# An Ideal Thyratron-Less Repetitive TE- Laser Pulser

#### Dhruba Jyoti Biswas

Laser and Plasma Technology Division Bhabha Atomic Research Centre

### Abstract

Laser and Plasma Technology Division has developed a thyratron-less, repetitive, transverselyexcited (TE) laser pulser that has complete latch proof operation capability with D-C resonant charging. Thyratrons, a crucial component of the LIS programme of the DAE, are not manufactured in India and embargo applies to their sale. The heart of this novel TE laser pulser is a rotating dielectric spark gap, which has been conceived, developed, and operated in our laboratory. Its unique geometry has been fully exploited to obtain diode-less operation of the pulser and also to drive two high repetition rate TE lasers either simultaneously or with a variable delay.

# Introduction

The TE laser pulser performs the crucial job of subjecting the gaseous medium to a transverse electric discharge leading to the inversion of population. The function of a pulser in the operation of a pulsed gas laser begins with the drawing of energy from the source and ends with the realisation of most of this as the internal energy of the (lasing) Undoubtedly therefore, the overall gas. efficiency of the laser depends guite strongly on the performance of the pulser. In the operation of pulsed gas lasers, energy is initially stored in a condenser, which is then made to discharge rapidly into the laser load with the help of a fast high voltage high current switch. The performance of the pulser during the charging process thus dictates the wall plug efficiency of the laser. Lesser the energy expended by the pulser while drawing energy from the source, the better the efficiency of the laser.

A typical pulse generator for a TE laser is shown in Fig 1. A DC high voltage supply charges up a condenser through a charging element, normally a resistance or an inductance. The charging bypass provides a path for the charging current. Once the



Fig.1 : Typical pulse generator for a TE gas laser

condenser is charged to the required voltage. the rapid closure of the high voltage and high current switch enables the condenser to deliver its stored energy into the laser load before glow to arc transition can occur. The charging bypass must offer an impedance that is many times more than that of the laser load lest this should eat up a significant fraction of the energy stored in the condenser lowering, thereby, the plug in efficiency of the laser. At the same time its impedance should be much less than that of the charging element so that the current flowing through the conducting switch from the source following a discharge can be kept low for a given repetition rate. In the single shot operation, the condenser is normally

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charged resistively and a spark gap is traditionally used as a switch. For repetitive operation, however, more efficient charging by means of inductance is employed and a thyratron replaces the spark gap. Following a discharge when the switch is still in a state of conduction, all the charging current delivered by the power supply gets diverted through this conducting switch. This current must be kept lower than the hold over current of the switch to ensure its recovery. Low charging current limits the maximum achievable repetition rate from the pulser. An ideal pulser would be one that allows recovery of the switch however high the charging current, and in turn repetition rate, is. We have conceived, developed, and operated in our laboratory a so-called 'ideal TE gas laser pulser' the repetitive operation of which is not hindered by the recovery problem of the switch. It is imperative that an account of this work here follows a brief review of the D-C resonant charging scheme on which a conventional repetitive TE gas laser pulser is normally based. Interested readers are referred to a review article [1] for a deeper insight to the various aspects of charging and discharging processes of a TElaser pulser.

# Direct - Current (D-C) Resonant Charging

The main condenser can be charged to the required voltage, ranging within tens of kV depending on the type of the TE laser load, normally in two different ways: resistively or resonantly by a DC source although resonant charging of a condenser by an AC source is also not uncommon. Resistive charging not only suffers from poor charging efficiency but also offers low charging frequency as the recovery problem of the switch assumes greater significance here [1]. The charging of the condenser through an inductance. commonly known as D-C resonant charging. finds wide application in the repetitive operation of TE gas lasers because of its inherent high plug-in efficiency [2] and high repetition rate capability [3].



Fig. 2 : a) Typical D-C resonant charging network b) The charging current (i), the voltage across the capacitor (V<sub>c</sub>), and the voltage across the inductance (V<sub>u</sub>) as a function of time (t).

