# Outlook : Accelerator Science

ATSUTO SUZUKI
(KEK)

*ICFA Seminar,*
*SLAC, October 31, 2008*

# Goal of Accelerator Science:
# To Answer Fundamental Questions

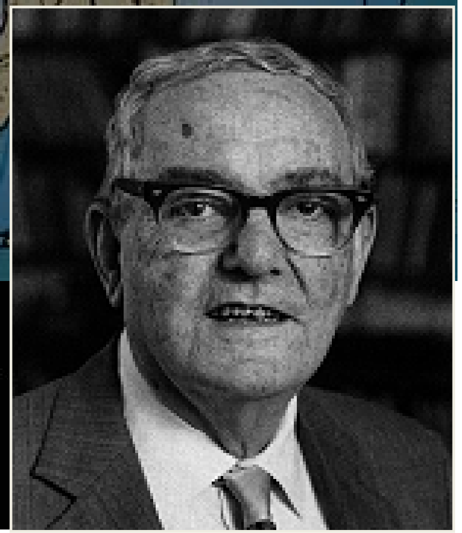
*We humans have long been obsessed with four great questions:*

*the nature of matter,*
*the origins of the Universe,*
*the nature of Life,*
*the workings of mind.*

*Herbert A. Simon*

*Nobel Laureate in Economics*

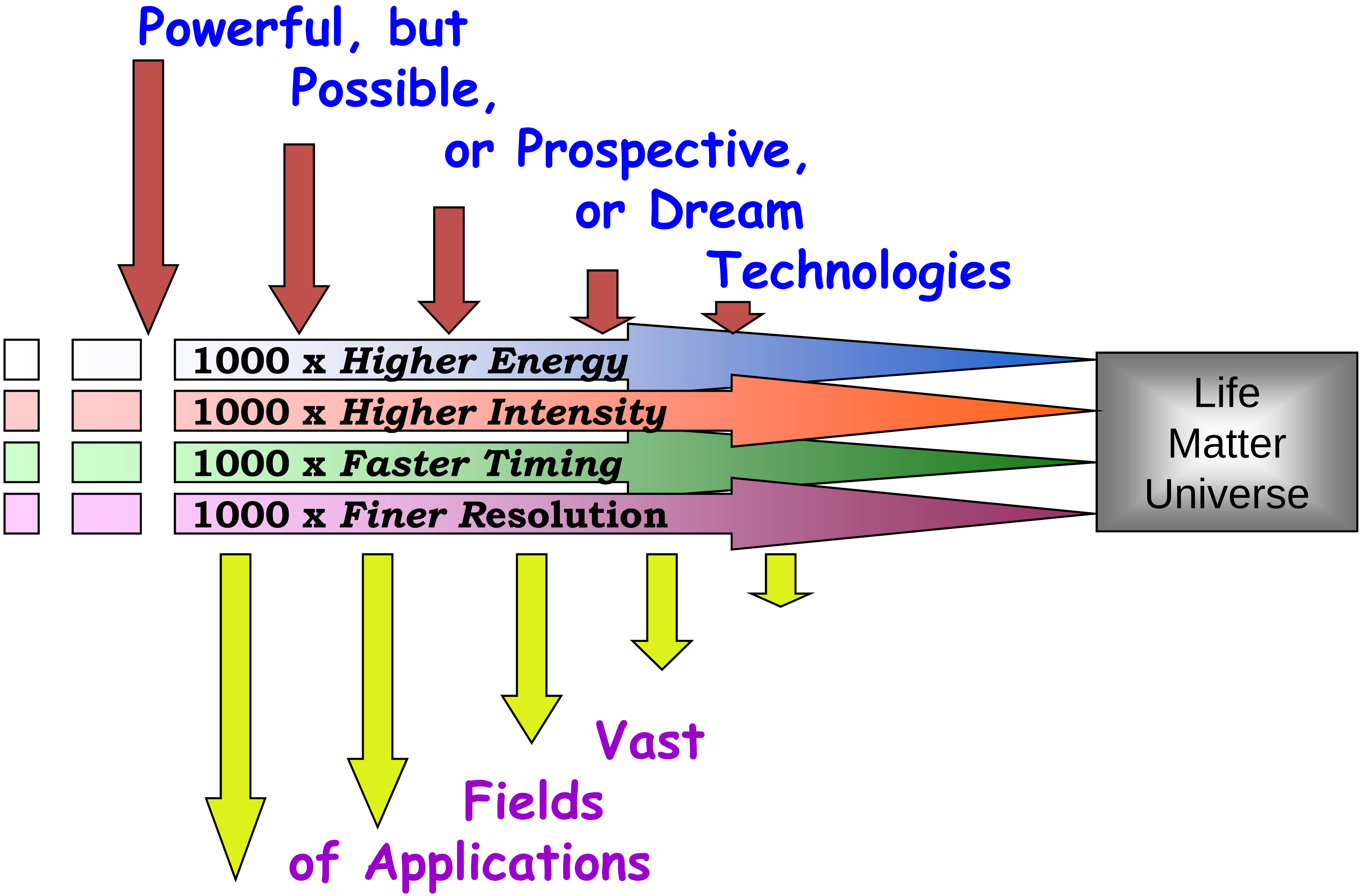
*from the Lecture in 1986*



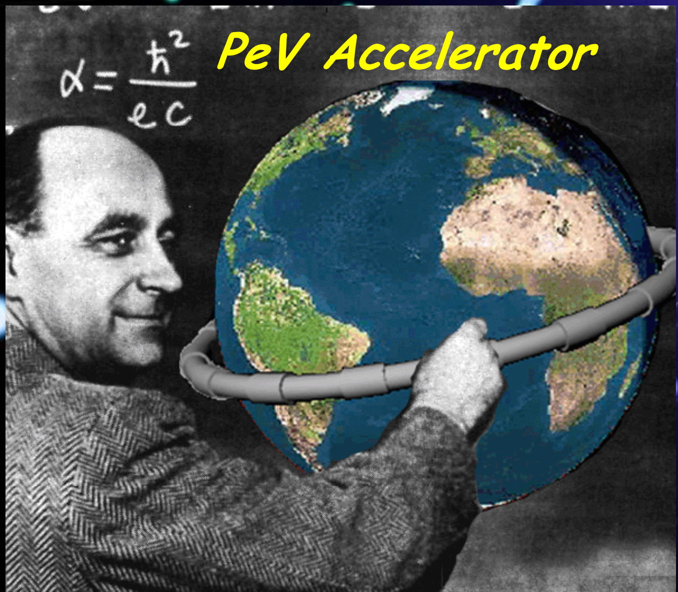
# To Open up New Horizon of Sciences


***Accelerators have been and will be a powerful tool to challenge for answers to them.***

# Outline


Powerful, but
Possible,
or Prospective,
or Dream
Technologies
1000 x *Higher Energy*
1000 x *Higher Intensity*
1000 x *Faster Timing*
1000 x *Finer Resolution*
Life
Matter
Universe
Vast
Fields
of Applications

