Chaires internationales de recherche Blaise Pascal

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The Seventh Blaise Pascal Lecture
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Ecole Polytechnique
Amphi Faurre

Medical Applications of Laser Ion Acceleration

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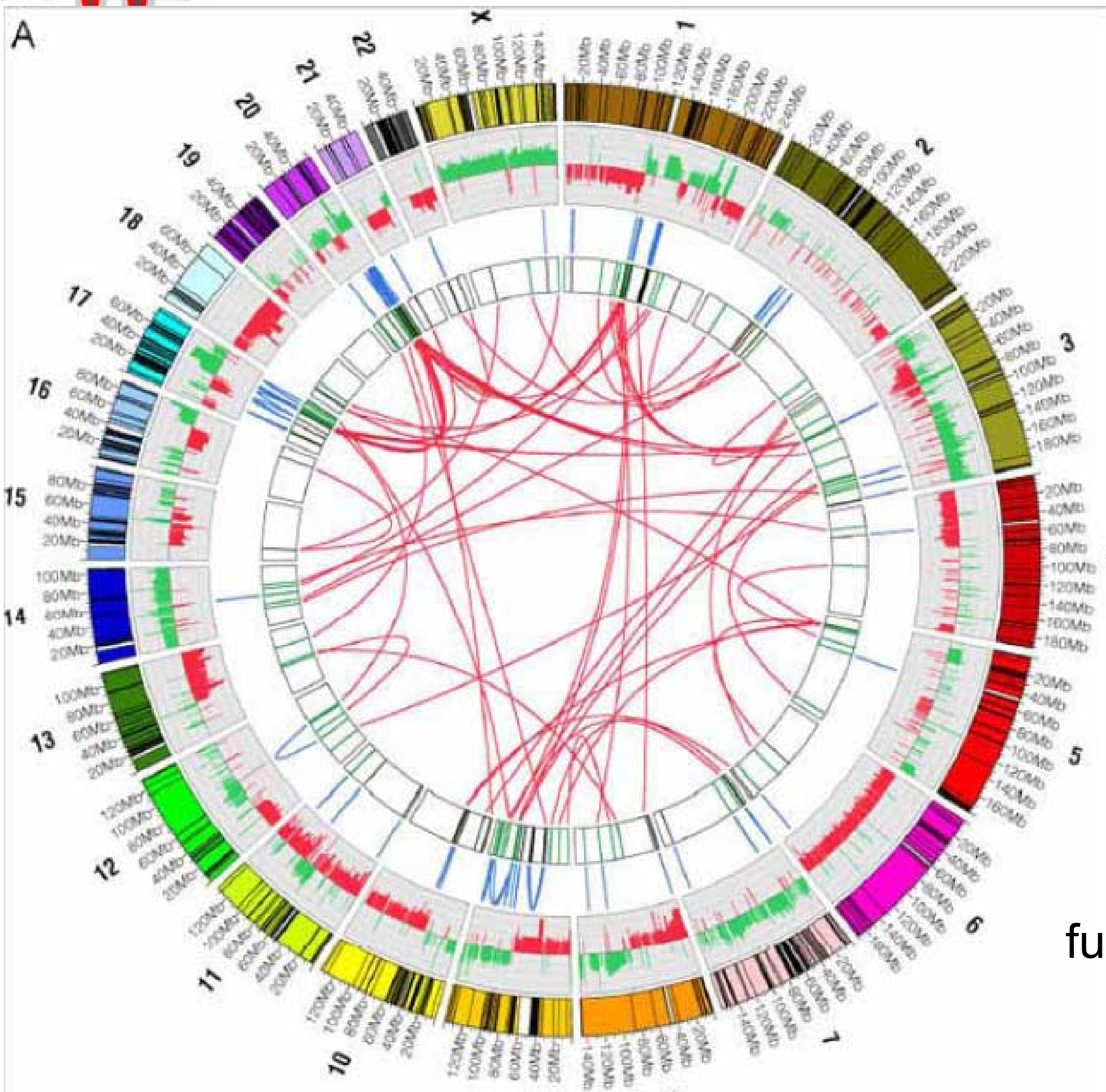
Chaotic (and thus Violent) Mutations



Cancer causing human genome mutations: scary! (Time Magazine)

fundamental to biology

5-year survival rates after curative treatment in early cancer stages

M. Molls/ Japan Apr 09

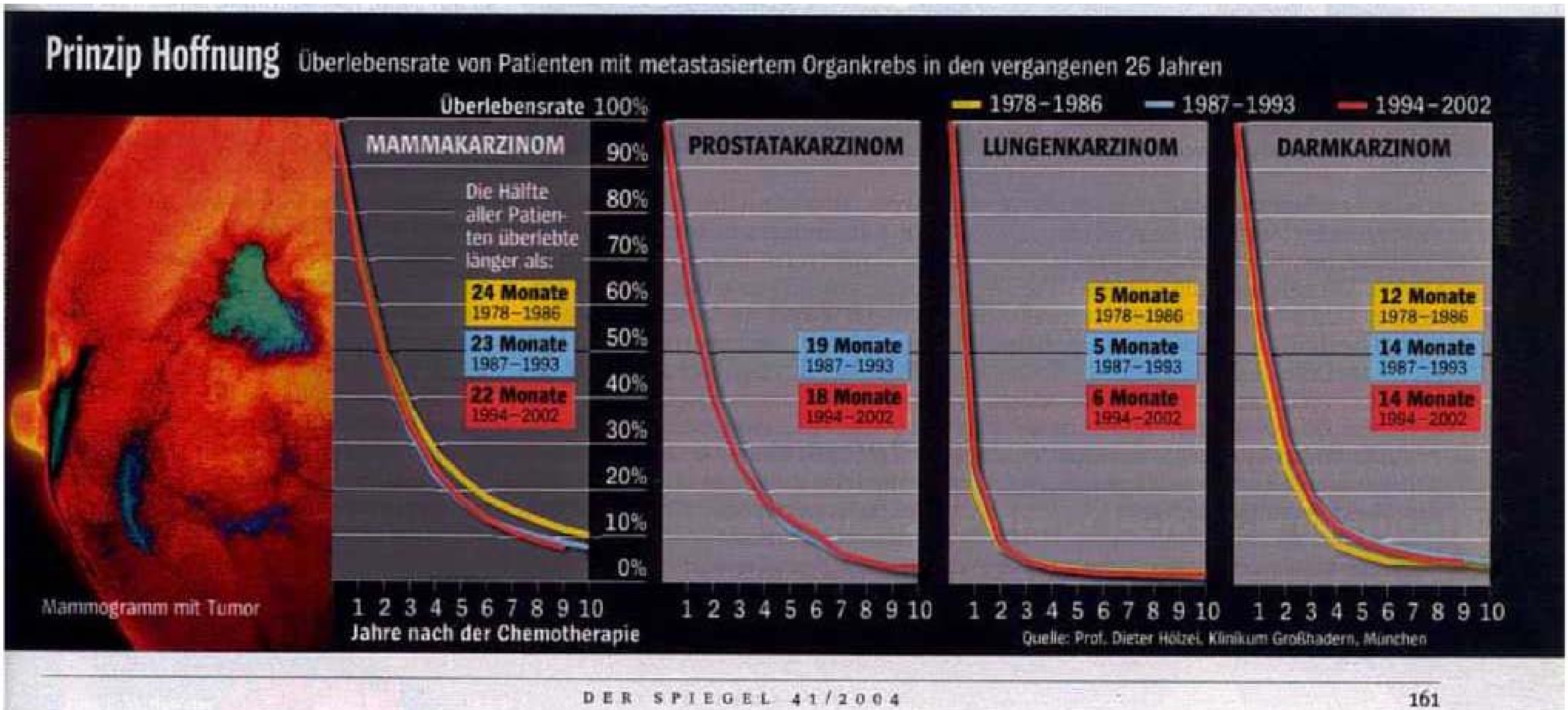
	Radiotherapy alone	**Surgery** alone	**Chemotherapy** alone
Prostate	79 % (5 y) 66 – 79 % (10 y)	75 – 85 %	Ø
Lung	6 – 50 % (Stereotact. RT: > 50 %)	30 – 80 %	Ø
Cervix	63 – 91 %	74 – 91 %	Ø
Skin	up to 100 %	up to 100 %	Ø
Anus	60 – 80 % (T1, T2) 33 – 58 % (T3, T4)	comparable with results after RT	Ø
Rectum	~ 65 %	78 – 82 %	Ø

Ø: no data in the literature: CHEMOTHERAPY has no curative potential in solid tumors (exception: testicular cancer)

In the last decades: no improvement of survival in metastatic cancer diseases

(macroscopic metastases)

M. Molls/ Japan Apr 09



Data from "Tumor Center München"

Chemotherapy (medical cancer treatment) has no curative potential in solid tumors!

WHY?

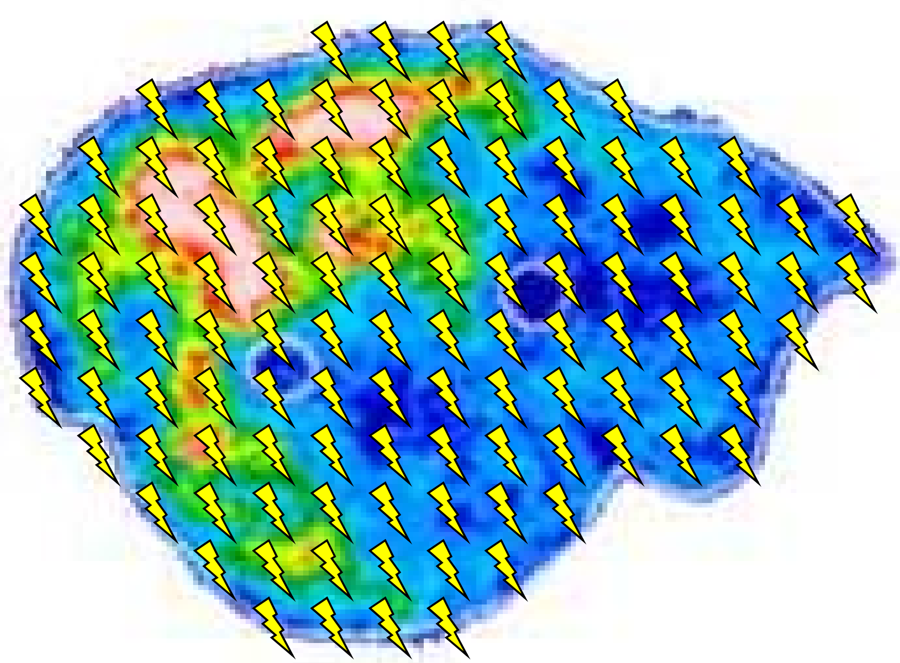
Radiation | Chemotherapy

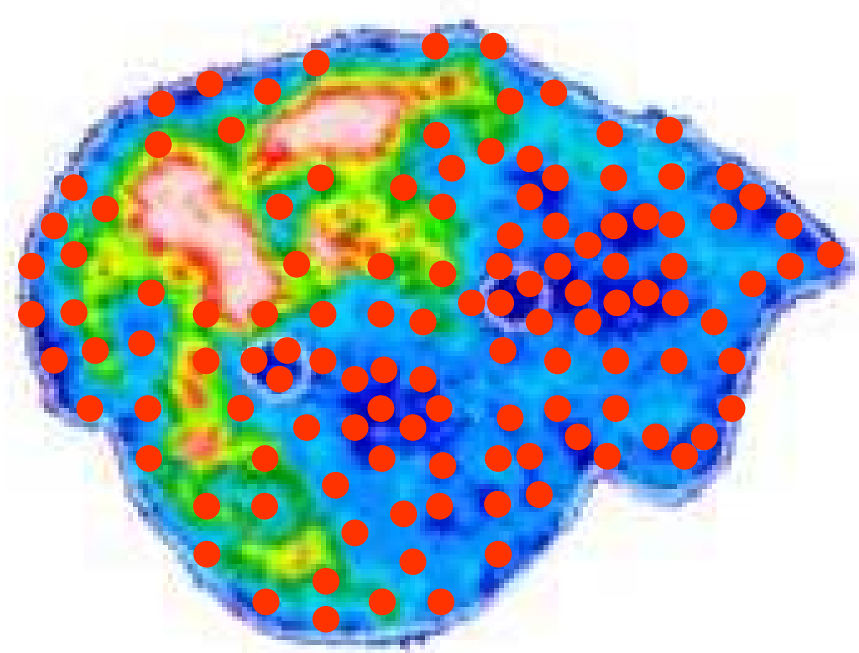
Homogeneous dose distribution

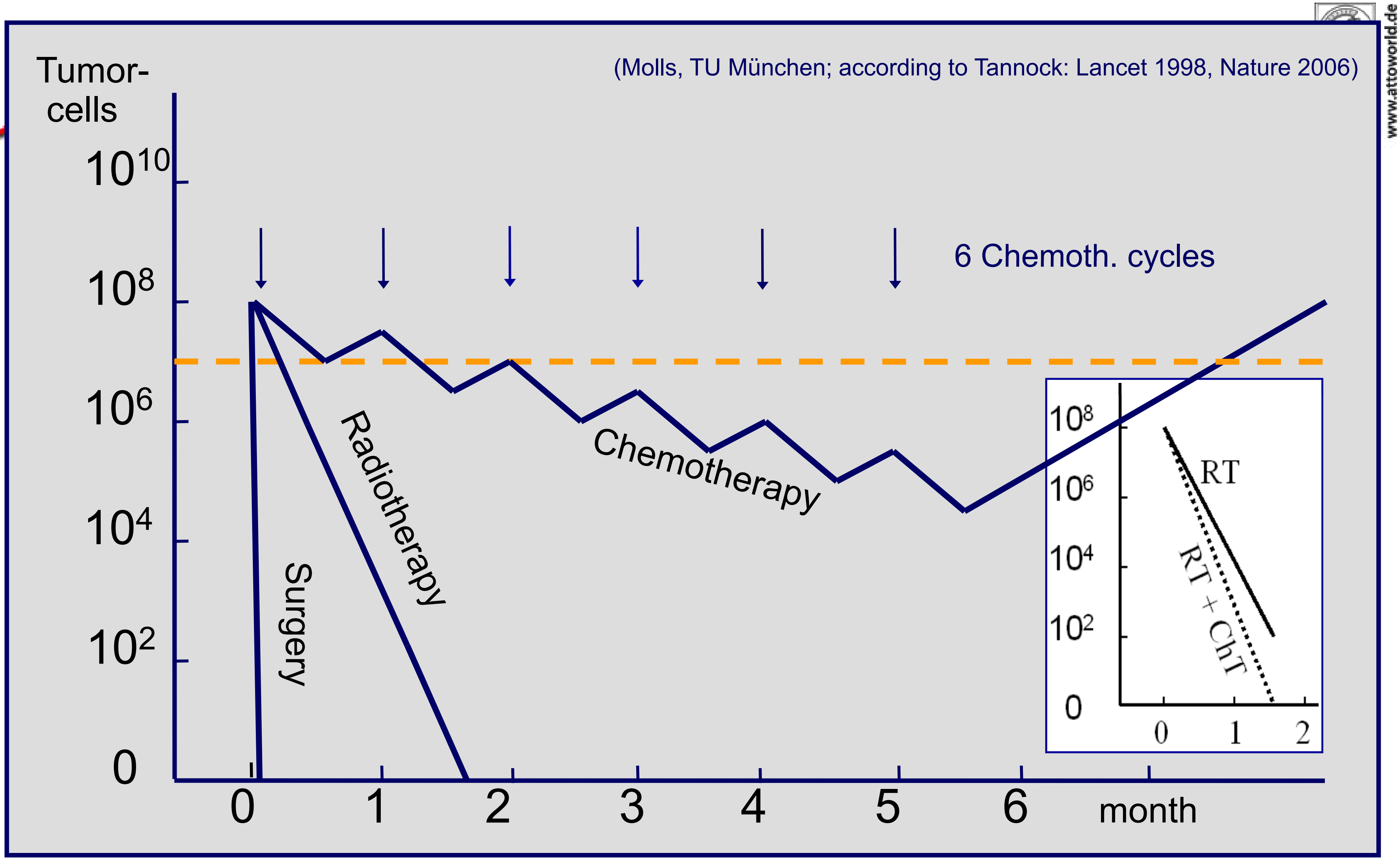
The tumor cell kill depends on intrinsic radiation sensitivity, DNA repair capacity, repopulation, oxygenation status etc.. However, the entire tumor can be irradiated homogeneously with that dose, which is necessary to kill all clonogenic tumor cells, even the most resistant ones.

Inhomogeneous dose distribution

The tumor cell kill depends on the transport of the substance to the clonogenic cells and molecular targets, DNA repair capacity, repopulation, pO2, pH, MDR, etc.. In macroscopic tumors not all the subvolumes of the tumor, clonogenic cells and relevant molecular targets are reached by those doses of the medical substance which are needed for cell kill.







Macroscopic Tumor: ≥ 5mm (more than 10^7 cells)
Microscopic Tumor: < 5mm (1 – 10^7 cells)

Cell kill after Chemotherapy: only about 3 logarithmic steps (ordinate)

Prof. Molls (TUM/MAP) says:

"Solid tumors which consist in more than about 1000 cells apparently can not be cured by medical treatment. This holds true especially for macroscopic tumors which consist in more than 1 to 10 million cells (exception: testicular cancer)

The main problem:

The medical substances don't reach all dividing tumor cells and respective molecular targets in a concentration which is high enough to kill the cells. After medical treatment there remain dividing cells from which tumor regrowth is starting."

