



High Power Laser Amplifiers

- Considerations as potential LPP drivers for EUVL HVM

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Outline

Simple laser physics together with current operational data are used to compare & identify key issues of high power laser amplifiers as potential drivers for LPP sources for EUVL HVM

- Assumptions and data
- High power laser amplifiers
 - *oscillator-amplifier configurations*
 - *pulse energy extraction considerations*
- XeF power amplifiers
 - *pulsed discharge*
- Nd:YAG power amplifiers
 - *laser diode pumped*
- CO₂ power amplifiers
 - *rf-pumped slab waveguide*
 - *transversely excited atmospheric pressure*
 - *high pressure, high pulse energy*
 - *modified litho excimer*
- High power amplifiers
 - *efficiencies, facility requirements & cost estimate comparisons*
 - *stop light chart*
- Conclusions



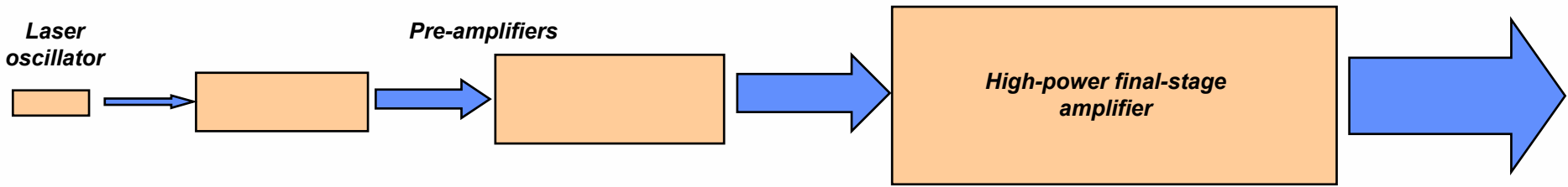
Assumptions & data

- **Assume 20kW average power is min requirement from laser driver**
 - for 180W at IF?
- **For higher/lower powers:**
 - Estimates of module numbers, cost & facility requirements will increase/decrease roughly linearly
 - Costs/watt may reduce slightly due to savings by greater volume purchases of components
- **Data used:**
 - Experimental data from scientific literature – ‘typical’ not ‘hero’ values chosen
 - Commercial product literature & discussions with laser suppliers
 - When experimental data lacking, theoretical values or best estimates from experts
- **A typical 300mm wafer fab has¹:**
 - A total power consumption of 50MW
 - A total of 10 exposure tools
 - All exposure tools currently consume ~1.5% of total fab power
 - *A current 193nm exposure tool consumes ~ 75kW*

¹ V Bakshi, EUV source workshop, San Jose, Feb ‘05



High power laser amplifiers - oscillator-amplifier configurations



• **Laser oscillator**

- Low power front end. Small beam aperture
- Used to define wavelength, coherence, temporal & timing requirements of final beam
- Gain medium in oscillator operates in fully saturated mode

• **Pre-amplifiers:**

- Operated in the small-signal, high-gain regime (~x10,000 – x100)
- Rapidly amplifies power of injected beam

• **Final power amplifier(s):**

- Where nearly all of the power comes from & most of the cost
- Operated in fully-saturated, low-gain (~x2 – x4) regime
- Large beam aperture:
 - *Increases area of gain medium available for high-power extraction*
 - *Reduces risk of optics damage & distributes thermal load*

