INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

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TRAINING COLLEGE ON PHYSICS AND CHARACTERIZATION OF LASERS AND OPTICAL FIBRES

(5 February - 2 March 1990)

EXCIMER LASERS

T. Letardi

ENEA
Centro Ricerche Energia
Roma, Frascati 00044
Italy

EXCIMER LASERS

T.LETARDI

ENEA - TIB - CRE FRASCATI

1 - INTRODUCTION - Definitions - Properties of short wavelength radiation

2 - GENERAL INFORMATIONS - Excimers as efficient u.v. laser active media - General properties of Rare Gas Halides (emission w.l., stimulated emission cross section etch) - Composition of lasing media

3 - PUMPING SCHEMES - Electron beams, RF, self-sustained discharge - Excimer formation reactions and efficeincies

4 - TECHNOLOGIES OF RGH LASERS WITH SELF-SUSTAINED DISCHARGE - General structure of the systems - Materials - Preionization sources: u.v. and X-rays - The discharge circuit - Electrodes design - Switches for the discharge: spark-gaps, thyratrons, saturable inductors - Recirculation systems and related requirements - Gas purification systems

5 - CHARACTERISTICS OF THE ACTIVE MEDIUM - Discharge instabilities - Gain and absorption - Saturation intensity - Simulation codes

6 - EXTRACTION OF THE ENERGY - Limits on the maximum extraction efficiency - configuration of the optical cavities

7 - STATUS OF COMMERCIAL SYSTEMS - Energy. power, beam divergence etch of commercially available excimer sources

8 - SPECIAL TECHNIQUES FOR EXCIMER LASERS - Low divergence beams - Narrow-bandwidth beams - Ultrashort pulses and very long pulses

9 - TECHNIQUES FOR THE MEASUREMENTS OF SOME LASER PARAMETERS - Smal signal gain and absorption - Measurements of electron density evolution during the discharge

APPLICATIONS

SHORT WAVELENGTH

IMPROVED ABSORPTION

IMPROVED FOCUSSABILITY

MATERIAL PROCESSING

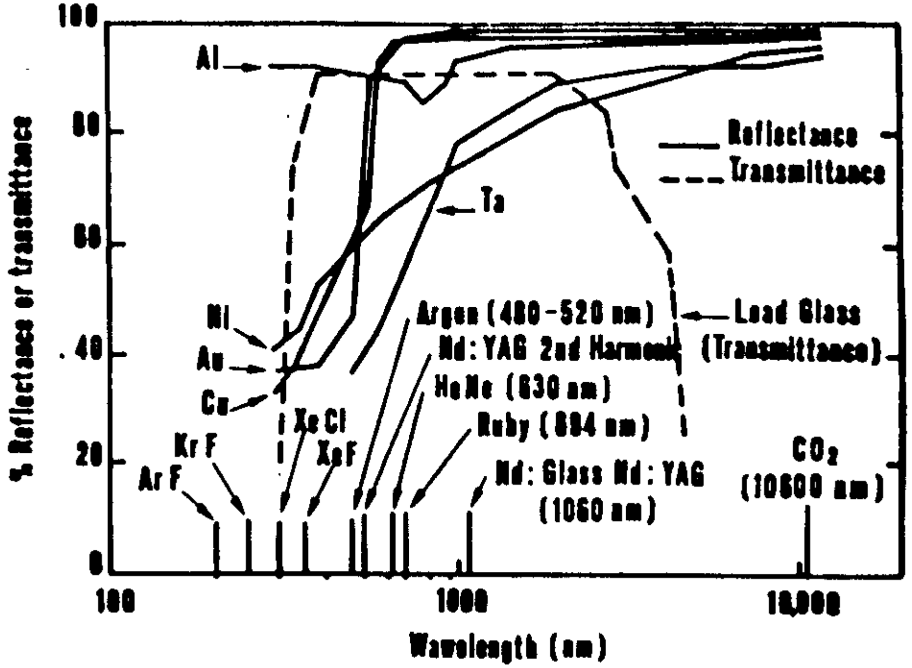
CERAMIC,GLASS	Large area ablation Patterning, drilling Welding, marking
POLYMERS	Ablation Patterning Marking
SEMICONDUCTORS	Photolytography Ablation,deposition annealing Doping, mask repair, mask production
METALS	Cutting, welding,drilling, surface treatments, surface coating
COMPOSITE MATERIALS	Ablation Patternig

WHY UV LASERS ARE IMPORTANT (COMPARED TO VIS OR IR)

BECAUSE FOR UV RADIATION:

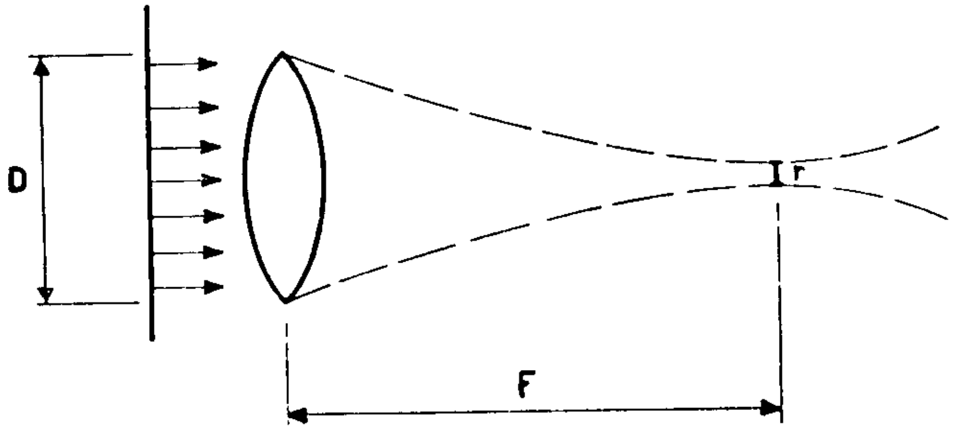
1 - The absorption of materials increases
2 - Decreases the minimum divergence of the beam
=> decreases the minimum cross section
=>increases the resolution in material processing
=>increases the power density, at a given beam power
3 - The ablative mechanisms for material removal change from thermal to non thermal (Photoablative processes - direct break of chemical bonds -lo
temperature increase of non removed materials)

4 - The laser radiation can travel in silica fibers (important for medical applications)



Room temperature reflectance (or transmittance) versus wavelength for the materials shown.

Reflectance $\propto \lambda$



$$\theta_{min} \cong \frac{\lambda}{D\pi}$$

$$r_{min} \cong \frac{F\lambda}{D\pi}$$

fasci gaussiani TEM00

Per TEM_{pq} $\quad r = \frac{F\lambda}{D\pi}(2p+q+1)$

⇒ necessità di selezionare il TEM_{00} per avere la massima focalizzabilità dati F e λ

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HIGH PHOTON ENERGY
HIGHER PHOTOCHEMICAL ACTIVITY

Laser induced synthesis reactions
Polymerization processes
Laser induced production of pharmacetical vitamines
Photochemical purification purification of SiH_4
Photochemical destruction dioxine, pestizides

-X-RAY GENERATION

-INERTIAL CONFINEMENT FUSION

EXCIMER = EXCITED DIMERS : BIATOMIC MOLECULES WHICH ARE:

-BOUND ONLY IN THE EXCITED ELECTRONIC STATES
-UNBOUND, OR WEAKLY BOUND, IN THE GROUND STATE
-DECAY WITH LIFETIMES OF THE ORDER OF TENS OF NANOSEC

THESE MOLECULES DECAY EMITTING ONE PHOTON WITH ENERGY OF FEW eV THAT IS WITH WAVELENGTH RANGING BETWEEN VISIBLE AND VUV

THESE CHARACTERISTICS ARE EXTREMELY INTERESTING WHEN EXCIMERS ARE USED AS ACTIVE MEDIA FOR UV LASERS

The most promising excimer lasers

- Rare gas dimers: Ar_2^*, Kr_2^*, Xe_2^*

  First to be discovered as active media

  Wavelength emission range: vacuum ultraviolet

- Mercury halides: HgCl, HgBr, HgI

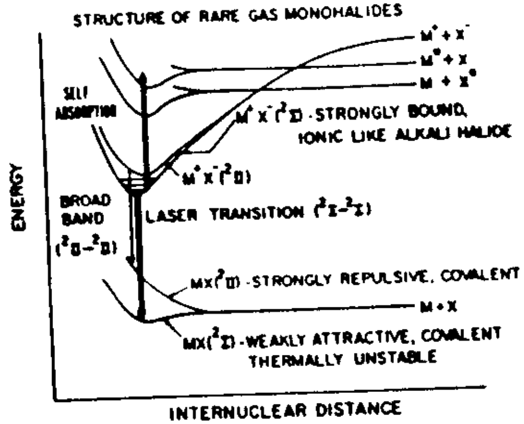
  Efficient sources of blue-green light

  W.e.r.: visible

- Rare gas halides: KrF^*, XeF^*, $XeCl^*$, ArF^*, $KrCl^*$, $XeBr^*$

  The most studied and carried out excimer lasers.

  W.e.r.: near ultraviolet



GROUND STATE SPLITTED IN TWO STATES A – X

EXCITED STATE SPLITTED IN TWO STATES C – B

LASING ACTION USUALLY B-->X BUT POSSIBLE ALSO C-->A (BROADBAND)

EXCITED STATE BY NEUTRAL CHANNEL IS UNSTABLE: WHEN LOWER THAN IONIC CHANNEL, NO LASING ACTION

ENERGY CHANNELED IN THE UPPER LASER LEVEL/ENERGY DEPOSITED IN THE PLASMA = FORMATION EFFICIENCY

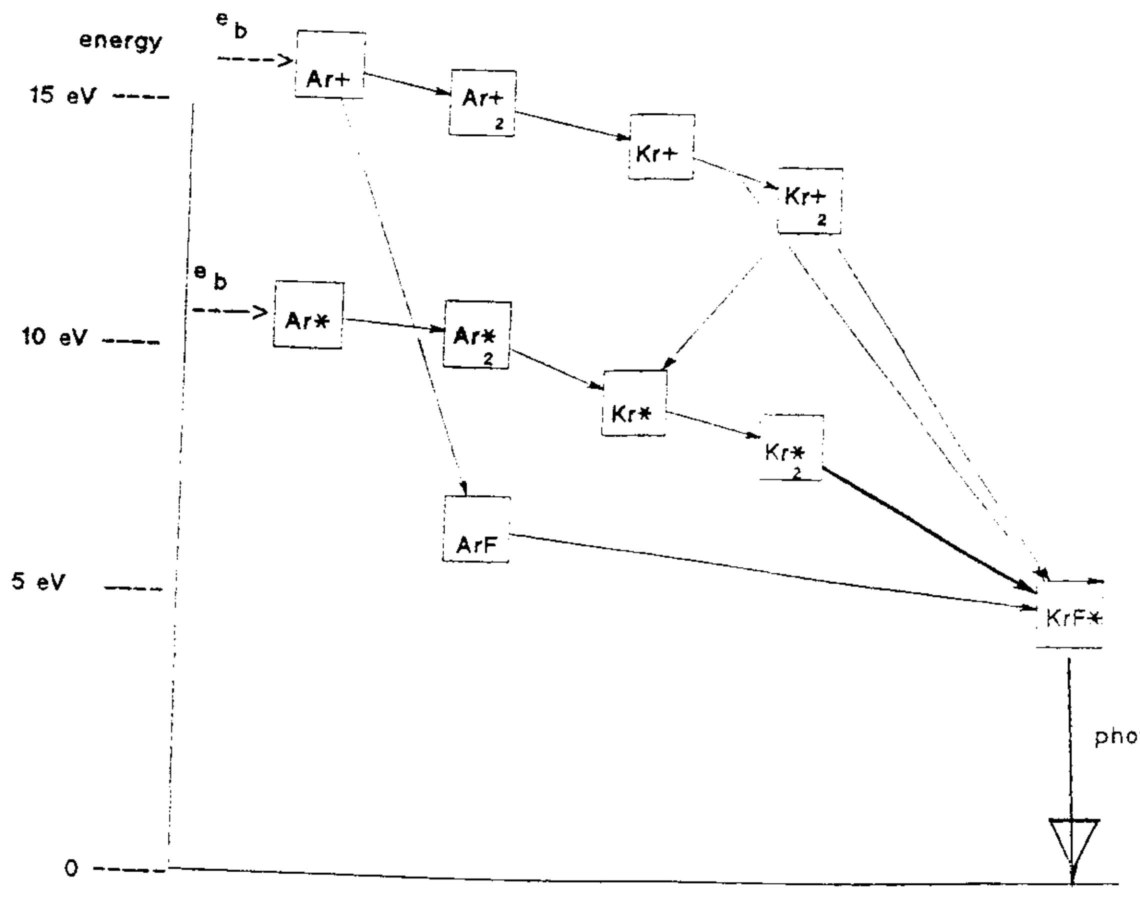
IT IS VERY HIGH : FOR KrF 40% – THIS DEPENDS FROM THE FACT THAT ESSENTIALLY THE UPPER LASER LEVEL IS ENERGETICALLY THE LOWEST ELECTRONICALLY EXCITATED STATE IN THE SYSTEM

THE EXCIMER IS FORMED ESSENTIALLY THROUGH A IONIC CAHNNEL OR THROUGH A NEUTRAL CHANNEL

IONIC CHANNEL $Kr^{+} + F^{-} + A \Longrightarrow KrF(B,v) + A$

NEUTRAL CHANNEL $Kr^{*} + F_2 \Longrightarrow KrF(B,v) + F$

HIGH PRESSURE OF THE GAS IS REQUIRED BECAUSE THE EFFICIENT IONIC CHANNEL MUST COMPETEWITH THE ION-ION RECOMBINATION $Kr^{+} + F^{-} \Rightarrow Kr + F$



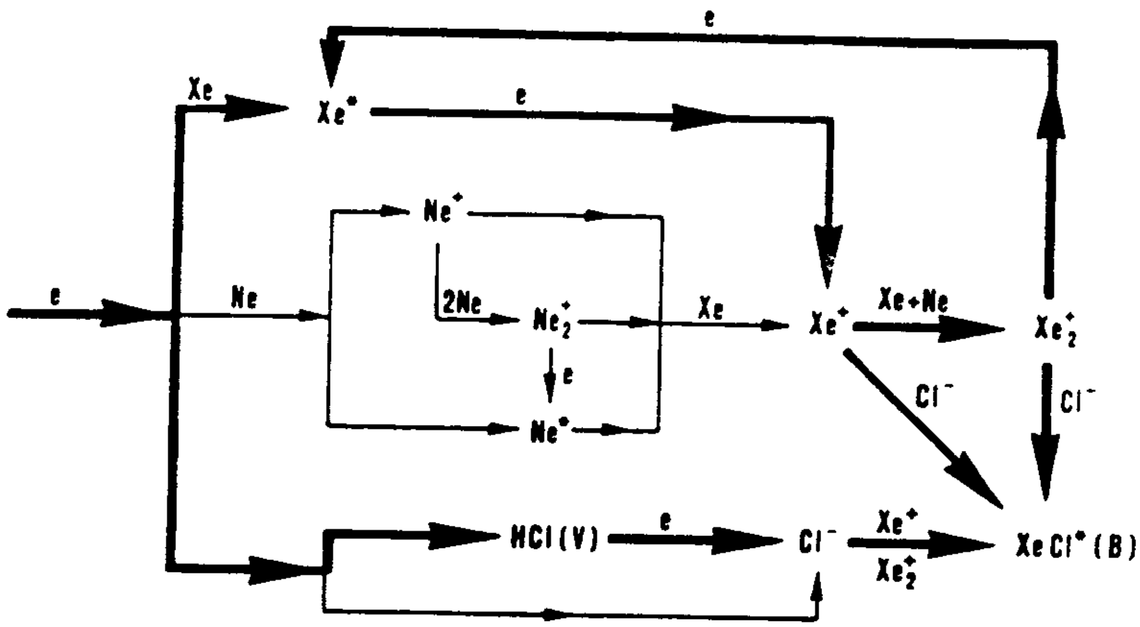
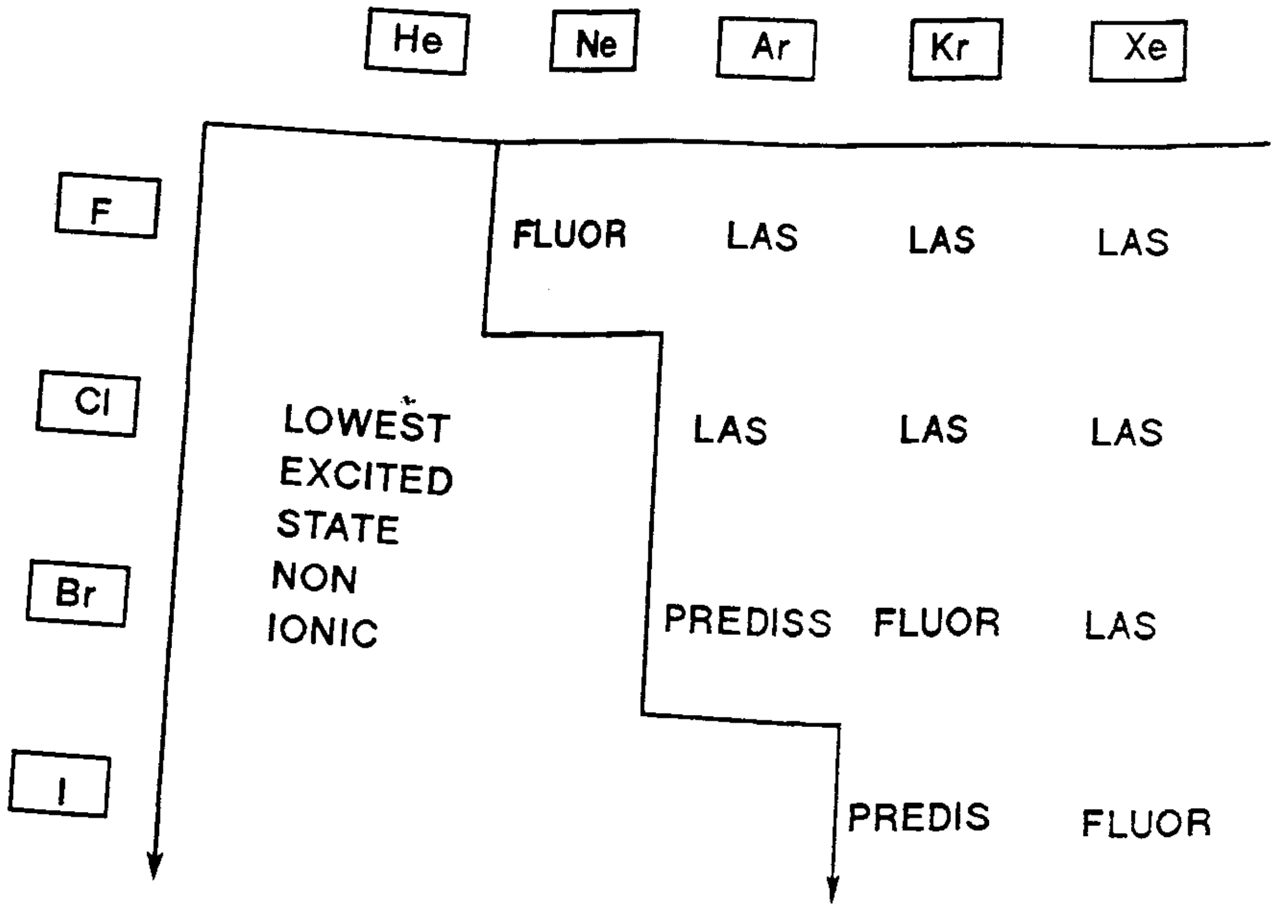


Fig.1 _ SEQUENCE DIAGRAM SHOWING THE KEY KINETIC PATHS FOR THE XeCl*(B) FORMATION CHAIN IN DISCHARGE-EXCITED Ne-Xe-HCl MIXTURES.

