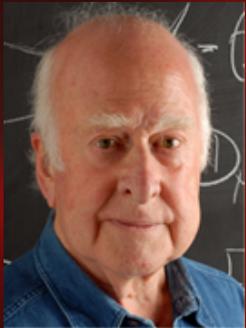




IZEST
International Zeta-Exawatt
Science Technology



"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 Townes

Extreme Light Beyond the Horizon: *X-ray Wake Field Acceleration Route* to *TeV/cm*

Gérard Mourou,

INFN Frascati 13/2/2017

IZEST Ecole Polytechnique



International
Year of Light
2015

Laser Exploration : From Atomic to Sub-Atomic

eV



TeV

ATOMIC

SUB-ATOMIC

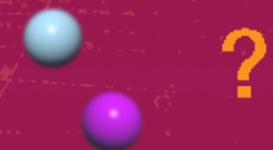
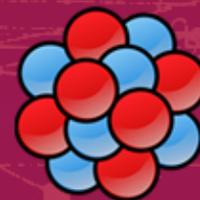
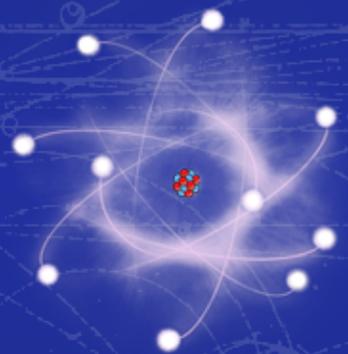
molecules

atoms

nucleii

protons

electrons/quarks



10^{-10} m

10^{-14} m

10^{-15} m

$\leq 10^{-18}$ m

1PW, is 1000 times the world grid power
(10^{-15} secondes)



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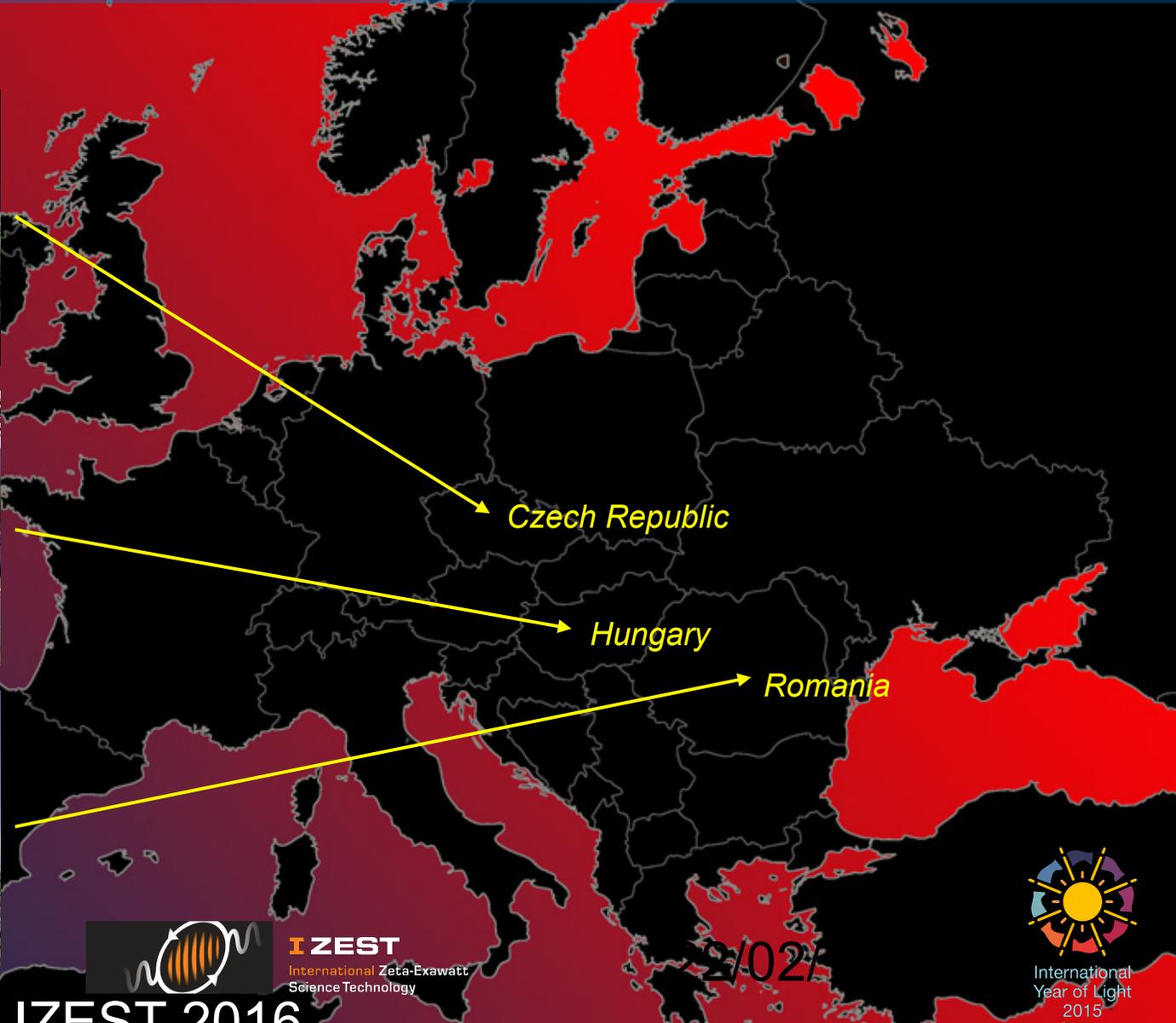


IZEST 2016

22/02/17

Extreme Light Infrastructure - ELI

The Largest Civilian Laser Infrastructure
Initiated and Coordinated (PP) by, G. Mourou (EP)
ELI (Delivery Consortium) W. Sandners



Czech Republic

Hungary

Romania



IZEST
International Zeta-Exawatt
Science Technology

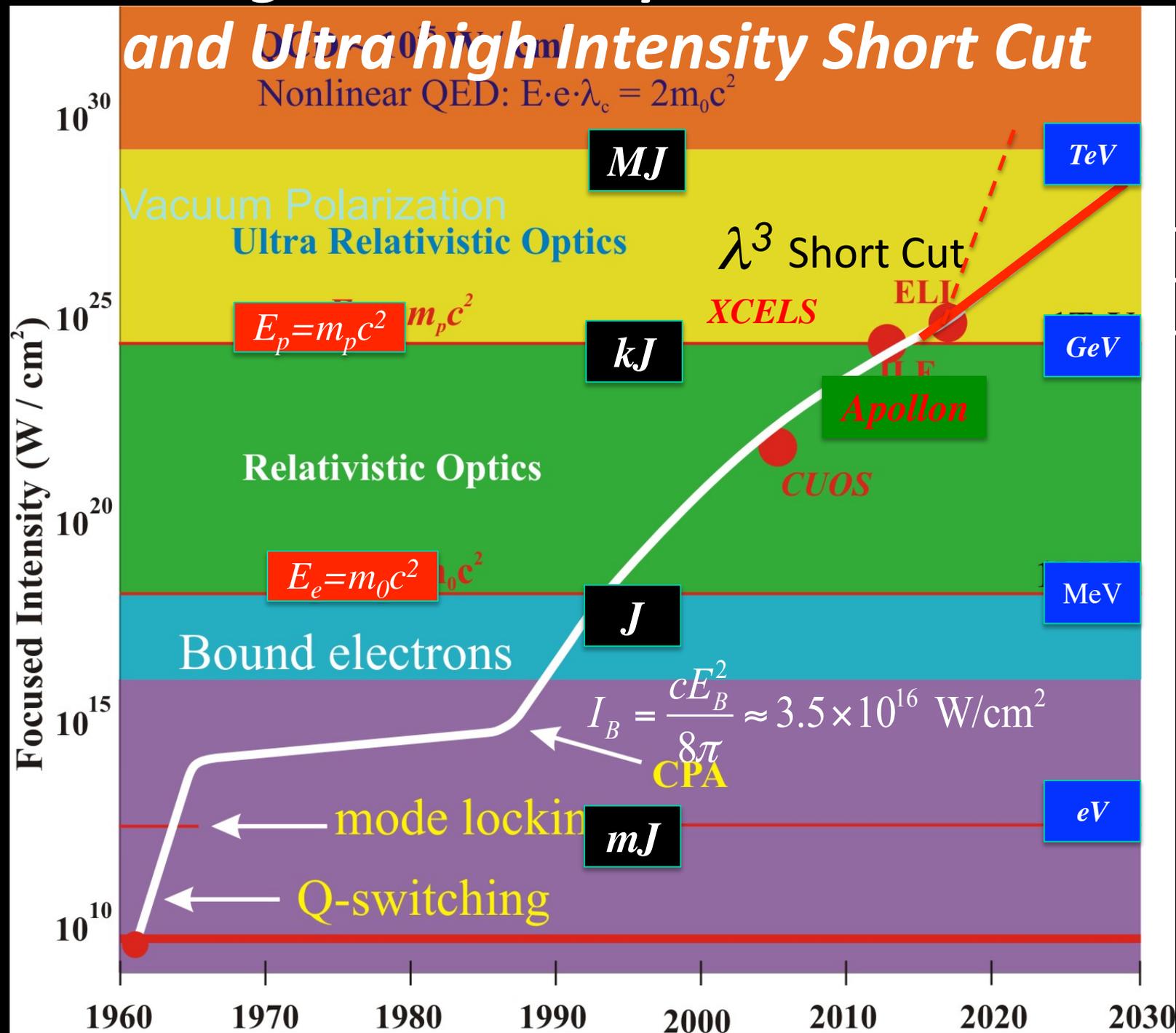
IZEST 2016

2021



International
Year of Light
2015

Extreme Light Road Map



1 EW
1 Joule in
1 attosec

Pulse compression to the single cycle

Atto-Zeptosecond Exawatt Pulse

1. High Energy Single Cycle Pulse Compression in the Visible
2. High Energy Atto-Zeptosecond Pulse Compression X-ray, γ -ray Regime
4. Giant Wake Field Acceleration TeV/cm
5. Relativistic Proton generation
6. Table Top Cosmology
7. Solving the High Average Power Quandary

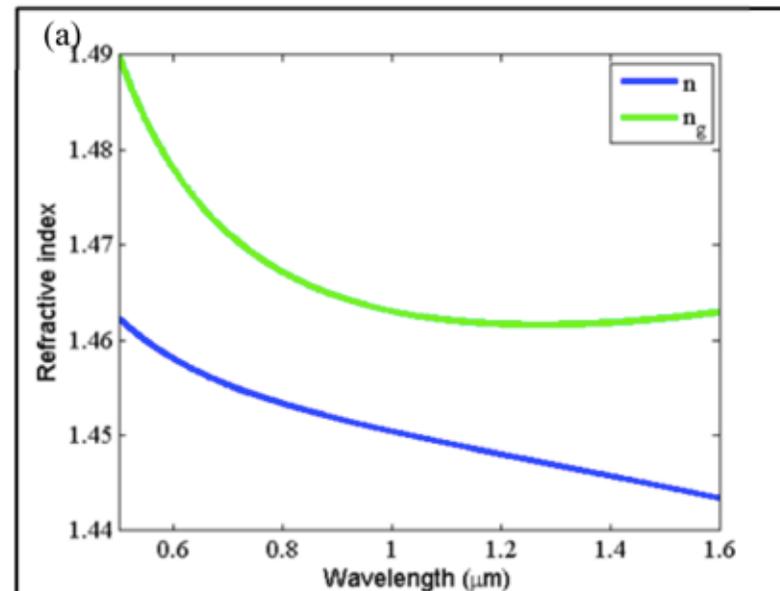
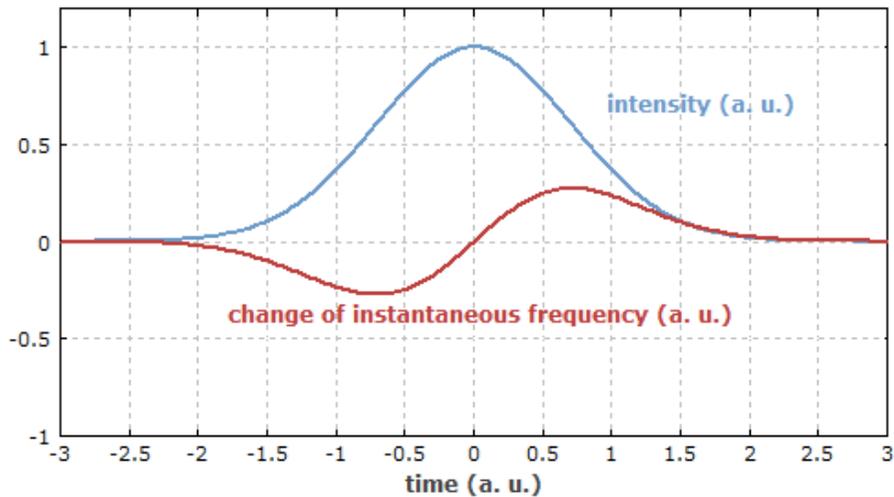
Pulse Compression in the Visible

The laser pulse duration is limited by the gain bandwidth.

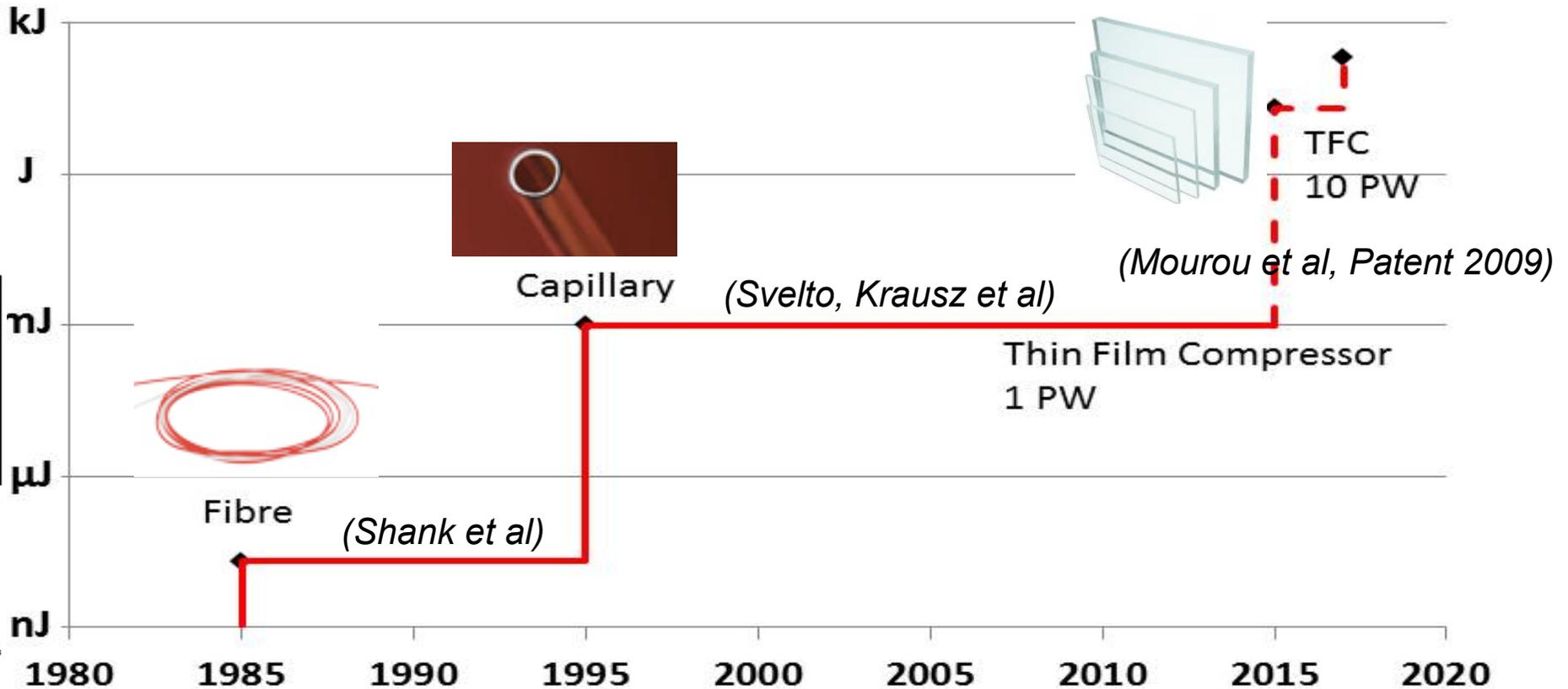
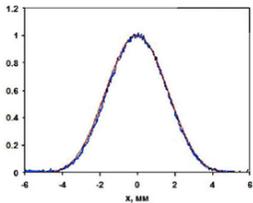
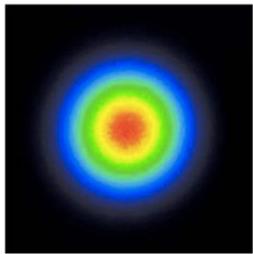
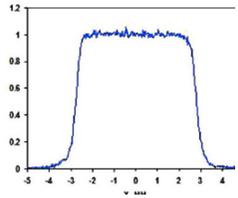
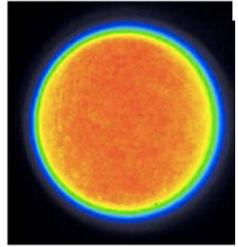
To go shorter, we need to produce a pulse:

1. with larger spectrum by self-phase modulation
2. and stretching it GVD before compression.

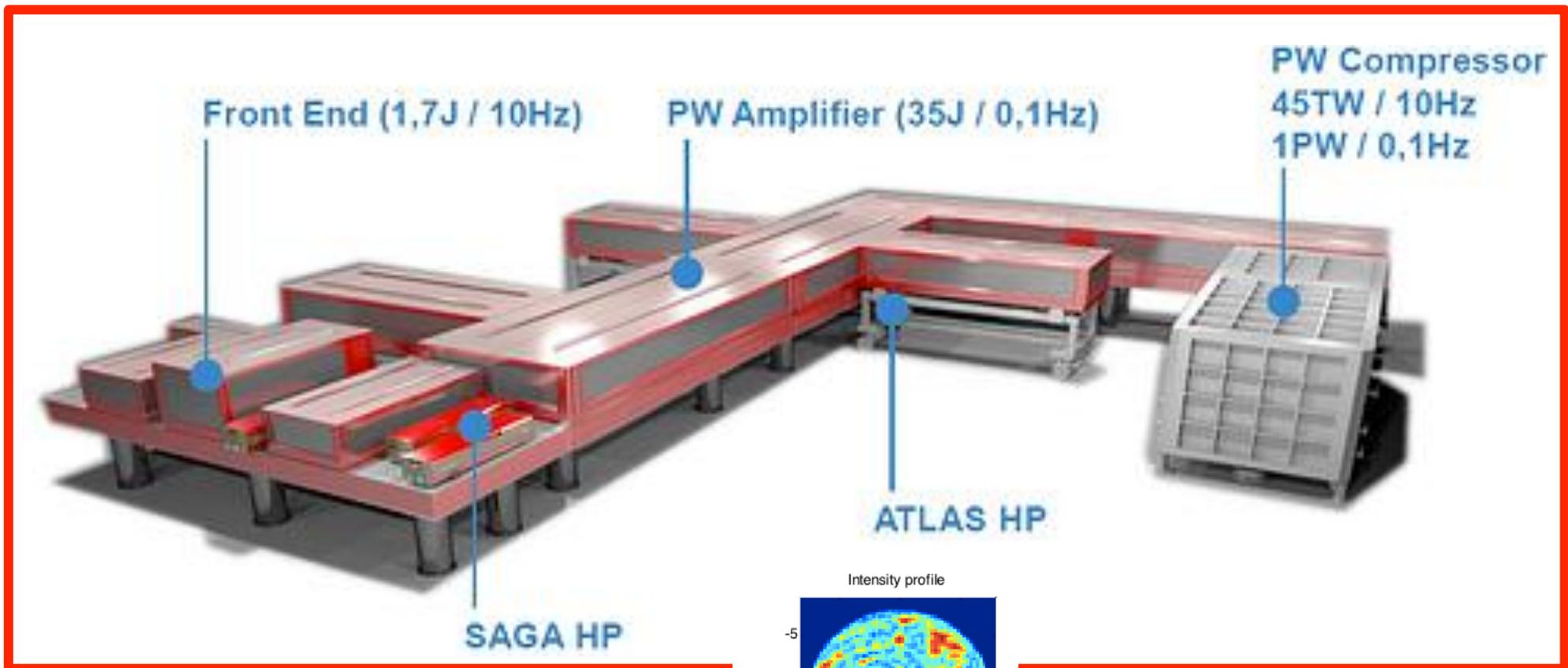
$$1) n(x, t) = n_0 + n_2 I(x, t)$$
$$2) \frac{\partial n(x, t)}{\partial t} = n_2 \frac{\partial I(x, t)}{\partial t}$$



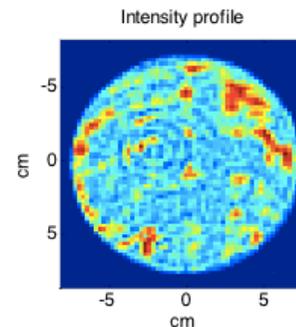
Pulse Compression and Single Cycle History