The Kirchoff's loop equations in a typical D-C resonant charging circuit (as shown in Fig 2a), considering an ideal case where there is no resistance in the charging loop and a D-C source  $(V_s)$  charges the capacitance C through an inductance L, can be written as follows:

$$V_{S} - L(di/dt) - (q/C) = 0$$
 (1)

Substituting i = (dq/dt), we obtain

$$(d^2q/dt^2) + q/(LC) - V_S/L = 0$$
 (2)

The solution of the above equation can be shown to be

$$q = V_S C (1 - \cos(\omega t))$$
(3)

where  $\omega$ , the resonant frequency of the circuit, is given by

$$\omega = 1/(\sqrt{LC}) \tag{4}$$

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The expressions for current (i) and voltages across the condenser (V<sub>C</sub>) and the inductance (V<sub>L</sub>) can be worked out to be,

 $i = dq/dt = V_s C \omega sin(\omega t)$  (5)

 $V_{C} = V_{S} (1 - \cos(\omega t)) \tag{6}$ 

$$V_L = V_S \cos(\omega t)$$



Fig. 3 a) Typical resonantly charged TE laser pulser b) The charging current and voltage across the condenser in the above figure

The current and the voltages represented by the above equations are illustrated in Fig 2b. Understandably, the sum of voltages across the inductance and the condenser at any instant equals the supply voltage Vs. It can be seen from this figure that during a half cycle when the charging current is in the forward direction, the condenser acquires a voltage twice that of the supply. During the next half cycle, the current flows in the reverse direction and the condenser loses all its charge. If, however, a diode were introduced in the circuit (Fig 3a) to arrest the flow of reverse current the condenser would then retain its voltage. This figure also shows the discharge path of the condenser that includes the switch and the load. As the

switch closes, condenser discharges through it into the load and the voltage across it drops to zero. The current flows in the forward direction once again and the condenser acquires twice the supply voltage and so on (Fig 3b).



- Fig. 4 : Few charging and discharging waveforms and the charging current (i) in a resonantly charged pulser
  - (a) Operation at 100% duty cycle
  - (b) Operation at a lower duty cycle, the droop in the voltage across the condenser is apparent here.

The time required for the condenser to get charged to  $2V_5$  is  $\pi \sqrt{(LC)}$ , half the period of oscillation. Thus at 100% duty cycle, i.e., the condenser discharges as soon as its acquired voltage is 2Vs, the repetition rate is double the resonant frequency of the D-C resonant charging network (Fig.4a). If, however, the network is operated at a lower duty cycle, i.e., the condenser discharges long after acquiring the peak voltage, the voltage across it would then droop (Fig 4b). This is because current, though small, may flow for longer duration through the voltage measuring circuitry. The voltage may also fall due to the flow of minority current in the reverse biased diode. This effect would assume significance in the operation at a very low duty cycle.

Immediately following a discharge, as the switch is still in the state of conduction, the power supply makes a short through it (Fig5a). However, unlike in the case of R-C charging, where the peak charging current

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(7)

(/=V<sub>s</sub>/R) appears immediately after the discharge, the charging current here builds up from zero value and can be expressed by the following equation:

$$\Delta I(t) = V_S \times \Delta t / L$$
(8)



Fig. 5 : a) The power supply making a short through the conducting switch

b) Short circuit current as a function of time for two different values of charging inductance L.

The build up of the short circuit current (shown in the Fig 5b for two values of charging inductance) should be such that it does not exceed the hold over current of the switch until it's complete recovery. Higher the inductance, slower the rise of the current and better is the chance of the recovery of the switch although at the expense of the maximum achievable repetition rate,  $f_{max}$ , which is given by

$$f_{\rm max} = 1/[2\pi \sqrt{(LC)}]$$
 (9)

As is seen from eqn.5, the same recovery condition of the switch can also be met for smaller values of  $V_5$ . However,  $V_5$  is fixed from the consideration of the laser load and

cannot be utilised to control rise of the short circuit current. Thus for a particular load and a given switch, the value of L needs to be appropriately fixed to ensure recovery of the switch.