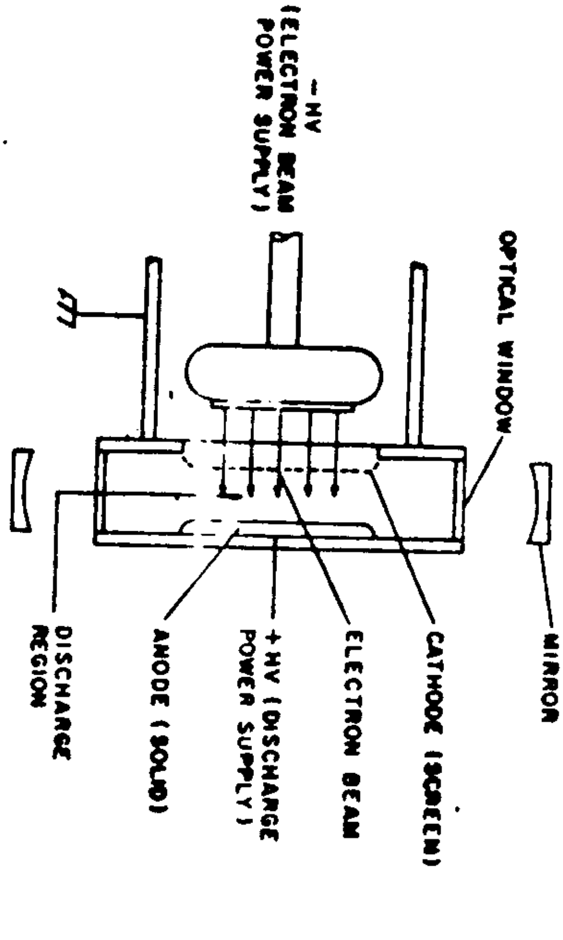


.MISSION WAVELENGTH OF MOST .MPORTANT RGH LASERS

RGH	w.l. (nm)
ArF	193
KrCl	222
KrF	248
XeCl	308
XeF	351

For typical gas mixtures, three components:
a buffer gas (Ne, Ar, He) at a pressure between 1 bar and 10 bar
the reacting rare gas (Xe, Kr) at a pressure between 10 torr and 100 torr
the reacting halogen gas (F2, HCl) at a pressure between 1 torr and 10 tr

ELECTRON BEAM [redacted] PUMPING
TYPICAL GEOMETRY



E-BEAM PUMPING SYSTEM

ADVANTAGES

- EASY TO SCALE TO LARGE VOLUMES ==> TO HIGH ENERGY PER PULSE
- IT IS POSSIBLE TO ACHIEVE HIGH PUMP DENSITY ==> HIGH PEAK POWER LASER PULSES

DISADVENTAGES

- THE SYSTEM IS TECHNICALLY COMPLICATED
- RADIATION (AND SHIELDING) PROBLEMS
- LIMITED LIFETIME OF SOME COMPONENTS (WINDOW....)

E-BEAM PUMPING SYSTEM

PUMPING POWER DENSITY

$P_d = J * dE/dx$ (W/cm^3)

J = E-BEAM CURRENT DENSITY (A/cm^2)

dE/dx = ELECTRON ENERGY LOSS (eV/cm)

LIMITATIONS ON THE ENERGY OF THE E-BEAM:
< 100 KeV: ELECTRONS ARE STOPPED BY INPUT WINDOW FOIL
> SOME MeV : DEPOSITED ENERGY IN THE GAS IS TOO LOW

ES. E-ENERGY 500 KeV
GAS : Ar AT 3 bar
J = 1 KA $/cm^2$
dE/dx = 8 KeV/cm
Pd = 8 MW/cm^3

PROTON BEAM PUMPING

-Specific energy loss of protons is about 100 times that of electrons at the same energy ==> higher pumping density can be achieved, and also higher energy coupling to the gas

-The technology of proton beams is more difficult , and so the problems of windows

-Few succesfull results:
1.5 J/p with 6% eff. in XeCl
S.V.Baranov et al – Sov.J.Q.E. 12 (1982)p.70

NUCLEAR PUMPING

-It uses the fission fragments as esciting particles

-High energy density can be stored in the fissionable material:

up to 10^{11} J/gm, it is 10^{9} times the energy density in electrostatic capacitors

-Low efficiency has been reported up to now

RADIO FREQUENCY EXCITATION

Active region in a glass or ceramica tube with diam < 1 mm , length ca 30 cm

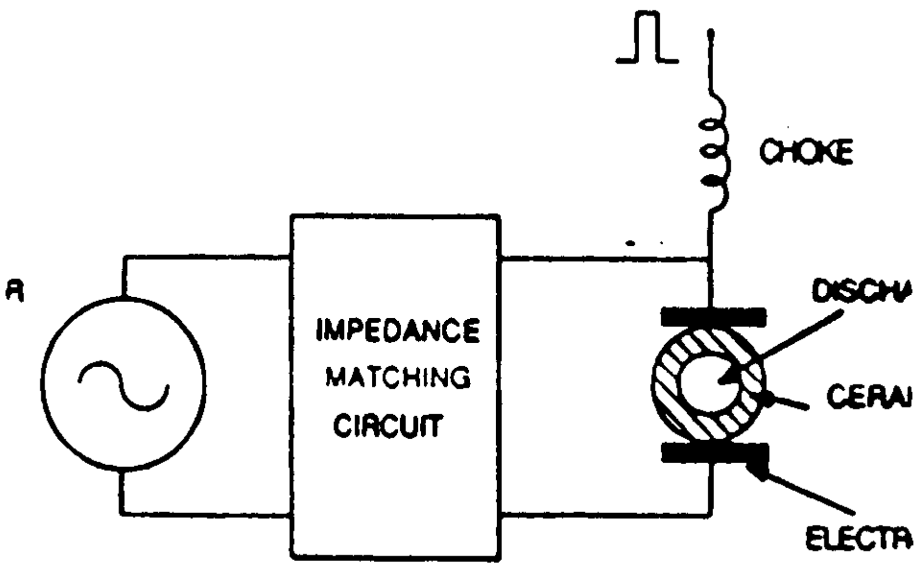
RF : 1 GHz -- pumping power 10 KW/cm^3

Advantages

- -Electrodeless discharge
- -High rep.rate because the gas is quickley cooled by diffusion to the walls
- -100 KHz feasible?
- -Long pulses, up to hundreds of nanosec
- -Quasi-c.w. operation

Disadventages

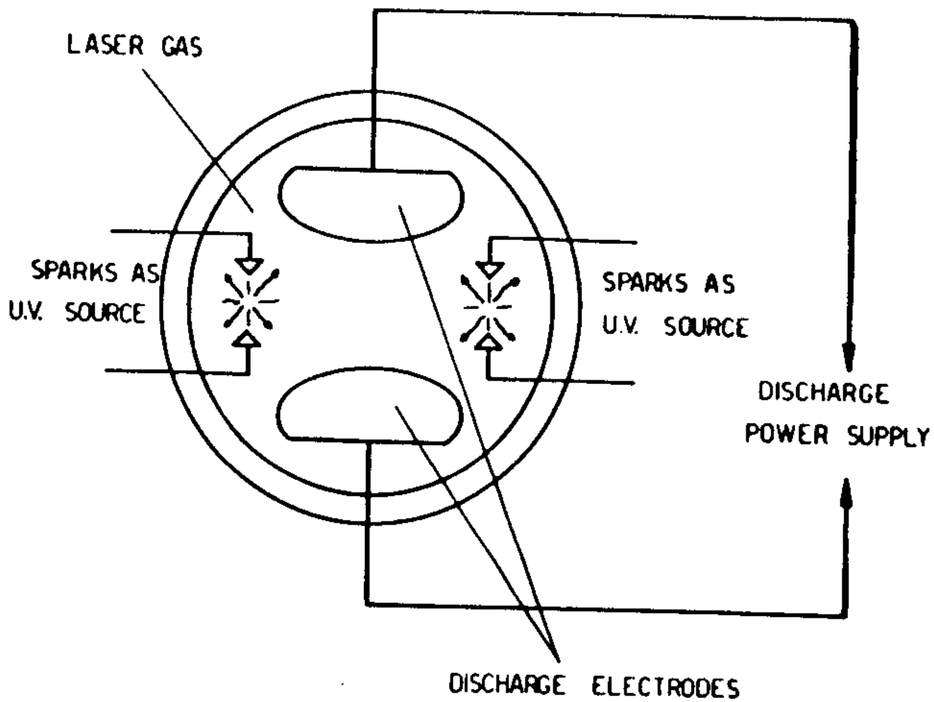
- -Low efficiency
- -Small active volume
- -Low energy/pulse

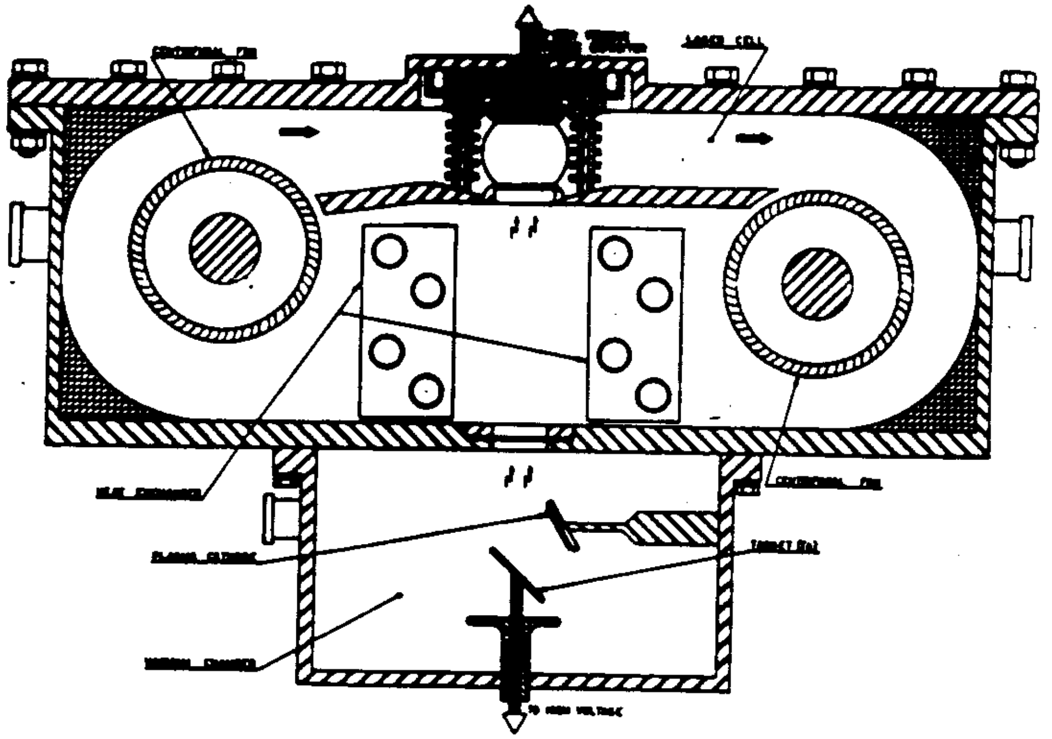


Electrical configuration used for excitati
ılse-repetition rate XeCl laser.

ptical Society of America

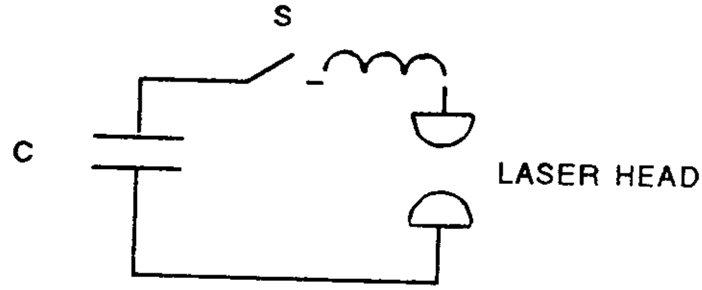
(C.P. CHRISTENSEN ET AL. 1987)

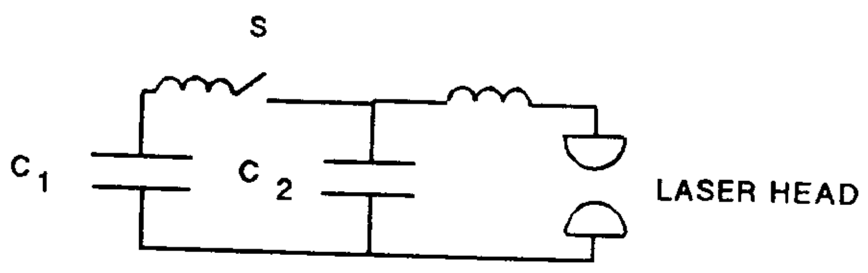




SELF-SUSTAINED DISCHARGE PUMPING

BASIC ELECTRICAL CIRCUIT





CHOICE OF MATERIALS:

- WALLS MUST WITHSTAND PRESSURES OF MANY BAR

- WINDOWS MUST KEEP THE REQUIRED OPTICAL CHARACTERISTICS UP TO THE WORKING PRESSURE

-MATERIALS MUST BE COMPATIBLE WITH HALOGEN ENVIRONMENT

-ALL THE CONSTRUCTION MUST AIM AT PREVENTING CONTAMINATION OF EXCIMER LASER GASES

-GAS IMPURITIES < 100 ppm

-TO PREVENT CONTAMINATION OF EXCIMER LASER GASES

Find a dependable source of high purity gases
Use premixed gases
Design a gas handling system that maintains high gas purity
Don't fully empty halogen cylinders
Use a gas purifier
Use compatible materials for your lasers

TABLE OF MATERIAL COMPATIBILITY

	HCl	F_2
Nickel	G	G
Ceramics	G	G
PVC	P	P
Teflon	G	G
Viton	P	P
Monel	G	G
AISI 316	G	G
Al	A	A
Brass	A	P
Cu	P	P

G = GOOD

P = POOR

A = TO BE AVOIDED

PREIONIZATION SOURCES

- U.V → SPARKS, CORONA
- X-RAYS

-due to the presence of attaching species in the gas (HCl, F2) the lifetime of electrons is limited : at usual halogen concentration and electric fields, is of the order few hundreds of nanosec

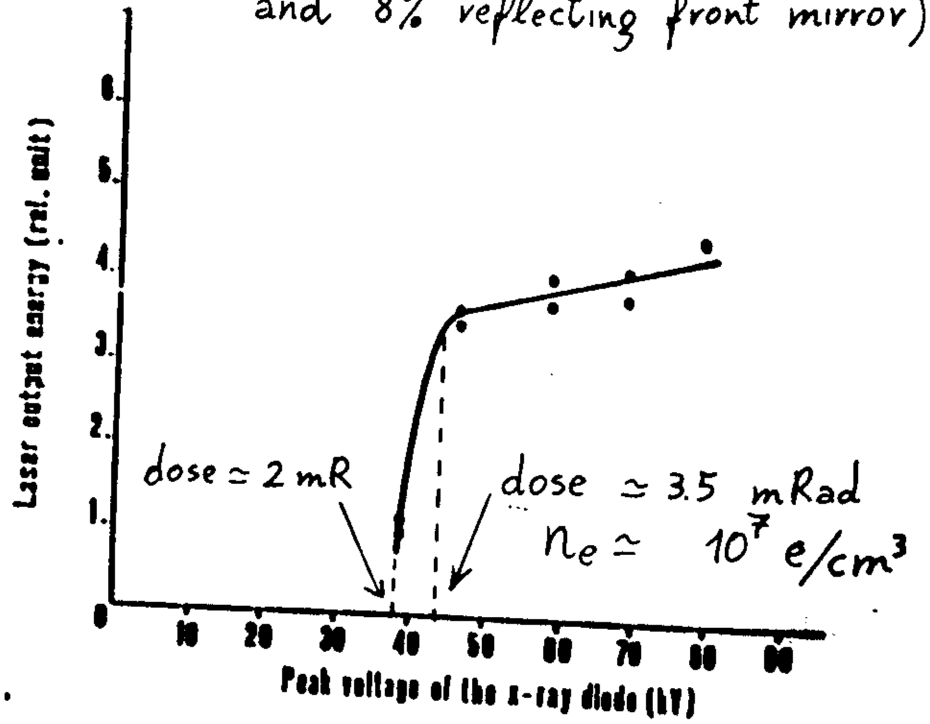
- If R is the electron production rate of the preionization source, T the lifetime of electrons, than the electron concentration at time t $n_e(t)$ is

$$n_e(t) = t*R*(1-\exp(-t/T))$$

-at the end of the preionization pulse, must be $n_e > 10^6$ e/cm^3

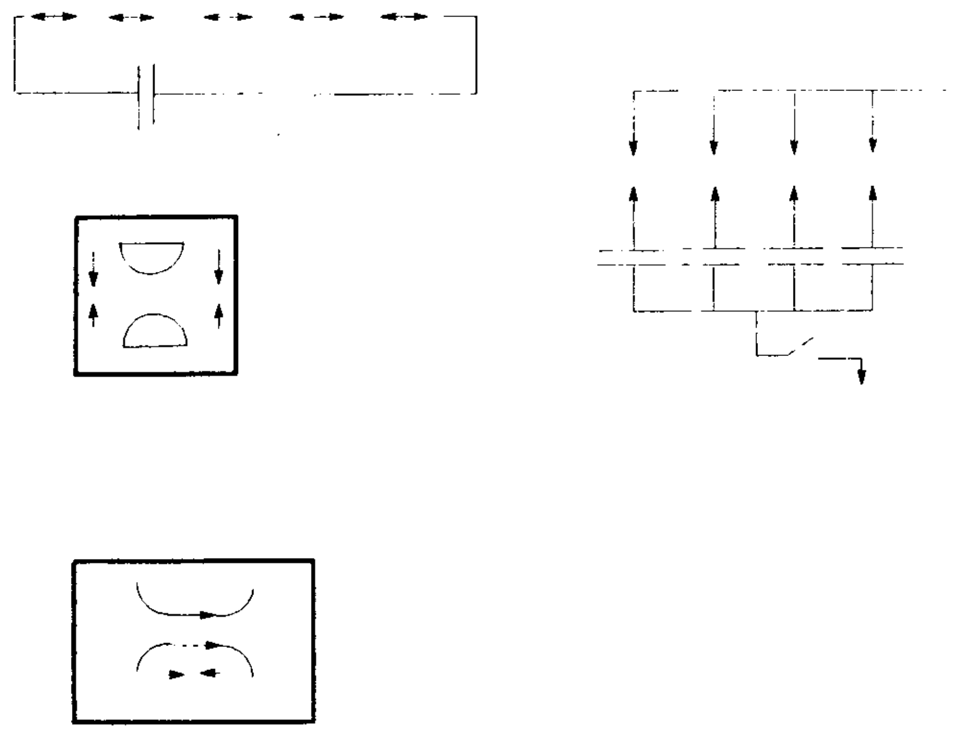
In order to have stable discharge (high efficiency)

