ICAN Kickoff Meeting
CERN, Geneva
Feb. 22, 2012

ICAN: Luminosity=<Power>

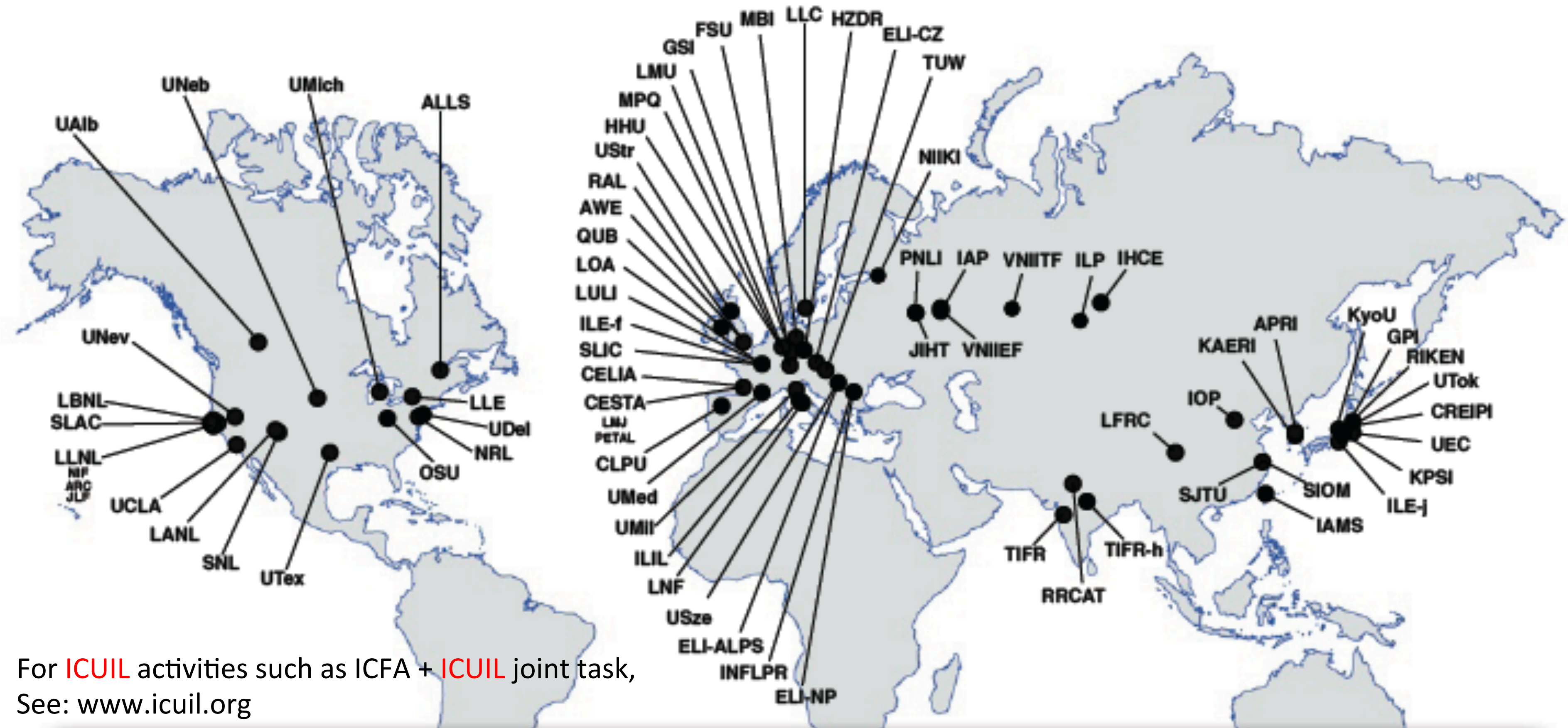
T. Tajima
IZEST, LMU

- ***ICAN*** cultivates the frontier: large average-power lasers
- Laser electron acceleration: experimentally well established; its unique properties getting known
- Laser has come around to match the condition set 30 years ago; Still some ways to go to realize the dream
- GeV electrons; 10 GeV soon; 100GeV considered(IZEST);

  TeV laser collider contemplated
- Other **applications** emerging: radiolysis, intraoperative therapy,compact FEL source, ultrafast diagnosis, laser fusion driver, radioactive isotope isolation,…); other **fundamental physics** (strong acceleration physics, photon nonlinearities=vacuum physics,…)
- Need to establish a center/network (such as *IZEST, EuroNNAc*) which carries laser acceleration science proof-of-principle experiments at collider level energies, as well as incubates collider-fit laser driver technology (*ICAN*)

2010 ICUIL World Map of Ultrahigh Intensity Laser Capabilities

ICAN/IZEST constituency resides in UHIL community



For ICUIL activities such as ICFA + ICUIL joint task,
See: www.icuil.org

- the total peak power of all the CPA systems operating today is ~11.5 PW
- by the end of 2015 planned CPA projects will bring the total to ~127 PWs
- these CPA projects represent ~$4.3B of effort by ~1600 people (no NIF or LMJ)
- these estimates do not include Exawatt scale projects currently being planned

Brief History of *ICUIL* – *ICFA* Joint Effort

- *ICUIL* Chair sounded on A. Wagner (Chair *ICFA*) and Suzuki (incoming Chair) of a common interest in laser driven acceleration, Nov. 2008
- Leemans appointed in November 2008 to lay groundwork for joint standing committee of *ICUIL*
- *ICFA* GA invited Tajima for presentation by *ICUIL* and endorsed initiation of joint efforts on Feb. 13, 2009
- *ICFA* GA endorsed *Joint Task Force*, Aug. 2009
- *Joint Task Force* formed of *ICFA* and *ICUIL* members, W. Leemans, Chair, Sept, 2009
- First Workshop by *Joint Task Force* held @ GSI, Darmstadt, April, 2010
- Report to *ICFA* GA (July,2010) and *ICUIL* GA (Sept, 2010) on the findings
- 'Bridgelab Symposium' near Paris (Jan., 2011)
- Second Workshop by JTF @ Berkeley (Aug., 2011)
- White paper by JTF of ICFA and ICUIL published in ICFA Newsletter, Nov., 2011

Main challenges for laser driven accelerators

W. Leemans(2010)

- Phase space quality and control of e-beam
- Staging of modules/structures
  - Pointing alignment tolerances
  - In- and out-coupling of high power beams
- Power handling inside structures:
  - Can they survive?
  - How can we extract as much laser energy as possible into e-beam so that energy leaves structure at speed of light?
- Repetition rate for plasma based schemes:
  - Can we handle gas and plasma production at >10 kHz rep rates?
- Can we avoid the use of conventional magnets?
  - Would be big cost saving in construction and operation
  - etc.

However, most glaringly,

- ***Needs of <u>high average-power</u>, <u>high efficiency</u>, <u>high rep-rate</u> laser technologies:* Candidates identified =**

  slab laser; thin disk laser ; fiber laser

IZEST's Missions

- An international endeavor to unify the high Intensity laser and the high energy / fundamental physics communities to draw

"The Roadmap of Ultra High Intensity Laser"
and apply it to
"Laser-Based Fundamental Physics"

