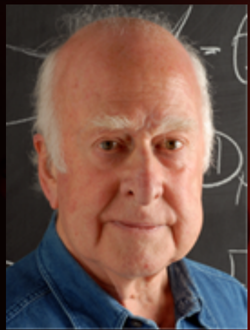
I ZEST
International Zeta-Exawatt Science Technology

Can the Futur of Accelerator Be Fibers?

1st European Advanced Acceletrator Concept 2013

Elba, June 2-7, 2013



"The discovery of this particle is potentially the beginning of another road, which is to explore what lies beyond the Standard Model"

- Peter Higgs

"I realized there would be many applications for the laser, but it never occurred to me that we'd get such power from it!"

- Charles H. Townes

Gerard Mourou
IZEST Ecole Polytechnique – Paris – France

150th Anniversary of Politecnico di Milano

Gerard Mourou S.L Chin, Laval

Laser-Accelerator concepts Scientific and Societal Applications

- ***Applications***

  electron-positron Collider
  - ***Proton Colliders (Tevatron, LHC)***
  - ***Neutron sources (SNS, ESS)***
  - ***Neutrino Sources(SNS, ESS)***
  - ***Radioactive Ion Beam (FRIB, Eurisol)***
  - ***Accelerator Driven Systems(Ch-ADS,MYRRHA)***
  - ***Muon collider***
  - ***Free Electron laser at 10kHz***
  - ***Higgs Factory***

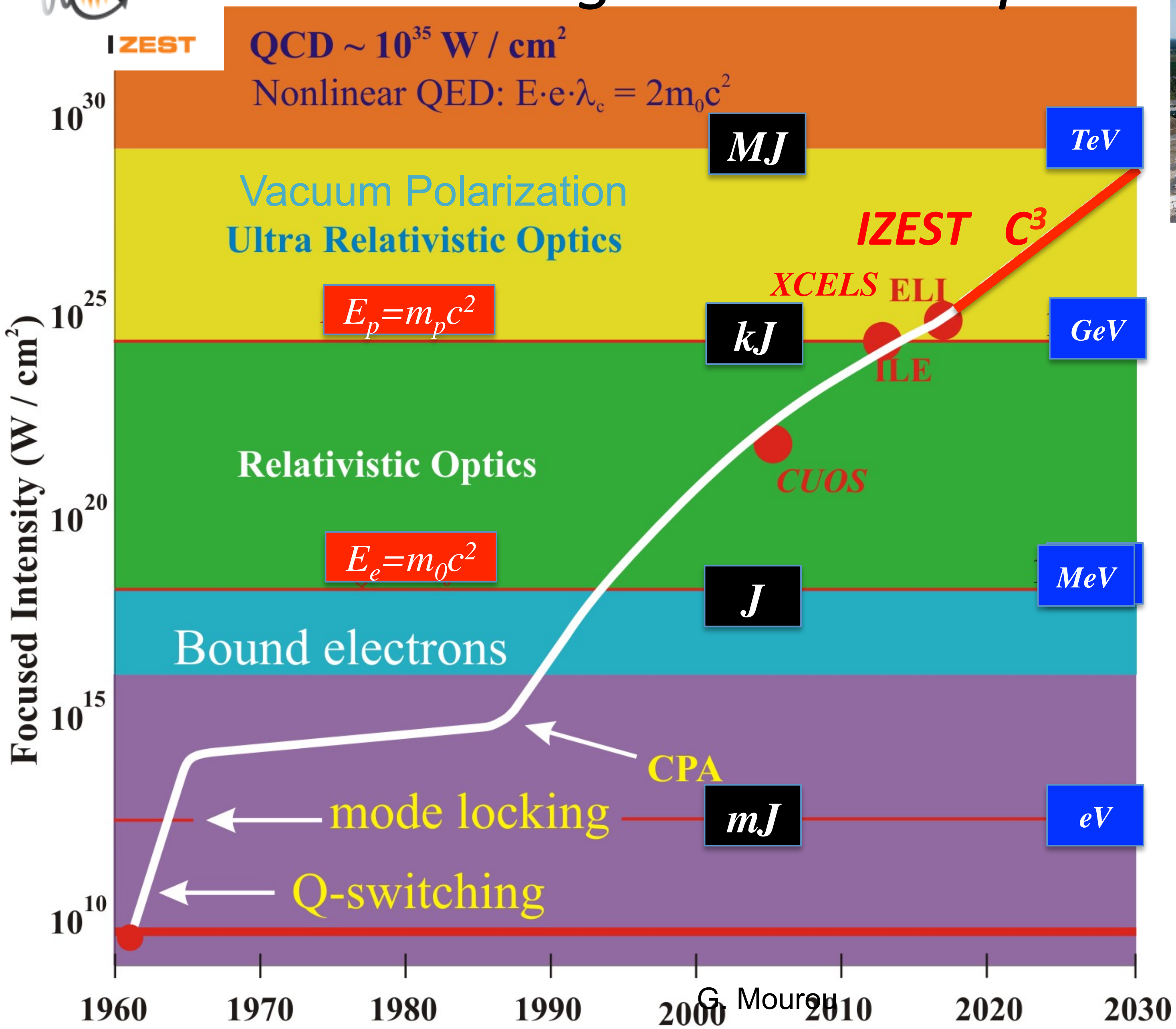
Introduction
Laser Driver concepts
Basic requirements

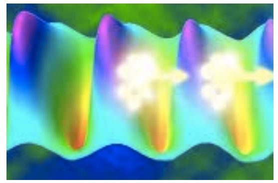
1) Peak Power 100TW to PW, Relativistic and Ultra relativistic regime for electrons (10^{18}W/cm^2) and protons (10^{23}W/cm^2), with MW average power

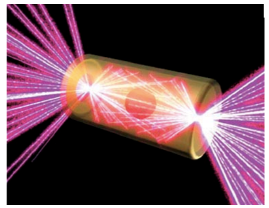
2) High Wall Plug Efficiency >30%.

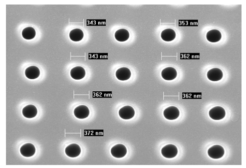
3)Way to Optimize laser Plasma interaction for laser-plasma Interaction efficiency, Smart-laser.

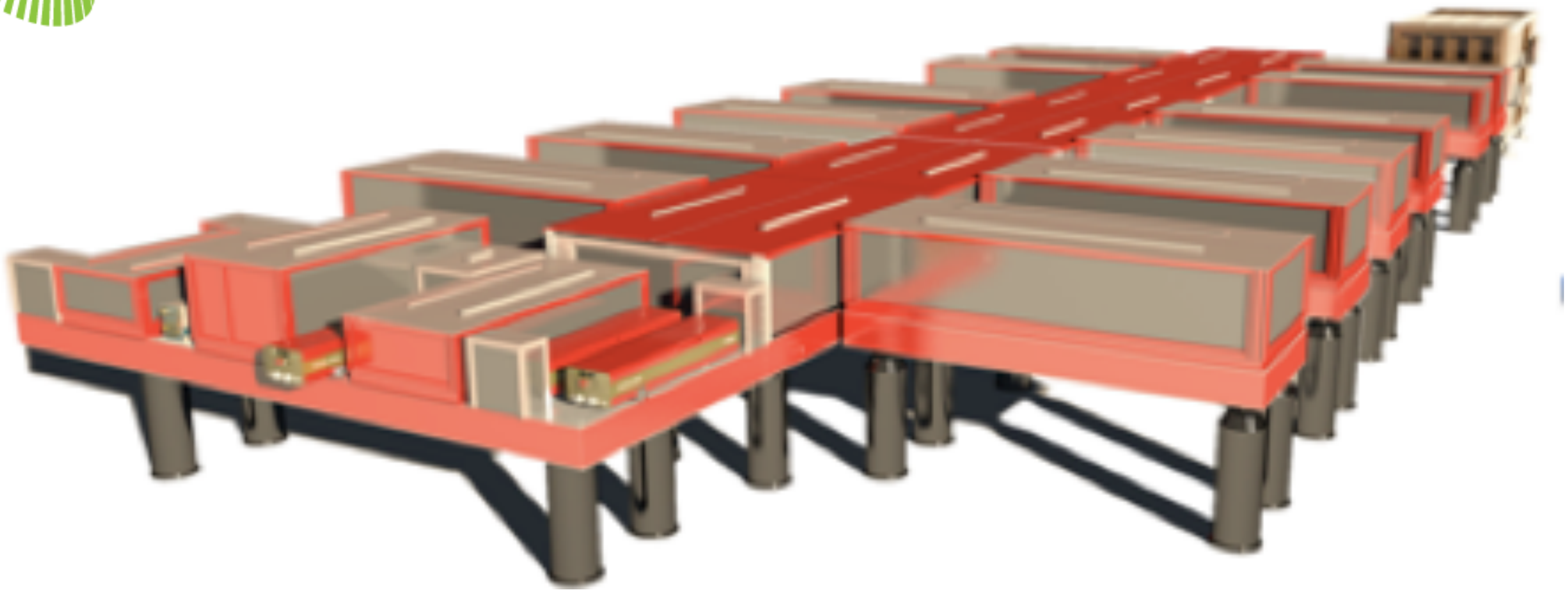
Extreme Light Road Map





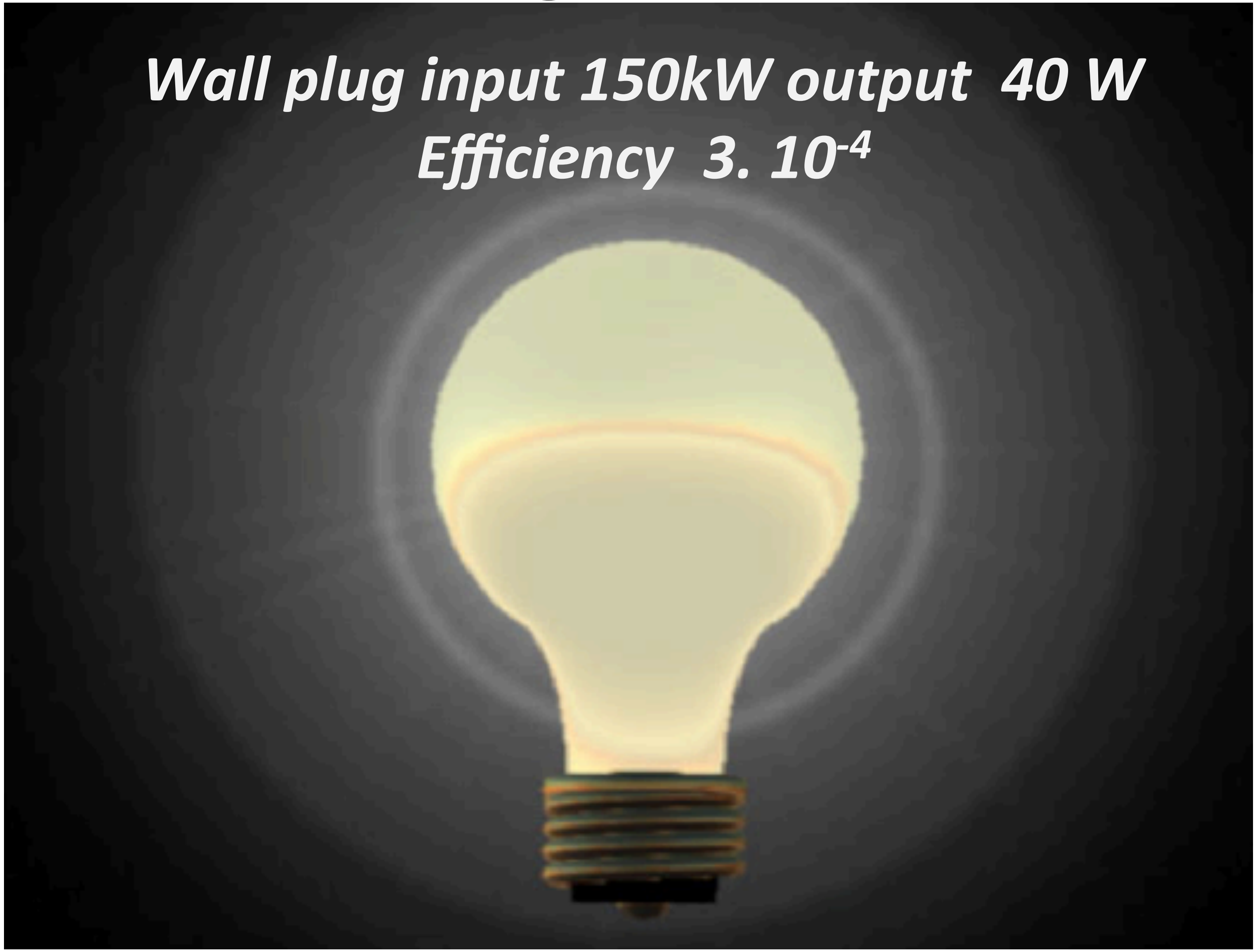






Output: 40J@1Hz = 40W

It’s a light bulb!



