Physics and computation of laser stripping

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On behalf of the ORNL Laser Stripping Team of SNS

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OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Purposes

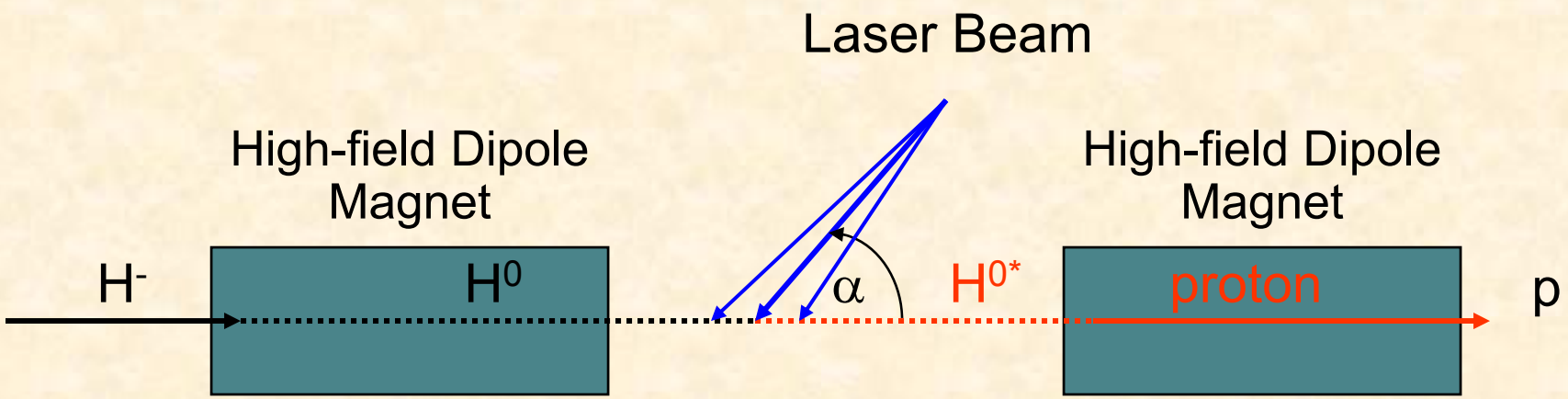
- General purpose: replacement of stripping foil for proton beam injection into the ring
- The developed physical model will allow to understand processes of LS
- The created application based on the model will allow to create most optimized facility for LS

Overview

- General scheme of laser stripping
- Definition of problem of LS for the scheme
- Theoretical basis and approaches to solution of the problem
- Computer application and benchmark of the application
- Examples of investigation with this application

Three-Step Stripping Scheme

(Slava Danilov's report, 2006)



Step 1: Lorentz Stripping

$H^- \rightarrow H^0 + e^-$

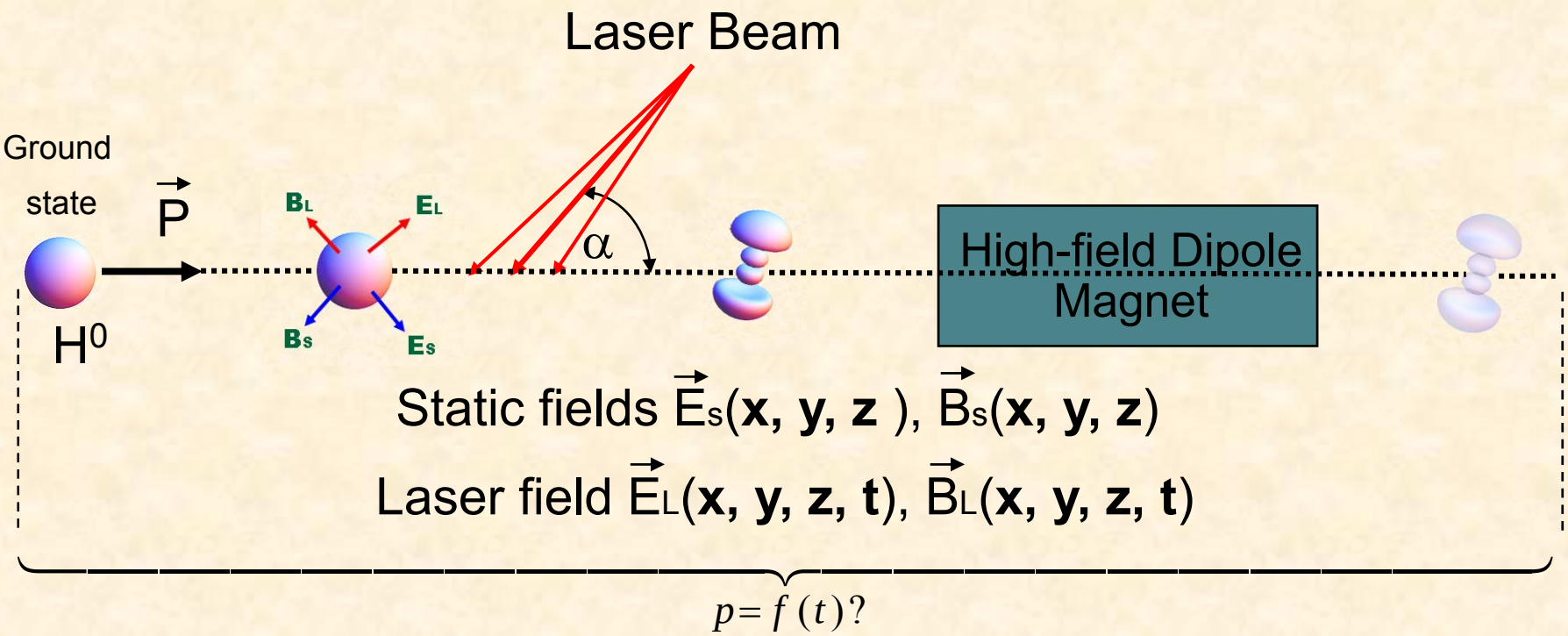
Step 2: Laser Excitation

$H^0\ (n=1) + \gamma \rightarrow H^{0*}\ (n=3)$

Step 3: Lorentz Stripping

$H^{0*} \rightarrow p + e^-$

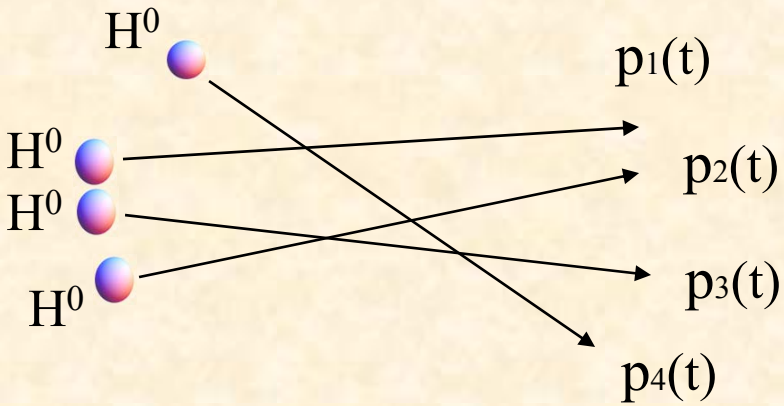
Definition of problem

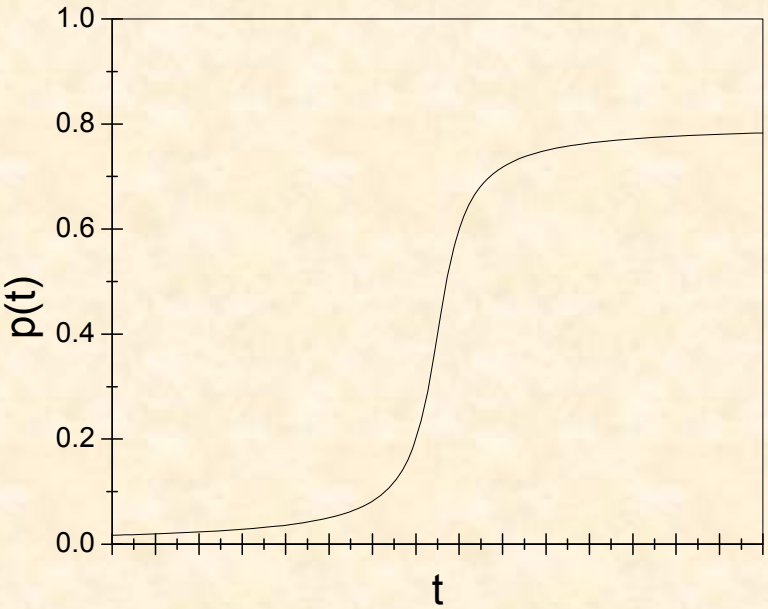


It is required to find probability of ionization of hydrogen atom as a function of time $p=f(t)$

