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DRAFT

LAUNCHING OF MICRO-SATELLITES USING GROUND-BASED HIGH POWER PULSED LASERS

DEPS 6TH Annual Directed Energy Symposium

20-24 October 2003



**V. Hasson
Trex Enterprises, San Diego, CA**

**F.B. Mead, Jr. & C.W. Larson
Propulsion Directorate
Edwards Air Force Base, CA
Air Force Research Laboratory**

Agenda

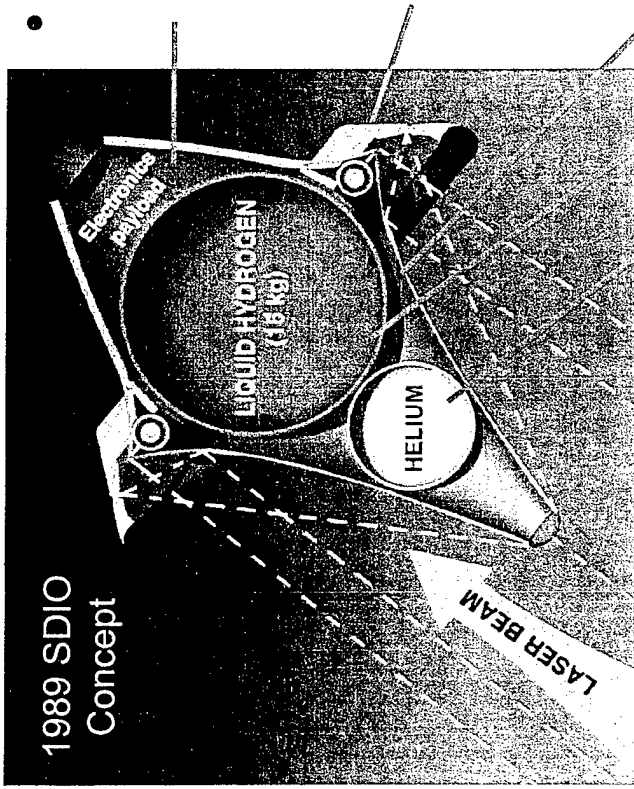
- **Laser Propulsion Concept**
- **Candidate High-Power Lasers**
- **Pulsed Carbon Dioxide Laser Technology Overview**
- **Relevant Legacy Programs**
- **Candidate Concepts/Architectures**
- **Propagation Enhancement Concepts**
- **Program Plan/Schedule**
- **Conclusions**

Why Laser Propulsion?

- **Benefits**
 - Avoids carrying heavy propulsion system components through the atmosphere and into space; the laser is not on board
 - Higher performance potential than chemical rockets
 - Higher thrust than electric propulsion concepts
 - None of the polluting or radioactive exhaust associated with chemical or nuclear rockets
 - Can be accomplished by extensions and integrations of existing rocket propulsion technologies; no physics breakthroughs required
 - Repeatedly shown to be economically viable; AF, NASA, and DARPA have all done independent studies
- **Draw Backs**
 - Requires expensive, high power laser which is typically not mobile
 - Lacks complete demonstration after 33 years from conception

The benefits outweigh the negative aspects!

The Lightcraft Concept



- A Lightcraft is a small spacecraft; diameter is about 1 m, weight is about 2 kg (1 kg payload)

Forebody

- Aerodynamically contoured surface
- Analogous to rocket payload bay; opens in space to release payload and expose solar cells

Shroud

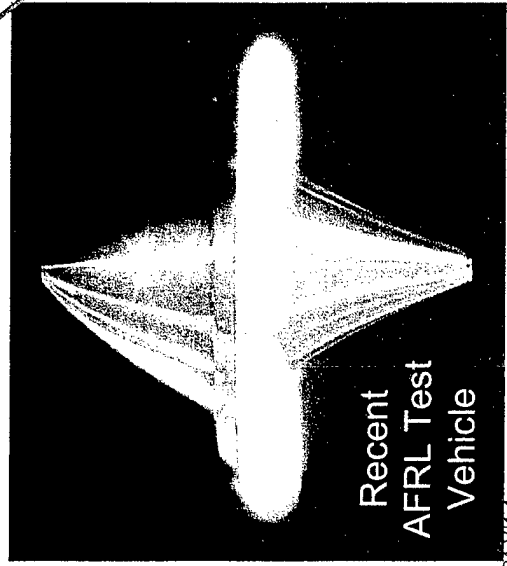
- Centrally located "belt"
- Analogous to rocket combustion chamber; ejected plasma provides thrust

Afterbody

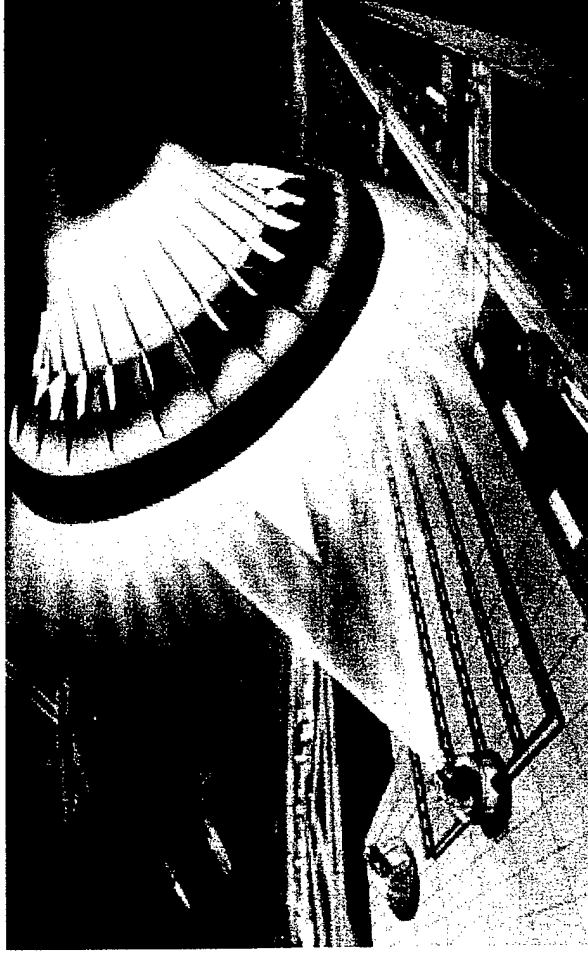
- Analogous to rocket nozzle; parabolic mirror and plug nozzle (resolution: 7 to 15 cm)