OUTPUT Energy versus x-ray dose
(plano-plano cavity with Al back mirror and 8% reflecting front mirror)

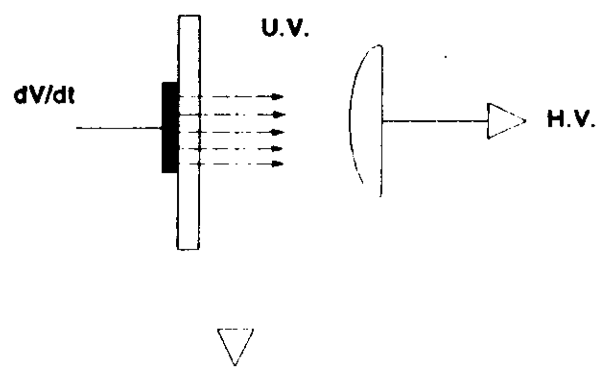


Laser output energy v.s. preionization intensity.
Plasma trigger voltage: 36 KV.
XeCl* laser mixture pressure: 3 atm.
Discharge capacitance: 0.48 μF.
Charging voltage: 50 KV.

SPARK PREIONIZER

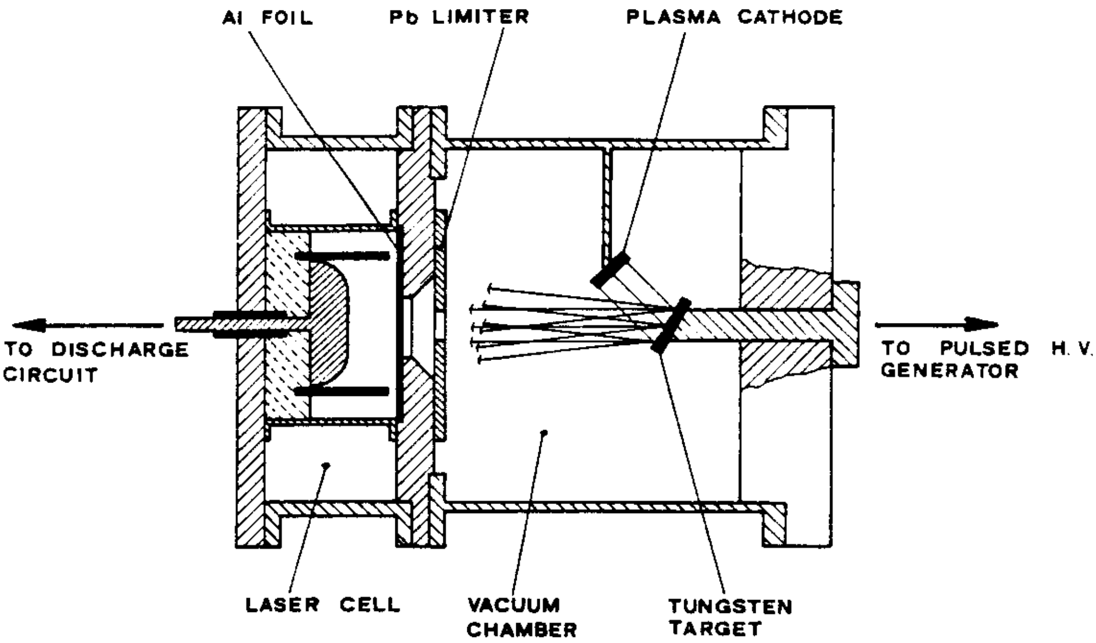


U.V. Corona preionization



U.V.Corona,behind a mesh
H.V.Trigger electrode behind the dielectric

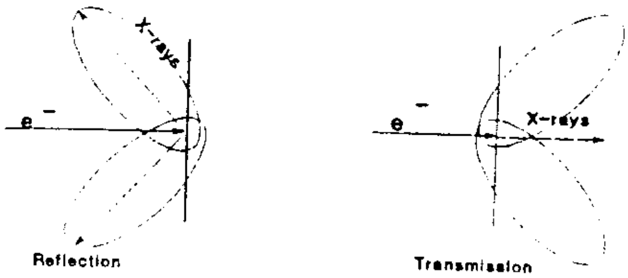
Dielectric materials: alumina, macor, sapphire.
$dV/dt = 3*10^{3}$ V/ns
Rep. rate up to 10 KHz



X-RAY PREIONIZATION

General properties

Two basic geometries:reflection and transmission



Energy spectrum: $I(\lambda) \propto V^2 * \lambda_0 * (\lambda - \lambda_0) / \lambda^3$

λ_0 = hc/eV is the minimum w.l. (all the energy of the electron eU is converted in one photon)

Angle of max. emission: depends on the energy of electron– At 60 KeV, about 45°

X-rays production efficiency E(X) : can be expressed roughly as

$$E(X) = 10^{-9} * Z * E_e \quad (E_e \text{ in eV})$$

X_RAY PREIONIZATION

Anode : it must be made with a high Z material (W, Mo, Pb, Ta)

Cathode : high peak current is required (> 1A / cm for T < 300 ns)

Thermoionic – low peak current

Cold emission : not suitable for high rep.rate. – limited lifetime

Plasma cathode : high peak current, limited lifetime

Voltage : between 50 KV and 200 KV

Energy : in the reflection mode, with 10 J an active volume of 10 l. can be preionized up to a level of 10 mR quite uniformily

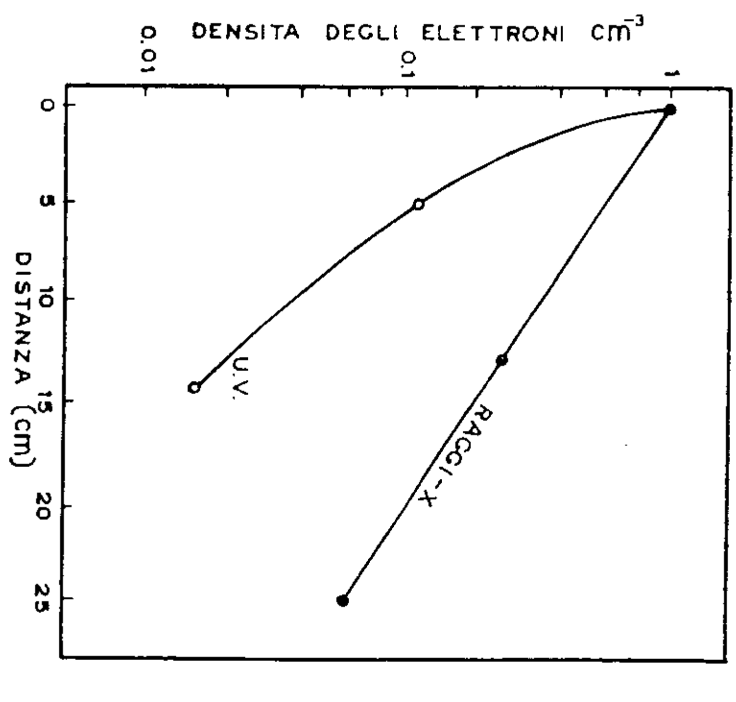
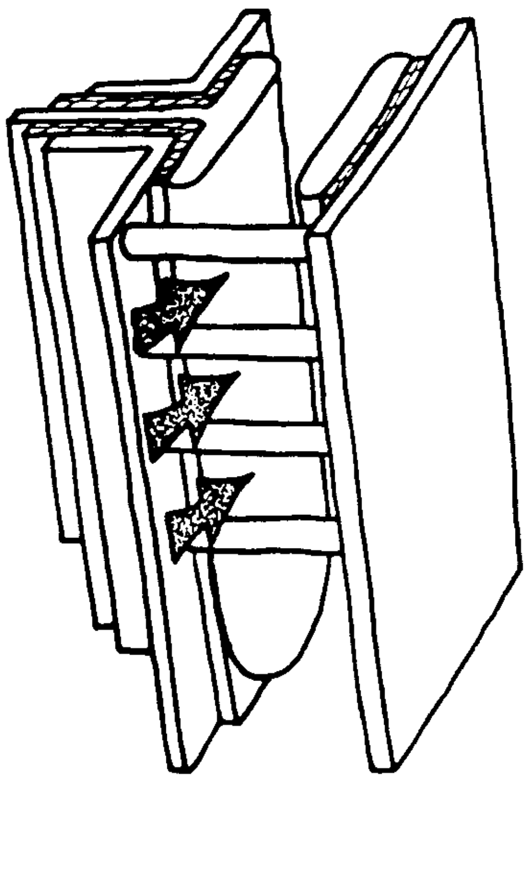


fig. 5

Comparison between the different types of preionization

	Advantages	Disadvantages
U.V. Sparks :	-High preionization density -Simplicity, low cost	-Poor uniformity -Limited lifetime -Contamination of gas -Limited rep.rate
U.V.Corona	-Long lifetime -Low contamination of gas -High rep.rate (10 KHz reported) -Simplicity, low cost	-Low preionization -Poor uniformity
X-Ray	-Potentially,long lifetime -Good uniformity -Preionization only in the active region (improved efficiency) -No contamination of gas	-Low preionization density -Limited rep.rate -Complicated, expensive -Radiation shielding problems



1

ELECTRODE DESIGN

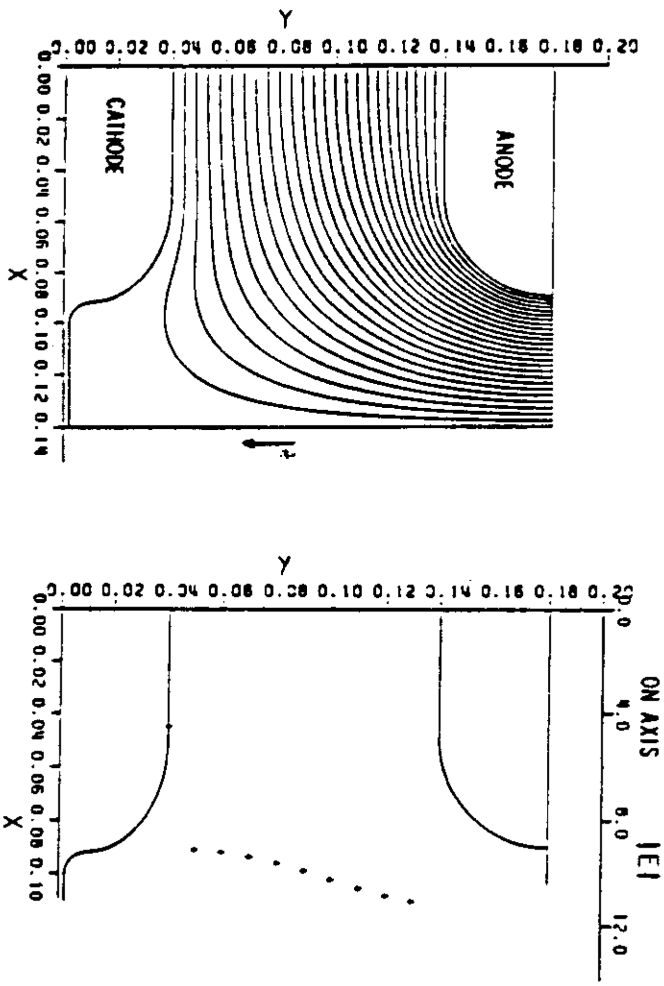
-Uniform electric field in the active region (uniform gain)

- Zero electric field outside the active region (return current bar as near as possible to active region to reduce inductance - no stray currents in the gas to have high efficiency - no electric field in insulators to prevent flashover)

-Many profiles have been studied .

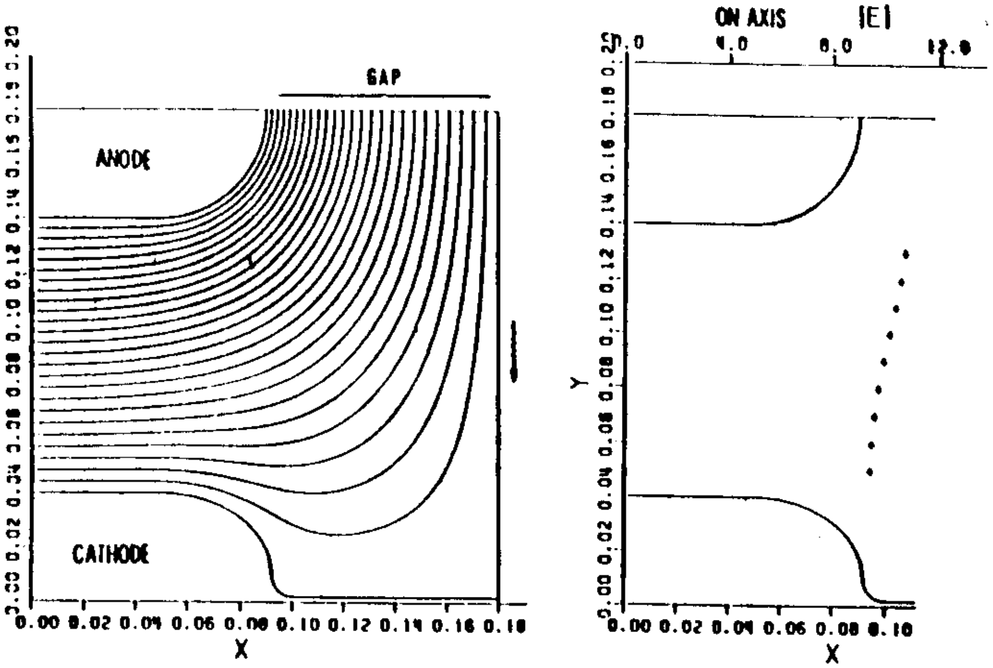
Rogowski (Arch. Elekt. 12 (1923) 1
Chang (Rev Sci. Instr. 44 (1973)405)
Ernst (Opt. Comm. 47(1983)47)
Stappaerts (Appl. Phys. Lett. 40(1982)1018)
Hermsen (Opt. Comm)

UNIFORM FIELD ELECTRODE DESIGN IN THE PRESENCE OF CURRENT RETURN.

