Development Proposal for the CTF3 Probe Beam Laser

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The specification for the CTF3 probe beam was revised in September 1999, the earlier plan had been to re-use the existing CTF2 laser, possibly with the regenerative amplifier pump chamber replaced by a diode-pumped system for increased reliability. The electron bunch charge required was 1nC, only two bunches were foreseen, with variable spacing between them. This low charge would need 2 x 3uJ UV at the cathode, which the CTF2 regenerative amplifier could produce without the need of further amplification.

After some experience with CTF2 dual-beam acceleration tests, it became apparent that shorter bunches would have less energy spread and enable a better measurement precision. This could be achieved by a magnetic bunch compressor, or with shorter laser pulses on the photo-cathode. The cost of the magnetic bunch compressor would be between 50-100kCHF. The requirement of a 40-bunch mode of operation was also added, as was a tighter specification on the charge stability.

The charge density in the proposed short pulses is comparable to that generated in the CTF2 drive beam, where 10nC/8ps bunch is transported. The response time of the photo-cathodes is thought to be less than 2ps. No measurements have been made at these pulse lengths in RF guns, but pulse lengthening has not been observed with 8ps bunches. It is also known that photo-cathodes in low-current applications (streak cameras) have response times of <250fs.

- Energy stability down to 0.1% if possible
- Phase stability better than 1ps
- “Train mode” of 40+ bunches at 1.5GHz rate
- “2-pulse mode” intervals of n x 3GHz
- Bunch length between 500fs to 2ps for smaller energy spread
- 0.6nC / bunch, 0.3% cathode efficiency requires 2uJ UV/ bunch
- 20uJ IR / bunch, total ~800uJ IR

The Probe (Main) beam laser will be required to operate in 2003, so final testing before installation should be in late 2002. The CTF3 Drive beam laser will not be required before 2006.

Implications:

The short pulses cannot be directly generated from the existing Nd:YLF system, which is limited to 8ps. It is possible to shorten the pulses using an optical fiber to generate the extra bandwidth by self phase modulation, followed by a grating pulse compressor as in the CTF2 laser system. One disadvantage of this approach is that the pulse stretching in a fiber is a non-linear effect, dependent upon the pulse energy[i]. (Pulse stretching by gratings, as in the CTF2 laser, is a linear effect). Fluctuations in the input energy will lead to variations in the output pulse width and cause timing jitter. This is not a problem when all-optical measurements are made with the resulting pulse, but is a concern when timing stability is important.

A second difficulty is that when compressed, part of the energy will recombine into a “pedestal” pulse or “wings”. Only those spectral components of the stretched 8ps pulse which exactly match the negative dispersion of the grating system will be combined into the desired short pulse[ii].

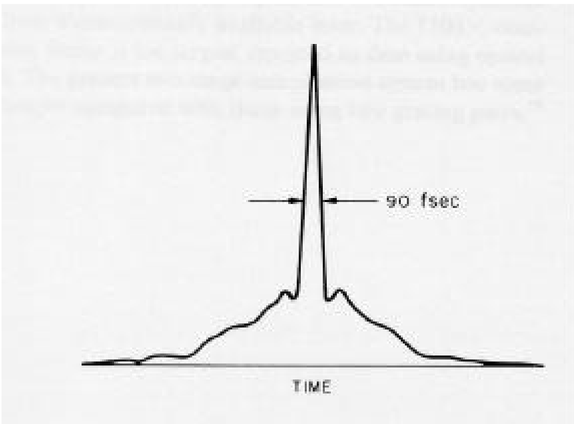

fig.1 autocorrelation trace of a fiber-stretched, grating compressed pulse. (from ref.ii)

The pulse compression is also limited by the energy that can be injected into the fiber without damage, the losses of the stretcher-compressor system result in output energy levels that could be too low to produce the levels of 4th harmonic energy needed for the CTF probe beam.

The choice then falls upon a different laser material, in order to directly generate the short pulses, there are several candidates, which fall into four groups: Titanium-Sapphire, Chromium-doped, Neodymium-doped and Ytterbium-doped materials.