1000 times
higher energy




**1 PeV=$10^{15}$ eV**

**“ New paradigm”**

Leptogenesis

SUSY breaking

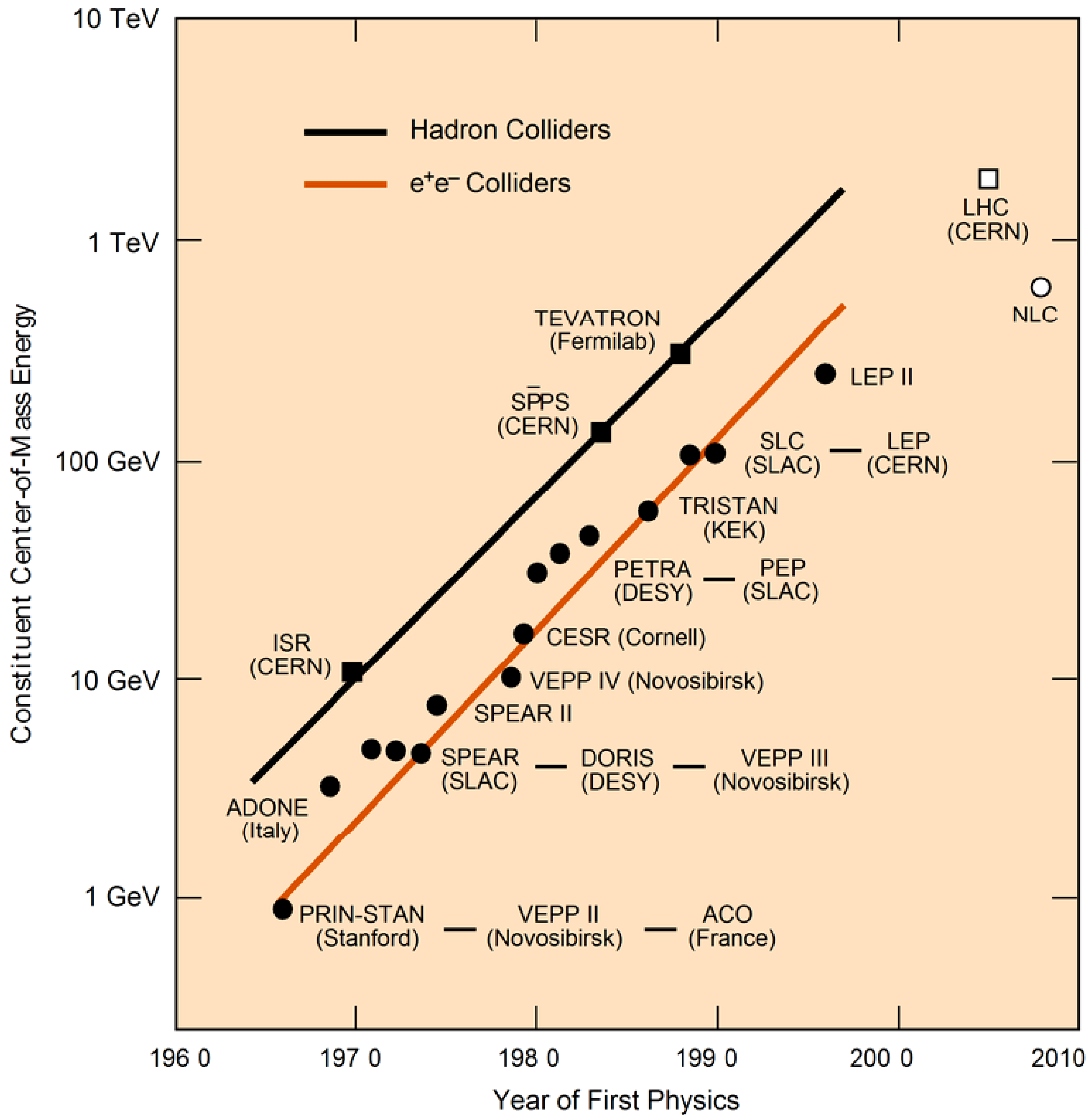
Extra dimension
Dark matter
Supersymmetry

**1 TeV=$10^{12}$ eV**

“Standard model”
Higgs
Quarks
Leptons

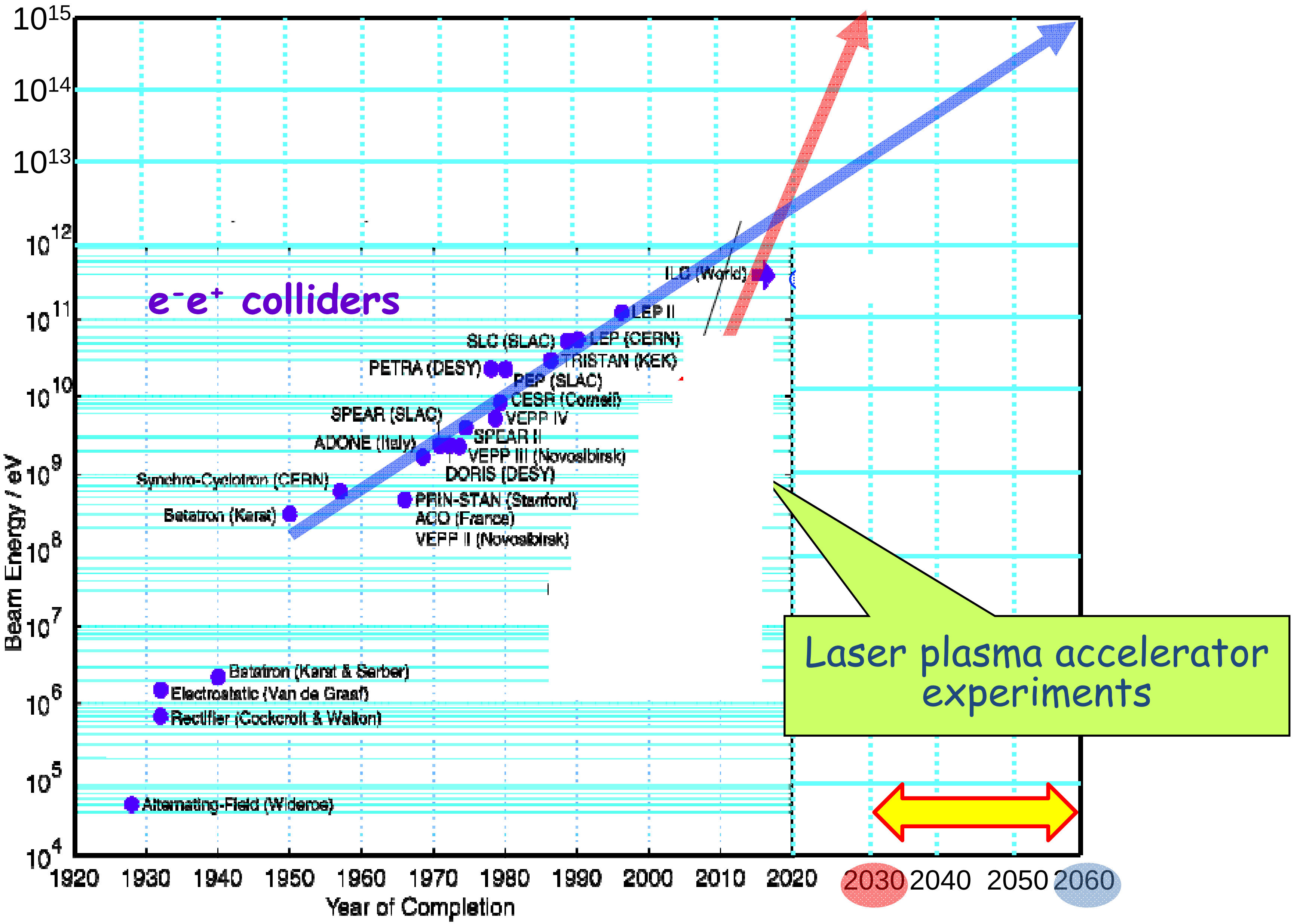
………..
………..
***Acceleration Technology***

# When can we reach to 1 PeV ?




(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)