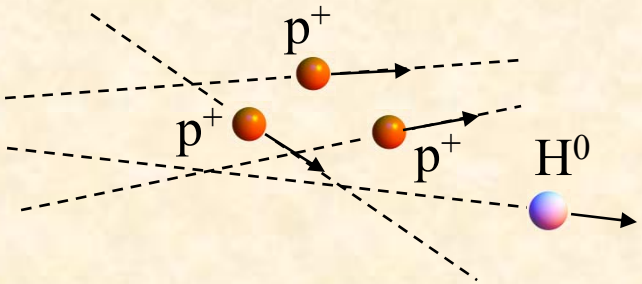
Ionization probability function

Hydrogen Beam





Proton beam

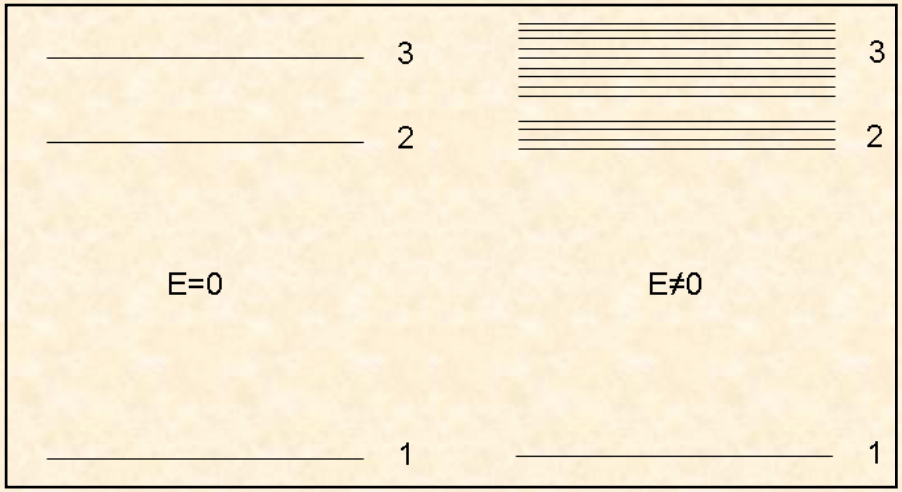


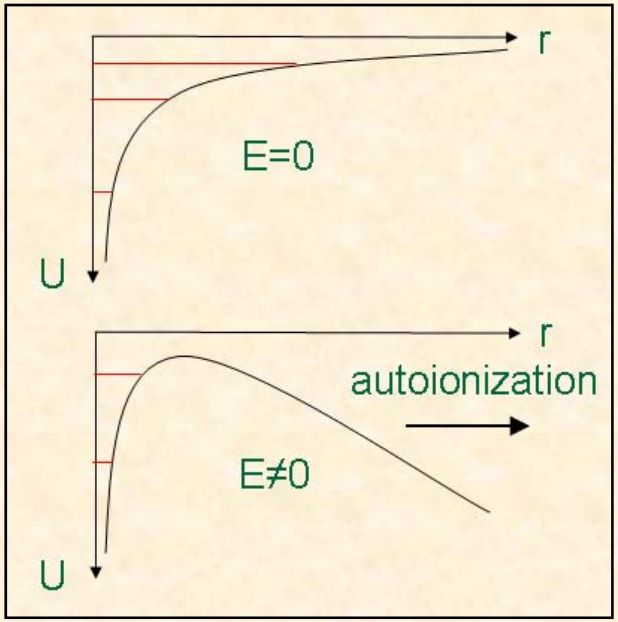
We can calculate the number of protons and their coordinates of origin (x, y, z, px ,py ,pz ,t).

We can also calculate the number of unstripped (lost) particles H^0 and their trajectories

Stark effect

Magnetic field in laboratory frame → **Lorentz Transformation of EM fields** → **Electric field in particle rest frame**





Energy
$E_i = f(E)$

Lifetime
$1/\tau_i = \Gamma_i = f(E)$

Dipole moment $\vec{d}_{ij} = e\int \Psi_i^* \vec{r} \Psi_j dv = f(E)$

Different approach to the Stark effect

- **Perturbation theory**

  (Allows to obtain analytical formulas for energies, lifetimes and wave functions in a weak field)

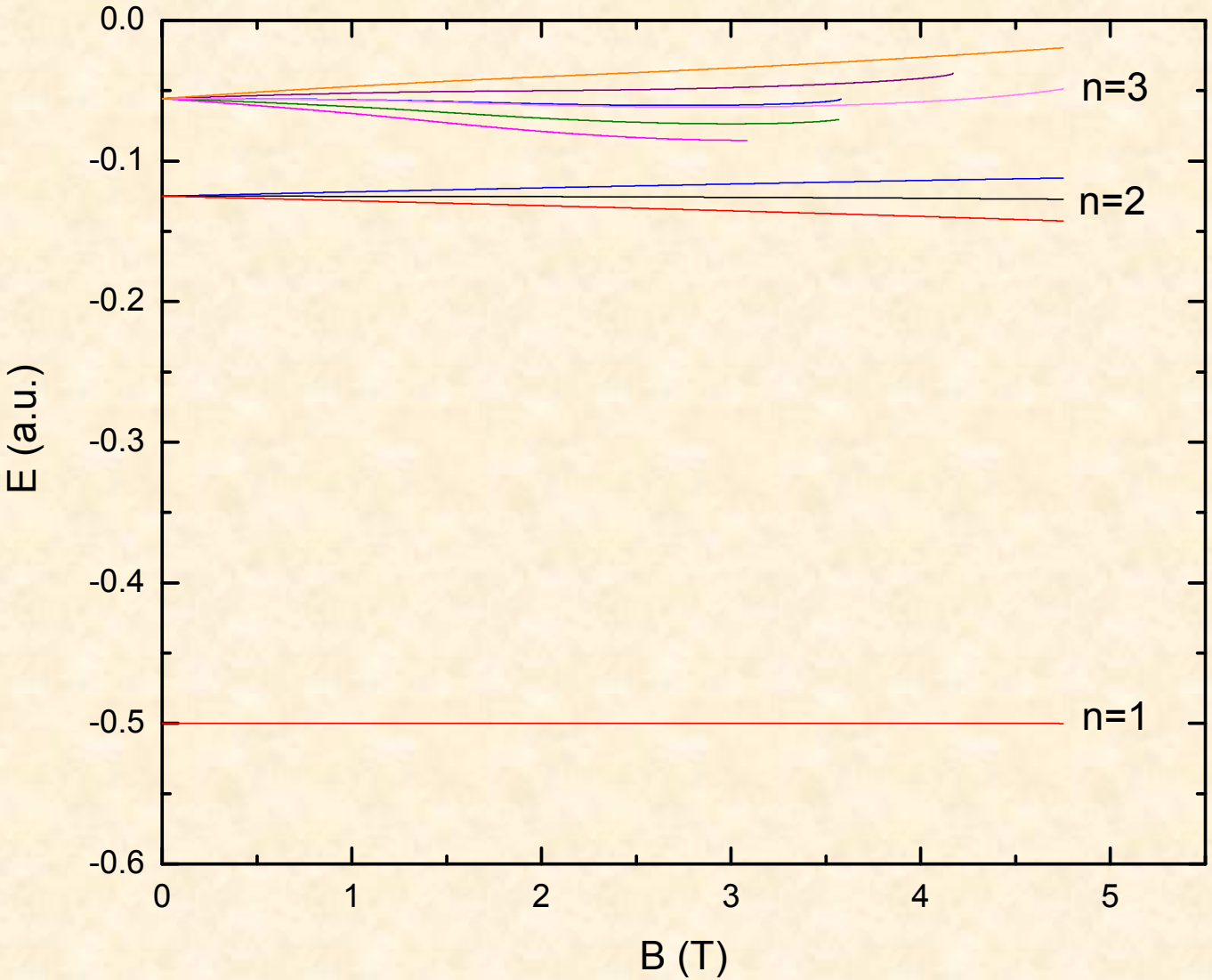
- **Breit-Wigner approximation**

  (Allows to obtain numerical solution for energies and lifetimes for moderately strong fields. *R. Damburg, V. Kolosov, 1976*)

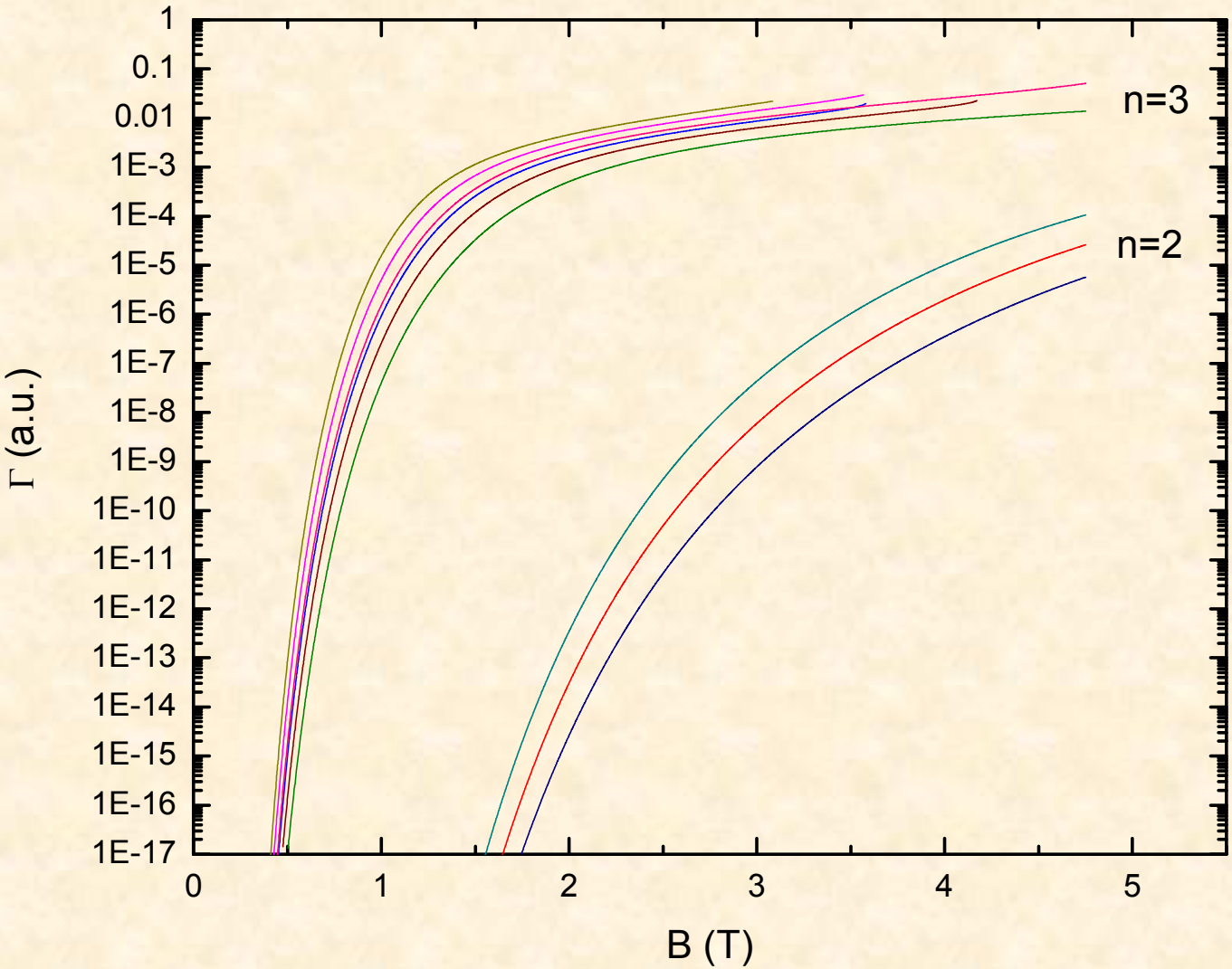
- **Exact numerical solution**

  (Allows to obtain exact energies, lifetimes, and wave functions for all fields. *R. Damburg, V. Kolosov, 1986*)