Breast Cancer: Improvement of survival by better diagnostic and earlier detection of the tumor

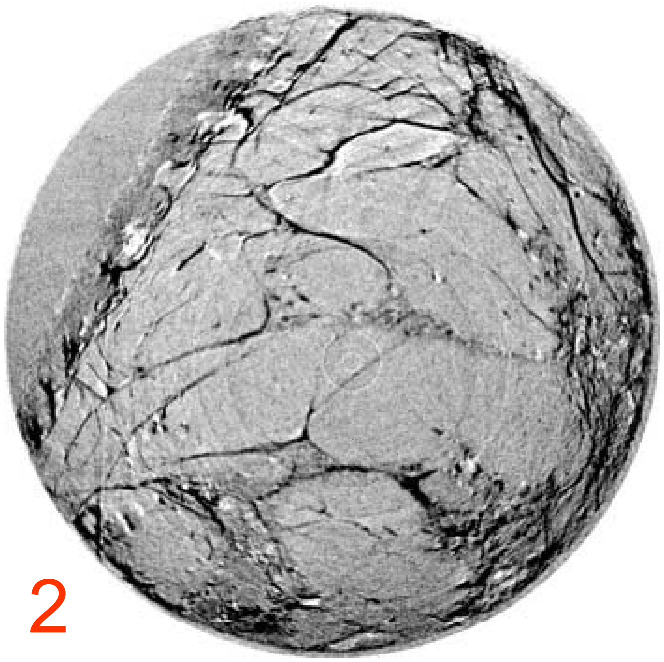
(Patients with breast carcinoma in Brisbane, Australia; Webb et al, The Breast 2004)

	Diagnosis 1981 - 84	Diagnosis 1990 – 94
Patients	469	520
Average age	56 J	53 J
Tumor < 1cm	11%	22%
Tumor > 2cm	44%	34%
Lymph node metast.	50%	38%
Stage 1	32%	46%
Stage 2	61%	47%
Stage 3	7%	7%
5 y survival	74%	84%

Brilliant X-rays
Diffraction enhanced imaging: breast, ex vivo

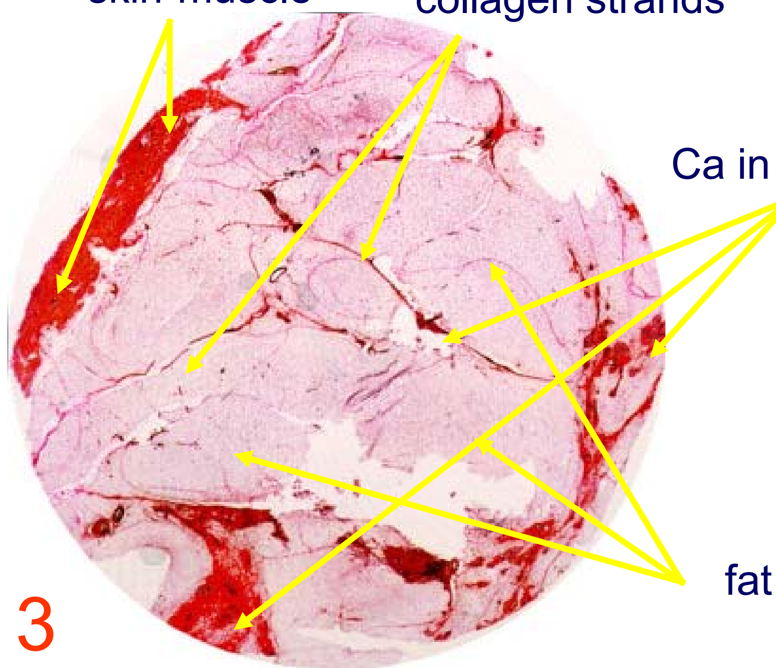
1 CT ex vivo, 2 Brilliant X-ray image ex vivo, 3 Histology

2



2: DEI 33 keV

3

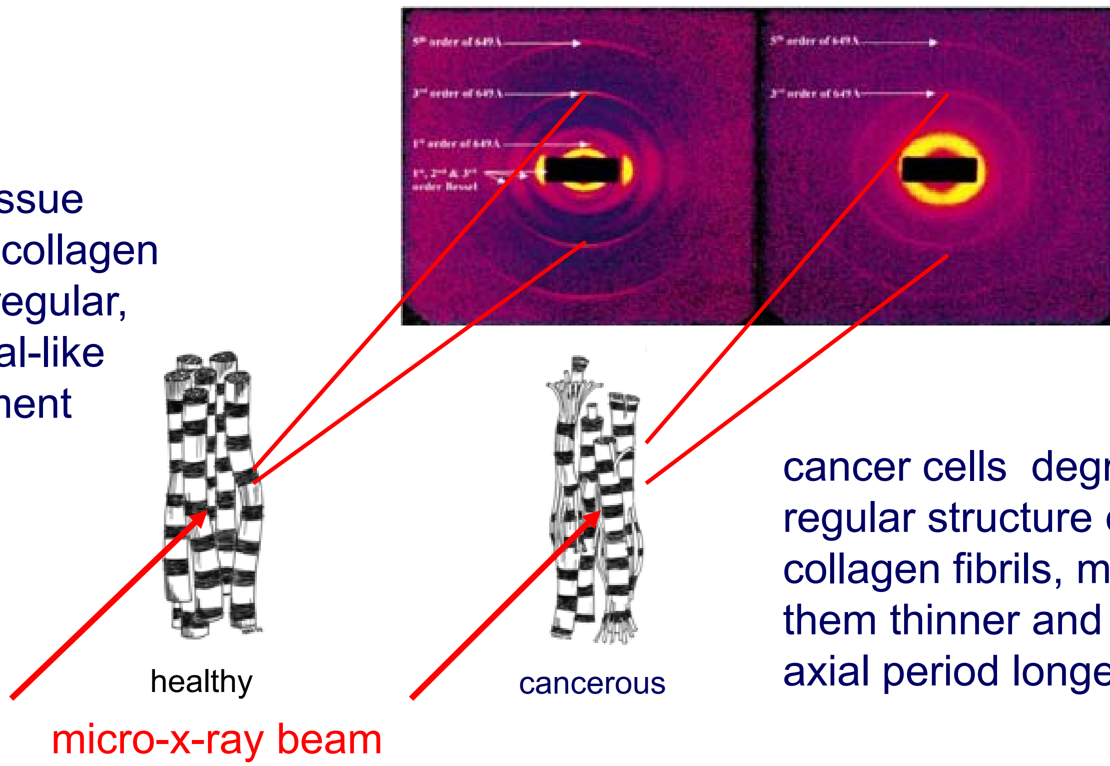


3: Histology

Bravin et al. Phys Med Biol 52:2197-211, 2007

Small-angle X-ray scattering (SAXS)

normal tissue contains collagen fibrils in regular, hexagonal-like arrangement



cancer cells degrade regular structure of collagen fibrils, making them thinner and their axial period longer

vision: direct cancer diagnosis without biopsy

from © D.Habs

Phase contrast imaging: F. Pfeiffer

The Economist
APRIL 1ST–7TH 2006 www.economist.com

ger in patent) by signing contracts with manufacturers in India and South Africa that guarantee large order-volumes and reliable payment. As a result of this and similar initiatives, the price of a course of these drugs has, in some cases, fallen below $150 per person per year—down from over $1,000 at the turn of the century.

Progress, then, is being made. And perhaps the most telling sign of that is what has not happened. The AIDS-activists' organisations, normally sensitive to the least failure to honour a pledge, have, by and large, kept quiet. Dr De Cock will not be drawn into predictions about what progress to expect over the next few years, but Mr Clinton (admittedly not an epidemiologist) says he will be both disappointed and surprised if the 3m figure is not reached by the end of this year. With an epidemic the size of AIDS, that means a lot of extra deaths. But, realistically, it is not that great an overrun. ■

Imaging technology

A discerning view

A new way of processing X-rays gives much clearer images

X-RAYS are the mysterious phenomenon for which Wilhelm Röntgen was awarded the first Nobel prize in physics, in 1901. Since then, they have shed their mystery and found widespread use in medicine and industry, where they are used to reveal the inner properties of solid bodies.

Some properties, however, are more easily discerned than others. Conventional x-ray imaging relies on the fact that different materials absorb the radiation to different degrees. In a medical context, for example, bones absorb x-rays readily, and so show up white on an x-radiograph, which is a photographic negative. But x-rays are less good at discriminating between different forms of soft tissue, such as muscles, tendons, fat and blood vessels. That, however, could soon change. For Franz Pfeiffer of the Paul Scherrer Institute in Villigen, Switzerland, and his colleagues report, in the April edition of *Nature Physics*, that they have manipulated standard x-ray imaging techniques to show many more details of the inner body.

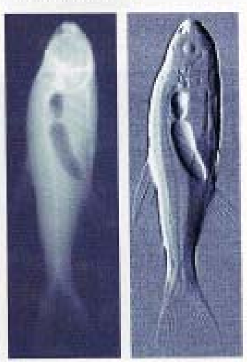
The trick needed to discern this fine detail, according to Dr Pfeiffer, is a simple one. The researchers took advantage not only of how tissues absorb x-rays but also of how much they slow their passage. This slowing can be seen as changes in the phase of the radiation that emerges—in other words of the relative positions of the peaks and troughs of the waves of which x-rays are composed.

Subtle changes in phase are easily picked up, so doctors can detect even small variations in the composition of the tissue under investigation, such as might be caused by the early stages of breast cancer. Indeed, this trick—known as phase-contrast imaging—is already used routinely in optical microscopy and transmission electron microscopy. Until now, however, no one had thought to use it for medical x-radiography.

To perform their trick, the researchers used a series of three devices called transmission gratings. They placed one between the source of the x-rays and the body under examination, and two between the body and the x-ray detector that forms the image. The first grating gathers information on the phases of the x-rays passing through it. The second and third work together to produce the detailed phase-contrasted image. The approach generates two separate images—the classic x-ray image and the phase-contrasted image—which can then be combined to produce a high-resolution picture.

The researchers tested their technique on a Cardinal tetra, a tiny iridescent fish commonly found in fish tanks and aquariums. The conventional x-ray image showed the bones and the gut of the fish, while the phase-contrasted image showed details of the fins, the ear and the eye.

Dr Pfeiffer's technique would thus appear to offer a way to get much greater detail for the same amount of radiation exposure. Moreover, since it uses standard hospital equipment, it should be easy to introduce into medical practice. X-rays may no longer be the stuff of Nobel prizes, but their usefulness may just have increased significantly. ■



Before and after

Encyclopedias

Battle of Britannica

War has broken out between Encyclopaedia Britannica and Nature

AT FIRST, it was an innocuous test of accuracy. Last year, journalists at *Nature* wondered how scientific entries in Wikipedia—a free web encyclopedia that anyone can edit—compared with those in "Encyclopaedia Britannica". They compiled a list of subjects, downloaded relevant entries from each website, and sent the results to experts.

The findings were published in December and Britannica won—a blow had been struck by the gold-standard encyclopedia compiled by experts over the collective knowledge of a bunch of hobbyists and amateurs. Except that the results held a surprise. Britannica contained a lot of errors, and it was only 30% more accurate than the free encyclopedia.

This was all too much for Britannica. So, five weeks ago, it launched a 50-strong team of rebuttal editors and experts to pick apart the *Nature* study. The team's 20-page report concluded that "almost everything about the journal's investigation was wrong and misleading". Oh, and it demanded that *Nature* retract its study. *Nature* hit back with its own rebuttal and refused to retract anything. On March 27th Britannica fired another salvo, with advertisements in the *Times* and the *New York Times*. *Nature* returned fire with a rebuttal editorial.

Some of Britannica's criticisms are quibbles. It didn't like *Nature*'s headline, and Ted Pappas, Britannica's executive editor, says *Nature* didn't allow Britannica to see any of the evidence on which the study was based until a week after it was published. That was a bit unsporting. In the media binge after the study's release, *Nature*'s journalists talked widely about their findings, while Britannica's editors felt they could not defend themselves.

Besides these quibbles, there are a couple of more serious issues. One is the overall accuracy of Britannica, the other is its relative accuracy compared with Wikipedia. On the first, *Nature* identified 123 errors in 42 Britannica articles. These comprise factual errors, misleading statements and critical omissions.

However, many of these "errors" are really the opinion of the reviewers. For example, a *Nature* reviewer says of the Britannica entry on the Cambrian period that the "evolution of hard parts at the beginning of the Cambrian involved much more than development of calcium carbonate." Britannica replies: "the article ▸▸

FOREFRONT 前沿

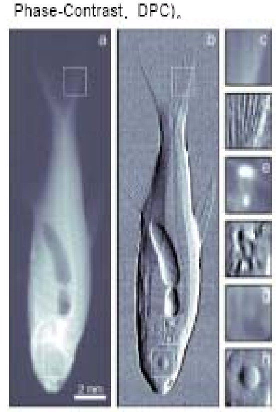
应用普通 X 射线源进行相位对比度成像

Franz Pfeiffer 等
Franz Pfeiffer先生，博士，瑞士 Paul Scherrer 研究所组长；Timm Weitkamp 先生，博士，德国 Forschungszentrun Karlsruyhe 研究所成员；Oliver Bunk 先生，瑞士 Paul Scherrer 研究所成员；Christian David 先生，瑞士 Paul Scherrer 研究所成员。
刘红霞 编译
2006 年 8 月 30 日收到。

关键词：普通 X 射线源 相位对比度成像

前言

在医学诊断领域，放射诊断是建立在 X 射线吸收对比度成像基础上的。然而对于人体软组织及一些生物组织样本而言，由于它们对 X 射线吸收能力较弱，X 射线吸收对比度成像的应用受到了限制。这一缺陷可通过采用同步加速器高亮度同步辐射或者微焦 X 射线源等设备应用相位对比度成像方法加以解决(见 IMD Vol.10 No.3 及 IMD Vol.12 No.6)。可是，要将产生高亮度同步辐射的装置——大型同步加速器安装在临床医院中是不切实际的。在本文中，我们介绍的是在应用普通 X 射线发生器的情况下，利用一种由 3 个透射光栅(Transmission Grating)组成的装置来产生定量微分相位对比图像(Differential Phase-Contrast，DPC)。



来的吸收对比放射线片就很难将某些病变组织从非病变组织中区分开来。

本文作者 Franz Pfeiffer 先生

为了克服这一缺陷，目前许多人研究了利用 X 射线穿透样品时的相位移动来产生放射成像对比度的方法。这些方法可归类为干涉计法、分析仪法以及自由空间传输法等。这些方法在信号记录、实验装置和对辐射亮度的要求等方面有很大的不同。干涉计法和分析仪法需采用光学晶体，这两种方法需要高度平行的单色 X 射线束。自由空间传输法可放松对时间相干性的要求，但该种方法要求用微焦 X 射线源或者同步加速器发射的射线才能达到。以上种种限制的存在，使得迄今为止研究者们依然不能使相位对比度成像成为医疗或工业应用的标准方法。

在本文中，我们将展示一套基于光栅的 DPC 装置，采用该方法可以在使用低亮度多色 X 射线源的情况下有效地对定量相位图像进行恢复。

下文会描述如何应用 3 个光栅就低亮度 X 射线源进行物体成像。三光栅 DPC 成像装置由光源光栅 G_0、相位光栅 G_1 和带有分析器的吸收光栅 G_2 组成(*图 1a*)，光栅周期分别为 p_0、p_1 和 p_2。光源光栅 G_0 是带有吸收掩模的传输狭缝，放置在 X 射线管阳极附近，使得 X 射线管产生各个独立相干，但相互之间不相干的光源。每束光源的宽度同周期 p_0 的比率 γ_0 足够小，只有这样才能为 DPC 成像形成过程提供充分的空间相干性。

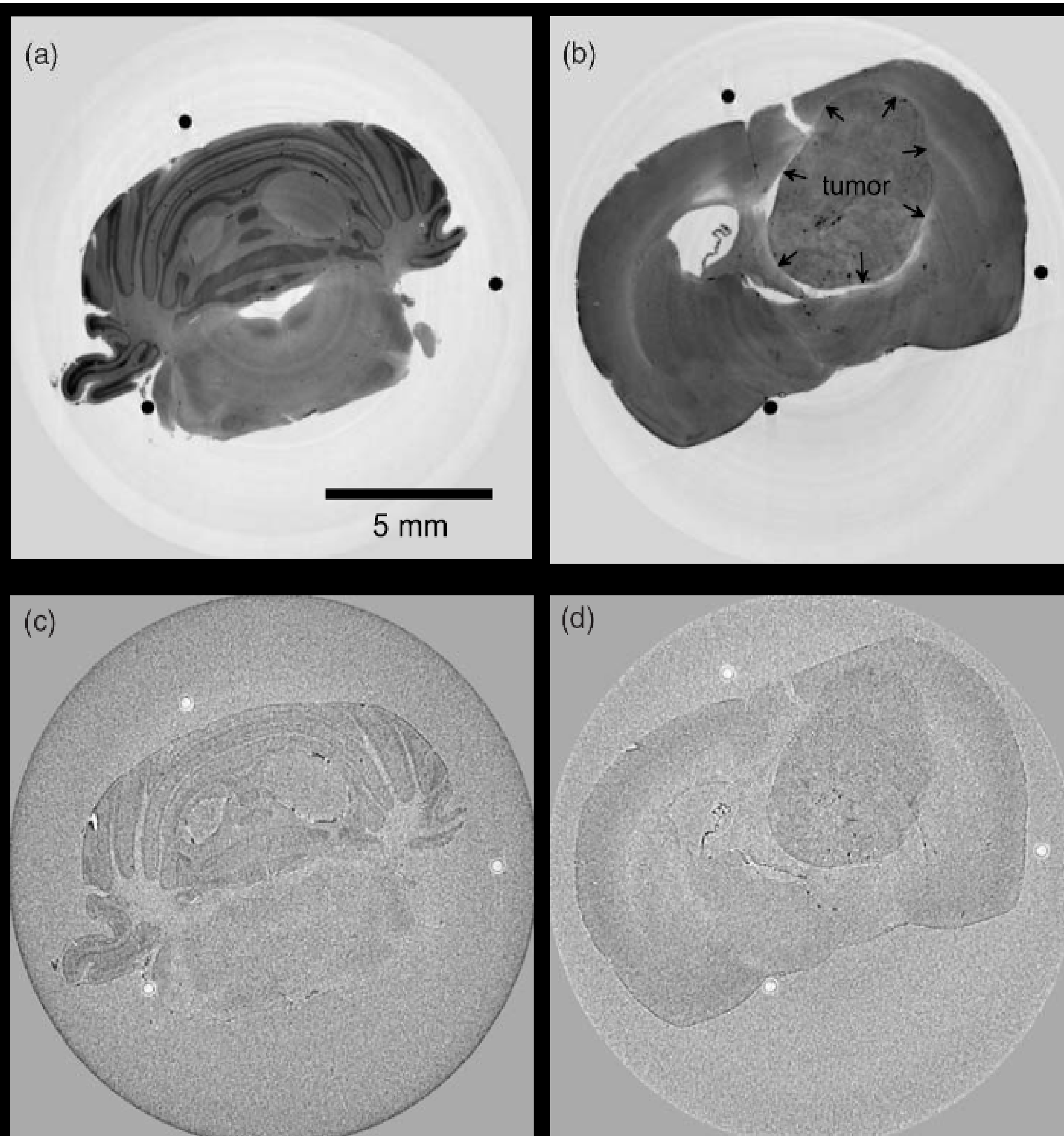
由于光源光栅 G_0 包括大量的独立狭缝，每个狭缝都可产生充分相干光线，因此一个源面积大于 1 mm^2 的普通 X 射线发生器就足够用。本文所用 X 射线发生器为 40 kV/25 mA，Mo 靶，焦点为 8 mm(水平) × 0.4 mm(垂直)，由于靶相对于光轴倾斜 6°，有效源面积为 0.8 mm × 0.4 mm。为了确保由 G_0 产生的每一条射线都能够在图像形成过程中发挥作用，这个光栅装置的几何学设计必须满足以下条件(*图 1b*)：

$$p_0 = p_2 \times \frac{l}{d}$$

需要注意的事是：总源面积 w 决定了最后成像的分辨率，即 wd/l。在 G_1 和 G_2 两个光栅之间完成的 DPC 图像形成过程类似于 Schlieren 成像或衍射增强成像(Diffraction Enhanced Imaging，DEI)。其成像的本质是当一目标物体放置于 X 射线束经过通路时，通过物体进行传输的光束发生了轻微的折射，DPC 成像基本原理依赖于所探测到的局部偏转角(*图 1b*)。偏转角 α 的大小同物体的局部相位移动梯度成正比，定量表示