See more:
www.int-zest.com/

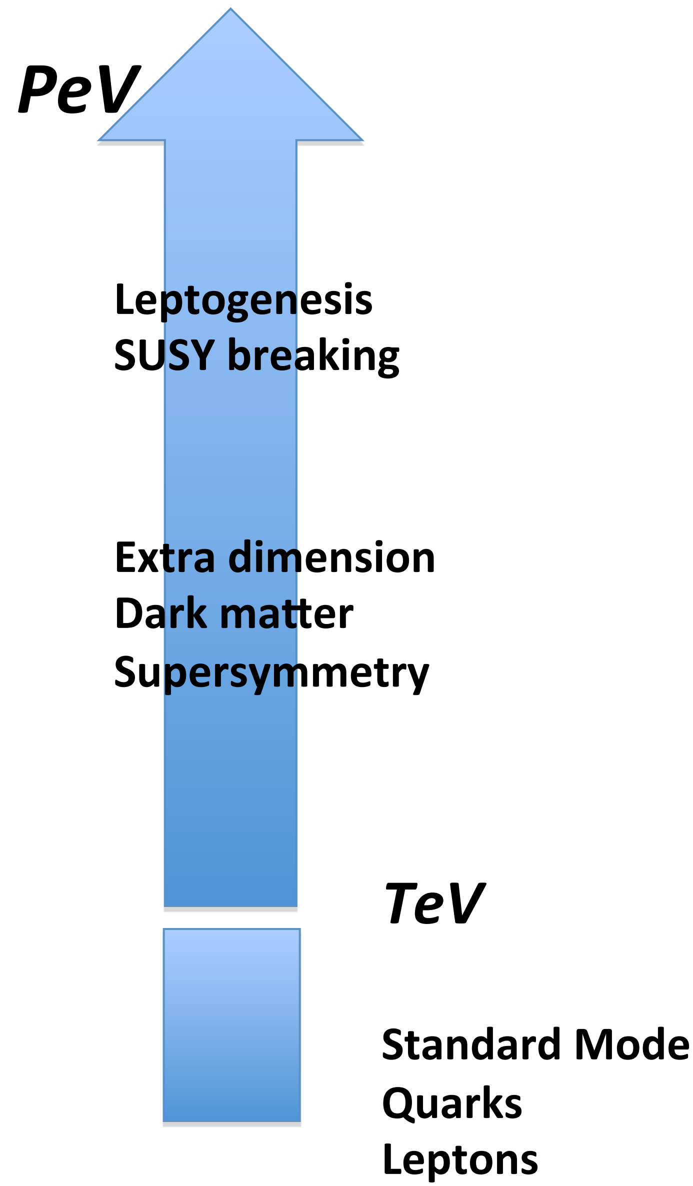
- To form an international team of scientists that can foster and facilitate scientific missions of EW/ZW class lasers

- **Explore high average-power lasers ----*ICAN* mission**

IZEST's Mission: Responding to <u>Suzuki's Challenge</u>

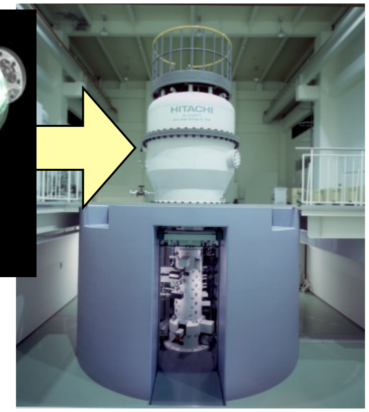
Atsuto Suzuki:
KEK Director General,
former ICFA Chair

New Paradigm



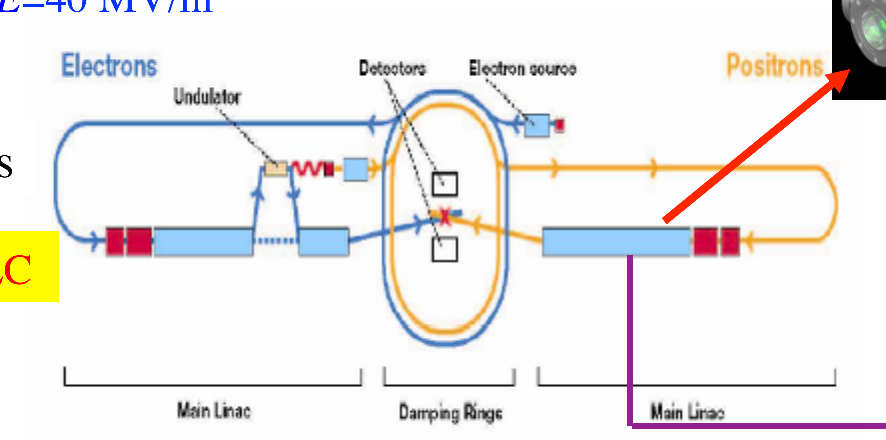
Accelerator

Evolution of Accelerators and their Possibilities（Suzuki,2008)



