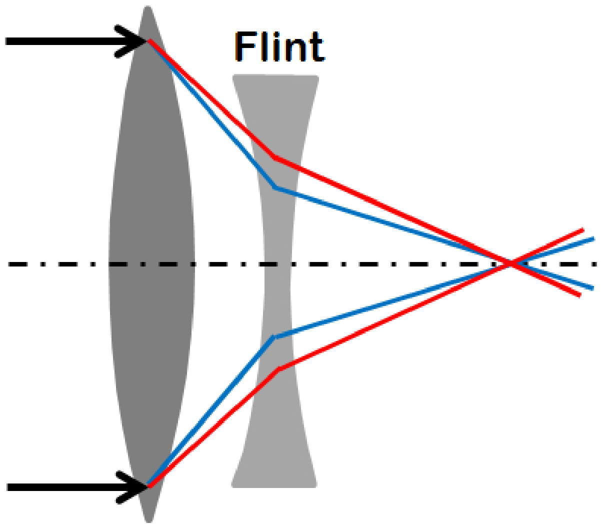
Weak or strong focusing => chromatizm





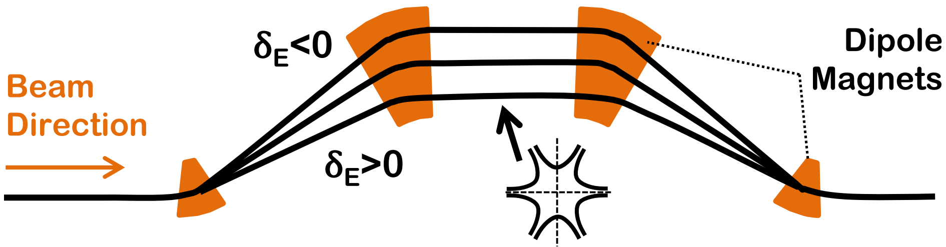
Aberrations for light and beam

For light, one uses lenses made from different materials to compensate chromatic aberrations



The use of a strong positive lens made from a low dispersion glass like crown glass coupled with a weaker high dispersion glass like flint glass can correct the chromatic aberration

For particle beams, chromatic aberrations compensated by nonlinear magnets placed in a dispersive region



Sextupole kick:
$x' = x' + S\,(x^2 - y^2)$
$y' = y' - S\,2xy$

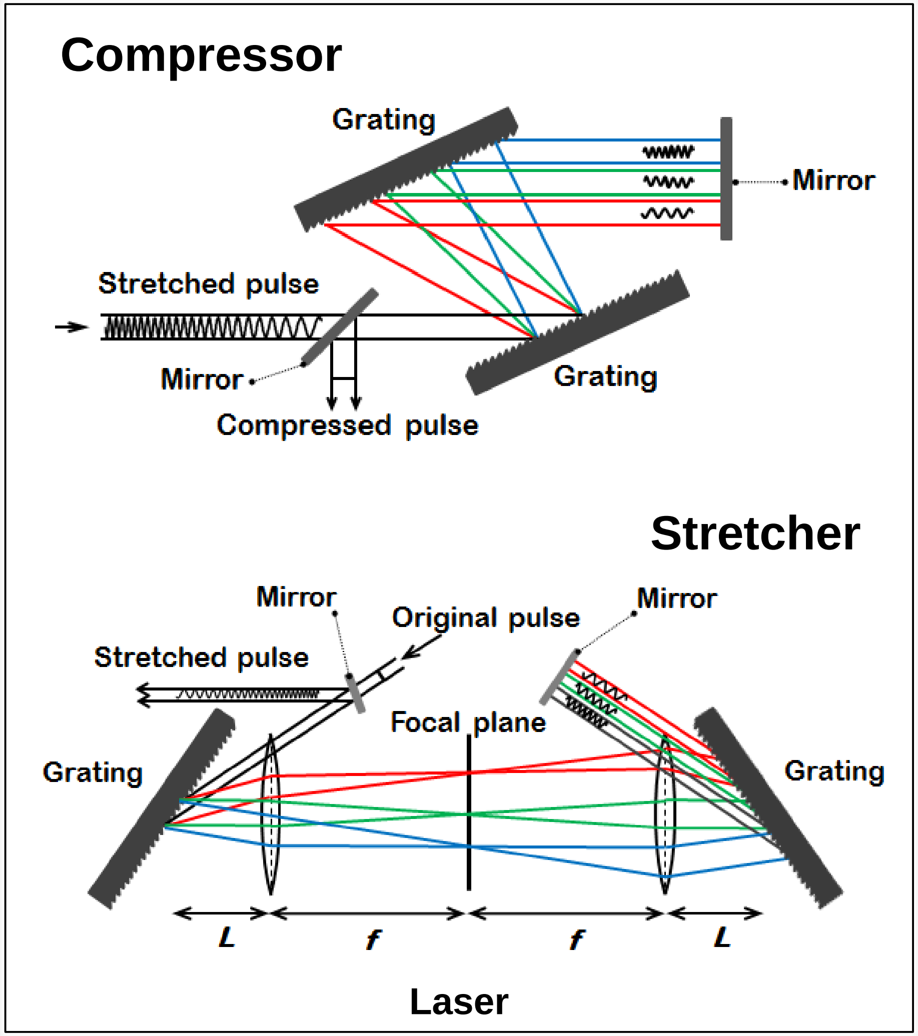
In dispersive region sextupole kick will contain energy dependent focusing:

