Advancements in Laser Technology and Applications to Accelerators

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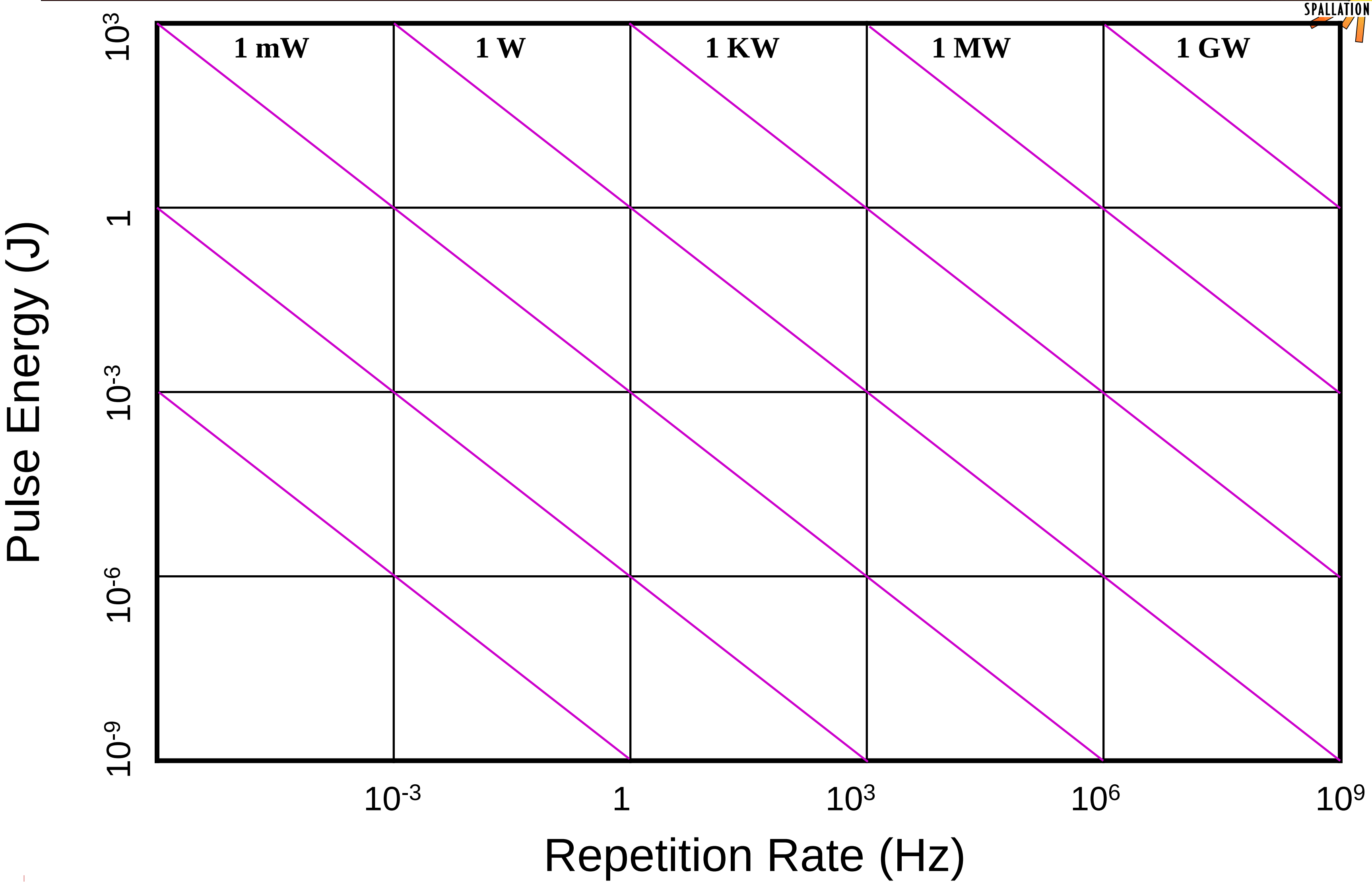
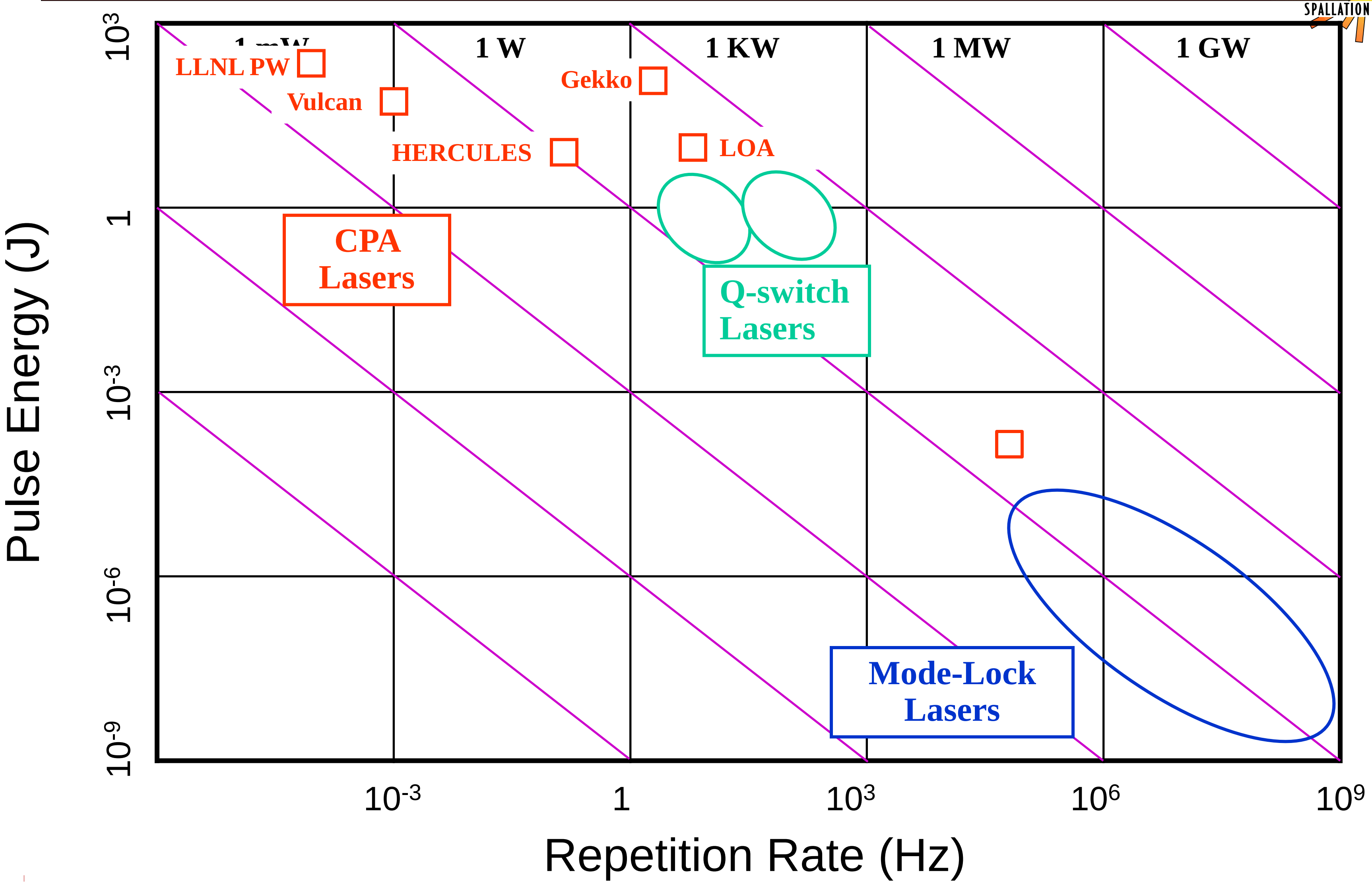
Applications of laser technology to accelerators

- Laser-based nonintrusive beam diagnostics
- Photoinjectors
- Laser stripping
- Compton scattering based light source
- Laser wakefield plasma acceleration
- Laser driven ion acceleration via thin films