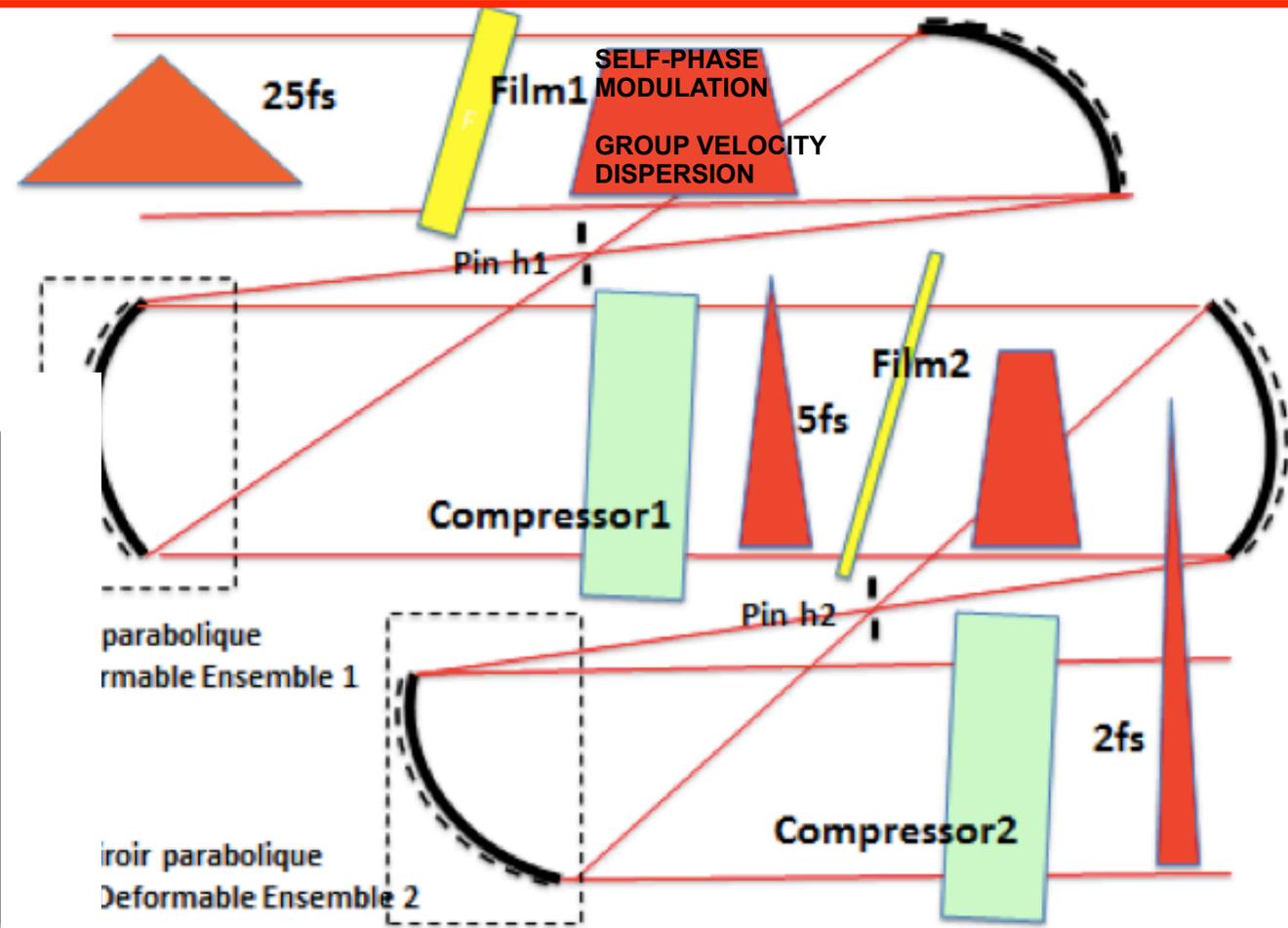
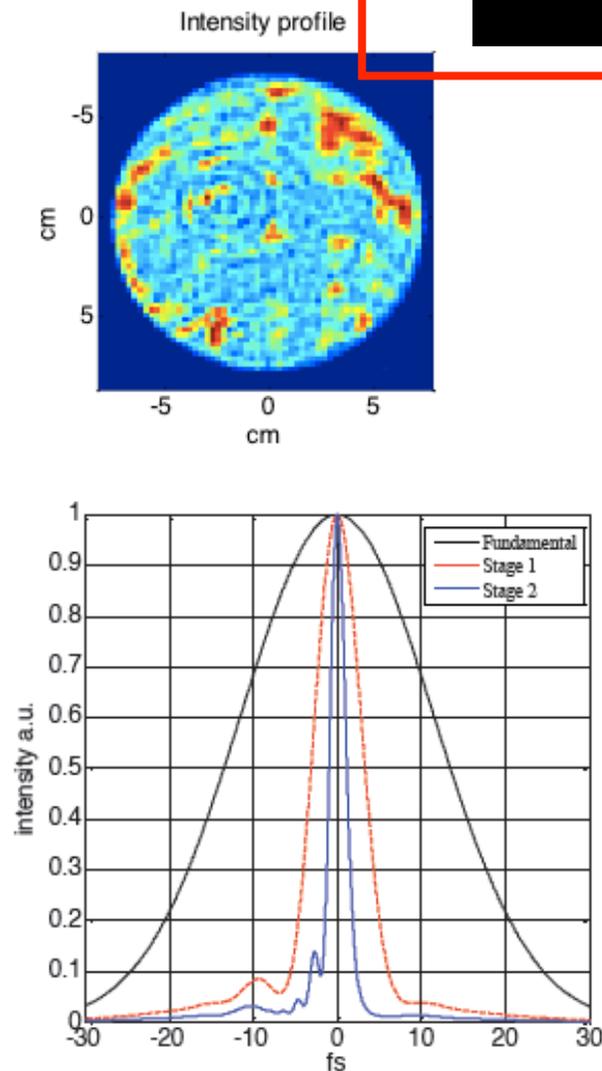
Petawatt Laser Provides A 10-1000J Uniform wave front in Phase and Amplitude



22/02/17



Single Cycle Thin Film Compressor TFC



G. Mourou, S. Mironov, E. Khazanov and A. Sergeev, Single cycle Physics , Eur. Phys. J. Special Topics, 223, 1181(2014)

A.A. Voronin, A.M. Zheltikov, T. Ditmire, B. Rus and G. Korn Optics. Com. 2011

G. Mourou, G. Cheriaux, C. Radier Patent 2009

Thin Film Pulse Compression

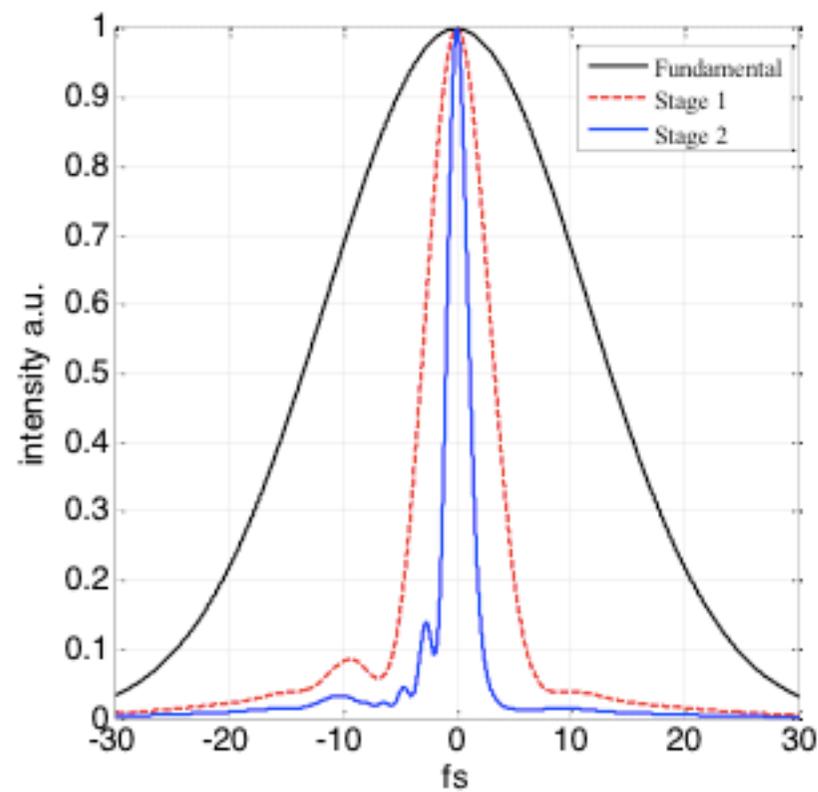
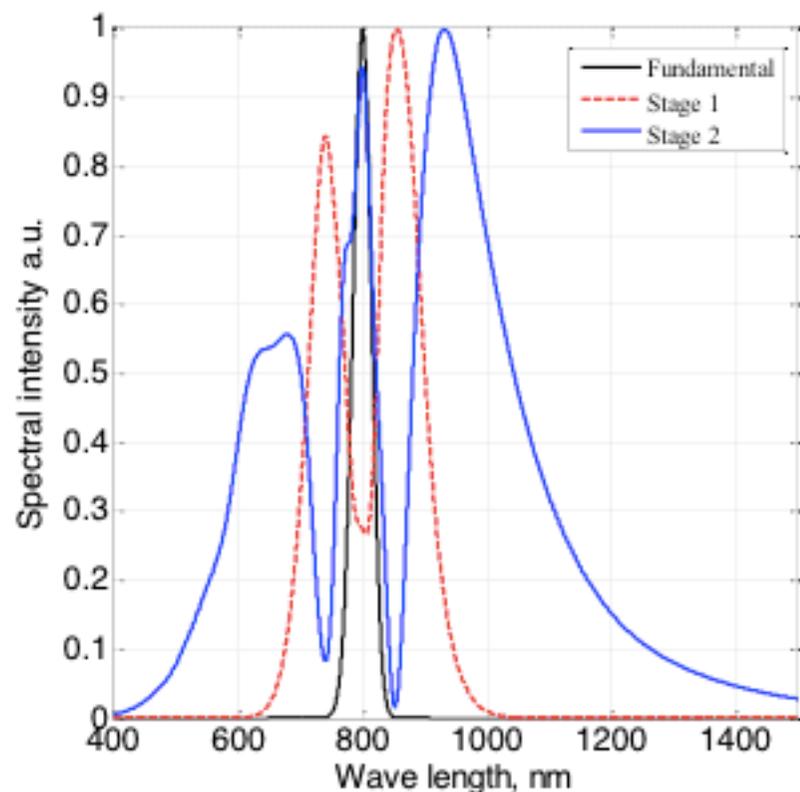
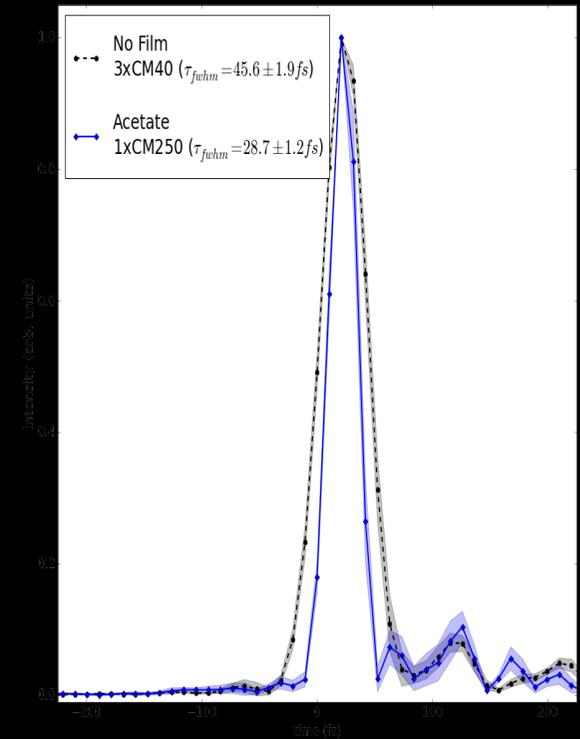
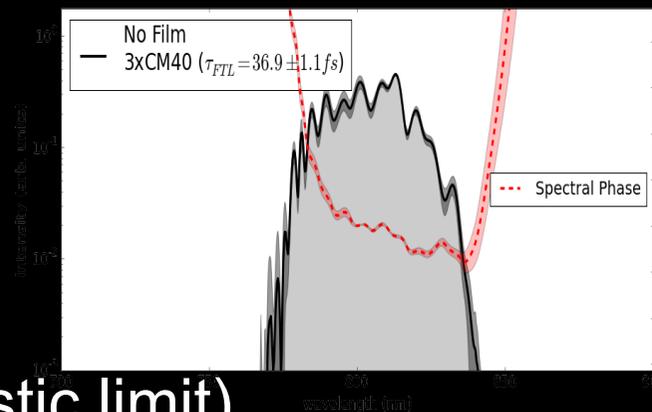
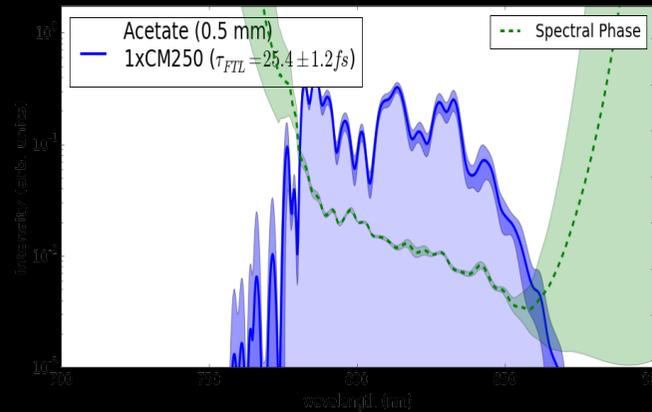
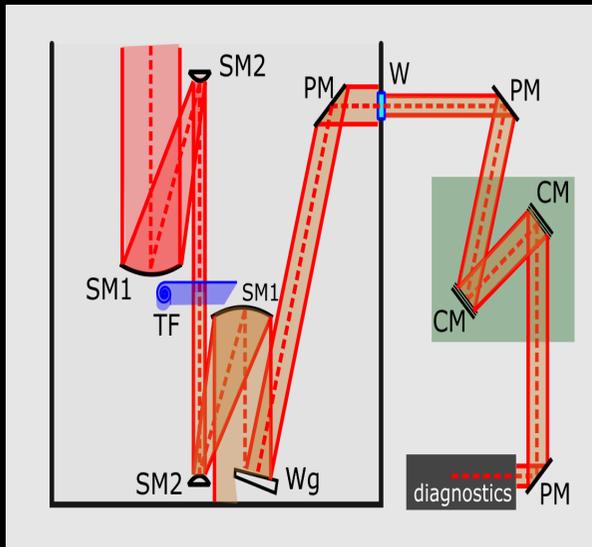


Fig. 4 shows the successive spectra and pulse durations corresponding to the laser output, after the first stage and second stage. After the first stage the pulse 6.4fs, after the second stage the pulse is shrunk to 2.1fs

Cellulose Acetate (0.5 mm)



45 fs to 25 fs (at diagnostic limit)
 Using 0.5mm films of 2 materials
 Single chirped mirror pair

Low Hanging Fruits



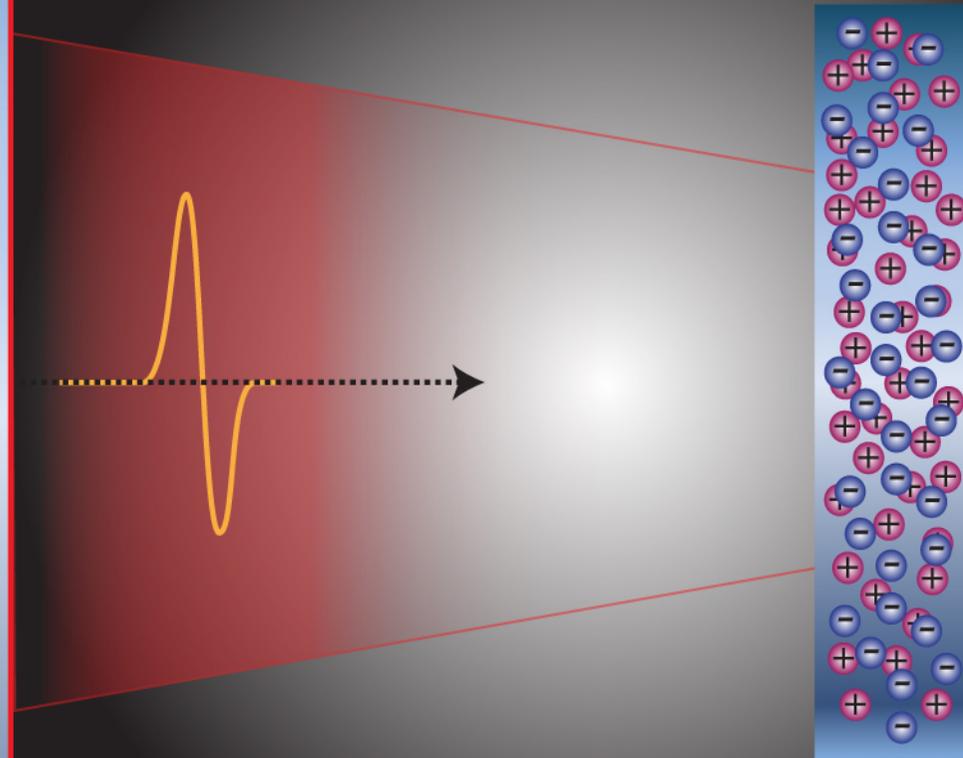
Relativistic Compression

Scalable Isolated Attosecond Pulses

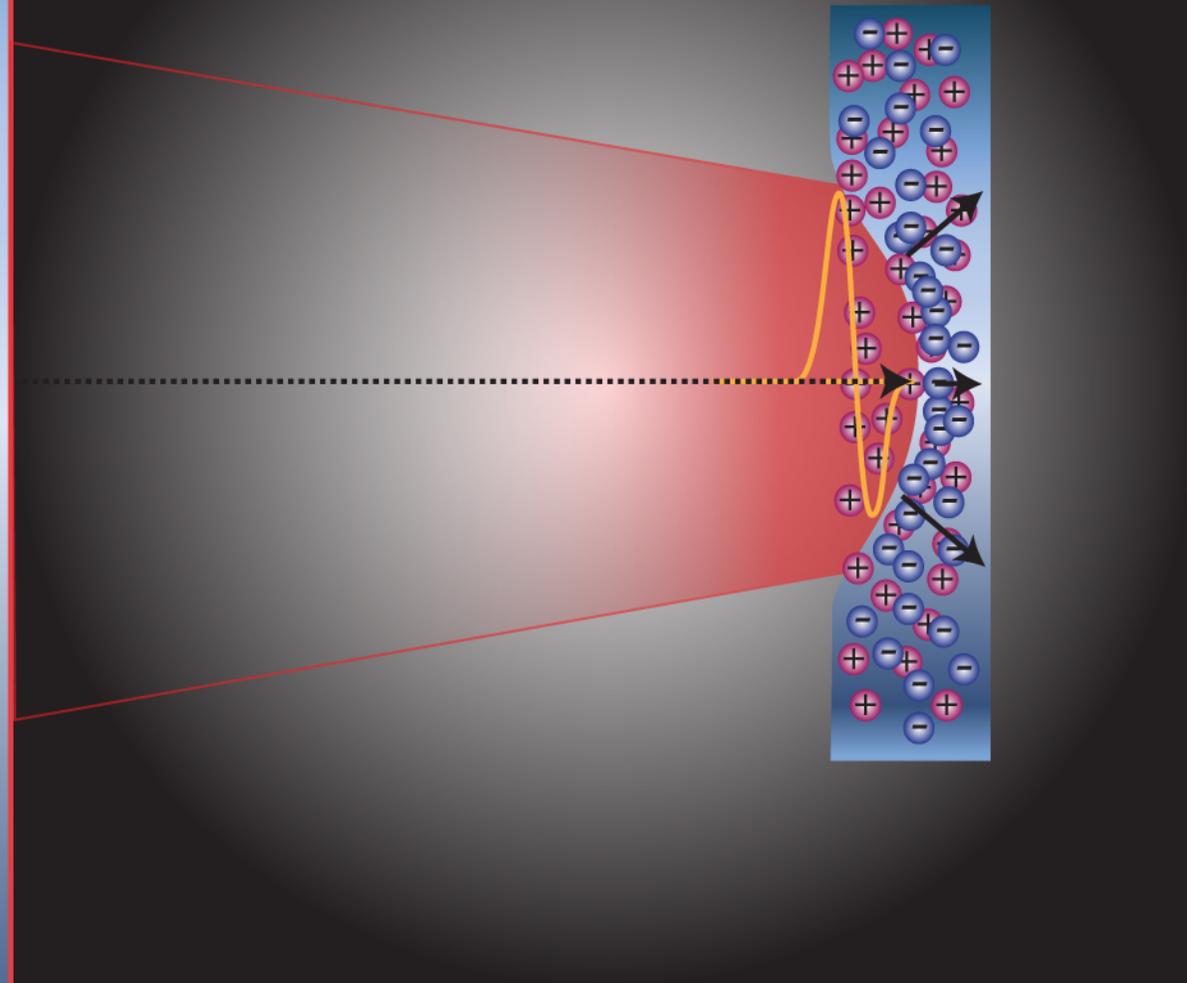
N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou,

Relativistic generation
of isolated attosecond pulses in a λ^3 focal volume, Phys. Rev. Lett.
92, 063902-1 (2004).

