Perspectives of High Power Laser Technology for Particle Beam Acceleration

BASED ON WORK PRESENTED AT THE FIRST ICFA-ICUIL JOINT WORKSHOP ON HIGH POWER LASER TECHNOLOGY FOR FUTURE ACCELERATORS

APRIL 8-10, GSI, DARMSTADT, GERMANY

WIM LEEMANS

46th ICFA Advanced Beam Dynamics Workshop on
High-Intensity and High-Brightness Hadron Beams

Sept. 27- Oct. 1, 2010
Morschach, Switzerland

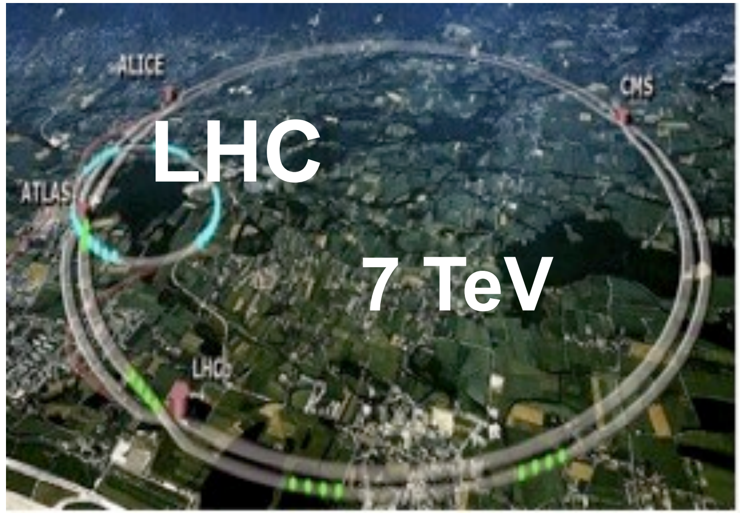
ICFA
International Committee for Future Accelerators
Sponsored by the Particles and Fields Commission of IUPAP

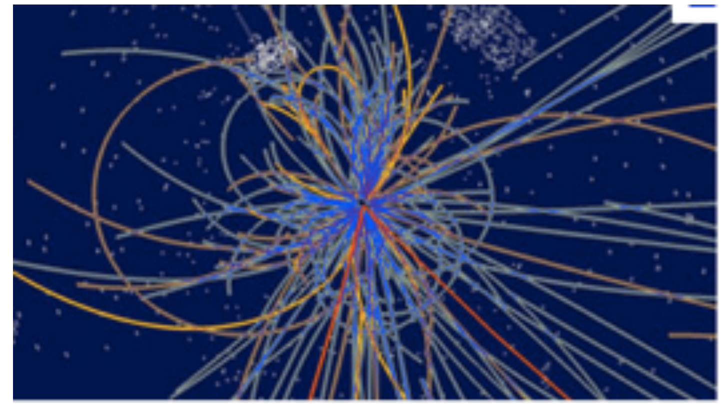
ICUIL

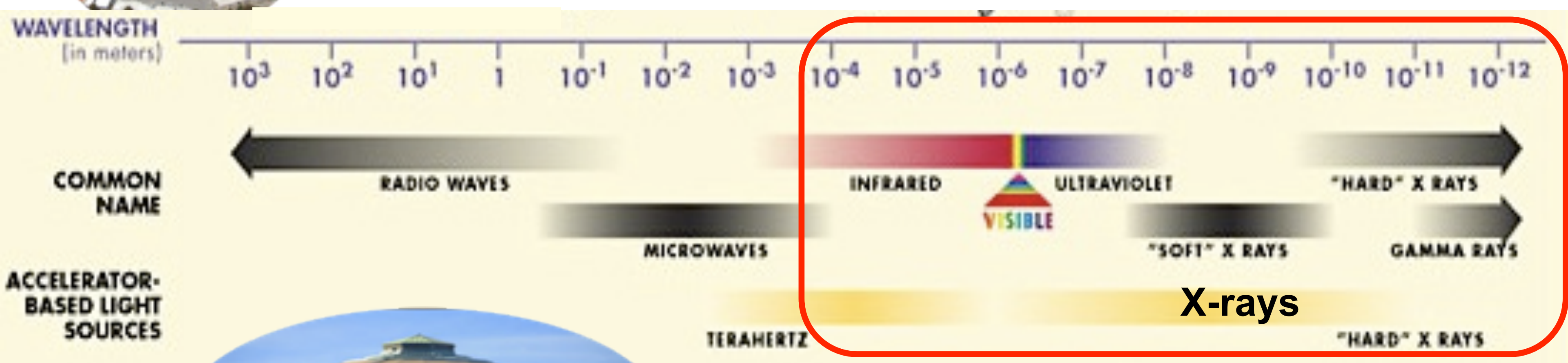
OUTLINE

- Introduction
- ICFA-ICUIL Taskforce
- Output from 1st workshop:
  - Laser requirements for:
    - Colliders
    - Light source
    - Medical applications
  - Laser technologies
- Summary and conclusion

Accelerators: drivers for science



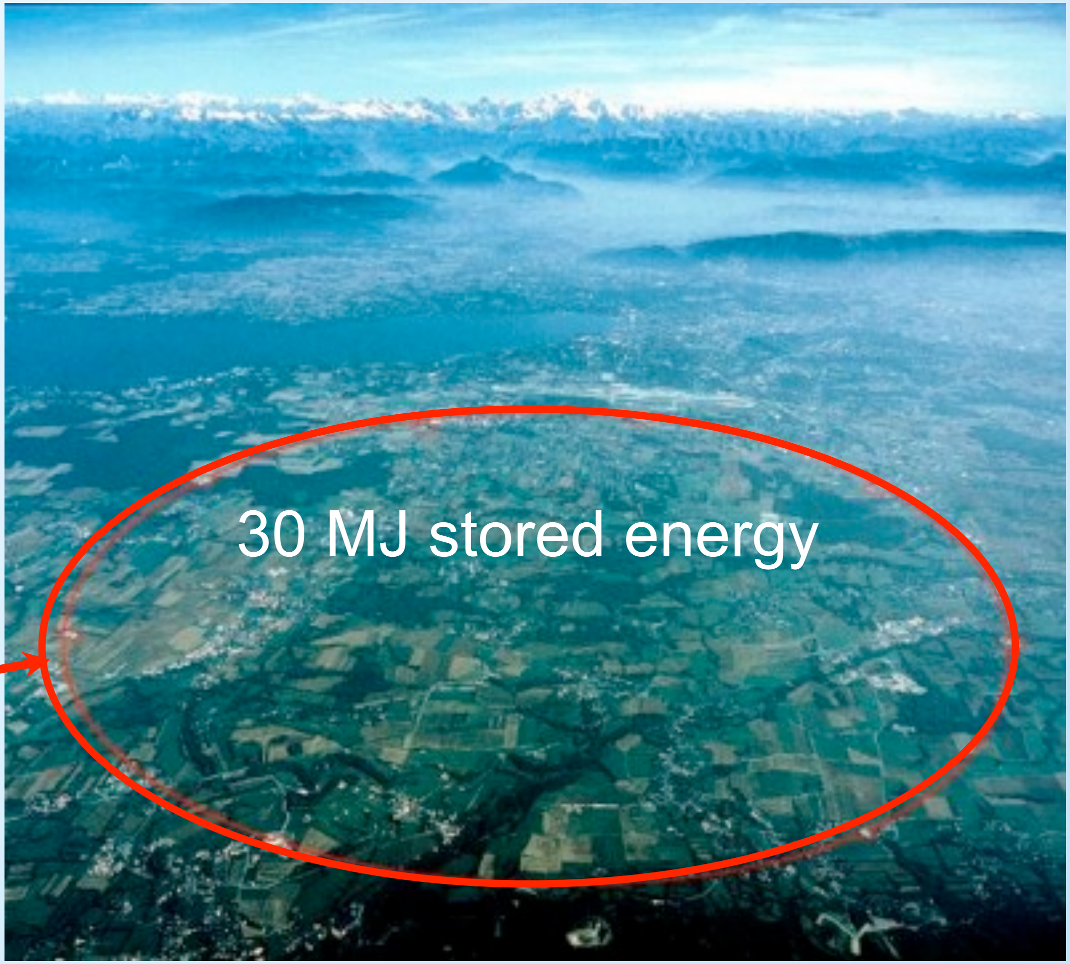




Accelerators: from handheld to size of a small country

1929

LHC, 2010



Size x 10^5 Energy x 10^9

DOE-HEP is investing in advanced plasma based accelerator facilities

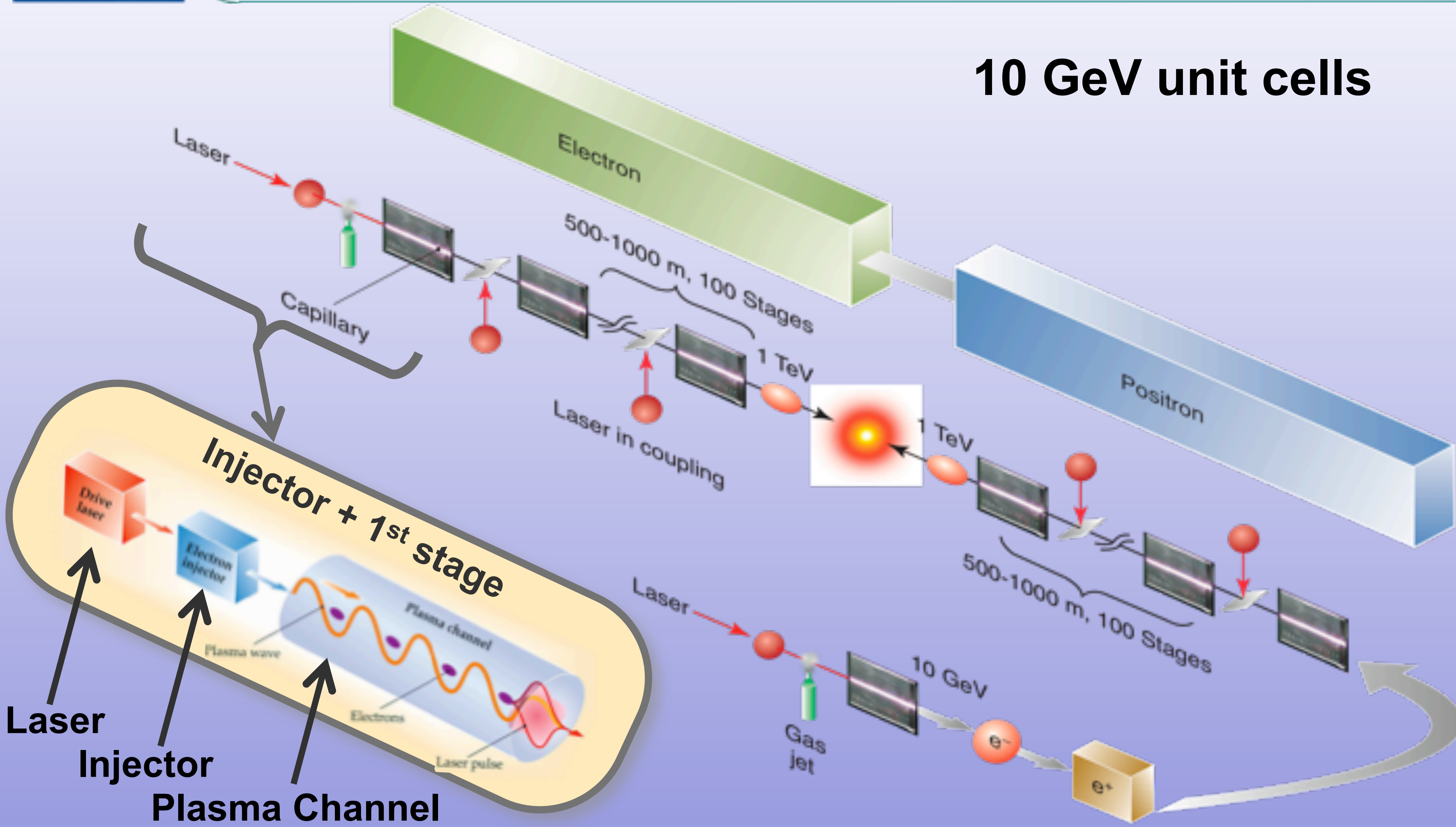
- Collider size set by maximum particle energy and maximum achievable gradient limited by material breakdown
- Motivates R&D for ultra-high gradient technology

Driver technology
- Laser
  - Direct laser accelerator
  - Laser plasma accelerator
- E-beam
  - Plasma wakefield accelerator
  - Dielectric accelerator

