Short Pulse Laser Inverse Compton Scattering to Measure the Runaway Electron Distribution during Tokamak Disruptions

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We are designing a new diagnostic based on laser inverse Compton Scattering (LICS) to study the dynamics of runaway electron formation during killer-pellet triggered disruptions in DIII-D, and their subsequent loss. We can improve the expected S/N ratio by using a high-intensity short-pulse laser combined with gated x-ray imagers. With 80 picosecond sampling, time-of-flight spatial resolution within the laser chord can be obtained. We will measure the time-resolved spatial profile and energy distribution of the runaway electrons while they are in the core of the tokamak plasma.

During a major disruption in a tokamak, electrons can be accelerated to 10's of MeV energies[1], and they can cause serious damage to the tokamak armor and vessel walls. These "runaway electrons"[2-4] can quickly build up to a significant fraction of the original toroidal plasma current before they are eventually lost. For ITER, if runaways cannot be prevented and eliminated, they are expected to be a serious threat to machine operation. Therefore it is imperative that we gain an increased understanding of runaway electron dynamics, including generation and loss mechanisms in present-day tokamaks. In present day tokamak experiments, 100–1000 kA of runaways, at energies of up to 30-50 MeV can be created[5]. In larger machines the secondary avalanche mechanism becomes dominant[6]. With extremely large amplification gains in ITER, it is expected that a non-mitigated major disruption could produce 5-15 MA of ~ 20 MeV runaways[7]. In both cases, current densities of the runaways we can expect are in the range of 1-10 kA/cm^2.

We propose to build and field a powerful new diagnostic tool, called Laser Inverse Compton Scattering (LICS), to allow direct, time and space-resolved, in-situ, non-invasive measurements of the energy and spatial distribution of runaway electrons generated in the DIII-D tokamak. Laser inverse Compton scattering (LICS) to measure relativistic electron beams is an old idea in the high-energy accelerator community[8], involving the detection of gammas up-scattered from the laser pulse. Compton scattering is the inelastic scattering of electromagnetic radiation (often a gamma ray) by a free charged particle, such as an electron. For inverse Compton scattering, consider instead starting with high energy electrons, and then scattering photons off of them. LICS is in some ways similar to conventional Thomson scattering off of the bulk plasma electron distribution. A short pulse of laser light is sent through the plasma, and the returned scattered light is weak. In the Thomson limit, the energy of the incident photons $E_i << m_e c^2$. However, in our case the electron beam $E_{runaway} >> m_e c^2 >> E_i$, so the incident photon radiation is up-scattered by the relativistic electrons into the soft x-ray range, with their energy increased by a factor of $4\gamma^2$, where γ is the runaway energy normalized to the electron rest mass. Furthermore, they become highly forward scattered (relative to the e-beam direction), with a half angle of width $1/\gamma$. This gives the experimenter two significant advantages...the laser is no longer a source of interfering light, and one can collect light from a much smaller solid angle than for conventional Thomson scattering.

In 2002 LICS was carried out in successful experiments with 20 MeV electrons at the Idaho Accelerator Center[9], with observed photons in the 5-10 keV range. About this time it was suggested to use it to measure runaway electrons in a tokamak, and parameters were scoped out extensively from 2004-2007 for JT-60U by Yasunori Kawano (JAERI)[10]. In 2007, a version of the diagnostic was in the process of being fielded on JT-60U, when JT-60U operation was discontinued (for upgrading to JT-60SA). Consequently, to-date there has been no actual demonstration of this technique in any tokamak or fusion device, anywhere in the world. Kawano's 2006 analysis[10] for JT-60U starts with a 10 Joule, 1-ns, 1.06um laser pulse, in a head-on laser-e-beam geometry, while detecting forward-directed soft x-rays. He concludes that a 6000 count signal would be collected, but with about 2000 counts in background noise (coming from relativistic bremsstrahlung emission), for a S/N of only 3:1.

We suggest that shorter time gating is necessary to beat down the noise problems. In fact, at LANL we have the short-gated (60 ps) soft x-ray detector heads already at hand, developed for NIF inertial fusion diagnostic purposes[11, 12]. A gold photo-cathode is the active detection area, 105 mm x 13 mm in size, on each of six strips, bonded on top of a multichannel plate (MCP), shown in Figure 1. For our purposes, six different timing gates (one for each strip) will give us measurements from six different spatial locations along the laser beam. Multiple (and different thickness) foils can be placed above each strip, as indicated in Figure 1, to further enhance energy discrimination. In addition, since 2005, there are now intense short pulse lasers commercially available to match the desired short gating time…. for example, EKSPLA model PL2251C Nd:YAG laser, producing 100 mJ, 30 ps pulses at 10 Hz and 1.06 um wavelength[13]. With the addition of 1” amplifier rods, the beam energy can be boosted into the 1-5 Joule range, albeit for only one pulse per shot.

