CAN Lasers and Their Applications

The Einstein Lecture (2)
SIOM,Shanghai
September 9, 2013

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Acknowledgments for Collaboration: G. Mourou, C. Barty, W. Brocklesby, K. Nakajima, R. Hajima, T. Hayakawa, S. Gales, K. Homma, M. Kando, S. Bulanov, B. Holzer, T. Esirkepov, , F. Krausz, D. Habs, B. LeGarrec, J. Miquel, W. Leemans, D. Payne, P. Martin, R. Assmann, R. Heuer, M. Spiro, B. Holzer, W. Chou, M. Velasco, J.P. Koutchouk, M. Yoshida, T. Massard, G. Cohen-Tannoudji, V. Zamfir, T. Ebisuzaki, R.X. Li, X. Q. Yan, X. M. Zhang, B.F. Shen, R. Sheffield, J. Limpert, D. Payne, K. Koyama, A. Suzuki, Y. Okada, K. Ishikawa, N. Rostoker

IZEST

I would like to dedicate this lecture to Prof. Norman Rostoker, my mentor.

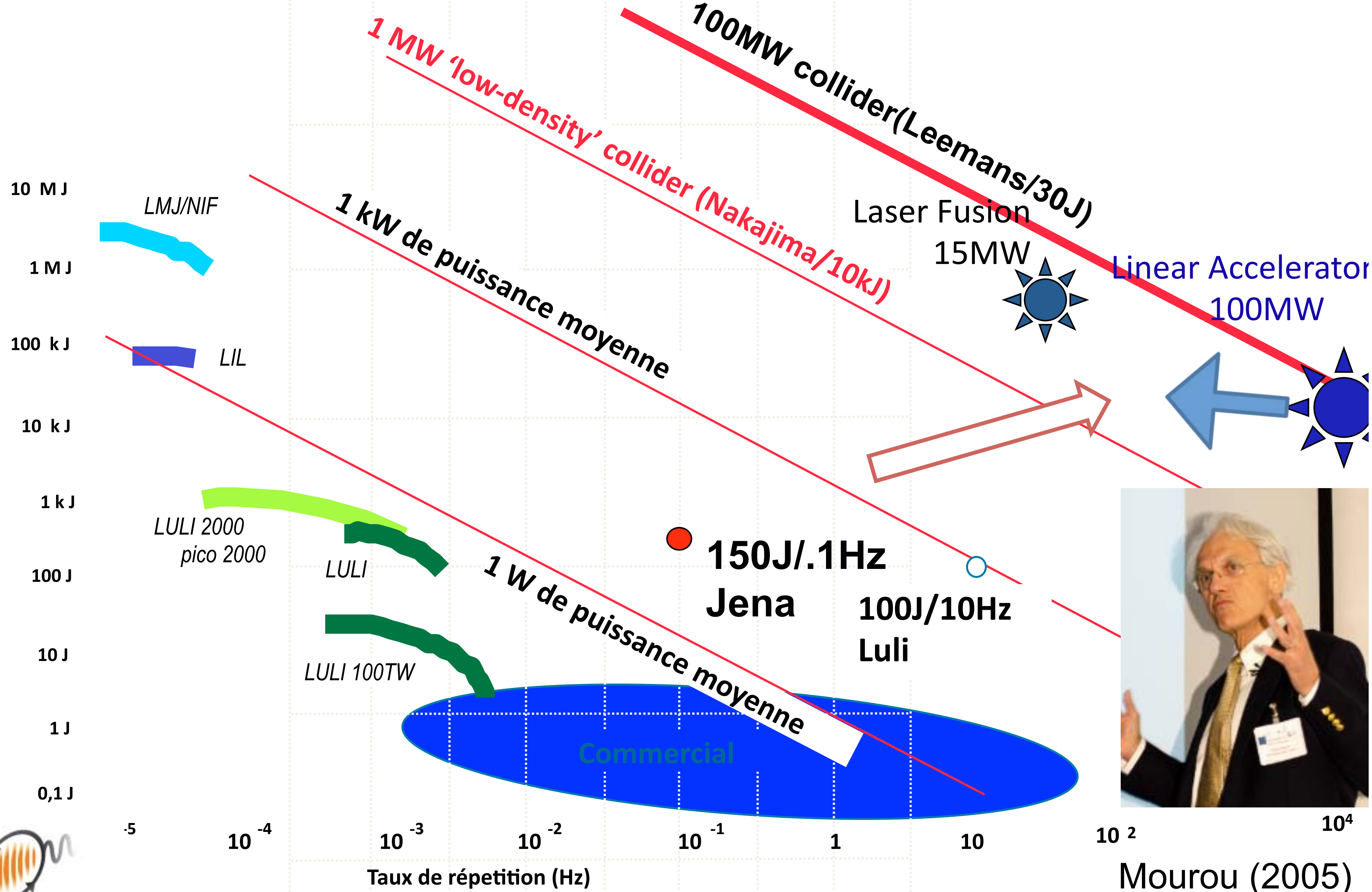
ican International Coherent Amplification Network

Content

- From W to MW (on average power)
- Fiber laser properties
- Coherent addition of phases and CAN laser
- Smart laser: digital phase control
- High energy accelerators: $e^- e^+$ collider, $\gamma\ \gamma$ collider, dark field search
- Opportunities enabled by CAN laser: high rep rate, high efficiency, high controllability
- Brilliant directed laser Compton γ-beam: nuclear resonance fluorescence (radioactive waste monitor); nuclear medicine/ pharmacology; positron source; cold neutron source
- Laser ion accelerators: compact proton therapy; hot neutron source for ADS/ADR

It’s a light bulb.

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



Mourou (2005)

Mourou/ICAN (2013); Nakajima (2011)

IZEST

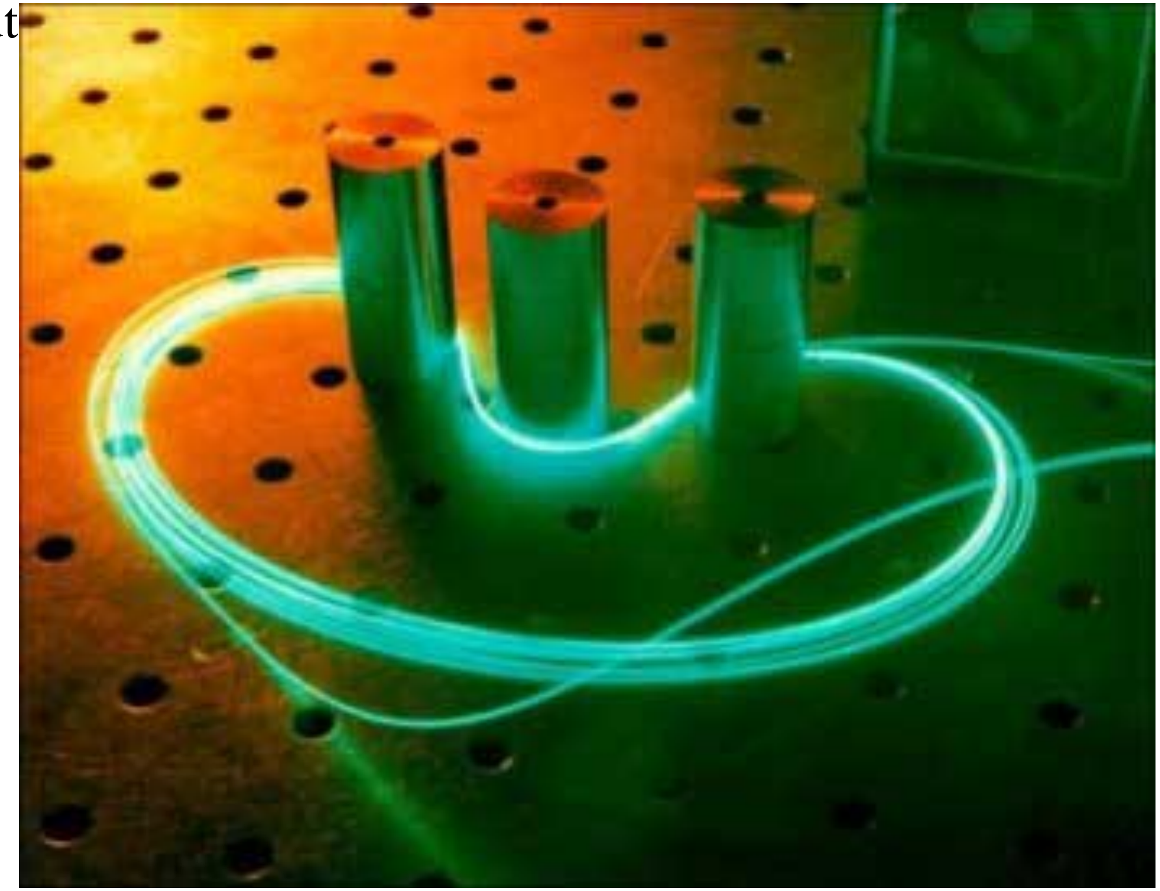
(International Center for Zetta- Exawatt Science and Technology)

aspires to push the average power
of ultraintense laser from **Watt** to **MW**

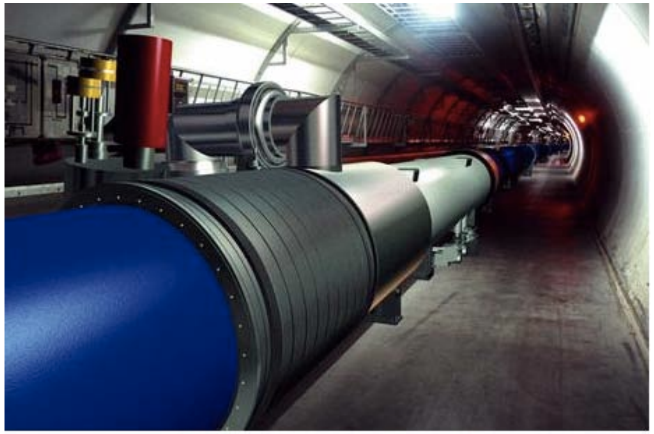
(ICAN-International Coherent Amplification Network)

Bulk vs. Fiber Lasers (CAN)

- 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
- mass-produced at low cost.

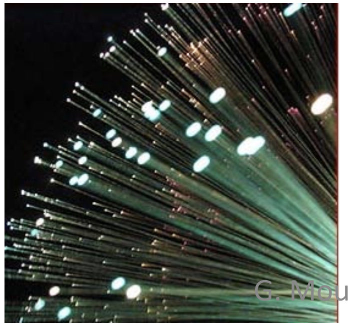


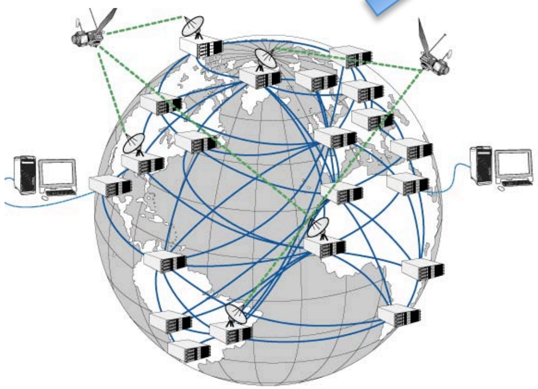
Laser Acceleration-Telecom Virtuous Cycle



WWW
Tim Berners-Lee

Optical Fiber
Charles Kao





Coherent Amplifying
Network+ Laser Wake Field

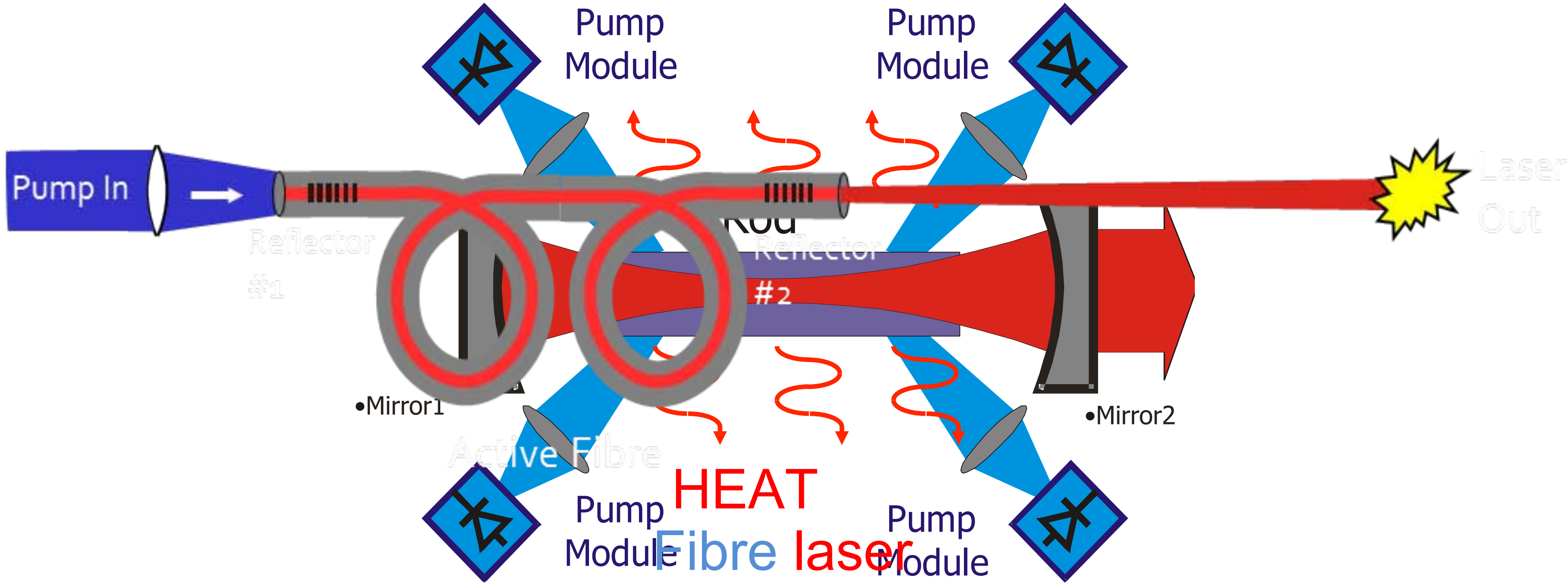
Rationale for fiber laser

- ***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



Conventional Laser

What is a fibre laser?

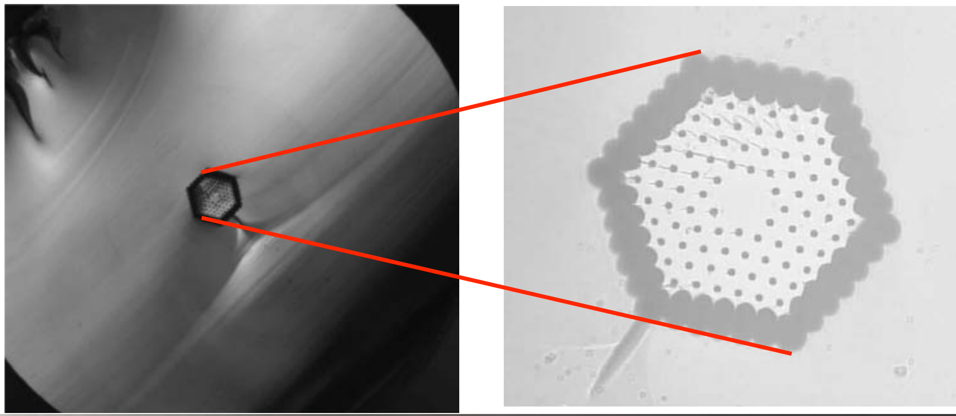
D. Payne

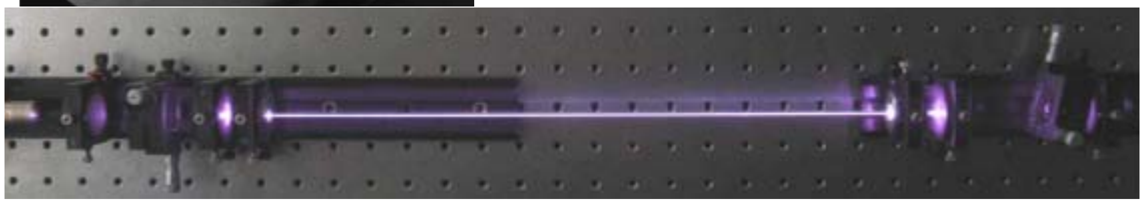
Fiber lasers withstand heat because:

- Large surface area
- Core is close to heatsink
- Guided mode resists thermal distortion
- Silica has excellent heat resistance

Another Approach:
Single-mode core with very low NA

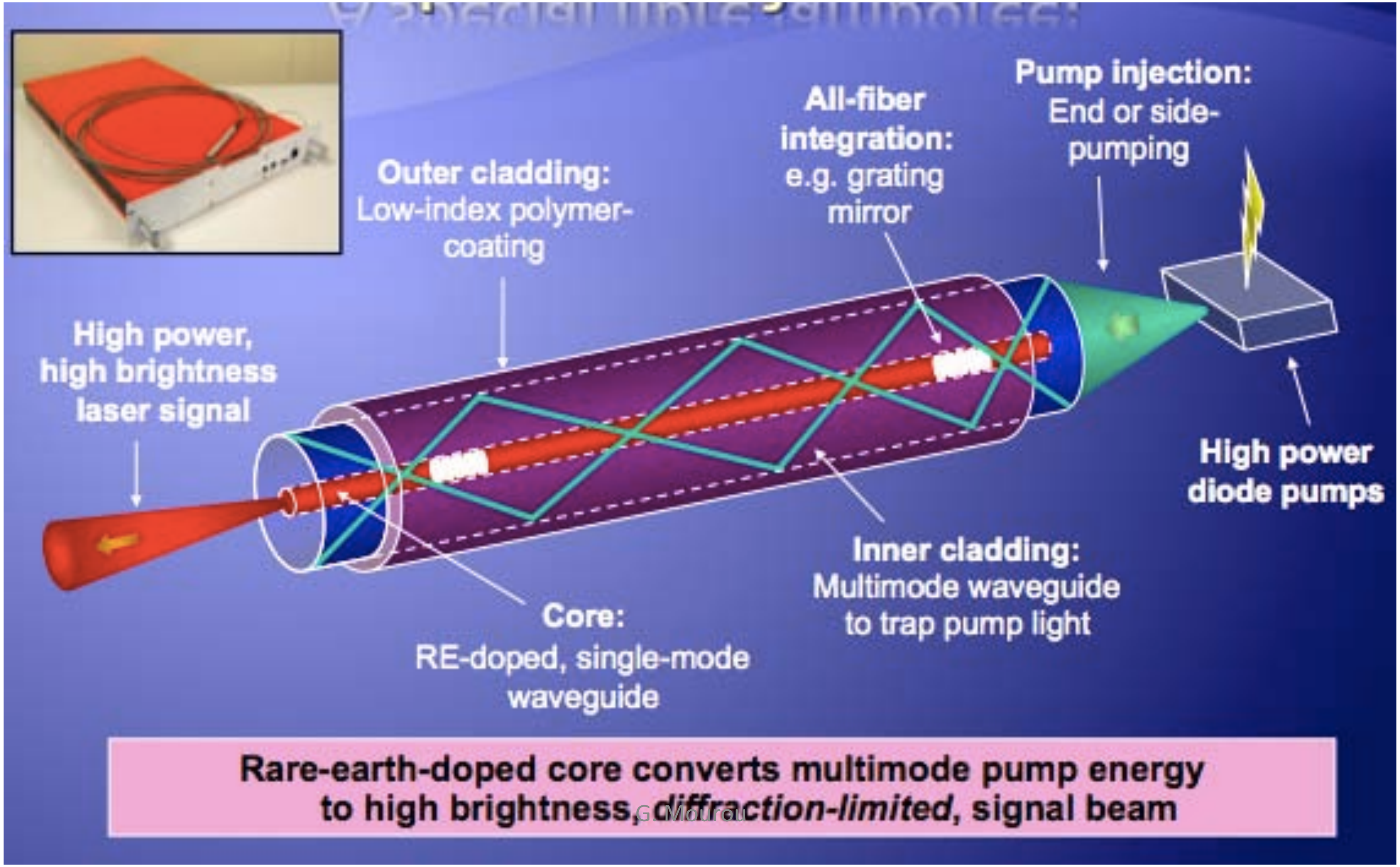
- Because of low NA, fiber needs to be straight to suppress macro-bending losses
  - Therefore must be short, up to 0.5 – 1 m?
- 1 kilowatt limit suggested
  - Tino Eidam, Stefan Hanf, Enrico Seise, Thomas V. Andersen, Thomas Gabler, Christian Wirth, Thomas Schreiber, Jens Limpert, and Andreas Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," *Opt. Lett.* ***35, 94-96 (2010)***