Stark effect, computation of energy for 1GeV

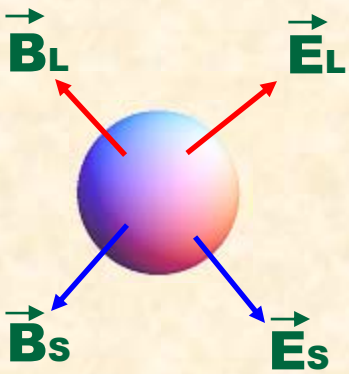


Stark effect, computation of energy for 1GeV



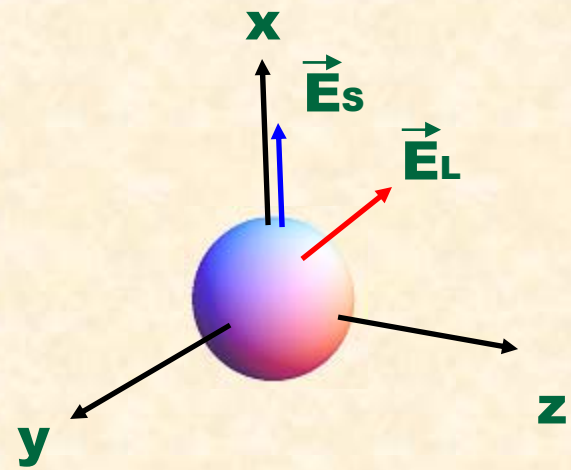
Approach to the solution of the problem

Laboratory frame



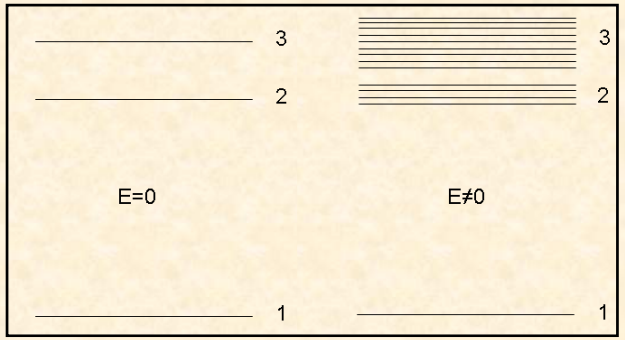
Lorentz Transformation of EM fields

Particle rest frame



Wave function has the following form

$$\Psi(\vec{r},t)=\sum_{j=1}^{14} c_j(t)\psi_j(\vec{r}) \qquad \Psi(\vec{r},0)=\psi_1(\vec{r})$$



Number of levels

$$1^2+2^2+3^2=14$$

Probability to find electron in atom

$$c_j^2(t) - population\ of\ \ j\ level \qquad p_{in}(t)=\sum_{i=1}^{14} c_j^2(t)$$

$$p_{autoionization}(t)=1-p_{in}(t)$$

Approach to the solution of the problem

- ***Density matrix formalism***

  Laser field interaction, static fields, autoionization and spontaneous decay can be included into calculations

- ***Schrödinger equation formalism***

  Laser field interaction, static fields, autoionization can be included into calculations. Spontaneous decay into lower levels can not be included!!!

Density matrix

$$Elements \quad \rho_{nm} = \langle \psi_n | \hat{\rho} | \psi_m \rangle$$ **n, m=1…14**

$$\rho_{nn}(t) \rightarrow population\ of\ \ n\ level$$

$$p_{ionization}(t) = 1 - \sum_{j=1}^{14} \rho_{jj}(t)$$

Master equation

$$\begin{cases} \dfrac{d\rho_{nm}(t)}{dt} = \dfrac{i}{2h}\left(\sum_{k=1}^{n-1} e^{it\omega_{nk}(E_S)} (\vec{E}_L(t)^*, \vec{d}_{nk}(E_S))\rho_{km}(t) + \sum_{k=n+1}^{N} \left(e^{it\omega_{kn}(E_S)} (\vec{E}_L(t)^*, \vec{d}_{kn}(E_S)) \right)^* \rho_{km}(t) - \sum_{k=1}^{m-1} \left(e^{it\omega_{mk}(E_S)} (\vec{E}_L(t)^*, \vec{d}_{mk}(E_S)) \right)^* \rho_{nk}(t) - \sum_{k=m+1}^{N} e^{it\omega_{km}(E_S)} (\vec{E}_L(t)^*, \vec{d}_{km}(E_S))\rho_{nk}(t) \right) + \\ + \delta_{nm} \left(\sum_{k=m+1}^{N} \gamma_{km}(E_S)\rho_{kk}(t) - \rho_{nm}(t) \sum_{k=1}^{m-1} \gamma_{mk}(E_S) \right) - (1-\delta_{nm}) \dfrac{\rho_{nm}(t)}{2} \left(\sum_{k=1}^{m-1} \gamma_{mk}(E_S) + \sum_{k=1}^{n-1} \gamma_{nk}(E_S) \right) - \dfrac{\Gamma_n(E_S) + \Gamma_m(E_S)}{2} \rho_{nm}(t) \\ \ldots \\ \ldots \\ \ldots \\ n, m = 1 \ldots 14 \end{cases}$$

It is necessary to solve system of 196 differential equations for complex elements

Laser field

Presented in form of Hermite-Gaussian Elliptical modes

Laser beam parameters

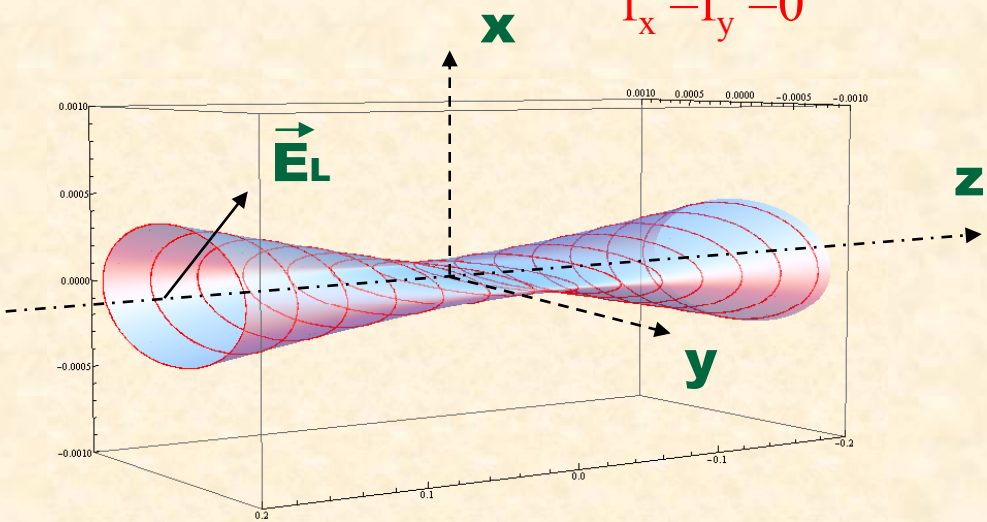
n, m	number of harmonics
w_x, w_y	waists on x and y axes
f_x, f_y	positions of waists
λ	wavelength
P	power of the beam

Orientation parameters

$\vec{n}_{\vec{k}}$	direction of k-vector
$\vec{r}_0$	position of laser beam
$\vec{n}_{\vec{E}}$	polarization of E field
$\vec{n}_m$	mode orientation

Example of zero-mode of the beam

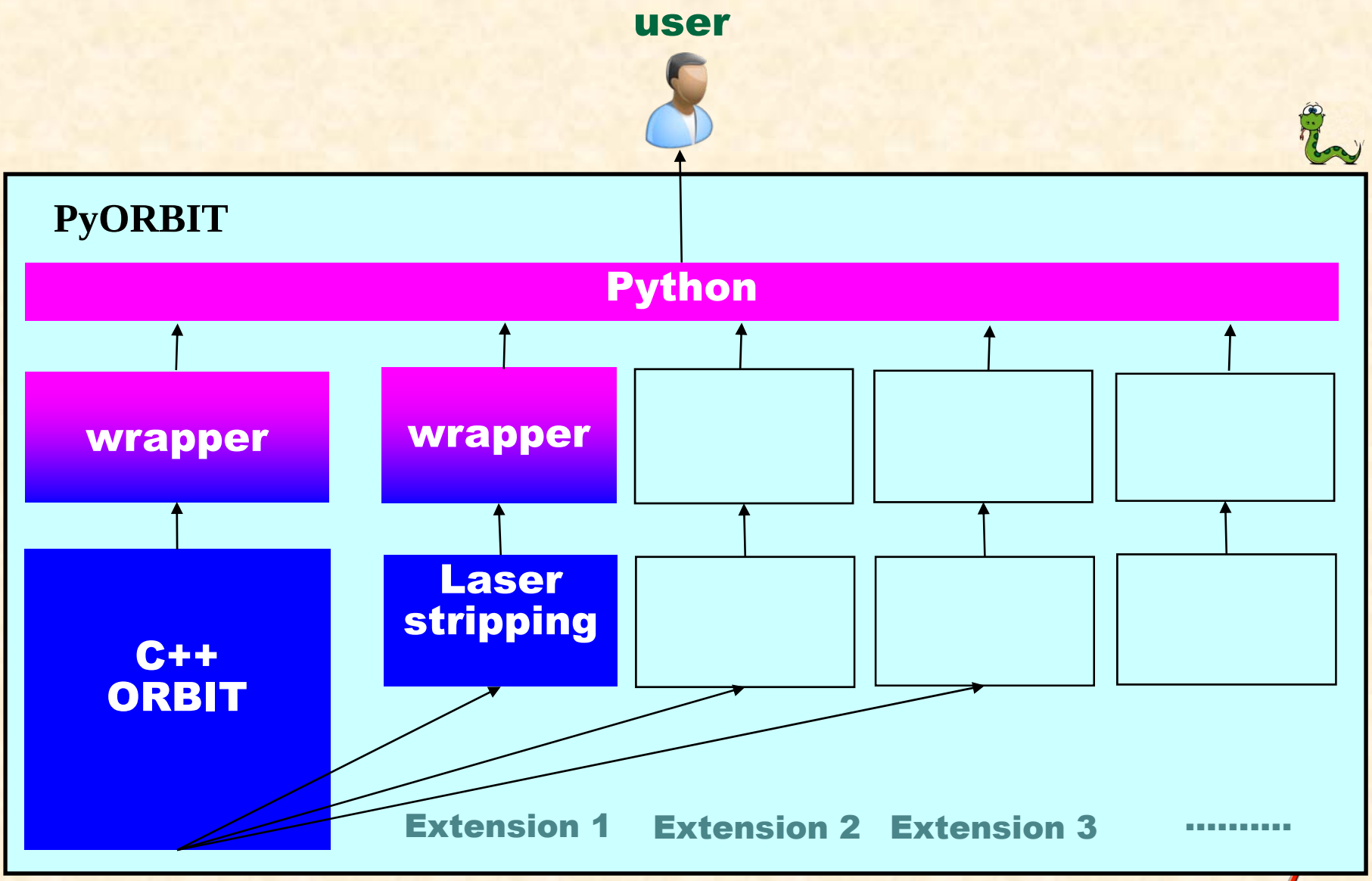
$n=m=0$
$w_x = 59\ \mu$
$w_y = 850\ \mu$
$\lambda = 355$ nm
$f_x = f_y = 0$