Both launched in 2009

Strawman design of a TeV laser plasma accelerator (LPA) based collider

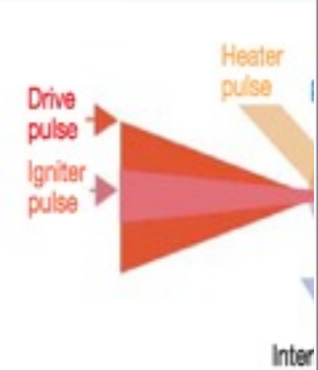
10 GeV unit cells



Leemans & Esarey, Physics Today, March 2009

Laser Plasma Accelerators

200



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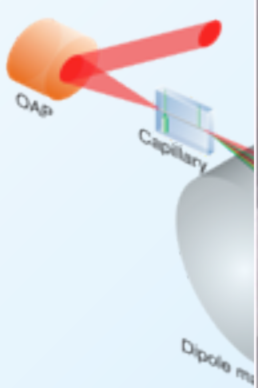
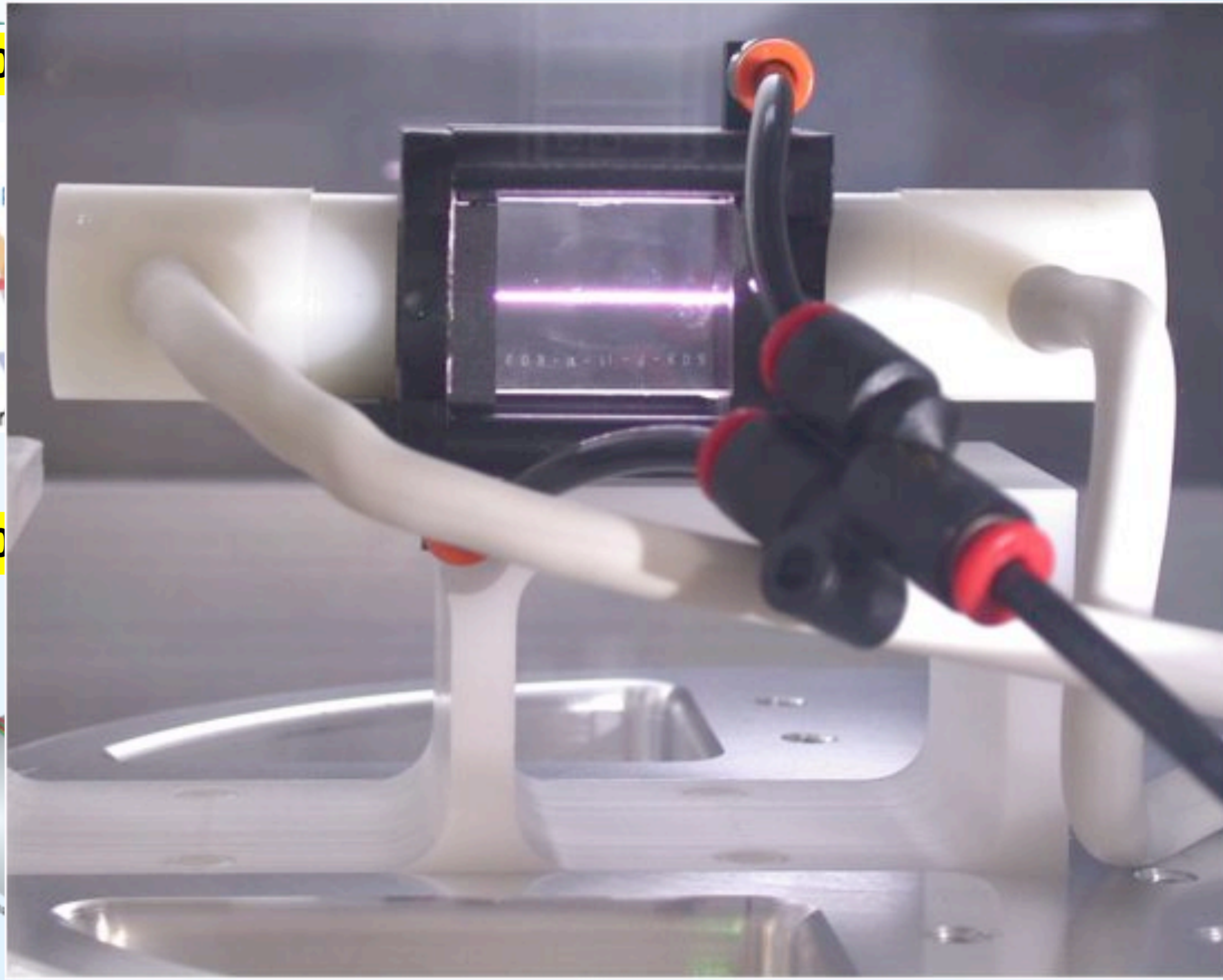
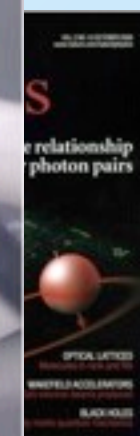
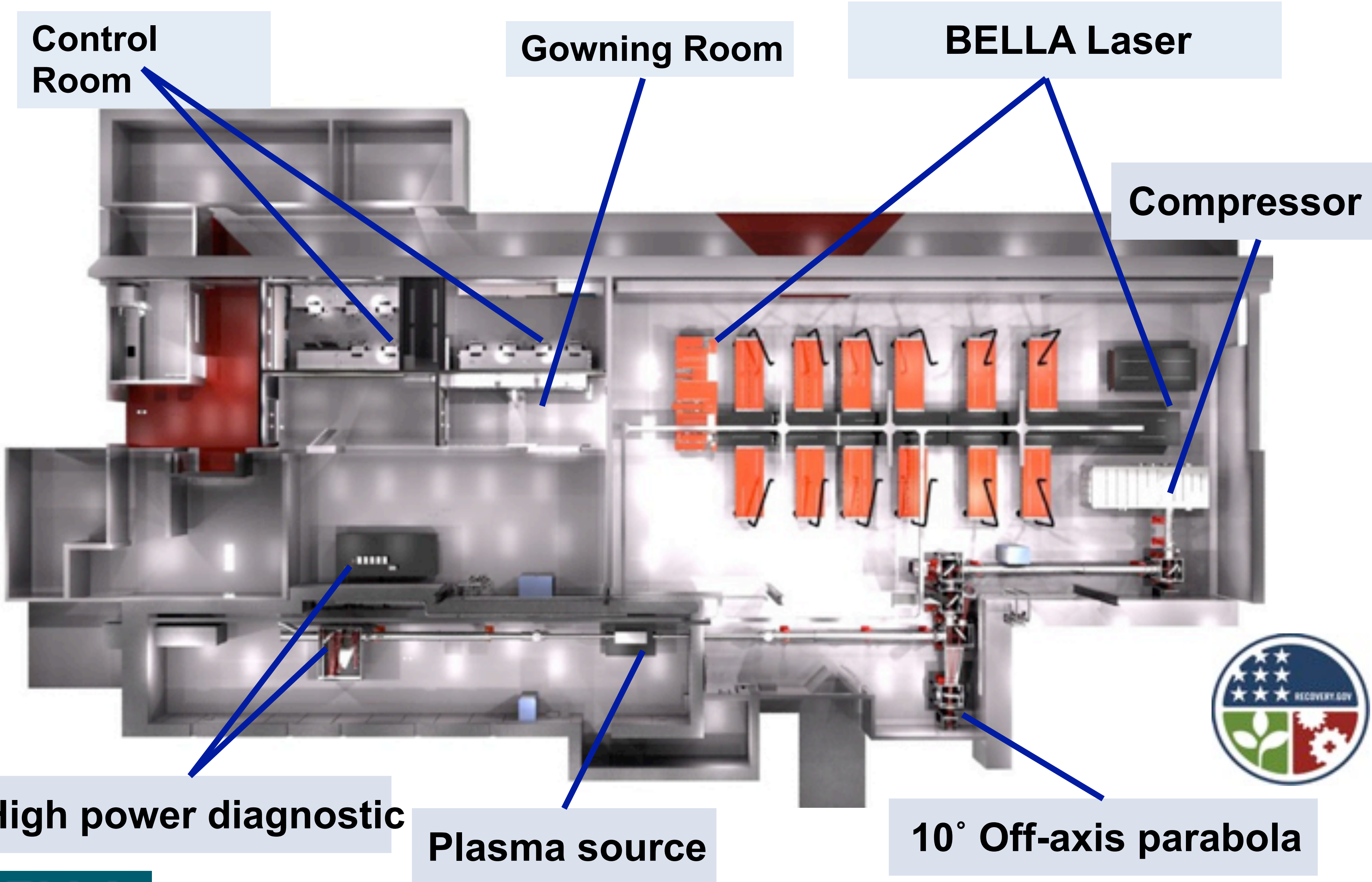






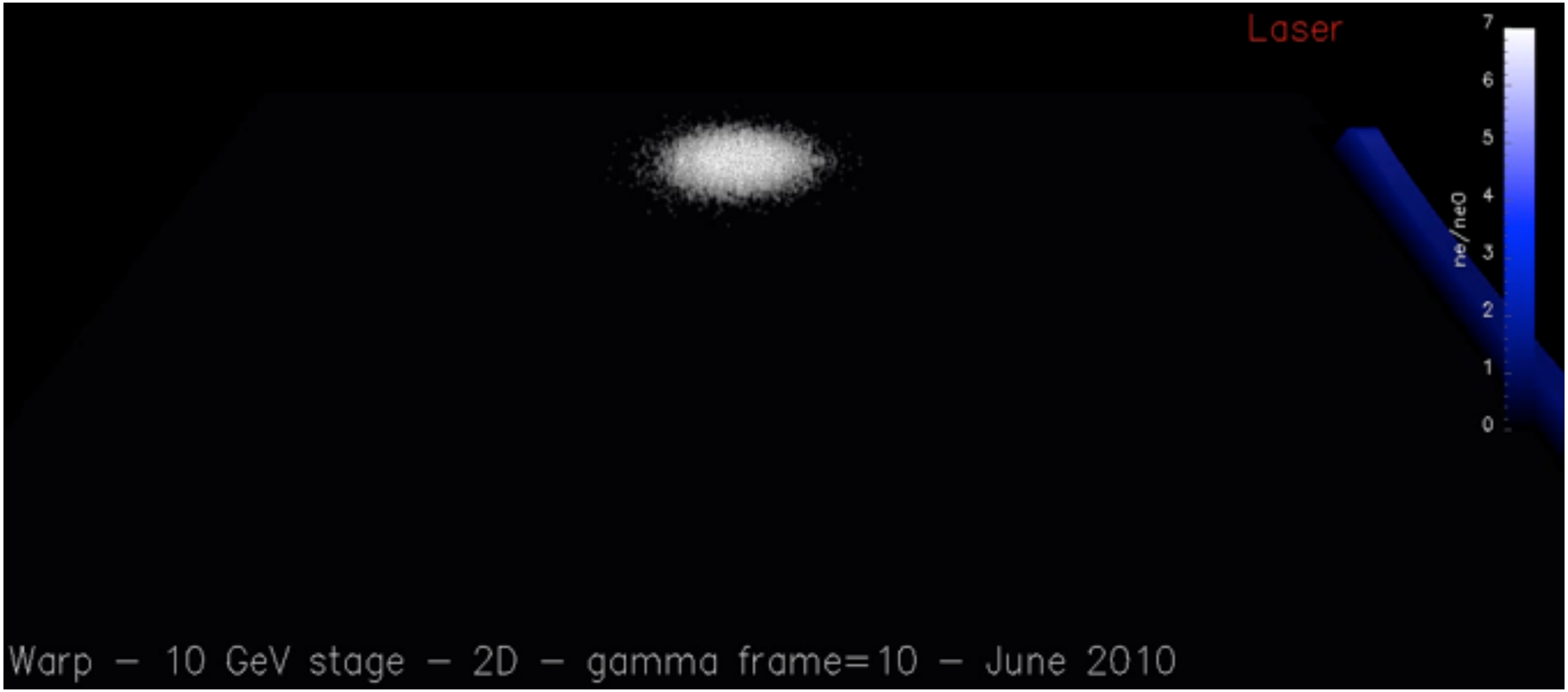
(in collaboration with Oxford University)