We need to Power a TGV (10MW)
TeV, 4nC, 13kHz

ICFA-ICUIL Joint Task Force on laser acceleration (Darmstadt, 2010)

W. Leemans,
Chair of JTF

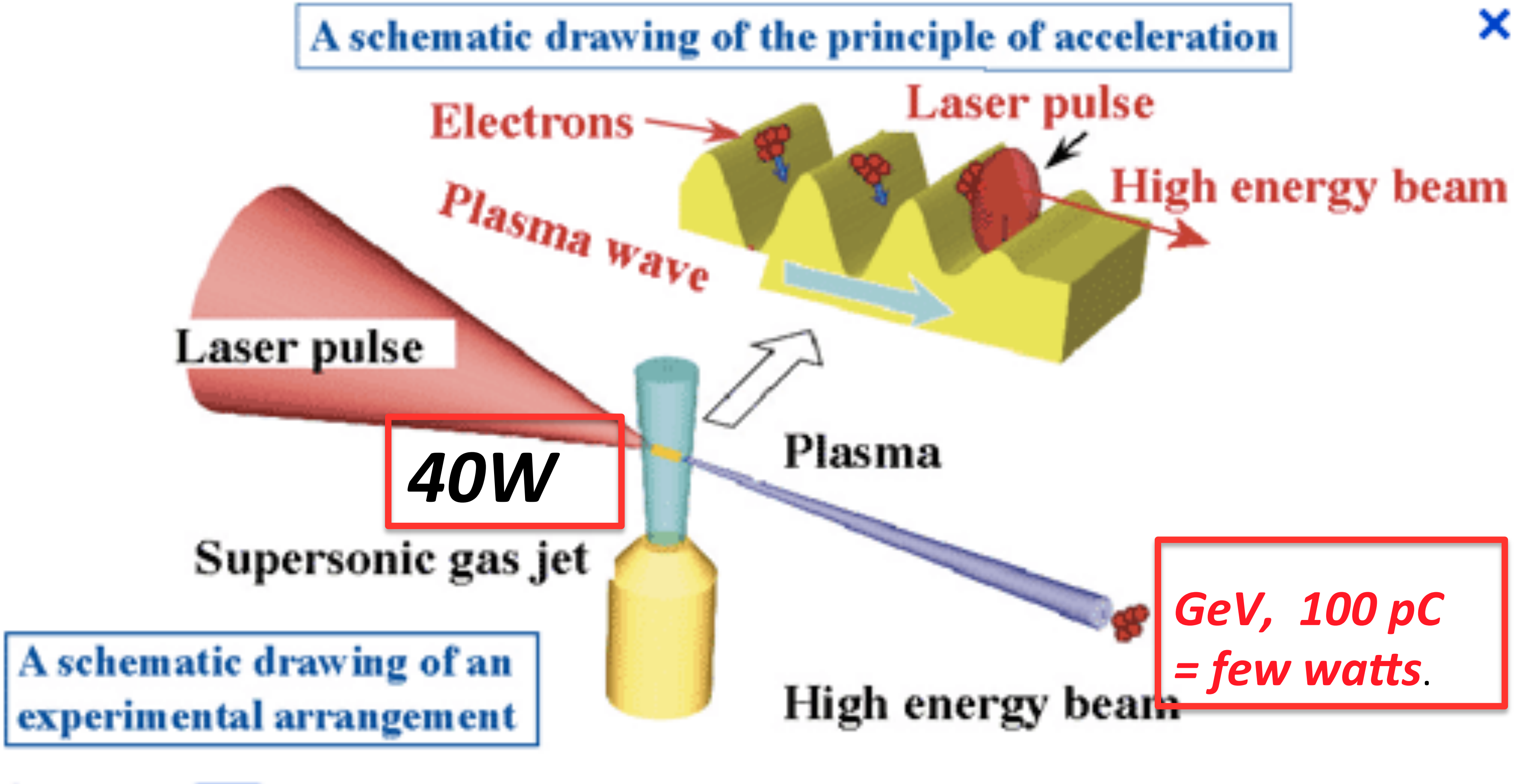
Case	1 TeV	10 TeV (Scenario I)	10 TeV (Scenario II)
Energy per beam (TeV)	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	1.2	71.4	71.4
Electrons per bunch ($\times 10^9$)	4	4	1.3
Bunch repetition rate (kHz)	13	17	170
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	700	200	200
Vertical emittance $\gamma\varepsilon_y$ (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) **.4TGV**	4.2	54	170
Wall plug to beam efficiency (%)	10	10	10
One linac length (km)	0.1	1.0	0.3

Collider subgroup
List of parameters
(W. Chou)

Table 1
Collider parameters

1TGV=10MW

Laser Wake field Acceleration

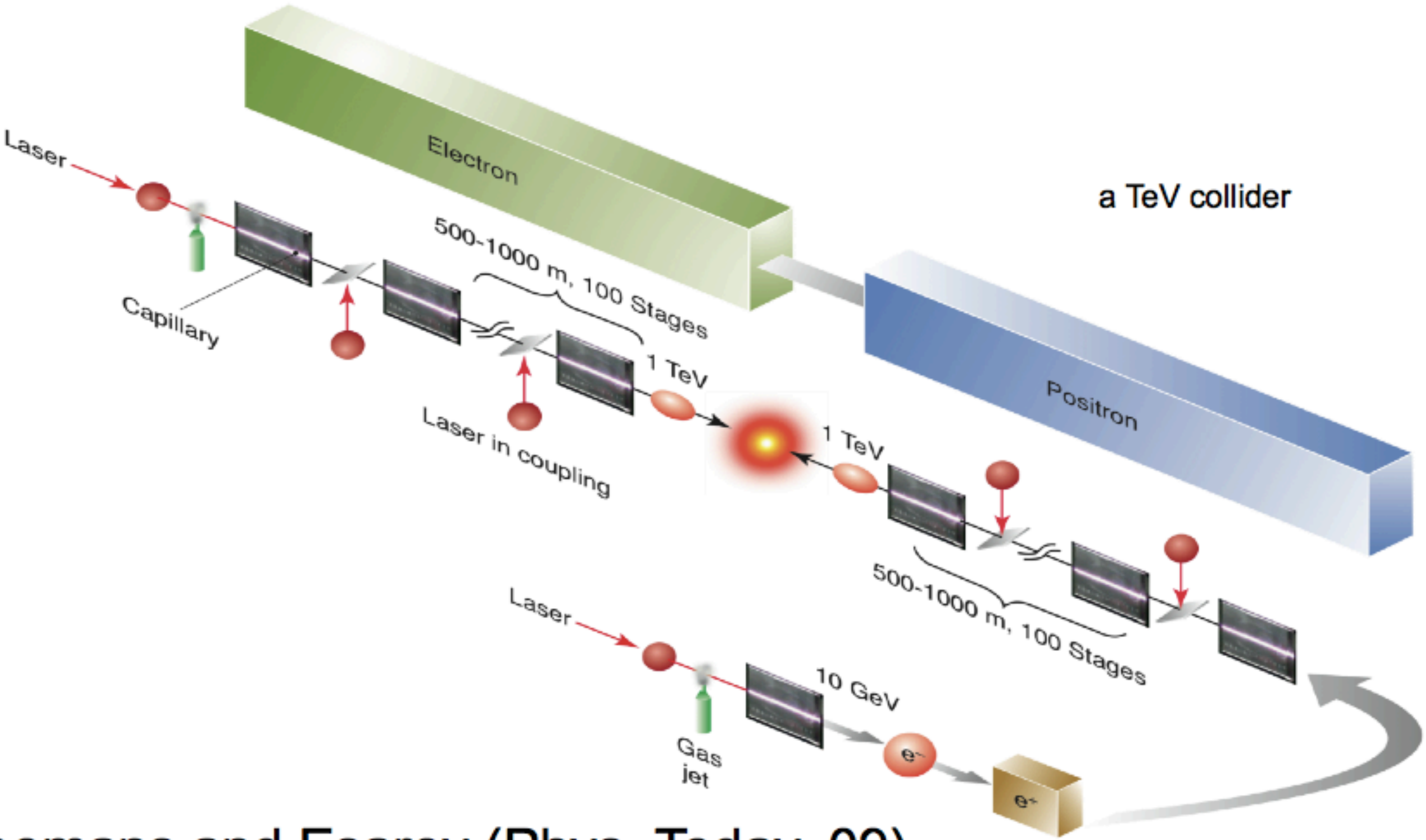


Laser requirements for such colliders

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

Laser driven collider concept

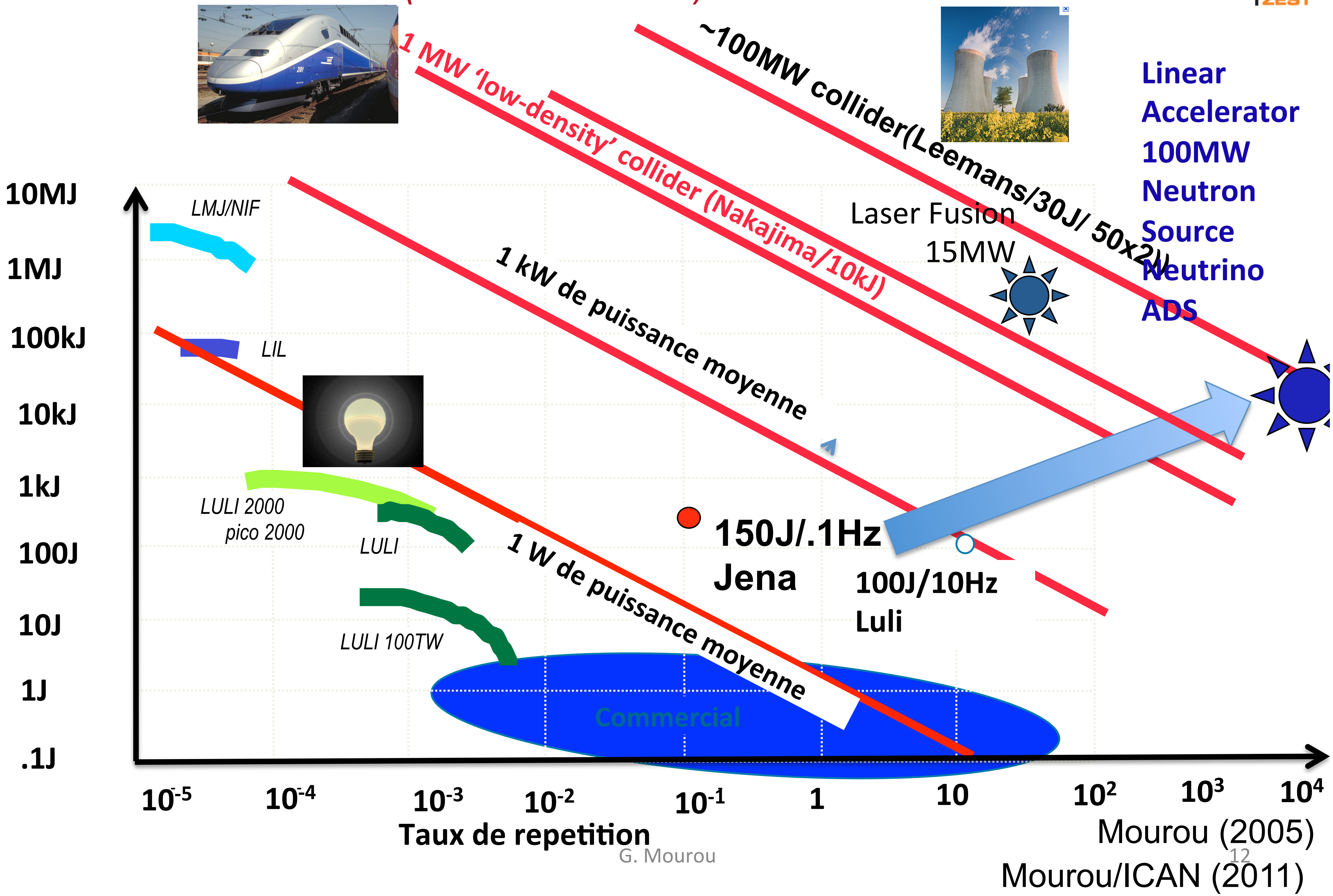
TeV Collider



Leemans and Esarey (Phys. Today, 09)

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

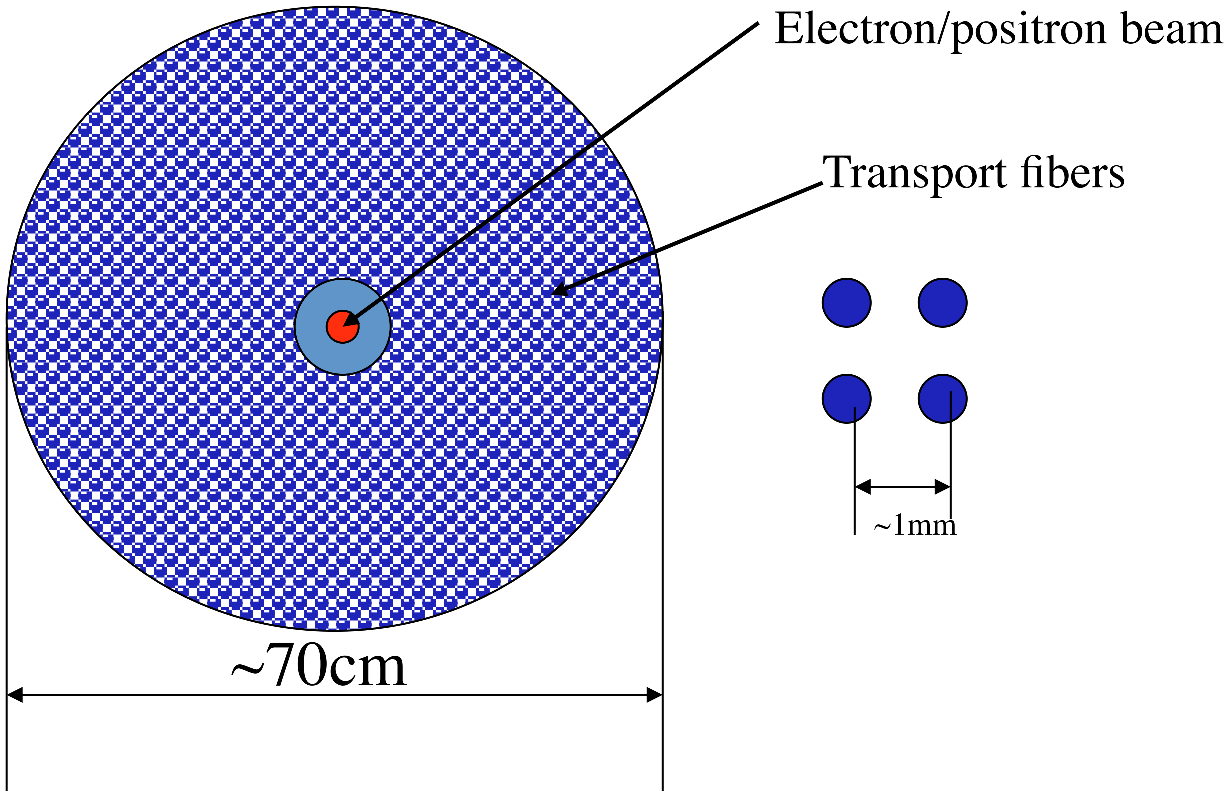
Etat de l'Art (HEEAUP 2005): collider consideration



However Need to Phase /1mJ/fiber~ 30 10^3 Phased Fibers!!