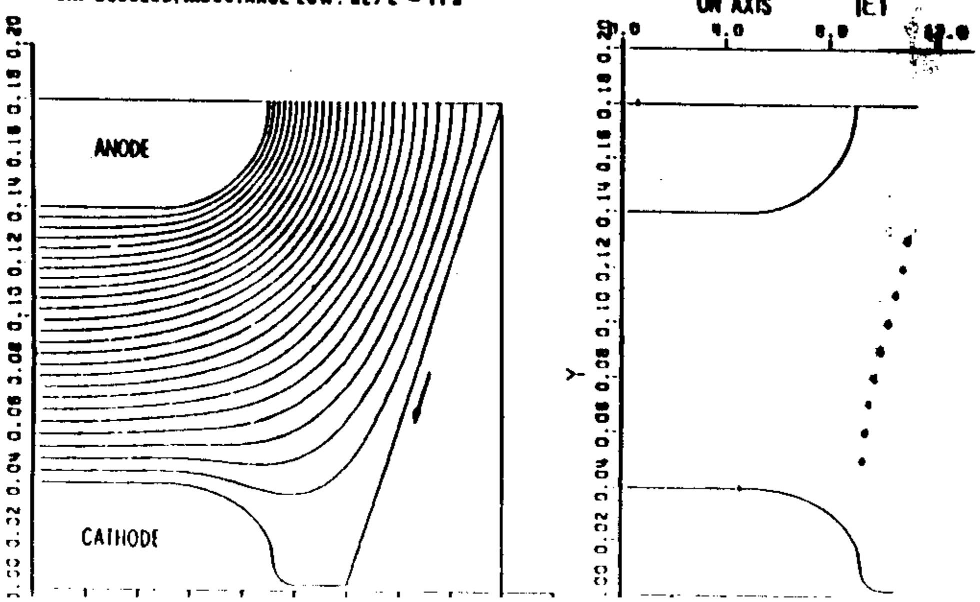


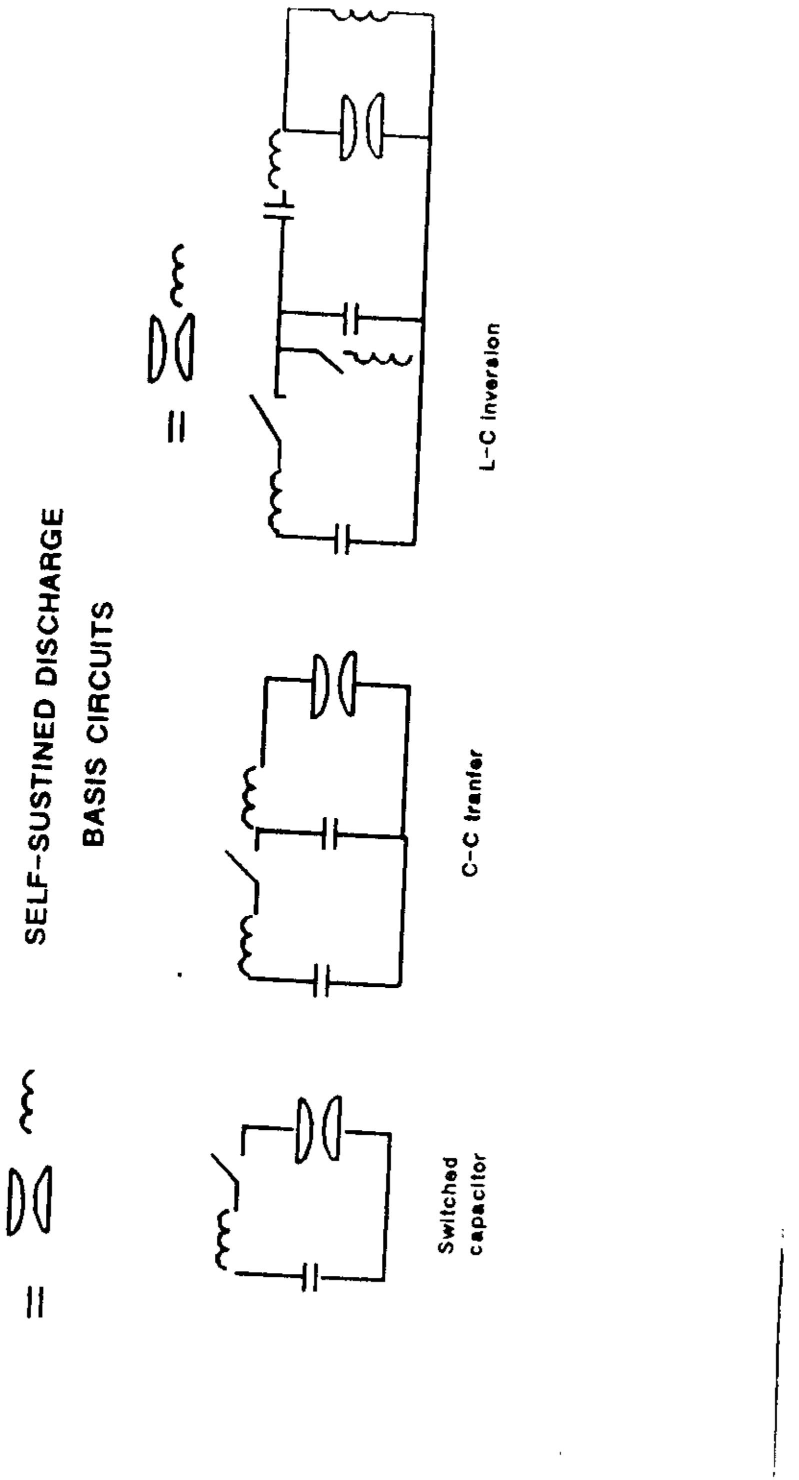
ACTUAL 101 DISCHARGE CHAMBER FIELD NON UNIFORMITY: ΔE/Ē ≈ 20% ON AXIS.

GAP DOUBLED: $\Delta E/\bar{E} \simeq 10\%$



GAP DOUBLED, INDUCTANCE LOW: $\Delta E/\bar{E} \simeq 11\%$





SELF-SUSTAINED DISCHARGE

σ = stimulated emission cross section

g° = small signal gain coefficient

N^* = upper state population

for excimer laser it is always $g^{\circ} = \sigma N^*$ (lower state empty)

It must be $g^{\circ} > 10^{-3}\ cm^{-1}$ because :

-static losses (HCl, F_2 are of this order

-discharge is unstable on long times (>µsec)==> laser saturation before 1 µsec

This set a minimum value of power density deposition:

P=power density deposition
ε = efficiency for creating excited states
E = energy of excited state
τ = lifetime of excited state

$$\frac{dN^*}{dt} = \frac{\varepsilon P}{E} - \frac{N^*}{\tau}$$

$$N^* = \frac{\tau \varepsilon P}{E}$$

$$g^{\circ} = \sigma N^* = \frac{\sigma \tau \varepsilon P}{E}$$

$$P > \frac{E g^{\circ}}{\sigma \tau \varepsilon}$$ (for typical values $P > 20\ KW / cm^{-3}$

SELF-SUSTAINED DISCHARGE

Conditions on the resistivituy of the discharge

The electric field, for a stable discharge, mustbe such that electron number density = constant ==>electron production = electron losses
The sustaining electric field Es which fulfill these conditions, for typical gas mixtures, is:

$Es/N = 2 - 5$ Td (1 Td = $10^{-17}\ V{*}cm^2$

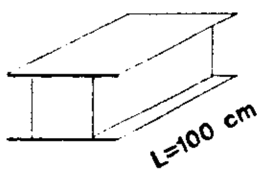
$Es/p = .4 - 1.0$ KV/cm*atm

P = power density
p = pressure

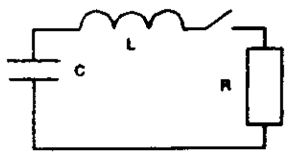
If $P > 20\ KW/cm^3$ beeing $P = \frac{E^2}{\rho}$

It follows $\rho < \frac{E^2}{P}$

In typical case, square cross section,L=100cm
It follows R < 1 ohm



SELF-SUSTAINED DISCHARGE



Basic discharge circuit: RLC circuit
With normal operating conditions:
R < 1 ohm
L > 20 nH
C > 30 nF
===> we have an oscillating discharge

The period of the oscillating current $\frac{2\pi}{T} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$

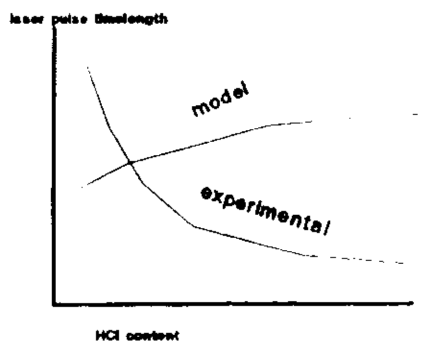
must be as short as possible because the discharge is stable only for times < 1 microsec

The fraction of the energy delivered to the gas in the firsyt half period (usefull time) is

$$\eta = \left\{ 1-\exp(-T/\tau) \right\} \quad \text{and} \quad \tau = 2*L/R$$

ONLY IF R IS NOT << $\sqrt{L/C}$ EFFICIENT UTILIZATION OF STORED ENERGY CAN BE DONE

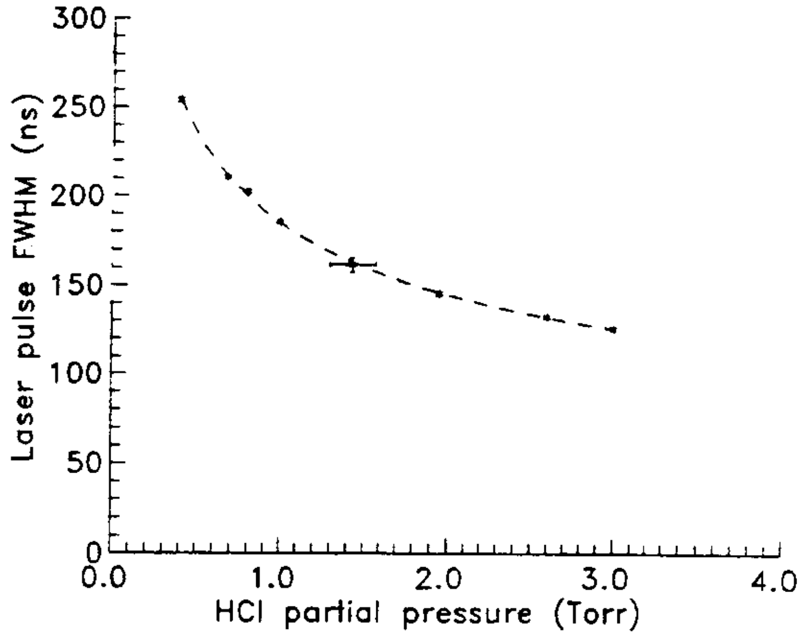
Discharge instabilities



-The discharge is unstable on long time scale
-This instability causes a premature end of the laser pulse
-The instabity is connected with the halogen content

-Model of the local depletion of the halogen donor (J.Coutts, C.E.Webb 1986)
-A disomogeneity in electron density distribution is created by some fluctuation
-Where the electron density is higher, due to the attachment process the number of halogen molecules will decrease
-this will cause an increase of electron density at higher rate than in the other regions of the discharge
-this "positive feedback" can cause the development of arcs which destroy the glow discharge

-This model can predict the experimental fact that the useful time of the discharge is inversely proportional to the initial concentration of the halogen donor



THE DISCHARGE INSTABLITIES

The diffuse discharge tends to collapse in arcs, terminating the laser action

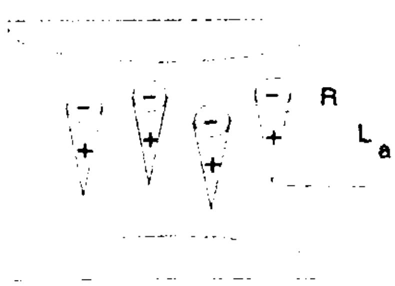
The useful time of the discharge :
-decreases when the preionization density decreases
-decreses when the HCl concentration increases

Instability due to the preionization

For each working condition, there is a minimum preionization electron density, in order to initiate a uniform discharge

The model of overlapping microdischarges (J.I.Levatter, S.C.Lin - 1980)
The small avalanches, created by drifting electrons, must overlap before the electric field, on the head, becomes comparable with the external electric field

$$L_a = v * T = \mu * E * T$$



$$n_f = \exp(\alpha * L_a)$$

α = Townsend first ionization coefficient

THE DISCHARGE INSTABILITIES

Radius of the avalanche head

$$R = \sqrt{2 * D * T}$$

D = diffusion coefficient

Specific case: $E_{appl} = 2 * 10^4$ V/cm
$p = 3$ bar

$E_{av} = E_{appl}$ after 100 ns

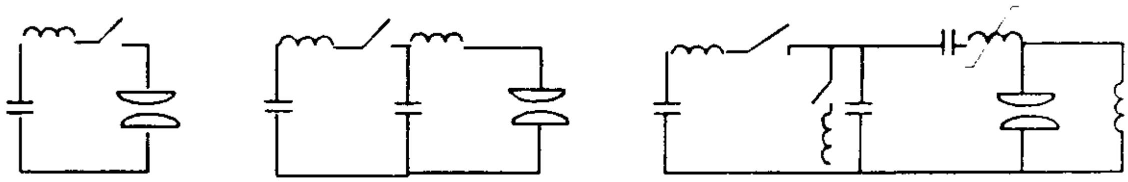
R_a (at T = 100 ns) $2.5*10^{-2}$ cm

$n_{min} = 10^5$ e / cm^3

Instabilities due to the HCl content
Model of the " Local depletion of the halogen donor" J.Coutts, C.E.Webb, 1986)

-a disomogeneity in electron density distribution is created by some fluctuation
-where the electron density is higher, due to the attachments process the number of halogen molecules will decrease
-this will cause an increase of electron density at higher rate than in other regions of the discharge
-this " positive feedback" can cause the development of arcs which destroy the glow discharge.

SELF-SUSTAINED DISCHARGE
BASIC CIRCUITS



Switched capacitor — **C-C tranfer** — **L-C inversion**

Source: 1 J/p
Eff.2%
V=40KV
C=62.5 nF

→ T/2 < 100 ns
L < 16 nH

→ Ip = 78 KA
dI/dt = $2.5*10^{12}$ A/s

Laser-head circuit

T/2 = 400 ns
L<260 nH

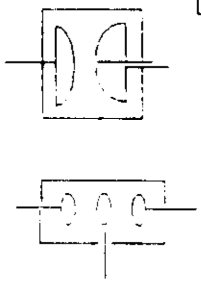
→ Ip = 20 KA
dI/dt = $1.5*10^{11}$ A/s

Charging circuit

SWITCHES

- Spark-gaps
- Thyratrons
- Saturable inductors

Careful choice of materials for electrodes
Very dry gases (< 10 ppm):Air, N_2, SF_6, H_2 are suitable
Use of u.v.to decrease the jitter



Spark-gaps

Hold-off voltage: up to MV
Peak current: up to MA
Stray inductance: possible few nH

EG&G ELECTRONIC COMPONENTS

LS-5101 Ceramic-Metal Deuterium Thyratron

The LS-5101 is designed for operation in high peak power laser excitation circuits, and other applications where high reverse anode currents are likely to occur. For pulse widths less than 500 ns, the LS-5101 can be operated under conditions where the peak reverse anode current is as high as 50 percent of the peak forward anode current.

SPECIFICATIONS

MAXIMUM RATINGS

epy,	Peak Forward Anode Voltage	40 kv
iby,	Peak Forward Anode Current	20 ka for tp < 500 ns 5 ka for tp=5 μs
ibx,	Peak Reverse Anode Current	10 ka for tp < 500 ns
Ib,	DC Average Current	4 Adc
Ip,	RMS Anode Current	70 Aac
Pb,	Plate Breakdown Factor (v x a x pps)	100 x 10^9

HEATER REQUIREMENTS

Cathode Heater Requirements		
If,		35A Maximum at Ef=6.3 Vac
Reservoir Heater Requirements		
Ires,		15A Maximum at Eres=4.5 Vac

TRIGGERING

Control Grid (g_2)		
egy,	Open Circuit Peak Trigger Voltage (Min.)	1.5 kv
	Open Circuit Voltage Pulse Width (Min.)	2 μs
Zg,	Trigger Source Impedance (Max.)	100 ohms
	Trigger Current Pulse Width (FWHM, Min.)	2 μs
Ecc,	Negative Grid Bias Voltage	−50 to −150 Vdc
Auxiliary Grid (g_1)		
Eg_1,	Open Circuit Voltage (Typ)	300 Vdc
Ig_1,	Current (Typ)	50 ma

WARMUP TIME

tk,	900 sec

THYRATRONS VS. TRIGGERED SPARK GAPS
(from EG&G guidelines)

SPARK GAPS

- Smaller, lighter, cheaper
- No power, no warm-up time
- Can handle much higher level of voltage, current, charge and energy
- Very low stray inductance

- Limited rep. rate
- Limited lifetime ($< 10^8$ shots)
- Jitter, voltage instabilities

THYRATRONS

- Long lifetime
- High rep.rate
- Low jitter
- Easy to trigger

- Expensive
- Limited voltage hold-off
- Higher stray inductance

WHEN IT IS MORE CONVENIENT TO USE

Spark gaps

- Peak forward current greater than 20 KA
- Anode voltage greater than 40 KV
- Pulse energy greater than 500 J
- Stored charge greater than 10 mC
- Inverse current greater than 5% (in special cases, 50% possible)
- Circuital difficulties to ground one electrode

Thyratrons

- Pulse rep.rate greater than 25 Hz
- Required lifetime $> 10^7$ shots
- Jitter < 10 ns
- Trigger voltage < 5 KV

COMPARISON OF THYRATRON & TRIGGERED SPARK GAP ELECTRICAL CHARACTERISTICS

All Numbers Are Typical

	THYRATRONS	TRIGGERED SPARK GAPS
VOLTAGE HOLDOFF	Limited, Approx 40 KV per stage	Vast holdoff range due to flexibility in gas pressure and electrode spacing.
TRIGGERING	200-1500 Volts depending on tube	10-25% of Static Breakdown Voltage (SBV)
TIME JITTER	1-5 ns	10-50 ns
SWITCHING SPEED	15-40 ns	5 ns
PULSE REPETITION RATE	10 KHz	100 Hz
PEAK CURRENT, CHARGE TRANSFER AND ENERGY TRANSFER	Generally Lower	Generally Higher.
LIFE (See Text)	Expressed in Shots 10[illegible] to 10[illegible]	Expressed in Coulombs 5000-20,000 Coul.