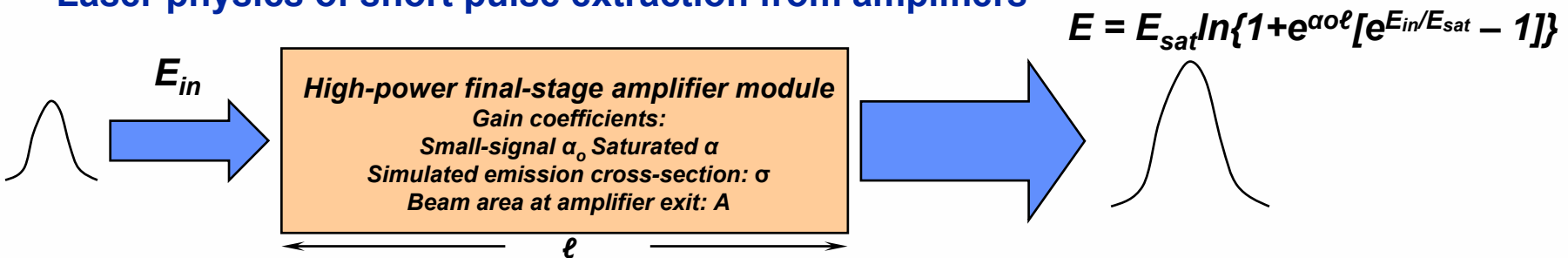


High power laser amplifiers – pulse energy extraction considerations

Efficiency considerations

- Optical energy extraction from chain is efficient only when final amplifier gain is fully saturated
- Power obtained from gain medium when operated as a laser oscillator is indicative of the maximum power available for extraction when operating same medium as an amplifier
- Efficiency of the final (high-power) amplifier is the most important component when assessing electrical power requirements & CoO of oscillator-amplifier configurations
- Lasers at short wavelengths:
 - Require much higher pump powers than longer wavelength lasers
 - Pump rate $\propto 1/\lambda^{3-6}$ with power depending on line broadening mechanism (pressure, Doppler, natural, etc) $\geq \times 28,000$ higher pump rates required for lasers at $0.35\mu\text{m}$ compared to $10.6\mu\text{m}$
 - Are less efficient than lasers at longer wavelengths

Laser physics of short pulse extraction from amplifiers



- Small-signal amplifier gain per pass
- Saturation fluence for pulses to reduce gain to $\alpha_0/2$
($2^* \equiv 1$ if lower laser level empties during pulse)
- Energy extraction efficiency for short pulses
- Max fluence extractable in amplified pulse (when $\alpha = 0$ & $\varepsilon = 1$)
- N° power amplifier modules at rep rate r to produce drive power P_T
- Amplifier slope efficiency
Pumping ε_p , Quantum efficiency ε_q , Volume extraction ε_t

$$g_0 = \alpha_0 \ell$$

$$E_{sat} = h\nu/2^* \sigma$$

$$\varepsilon_c = 1 - \alpha/\alpha_0$$

$$E_{max} = \alpha_0 \ell \cdot E_{sat}$$

$$n = P_T/P_{ave} = P_T/(\alpha_0 \ell A \cdot r E_{sat})$$

$$\varepsilon_s = dE/dE_{in} = \varepsilon_p \varepsilon_q \varepsilon_t \varepsilon_c$$



XeF excimer lasers

- *ArF, KrF & XeCl excimers industrially proven for DUVL light sources, annealing LCD's, drilling, marking, scribing, micromachining*
- *Annual sales for all excimers ~\$370M*



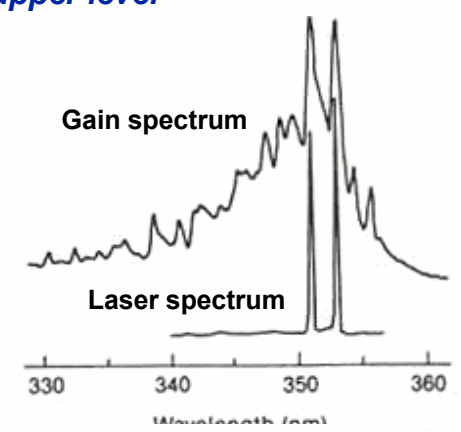
XeF laser amplifier considerations

• Laser kinetics

- **Wavelength:** *351 & 353nm (ultraviolet)*
- **Saturation fluence:** *$E_{sat} = 8.6\text{mJ/cm}^2$ – for multi-line extraction*
- **Upper laser level lifetime:** *$\tau \sim 17\text{nsec}$ - no energy storage in upper level*
- **Small signal gain:** *$\alpha_o \sim 13\% \text{ cm}^{-1}$*

• Narrow line extraction

- *XeF laser has ~7 lines between 349 – 354nm with two strongest at 351 & 353nm*
- *Efficiency for extracting energy on single narrow line at 351nm ($3\omega \times \text{Nd:YLF}$) is $\leq 60\%$ of total*



