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Towards 20kW CO2 laser system for Sn-LPP EUV source – review of developments at Gigaphoton

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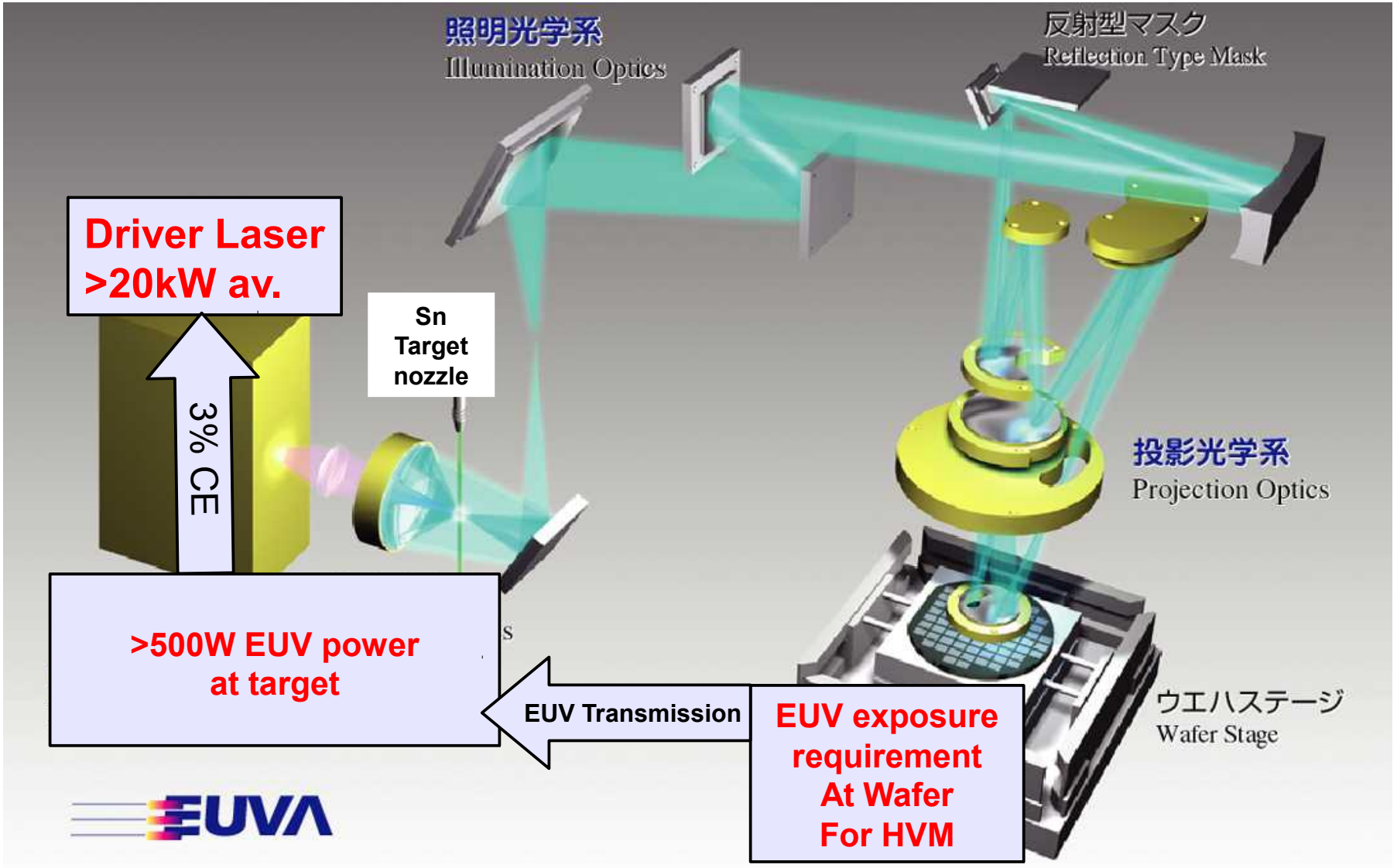
In this talk

- **Introduction**
  - ✓ Drive laser power requirements
  - ✓ Approach to realization of LPP laser driver
  - ✓ Challenges
- **Pursuit of efficient pulsed amplification**
  - ✓ Development of multi-pass amplifiers
  - ✓ Multi-line tunable Master Oscillator
  - ✓ Multi-kW multi-line output achieved to date

Introduction

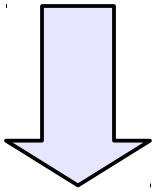
- Sn-LPP EUV source - Laser Driver power requirements
- Viable solution - MOPA-type Laser Driver
- Technical challenges on a route to 20kW Laser Driver power

Laser-Produced-Plasma Sn EUV source – current power requirements for HVM (2010)



Output requirements for a LPP laser driver (2010-onwards)

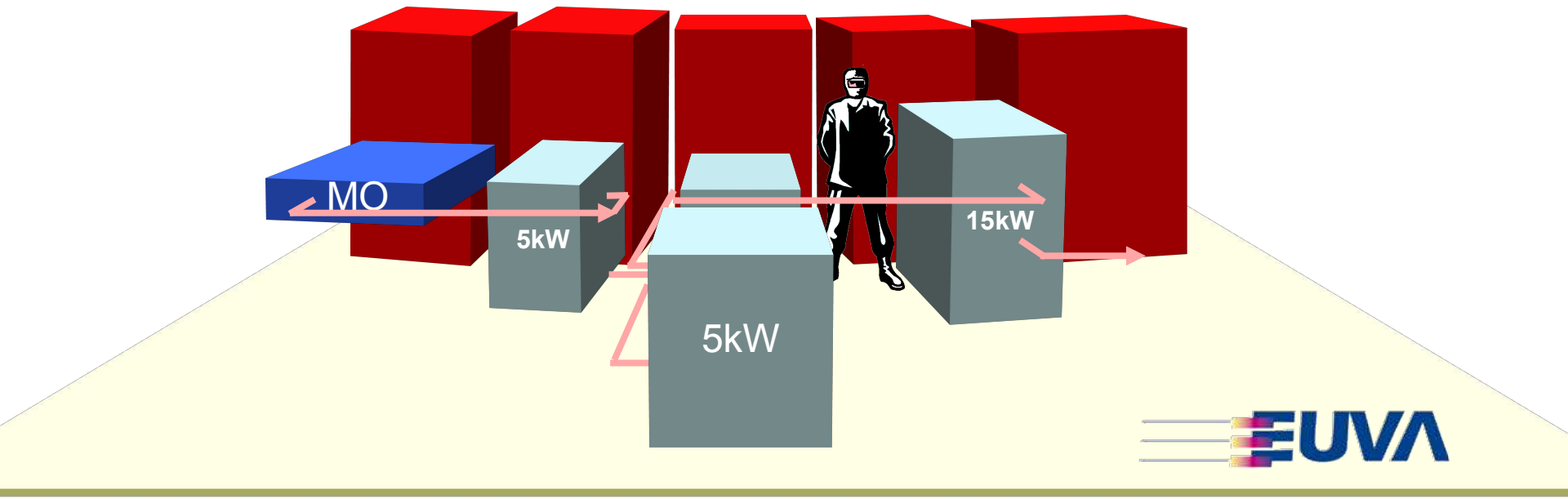
- High average power output >20kW
  - ✓ 500W clean EUV at IF
- Pulse duration 15-50ns
- High pulse repetition frequency (hundreds of kHz range)
- Pulses On-Demand – must be synchronised with droplet target



A viable solution – a pulsed CO_2 Master-Oscillator-Power-Amplifier (MOPA) system employing Fast-Axial-Flow (FAF) multi-kW amplifiers

Record output power achieved from a pulsed CO_2 MOPA* system (2008)

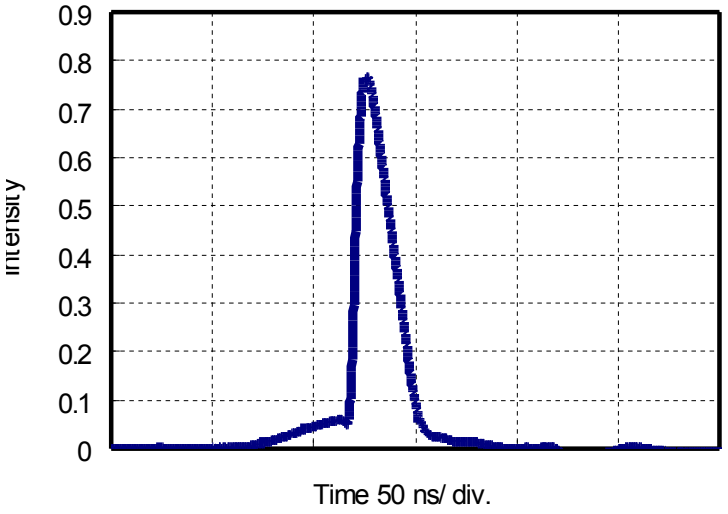
- 12.5kW (1.25kW at 10% duty factor) at 100kHz repetition, 20ns pulse duration
- Beam quality M^2 ~1.2 (at 10% duty).