Ultra-High Voltage STEM with Superconducting RF cavity

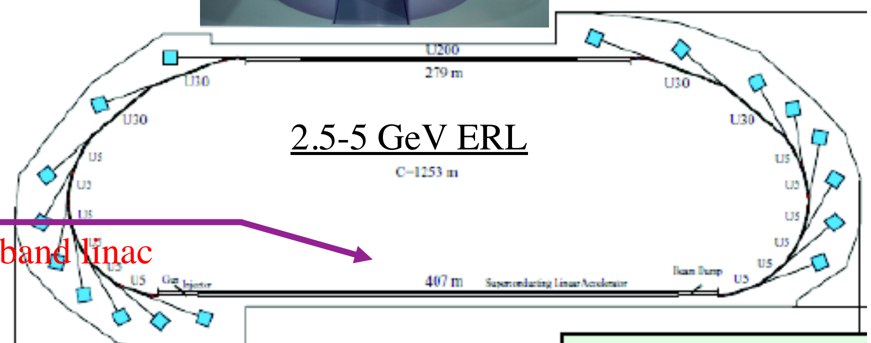
E=40 MV/m



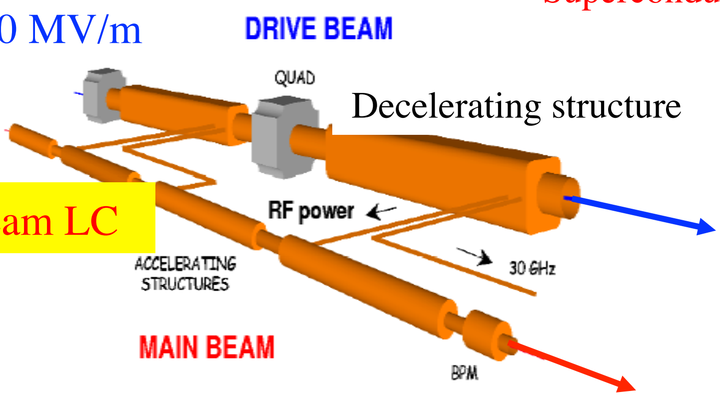
2020s

ILC

Superconducting L-band linac

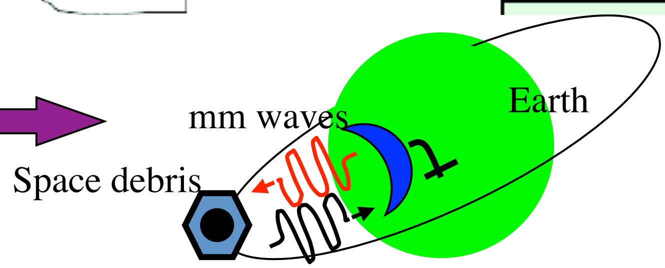


E=200 MV/m



2030s

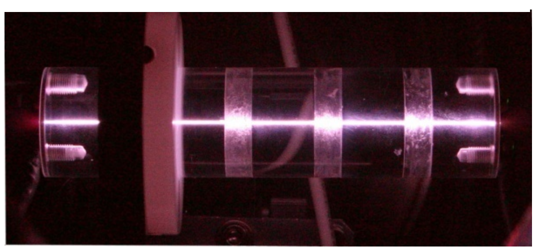
Two-beam LC



Earth-based space debris radar

E=10 GV/m

10cm-10GeV Plasma Channel Accelerator

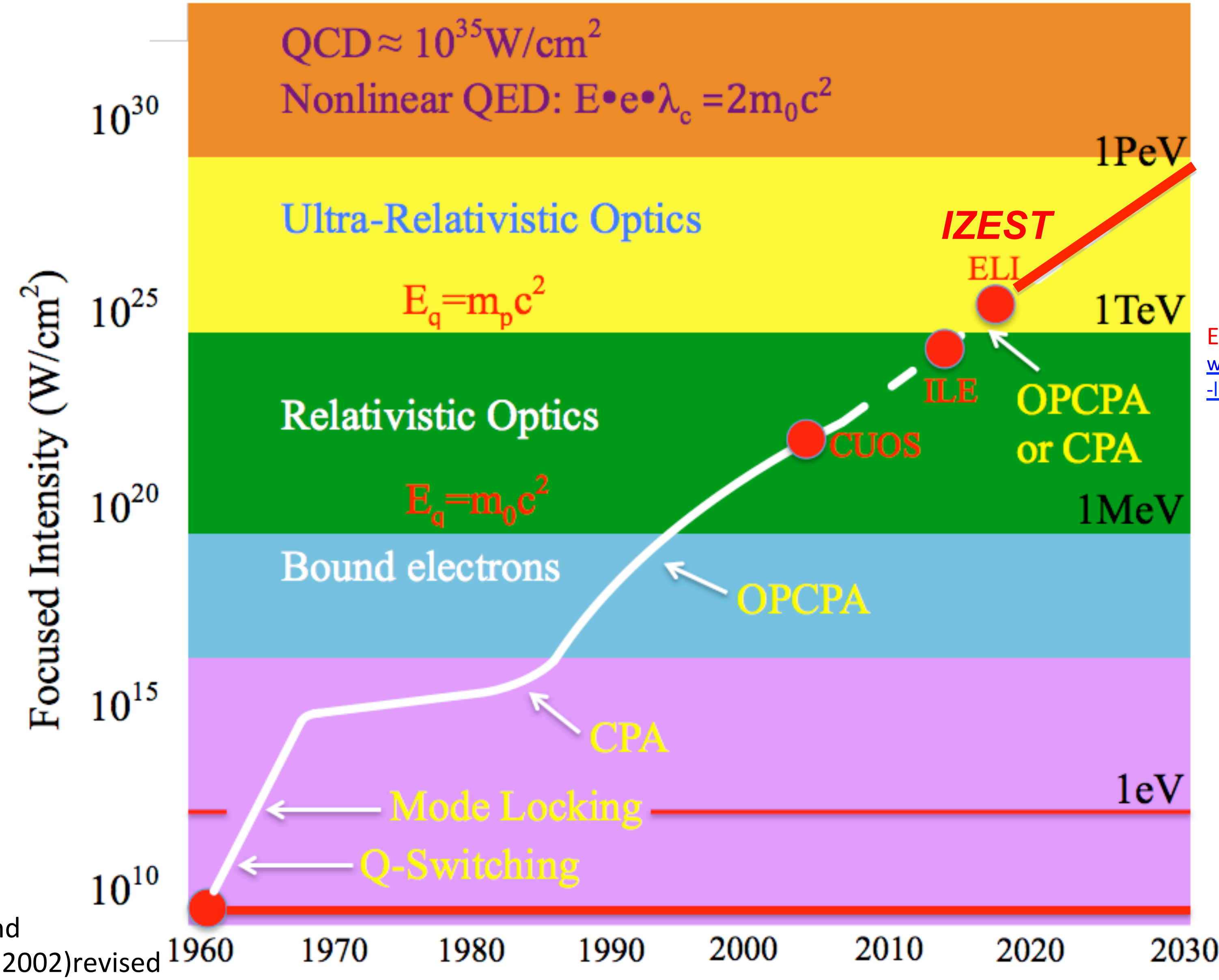


2040s

Laser-plasma LC

Table-top high energy accelerator

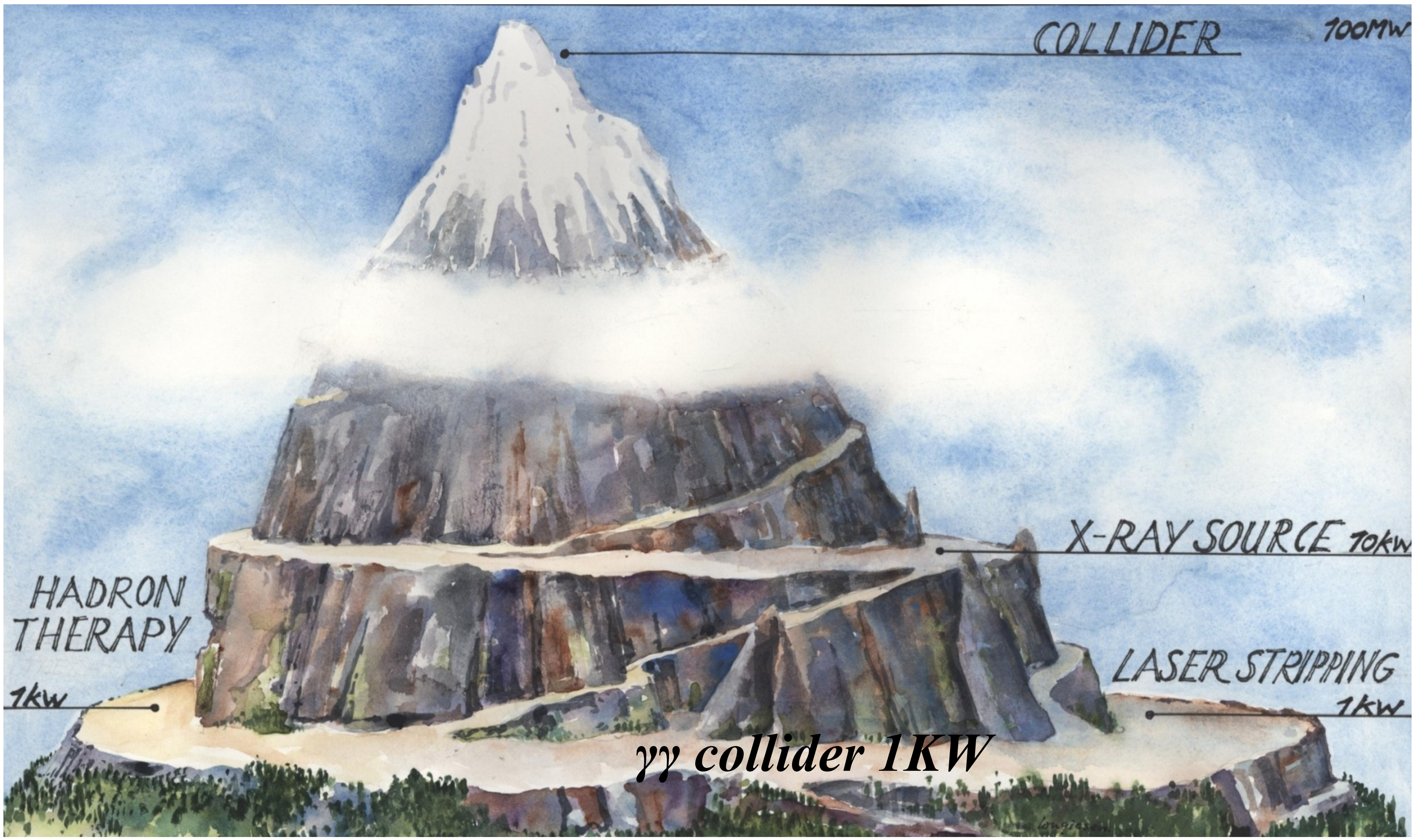
Laser Intensity vs. Years



Tajima and Mourou (2002)revised

ELI : www.extreme-light-infrastructure.eu/

Mountain of Lasers
(average power) for HEP



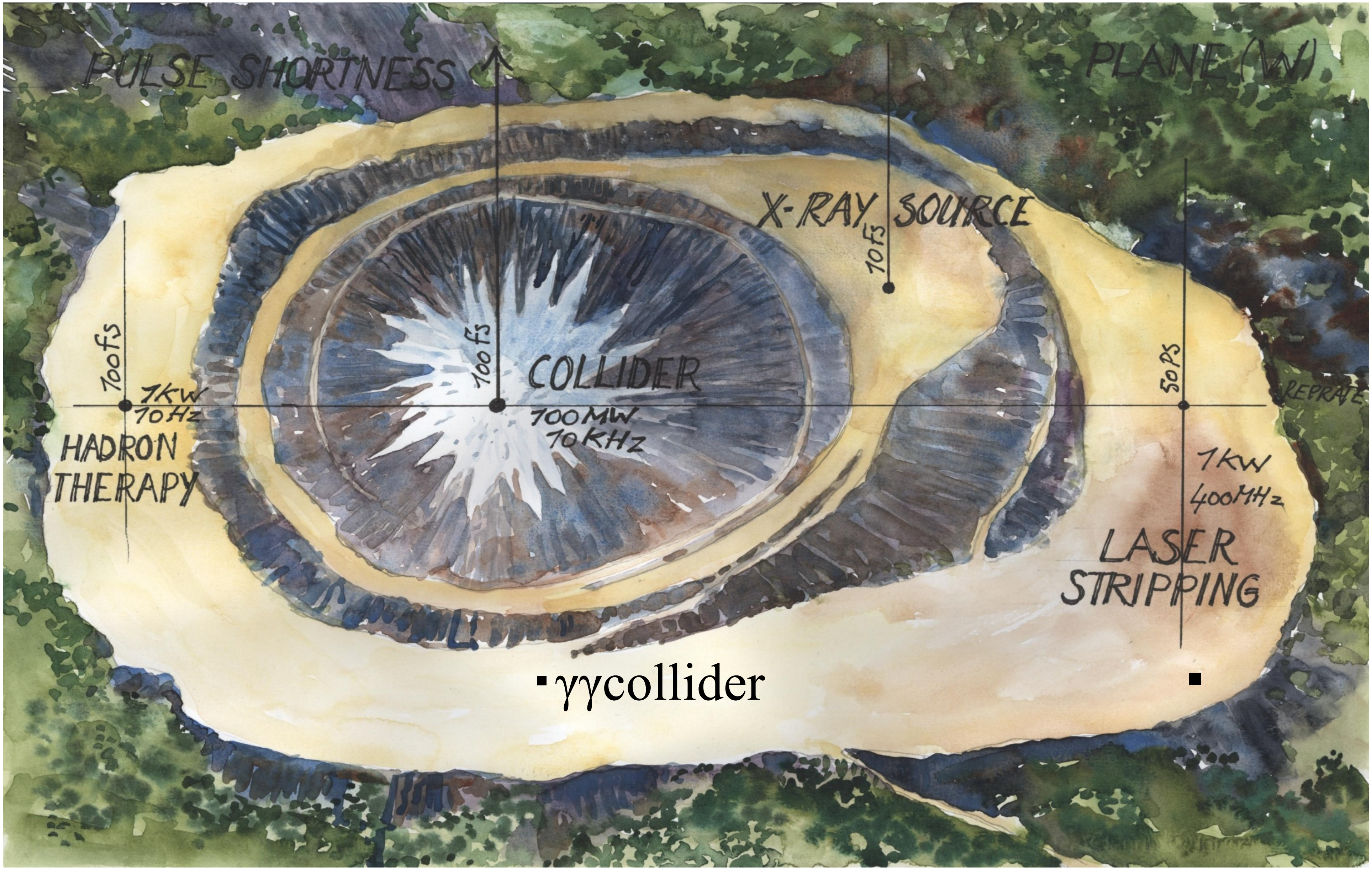
↑ average power

→ rep

↗ pulse shortness

(HEP Examples from *ICFA-ICUIL* JTF)
Friday 6pm Rochester: open JTF

Range of hep laser parameters



The challenge in high-power lasers is
 the average power !

„Beyond Petawatt means Kilowatt“

W. Sandner (2010)

Laserlab
Europe

Areas of improvement in LPA performance for various applications

	THz	X-rays (betatron)	FEL (XUV)	Gamma-rays	FEL (X-rays)	Collider
Energy	✓	✓	✓	✓	↑	↑↑
ΔE/E	✓	✓	↓	↓	↓↓	↓↓
ε	✓	✓	✓	✓	✓	↓↓
Charge	✓	✓	✓	↑	✓	↑
Bunch duration	✓	✓	✓	✓	✓	✓
Avg. power	↑	↑	↑	↑	↑	↑↑

