Coherent light sources and optical techniques for Thomson scattering experiments

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16/12/2014
Outline:

1. Introduction to Thomson Scattering and STAR project

2. Setup for the new STAR facility
   A. Optimization of laser transport line
   B. Study of pump laser for the main amplifier

3. Study of laser beam propagation in a capillary

4. Advanced diagnostics for ultrashort and ultraintense accelerated electron beams
Thomson Scattering

- Elastic Compton scattering for low photon energy:
  \[ \hbar \omega \ll m_e c^2 \]

- Powerful source for X-ray and γ-ray beams:

\[
\omega_{\text{out}} = \frac{4 \gamma_e^2 \omega_{\text{in}}}{1 + \gamma_e^2 \theta^2 + \frac{a_0^2}{2}}
\]

\[
a_0 = 8.5 \cdot 10^{-10} \sqrt{I \lambda^2}
\]

Some numbers:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_{\text{in}} )</td>
<td>( \sim 2.36 \cdot 10^{15} \text{rad/s} )</td>
</tr>
<tr>
<td>( \lambda_{\text{in}} )</td>
<td>( \sim 800 \text{ nm} )</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>( \sim 100 )</td>
</tr>
<tr>
<td>( \theta )</td>
<td>( \sim 0 )</td>
</tr>
<tr>
<td>( \omega_{\text{out}} )</td>
<td>( \sim 6.3 \cdot 10^{19} \text{rad/s} )</td>
</tr>
<tr>
<td>( \lambda_{\text{out}} )</td>
<td>( \sim 0.03 \text{ nm} )</td>
</tr>
<tr>
<td>( a_0 )</td>
<td>( \sim 1 )</td>
</tr>
</tbody>
</table>
Thomson Scattering
STAR Project

• **Southern european Thomson source for Applied Research**: X-Ray Factory based on Thomson scattering

• Scattered Photon Energy: 20-140 KeV

• User Facility for:
  - science of matter,
  - cultural heritage,
  - advanced medical imaging
STAR Project
Laser transport line to photo injector

• New Yb:KGW technology allows to low thermal load and high efficiency and reliability

• ~30m long laser transport line with High Reflectivity Mirrors

• Optical magnification system for safe transport in air

• Imaging system to improve pointing stability
• Development of a toolbox to study pump laser for optimizing its performances

• Start to study new design for the interaction chamber
Laser beam propagation in a capillary

- Capillary structure consists in:
  
  1. vacuum *core* with \( n = 1 \)
  
  2. *cladding* with \( n > 1 \) (usually borate silicate \( n \sim 1.5 \))

- Waveguide different from optical fiber: no total internal reflection (wall losses)
Laser beam propagation in a capillary

**Advantages**

- Extend the Rayleigh length of a laser beam, particularly useful in Thomson scattering
- Possibility to guide also the electrons in the capillary by means of a plasma channel waveguide

**Disadvantages**

- Laser and electron alignment very critical
- Possibility to damage or break the capillary at high laser energy
- Precise best coupling conditions to avoid energy losses
Laser beam propagation in a capillary

Quasi-mode of E.M. field

By solving Maxwell Equations in cylindrical coordinates one find a solution for electric field

\[ EH_{1m} \propto J_0 \left( \frac{u_m r}{a} \right) \]

Longitudinal wavevector

\[
\beta(\omega) = \frac{\omega n_{core}(\omega)}{c} \left[ 1 - \frac{1}{2} \left( \frac{u_m c}{\omega n_{core}(\omega) a} \right)^2 \right]^{\text{dispersion}} + \frac{i}{a^3} \left( \frac{u_m c}{\omega n_{core}(\omega)} \right)^2 \frac{n^2(\omega) + 1}{\sqrt{n^2(\omega) - 1}}^{\text{attenuation}}
\]

The mode with lowest losses and best energy coupling is \( EH_{11} \)

Hybrid modes:
Electric field components in every directions (no TE or TM modes). The order of mode is given by \( \beta \) parameter and derives from the solution of the transcendental equation of boundary conditions.
Laser beam propagation in a capillary

Coupling efficiency

Next experiments @ SPARC_LAB will concern laser-plasma interaction in capillary by means of 200TW FLAME laser (6J 30fs)

**Task:** find the parameters for the best coupling efficiency for a focused flat-top laser beam
Laser beam propagation in a capillary

Coupling efficiency

Best coupling efficiency ~90%
for \( w/a = 0.708 \)

Energy coupling efficiency:

\[
\eta_m = \frac{\left( \int_0^a rE_{1m}E_{\text{laser}} \, dr \right)^2}{\int_0^a rE_{1m}^2 \, dr \int_{-\infty}^{+\infty} rE_{\text{laser}}^2 \, dr}
\]