Map of laser specs



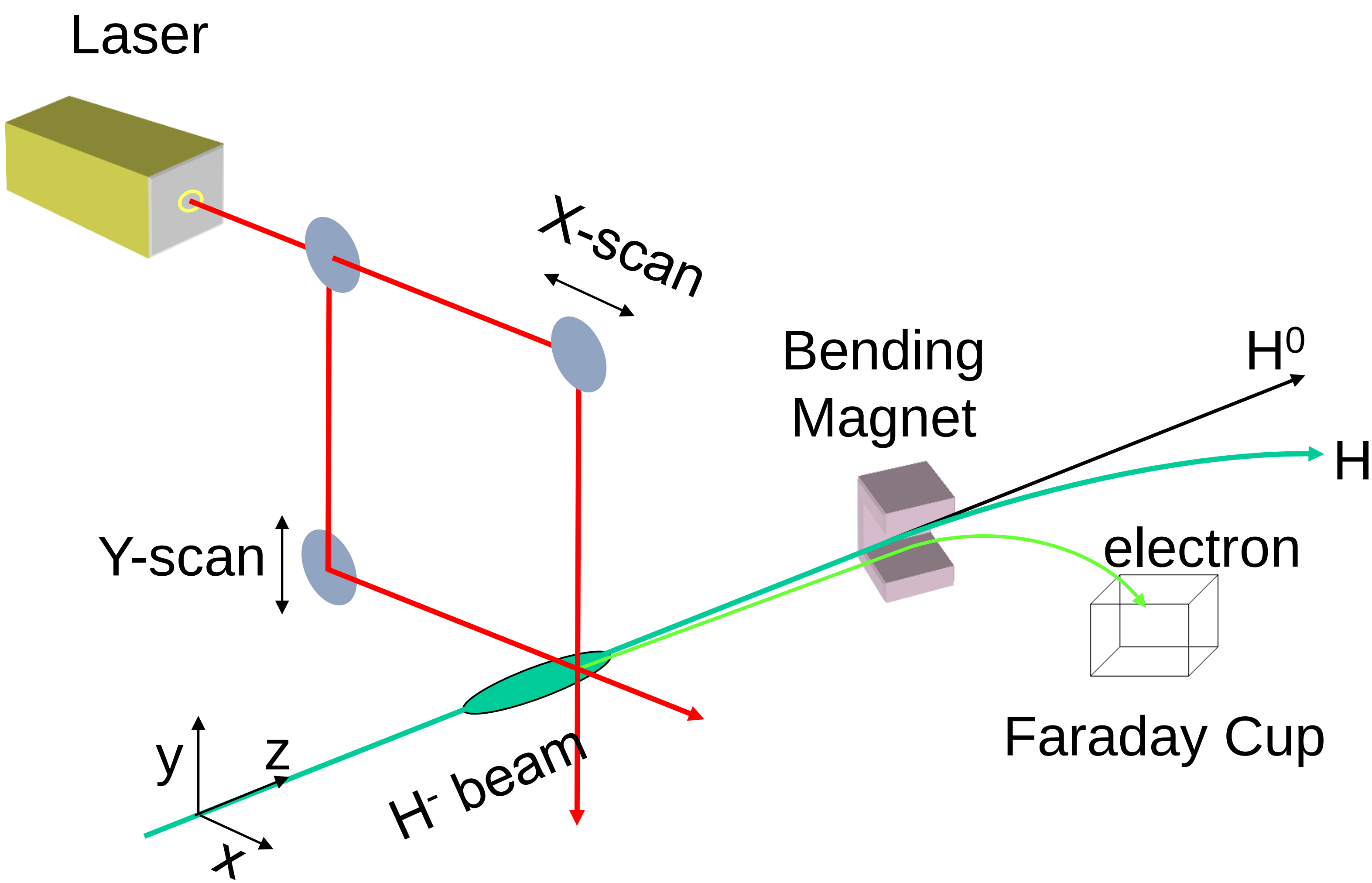
Pulse energy and repetition rate in laser specs



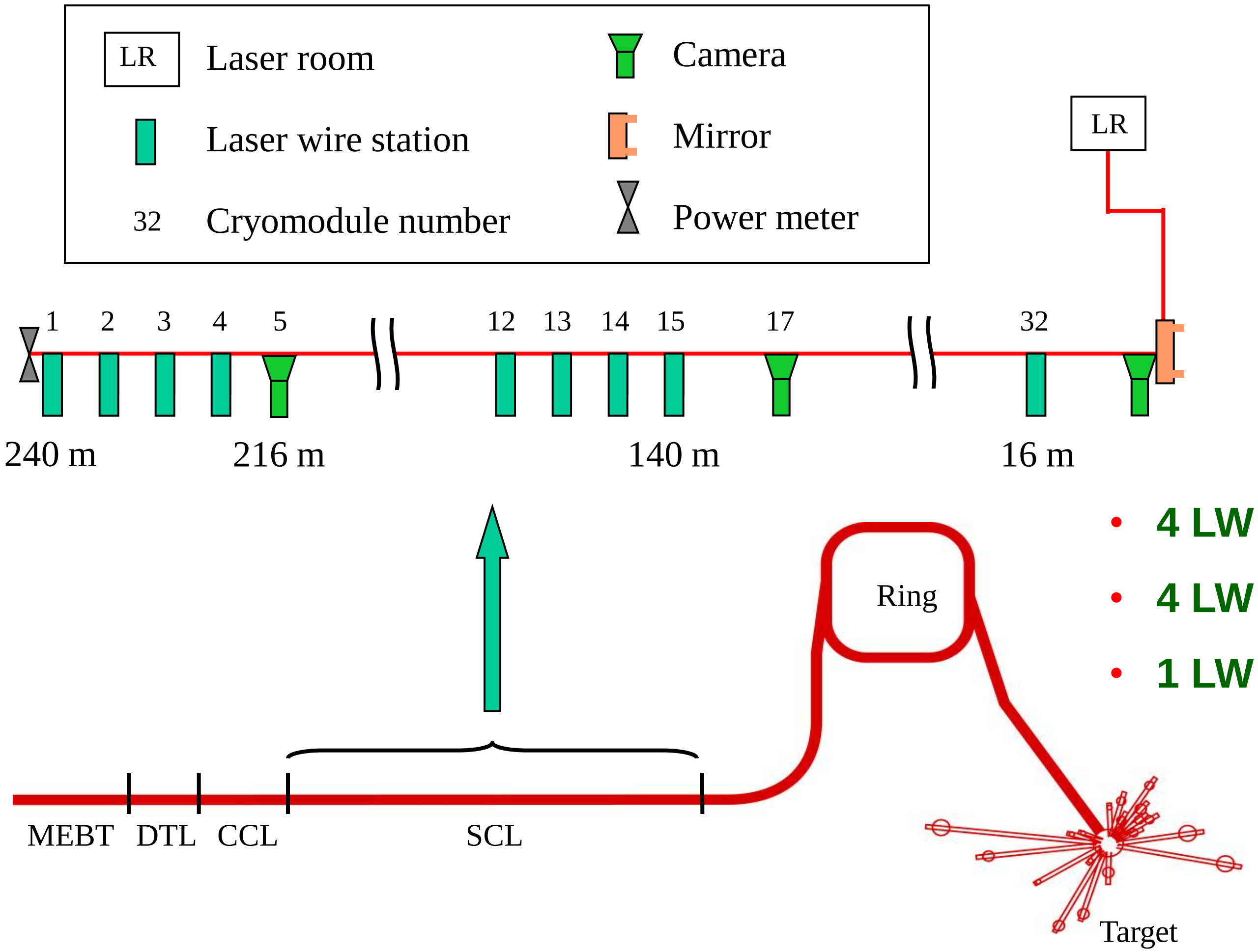
Laser based nonintrusive beam diagnostics

- Lasers are commercial off-the-shelf
- Optical engineering effort for operational service

Laser wire beam profile monitor

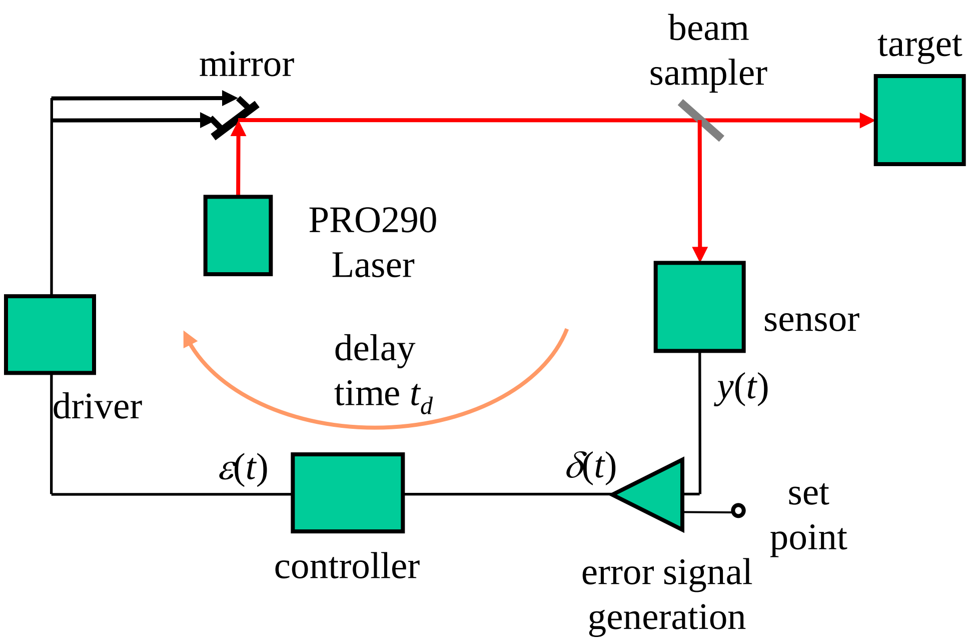


Layout of the SNS SCL laser wire system



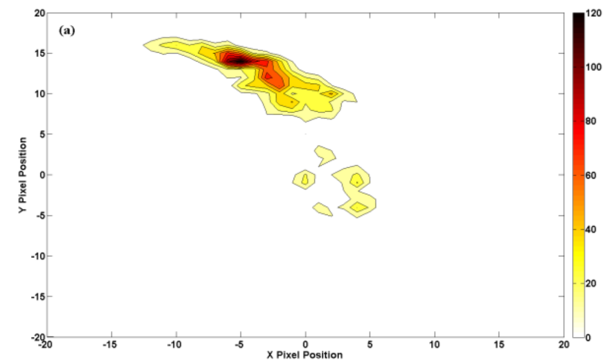
- **4 LW from 200 MeV**
- **4 LW from 450 MeV**
- **1 LW at 1 GeV**