* H. Hoshino, T. Suganuma, T. Asayama, K.M. Nowak, M. Moriya, T. Abe, A. Endo and A. Sumitani, "LPP EUV light source employing high power CO2 laser", SPIE Adv. Lithography 2008, 6921-115, 24 - 29 Feb, San Jose, US

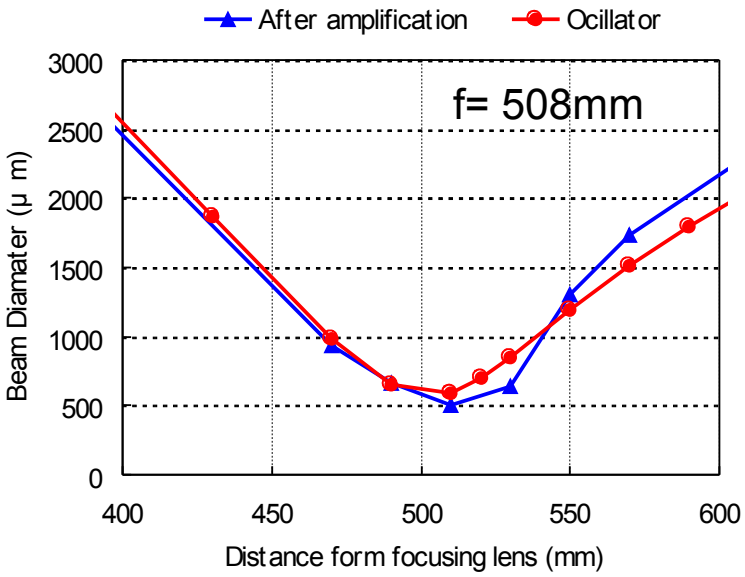
Some performance figures of the MOPA* system (2008)

Temporal pulse shape



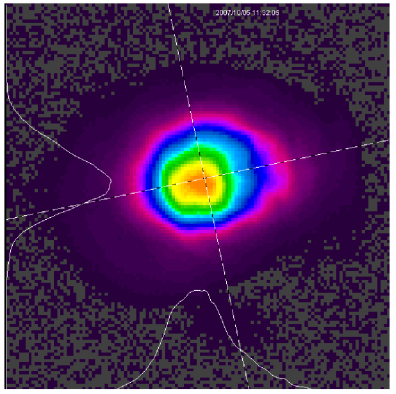
Pulse duration : 20 ns (FWHM)
Pedestal component : <10%

Beam quality



Beam quality: M2=1.2
(10% duty factor).

Laser beam profile



* **H. Hoshino, T. Suganuma, T. Asayama, K.M. Nowak, M. Moriya, T. Abe, A. Endo and A. Sumitani, "LPP EUV light source employing high power CO2 laser", SPIE Adv. Lithography 2008, 6921-115, 24 - 29 Feb, San Jose, US**

Some of encountered technical difficulties en route to 20kW power

- **Low amplification efficiency of 15-50ns CO2 laser pulses in FAF amplifiers**
  - ✓ **Max pulsed power extraction down to 35% of CW extraction in single-pass amplifier systems, resulting in many amplifiers needed**
  - ✓ **Multi-pass arrangements are impractical with FAF amplifiers**
  - ✓ **High input power requirement for reasonable extraction**
- **High system pass-through gain**
  - ✓ **Presence of ASE and self-oscillations**
- **MO instability due to retro-light**
  - ✓ **Reflections from plasma**
  - ✓ **ASE/self-oscillations**
- **Thermal loading of optical components**
  - ✓ **Serious at multi-kW levels**

This talk adresses the problem of Extraction Efficiency

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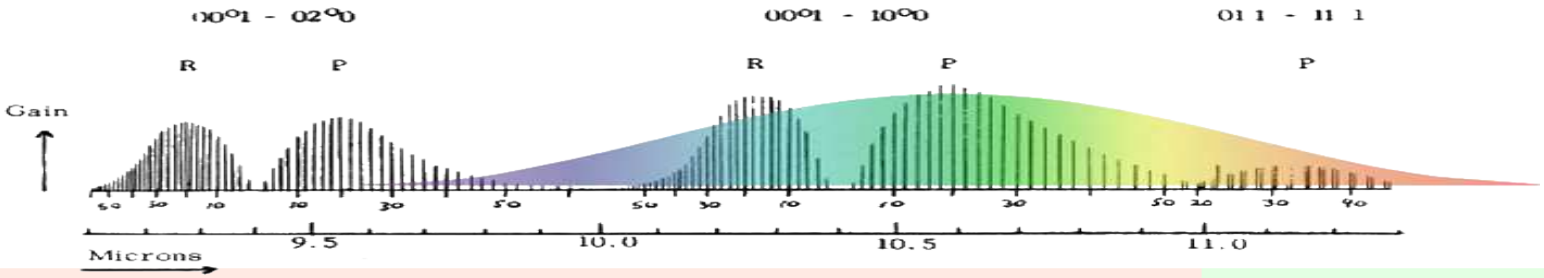
Efficient pulsed amplification of ns CO_2 pulses

- What “efficient” means and why we need it
- Difference between CW and pulsed amplification - where is the “missing” laser power?
- Routes to increased amplification efficiency

What is “efficiency” and why it is welcome

- **“Efficiency” is a short for Power Extraction Efficiency from a laser amplifier**
  - ✓ **It describes the relative performance of the amplifier with pulsed input as compared to a laser output before conversion into an amplifier operated at the same RF duty level**
  - ✓ **It is NOT a wall-plug efficiency of the laser system**
- **High efficiency is key to:**
  - ✓ **Reduction of system cost (footprint and power supply)**
  - ✓ **Reduction of residual gain available to retro-pulses**
  - ✓ **Reduction of average gain level in the period between pulses**
    - Reduction of ASE
    - Reduction of all-system (global) self-oscillations

Why CW and pulsed operation are different?

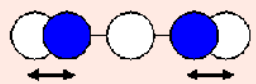


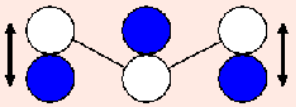
CO_2 molecular vibrational mode

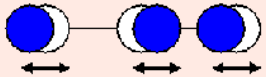
Symmetric stretch mode (ν_1)

Bending mode (ν_2)