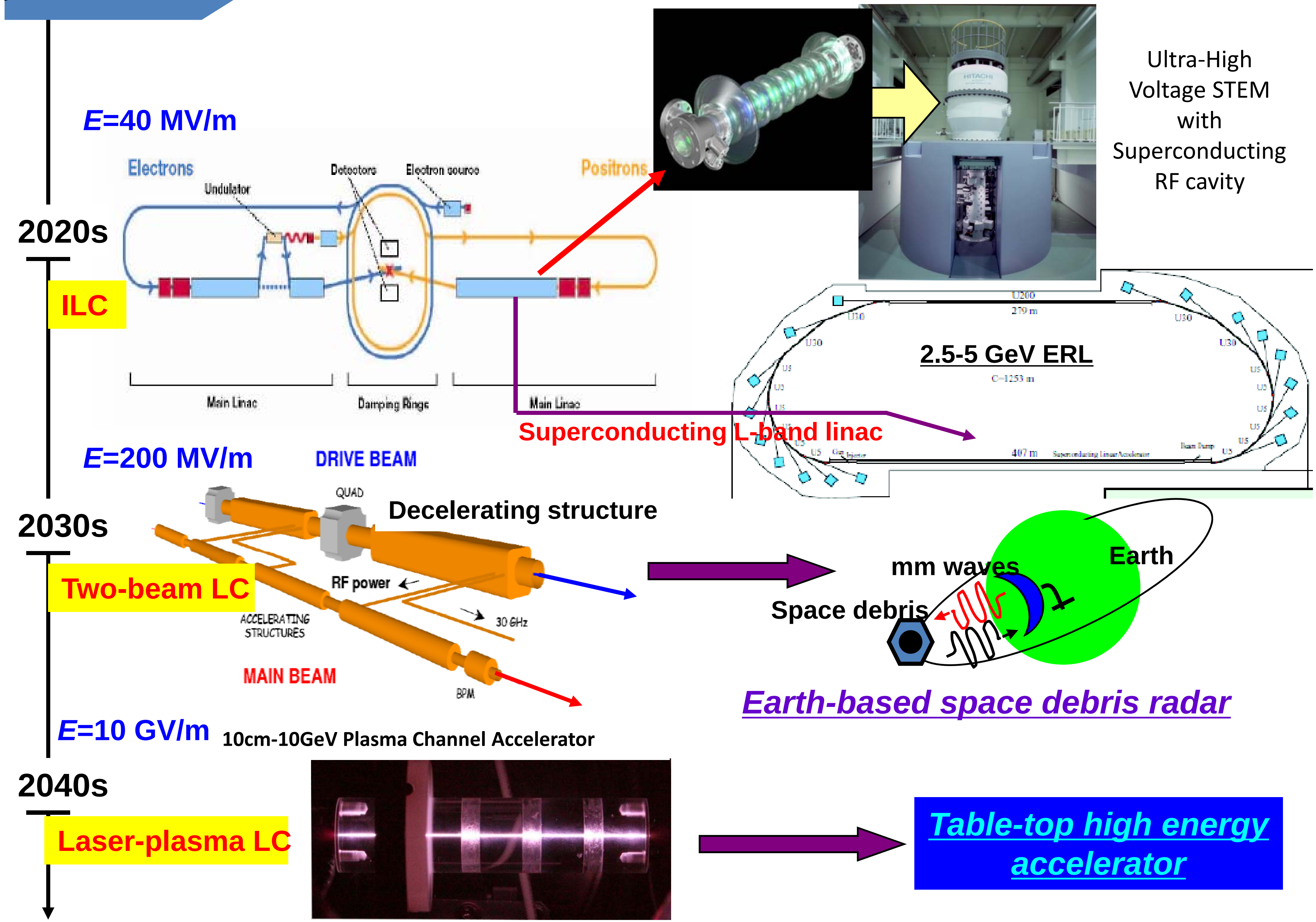
# When can we reach to 1 PeV ?




V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4

Accelerator

# Evolution of Accelerators and their Possibilities

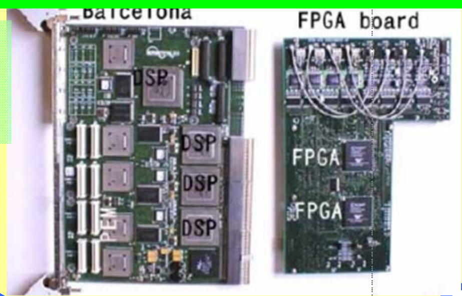


# Ultra-High Voltage STEM

## (Scanning Transmission Electron Microscope)

**Advanced technology of digital RF control**

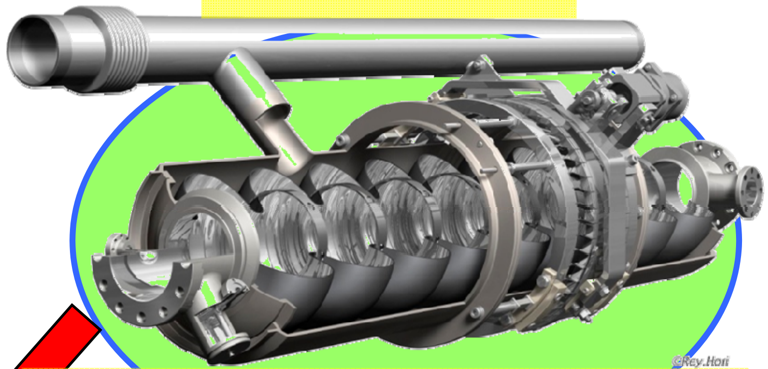
*Successful achievements:*
*J-PARC Linac, ILC R&D, etc.*




+

$\Delta E/E$: $10^{-(6\sim7)}$

*CW stable beam*



**Superconducting RF acceleration**

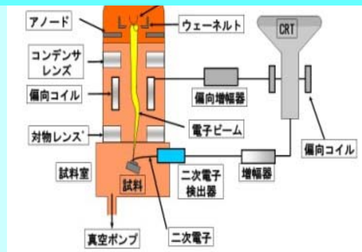

***Existing STEM***

- *huge size*
- *linear optics*
- *more transmission power*

**Full utilization of accelerator technology**

- compact
- low cost
- high resolution
- excellent transmission power
- versatile
- well functional

**Accelerator beam optics**

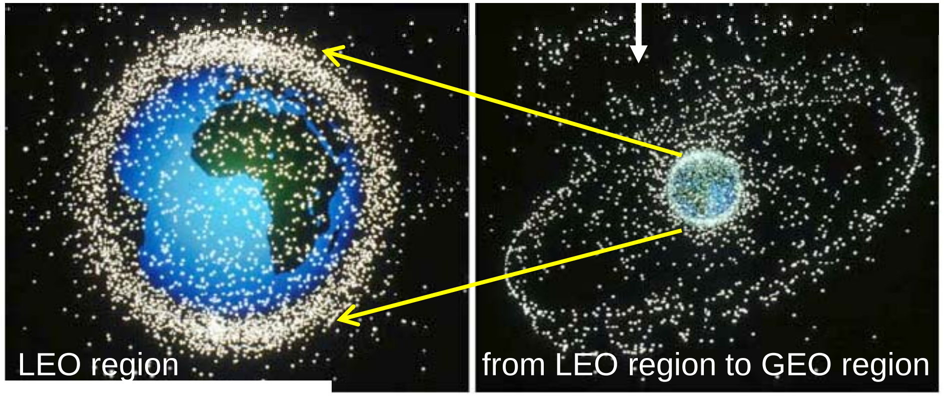



*Nonlinear optics*

*→ non-axially symmetric optics*

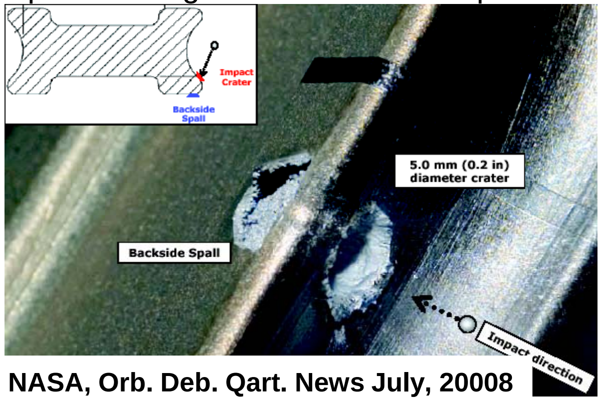
# Two-Beam Accelerator Application to Space Debris Radar System

Distribution of cataloged space debris (~ 9,000 beyond σ = 100 cm)



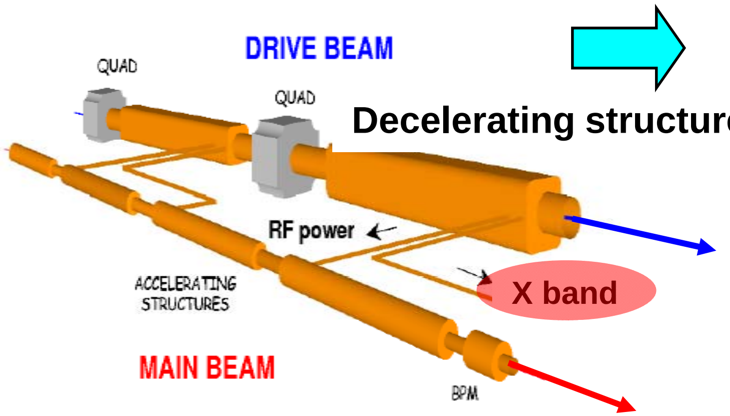

Low Earth Orbit (LEO) Geostationary Orbit (GEO)