✓: OK as is
↑: increase needed
↓: decrease needed

Proposed Study:

ICAN, International Coherent Amplification Network

"Solving the efficiency problem in high peak and high average power laser: an international effort"

(Coordinator G. Mourou, submitted to the EU November 25, 2010; approved Jan., 2012; starts now)

CEA kJ and MJ lasers underpin IZEST missions

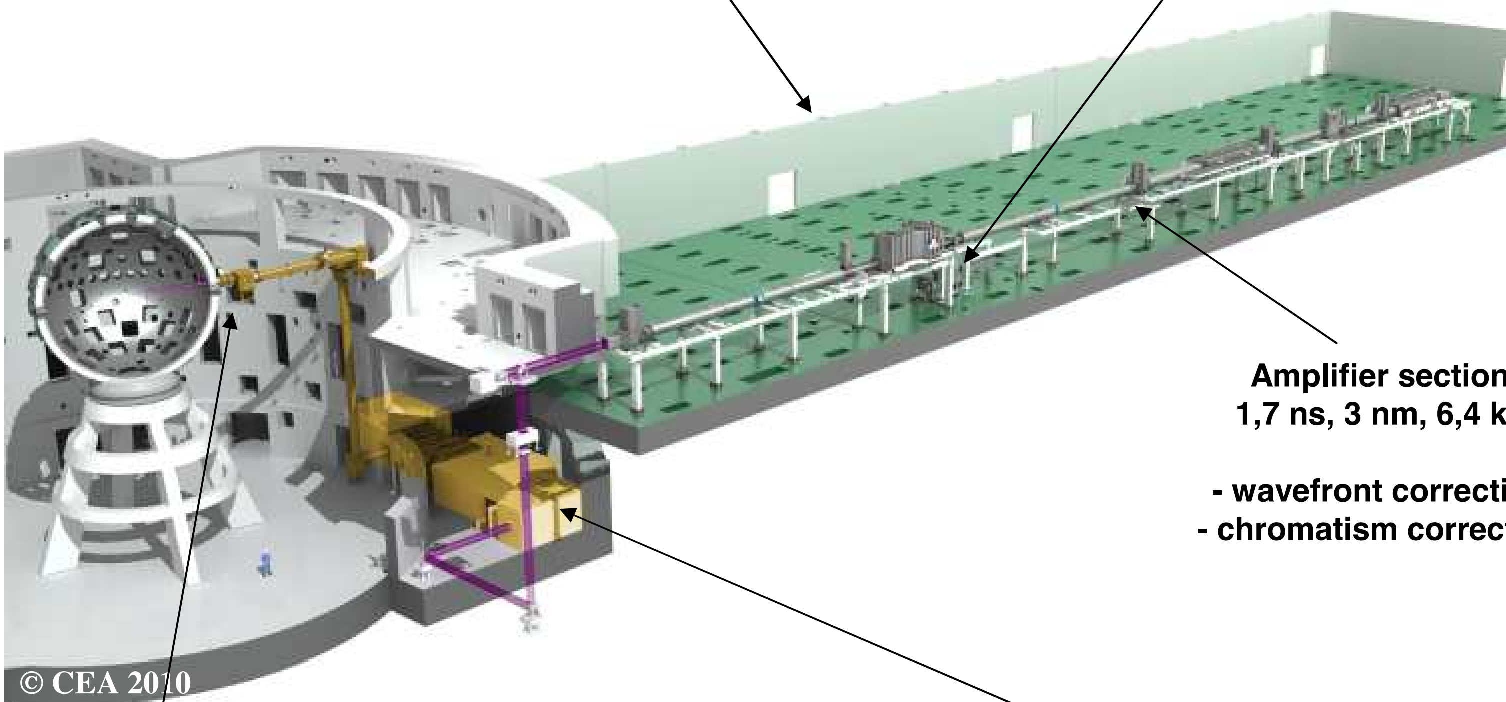
PETAL : Main characteristics (One arm of LMJ)

energie atomique · energies alternatives

- **Energy > 3 kJ*,**
- **Wavelength > 1053 nm,**
- **Pulse duration between 0,5 and 10 picoseconds,**
- **Intensity on target > 10^{20} W/cm^2,**
- **Intensity contrast (short pulse): 10^{-7} at -7 ps,**
- **Energy contrast (long pulse): 10^{-3}.**

B. LeGarrec (2011)

PETAL in the LMJ Building



Front end (oscillator, Offner)
100 fs → 9ns, 16 nm

Preamplifier Module PAM (OPCPA)
4,5 ns, 8 nm, 100 mJ

Amplifier section
1,7 ns, 3 nm, 6,4 kJ

- wavefront correction
- chromatism correction

Transport / Focusing section: (vacuum)
10^{20} W/cm²

- pointing mirror after parabola
- 90° off-axis parabola

Compression section: 2 stages (air & vacuum)
500 fs, 3 kJ

- wavefront correction (gratings deformation)
- beam phasing instead of mosaic gratings

LeGarrec (2011)