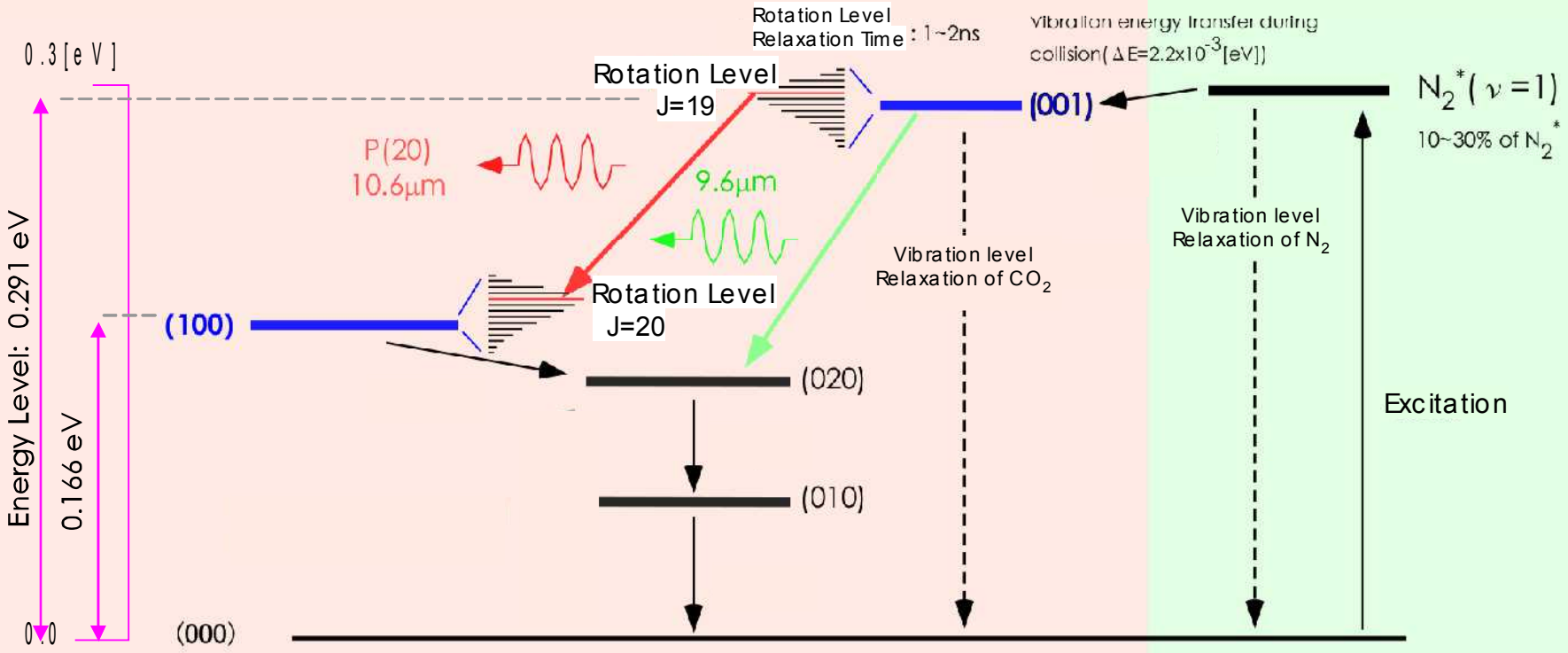
Asymmetric stretch mode (ν_3)





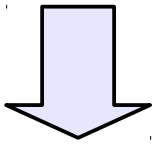


N2 molecule



Routes to CO_2 MOPA efficiency increase

- **Bandwidth-matched input signal**
  - ✓ **Provide input bandwidth matching the bandwidth of laser gain line for maximum interaction cross-section**
  - ✓ **Excite multiple laser transitions of the gain medium simultaneously**
- **Maximize signal-medium interaction time and rate**
  - ✓ **Multi-pass amplifier arrangement**



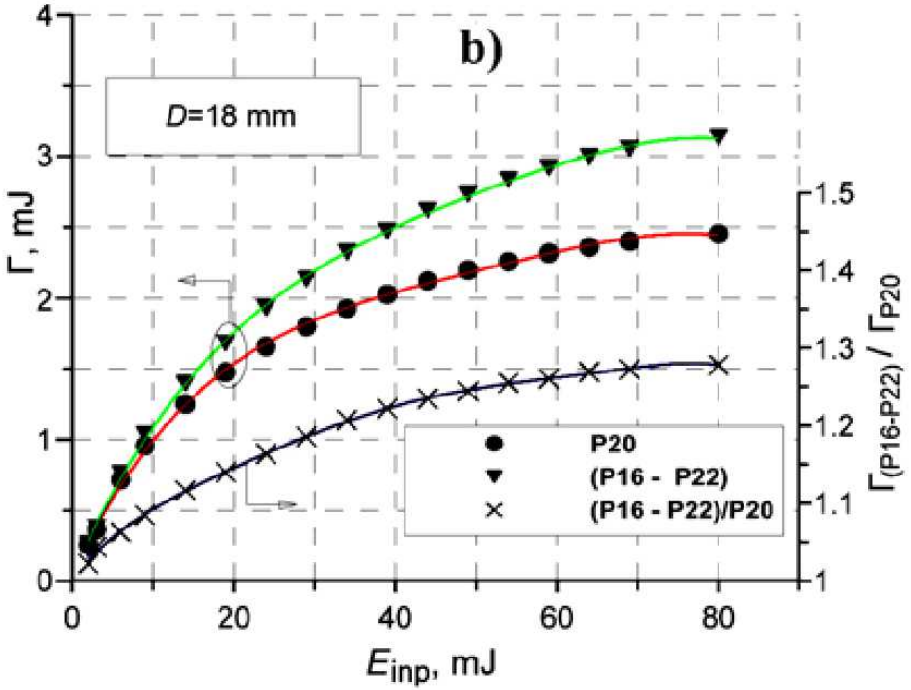
Key aspects:
Master Oscillator
Pre-amplifier arrangement

Multi-line Master Oscillator

- **Predictions of Multi-Line amplification**
- **Novel solid-state seeded CO2 multi-line oscillator**
  - Custom design for LPP

Multi-line amplification for 20ns pulses – prediction (2005)

Numerical Calculation Result of Amplification with Multi-Line Oscillator

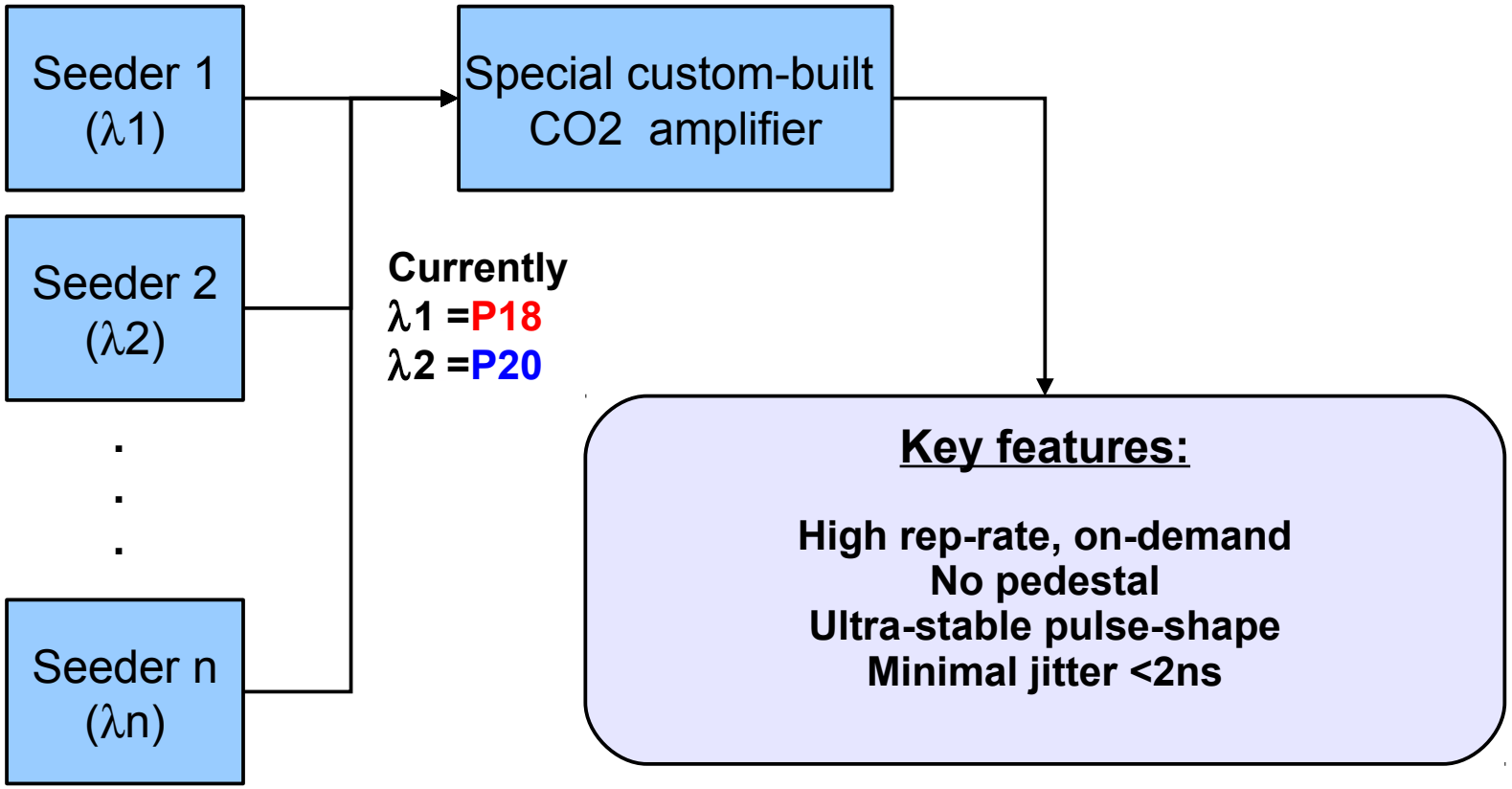


This work was preformed by
Research Institute for Laser Physics,
St. Petersburg, Russia [V.E. Sherstobitov]