Laser beam position stabilization with feedback control

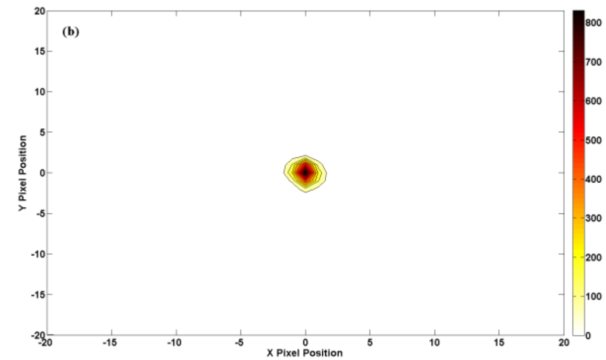


$$y(t) = x(t) + g\varepsilon(t - t_d),$$
$$\varepsilon(t) = \lambda\varepsilon(t - t_d) + k\delta(t),$$
$$\delta(t) = Y_T - y(t).$$

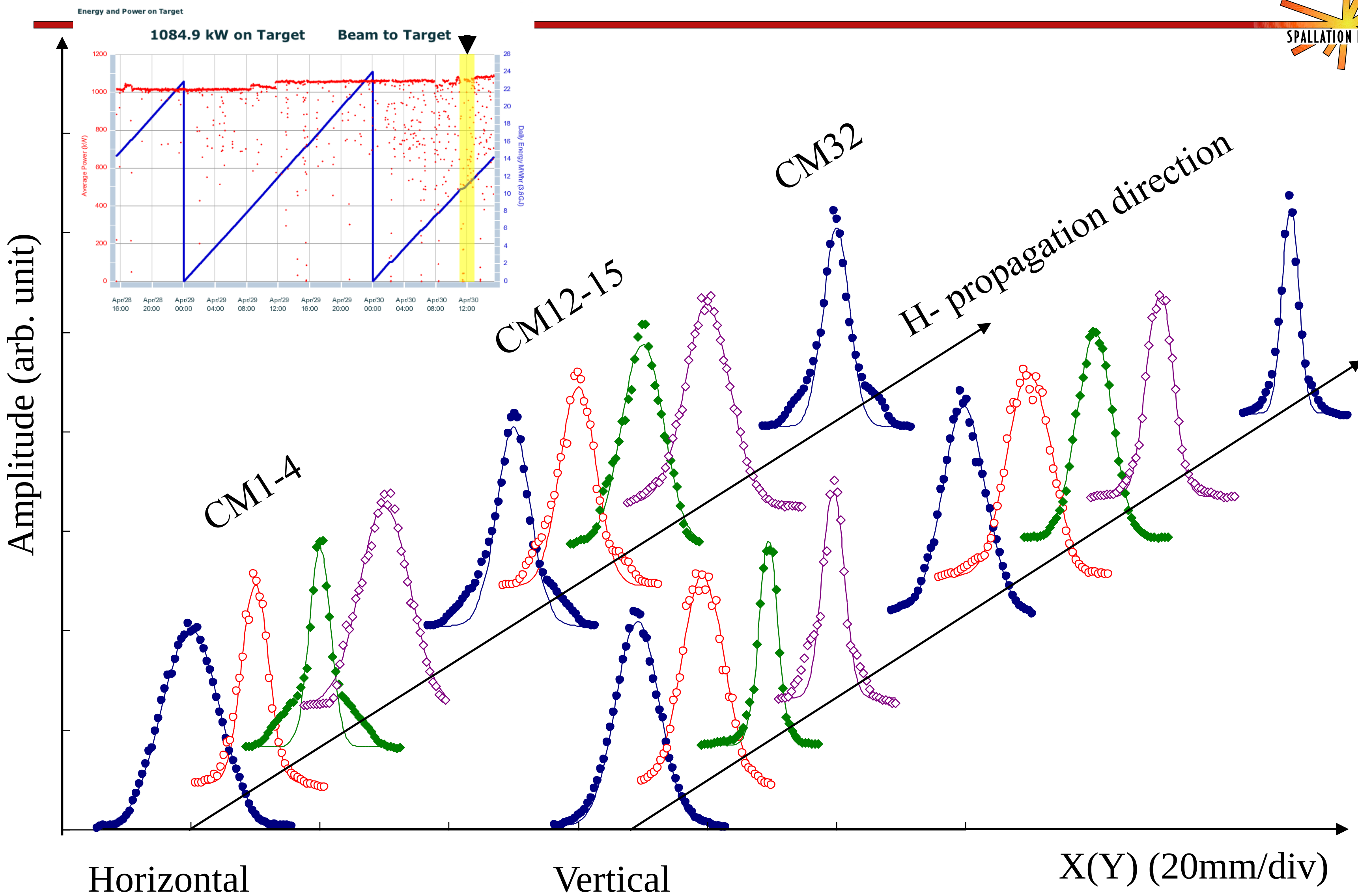
Feedback off



Feedback on



1-MW H$^-$ profiles measured by laser wire at SCL



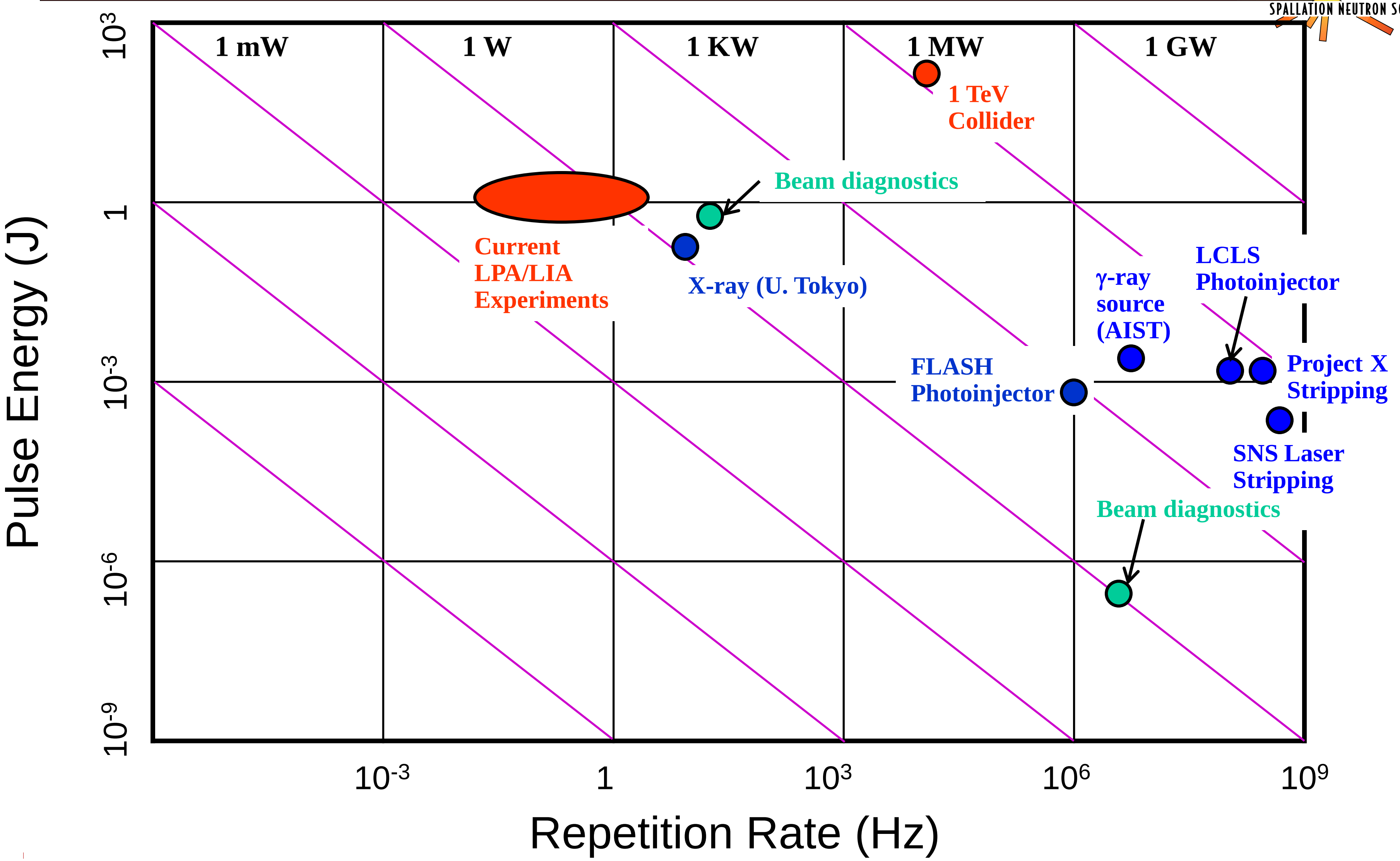
Laser specs for photoinjectors and laser stripping

	λ (nm)	Micropulse Length	Micropulse Frequency	Micropulse Energy	Macropulse Length/Rep Rate	Power in Burst	Average Power
Fermilab NICADD Photoinjector	351	5 ps	81.25 MHz	20 uJ	800 us @ 1 Hz	1.6 KW	1.3 W
TTF Photoinjector	262	10 ps	1 MHz	53 uJ	800 us @ 10 Hz	53 W	0.4 W
FLASH Photoinjector	800	7 fs	1 MHz	1 mJ	800 us @ 10 Hz	1 KW	8 W
European XFEL Photoinjector	800	10 fs	4.5 MHz	5 mJ	650 us @ 10 Hz	22 KW	150 W
NLS Photoinjector	800	30 fs	1 MHz	50 mJ	CW		50 KW
CEBAF Photoinjector	780	100 ps	499 MHz	4 nJ	CW		2 W
LCLS Photoinjector	255	10 ps	119 MHz	2.5 mJ	1-40 micropulses @ 120 Hz	300 KW	<12 W
SNS Laser Stripping (Intermediate Stage)	355	50 ps	402.5 MHz	50 uJ	10 us @ 10 Hz	20 KW	2 W
SNS Laser Stripping	355	50 ps	402.5 MHz	50 uJ	1 ms @ 60 Hz	20 KW	1.2 KW
Project X Laser Stripping	1064	81 ps	325 MHz	1.2 mJ	1.25 ms @ 5 Hz	390 KW	2.4 KW