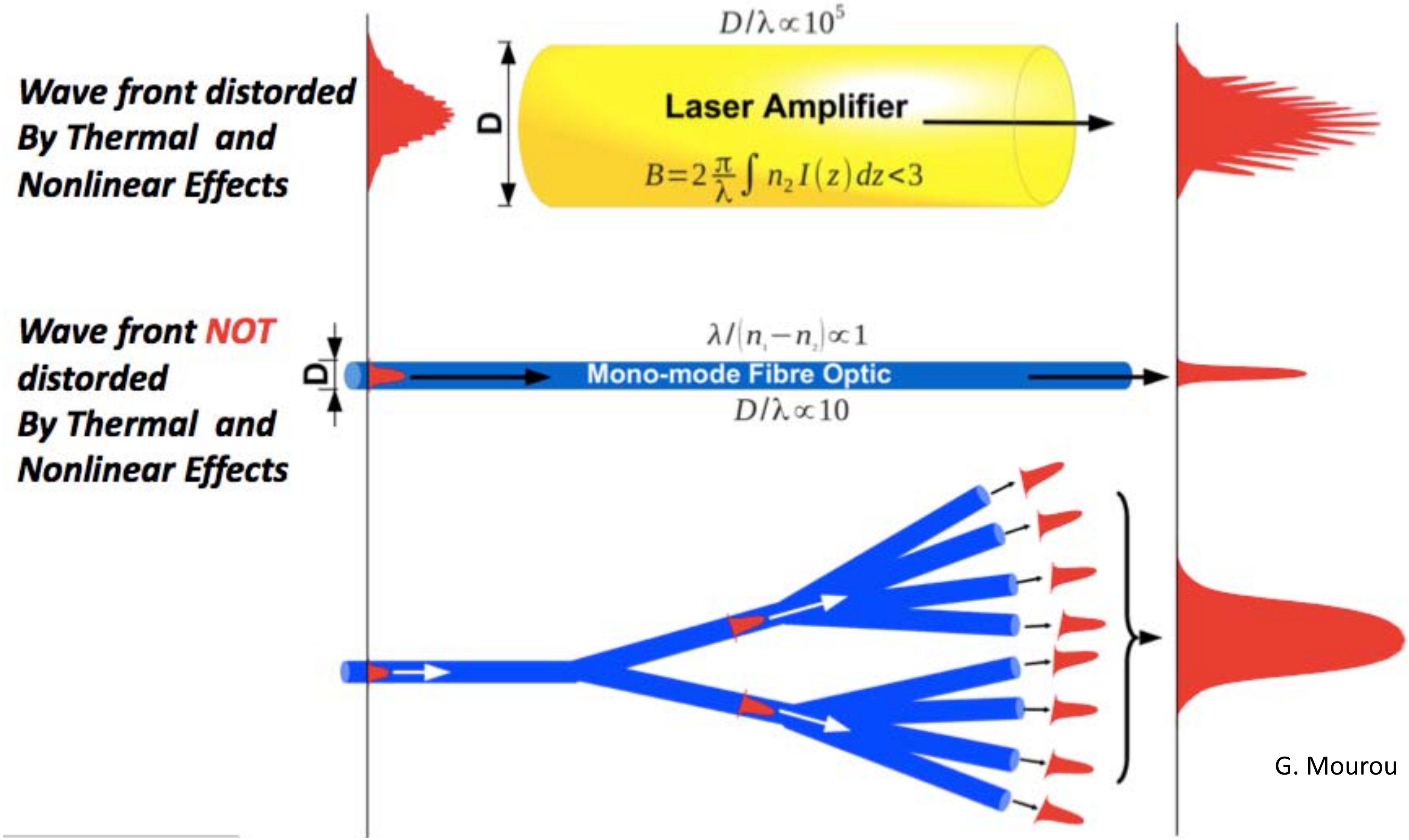


D. Payne

The basic brick: the Yb doped Single mode fiber



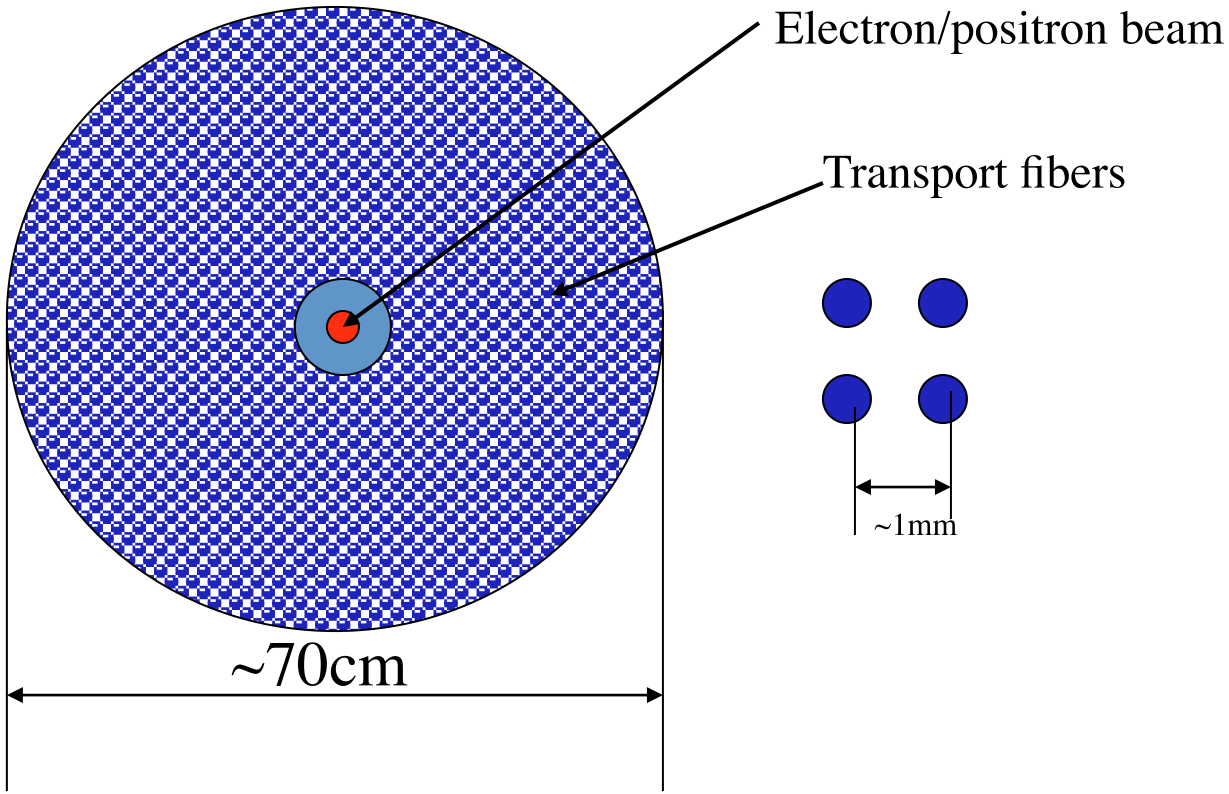
Laser beam quality: bulk vs. fiber



G. Mourou

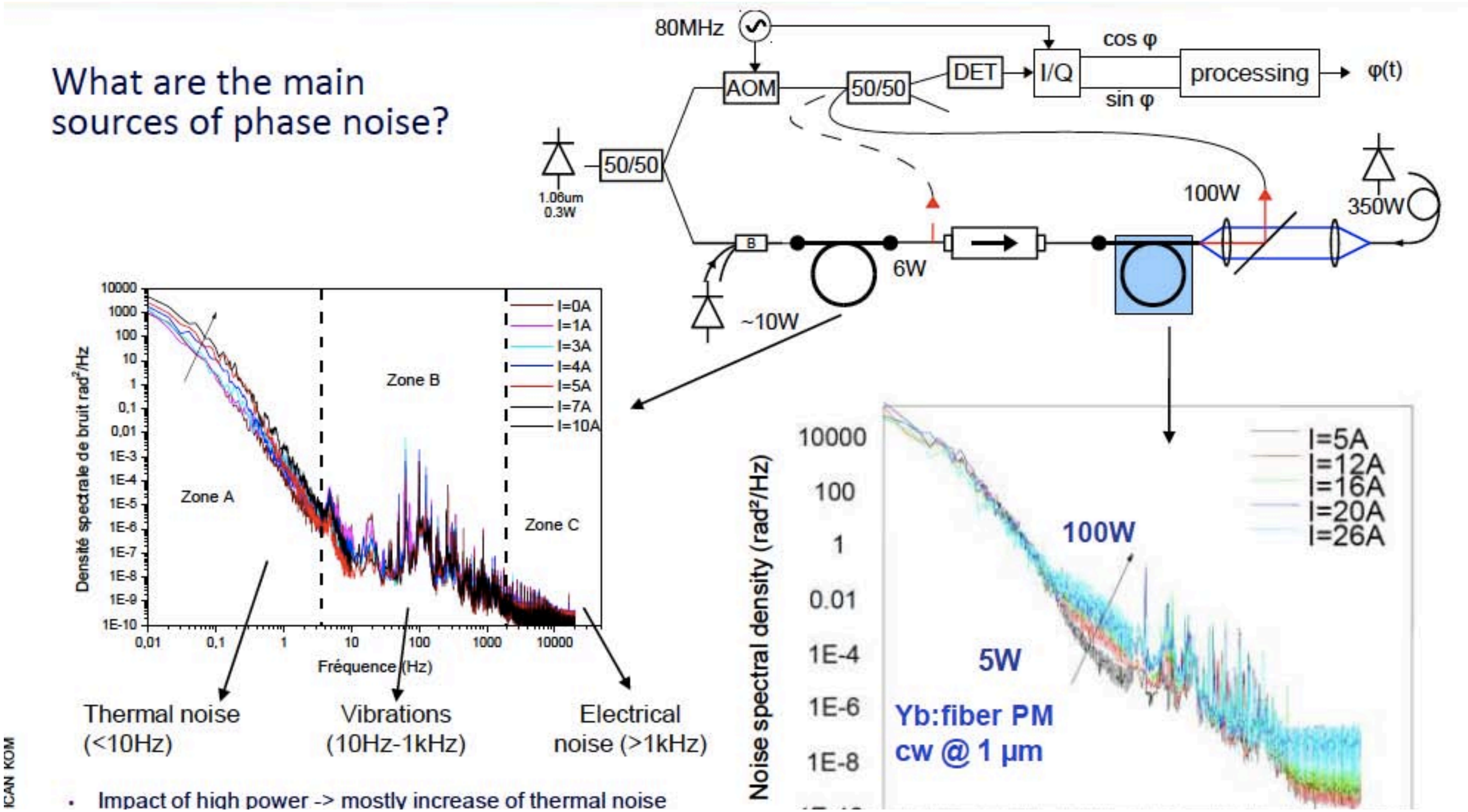
However, Need to Phase
1mJ/fiber~ 30 10^3 Phased Fibers!!

(G. Mourou patent 2005)



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

Phase-coherent addition: Feedback control of major noise



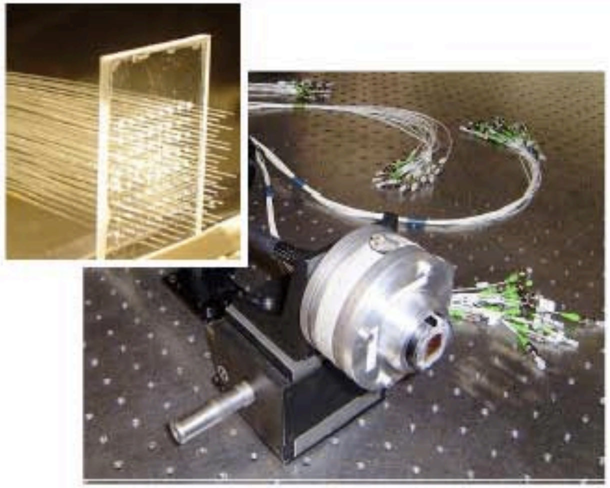
Nature Photon. 2013 (Mourou, W. Brocklesby, T. Tajima, and J. Limpert.)

Microlens Arrays for Phase Control

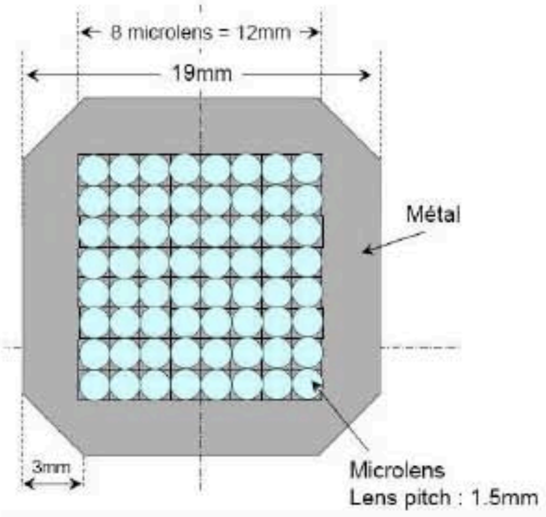
1. Fiber and microlens arrays

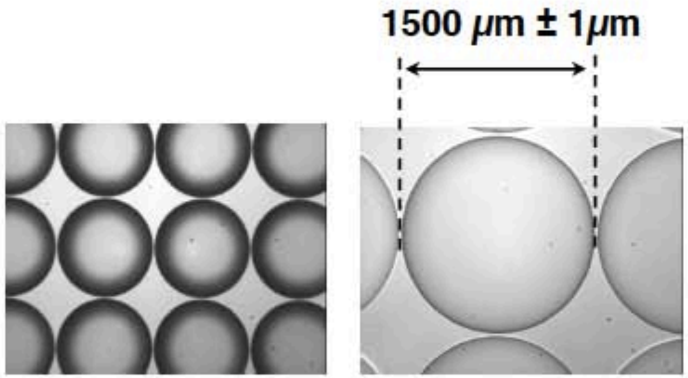
Fiber array:

- 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:

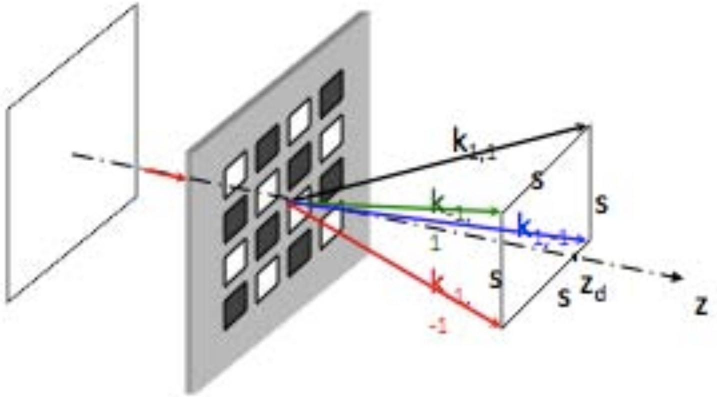




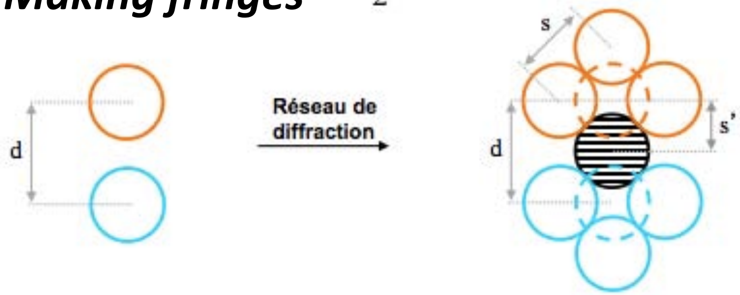
THALES

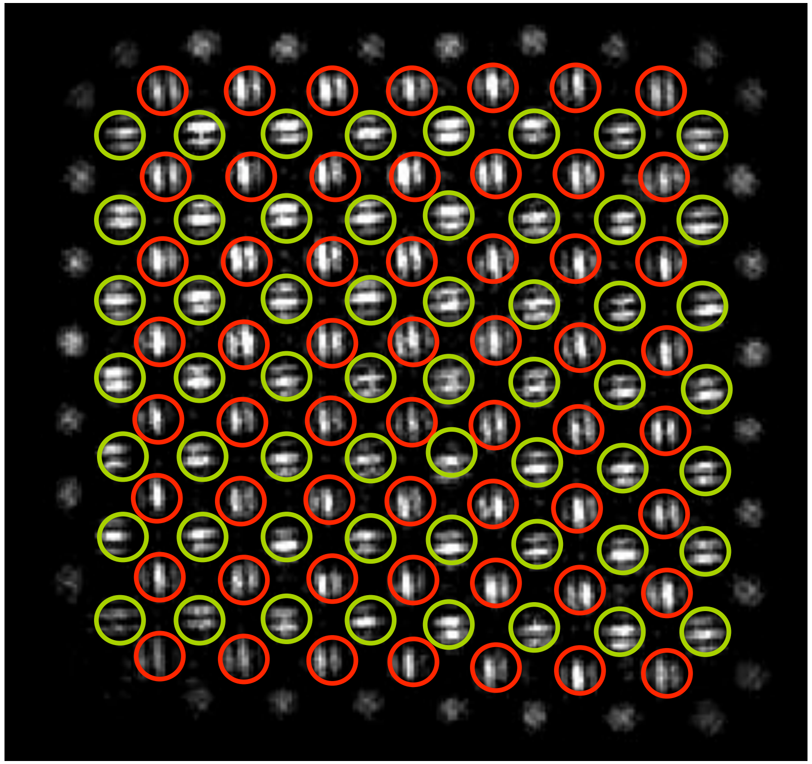
Phase Noise Measurement with a Quadrilateral Shearing Interferometer

1) Grating Making 4 replicas s of each fiber



2) Neighbor fibers interfere with replicas Making fringes



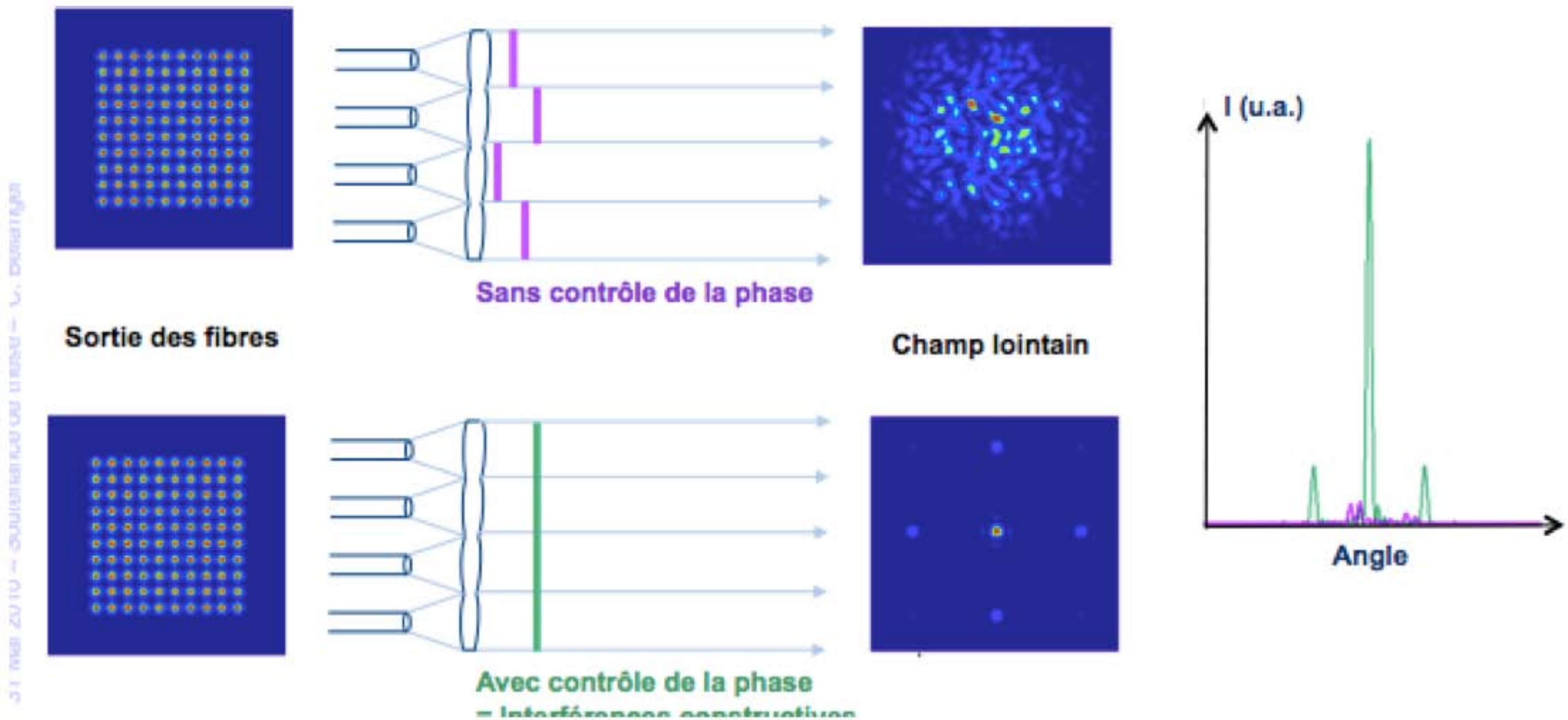


3) A phase map is captured every ~30ms making possible phase correction with phase modulator

G. Mourou

Coherent amplification

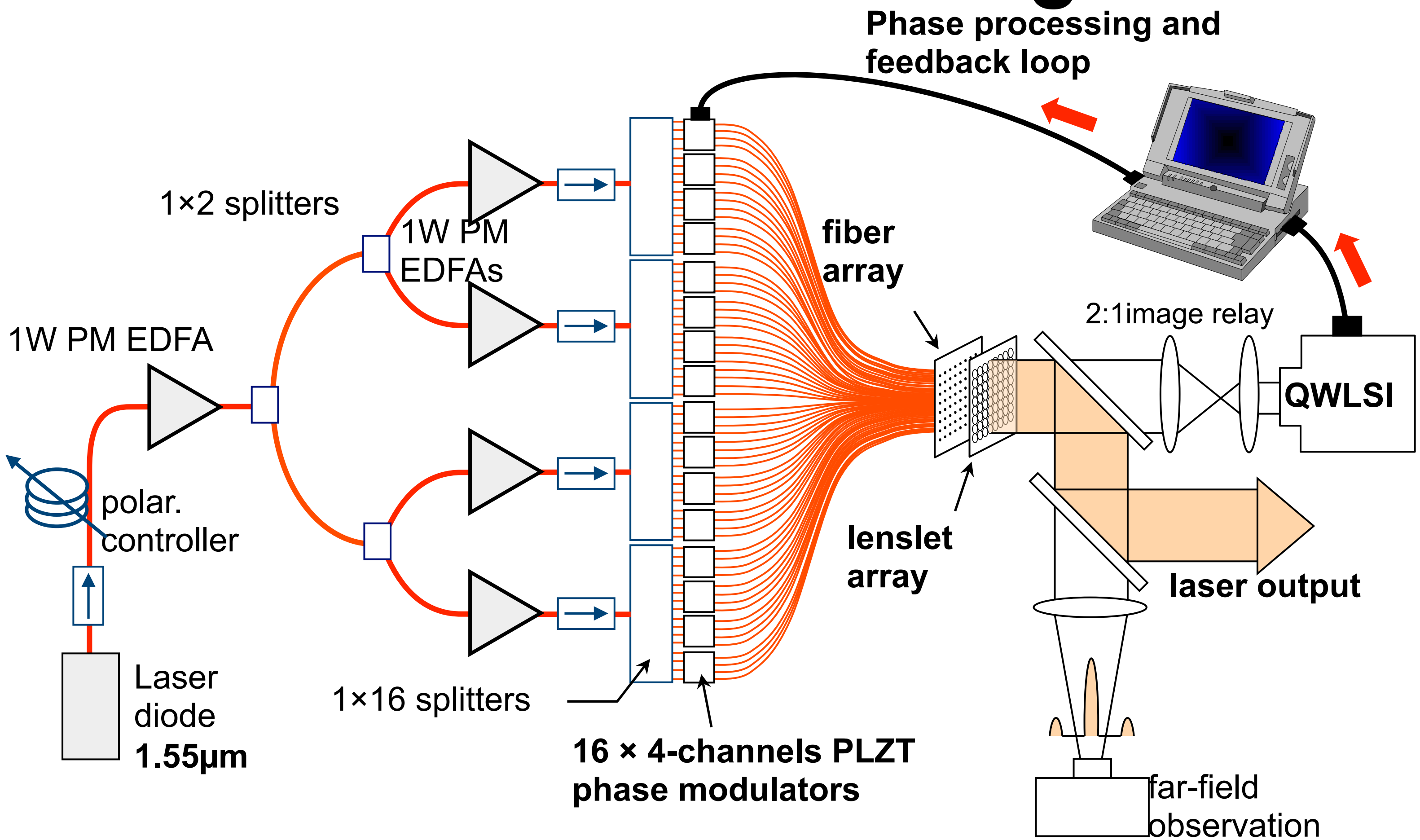
After <u>attosecond phase control</u> discussed before, voila!
= pristine laser



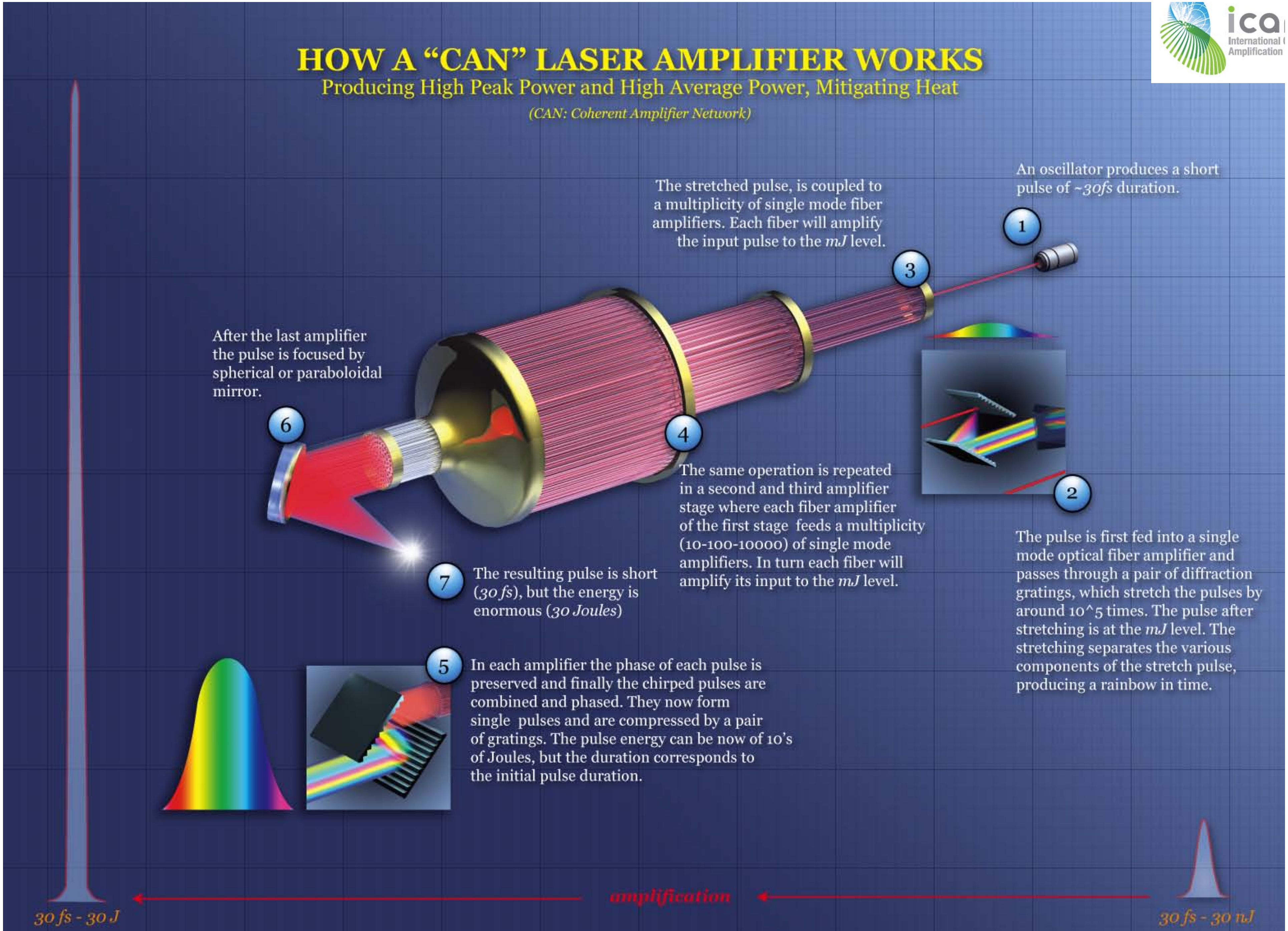
G. Mourou et al.