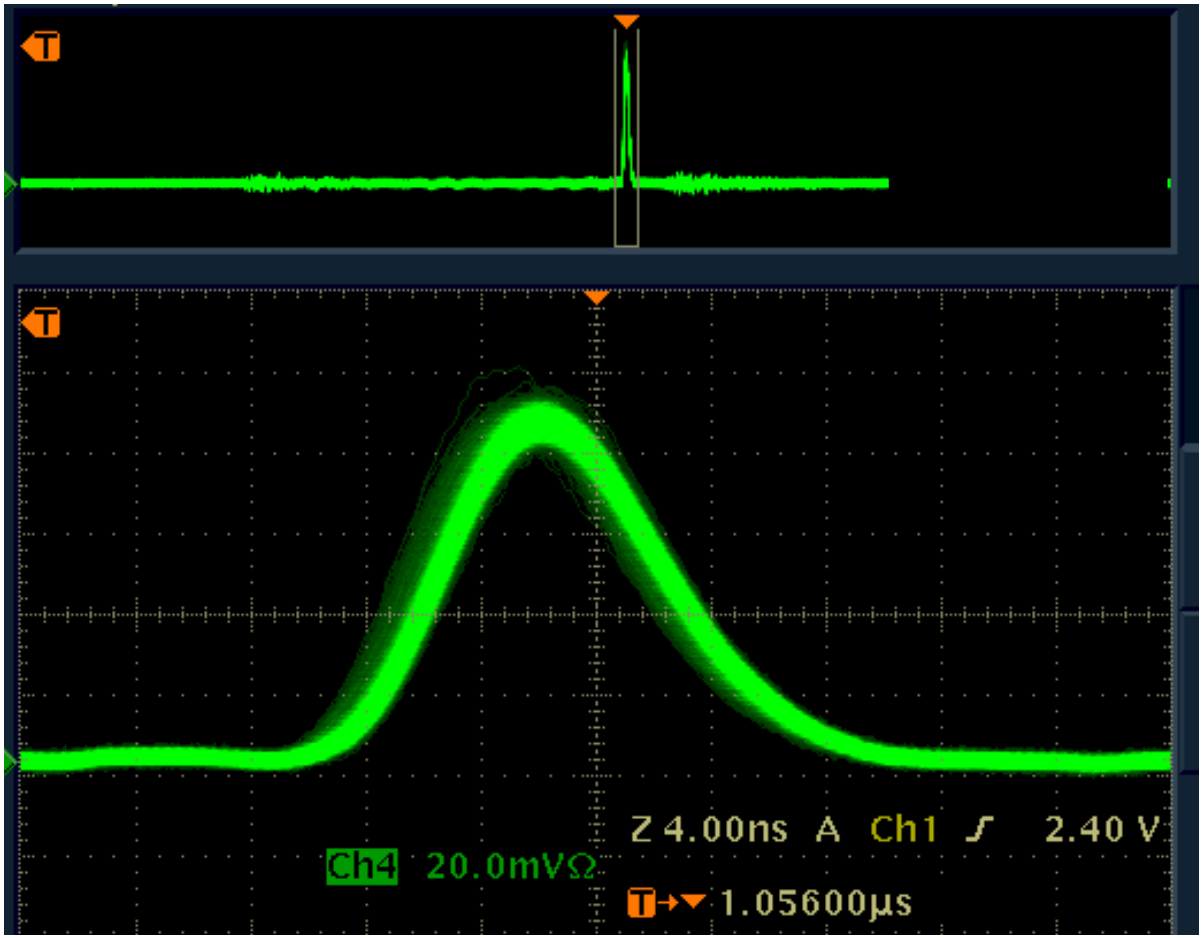
-X- is the amplification ratio between the (P16-P22) spectrum and the P20 line

Up to 30% energy extraction improvement predicted with 4 lines P16-P22 of $00^0 1\text{-}10^0 0$ rotational manifold of CO_2

Novel approach to multi-line ns pulse generation at 10.6 microns – amplification of QCL seed (2009)



Performance of multi-line Master Oscillator – Exceptional stability of pulse envelope (early 2010)

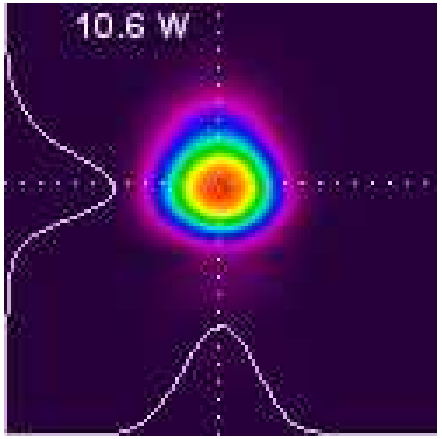


Accumulated traces of 3.5million pulses (35 seconds “exposure”)

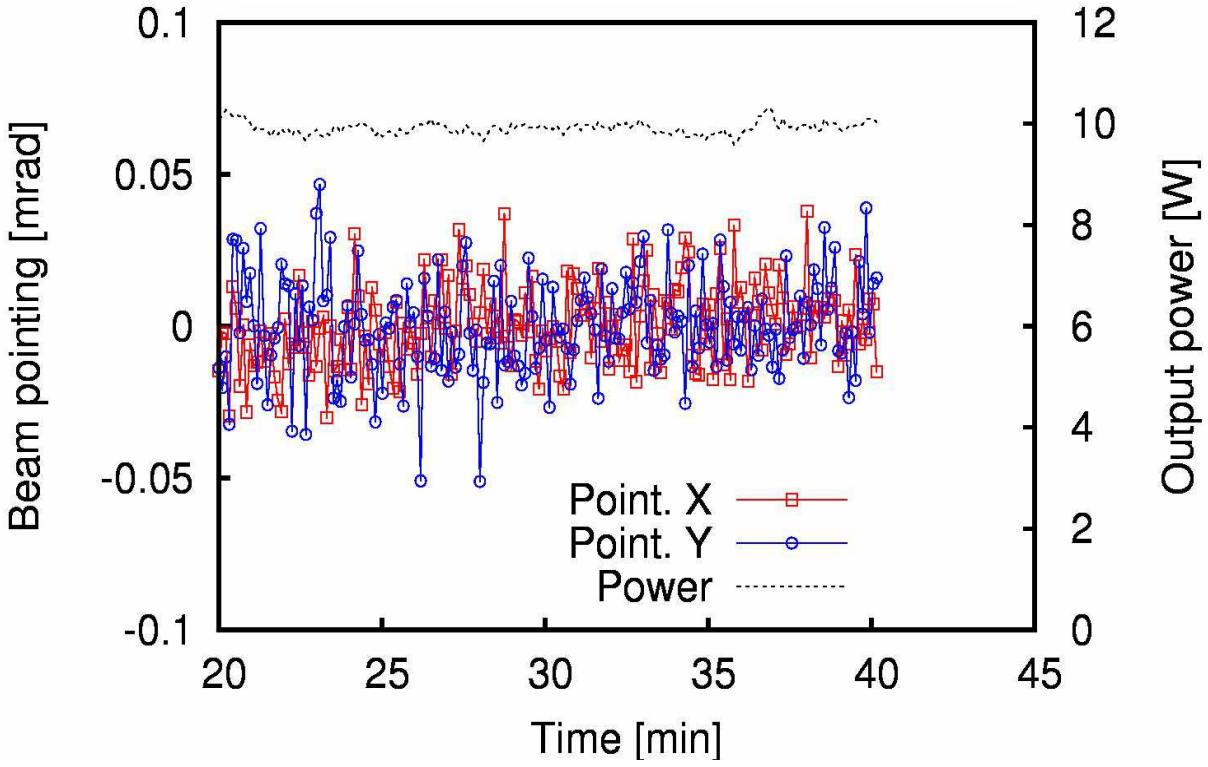
Performance of multi-line Master Oscillator – Stable output beam of high quality (early 2010)