The efficiency (η) of resonant charging is given by the following expression [3].

$$\eta = 1 - \pi / (4Q),$$
 (10)

where the Quality factor Q is defined as

$$Q = 2\pi f_{max} L/R.$$
 (11)

R being the total ohmic component of the charging loop impedance and L the charging inductance. If R/(fmaxL)<<1, the condition generally met while designing a resonant pulser, the charging efficiency approaches 100%. Thus almost the entire energy drawn from the source is deposited into the laser load contributing to the increased plug in efficiency compared to the case of resistive charging. As the condenser is charged to twice the supply voltage, the requirement of voltage from the source is lowered by a factor of half. The charging current arrives at a low rate starting from a zero value if the operating conditions are chosen properly. This helps in the recovery of the switch that, in turn, allows high pulse repetition frequency (prf).

This scheme too suffers from few shortcomings. If the prf is considerably lower than the resonant frequency of the network, i.e., the pulser is operated at a low duty cycle, discharge voltage may droop the considerably. Secondly, the value of L cannot be made arbitrarily small as then the rapid build up of the short circuit current would prevent the conducting switch to go into the off state following a discharge. This effect, which limits the maximum achievable repetition rate, has been the subject of investigation in a number of studies [4,5] aimed at enhancing the repetition rate capability of a resonant charging network. The central point of these studies is to isolate the power supply during a discharge so that flow of short circuit current through the conducting switch is prevented. The most

effective means of controlling the rise of short circuit current without jeopardising the repetition rate capability of the pulser network is to introduce a second switch in the charging loop, [6-8] commonly known as command resonant charging

#### Command Resonant Charging:

Schematic diagram of a pulser based on command resonant charging is as shown in Fig 6. As is seen, a second switch S<sub>2</sub> is now introduced in the charging loop. The operation of the circuit can be explained as follows. When a trigger pulse T<sub>2</sub> arrives in



Fig. 6 : Typical command resonant charged TE laser pulser network

the charging switch S<sub>2</sub>, it closes and the condenser C gets charged. As the charging this switch current becomes zero. automatically turns off isolating the power supply from the rest of the circuit. At this point, a second trigger T1 arrives at the discharge switch S1, which then closes enabling the condenser to discharge through it into the load. During and following a discharge, the switch S2, which is in the off state, forbids the flow of any short circuit current enabling St to recover within its deionisation time. Thus in this mode of operation, maximum achievable repetition rate is not limited by the switch latch up problem. Simply lowering the value of L can reduce charge-up time of the condenser. Few charging and discharging waveforms in this mode of operation are shown in Fig 7. As the condenser is charged on command here, this network can be operated at any duty cycle with almost no voltage droop. The condenser can be made to charge just before it has to be discharged. This increases the life of both the discharge switch as well as the storage capacitor as the hold off voltage



Fig. 7 : The charging current (i) and few charging and discharging waveforms in a command resonant charged pulser network

appears across them briefly. The droop free operation of this pulser has been illustrated in Fig 8 for a duty cycle of 10%. The resonant frequency shown here is 1kHz while the operating frequency is 100 Hz. 8 ms after a discharge the trigger arrives in S<sub>2</sub> allowing the condenser to be fully charged within 1 ms. The condenser holds the charge for 1 ms when the second trigger arrives in S<sub>1</sub> causing it to discharge into the load. The voltage droop in a similar operation with conventional resonant charging network can be seen in Fig 4b.



Fig. 8 : Droop free operation in a command charged pulser network at a low duty cycle operation

This method of charging too, however, is not devoid of disadvantages. Firstly, both the anode and the cathode of the charging switch have to be maintained at high voltages. High voltage isolation transformer is therefore required for the filaments. Much art is also needed in the design of the grid and bias circuits. False triggering of the charging switch also cannot be ruled out which can be caused by the electromagnetic

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noise associated with the high voltage high current discharge pulse initiated by the closure of the discharge switch. This would mean that both the switches are simultaneously in conduction once again bringing in the switch latch up problem with a much graver consequence as the value of charging inductance is kept low to make the command resonant charging high repetition rate compatible.

# An Ideal Repetitive TE Laser Pulser

We have seen that short circuit proof operation of a pulser based even on a command resonant charging network cannot be guaranteed. This makes the switches. normally two thyratrons, vulnerable to damage. Thyratrons are expensive, have limited life, and embargo applies to their sale in India. Against this background we have conceived. designed, developed, and operated a novel, inexpensive, and simple switch that as a driver of a resonantly charged TE laser pulser offers complete latch proof operation. By exploiting the unique geometry of this device we have achieved a number of advantages that even a command resonant charged pulser cannot match [9-14]. The heart of this device is a suitably configured circular dielectric plate that rotates between the electrodes of an ordinary Such spark dap. rotation intrinsically isolates the power supply from the rest of the circuit during a discharge and, as explained below, is instrumental in making a TE-laser pulser driven by this switch a near ideal one.