BELLA Facility: state-of-the-art PW-laser for laser accelerator science



Meter scale laser plasma accelerator driven by PW-class laser: 10 GeV beam

Full scale simulation of 10 GeV stage using Lorentz boosted frame

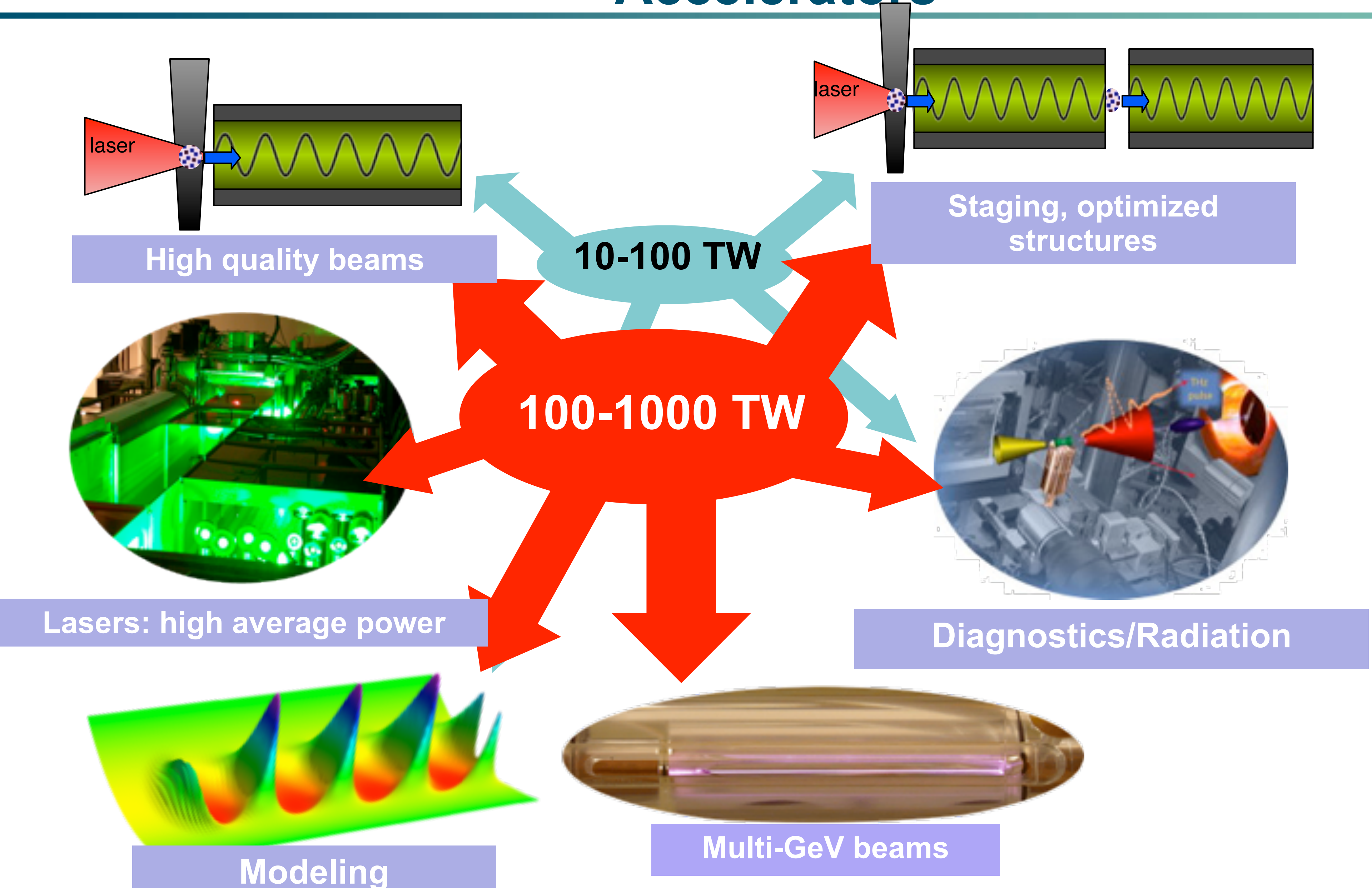


Plasma density ~ 10^{17} cm^{-3}

Run time: Min. in 2D, Hours in 3D

***Courtesy J.L. Vay – PRL 2007**

Key technical challenges for Laser Plasma Accelerators



Brief History of ICFA – ICUIL Joint Taskforce

– New *ICUIL* Chair (T. Tajima) advocates joint ICFA-ICUIL efforts and requests suggestions for activity (Nov. 2008)

– Leemans suggests "Roadmap development for laser technology for future accelerators" and appointed by ICUIL to lay groundwork for joint standing committee of *ICUIL (Nov. 2008)*

– *ICFA* GA invites Tajima for presentation by *ICUIL* and endorses initiation of joint efforts (Feb. 13, 2009)

– Idea of joint taskforce endorsed at PAC09 by ICFA-ANA (chair: Uesaka) and BD (chair: Chou) panels (May 2009)

– *ICFA* GA endorses *Joint Task Force*, Aug. 2009 – *Joint Task Force* formed of *ICFA* and *ICUIL* members, *Leemans, Chair, (Sept. 2009)*

– First Workshop by *Joint Task Force* held @ GSI, Darmstadt, April, 2010 with Hoffman local organizing committee chair

– Report to *ICFA* GA (today) and *ICUIL* GA (Sept, 2010) on the findings

ICFA-ICUIL taskforce

	Institution	ICFA BD	ICFA ANA	ICUIL
Ralph Assmann	CERN	X		
Chris Barty	LLNL			X
Paul Bolton	JAEA			X
Robert Byer	Stanford			X
Bruce Carlsten	LANL		X	
Weiren Chou	FNAL	X		
Almantas Galvanauskas	Michigan			X
Ingo Hofmann	GSI	X		
Dino Jaroszynski	Strathclyde		X	X
Wim Leemans (Chair)	LBNL		X	X
Akira Noda	Kyoto U.		X	
James Rosenzweig	UCLA		X	
Wolfgang Sandner	MBI			X
Siegfried Schreiber	DESY		X	
Mitsuru Uesaka	U. Tokyo		X	
Kaoru Yokoya	KEK	X		

Local organizing committee for first workshop was headed by Ingo Hoffman, GSI

First workshop at GSI, April 8-10, 2010

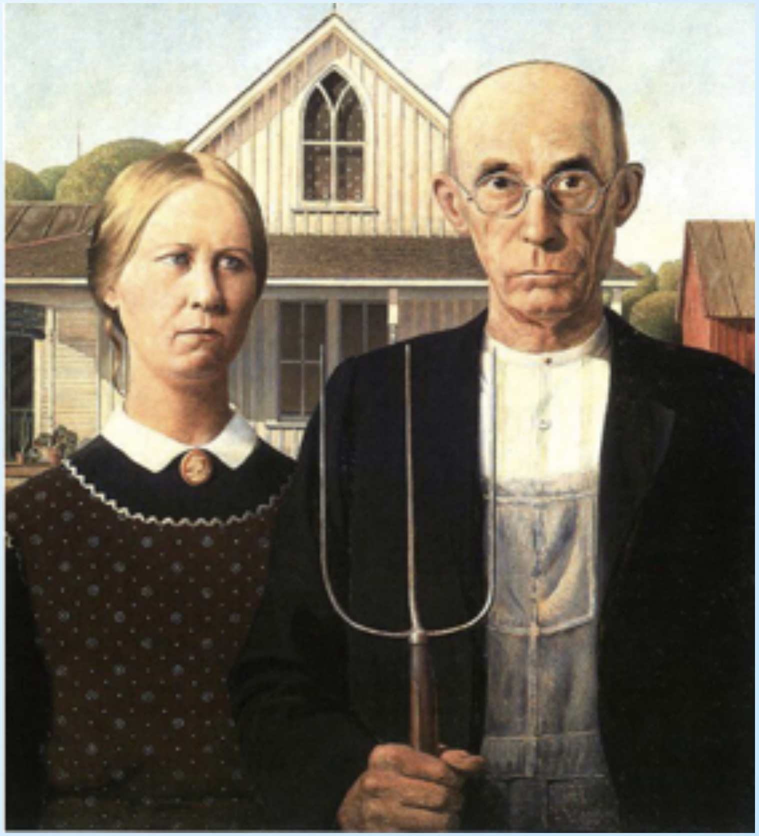
Local organization chaired by Ingo Hofmann

47 attendees: China (1), France (4), Germany (18), Japan (4), Switzerland (2), the UK (4) and the US (14)

How laser guys see lasers and accelerator guys see accelerators

after Bob Hettel

How we see the other guy's technology



- Learned about each others strengths and needs
- Learning what is and what is not negotiable

Goals of first strategic workshop

- Establish comprehensive survey of requirements for laser-based light and particle sources with emphasis on sources that can advance light and particle science AND require lasers beyond state-of-the-art or state-of-current-use:
  - Not a down selection of specific designs; inclusive approach
- Identify future laser system requirements and key technological bottlenecks
- From projected system requirements, provide visions for technology paths forward to reach survey goals and outline required laser technology R&D steps that must be undertaken
- Write a technical report.

Workshop organization

- Four work packages:
  - Colliders -- lead by Chou
  - Lightsources -- lead by Leemans
  - Medical applications -- lead by Uesaka
  - Lasers -- lead by Barty and Sandner
- First day:
  - Plenary talks + discussion
- Second day:
  - Working group discussions and material development
- Third day:
  - Final discussions and summary + assignments

- Colliders -- most challenging requirements of all accelerators

1 -10 TeV collider specs

Case	1 TeV	10 TeV (Scenario I)	10 TeV (Scenario II)
Energy per beam (TeV)	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	1.2	71.4	71.4
Electrons per bunch ($\times 10^9$)	4	4	1.3
Bunch repetition rate (kHz)	13	17	170
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	700	200	200
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	700	200	200
β^* (mm)	0.2	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	12	2	2
Vertical beam size at IP σ^*_y (nm)	12	2	2
Luminosity enhancement factor	1.04	1.35	1.2
Bunch length σ_z (μm)	1	1	1
Beamstrahlung parameter Υ	148	8980	2800
Beamstrahlung photons per electron n_γ	1.68	3.67	2.4
Beamstrahlung energy loss δ_E (%)	30.4	48	32
Accelerating gradient (GV/m)	10	10	10
Average beam power (MW)	4.2	54	170
Wall plug to beam efficiency (%)	10	10	10
One linac length (km)	0.1	1.0	0.3

Laser requirements for such colliders

Case	1 TeV	10 TeV (Scenario I)	10 TeV (Scenario II)
Wavelength (μm)	1	1	1
Pulse energy/stage (J)	32	32	1
Pulse length (fs)	56	56	18
Repetition rate (kHz)	13	17	170
Peak power (TW)	240	240	24
Average laser power/stage (MW)	0.42	0.54	0.17

1 TeV case: 420 kW/laser, 13 kHz (32 J/pulse) with 50% wall plug efficiency and we need 100 of them

Total laser power (MW)	42	540	1700
Total wall power (MW)	84	1080	3400
Laser to beam efficiency (%) [laser to wake 50% + wake to beam 40%]	20	20	20
Wall plug to laser efficiency (%)	50	50	50
Laser spot rms radius (μm)	69	69	22
Laser intensity (W/cm²)	3×10^{18}	3×10^{18}	3×10^{18}
Laser strength parameter a_0	1.5	1.5	1.5
Plasma density (cm⁻³), with tapering	10^{17}	10^{17}	10^{18}
Plasma wavelength (μm)	105	105	33

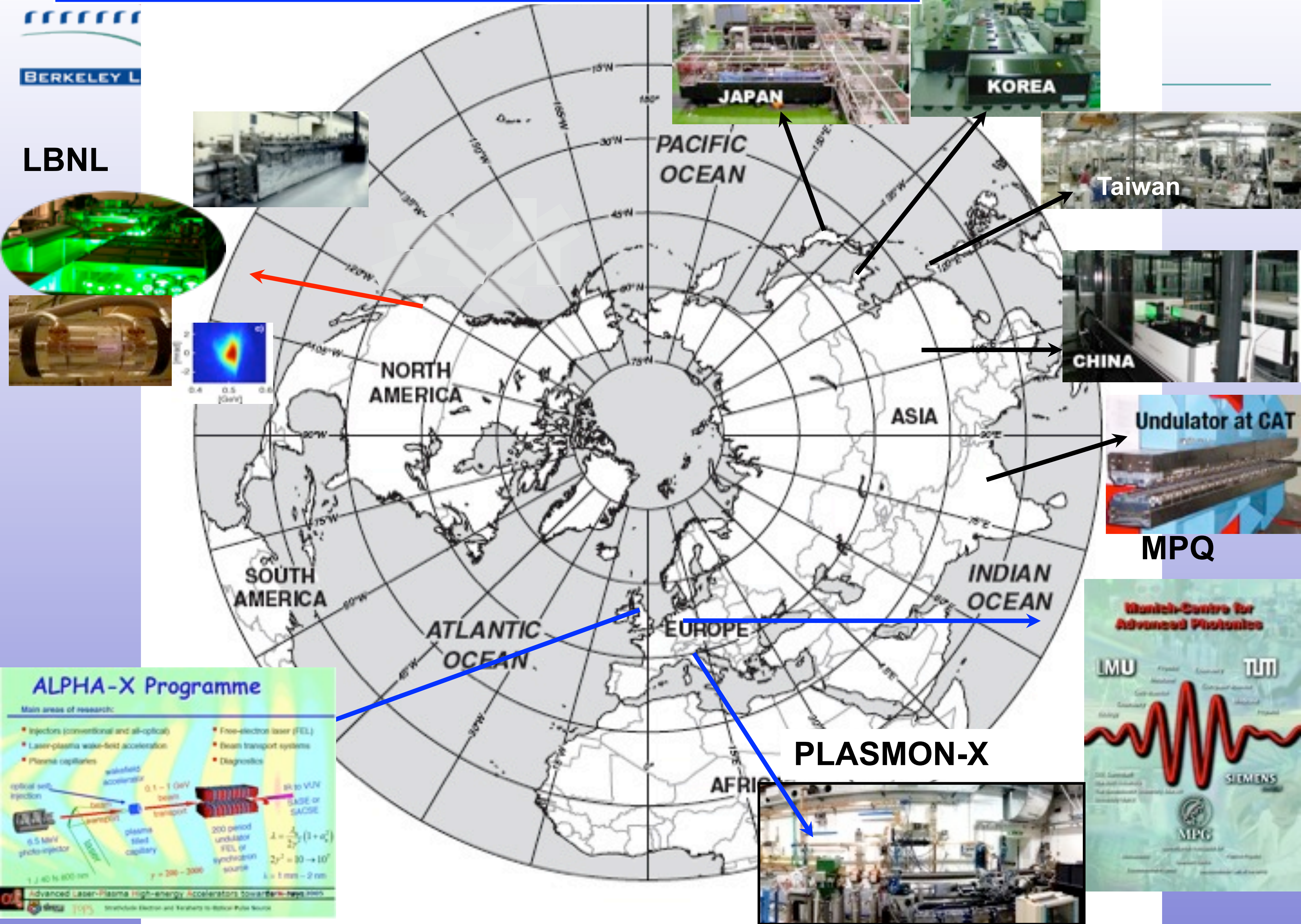
- Light sources -- applications seem reachable in next 5-10 yrs