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

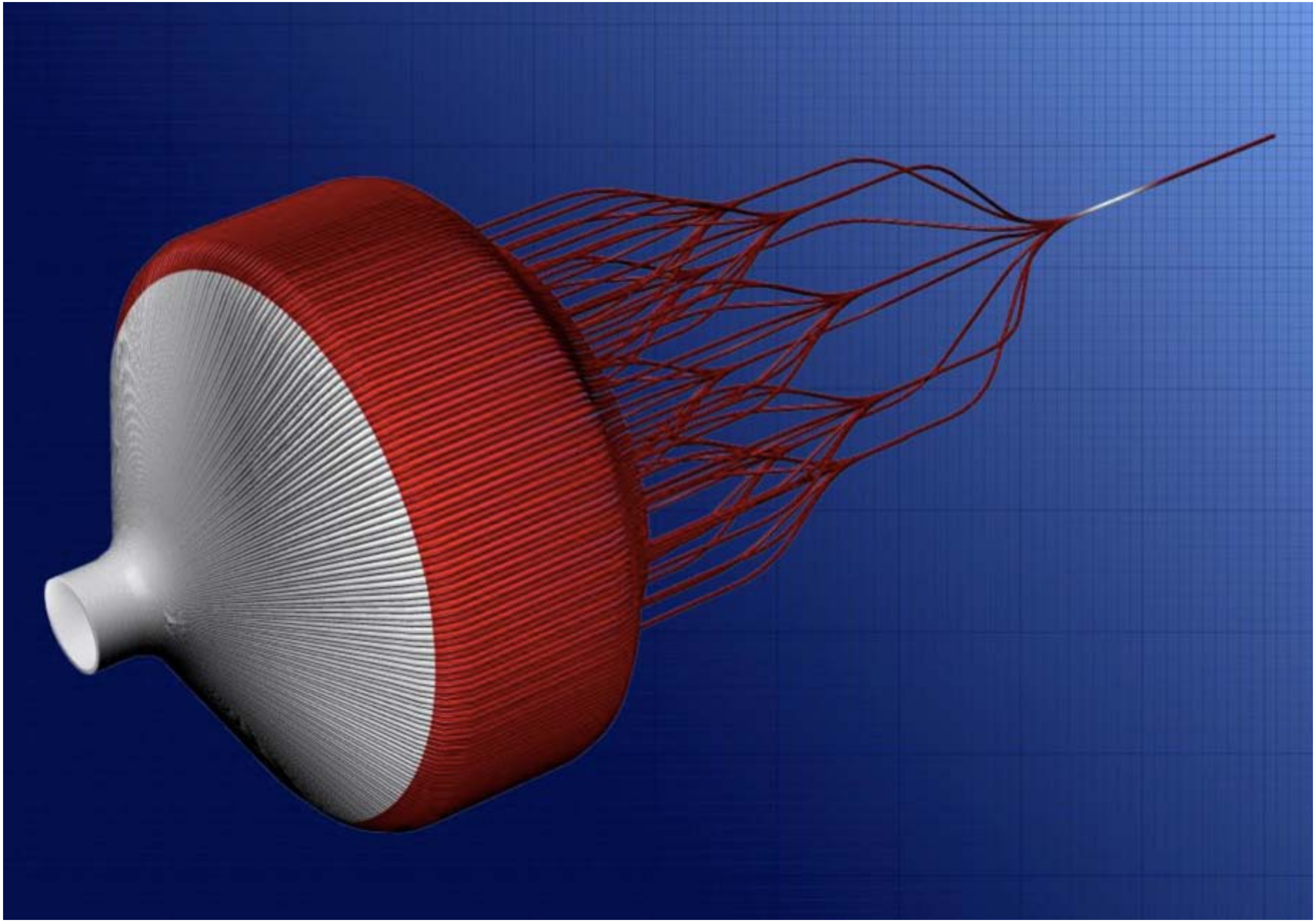
Coherent Fiber Combining



Achievement 2011
→ 64 phase-locked fibers

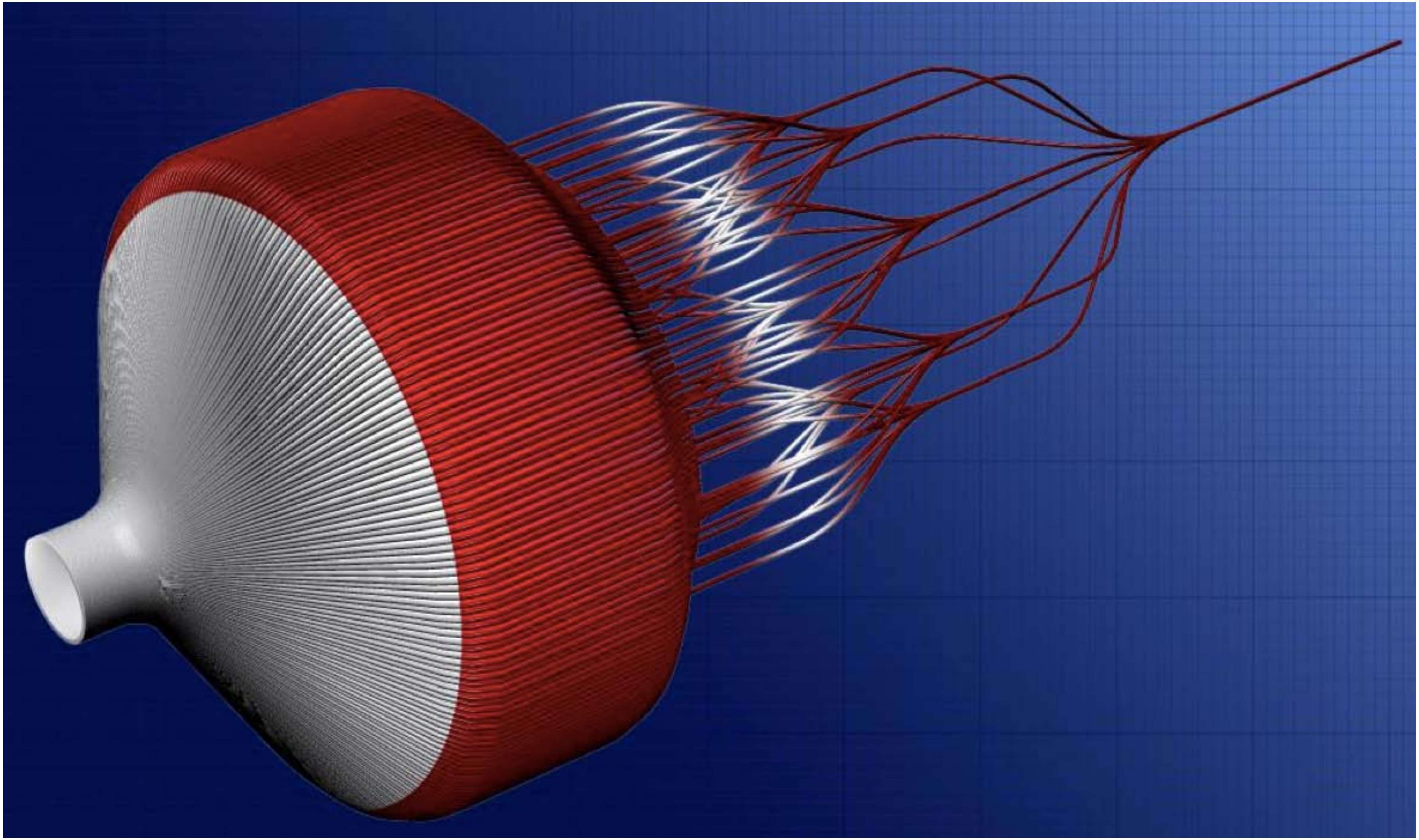


(Mourou, Brocklesby, Tajima, Limpert, 2013)



CAN laser

G. Mourou et al.



G. Mourou et al.

Cardinal properties of CAN Laser

- ***Total phase and amplitude control of each fiber :***
- ***High precision on the phase <1% and amplitude <1%***
- ***High spatial definition 10^6 fibers.***
- ***Extreme agility ~ 1kHz***

Digital control of laser

We see additionally:

CAN laser property of **smartness**

higher rep rate, easier to operate CAN laser

higher rep rate, easier to feed-forward control

feedforward control → quality of beams

CAN laser : coherently connected (both in *parallel*, but also in *tandem*)

each fiber (digital unit): coherently and digitally controllable

→ **digitally** controlled **smart laser :** a new paradigm

Emittance (and thus luminosity) of the particle beam

rapidly increases with the jitters of laser [in multi-stage acceleration, Cheshkov et al.2000]

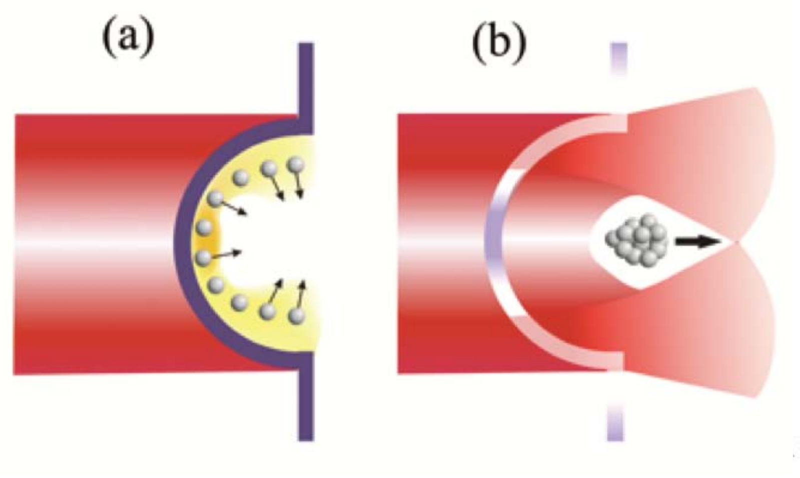
smart control of laser →contains jitters

Sensitivity of the laser phase

In many further applications, delicate control of the laser: **paramount**

- Ion acceleration---
  - concave phase front arrangement (Tajima patent 2001; Yan)
  - focusing of ion beams (Wang/Yan)
- Intense fields---
  - focusing multi-beams of laser in the dipole pattern (Sergeev)
- Direct electron acceleration---
  - specific phase delay of laser pulses (Pukhov)

etc.......



013107-6 Zheng *et al.* Phys. Plasmas **20**, 013107 (2013)

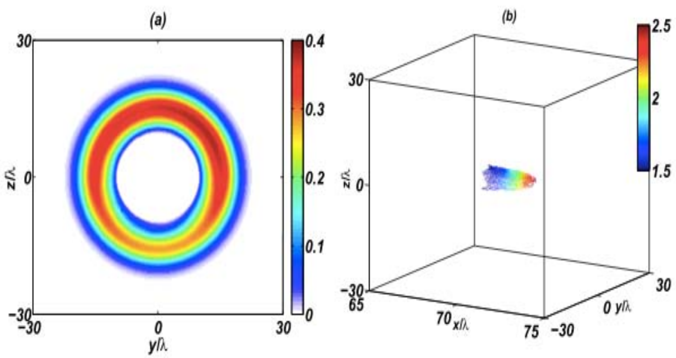


FIG. 6. (a) (z, y) section of the square root of the laser front intensity $\sqrt{E_y^2+E_z^2}$, normalized by $\mathcal{E}_0$; (b) energy density of the accelerated protons (in units of GeV), at $t = 80T$.

Opportunities Enabled by CAN

CAN Fiber Laser

Average power
rep rate x peak power
Efficiency
Smartness (digital control)
Intensity

Collider requirements

Average power → luminosity
Efficiency → cost
Smartness (digital control) → emittance
Intensity → gradient

R. Aleksan (Court. A. Oeftinger(CERN))

γ-γ collider requirements

1-50kHz rep rate (other reqs are easier)

Dark matter search

average power → luminosity

Proton acceleration

intensity (energy of beam), smartness (beam quality), average power (fluence)

much more

University of Southampton
Fraunhofer IOF
CERN

ICAN Applications

Scientific : (Sept. 6)

- **Laser acceleration toward TeV**
- **Higgs factory with γ-γ collider**
- **Physics beyond the Standard Model: Dark Matter search with laser**
- **ZeV astrophysics (astrophysical manifestation of wakefields)** inspires us

Societal:

- **Laser proton acceleration and applications:**
  - Neutron sources (high energy)
  - Accelerator Driven System(ADS) for transmutation of nuclear waste
  - Accelerator Driven Reactor(ADR) for safer energy production
  - compact proton therapy
- **Laser-driven gamma beam applications:**
  - Fukushima (isotope identification of molten fuel)
  - Homeland security
  - pharmaceutical, nuclear medicine
  - positron source, cold neutron source

Cost estimates (trial)

Linear collider (ILC @ 250GeV x 250GeV)

~8MW (in beams), cost for accelerators ~ 4GEuro

→ ~500Euro / W (beam)

Laser-driven collider (if we design @ 250GeV x 250GeV)

same at 8MW (in beams)

laser diode 7*Euro / W x 3 (to give total optics) = 21Euro/W

assume efficiencies: laser/wallplug =0.5, compressor=0.4, excitation of wake=0.4, acceleration=0.5. → total efficiency = 0.04

→ ~500Euro/W (beam)

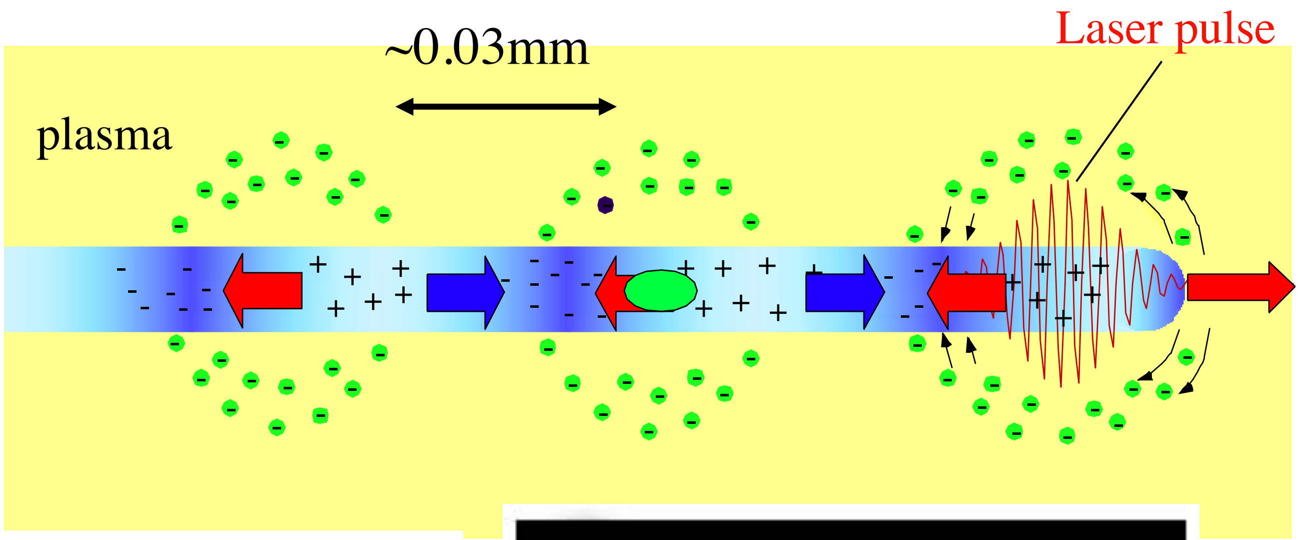
however, (1) far less other cost s.a. civil eng., (2) *could come down substantially (a) yet to be demonstrated. [laser path after the RF design]

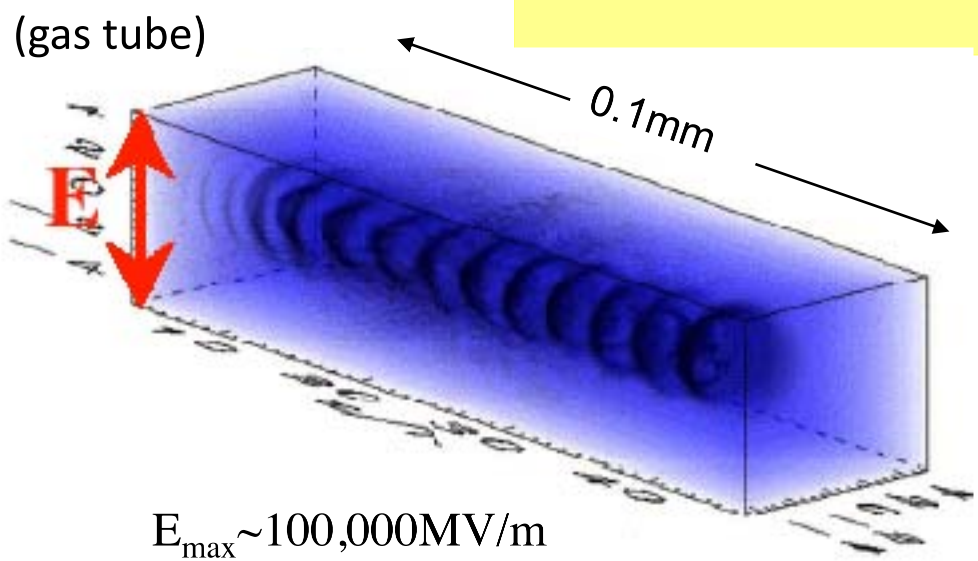
Laser-driver for γ-γ collider (@80 x 80GeV)

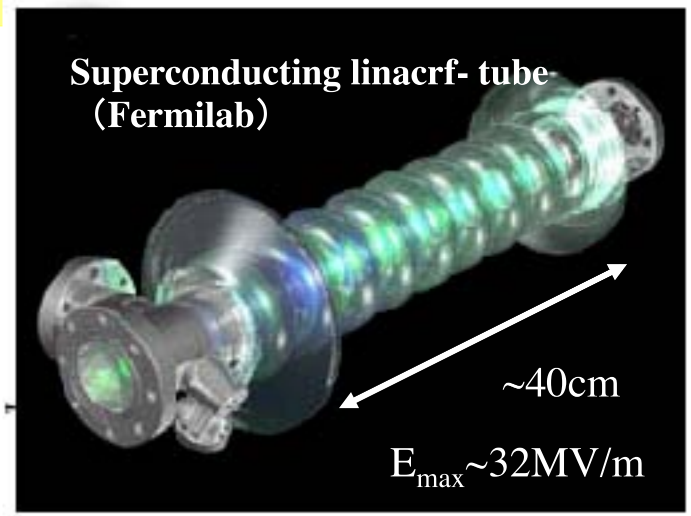
5J x 100kHz → ~50MEuro (times ~2 for the total system)

Thousand-fold Compactification

Laser wakefield: thousand folds gradient (and emittance reduction)

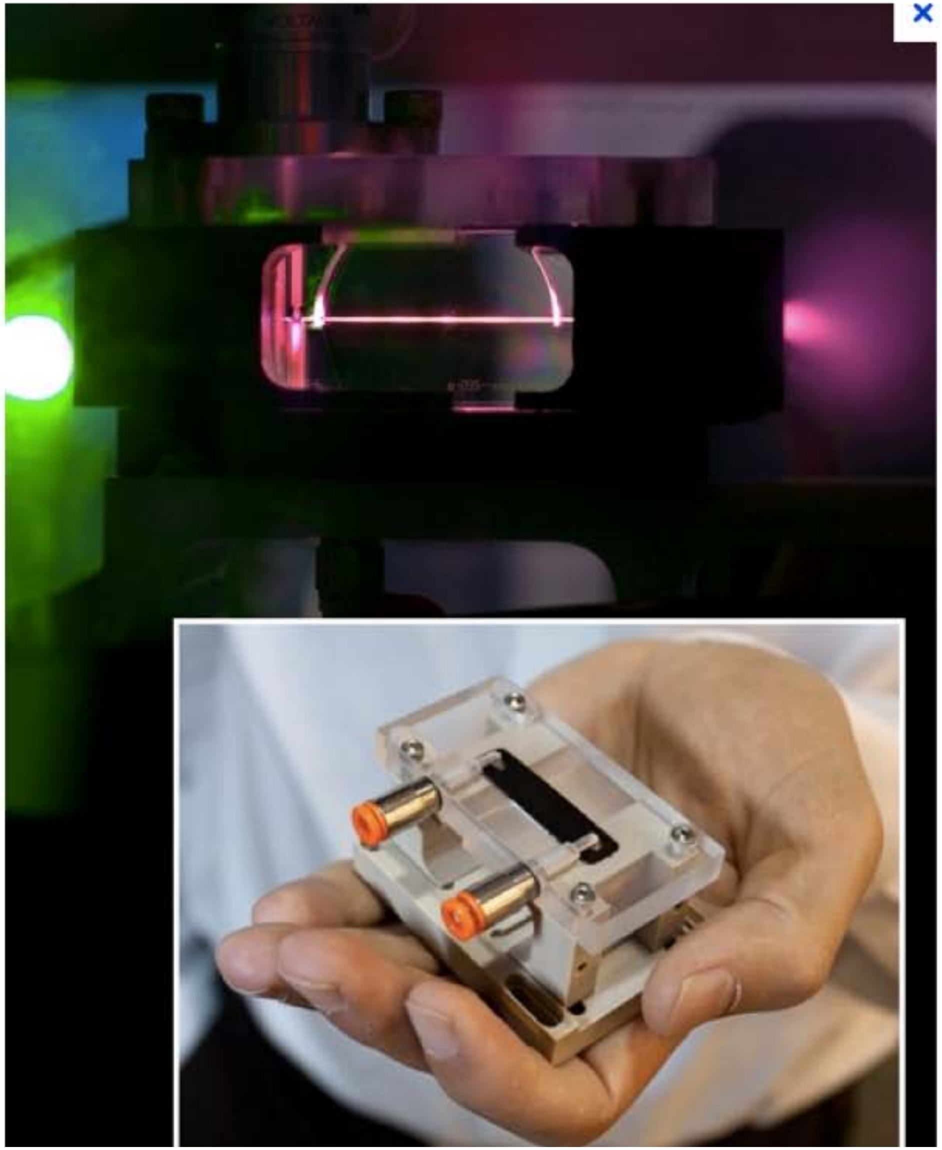






GeV in the Palm

First GeV on few cm
(W. Leemans et al)



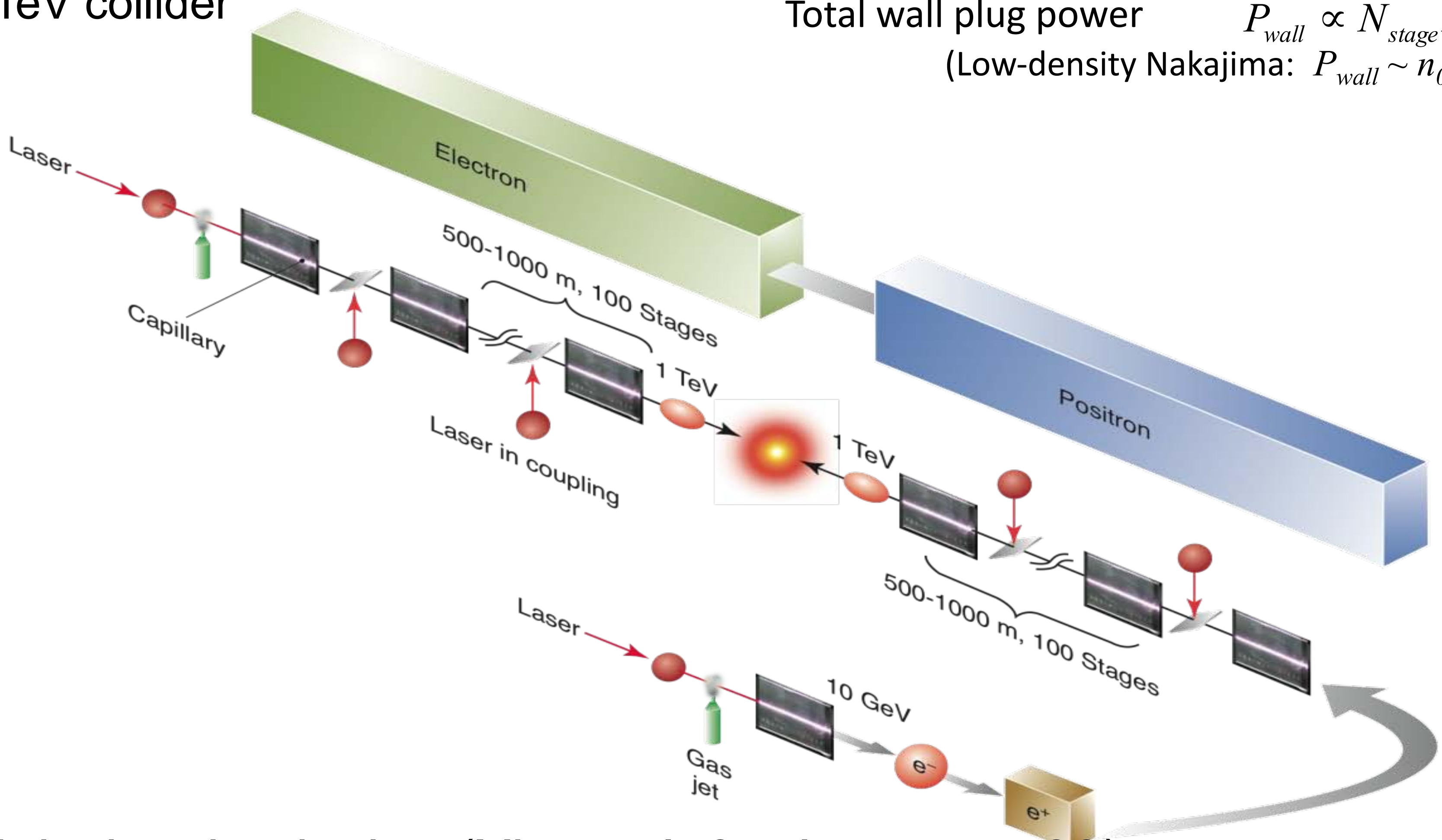
Laser driven collider concept

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 et al.,97; Leemans,09)