$$\vec{U}(\vec{r}) = \sum_{j=1}^{N} c_j \vec{u}_j(\vec{r})$$

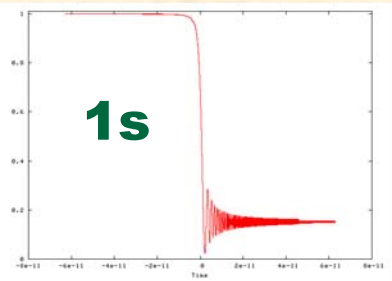
Superposition of modes

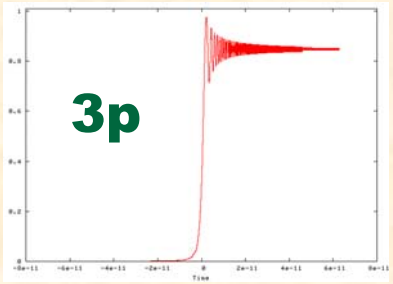
Implementation of laser stripping code



Benchmark of the LS module

Spherical coordinates

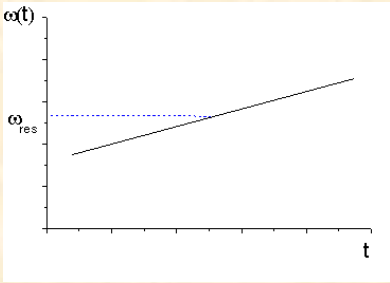




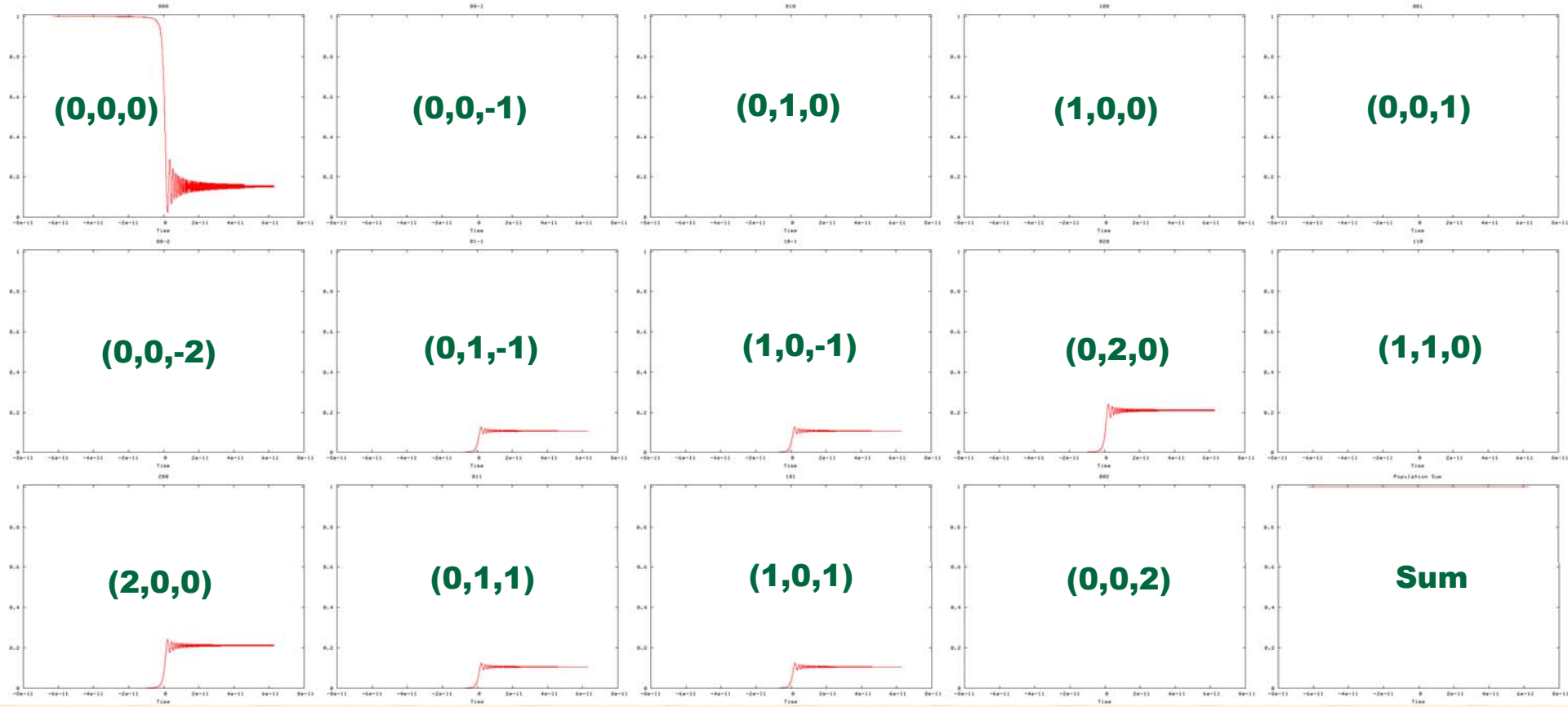
$\vec{E}=0$

Froissart Stora formula

$$C_n^2 = 1 - \exp\left(-\frac{\pi\Omega^2}{2\Gamma}\right)$$

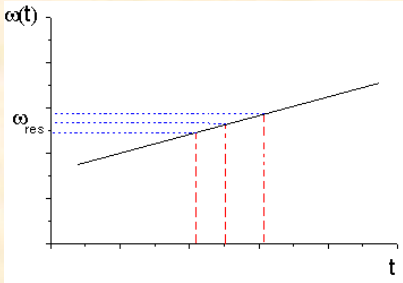


Parabolic coordinates. Quantum numbers: (n_1, n_2, m)

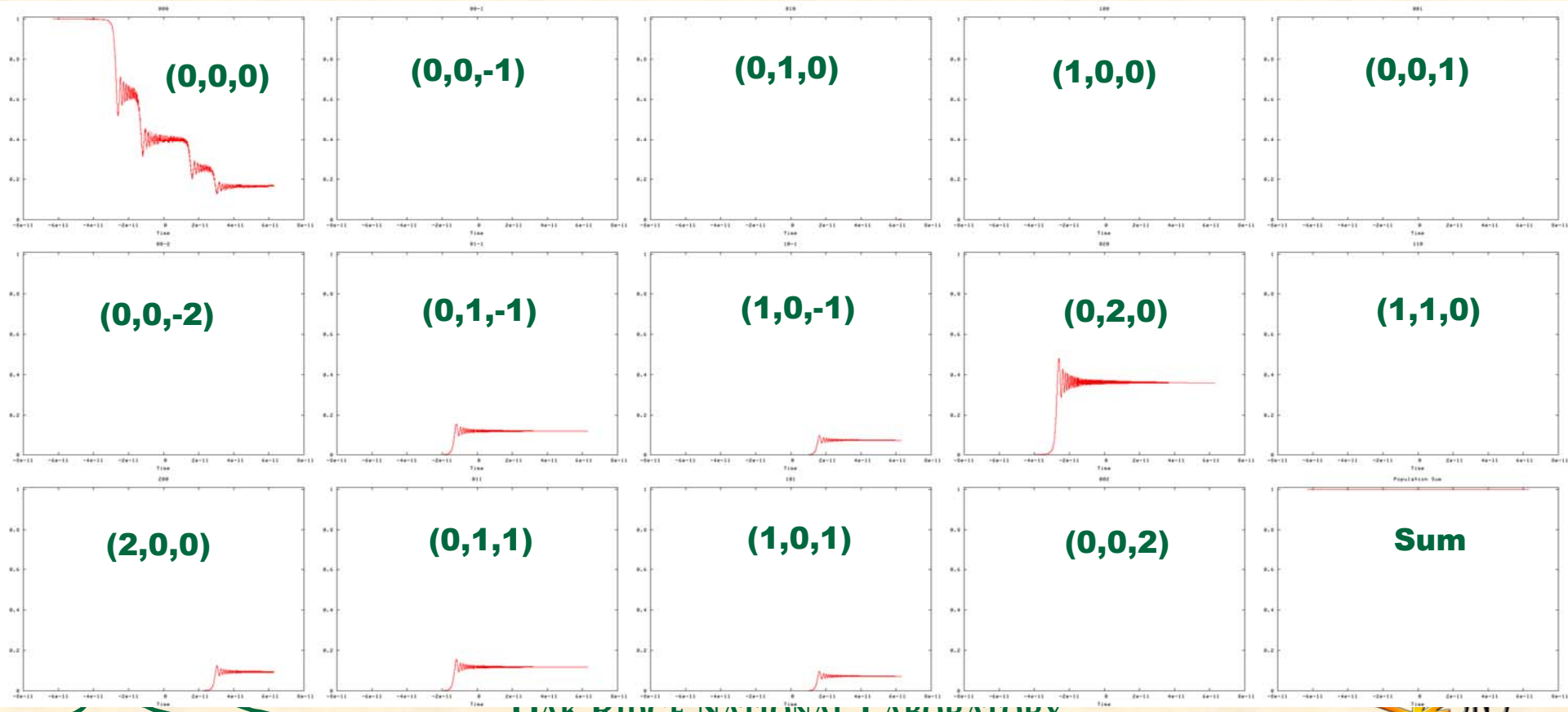


“Froissart-Stora” in presence of field

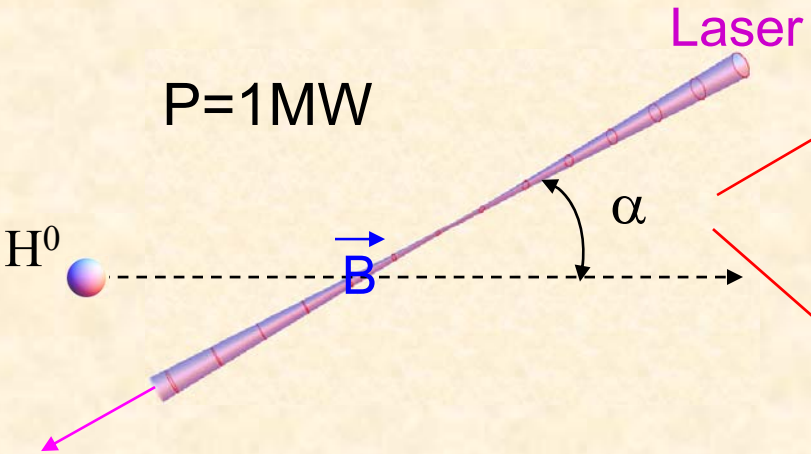
$\vec{E} \neq 0$

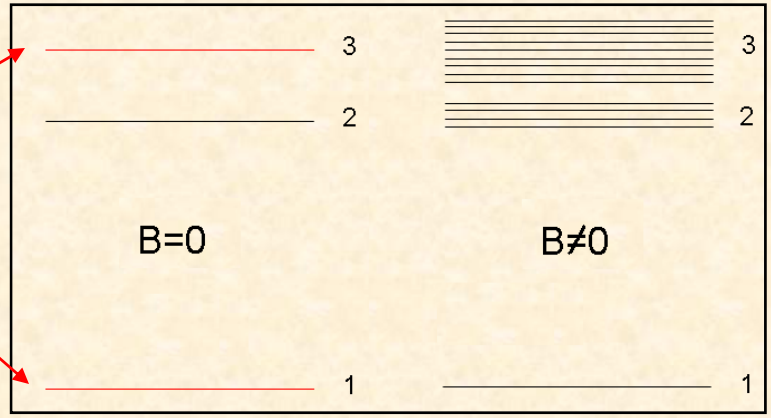


Parabolic coordinates. Quantum numbers: (n_1, n_2, m)