Fields, where lasers are employed

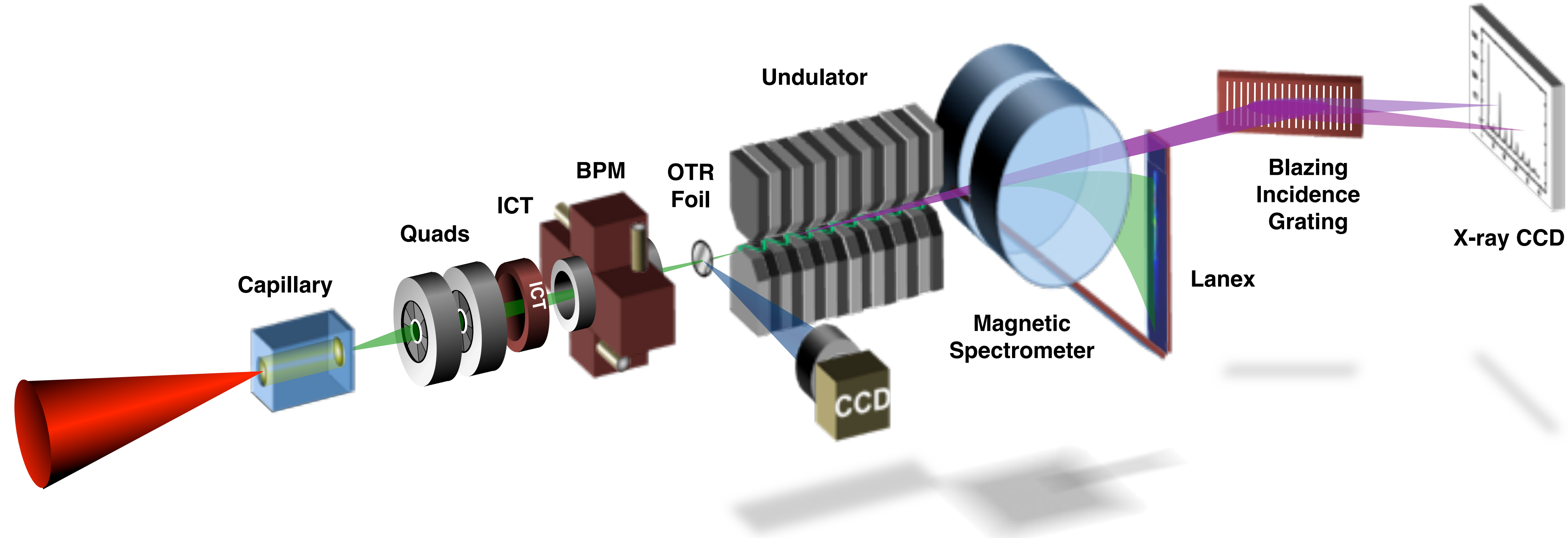
in conventional accelerators

- Electron source
  - photo injectors
- Electron beam diagnostics and manipulation
  - laser heater
  - electro-optical sampling
  - inverse Compton scattering
- Synchronization
  - optical: based on fiber lasers
  - EO methods
- External Seeding
  - HHG, HGHG, ESASE etc
- Pump-probe experiments
  - short fs type pulses
  - high power densities

World-wide effort aimed at FEL using laser accelerator



Laser – Plasma FEL
(tunable, coherent, ultrashort source)



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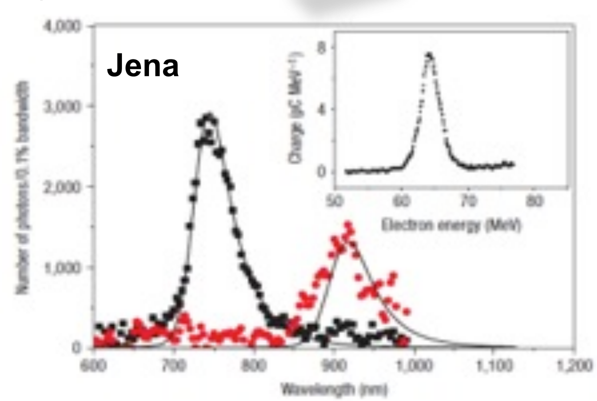
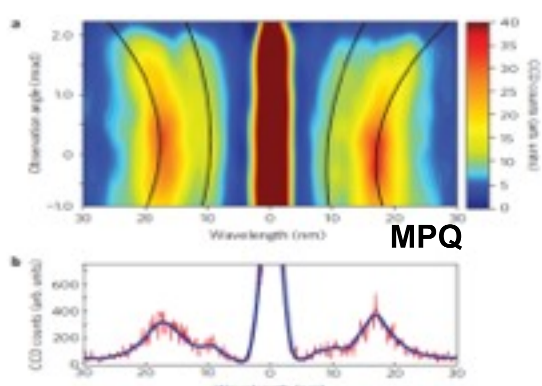


Schlenvoigt et al, *Nature Phys* 4, 130 (2008)

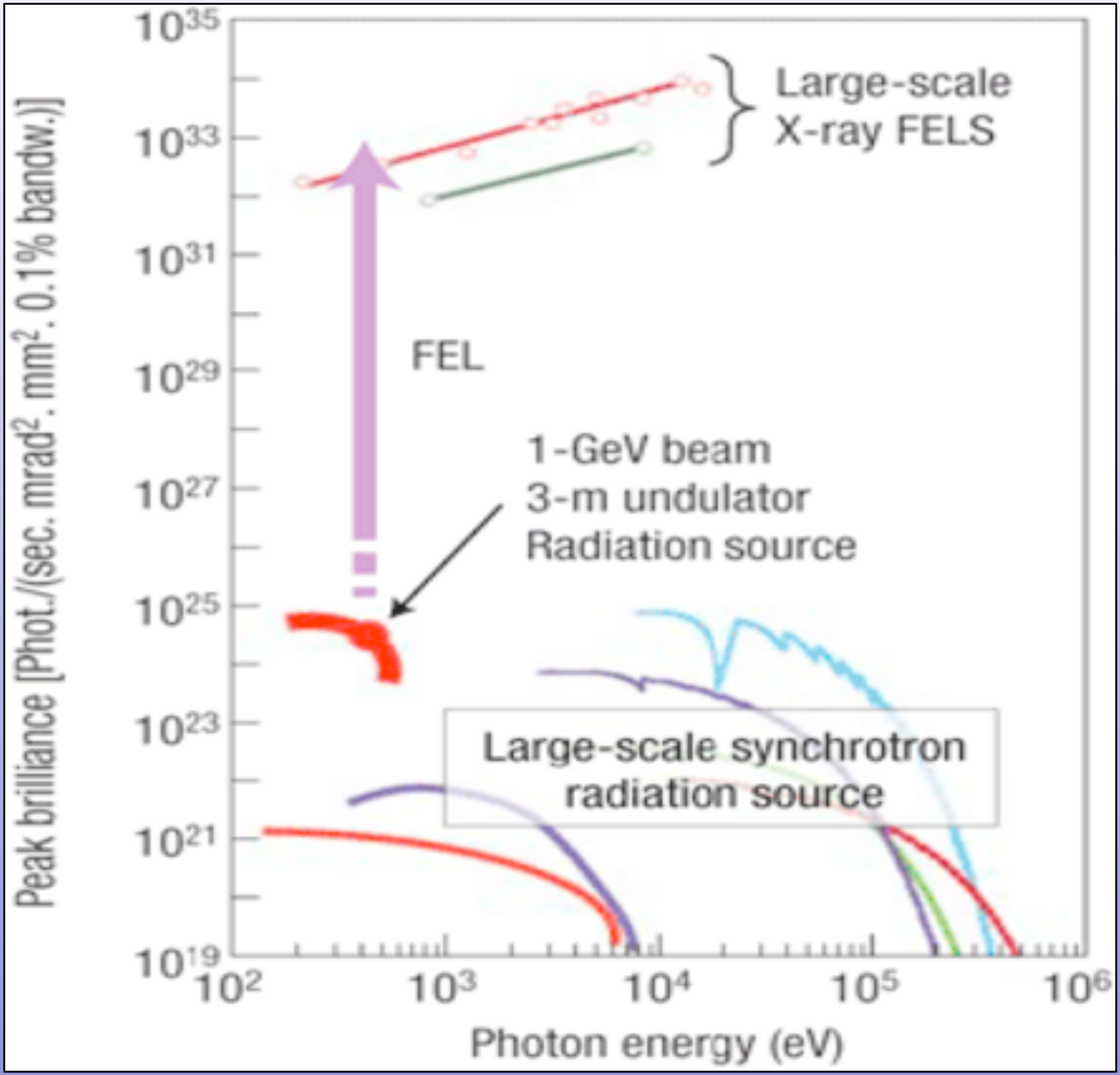
XUV



Fuchs et al, *Nature Phys* 5, 826 (2009)

XUV (30 nm) experiment at LBNL with THUNDER Undulator

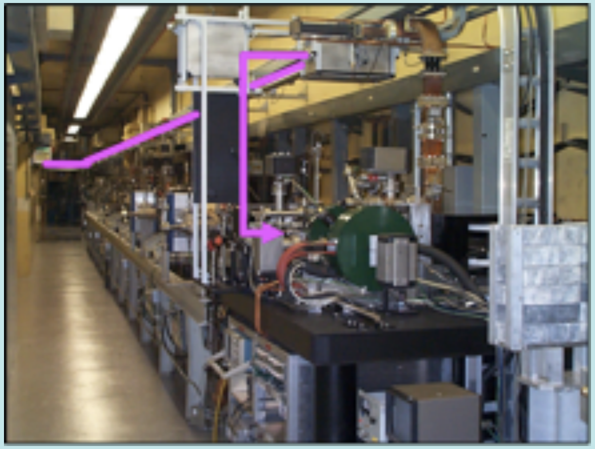
Peak brightness of FEL driven by GeV beam from LPA compares favorably



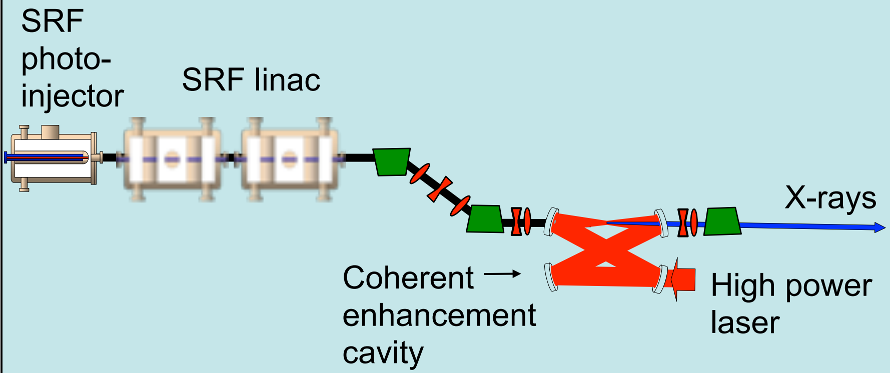
K. Nakajima, Nature Phys. (2008)