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

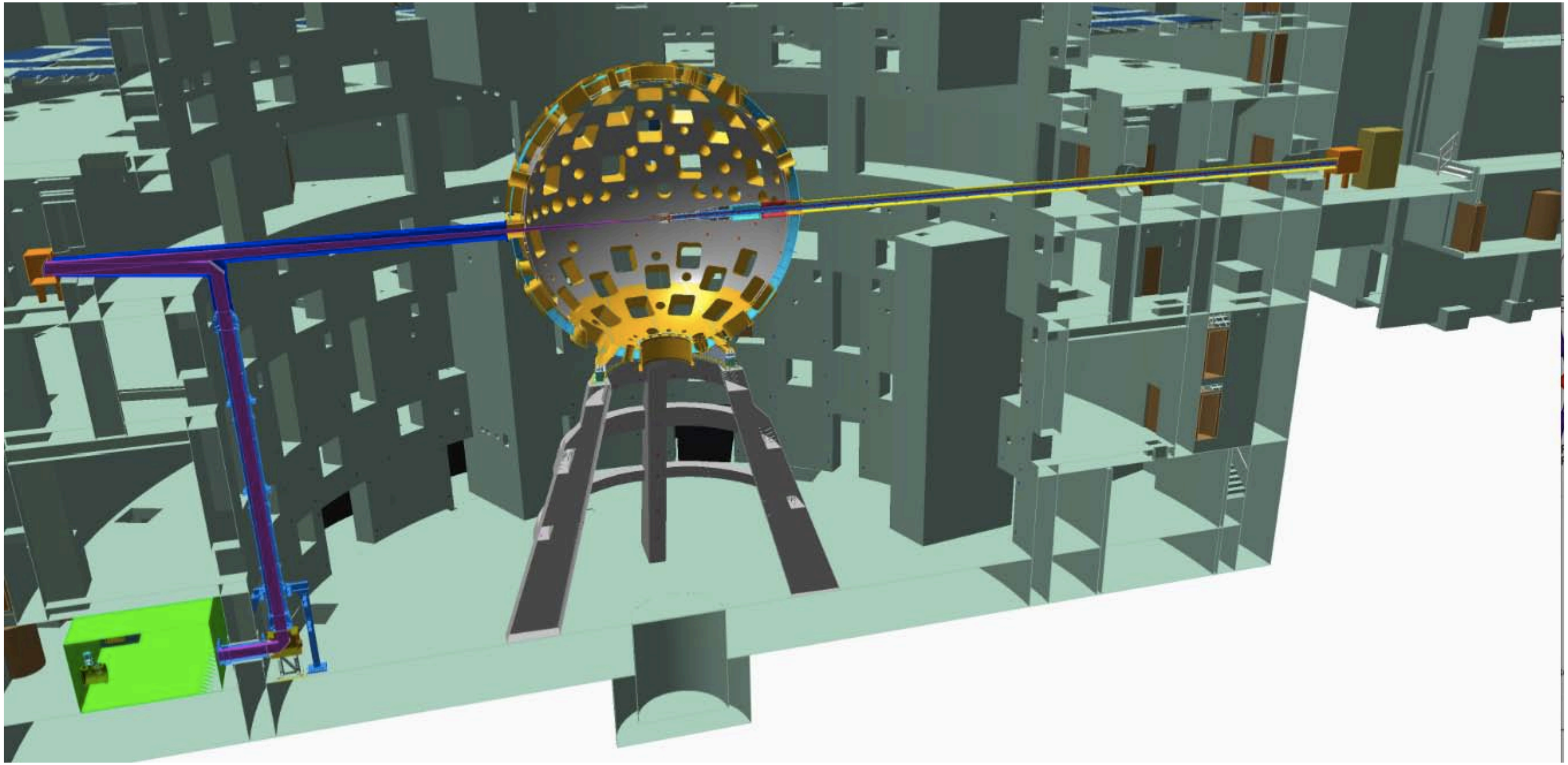
Density scalings of **LWFA**
for collider

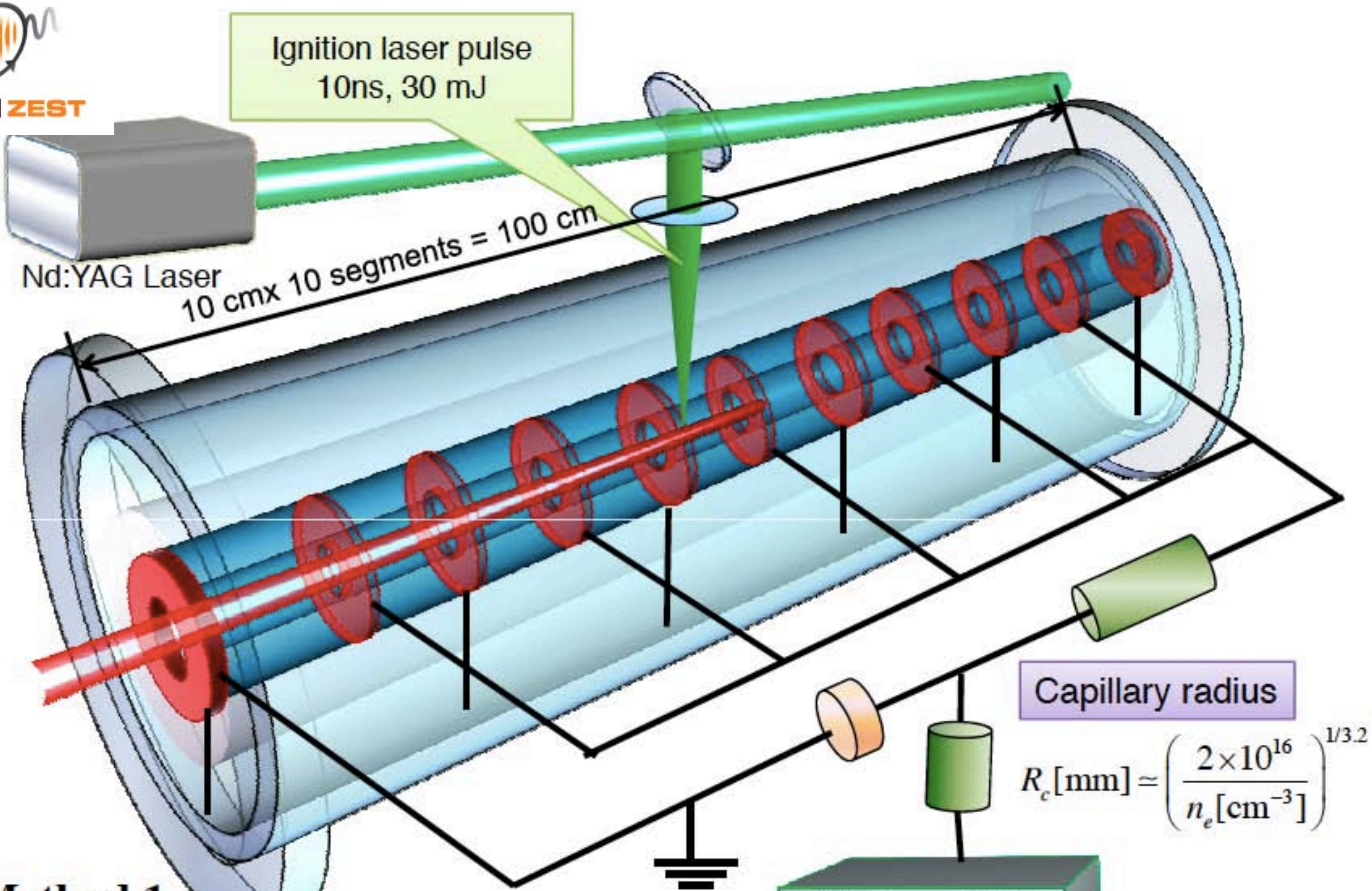
Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length L_{stage}	$\propto n_e^{-3/2}$
Energy gain per stage W_{stage}	$\propto n_e^{-1}$
Number of stages N_{stage}	$\propto n_e$
Total linac length L_{total}	$\propto n_e^{-1/2}$
Number of particles per bunch N_b	$\propto n_e^{-1/2}$
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_{avg}	$\propto n_e^{-1/2}$
Wall plug power P_{wall}	$\propto n_e^{1/2}$

(Nakajima, PR STAB, 2011)

10^{18} /cc (conventional) → 10^{16} /cc

130GeV (Higgs energy) Experiment on the *PETAL* laser



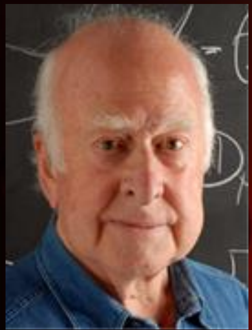


Method 1

Ablative Discharge Plasma Waveguide-Meter Module

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 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

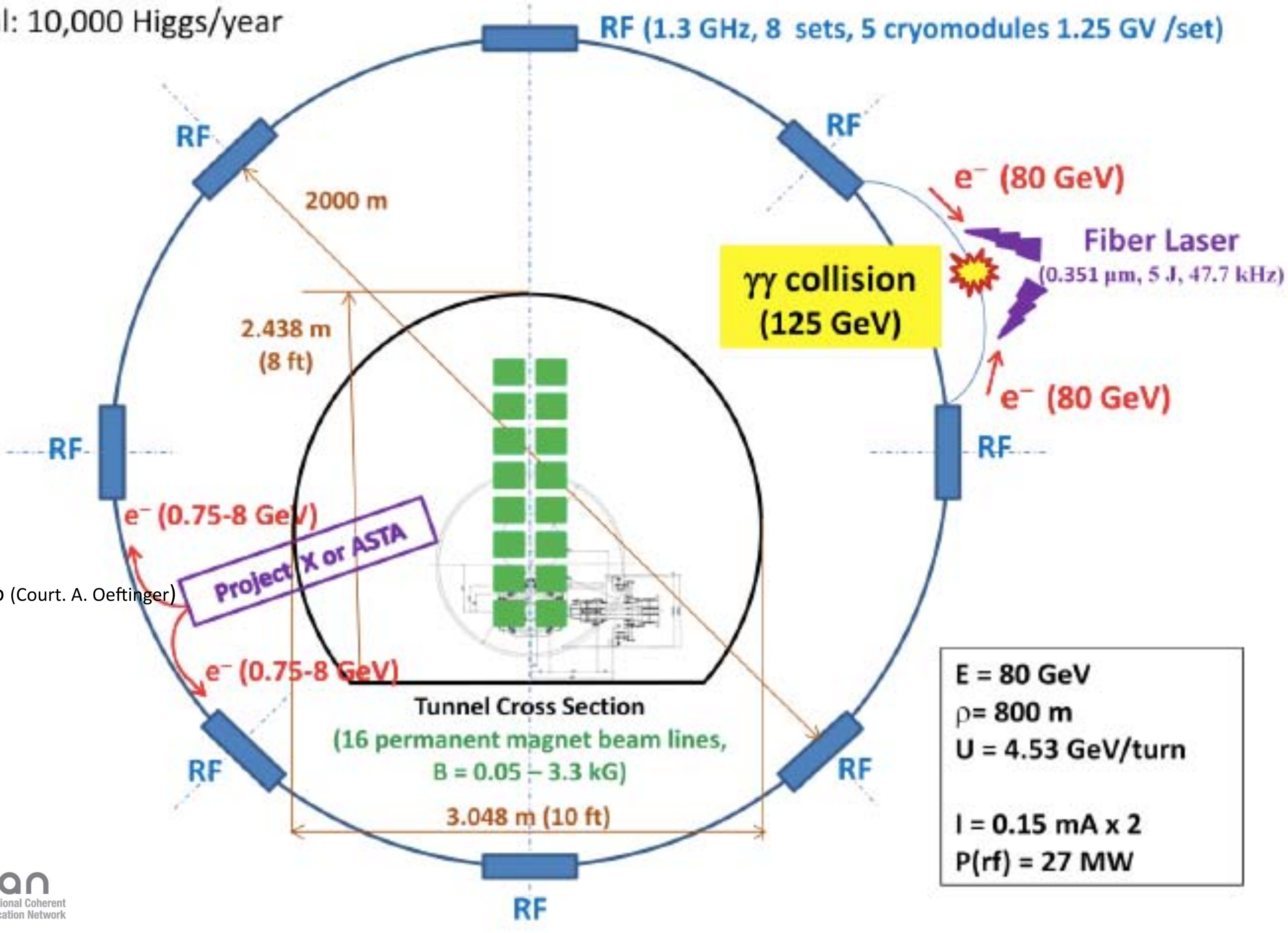
IZEST Ecole Polytechnique – Paris – France

150th Anniversary of Politecnico di Milano

HFiTT – Higgs Factory in Tevatron Tunnel

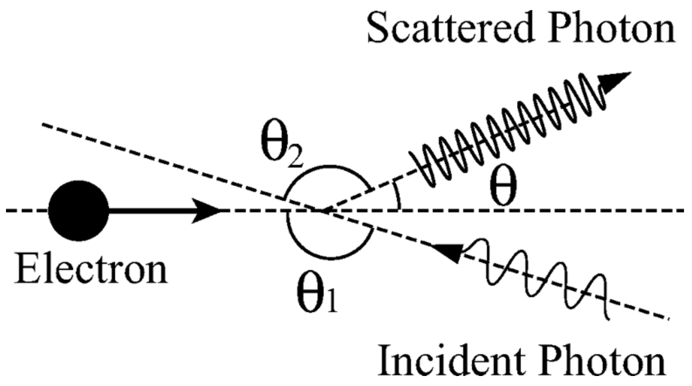
($\gamma\gamma$ collider) (W. Chou et al.)

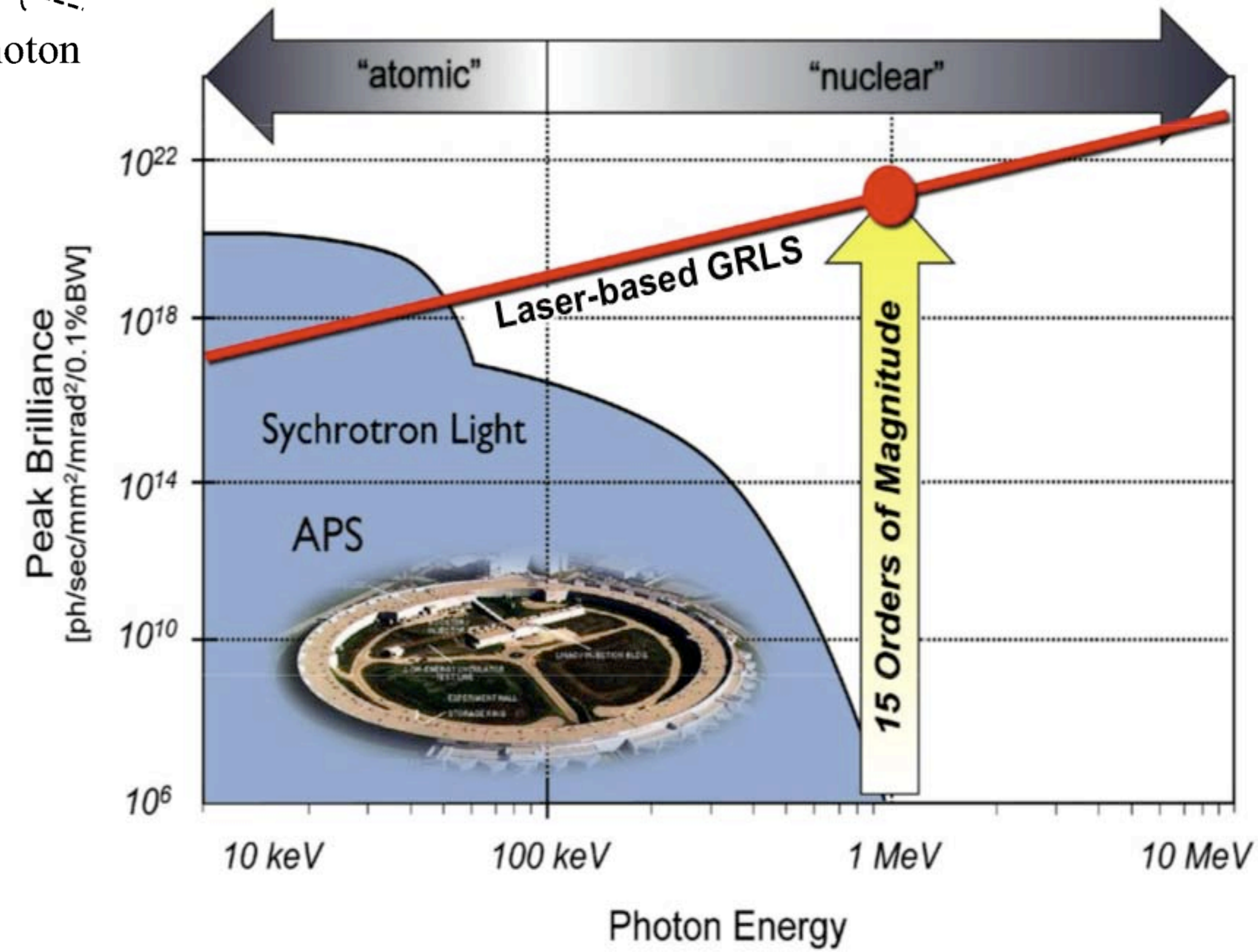
Goal: 10,000 Higgs/year



M. Velasco (Court. A. Oeftinger)

Laser Compton gamma source





Barty and Tajima, 2008

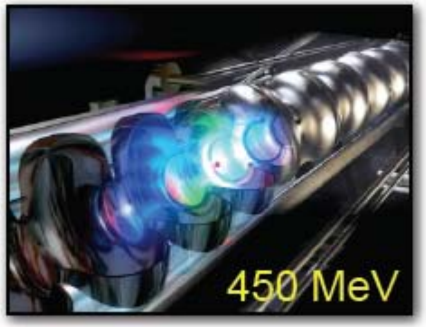
Extremely high average-power gamma ray sources

Detection of 1% ^{238}U in 0.1sec → 200W laser in supercavity x ERL @130MHx
10^{10} /sec/keV γ' s

(Hajima et al, 2008)

By combining state of art existing technologies a 100 kW T-REX system could be realized

10 Hz ▶ 10 MHz



+

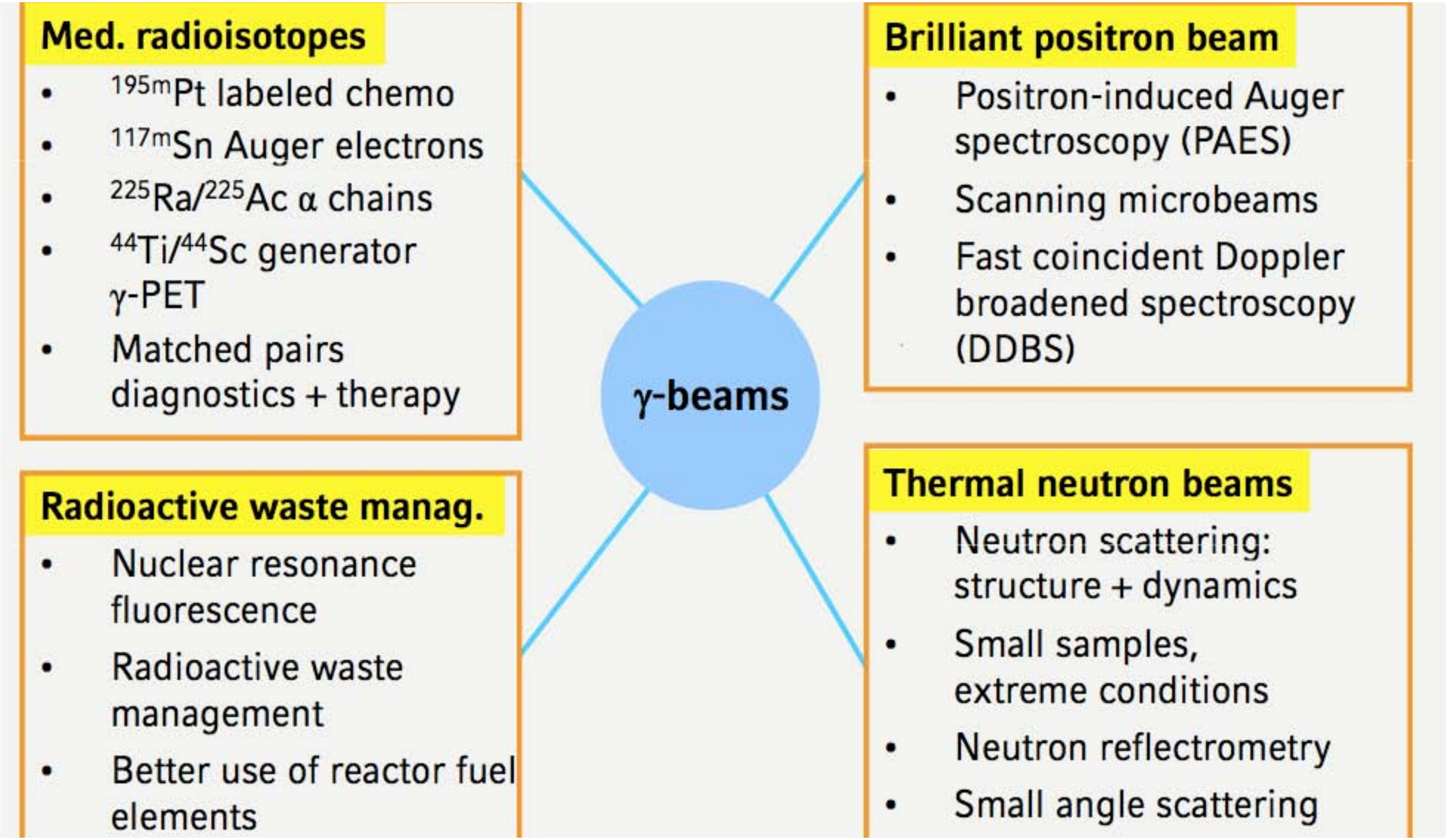
10 W ▶ 1 MW
+ recirculation

=

C.Barty(2007)