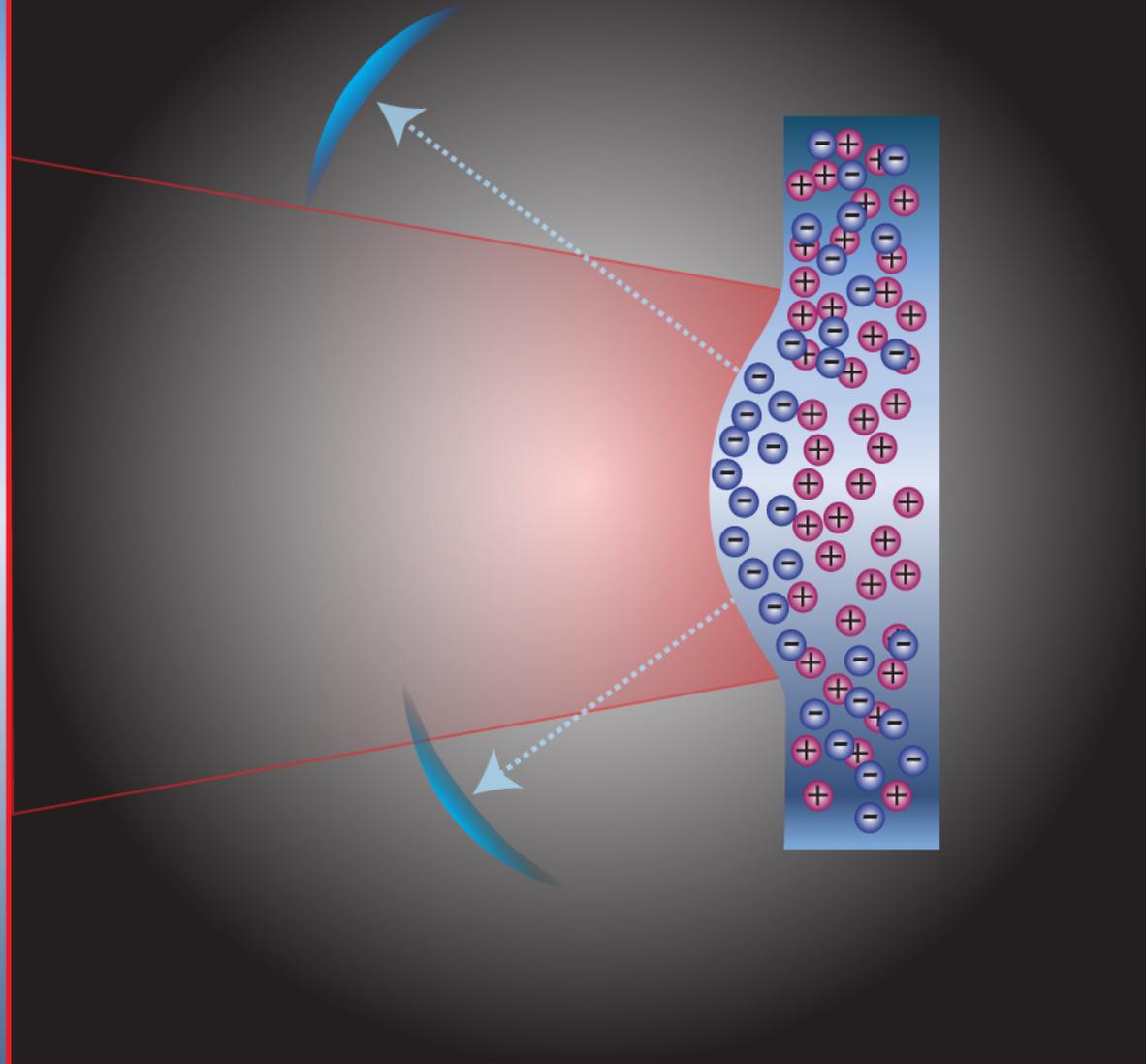
Relativistic Compression



Relativistic Compression

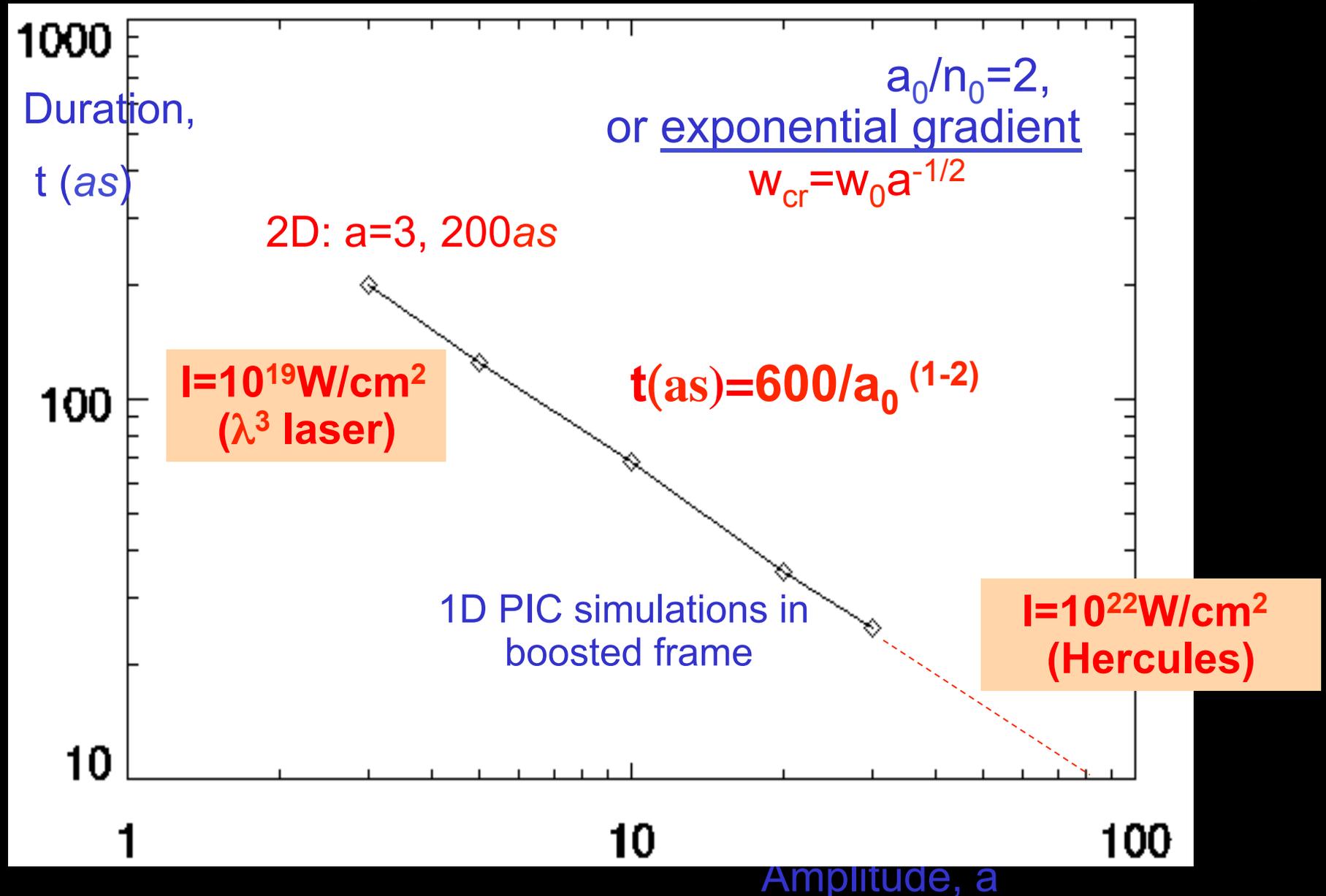


Relativistic Compression

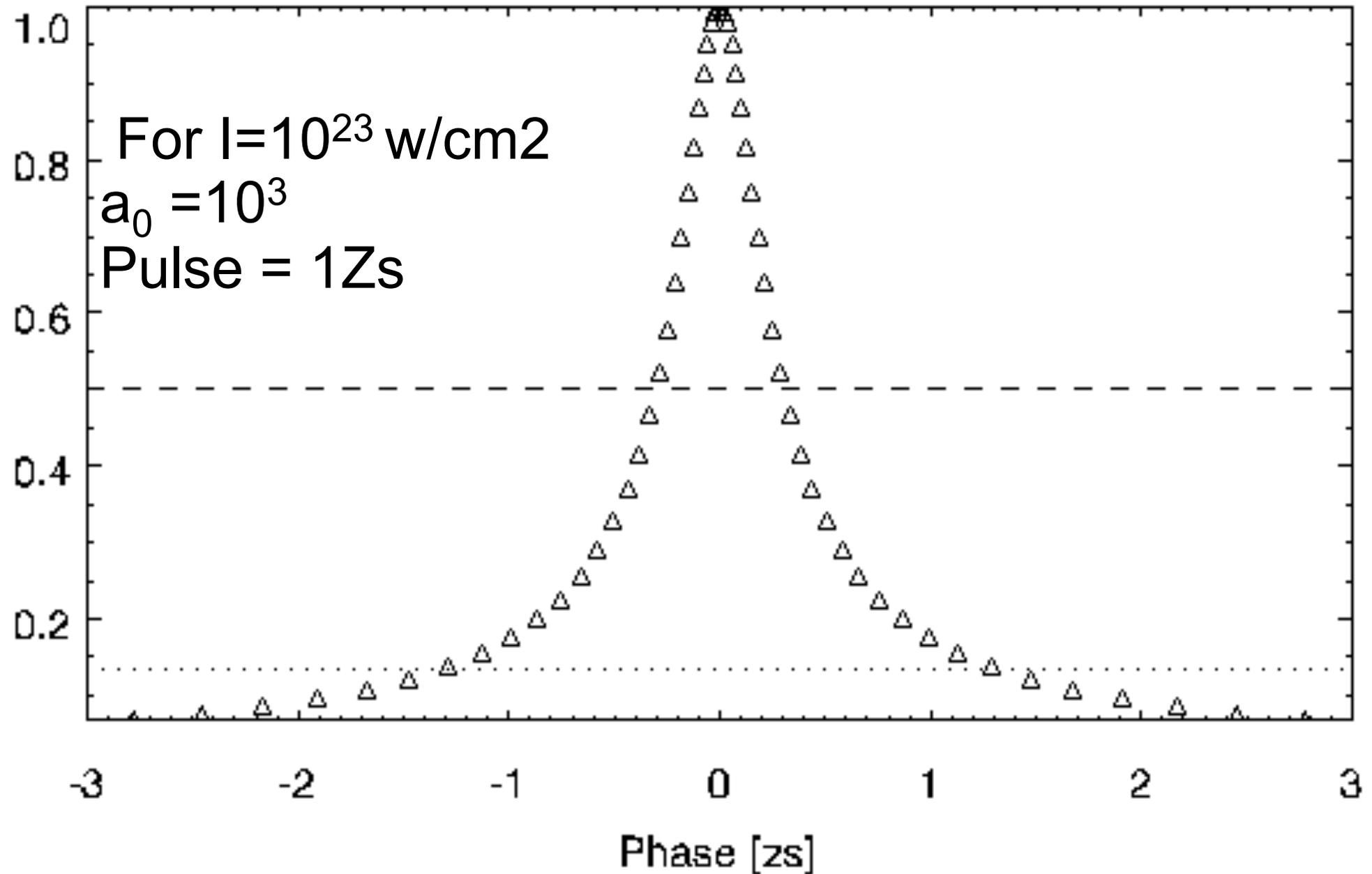


Scalable Isolated Attosecond Pulses

N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou, Relativistic generation of isolated attosecond pulses in a λ^3 focal volume, Phys. Rev. Lett. 92, 063902-1 (2004).



Zeptosecond pulses, (N. Naumova, I. Sokolov, G. Mourou) (Preliminary Result)



But a zeptosecond pulse is also:

1. 1J in a Zs (10^{-21} s) is a Zettawatt Zw (10^{21} W)
2. A Zs (10^{-21} s) is a 1MeV Coherent Gamma-ray

Giant Laser Acceleration in solid: TeV/cm
(CERN on a Dime) towards ZeV

3. 1Zw over λ^2 spot size is 10^{29} W/cm²
Schwinger Intensity:

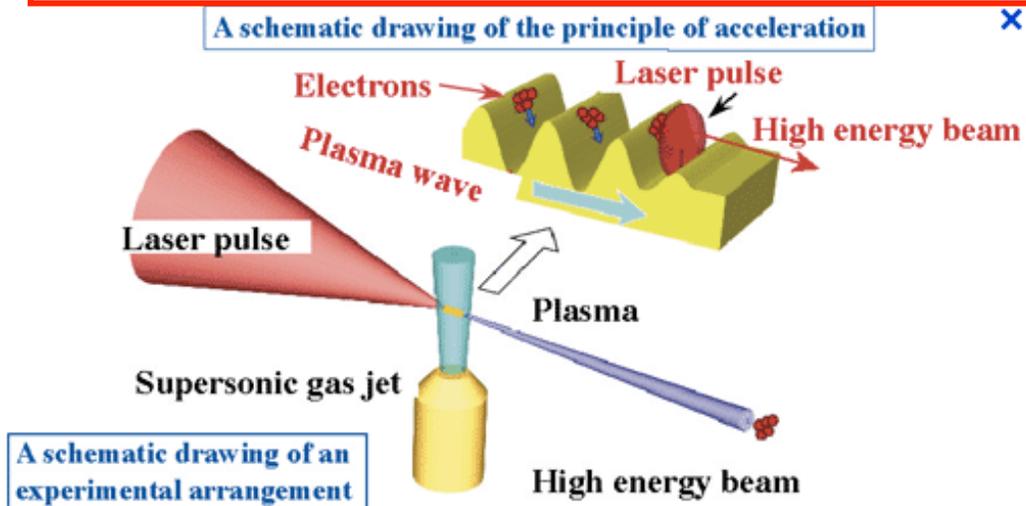
Light Turns into Matter and Antimatter

Low Hanging Fruits TeV/cm Acceleration



Giant Wake Field Acceleration in Gas and Solid

Femtosecond Visible Light Driver in Gas *Tajima et Dawson 1979*



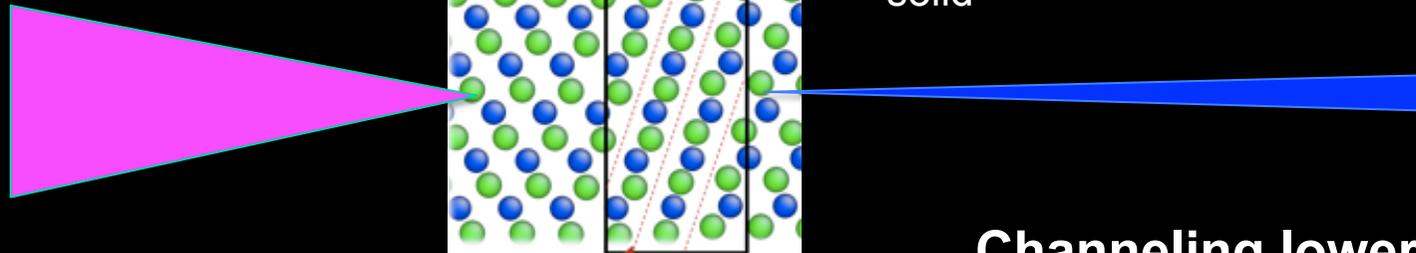
Plasma Acceleration Energy Gain
 $G \propto n^{1/2} \text{ eV/cm}$

1eV light $n_c \sim 10^{21} \text{ cm}^{-3}$

$n_{\text{gas}} = 10^{18} \text{ cm}^{-3}$, $G \sim 10^9, \text{ GeV/cm}$

Atto-zepto, X-ray Driver, Solid, *Tajima et Cavenago 1987*

$n_{\text{solid}} = 10^{24} \text{ cm}^{-3}$, $G \sim 10^{12} \text{ eV/cm, TeVcm}$



Drive pulse X-Ray,
 600zs + as electron
 pulse

Channeling lower the emittance
 Valid for electron, muons, heavy ions

Laser-Wake-Field Acceleration Gas/Light vs Solid/ X-Ray

Serendipity at its best

n_c for X-ray $10^{29} / \text{cm}^3$

$$\text{Energy Gain } E = a_0^2 m_0 c^2 (n_c / n_e)$$

In the visible $n_c = 10^{21} / \text{cm}^3$ Low gaz density

In the X-ray, $n_c = 10^{29} / \text{cm}^3$ Solid density

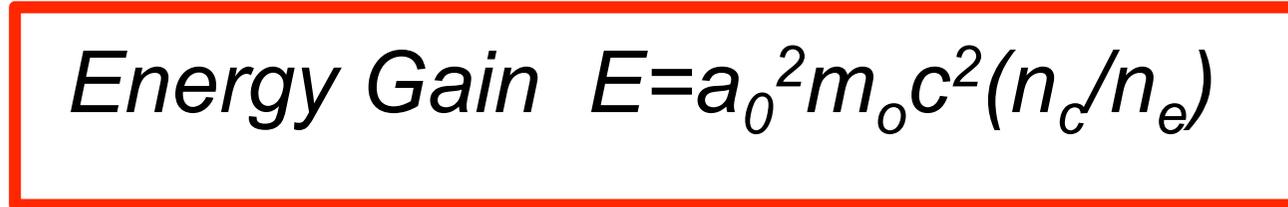
$n_{c \text{ light}} 10^{21} / \text{cm}^3$