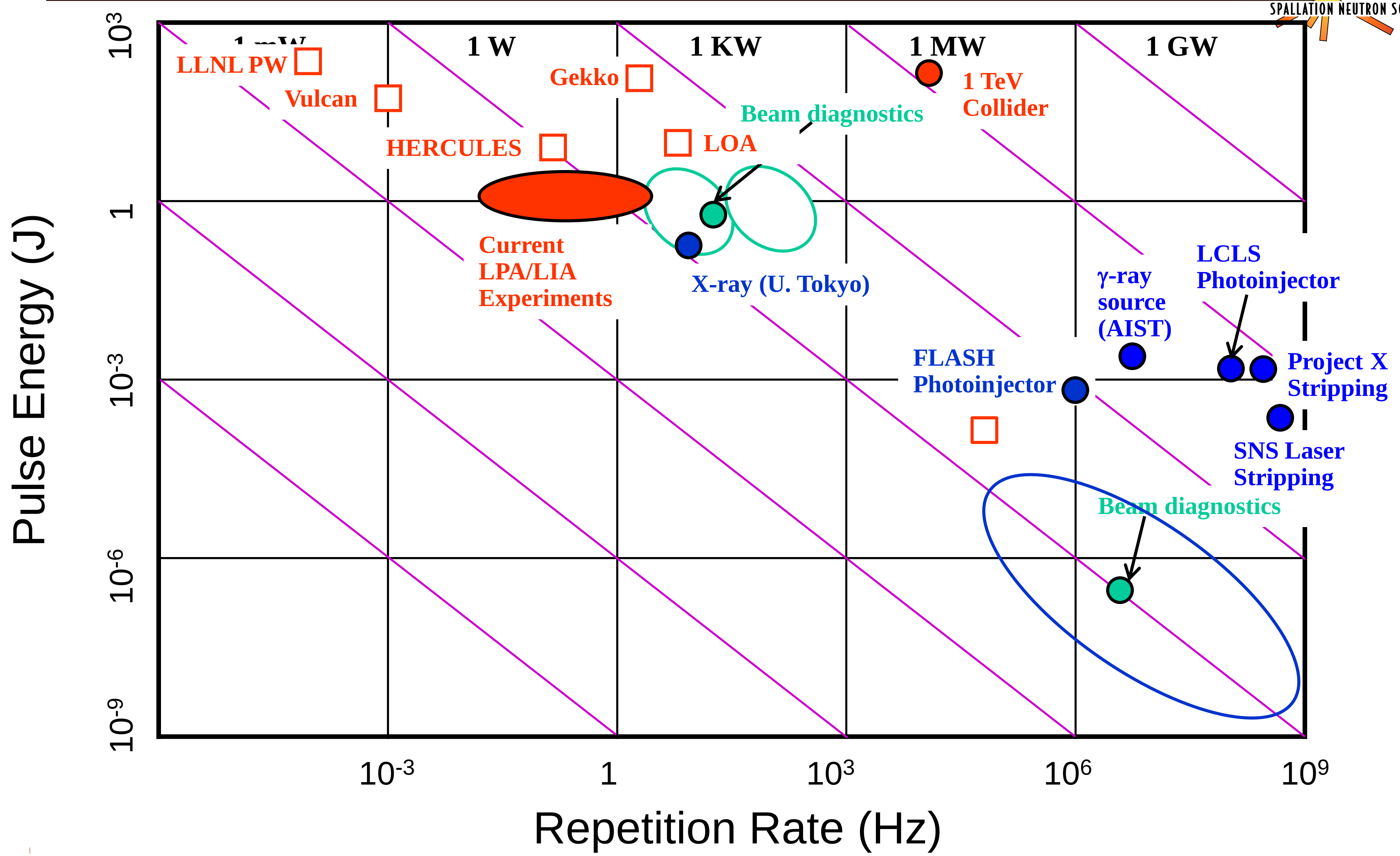
Laser Specs in ICS Experiments

Facility	Laser System	λ (nm)	Pulse Energy/Width	e-beam Energy	X-/γ-ray Energy	Yield
U. Tokyo	Nd:YAG	532	25mJ / 10ns	45 MeV	10-60 KeV	10^5 Hz
KEK	Nd:YAG	1064	112uJ / 7ps	50 MeV	30 KeV	10^5 Hz
BNL/ATF	CO_2	10,600	2J / 6ps	64-72 MeV	8 KeV	10^8 per shot
AIST/Japan	Ti:Sapphire	800	100mJ / 100fs	40 MeV	20-40 KeV	10^6 Hz
RadiaBeam	Nd:YAG	532	620mJ / 10ps	547 MeV	10.8 MeV	10^{14} Hz
JAEA	Nd:YAG	1064	1.8uJ / 1ps	350 MeV	0.5-9 MeV	10^{13} Hz
ELSA/France	Nd:YAG	532	200mJ / 30ps	19 MeV	13.6 KeV	10^8 per pulse

