A novel single-shot, spectrally resolved X-ray imaging technique of ICF relevant plasmas

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Scenario and motivations. Overview of fast electron transport diagnostics

Single-hit CCD spectroscopy

The EEPHC (Energy-Encoded PinHole Camera) diagnostic

General principles

The single-shot EEPHC

A few examples of recent experimental results
The fast ignition approach to the Inertial Confinement Fusion, proposed in 1994 by M. Tabak et al., aims at a) relaxing most of the requirements for the ignition, in terms of irradiation symmetry/uniformity, total energy required and b) allowing a higher gain to be obtained.

The EU project for the infrastructure HiPER (High Power laser Energy Research), currently at the end of its preparatory phase, is expected to demonstrate high gain fusion reactors through advanced (fast or shock ignition) schemes.

Scenario: fast electron beams

- Typical figures for the fast electron beam (for a compressed target density ~300 g/cm$^3$): beam total energy ~10kJ, deposited over a region ~10µm in a time ~10ps.

- In terms of laser params, these requirements demand for the ignition laser to deliver a PW pulse with pulse duration ~10ps.

Open issues:
- laser-to-electron energy conversion efficiency
- scaling laws for the electron kinetic energy versus laser intensity
- fast electron beam divergence
- fast electron transport in the compressed target material

Motivations: studying fast electron transport

- The expected fast electron currents are of the order of MA, which requires the (resistive) propagation of a “return current” to be established
- Transient electric/magnetic fields are also expected to be established
- Electron current instabilities are also expected to build up
- Return current will give rise to resistive thermal heating that acts to modify the spectral features of the X-ray emission
- X-ray spectroscopy is a powerful tool to study this fast electrons transport

Foil targets can be used to investigate f.e. transport in solids and plasmas through detection of Kα emission
Motivations: studying fast electron transport [2]

Fast electron energy deposition gives rise to local heating in the target substrate. Heating will generate weakly ionised (warm) dense matter.

Spectra calculated using the kinetic code FLYCHK for a cold/warm target and for a hot, critical density plasma. K-shell emission components fall in the 4.5 - 4.8 keV range.

X-ray spectroscopy of shifted Kα components can be used to infer the electron temperature of the bulk target and to speculate on the role of refluxing of the fast electron beam at the target rear side.
Experimental study of fast electron transport

Space resolved imaging is needed to identify regions of X-ray emission characterised by different physical conditions.

Multi layer targets with multi-energy tracing elements would provide a detailed fast electrons propagation history.
Bragg crystals as an experimental tool

As an experimental tool, flat (seldom) or bent Bragg crystals are employed.

Bragg crystal suffer from two major drawbacks:
- the collection efficiency is strongly dependent upon the target temperature, due to the shift of the observed emission lines. When used in an imaging configuration, this may also affect the observed shape of the object being imaged out.
- the efficiency of the available configurations is quite poor at high photon energies. On the other hand, the behaviour of the ionization cross section by fast electrons as a function of the Z atomic number would push for the use of high Z number tracer layers (see figures below).

Furthermore, bent Bragg crystals are difficult to be used at PW, “harsh” environments, where noise from high energy particles/photons is a major issue.
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Single-hit CCD spectroscopy

CCD working in the so-called single-photon regime allows a direct, dispersive element free, spectroscopy in a large spectral range with spectral resolutions of the order of $\delta\lambda/\lambda \sim 10^{-1}$.

As it is well known, this detection technique basically relies on the linear relationship between the X-ray photon energy and the released electron charge, so that when only 1 photon (actually much less on average) hits each pixel the spectrum of the incoming radiation can be retrieved by simply taking an histogram.

Deviation from linearity of X-ray CCDs is found to occur only for photon energies lower than $\sim 1\text{keV}$.
Single-hit spectroscopy data analysis

- Charge spreading across neighbouring pixels, dark current, dead layers and channel stops

- Need of a careful (and tricky) analysis
  - Background subtraction
  - Event reconstruction
  - Local background subtraction
  - Event shape fit with a suitable 2D function
  - ...

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An Energy-Encoded PinHole Camera (EEPHC)

- Simple PH camera scheme with a CCD detector

- The CCD detector is forced to operate in the single-hit regime by using suitable X-ray attenuators (e.g., mylar foils in the simplest case or more complex combination of materials when a flat transmission is required over a broad energy range)

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From each shot a “single-photon image” is obtained, that is a collection of single-photon events whose position on the detector plane is related to its origin in the object (plasma) plane.