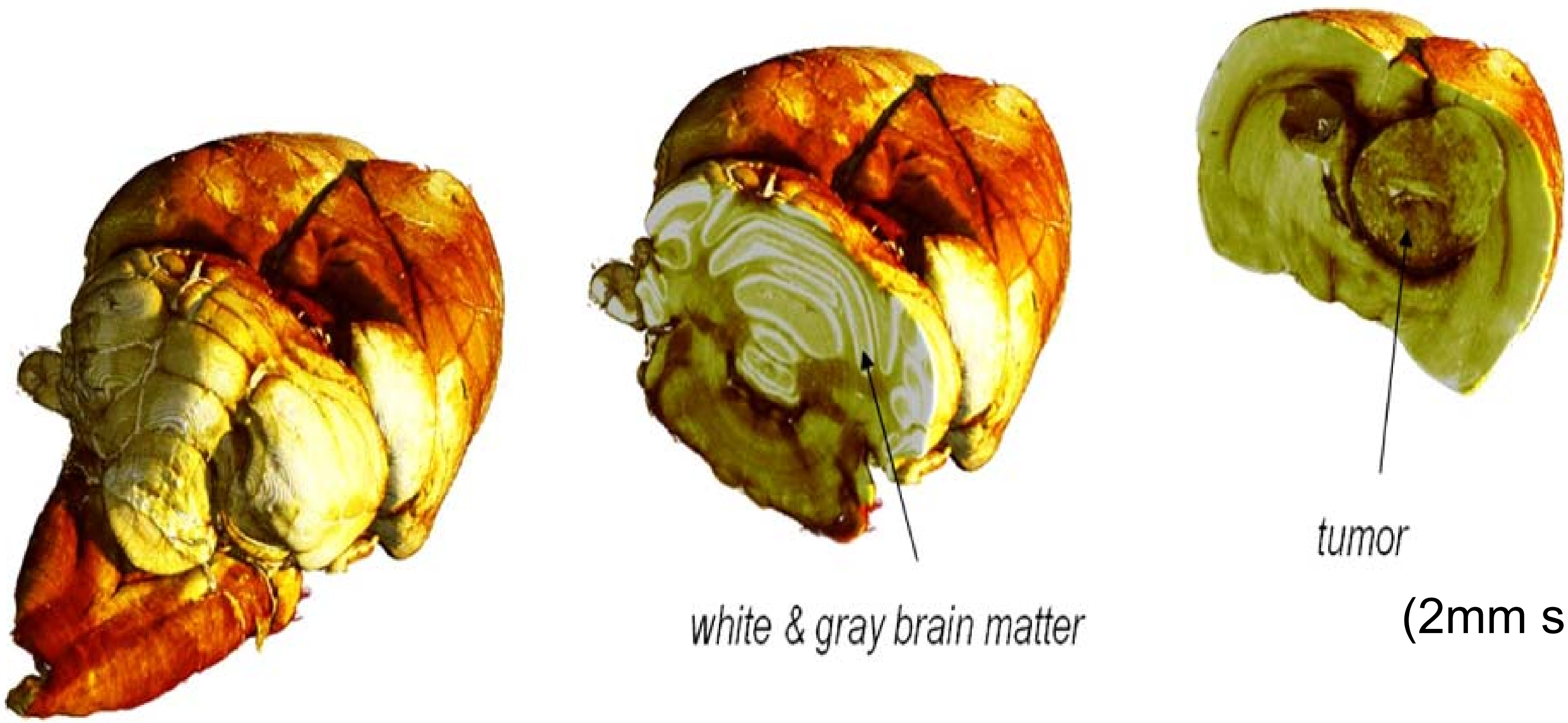
phase tomograms

absorption tomograms



F. Pfeiffer et al., Phys. Med. Biol. 52, 6923

State-of-the-art 3D phase-contrast tomography at highly brilliant synchrotron radiation sources (@ESRF Grenoble/ France)



(2mm size)

contact:
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www:
http://people.epfl.ch/franz.pfeiffer

F. Pfeiffer et al., Phys. Med. Biol. 52, 6923 (2007)

Small tumor detection

(by such method as <u>Phase Contrast Imaging</u>)

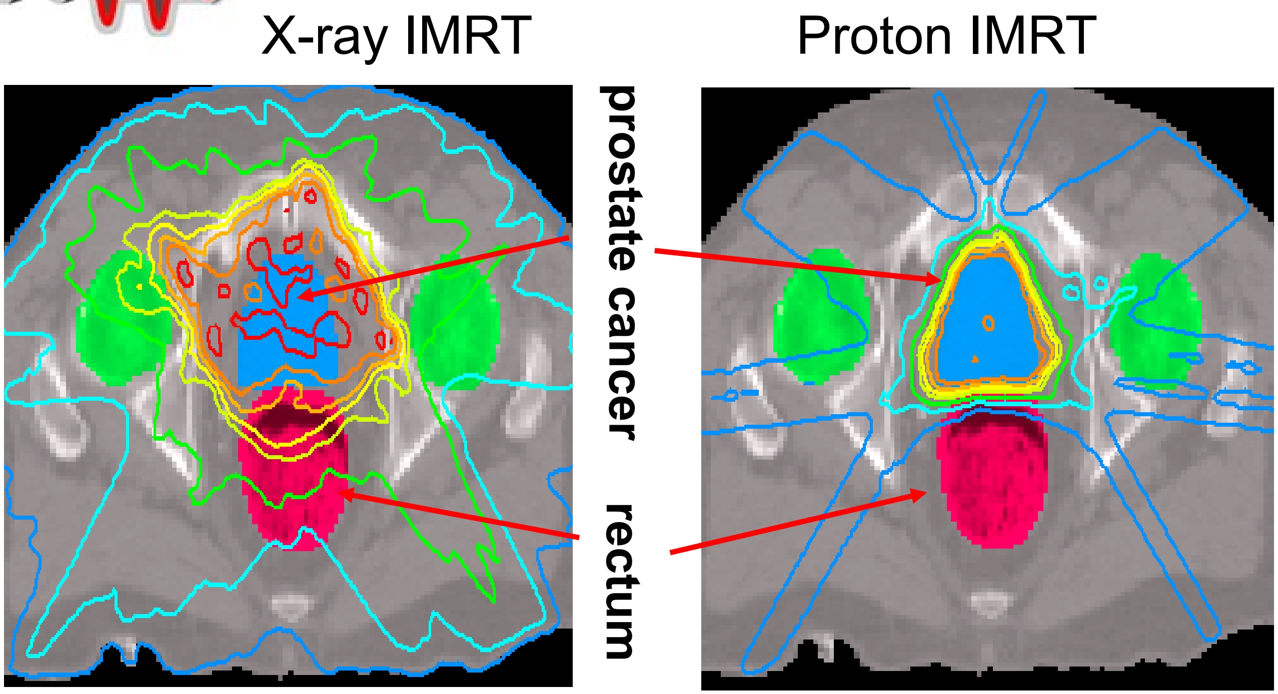
Early tumor detection:

- Less chance of metastasis
- Higher Quality-of-Life (QoL)
- Fit for laser acceleration approach

(compact laser accelerator:

not good for large dose)

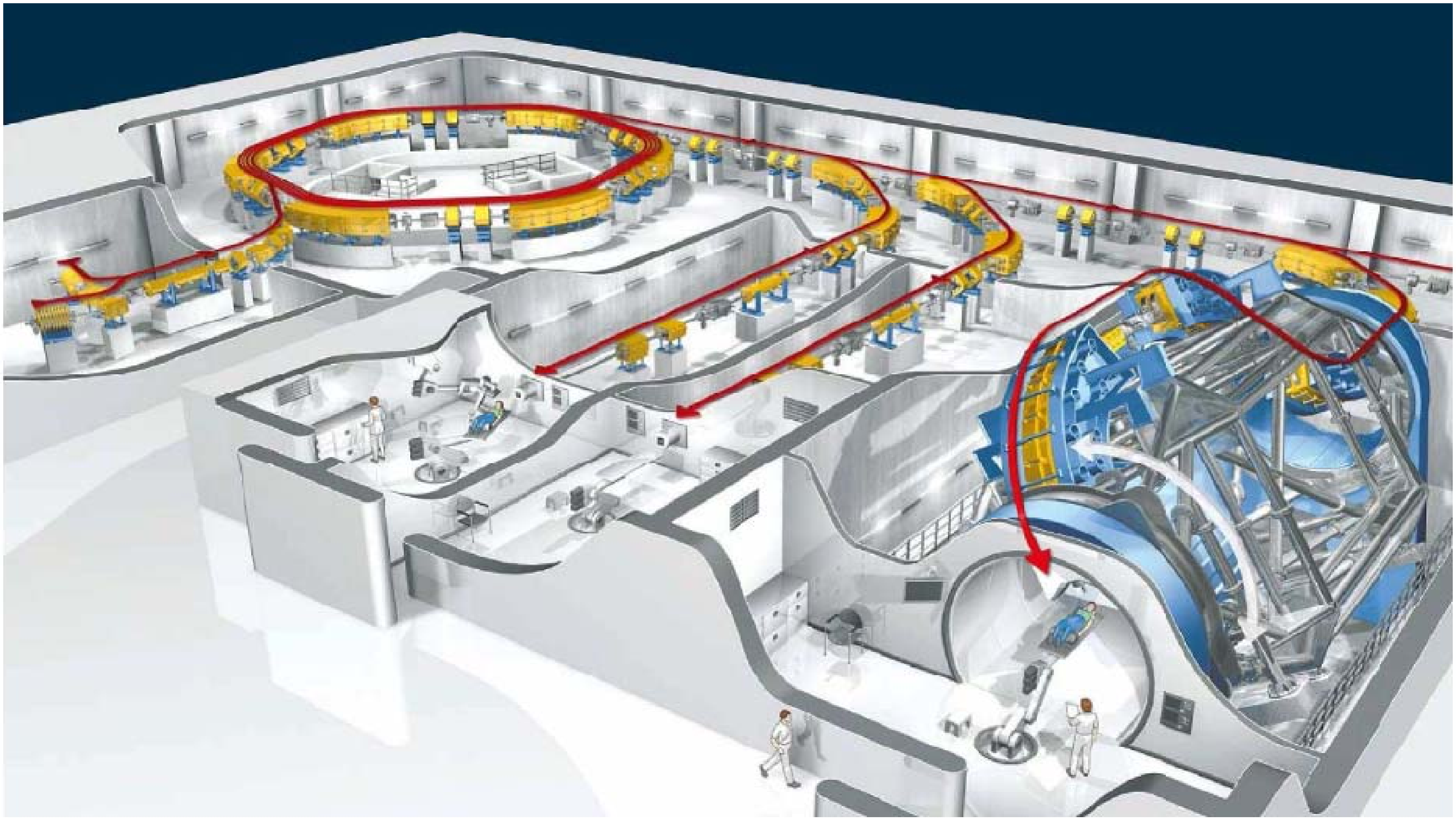
Sharpness of Dose of Proton Therapy



↑

Surgical sharpness of dose compared with X-ray Intensity Modulated Radio Therapy (X-ray IMRT)

Artist's view of the Heavy Ion Therapy Center (HIT) in Heidelberg



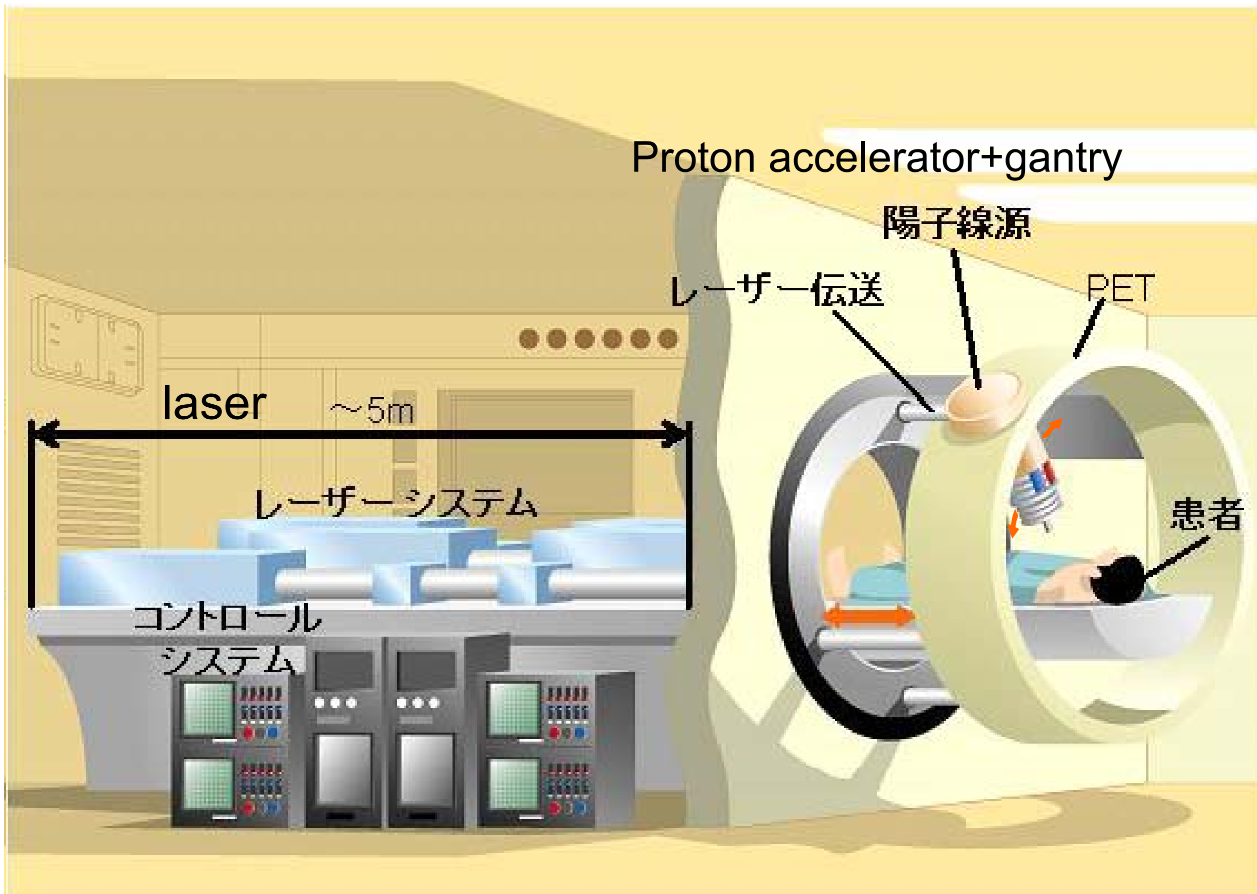
Suggested Strategy for Laser Ion Accelerator

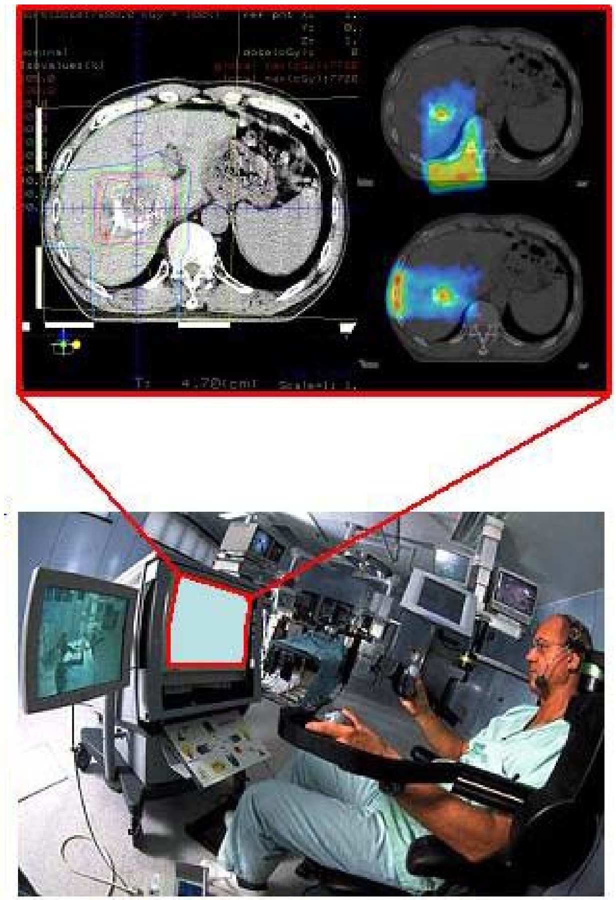
- Detect early and small (laser-driven brilliant coherent X-rays): micro tumors
- Small spot irradiation(including scanning): ideal for laser acceleration of ions, as ion therapy is nearly surgically sharp
- Feedback necessary:

  irradiate→verify→irradiate→verify→….
- Shallow tumors and other shallow treatments (e.g. ARMD) first
- Other industrial applications

Toward Compact Laser-Driven Ion Therapy

PET or γray image of autoradioactivation





治療計画（診断と照射）

Laser particle therapy (image-guided diagnosis→irradiation→dose verification)

targeting at smaller pre-metastasis tumors with more accuracy

Small tumor treatment

- 1kg tumor (10cm x10cm x 10cm): 70J proton energy @ 70Gy
- 1g tumor (1cm x 1cm x 1cm): 70mJ
- 1mg tumor (1mm x 1mm x 1mm): 70μJ

takes about 10^8 protons at ~100MeV (only 10% of the beam assumed to be used to inject, and in turn 10% of which stops at tumor; with 10% laser to proton efficiency, laser energy of 70mJ); takes 10^5 protons per laser shot (if 2minutes therapy at 10Hz)

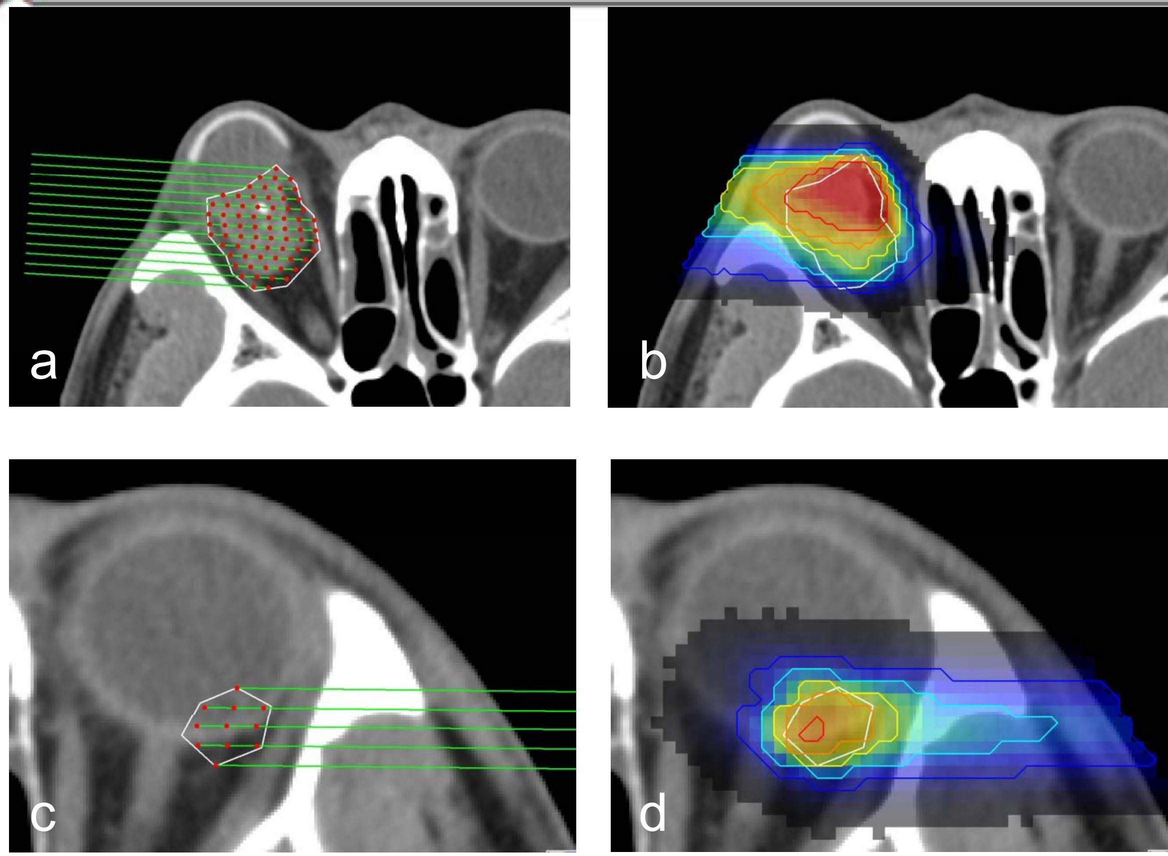
Within grasp!