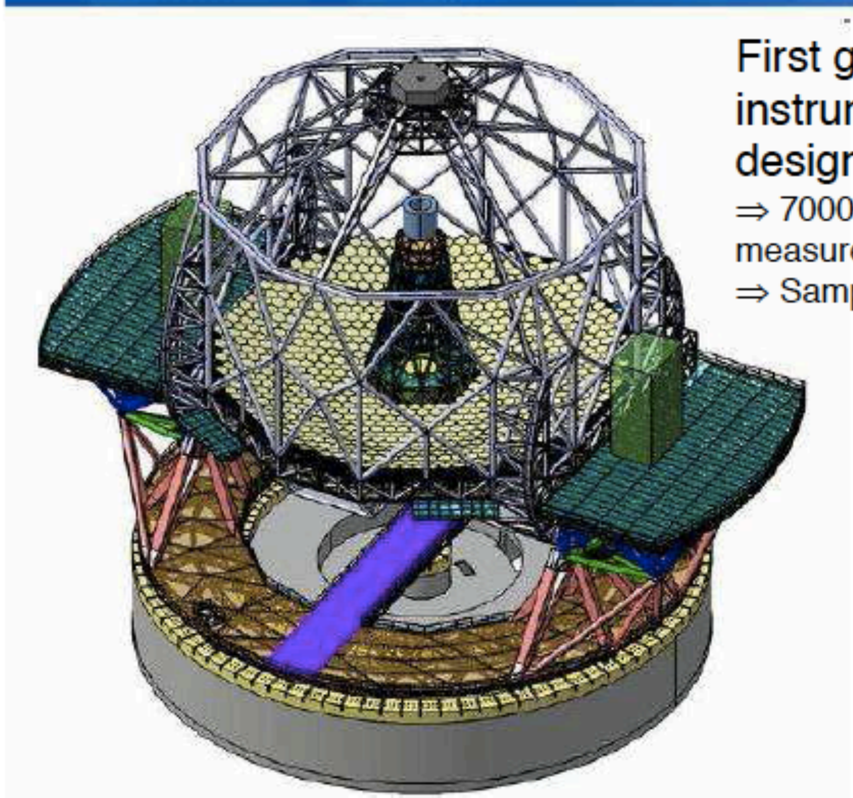
(G. Mourou patent 2005)

Eidam, T. *et al.* Fiber chirped-pulse amplification system emitting 38 GW peak power. *Optics Express* **19**, 255 (2010).



Length of a fiber ~2m   Total fiber length~ 5 10^4km

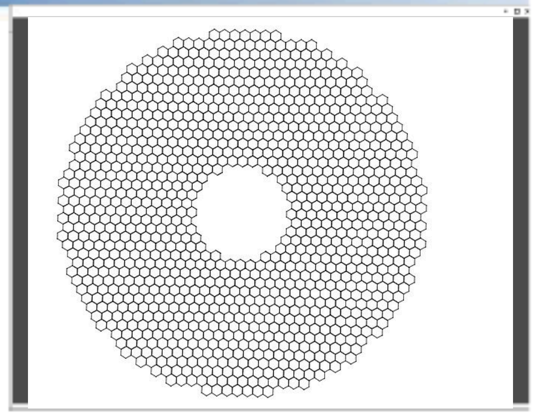
There is a parallel between ICAN and the ELT (Extreme Large Telescope (42m): 1000 mirrors, 40000 actuators, 2kHz sampling rate

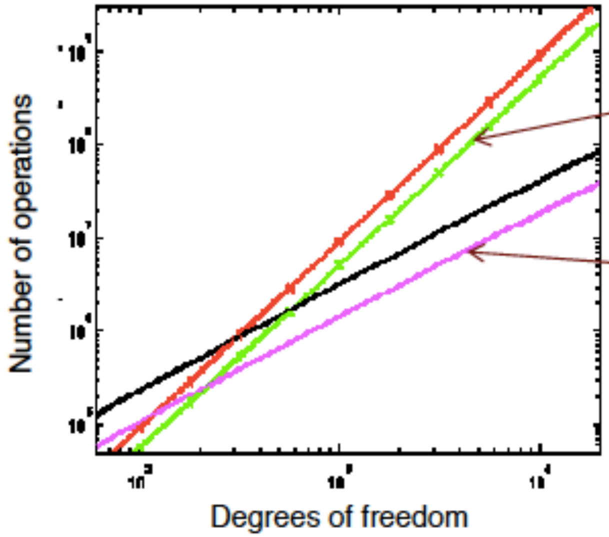


First generation instruments: AO system design led by Onera

⇒ 7000 actuators / WFS measurements

⇒ Sampling frequency = 500 Hz





Next generation: XAO system

⇒ 7000 + 40000 actuators / WFS measurements

⇒ sampling frequency > 2000 Hz

Coherent Amplifying Network
CAN
A Revolution in Laser Architecture

G. A. Mourou,et al D. Hulin and A. Galvanauskasi,
AIP Conference Proceedings, vol. 827, 152-163 (2006).

G. Mourou, W. Brockelby, J. Limpert, T. Tajima,
Nature Photonics April(2013)

What is ICAN?

- ***A European Uion funded Project***
- ***A Revolutionary laser Architecture with the mission to provide:***

1. ***Peak Power PW***
2. ***Average Power MW (leap of 10^4)***
3. ***Excellent wall plug to laser efficiency 30-40% (leap of 10^4)***
4. ***Rep. Rate 10^4 (leap of 10^4)***
5. ***Total Phase and Amplitude Control***

ICAN : An Enormous Challenge that takes the World Wide Community

ICAN International Coherent Amplification Network

A Search for Ultra-high Average Power

BENEFICIARIES

1 Ecole Polytechnique [Coordinator] - Palaiseau, France
2 ORC - Optoelectronics Research Centre, Southampton, UK
3 FhG - Fraunhofer Gesellschaft, Munich, Germany
4 CERN - Organisation Européenne pour la Recherche Nucléaire, Genève, Switzerland

EXPERTS

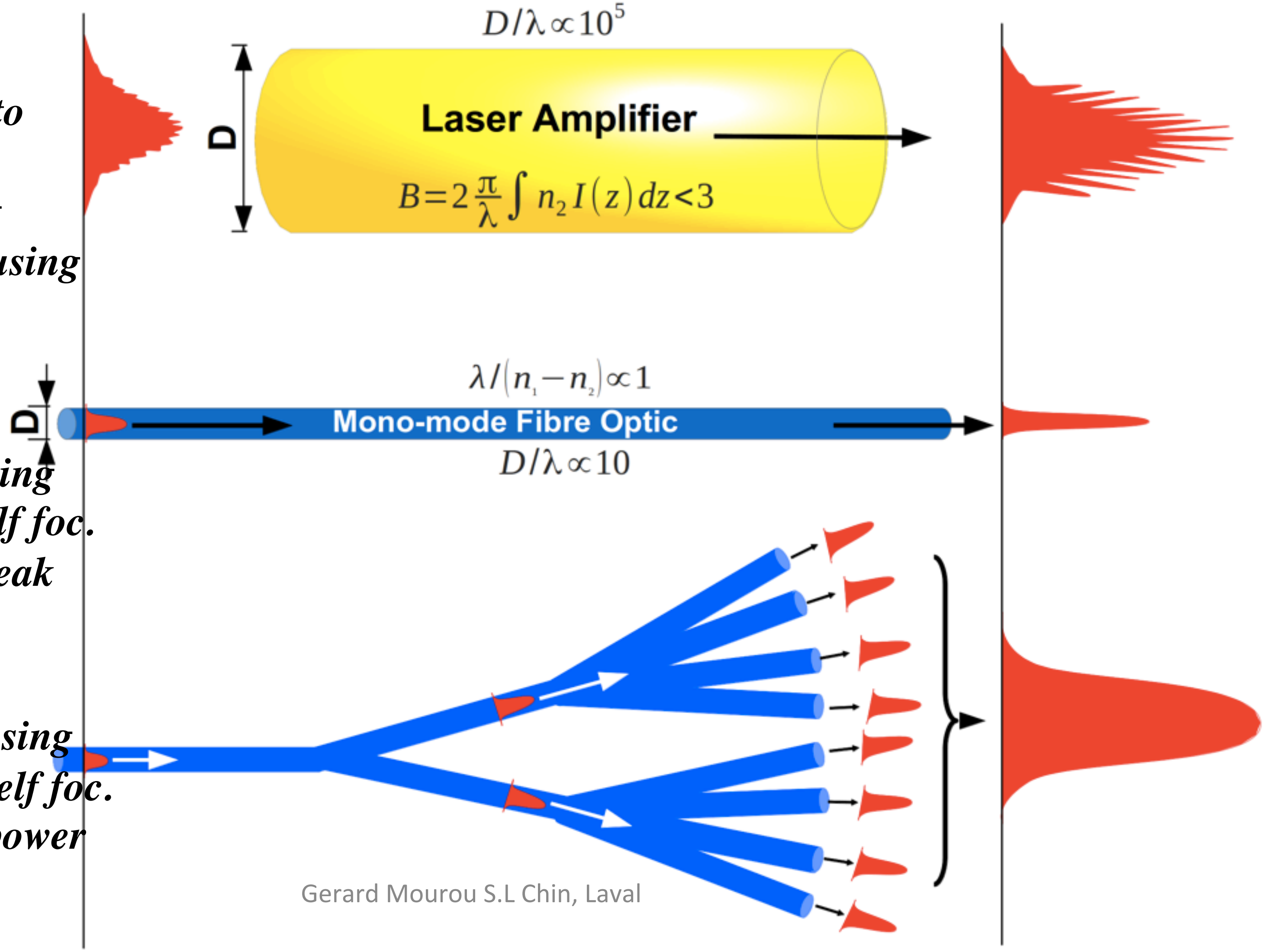
5 LMU/MPQ - Ludwig-Maximilians-Universität Max-Planck-Institut für Quantenoptik, Germany
6 CUOS - Center for Ultrafast Optical Science, Ann Arbor, Michigan, USA
7 LCFIO - Laboratoire Charles Fabry de l'Institut d'Optique, Palaiseau, France
8 ONERA - L'Office Nationale d'Etudes et Recherches Aérospatiales, France
9 TRT-Fr - THALES Research and Technology, Palaiseau, France
10 CEA - Commissariat à l'Energie Atomique, Bordeaux, France
11 KEK - High Energy Accelerator Research Organization, Tsukuba, Japan
12 FERMILAB - Fermi National Accelerator Laboratory, Chicago, Illinois, USA
13 LULI - Laboratoire pour l'Utilisation des Lasers Intenses, France
14 ILC - International Lasers Centre, Moscow, Russia
15 HZDR - Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
16 DESY - Deutsches Elektronen-Synchrotron, Hamburg, Germany
17 University of Strathclyde - Strathclyde, UK

ICAN
Mitigating Thermal and Nonlinear Focusing in Amplifiers

Large Amplifier
Small cooling area/to
Volume ratio
Thermal defocusing
Small scale self focusing

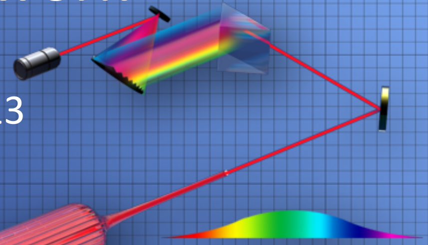
Single mode
Little thermal focusing
Little small scale self foc.
Small energy and peak power.

ICAN
Little thermal focusing
Little small scale self foc.
Energy and peak power

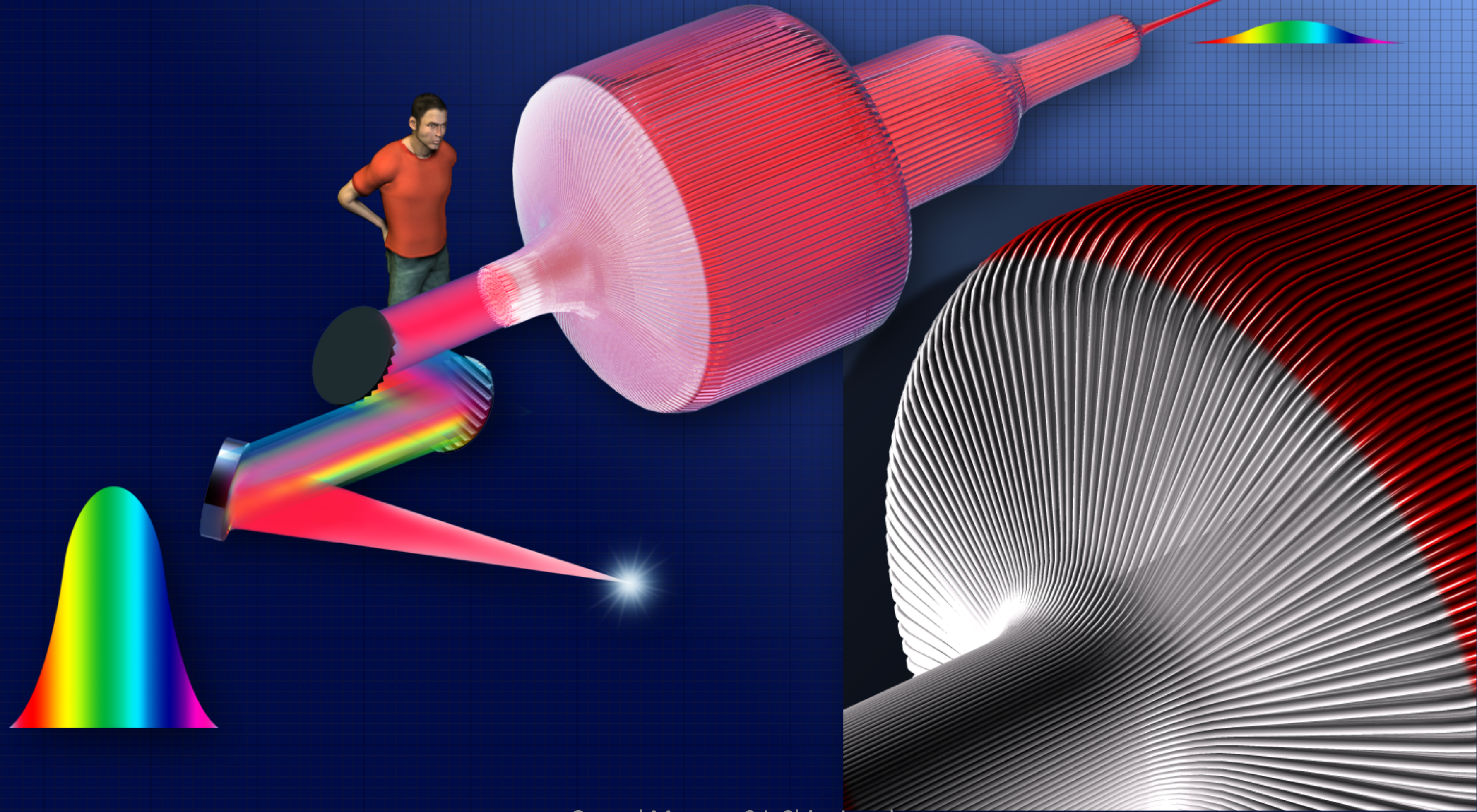


ICAN (European Project)