Of presently operating US tokamaks, DIII-D (major radius R_0= 1.67 m, I_p = 1.5 MA) can make the most runaways (up to ~700kA) in disruptions triggered by injecting high-speed argon impurity pellets[14, 15]. Assuming this is localized in a 10 cm x 10 cm poloidal cross section, then the current density of runaways in DIII-D would be $n_r \sim 10^{12}$ cm^{-3}. We choose a head-on collision geometry and forward scattering (collision angle α= 0° between the fast electron and incident photon, and scattering angle θ= 180° between the fast electron and the scattered photon), as depicted in Figure 2. On the DIII-D tokamak, an equatorial tangential access port would be ideal, both to inject the laser pulse, and also to mount the in-vacuum soft x-ray imager head. If we choose a 1-Joule short pulse (80 psec, 1.06 μm) Nd:YAG laser, then the light pulse has a corresponding 2.4 cm long packet inside the tokamak. By sampling the laser pulse at different times along the 3-meter long tangential flight path of the laser, with 2.4 cm resolution, we can obtain spatial profile information of the runaway current density in one-shot. By using different foils on the multi-strip, multi-frame soft x-ray detector placed at a small angle to the laser beam, we can sample different energies as the runaways develop during the disruption.

To determine the total number of scattered photons, we multiply the number of incident laser photons in the interaction volume, times the density of relativistic electrons in the same volume, times the usual Thomson scattering total cross section at (σ_{ts}= 6.65x10^{-25} cm^{-2}), times the interaction length L. For 1-Joule laser pulse (5.4x10^{18} photons), a 2.4 cm interaction length L, then $N_s = N_i n_r \sigma_{ts} L$, and the total number of scattered photons is N_s=8.6x10^6. But unlike conventional Thomson scattering, most of these will be forward directed into a half-angle of 1/γ, where for the case of 40 MeV electrons, γ= 80. This means a relatively small detector can collect a large fraction of the scattered light. We will use a 10 cm x10 cm soft x-ray sensor, located 2.3 meters from the interaction volume. The sensitive strips will be placed with offsets of 12-60 milliradians from the incoming laser beam entrance port, in vacuum, corresponding to 40 to 8 MeV energies, respectively. About 1/8 of the 1/γ subtended solid angle will be covered at the detector location, suggesting up to 1x10^6

signal photons will be incident on the detectors. The primary noise contribution will be from runaway electrons slowing down on the argon impurities (bremsstrahlung radiation). For a $Z_{eff} \sim 3$ post quench plasma (mostly due to argon), and 50 cm interaction lengths, we estimate ~$2x10^4$ noise photons into the 2-30 keV band on the detectors, for a S/N ratio of ~50:1. In the future, a rep-rated instrument could be made, in a sheet beam configuration, which would allow for following the motion of the runaway electron beam centroid.

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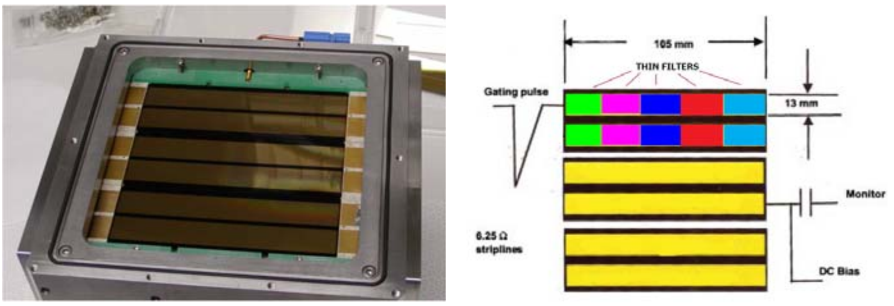

Fig. 1 The gated X-ray camera head with six gold photocathode strip lines, and a schematic with the first two strips having five representative x-ray filters of different materials and/or thicknesses.

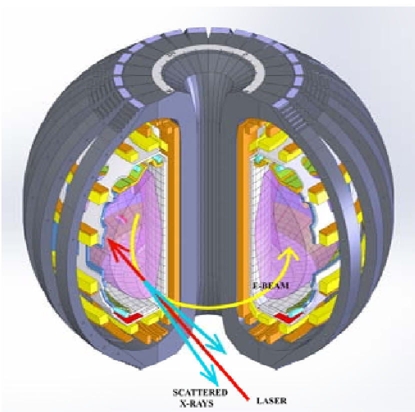

FIG. 2. Schematic head-on scattering geometry of laser beam (red), runaway electrons (yellow), and up-shifted x-ray photons (blue), in a cutaway of DIII-D.