### Rotating Dielectric Spark Gap:

The rotating disc, the most important part of this switch, is shown in Fig 9. The disc is a circular plate of ~20 cm diameter with even number of equidistant holes (~6mm diameter) drilled along a circle close to its periphery. By mounting the disc on a motor, it can be so rotated that the holes pass symmetrically between the electrodes of the spark gap. The operation of this switch can be easily understood by considering a



Fig. 9 : Schematic diagram of a rotating dielectric disc



Fig. 10 : Resistively charged pulser network driven by a rotating dielectric spark gap

resistively charged pulser as shown in Fig 10 Within the travel time between two adjacent holes the condenser C gets charged close to the supply voltage Vs, which is more than the air breakdown voltage of the spark gap. Every time a hole appears between the electrodes of the spark gap, it closes allowing the condenser to discharge into the load. Following a discharge, the appearance of the dielectric between the electrodes truncates the flow of any charging current through the switch causing thereby its forced recovery. The charging current thus can assume very high value reducing thereby the charging time of the condenser. If the rotation speed of the dielectric plate is made compatible with the charge up time of the condenser, the repetition rate would then be accordingly enhanced. In contrast, the repetitive operation capability of a

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conventional spark gap when used with this pulser is restricted, as the charging current has to be less than the holdover current of the switch. In the operation with rotating dielectric spark gap as the switch, ~2kW of power was dissipated into a dummy load at a repetition rate of 300Hz [9]. The fins on the dielectric disc, when rotated, blow air jet into the spark gap and facilitate, thereby, such high repetition rate operation of the switch.



Fig. 11: Schematic diagram of the rotating dielectric spark gap driven resistively charged pulser along with optical sensor based triggering circuity: 1 Rotating dielectric disc. 2. Fins, 3. Motor, 4. Triggerable spark gap, 5. Trigger, 6. Load, 7. Pulse transformer, 8. Opto electronic sensor, 9. Current amplifier, 10. SCR.

In the un-triggered mode of operation, the large jitter associated with the fluctuation of the breakdown voltage marred the performance of the pulser. The triggering of the switch was accomplished by mounting a light emitting diode and a photo detector face to face on either side of the rotating dielectric in such a way that whenever a hole passed between them another hole also passed between the electrodes of the spark gap (Fig 11). At every such coincidence, the detector received light from the emitter and gave out a pulse, which after processing was used to trigger the spark gap. In the triggered mode of operation the jitter significantly reduced to ~ 25 nsec [10].

As demonstrated in ref 11, a rotating dielectric spark gap also has latch proof operation capability when used with resonantly charged pulsers. However, such an operation is not possible utilising a simple circuit as of Fig 10 where the charging resistance is replaced by an inductance. This is because following a discharge the short circuit current (i) can build up during the travel time of the hole (t) between the electrodes of the conducting switch. For a TE laser load, this current and hence the energy stored in the charging inductor can be appreciable [11]. As the flow of this current is intercepted by the moving dielectric, the inductor releases the stored energy causing the dielectric plate to ignite. The energy stored can be reduced by increasing the value of L (as E =  $Y_2$  ( $\mu^2$ ) =  $(V_s^2 t^2)/(2L)$ , from eqn 6). This, however, is not a practical solution as it would be at the expense of the achievable repetition rate.