Macular degeneration

ARMD (Age Related Macular Degeneration;加齢性黄斑症)

Spot-Scanning Simulation of Laser Proton Radiotherapy

(Simulation of dose distribution)



Spot-scanning simulation of laser proton radiotherapy for eye melanoma (a,b) and ARMD (c,d).

Particle-in-cell simulation (PIC) software which calculates the properties of laser-accelerated protons, Monte-Carlo simulation software, and visualization tools for the dose evaluation were used. Iso-dose curve:Blue: 25%, Sky blue: 50%, Yellow: 75%, Orange: 90%, Red: 110%. Miyajima(JAEA)2005

Recent breakthroughs in LIA

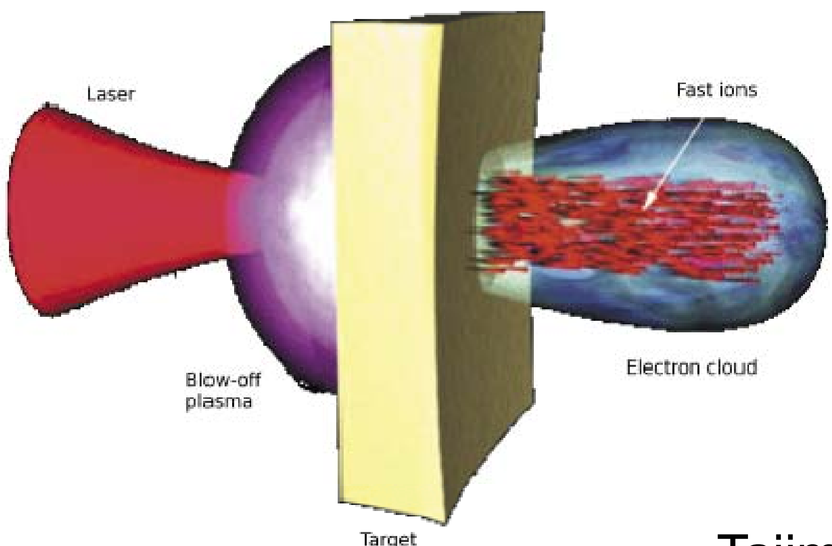
From **incoherent (or heating)** of electrons

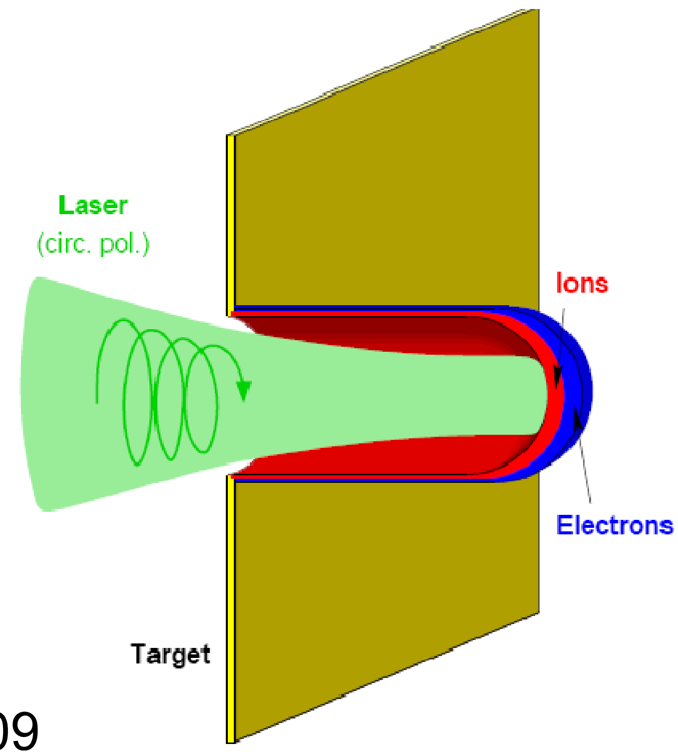
to **Coherent drive of them**

↓ ↓

CAIL (Coherent Acceleration of Ions by Laser)

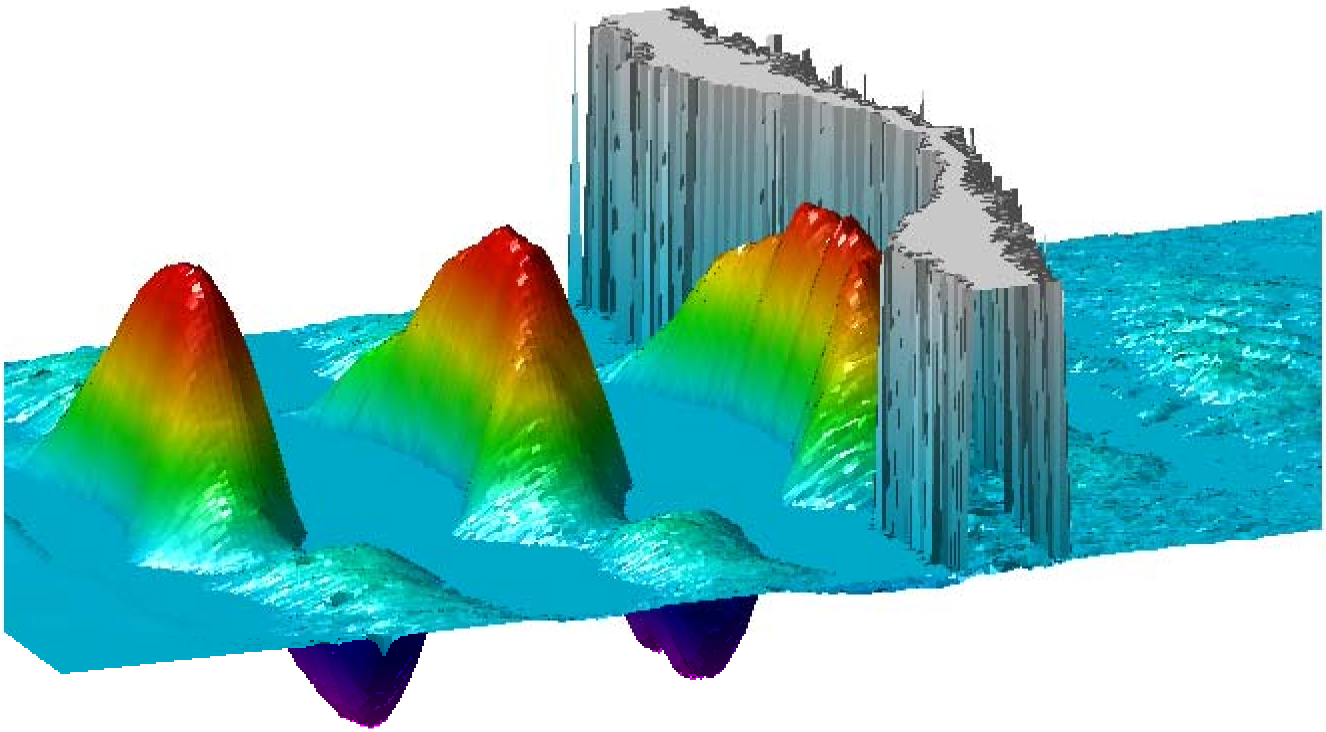
TNSA (Target Normal Sheath Acceleration)





Taiima et al.. 2009

Laser -Thin Foil Interaction

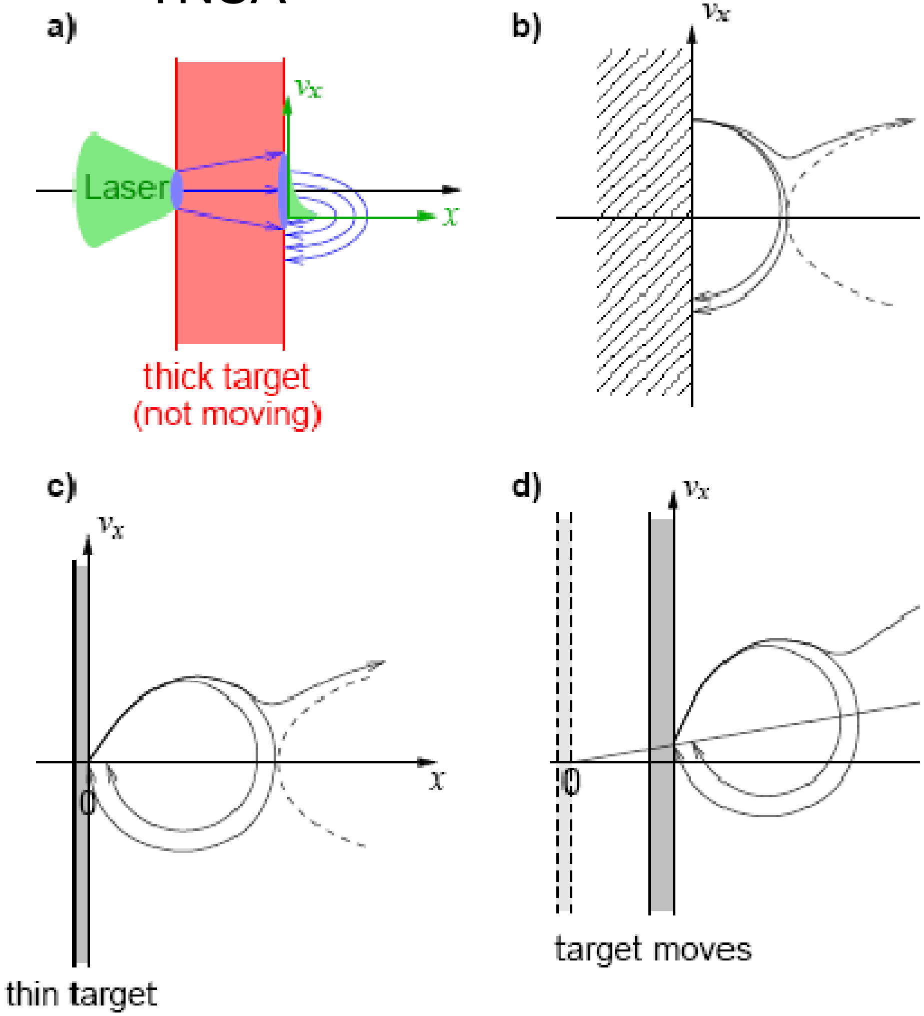


X. Yan et al., 2009

Comparison of the phase space dynamics: toward more Adiabatic Acceleration

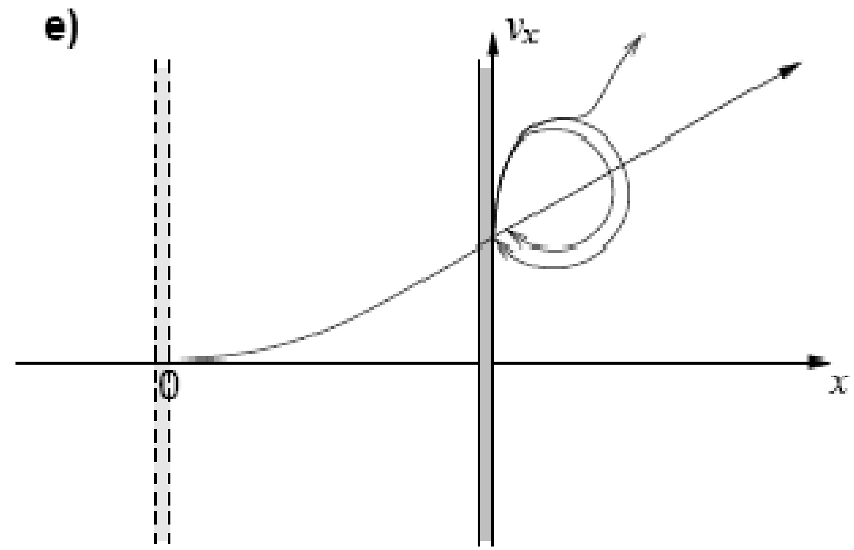
TNSA

(metallic boundary)



Ion trapping width:

$v_{tr,ion} \sim c\sqrt{a_0(m/M)}$



CAIL (with **CP**)

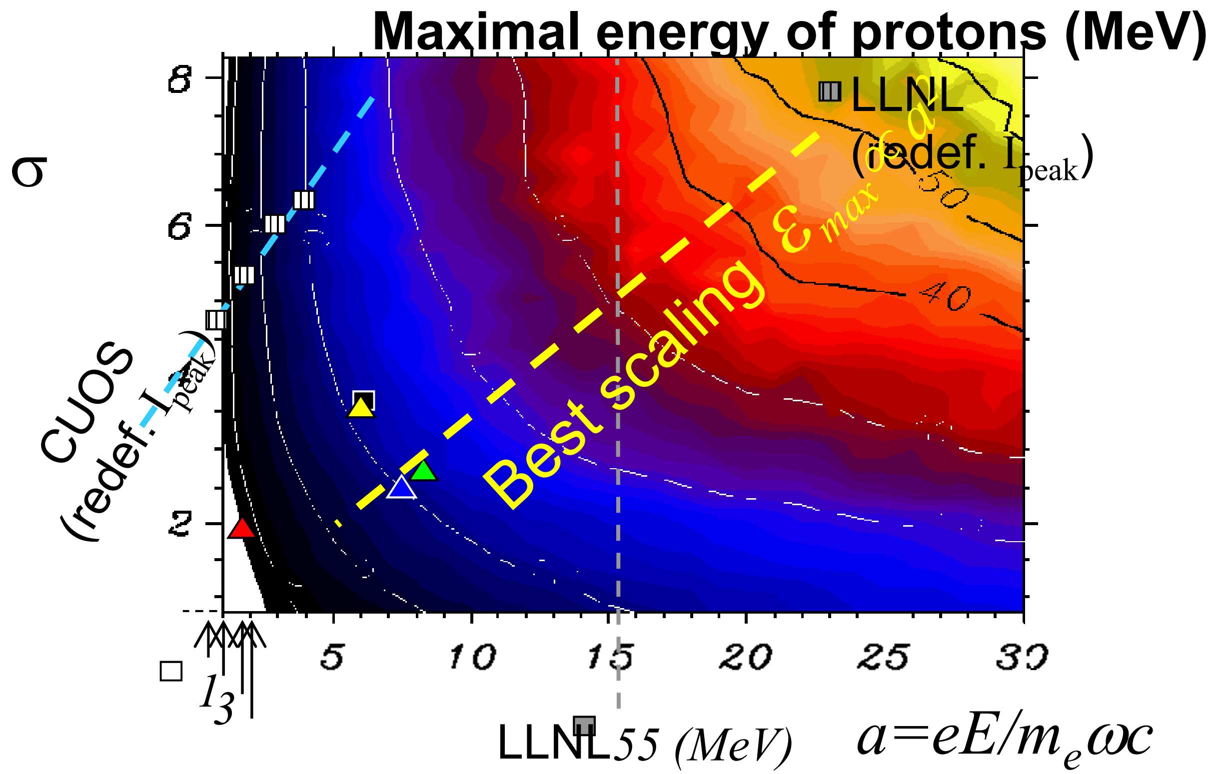
CAIL

Rev. Accel. Sci. Tech.
(Tajima, Habs, Yan, 2009)

Optimal Thickness Scaling

Optimal acceleration of ions

Normalized thickness σ ~ a_0 (normalized intensity)



(T.Esirkepov et al.2006)

Recent Experimental Breakthroughs

Leadership
by Dieter Habs

LMU,
MPQ,
Max-Born Institute,
LANL,
RAL,
PMRC

Nanometer target:
DLC
Sharp contrast laser
double plasma
mirrors

↓

More coherent
electron dynamics
in $\sigma \sim a_0$

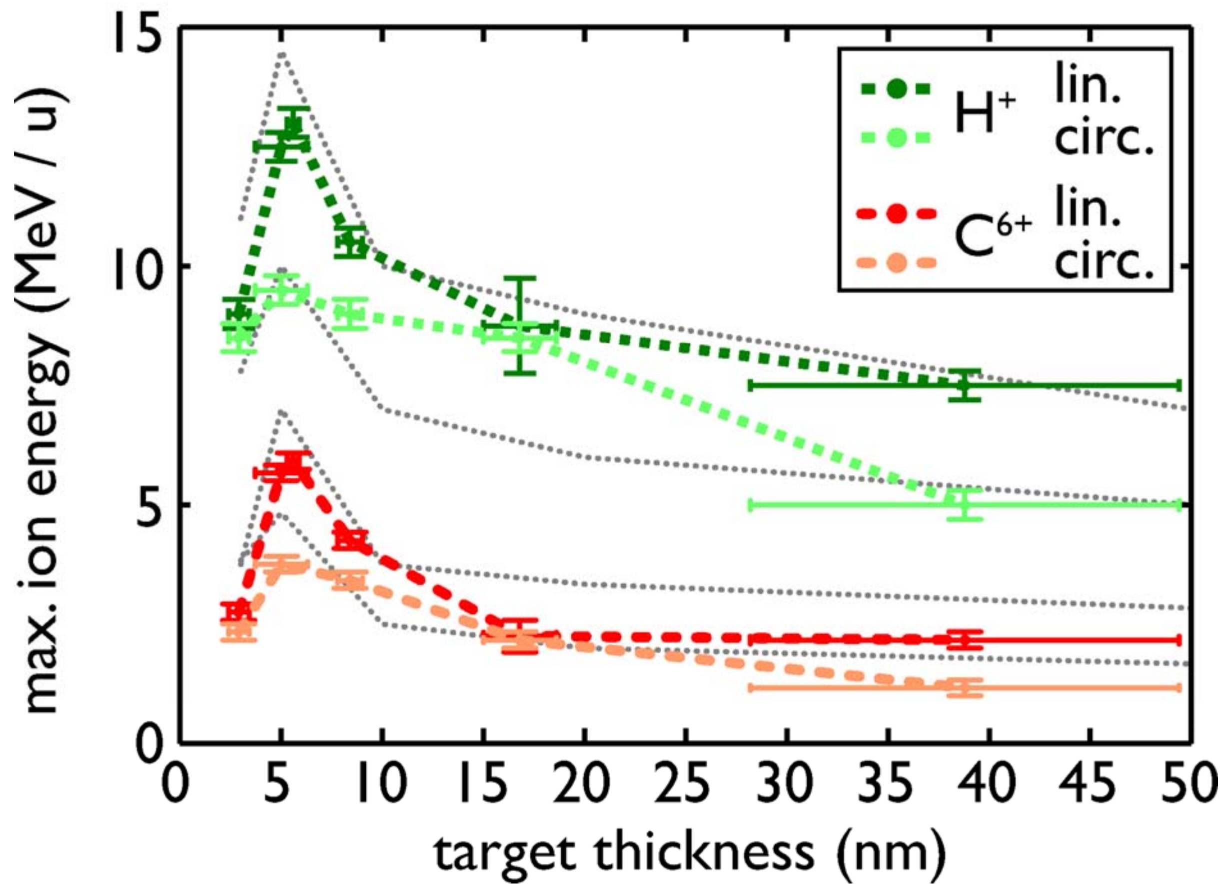
Recent experiments in CAIL Regime

CAIL Regime: Overcomes old TNSA 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