CAN Coherent Amplification Network

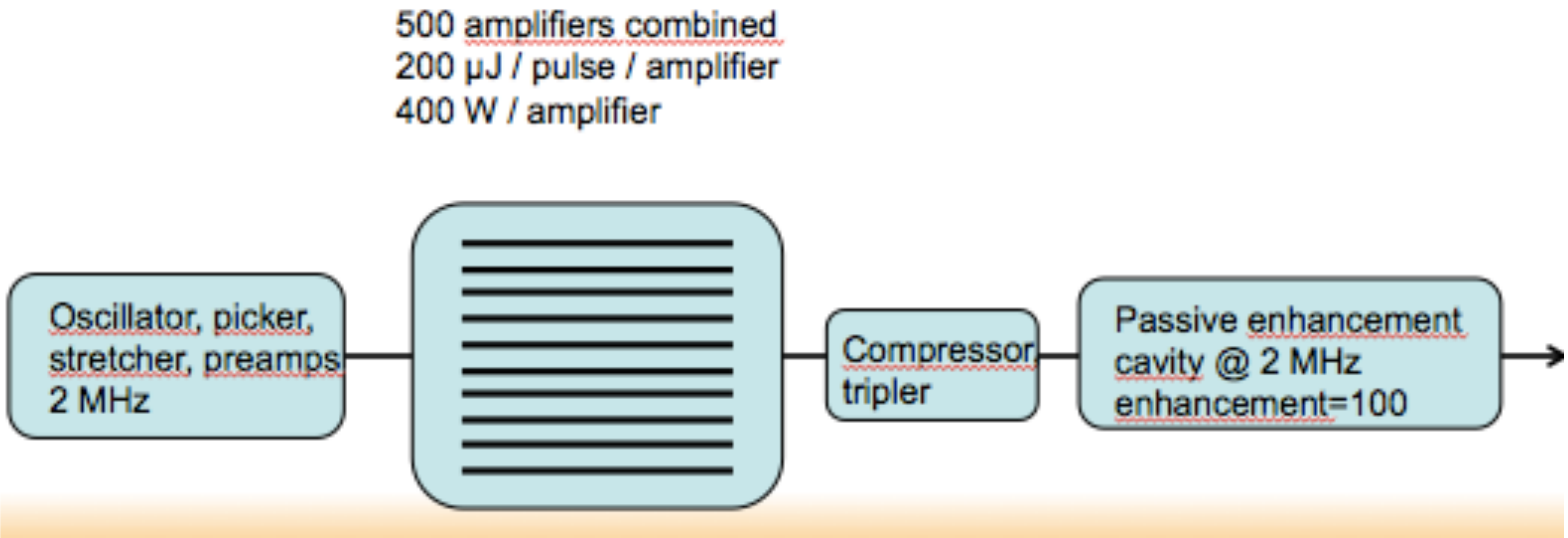


G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »



Reducing the Number of fibers DPA (Division Pulse Amplification) and enhancement Cavity combination

J. Limpert et al



Rational Behind Fiber Choice

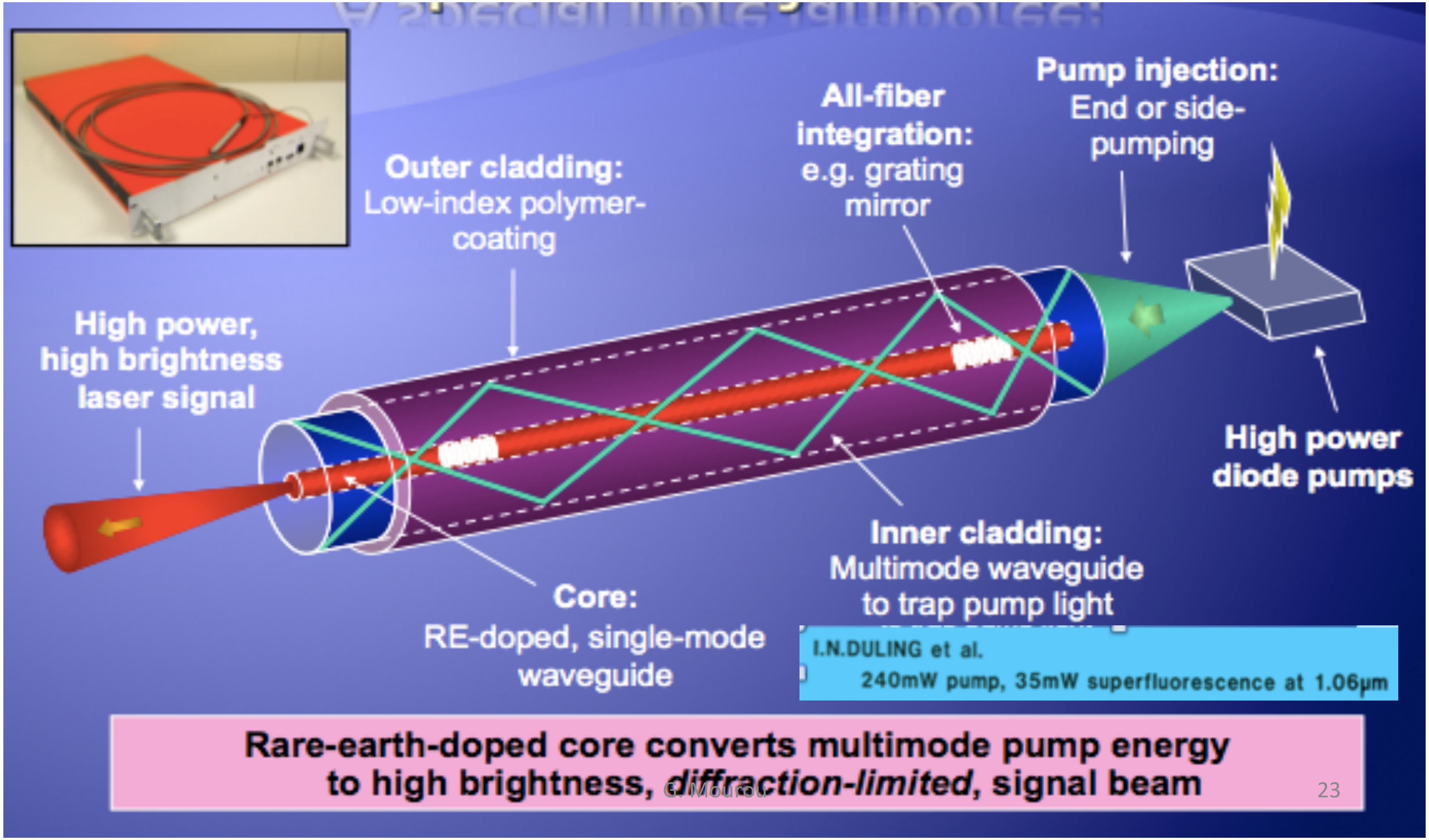
- ***The fiber choice comes from the current thinking in the community that the highest brigthness will come from advances in fiber lasers.***

- ***Modern lasers will try to eliminate bulk components as much as possible to the benefit of fibers.***

- ***We can use all the low cost fibre telecom tricks: special fiber, filters, compression ,Couplers, etc..***

- **Thin disk Complex systems for pump are cycling and regeneratieve amplifiers**
- **SlabThermal effect modify the beam**
- **Complex Management of pump and signal beams**
- But

The basic brick: the Yb doped Single mode fiber



ICAN Basic Bricks
The Yb-doped Fiber (continued)

- *Yb:fiber transforms efficiently (70%) of low quality inexpensive ($10/W) light from a diode laser into a high quality single mode light with outstanding beam quality.*
- *Fiber provides the highest beam quality with the highest laser efficiency.*
- *The fiber can be precisely reproduced and pumped with 0.1% pump power precision/fluctuation*
- *Single fiber can produce up to 2mJ, 200fs pulse with an average power ~ 800W, 40kHz (Jena Group)*
- *A Phased-Fiber-Array emitting 50J, 50fs will be composed of 2 10^4 fibers.*

Is it conceivable?

First Step:
Understanding the Fiber Laser Noise

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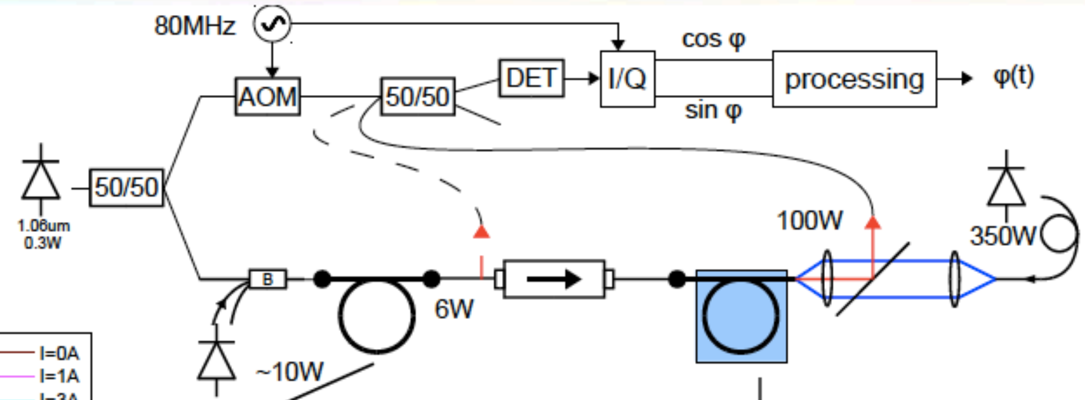
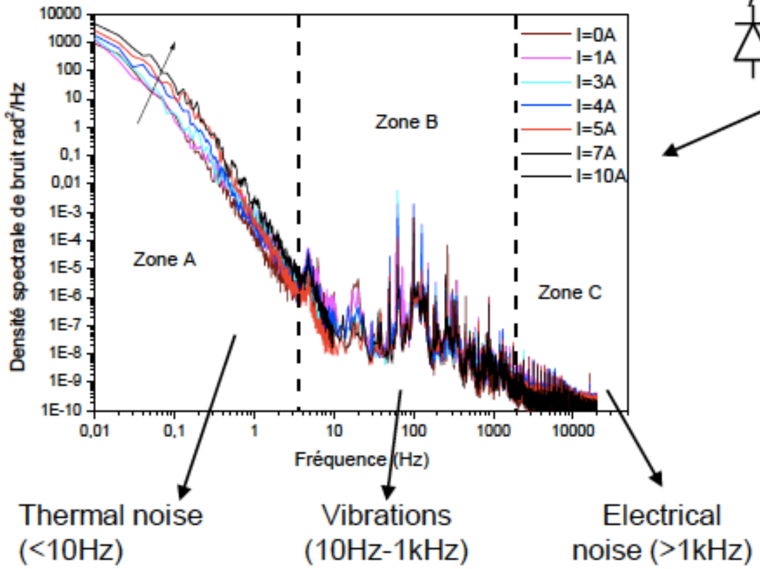
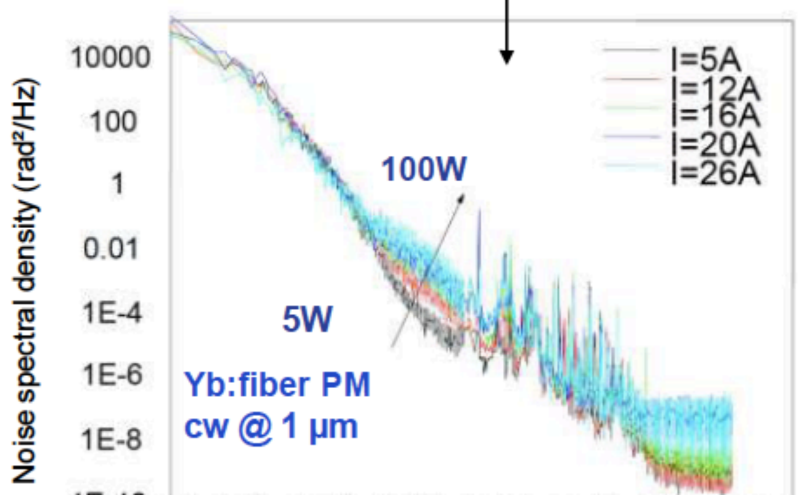
Sources of Phase Noise

What are the main sources of phase noise?