• KrF/ArF dual chamber litho laser adaptation

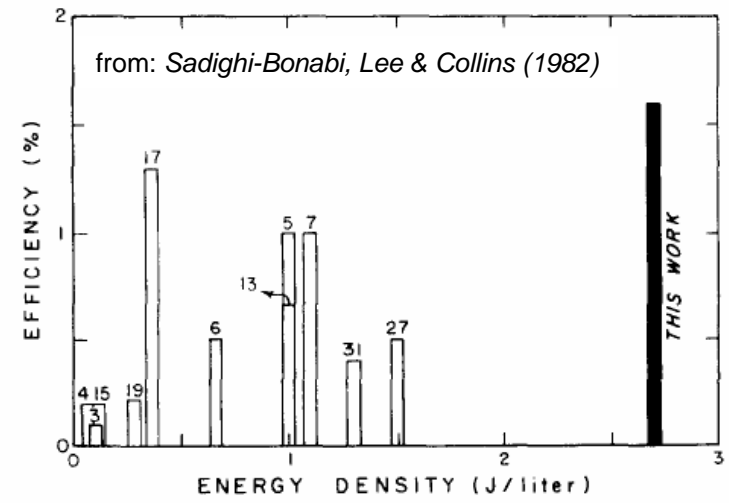
- **Beam size at amplifier exit** *$\sim 1\text{cm}^2$*
- **Max energy extractable $\ell=2\text{m}$** *$\sim 224\text{mJ/pulse}$ – multi-line*
- **Max ave power at 6kHz** *$\sim 1.34\text{kW}$*

- **N^o of modules for 20kW driver:** *~ 15*



XeF laser efficiency

- **Measurements of XeF laser efficiency**
 - Results from 12 scientific groups
 - Storage capacitor to multi-line light output 349-354nm
 - Max efficiency ~1.6%
 - Wallplug to capacitor not included (90%?)
 - Single line extraction from amplifier not included (60%)
 - Including these then max slope efficiency: $\epsilon_s = 0.9\%$



- **Facility requirements from various XeF laser manufacturers**

Manufacturer	Model	Ave Power in multi-line	Rep rate	Facility requirements	Facility Efficiency
Lambda Physik	Novaline 100	44W	250Hz	12kVA	0.4%
Lambda Physik	LPX325i	70W	250Hz	20kVA	0.35%
Lumonics	PM-840	45W	200Hz	11kVA	0.4%
TUI Laser	ExiStar M100	10W	100Hz	3kVA	0.33%
GAM Laser	EX100	28W	1kHz	11kVA	0.26%



↑
Facility efficiency ~ 0.4%
 ~ 1/2 max slope efficiency



XeF laser technology

- **Attractions**
 - *'Simple' adaptation from KrF & ArF litho lasers?*
- **Front-end oscillator**
 - *Little development required*
- **Back-end power amplifier**
 - *x14 power scaling/module required from litho laser powers*
- **Uncertain (risk) areas**
 - *High capital costs & cost of entry to build prototype HVM demonstrator*
 - *High CoO for laser gases, replacement uv optics, etc*
 - *Multiple high power dual chamber amplifier modules required*
 - *Efficiency for spatially & temporally multiplexing many beams on target – top priority to measure*



Nd:YAG lasers

- ***Industrially proven in many applications including cutting, welding, drilling, scribing, marking, rapid prototyping***
- ***Annual sales for all types ~\$1B***
- ***Diode laser pumped:***
 - ***~\$300M/year sales***
 - ***All solid state with outstanding reliability & operational lifetime***