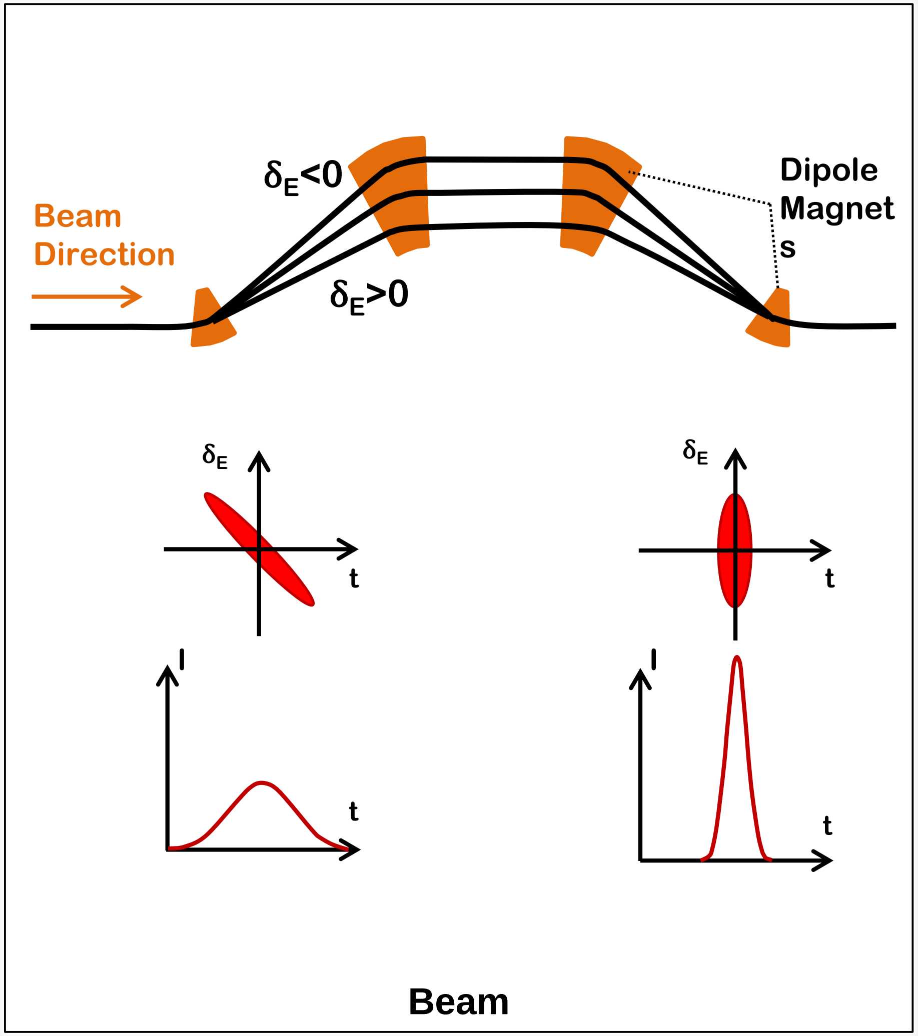
$x' \;\Rightarrow\; S\,(x+\delta)^2 \;\Rightarrow\; 2S\,x\,\delta + ..$