$n_e 10^{18} / \text{cm}^3$

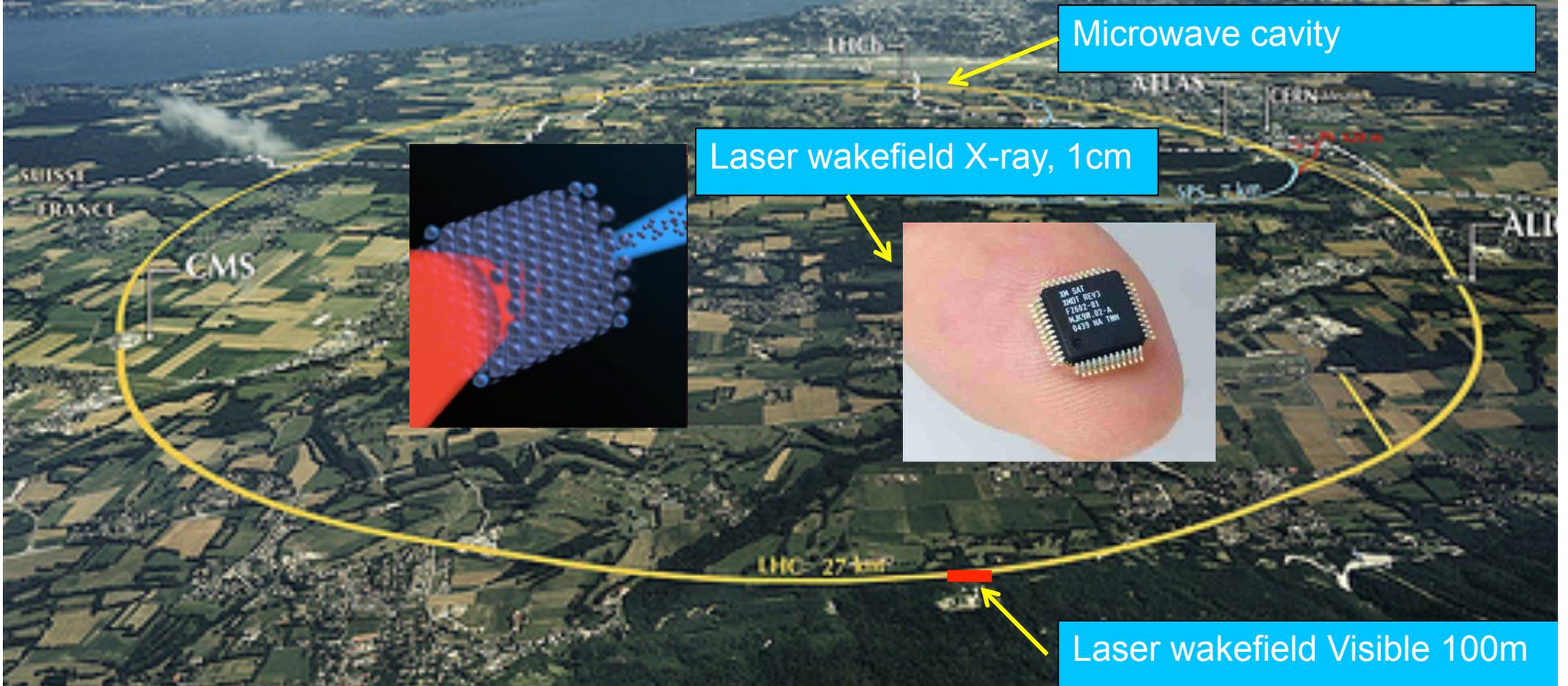
1eV

10keV

$n_{\text{solid}} 10^{23} / \text{cm}^3$

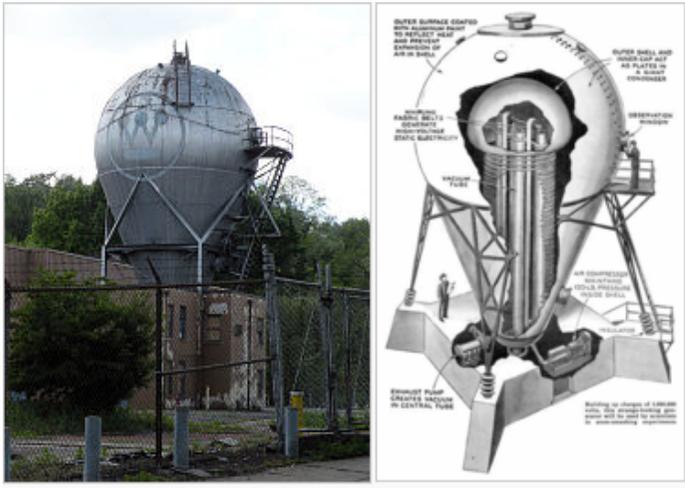


Outlook for Laser-Particle acceleration TeV

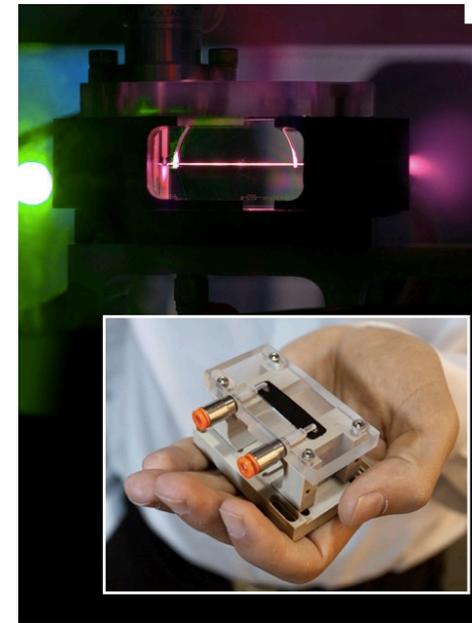


Historical Trend in Particle Acceleration From DC to X-ray

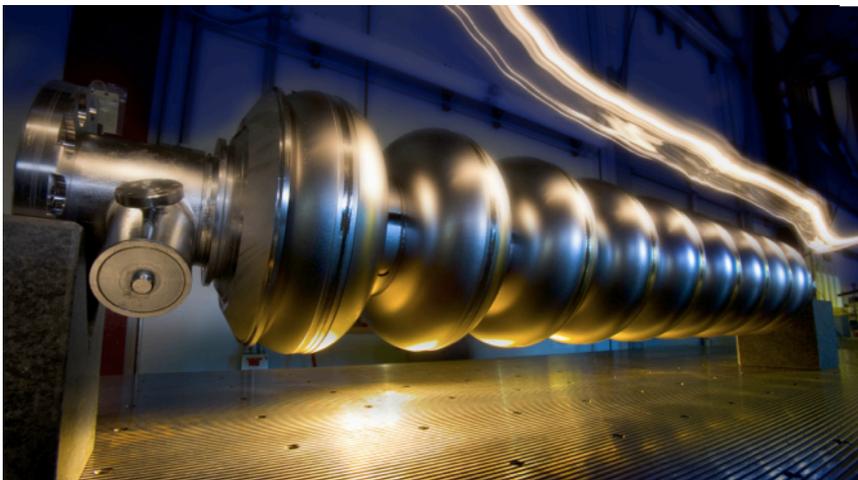
0 Hz Van de Graff, MeV



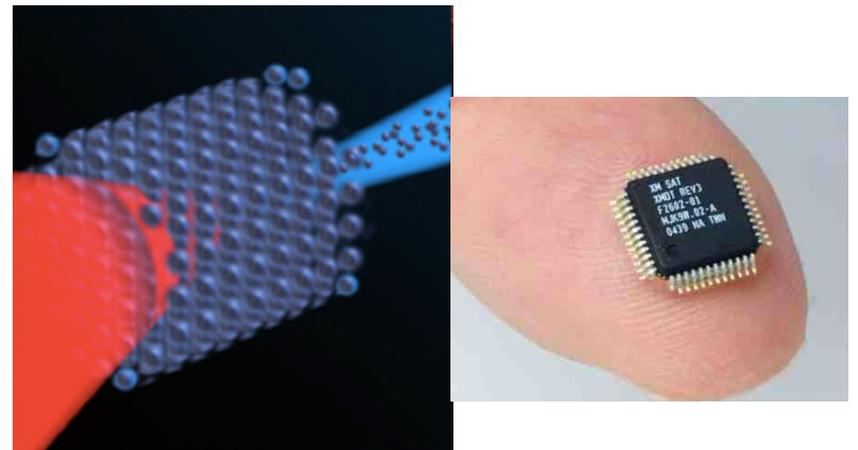
LWA, Visible 10^{14} Hz, GeV/cm



RF Cavity 10^9 Hz, MeV/cm



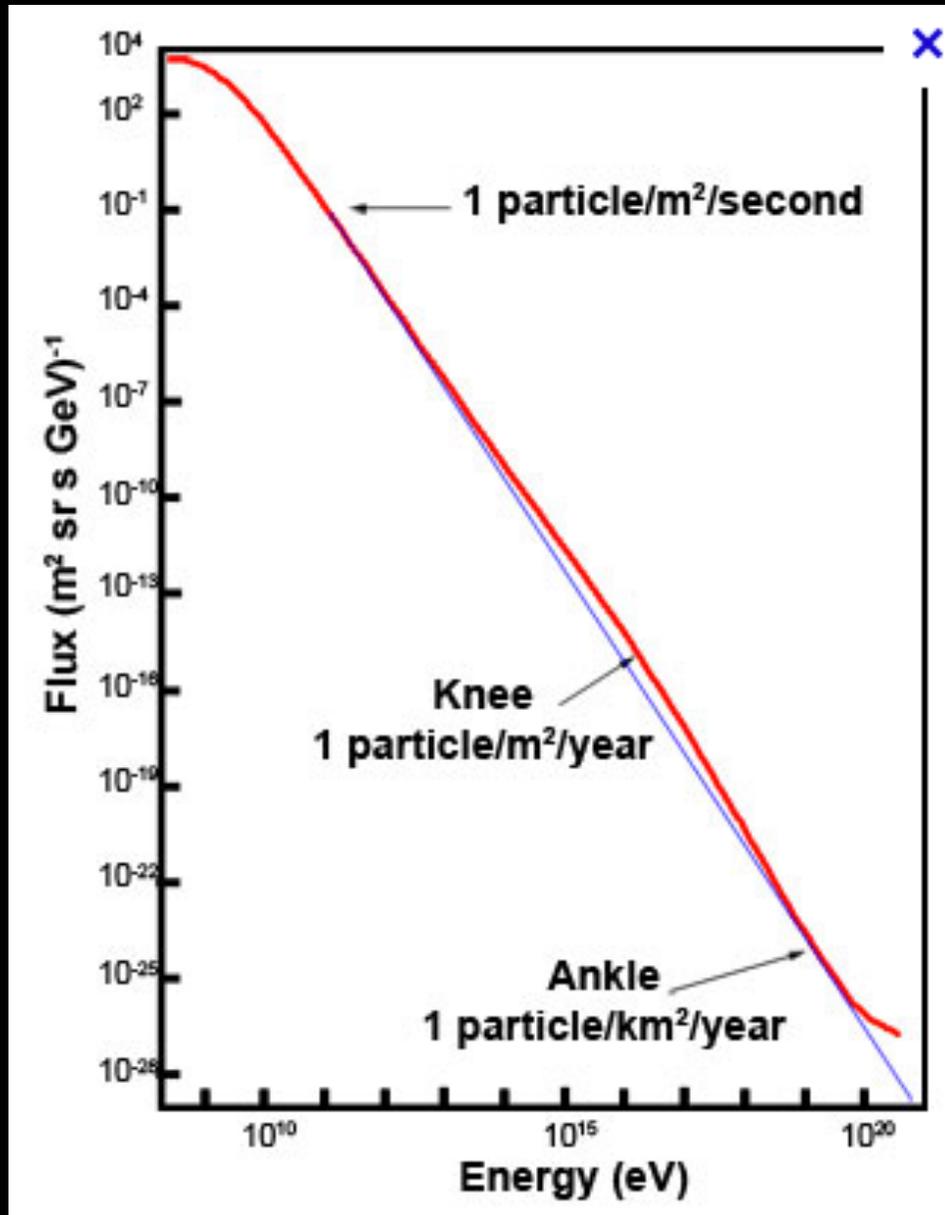
LWA – X-ray 10^{18} Hz, TeV/cm



TeV Particle Astrophysics



Cosmic Ray Spectrum



Cosmos on a Table

Lorentz Invariance

Light Dispersion
From quantum Vacuum

Gamma Ray Burst
mn Duration

1billion years,

10mn spread



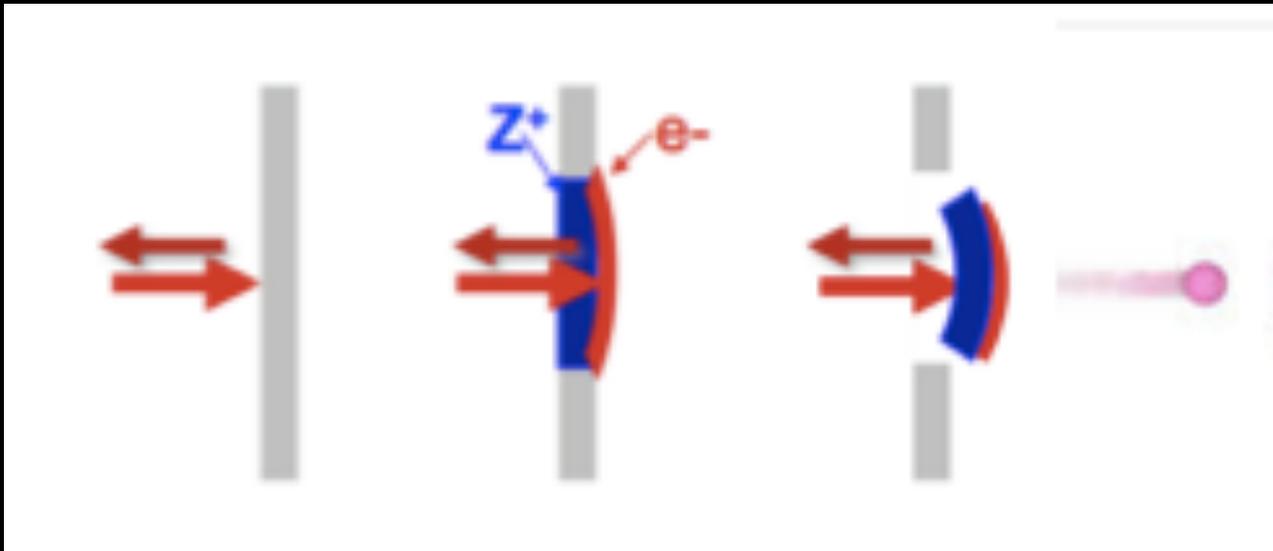
Low Hanging Fruits

High Energy Proton Generation

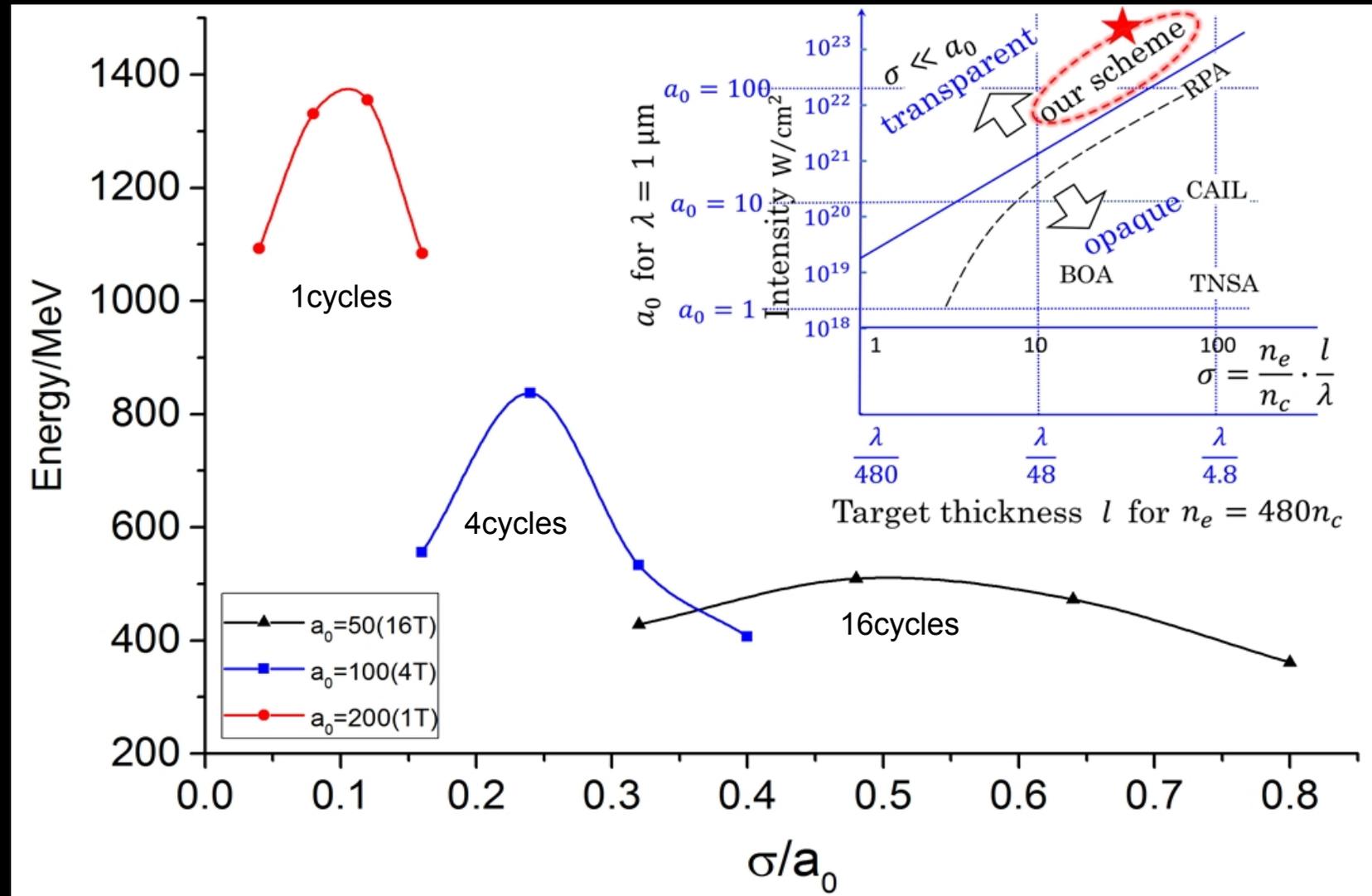


Low Hanging Fruit:

GeV Proton Generation

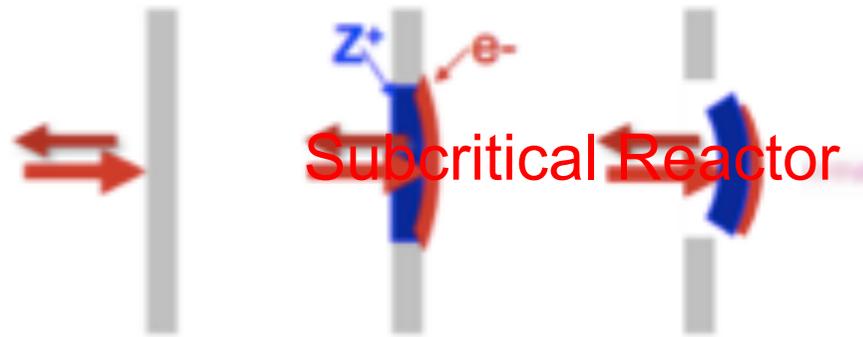


Applications of Single Cycle to Proton Generation vs a_0

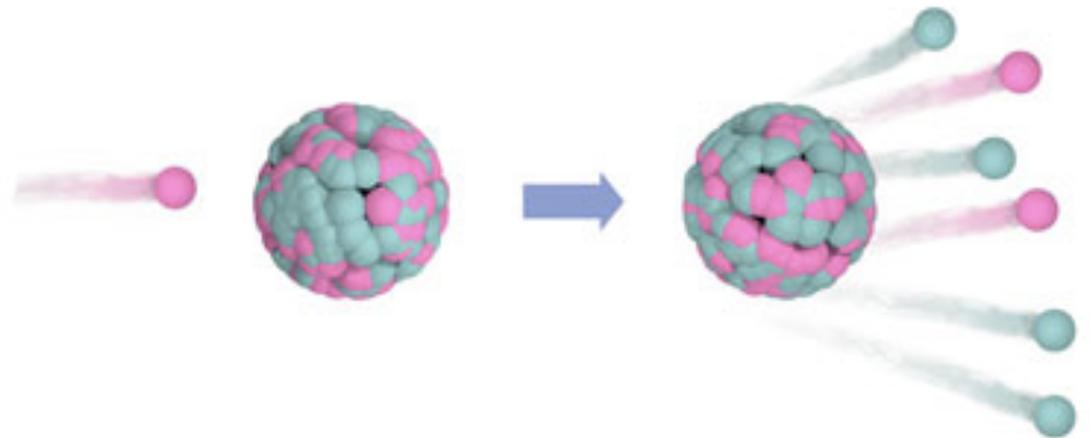


High Energy Proton Applications

GeV Proton Generation



Neutron source



Extreme Light Societal Applications

The most recent development in extreme light laser technologies, such as UV generation, x-ray generation and proton acceleration, open the way to the incredible potential of high-tech applications development; a "blue sky" of innovation in a completely new market, especially in medical fields. These are some examples :

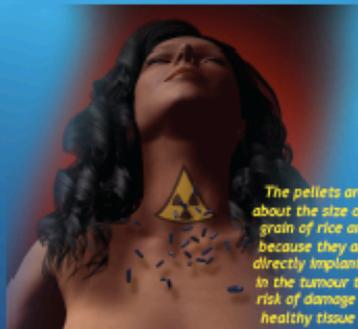
1 PROTON THERAPY

Proton therapy is not new, but present technology involves very large scale engineering and construction. Extreme light technology will be tens of times more compact, more precise and less expensive.

Maryland Proton Treatment Center, 2015 - 350 metres x 180 metres, five floor levels



University Hospital Essen, proton generating cyclotron

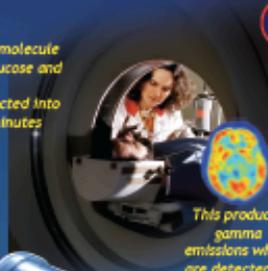


The pellets are about the size of a grain of rice and because they are directly implanted to the tumour the risk of damage to healthy tissue is greatly reduced

3 NUCLEAR THERAPY

Radionuclides are also used to treat patients directly, often by implanting tiny radioactive pellets directly into a tumour. Again, the only available radioactive source at present is a nuclear reactor, and so the potential application of extreme laser proton acceleration is an attractive proposition.

A biologically active molecule called fluorodeoxyglucose and a positron emitting radionuclide are injected into a patient about 45 minutes before the scan.



This produces gamma emissions which are detected by the scanner

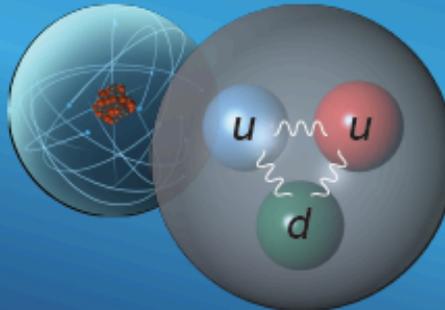
2 NUCLEAR DIAGNOSTICS

Medical scanners, such as positron emission tomography (PET), depend upon a radioactive isotope being injected into a patient. Although this presents no great risk, the isotope can only be produced in a nuclear reactor. It takes time to get it to a clinic, so the radioactive content has to be much higher to compensate.

Extreme laser proton acceleration means that isotopes could be produced in the clinic instead of a distant nuclear reactor.

THE MAGICAL PROTON

A proton is a sub-particle within an atom. It has a positive charge and is made up of six smaller pieces; 2 up-quarks, 1 down-quark and 3 gluons, which stick the quarks together.



4 NUCLEAR WASTE DISPOSAL

Extreme laser proton acceleration may also provide a means to transmute dangerous nuclear waste into something relatively harmless and much shorter lived.

The staggering cost of collecting and disposing of toxic nuclear waste makes this application very exciting.