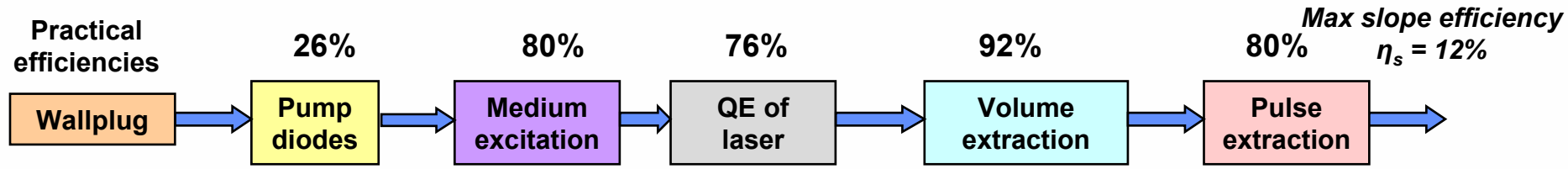
Nd:YAG laser amplifier considerations

• Key laser parameters

- *Wavelength λ* *1.064 μ m (near-infrared)*
- *Stim emission cross-section σ* *2.8x10⁻¹⁹ cm² - including effects of level degeneracy*
- *Saturation fluence E_{sat}* *0.33J/cm²*
- *Upper laser level lifetime τ* *230 μ sec – energy storage medium*
- *Small signal gain α_o* *~10% cm⁻¹*
- *Max slope efficiency ϵ_s* *12%*

• Efficiencies

- $\eta_r = 26%$ (radiative efficiency of diode array) , $\eta_p = 80%$, $\eta_q = 76%$, $\eta_t = 92%$, $\eta_c = 80%$



• Attractions

- *All solid state components with >10,000hrs MTBF*
- *Proven technology in widespread industrial use*

• Front-end oscillator

- *Little development required*

Nd:YAG laser power amplifier – DPSS

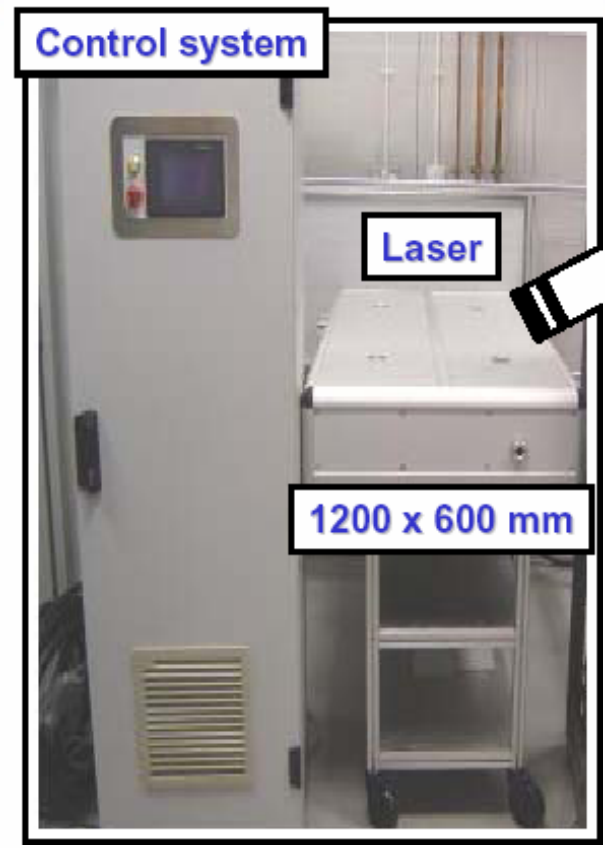
- **Q-switched diode laser pumped**
 - Diode pumped Nd lasers are a mature technology in widespread industrial use.

- **Demonstrated already**
 - Electro-optic Q-switched 6nsec pulses
 - Max energy = 120mJ/pulse at 10kHz
 - Max ave power = 1.2kW
 - Wallplug efficiency = 10%

- **Nº of 1.5kW modules for 20kW driver: 14**

1.2kW, 6nsec 10kHz power module
(Powerlase)

- **Uncertain (risk) areas**
 - Currently high capital costs
 - High cost of entry to build HVM prototype demonstrator
 - Lower capital costs for HVM sources make assumptions on substantial future cost reductions
 - Efficiency for spatially & temporally multiplexing many beams on target – **top priority to measure**





CO₂ lasers

- *The most industrially mature of all high power laser technologies*
- *Industrially proven in many applications particularly cutting, welding, drilling, forming, scribing, marking*
- *Lowest capital cost (\$30 - \$60/CW watt) & CoO of all high power lasers*
- *Smallest footprint & lowest facility power requirements per watt*
- *Annual sales of all types ~ \$680M*