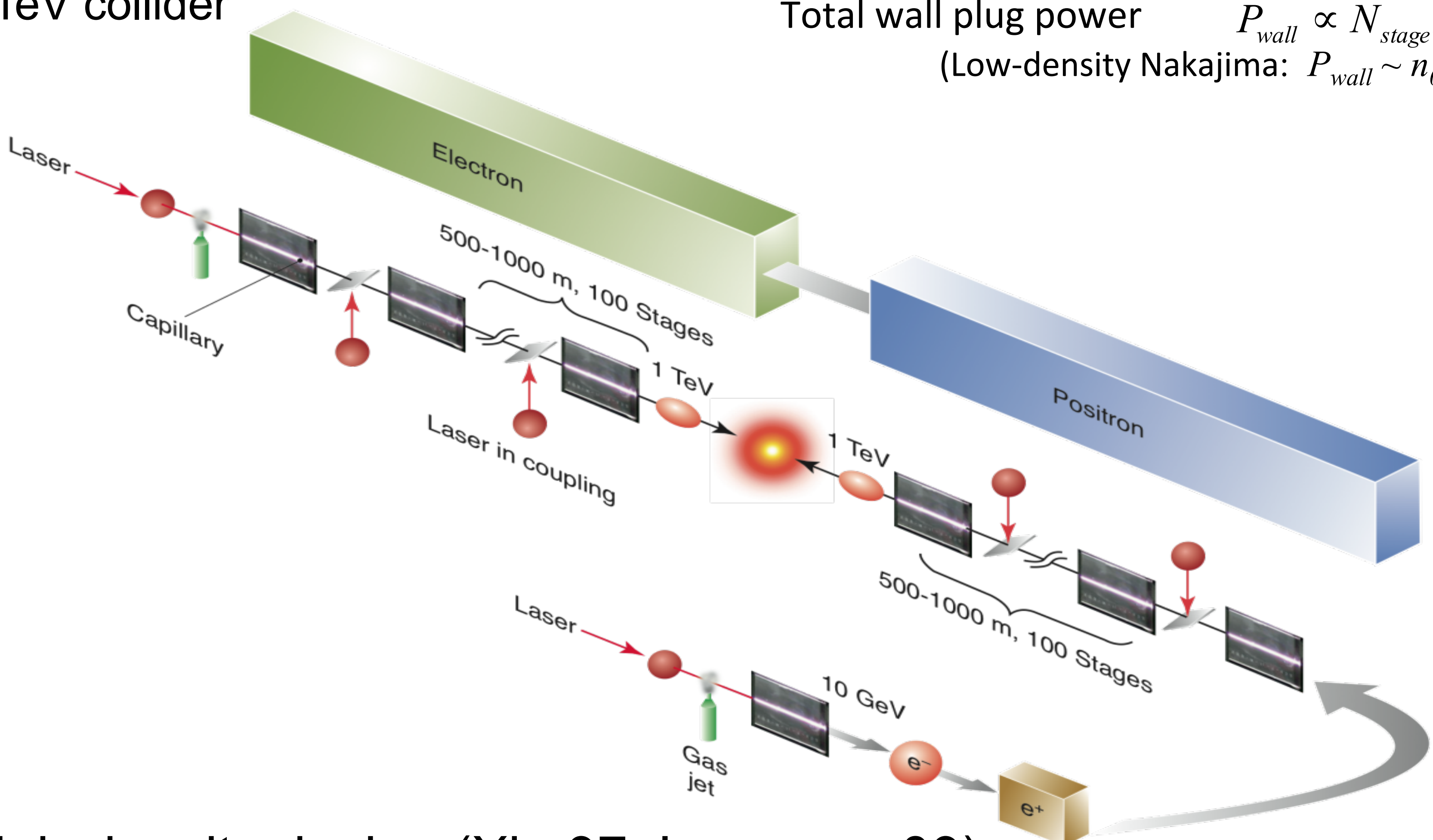
Laser driven collider concept

Laser energy: $U_L \sim n_0^{-3/2}$

a TeV collider

Total wall plug power $P_{wall} \propto N_{stage} P_{avg} \propto n_0^{1/2}$

(Low-density Nakajima: $P_{wall} \sim n_0^{3/2}$)



High-density design (Xie,97; Leemans,09)

ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)

Plasma density could be determined by beam quality and power requirement

Radiation damping effect

- Electrons accelerated by LPA undergo betatron oscillations due to strong focusing force
- Emission of synchrotron radiation results in a energy loss and radiation damping with its rate.

$$P_x \cong \frac{2e^2\gamma^2}{3m^2c^3}F_\perp^2 \qquad \nu_\gamma = \frac{P_s}{\gamma mc^2} = \frac{\tau_R \gamma}{m^2c^2}F_\perp^2$$

where $\tau_R = 2r_e/3c \cong 6.26\times10^{-24}$ s

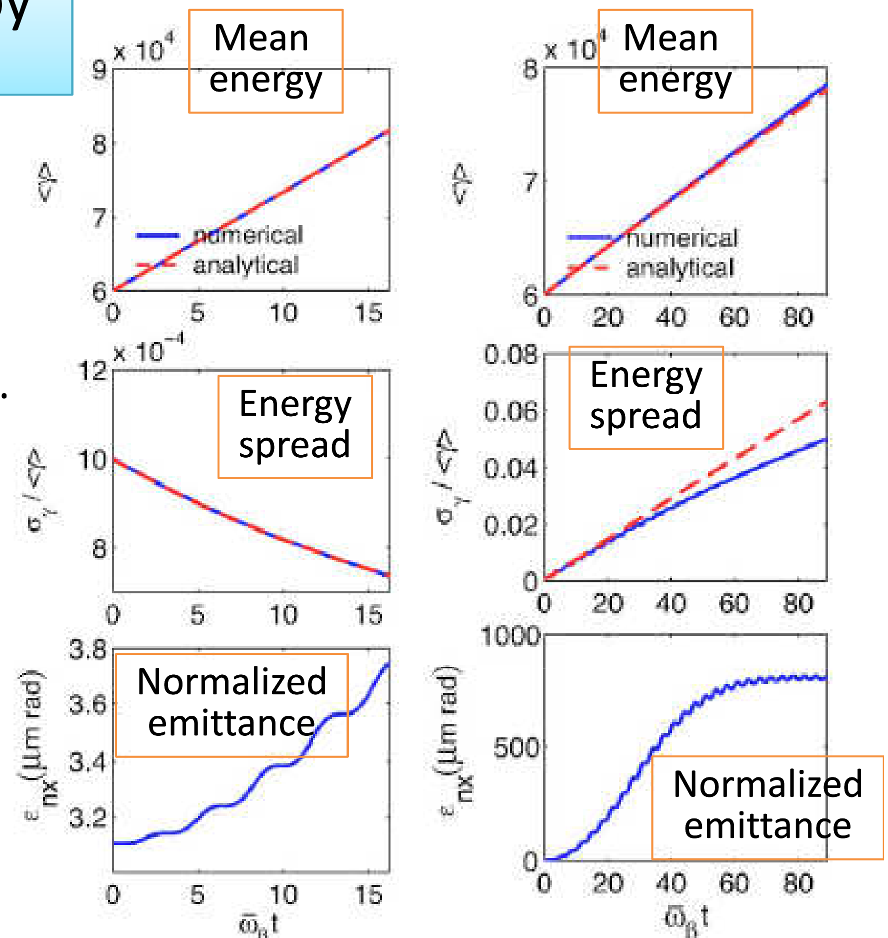
$r_e = e^2/mc^2 = 2.818\times10^{-13}$ cm

$F_\perp = -mc^2K^2x$
$K^2 = 2x_c^{-2}\left(e\phi_0/mc^2\right)$ for the linear regime with potential ϕ_0, characteristic channel width x_c

$K = k_p/\sqrt{2}$ for the blowout (or bubble) regime

Power requirement for the linear collider

- Collision frequency: $f \propto N^{-2} \propto n_0$ for a constant required luminosity
- Beam power: $P_b = fNE_b \propto n_0^{1/2}$
- Average laser power per stage: $P_{avg} \cong fU_L \sim f\cdot P_L\tau_L \propto n_0 \cdot n_0^{-1}\cdot n_0^{-1/2} \propto n_0^{-1/2}$
- Total wall plug power $P_{wall} \propto N_{stage}P_{avg} \propto n_0^{1/2}$