Complete toolbox for simulating the propagation by taking into account any diffraction effect (not yet plasma)
Laser beam propagation in a capillary
Longitudinal transmission efficiency

Electric field in longitudinal and radial coordinates:

\[ E_{1m}(r, z) = J_0\left(\frac{u_m}{a}r\right) \exp(-k_m^l z) \]

where

\[ k_m^l = \frac{u_m^2}{2k_{zm}a^3} \frac{\sqrt{n^2 - 1}}{1 + n^2} \]

\[ k_{zm} = \frac{2\pi}{\lambda} - \frac{u_m}{a} \]

\( 1/e^2 \) characteristic decay length

\[ L_m = \frac{1}{k_m^l} = \frac{2k_{zm}^2 a^3}{u_m^2} \frac{1 + n^2}{\sqrt{n^2 - 1}} \sim \frac{a^3}{u_m^2} \]

- The bigger is the core the higher is the transmission
- Higher modes have bigger losses: propagation purifies the transversal profile (only \( E_{11} \) survives)
Laser beam propagation in a capillary

Longitudinal transmission efficiency

Transmission efficiency through the capillary for $a=50 \mu \text{m}$

Transmission

Longitudinal coordinate (mm)
Advanced diagnostics for ultrashort and ultraintense accelerated electron beams

**Longitudinal diagnostics**

Electro-Optic Sampling: single shot measure of temporal length of a relativistic electron beam

Resolution is **limited** by:
- crystal depth
- temporal length of probe laser
Advanced diagnostics for ultrashort and ultraintense accelerated electron beams

Electro-Optic Sampling (EOS)

**Task:** Increase the resolution by lowering the laser time length

Spectral broadening (e.g. fiber white light generation) and recompression down to 50fs rms

Idea for experimental setup

- Laser 96fs rms
- Fiber for spectral broadening
- Compressor (diffraction grating)
- Laser 50fs rms
Advanced diagnostics for ultrashort and ultraintense accelerated electron beams

**Transversal diagnostics**

Optical Transition Radiation: measure of energy and transversal beam shape

Intensity angular distribution:

\[
\frac{d^2 W_{TR}}{d\omega d\Omega} = \frac{\alpha}{\pi^2} \frac{\theta_x^2 + \theta_y^2}{\gamma^{-2} + \theta_x^2 + \theta_y^2}
\]

**New scheme** for fully optical single shot emittance measurements with incoherent TR:

- transversal correlation position vs. angular distribution
- measure on light in air: much easier than conventional electron measurements
• The electron beam is split in different beamlet

• From the diffraction pattern made on the screen (intensity and width) one can measure the beam emittance

\[
\varepsilon_{\text{rms}}^2 \approx \frac{1}{N^2} \left\{ \sum_{j=1}^{p} n_j (x_{sj} - \bar{x})^2 \left[ \sum_{j=1}^{p} n_j \left( \frac{\sigma_j}{L} \right)^2 + n_j (\bar{x}_j - \bar{x})^2 \right] \right\} \\
- \left[ \sum_{j=1}^{p} n_j x_{sj} \bar{x}_j - N \bar{x} \bar{x}' \right]^2
\]
Advanced diagnostics for ultrashort and ultraintense accelerated electron beams
Optical Transition Radiation (OTR)

1. Metallic screen for TR creation
2. Interferential Filter for selecting $\lambda$
3. Imaging system to measure beam profile
4. Imaging system to copy the OTR source
5. Mask “Pepper pot” to measure correlation position-angular distribution
6. Intensified camera in the focus

A. Cianchi, New challenges in emittance measurements SIF - Pisa 2014
Advanced diagnostics for ultrashort and ultraintense accelerated electron beams

Optical Transition Radiation (OTR)

• Optical design study with ZEMAX to analyze any possible aberration that could affect the measure.

• Current work: reconstruct the image by simulating the propagation of TR field of each electron in the bunch and sum their intensities.

• For this purpose, a specific code in Zemax Programming Language (ZPL) has been written.
Advanced diagnostics for ultrashort and ultraintense accelerated electron beams

Optical Transition Radiation (OTR)

Single electron OTR field:

\[
E_{TR}(r) = \alpha K_1(kr) - \frac{J_0(kr)}{r}
\]

\[
\begin{align*}
\alpha &= \frac{2\pi}{\gamma\lambda} \\
k &= \frac{2\pi}{\lambda}
\end{align*}
\]

\[
\gamma = 200 \\
\lambda = 500 \text{ nm}
\]
Future Plans

• Finalize the whole experimental setup from laser clean room to interaction point for STAR facility

• Start the measurements with capillary to verify the theoretical matching conditions and start to consider plasma inside the core

• Develop the setup for white light generation and pulse compression for EOS

• Conclude the analysis for OTR by considering various wavevectors and start with measurements
Thank’s for your attention!