High output beam quality M <1.3

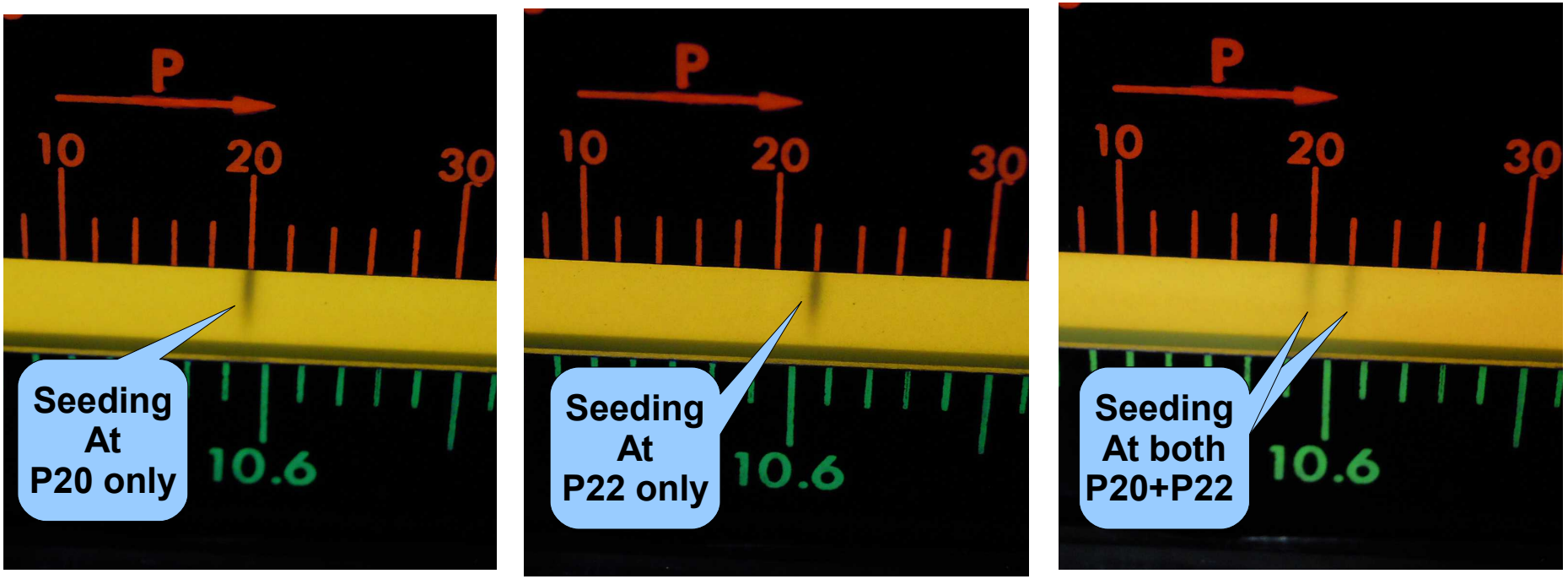
(Far-field beam profile shown below)



Typical long-term beam pointing stability (open-loop, free-run)

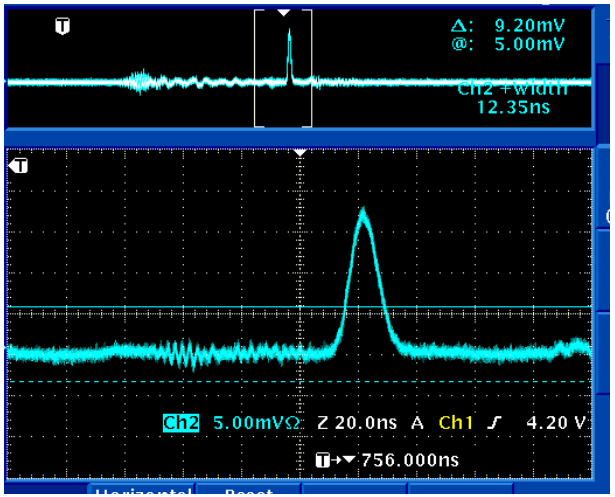


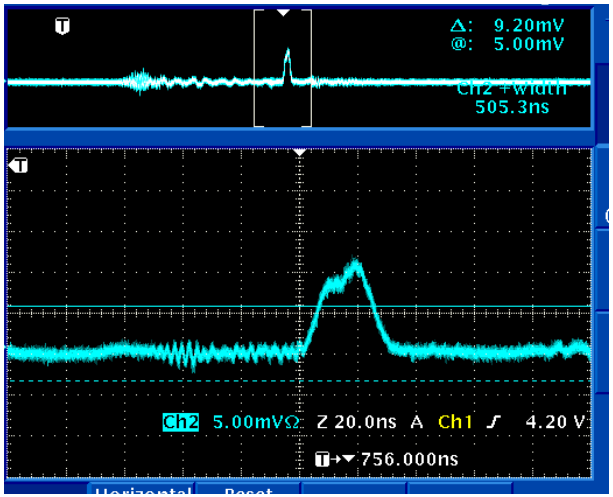
Performance of multi-line Master Oscillator – experimental confirmation of multi-line output (early 2011)

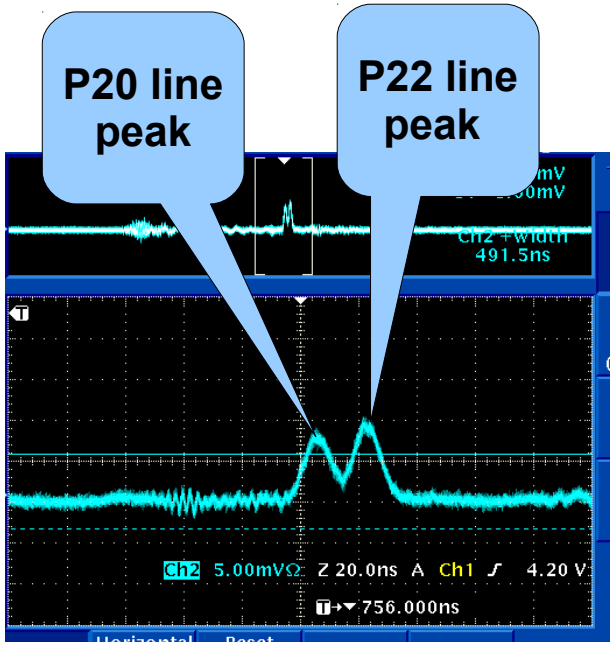


Demonstration of electronic spectrum control by switching individual seeders on and off – operation at P20+P22 lines

Performance of multi-line Master Oscillator – pulsewidth tunability demonstration (early 2011)







0ns relative offset
13ns FWHM
10.5W output

10ns relative offset
20ns FWHM
10.5W output

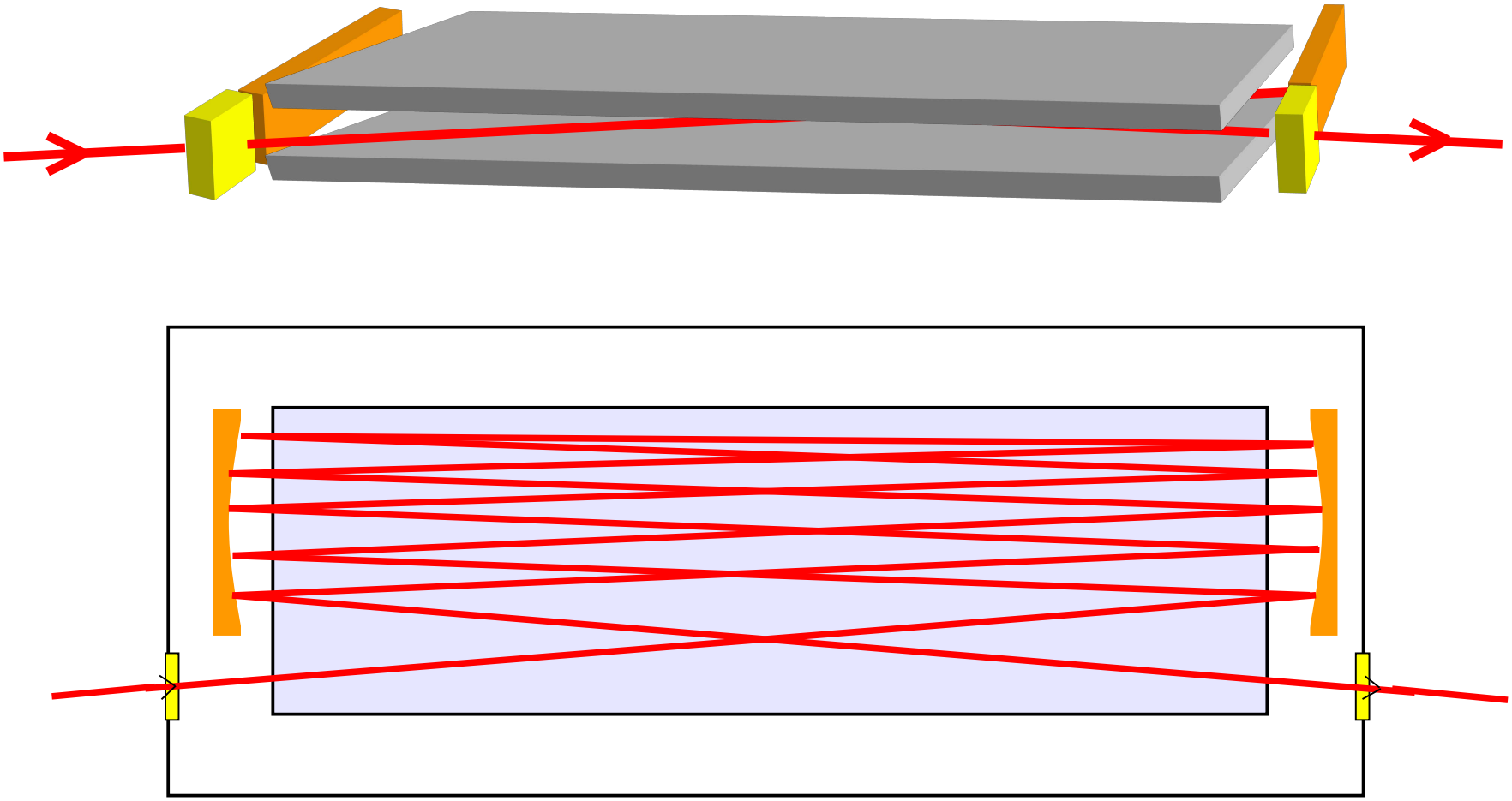
15ns relative offset
25ns FWHM
10.5W output