$\xi = 1$ ↓

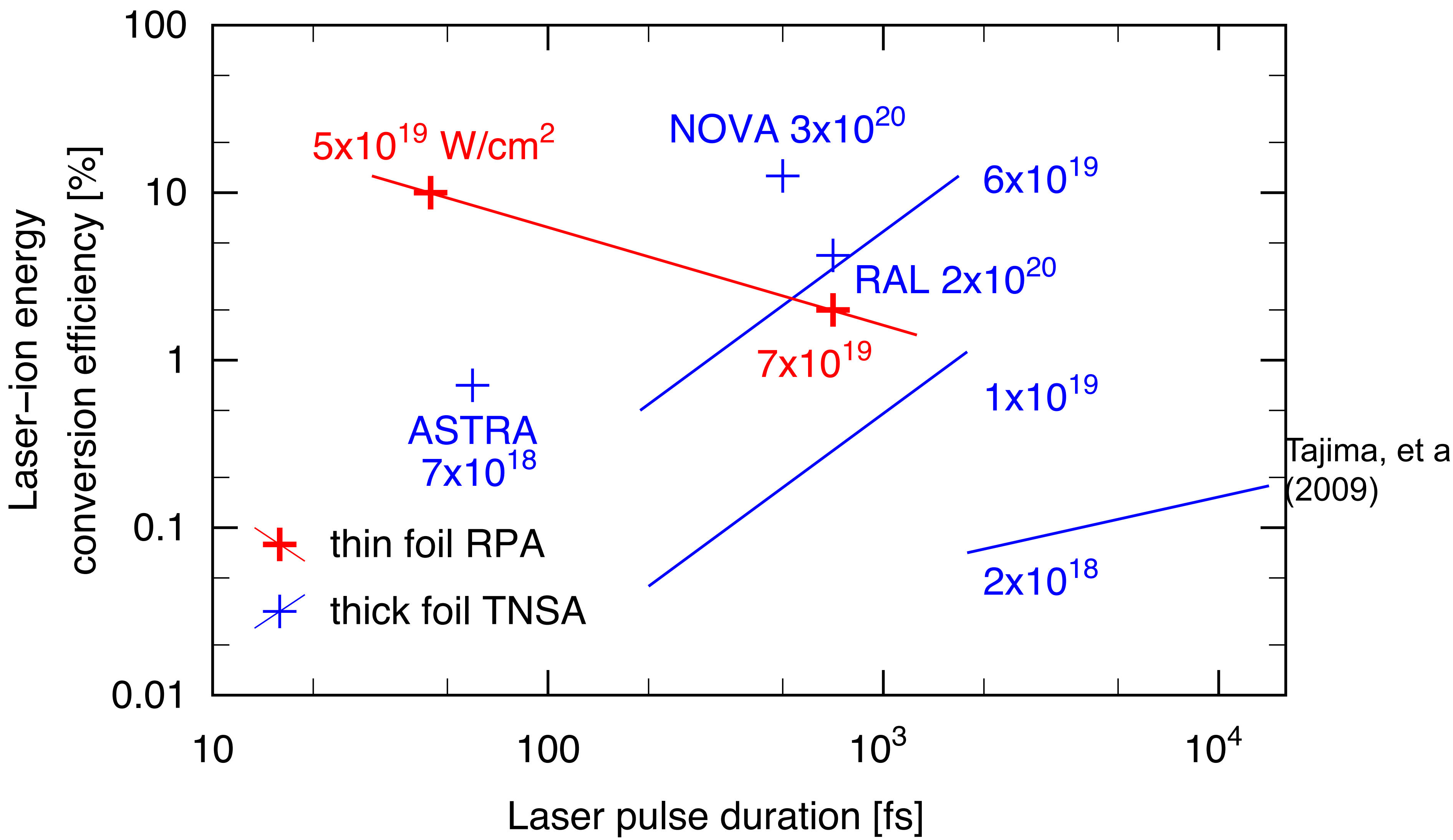


MAP + MBI

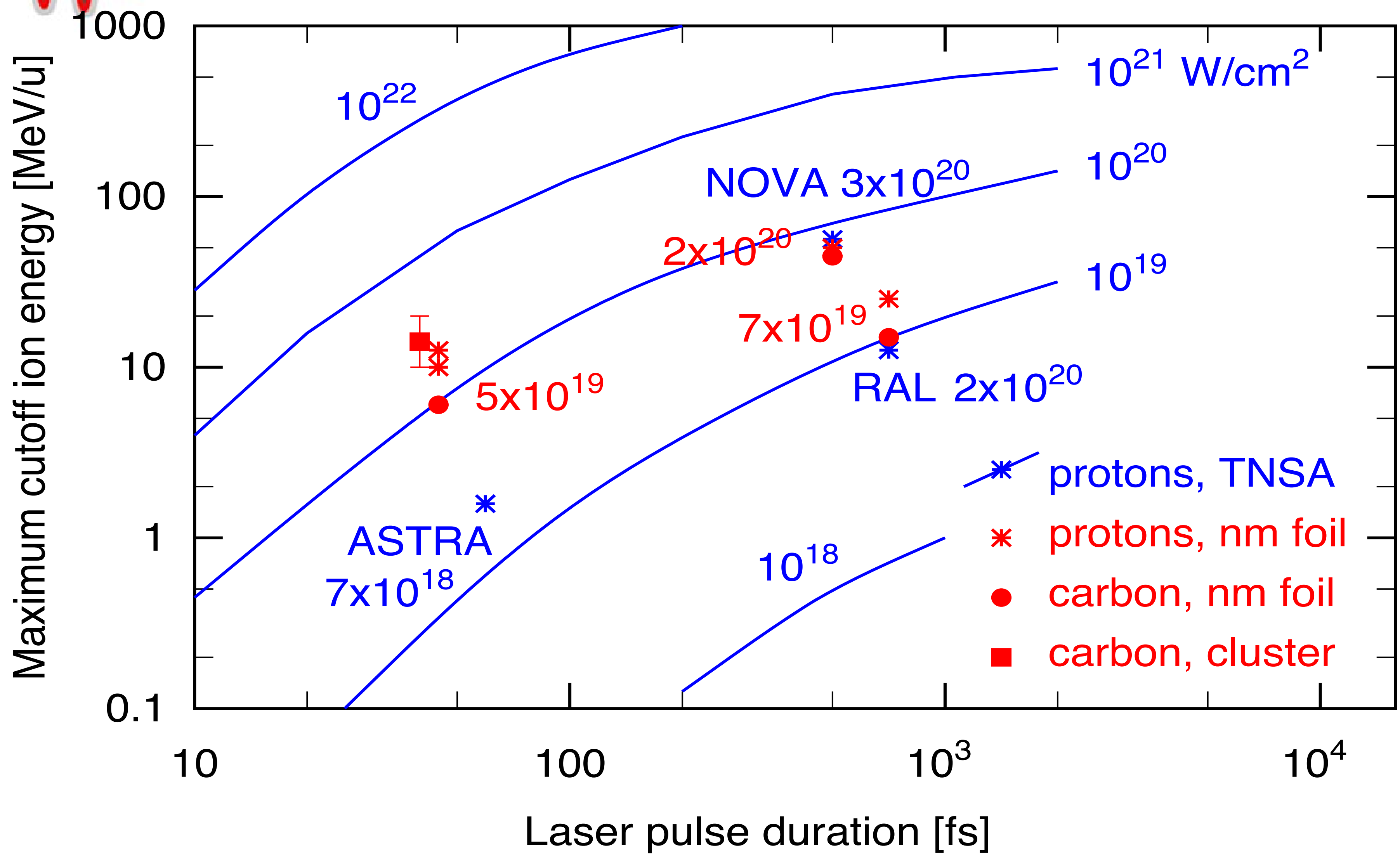
(Henig et al, 2009;
Steinke et al.)

Conversion efficiency of laser to ion energy

Two orders of magnitude higher efficiency in **CAIL**



Maximum energies of ions

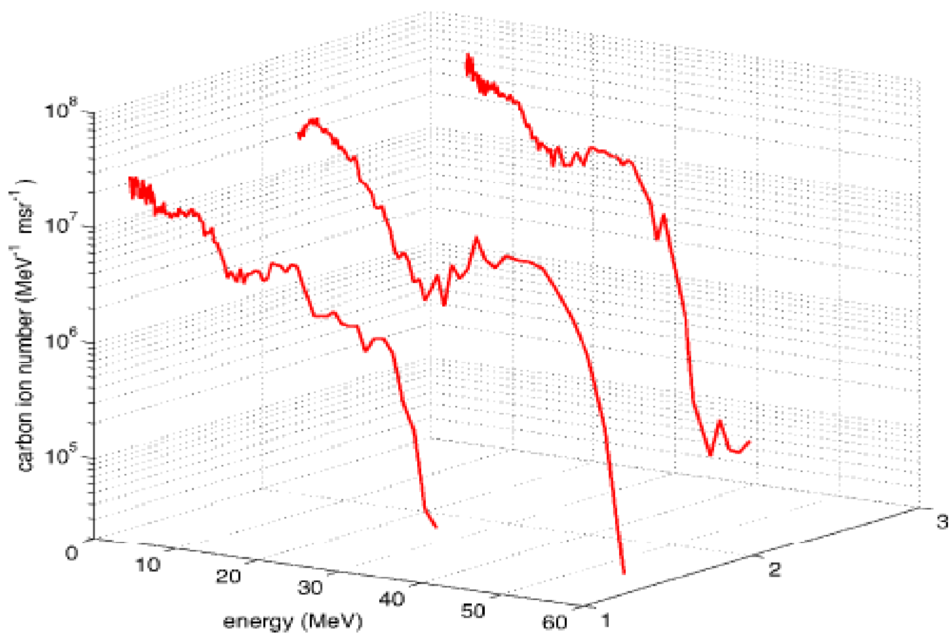


Tajima et al. (2009)

Toward monoenergy spectrum

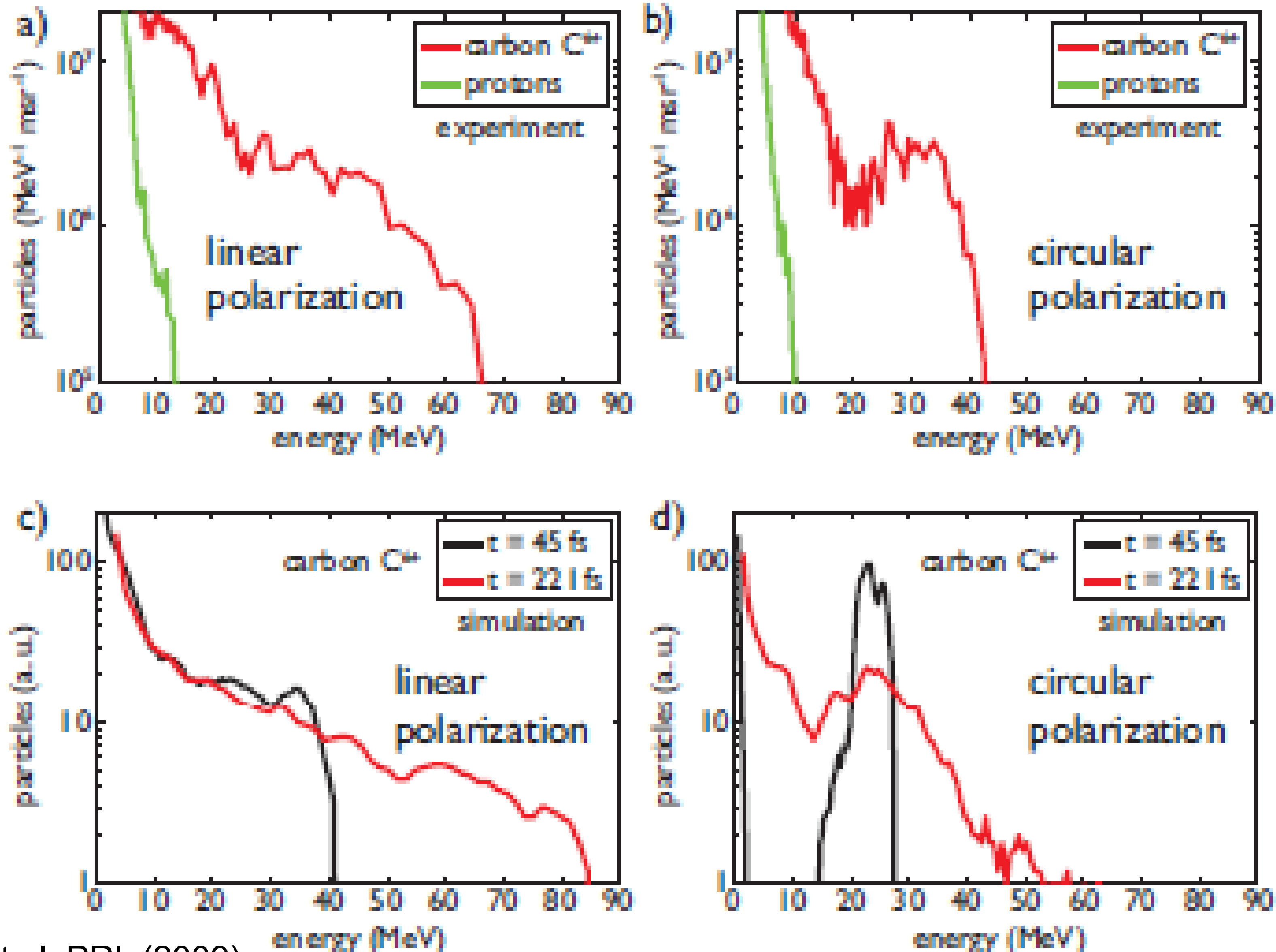
- **Circularly polarized** laser irradiation

  more **adiabatic acceleration**→ more **monoenergy**



Carbon spectrum for three consecutive shots using circular polarized light at 5 *10^19 W/cm2 and a DLC foil target thickness of 5.9 nm

Comparison of CP and LP toward monoenergy



Henig et al, PRL (2009)

Energy Gain in Laser Ion acceleration: CAIL (Coherent Acceleration of Ions by Laser) regime

- When electron dynamics by laser drive is sufficiently coherent, with coherence parameter α of electrons, the ion energy in terms of electron energy is :

$$\varepsilon_{\max,i} = (2\alpha + 1)\, Q\, \varepsilon_0$$

Ion energy

(*the more coherent the electron motion, the higher the ion energy*)

$$\varepsilon_0 = mc^2 \left(\sqrt{1 + a_0^2} - 1 \right)$$

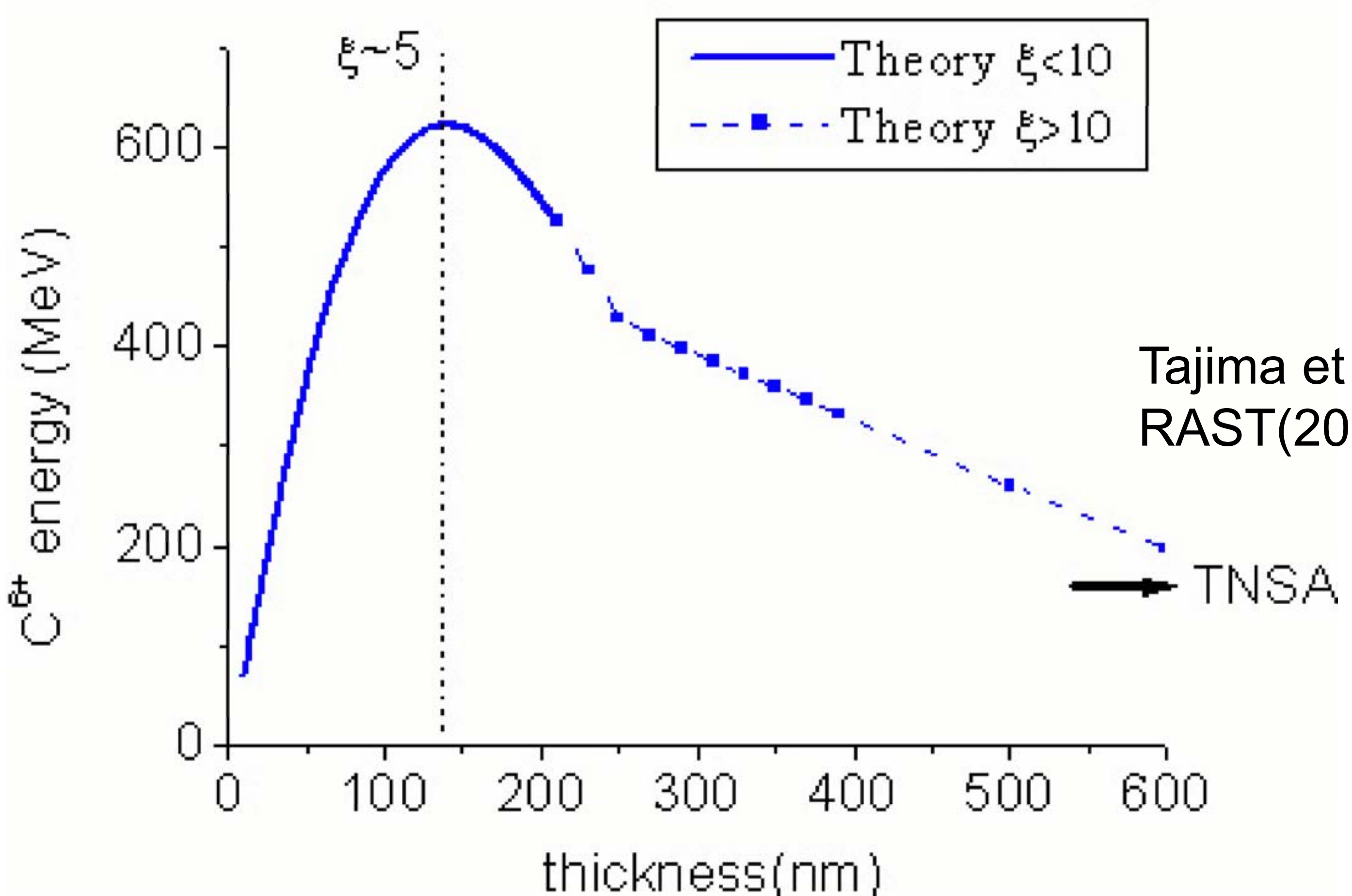
Electron energy = ponderomotive energy

$$\varepsilon_{\max,i} = (2\alpha + 1)\, Q \bar{\varepsilon}_0(t_1) \left((1 + \omega_L\, t_1)^{1/2\alpha + 1} - 1 \right)$$

α maximizes at ξ = 1

CAIL Theory Prediction

CAIL (Coherent Acceleration of Ions by Laser) theory has definitive prediction of max energies



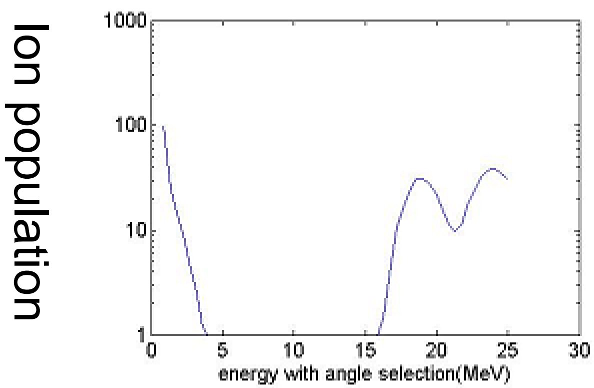
Tajima et al.
RAST(2009)

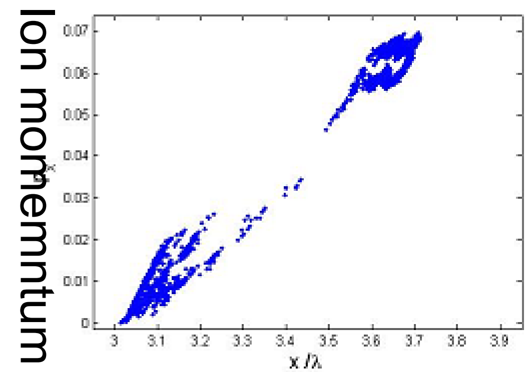
For the case of LANL
experiment prediction (relative long pulse with nm targets)

Circularly polarized laser driven

CP laser drives ions out of ultrathin (nm) foil **adiabatically**
Monoenergy peak emerges