CO₂ laser considerations

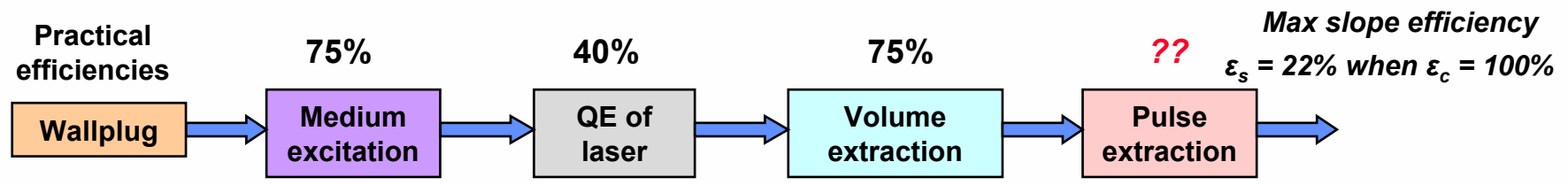
• Key laser parameters

When chamber pressure $p > 50$ torr laser transition is dominated by gas collisions

- Wavelength λ *10.6 μ m (mid-infrared)*
- Stim emission cross-section σ *1.02x10⁻¹⁹(760/p) cm² - including rotational level partitioning*
- Saturation fluence E_{sat} *0.092(p/760) J/cm²*
- Rotational level relaxation time τ_{rot} *2.35(760/p) nsec*
- Upper laser level lifetime τ *~5(760/p) μ sec - for $p > 50$ torr energy storage in upper level very limited*
- Small signal gain α_o *~3-5% cm⁻¹ for pulsed pumped devices at $p \geq 1$ atm
~1% cm⁻¹ for RF pumped devices at $p \sim 150$ torr*

• Efficiencies

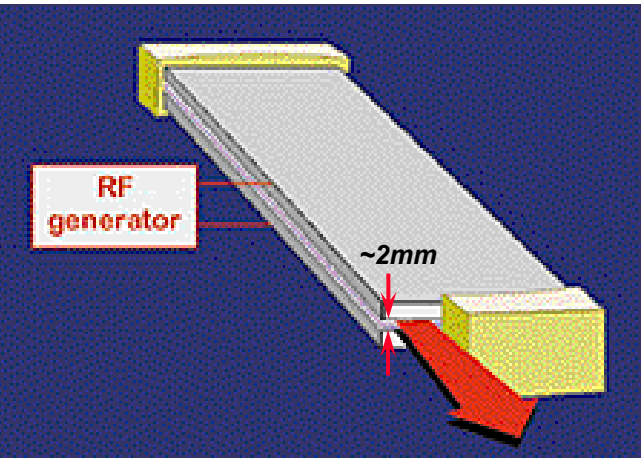
$\epsilon_p = 75\%$, $\epsilon_q = 40\%$, $\epsilon_t = 75\%$, $\epsilon_c = ??$



• Attractions

- Commercial products available from front end Q-switched oscillator to power modules
- Mature fully industrialized technology from many potential suppliers
- Little power scaling required of current commercial modules
- Capital costs well understood with proven CoO
- Low cost of entry for HVM prototype demonstrator

High power CO₂ amplifiers – RF excited slab waveguide type



- **‘Low pressure’ discharge**
 - **Mature technology in widespread industrial use for cutting & welding**
e.g. 8kW average power Model DC 080 from Rofin-Sinar
 - **RF frequency ~100MHz (pump pulses every ~10nsec)**
 - **Little energy storage capability in upper laser level**