Inverse Compton Scattering Architectures

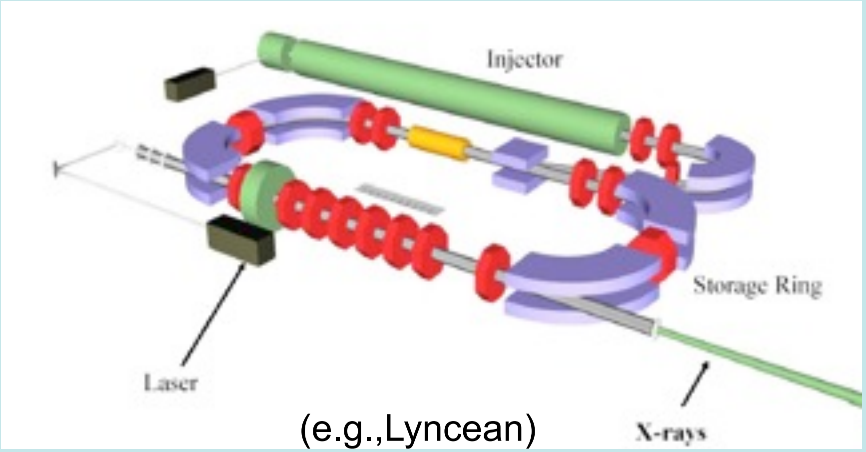
Pulsed linac & high peak power laser



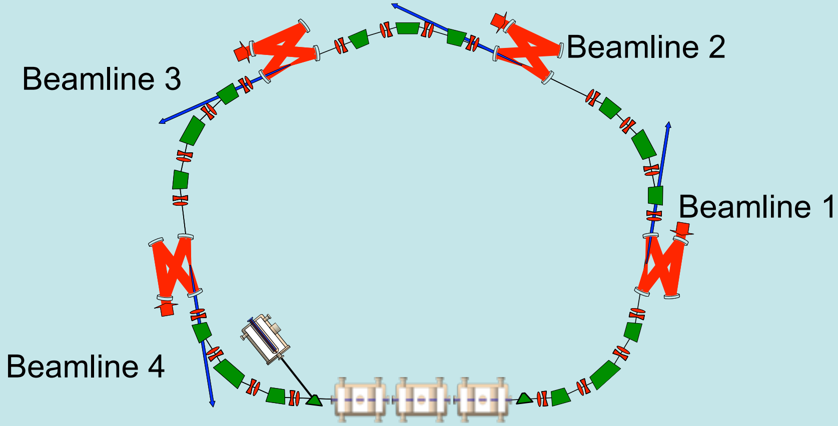
SRF linac & high avg power laser



Compact storage ring



Multi-user ERL with SRF linac and multi high power lasers



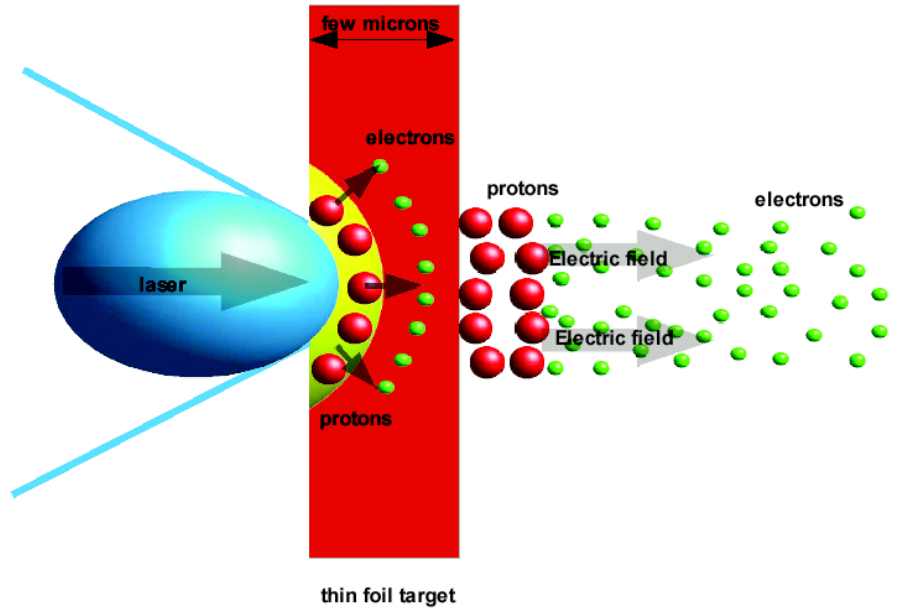
Bill White
wewhite@slac.stanford.edu

Laser requirements for light sources

- Electron sources:
  - Watts to kWatts, wide range of repetition rates, microJoules to mJoule
- Seeding, beam manipulation and user experiments:
  - 0.1 - 3 kW short pulse lasers (10s of mJ @ 10s - 100s kHz)
- Laser plasma accelerator based FELs:
  - 1- 10 kW short pulse lasers (1-5 J @1-10 kHz, 100 - 500 TW peak power)
- Inverse Compton sources:
  - Same as for LPA based FEL

Medical Applications

- Primary topic: laser-matter interaction based acceleration of protons, carbon, etc...



Proton Beams from laser-plasma interactions

Applications

- Proton radiography of dense targets

  M. Borghesi, *et. al.*, Fusion Science and Technology 49, 412 (2001)

- Proton/carbon beams for oncological hadrontherapy

  C.- M. Ma, *et al.*, Med. Phys. 28, 1236 (2001)

  S. V. Bulanov and V. S. Khoroshkov, Plasma. Phys. Rep. 28, 453 (2002)

- Fast ignition

  M. Roth, *et. al.*, Phys. Rev. Lett. 86, 436 (2001)

- Injection into accelerators

  K. Krushelnick, et. al., IEEE Trans. Plasma Sci. **28**, 1184 (2000).

Beam Requirements

- Low emittance
- Short duration
- High energy

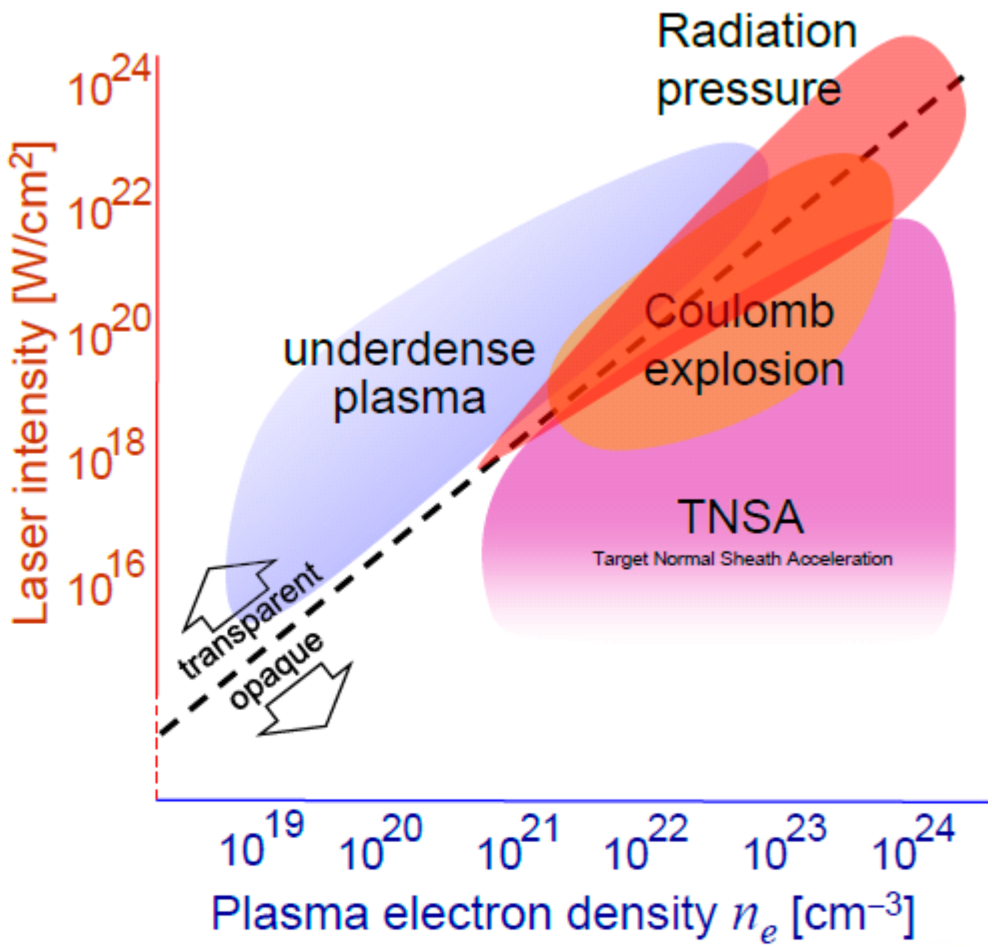
  (for dense matter probing)

- Small energy spread ~1%
- High energy (50-250 MeV)
- Number of particles ~10^{10} sec^{-1}

- Low emittance, focusability
- High flux

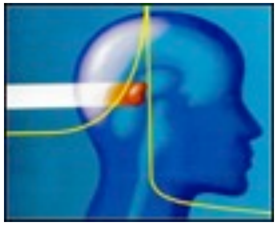
- Ultralow emittance
- High flux
- Small energy spread
- High repetition

Ion acceleration regimes

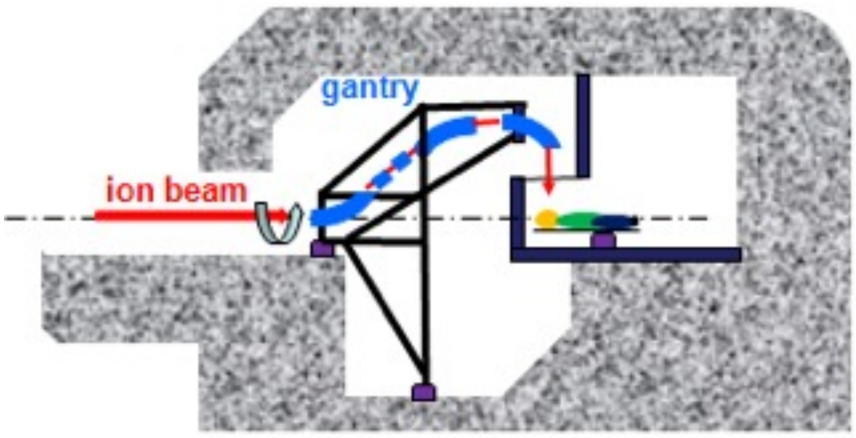


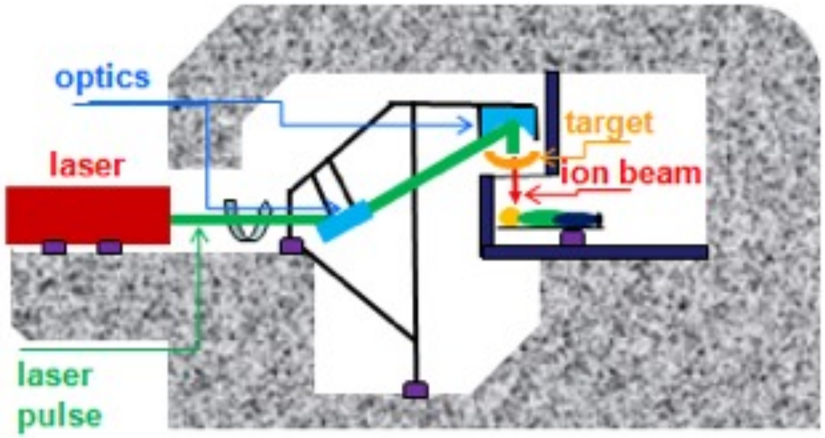
Courtesy of T. Esirkepov

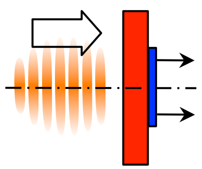
Applications for Hadron Therapy



S. V. Bulanov and V. S. Khoroshkov, Plasma. Phys. Rep. 28, 453 (2002)





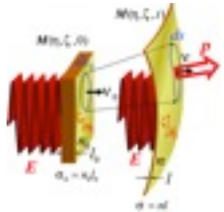


Directed Coulomb Explosion

500 TW 30 fs laser pulse
nm-scale double layer solid foil

10^8 s^{-1} protons 230 MeV

S.S. Bulanov, et al., Phys. Rev. E 78, 026412 (2008)