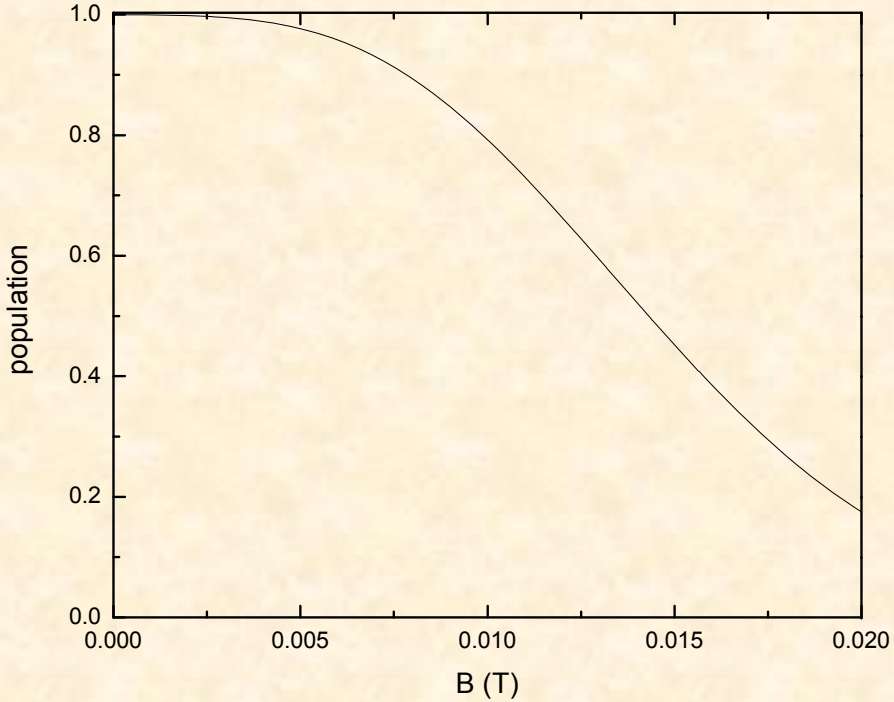
Effect of magnetic field



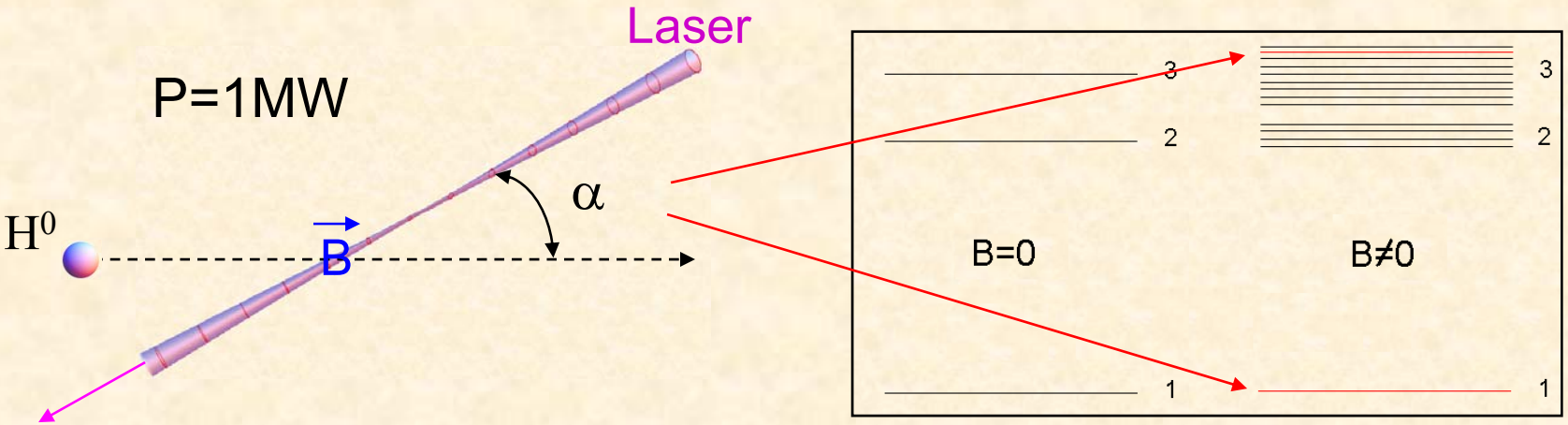


Incident angle of laser is tuned on unperturbed resonance energy

α=const

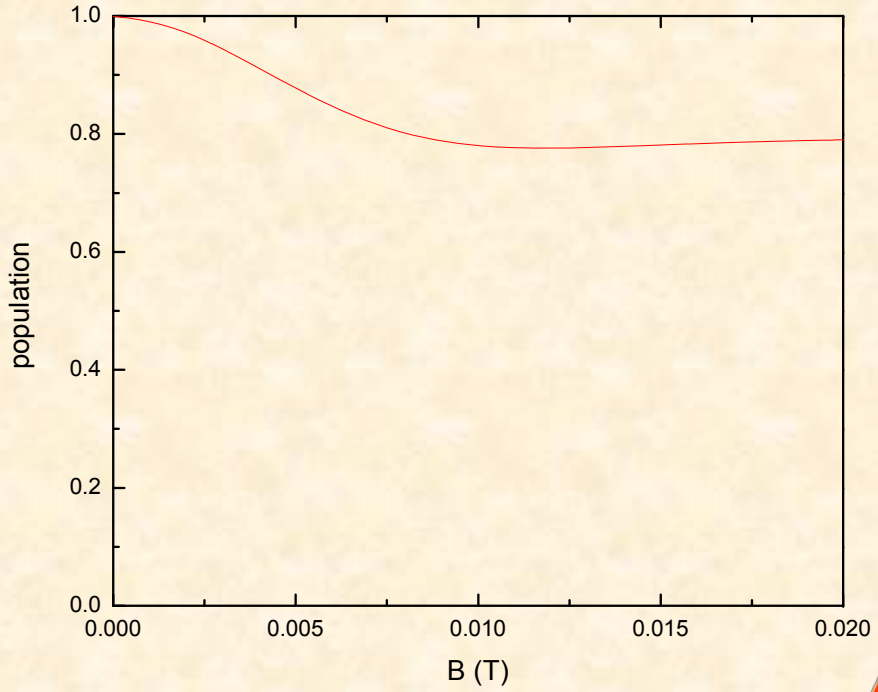


Effect of magnetic field

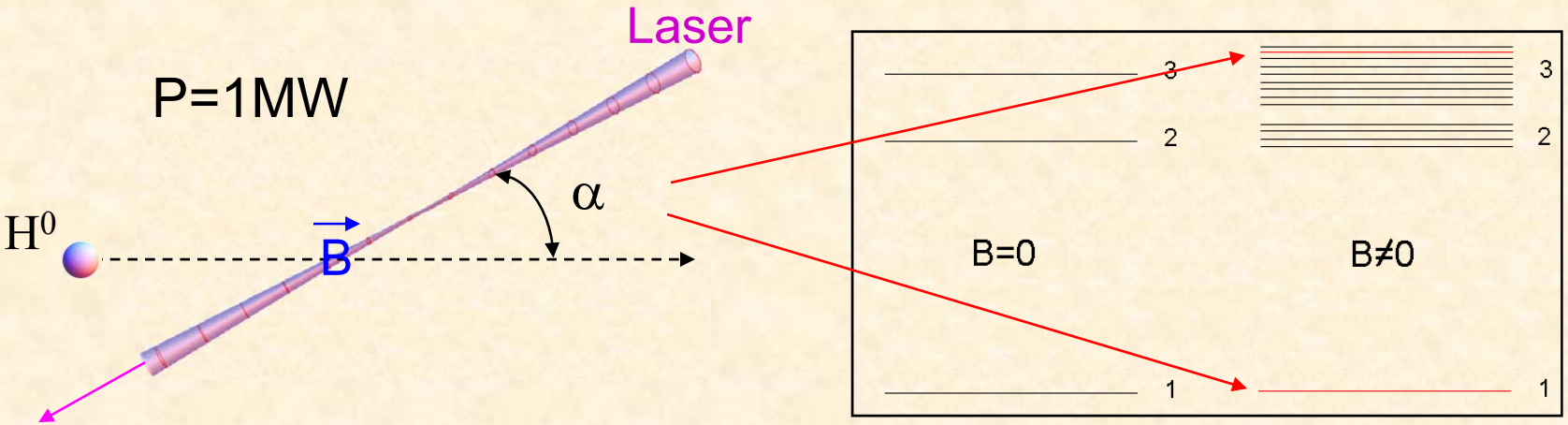


Incident angle of laser is tuned on one of Stark energy

α=f(B)