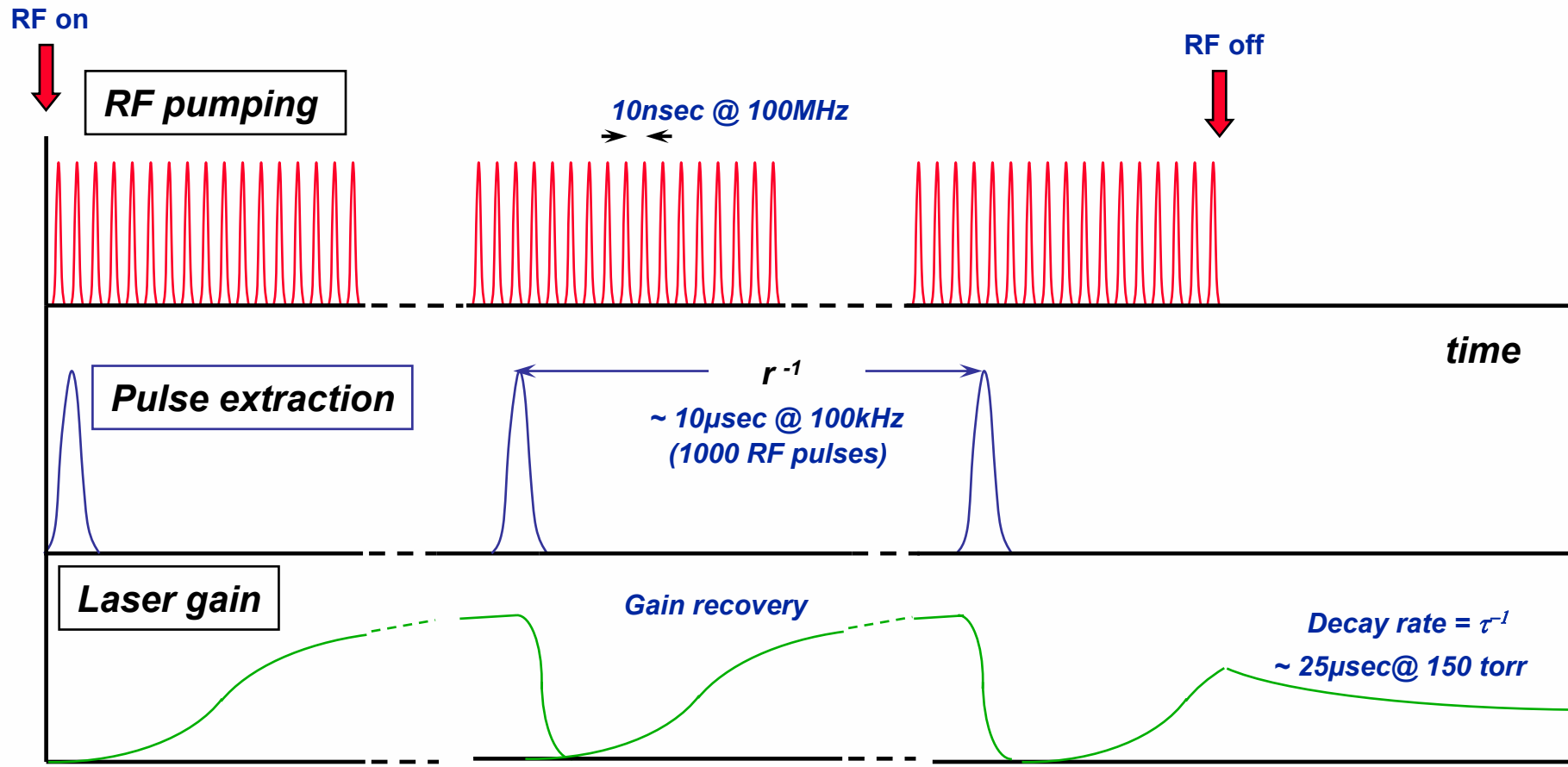
- **Gas pressure p** **~150 torr**
- **Upper laser level lifetime τ** **~25 μ sec**
- **Stim emission cross-section σ** **$5.2 \times 10^{-19} \text{cm}^2$**
- **Saturation fluence E_{sat}** **18mJ/cm²**
- **Max energy stored during upper level lifetime** **0.2J/pulse**
- **Min rep rate for ~100% power extraction ($\sim \tau^{-1}$)** **$\geq 40\text{kHz}$**
- **Max average power extractable** **8kW**
- **Facility efficiency of 8kW CW laser** **7%**
- **N^o modules at 40kHz extraction for 20kW driver:** **3**
- **Slope efficiency** **~12% for extraction at >40kHz**