Large tank holds liquid propellant (N_2 , NH_3 , or H_2) for use in space

Small tank holds gas (He) for attitude control

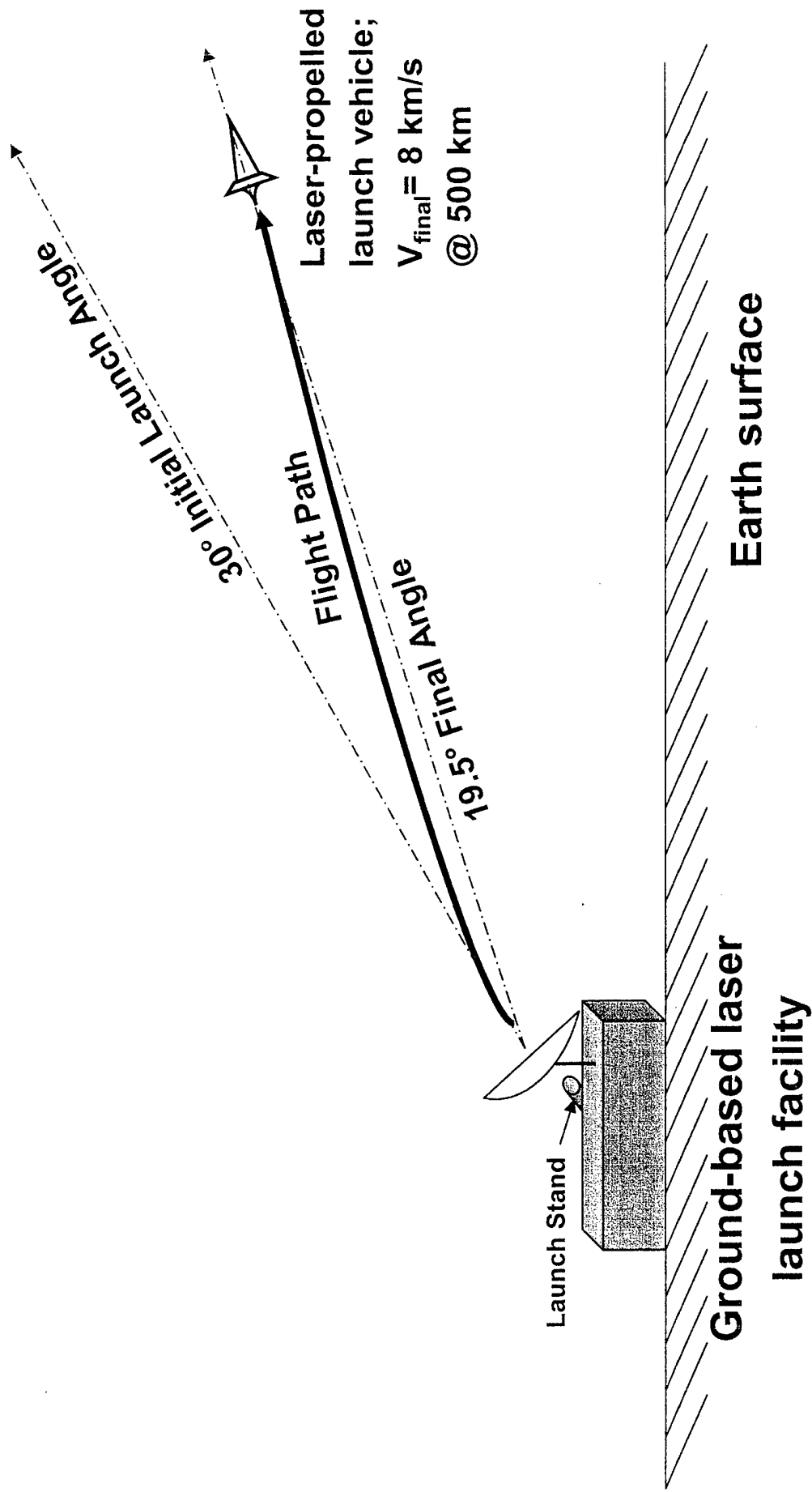


Low Cost Access To Space: The Primary Lightcraft Application

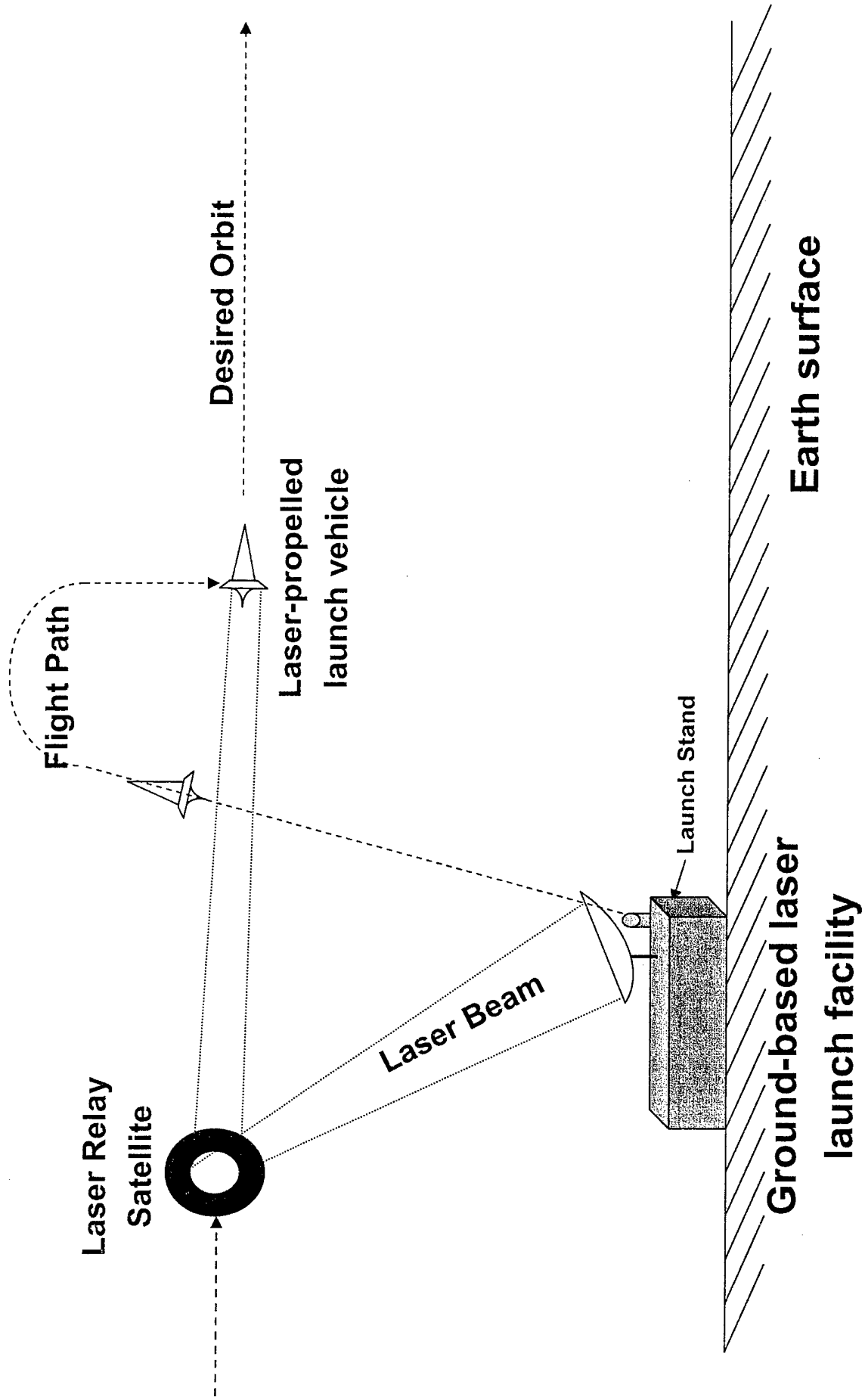


- Laser-propelled beam rider
 - Rides ground-based laser beam into space
 - Single stage to orbit
 - Very high performance
 - Airbreathing in atmosphere, uses propellants in space
 - Launch on demand to anywhere in low Earth orbit
- Simple, reliable, safe, environmentally clean
- High launch rate – anywhere, anytime with electric laser
- Less than \$500 of electrical power (~\$150/lb) needed to reach low Earth orbit
- Vehicle production cost estimated at \$3,000 per vehicle (1 kg payload)
- Interest in this concept expressed by AF, NASA, DARPA, NRO

Ground-Based Laser Launch: Launch From A Single Site ("89" SDIO Study)

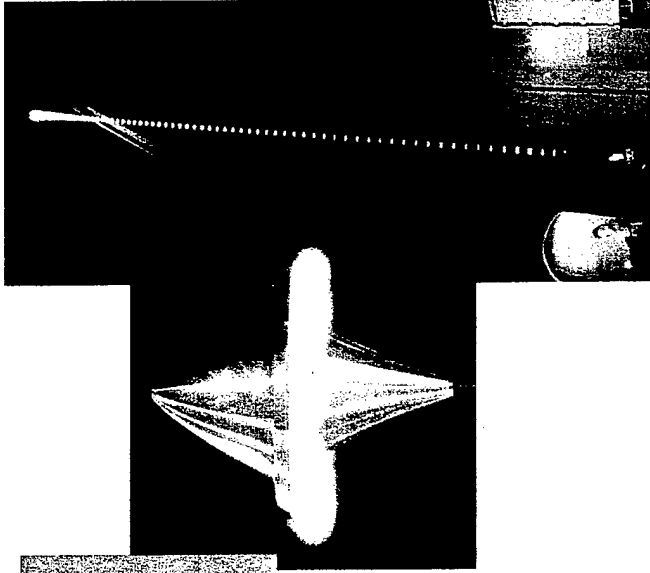


Ground-Based Laser Launch: With Use Of Space Assets ("89" SDIO Study)



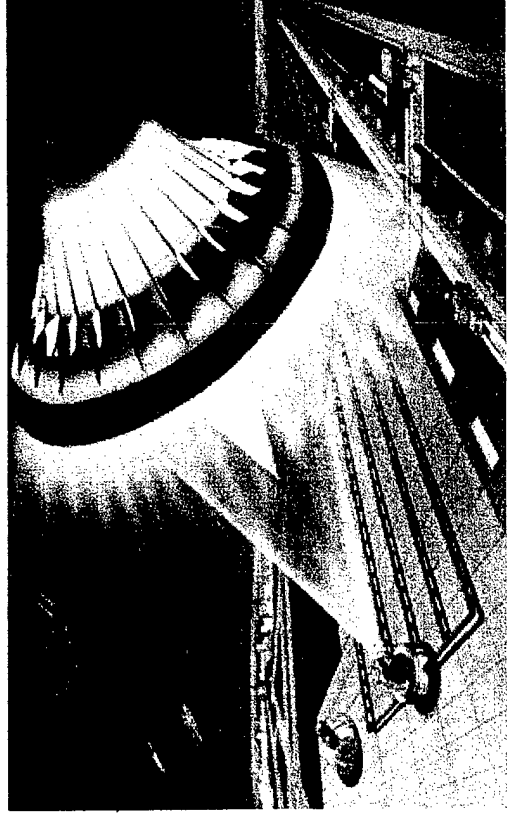
Program Summary

- Feasibility demonstrated through a series of historic flights and experiments at White Sands
- Composite materials and a 100-kW laser will enable vertical flights to the edge of space within a few years
- No technology breakthroughs are needed, although construction of a MW class laser and large beam director will be required
- Laser propelled vehicles could be useful in a wide range of applications



***Taking us
from here ...***

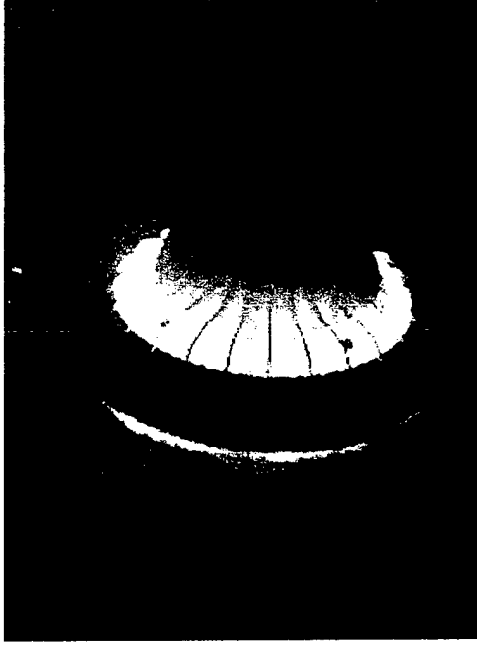
... To there.



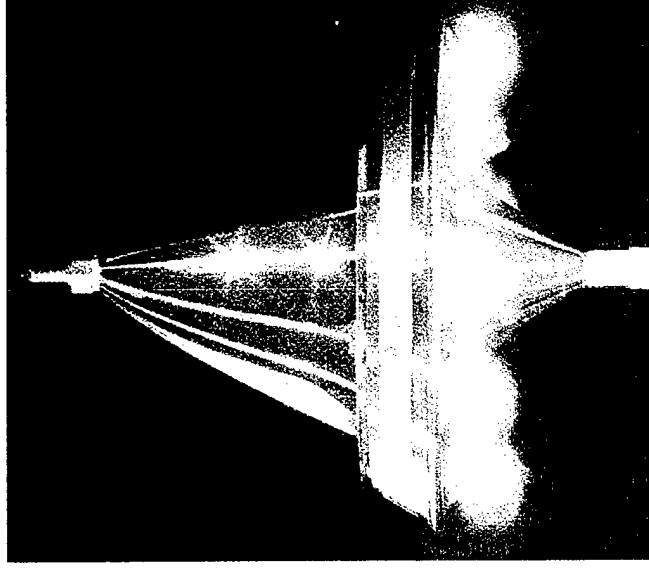
Laser Propulsion technology has the potential to make low-cost access to space a reality in the near future

Additional Laser Propulsion Applications

- “Nanosatellites” : 1 to 10 kg – for a wide range of applications
 - Potential use by AF, NASA, BMDO, NRO, communication companies, private industry, individuals
 - Launch on demand to anywhere in low Earth orbit



- A vehicle can be configured as one-meter diameter telescope, making it useful for:
 - High-resolution imaging, surveillance, and mapping
 - Global positioning and tracking
 - Threat detection and tracking
 - Communications and relay
 - Astronomy



CANDIDATE HIGH-POWER LASERS

LASER

ISSUES

CO₂*

LARGE λ , ATM. ABSORPTION

CO*

LARGE λ , ABSORPTION, TOXICITY

HF/DF*

ABSORPTION, CORROSIVE
CHEMICALS,
PULSE ENERGY (?) RUNNING COST,
BEAM QUALITY

OXYGEN IODINE*

CHEMICALS, PULSE ENERGY (?)
RUNNING COSTS

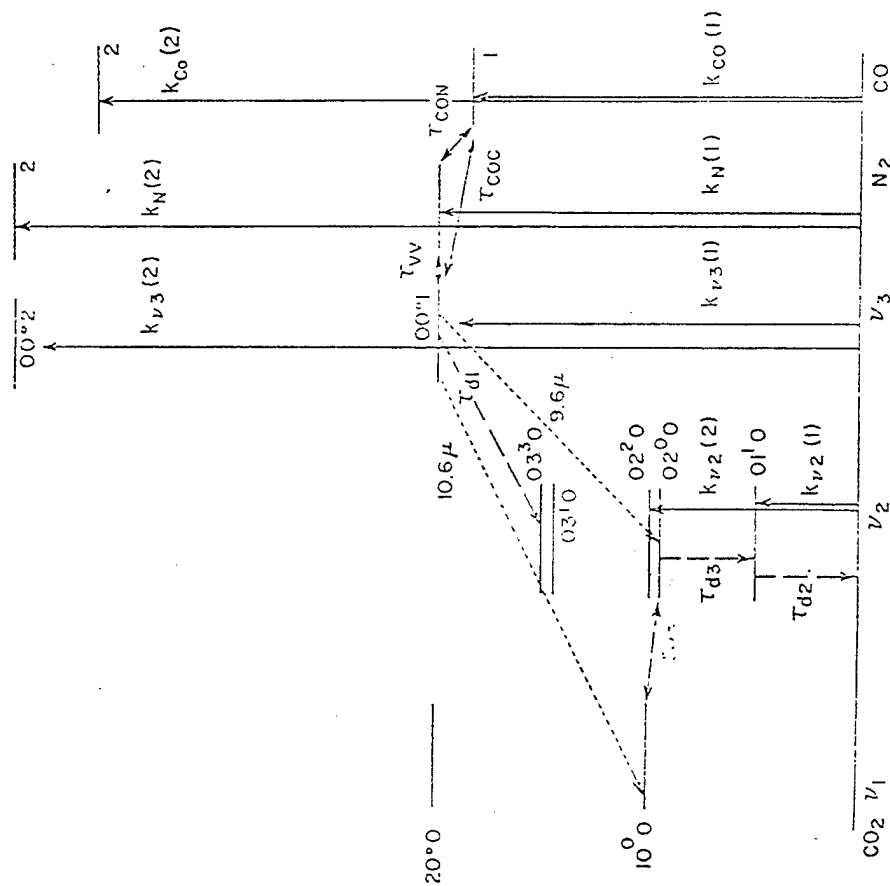
NEODYMIUM

COST, AVERAGE POWER, RUN
DURATION

*MW-CLASS AVERAGE POWER LEVELS DEMONSTRATED

PULSED CARBON DIOXIDE LASER TECHNOLOGY OVERVIEW

Energy Levels for the Three Vibrational Modes in the CO₂ Molecule with those of N₂ and CO