Effect of magnetic field

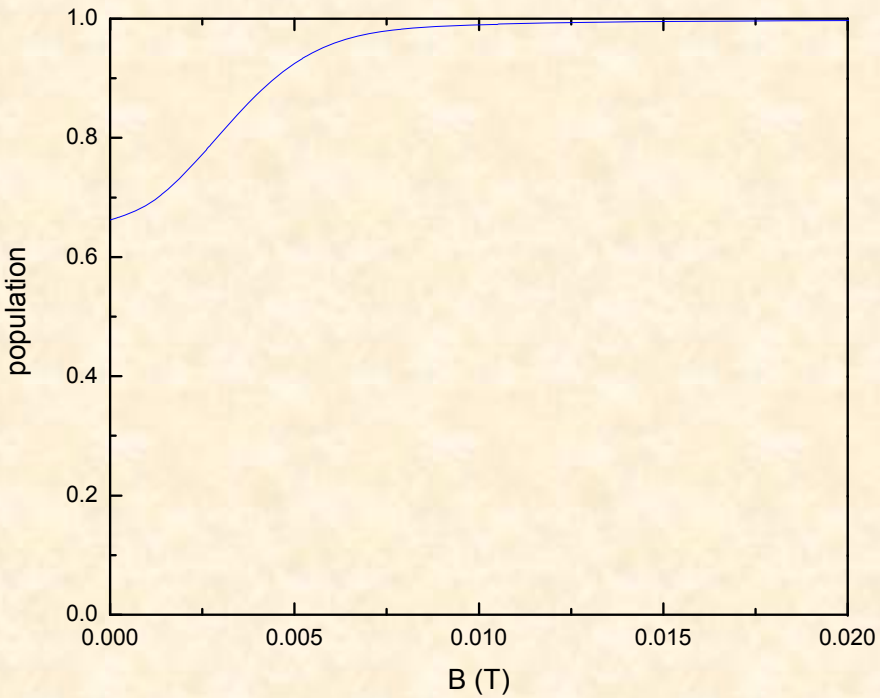


Incident angle of laser is tuned on one of Stark energy

α=f(B)

Parameter of waist has been changed from

94 [um] to 194 [um]



Conclusion of the last 3 slides

- It is not true that magnetic field makes only a harmful effect
- By optimizing of Laser parameters it is possible to provide high efficiency of LS at rather strong external magnetic field

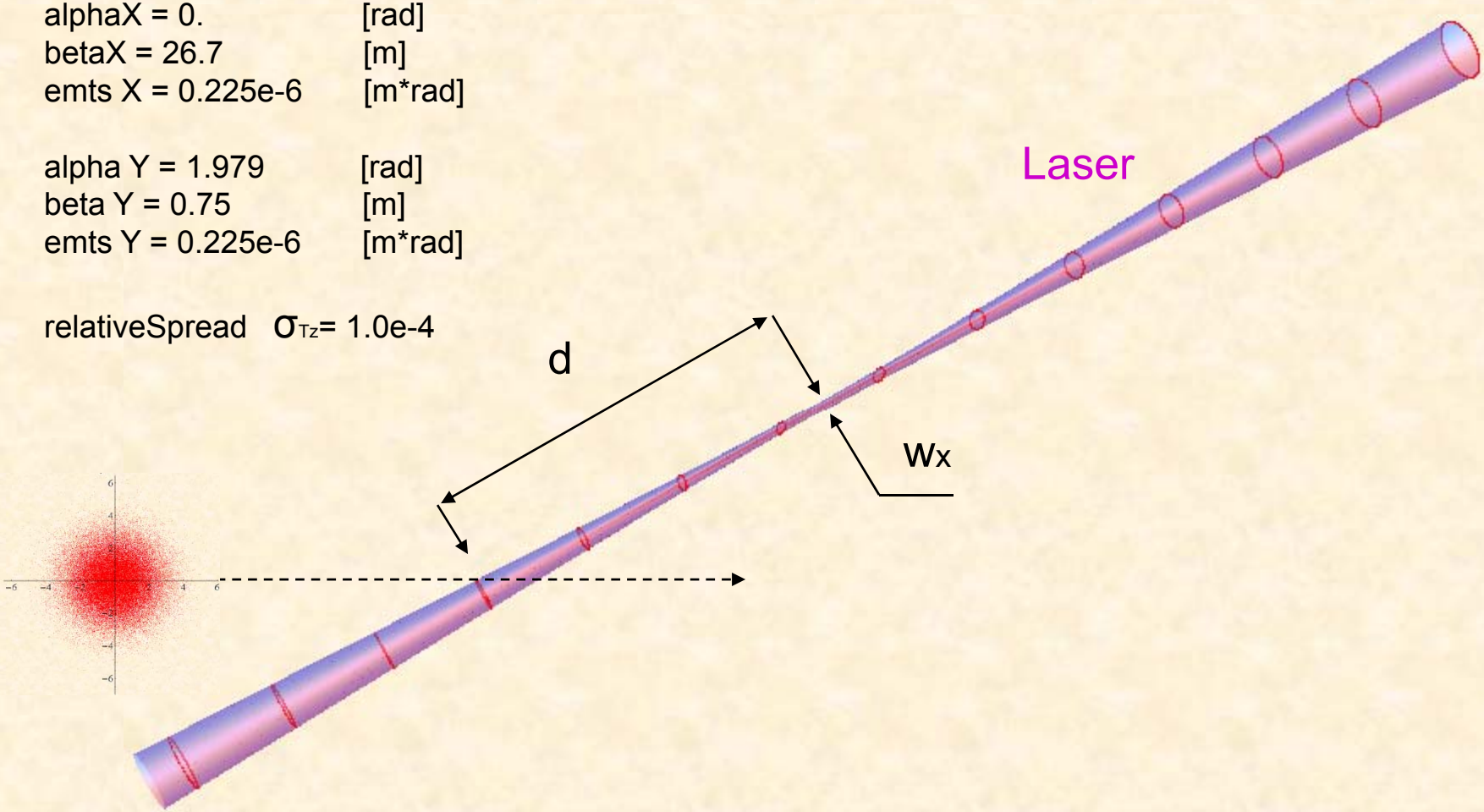
Investigation of realistic SNS beam

H^0 Beam emittance parameters

alphaX = 0. [rad]
betaX = 26.7 [m]
emts X = 0.225e-6 [m*rad]

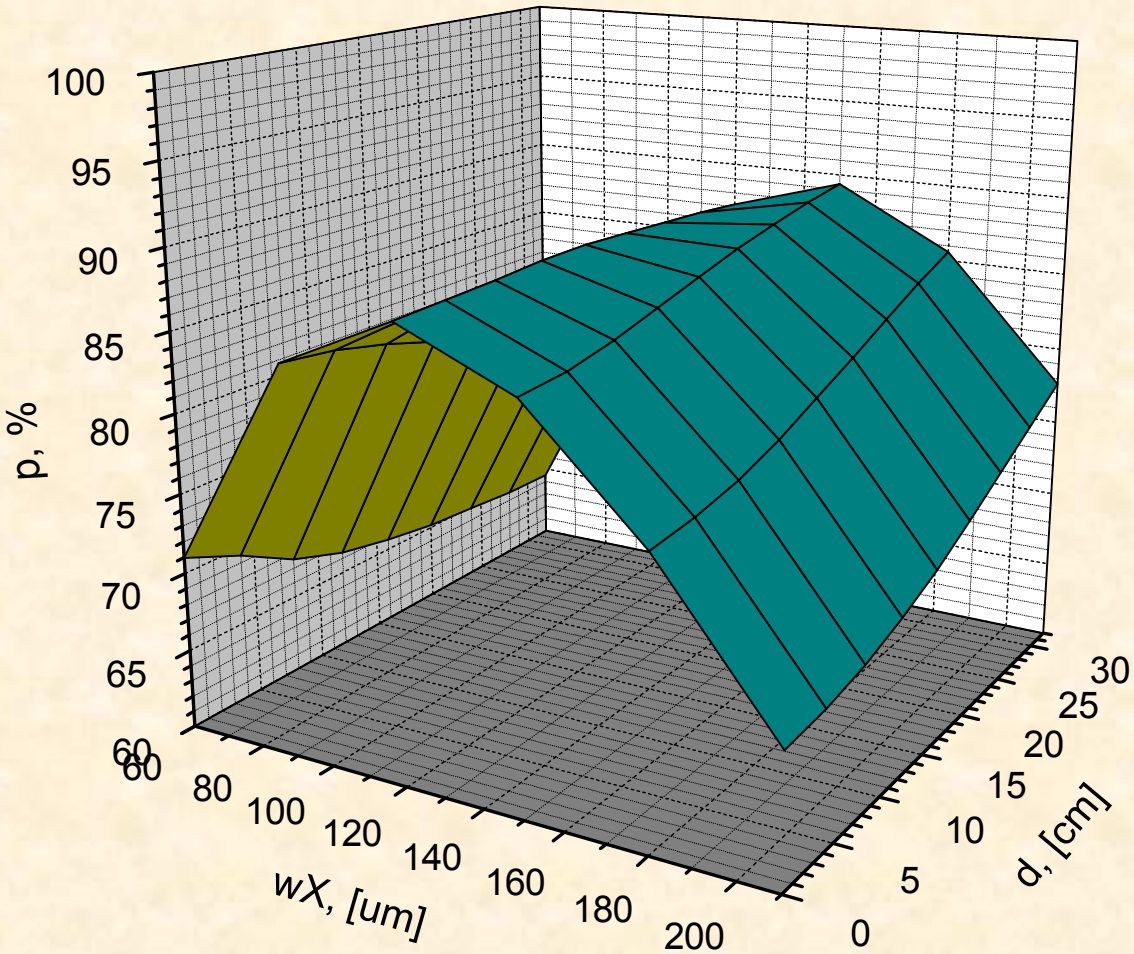
alpha Y = 1.979 [rad]
beta Y = 0.75 [m]
emts Y = 0.225e-6 [m*rad]