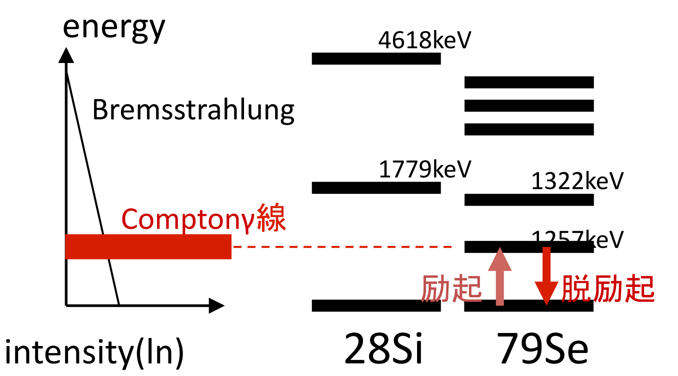
mW's @ 1 MeV ▶ 100s kW @ 10 MeV

Applications of laser Compton γ-beams

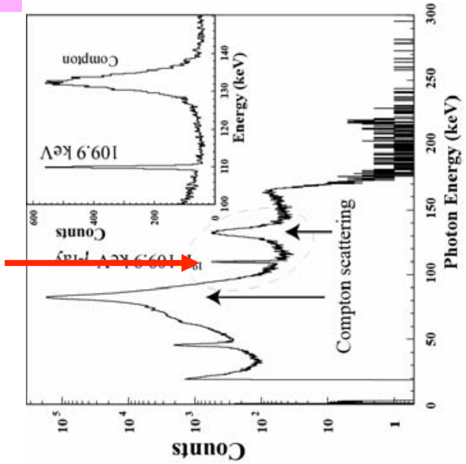


Detection of nuclei in waste and/or containers

Nuclear Resonance Fluorenscence



SPring-8 experiment



Gamma at given energy level

⇒ **sensitive detection**

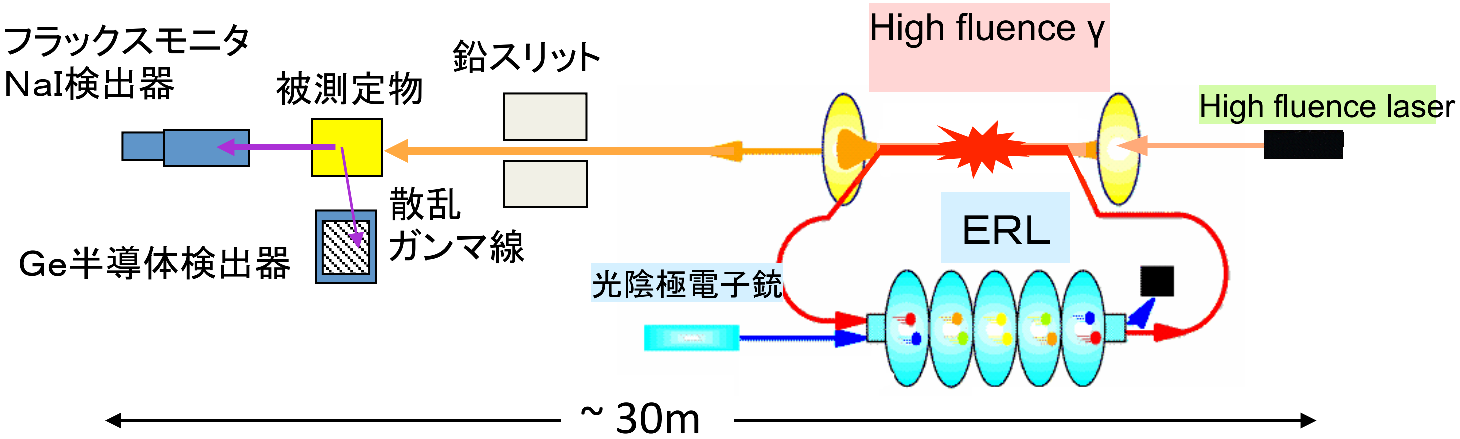
Clearance 20B$
（quantity reduction）

- shallow 270kY／drum
- midlevel 3MY／drum
- deep 8MY／drum

Segregation by radioactivity

⇒ cost reduction

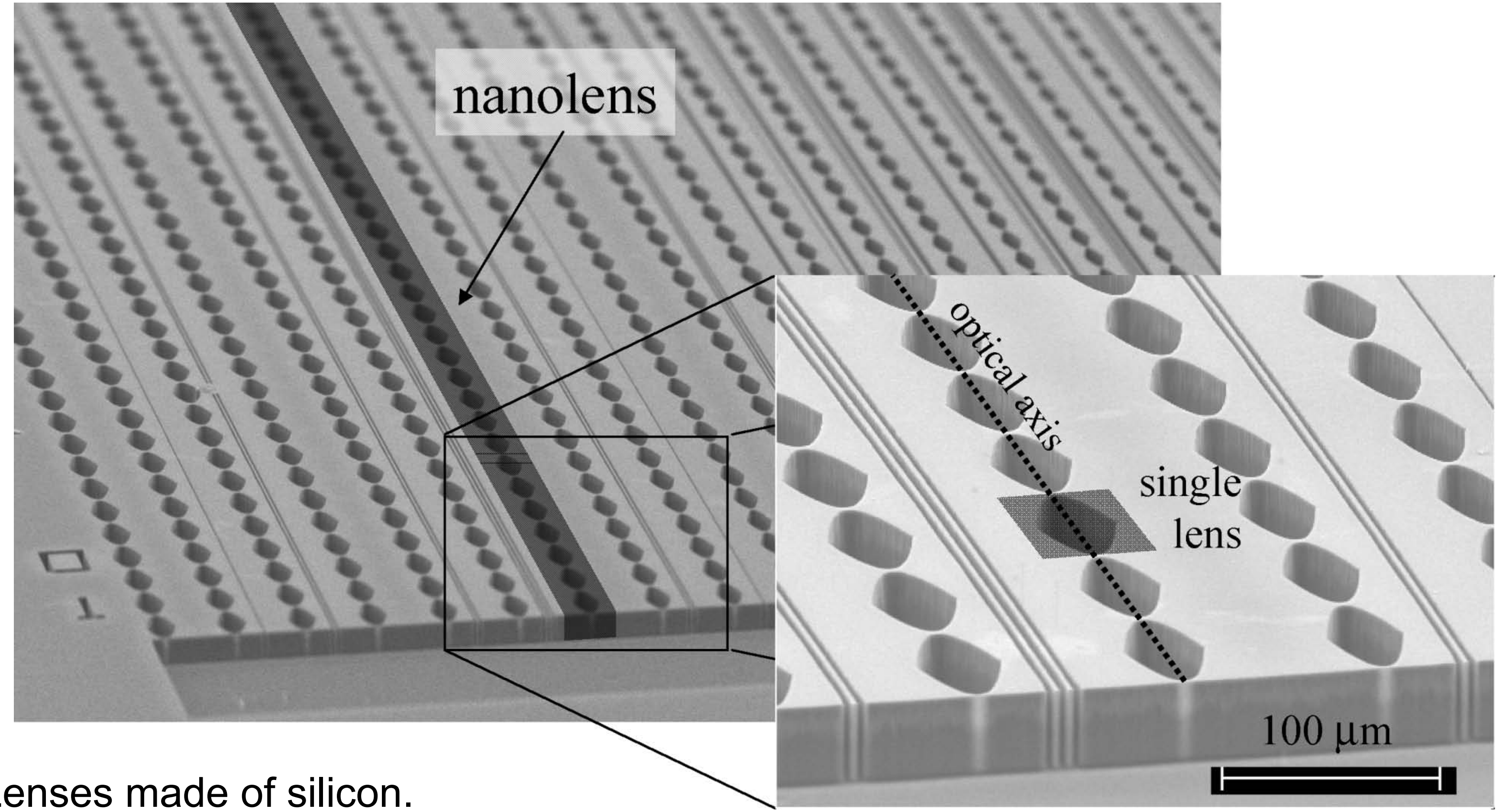
Enhancement of γ flux over the conventional method by **10^7**



Hajima(2007)

Refractive γ lens

Nanofocusing lenses



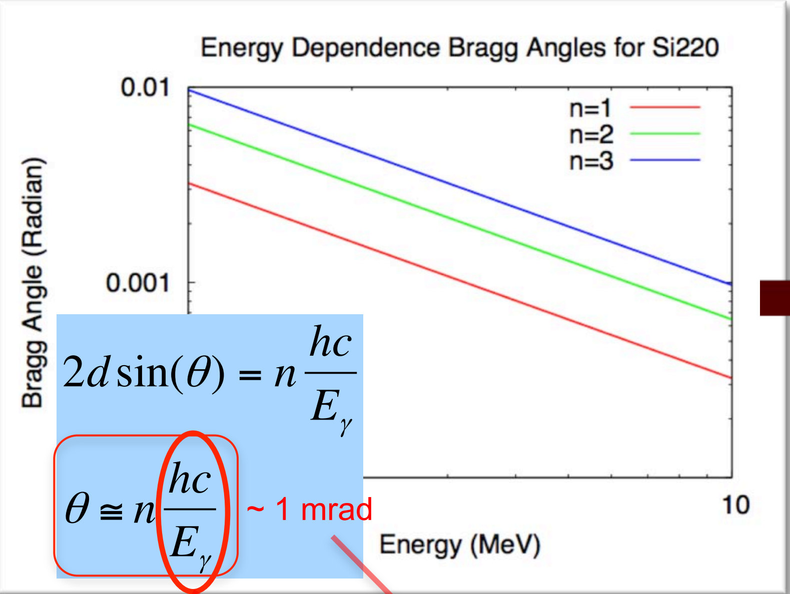
Lenses made of silicon.

Ch. Schroer et al., APL **82**, 1485 (2003).

D. Habs, 2010

Gamma ray spectroscopy

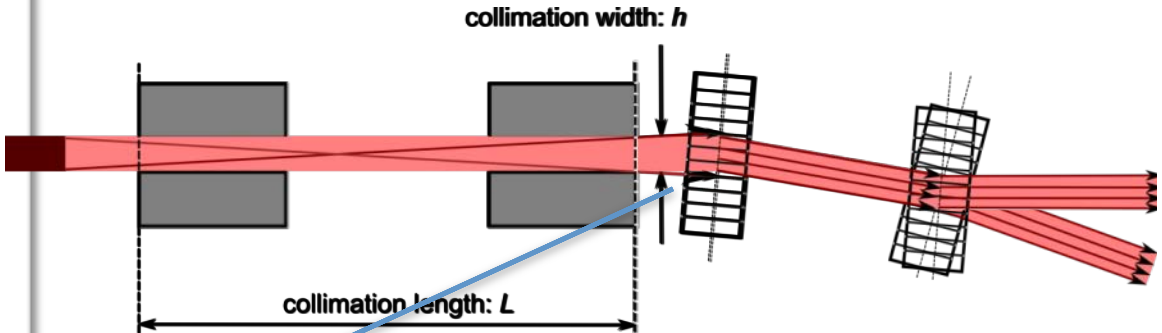
with a double crystal spectrometer (M.Jentschel, ILL)



$$2d\sin(\theta) = n\frac{hc}{E_\gamma}$$

$$\theta \cong n\frac{hc}{E_\gamma}$$ ~ 1 mrad

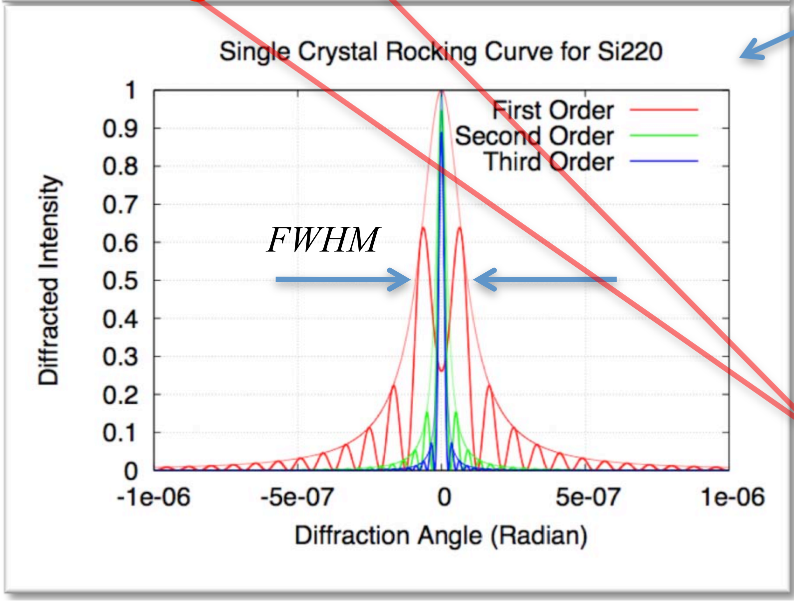
Single crystal – resolution is defined by beam divergence: *h/L* ➔ TOO LARGE for eV resolution



$$R(\theta) \propto \frac{\sin^2\left(A\sqrt{1+y^2}\right)}{1+y^2}$$

$$y \propto \frac{\theta}{\lambda_\gamma}, \quad A \propto \lambda_\gamma, \quad E_\gamma = \frac{hc}{\lambda_\gamma}$$

$$FWHM = 2\frac{hc}{E_\gamma}$$ ~ 10 nrad



<u>Double Crystal Spectrometer:</u>

- First Crystal defines beam axis with nrad
- Bragg Angle is measured @ second crystal
- Resolution is energy independent
- Resolution: $\Delta E/E \sim 10^{-6}$ --------- good for NRF!

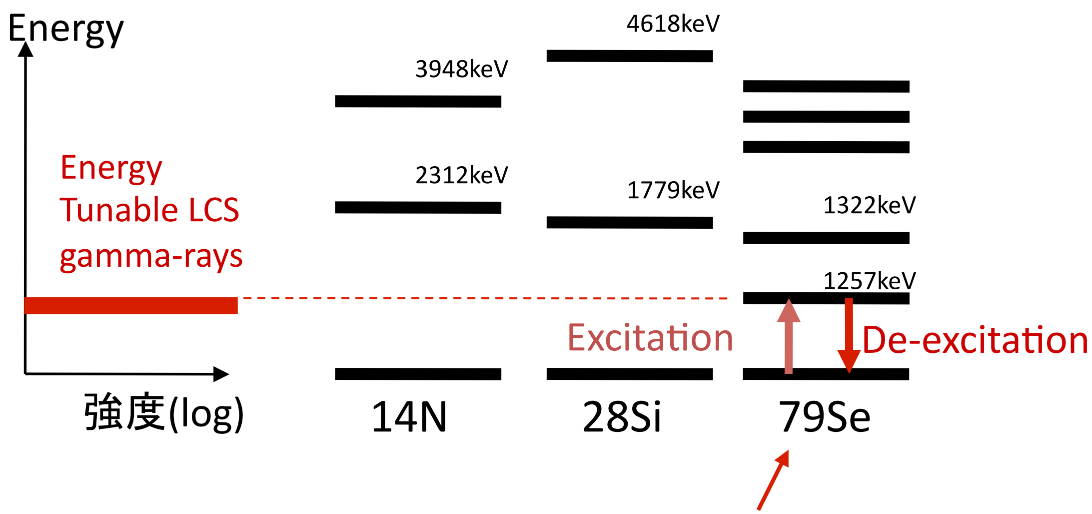
Proposal of Nondestructive Assay of Radionuclides

using nuclear resonant fluorescence technique

There are many minor actinoid (MA) and long-lived fission products (LLFP) in the nuclear waste drum.

How do detect such the MA and LLFP ?

A new Method



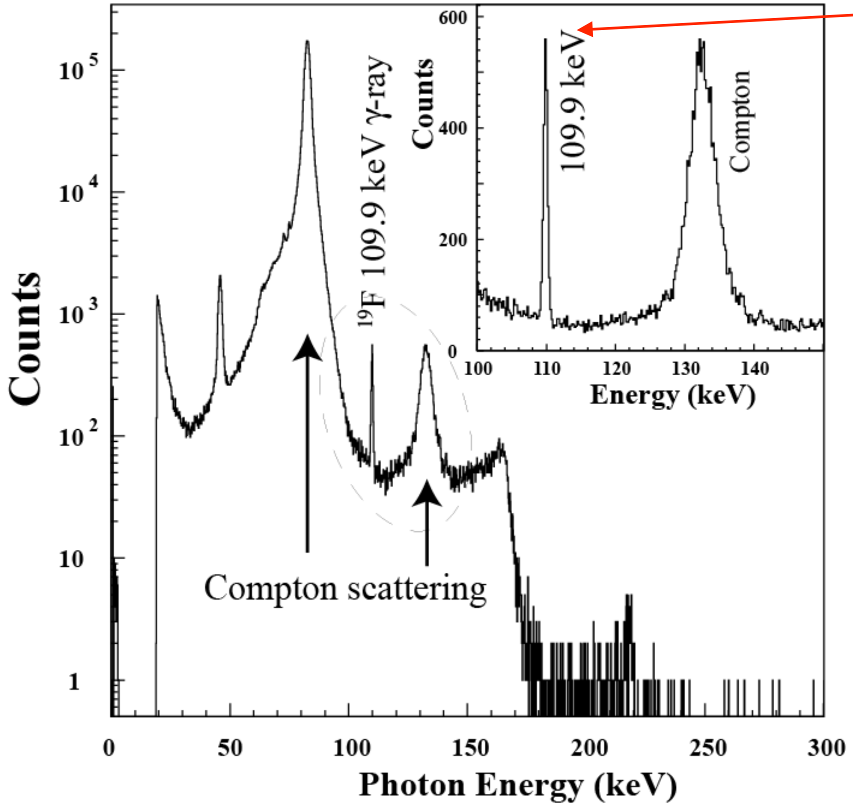
Only Nucleus of interest can be detected

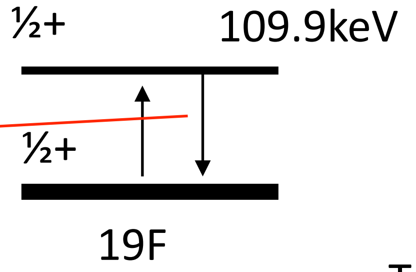
Hajima(2008)

- **This method can detect all radioactivities except ^3H**
- **However, this method require a very high-flux gamma-ray source.**

NRF experiment using Synchrotron Radiation γ at SPring-8 for Parity Mixing Measurement

K.Kawase, et al. (2008)





Target and detector

Sharp discriminatory capability of monoenergetic γ rays

Nuclear resonance fluorescence

applications to homeland security, Fukushima, ……

Nuclear Resonance fluorescence signal

Bremsstrahlung gamma rays

vs

Laser Compton gamma rays

C. Barty and T. Tajima (2008)

Germans move radioactive barrels

Long neglected ‘toilet side’ of nuclear energy, in contrast to its production (‘kitchen side’)

We need science (brain) of how to handle this; not just management (muscle)

Japanese Nuclear Waste Unidentified (JAEA)

Handled by Hand Individually at this time (2008)

Now, far more serious and imminent:

large amount of exposed molten fuel

(*Fukushima*-----Need to know isotopic composition;

Need to be compact / portable to the site

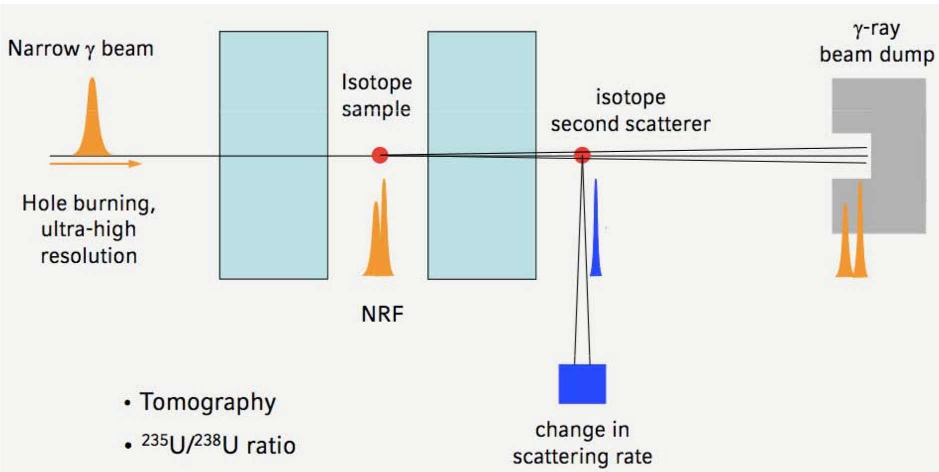
← laser-driven Compton γ beams)

Can we apply NRF of laser C γ-beams to Fukushima?

Molten fuel is a BIG problem.
Need to understand composition of isotopes for decommissioning.
We need portable remote-controlled (robotic) beam driven by laser Compton **γ-beams** and Nuclear Resonance Fluorescence absorption spectrometer.

Latest crisis at Fukushima Daiichi

Notch detector by NRF



Reduction of radiotoxicity (in time)

以下数枚はMizumoto(JAEA)のものを基にした

長寿命・放射性毒性が大きい核種を核反応を利用して短寿命及び安定核種に変換

対象核種：

マイナーアクチノイド（MA：Np、Am、Cm）

長半減期核分裂生成物（LLFP：^{129}I、^{99}Tc等）

発熱の大きい核分裂生成物（^{90}Sr、^{137}Cs等）

意義：

廃棄物蓄積量、潜在的毒性、発熱量を低減して、地層処分の負荷を軽減。

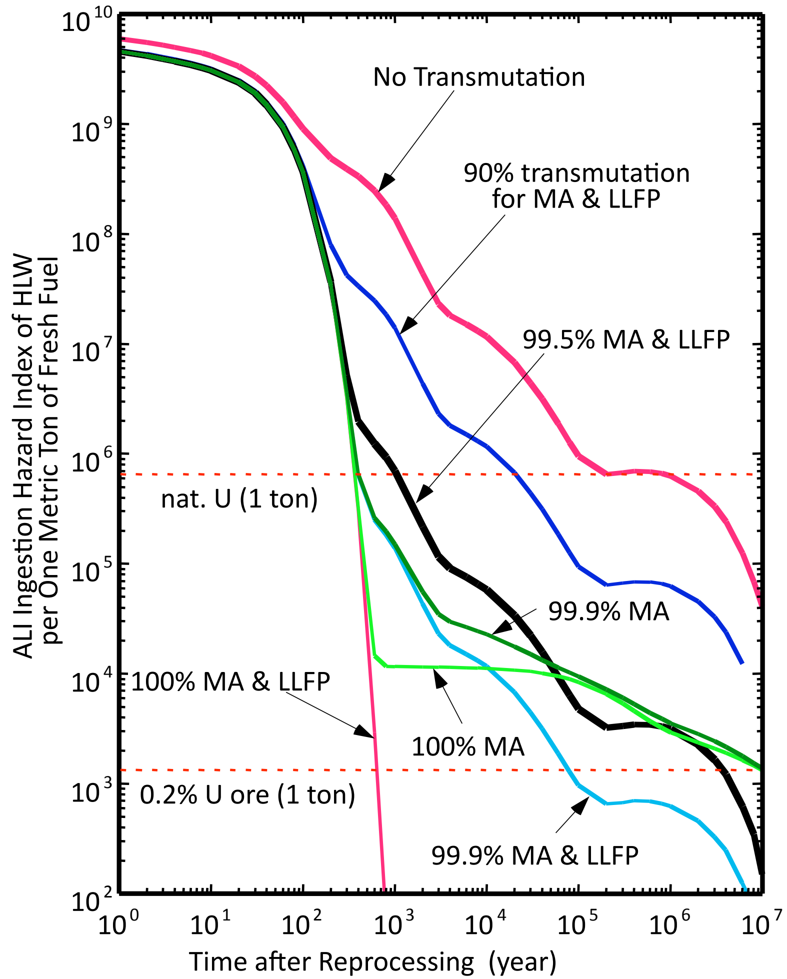
目標：

MAやLLFPの99.5%を核変換し、毒性指数を約300年後には2桁以上低減。（天然ウランの毒性指数と同等にする）

主な廃棄物の年間摂取限度(経口)
（ALI：Annual Limit of Intake (Ingestion)）

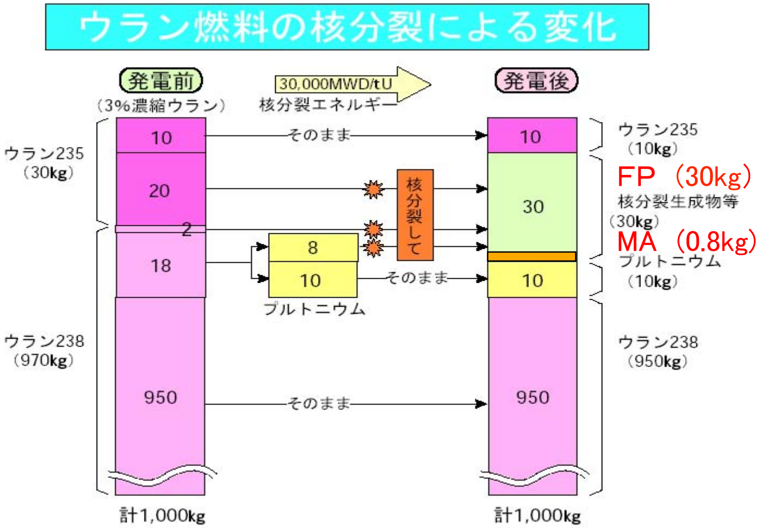
核種	ALI(Bq)
^{90}Sr	1×10^6
^{137}Cs	4×10^6
^{99}Tc	1×10^8
^{129}I	2×10^5
^{237}Np	3×10^3
^{241}Am	5×10^4

毒性指数：含まれる核種の質量をそれぞれの年摂取限度(ALI)で除した数



LLFP：FPs with $T_{1/2}$ ≥ 30 years

Annual production of High Level Waste (HLW)



inventry ～30ton

produced quantity of minor actinides

冷却期間 / 核種	半減期 (year)	3410MWt-PWR 3年 (%)	3410MWt-PWR 10年 (%)
^{237}Np	2.1×10^{6}	57.9	41.3
^{241}Am	432	27.4	48.8
^{243}Am	7380	11.9	8.33
^{243}Cm	28.5	0.03	0.02
^{244}Cm	18	2.67	1.44
^{245}Cm	8500	0.15	0.1
全重量		23.8(kg/年)	33.9(kg/年)

計算：　データJENDL-2、計算コードSRAC-FPGS
燃焼度：　33GWd/MT(PWR)
再処理から群分離までの冷却期間：　5年
U,Puの回収率：　100%

～25kg

annual production of fission products[1)]
(nuclei with more than 10year decay)

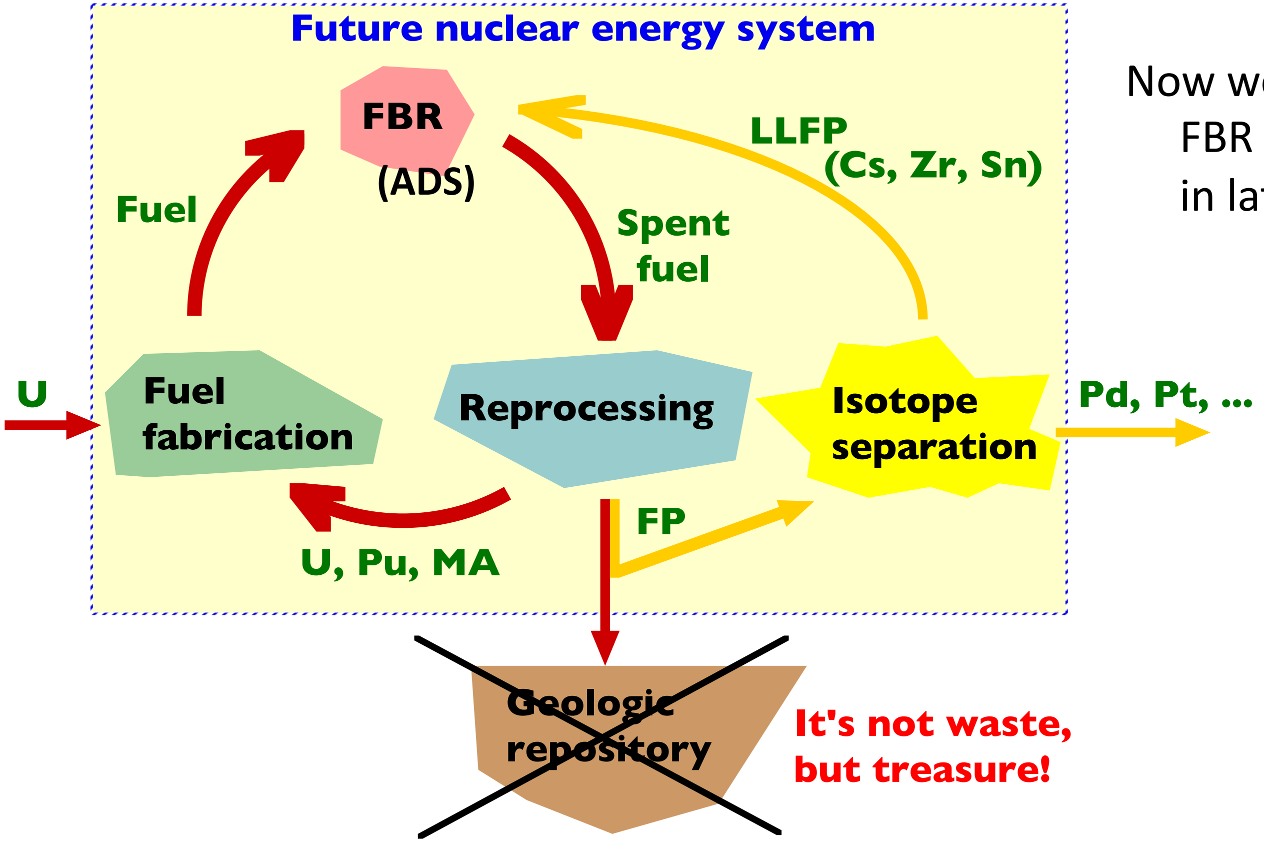
半減期区分	核種名	半減期(year)	重量(kg/年)
10年～100年	^{85}Kr	11	0.70
	^{90}Sr	29	16.3
	^{137}Cs	30	36.4
	^{151}Sm	90	0.37
100年～10^{4}年	該当無し		
10^{4}年～5×10^{9}年[2)]	^{79}Se	6.5×10^{4}	0.15
	^{93}Zr	1.53×10^{6}	21.3
	^{99}Tc	2.13×10^{5}	23,4
	^{107}Pd	6.5×10^{6}	6.21
	^{126}Sn	1.0×10^{5}	0.64
	^{129}I	1.57×10^{7}	5.00
	^{135}Cs	2.3×10^{6}	9.52
合計[3)]			120
5×10^{9}年以上(準安定核)	^{87}Rb, ^{115}In, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{148}Sm, ^{149}Sm		76.5

1)　生成量1g以上の核種のみ記載
2)　^{238}Uの半減期は4.47×10^{9}年
3)　半減期が10年～5×10^{9}年の核分裂生成物の合計値
計算：データJENDL-2,計算コードSRAC-FPGS
燃焼度：30GWd/MT
冷却期間：照射停止150日後の値
全FP生成量：1,002kg/年

～1ton

Laser Quantum Control for Isotope Separation

Isotope separation is a key technology for the future nuclear energy system which has zero emission of radioactive waste and which can be regarded as a "mine" of rare metals.