Basic Rate Equation and Discharge Categories

$$\dot{n}_e = S - (a + \beta)n_e - \gamma n_e^2 \quad (1)$$

S = E-BEAM SECONDARY ELECTRON GENERATION RATE

a = IONIZATION RATE

β = ATTACHMENT RATE

γ = RECOMBINATION RATE

• E BEAM SUSTAINED

$$N_E \approx \sqrt{S/\gamma}$$

• S/SUSTAINED LONG-PULSE

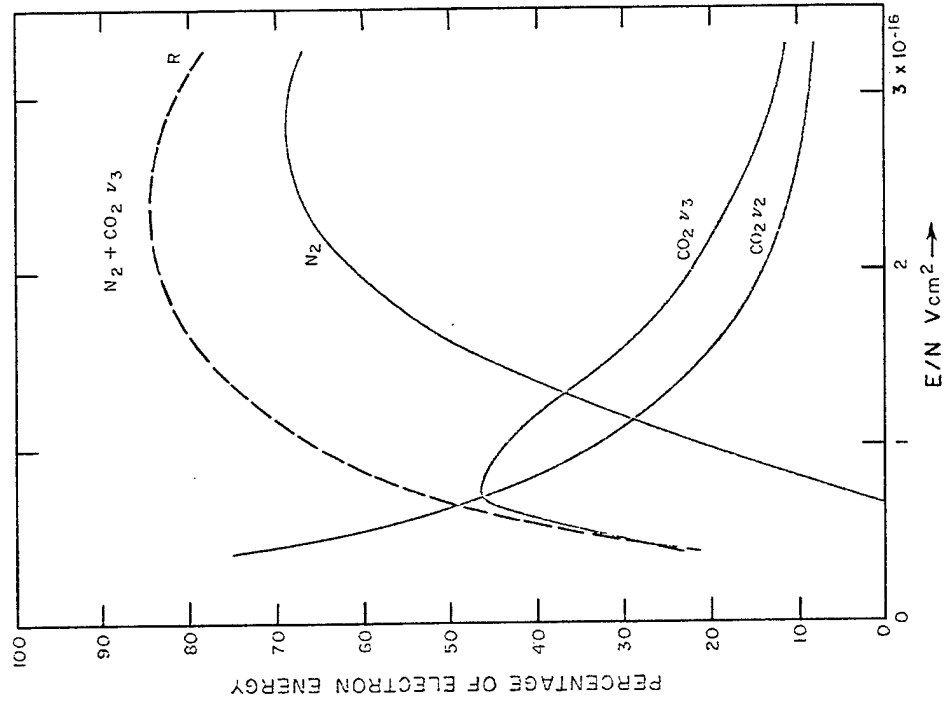
$$a = \beta \alpha(E/N)_G$$

• S/SUSTAINED SHORT-PULSE

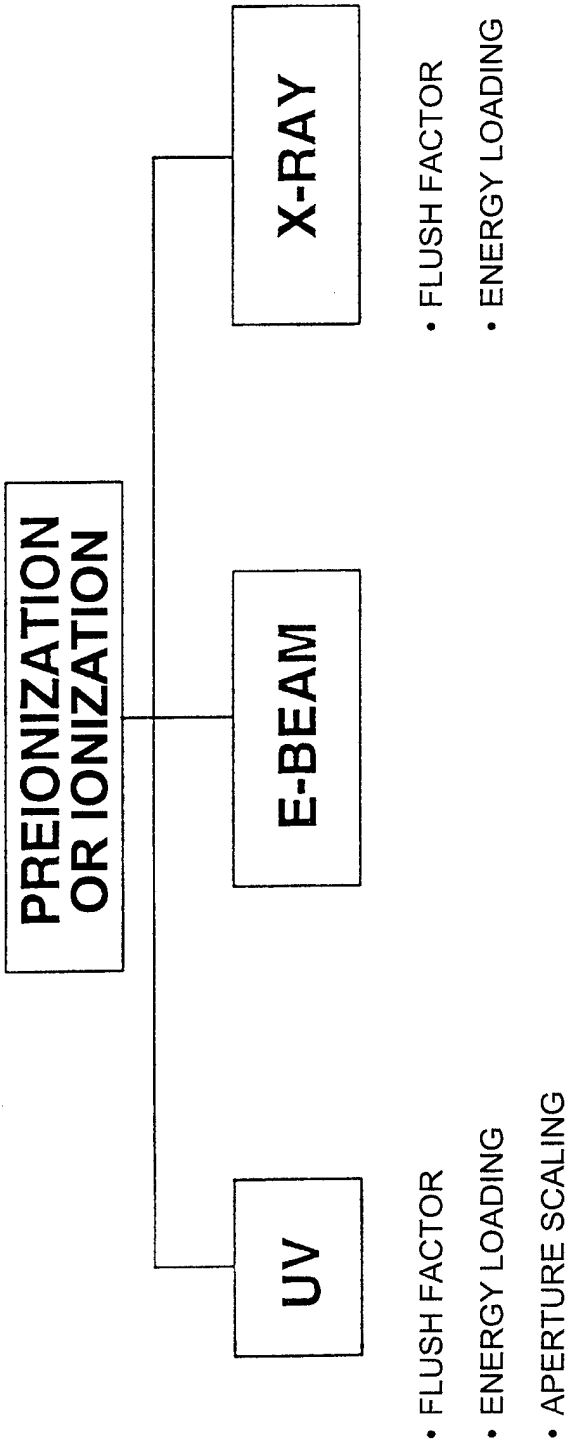
$$\gamma N_E \gg \beta$$

$$a \approx \gamma N_E$$

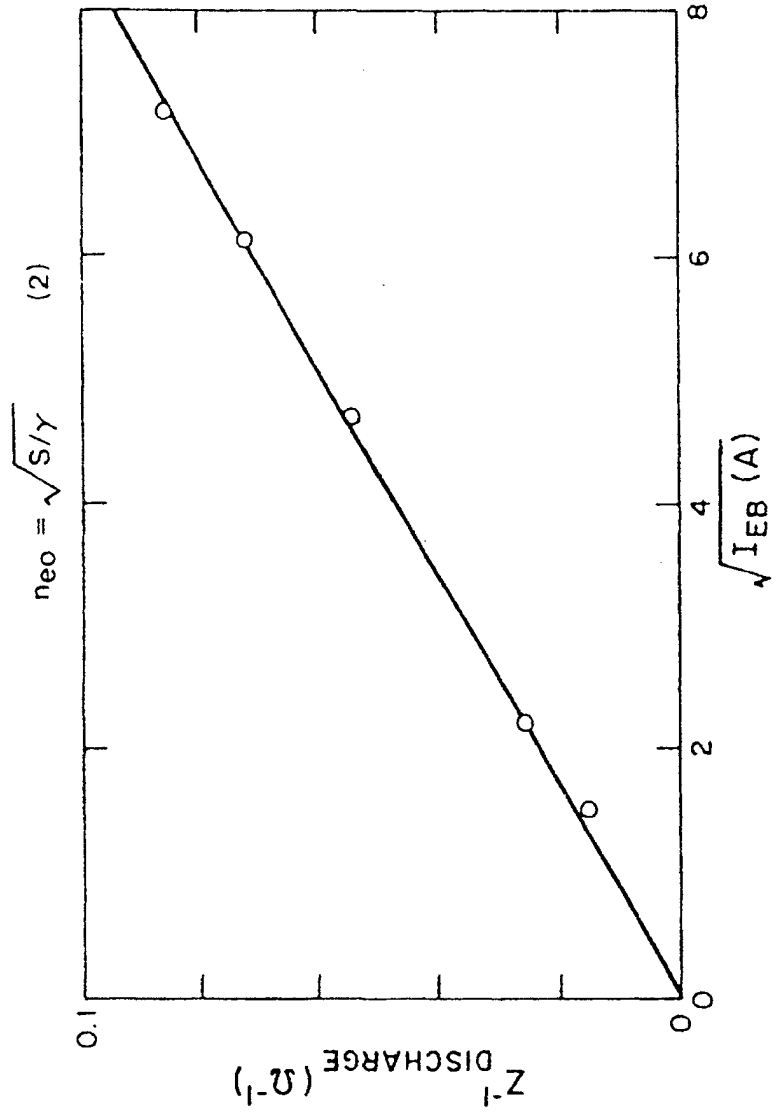
Fraction of Discharged Energy Deposited in Various Modes of a He: N₂: CO₂ 3:2:1 Mixture



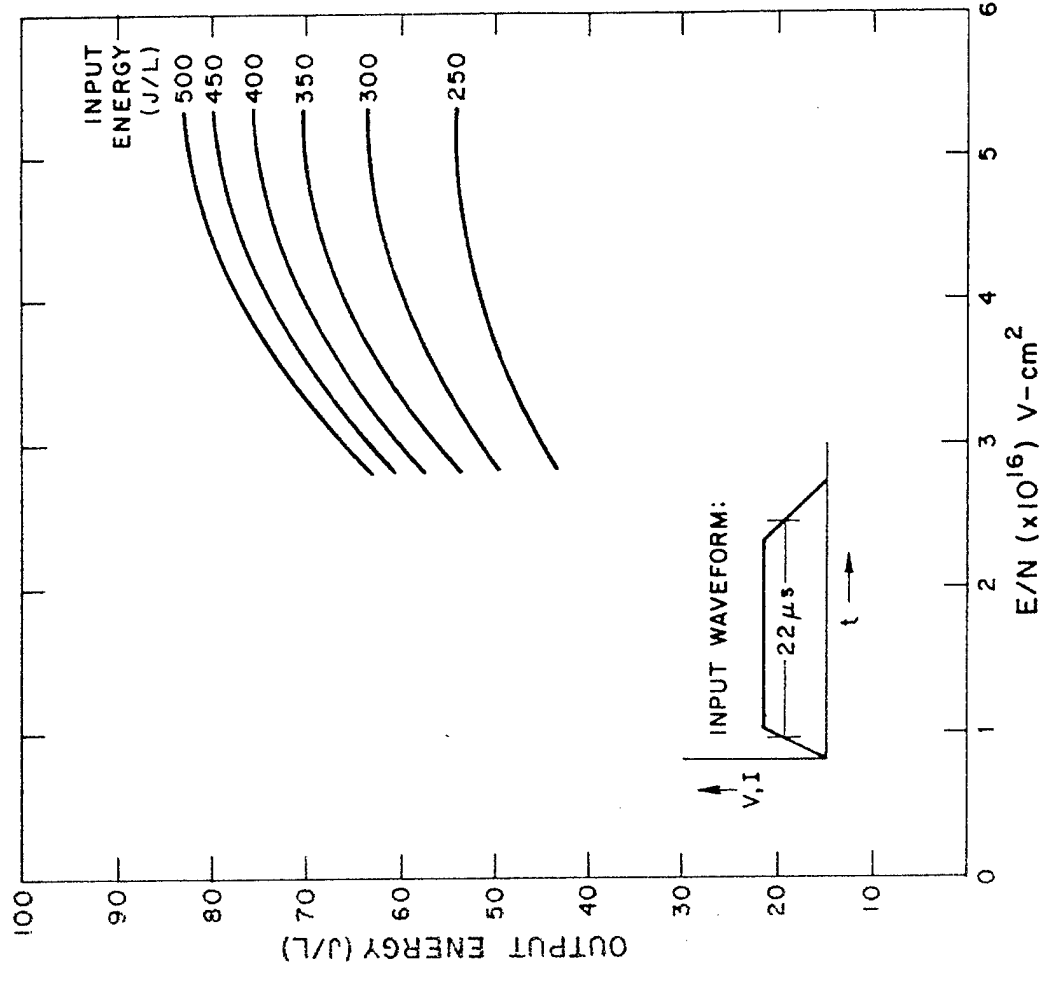
Discharge Preionization or Ionization Options