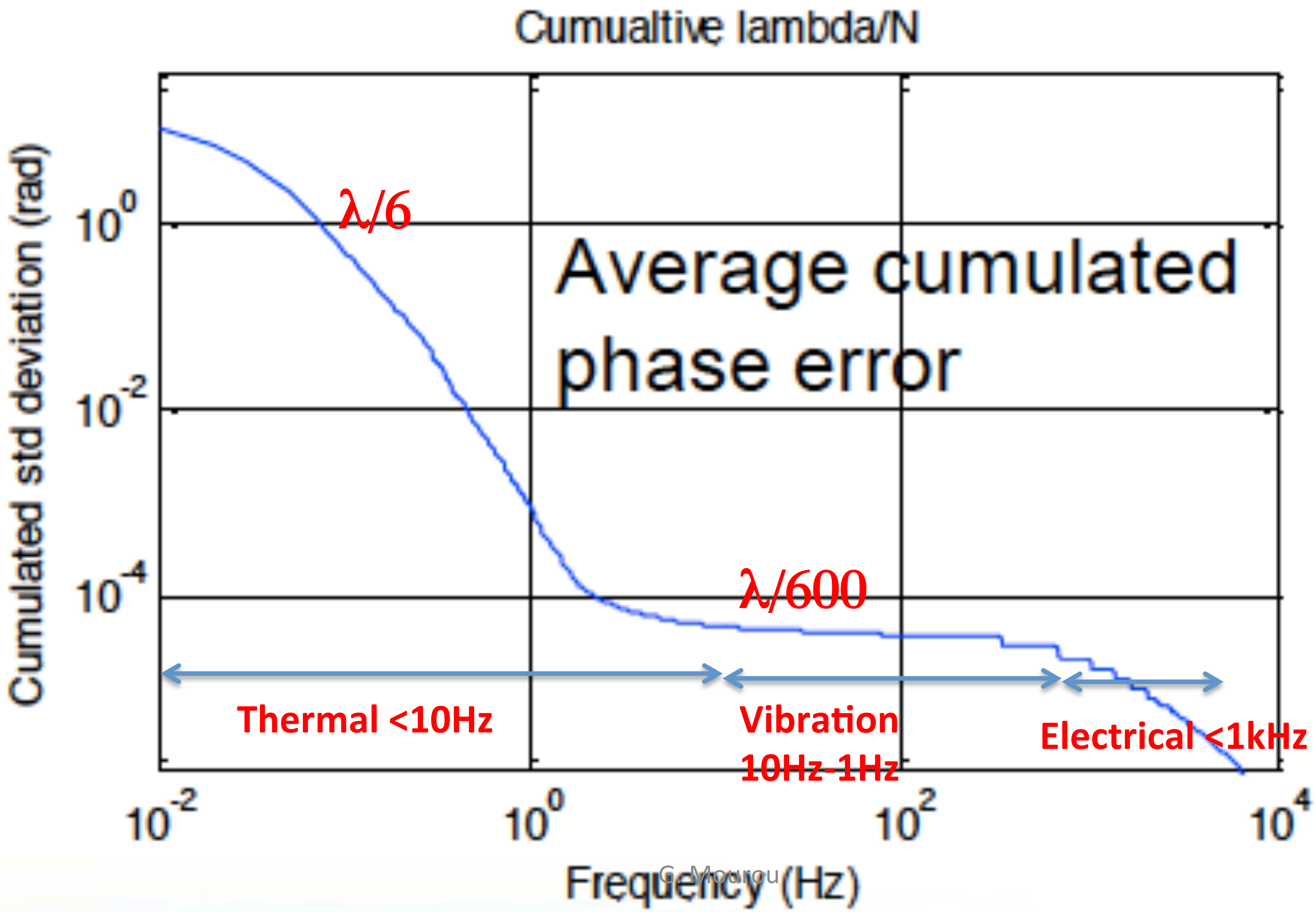




ICAN KOM

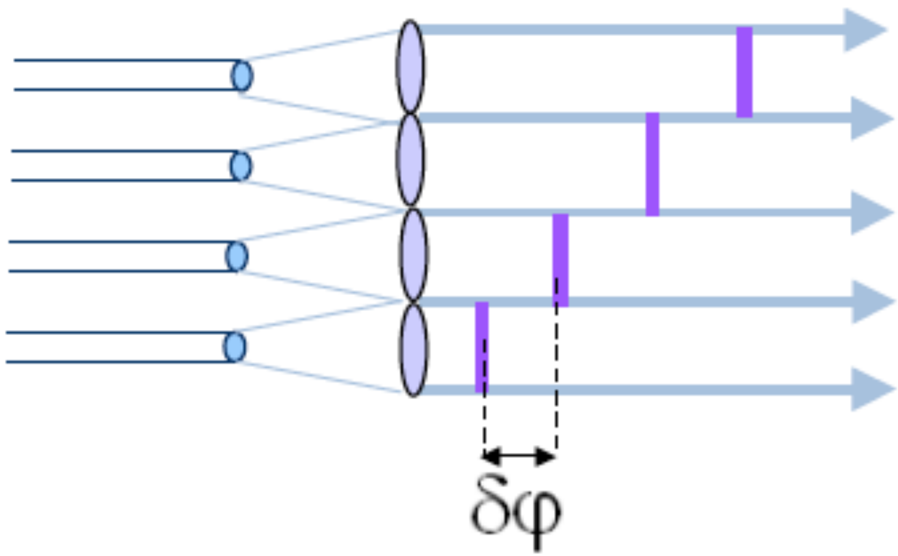
- Impact of high power -> mostly increase of thermal noise

Source of Phase Noise (100W CW) (Extremely low f> 10Hz)



Second Step:
Micron Precision
Fiber Assembly Fabrication

The fiber must be mounted on a precision mechanical mount. Each fiber is at the focus of a lens,forming a microlens array matrix



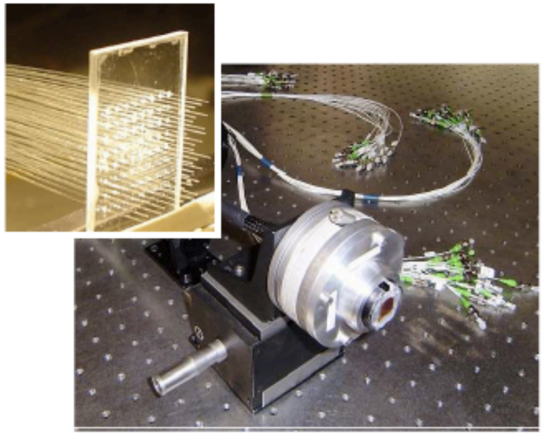
Microlens Arrays

4 /

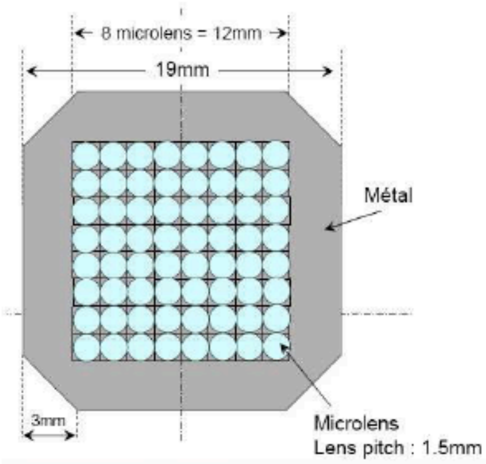
1. Fiber and microlens arrays

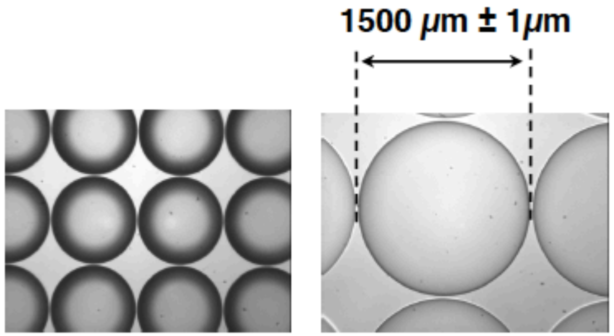
Fiber array:

- Deep X-lithography on PMMA substrate (LIGA team, UMR CNRS/Thales)
  - 1.5mm pitch, 1μm precision on fiber positioning
- Insertion, PM alignment, gluing and polishing of the 64 fibers



Microlens array:





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Third Step:
Fiber-to-Fiber Phase Shift Measurement:

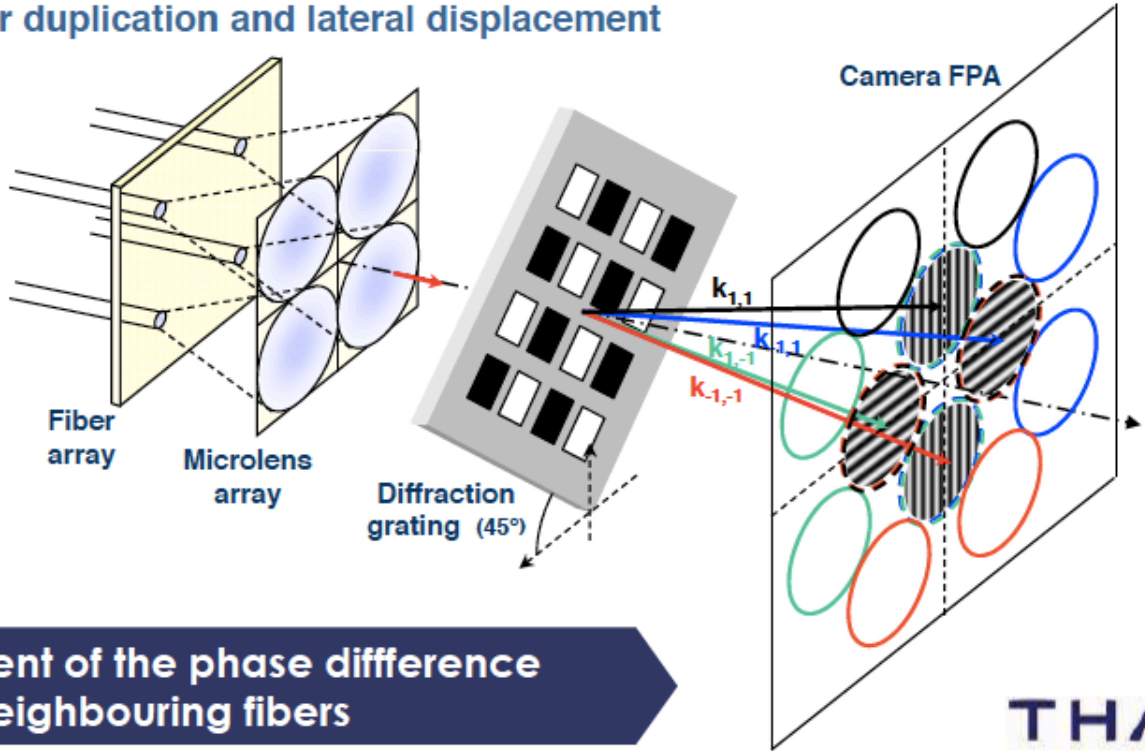
The Quadriwave Lateral Shearing Interferometer

2. Fiber-to-fiber phase shift measurement

QWLSI: Quadriwave Lateral Shearing Interferometer

→ in collaboration with ONERA (J. Primot)

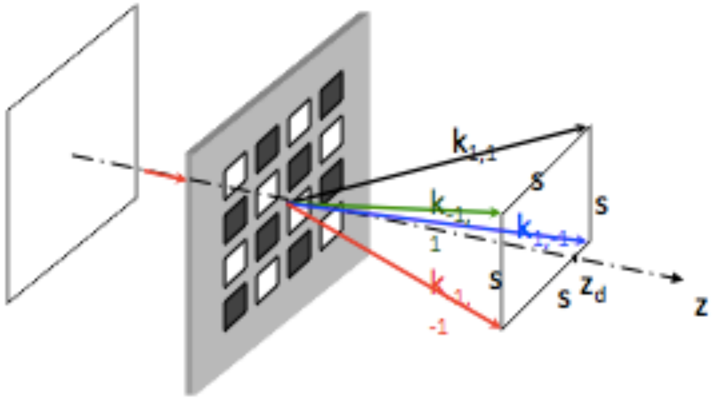
- Self-referenced wavefront analysis technique
- Principle: analysis of the interference pattern of the wavefront with itself after duplication and lateral displacement



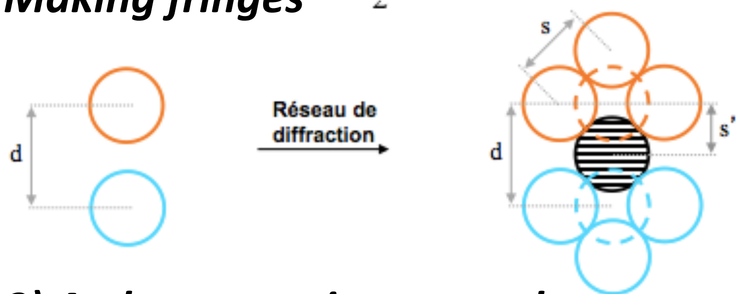
Measurement of the phase difffference between neighbouring fibers

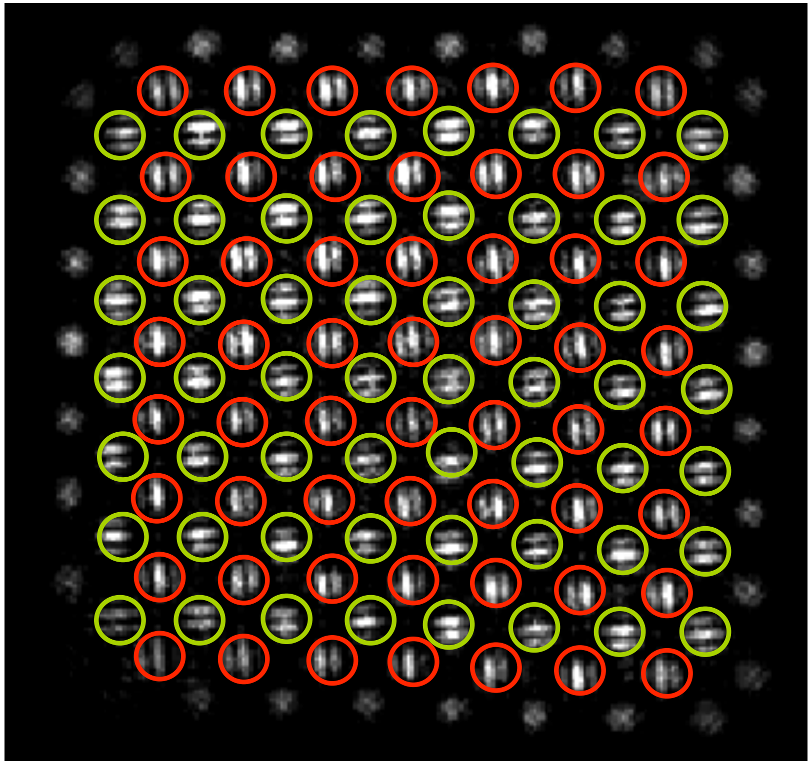
Phase Noise Measurement with a Quadrilateral Shearing Interferometer (10^4 fibers with $\lambda/60$ precision at kHz)

1) Grating Making 4 replicas of each fiber



2) Neighbor fibers interfer with replicas Making fringes





3) A phase map is captured every ms, making possible phase correction with phase modulator

Only 6 pixels are necessary to reach $\lambda/60$ precision.