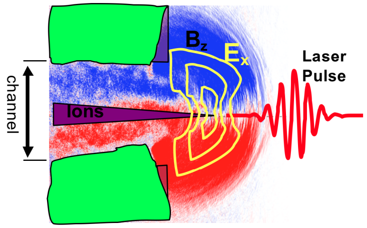


Radiation Pressure Acceleration

200 TW 30 fs laser pulse
nm-scale solid density foil

10^8 s^{-1} protons 200 MeV

S. V. Bulanov, et al., Phys. Plasmas 17, 063102 (2010)



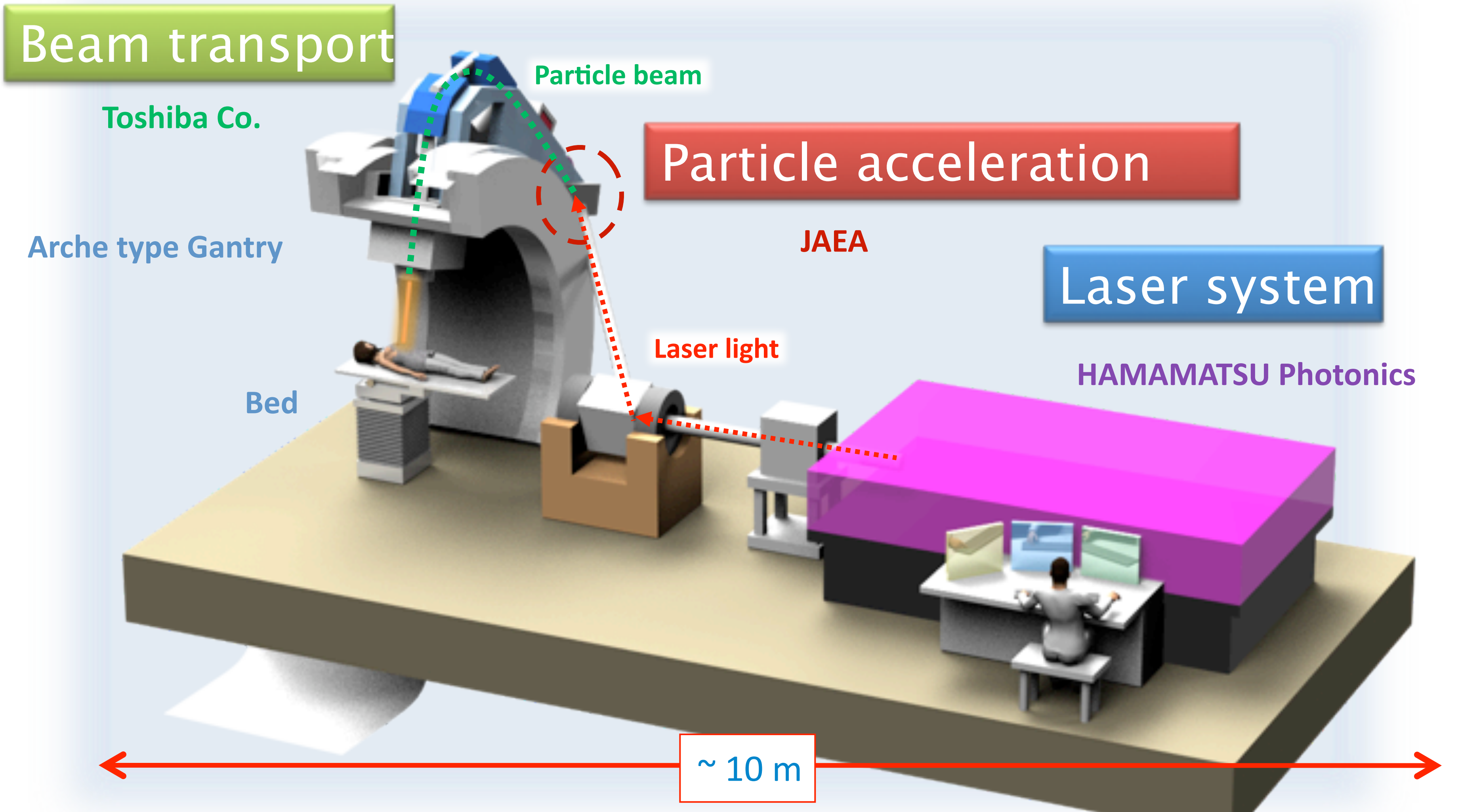
Magnetic acceleration mechanism

100 TW 30 fs laser pulse
1 n_{cr} 60λ hydrogen plasma

10^8 s^{-1} protons 250 MeV

S. S. Bulanov,et al., Phys. Plasmas 17, 043105 (2010)

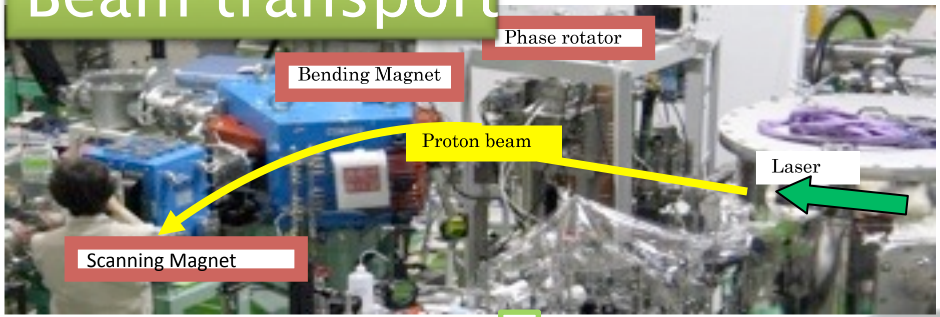
Laser driven cancer therapy machine



Particle energy：80 MeV/nucleon, which corresponds to reach 5 cm from the body surface.

Key technologies developed with companies

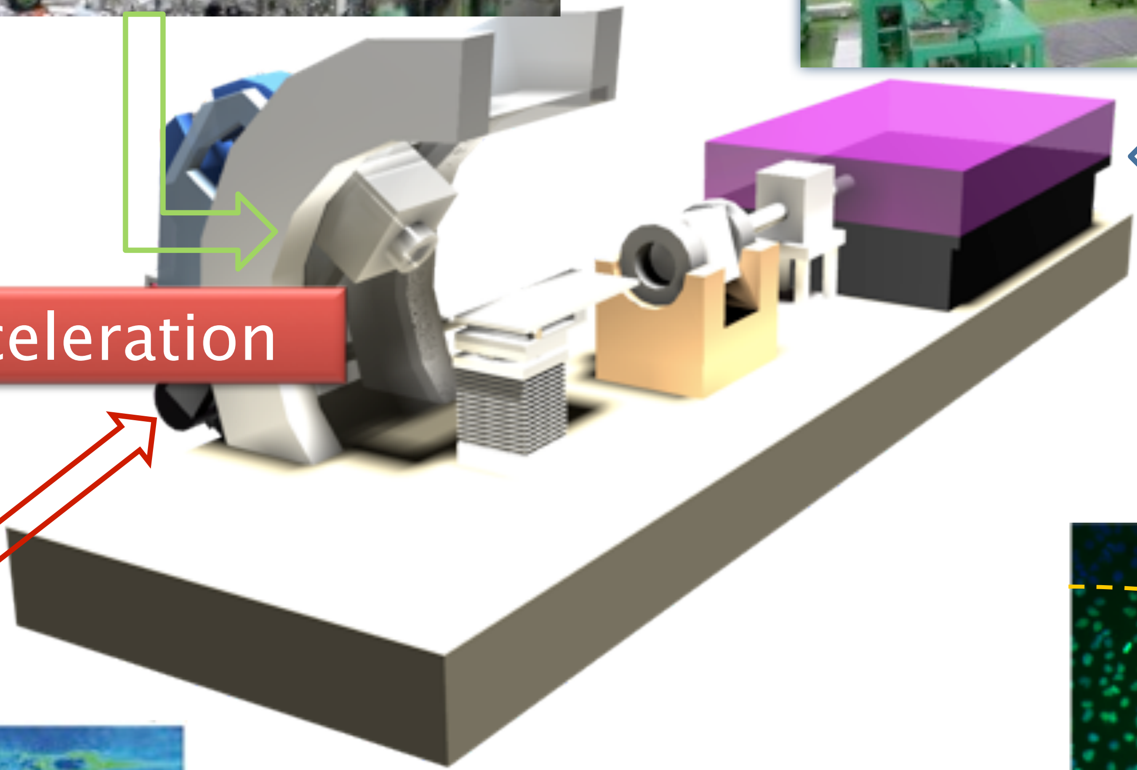
Beam transport



Toshiba Co.

Laser system

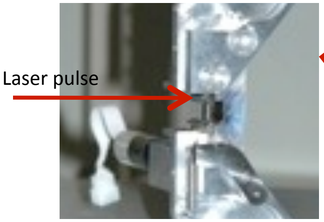
HAMAMATSU Photonics Co.