DANGEROUS AND EXPENSIVE!

In February, 2013, the UK government estimated that the total lifetime cost of removing all radioactive nuclear waste from the UK's nuclear reactors and Low Level Waste Centres would cost over €90 billion!

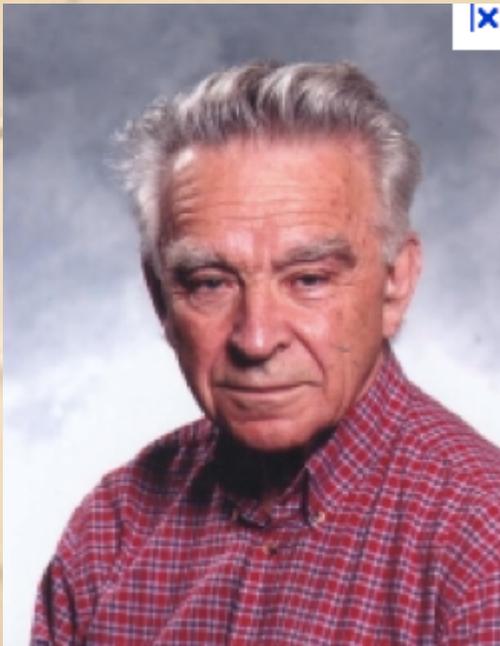


Protons are accelerated into the waste container

They slam into a Pb-Bi liquid which produces an avalanche of neutrons

When the neutrons collide with the waste the atomic structure collapses and it is transmuted

Vacuum Polarization
Pair Generation
Vacuum breakdown



L. Keldish



J. Schwinger

From N. Narozhny

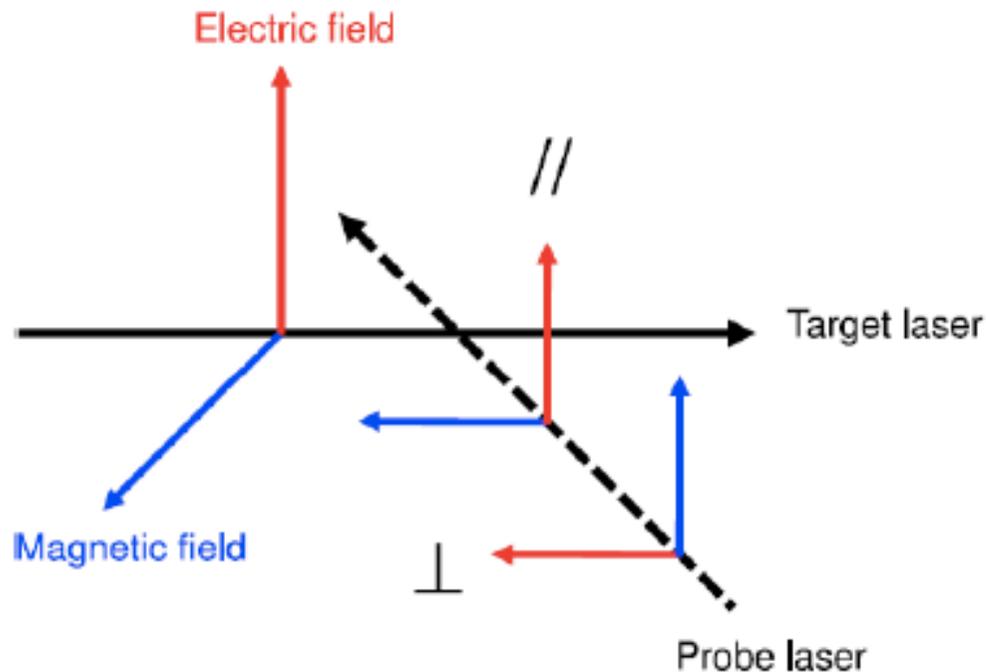
Birefringence by QED in eV range

Euler-Heisenberg one-loop Lagrangian

$$L_{QED} = \frac{1}{360} \frac{\alpha^2}{m^4} [4(F_{\mu\nu}F^{\mu\nu})^2 + 7(F_{\mu\nu}\tilde{F}^{\mu\nu})^2]$$



Refractive index depends on polarizations



$$n_{\parallel} = 1 + \frac{16 \alpha^2 U}{45 U_e}, \quad n_{\perp} = 1 + \frac{28 \alpha^2 U}{45 U_e}$$

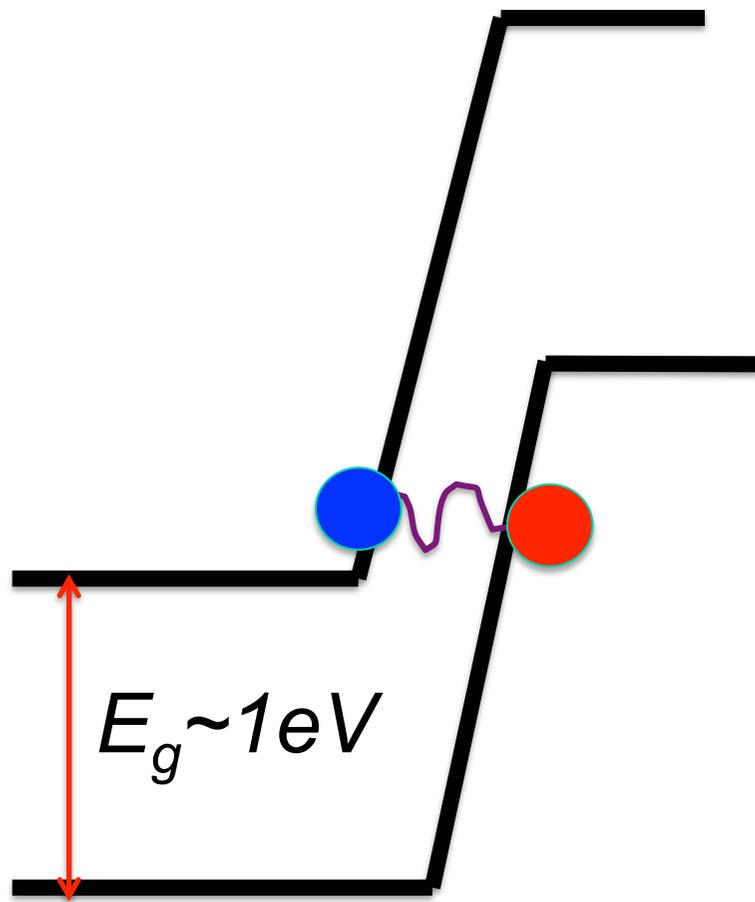
$$U_e = m_e^4 c^5 / \hbar^3 \approx 1.42 \times 10^6 \text{ J}/\mu\text{m}^3$$

ELI (~200J per ~20fs)
can reach $\Delta n \sim 10^{-9} \sim 10^{-10}$

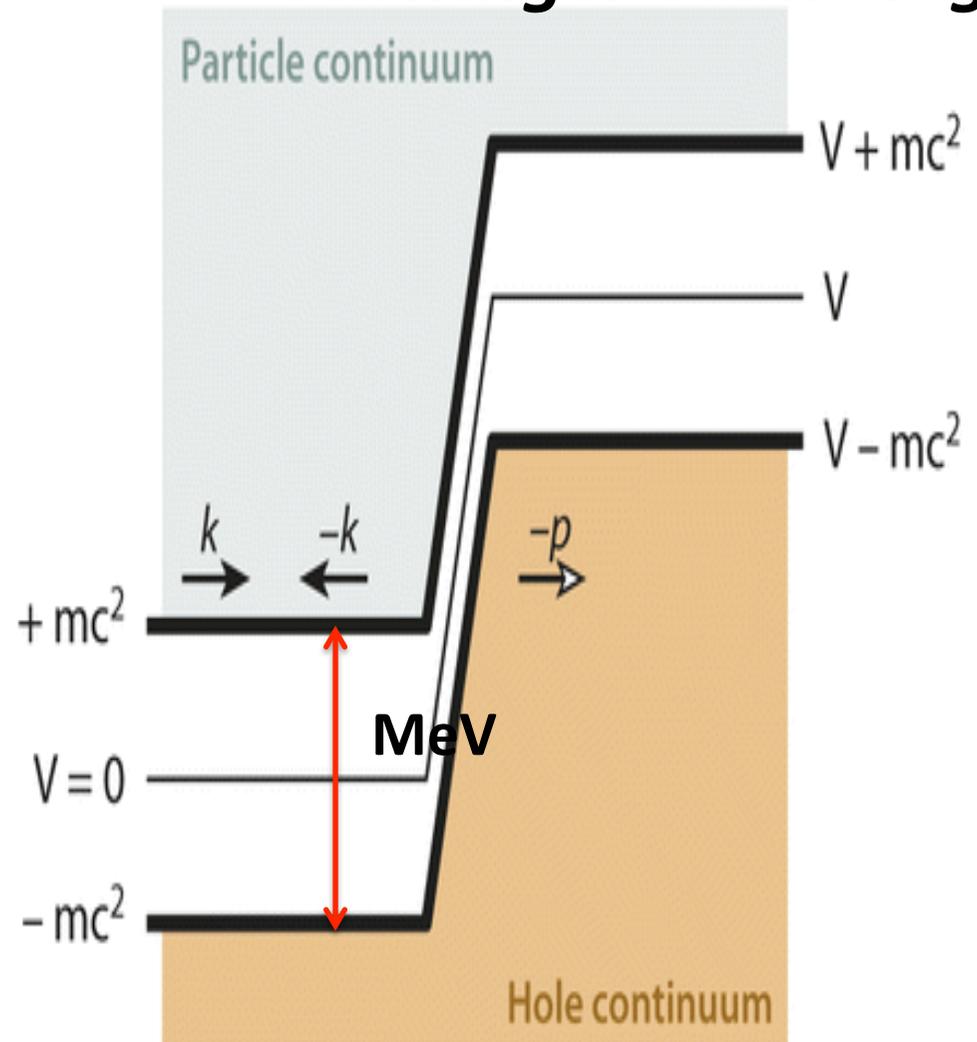
(Homma, Habs, Tajima)

22/02/17

Keldysh Tunneling



Schwinger Tunneling



Keldysh Tunneling Hydrogen

$$W \propto \exp\left(-\frac{2 E_a}{3 |E|}\right)$$
$$E_a = \frac{m^2 e^5}{\hbar^4}$$

Schwinger Tunneling

$$W \propto \exp\left(-\frac{8E_s}{3E}\right)$$
$$E_s = \frac{m^2 c^3}{e\hbar}$$

$$\frac{E_a}{E_s} = \alpha^3 = \left(\frac{1}{137}\right)^3 \Rightarrow \frac{I_a}{I_s} = \left(\frac{1}{137}\right)^6 \approx 10^{13}$$

Nonlinear Filament in Vacuum

$$\text{Critical Power } P_c = \lambda^2 / n_2$$

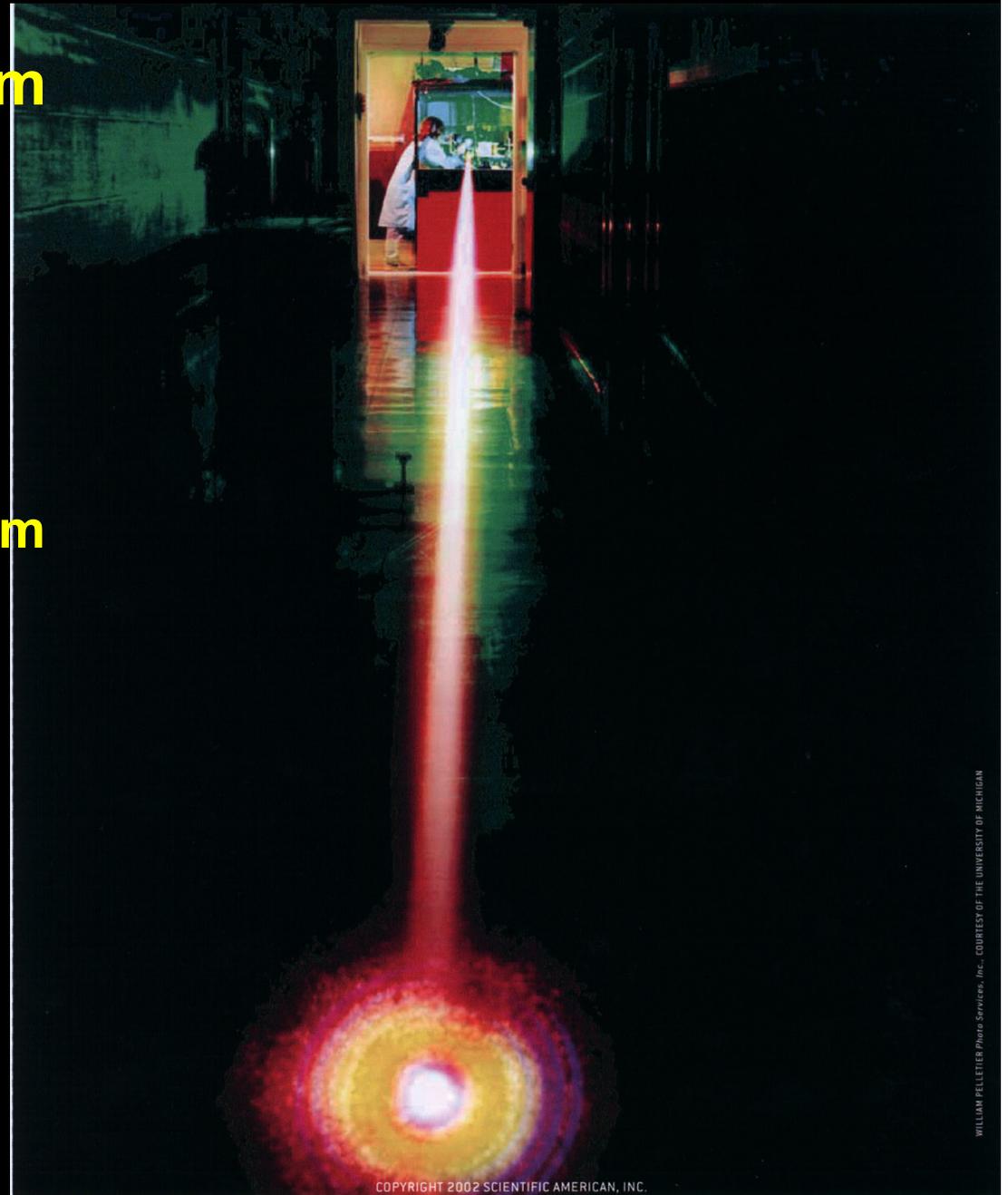
For zepto second pulse $\lambda = 10^{-10} \text{ cm}$

$n_{2 \text{ vac}} = 10^{-18}$ of $n_{2 \text{ material}}$

$$P_{c \text{ vac}} = 10^{14} \text{ W}$$

$$\text{Size filament} = \lambda_{\text{compton}} = 10^{-10} \text{ cm}$$

$$\text{Energy per filament} = 1 \text{ } \mu\text{J}$$



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Extreme Light Sub-critical Reactor Transmutation of Nuclear Waste



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International
Year of Light
2015

Extreme Light Grand Challenges: Scientific and Societal Applications

Scientific Applications

Laser Astrophysics and Cosmology
Polarization of Vacuum, Materialization of Light
Beyond the Standard Model
Higgs Factory
Dark Matter

Societal Applications

Transmutation of Nuclear Waste
Under Critical Reactor
Nuclear Pharmacology
Proton Therapy
Orbital Debris Elimination by Deorbitation



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2015

The Next Step: Solving the Laser Peak and Average Power Quandary

High Peak Power PW

High average power >100kW

High Repetition Rate 10kHz

Efficiency 30%

Single mode fiber can handle >10kW average Power

Coherent Amplifying Network

G. A. Mourou, D. Hulin and A. Galvanauskas,
“The road to High Peak Power and High Average
Power Laser: Coherent Amplification Network (CAN),
AIP Conference Proceedings, Third International
Conference on Superstrong Fields in Plasmas, vol. 827,
Dimitri Batani and Maurizio Lontano, 152-163 (2006).

Study group sponsors by EC called ICAN to evaluate the
concept mainly to try to decrease the number of fibers.



CAN Basic Brick

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

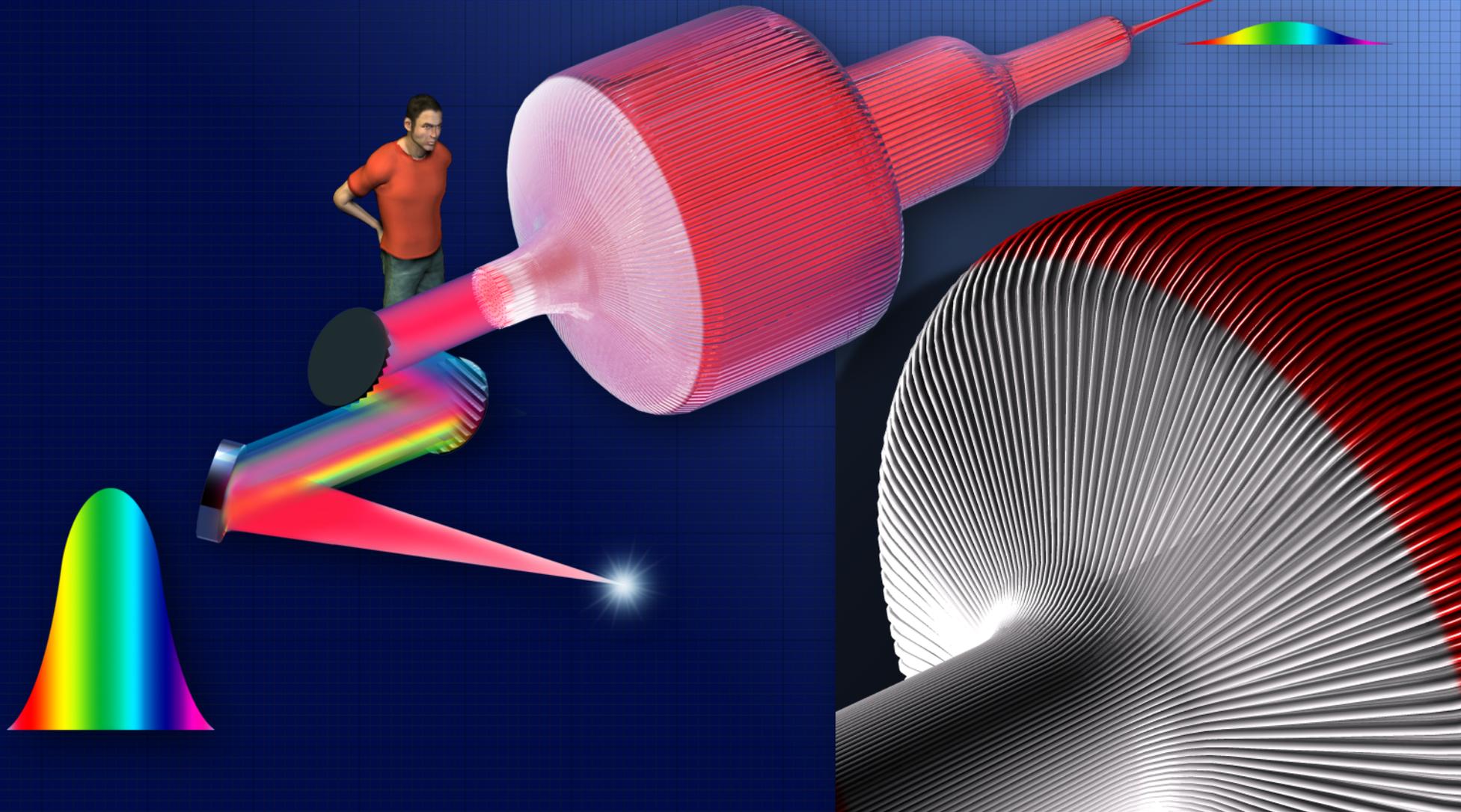
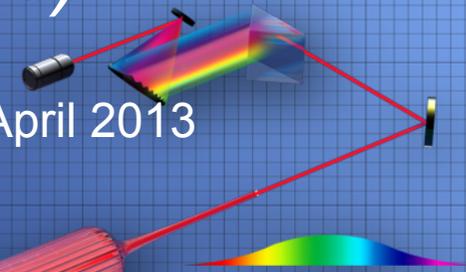
Single fiber can produce up to 2mJ, 200fs pulse with an average power ~ 800W, 40kHz (Jena Group)

A Phased-Fiber-Array emitting 50J, 50fs will be composed of $2 \cdot 10^4$ fibers.

Is it conceivable?