Pulse energy and repetition rate in applications

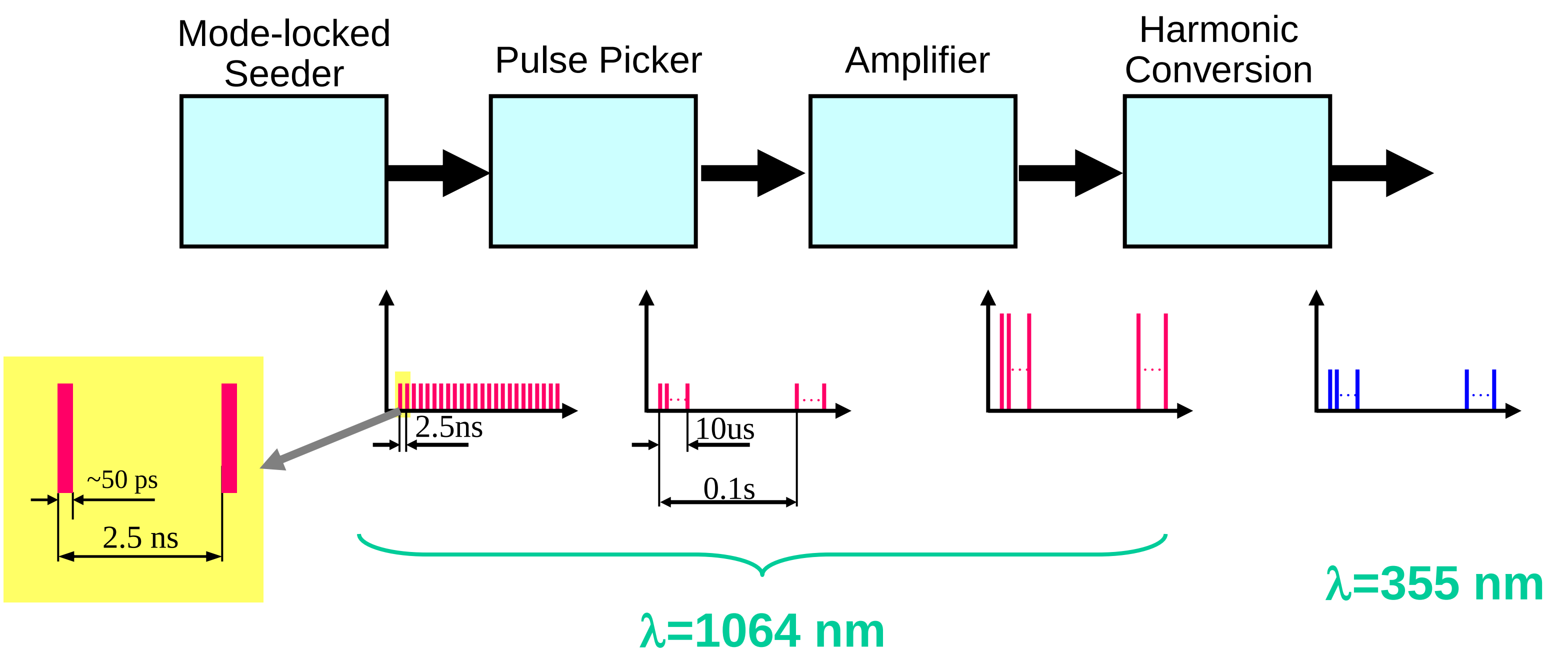


Gap between application requirements and available specs

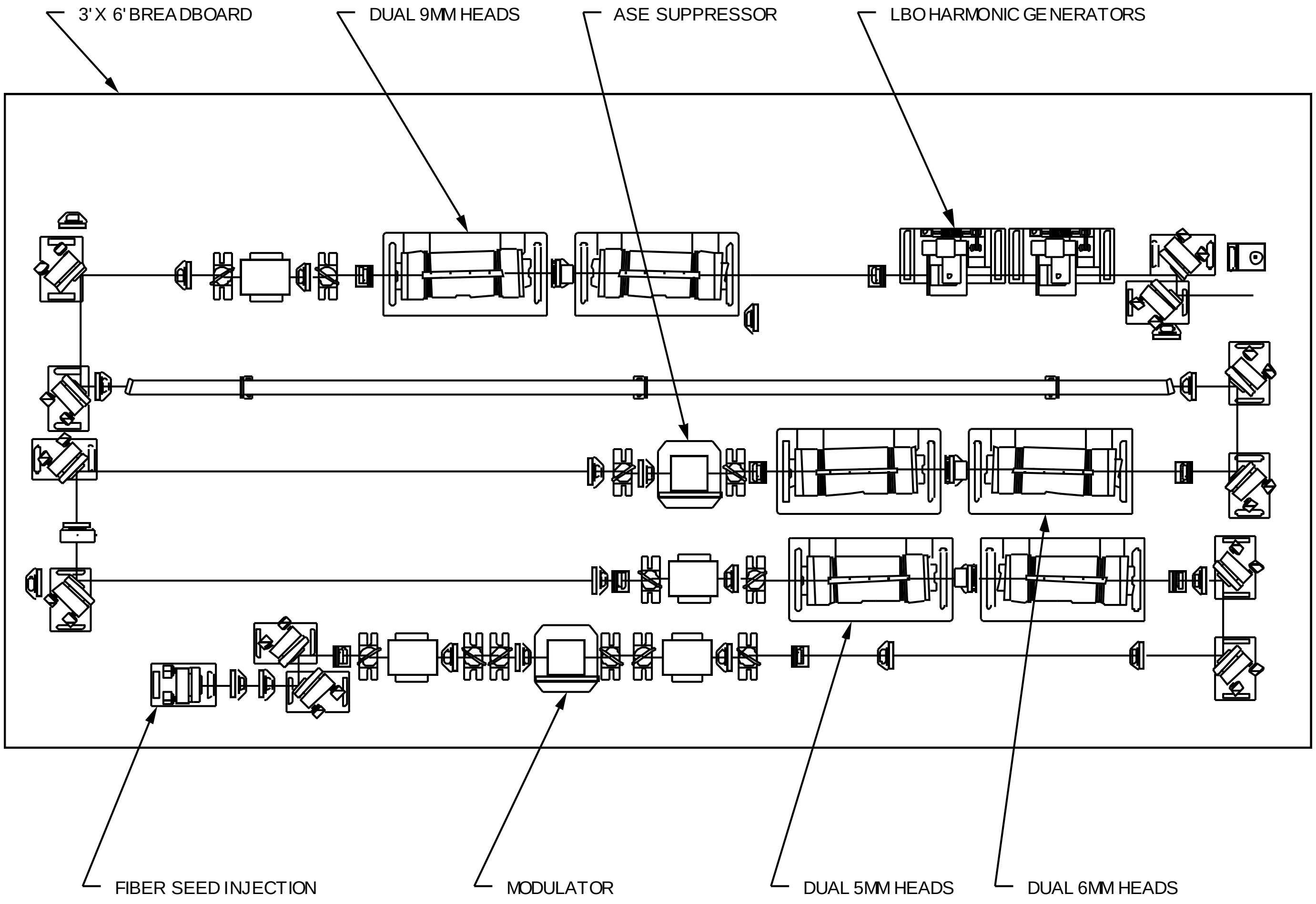


Burst-mode laser system

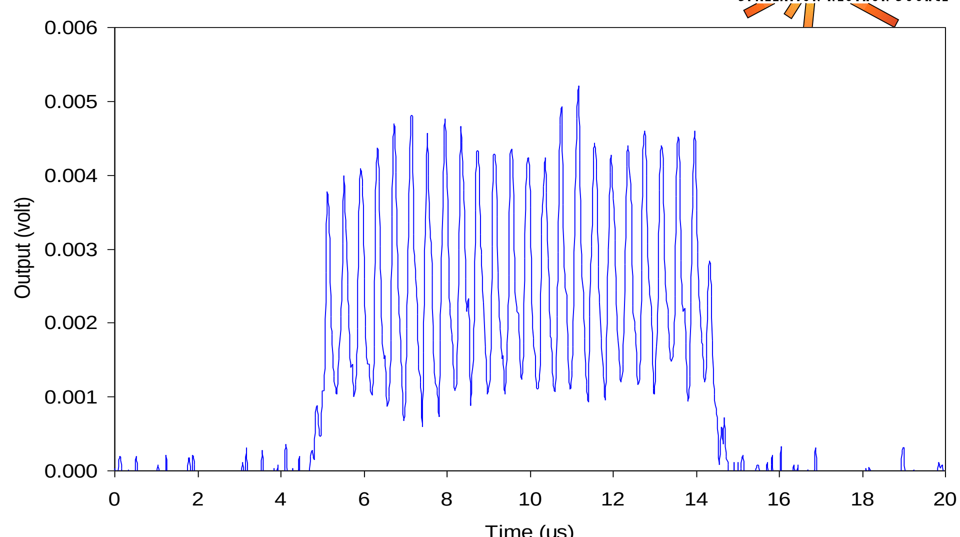
- High-frequency mode-locked seed laser with micro-pulse width ~ 50 ps
- Pulse picker to select a portion (macropulse) of the seeder output
- Amplification of macropulse (100us – 1 ms) at a low repetition rate
- Harmonic generation for UV output
- Each micro-pulse has ~ MW peak power at UV

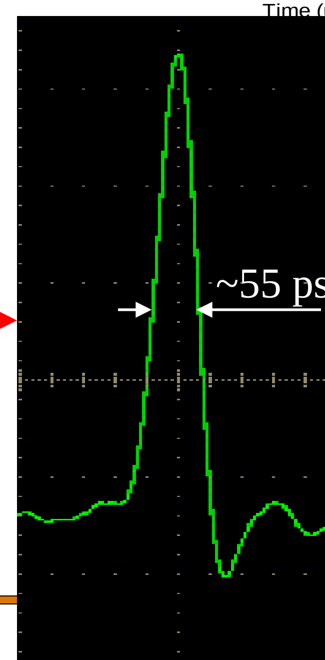


Continuum burst-mode laser amplifier

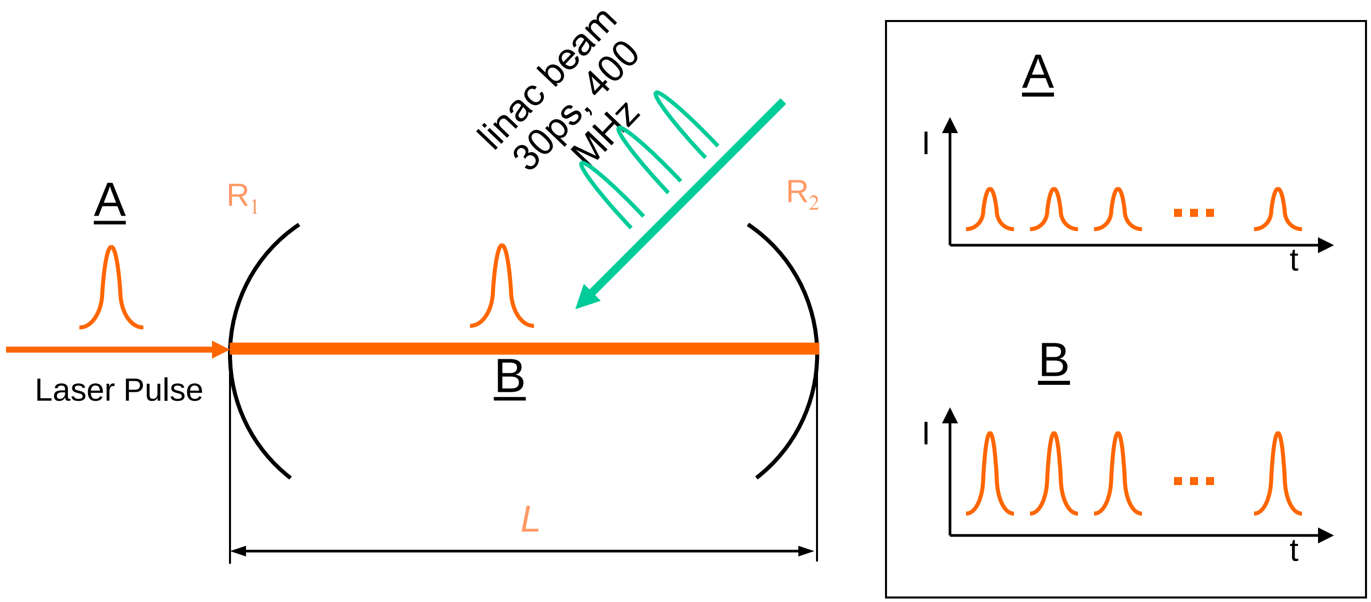


Burst-mode laser installed at SNS (2009)