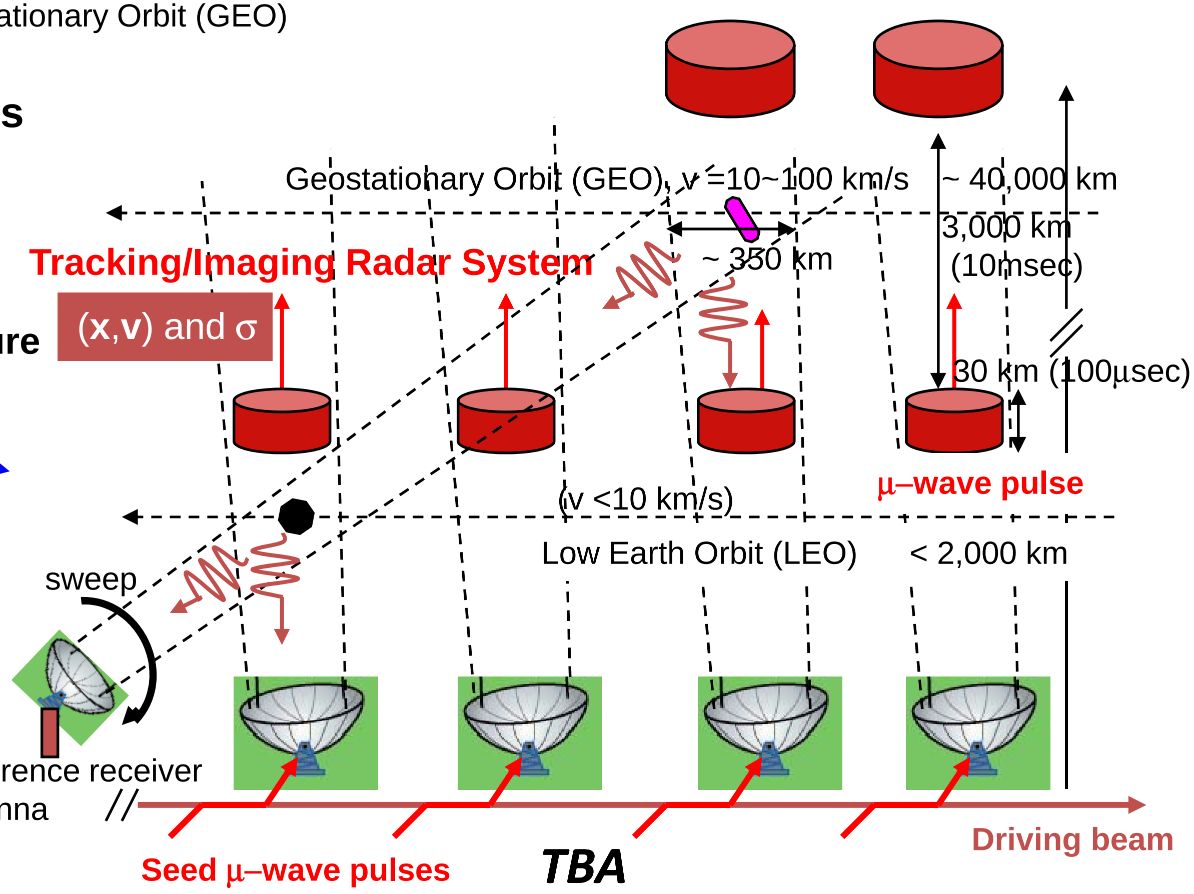
Impact Damage on International Space Station