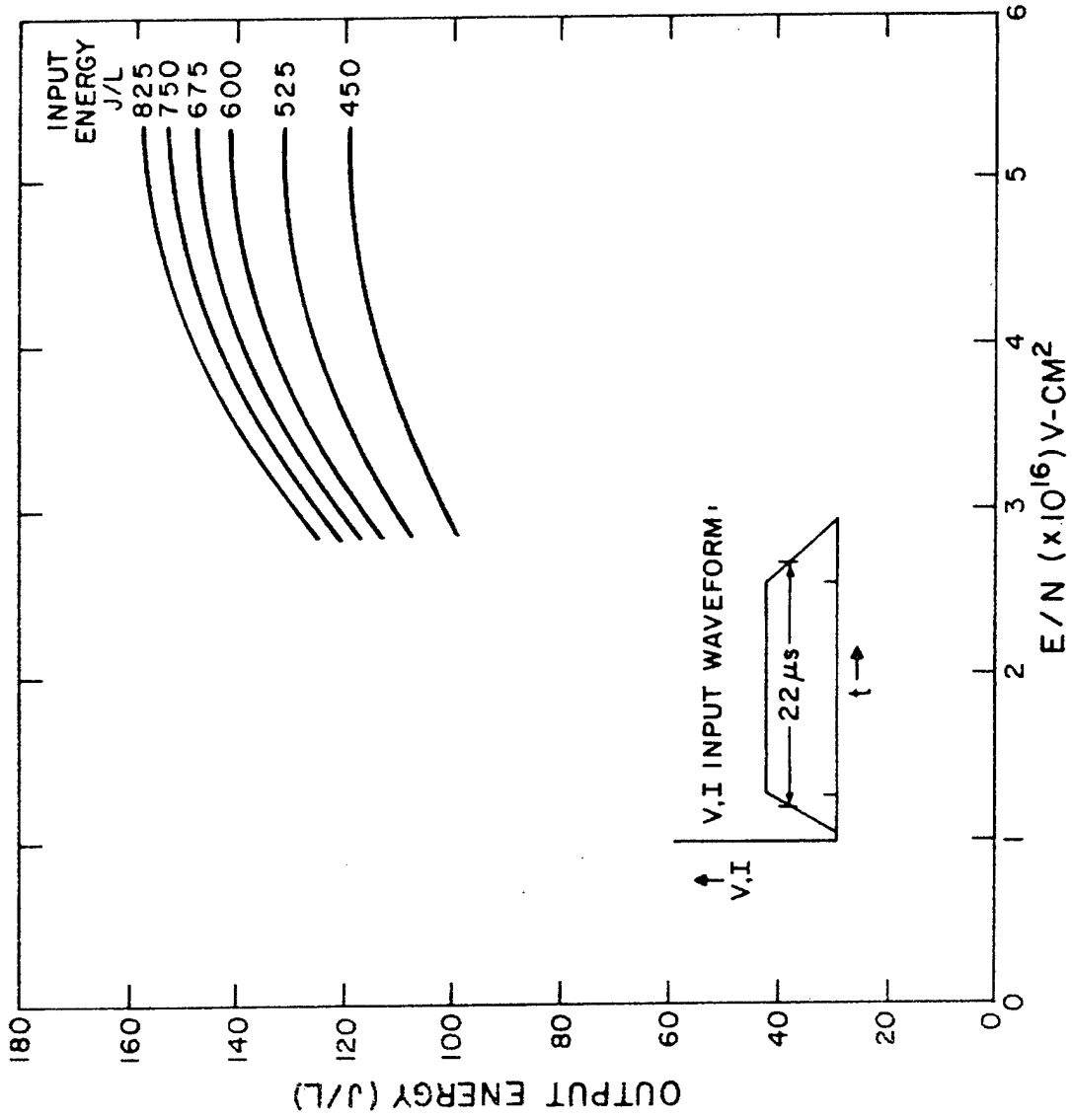
Experimental Data Verifying Conductivity Dependence of E-beam Stabilized Discharge



Specific Output Energy (Room Temp-gas)

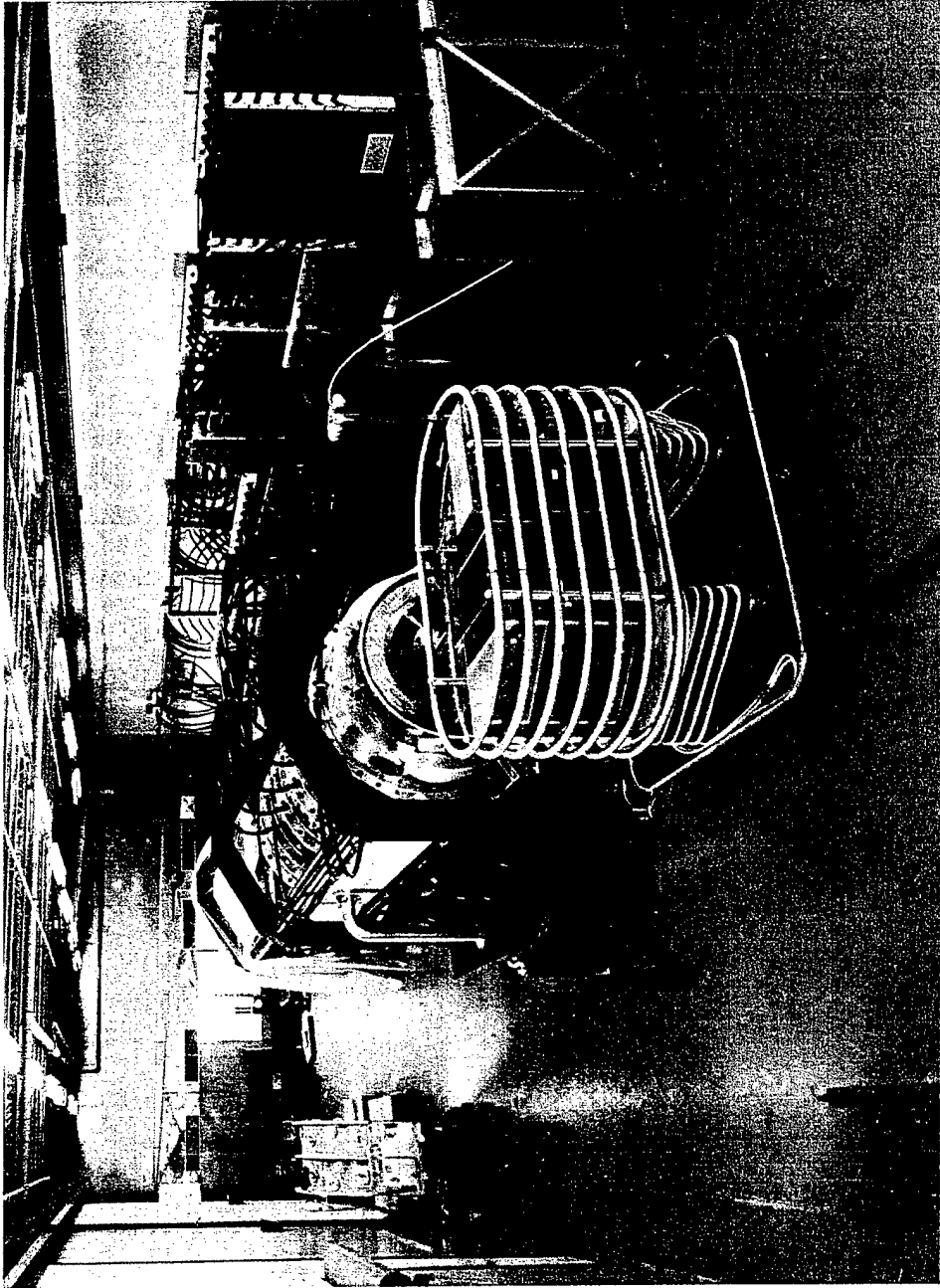


Specific Output Energy (Cold-gas - 220°K)