relativeSpread σ_{Tz}= 1.0e-4



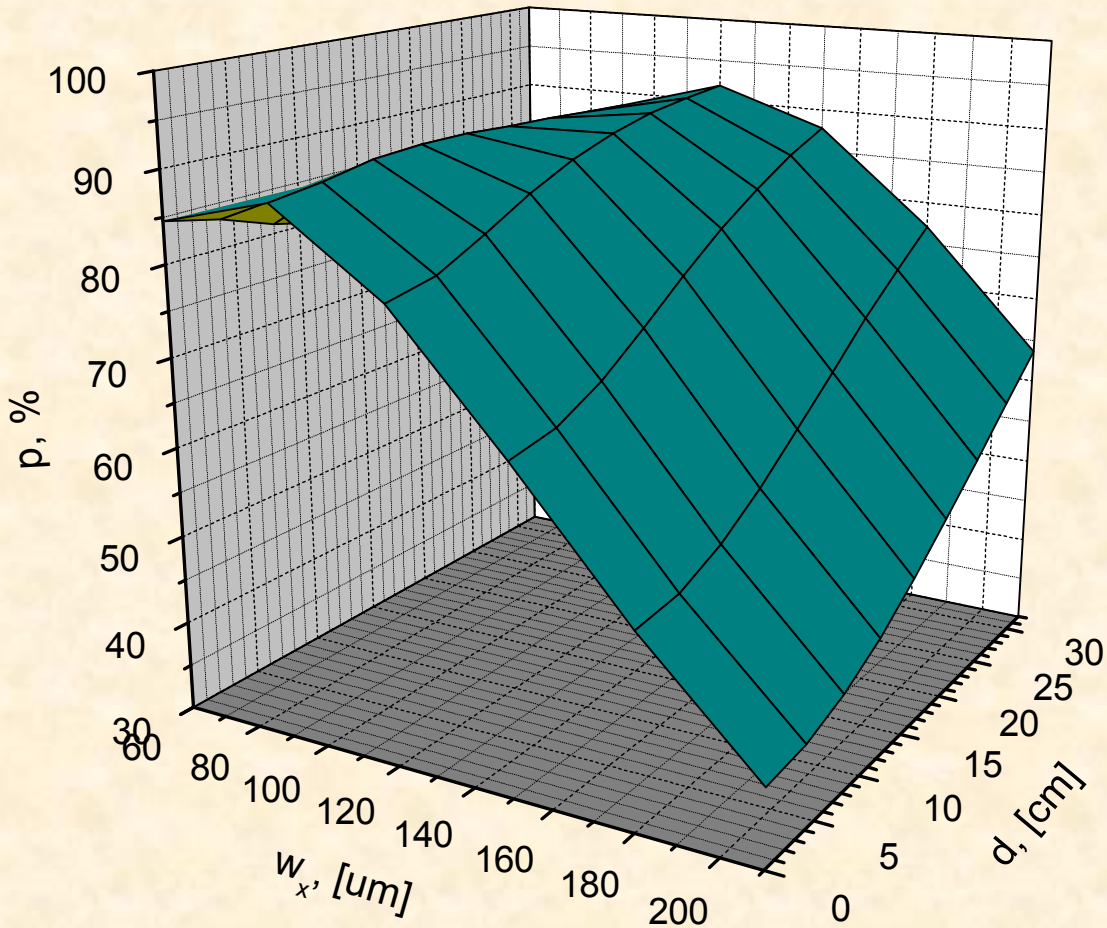
Investigation of realistic SNS beam

Laser Power = 1 MW, p_{max} = 90 %



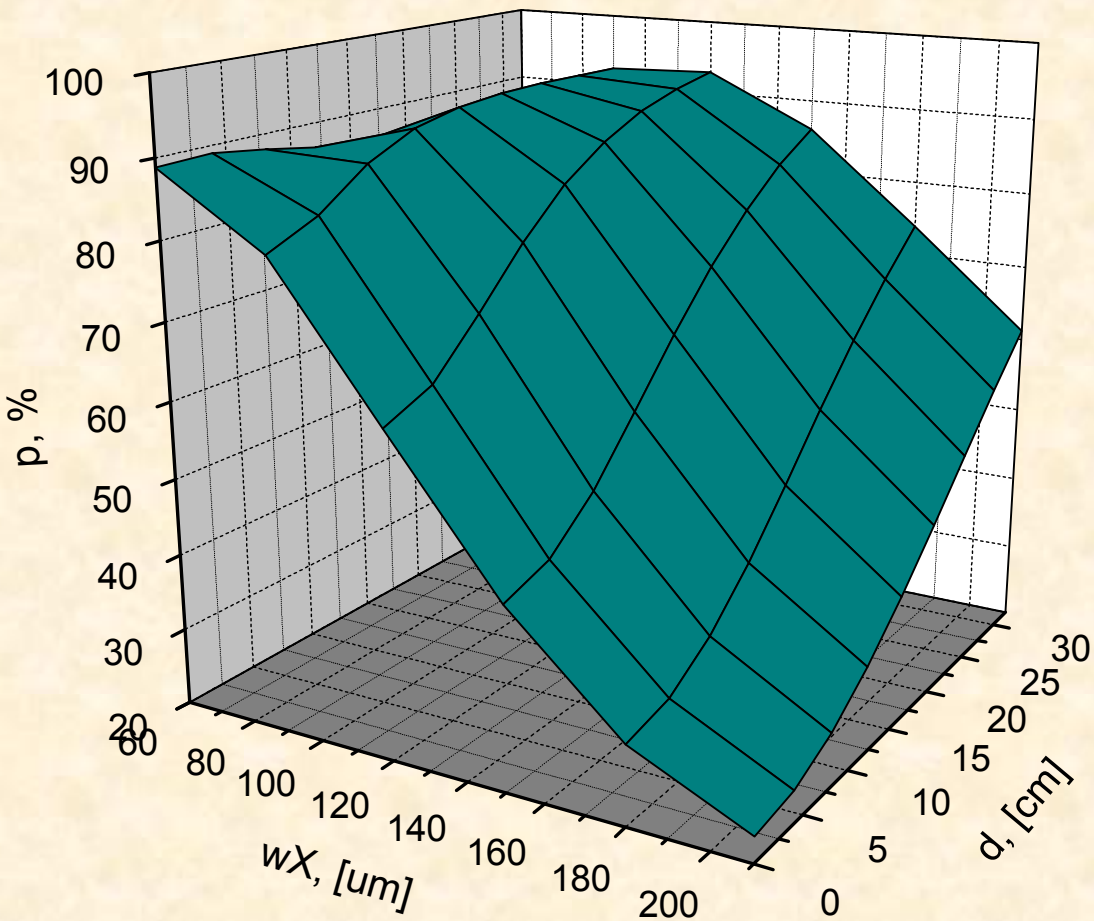
Investigation of realistic SNS beam

Laser Power = 1.5 MW, p_{max} = 92%



Investigation of realistic SNS beam

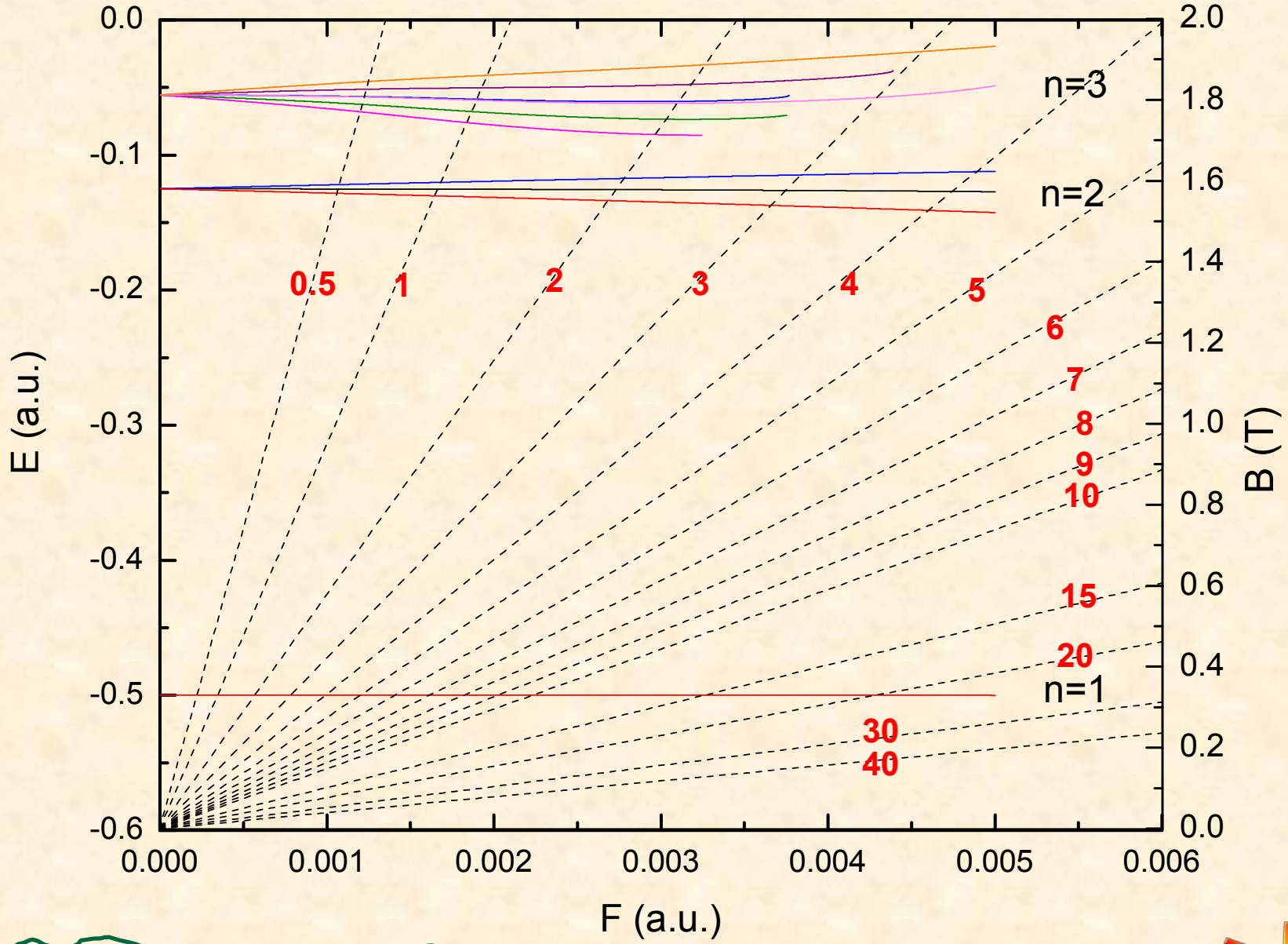
Laser Power = 2 MW, p_{max} = 94 %



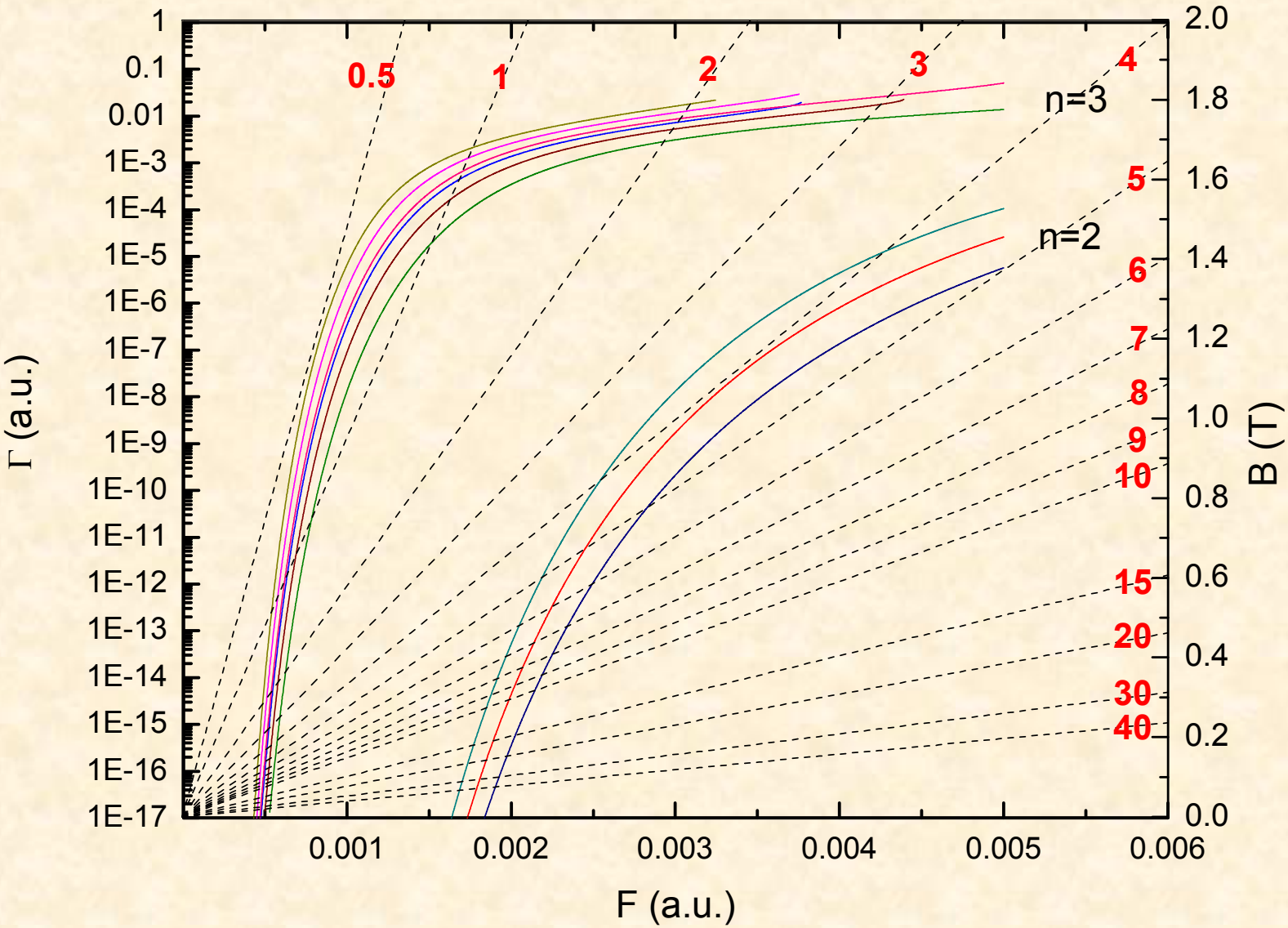
Future plans and problems

- Optimization modules
- Additional module for LS <u>without</u> spontaneous transition allowing to accelerate computation during optimization by factor of 10…100
- Module for calculation of two level system with $\vec{B}$, $\vec{E}=0$