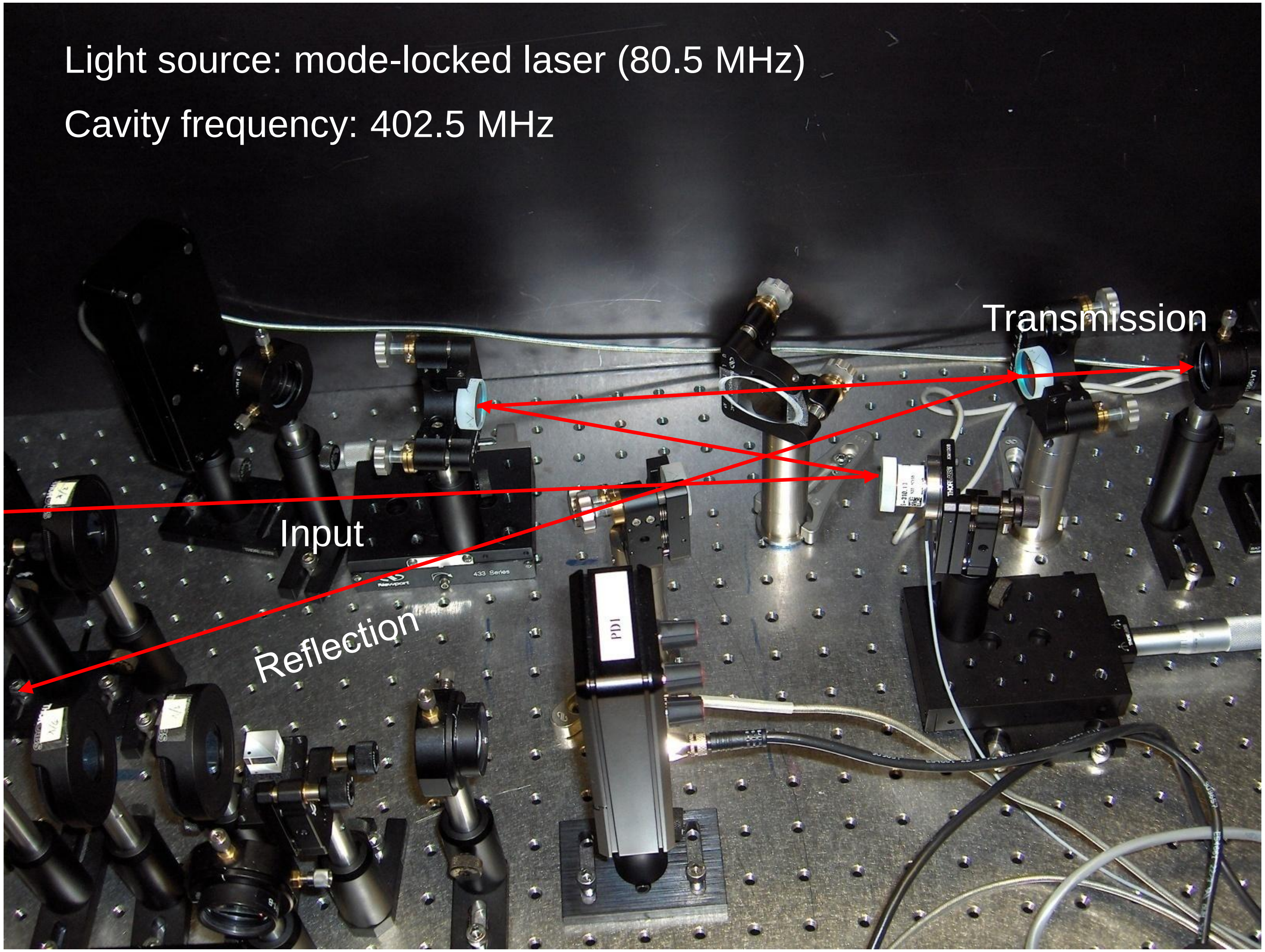




Negligible loss in photon-particle interaction

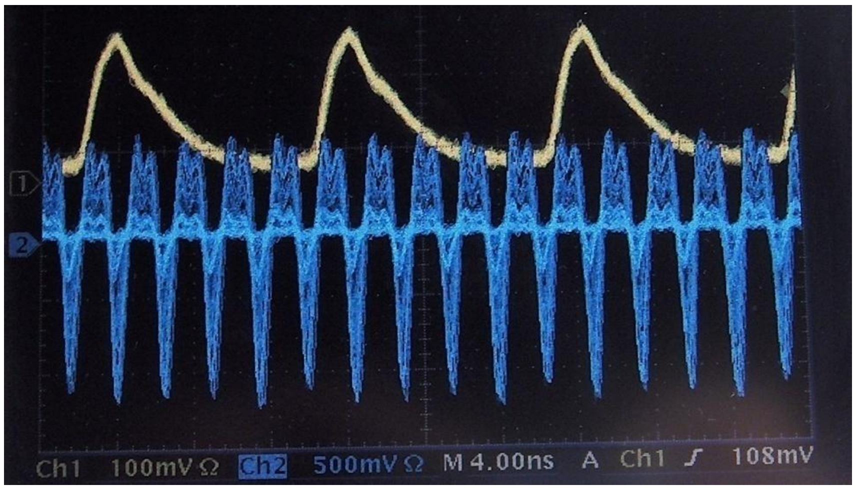


Optical ring cavity

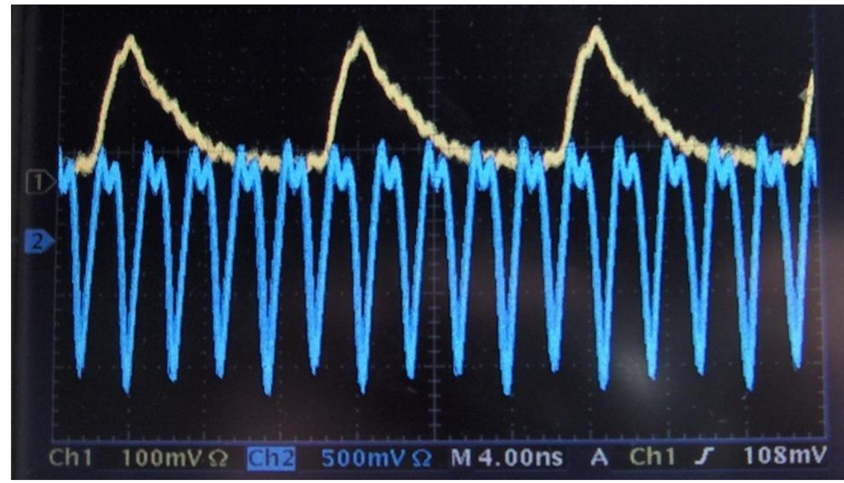


Stabilization of optical cavity

Unlocked cavity



Locked cavity



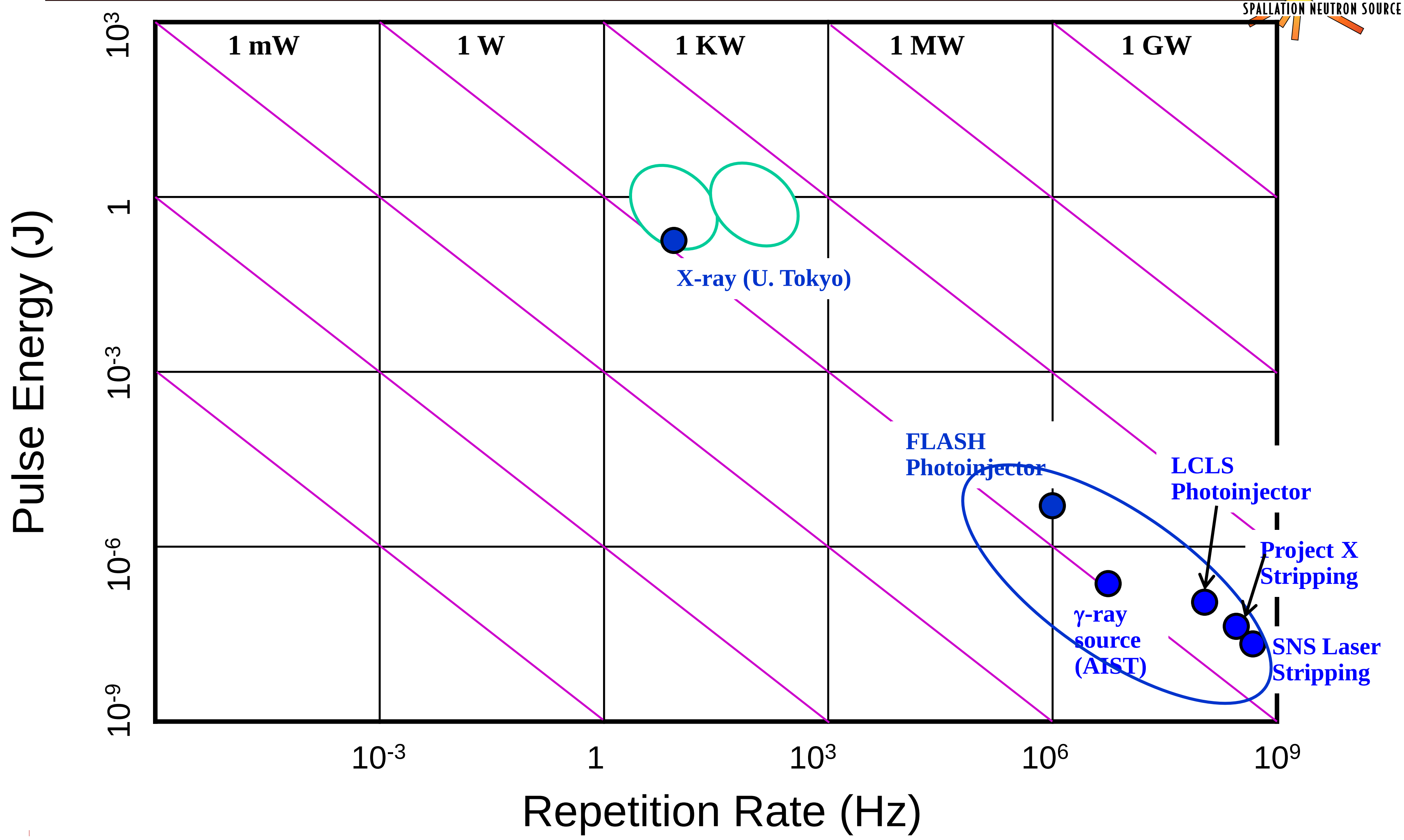
Upper: input laser pulse

Lower: intra-cavity laser pulse

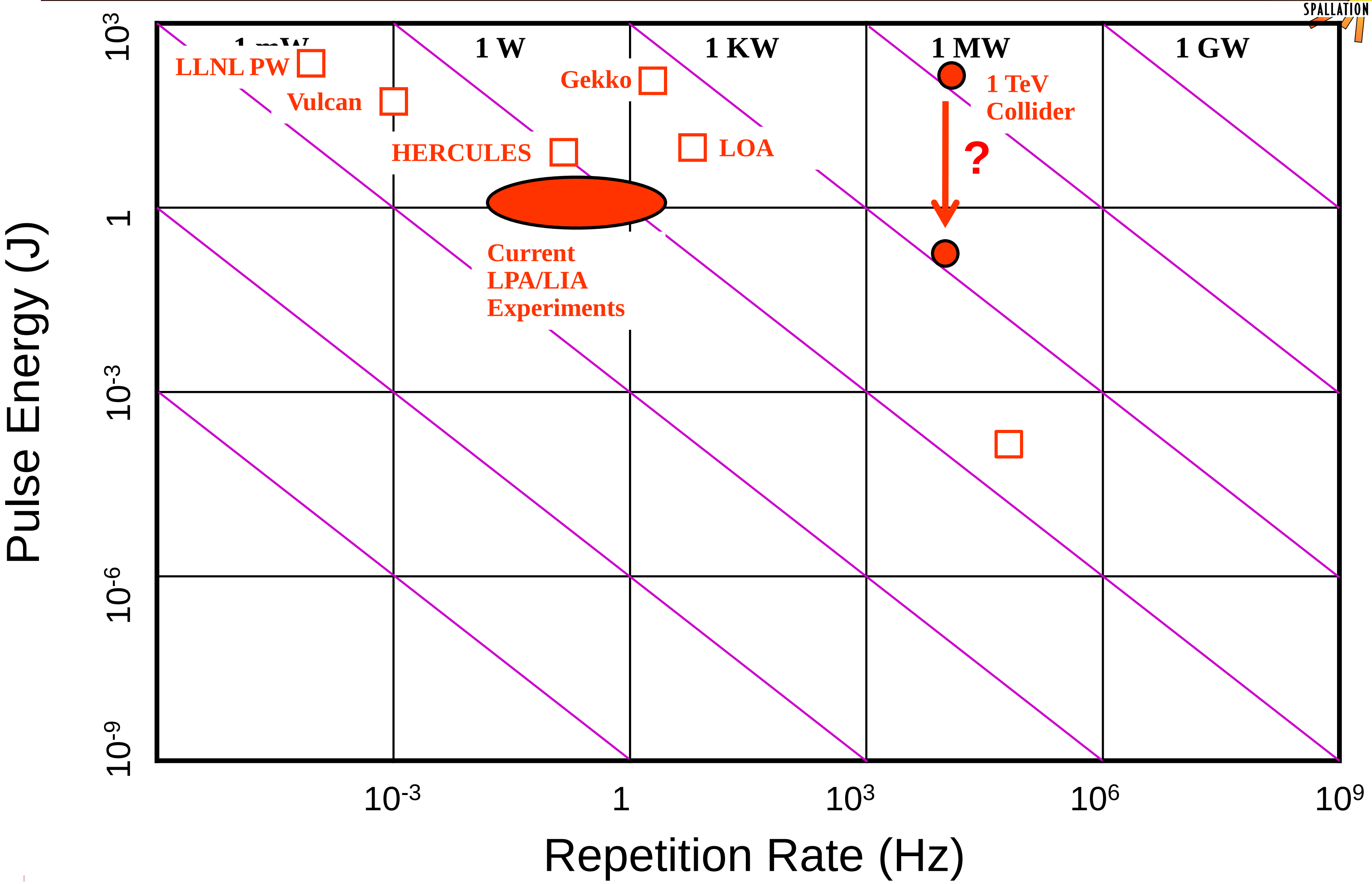
Examples of optical cavity

Finesse	Wavelength	Pulse Width	Reference
16000	657 nm	CW	Fortier et al, PRL 97 (2006) 163905
349	835 nm	3.4 ps	Potma et al, Opt. Lett. 28 (2003) 1835
3000	800 nm	52 fs	Jones et al, PRA 69 (2004) 051803