$y' \;\Rightarrow\; -S\,2(x+\delta)y \;\Rightarrow\; -2S\,y\,\delta + ..$

this can be used to arrange chromatic correction

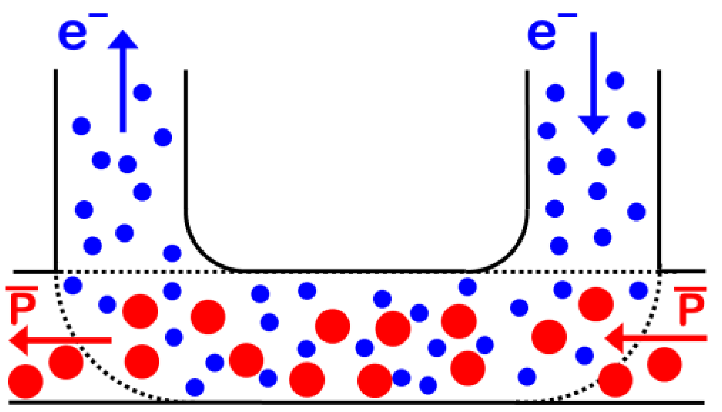
Beam and laser bunch/pulse compression



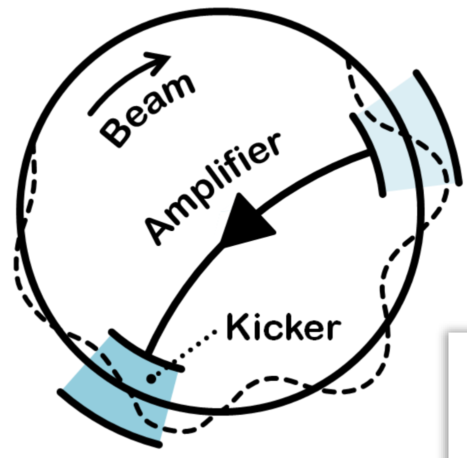


Both in laser and beam use z-Energy correlation to compress/stretch the pulse – general principle connecting two areas

Beam cooling



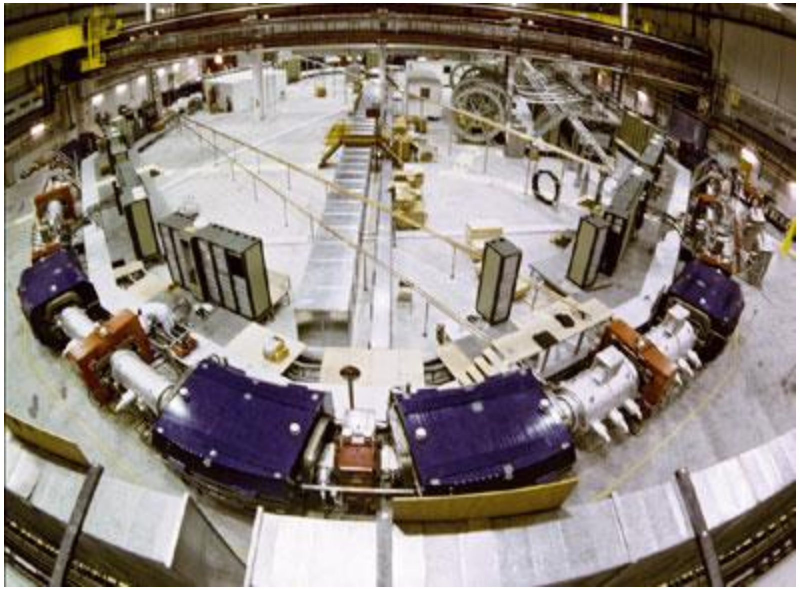
Electron cooling



Stochastic cooling

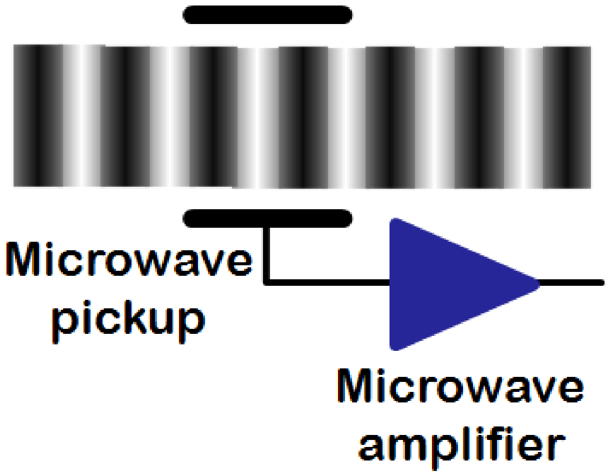
Nobel of 1984 for discovery of W and Z Bosons