Demonstration of electronic pulse-width control by relative time offset of seeding pulses – operation at P20+P22 lines

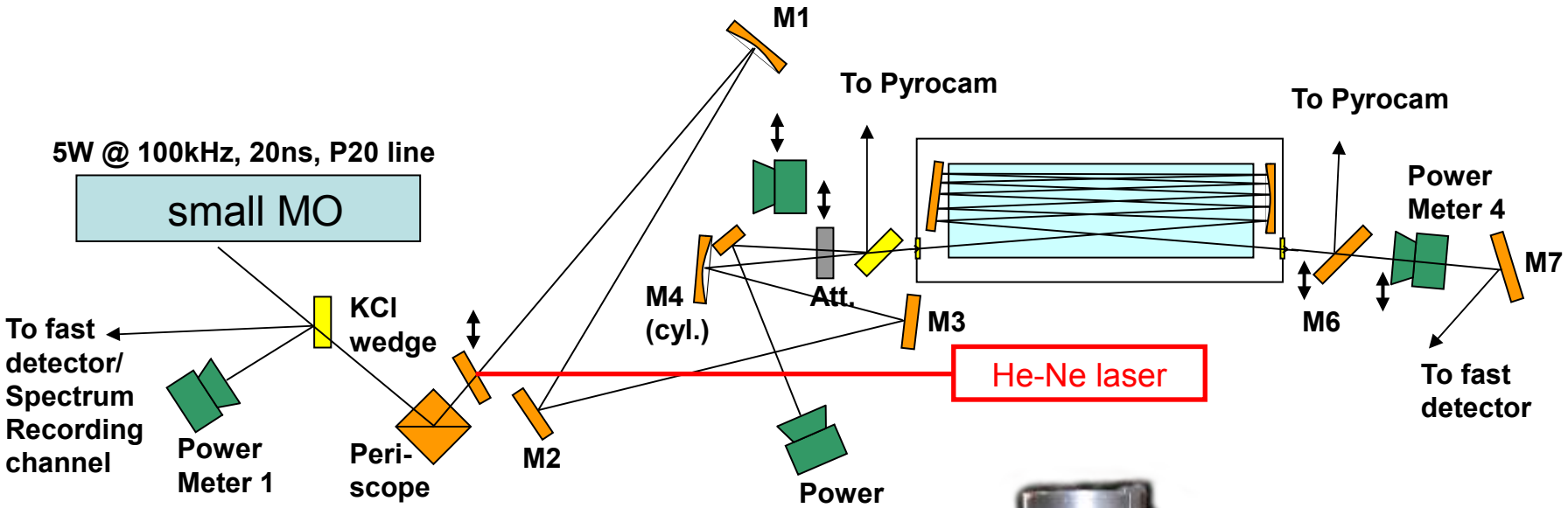
Efficient pre-amplification up to Multi-kW power level

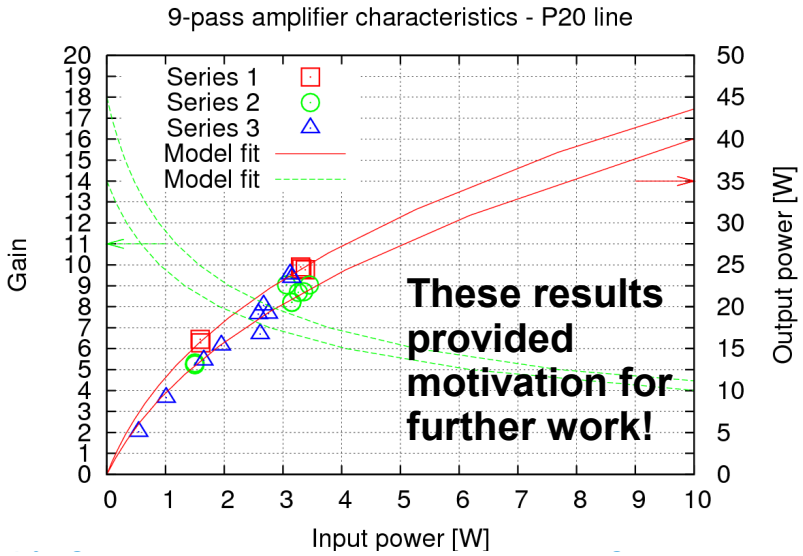
- Slab-waveguide amplifiers - concept
- Small-scale slab amplifier development
- Large-scale slab amplifier development
- Recent experimental results

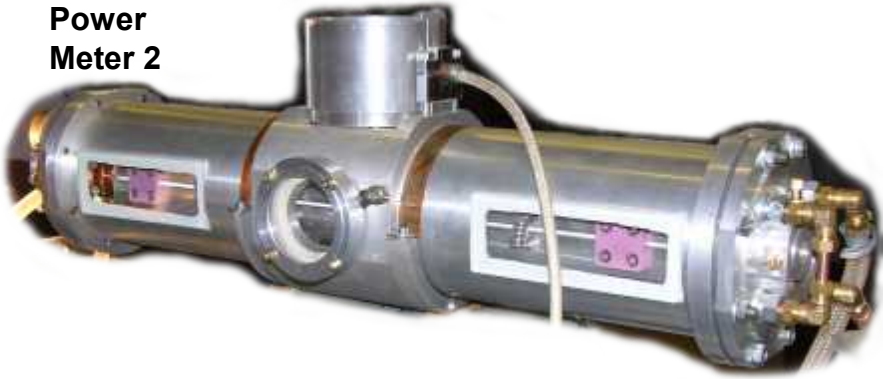
Slab-waveguide amplifier based on RF-discharge-excited diffusion-cooled CO_2 lasers - concept



First experiments in ILP in St. Petersburg with small-scale slab amplifier* (2007)