6000	823 nm	63 ps	Xiong et al, Opt. Eng. 46 (2007) 054203
2000	1560 nm	150 fs	Chen et al, Opt. Lett. 33 (2008) 959

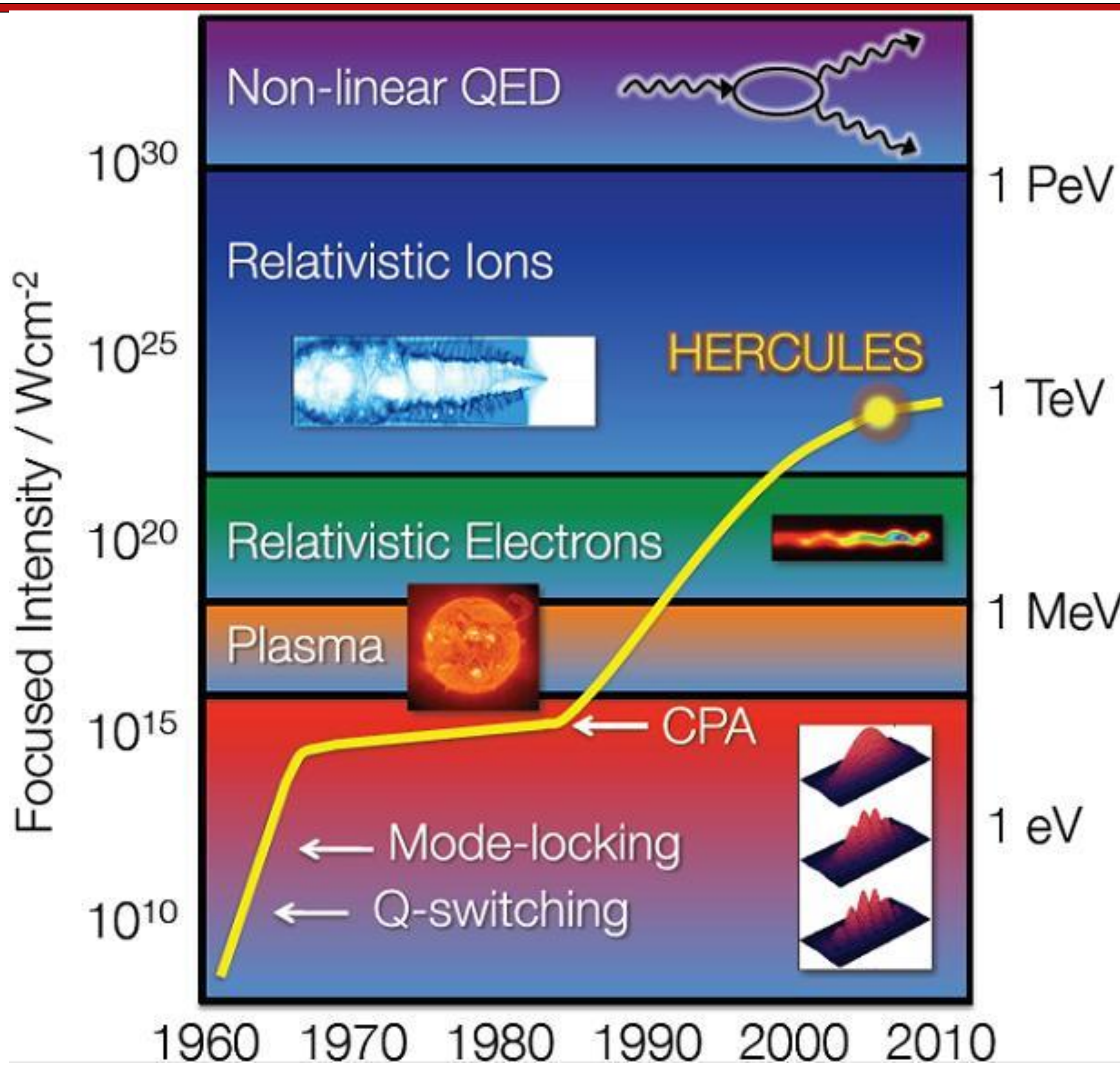
Average power dropped more than 1000 times!



Play the same game for the laser acceleration?



High peak power laser technology - Chirped Pulse Amplification



http://www.engin.umich.edu/research/cuos/ResearchGroups/HFS/Experimentalfacilities/Chirped_Pulse_Amp.html

High average power is a real challenge!

Ultimately most ultrahigh-intensity applications will require high average power. …. average power is a serious difficulty that will have to be surmounted for real world applications.