First e-cooler at BINP



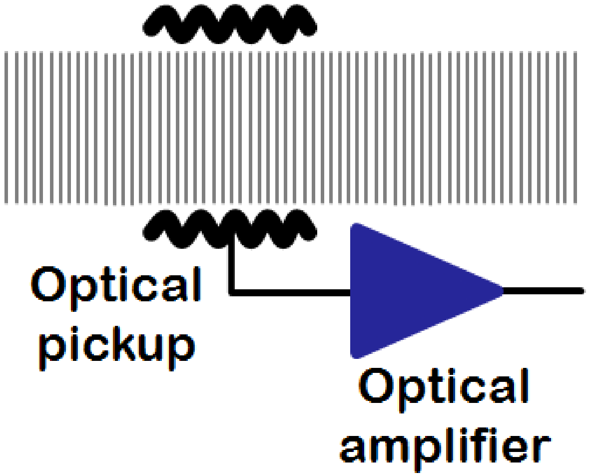
Antiproton accumulator at CERN

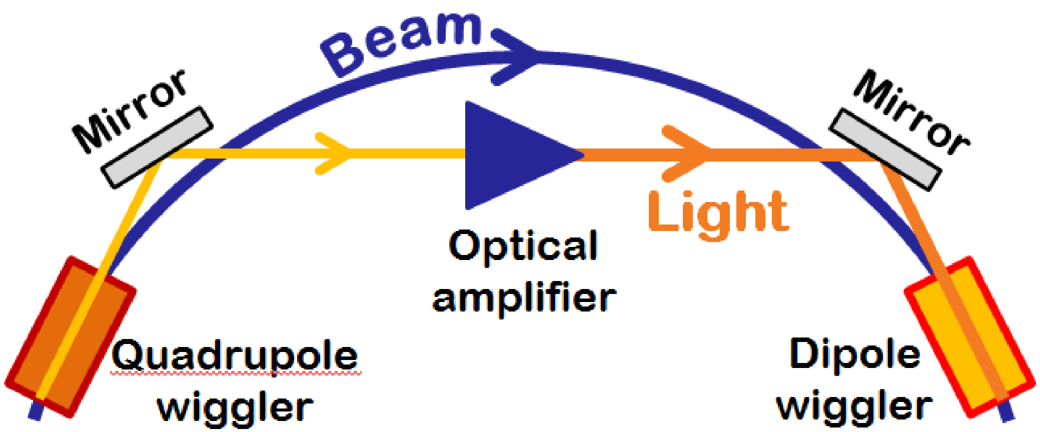
Faster stochastic cooling



"Standard" stochastic cooling – sampling of the beam and thus the cooling rate is limited by system bandwidth (pick-up length, etc)

Optical stochastic cooling – use optical pick-ups and optical amplifiers – increase bandwidth and cooling rate 1E4 times





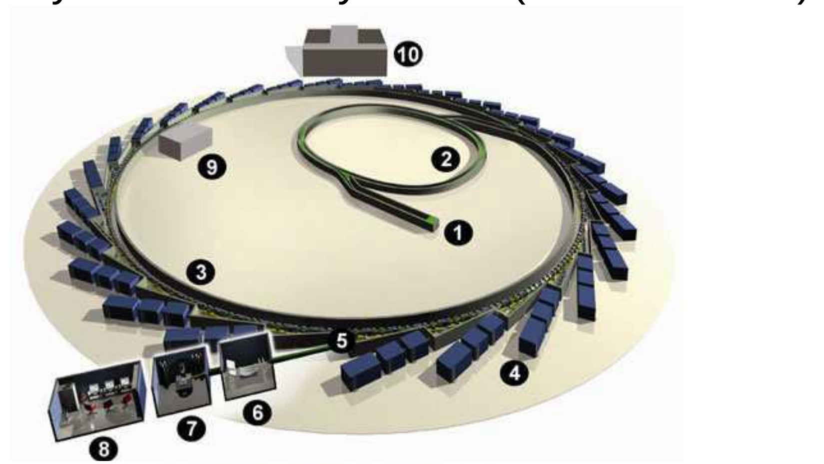
Create – Energize – Manipulate – Interact