Phase Noise Measurement with a Quadrilateral Shearing Interferometer (10^4 fibers with $\lambda/60$ precision at kHz)

- ***For 10^4 fibers , 6 pixels per fiber for a resolution of $\lambda/60$ @ 1kHz, off-the-shelf camera with 10^6 /1kHz are available.***

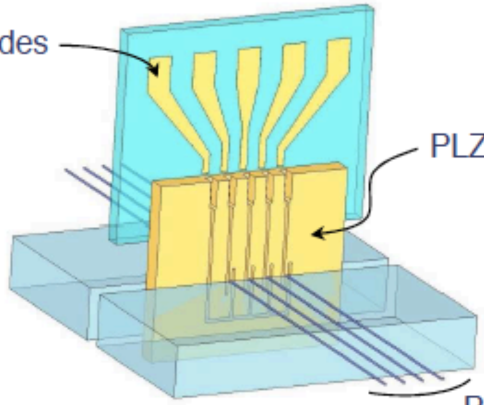
- ***Algorithm to control the phase distribution of fibers 40Gops Possible with a GPU.***

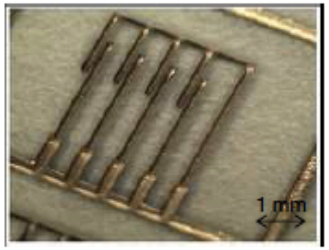
Fourth step: Phase Correction by Optical Modulator

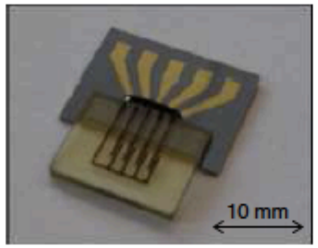
3. 16 × 4-channels phase modulators

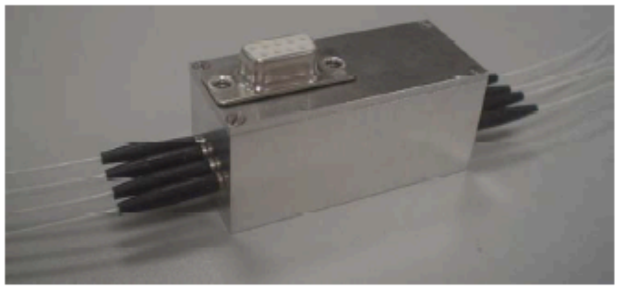
PLZT opto-ceramic fibered phase modulators

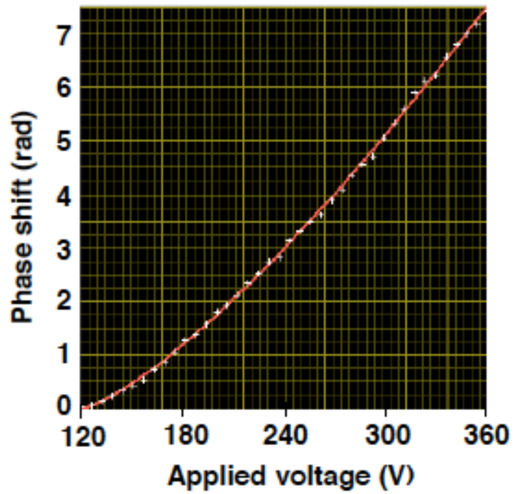
- Phase shift > 2π @1.55μm
- Response time ~μs range











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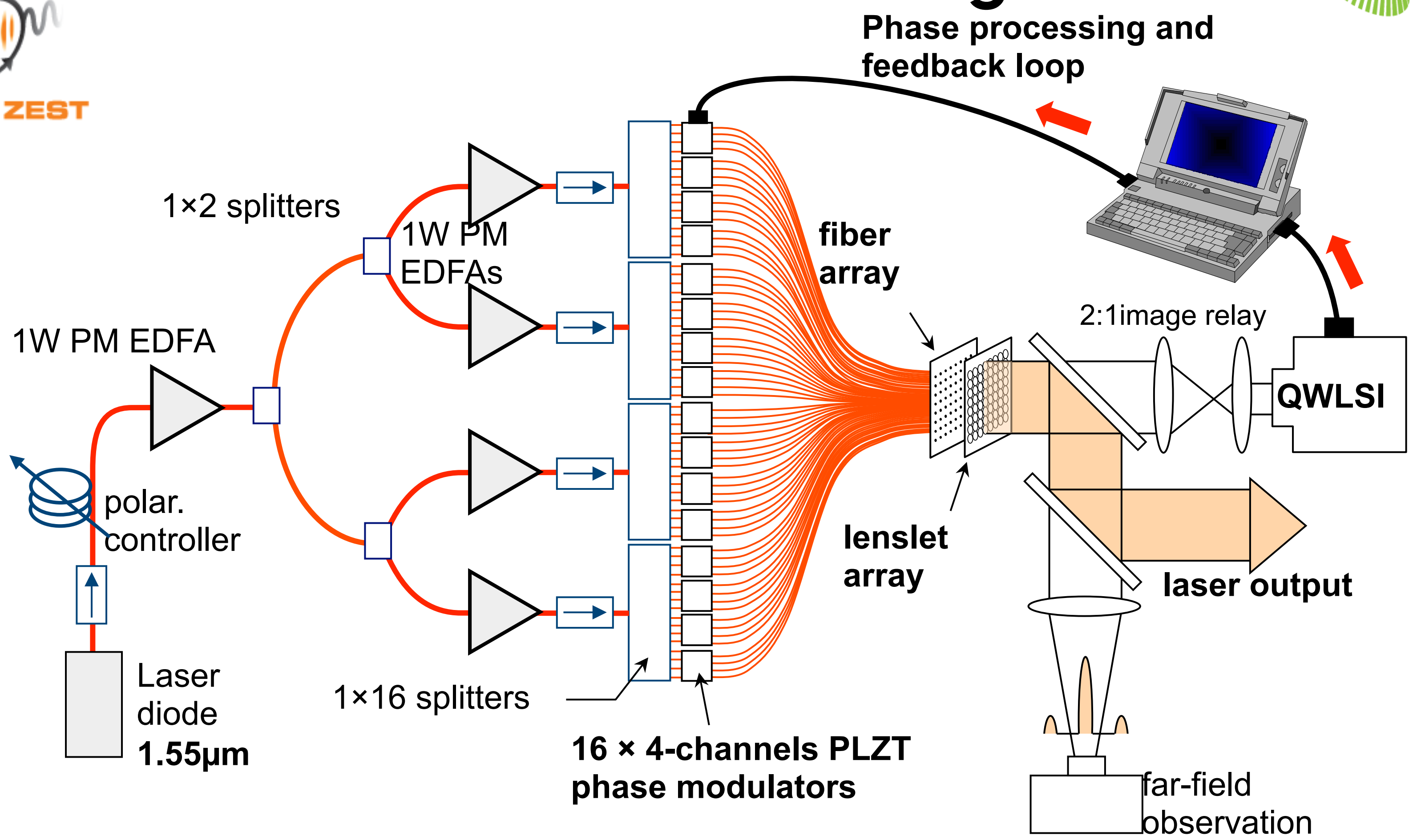
J. Bourderionnet, A. Brignon (Thales), C. Bellanger, J. Primot (ONERA)

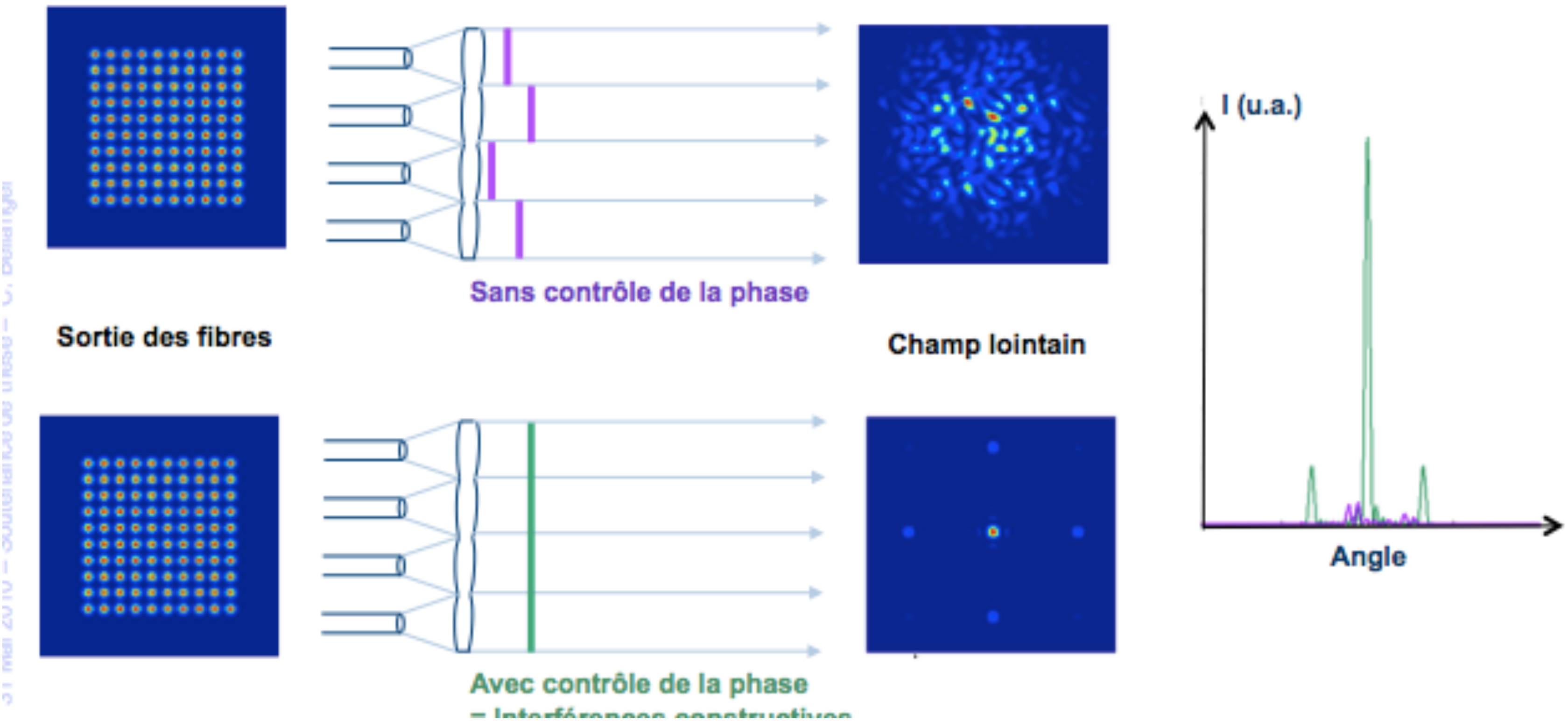
Coherent Fiber Combining



Achievement 2011
→ 64 phase-locked fibers

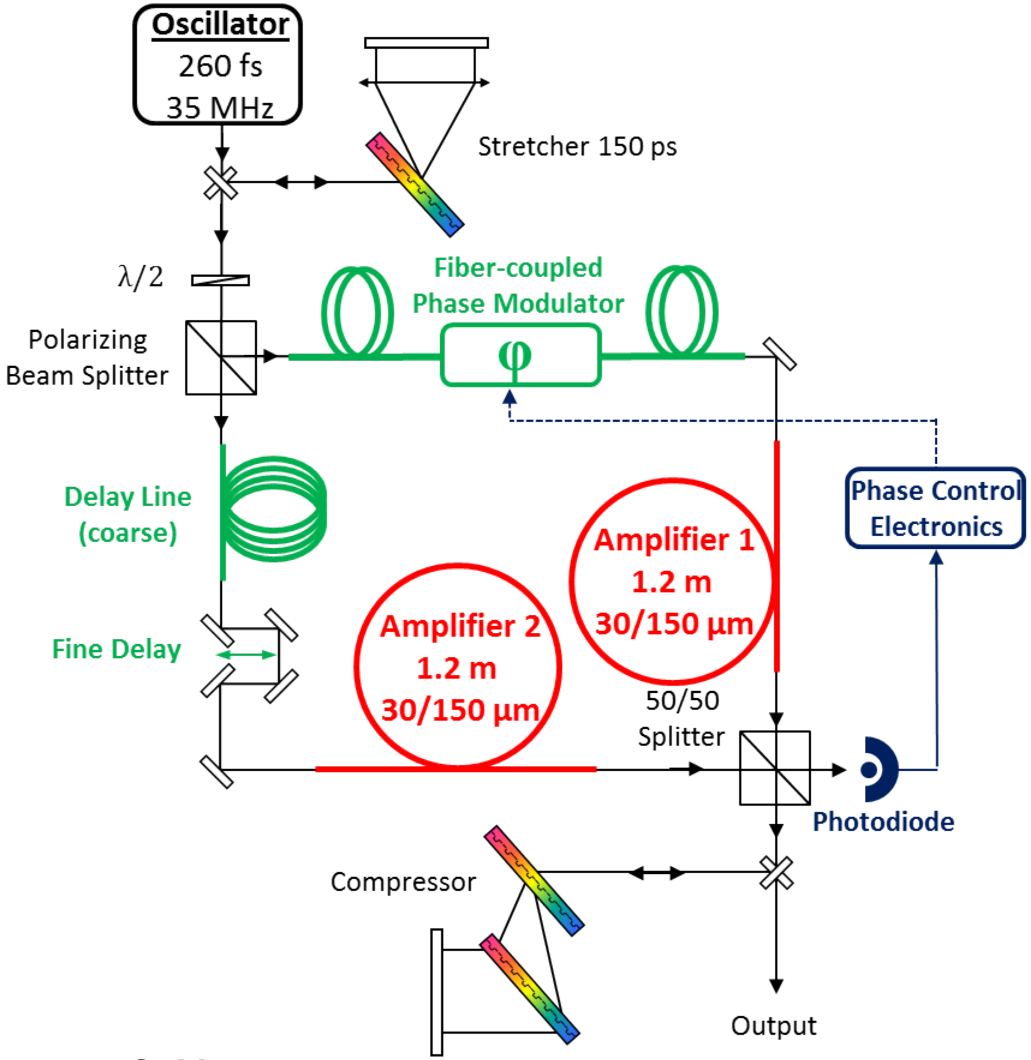
64 CW fibers have been phased

(This experiment in fact validates an extension possible to >10^4 phased fibers at 1kHz)