EG&G ELECTRONIC COMPONENTS
35 CONGRESS STREET, SALEM, MA 01970
TEL (617) 745-3200 ■ TELEX [illegible]

PULSE COMPRESSION BY MEANS OF SATURABLE INDUCTORS

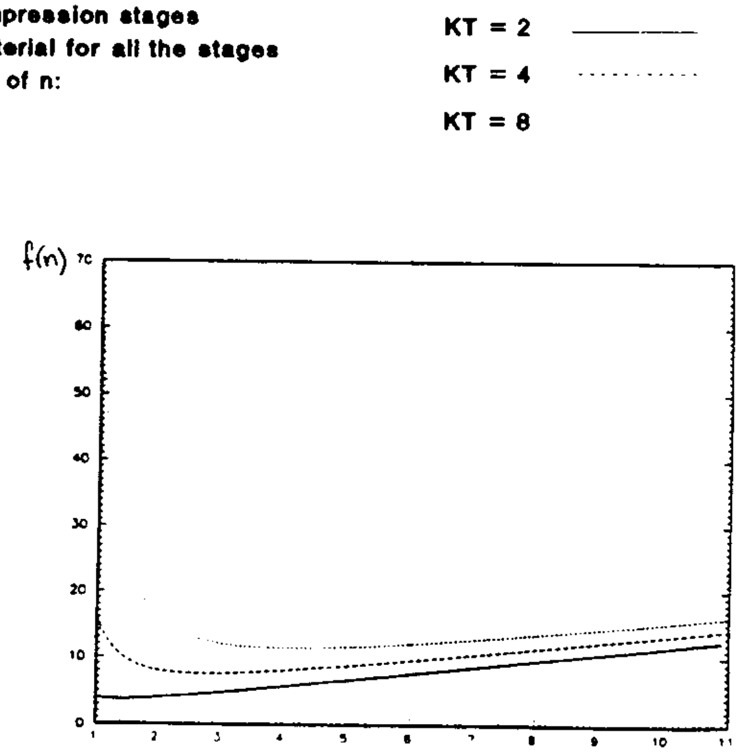
- Given a total compression factor KT
- Calling Vt the total volume of magnetic material
- Calling n the total number of compression stages
- If we use the same magnetic material for all the stages
- We can express Vt as a function of n:

$$V_t = A * f(n)$$

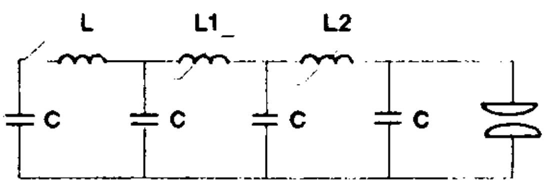
A = constant depending on magnetic material

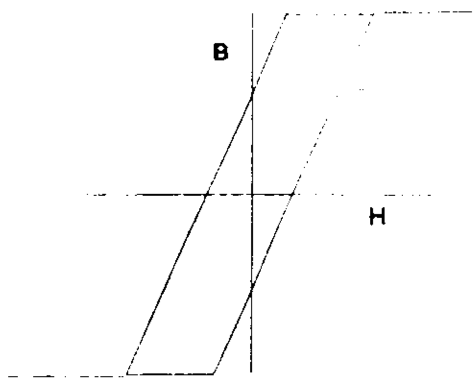
- There is a number of stages n(opt) which minimizes the overall volume Vt

$$n_{opt} = 2 * \ln(KT)$$



PULSE COMPRESSION BY MEANS OF SATURABLE INDUCTORS





- L1, L2..saturable inductors
- Ln saturates when previous stage fully charged
- $Tn/Tn-1 = \sqrt{Ln/Ln-1}$

= Compression factor per stage K

The volume Vl of magnetic material depends on the compression factor

$$Vl = K^2 * E * \left\{ \frac{\mu^{sat} * \pi^2}{4 * (DB_s)^2} \right\}$$

E pulse energy

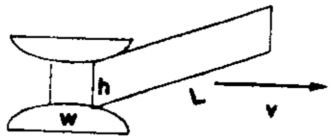
μ^{sat} absolute permeability of the saturated magnetic material

DB variation of magnetic induction from the unsaturated to the saturated state

Increasing the number of stages, it decreases the required total volune of magnetic material to realize a required compression factor

RECIRCULATION SYSTEM

In high-rep systems, the gas in the discharge region must be changed from shot to shot



- -h distance between electrodes
- -L electrodes length
- -v speed of the gas
- -w width of the discharge region
- -V volume flow rate of the gas

P_l laser power that can be extracted from a given active volume

$V = v * h * L$

$$P_l = \frac{E_d * V}{K}$$

E_d = Extracted laser energy density

E_p = laser energy / pulse

$E_d = E_p / (w*h*L)$

$$K = \frac{v}{f*w}$$

K clearing factor
f rep. rate of the laser

RECIRCULATION SYSTEM

Introducing the following definitions:

Kinetic energy flow P_f

$$P_f = \frac{V * d * v^2}{2}$$

d = gas density

P_r = power required to the recirculation system

$$E_r = \frac{P_f}{P_r}$$

as the ratio between the kinetic energy flow and the power required to the recirculation system

In conventional systems, E_r between .5 and 1

We can express the power requirements to the recirculation system in terms of current parameters of the laser system

$$P_r = \frac{K^3 * P_l^3 * d}{2*E_r *E_p *E_d^2 *L}$$

RECIRCULATION SYSTEM

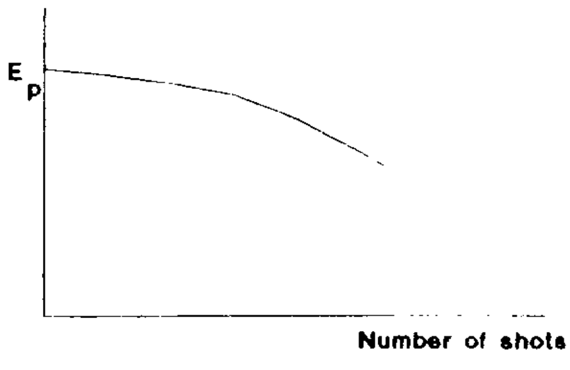
-Tangential fans: high volume gas flow,high efficiency, low speed, low pressure drop, easily integrated in the system

-Axial fans : high efficiency (up to 90%), high volume gas floiw,high pressure drop, difficult to integrate in the system

-Centrifugal fans: good efficiency (40 %),high volume gas flow, high pressure drop, easy to integrate on the system

GAS PURIFICATION SYSTEMS

Energy/pulse Ep vs number of shots in a repetitive system



-Build-up of UV absorbing molecules in the gas mixture which increases losses in the cavity (decrease of extraction efficiency)

-Build-up of impurity species which adversely affect laser kinetic reactions

-Loss of halogen donor due to reaction with component parts of the laser

-Dust creation within the laser (Al powder etch)

Solution

-Impurities have high vapor pressure: can be removed by low temperature traps
-Powder can be filtered
-Halogen gas content can be recovered by gas addition
-In the case XeCl and other clorine compunds, HCl content can be stabilized by carefull control of a cold trap

1. INTRODUCTION

The GP2000 is a cryogenic trap which significantly increases the single gas-fill lifetime of excimer lasers by the selective removal of impurities from the laser gas mixture. When used in conjunction with periodic halogen donor replenishment, the GP2000 enables the output of the laser to remain constant for greatly extended periods. The device is designed to be used with any excimer laser system and all the commonly used excimer laser gas mixtures, i.e. *KrF, ArF, XeCl and XeF.*

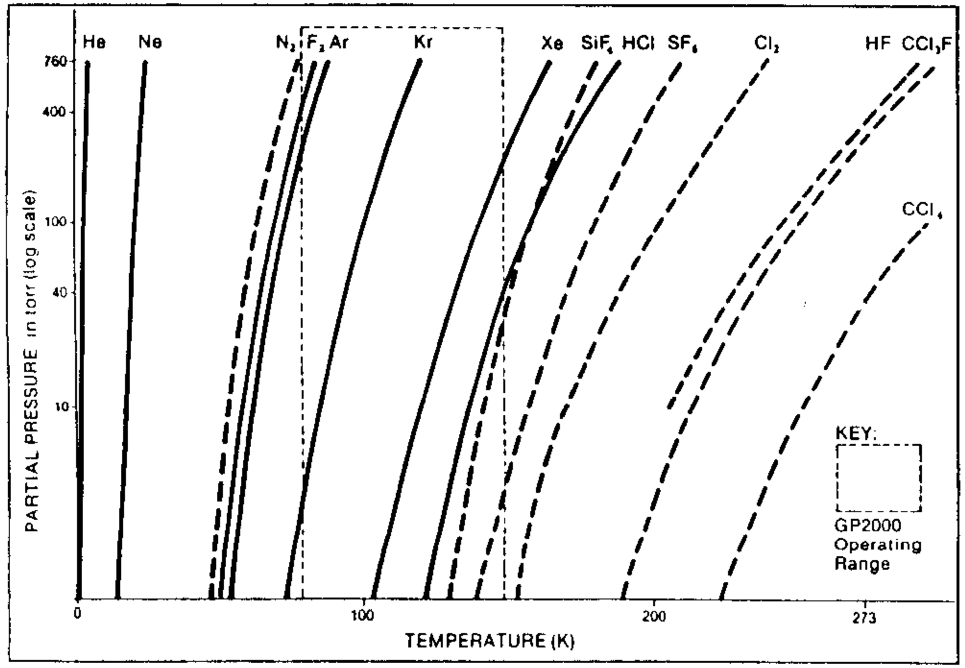


Figure 1 Partial Pressures of excimer laser gases and common impurities as a function of temperature

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mixture.

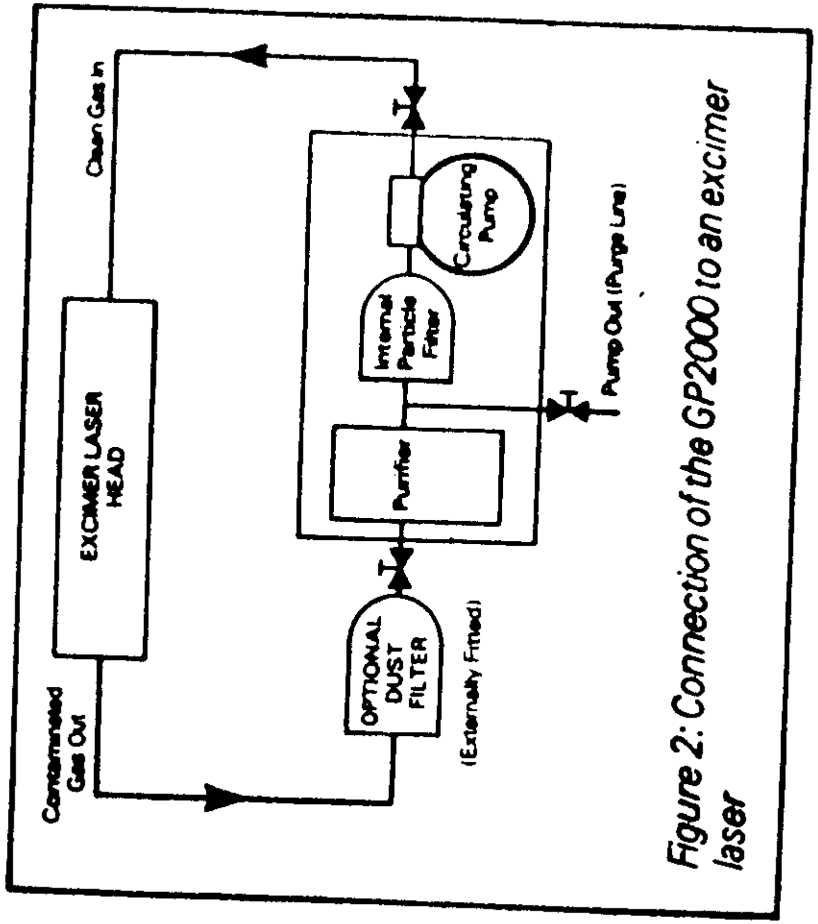


Figure 2: Connection of the GP2000 to an excimer laser

EXTRACTION EFFICIENCY

$$g^{\circ} = \sigma N^* = \frac{\sigma \tau \varepsilon P}{E}$$ small signal gain coefficient

α = coefficient of non saturable losses
is rougly linearly related to pumping density

$\Phi = I / I_s$ = intracavity normalized flux

I_s = saturation intensity = $\dfrac{h \nu}{\sigma \tau}$

(J.H.JACOB et al. APPL. PHYS. LETT. 48(318)1986)

$$\frac{d \Phi}{dz} = \frac{g^{\circ} \Phi}{1 - \Phi} - \alpha \Phi$$

$$\frac{d \Phi}{g^{\circ} * dz} = \varepsilon(\Phi)$$ local extraction efficiency

EXTRACTION EFFICIENCY

$\varepsilon(\Phi)$ is maximum when

$$\Phi = \sqrt{\frac{g^{\circ}}{\alpha}} - 1$$

$\varepsilon(\Phi) = 0$ when

$$\Phi = \frac{g^{\circ}}{\alpha} - 1$$

maximum value of extraction efficiency $\varepsilon(\Phi_{max})$

$$\varepsilon(\Phi_{max}) = 1 - 2\sqrt{\frac{\alpha}{g^{\circ}}} + \frac{\alpha}{g^{\circ}}$$

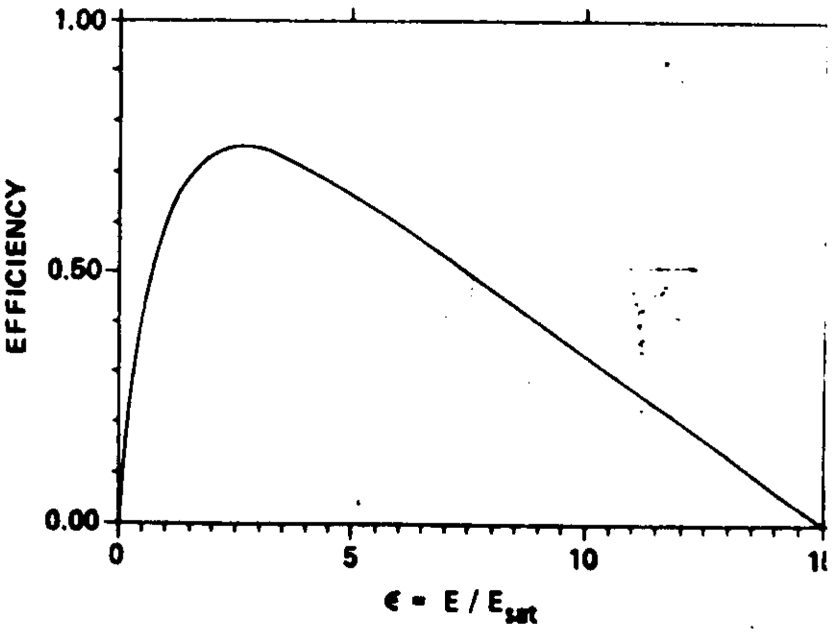
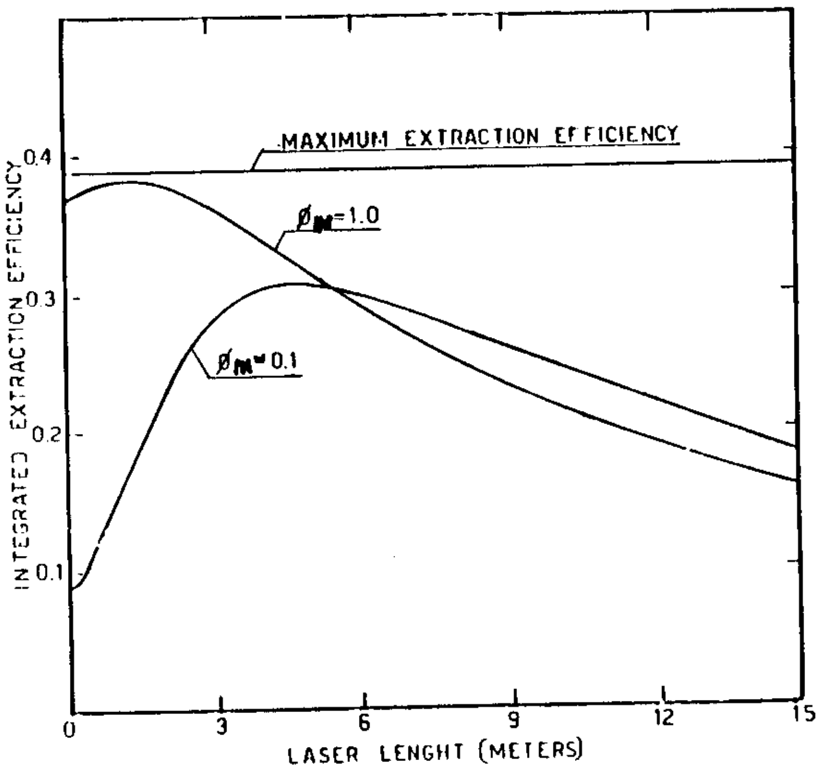


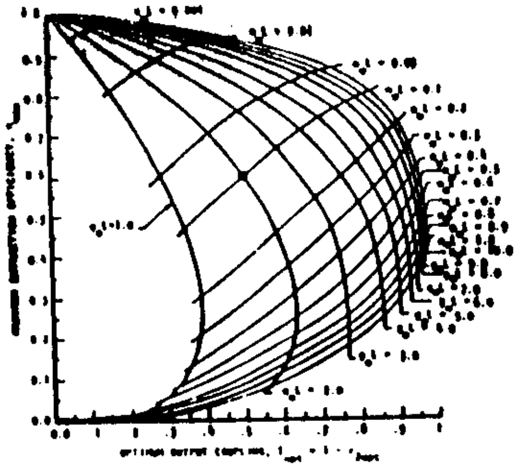
FIG. 3. Local extraction efficiency as a function of E/E_{sat}. Note t[illegible] $\epsilon = 15$ the local efficiency is zero. At larger values of ϵ the efficiency is [illegible] tive because the absorption is larger than the gain.

M. M. Tilleman and J. H. Jacob



$g_o = 2 \times 10^{-2}\ cm^{-1}$

$g_o / \alpha = 7$



(G.M. SCHINDLER, 1980)

OPTICAL CAVITIES (1)

Main macroscopic parameters characterizing an active medium:

Gain coefficient:

$$g = \sigma \cdot n$$

σ = stimulated emission cross section

n = population invertion

Saturation intensity for the gain:

$$I_s = \frac{h\nu}{\sigma \cdot \tau}$$

τ = life time of the upper level

Absorption coeff.:

$$\alpha = \frac{1}{c} \cdot \sum_i K_i^{(a)} \cdot [X]_i^{(a)}$$

c = light speed

$K_i^{(a)}$ = rate coefficient for the i^{th} absorption reaction

$[X]_i^{(a)}$ = concentration of the i^{th} absorber species.

he gain saturates

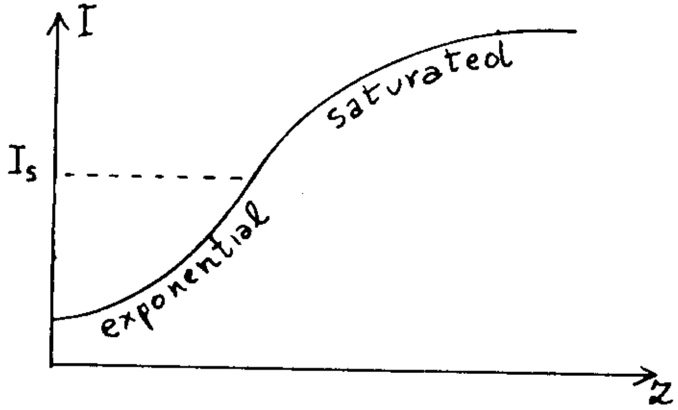
at $I = I_s$:

$$g = \frac{g_0}{1 + I/I_s}$$

Light amplification: Rigrod equation:

$$\frac{dI}{dz} = I \cdot \left(\frac{g_0}{1 + I/I_s} - \alpha \right)$$

When $I \ll I_s$ → $\frac{dI}{dz} = I \cdot (g_0 - \alpha)$ → $I(z) = I_0 \cdot e^{(g_0-\alpha)\cdot}$
exponential



Local extraction efficiency:

$$\eta_{loc} = \frac{\Delta I}{I_s \cdot g_0 \cdot \Delta z}$$

ΔI = intensity incremen during the path Δ

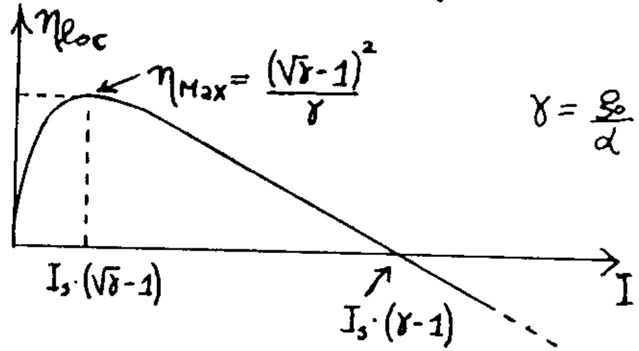
$I_s \cdot g_0 \cdot \Delta z$ is the intensity increment that a beam of infinite intensity would gain if α where $= 0$.