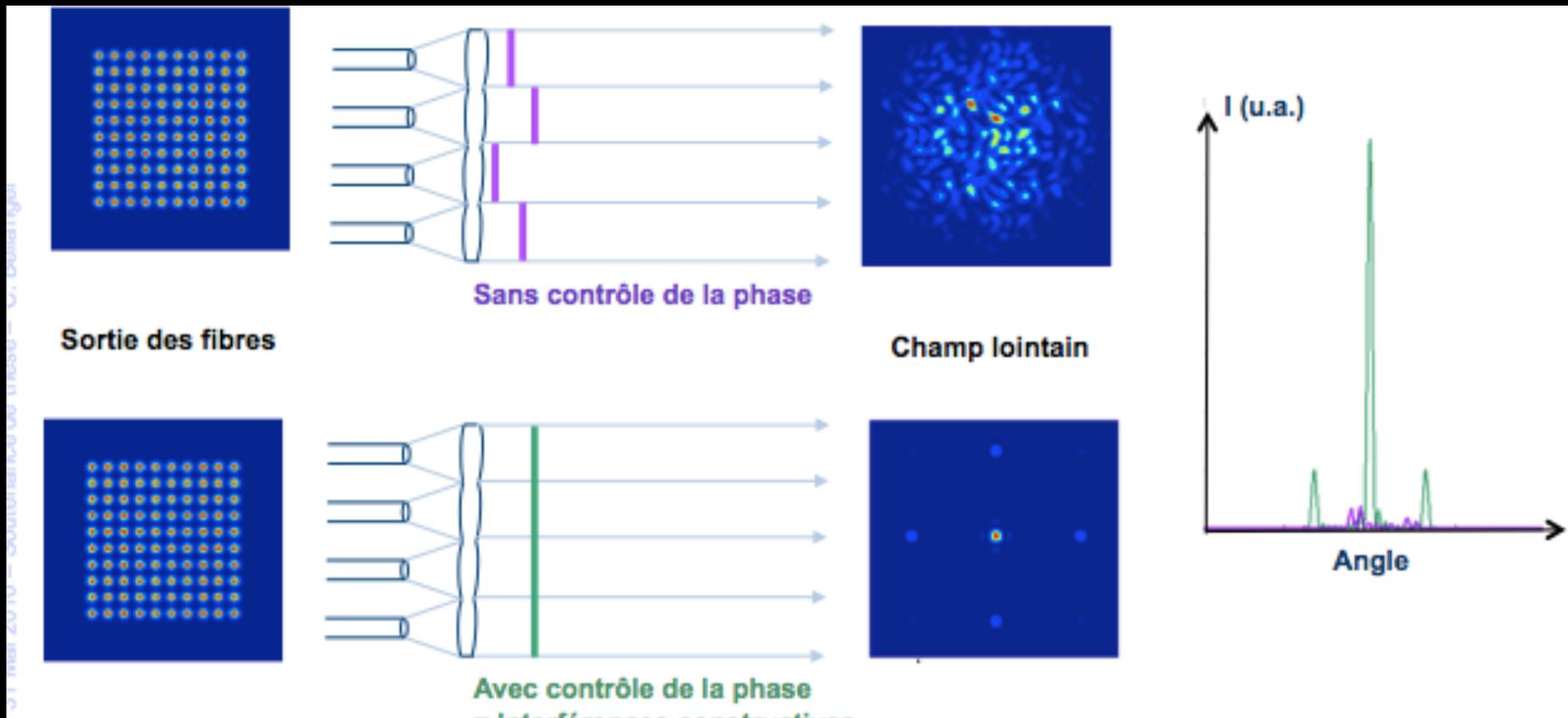
CAN Coherent Amplification Network (X-CAN Prototype 61 fibers)

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



64 CW fibers have been phased

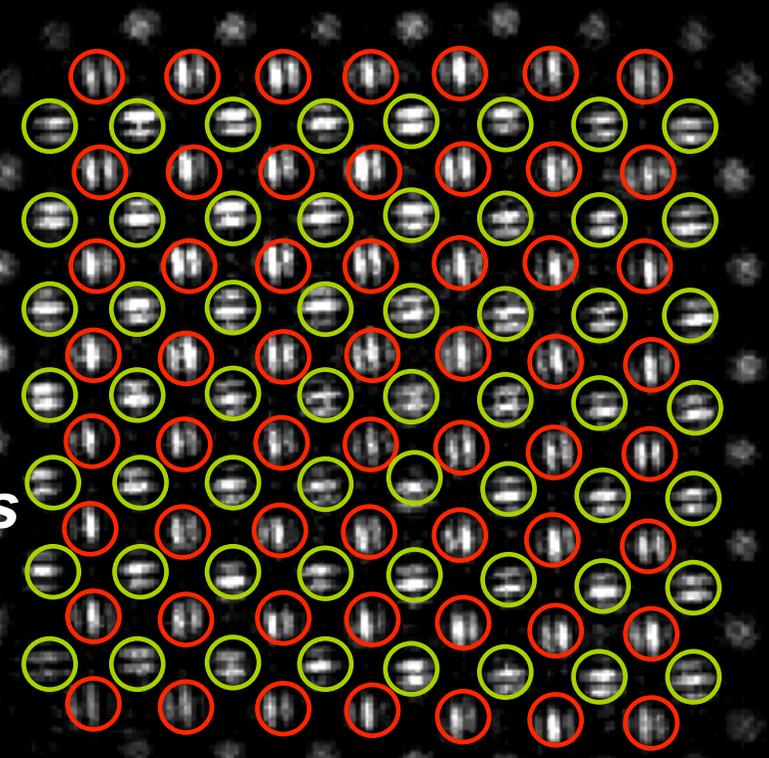
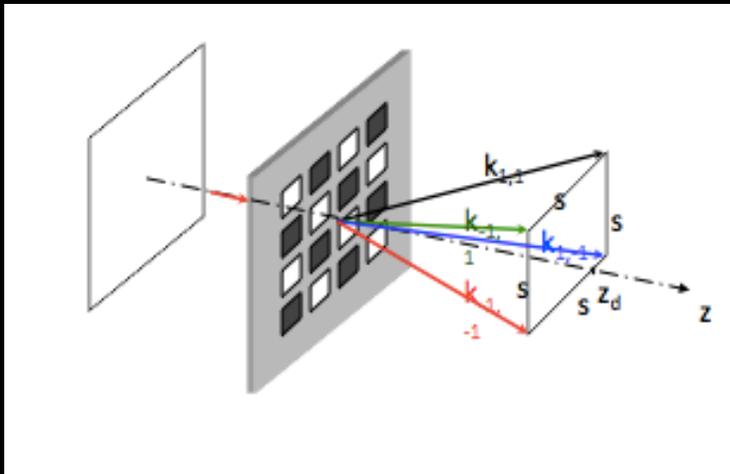
(This experiment in fact validates an extension possible to $>10^4$ phased fibers at 1kHz)



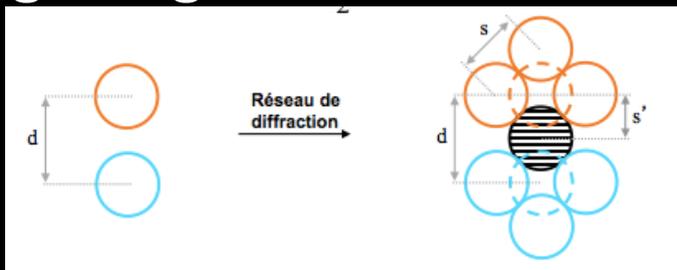


Coherent combining of 64 fibers with a Quadrilateral Shearing Interferometer (10^4 fibers with $\lambda/60$ precision at kHz)

1) Grating Making 4 replicas of each fiber



2) Neighbor fibers interfere with replicas Making fringes

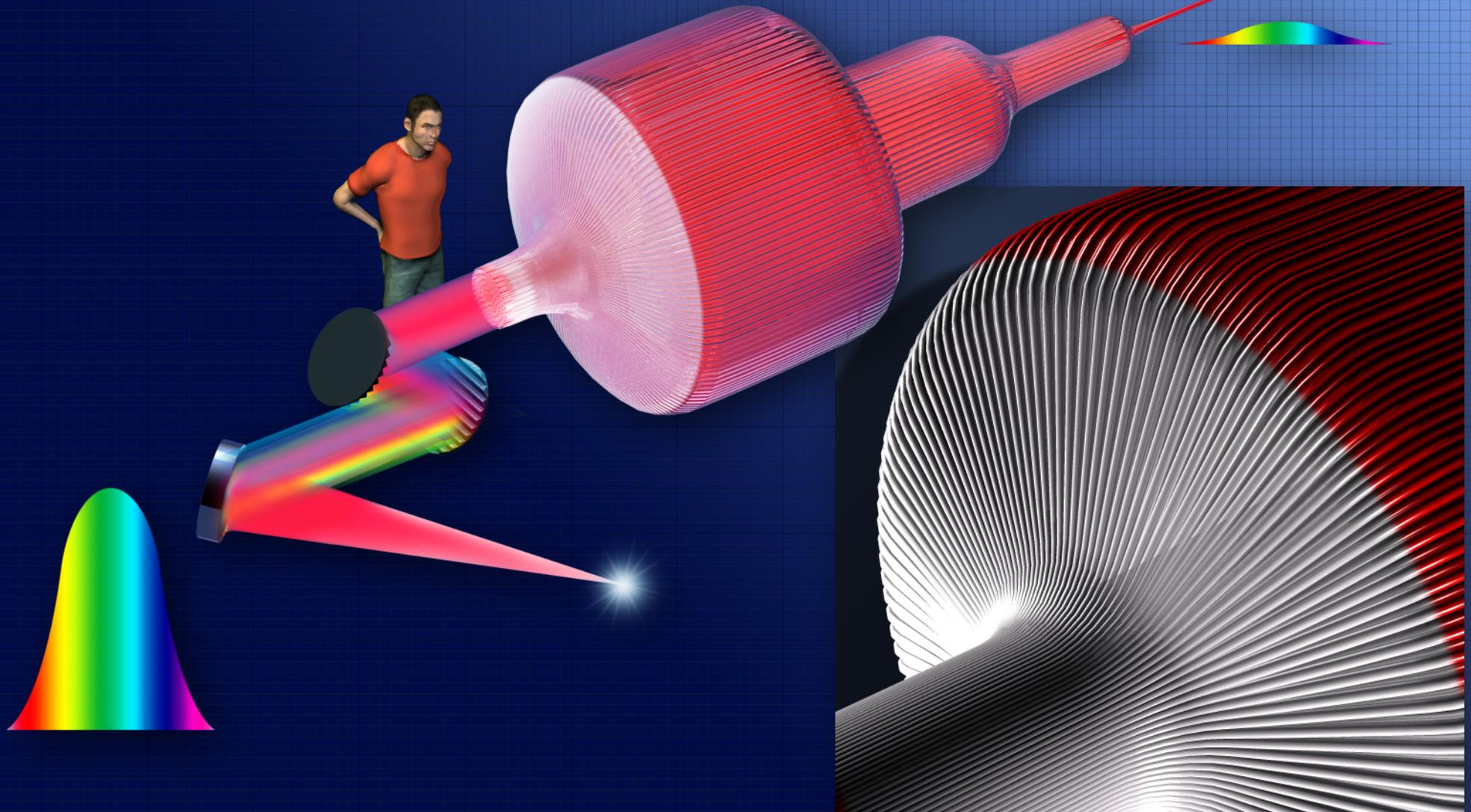
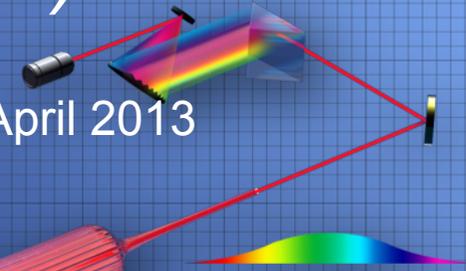


3) A phase map is captured every ms, Only 6 pixels are necessary to making possible phase correction with $\lambda/60$ precision. modulator

G. Mourou

CAN Coherent Amplification Network *(X-CAN Prototype 61 fibers)*

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

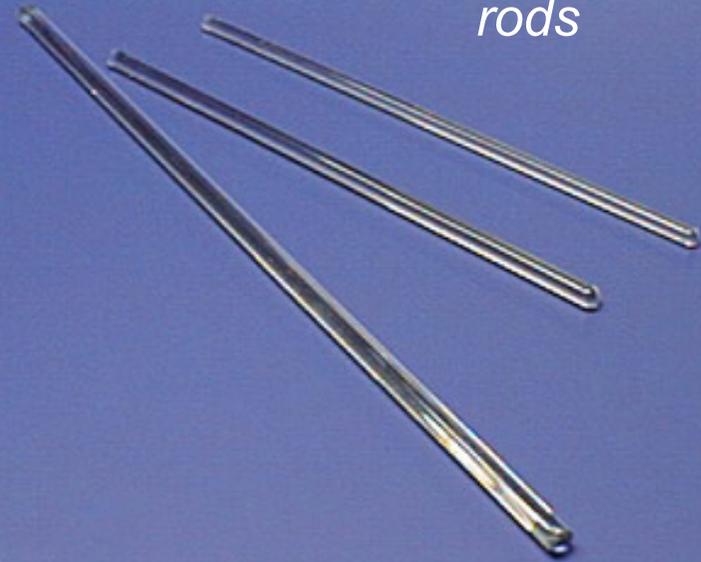


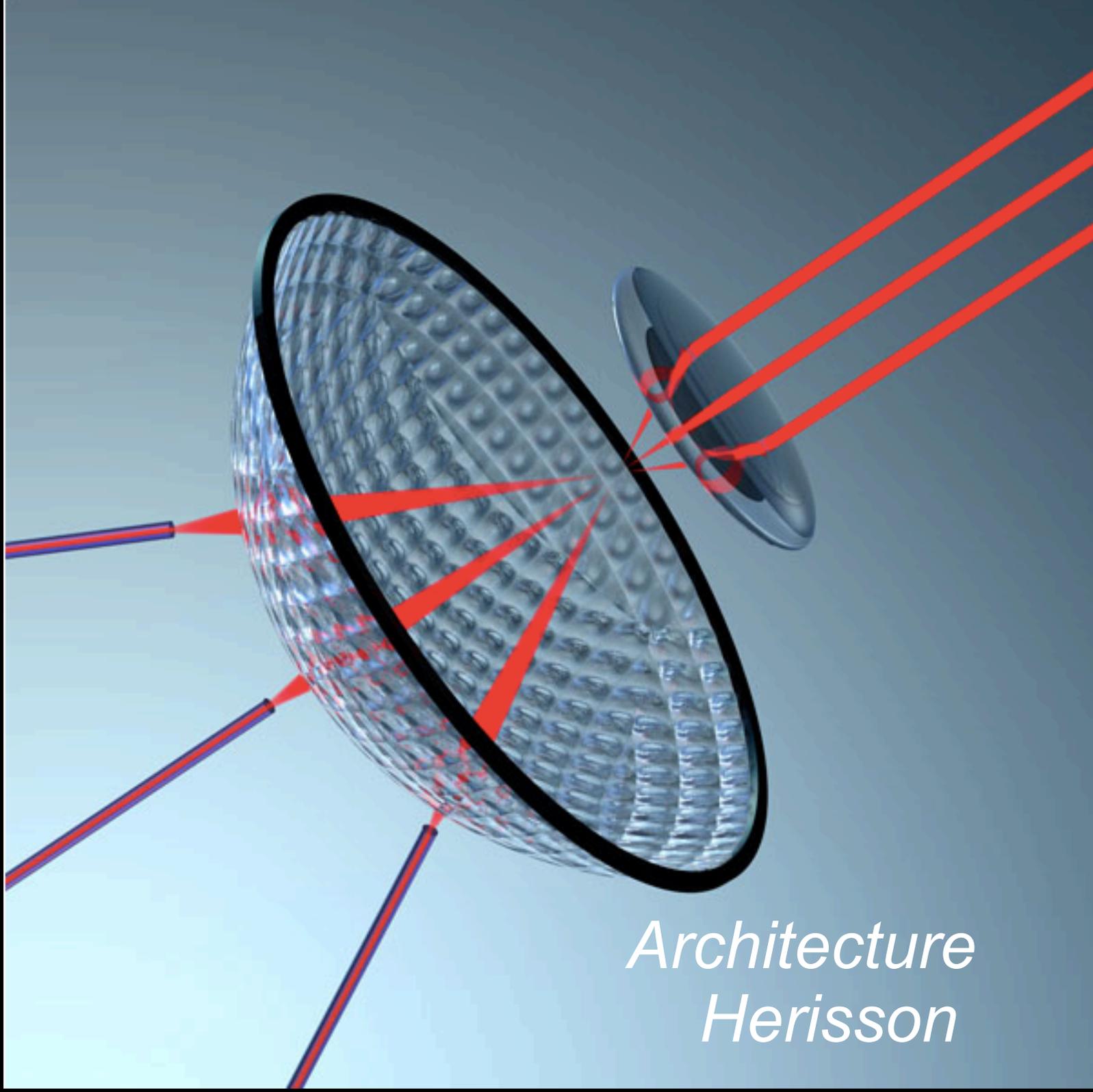
Moving from sub-mJ/ fiber to 10mJ /Rod

*Single mode
fibers*

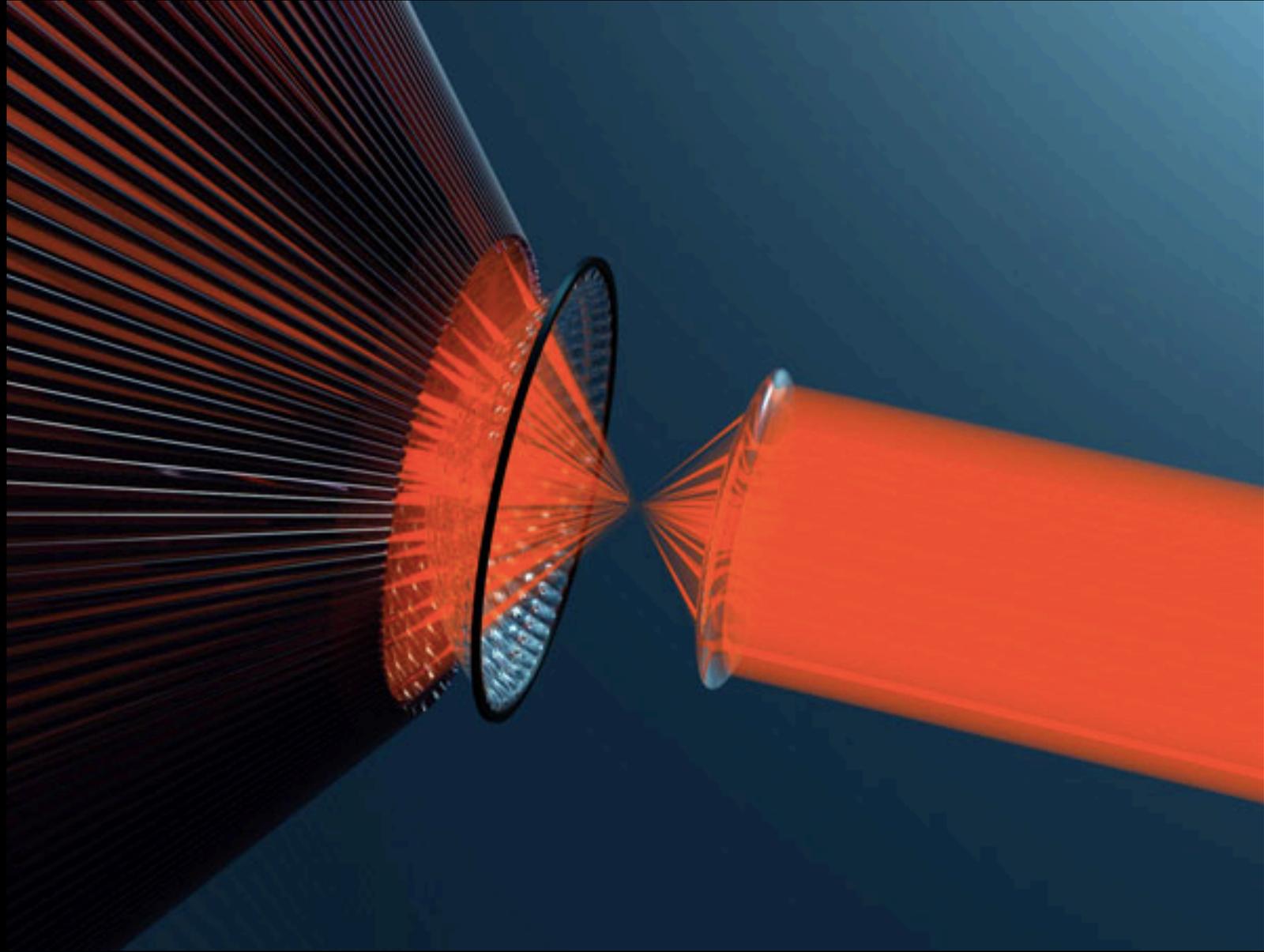


*Single mode
rods*





*Architecture
Herisson*



Coherent Amplification System Using Rod



After a ICAN study of 3 years the conclusions have been:

No simple way has been found to decrease the number of fibers without sacrificing: reliability, pulse quality, beam quality, simplicity, robustness, agility(bandwidth)

The initial design with 10^3 to 10^4 independent using Rods at few mJ/fiber can work at 1KHz and offers the unique properties :

The large number N of independent fibers(beams) makes possible:

1. superior beam quality, stability because of the number SQRT (N)
2. Provide flexibility pulse shape in time and space
3. superior beam pointing SQRT (N)
4. easy to align and maintain
5. it can work at kHz bandwidth.