Fifth Step: Measuring and keeping at Bay the Nonlinear effects

CAN results / phase locking technique In the femtosecond



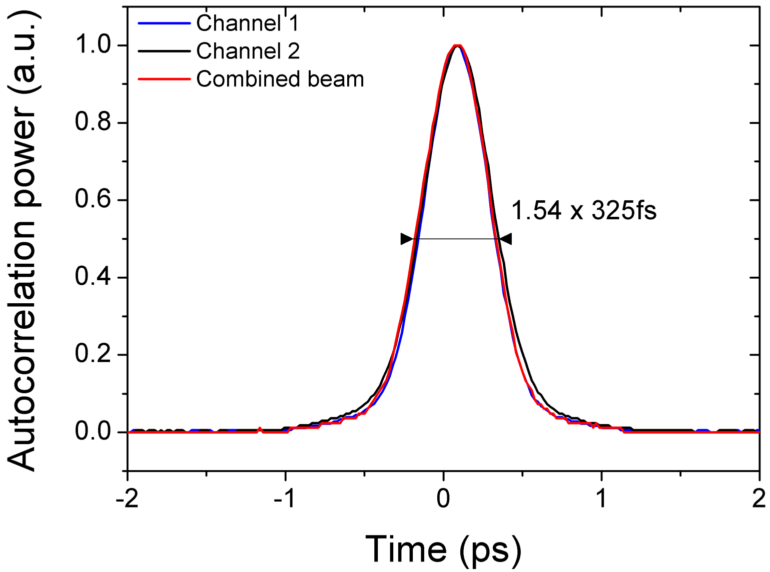
Combining efficiency > 90%

L. Daniault, M. Hanna, L. Lombard, D. Goular, P. Bourdon, F. Druon, P. Georges
"Coherent combining of two femtosecond fiber chirped pulse amplifiers"
Oral : Advanced Solid State Photonics, ASSP 2011, Istanbul, Turkey (February 13-16 2011)

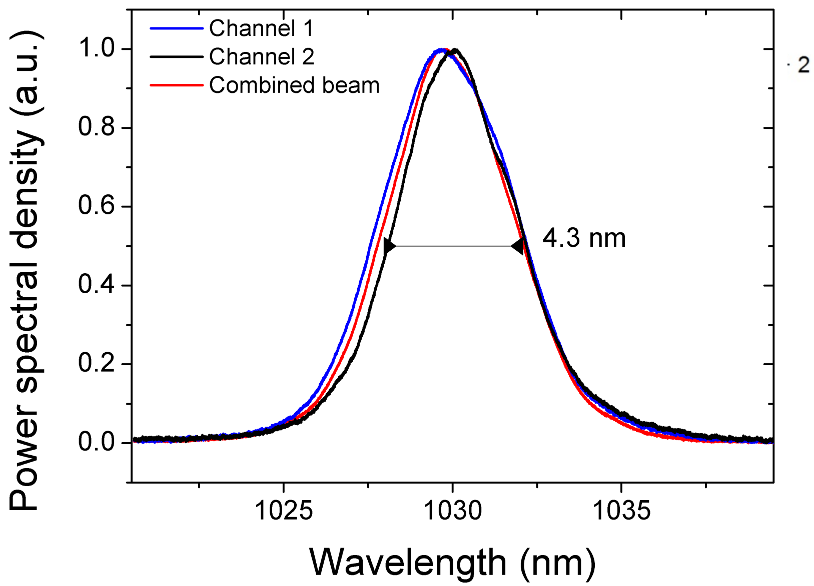
Accepted: Optics Letters, L. Daniault et al,
« Coherent beam combining of two femtosecond fiber chirped pulse amplifiers »

G. Mourou

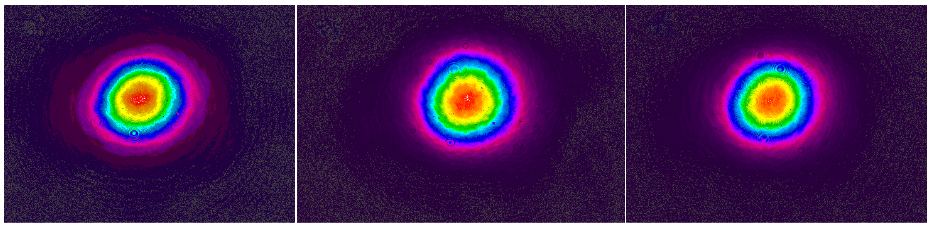
CAN recent results / phase locking technique *(2)*



Autocorrelations
325 fs pulsewidth



Spectra
4.3 nm FWHM



G. Mourou

6th Step: The cost

Cost of a PW@10kHz

- ***Cost based on 7€/watt for a 50J/pulse at 10kHz***
- ***Average power 500kW***
- ***Wall plug efficiency: 30%***
- ***Factor 50% for the grating efficiency***
- ***A factor of 3 is taken to go from diode cost to the full system cost***
- ***System cost ~ 70M€***

Autres Avantages
Total Phase control:
Towards the Digital laser

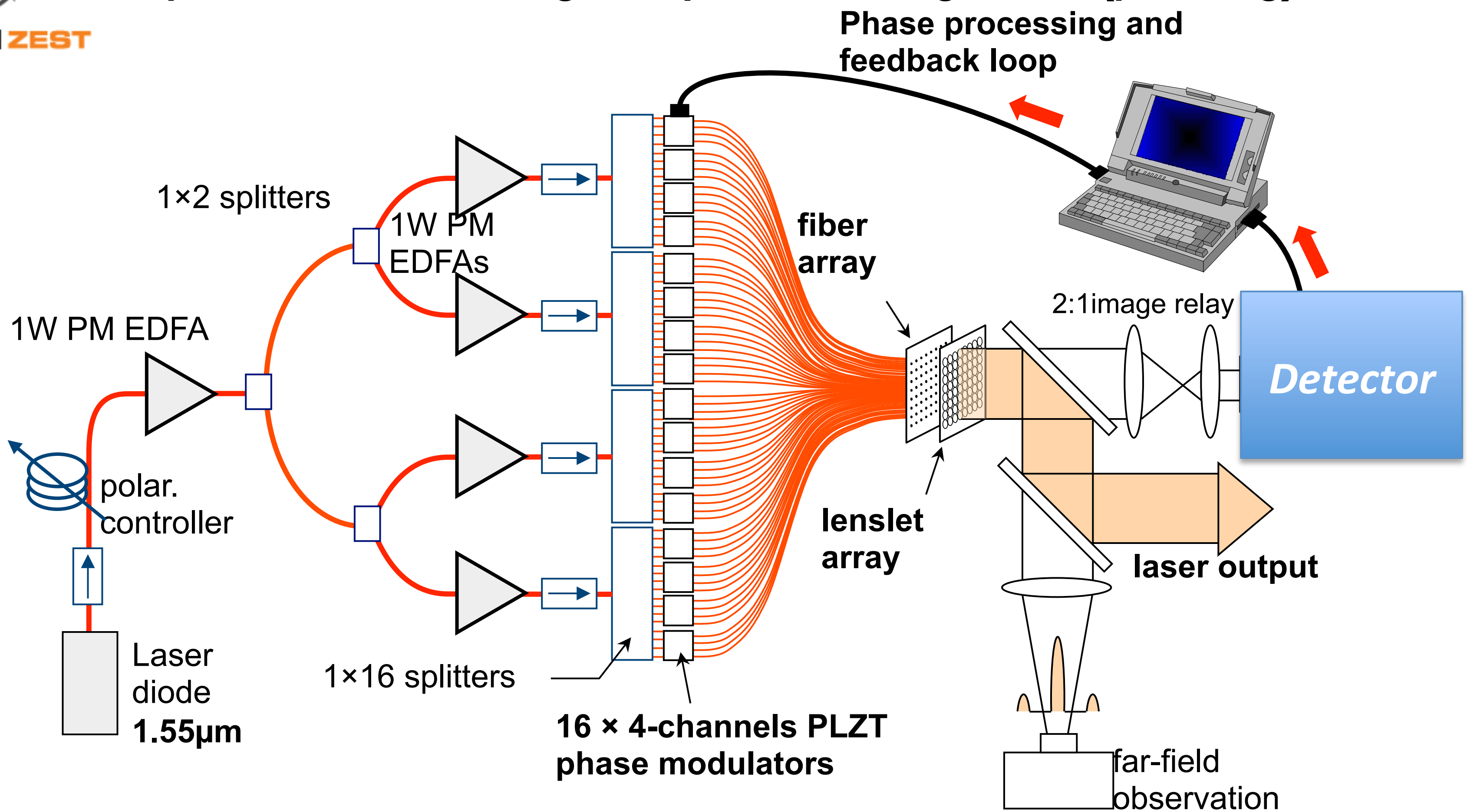
Towards the Smart Laser

Total Phase and Amplitude Control of each Fiber over the Beam Cross Section

- ***Total phase et amplitude control of each fiber avec:***
- ***Une grande precision sur la phase <1% et amplitude <1%***
- ***Une grande definition spatiale 10^6 fibers.***
- ***Une Extreme agility 1kHz***

Smart Laser

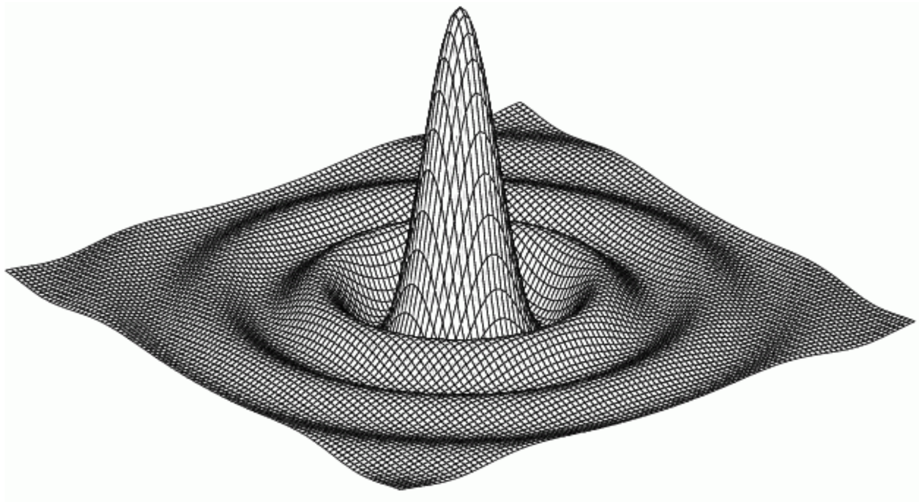
Optimization of the signal by Genetic Algorithm (pending)Patent



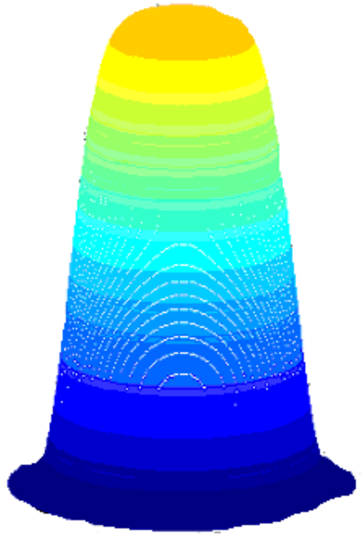
For 10^4 fibers The laser can fire at 10kHz, the wave from can be changed in phase and Amplitude at a kHz.

The ICAN-concept: a versatile digital laser

Choose a far-field of your liking ➔ **Fourier transform** provides E and ϕ distribution for fibres



Bessel $J_1(r)/r$



top-hat

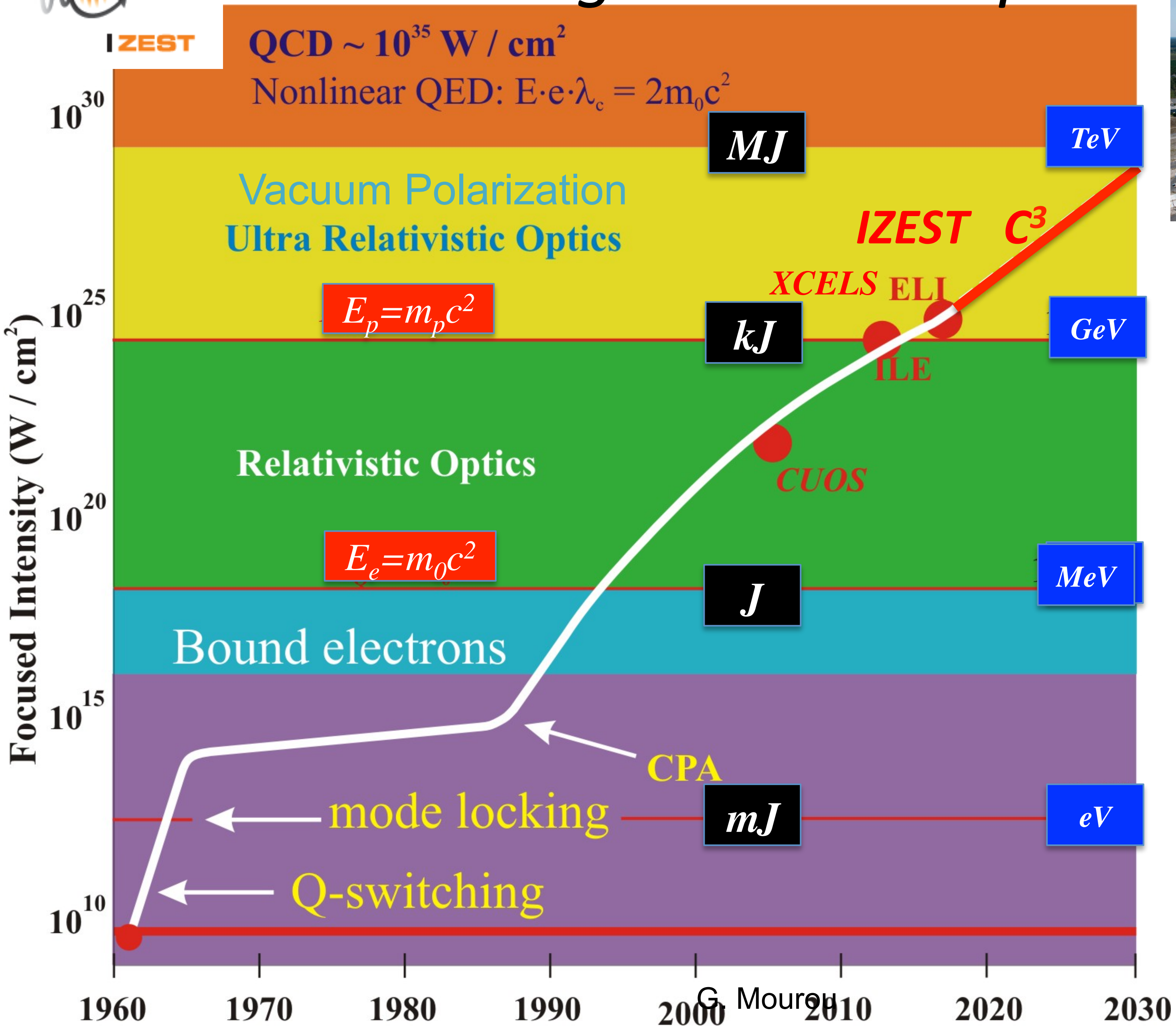
High Resolution Phase and Amplitude control across the out put pupil at 1KHz