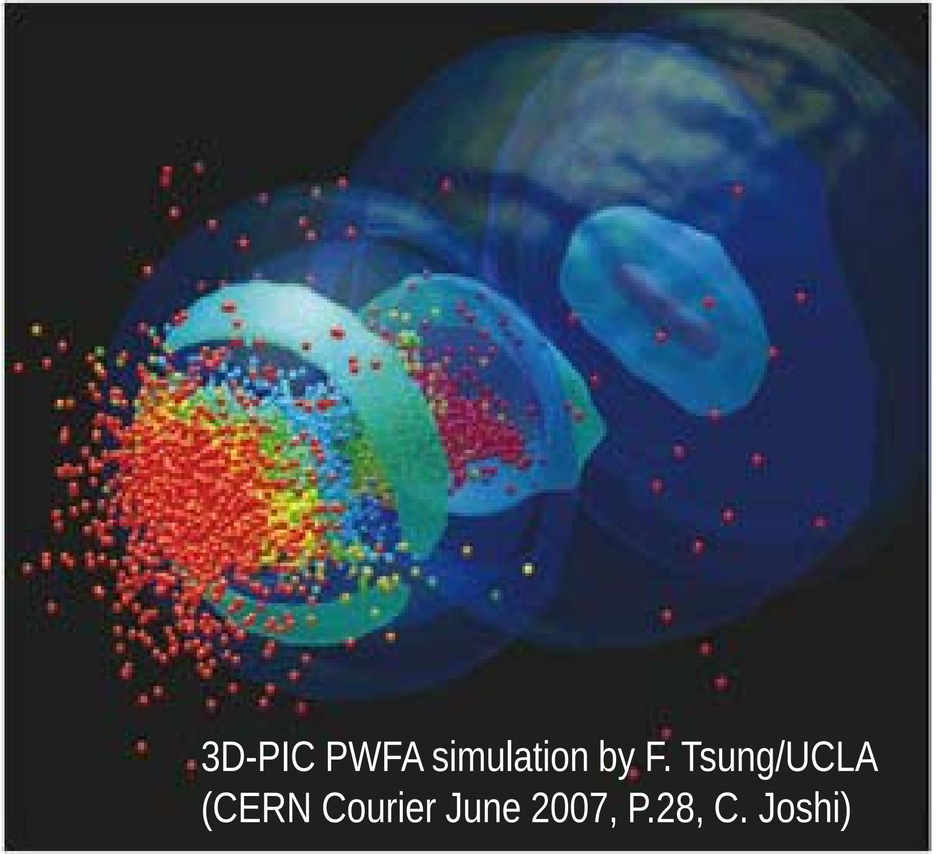

NASA, Orb. Deb. Qart. News July, 20008

## Use of High Power Pulse μ-waves from a TBA in Open Space



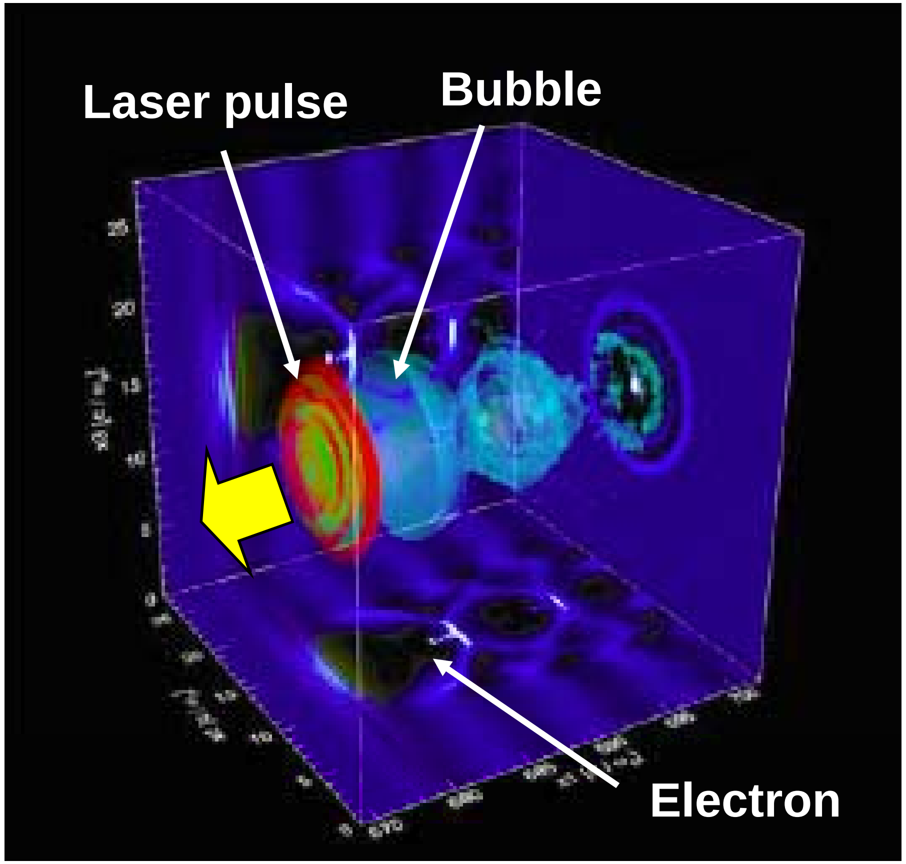




Properties:
- well-defined phase
- well-shaped pulse trains
- high peak power -> deep space
- short wave length -> size σ ~ 1 cm