An infinite intensity beam disexcitates the excited molecules until the population inversion is annulled.

From the Rigrod equation one gets:

$$\eta_{loc} = \frac{I}{I + I_s} - \frac{\alpha}{g_0} \cdot \frac{I}{I_s}$$

is a local function of the beam intensity!



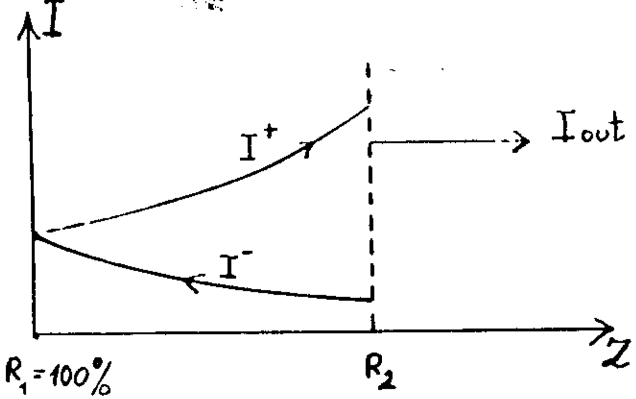
$$\gamma = \frac{g_0}{\alpha}$$

For each particular active medium, characterized by I_s, g_0 and α, the <u>extraction efficiency is maximized by one value of the intensity.</u>

The average exctraction efficiency (η), obtained integrating η_{loc} in the whole active medium volume, is the ratio between the power extracted by the beam and the available powe

$$\eta = \frac{P_{extracted}}{P_{available}}$$

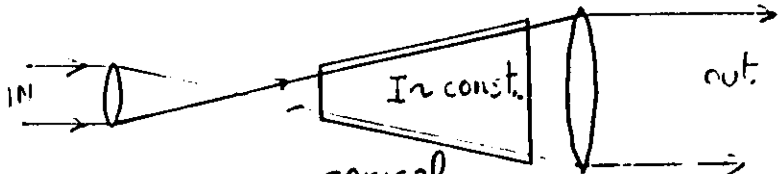
Case A):
RESONATOR



$I^+ + I^- \approx$ constant (it is R_2 dependent)
is possible to find a value of R_2 which gets
$\langle I^+ + I^- \rangle \simeq I_{optimum} \Rightarrow \eta \simeq \eta_{Max}$

Case B):
amplifier problems: - I is not constant
- often it is $I_{in} << I_{optimum}$

Ideal solution:



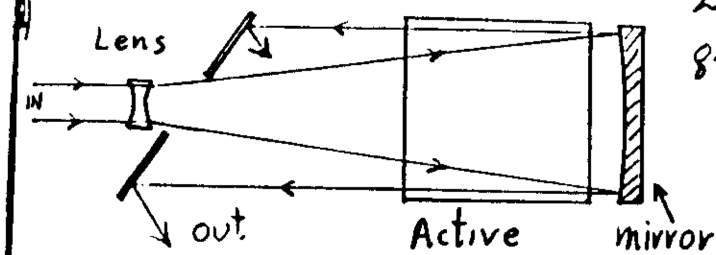
$I_{in} \to I_{optimum}$
$I(z) \simeq$ constant, since $\Delta I_{ampl.} \simeq - \Delta I_{expansion}$

$\Downarrow$

$\eta \simeq \eta_{Max}$

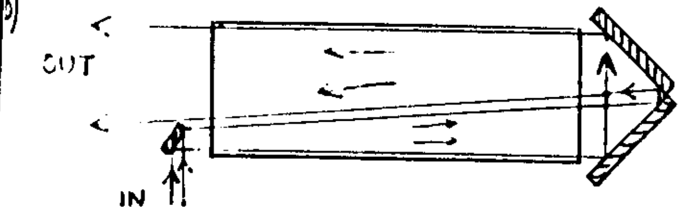
Reasonable solutions:

a)



2 counter propagating passages.
$I^+ + I^- \sim$ const.
(often << I_{opt})

b)

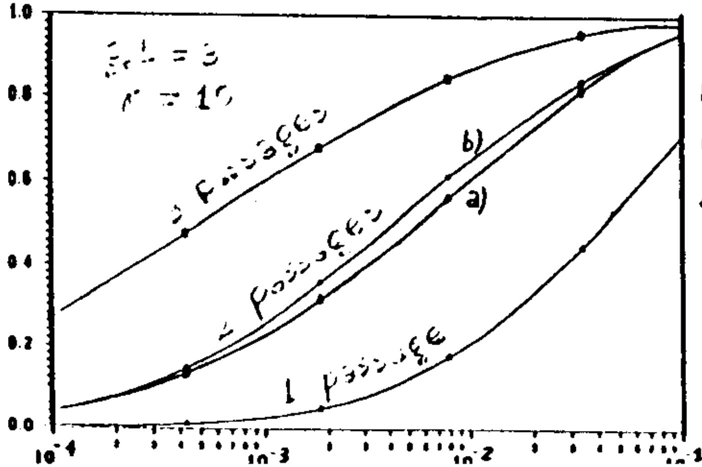


2 passages in different regions

c) More than 2 passages according with idea b)

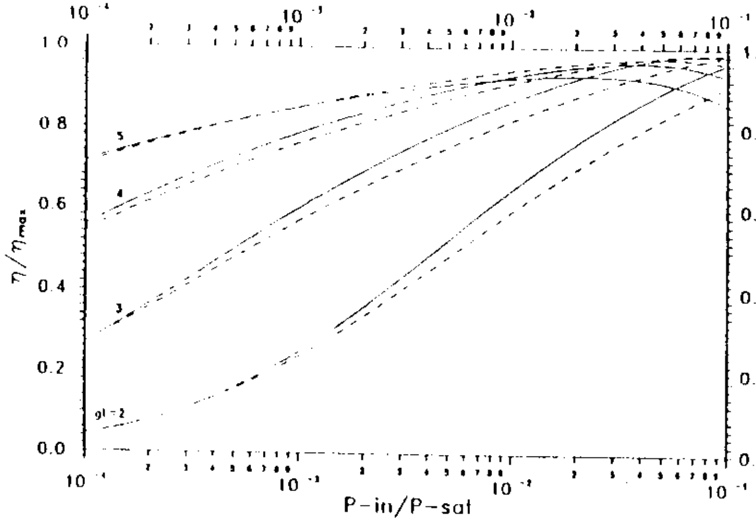
Smaller is the input power, the higher is the optimum number of passages!

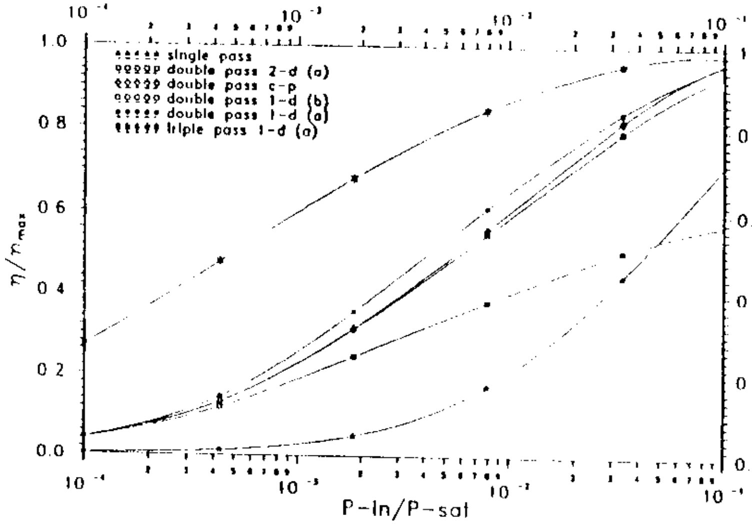
Example:



Input power is normalized to P_{AT}, i.e. to the available power!

$P_{AT} = g_0 \cdot I_s \cdot$ Volume


η/η max
P-in/P-sat
5
4
3
gl=2


single pass
double pass 2-d (a)
double pass c-p
double pass 1-d (b)
double pass 1-d (a)
triple pass 1-d (a)
η/η max
P-in/P-sat

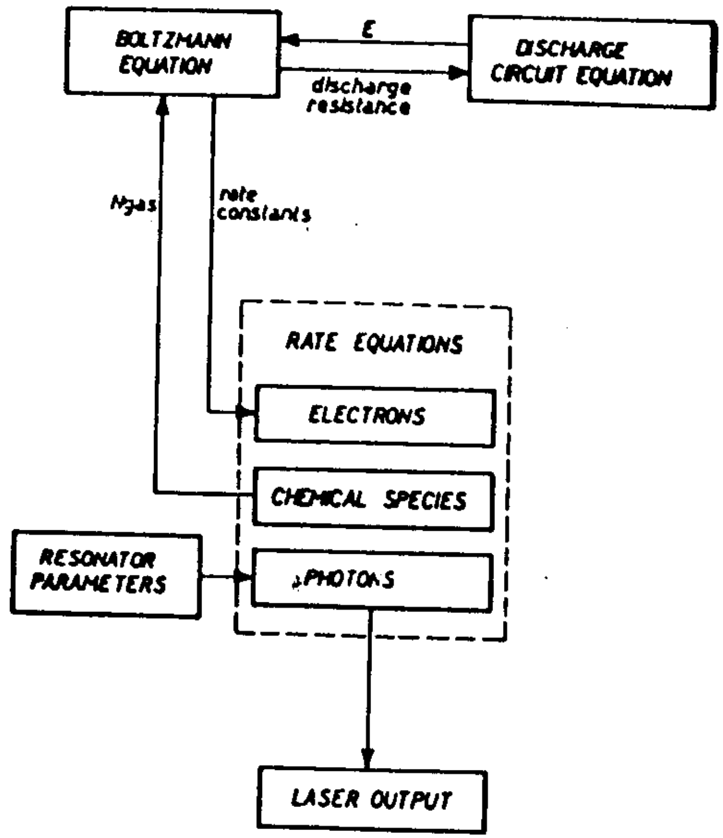
SIMULATION CODE MAIN PARTS:

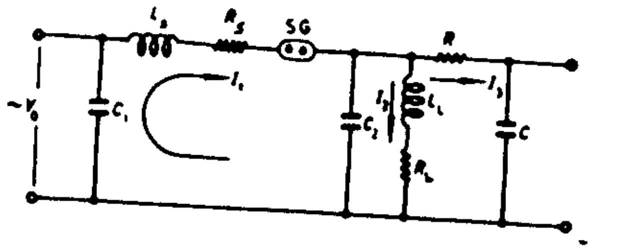
1) *Species evolution*

2) *Boltzmann equation*

3) *Discharge circuit*

4) *Laser output*





Equivalent discharge circuit

$$\begin{cases} \ddot{Q}_1 = -\dfrac{Q_1}{L_s}\left(\dfrac{1}{C_1}+\dfrac{1}{C_2}\right)+\dfrac{1}{C_2L_s}(Q_2+Q_3)-\dfrac{R_s\dot{Q}_1}{L_s}+\dfrac{V_0}{L_s}, \\ \ddot{Q}_2 = \dfrac{1}{C_2L_L}(Q_1-Q_2-Q_3)-\dfrac{R_L\dot{Q}_2}{L_L}, \\ \dot{Q}_3 = \dfrac{1}{C_2R}(Q_1-Q_2)-\dfrac{Q_3}{R}\left(\dfrac{1}{C_2}+\dfrac{1}{C}\right) \end{cases}$$

Circuit equations used in the code

The parameters used in the code :

C_1 = 320 nF, C_2 = 2.5 nF, L_s = 42 nH, L_L = 15 nH,
R_s = 20 m , R_0 = 80 m , V_0 = 40 KV.

HCl : Xe : Ne = 1 : 6.7 : 2010, 4 atm.

Resonator : flat-flat, R_1 = 85 %, R_2 = 7 %, cavity length 130 cm

active volume : 3.5 X 3.5 X 80 cm^3

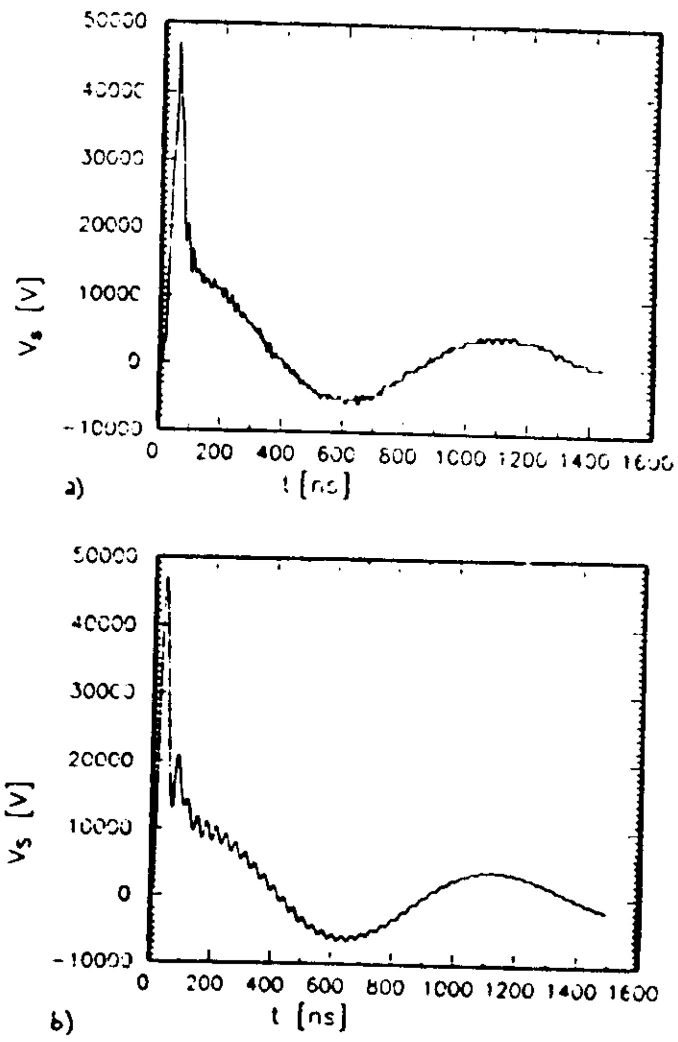


Fig 5.15. Tensione di scarica a) sperimentale, b) numerica relativa al punto di lavoro C_1 = 440 nF, V_0 = 30 KV.

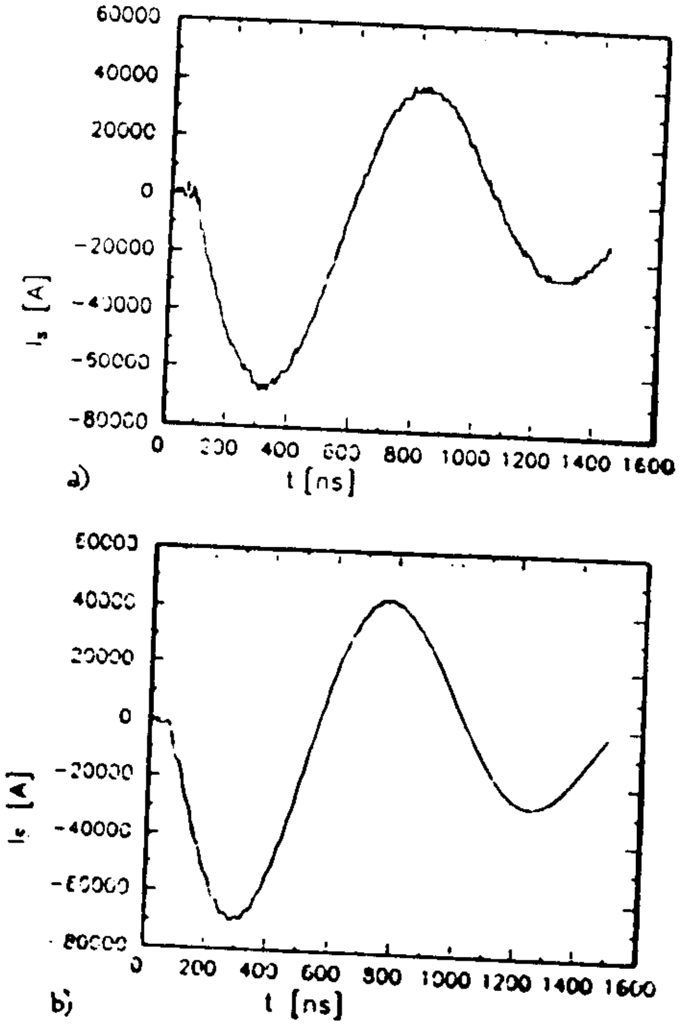
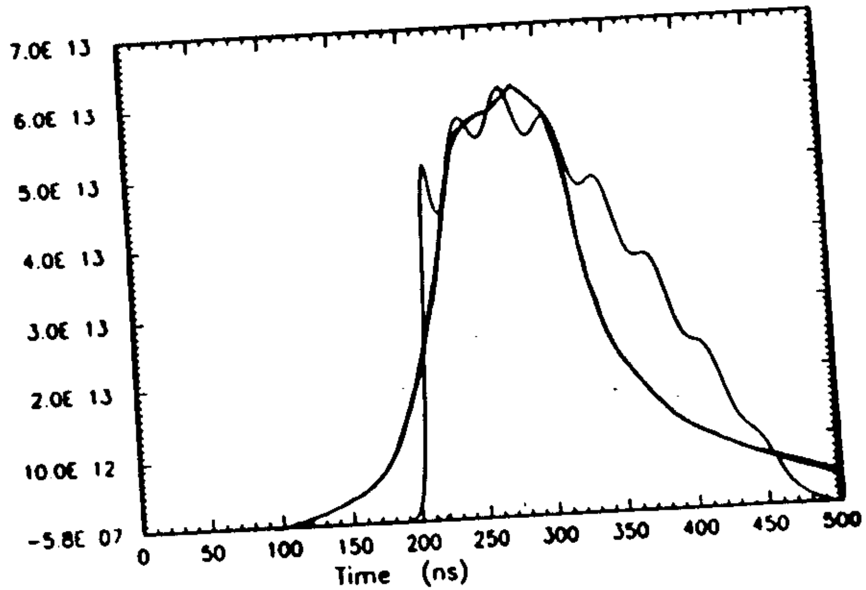


Fig.5.14: Corrente di scarica a) sperimentale, b) numerica relative al punto di lavoro C_1 = 440 nF, V_0 = 30 KV.