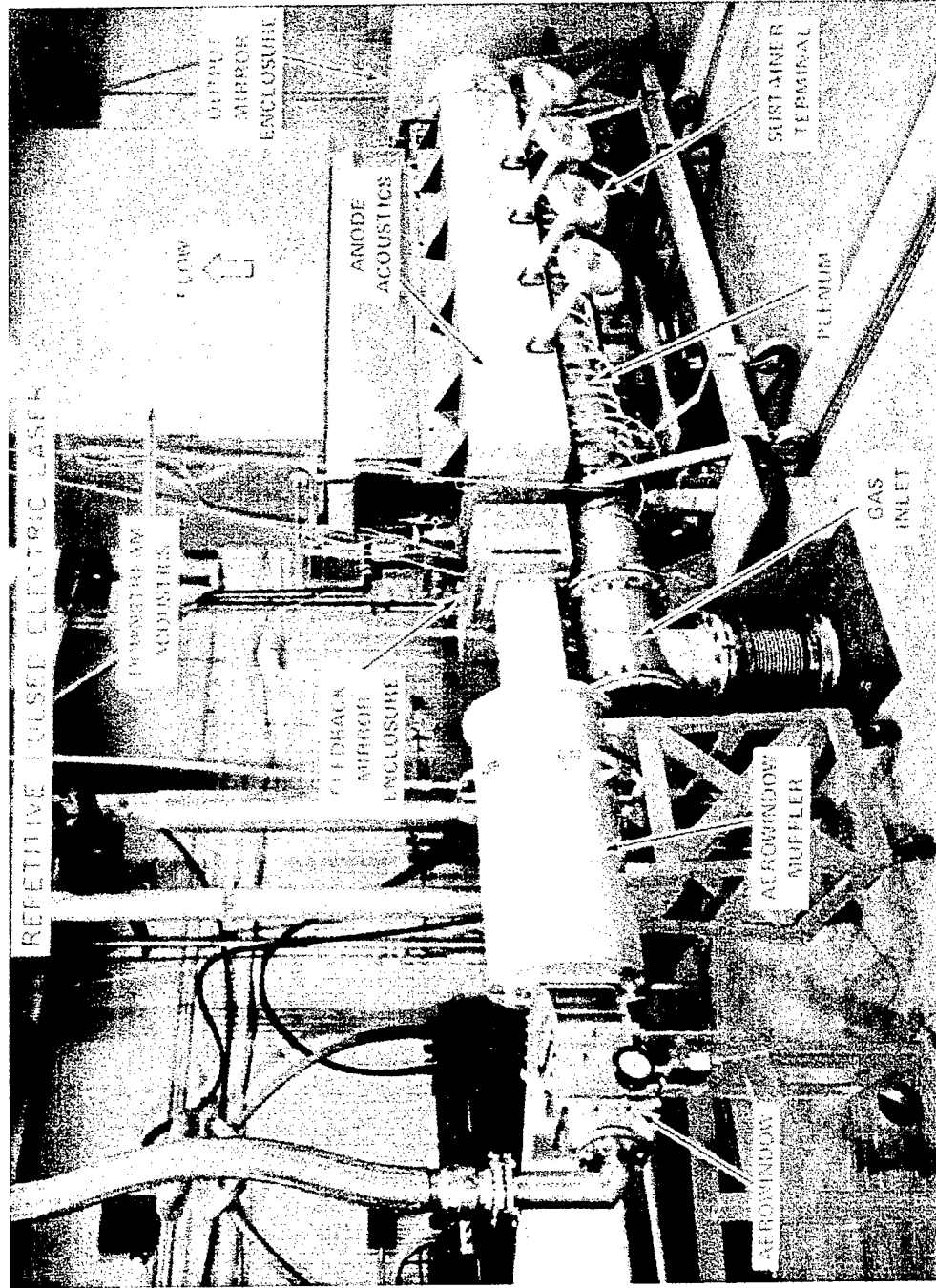


RELEVANT LEGACY PROGRAMS

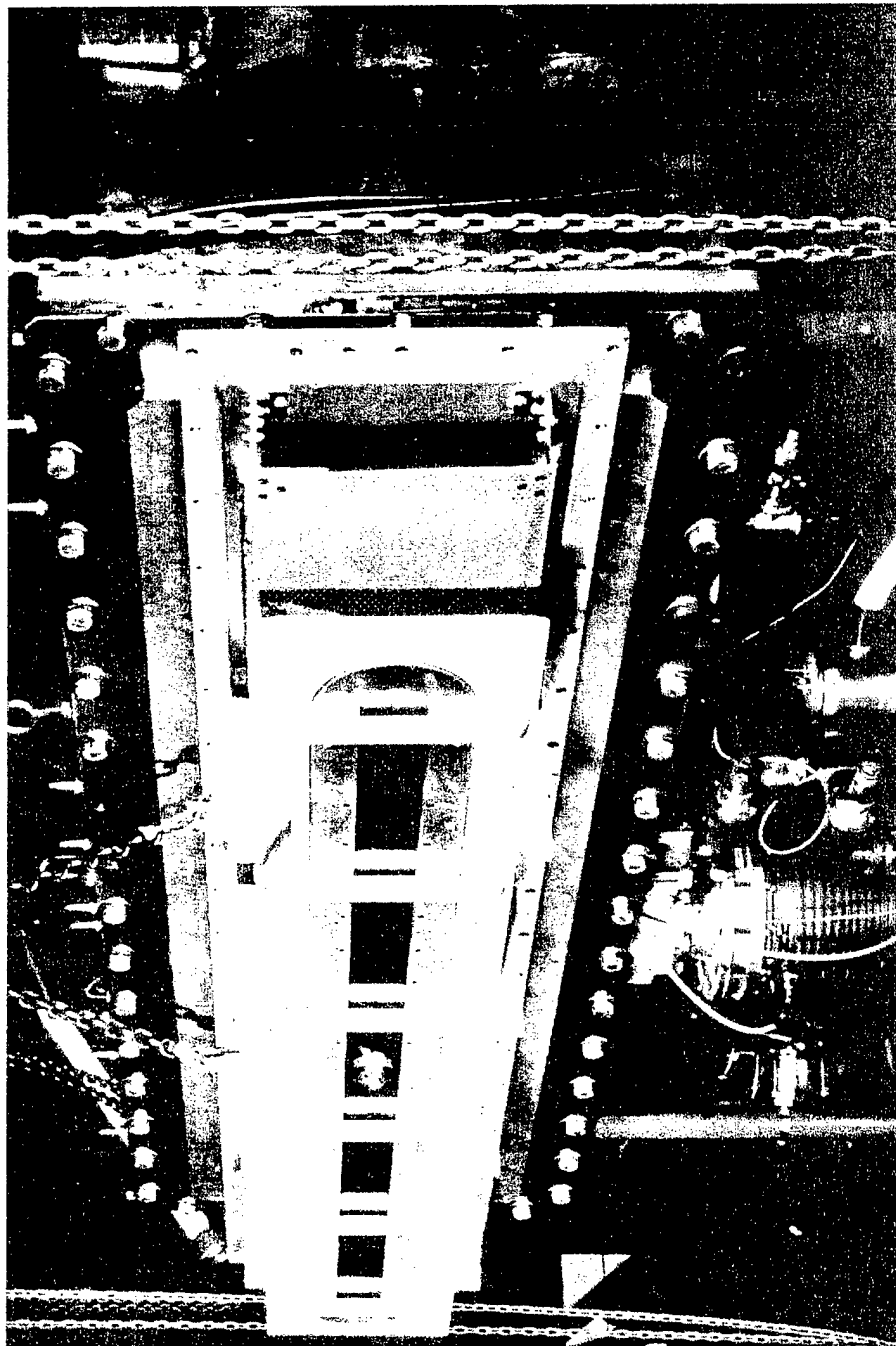
Thumper Laser



ABEL Breadboard Laser



25 X 200 CM ABEL E-Gun



Candidate Concepts/Architectures

- ***100 kW CO₂ Pulsed Laser***
- ***Multi-Megawatt Class Pulsed CO₂ Laser***

Closed-Cycle 100 kW Transmitter

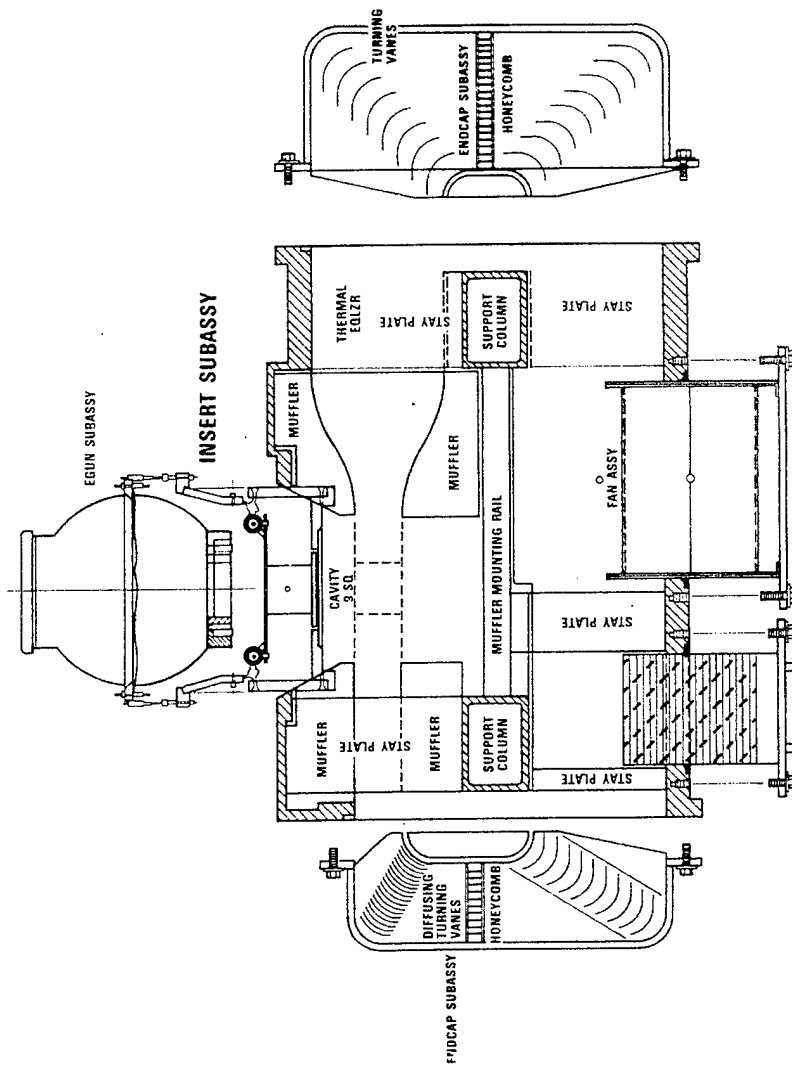
ADVANTAGES

- DESIGN BASED ON PREVIOUSLY DEVELOPED POWER AMPLIFIER (GOVERNMENT FUNDED LICD CONTRACT)SYSTEM
- AVOIDS DIFFICULTIES OF SIGNIFICANT SCALING + RETROFIT
- RUNS ANY GAS MIXTURE/ISOTOPES
- RELATIVELY SMALL FOOTPRINT
- COULD USE SOME EXISTING HARDWARE (e.g., E-GUN, BUSHINGS, ETC)

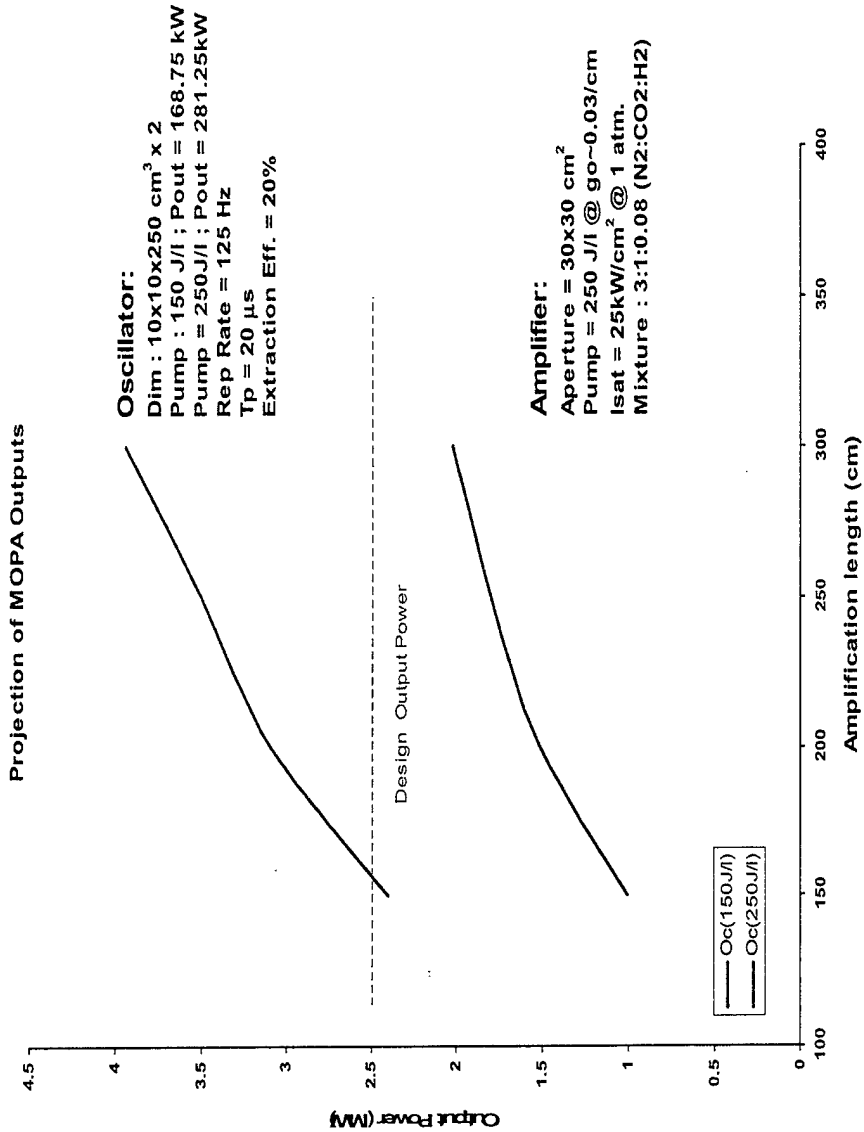
DISADVANTAGES

- REPRESENTS STATE-OF-THE-ART WHICH ENTAILS SOME RISKS
 - DVT's will be required to support PDR
- IN-LINE CATALYSIS WILL BE REQUIRED FOR LONG-DURATION ISOTOPE RUNS
- LONGER DEVELOPMENT TIME COMPARED WITH OTHER OPTIONS

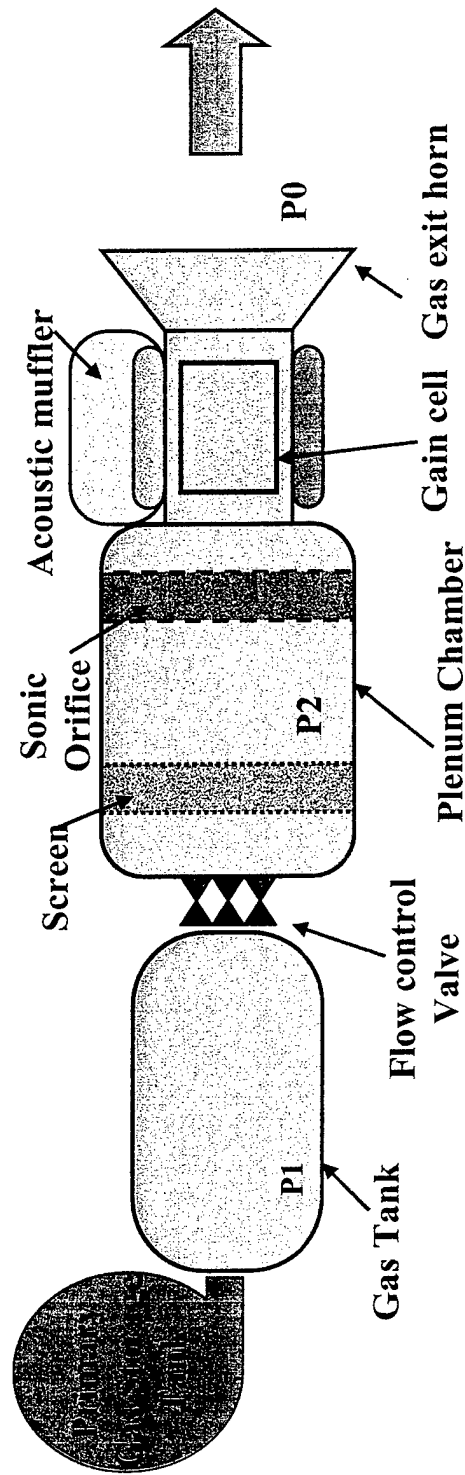
Representative Schematic of Flow Loop Components



Projected MOPA Outputs



Schematics of Flow system



Gas Pressure :

P1 = 150 Atm

P2 = 2 - 2.5 Atm

P0 = 1 Atm (ambient)

Flow speed : 50 m/s

Gas Physical Parameters:

Mixture : N₂:CO₂:H₂ (3:1:0.08)

a = 271 m/s (acoustics)

M = 0.18 (Mach No)

m=31.5 (Effective Molecular Weight)

Density = 1.3 kg/m³

Laser Operation Requirements

Flow System: Blow down

- Gain section

Cross Section : $A=0.3 \times 3.0 = 0.9 \text{ m}^2$

Volume : $V = 0.3 \times 0.3 \times 3.0 = 0.27 \text{ m}^3$

Flow speed : $u=50 \text{ m/s}$ (@ 125 Hz & flash factor=1.3)

Dynamic pressure : $\Delta P=2000 \text{ Pa}$ (0.02 Atm)

Mass flow rate : $q=60 \text{ kg/s}$ / module (45m³/s std)

Run time : $t = 300 \text{ sec}$

Total : $Q=240 \text{ kg/s}$ (72m tons)

- Plenum chamber:

Volume : $V2=0.5 \times 3.0 \times 1.5=2.25\text{m}^3$

Static pressure : $P2 = 2.02 \times 10^5 \text{ Pa}$ (2 atm)

Sonic orifice plate : perforation = 17.5 %

Flow screen : loss > 0.2 - 0.3

Skin friction : loss ~ 0.08

- Gas Storage Tank: Run time=300 Sec & 4 - 5 Runs

Pressure : $P1 = 2.066\text{e}+7 \text{ Pa}$ (200 atm)

Volume : $V1 = 68 \text{ m}^3 \times 4$

Laser Operation Requirements:

Flow Acoustics:

- Physical parameters :

$\gamma = 1.39$, $M = 31.25\text{g}$, $C_p = 730.4 \text{ J/kg-K}$, & $c = 286.3 \text{ m/s}$

$\beta = 4.063 \times 10^{-4}$ (Gladstone- Dale Coeff.)