Now we could replace FBR by **ADS** in later slides

There are several scientific and engineering difficulties to realize such isotope separations. Laser and coherent quantum control may provide a breakthrough for those problems.

Paradigm Shift:
20th Century Science to 21st Century One

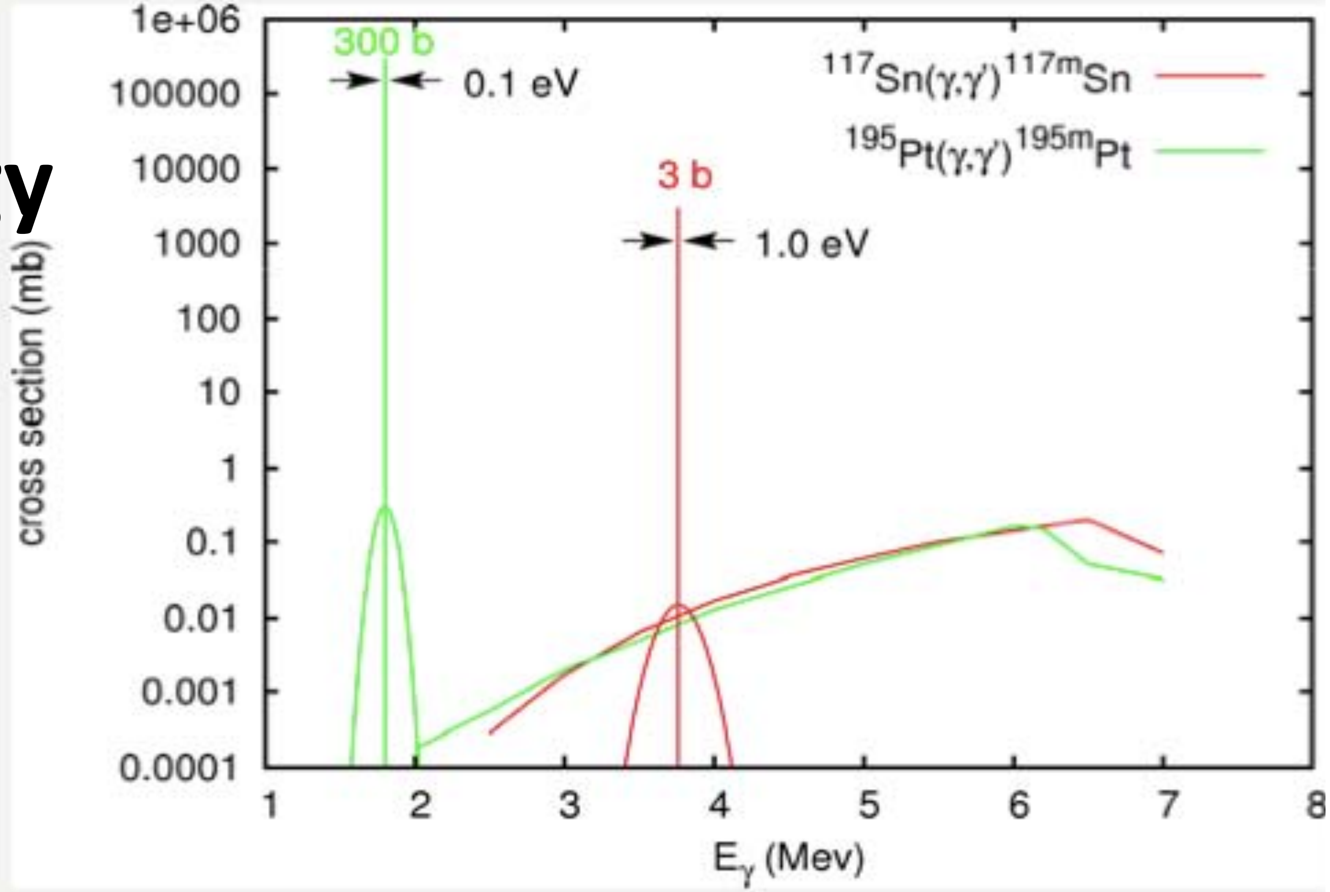
Physiology	Pathology
Manufacturing	Resource recycling
Consumption	Waste treatment
Energy production	Entropy minimization
Discovery and conquering	Ethics and societal solution
Food stock cooking	Garbage management
Individual	Collective
Linear	Nonlinear
Kitchen function	Toilet function

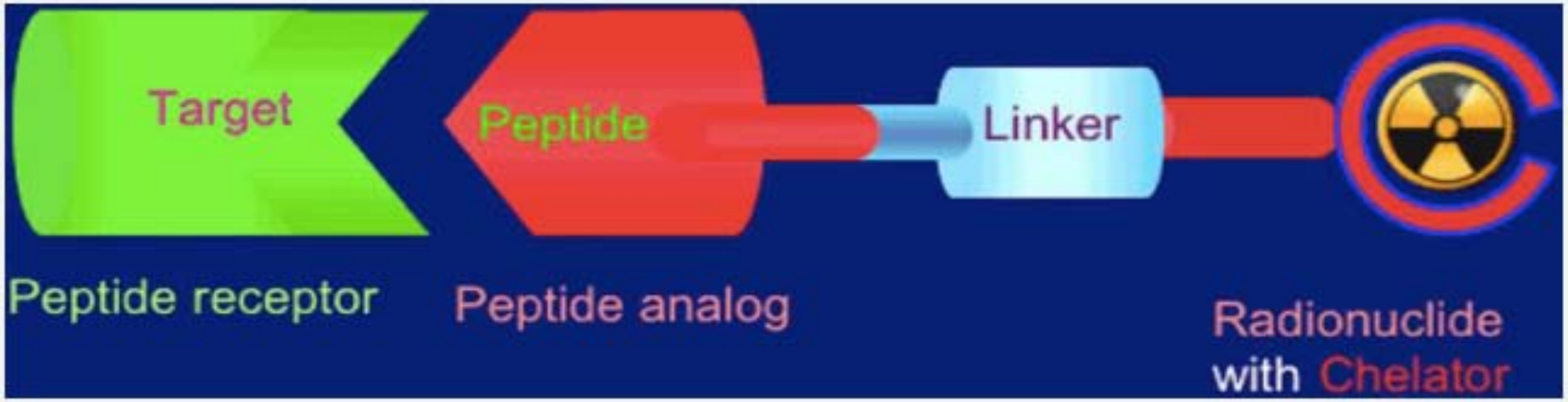
Kitchen Science → ***Toilet Science***

Nuclear Pharmacology

e.g. 195m
Pt
label chemotherapy and
study anti-tumor efficiency

(Habs, Tajima, Koester, 2011)





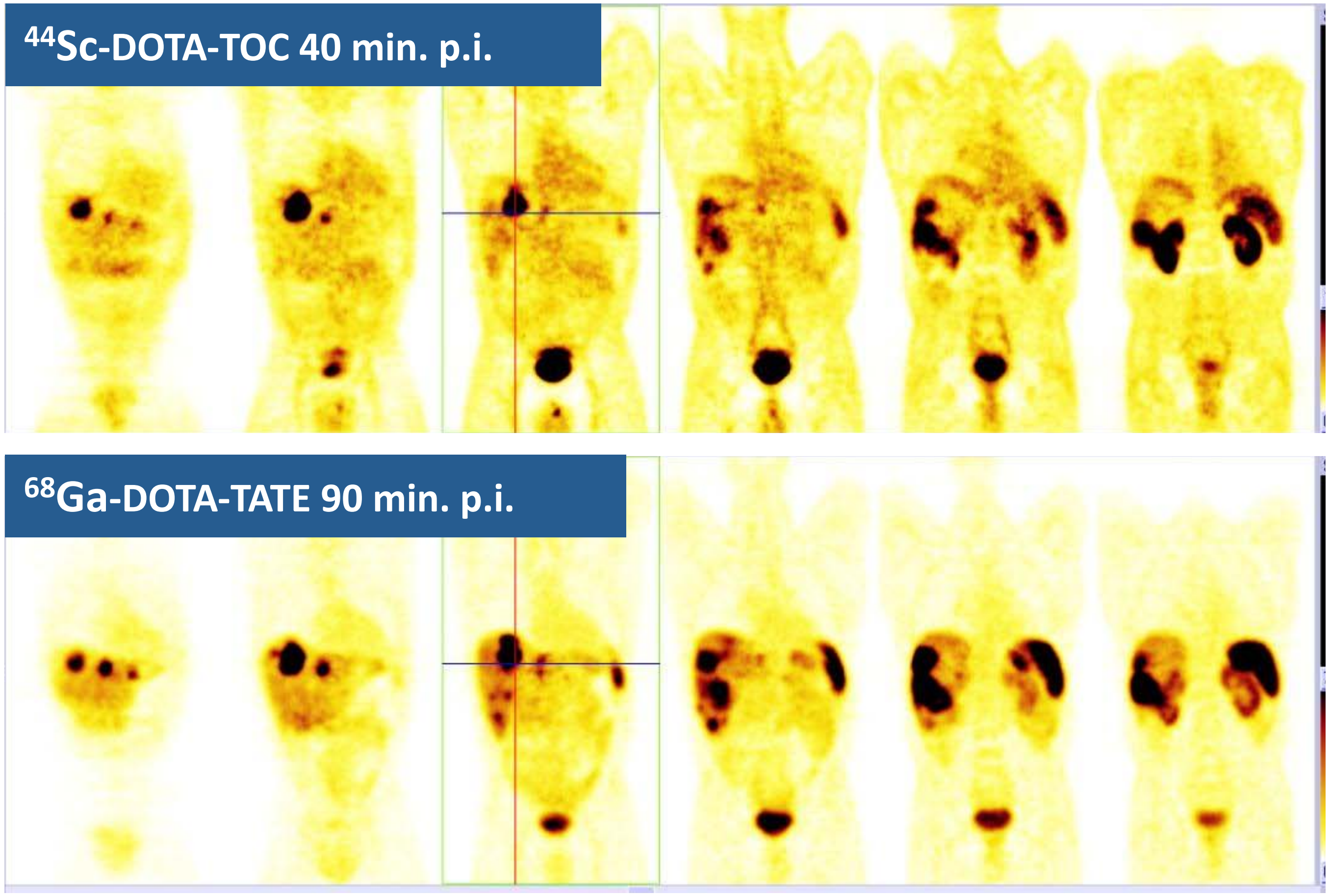
Habs, 2

$^{44}Ti/^{44}Sc$ generator (1)

First clinical application

^{44}Sc-DOTA-TOC PET/CT (1 mCi injected)

(Habs, 2010)



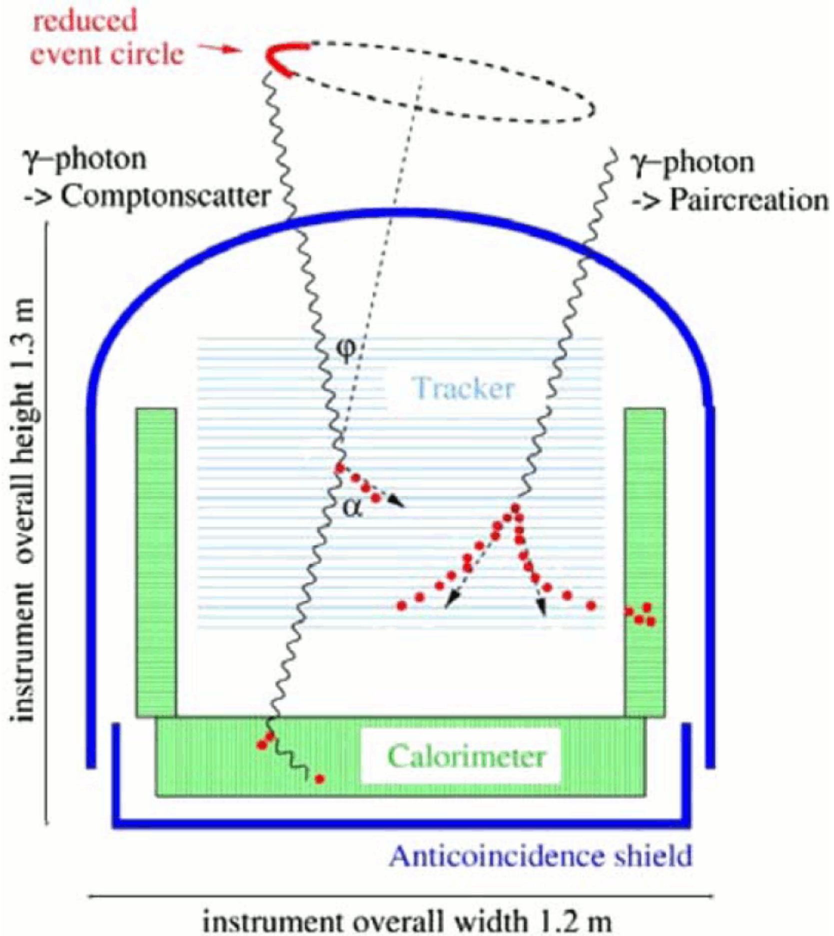
radiodiagnosis

R. M. Baum **Dept. of Nuclear Medicine/P.E.T. Center, Zentralklinik Bad Berka**

$^{44}Ti/^{44}Sc$ generator (2)

Compton camera

(Habs, 2010)



Measure momentum of Compton electron in stack of double-sided silicon strip detectors

GRIPS
Gamma-**R**ay **I**nvestigation via **P**olarimetry and **S**pectrometry

Test system MEGA
(**M**edium-**E**nergy **G**amma-ray **A**stronor

Astronomy ↔ medical imaging

A. Zoglauer et al., New. Astron. Rev. **52**, 431 (2008),
G. Kanbach et al., NIM **A 541**, 310 (2005).

Radioisotopes

from intense, brilliant γ beams

Matched pairs: diagnostic and therapy **isotope**

frequently one of these isotopes was not available from reactor or cyclotron

^{44}Sc/^{47}Sc; ^{61}Cu or ^{64}Cu/^{67}Cu; ^{86}Y/^{90}Y; ^{124}I/^{131}I

Auger cascades: 5–30 Auger electrons, low energy, 1μm range

Special bioconjugates transport emitter to DNA

no damage during transport or at cell membrane

Chain of α emitters:

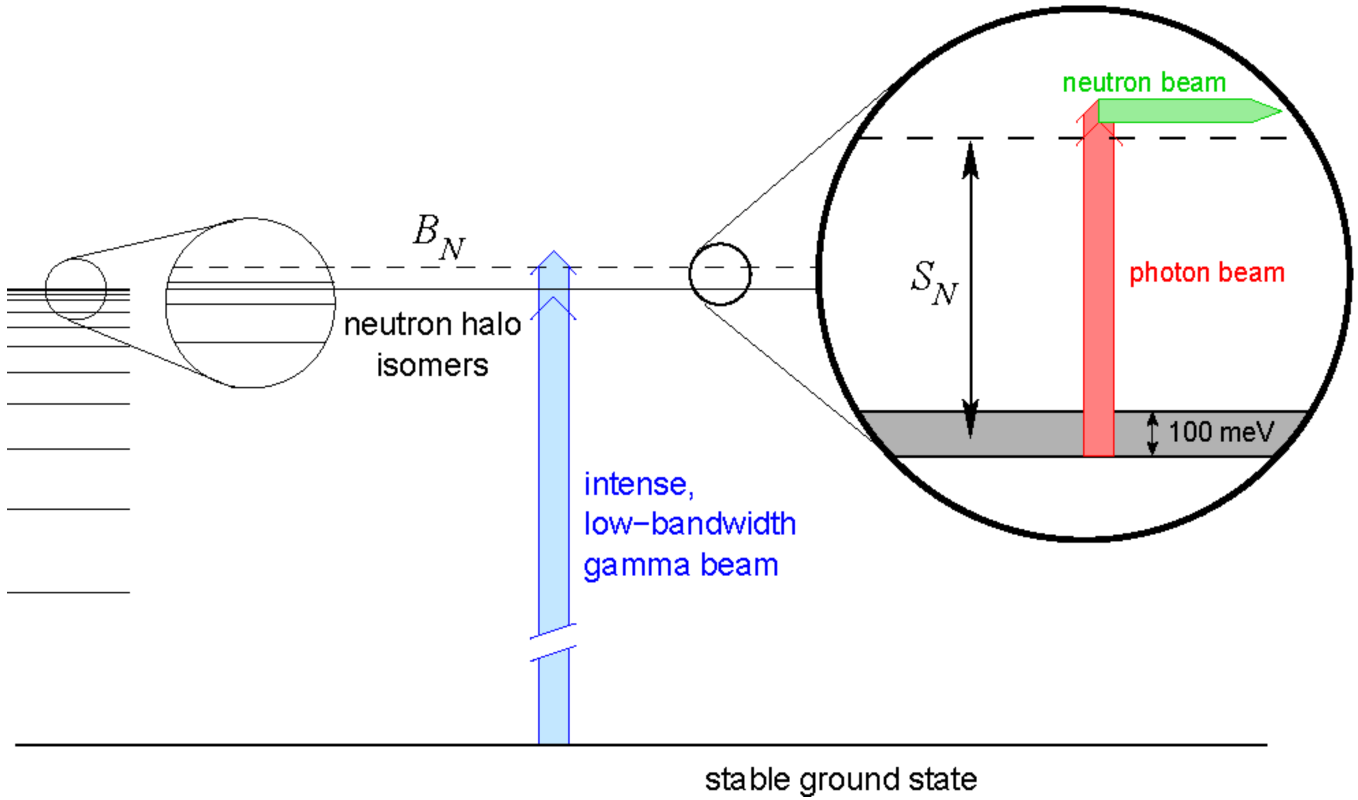
^{225}Ra/^{225}Ac: 4 large LET α particles at the same place

(Habs, 2010)

2-step neutron production

Gamma ray-driven. Neutron halo isomer, dissociation of n-halo isomer

(Habs, 2010)