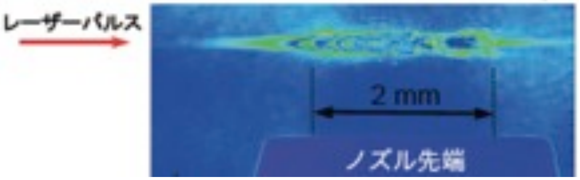


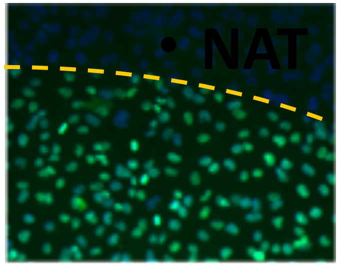
- Shimazu
- Ushio
- Fujikura
- NAT

Particle Acceleration

JAEA



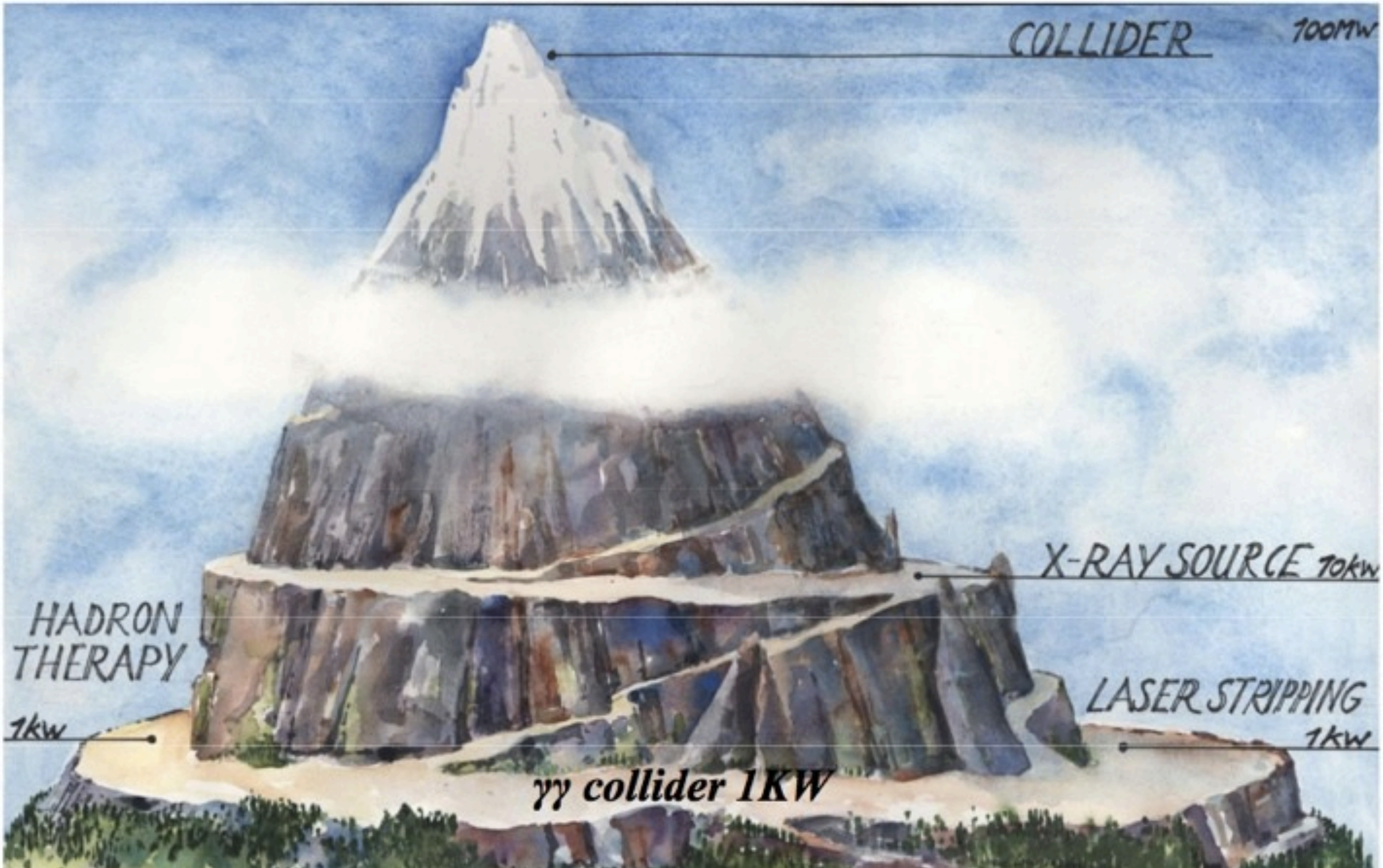




Clinical test

JAEA, HIBMC

Mountain of Lasers

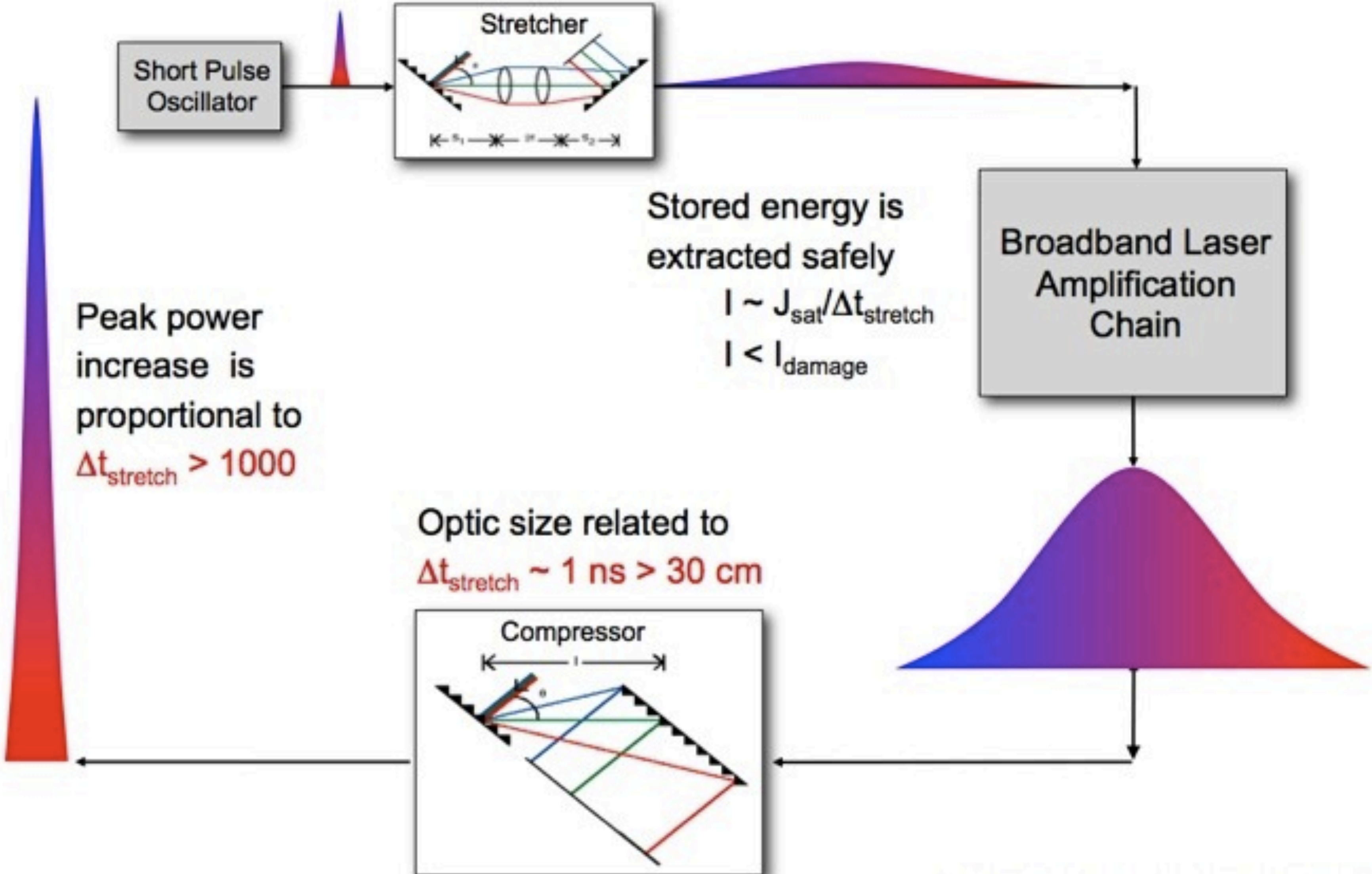


From T. Tajima

Main challenges for laser technology

- High average power:
  - Light sources – kW to 10 kW class
  - Colliders – 100 to 600 kW class
  - Medical – 1-10 kW class
- Short pulse:
  - Light sources – few fs to ps
  - Colliders – 100-300 fs pulses
  - Medical – 30-300 fs with superb contrast
- Contrast, spatial and temporal profiles
- Handling of enormous average power:
  - 0.1% loss in mirror is 600 W at 600 kW incident power
  - Cooling requirements; adaptive optics; beam dumps; etc

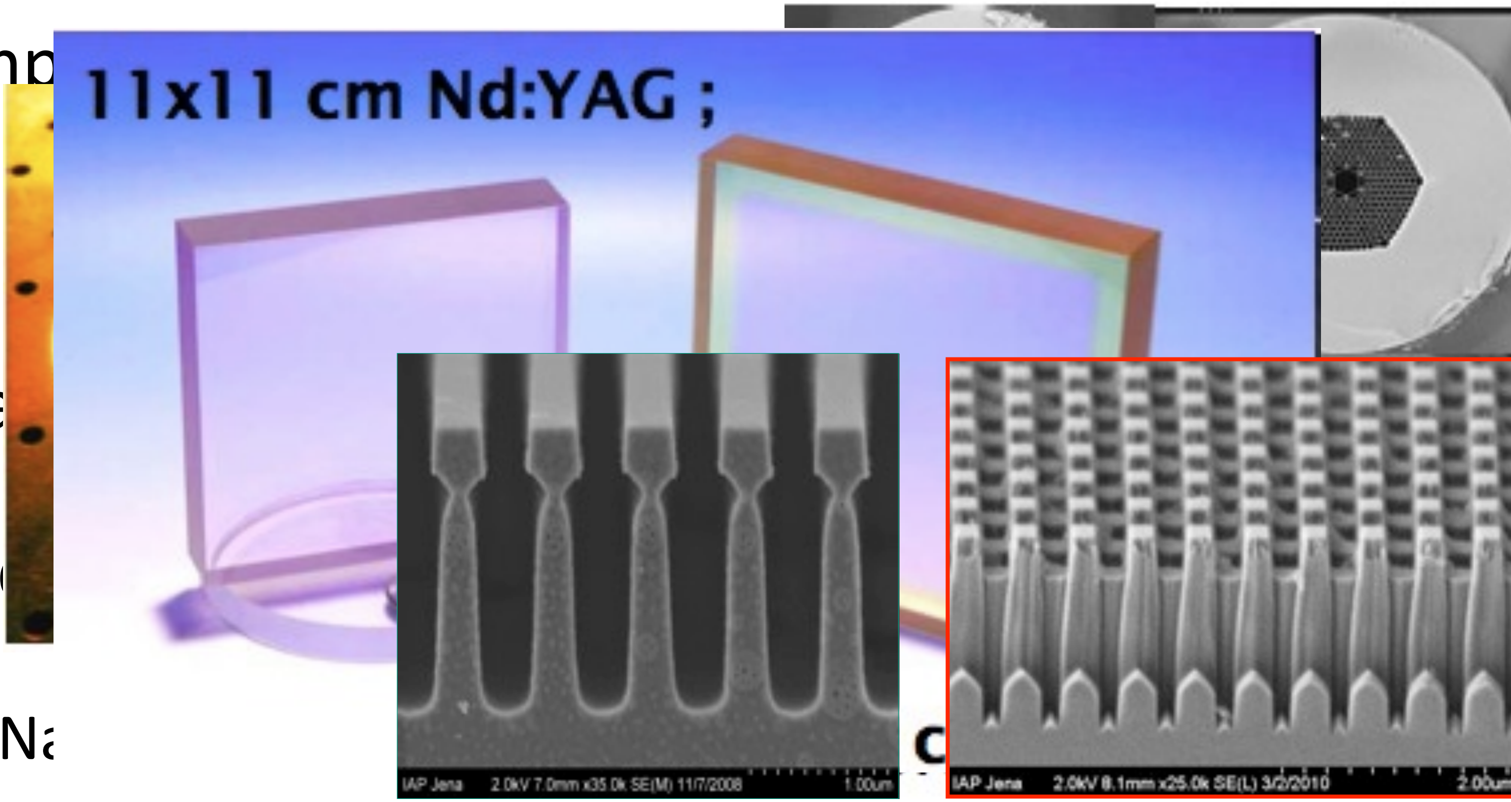
Chirped Pulse Amplification (CPA) is used to create high energy, short duration optical pulses



Strickland & Mourou, Opt. Comm. **56**, 219, 1985

Novel lasers and materials are being developed

- Amp
  -
- Ma… atings
  - (
  - Na… C

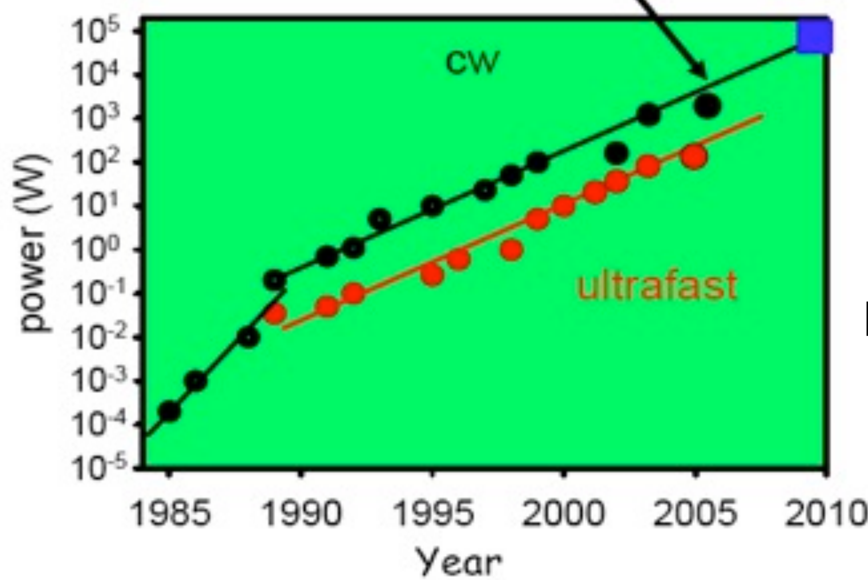


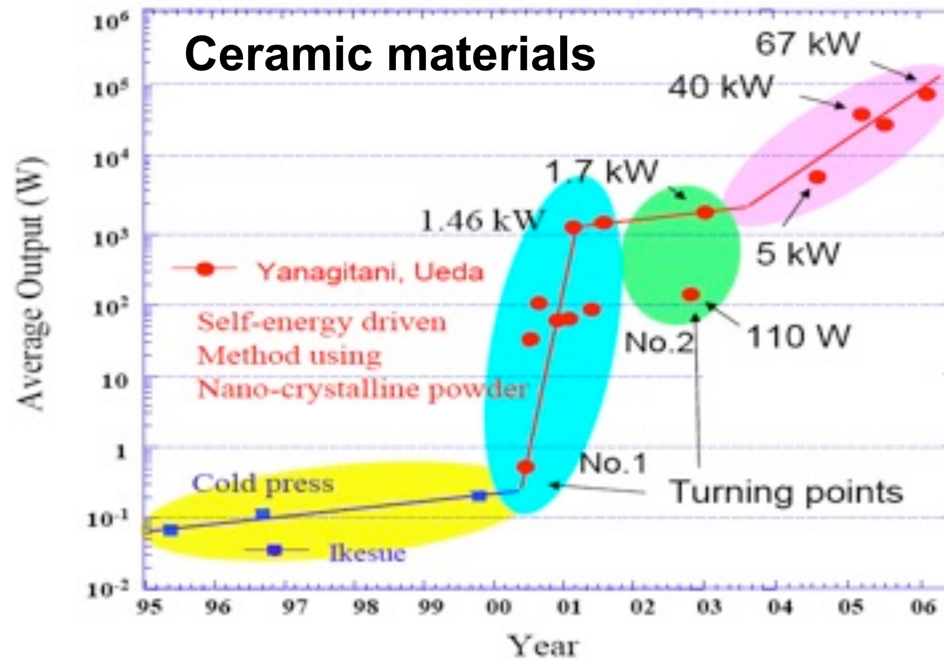
- Diodes and small quantum defect materials

Critical Technology:
High average and peak power lasers

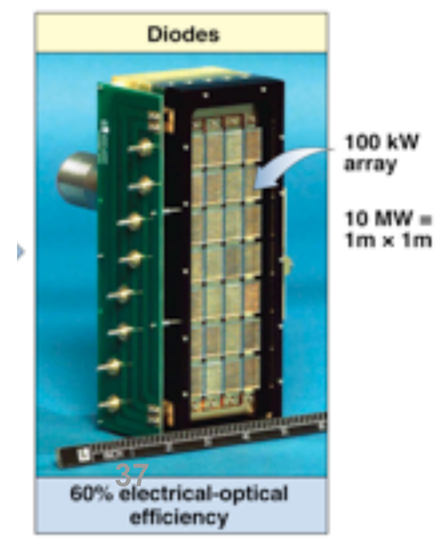
- Large core single mode fibers
- Multiplexing, coherent addition

Fiber laser progress





High power diodes
High efficiency pumping



Prospect for kJ, picosecond, multi-kHz systems at 30-50 % wallplug seems possible

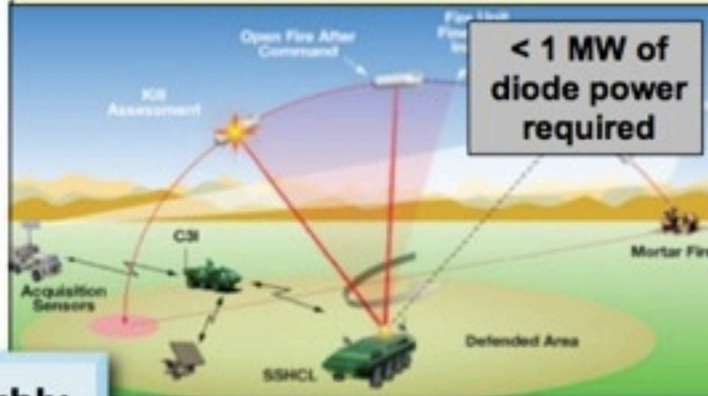
Courtesy: B. Byer and C. Barty

Science, energy and defense all have desires for efficient high power, diode-pumped lasers