- Medium homogeneity requirements :

$\Delta\rho/\rho$	BQ
1.38×10^{-3}	2.0
4.10×10^{-4}	1.1
2.72×10^{-4}	1.05

@ $\lambda = 10 \mu$ & $l = 3 \text{ m}$

Acoustics Suppression

Pumping induced medium in homogeneity:

- $\Delta P/P = 0.94$ @ $P = 300$ J/l

Acoustic Suppression :

- Flow direction

Expansion horn provides impedance match eliminating reflection of pressure waves

- Normal to flow direction

Using acoustics muffler to dump out transverse pressure waves

Muffler requirements:

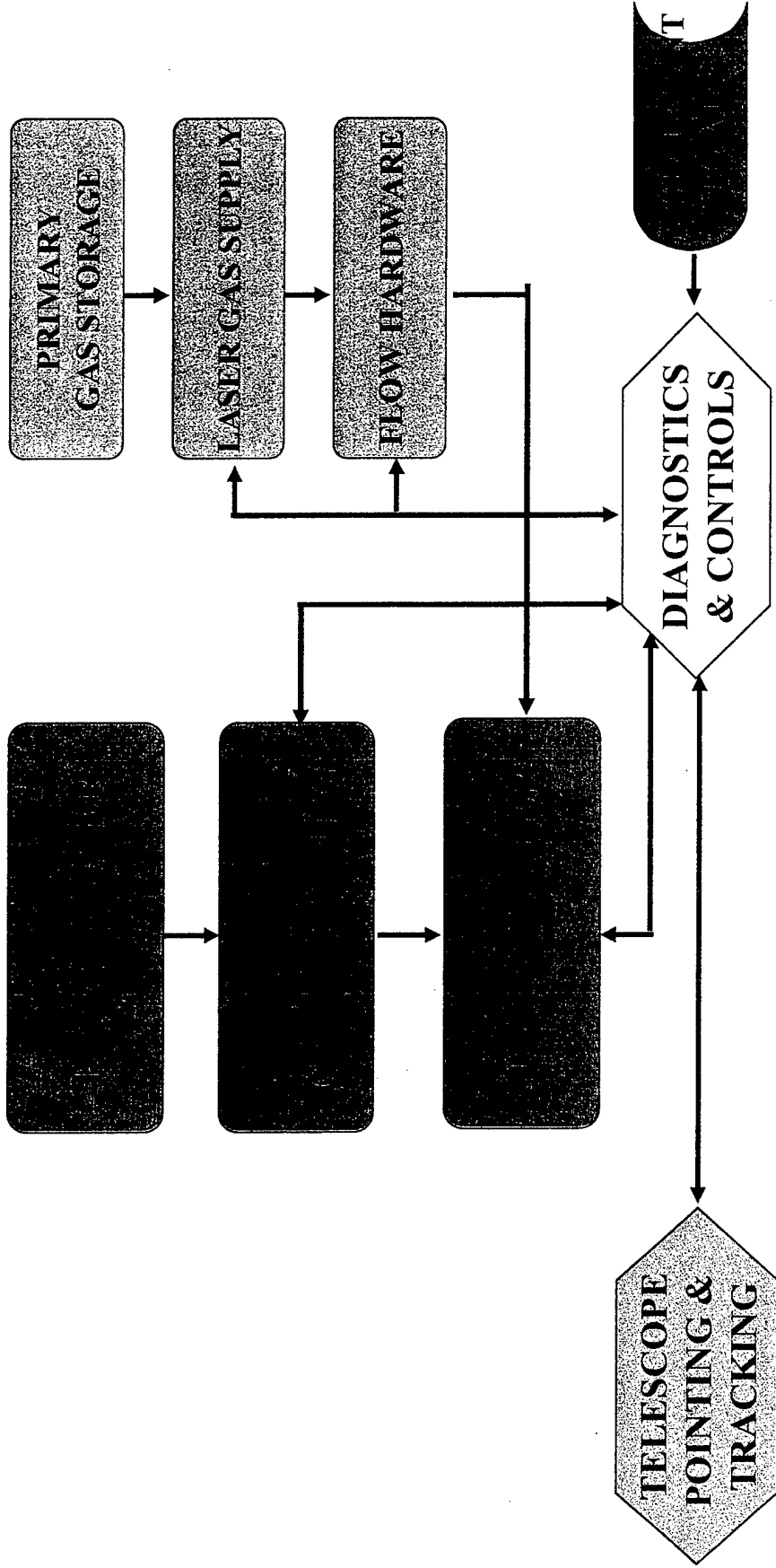
Attenuation factor < 0.55

Number of bounces between pulses : $n = 8$ ($\Delta p/p \sim 1.0 \times 10^{-5}$)

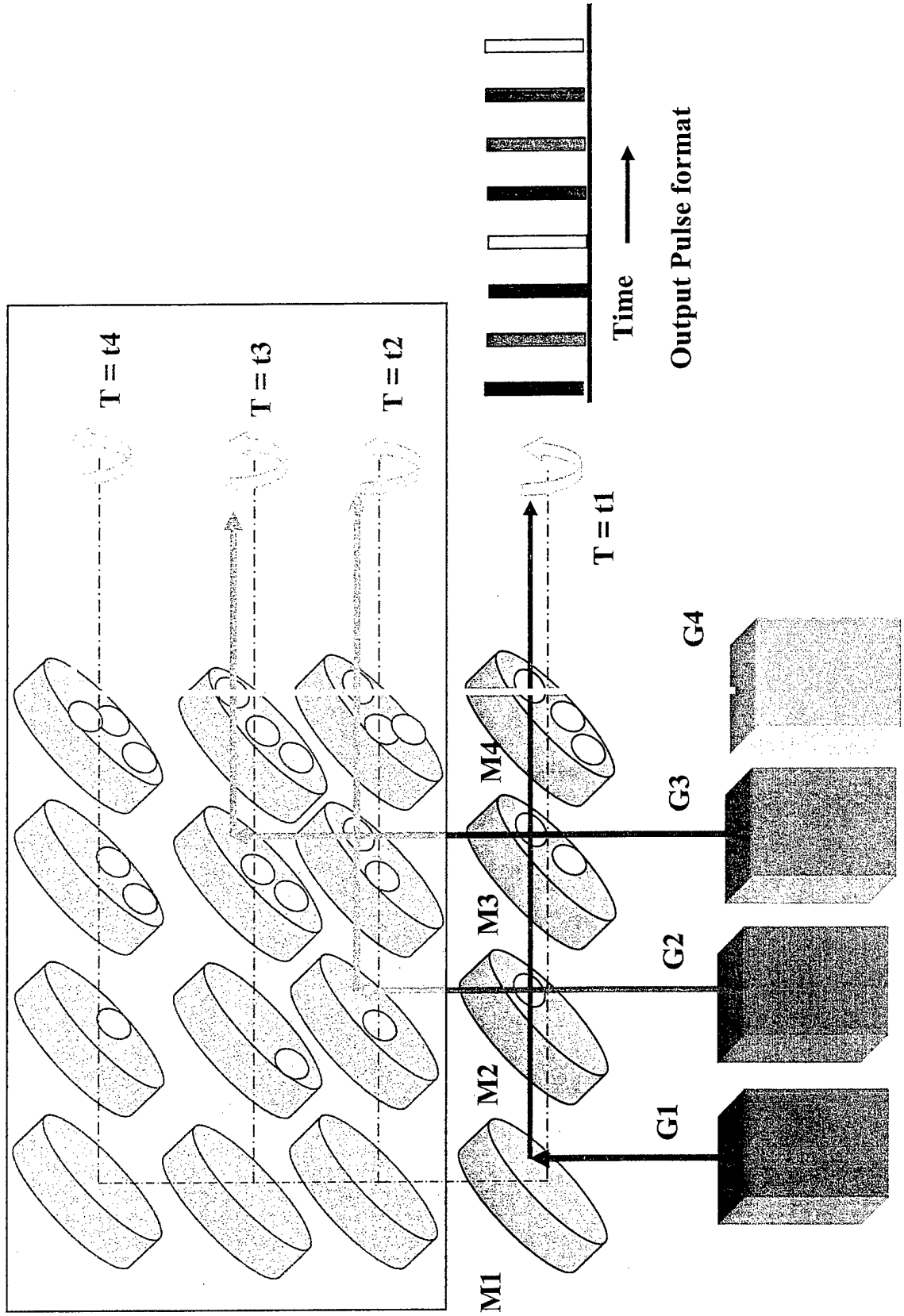
Conceptual Design of Four-Unit Multi-Megawatt CO₂ Laser

- **Beam Combining Concept**
- **Power Oscillator or Master Oscillator-Power Amplifier
Unstable Resonator Cavity
Grating & Rotating mirrors Beam-Combine Techniques**
- **Flow and Gas Handling System
Blow down - Exhaust to Atmosphere**
- **Acoustics Suppression
Expansion Horn Down Stream
Anode Muffler**