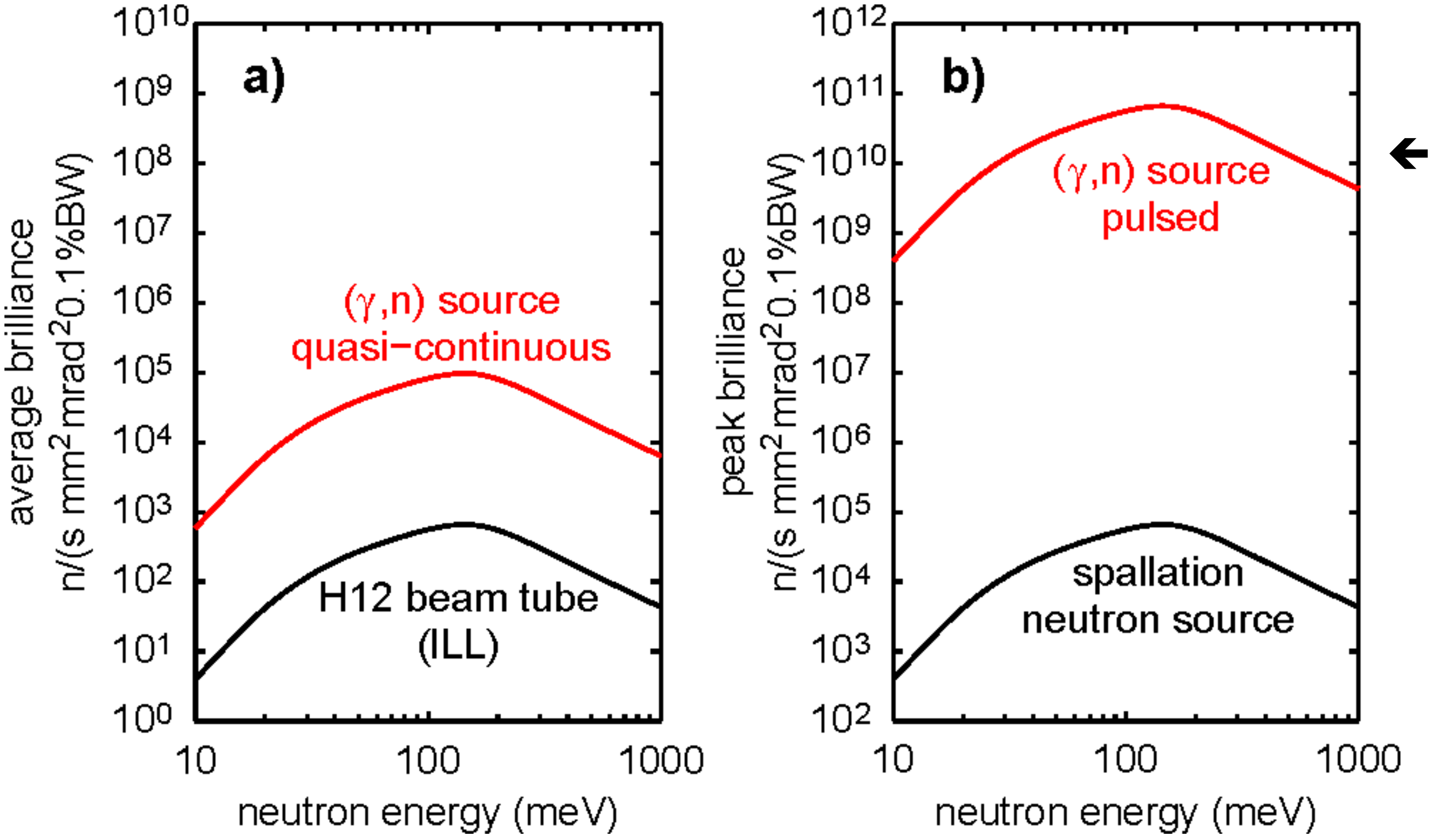


D. Habs et al., arXiv-1008.5324 [nucl-ex] (2010), accepted by Appl. Phys. B

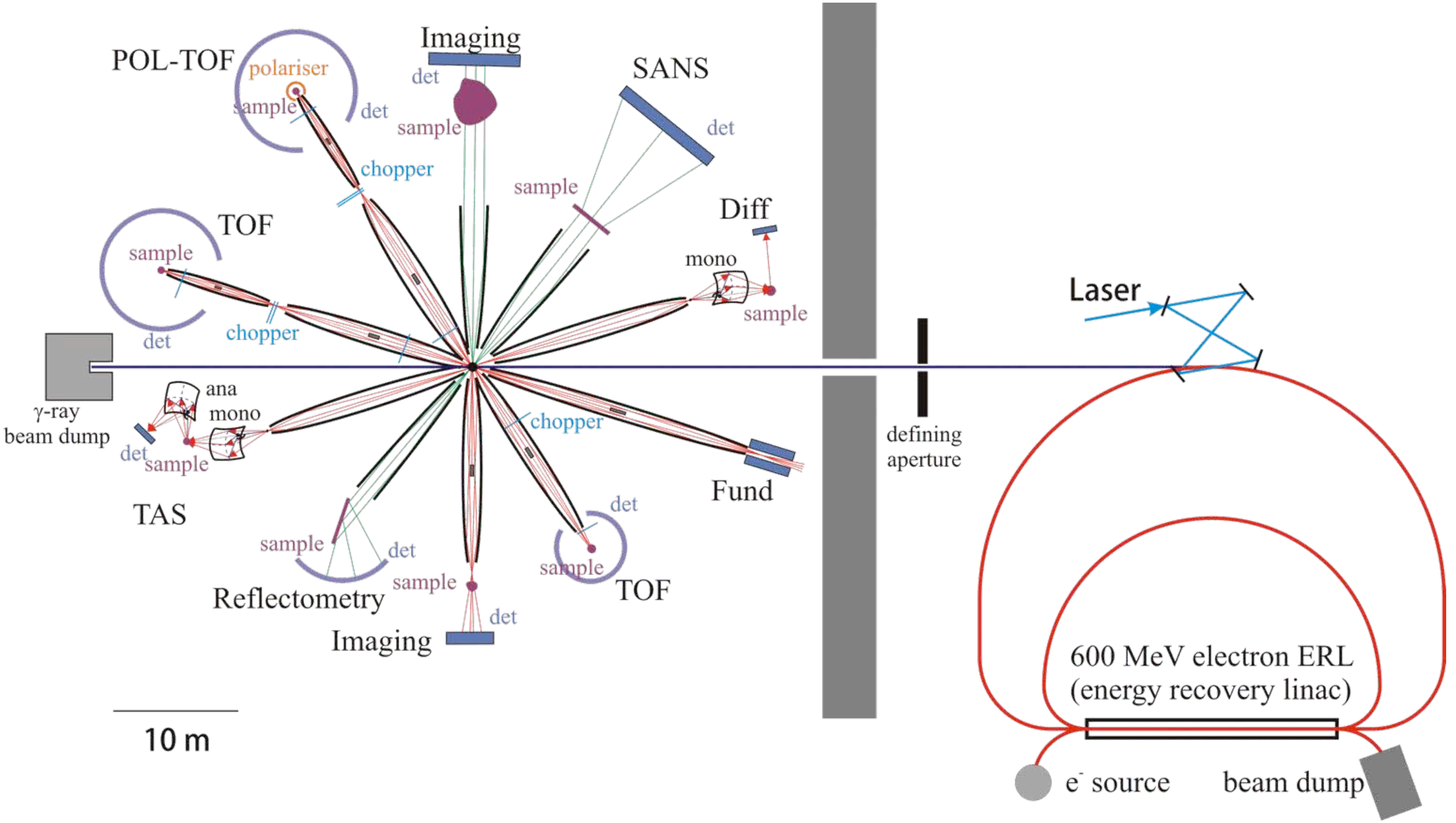
Neutron Brilliance

of new and old neutron sources

(Habs, 2010)



Neutron experiments @ *ELI-NP*

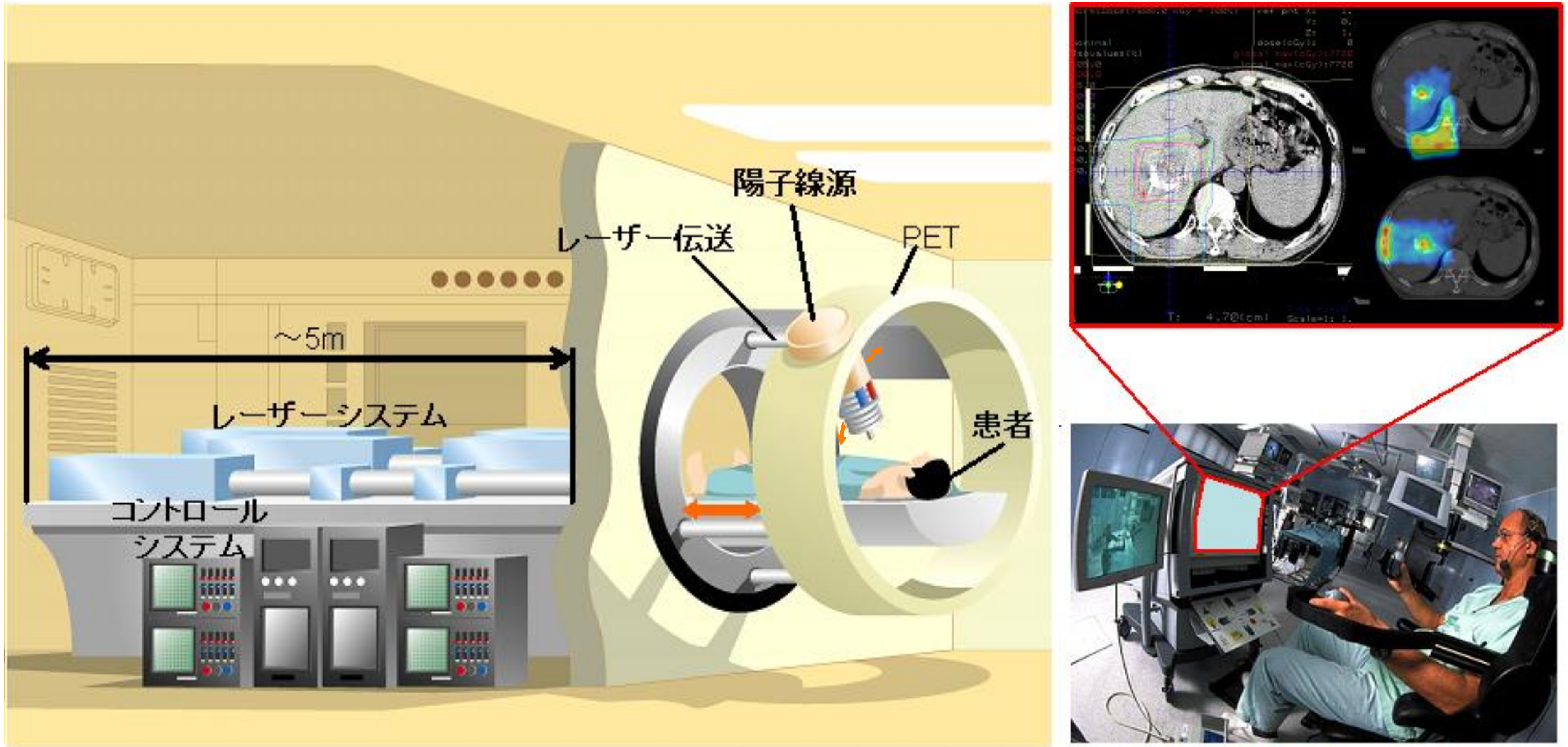


(Habs, 2010)

Conventional ion accelerator

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.

Concept of Laser-Driven Ion therapy



治療計画（診断と照射）

Toward more adiabatic acceleration of ions

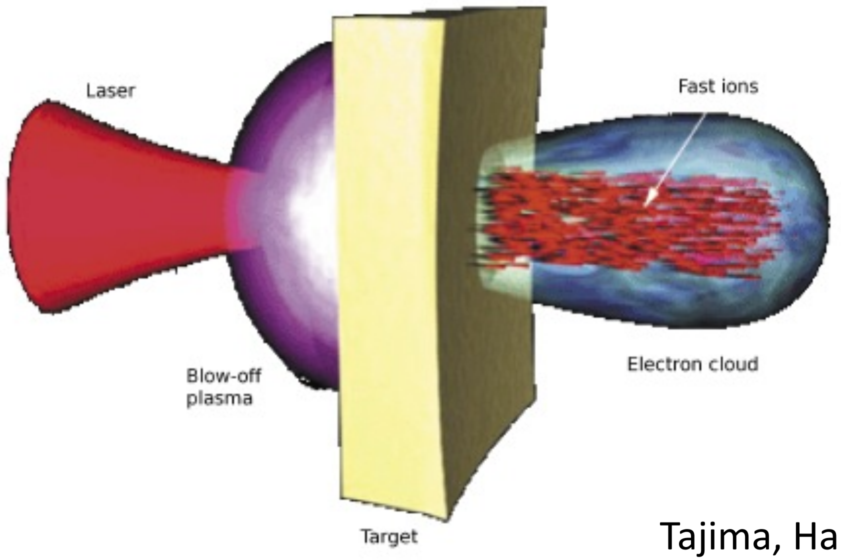
From **incoherent (or heating)** of electrons

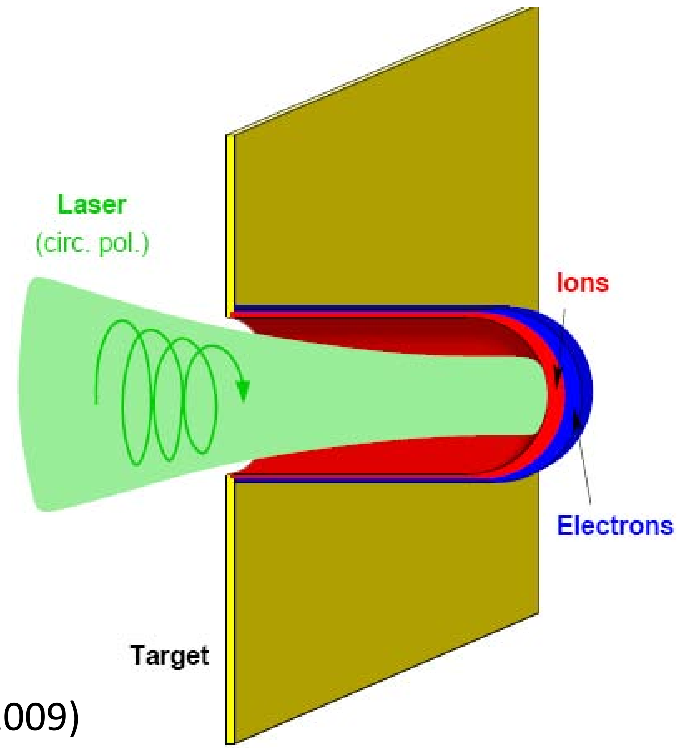
to **Coherent drive of them**

↓ ↓

CAIL (Coherent Acceleration of Ions by Laser)

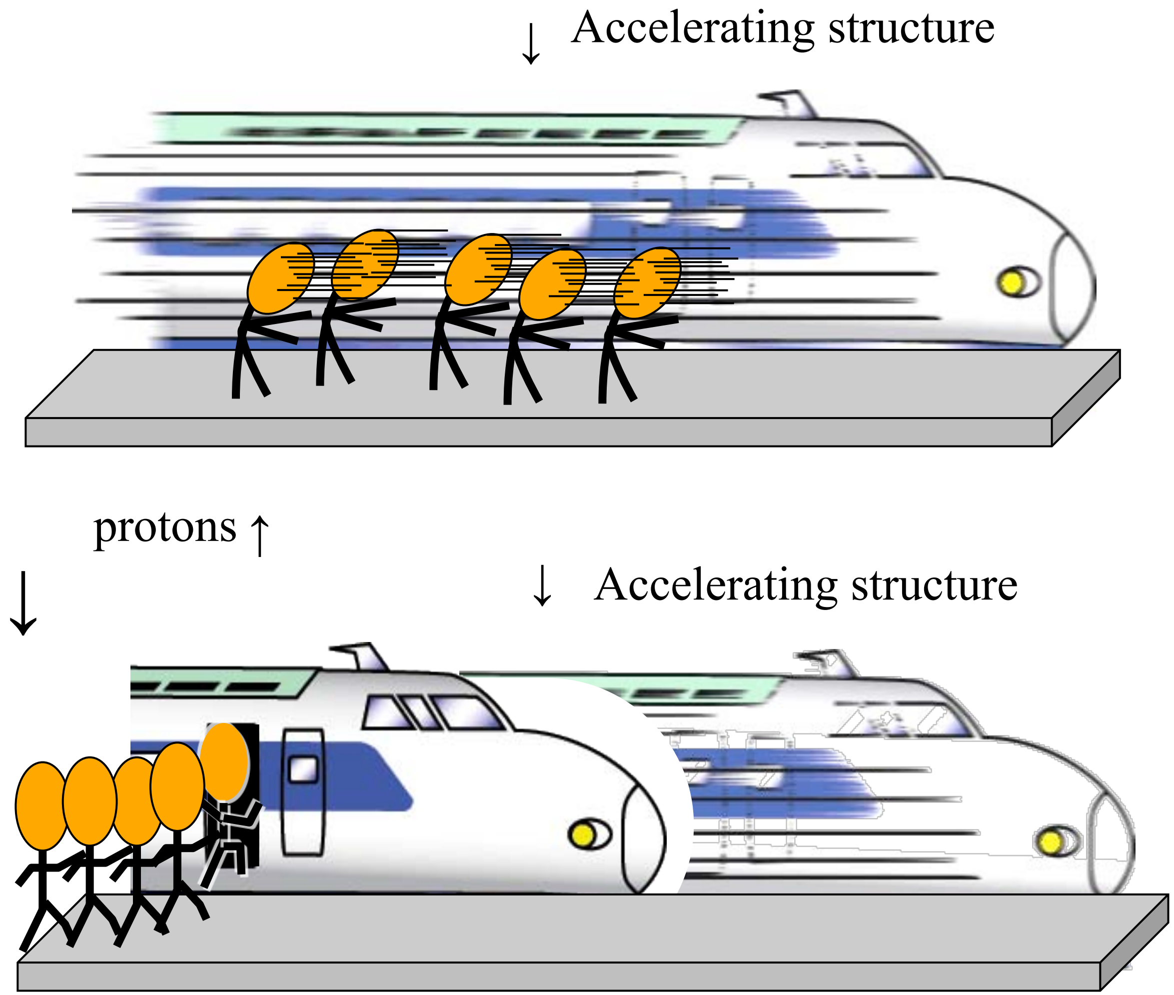
TNSA (Target Normal Sheath Acceleration)





Tajima, Habs, Yan: RAST (2009)

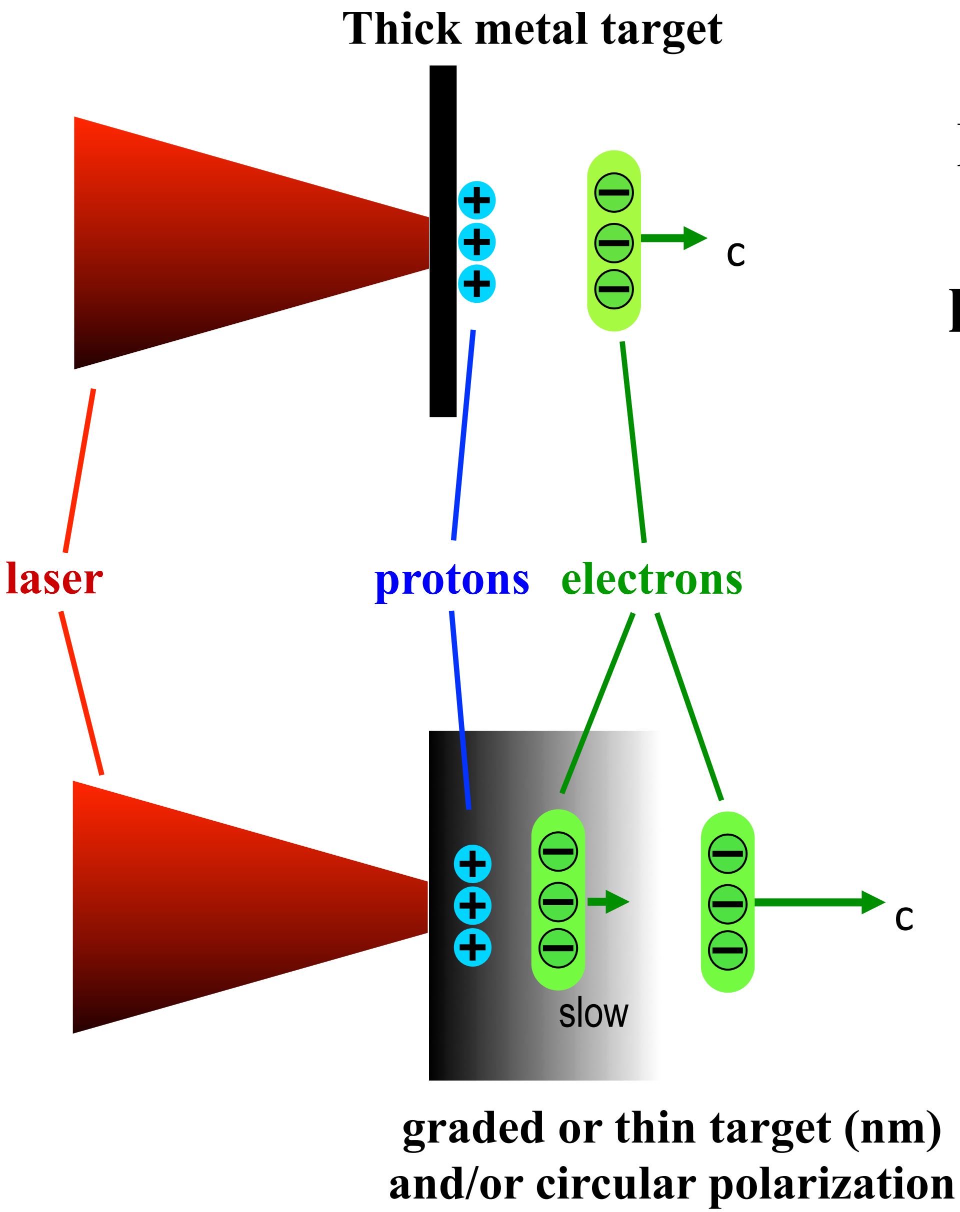
Adiabatic (gradual) acceleration



Inefficient if <u>suddenly</u> accelerated

Efficient when <u>gradually</u> accelerated

Adiabatic acceleration (2)



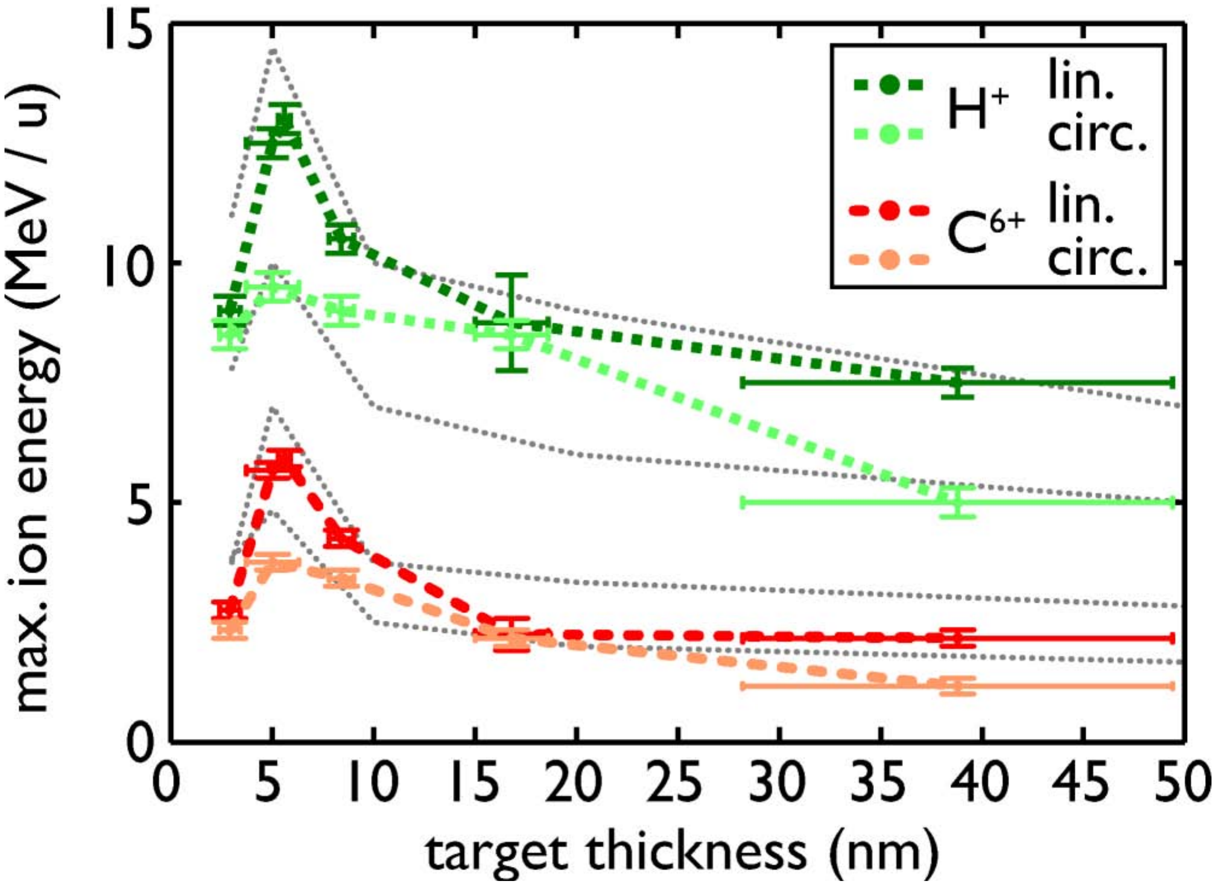
Most experimental configurations of proton acceleration (2000-2009)

"Adiabatic Acceleration" (2009-)

Recent experiments in CAIL Regime

Ultrathin film :$\sigma = a_0$, where $\sigma = d\, n / \lambda n_c$ ($\xi=\sigma/a_0$)
High laser contrast: not to destroy ultrathin target

ξ=1 ↓



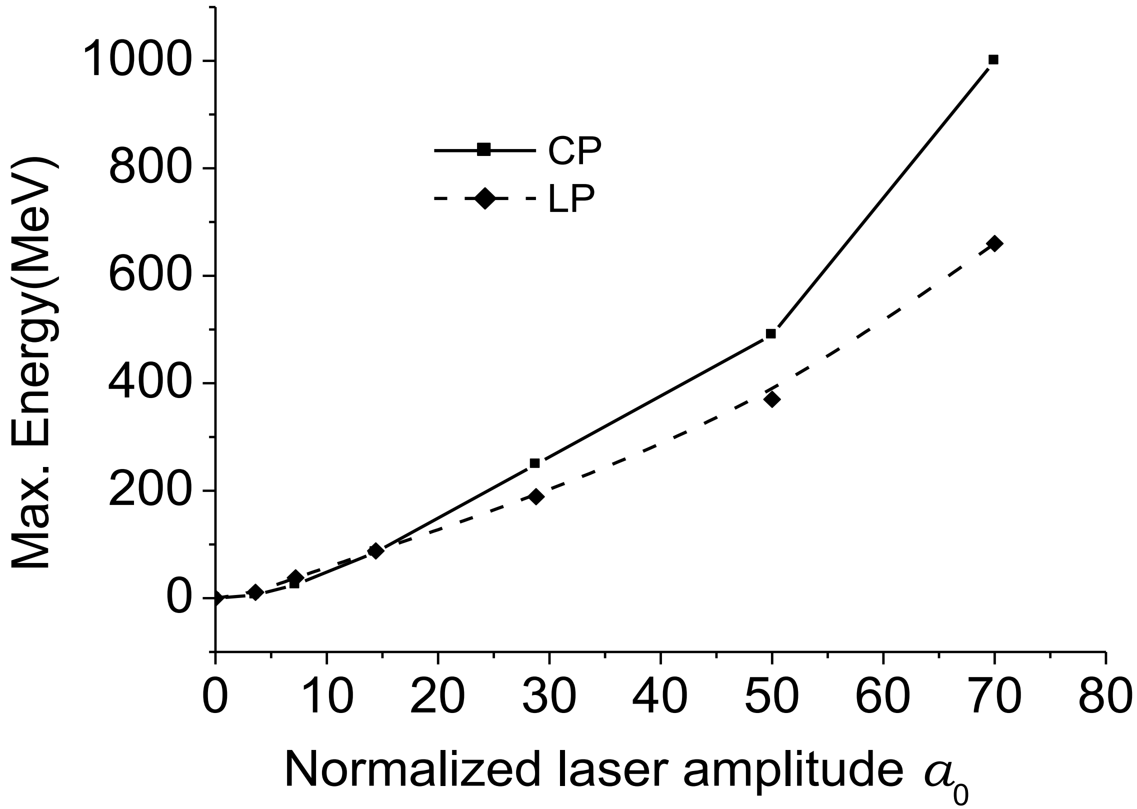
MAP + MBI

(Henig et al, 2009)