The modeled and measured laser pulse

MAIN CHARACTERISTICS OF COMMERCIAL RGH LASER SOURCES

	ArF	KrCl	KrF	XeCl	XeF
Wavelength (nm)	193	222	248	308	351
Average power (W)	125	15	200	200	30
Pulsewidth (ns)	5-25	5-15	2-50	1-300	30
Energy/pulse (J)	0.5	0.12	1.5	2	0.4
Repet. rate (Hz)	500	125	2000	2000	2000
Efficiency (%)	1		2	2.5	2
Beam cross section (mm^2)	2 x 4 - 25 x 30				
Beam divergence (mrad)	2 - 6 (< 0.2)				

EXCIMER LASER SOURCES WITH NON CONVENTIONAL CHARACTERISTICS

-Beams with low divergence

-Ultrashort pulses

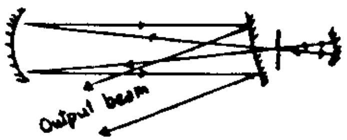
-Very long pulses

-Narrow bandwidth beams

-High energy/pulse

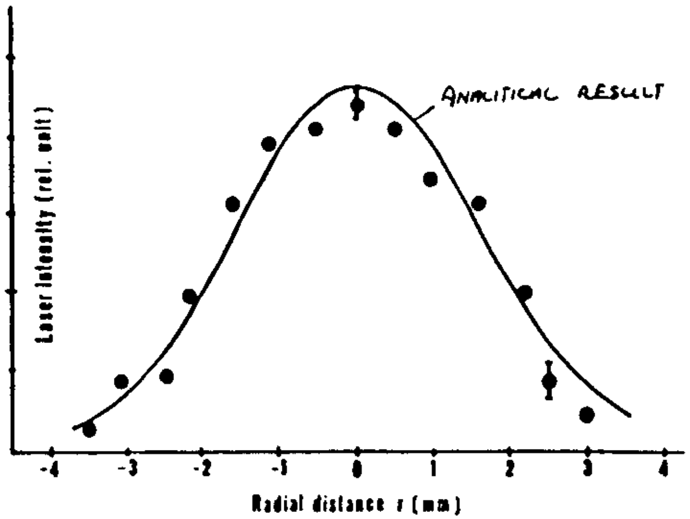
Low divergence beams

- The presence of the two cavity mirrors induces the formation of defined transverse modes of oscillation (lower order mode ↔ inner mode).
- The lower the order of the transverse mode, the lower the divergence of the output beam.
- From this, the need of introducing high losses on the higher order transverse modes.
- This can be accomplished by means of the so called "unstable cavities", in which the distance of a light ray from the optical axis is diverging, so that only the more internal oscillations can give rise to laser action.
- Example of unstable cavity: SFUR (Self Filtering Unstable Resonator)



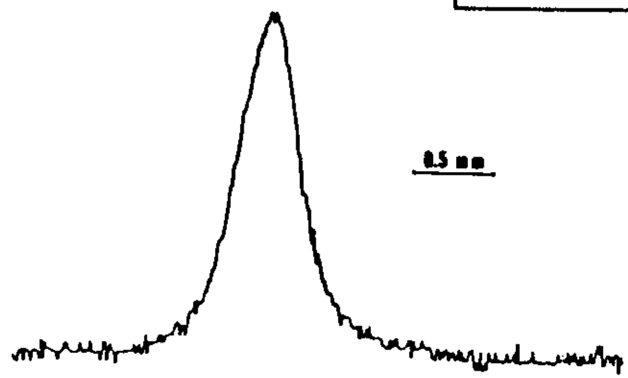
- The lowest transverse mode selected (gaussian spatial profile)
- Beam divergence : 0.15 mrad on XeCl

NEAR FIELD

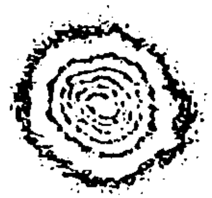


ENERGY/PULSE	120 mJ
DIVERGENCE	~ 0.15 mr

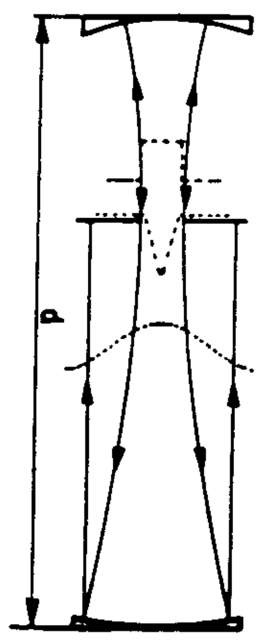
FAR FIELD



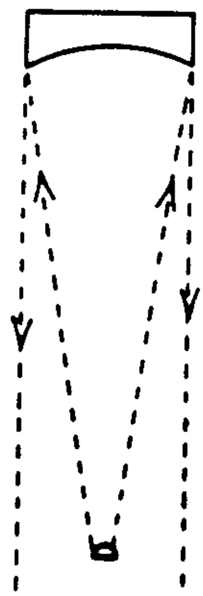
a)



b)



a)



b)

ULTRA-SHORT PULSES

-The minimum timewidth of a laser pulse amplified by an excimer laser depends on the fluorescence bandwidth

τ minimum pulsewidth

λ radiation w.l.

c light velocity

$\Delta\lambda$ fluorescence bandwidth

$$\tau = \frac{\lambda^2}{\Delta\lambda}$$

-for XeCl λ = 308 nm

$\Delta\lambda$ = 0.5 nm

τ = 150 fsec

Ultrashort pulses

The standard methods to obtain short pulses from lasers are: Q-switching and mode-locking.

- The Q-switching cannot be used with excimer lasers because of the very short lifetime of the active molecules ($\sim 10^{-8}$ s), compared with their formation time ($\sim 10^{-7}$ s), in which energy cannot be stored.

- With active mode-locking on a XeCl laser, Shay and his collaborators (Los Alamos) achieved 120 ps pulses with an energy of 15 μJ (125 kW peak power). This is, up to now, <u>the best result</u> obtained from an <u>excimer oscillator</u>.

- Shorter u.v. pulses can be obtained using the <u>excimer active medium as amplifier</u> generating the ultrashort pulse with another oscillator. Usually a ring laser with a dye as active medium, passively modelocked with a saturable absorber, is used as source of the ultrashort pulses (up to tens of fs). After amplification (in another dye) and u.v. conversion, the short pulse is sent in an excimer and greatly amplified due to the high gain coefficient.

Limits to obtain high peak powers

There are limitations both on the minimum temporal length of the pulse and on its maximum energy.

- The minimum length is determined especially by:
  - excimer narrow bandwidth ($\Delta t \propto 1/\Delta\nu$)
  - group velocity dispersion for the different frequencies

- The maximum energy is given theoretically by
  - maximum extractable energy:

$$\mathcal{E}_M = h\nu \cdot n \cdot V = \xi_s \cdot g_0 \cdot V$$

with $\xi_s = 1\,\text{mJ/cm}^2$, $V = 1\,\ell$, $g_0 = 10\%/\text{cm}$

$$\mathcal{E}_M = 100\ \text{mJ}$$

n = population inversion
V = active volume
ξ_s = saturation energy
g_0 = gain coefficient

  - in practice the amplification of the spontaneous emission (ASE) subtracts energy to the short pulse

Good experimental results have been obtained by:
- decreasing the temporal broadening due to the group velocity dispersion by means of negative dispersion systems;
- reducing the percentage of ASE on the total extracted energy to few percent by means of spatial filters.

From XeCl: 120 fs, 12 mJ = 100 GW (J. H. Glownia and coll.)
310 fs, 300 mJ ≤ <u>1 TW</u> (S. Watanabe and coll.)

From KrF: 80 fs, 15 mJ = 190 GW (S. Szatmari and coll.)

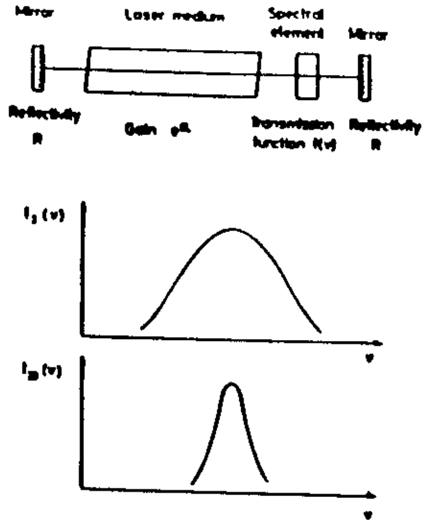
Narrowband beams

- The spectral profile of the laser light is determined by two factors: the gain bandwidth and the selection on longitudinal oscillating modes operated by the cavity.

- In order to have only one longitudinal mode, the distance between two modes next to each other $\Delta\lambda_m$ should be greater than the gain width $\Delta\lambda_G$. For excimer active media $\Delta\lambda_G$ is of ~20 Å ($\Delta\nu_G \sim 10^{12} \div 10^{13}$ Hz), while $\Delta\lambda_m = \lambda^2/2\ell \simeq 10^{-4}$ Å, for $\lambda = 100$ nm and a typical cavity length $\ell = 50$ cm, so that there are numerous oscillating modes.

- Oscillation on few longitudinal modes, up to the single mode, with a big reduction of the spectral linewidth, can be done by inserting dispersive elements in the cavity, like prisms and gratings, or etalons.

- Single mode operation has been obtained on XeCl lasers with more than one etalon in the cavity; the measured bandwidths were, 30 MHz (T. J. PACALA et al. - 1984)



VERY LONG PULSES

When they are important:

material processing, if high peak power, with ablative processes, must be
ided
en the laser beam must travel in silica fibers (e.g.in medical applications)
ause the damage limit of the fibers is associated with the
k power, not with the average power

T

conventional systems, the pulse length , when the laser is operayted in the
f-sustained discharge mode, is shorter than 200 nsec.

is is due to discharge instabilities

scharge has been stabilized by means of external ballast resistors (Webb) or
ng segmented cathodes (Sze)

crosec. pulses have been achieved

LONG PULSES - PREPULSE OR DOUBLE PULSE TECHNIQUE

-The self-sustained discharge has two different phases with respect to electron number density n_e

- in the first phase (few nanosec) n_e increases from about 10^8 to 10^{14} e/cm ^{3} , while t energy flow in the gas is very limited.
- in the second phase n_e is almost constant, while energy flow in the gas is high

- the two phases are driven by the applied external field, and optimization would require E(t) = 3*E(t)

- using only one discharge circuit optimization for the two phases cannot be achieved

- with the use of two different circuits higher efficiency (up to 4%) and longer pulses (up to 1 microsec) have been achieved

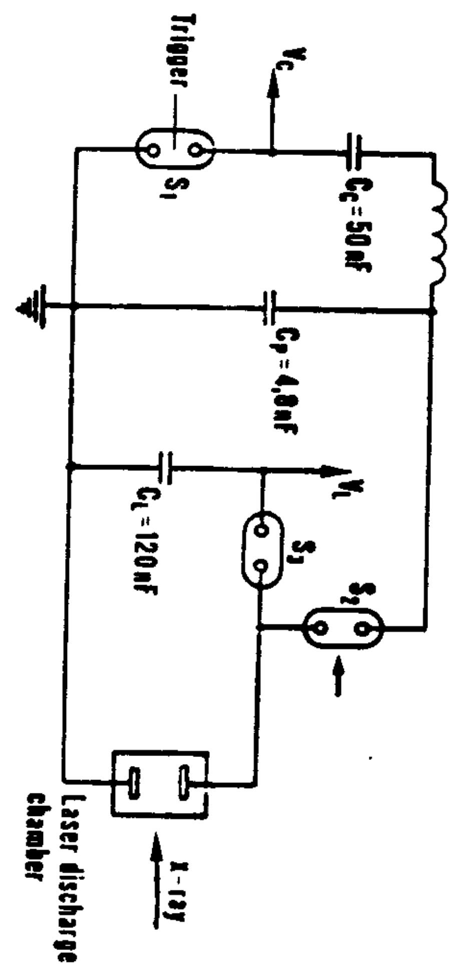


Fig. 18. Schematic diagram of the laser discharge circuit with a tentative voltage prepulse subcircuit.

HIGH ENRGY PULSES
SELF-SUSTAINED DISCHARGE OPERATION

-Several parameters limit the scalability of self-sustained discharge systems high energy/pulse

A - rise time of the discharge current on the laser head

$$T = \frac{L_{th}}{R_d}$$

L_{th} inductance of the laser head - increases with the cross section

R_d resistance of the discharge - in about ten ns, it drops to fraction of ohm

T rise time of the discharge current: it cannot be to high, due to discharge instabilities which limit the useful pumping time for laser action

B - skin depth effect - The discharge behaves as an electrical conductor: the larger is the cross section, the longer is the time required to rech the inner part

C - instabilities of the discharge : XeCl is more suitable for large volume operation than KrF

Best results obtained up to now in a self-sustained discharge module

(L.F.Champagne et al. J.Appl. Phys. 62 (1987)1576)

module : 20 x 20 x 100 cm^3

Max. Energy/p   60 J in a pulse 120 ns long

HIGH ENERGY PULSES – e– BEAM PUMP

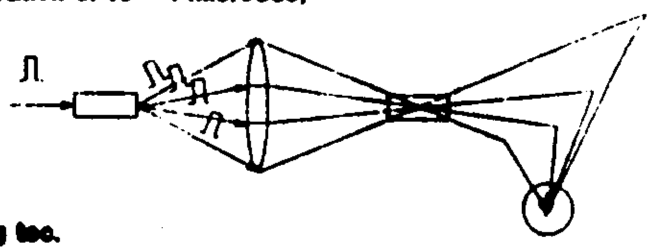
- Short w.l. laser pulses of very high energy (>> KJ/p) are required for inertial confinement fusion

-scaling to such high energies can be done only in systems with e–beam pumping

-KrF is (today) the best candidate for high efficiency (>10%) and short w.l. (248 nm)

-ICF requires short pulses (< 5 ns) while technically high energy pulses can made ,in e–beam pumped systems, with pulse duration of .5 – 1 microsec)

-angular multiplexing, as pulse compression technique, has been succesfully developed



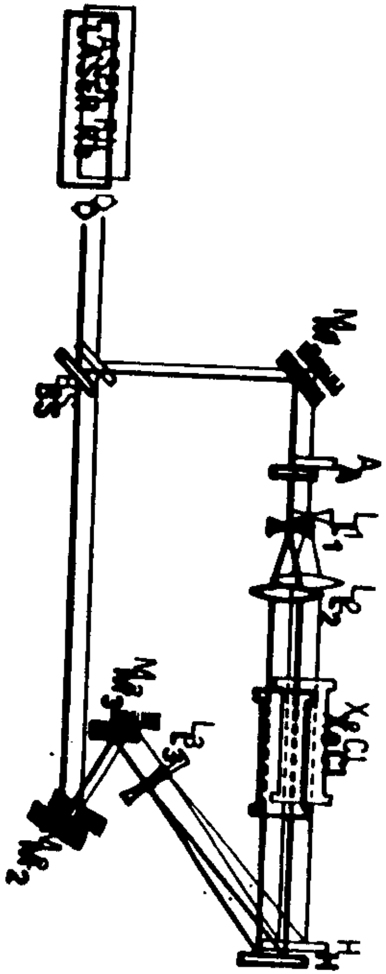
-Los Alamos Nat.Lab
LAM – Large Aperture Module
10 KJ in 600 ns – 2.5 KJ in 5 ns with multiplexing tec.