- Create
- Energize
- Manipulate
- Interact
  - Beam
    - Radiation (synchrotron, betatron)
    - Free Electron Laser
    - Colliders
    - Spallation neutron sources
    - Particle therapy
    - Industry
    - Security
    - Energy (ADS)
  - Laser
    - Compton x-ray source
    - Photon collider

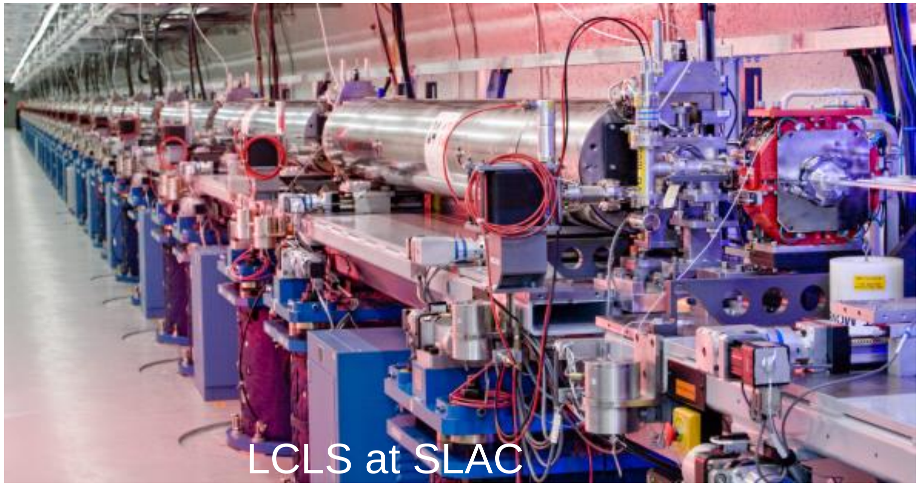
} Future lectures

Synchrotron sources, FEL, Compton source

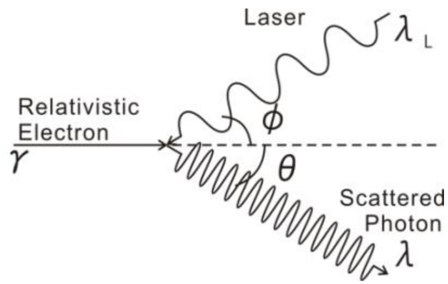
Synchrotron x-ray source (3rd Generation)



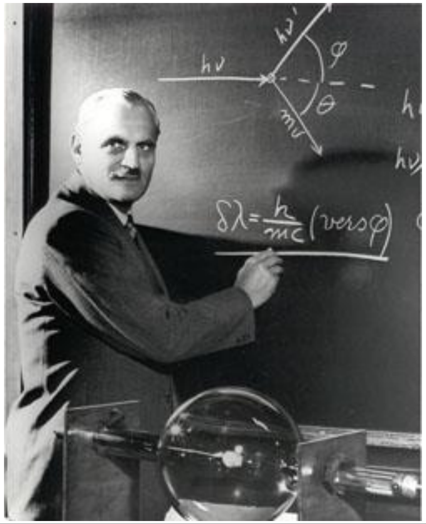
Free Electron Laser x-ray source (4rd Generation)