Transmitter Schematic Block Diagram For Single-Module Megawatt-Class Laser

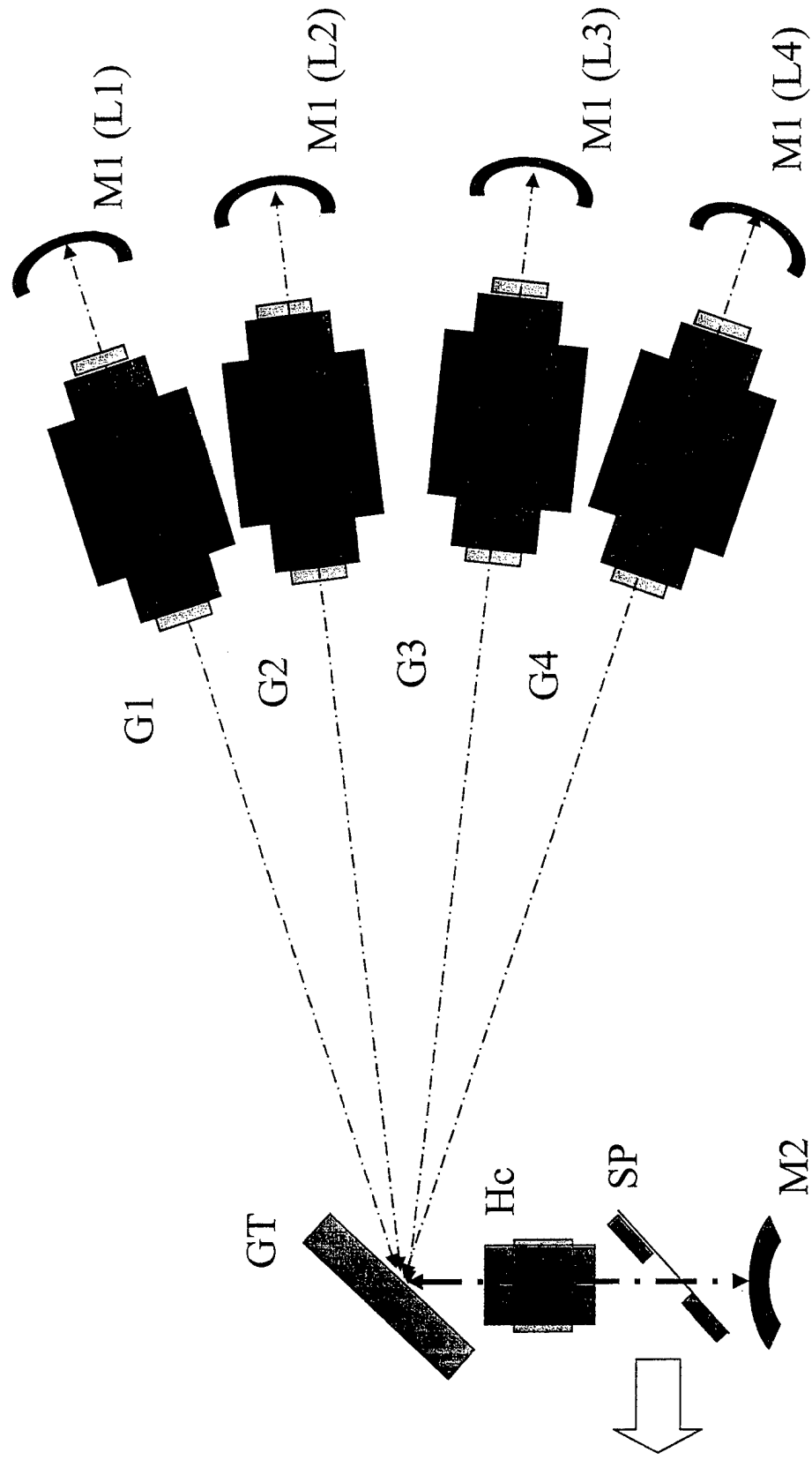


Beam Combining with Synchronized Rotating Mirrors

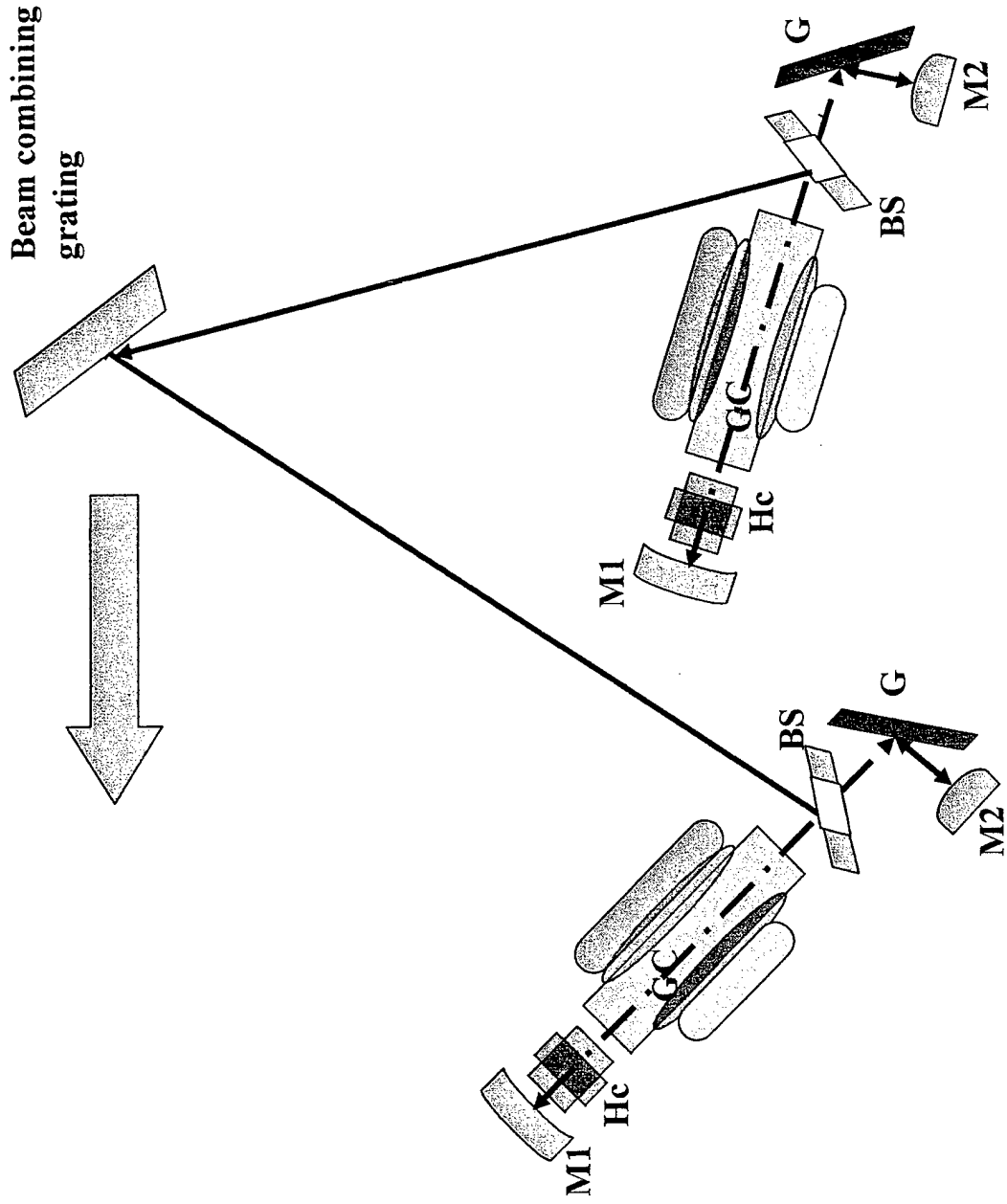


Conceptual Beam Combining with Hot Cell

Intra-cavity



Conceptual External Beam Combining Design



- M1 & M2 : Cavity mirrors
- BS : Beam splitter
- G : Intracavity Grating
- Hc : Hot cell
- GC : Laser Gain Medium

Oscillator Parameters for Each Transmitter

- Energy Loading: $E_p = 300 \text{ J/l}^*$
Gain Vol = $0.27 \text{ m}^3 \text{ (x4)}$
A - K = 0.3 m
Gain Length = 3 m
- Specific Laser Output = 65 J/l
- Estimated Extraction Efficiency: $\eta = 20\%$
- Rep Rate: $R = 125 \text{ Hz @ } 20 \mu\text{s}$
- Output Wavelengths **: $10.6, 10.2, 9.6, \text{ \& } 9.3 \mu\text{m (Mixed)}$
- Gas Mixture : $3:1:0.08 \text{ (N}_2:\text{CO}_2:\text{H}_2)$
- Pressure : $1.013 \times 10^5 \text{ Pa (1 Atm)}$
- Flash Factor : 1.3

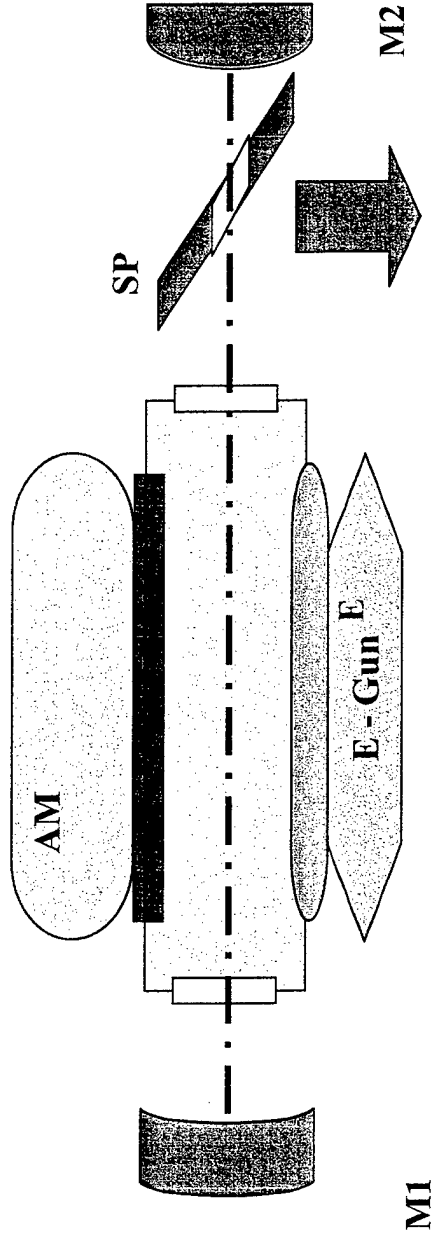
** Select P & R Branch Lines in Both Bands

* Higher loadings at reduced gas temperature

Optical Resonator Cavity : Optical Components

- **Resonator Type: Confocal Unstable with Rotating Mirrors Beam Combining**
 - Magnification : M=4**
 - Cavity length : L=36.5m**
 - Equivalent Fresnel Number = 3.4**
 - Cavity Mirrors : M1 = 97.3m (concave) M2 =24.3m (convex)**
- **Gain Cell : 0.3 x 0.3 x 3.0 m³**
 - Gain Length : l = 3 m**
- **Beam Combine Mirrors : 75 x 75 cm² Flat (30x30 cm² apertures)**
 - @ $\lambda = 10.591 \mu$ [I - P(20)]**
 - M1 (0 hole)**
 - M2 (1 hole)**
 - M3 (2 holes)**
 - M4 (3 holes)**
- **Low Pressure Hot Cell (He) : 0.3 - 0.5 Ghz suppression near line center**
- **Output Scraper Mirror : D = 0.075 m (tapered)**

Power Oscillator : Optics



End Mirrors : M1 Concave ($R1 = 97\text{m}$)

M2 Convex ($R2 = 24\text{m}$)

Magnification : $M=4$

Output Scraper: SP 36x36 cm (outer)
7.5x7.5 cm (inner)