A CAN system is heuristic at kHz. Ideally suited for multistage LWA, FEL,

Xcan

Coherent Amplification Network
POLYTECHNIQUE / THALES

From Prototype to Large Scale Applications

X CAN is an Ecole Polytechnique - Thales consortium to demonstrate that the CAN concept is capable to provide:

High Peak Power 100TW

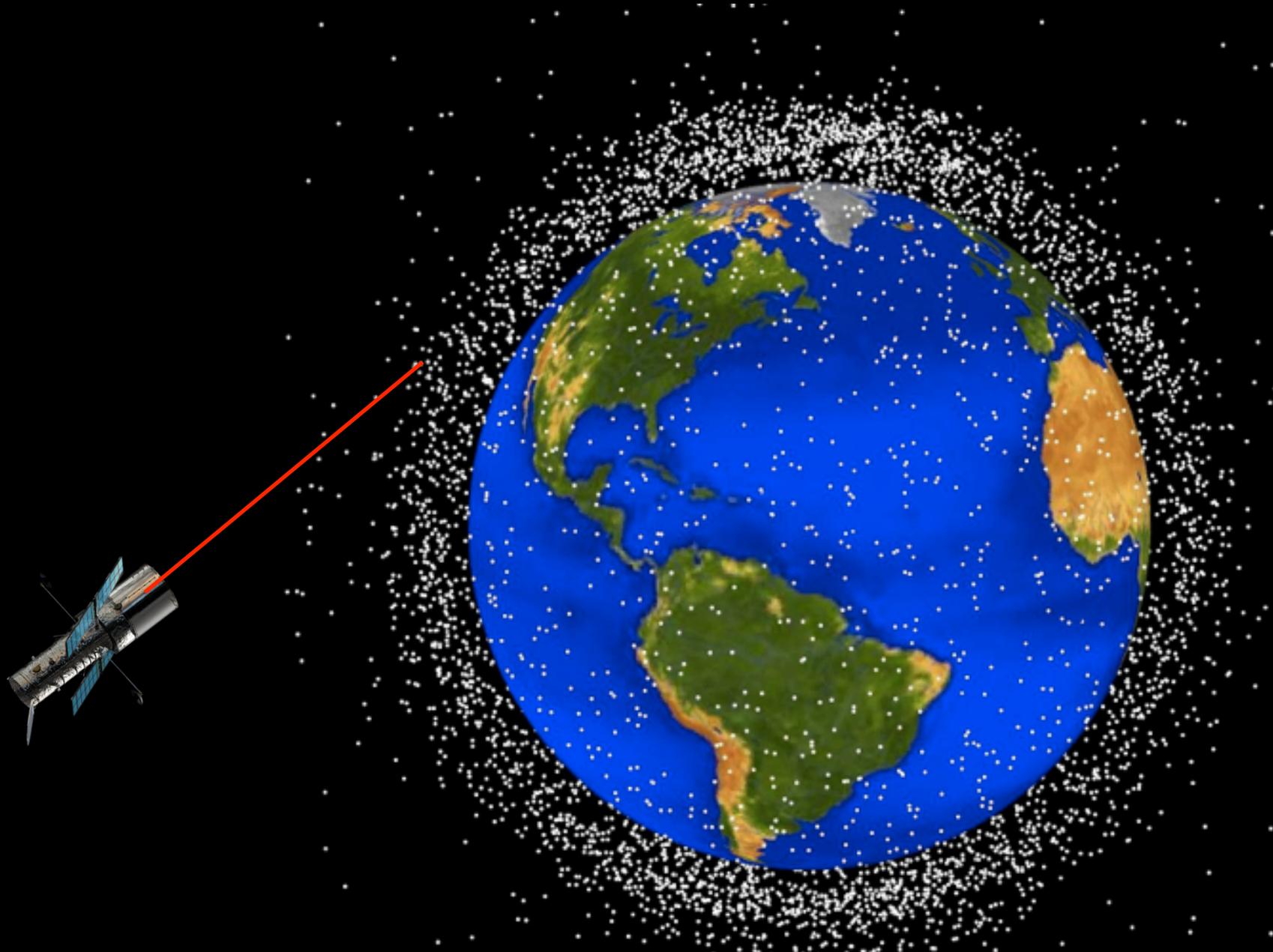
High Average power in the 100kW

High Efficiency >30%

A budget of 3M€ has been allocated to build a 61 high energy fiber prototype that will validate the construction a 10^4 fiber unit for grand scale applications.

ICAN Space Debris

Millions of orbital debris are cluttering space
ark Quinn, Remi Soulard, G. Mourou, IZEST-EP





Mourou Korea 2014

Conclusion

F. Sinatra

'The Best is yet to come'.

Thank you



IZEST
International Zeta-Exawatt
Science Technology



International
Year of Light
2015

Aknowledgements

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Rémi Soulard,

Ackowlegments

M. L. Zhou, X. Q. Yan Peking University, Beijing, China

J. Wheeler IZEST

N. Naumova LOA ENSTA

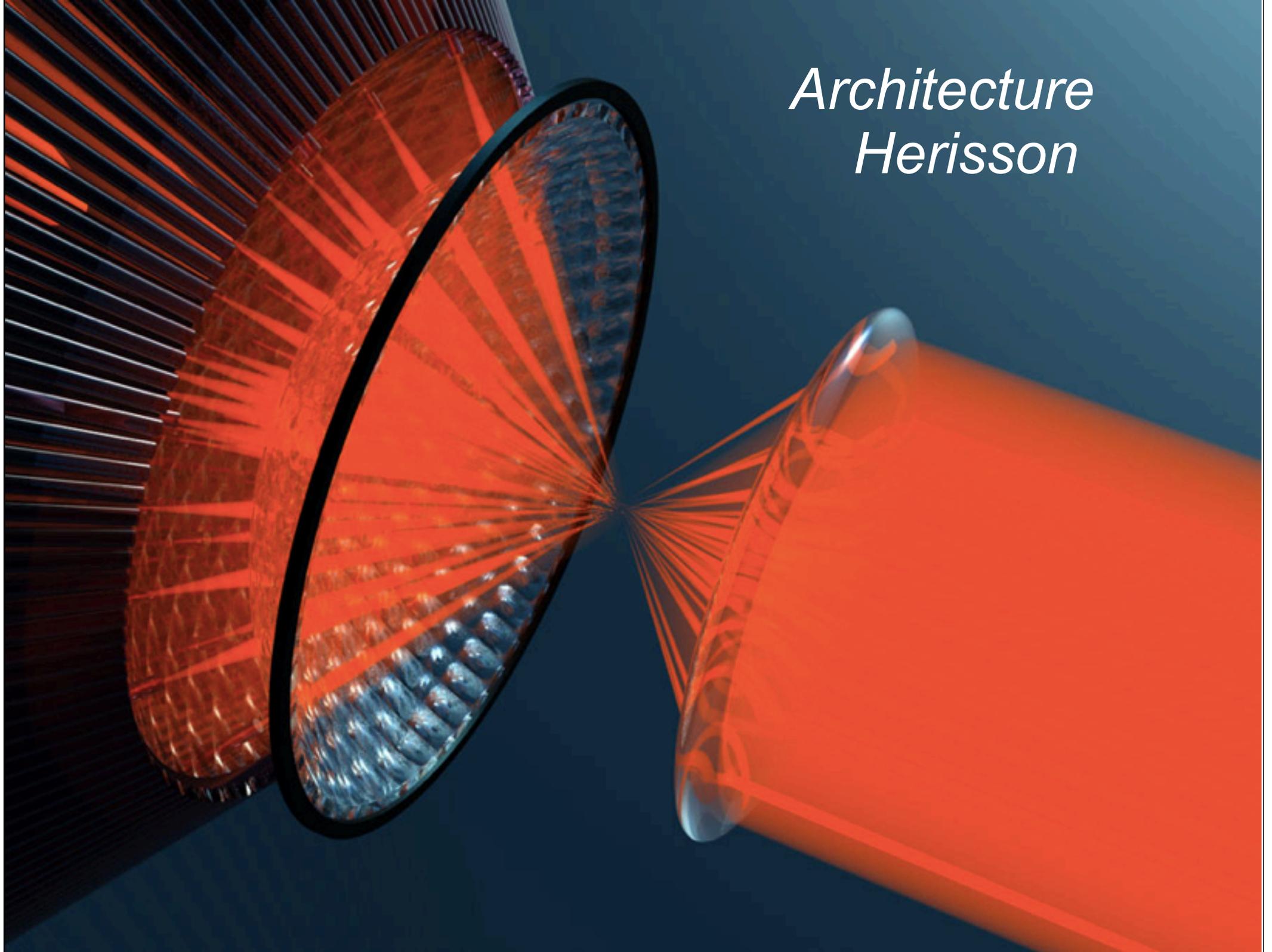
I. Sokolov U. of Michigan

T. Tajima Univerity of California Irvine

P. Chen Le COSPA Taiwan

S. Mironov, E. Khazanov and A. Sergeev, IAP Nizhny Novgorod Russia

*Architecture
Herisson*





CAN Basic Brick

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)

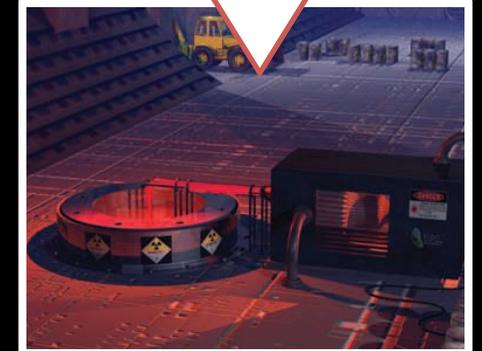
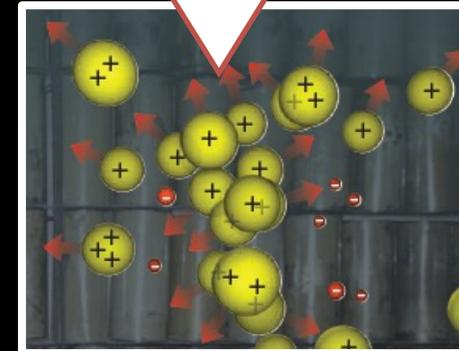
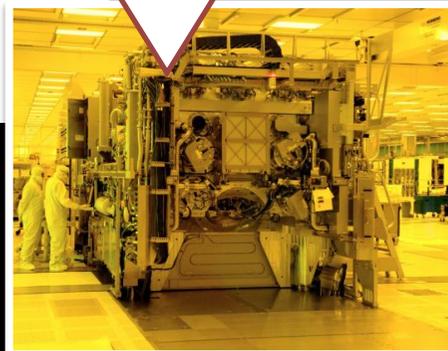
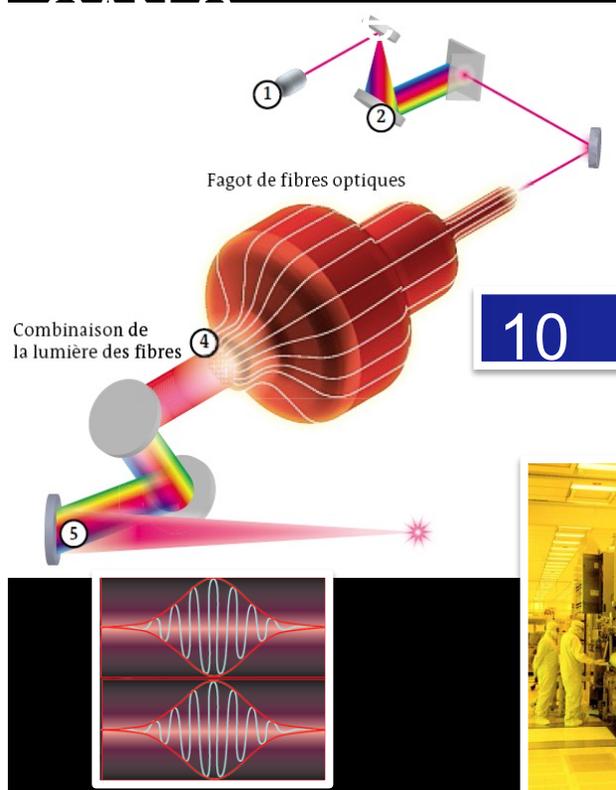
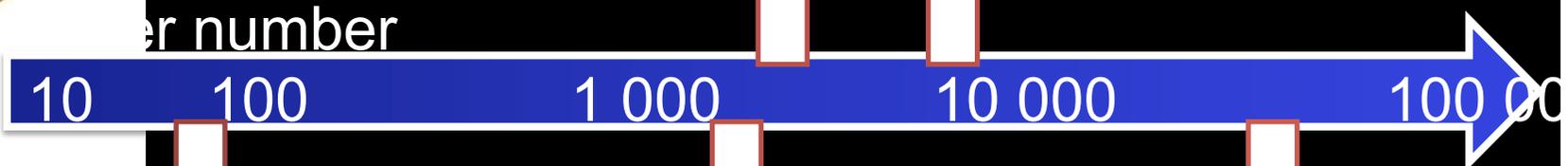
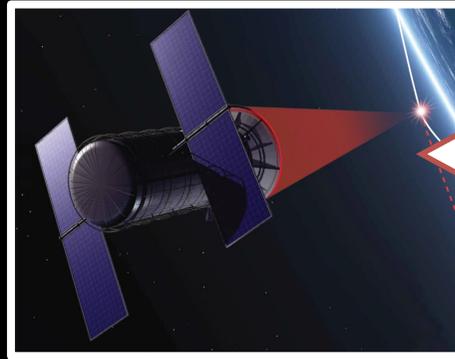
A Phased-Fiber-Array emitting 50J, 50fs will be composed of $2 \cdot 10^4$ fibers.

Is it conceivable?

Orbital debris removal

Particles

Acceleration



XUV Photolithography Chemical agent Neutralization Nuclear waste transmutation

The Pressure of Light?

$$I = 10^{23} \text{ w/cm}^2$$

10 millions Eiffel Towers on the tip of your finger!



Serendipity again!
Bridging Extreme Light
and Space Applications

Thin Plastic/Glass Optical Elements Can Have Good Optical Quality And Nonlinear Properties.

Unlimited size and very low cost



- . *Polyethylene terephthalate 0.7mm, 1.5TW/cm², B=3-4*
- . Very large aspect ratio, surface over thickness, Unlimited aperture inexpensive.
- . Uniformity within a fraction of λ .



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

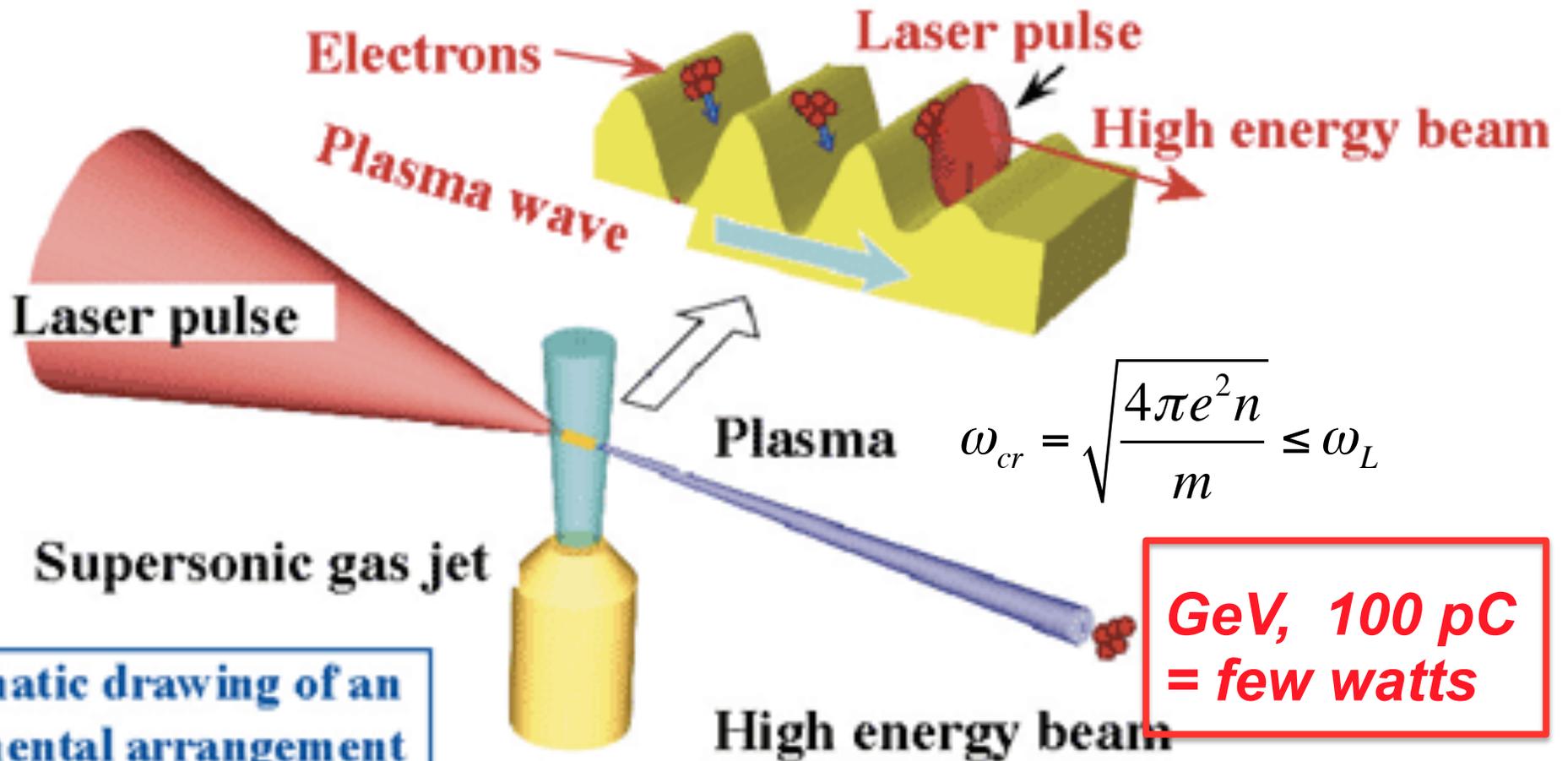
For 10^4 fibers , 6 pixels per fiber for a resolution of $\lambda/60$ @ 1kHz, off-the-shelf camera with 10^6 /1kHz are available.

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

Laser Wake Field Acceleration GeV/cm

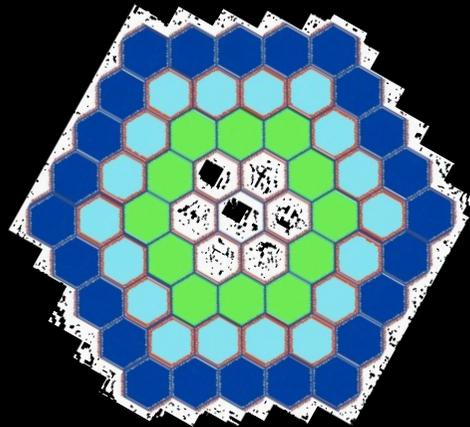
Tajima and Dawson 1979

A schematic drawing of the principle of acceleration



A schematic drawing of an experimental arrangement

61 channels
350 fs
>10 mJ
50 kHz



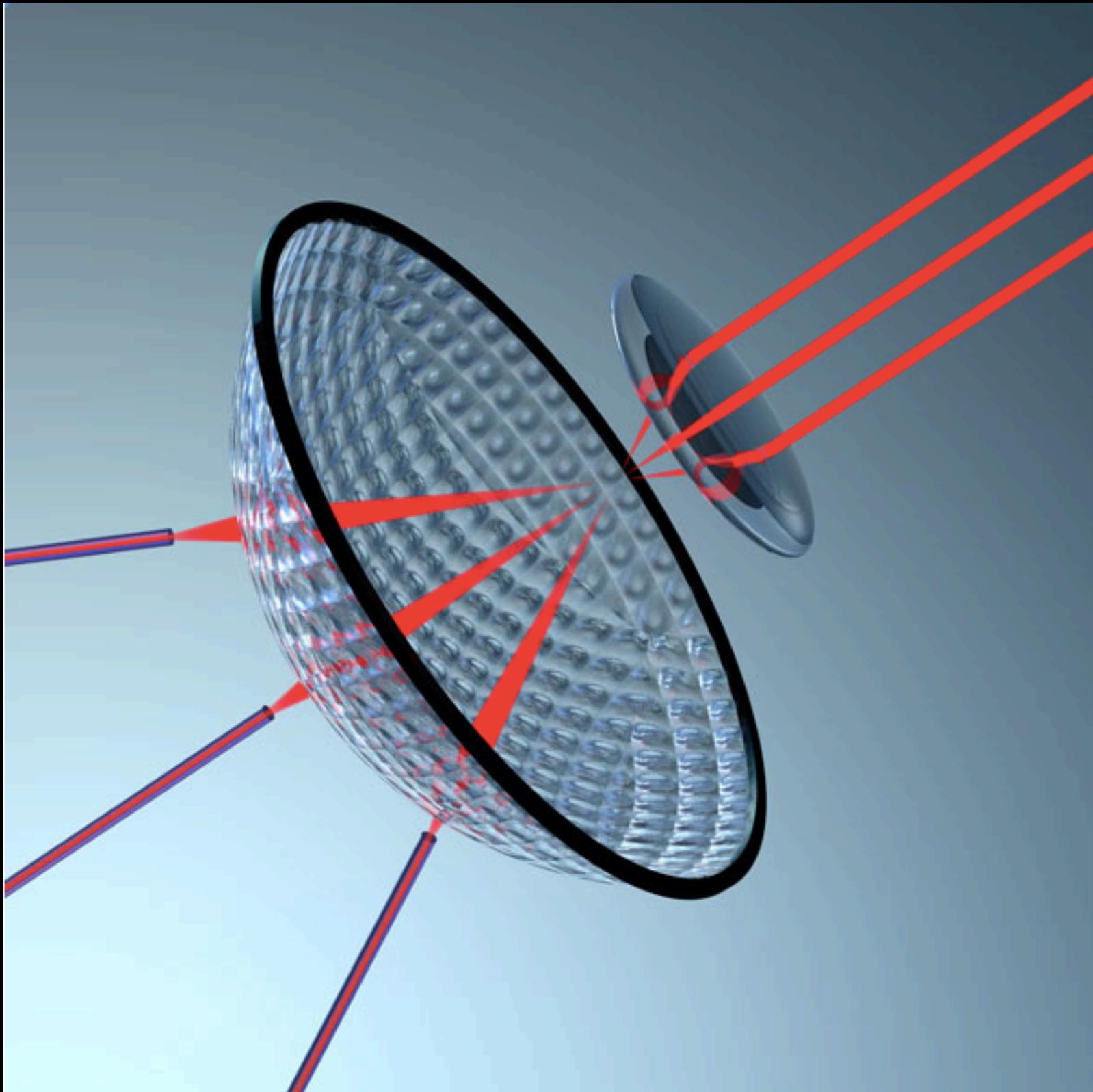
Where will the 4th Pillar be?