30 GeV injection 30 cm plasma channel E_z = 37 GV/m $n_0 = 10^{16}$ cm^{-3}	30 GeV injection 30 cm plasma channel E_z = 37 GV/m $n_0 = 3\times10^{17}$ cm^{-3}

P. Michel et al., PRE 74, 026501 (2006)

From points of high quality and power cost, choose plasma density of the order of 10^{16} cm^{-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
Energy gain/stage (GeV)	10	10	1
Stage length [LPA + in-coupling] (m)	2	2	0.06
Number of stages (one linac)	50	500	5000
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/cm^2)	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

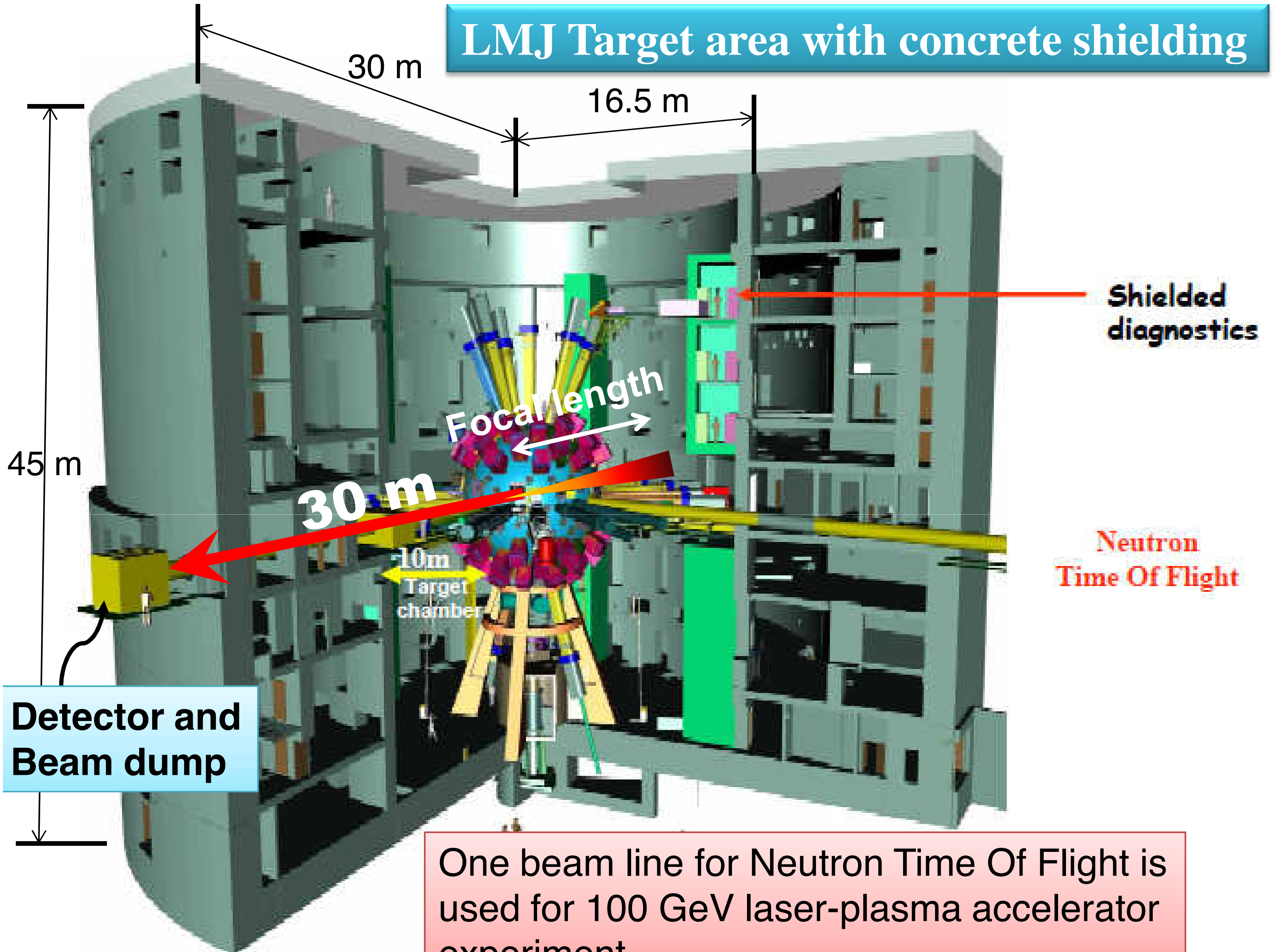
Density scalings of **LWFA** for collider

Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length $L_{\rm stage}$	$\propto n_e^{-3/2}$
Energy gain per stage $W_{\rm stage}$	$\propto n_e^{-1}$
Number of stages $N_{\rm stage}$	$\propto n_e$
Total linac length $L_{\rm total}$	$\propto n_e^{-1/2}$
Number of particles per bunch N_b	$\propto n_e^{-1/2}$
Laser pulse duration τ_L	$\propto n_e^{-1/2}$
Laser peak power P_L	$\propto n_e^{-1}$
Laser energy per stage U_L	$\propto n_e^{-3/2}$
Radiation loss $\Delta\gamma$	$\propto n_e^{1/2}$
Radiative energy spread σ_γ/γ_f	$\propto n_e^{1/2}$
Initial normalized emittance ε_{n0}	$\propto n_e^{-1/2}$
Collision frequency f_c	$\propto n_e$
Beam power P_b	$\propto n_e^{1/2}$
Average laser power $P_{\rm avg}$	$\propto n_e^{-1/2}$
Wall plug power $P_{\rm wall}$	$\propto n_e^{1/2}$

(Nakajima, PR STAB, 2011)