Fig. 12 : Short circuit proof operation of the resonantly charged pulser when driven by a rotating dielectric spark gap

An elegant solution to this problem is to incorporate a second spark gap in the charging loop and rotate the same dielectric plate between the electrodes of both the spark gaps in such a way that holes appear in them exactly out of phase (Fig 12). The operation of this circuit can be explained in the following manner. When a hole gets aligned with the charging spark gap SG3, it closes allowing the condenser to be charged to  $2V_s$  in a time ( $\pi\sqrt{(LC)}$  which is made smaller than the travel time of the hole inside the gap by proper choice of L. After the passage of the hole, the appearance of the dielectric in the gap of this switch virtually cuts off the power supply from the rest of the circuit. A hole now appears between the electrodes of the discharge spark gap (SG1) when it closes allowing the condenser to discharge into the load. During

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and immediately following the discharge, which is normally very short lived for a TE laser load, the open switch SG\_ prevents any short circuit current from flowing through SG<sub>1</sub>. The discharge switch thus readily recovers, as the inductor now does not store any energy during its conduction. The condenser would get charged once again when a second hole gets aligned with SG<sub>2</sub> and so on. In this mode of operation the pulser delivered ~3.2kW of power at a repetition rate of 200 Hz into a dummy load which resembled a typical TEA Co<sub>2</sub> laser.



Fig. 13 : Few charging and discharging waveforms of the short circuit proof operation of the resonantly charged pulser shown in Fig. 18. The inset shows the charging of the condenser in an expanded time scale.

Few charging and discharging waveforms shown in Fig 13 conform to the above description. The jitter in the operation of both SG1 and SG2 is apparent from this figure. When this pulser is used to drive a laser, the fluctuation in the closing of charging switch can be ignored, as it does not affect the performance of the laser. Therefore triggering of the discharge switch alone suffices which is accomplished using the optical sensor based mechanism described in ref 9. Proper positioning of the holes with respect to the spark gaps such that the condenser discharges soon after acquiring the peak voltage ensures droop free operation with this device.

The rotating dielectric spark gap switch can also drive simultaneously two high repetition rate lasers [12]. The two lasers can be operated synchronously or with a delay that can be as large as a millisecond. Schematic diagram of the circuit is shown in Fig 14. The



Fig. 14 : Rotating dielectric spark gap as a driver of two resistively charged high repetition rate lasers. Inset shows the positions of the holes with respect to the discharge gap SG<sub>1</sub> and SG<sub>2</sub>

same dielectric is rotated between the electrodes of SG1 and SG2 in such a way that holes appear in them simultaneously. SG1 triggered by the optical sensor based technique, causes the condenser C1 charged to the supply voltage to discharge into the load R<sub>1</sub> while a pulse derived from this first pulser triggers SG<sub>2</sub> causing C<sub>2</sub> to discharge into the load R2. A delay up to few microseconds between the two discharges has been obtained by varying the value of I. The diodes D1 and D2 are required to isolate the two discharge circuits. A larger delay, ranging from several microseconds to more than a millisecond, has also been obtained by positioning SG1 and SG2 with respect to the dielectric such that when a hole arrives in SG1, another hole is yet to arrive in SG2. The time interval between the arrivals of the two holes between the electrodes of their respective spark gaps is the delay between the two discharges. Triggering both SG1 and SG<sub>2</sub> has considerably reduced the jitter in such operation. The voltage enhanced pulse from the optical sensor triggers SG1 directly and SG<sub>2</sub> after being delayed by a delay generator. The performance of this device has been tested by switching a total of 2.5 kW of power at 200Hz into two identical dummy loads resembling a typical TE laser in terms of resistance. Though resistive charging has been employed in this operation, resonant charging can be used for better efficiency. We note here that this technique can be, in principle, employed for synchronisation of more than two lasers.

The unique geometry of the rotating dielectric spark gap also allows diode-less operation of a command resonant charging network [13]. In a conventional switch, thyratron, spark gap or SCR driven resonant charging pulser, the presence of diode is mandatory to arrest the flow of reverse current so as to maintain the voltage on the condenser (refer to Fig 3a). These diodes, which should be capable of withstanding high voltages and high currents, when form a part of the pulsers meant for repetitive operation of typical TE lasers are expensive and prone to damage, more so in the event of a short circuit. The principle of diode less operation can be understood by referring to Fig 15.