Bucket trapping ions ↓





← $V_{i,tr}$

laser →

$$V_{i,tr} = c\sqrt{(a_0 m/M)}$$

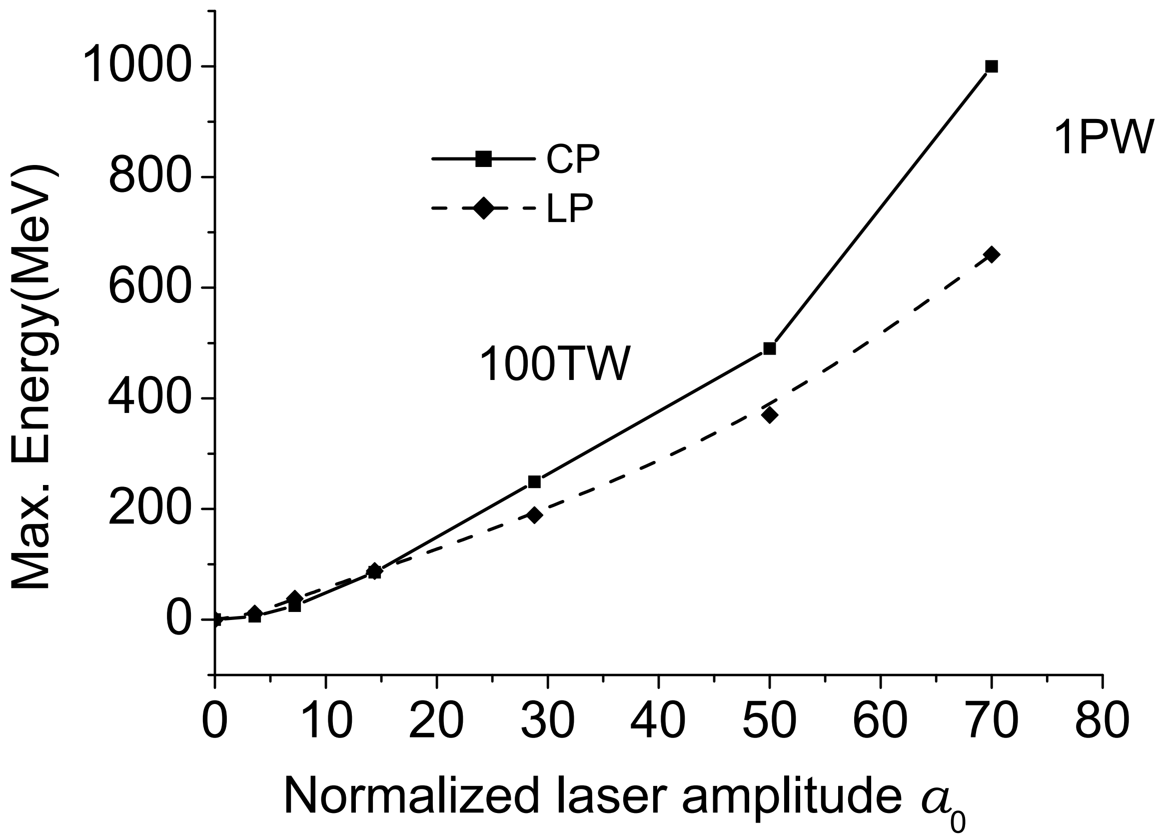
(X. Yan et al: 2009)

Ponderomotive force drives electrons,
Electrostatic force nearly cancels
Slowly accelerating bucket formed

Toward more adiabatic acceleration(4)

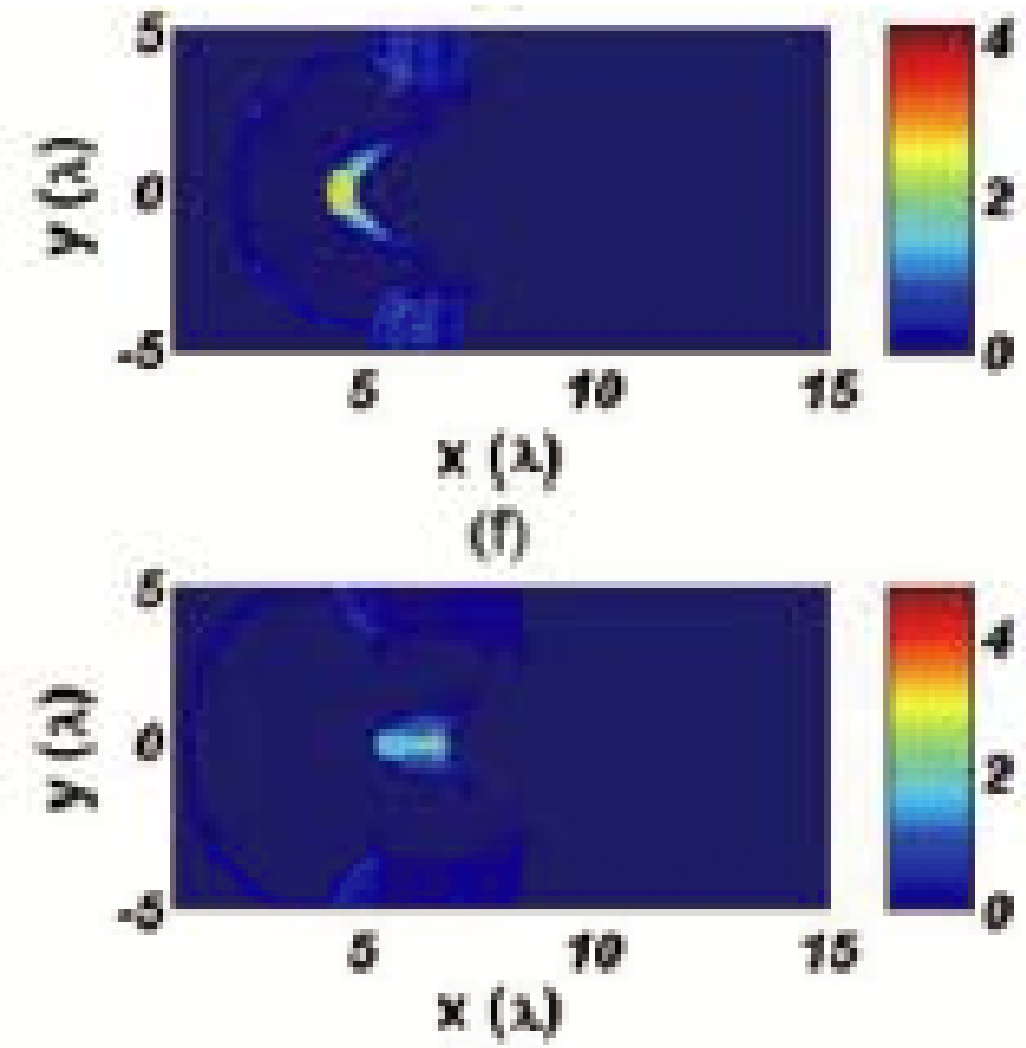
The more **adiabatic,** the longer accelerated, the higher energy

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



Concave Ultrathin Target Enhances Energy

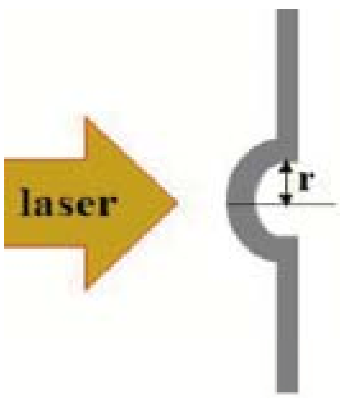
Concave target focuses laser energy, doubling the ion energy

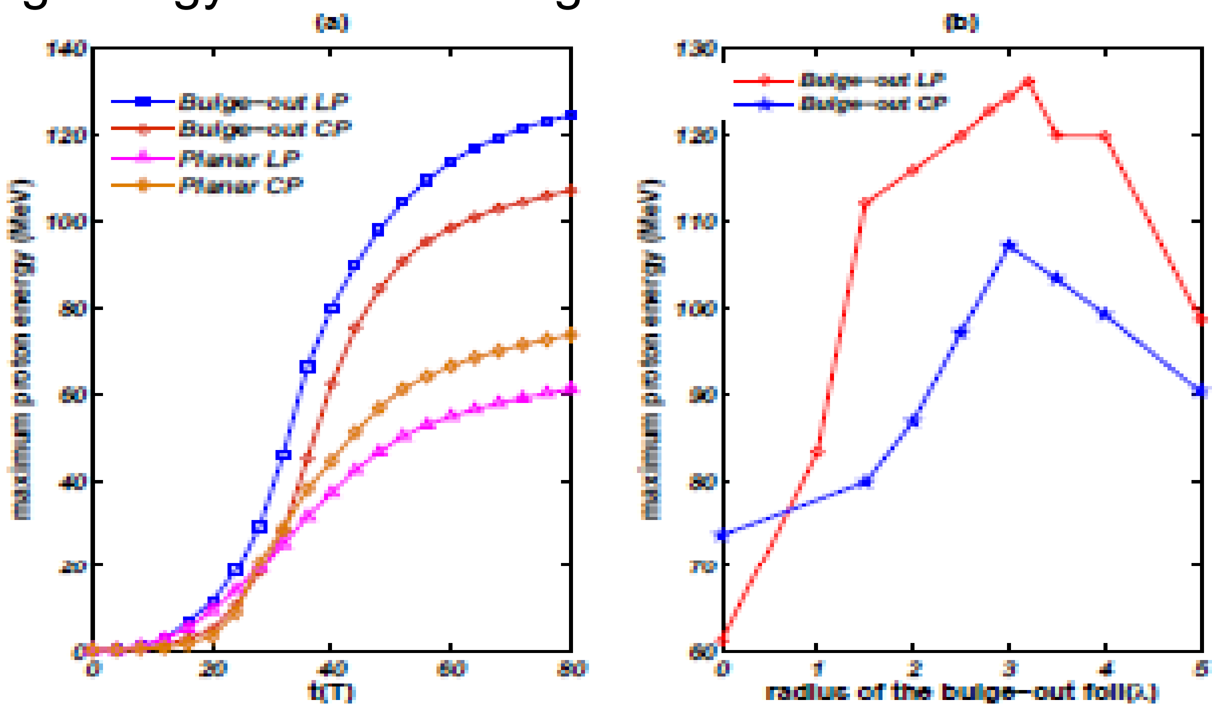


(Wang et al. 2010)

Energy Doubler: Concave Target

At 10^{20}W/cm^2 the concave target lets over 100MeV protons, doubling energy over a flat target





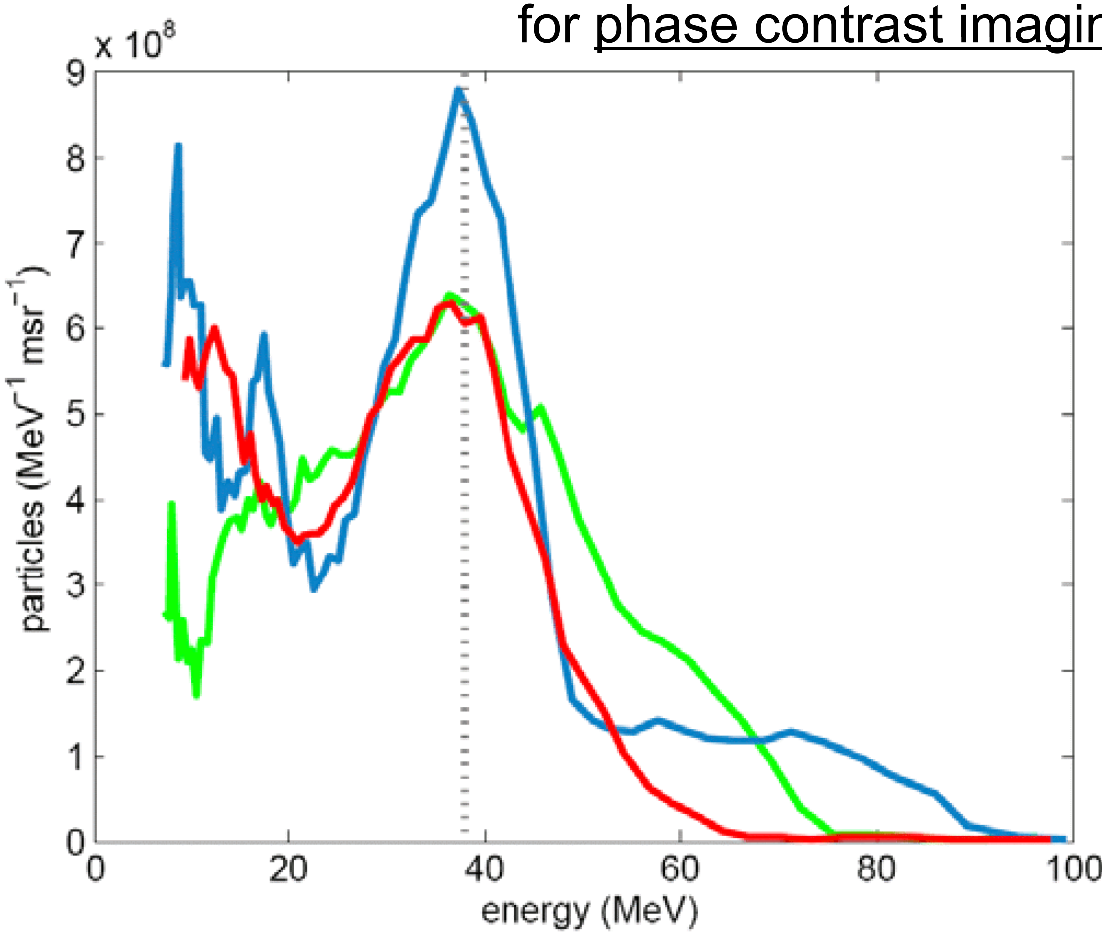
'IG. 4: (color online). (a)Proton energy evolution for LP ınd CP laser. (b)Maximum proton energy versus radius of ›ulge-out target for LP and CP laser.

Wang et al. 2010

Monoenergetic electron bunch

Ultrathin (2nm) foil (CP) irradiation drives monoenergetic electrons

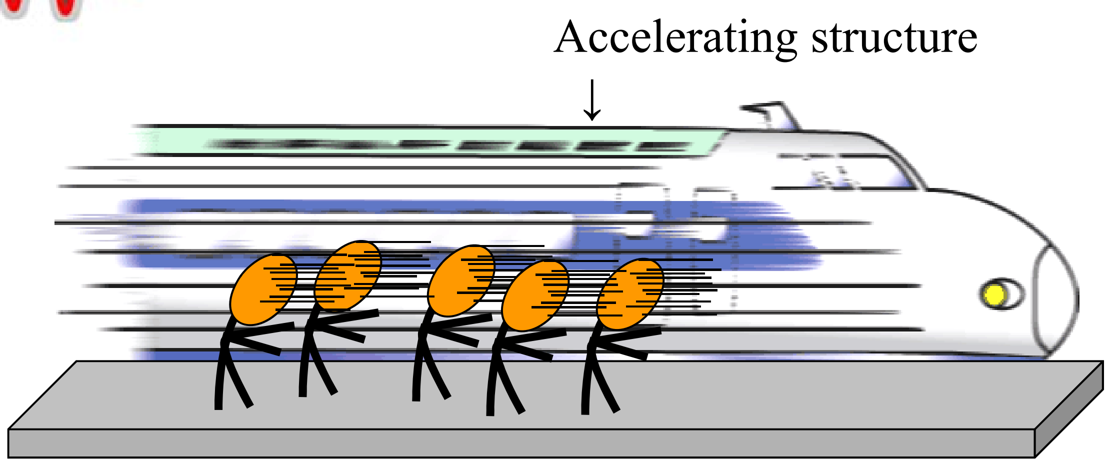
Ideal for driving coherent brilliant X-rays
for <u>phase contrast imaging</u>



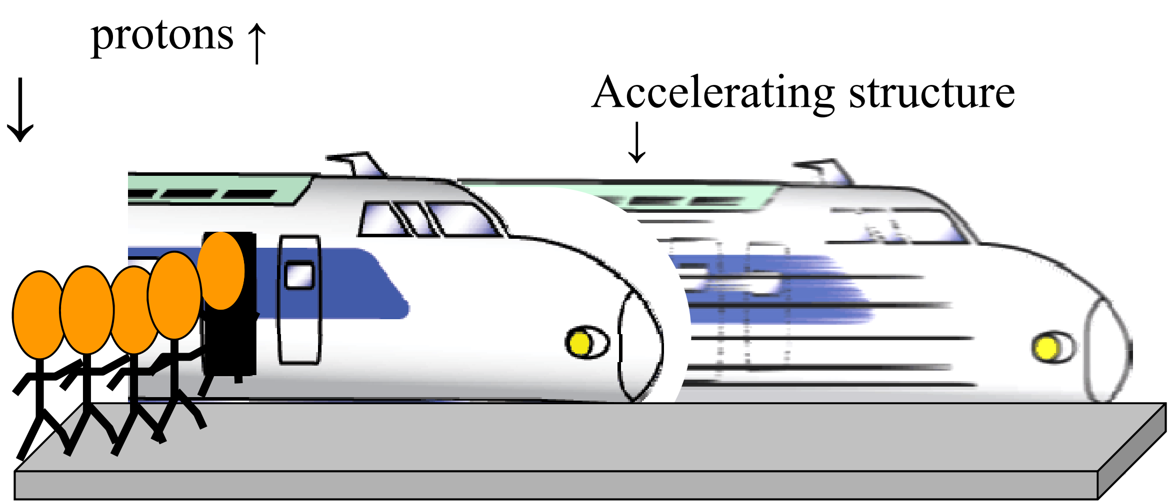
(Kiefer et al, 2009)

MAP + MBI

Adiabatic (Gradual) Acceleration



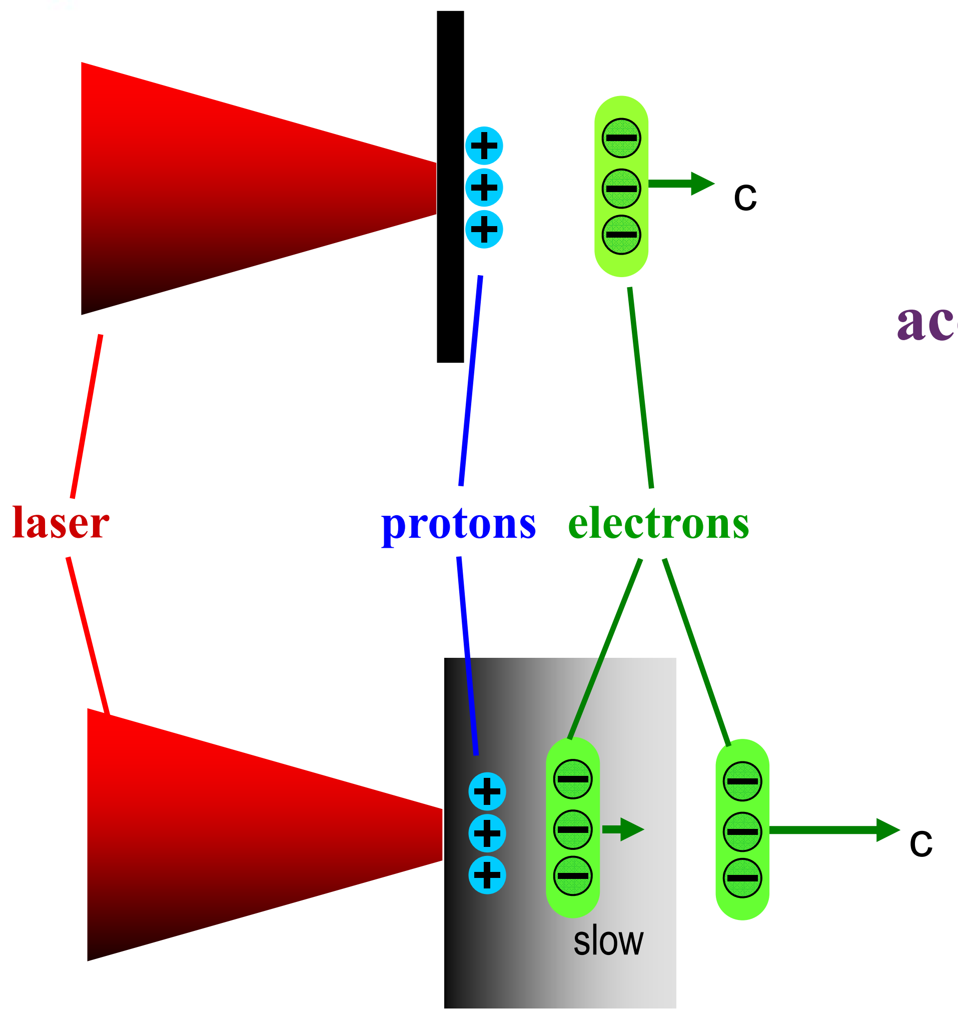
Inefficient if suddenly accelerated



(cf.human trapping width: $v_{tr,human} \sim 1m/s << c_s$)