Particle Driven Plasma Acceleration

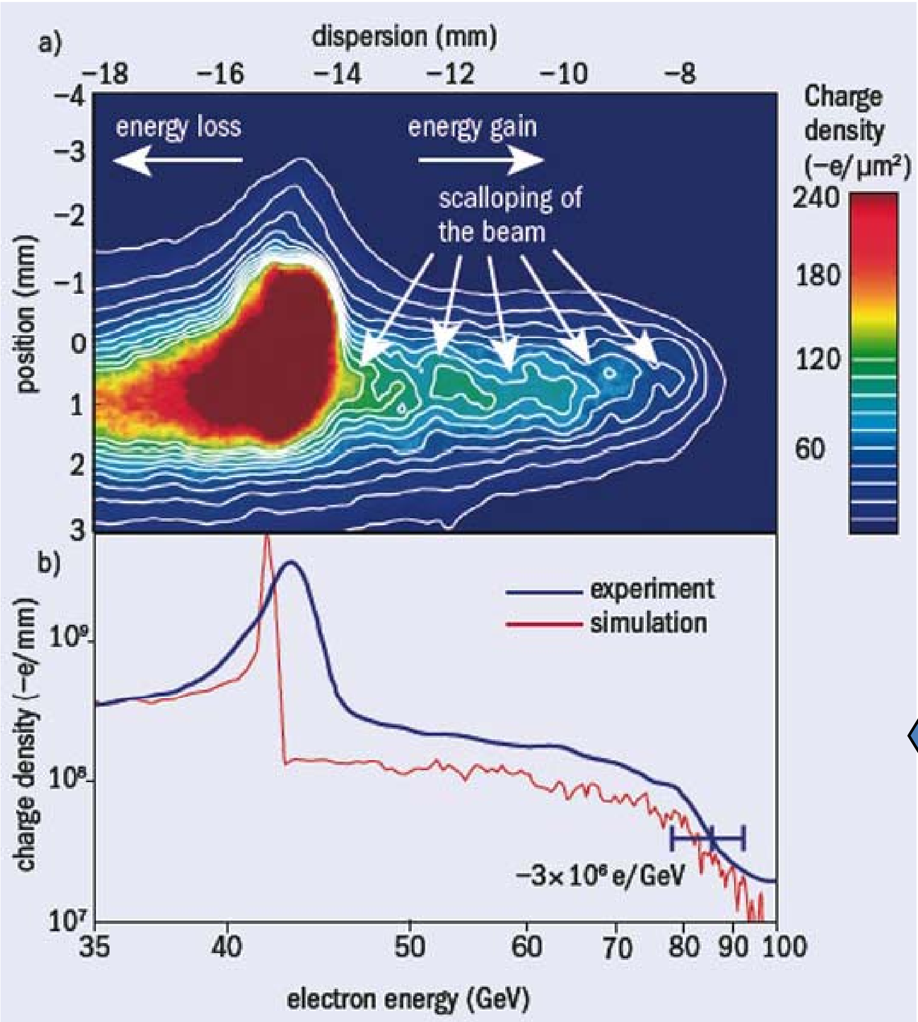
Laser Driven Plasma Acceleration

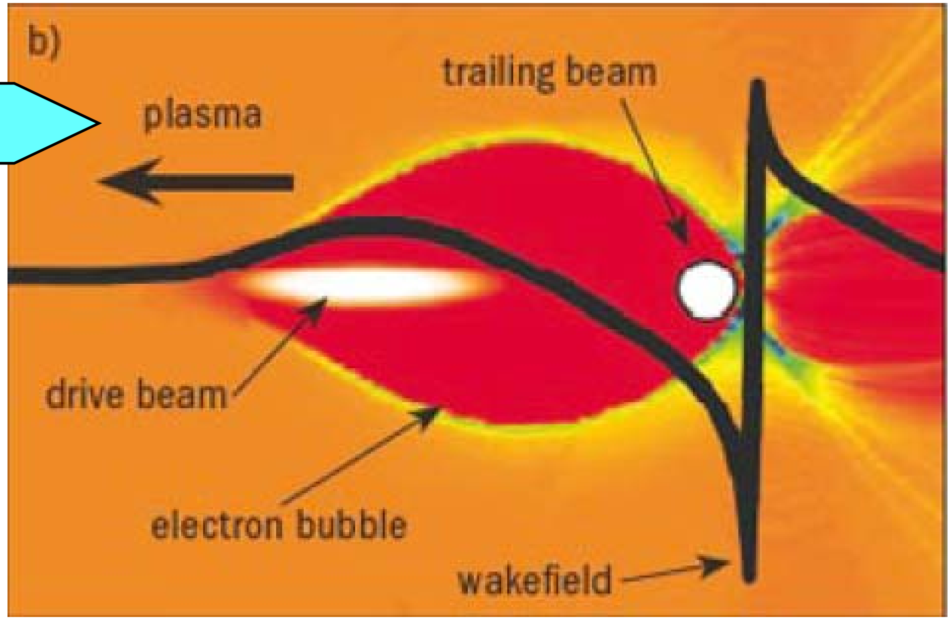


# 42GeV e-beam energy doubled by PLASMA WAKEFIELD ACCELERATOR

I. Blumenfeld et al., Nature 455, 741, 2007

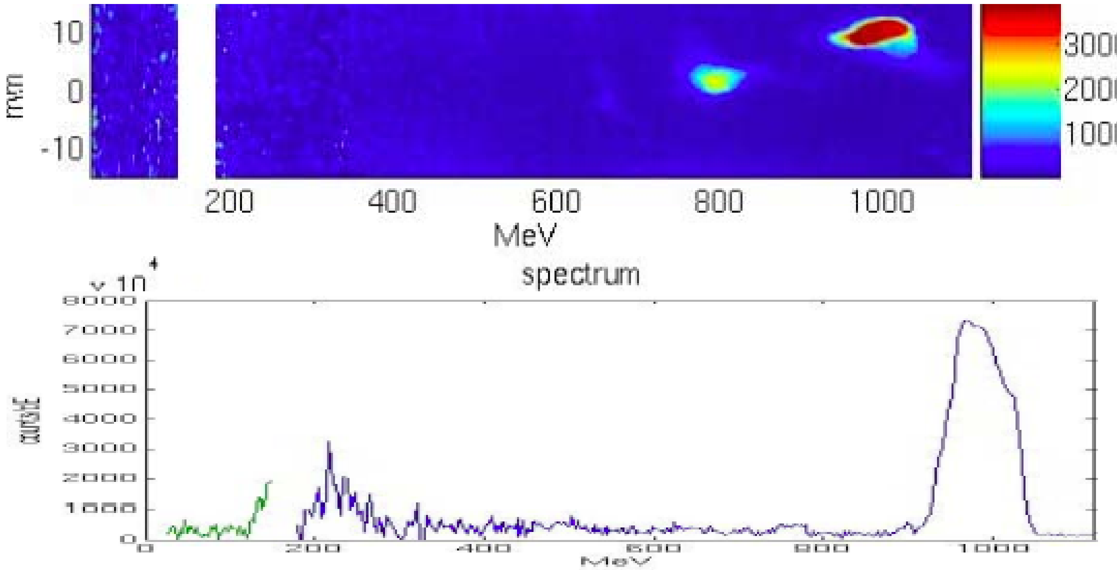
Plasma wakefield in the "bubble" regime

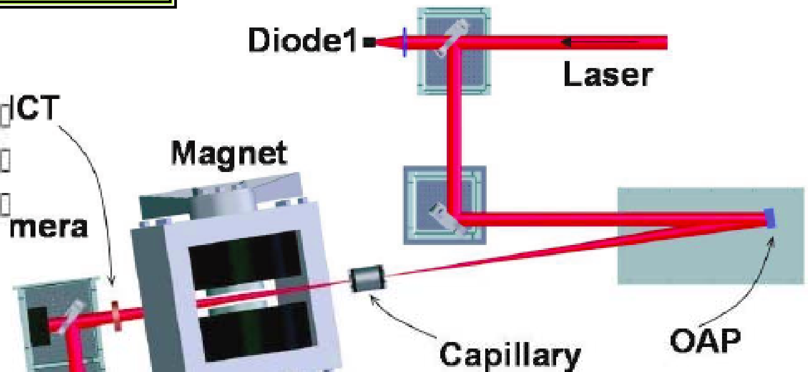


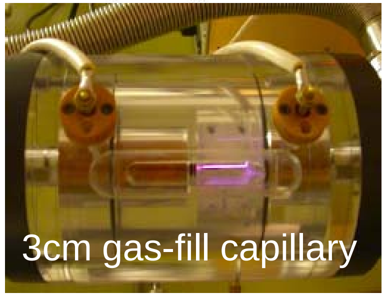




Energy spectrum of E167 SLAC Plasma Accelerator Experiment for the 42 GeV electron beam after passing through a 85 cm long plasma of density $2.7 \times 10^{17}$ cm$^{-3}$