Data analysis:
- Single-photon event reconstruction
- Image reconstruction for the desired photon energy range from a large number of shots

If small target/PH/detector displacements can be suspected to occur from shot to shot, potentially affecting the spatial resolution, an “event center-of-mass” alignment procedure can be performed to each acquisition.

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A way toward a single-shot EEPHC

- Our EEPHC requires a few hundreds of “low flux images” to collect a sufficient number of photons per spectral band to build up a full image.

- Experiments at high-energy laser facilities require single-shot measurements.

- One of the possible approaches to address this issue is to use an array of closely spaced pinholes to image out the source on a large area CCD (or CCD array) detector.

- A custom array of pinholes is needed, due to the constraints on the pinhole diameters (<10mm), substrate thickness (~100mm) and material.

- The distance between neighbouring pixels must be set according to:
  - the expected source size (in order to avoid an overlap of different neighbour “single-photon images”)
  - the required magnification
  - the available CCD chip size!
Custom pinhole array fabrication at ILIL-CNR

Custom pinhole arrays have been produced at the ILIL laboratory of the CNR in Pisa by laser drilling of suitable substrates.

To this purpose, the frequency-doubled low-energy (~15mJ, 0.2TW) “probe” beam of a TiSa system has been tightly focused by means of a microscope objective onto the substrate surface.

First 20X20 pin hole array sample made at ILIL on a 100µm thick W substrate.

Optical microscopy images

Custom pinhole array fabrication: SEM images

Front side

Rear side
The individual “single-photon images” can finally be collapsed into a single one to get the final results.
Issues related to the spectral and spatial resolution

The spectral resolution is of the order of a few % over a broad spectral range (up to a few tens of keV).

The Point Spread Function takes the form

$$\text{PSF}(x', y'; x_d, y_d) = \sum_{i,j} \prod_{\alpha} \left[ c_{\alpha}(E) + (1 - c_{\alpha}(E)) \sum_{k,l} \left[ 1 - H \left( \sqrt{\frac{\xi_{\alpha}^2 + \eta_{\alpha}^2}{R_{PH}}} \right) \right] \right]$$

with

$$\xi_{\alpha} = x' + \frac{z_p + \alpha \nu_s}{p + q} (x_d + x_{ij}^{(i)} - x') - x_{kl}^{(p)} \quad \eta_{\alpha} = y' + \frac{z_p + \alpha \nu_s}{p + q} (y_d + y_{ij}^{(i)} - y') - y_{kl}^{(p)}$$

where $x_{ij}^{(i)}$ is the position of the center of the image through the $ij$ pinhole, $x_{kl}^{(p)}$ is the position on the PHA plane of the $kl$ pinhole, ... The sum is carried out over all the pinholes and the product over “thin” slices of the PHA, each having a transmission coefficient $c_{\alpha}(E)$. $R_{PH}$ is the radius of each pinhole.

As a general rule of thumb, the source size must be much smaller than the neighbour pinholes separation in order for the overlapping effects to be negligible.
An example of the setup at RAL Target Area PW

The single-shot EEPHC has been recently employed in a PW environment in an experiment in Vulcan Target Area Petawatt.

Shielding tube:
- plastic 10mm
- Al 13mm
- plastic 7mm

CCD chamber
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EEP HC: some results [1]

Charged particle detector

"Rear" pin hole camera

"Front" pin hole camera

Evidence of non-isotropic emission, due to Bremsstrahlung

Provided a sufficient number of photons has been collected, the source can of course be imaged out at energy ranges where no spectral lines are supposed to be present and only continuum (low energy Bremsstrahlung) emission is expected to contribute to the X-ray spectrum.
Results from a recent experiment at RAL PW show that a high-energy X-ray emission comes from a small spot while the Ka emission region exhibits a minimum ~80μm.
In the past few years, a new concept X-ray spectroscopic tool has been being developed, based upon the use of single-hit CCD detectors.

This new diagnostic allows 2D X-ray images with simultaneous spectral resolution of ICF plasmas to be obtained, with spatial resolution of the order of a few μm and spectral resolution of a few %, over a large spectral range (up to a few tens of keV).

Although the spectral resolution is rather poor when compared to the one attainable by using Bragg crystals, this new tool is particularly suited for the study of fast electrons transport in high-energy-density plasmas, such as those encountered in the fast ignition approach to ICF.

This new diagnostic tool has been successfully employed in recent experimental campaigns carried out at multi-TW- and PW-scale laser facilities.
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EEPHC (multi-shot): some results (2)