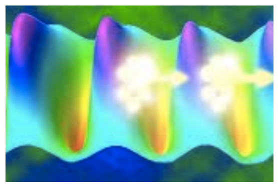
➔top-hat model is example of complete control of the laser electromagnetic field

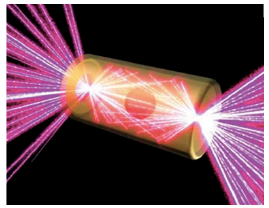
➔Megawatt ICF-application: randomize phase in order to minimize coherent excitation of parametric instabilities (SBS, SRS)

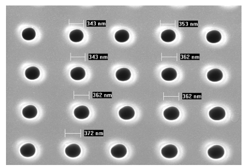
The 7th Step: the Applications

Extreme Light Road Map









Scientific and Societal Applications of Relativistic, electron Protons(>GeV) Megawatt Power level (B€)

- *Proton Colliders (Tevatron, LHC)*
- *Neutron sources (SNS, ESS)*
- *Neutrino Sources(SNS, ESS)*
- *Radioactive Ion Beam (FRIB, Eurisol)*
- *Accelerator Driven Systems(Ch-ADS,MYRRHA)*
- *Electron linear collider*
- *Muon collider*
- *Free Electron laser at 10kHz*
- *Higgs factory*

Societal Application

Nuclear Waste Transmutation

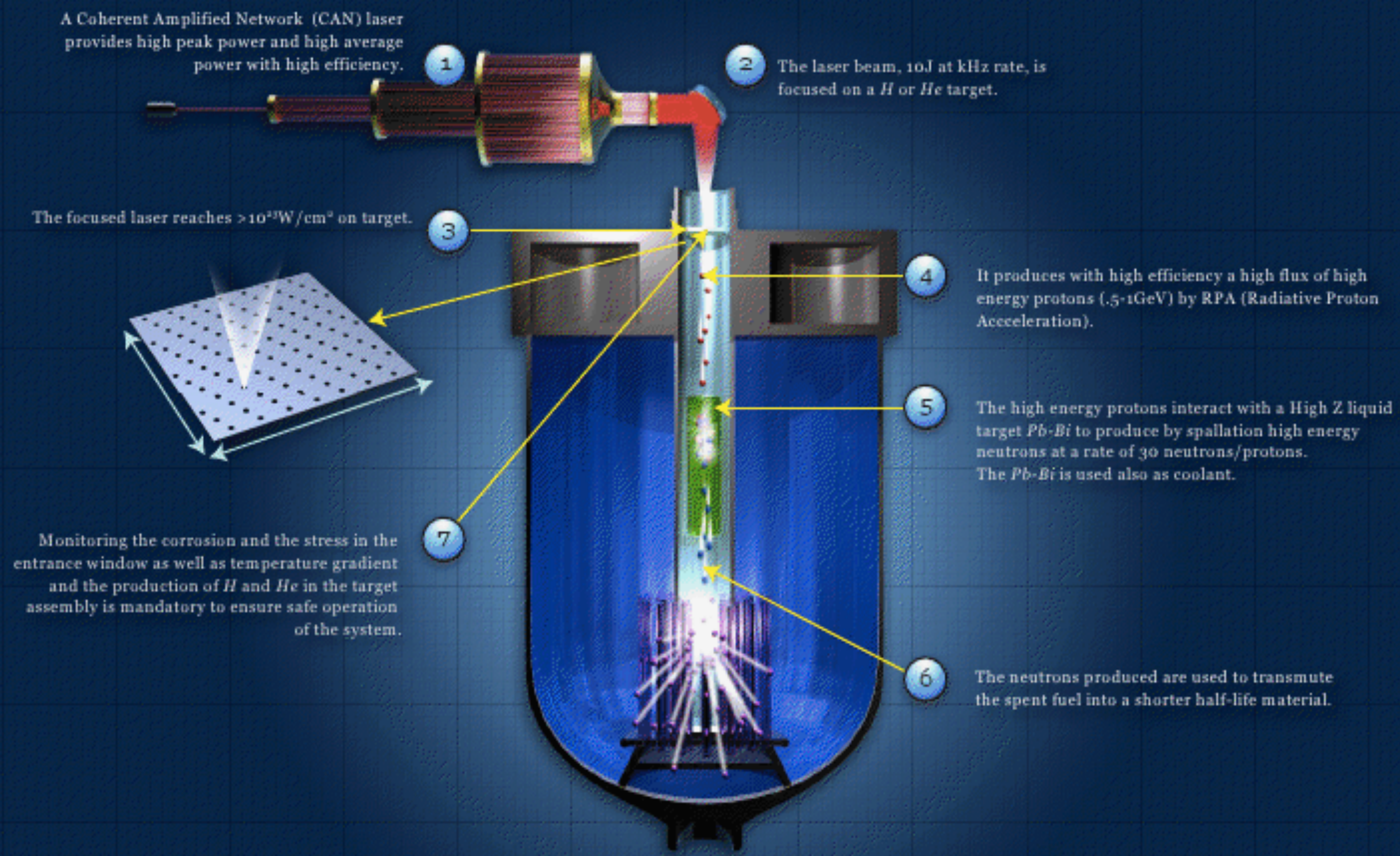
ADS(Accelerator Driven System)

Transmutation

Le processus de transmutation

Le processus de transmutation est connu dans son principe depuis longtemps en physique nucléaire : un isotope radioactif à vie longue A subit une réaction nucléaire qui le transformera en un isotope B stable ou à vie courte qui peut alors être stocké en surface durant un temps raisonnable. Un exemple connu concerne le produit de fission ^{99}Tc (Technetium) d'une demi-vie (temps à partir duquel il en reste la moitié) de 200 000 ans qui après capture d'un neutron devient le ^{100}Tc qui décroît en 16 secondes vers le noyau stable ^{100}Ru (Ruthenium).

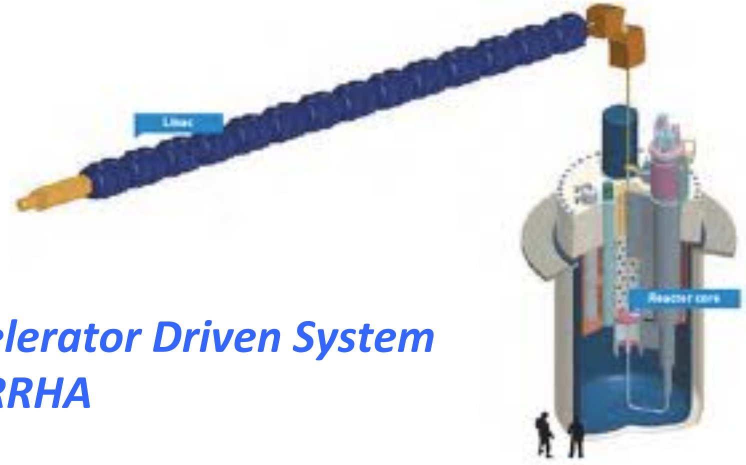
THE LASER DRIVEN TRANSMUTATOR CONCEPT



The superconducting RF proton linac at the SNS at Oak Ridge National Laboratory is providing valuable experience for a future ADS accelerator.
Image credit: ORNL.

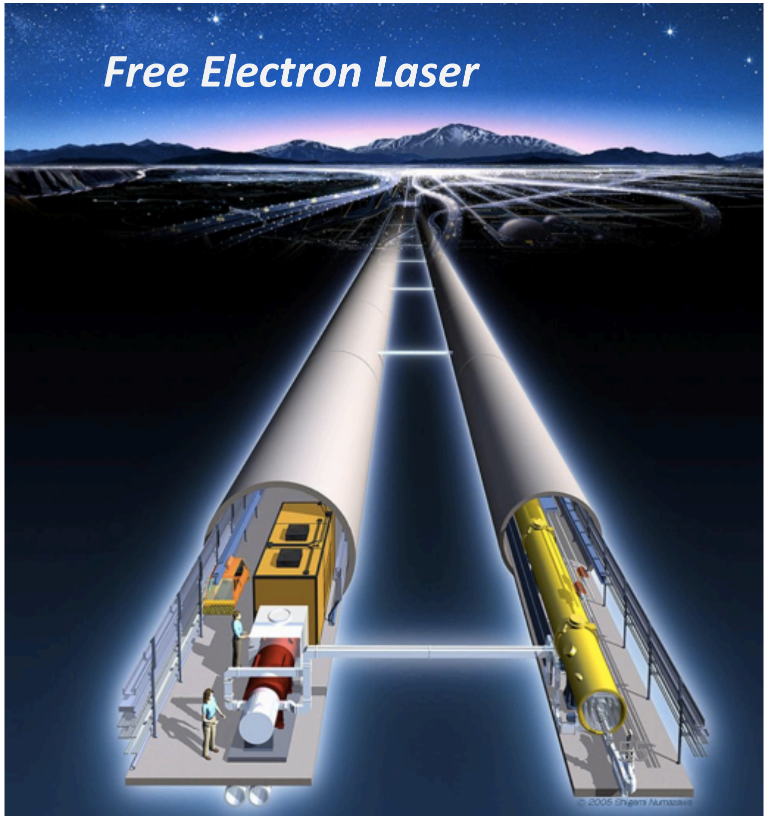
ICAN APPLICATIONS

Radioactive Ion Beam



Accelerator Driven System
MYRRHA

European Spallation Source



Free Electron Laser

G. Mourou

Conclusion

Moving from Analog to Digital Laser

- ***The key elements of CAN has been validated and have shown no Show stopper to produce simultaneously:***
  - ***Peak Power in the >PW***
  - ***Average Power in the >MW***
  - ***Wall plug efficiency >30%***

- ***The CAN Concept exhibits new and precious features:***
  - ***Each fiber can be individually control with 1pixel presicion***
  - ***High resolution Wavefront control in amplitude 1% at 1kHz***
  - ***High Resolution Wavefront contrôle in phase with l/60 at 1kHz***

- ***To move Further we will endeavor to form a world wide consortium, ICAN-C (read: I can see), Horizon 2020***

Next Action Item
An International Infrastructure
ICAN-B

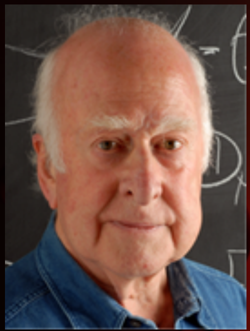
- ***Firts Create ICAN Consortium ICAN-B (Academe, industry)***
- ***An infrastructure highly relevant to science, societal Applications with the specifications >50J, >10kHz, >30% efficient (>10kW capable to produce 10GeV electrons and GeV(relativistic protons).***

Such an infrastruture could validate a:

1. ***TeV laser collider concept***
2. ***Free Electron Laser in the High X-ray regime comparable to LCLS-SLAC but at >1kHz.***
3. ***ADS Accelerator Driven System Transmutation***
4. ***Proton therapy***
5. ***X- ray, Gamma ray***

IZEST
International Zeta-Exawatt Science Technology

Can the Futur of Accelerator Be Fibers?



"The discovery of this particle is potentially the beginning of another road, which is to explore lies beyond the Standard Model"

- Peter Higgs

ICAN Symposium
June 27-28, 2013
CERN, Geneva

"I realized there would be many applications for the laser, but it never occurred to me that we'd get such power from it!"

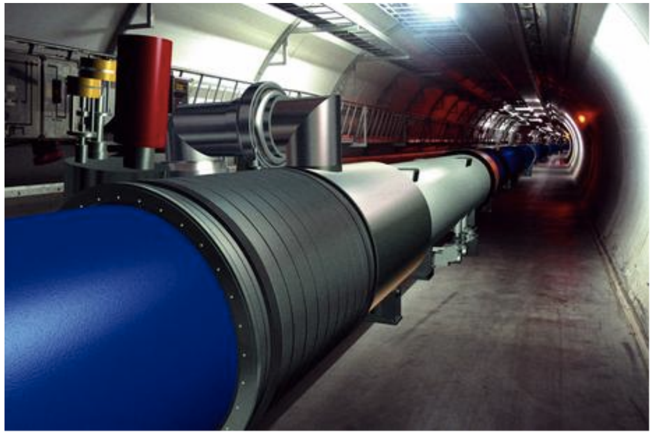
- Charles H. Townes

Gerard Mourou S.L Chin, Laval

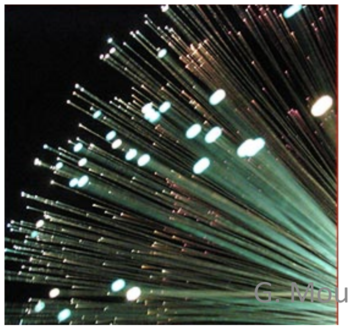
https://www.izest.polytechnique.edu/izest-home/ican/news-events-documentation/ican-conference-can-the-futur-of-accelerators-be-fiber-cern-geneva-switzerland-288403.kjsp?RH=D1_IZEST-EN

Laser Acceleration-Telecom virtuous Cycle

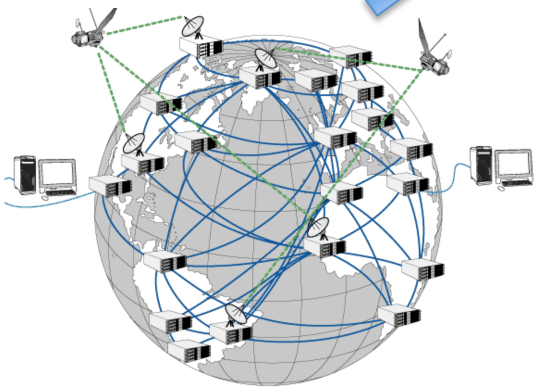
Coherent Amplifying Network+ Laser Wake Field



WWW
Tim Berners-Lee



Optical Fiber
Charles Kao



Acknowledgements

- **<u>CERN</u>**
- J.P. Koutchouck

- **<u>ORC, Southampton</u>**
- D. Payne
- W. Brocklesby
- D. Nilson

- **<u>Fraunhofer Institute, Jena</u>**
- A. Tunnermann
- J. Limpert
- T. Schrieber

- **<u>Ecole Polytechnique</u>**
  - **Thales**
    - A. Brignon
    - J. Borderionnet
  - **ONERA**
    - C. Bellanger
    - J. Primot
    - L. Lombard
    - V. Michau
  - **<u>Institut d',Optique</u>**
    - M. Hanna
    - L. Daniault
  - **<u>U. Michigan</u>**
    - A. Galvanauskas