Efficient when gradually accelerated

Adiabatic acceleration (2)



Graded, thin (nm), or clustered target and/or circular polarization

Most experimental configurations of proton acceleration(2000-2009)

Innovation ("Adiabatic Acceleration") (2009-)

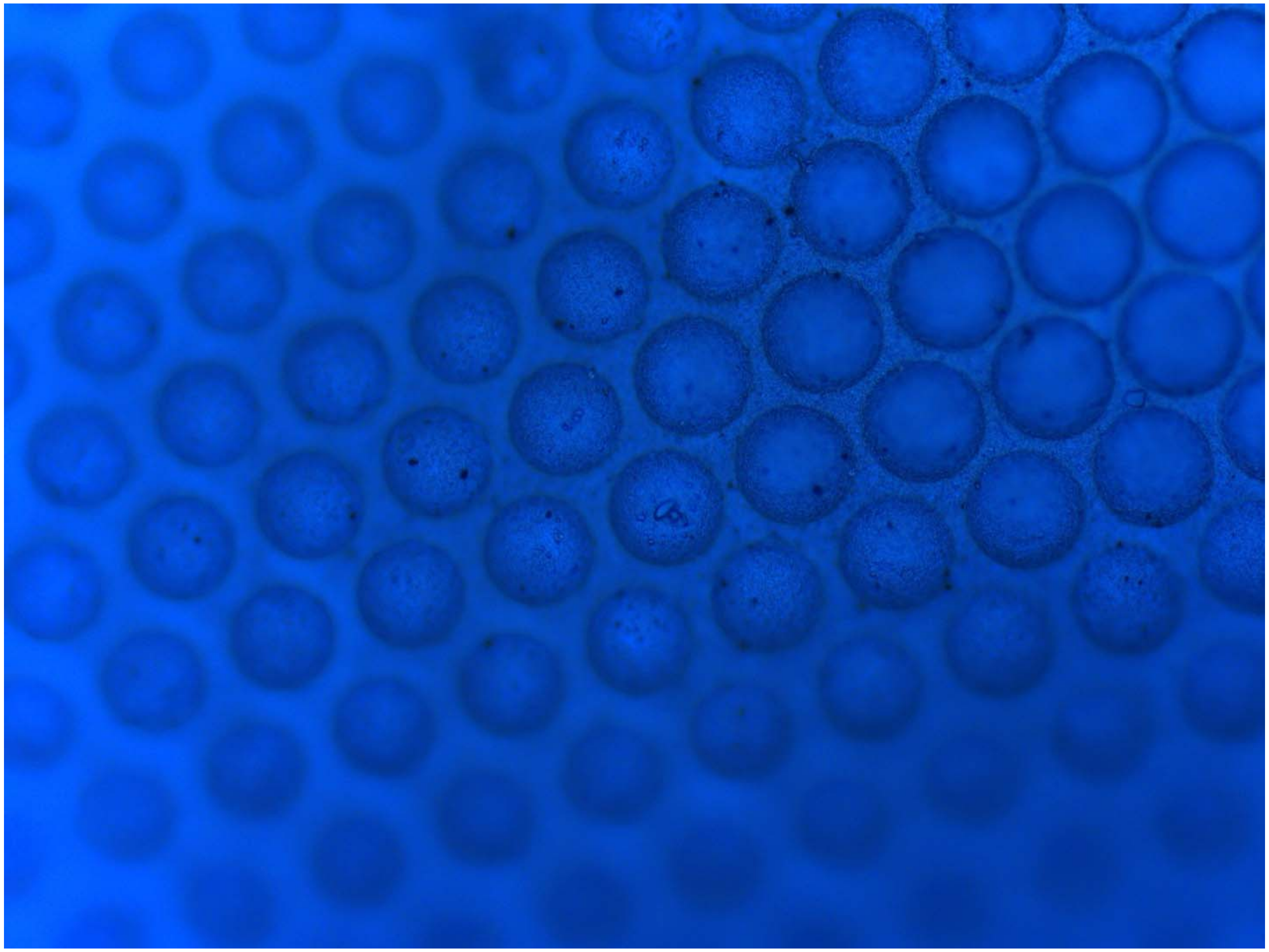
= Method to make the electrons within ion trapping width

However, in **ELI** automatic

$v_{tr,\ ion} \sim c\ \sqrt{a_0 (m/M)} \sim c$

(ultrarelativistic $a_0 \sim M/m$)

Nanostructured target



(Habs, 2009)

Toward Adiabatic Acceleration (ca.1999)

MPQ

www.attoworld.de

LMU

Energy conversion and acceleration of particles is strongly dependent on the state of the thin foil surface.

$a_0 = 30$

1 PW Laser Intensity;

electron density
Al
soild ; $6*10^{23}cm^{-3}$ ($416n_C$)

gas ; $1.5*10^{22}cm^{-3}$ ($10.4n_C$)

culster; $3*10^{23}cm^{-3}$ ($208n_C$)

H
soild ; $4.6*10^{22}cm^{-3}$ ($31.8n_C$)

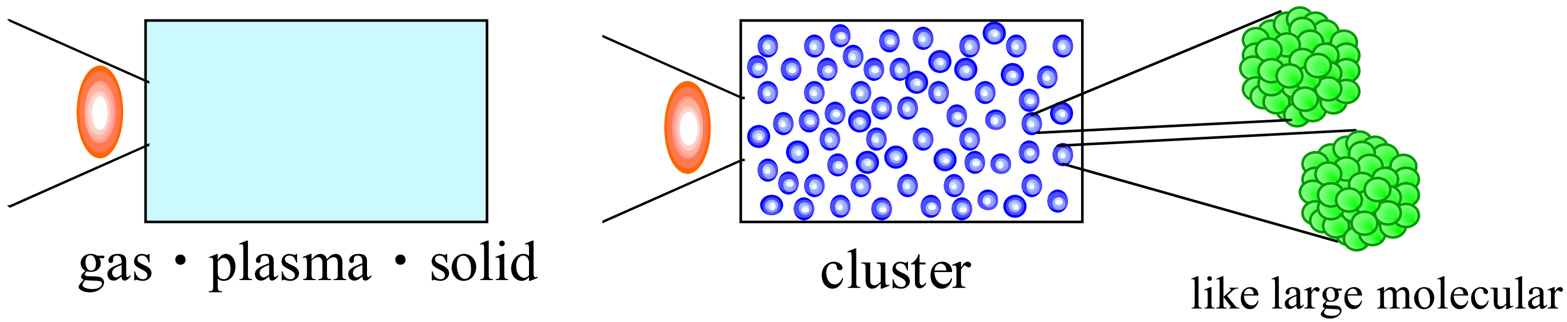
n_C: cut off density $1.4*10^{21}cm^{-3}$

target type $a_{0s} = 69$	Al^{10+}(56nm) solid H^+ (28nm) solid	Al^{10+}(2240nm) gas H^+ (28nm) solid	Al^{10+}(112nm) culster H^+ (28nm) solid
energy conversion	24%	50%	31%
ion;	8%	4%	14%
electron;	16%	46%	17%
peak (average) energy			
H^+;	0.4GeV (95MeV)	0.2GeV (58MeV)	0.8GeV (115MeV)
Al^{10+};	2GeV (500MeV)	1GeV (130MeV)	2GeV (500MeV)
electron;	15MeV	25MeV	20MeV

Patent (Tajima) : submitted from LLNL (2002); granted (2005)

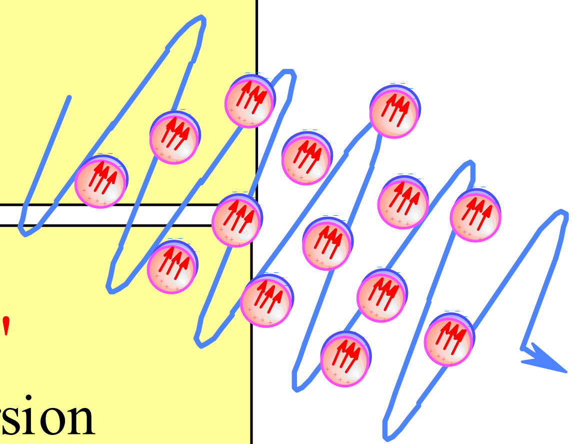
Why is Laser-Cluster Interaction Strong?

″clusterd phase" vs. "gas", "plasma", "solid phase"



Transverse polarization manifest!

- "Small particle system" and enhanced fluctuation
  - free energy originated from the surface is NOT neglected.
  - energy and structual deformation/fluctuation



- Freedom of tansverse polarization through "surface"
  - different nature in linear and non-linear dispersion

(Y.Kishimoto)

R. H. Doremus, J. Chem. Phys. 40, 2389 (1964)
A. Kawabata and R. Kubo, J. Phys. 40, 1765 (1966)

Cluster target: order of magnitude energy gain

With a modest (140mJ) laser, to go beyond 15MeV/nucleon by cluster target

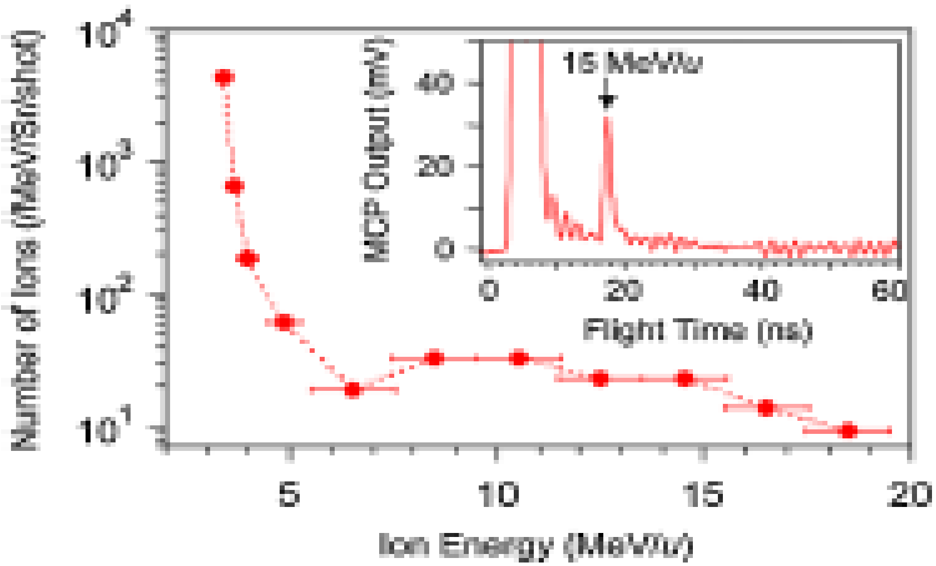
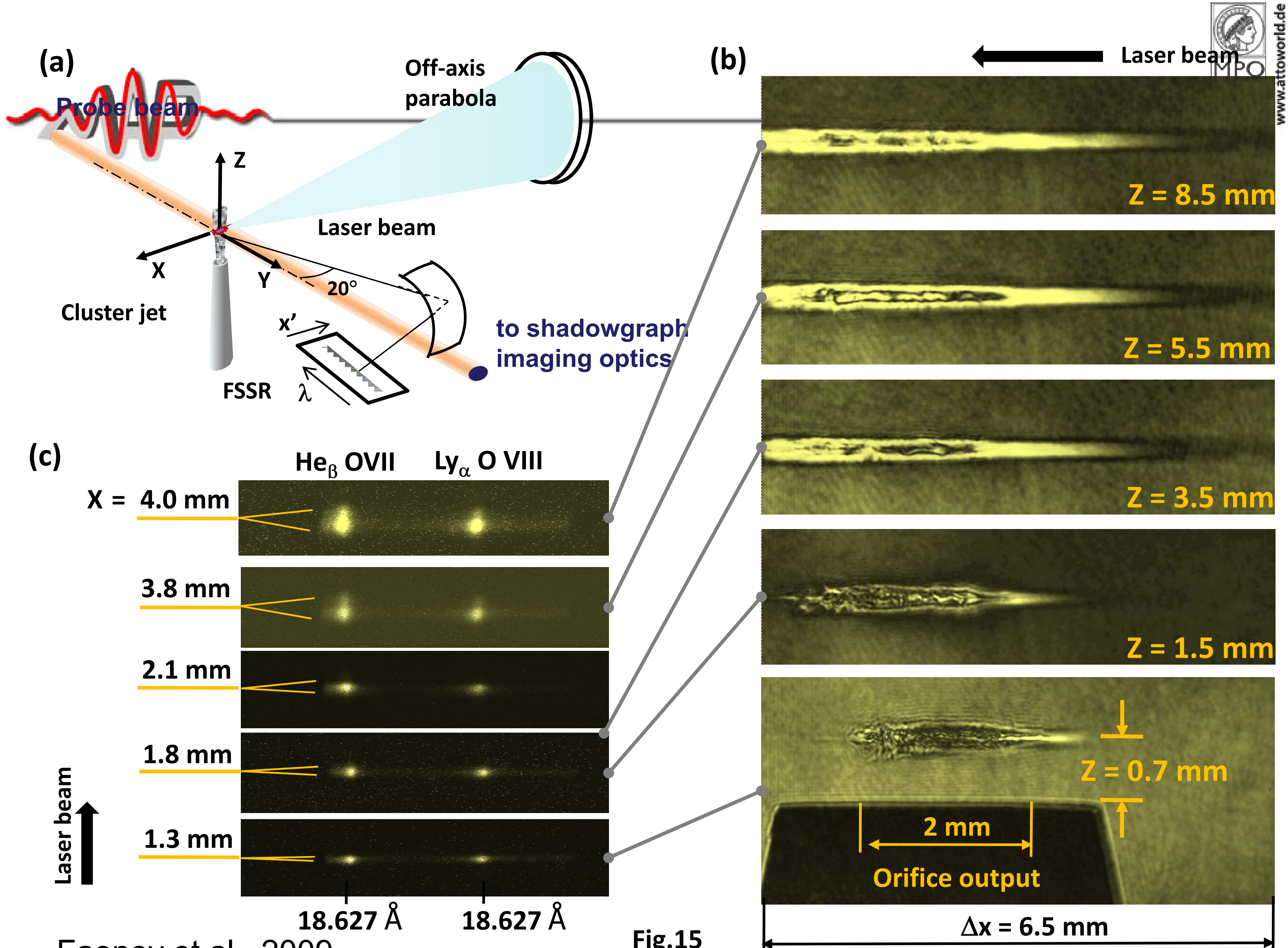


FIG. 3 (color online). The ion energy spectrum obtained by the TOF method. The inset shows TOF spectrum obtained in one laser shot which registers 15 MeV/u ion signal. A saturated signal around the flight time $t = 5$ is caused by hard x rays emitted from the laser-cluster interaction region.

Clustered target allows another leap in energy of ions

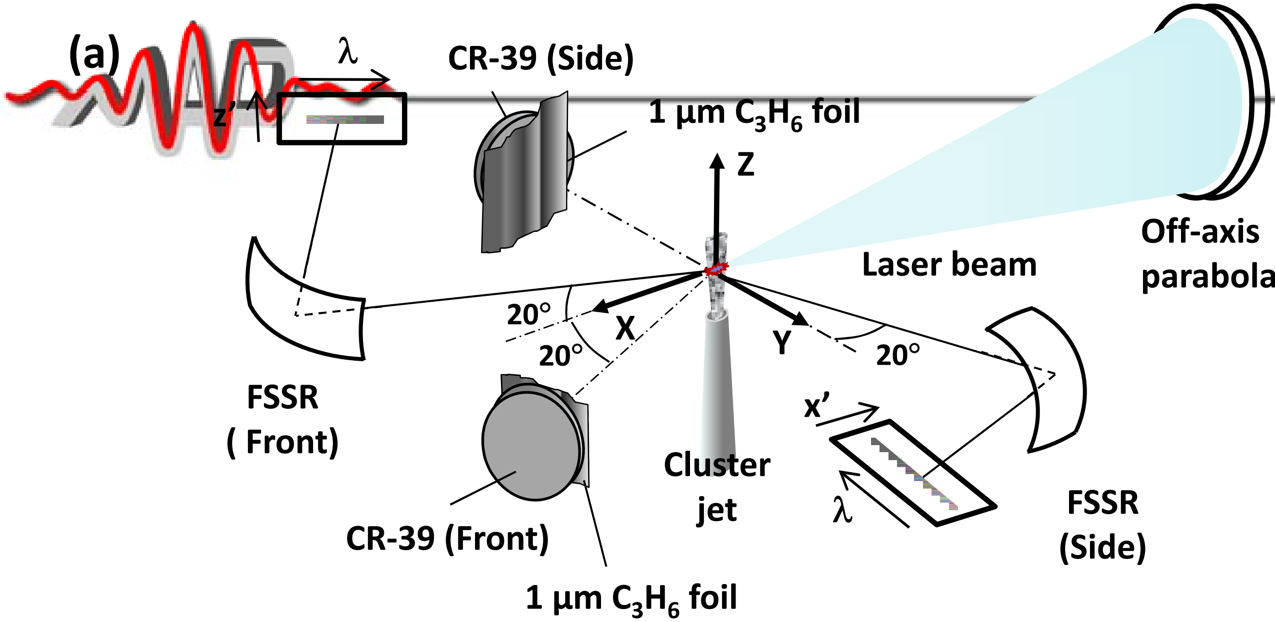
Fukuda et al. (PRL 2009)