- **Uncertain (risk) area**

- **Efficiency for short pulse extraction – top priority to measure**
- **Optically filling slab waveguide gain volume for pulse amplification a challenge**
– use of mirrors likely to induce parasitic oscillation. Line beam extraction?
- **Rep rate for extraction is critical in determining efficiency**



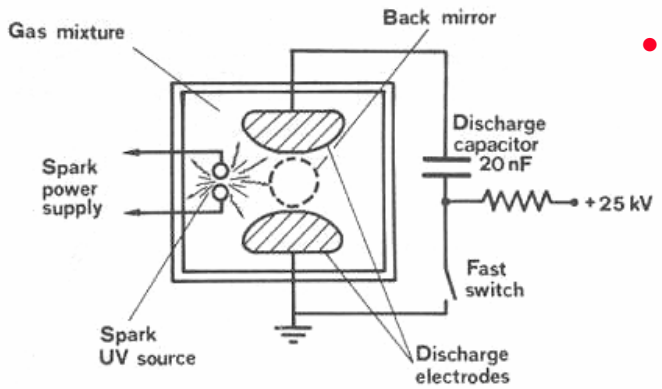
CO₂ RF-pumped slab waveguide lasers – pumping, pulse extraction & gain



- At 10kHz ~75% of energy left behind in amplifier
- Is pumping rate fast enough for gain to recover in a time $< 1/r$?
- x2 increase in efficiency for multi-line extraction measured for 1nsec pulses amplified at 760torr - Rooth & Witteman (1985)
- For pulse durations $\Delta\tau > \tau_{rot}$ (~ 12nsec @ 150torr) all energy from rotational sublevels extractable on single line



High power CO₂ amplifiers – pulsed TEA type



- **UV-preionized transversely excited atmospheric pressure**
 - *Low rep versions in widespread industrial use for marking*
 - *High rep & average power versions not mature but available*
 e.g. 850W, 245Hz Model Platinum 850 from SDI Ltd
 1kW, 1kHz Model CT-2/1000 from Crystaltechno Ltd



- **Gas pressure p** **~760torr**
- **Stim emission cross-section σ** **$1.02 \times 10^{-19} \text{cm}^2$**
- **Saturation fluence E_{sat}** **92mJ/cm²**
- **Beam size at amplifier exit** **~7cm²**
- **Max energy** **~1J/pulse**
- **Max ave power at 1kHz** **~1kW**

- **N^o of modules for 20kW driver: ≥ 20**

- **Uncertain (risk) area**
 - *Too many modules for further power scaling of driver?*
 - *Can lasers be commercialized with high reliability?*

High power CO₂ amplifiers – high pressure & high pulse energy type

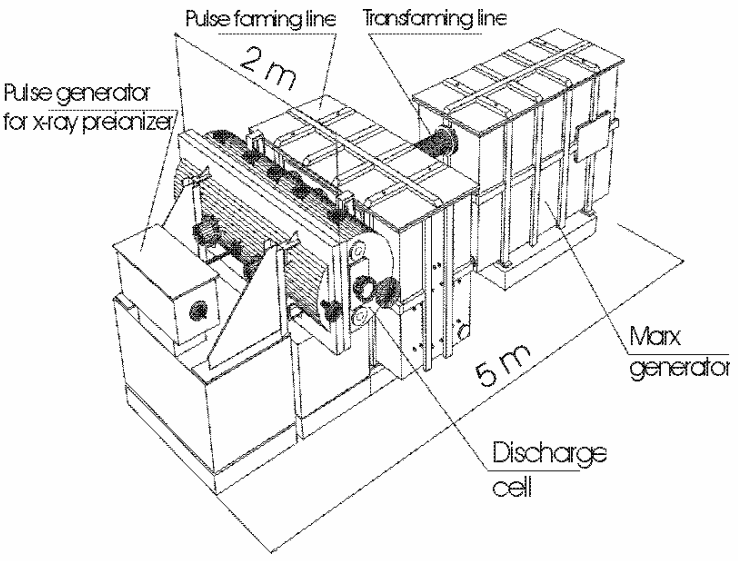


- **X-ray preionized or e-beam sustained discharge**
 - *Not used industrially. Custom built for R&D*
e.g. 10-50kW, ~1kHz, 50J/pulse 10 atm. Built by Optoel ,
St Petersburg, Russia for the Accelerator Test
Facility, Brookhaven National Laboratory