# 1 GeV capillary accelerator experiment at LBNL/Oxford U.

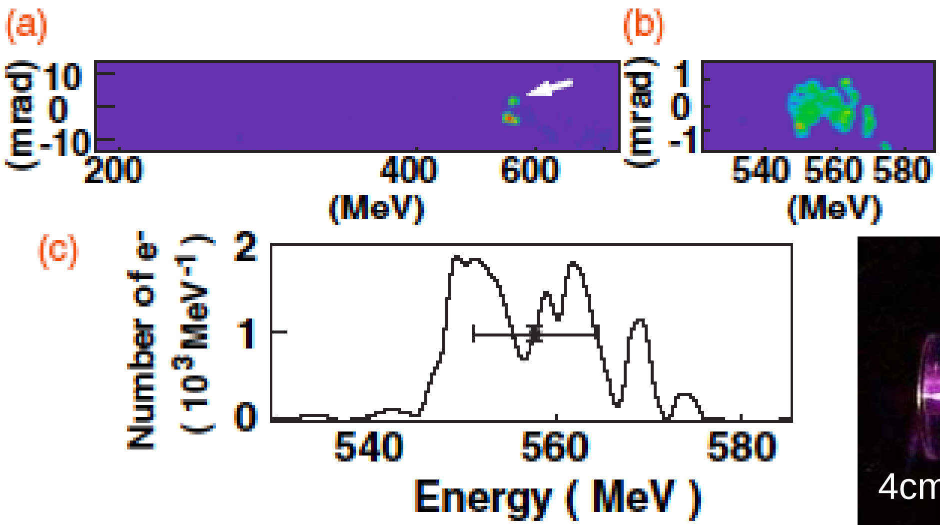


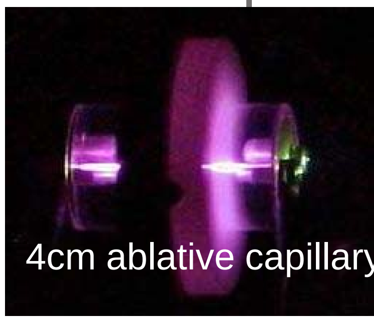



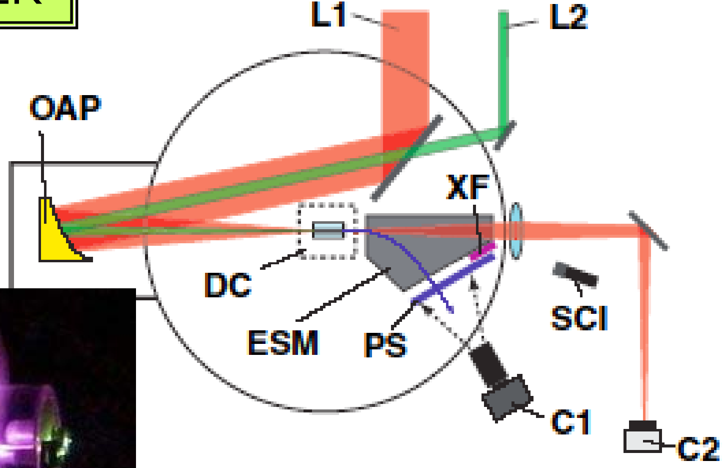
3cm gas-fill capillary

# 0.56 GeV capillary accelerator experiment at CAEP/KEK



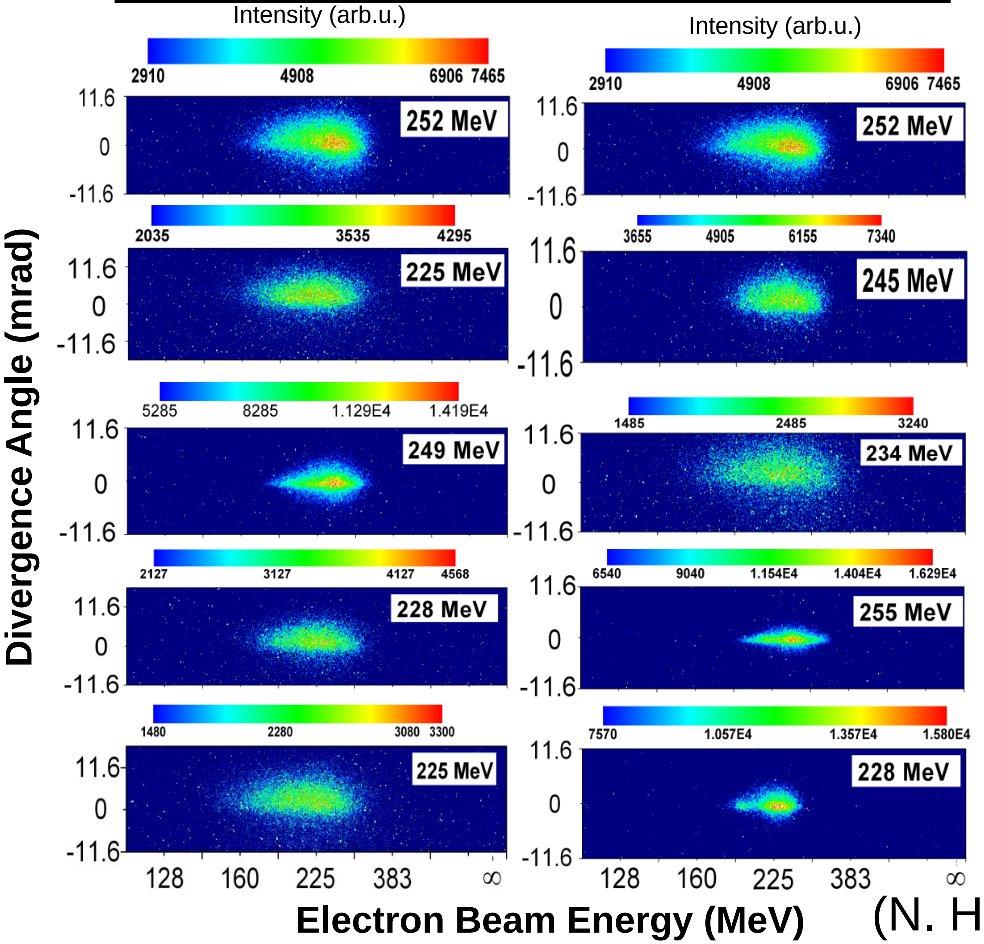
4cm ablative capillary

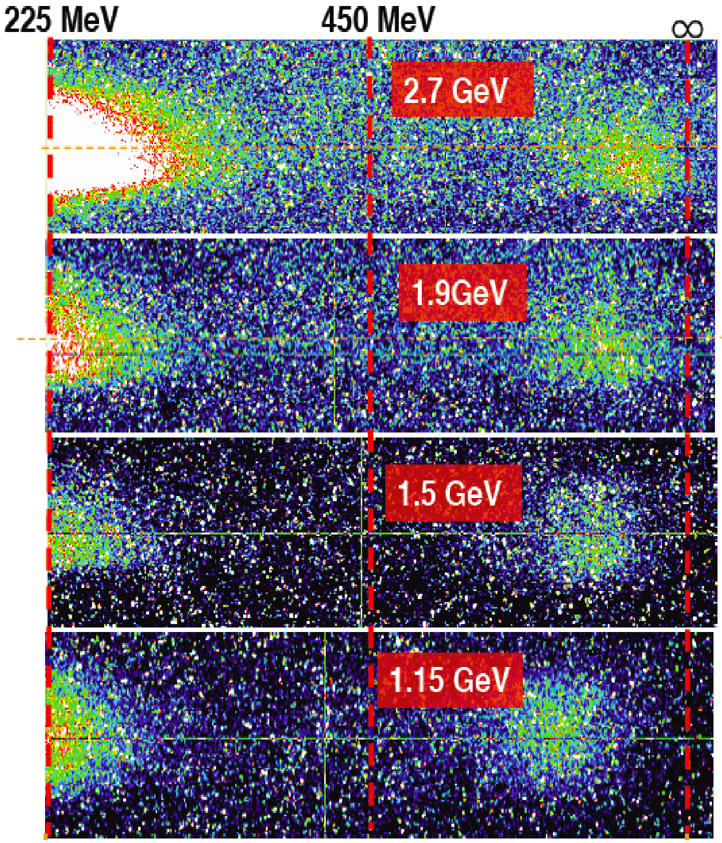


# Stable electron beams and more high-energies from 1 cm gas jet at GIST, Korea

**Mean electron energy = 236.9 MeV**
**SD/Mean E = 5 %**
**Charge: ~100pC**
**Divergence angle: ~a few mrad**

**100TW laser system at Gwangju Institute of Science and Technology**

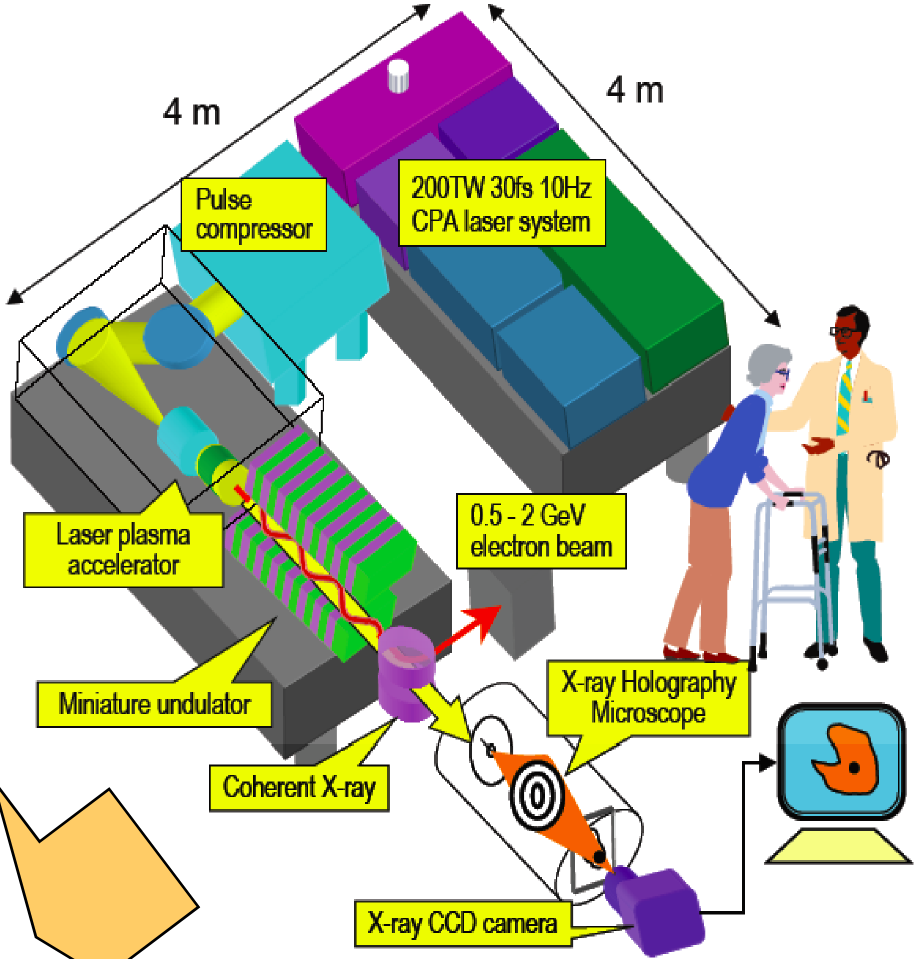


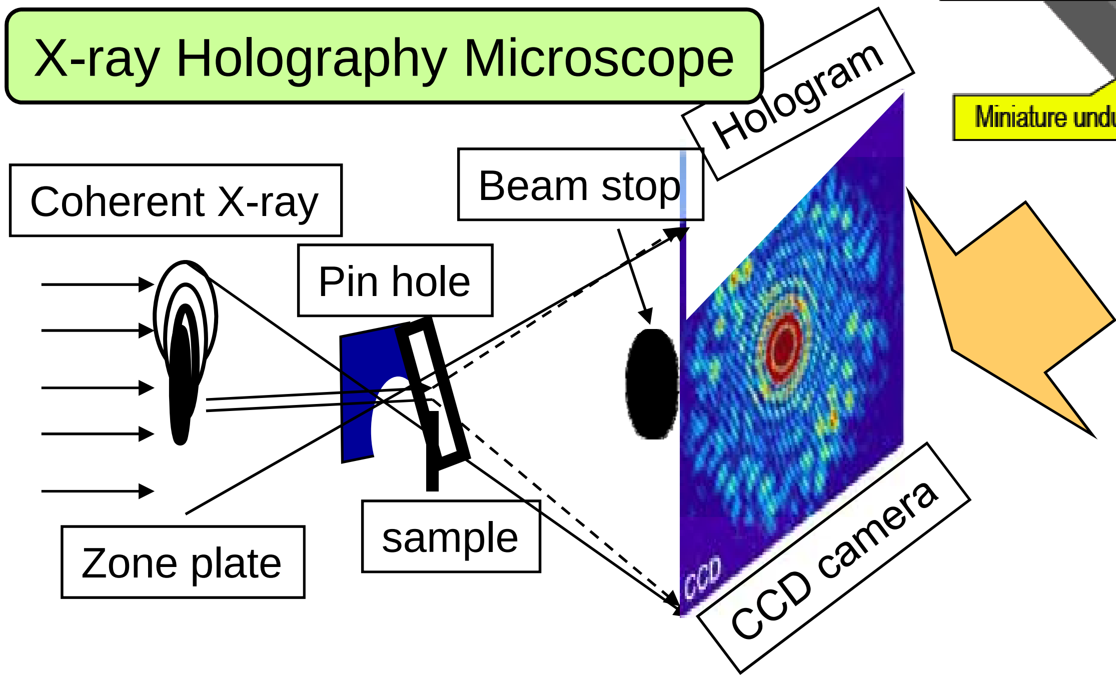




(N. Hafz et al., nature photonics, 2, 571, 2008)