Ti:Sapphire has a very short storage lifetime (2us), the input energy must come from another laser, generating light at 530nm. It would be possible to use parts of the CTF laser as the pump source, but this would be a project in itself. The major disadvantage of this material is the cost and complexity of implementation, it would require the purchase of a large quantity of optics due to its operating wavelength.

The Chromium-doped materials Cr:LiSGAF, Cr:LiSAF and Cr:MgO have very wide bandwidths between 750-1000nm, storage lifetimes of ~65us and all require optical pumping at 670nm, where they have a wide absorption band. The short storage lifetime requires a powerful pump source, which is not presently available, these materials are currently best suited to low power, femtosecond applications.

Ytterbium doped materials (YAG and Glass) have storage lifetimes of 1-2000us, wide absorption bandwidths and a low energy difference between the absorption and emission wavelengths, so there is little heating in the material. The cross-section is unfortunately low, so that disproportionately large pump powers are required to achieve a reasonable gain, this is coupled with an high fragility to thermal stress.

Neodymium doped glasses have greater bandwidths than the YAG and YLF host materials, but poor thermal properties. They are easily pumped by laser diodes as they have a large absorption band at ~805nm. The storage lifetime of Nd:Glass is 300us, indicating that a reasonable amount of energy can be stored for a modest pump power. In the low power application of the CTF3 probe beam laser, this is a reasonable choice.

Design goals

The proposed system of an oscillator and regenerative amplifier is not intended to become the CTF3 probe beam laser, but is a low-cost development tool which will serve to create feedback systems and pulse generating techniques which will be needed for the eventual probe and drive beam lasers. During the course of the development, we will increase our understanding of the difficulties associated with high frequency pulse train generation and amplification.

It should be possible within a short time to fully specify the CTF3 probe beam laser, which could then be produced commercially, in parallel with the continuing development of the fast switching, pulse selecting and stabilizing systems. The pump power level required for the CTF3 probe-beam laser is 80W, which would be pulsed Quasi-CW, which reduces the average power to 120mW at 5Hz operation.

The development system is not synchronized to an external signal, as this is not necessary for the projects that are to be studied. The addition of a piezo-controlled cavity mirror and phase-lock circuits could add this feature at any time.

There are several methods of train generation that can be evaluated with a simple, low power oscillator-amplifier system:

- A high-power (pulsed) oscillator with active modelocking (as in DESY)
- A Regenerative Amplifier with a cavity length of 5.66ns could be used to amplify 5 injected pulses, with three stages of splitting this would produce 40 pulses.
- The same amplifier with a partially reflecting mirror in the cavity could generate the five pulses by coupling energy between pulses, as has been observed in the CTF2 laser (satellite pulses).
- The principle of coupling energy between pulses could be used to fill a cavity with pulses at the required spacing of 667ps, these can then be progressively extracted by the output Pockels cell, to form the high-frequency pulse train directly.

The test-bed can also be used to study and develop the control and feedback systems that will be needed in all of the proposed CTF3/CLIC systems, such as:

- Fast pulse selection from a 1.5GHz train
- Energy stabilization in the pulse train by feed-forwards energy stabilizers
- Pre-programming the pump diode current
- Feedback to the drive current from the output UV (or electron bunch signal).

The conversion to the 4^{th} harmonic should also be studied. At low power levels it is necessary to focus the energy to a fine spot for best conversion efficiency, which is proportional to power density, but when a pulse train is converted the average heating effect could cause damage[iii]. Resonant enhancement cavities have also been used to improve the conversion efficiency[iv], but their operational stability when applied to a pulse train requires testing.

System Design

It is not intended to develop a new laser system, many research groups have successfully used a standard "x" configuration for the oscillator cavity. This design is well described in several published papers[v vi] and also forms the basis of a regenerative amplifier cavity, which with 4W of pump power, generated 45uJ pulses using Nd:Glass as the active material. The easiest oscillator system is a passively modelocked laser using a semiconductor saturable absorber[vii] (SESAM), which sets the pulse length, the repetition frequency being the cavity round trip time. Such lasers can be synchronized to an external signal with timing uncertainty (jitter) of less than 0.3ps. The SESAM devices are not currently commercially available, but thanks to excellent contact that exists between CERN, Time-Bandwidth products (Zurich) and the Institute of Quantum Electronics at ETHZ, a device can be made available for this study.