- **Gas pressure** ~10atm
- **Stim emission cross-section** $\sigma = 1.02 \times 10^{-20} \text{cm}^2$
- **Saturation fluence E_{sat}** 0.92J/cm²
- **Beam size at amplifier exit** ~100cm²
- **Max energy (limited by window damage)** ~50J/pulse
- **Max ave power at 1kHz** ~10-50kW

• **N^o of modules for 20kW driver:** **1**

- **Uncertain (risk) area**
 - *Can laser be commercialized with high reliability?*
 - *Route for volume manufacture?*





High power CO₂ amplifiers – ‘modified’ litho excimer TE gain module



- Not yet developed or demonstrated

For example

- Gas pressure p ~2atm
- Stim emission cross-section σ $5.1 \times 10^{-20} \text{cm}^2$
- Saturation fluence E_{sat} 0.18J/cm^2
- Beam size at amplifier exit ~1 cm²
- Max energy extractable for $\ell = 2\text{m}$ ~1.8J/pulse
- Max ave power at 6kHz ~10.8kW

- N^o of modules for 20kW driver: 2

- Uncertain (risk) area
 - Will it work?



High power laser amplifiers

Efficiencies, facility requirements & cost estimates






High power laser amplifiers – efficiencies, facility requirements & cost estimates

Laser type	λ . μm	Max E-O slope efficiency for short pulse extraction	Efficiency with 50% facility overload margin	Facility requirements for 15kW laser driver	No of power amplifiers for 15kW laser driver	Facility requirements for lasers for 10 steppers	Fraction of current fab power consumption	Laser cost estimates at 2005 prices
XeF discharge	0.351	0.9%	0.4%	5MW	15	44MW	88%	\$15M?
Nd:YAG DPSS	1.06	12%	6%	0.33MW	14	3.3MW	7%	\$10M
CO ₂ RF slab waveguide	10.6	12% <i>with extraction at 40kHz</i>	7%	0.28MW	3	2.8MW	6%	\$2M
CO ₂ 'modified excimer'	10.6	9%	4%	0.50MW	2	5MW	10%	\$3M?



High power amplifier comparisons – stop light chart

	CO ₂ slab waveguide	CO ₂ TEA	CO ₂ high pressure	CO ₂ modified excimer	Nd:YAG DPSS	XeF discharge
No of modules						
Module reliability demonstration						
Route for volume manufacturing & support						
Facility requirements						
Capital costs						
Operating costs						
Ready in time?						

-  Potential showstopper
-  Warning. Top issues to address
-  Should be OK



Conclusions

• **XeF lasers**

- **Highest capital cost per watt & CoO**
- **Facility power requirements very high**
- **High degree of spatial & temporal multiplexing adds to system complexity**
- **Top issues – power consumption, cost & complexity**
 - **Can electrical to optical conversion efficiency be increased from ~1% to ~10%?**
 - **Can costs/module be reduced by > x5 from current litho lasers?**
 - **Can spatial & temporal multiplexing many lasers on target be made efficient?**

• **Nd:YAG lasers**

- **Multiplexed Q-switched DPSS modules most viable option**
- **Capital cost & CoO currently too high**
 - **Diode pump arrays currently \$6 - \$10/CW watt**
- **Top issues – cost & complexity:**
 - **Can cost/watt be reduced by > x3?**
 - **Can spatial & temporal multiplexing many lasers on target be made efficient?**

• **CO₂ lasers**

- **Few high power amplifier modules required**
- **High pressure RF-excited slab waveguide is lowest cost option**
- **No power extrapolation required from industrially proven current commercial products**
- **Lowest facility requirements (~x4 of current 193nm tools)**
- **Modified litho excimer TE modules a possible option**
- **Top issue – energy extraction efficiency of pulses from amplifier:**
 - **RF-excited slab amplifier: Can pulses at high rep rates ($\geq \tau^{-1}$) be extracted efficiently e.g. $\geq 80\%$?**
 - **Modified excimer module: Can 10.8kW at 6kHz be made to work with $\geq 9\%$ wallplug efficiency?**



References - and further reading

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