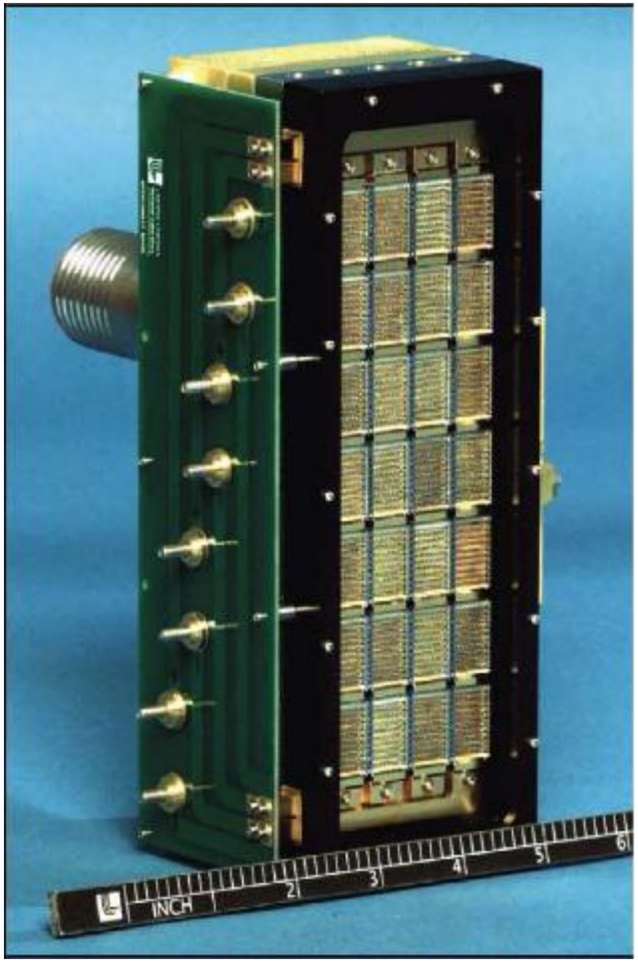
G.A. Mourou, T. Tajima, S.V. Bulanov, *Rev. Mod. Phys*. 78 (2006) 309.

A simple analogy

	Wall-plug to HV power supply	Power supply to RF cavity	RF cavity to Beam	total
Warm Linac	90%	50%	15-20%	5-10%
SCL	90%	50%	90%	~40%
Laser Driven	Wall-plug	Laser to plasma wave	Plasma wave to beam	total
	20-50%	50%	40%	4-10%

High efficiency, compact pump lasers

41KW laser diode stacked array



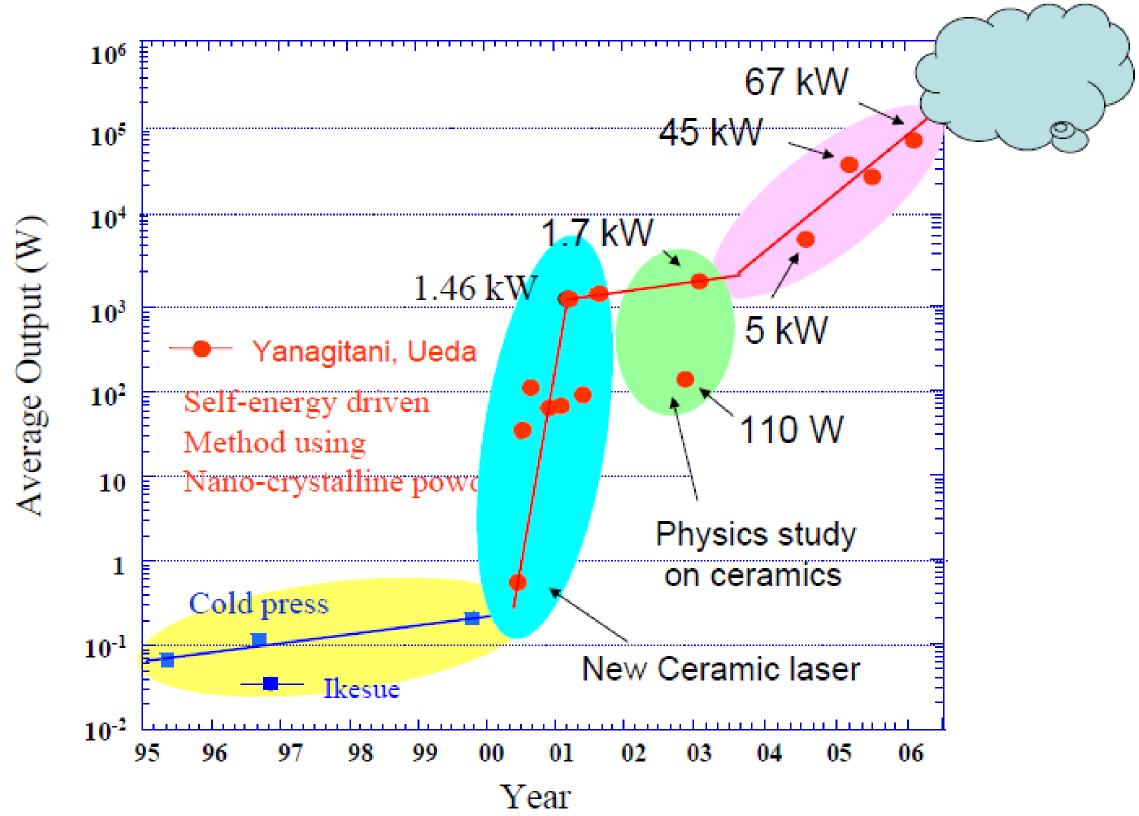
Wall-plug efficiency: 60%

50 KJ Flashlamp

Wall-plug efficiency: 10%

Novel gain material – ceramic lasers

- **Nd:YAG ceramic laser reached 40% efficiency**
- **High damage threshold**
- **Scaling to large aperture (1m x 1m) : effectively no limit**

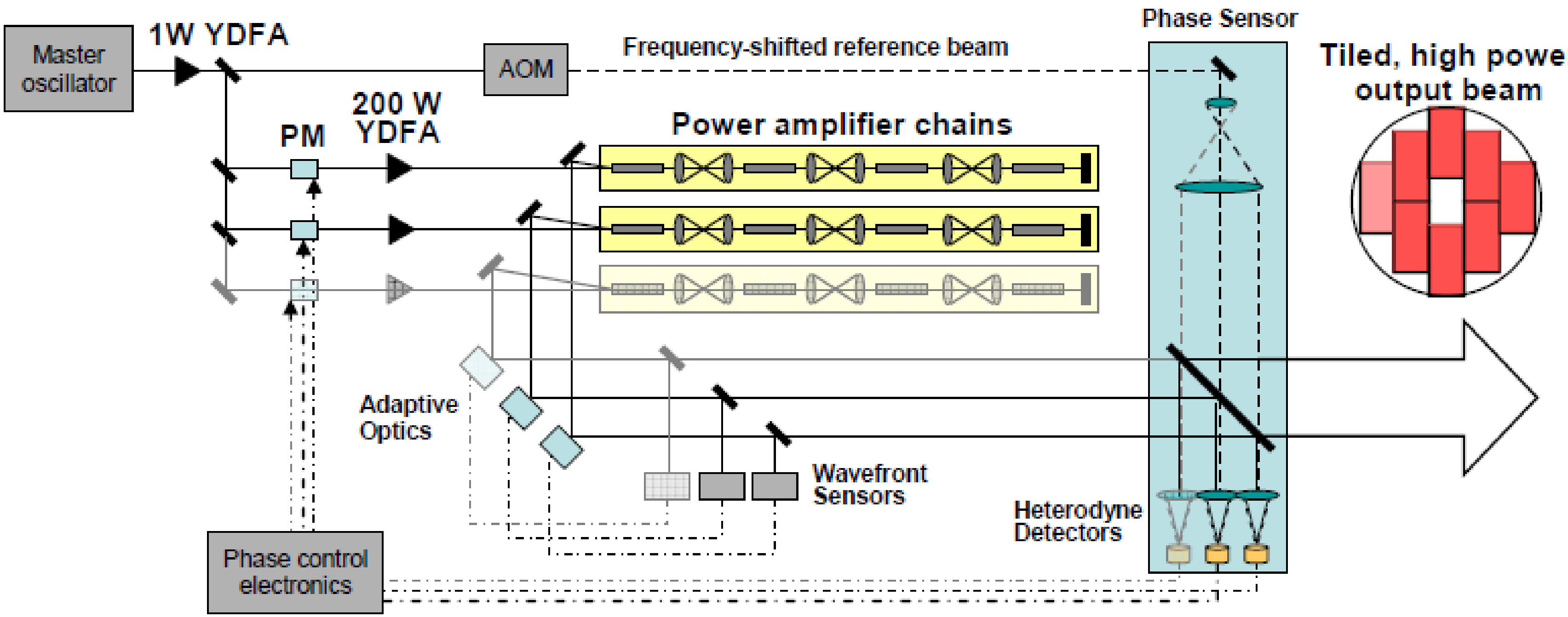


From Prof. Ken-ichi Ueda, "Recent progress of ceramic laser for ultrashort pulse laser", 2008.

Power scaling via beam combining

- An approach to building high-power lasers is to use arrays of relatively lower power lasers.
- Incoherent beam combining - a method of scaling up the laser power via multiplexing in position, angle, wavelength or polarization
  - total beam from the laser array cannot exceed that of each individual beam
- Coherent beam combining – all lasers occupy the same elements in phase space and behave as if they came from one coherent source.
  - Only coherent superpositioning allows truly scalable output powers and diffraction-limited quality of the combined beams

100KW Coherently Combined Lasers (Northrop Grumann)



From McNaught et al, in OSA FIO2009, paper FThD2 (2009)

Summary

- Laser-based nonintrusive beam diagnostics – Lasers are off-the-shelf. Engineer efforts for operational service.
- Photoinjectors, inverse Compton scattering, laser stripping – Key technical elements (mode-locked laser, burst mode amplifiers, optical cavity) are well understood. There is a clear path for development.
- Laser driven acceleration (wakefield plasma acceleration, ion acceleration) - basic concept demonstrated with ultra-short ultra-intense CPA lasers. Future development (e.g. new pump, new gain media, beam combining) needed to overcome average power requirement.