DoD Strategic Defense

> MW at 100's of km range

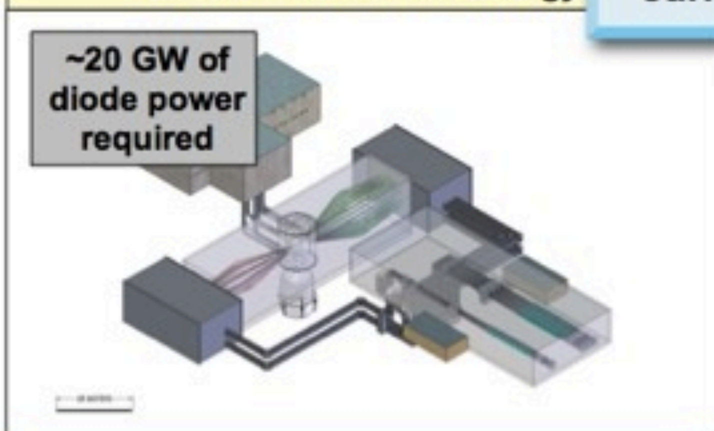
DoD Tactical Defense



> 100 kW at km range

LLNL has roughly 3-MW of operating diode laser arrays currently on site

DOE Inertial Fusion Energy

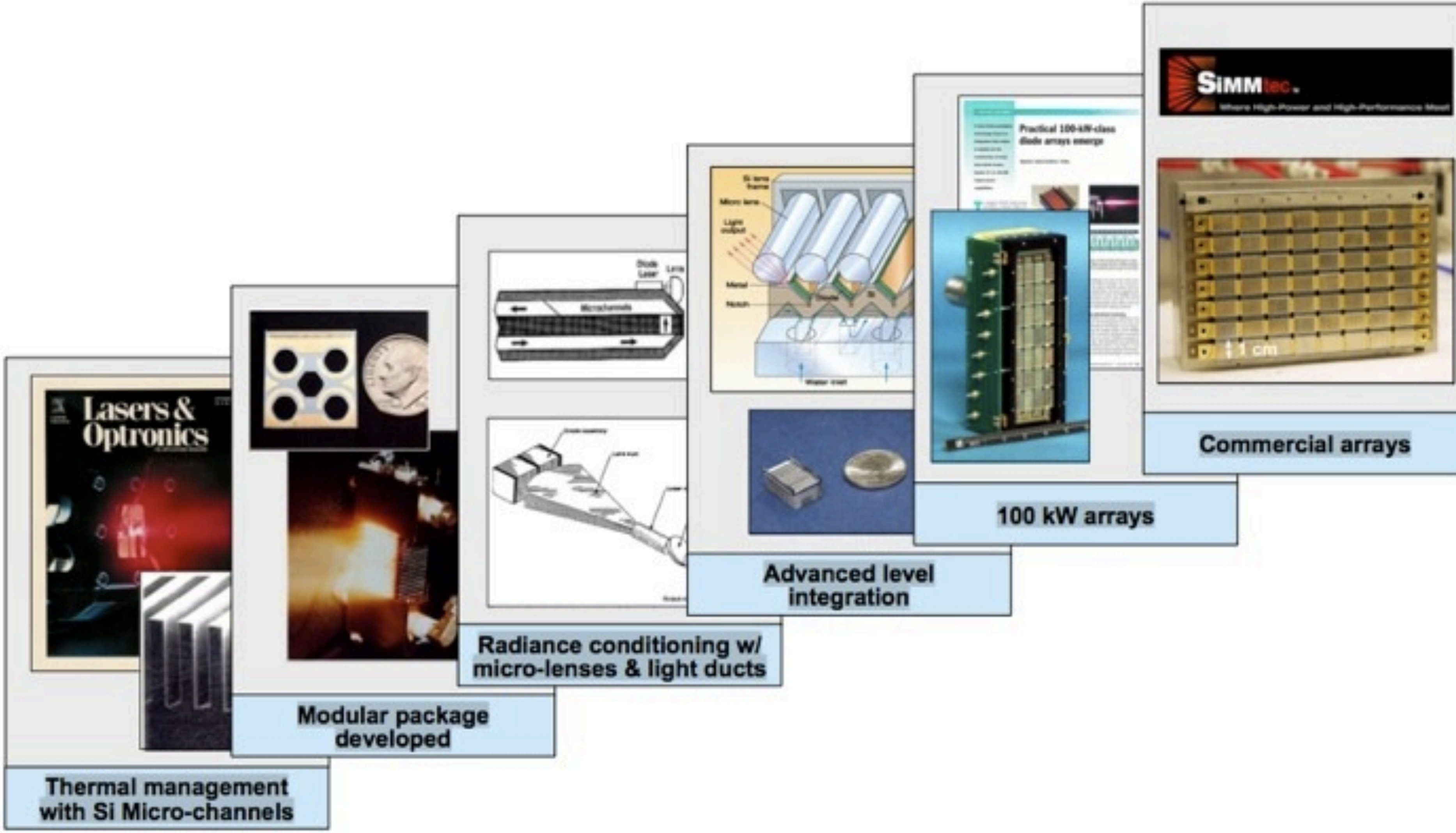


10's of MW and 24/7 operation

DOE Laser-based Accelerators

> 100 MW and 24/7 operation

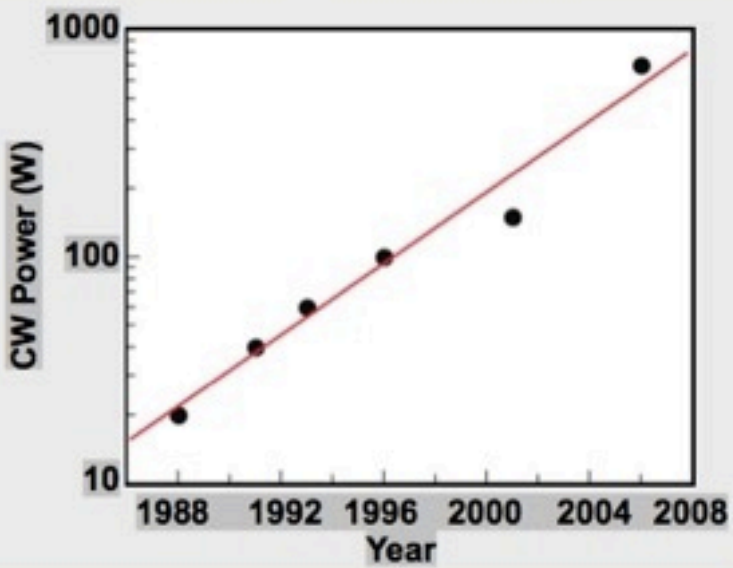
The key to high power, diode pumped lasers has been the development of high power diode arrays



1986 → 2009

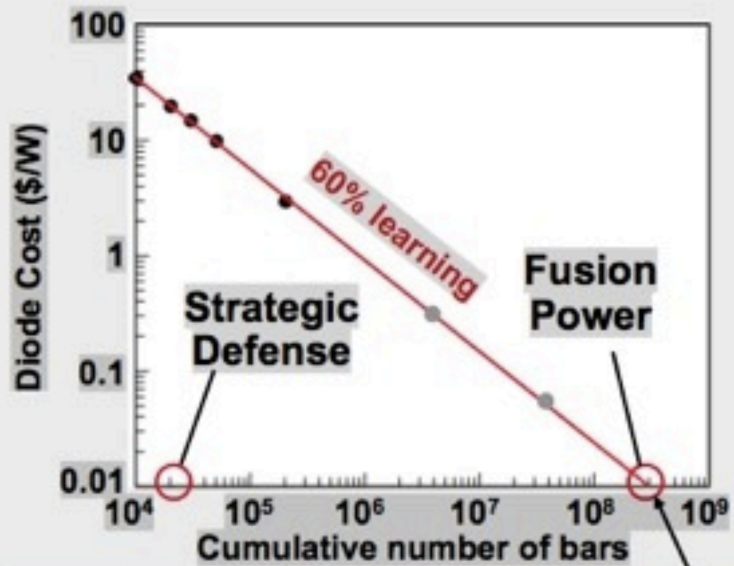
Fusion power is the most demanding diode application (cost & efficiency are primary metrics)

Continuous wave diode bar performance has increased by 35x since 1988



1 cm bar CW power

Diode bar prices are dropping with growing market



1 cm bar learning curve

Projected costs of less than 1¢/watt are in line with existing fabrication technologies

Industry is rapidly adopting diode-pumped laser technology for laser-based materials processing

	Fiber Laser	Nd:YAG	CO_2	Disc
Wall Plug Efficiency	30%	~5%	~10%	15%
Output Powers	to 50kW	to 6kW	to 20kW	to 4kW
BPP (4/5kW)	< 2.5	25	6	8
Diode Lifetimes	100,000	10,000	N.A.	10,000
Cooling	Air/Water	Dionized	Water	Water
Floor Space (4/5kW)	< 1 m^2	6 m^2	3 m^2	< 4 m^2
Operating Cost/hour	$21.31	$38.33	$24.27	$35.43
Maintenance	Not Required	Often	Required	Often

Source: Industrial Laser Solutions, Jan. 2005

Laser development crucial for success of field

- Key challenges for high peak/ultra-fast laser technology
  - Reliable turn-key operation: much progress in past 5 years but ways to go
  - Low cost systems:
    - Driver for GeV module: commercial 30 W (10 Hz), 100 TW system ~ $1.5 M (FY09)
    - High energy pump laser price has dropped from ~$75K/J in FY01 to ~ $30K/J in FY10 (factor 3 lower, accounting for inflation)
  - Average power:
    - Have 10-100 W systems, need 1-100 kW and even near MW-class high peak power lasers
    - Requires diodes, ceramics, fibers, etc…
- Many science communities need it (colliders, light sources, fusion) as well as medical and defense apps

Conclusion

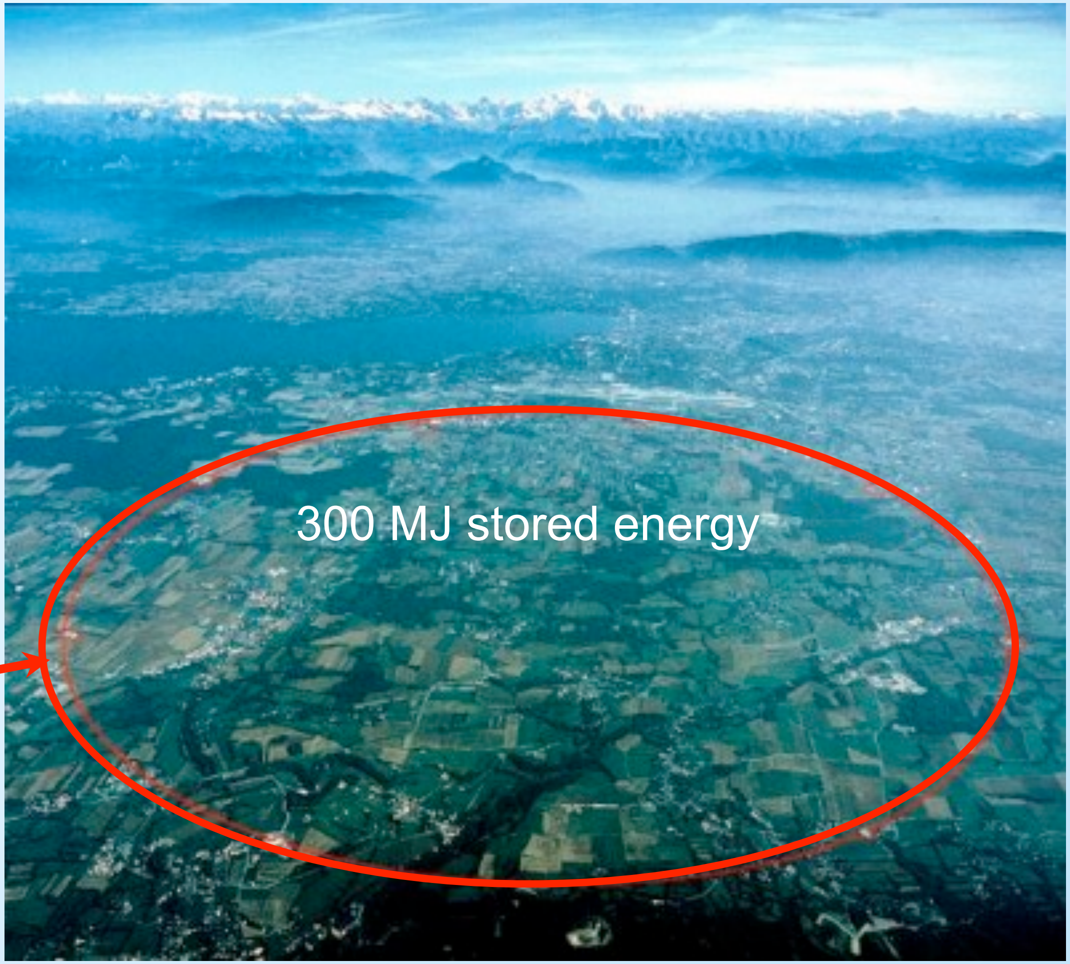
- Requirements for lasers for future accelerators largely identified
  - Case specific, no one solution fits all
  - All need high average and peak power!
- Laser technology candidates identified but 100 - 1000 x needed in power increase
  - Slab, disc, fiber lasers
  - Diode pumping
  - New materials
- Sustained, long range R&D needed with major investment into accelerator relevant lasers -- similar to klystron effort, 40 yrs ago
- Long ranged collaborative/complementary relation between ICFA-ICUIL is essential
- Report in progress, getting ICUIL input this week!

People who say it cannot be done should not interrupt those who are doing it.

George Bernard Shaw

1929

LHC, 2009



Size x 10^5 Energy x 10^9

Acknowledgment

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