Toward more adiabatic acceleration

The more **adiabatic,** the longer accelerated, the higher energy

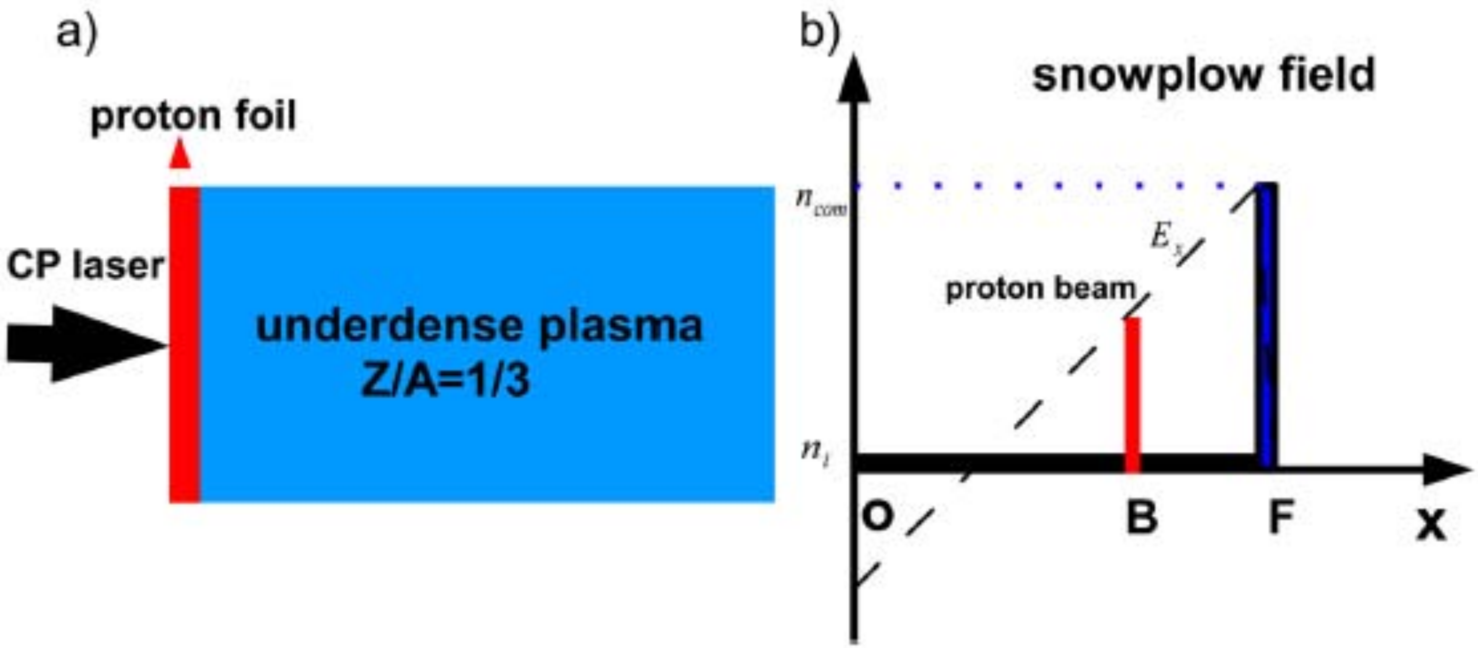
Energy by **CP** tends to increase as **$\sim a_0^2$**



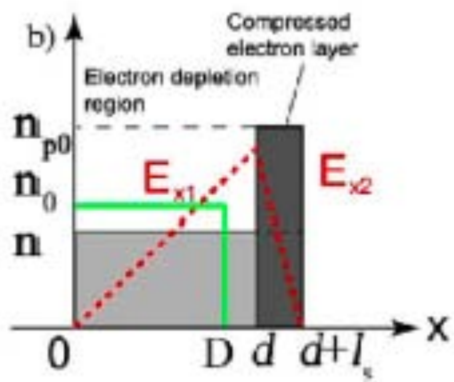
Tajima, Habs, Yan: RAST (2009)

Injection of ions into wakefield

Stability of ion beam in the electron layer



(Zheng, 2012; Shen et al.)



(Yan, 2008)

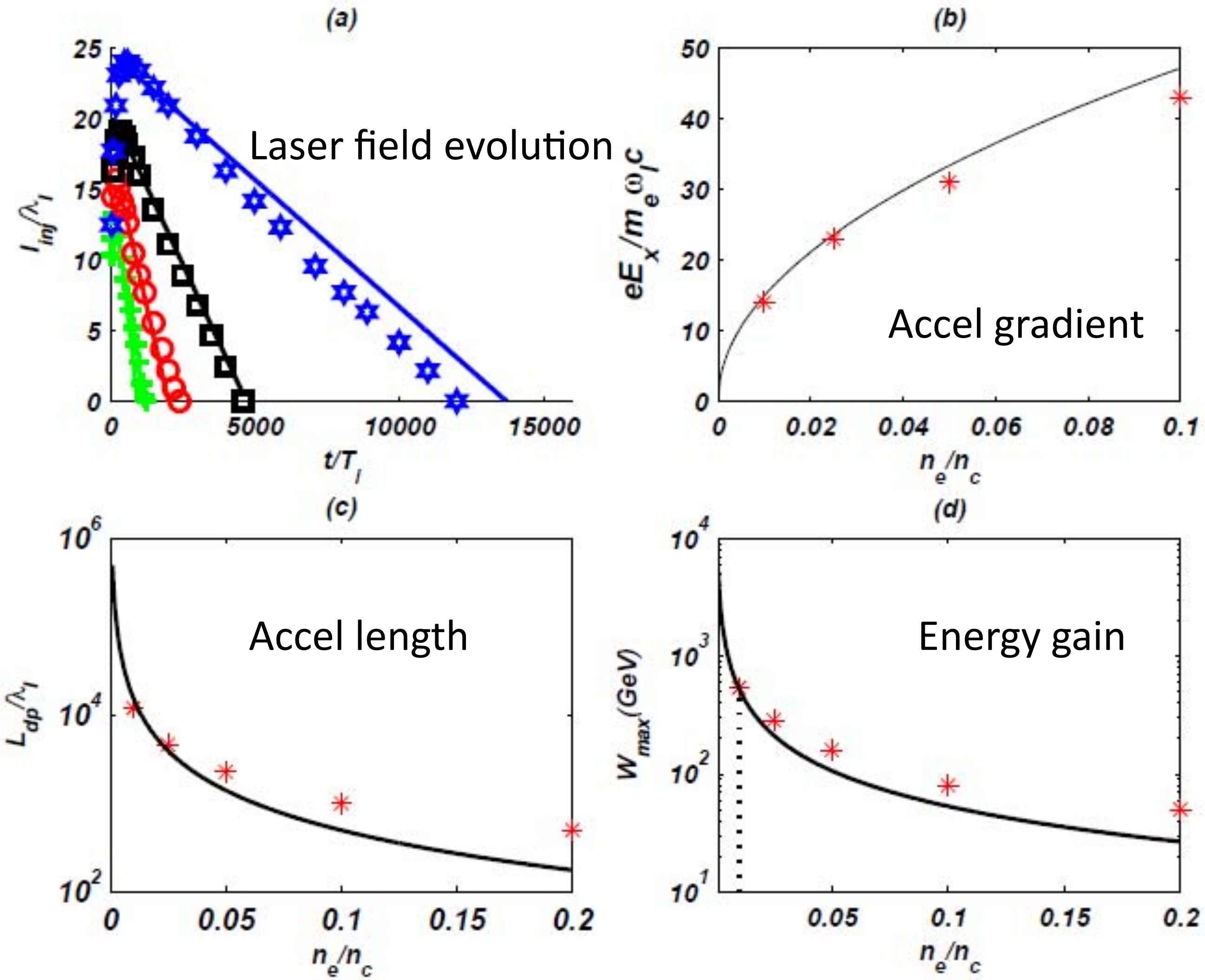
e.g. of application:

laser-driven compact neutrino source

(Bulanov e t al. 2005)

TeV proton Energy Scalings (RPA + LWFA)

TeV over cm @ 10^{23}W/cm^2

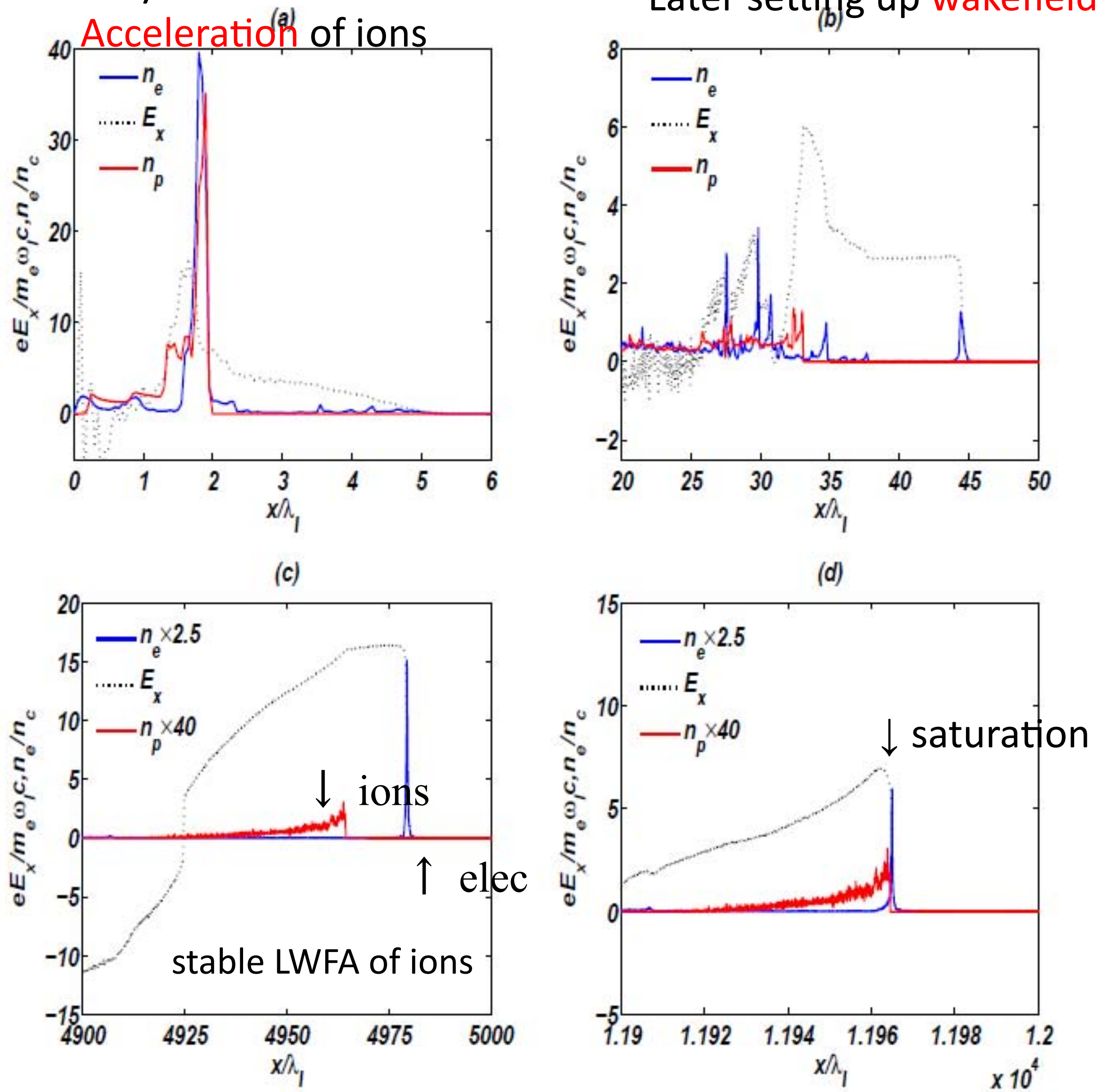


(Zheng et al. 2012)

TeV proton acceleration by LWFA

early Radiation Pressure Acceleration of ions

Later setting up wakefield



High Intensity regime

$I = 10^{23}$ W/cm^2

(using ELI type laser)

$$E_i = (1/6)\, a_0^2\, (n_c/n_e)\, mc^2$$

Snowplow LWFA
of ions injected by RPA
as injector at multi-GeV

0.5TeV over
dephasing length of 1cm

Zheng et al., 2011

GeV-TeV proton Energy Scalings(RPA x LWFA)

TeV over cm @ 10^{23}W/cm^2 (Zheng et al, 2012)
10GeV over mm @ 10^{22}W/cm^2 (Zheng et al, 2013)
200MeV @10^{21}W/cm^2 (Wang et al, 2013)

PHYSICS OF PLASMAS **20**, 013107 (2013)

Laser-driven collimated tens-GeV monoenergetic protons from mass-limited target plus preformed channel

F. L. Zheng,[1] S. Z. Wu,[1,2] H. C. Wu,[1] C. T. Zhou,[1,2] H. B. Cai,[1,2] M. Y. Yu,[3,4] T. Tajima,[5] X. Q. Yan,[1,6,a)] and X. T. He[1,2,b)]

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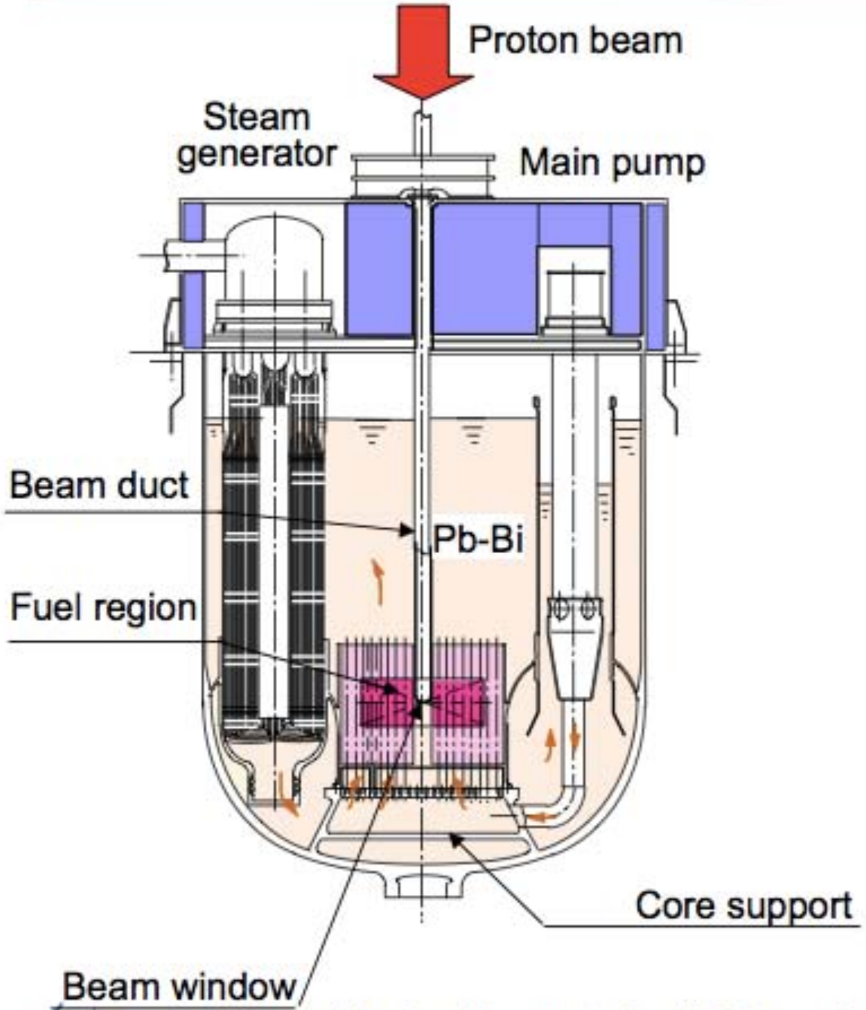
[3]*Institute of Fusion Theory and Simulation, Zhejiang University, Hangzhou 310027, China*
[4]*Institut für Theoretische Physik I, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[5]*Fakultät f. Physik, LMU München, Garching D-85748, Germany,*
[6]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

(Received 10 September 2012; accepted 27 December 2012; published online 11 January 2013)

Proton acceleration by ultra-intense laser pulse irradiating a target with cross-section smaller than the laser spot size and connected to a parabolic density channel is investigated. The target splits the laser into two parallel propagating parts, which snowplow the back-side plasma electrons along their paths, creating two adjacent parallel wakes and an intense return current in the gap between them. The radiation-pressure pre-accelerated target protons trapped in the wake fields now undergo acceleration as well as collimation by the quasistatic wake electrostatic and magnetic fields. Particle-in-cell simulations show that stable long-distance acceleration can be realized, and a 30 fs monoenergetic ion beam of >10 GeV peak energy and <2° divergence can be produced by a circularly polarized laser pulse at an intensity of about 10^{22} W/cm^2. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4775728]

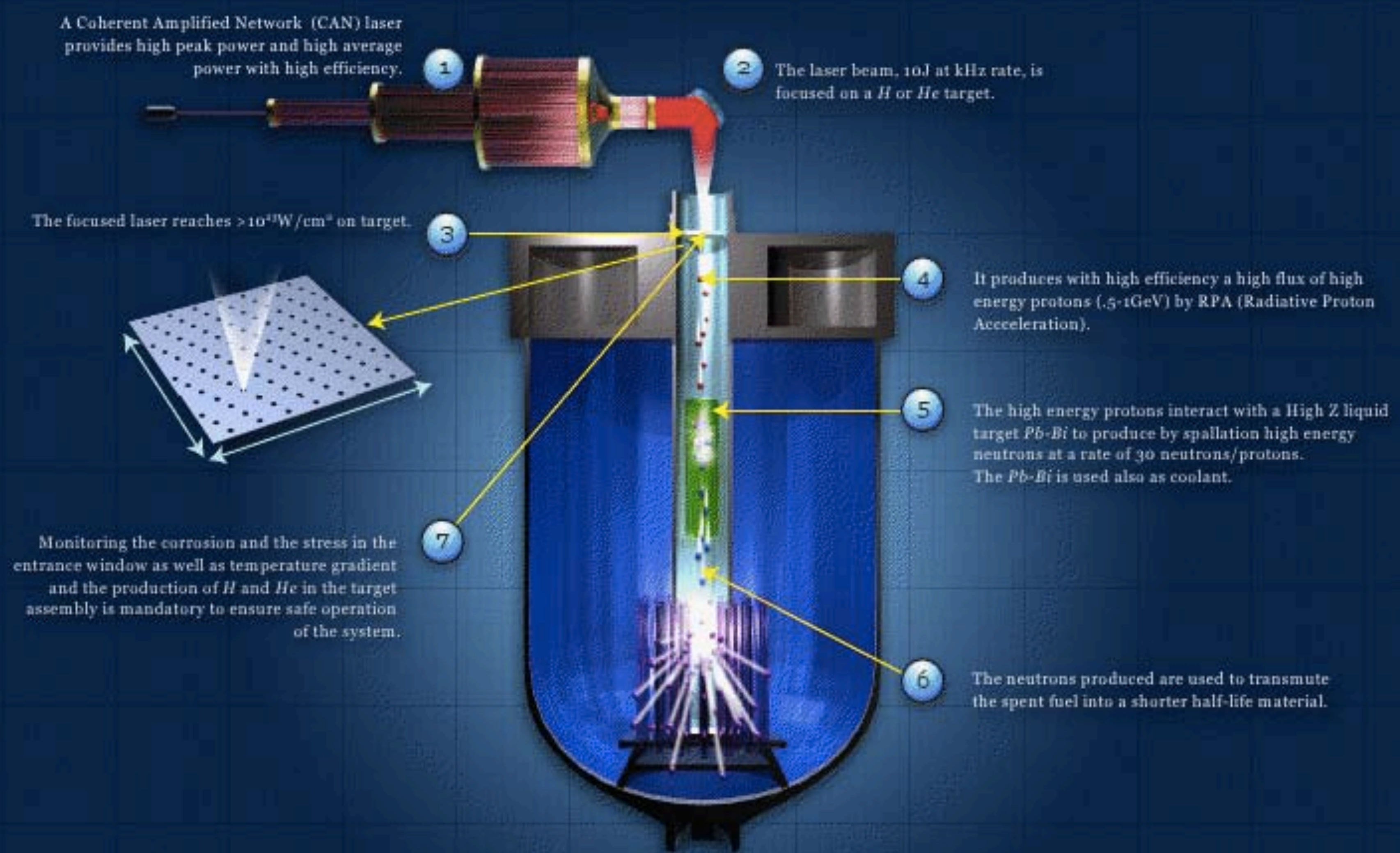
High Intensity Proton Accelerator Project in JAERI/Tokai: Preliminary Design of the Target



- Proton beam : 1.5GeV 22 - 30MW
- Spallation target : Pb-Bi
- Coolant : Pb-Bi
- Subcriticality : $k_{eff} = 0.95$
- Thermal output : 800MWt
- Core height : 1000mm
- Core diameter : 2440mm
- MA initial inventory : 2.5t
- Fuel composition :
  (40%Pu + 60%MA) Mono-nitride
- Transmutation rate :
  10%MA / Year (10 units of LWR)
- Burn-up reactivity swing :
  +1.8% k/k

Activities on Nuclear Transmutation H. Oigawa Group Leader, Transmutation Experiments Group

THE LASER DRIVEN TRANSMUTATOR CONCEPT



(Mourou, Tajima, Gales, 2013)

conclusions

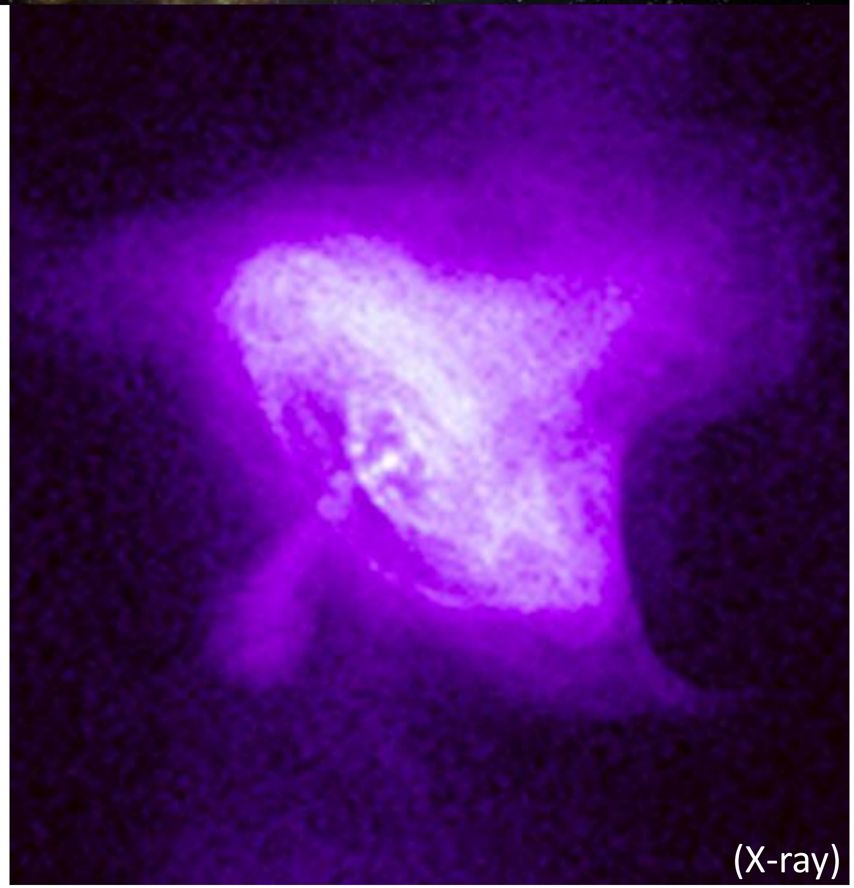
- CAN: Path to efficient, high rep rated, smart high intensity laser
- High intensity laser community x High energy physics community
- *IZEST* effort toward High energy accelerators: $e^- e^+$ collider, γ γ collider, dark field search
- 4th *IZEST* Conference Tokyo (Nov. 18-20, French Embassy)
- UCI: *IZEST* Hub = prepares to host *WAVEFRONT* (Wakefield Acceleration in Very Extreme Fields Resulting Out of New Technology) *Center*
- From *ICAN* toward *WE-CAN* (World Effort-CAN): proof of principle

  Please join us
- Many applications: brilliant directed laser Compton γ-beam = nuclear resonance fluorescence (radioactive waste monitor), nuclear medicine / pharmacology, positron source; cold neutron source; laser ion accelerators = compact proton therapy, neutron source for ADS, neutrino source

Aspiration unbound

Imagination unbound

Crab nebula:
Cosmic PeV accelerating machine



謝謝!