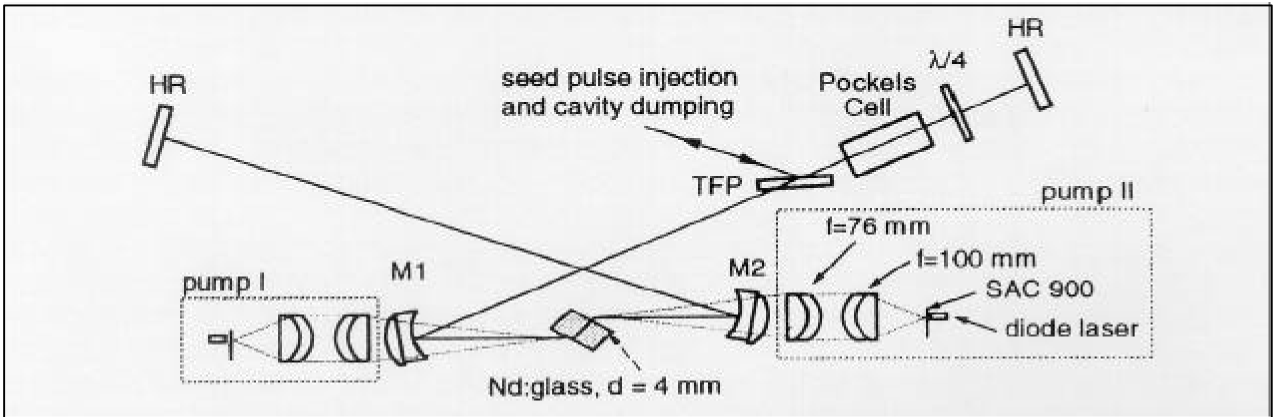

fig.1, Diode–pumped regenerative amplifier, from ref.iii, the same cavity configuration can be used for the oscillator.

Equipment

The operating wavelength for Nd:Glass is around 1061nm, a wavelength where many of our standard optics work, Pockels cells, harmonic conversion, waveplates and polarisors are all available.

The elements that must be purchased are:

15W fiber coupled CW pump source,	8kCHF
Sesam passive modelock device,	5kCHF
Nd:Glass elements,	3kCHF

The cost, including some special optics and fast Pockels cell drivers, would be about 20kCHF.

Plan of work

In order to extract the maximum benefit from this investment, the work plan would probably follow this general pattern;

High frequency oscillator, 500MHz
-fast pulse selector operation/development
-pump control to stabilise/modulate output

Lower frequency cavity, 100Mhz
-high order mode operation

Regenerative amplifier, with 100MHz osc.
-single pulse operation
-low-power harmonic generation, single pass
-harm.gen. resonant enhancement cavity tests
-multiple pulse amplification
-multiple pulse generation in RA cavity
-pulse splitting by RA Pockels cell control
-increase output energy by addition of telescope in cavity

A commercial laser company could then manufacture the Probe beam laser. This is preferred for reasons of reliability and integration, elements such as the phase-locking to an external source, piezo-controlled mirrors, Peltier-effect temperature controllers require careful mechanical assembly if the final laser is to perform reliably.

When the probe-beam laser studies have been completed, the diode pump source can be used in studies of other Neodymium laser materials, as they all have absorption bands at about 805nm. With only minor modifications it would be possible to re-use the cavity, pump source and feedback systems to produce a pulse train based on Nd:YLF, YVO or YAG, for drive beam amplifier studies. The drive beam amplifier studies will require a powerful and efficient pump chamber, of the type that will be constructed by E.Bente (Institute of Photonics, Strathclyde) in the study of high power lasers. It may be possible to arrange the construction of two units, one of which could be used at CERN for pulse train amplification tests. This represents a greater investment, which should be carefully studied.

References;

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