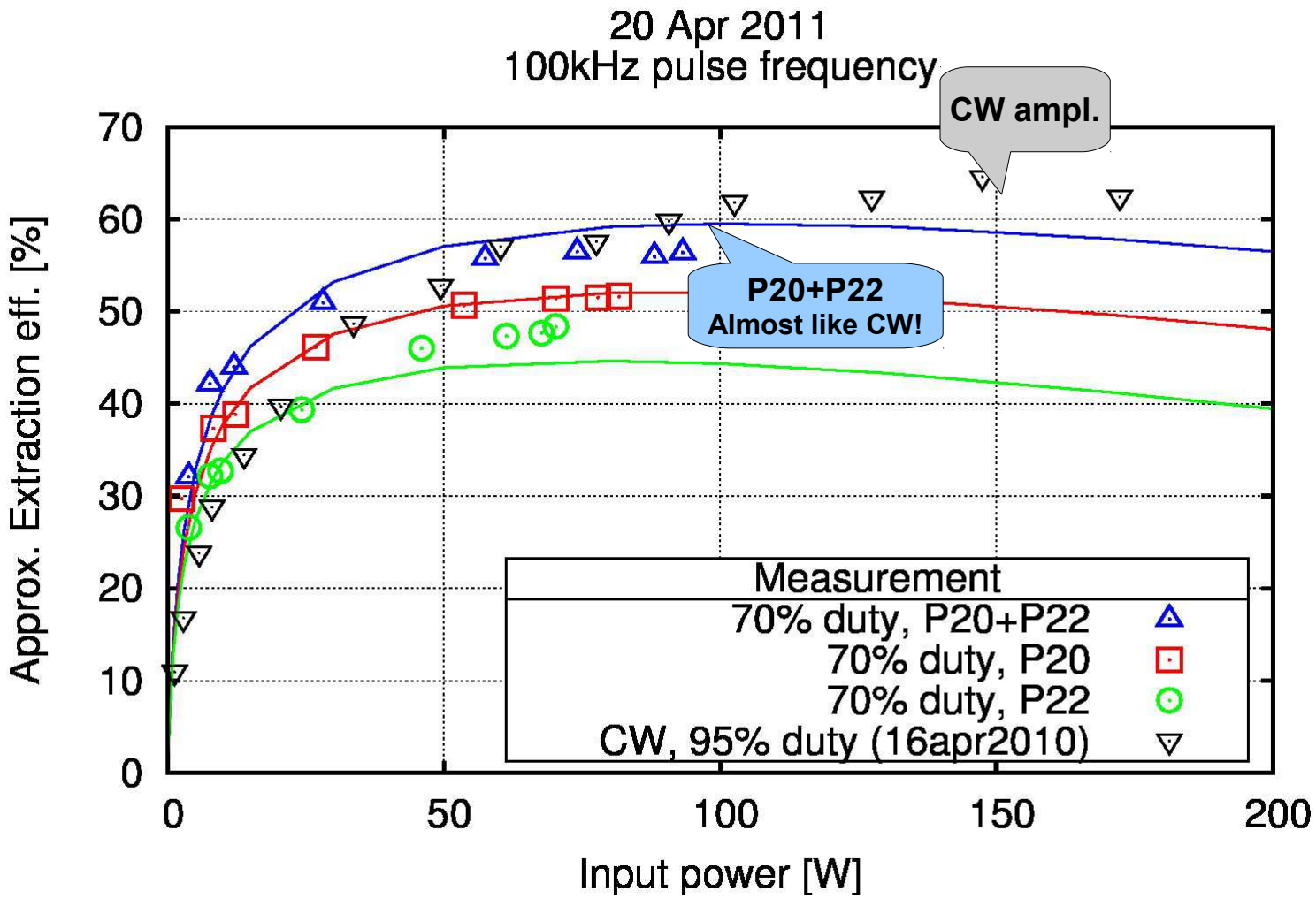


EUVA

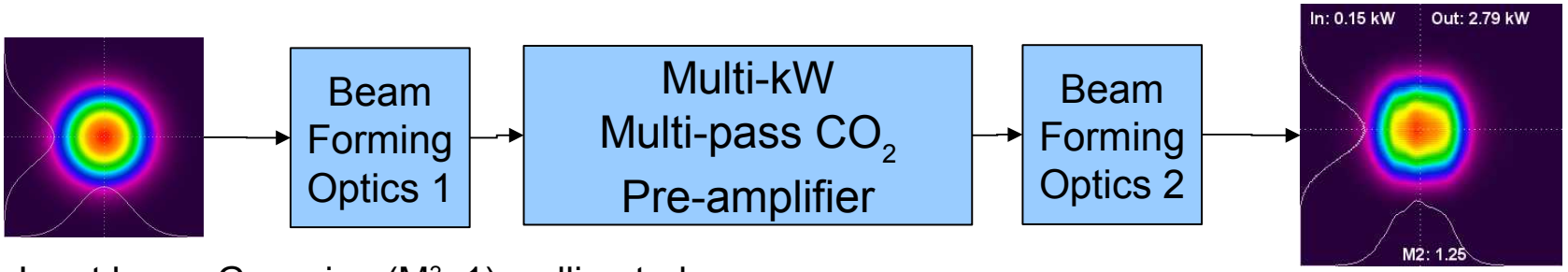
* Invited paper:

V. Sherstobitov, A. Rodionov, D. Goryachkin
N. Romanov, A. Endo, K. Nowak,
Multipass slab CO2 amplifiers for application in EUV lithography,
EUVL Litho Workshop, 10-12 June 2008, Maui, Hawaii, US

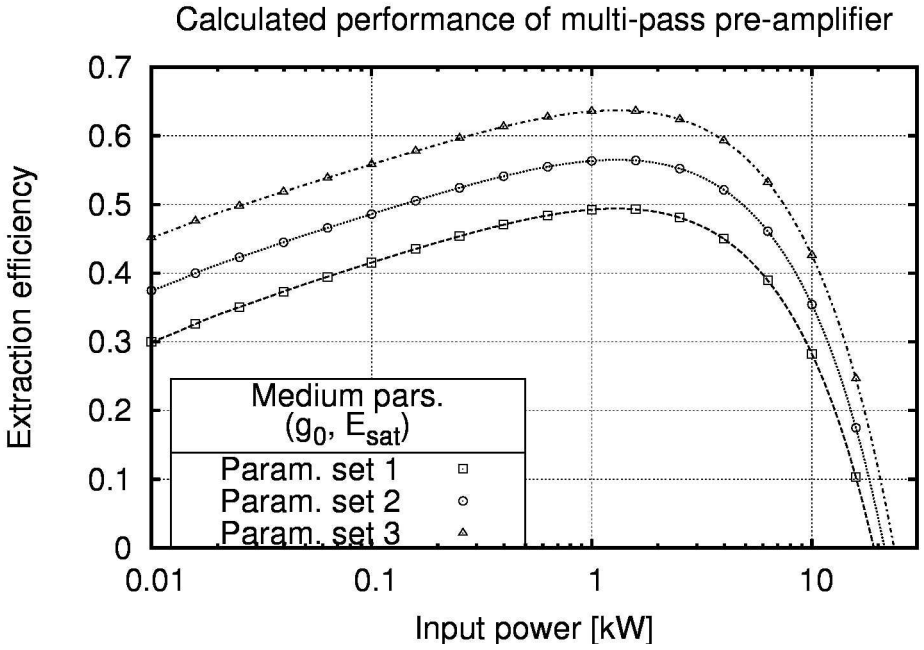
Small-scale slab-amplifier – recent developments (2008-2011) – achieved near-CW efficiency at multi-line operation



Multi-pass slab-waveguide based short pulse amplifier performance – model prediction (2009)



Input beam Gaussian (M^2=1), collimated

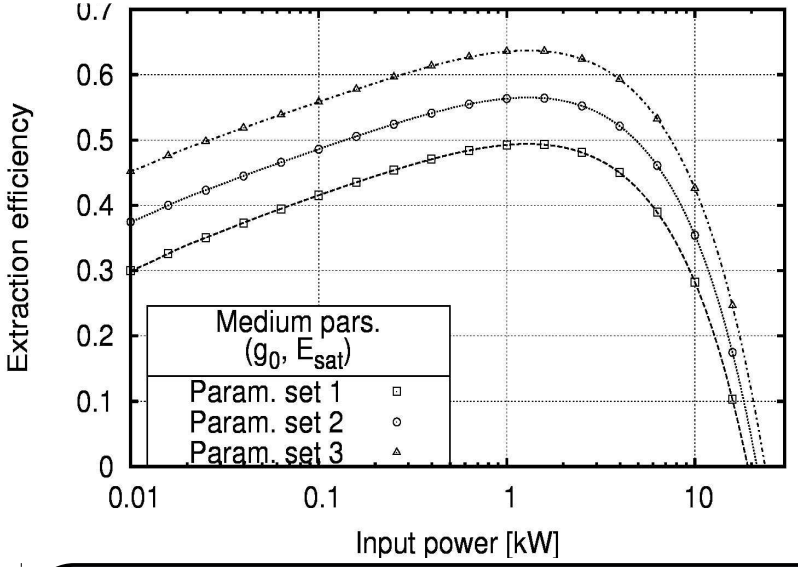


- Good beam quality $M^2 < 2$ at multi-kW level predicted
- Compact size
- Extr. Efficiency better than 40%