- Module for computation of $H^- \rightarrow H^0 + e^-$ stripping
- Application for exact numerical computation of Stark parameters
- Modules that utilize realistic designed configurations of LS

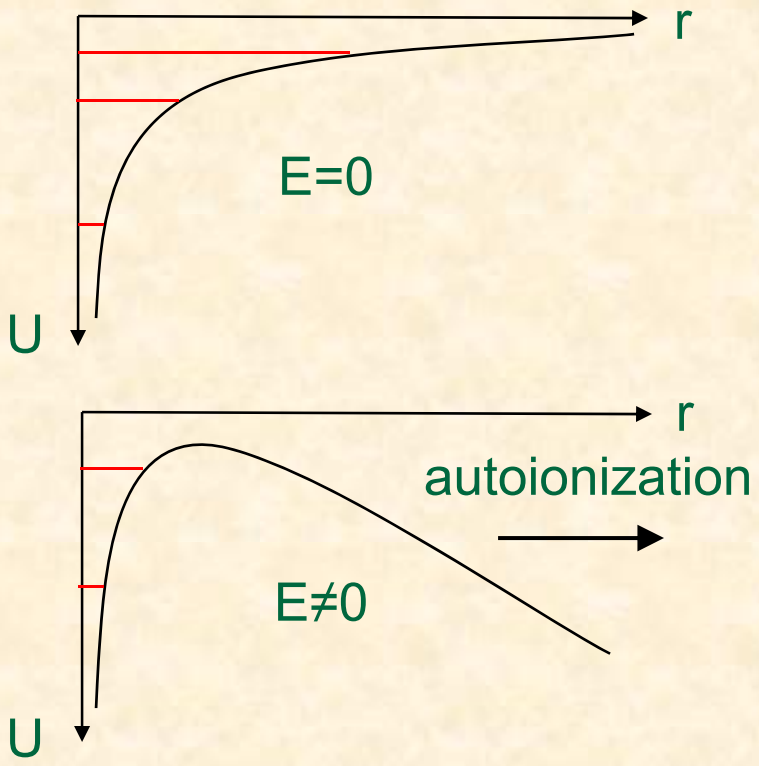
Stark effect, computation of energy

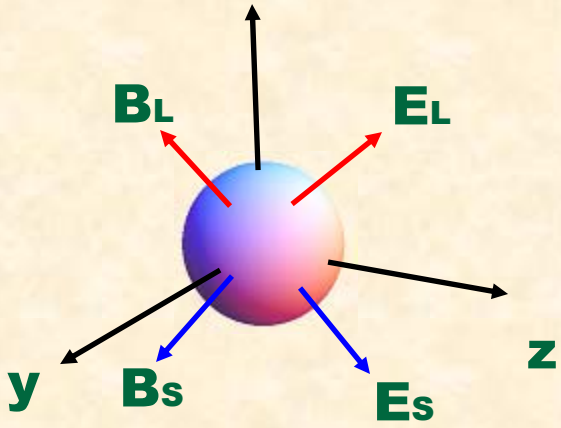


Stark effect, computation of lifetime



Stark effect

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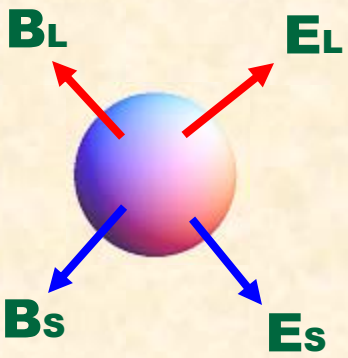
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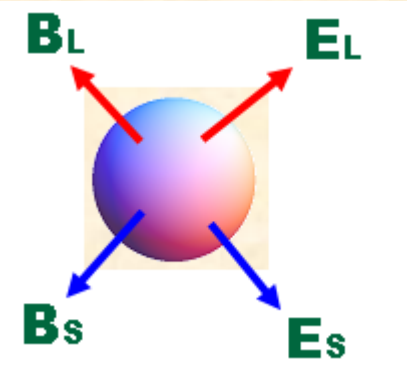
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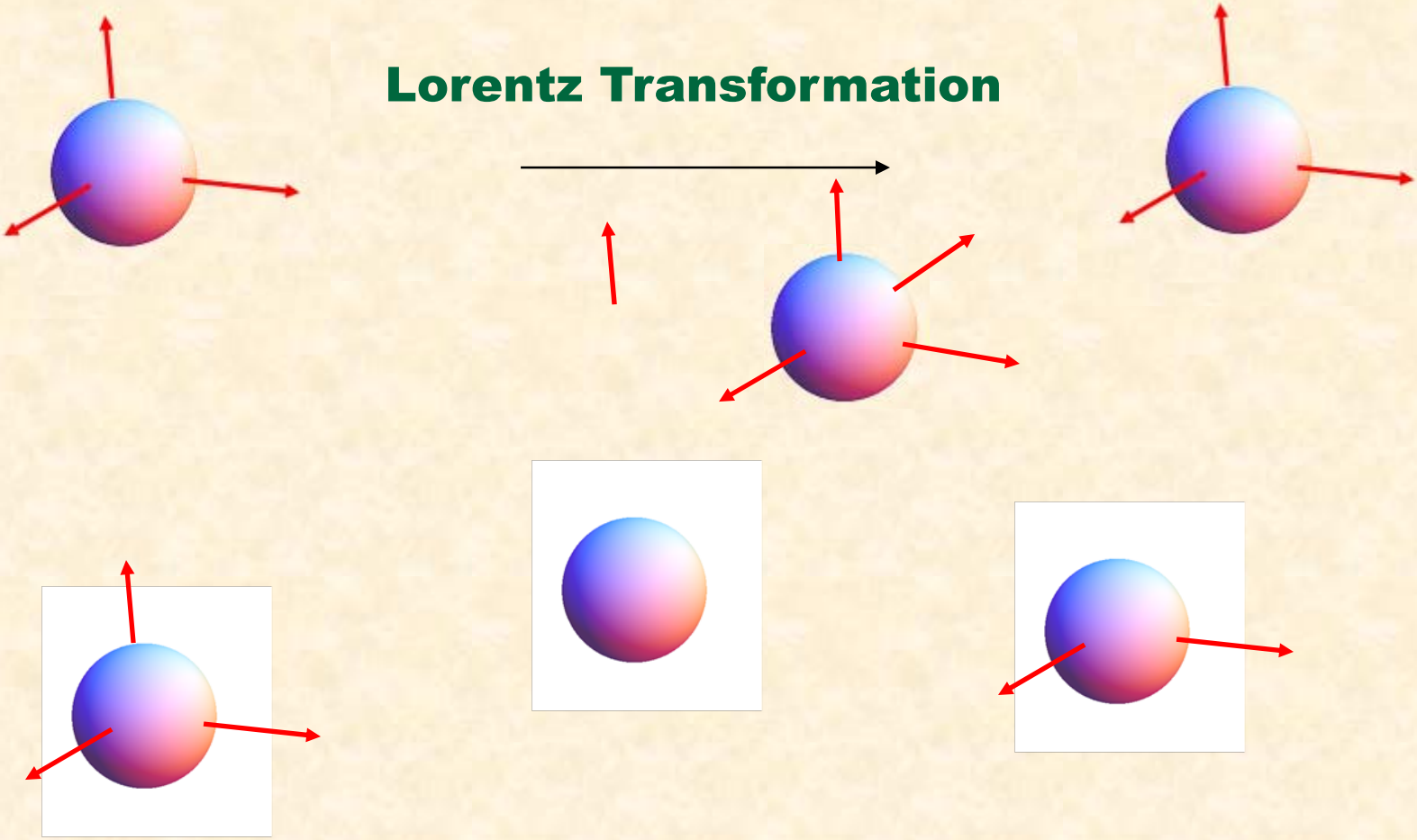
Stark effect

Laboratory frame

Particle rest frame

Lorentz Transformation