10^{17} /cc (conventional) → 10^{15} /cc

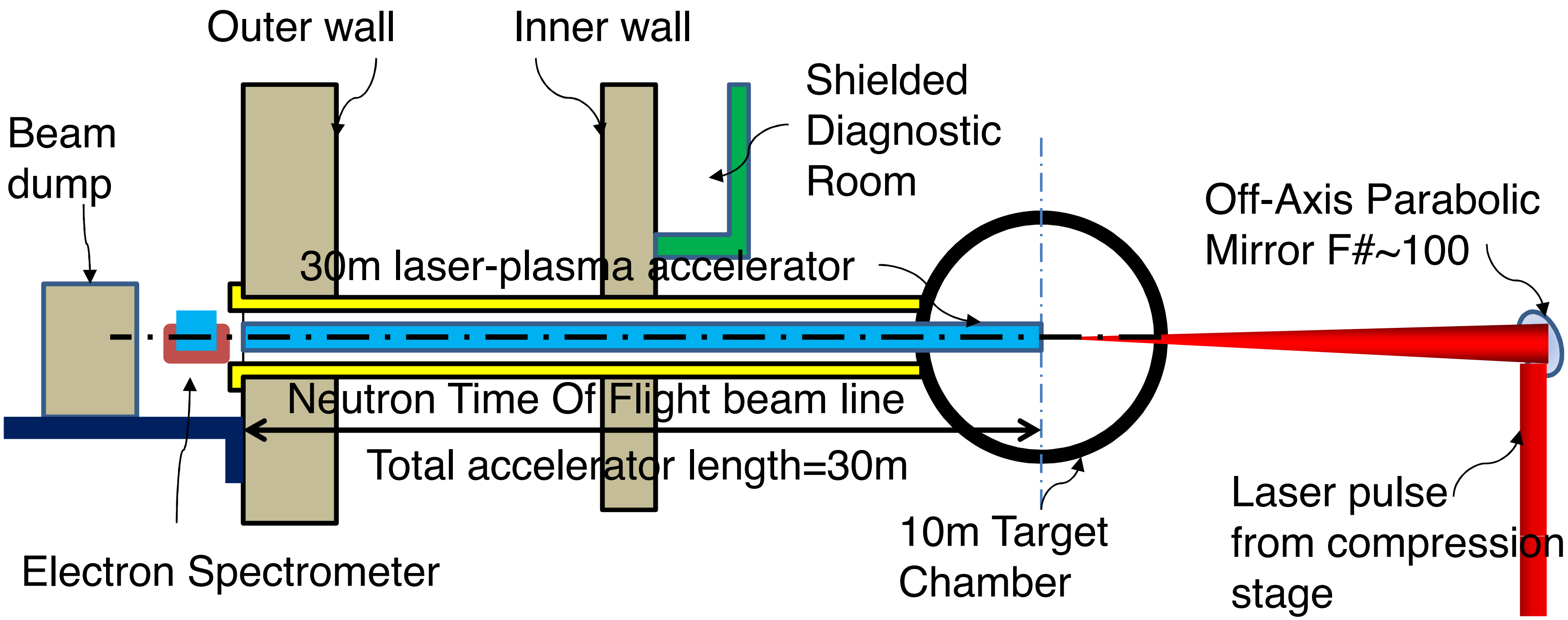
LMJ Target area with concrete shielding



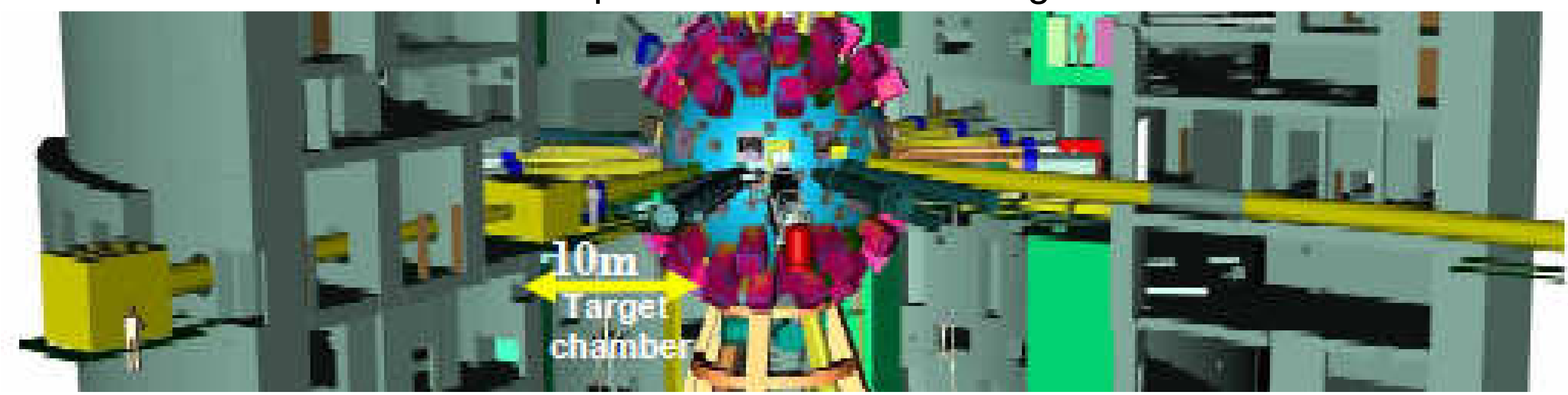
One beam line for Neutron Time Of Flight is used for 100 GeV laser-plasma accelerator experiment.

Nakajima, LeGarrec

A setup design for 100 GeV Laser-Plasma Electron Acceleration

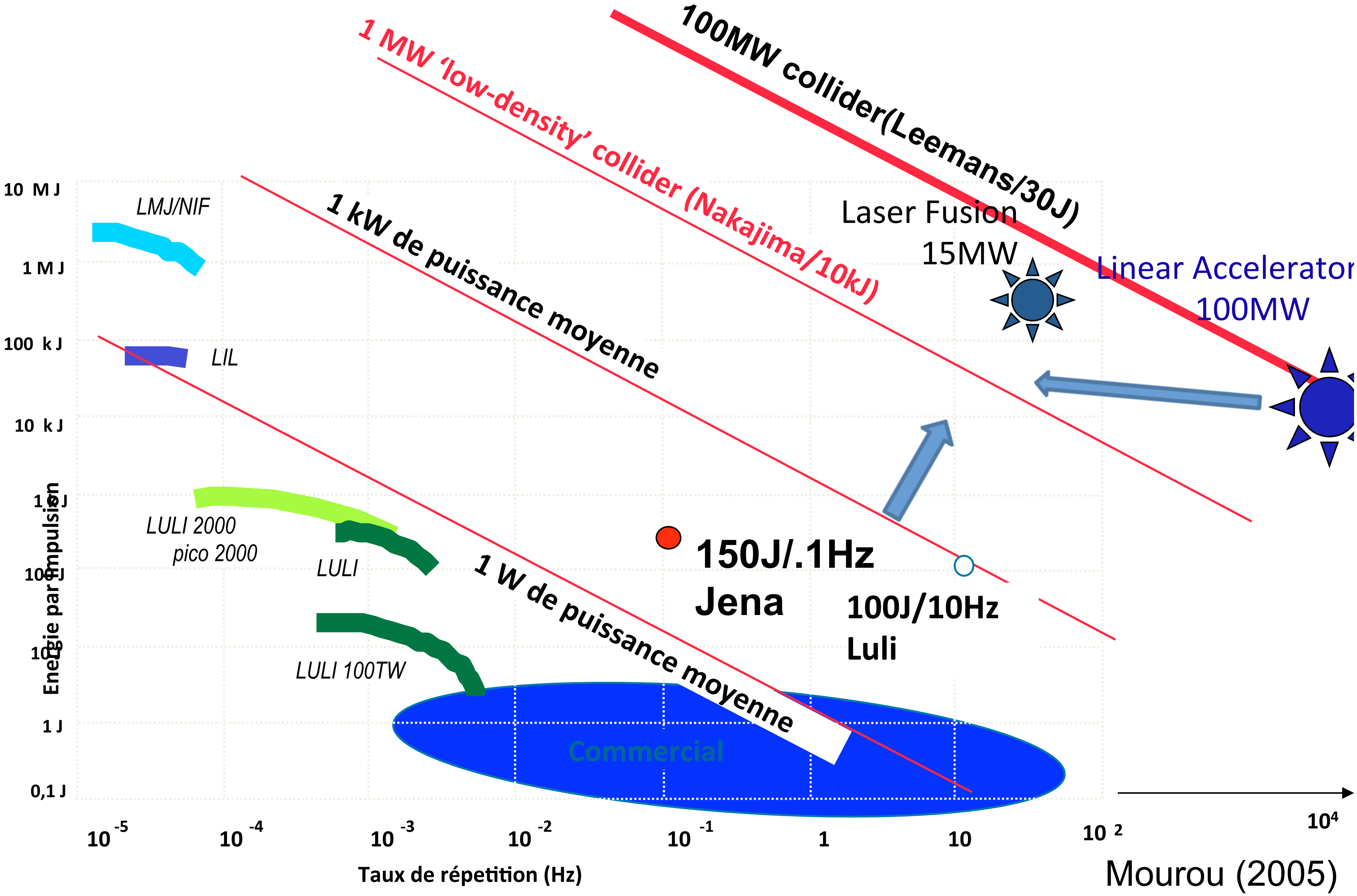


A view of equatorial level of LMJ target chamber



Le Garrec, Nakajima (2012)

Etat de l'Art (HEEAUP 2005): collider consideration

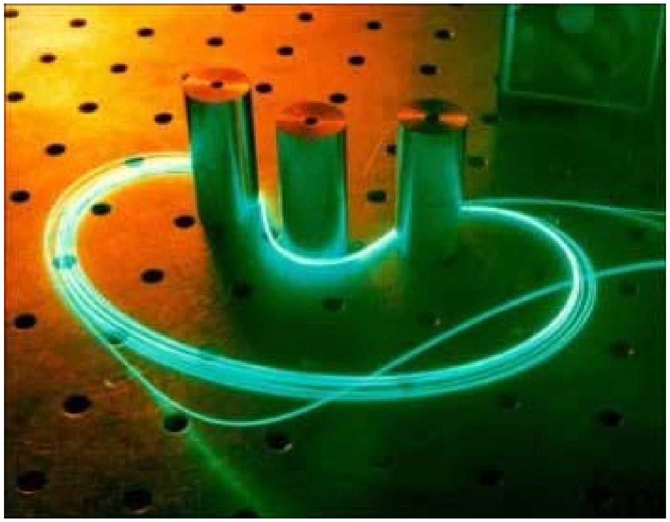


Mourou (2005)

Mourou/ICAN (2011); Nakajima (2011)

Fiber vs. Bulk lasers

- High Gain fiber amplifiers allow ~ 40% total plug-to-optical output efficiency
- Single mode fiber amplifier have reached multi-kW optical power.
- large bandwidth (100fs)
- immune against thermo-optical problems
- excellent beam quality
- efficient, diode-pumped operation
- high single pass gain
- They can be mass-produced at low cost.