Fig. 15 : Diode-less operation of a resonantly charged pulser network driven by a RDSG

SG1 and SG2 are so located that when the dielectric rotates, holes appear in them exactly out of phase. As a hole gets aligned with SG<sub>2</sub> it closes allowing the condenser to get charged through L. If the time of passage of the hole between the electrodes of SG2 exactly equals the time taken by the condenser to get charged fully  $(=\pi\sqrt{LC})$  the appearance of the moving dielectric in the gap thereafter forces the switch to go into the off state preventing the flow of any reverse current thus rendering the usage of a diode superfluous. As a second hole gets aligned with SG1 it closes and the condenser discharges into the load. A pulser has been operated in this mode at a repetition rate of 600 Hz with a dummy load resembling a typical TE laser. Few charging and discharging waveforms at this repetition rate are shown in Fig 16. It would be seen that the voltage of the condenser has dropped to about 90% of its initial value at the time of a discharge. This indicates that some reverse current had flown through SG<sub>2</sub> before the moving dielectric appeared between its electrodes and blocked it. Such a situation can be overcome by adjusting the charge up time of the condenser by making use of a variable choke or alternately by adjusting the rotation speed of the motor.



Fig. 16 : Few charging and discharging waveforms for the diode-less pulser

The geometry of this switch allows an easy scalability of the maximum achievable repetition rate. The repetition rate (f) in Hz here can be written as

$$f = n \times s$$
 (12)

where n is the number of holes on the disc and s is the number of rotations per second. Increasing n or s or both, therefore, can increase the repetition rate, however, up to a certain limit. If holes are too close the device no longer remains compatible with resonant charging. On the other hand, the speed of rotation increases at the expense of the mechanical stability of the device. Further increase in the repetition rate is possible by increasing the number of discharge gaps [14]. The schematic diagram of the circuit where a repetition rate of 1.2 kHz has been achieved with a rotating dielectric switch utilising two pairs of discharge gaps SG2 and SG3 is shown in Fig 17. Reliable short circuit proof operation was



Fig. 17 : Schematic diagram of the pulser used to obtain KHz repetition rate with rotating dielectric spark gap. The inset shows the staggered configuration of the holes

achieved with resonant charging by staggering the holes into an inner and an outer circle. The outer holes were aligned with the charging gap (SG1) while the inner holes were aligned with the discharge gaps. The condensers C1 and C2 get charged whenever SG1 conducts and C1 discharges through SG<sub>2</sub> and C<sub>2</sub> through SG<sub>3</sub> with a delay determined by the location of SG2 and SG3 with respect to the passing holes. Diodes D<sub>1</sub>and D<sub>2</sub> prevent the condensers from discharging through the same gap.

# Conclusions

We have shown that the repetition rate operation capability of an ordinary spark gap can be greatly enhanced simply by rotating a suitably configured dielectric plate between its electrodes. Such a rotating dielectric spark gap has been shown to provide complete latch proof operation of a repetitive TE laser pulser with D-C resonant charging. This is indeed an achievement because complete short circuit proof operation cannot be guaranteed even with the popular method of command resonant charging. Further in this operation a rotating dielectric spark gap replaces two (expensive) thyratrons mandatory for command resonant charging. The unique geometry of this switch has been exploited to use it as a driver of i) a diode less resonantly charged pulser, ii) more than one high repetition rate lasers synchronously or with desired delay and iii) of a repetitive pulser in the KHz range.

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Dr Dhruba J. Biswas was conferred the Homi Bhabha Science & Technology Award for the year 2000 for his outstanding contributions in laser technology and related fields.

#### About the author ...



Dr Dhruba J. Biswas received his M.Sc (physics) degree from I.I.T. Kharagpur in 1978 and joined the erstwhile MDRS, BARC in 1979 after graduating from the 22<sup>nd</sup> Training School batch. His experimental work on optical chaos fetched him the doctorate degree from the Heriot-Watt University, Edinburgh, in 1986 where he was on a two-year sabbatical. His current research interest includes physics and technology of mid-infrared gas lasers including optically pumped molecular lasers and laser induced physical processes. He has to his credit 64 scientific papers, including 5 review papers, in refereed international physical journals. He is a recognised Ph.D (physics) guide of Mumbal University. He is recipient of the INSA young scientist medal (Physics, 1987), A. K. Bose Memorial award of INSA

(Physical Science, 1989), N. S. Satyamurthy Memorial Award of IPA (1991), and Associate-ship of International Centre for Theoretical Physics, Italy (1994-2001).