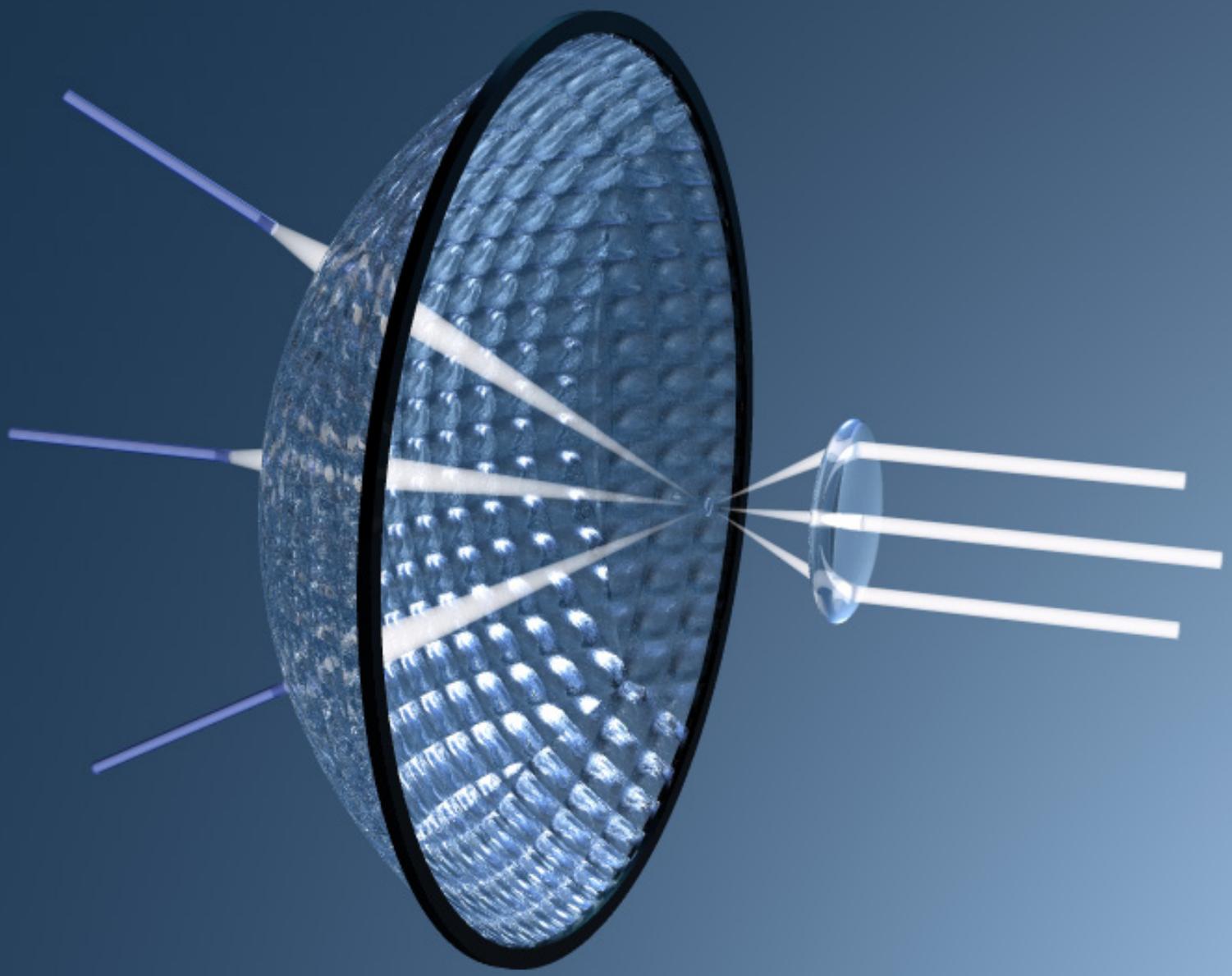


The 4th Pillar

Palaiseau (Apollon)
Nizny Novgorod (XCEL)
Kizu
Guanju
Shanghai
USA... Texas, MI. Ca,



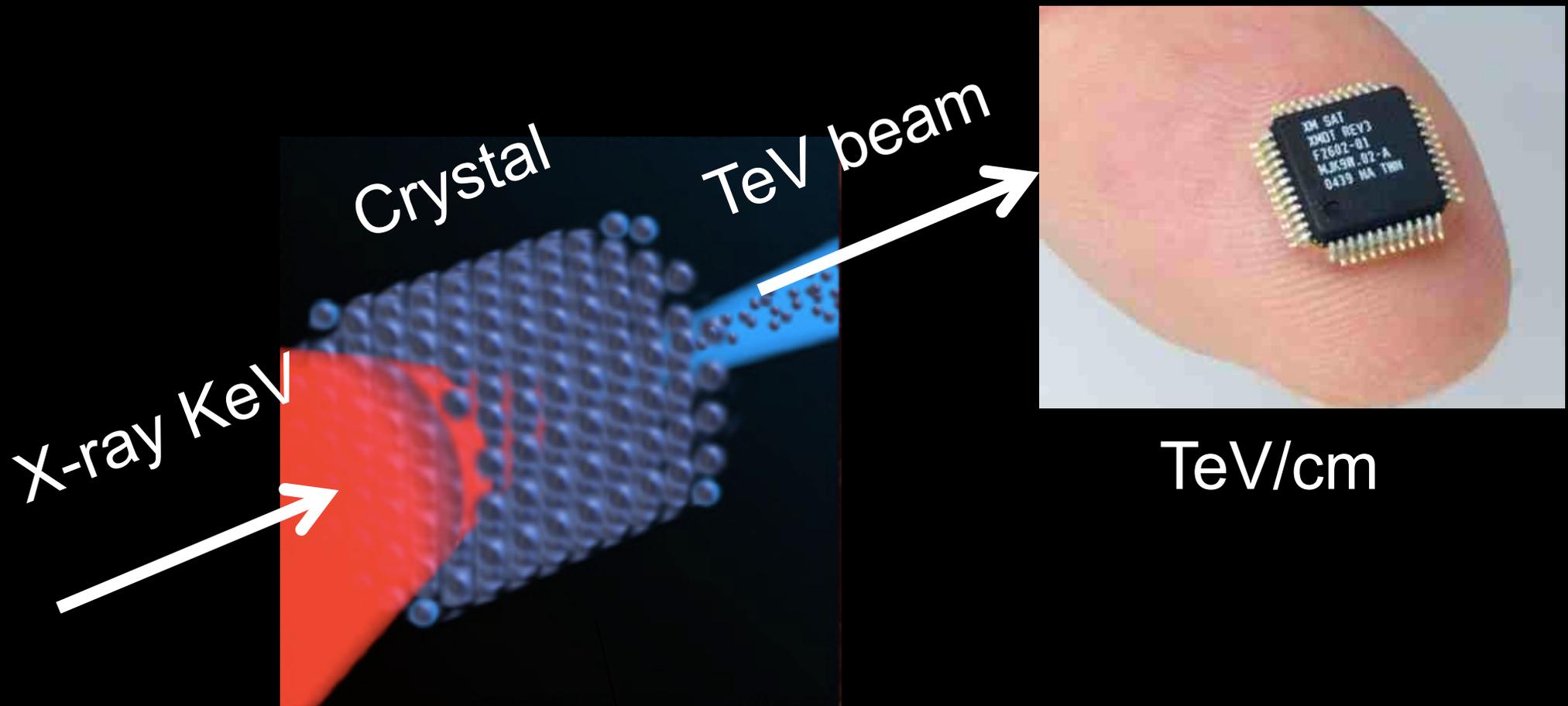




X-ray-Driven Crystal Accelerator

Increase of 10^6 in density

10^3 in Energy gain

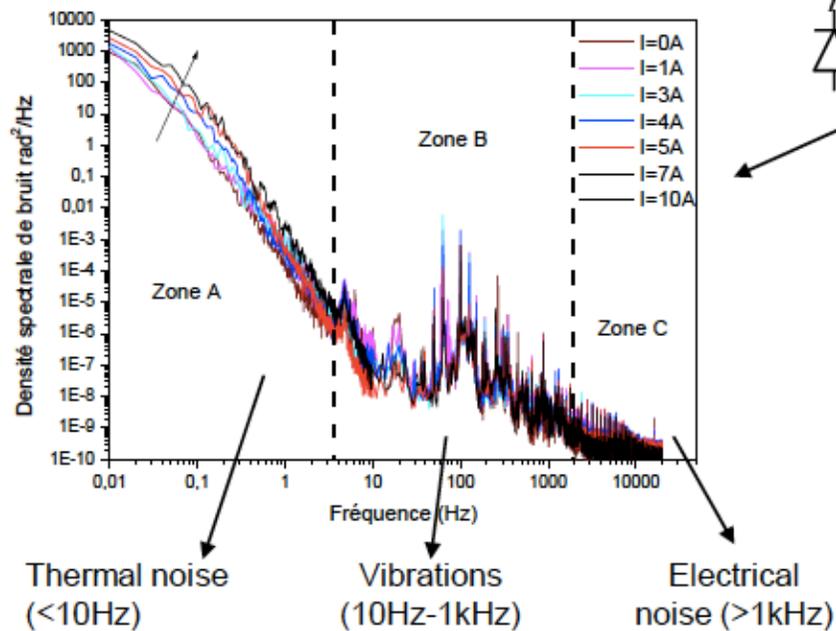




ICAN Sources of Phase Noise

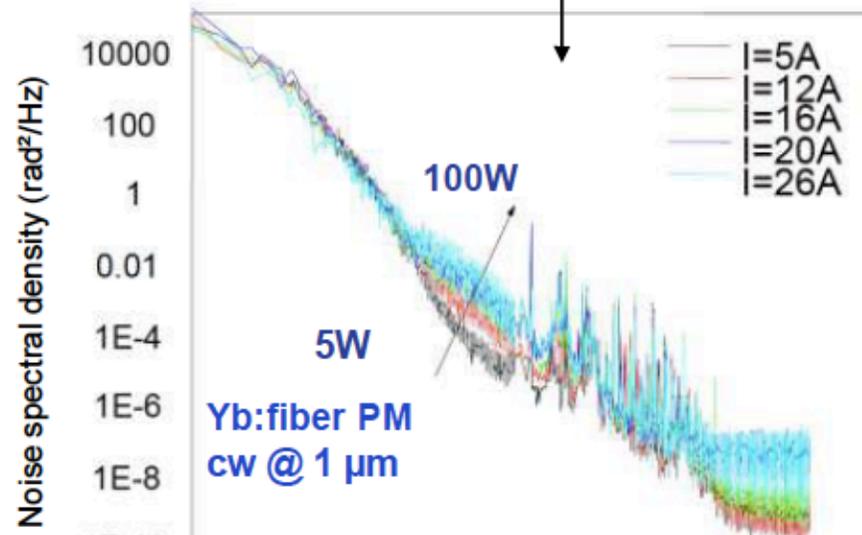
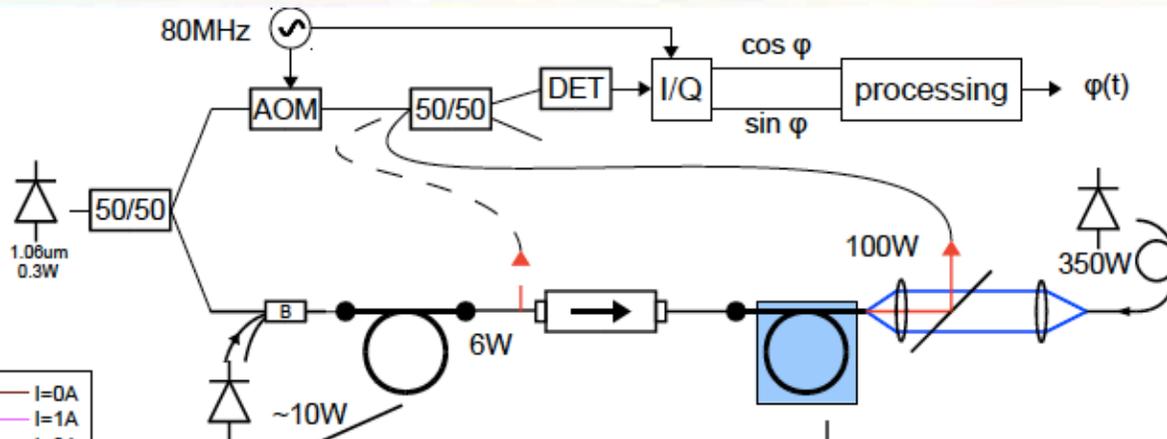


What are the main sources of phase noise?



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

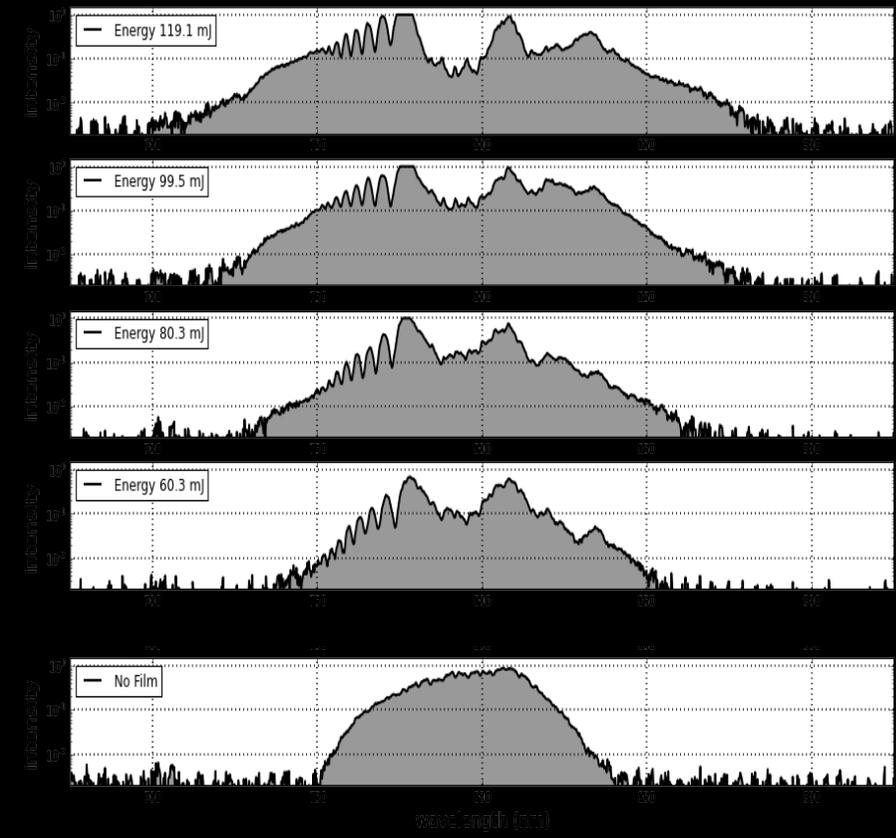
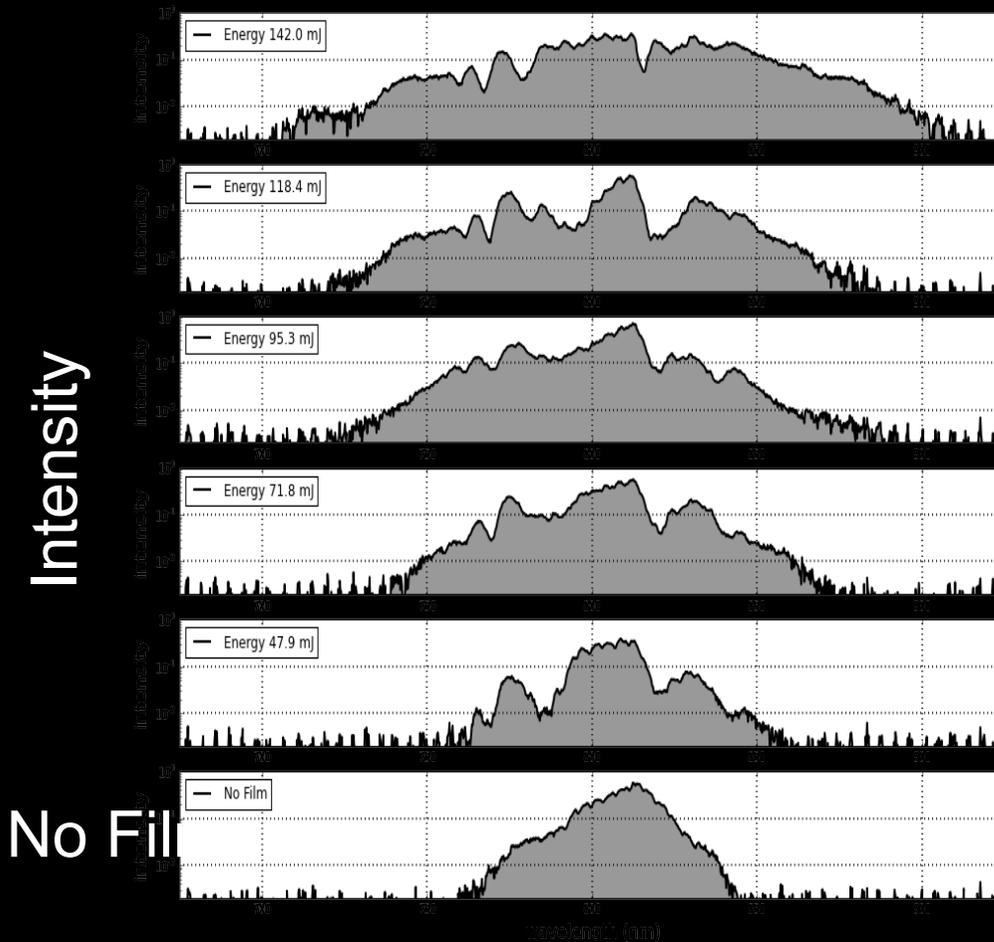
G. Mourou



Preliminary Experiment on PW CETAL (J. Wheeler et al)

Cellulose Acetate (0.5 mm)

PMMA (0.5 mm)



No Film

Vacuum is not nothingness but is full of activity i.e Quantum Fluctuations



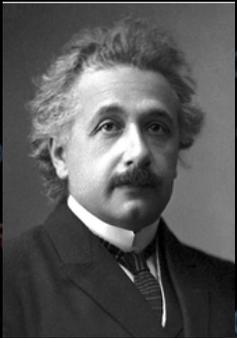
Fritz Sauter



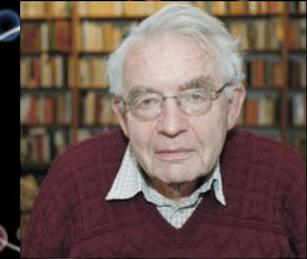
Werner Heisenberg



Julian Schwinger



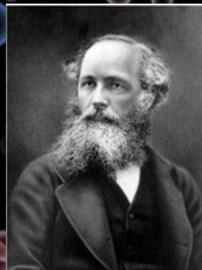
A. Einstein



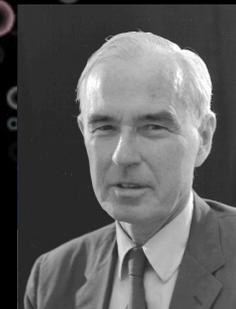
H. Casimir



L. Hertz



J. Maxwell



W. Lamb



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International
Year of Light
2015