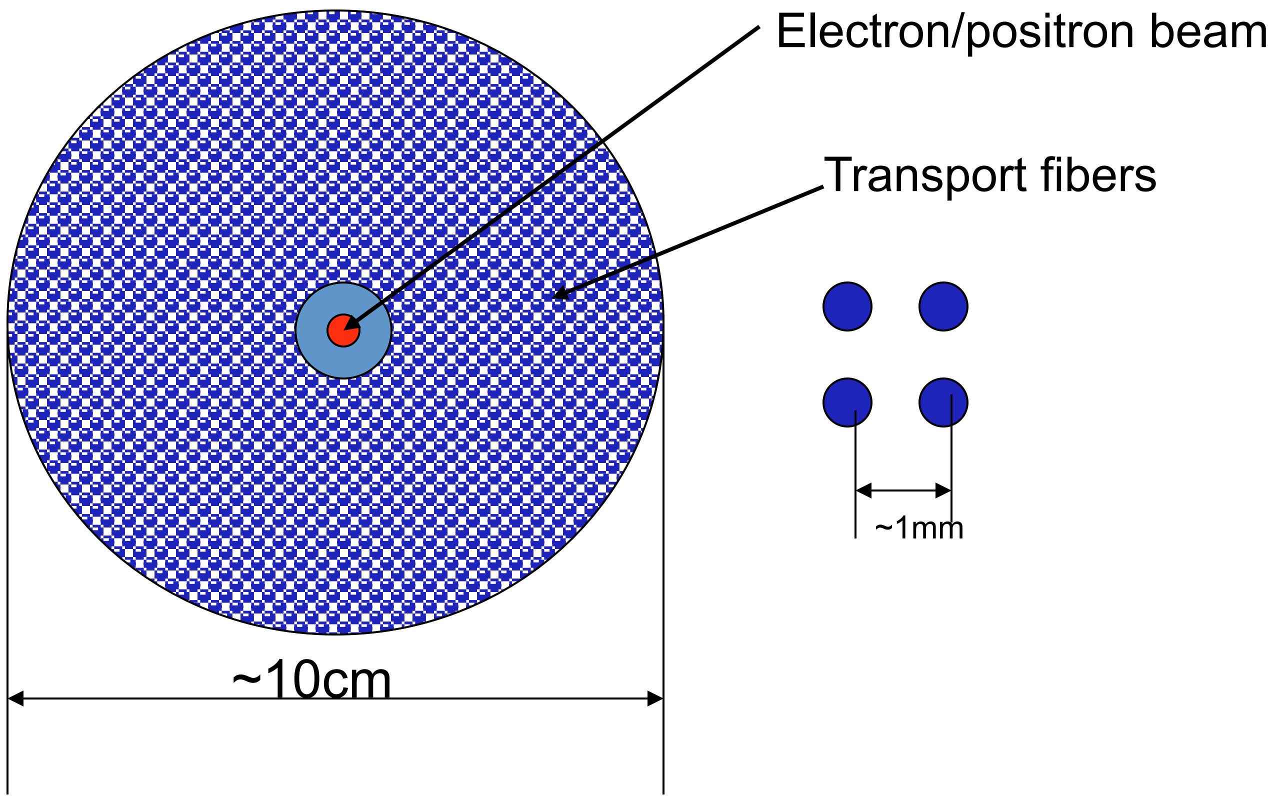


(G. Mourou)

Fiber laser bundle:

International Coherent Amplification Network (ICAN)

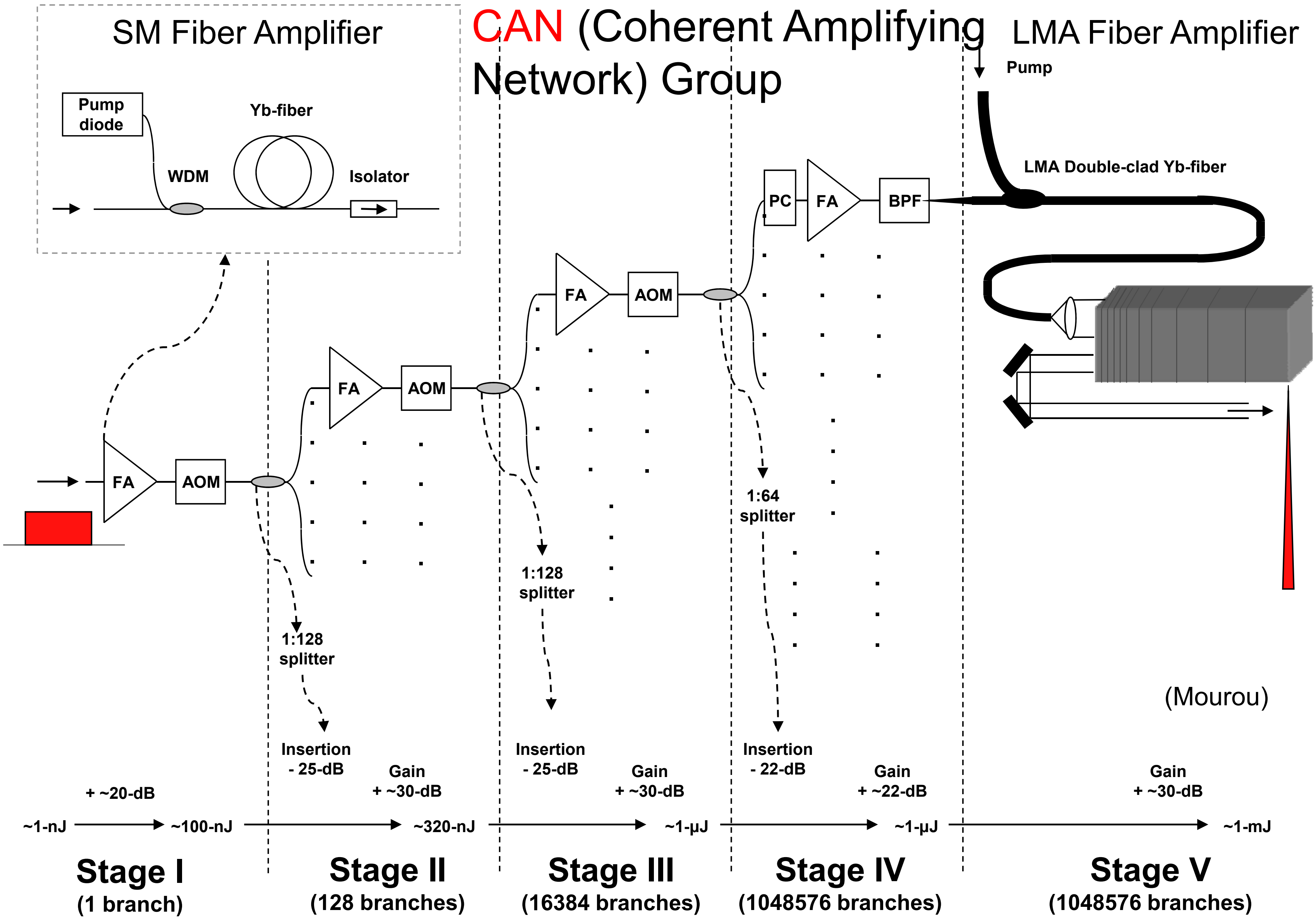
MW class bundle: all coherently phased (Leemans design x100
→ new low-density design x2)



Length of a fiber ~5m   Total fiber length~ 5 10^4km

(Mourou/ ICAN et al)

CAN (Coherent Amplifying Network) Group



Conclusions

- Fiber laser (and other possible technologies: *ICAN*) provides a hopeful path toward MW average power
- Low Density Operation of LWFA reduces the wall-plug power by one order of magnitude
- Low Density Operation provides other beam dynamics benefits, such as less betatron oscillations, less synchrotron radiation, less emittance, less number of stages (with larger single stage energy requirement)
- *IZEST* provides immediate platform to test Low Density Operation of LWFA
- *ICAN* laser technology: useful for other applications (such as radioactive isotope treatment, nuclear medicine, chemical factories and pharmaceuticals, fusion, etc.)