Acoustic Muffer : AM

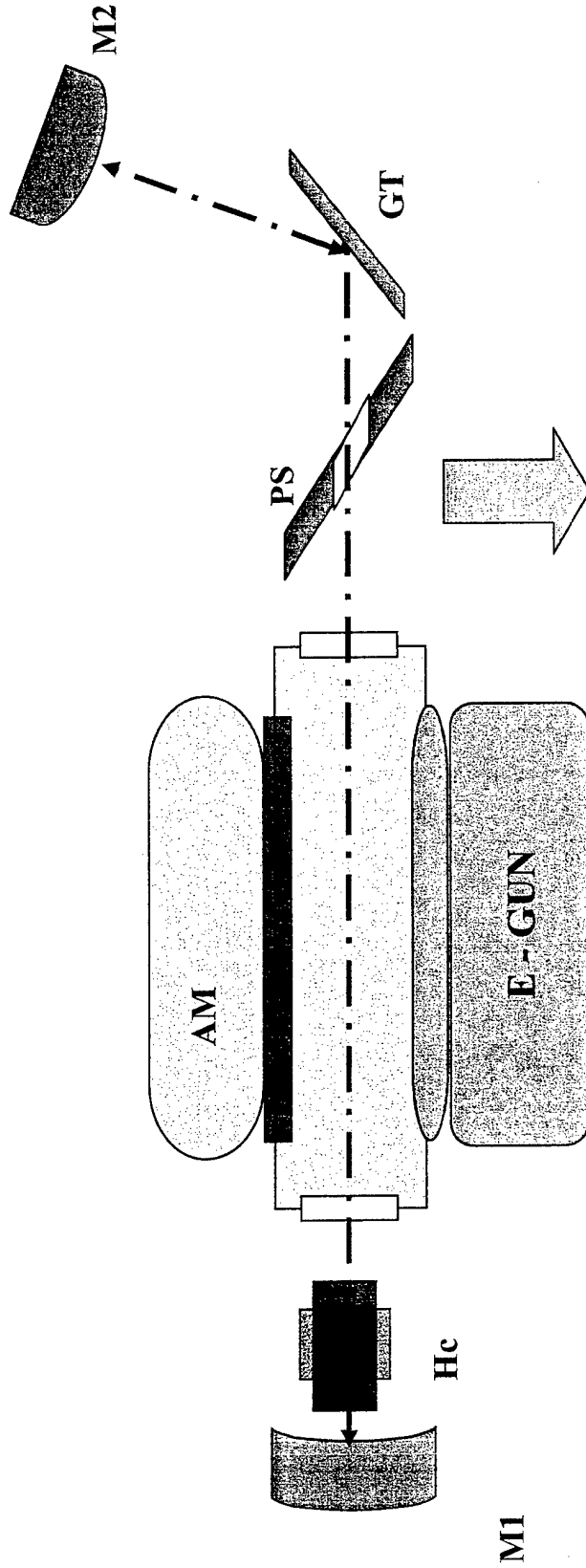
Electrodes : E

Cavity Length : 36.5m

Gain Length : 3m

Aperture : 0.3x0.3 m

Oscillator With Line Selection By Intracavity Hot Cell And Grating



M1 & M2 : End Mirrors

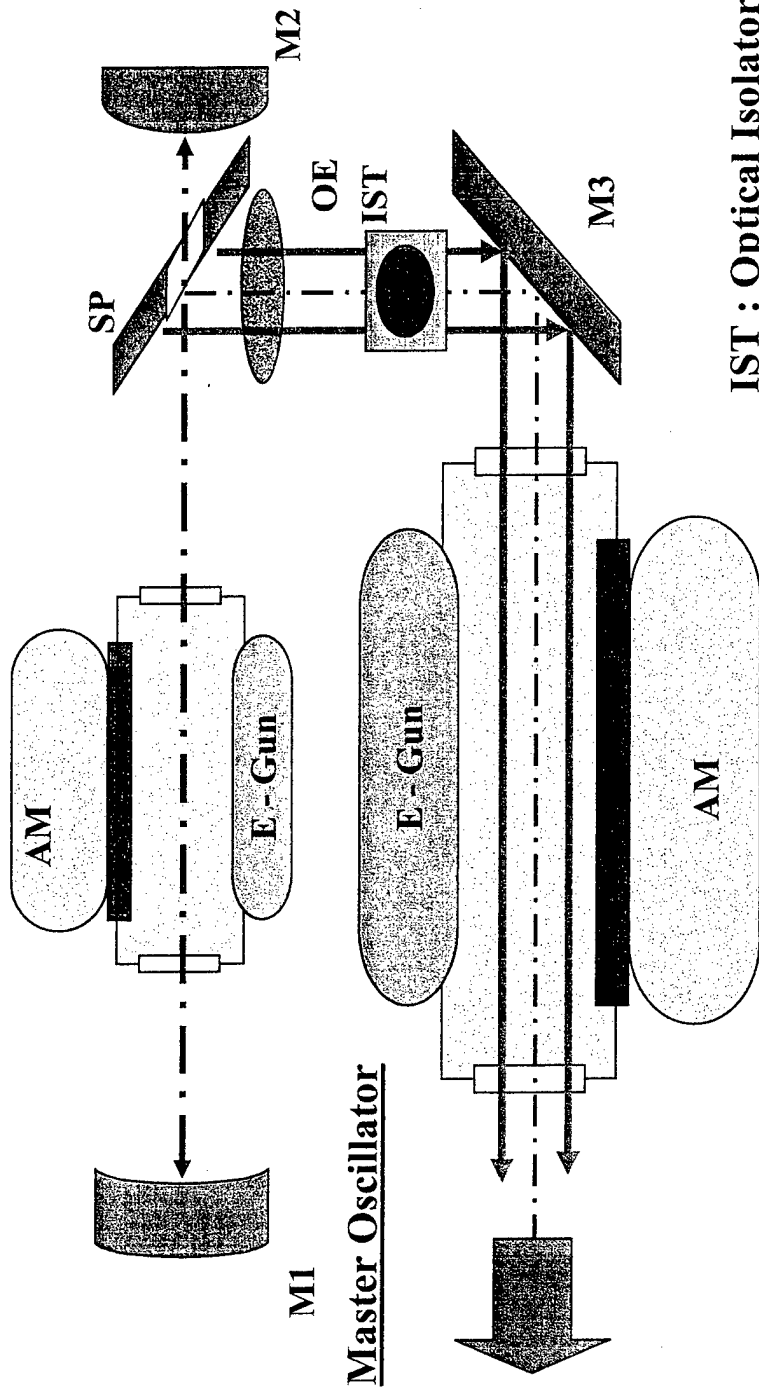
Hc : Hot Cell

AM : Acoustic Muffler

PS : Output Coupler

GT : Grating

Master Oscillator & Power Amplifier : MOPA

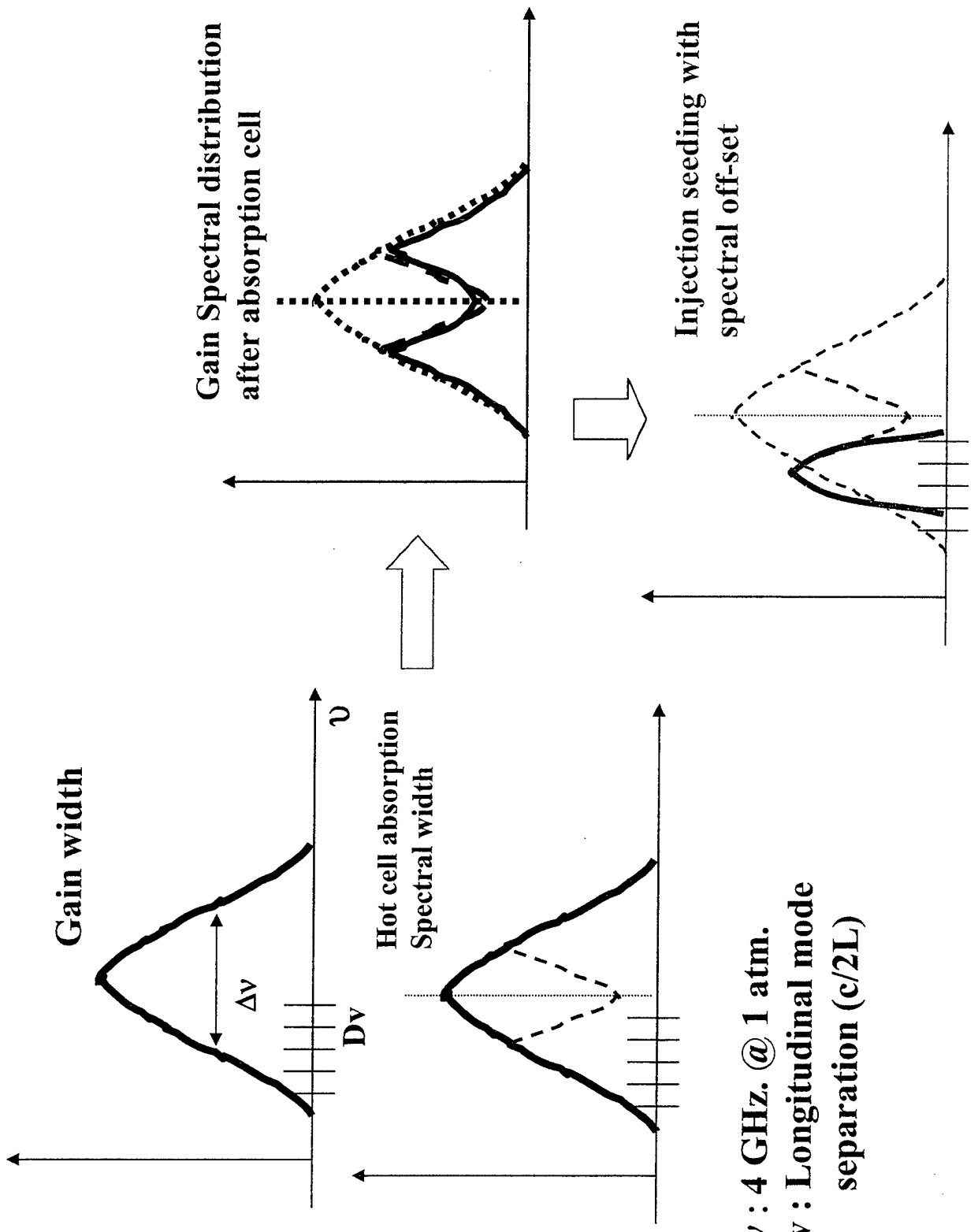


IST : Optical Isolator
M3 : Turning Flat
OE : Beam Expansion Optics
& Interface

Power Amplifier

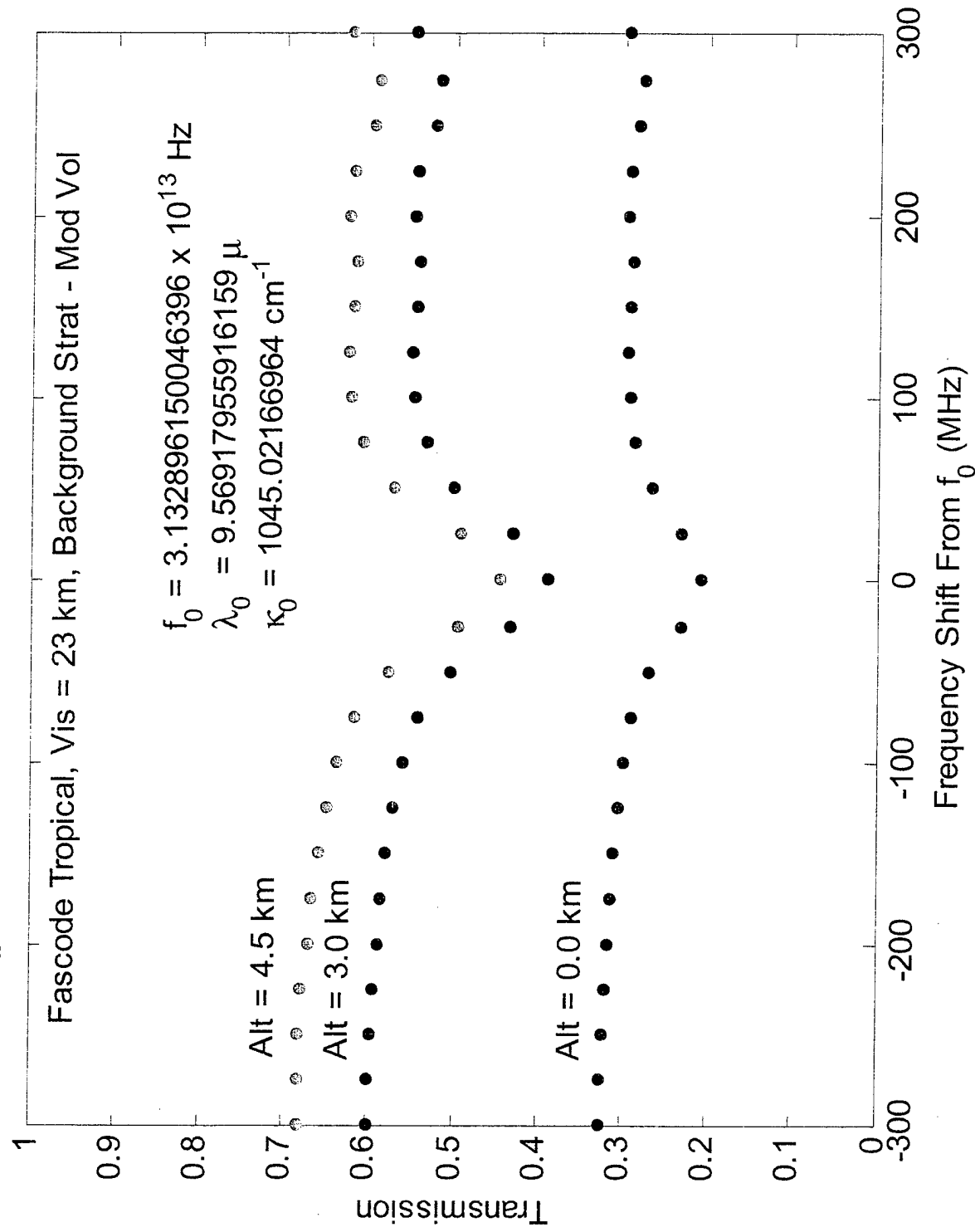
PROPOGATION ENHANCEMENT CONCEPTS

Peak Line Frequency Suppression Using Hot Absorption Cell



$\Delta\nu$: 4 GHz. @ 1 atm.
 $D\nu$: Longitudinal mode separation ($c/2L$)

C¹²O₂¹⁶ Band II P22 Transmission From Specified Alt to Space



CONCLUSIONS

- A PULSED CO₂ REPETITIVELY PULSED TRANSMITTER WHICH USES A 300-SECOND BLOWDOWN AND BEAM COMBINING CAN PROVIDE THE POWER LEVELS AND ENERGIES OF INTEREST
- SPECTRAL TAILORING AND MOUNTAIN TOP OPERATION SHOULD PROVIDE REASONABLE ATMOSPHERIC TRANSMISSION
- LOW COST OPERATION ACHIEVABLE WITH HELIUM-FREE GAS MIXTURES, WHICH USE NITROGEN, CARBON DIOXIDE AND SMALL QUANTITIES OF HYDROGEN
- SUBSCALE TEST WILL BE USED TO ANCHOR DESIGN AND THUS REDUCE RISK
- LEGACY PROGRAMS SUPPORT MANY ASPECTS OF THIS APPROACH
- GROWTH POTENTIAL WITH COLD-FLOW AND AERO WINDOWS SHOULD DOUBLE POWER OUTPUT