ELECTRON DENSITY MEASUREMENTS BY HOLOGRAPHIC INTERFEROMETRY

- This technique uses the dependence of plasma refractivity on electron density

-It uses the holographic inteferometry technique: two holograms, at a short time interval are overlapped in the same film plate: if the optical path changes between the two exposures, interference fringes are observed

-with double pulse operation high temporal resolution,high spatial resolution, and freedom from stability problems are possible



ACCURACY OF THE METHOD:

Plasma refractivity $(n-1) = (n_e - 1) + \bar{Z}_k (n_k - 1)$

If $\begin{cases} \omega_{laser} \gg \omega_{plasma} \\ \omega_{laser} \neq \omega_{k\ resonance} \end{cases}$

$$\Rightarrow (n-1) \approx \bar{Z}_k \left(A_k + B_k/\lambda^2\right) N_k - 4.47 \cdot 10^{-14} N_e \lambda^2$$

Normalized fringe shift S caused by introducing an optical path difference:

$$S = \frac{L}{\lambda} \Delta(n-1) = \Big[\underbrace{\bar{Z}_k \left(\frac{A_k}{\lambda} + \frac{B_k}{\lambda^3}\right) \overline{\Delta N_k}}_{\text{negligible if}} - 4.47 \cdot 10^{-14} \bar{N}_e \lambda\Big] L$$

negligible if

$$\frac{\overline{\Delta N_k}}{\bar{N}_e} \ll \frac{4.47 \cdot 10^{-14} \lambda^2}{A + B/\lambda^2} \approx 90 \text{ for } \begin{cases} k = \text{Neon} \\ \lambda = 694\,\text{nm} \end{cases}$$

SENSITIVITY OF THE METHOD:

Assuming $S_{min} = 0{,}1 \Rightarrow (\bar{N}_e L)_{min} \sim 3.2 \cdot 10^{16}\ \text{cm}^{-2}$

for $L = 80\,\text{cm} \Rightarrow (\bar{N}_e)_{min} \sim 4 \cdot 10^{14}\ \text{cm}^{-3}$

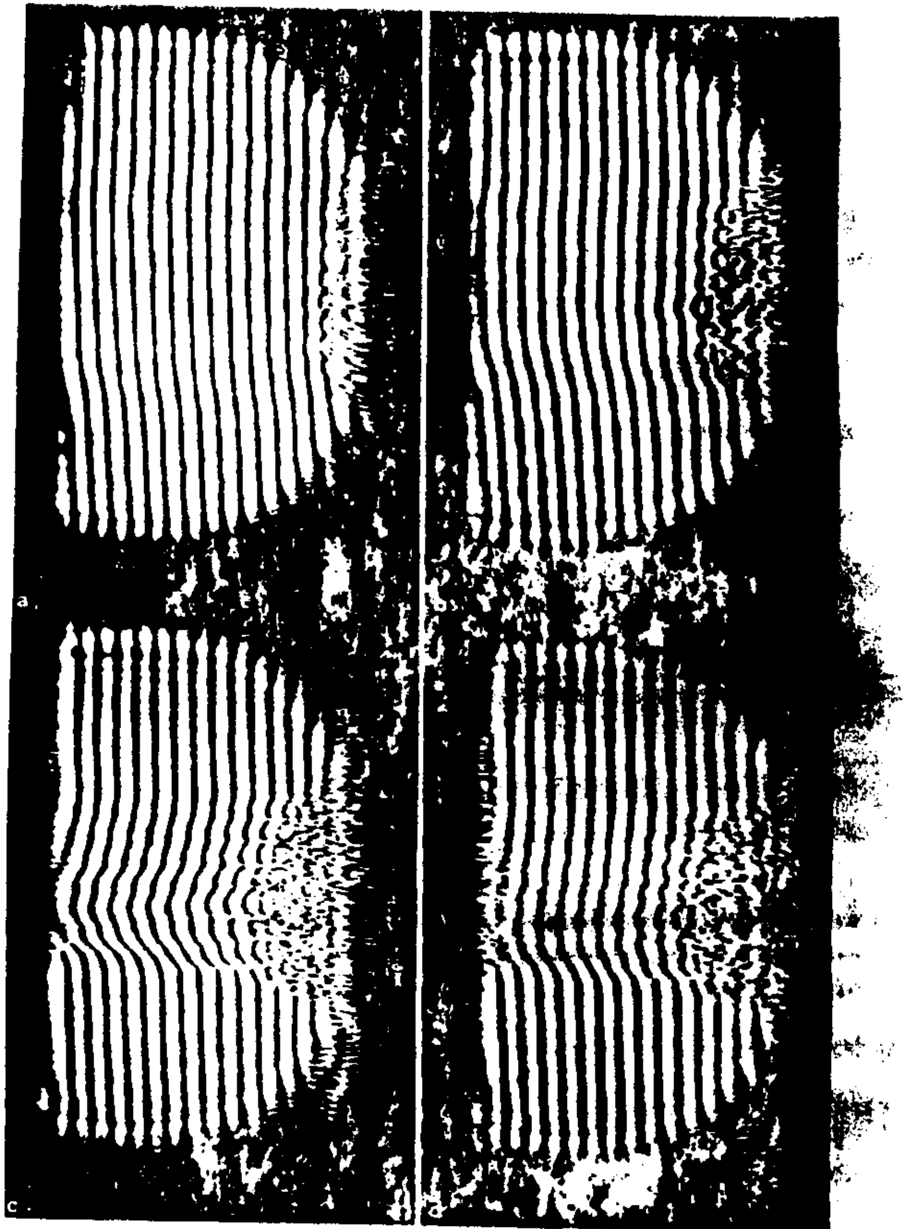
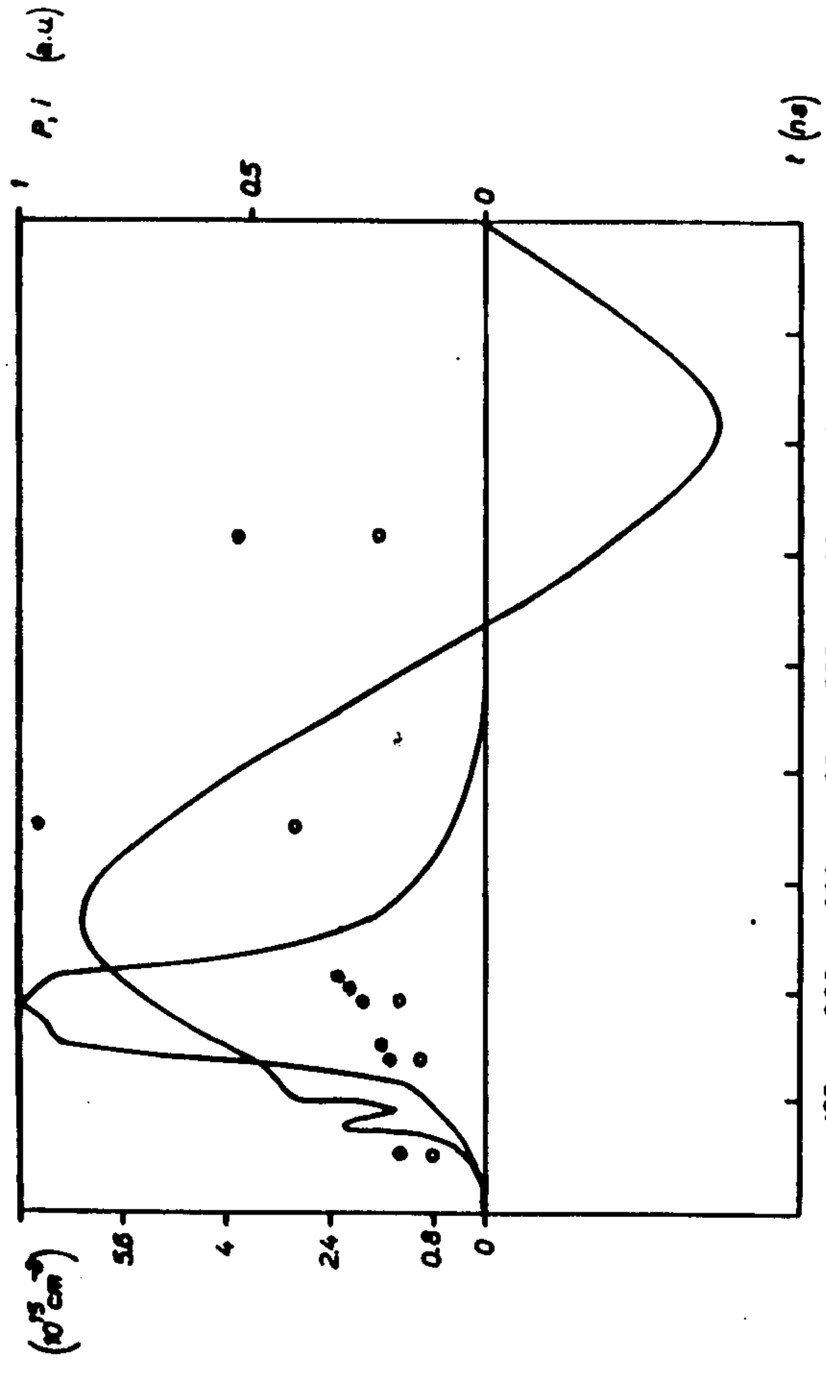
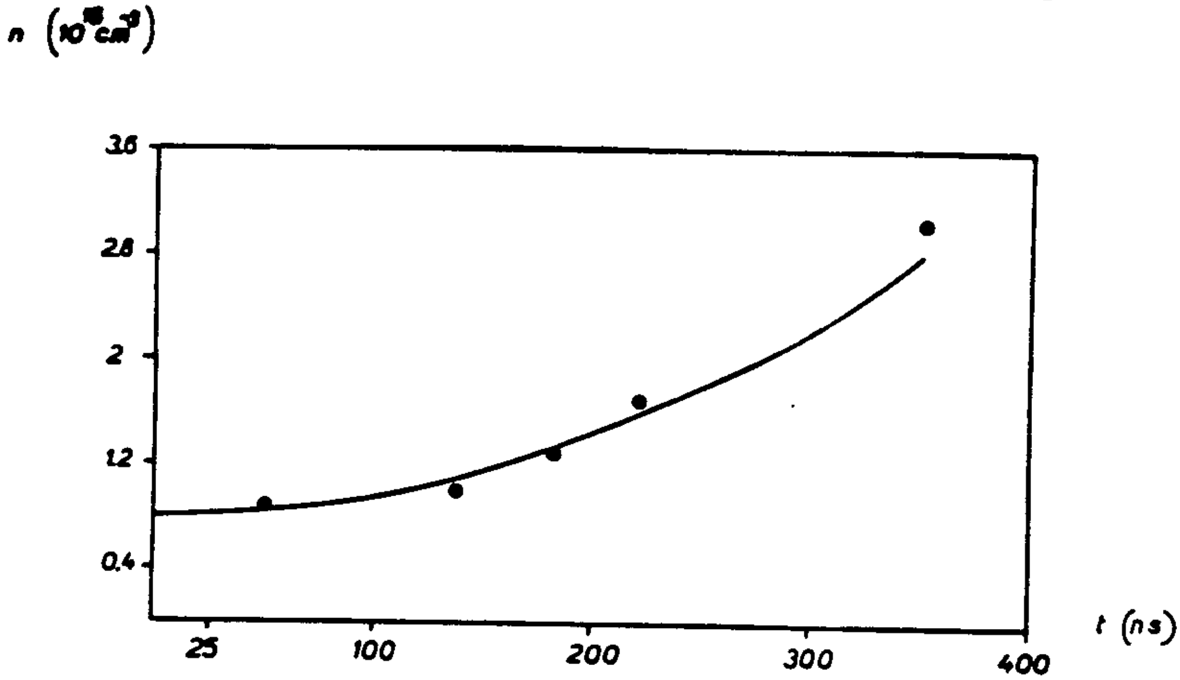


Fig. 2 - Typical interferograms of the XeCl active medium with an electrode separation of 4 cm. Delay time since the discharge breakdown: a) 135 ns; b) 215 ns; c) 350 ns; d) 615 ns. The discharge filamentation growth in the cathode region is clearly visible



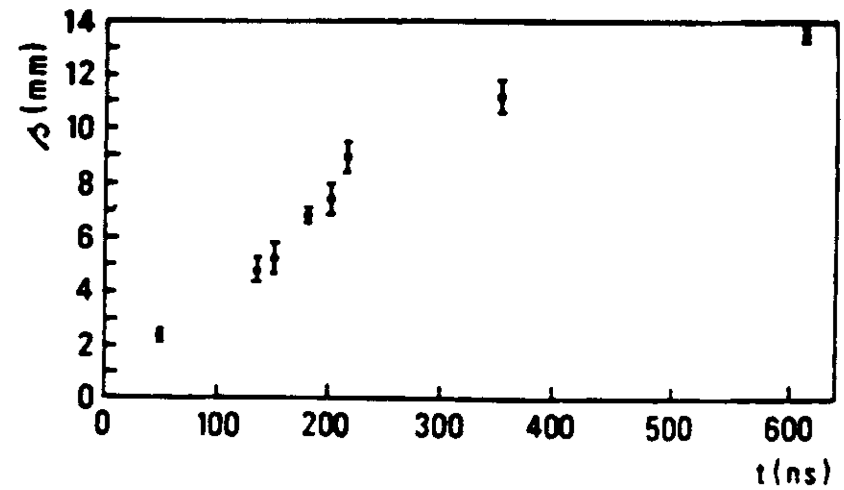
$$n_e(t) \sim n_e(0)\left\{1 + \frac{K^2 n_e(0)\, t^2}{2}[HCl]_0\right\}$$



$[HCl]_0 = 4.9 \cdot 10^{15}\ cm^{-3}$

$n_e(0) = 8 \cdot 10^{14}\ cm^{-3}$

$K = 10^{-9}\ cm^3/sec$



CONCLUSIONS

- AT THE INITIAL STAGE OF THE DISCHARGE, HOT SPOTS DO DEVELOP IN THE CATHODE SHEAT
- THEN, HALOGEN GAS PROMOTES THE INITIAL GROWTH OF A WELL DEFINED FILAMENT FROM EACH HOT SPOT
- THE FILAMENTS GROWTH (RATE 4•10^6 cm/s) LEADS TO THE GLOW DISCHARGE COLLAPSE
- ALTHOUGH ELECTRICAL POWER CAN STILL BE DEPOSITED INTO THE DISCHARGE IN A FULLY DEVELOPED FILAMENTARY MODE WITHOUT ARCING, STRONG INDUCED DISCHARGE INHOMOGENEITIES LEAD TO PREMATURE LASING DISRUPTION
- FIRST DIRECT EXPERIMENTAL CHECK OF THE LOCAL DEPLETION HALOGEN GAS MODEL

LONG OPTICAL PULSE XeCl LASER OPERATION CAN BE OBTAINED USING LOW [HCl] AND LOW ELECTRICAL POWER DEPOSITION, AT THE EXPENSE OF OUTPUT ENERGY AND EFFICIENCY OF THE SYSTEM.

Propagation of a laser beam in an active medium

g° small signal gain cofficient

α non saturable losses coefficient

I_s saturation intensity

$$\frac{dI(x)}{dx} = \left[\frac{g^{\circ}}{1+\frac{I(x)}{I_s}} - \alpha\right] I(x)$$

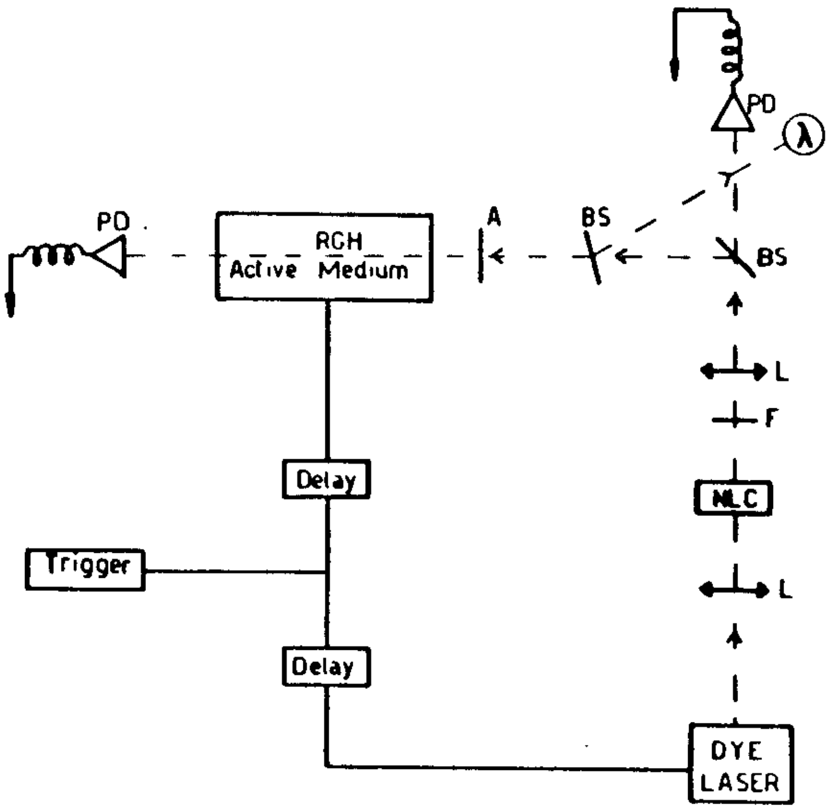
When the condition $I(x) \ll I_s$ is always fulfilled, we can write

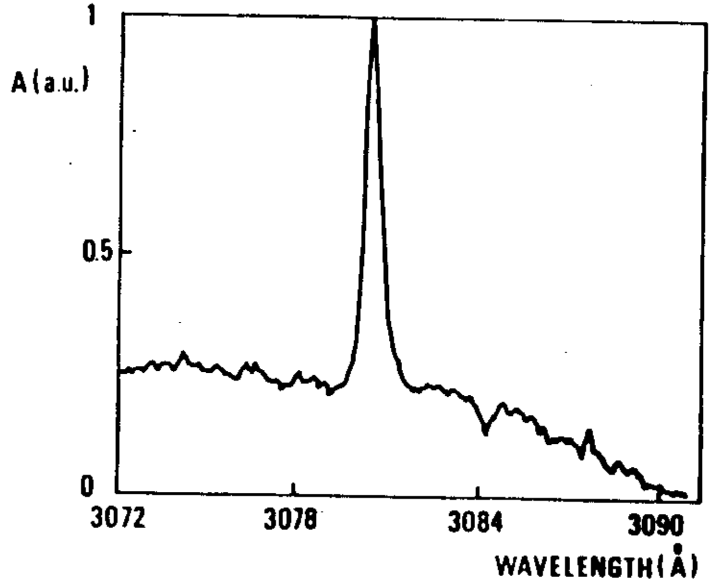
$$\frac{dI(x)}{dx} = (g^{\circ} - \alpha) I(x)$$

Integrating

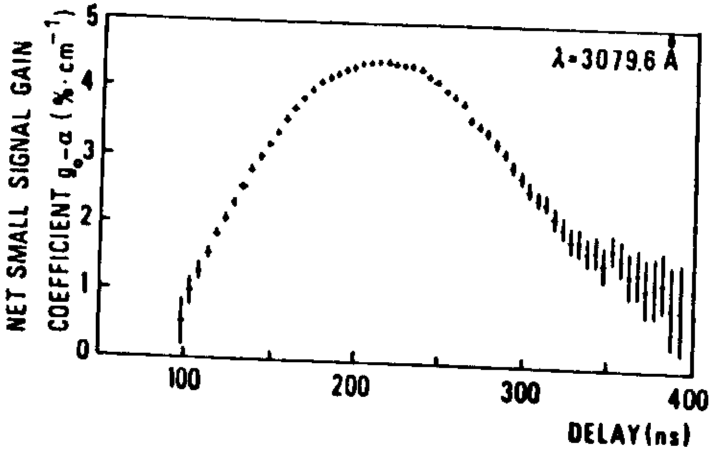
$$I(x) = I_{in} \exp\left[(g^{\circ} - \alpha)x\right]$$

$$\frac{I_{out}}{I_{in}} = \exp((g^{\circ} - \alpha)L)$$





Spectral dependence of the tunable probe dye laser g.



$P_d = 200\ Kw/cm^3$