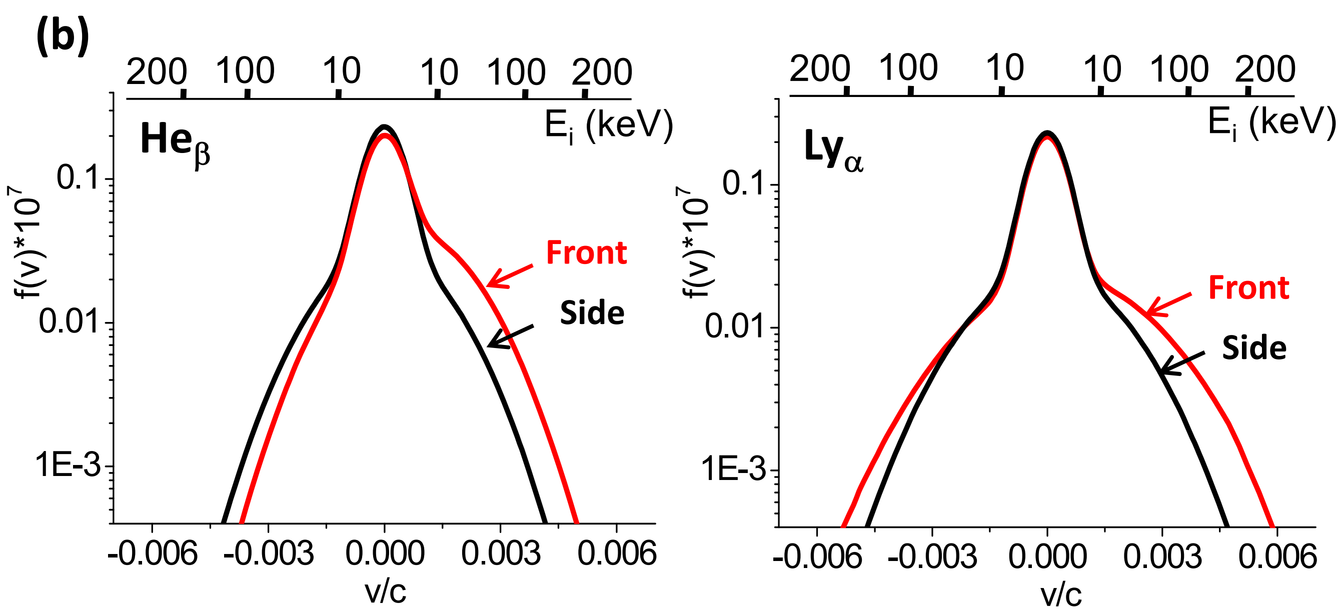


Faenov et al.. 2009

Fig.15

Cluster ions strongly energized



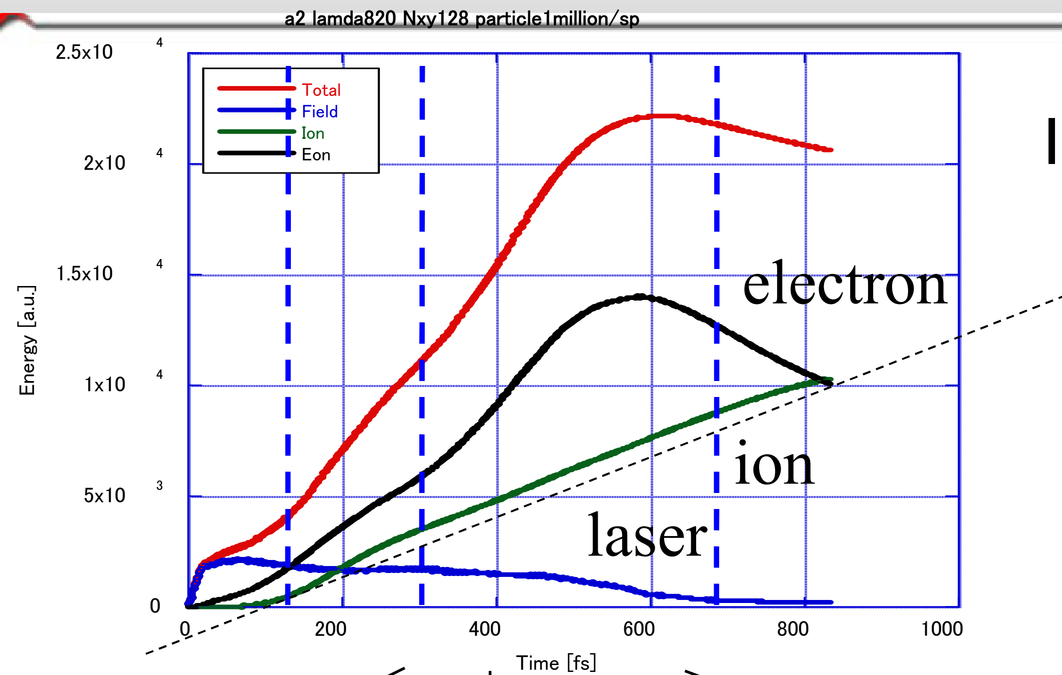


Faenov et al., 2009

Fig.11

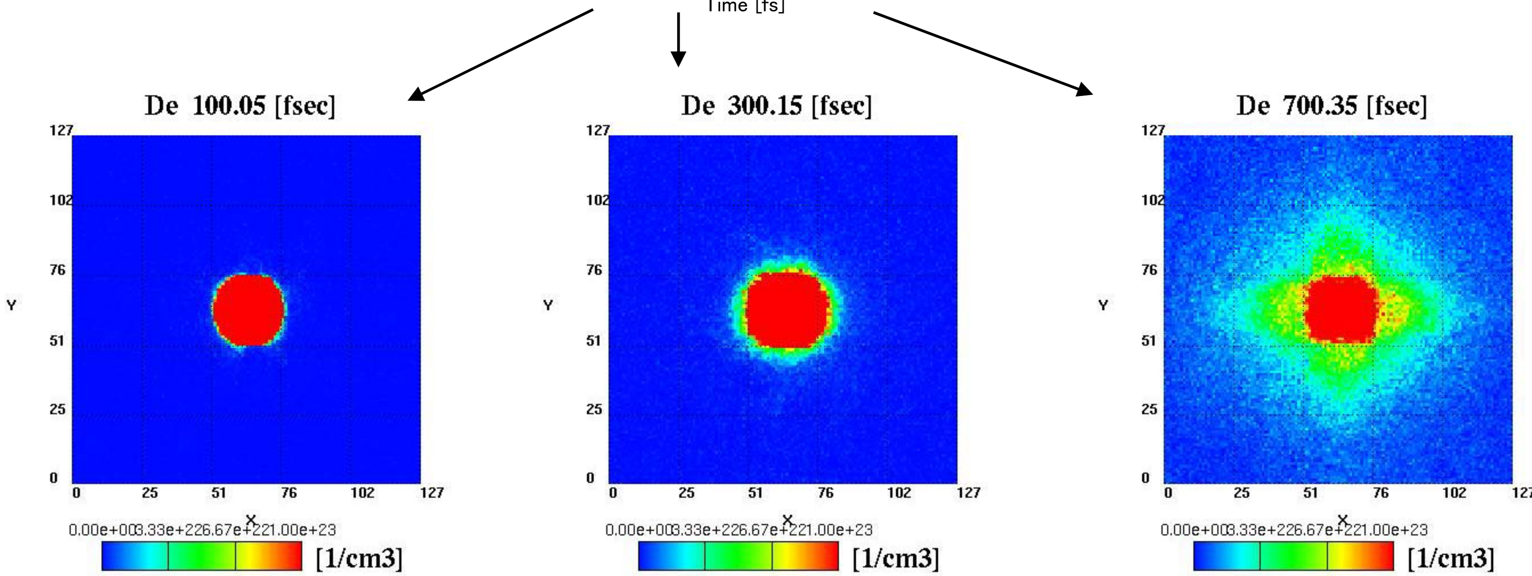
Laser-carbon cluster interaction

$a_0=4$

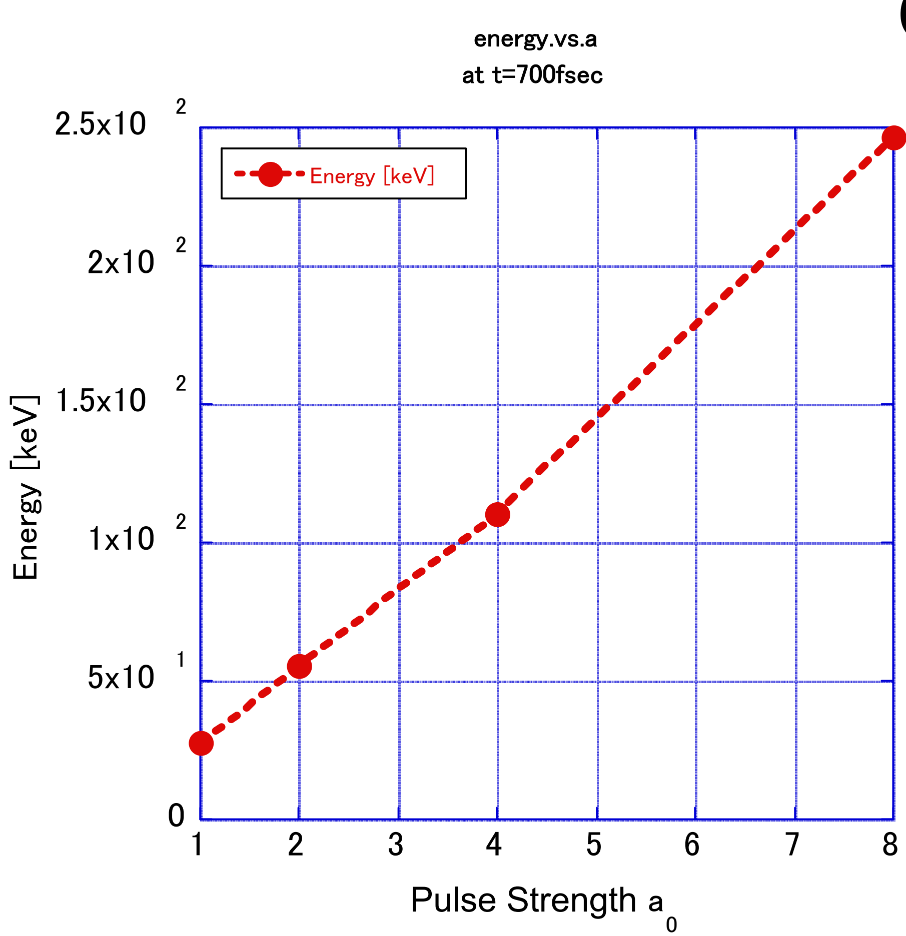


Ion energy
~ pulse length
(laser energy)

Kishimoto (2009)



Maximum energy vs. laser intensity



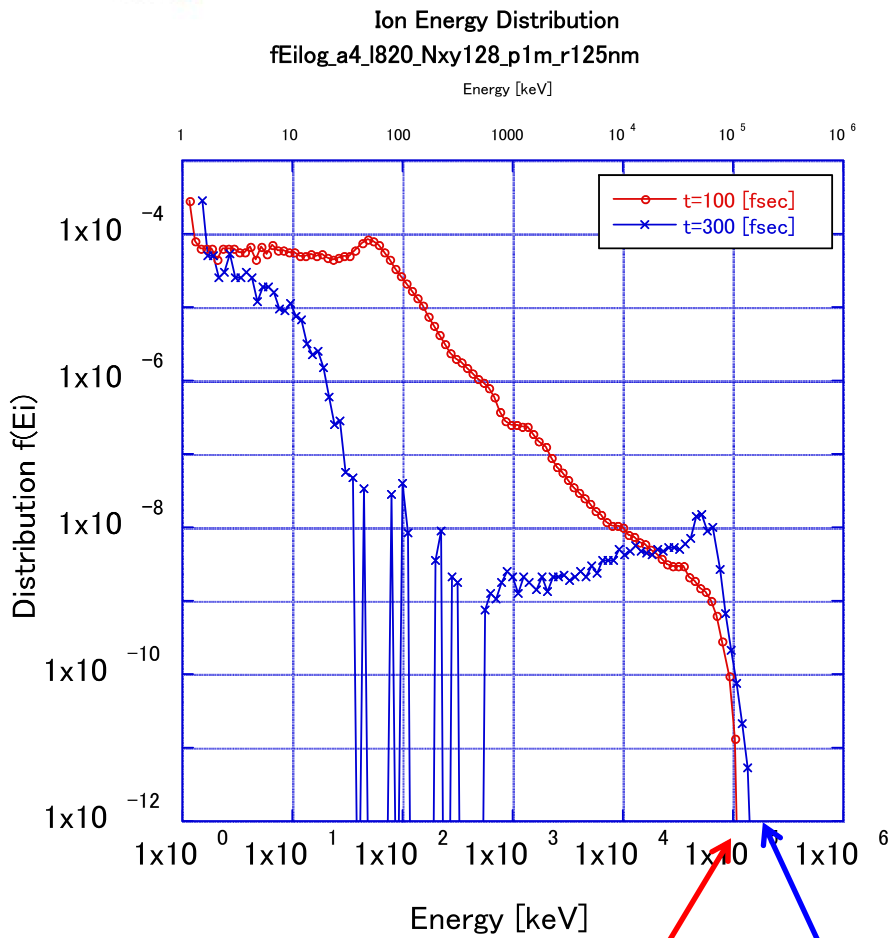
Cluster target scaling

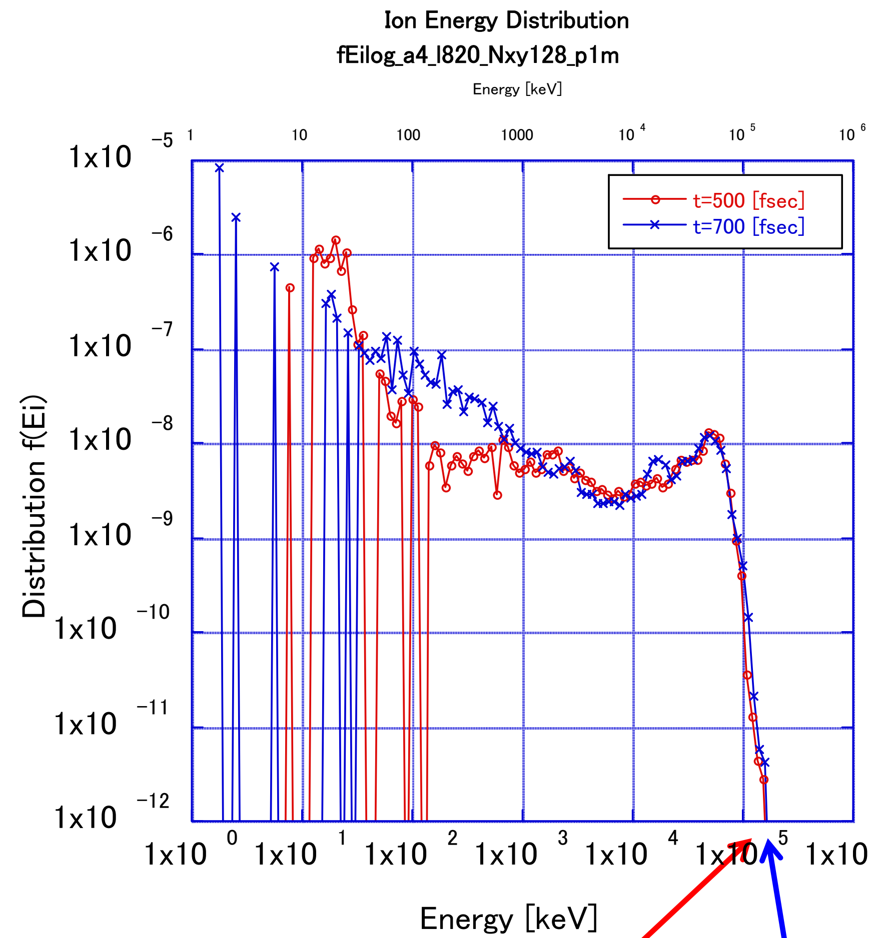
Consistent to the Theory by Yan et al. (2009), though it is based on thin film case

$$\varepsilon_{\max} = (2\alpha + 1)Q\sqrt{1 + a_0^2}$$

Kishimoto, 2009

Ion Energy spectrum r=125μm





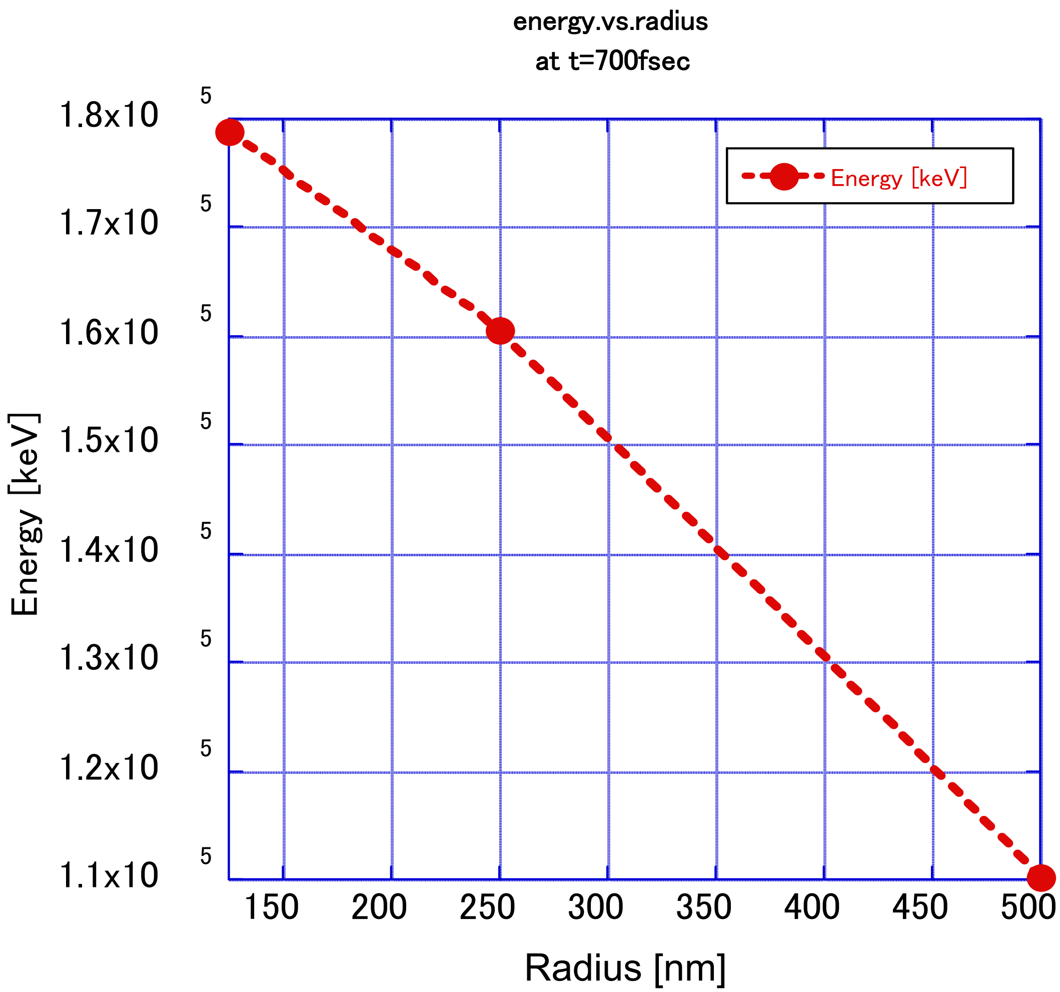
114.9MeV **150.98MeV**

171.71MeV **178.84MeV**

Kishimoto. 2009

Ion Energy vs. Cluster Radius

Cluster target scaling: ion energy ~ 1/(cluster radius)



Kishimoto,Tajima (2009)

Conclusions

- Cancer: unsolved problem, as fundamental to biology
- Ion beam radiotherapy: superior cure to chemotherapy, though expensive today
- Detection and cure of small unmetastasized tumor = future (fundamental cure, better quality of life, better fit for compact laser accelerator)
- Compact laser ion acceleration: niche for small tumors
- Breakthroughs in laser ion acceleration: overcomes the previous paradigm (TNSA) with the new conditions
- Higher energies, higher efficiency, and less energy spread
- With compact laser (10^{20}W/cm^2) 100MeV protons possible
- Feedback therapy essential for small tumors
- Laser-driven compact coherent X-ray source : detect small tumors
- A lot more medical applications on the horizon

Merci Beaucoup et a la Prochaine Fois