Compton x-ray source

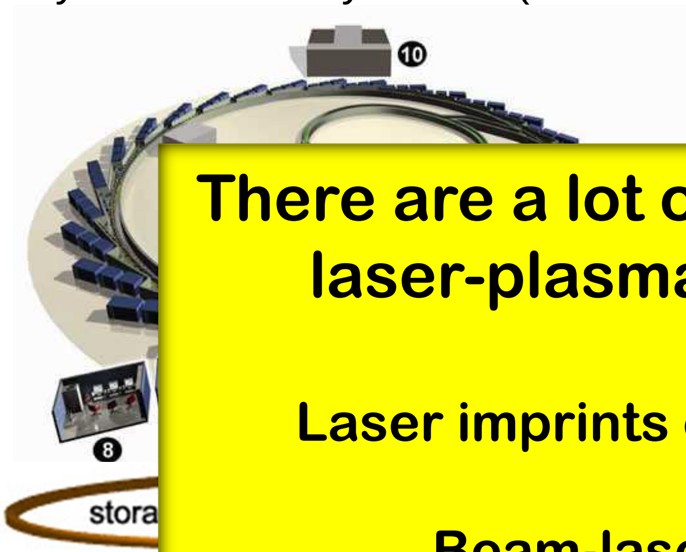


$$\lambda_2 = \lambda_1 (1+\theta^2\gamma^2) / (4\gamma^2)$$

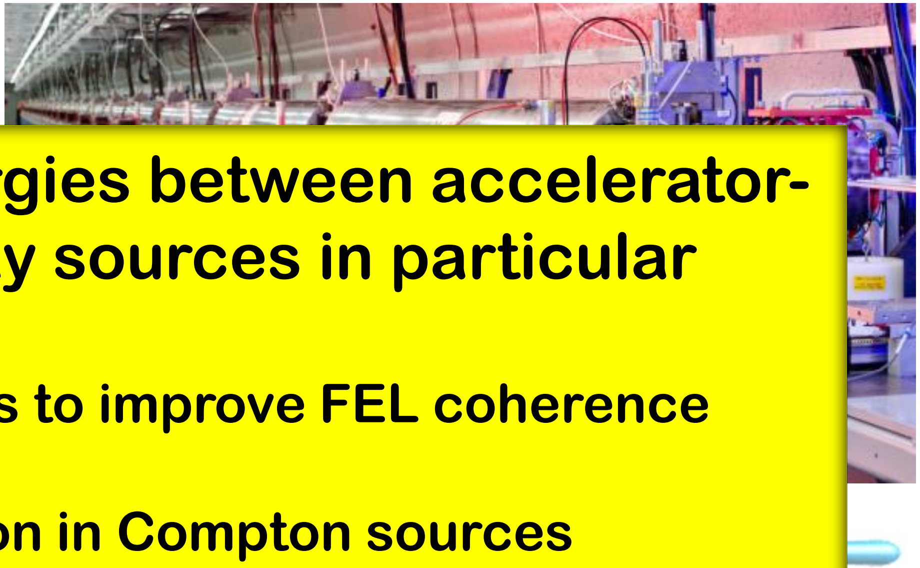


Synchrotron sources, FEL, Compton source

Synchrotron x-ray source (3rd Generation)



Free Electron Laser x-ray source (4rd Generation)



There are a lot of synergies between accelerator-laser-plasma in x-ray sources in particular

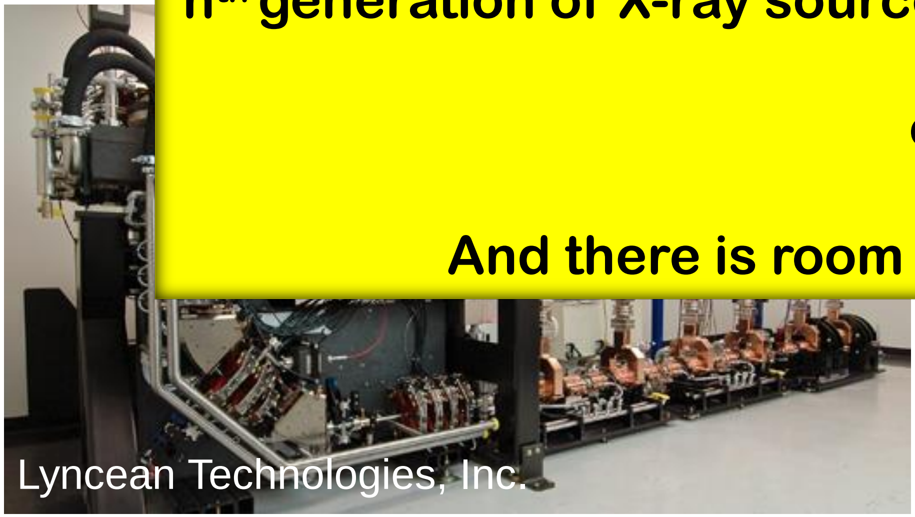
Laser imprints on beams to improve FEL coherence

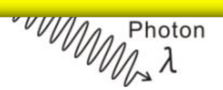
Beam-laser collision in Compton sources

nth generation of X-ray source based on plasma acceleration

etc.

And there is room for your contribution!





$$\lambda_2 = \lambda_1 (1+\theta^2\gamma^2) / (4\gamma^2)$$