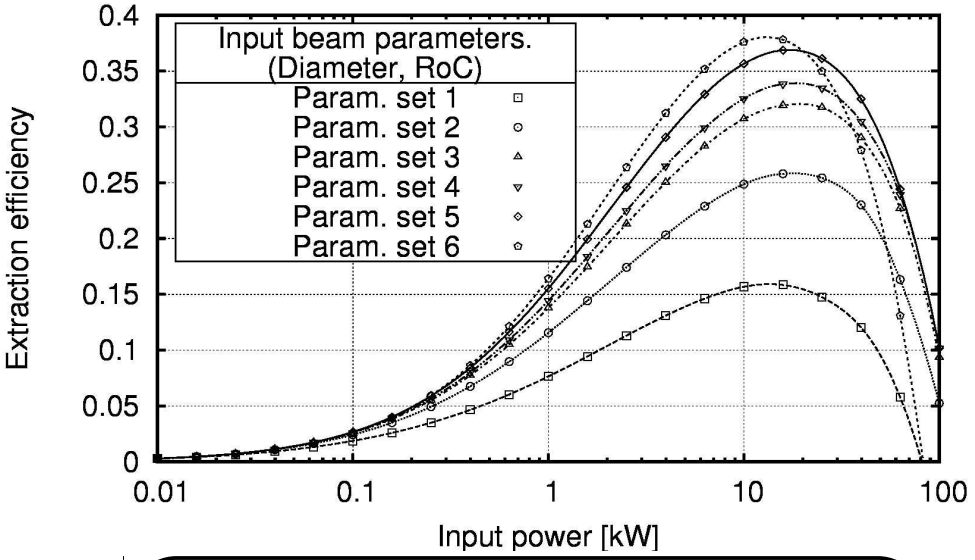
Multi-pass slab vs single-pass FAF amplifier – illustration of efficient pre-amplification

Single line operation P20 at 100kHz repetition, 20 ns

Prediction of pulsed performance of large-scale slab amplifier, 20ns, 100kHz



Simulated performance of FAF amplifer based on experimentally determined medium parameters, 20ns, 100kHz



Large-scale multi-pass slab amplifier

Max. Extr. Efficiency*:	35-60%
Max. extracted power:	~4kW
Input for max Extr. Eff.:	1-3kW
Power consuption:	~70kW

20kW FAF amplifier

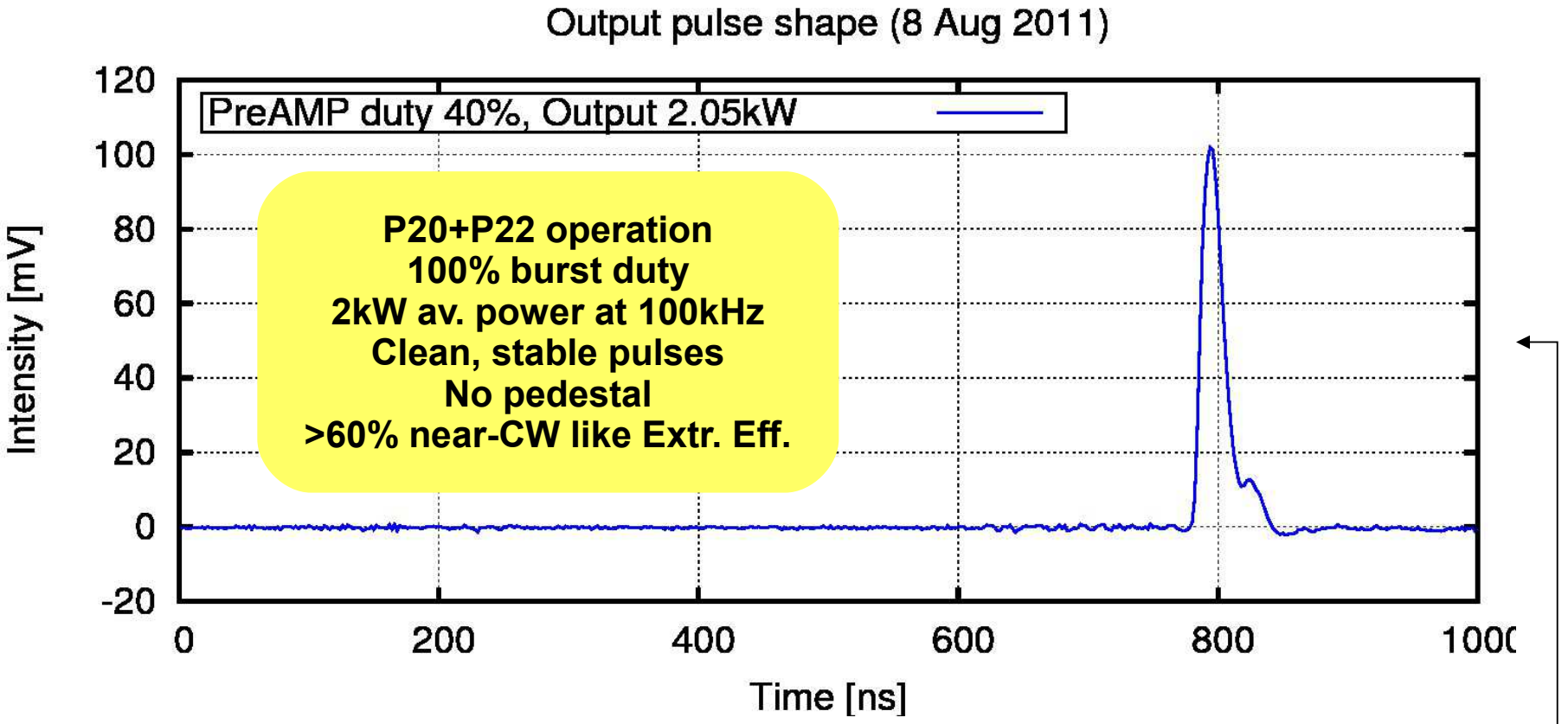
Max. Extr. Efficiency*:	35%
Max. extracted power:	~7kW
Input for max Extr. Eff.:	10-30kW
Power consuption:	~160kW

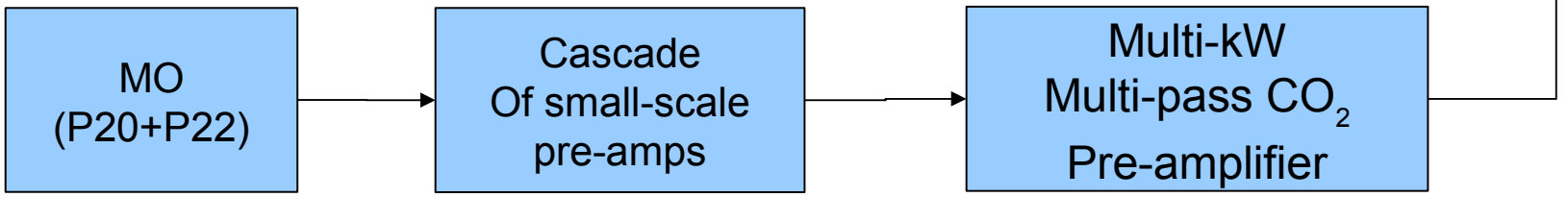
*** As compared to CW power output at full RF duty**

Multi-kW multi-line pulsed output achieved to date

- **Recent multi-line amplification results using prototype laser system**
  - Multi-line Master Oscillator
  - Small-scale amplifier cascade
  - Large-scale slab amplifier

Recent multi-line amplification results - 2kW achieved at near-CW extraction (August 2011)





Summary

- **A multi-line oscillator was designed and developed (10-20W output)**
  - ✓ **Multi-line (currently P20+P22, more planned soon)**
  - ✓ **High stability high quality output beam**
  - ✓ **Pulse-width tunable**
  - ✓ **Resistant to back-seeding by ASE**
- **A system of small-scale slab amplifiers was designed, developed and tested**
  - ✓ **boost from 10W input to 200W output**
  - ✓ **50-60% extraction efficiency recorded**
- **A large-scale slab amplifier was designed, developed and tested**
  - ✓ **Boost from 150-200W level to multi-kW level**
  - ✓ **>2kW output power achieved from 160-180W input (Aug 2011)**
  - ✓ **High extraction efficiency >60% confirmed at 2 line operation (P20+P22)**
    - >60% extraction at >20% RF duty recorded

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We at Gigaphoton aim at being a team of professionals who can build a strong relationship of mutual trust, both within and outside of the company.

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