# Laser-driven table-top X-ray Free Electron Laser

Kilometer-scale X-ray FEL

100 MW Beam Power
Inertial Fusion
Nuclear waste processing
Brighter neutron source
Muon Collider
Neutrino Factory
Linear Collider
100 kW Beam Power
1000 times more powerful beam
Rey.Hori
*Proton Driver
*Target/Capture
*Muon Accelerator
*Muon Storage Ring
E=20(50)GeV
Δθ<1/(5-10)γ
I>1 x 10^20 muon decays/year @one s.s
Muon-collider
Neutrino factory
J-PARC
Super-conducting Accelerator Technology

# Beam Power

Beam Power = Energy x Bunch Charge x Bunch Repetition

High field acceleration

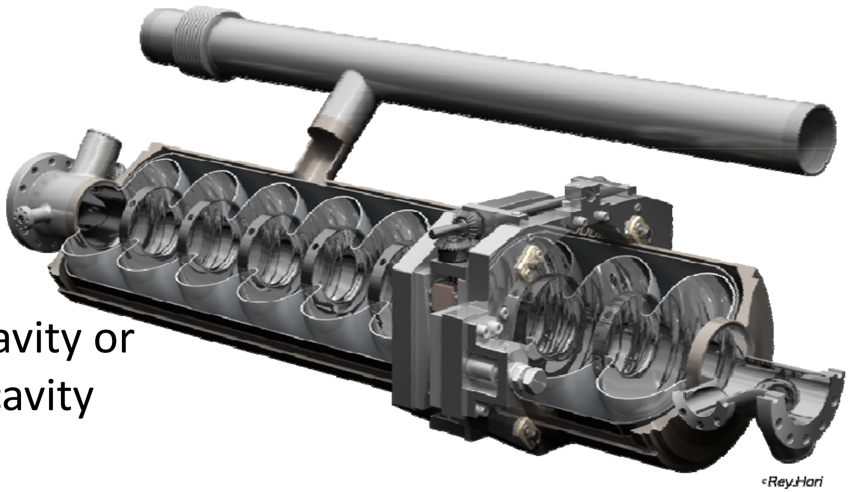
High beam current

continuous acceleration (CW beam)

HOM damping, large bunch size

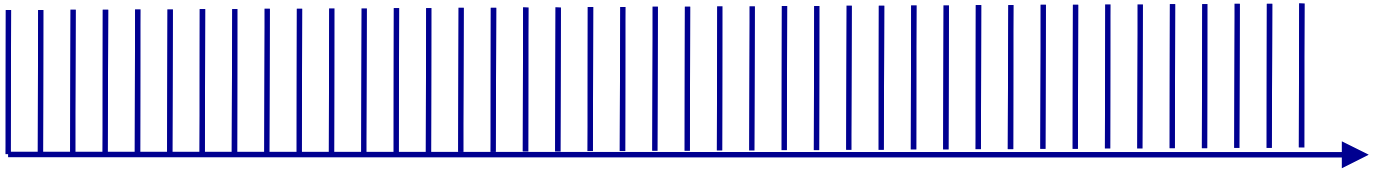
high power transfer to beam (small wall loss)

→ feasible solution : Acceleration by L-band Superconducting Cavities,
Continuous beam accelerated by Linac




ILC cavity or
ERL cavity

# Prescription of 100 MW Beam Power



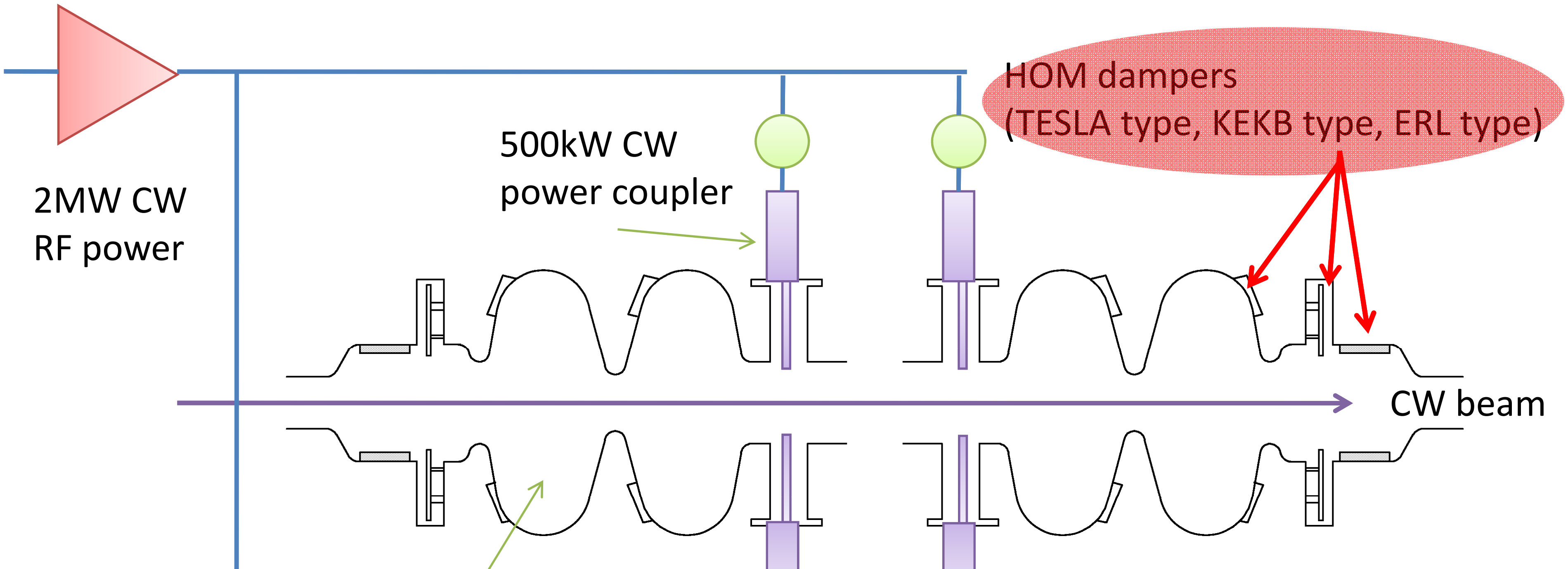

For example; taking
10nC/pulse, 10MHz repetition, CW : it is 100mA continuous beam,

developing 9-cell SC with 40MV/m and using only 2-cells,
40MV/m x 2cell/9cell = 8.9 MV energy gain
8.9MV x 100mA = 890kW power transfer to beam

developing 2MW CW RF power source,
it deliver RF power to two 2-cell cavities.
using this RF unit, 100,
then, 100 x ( 2 x 8.9MeV) = 1.78 GeV beam energy
100 x ( 2 x 890kW) = 178MW beam power
with 100m Linac length.

# Higher Order Mode (HOM) damped High Gradient Cavity

L-band superconducting 2 cell cavity with damped port



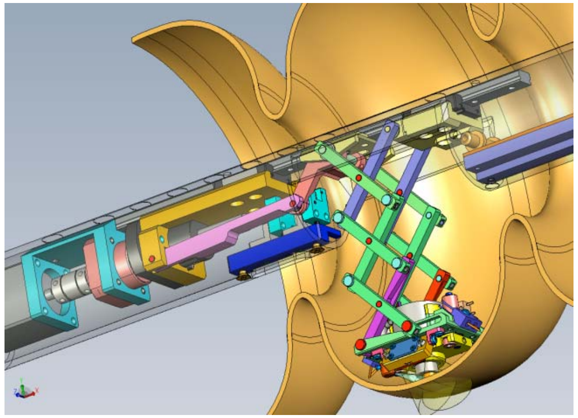

ERL 2-cell cavity for Injector line, as an example

# Surface Polishing for High Gradient Cavities

To improve superconducting cavity performance, for example,

Remove Nb surface defects (surface steep steps should be < 1-2µm )

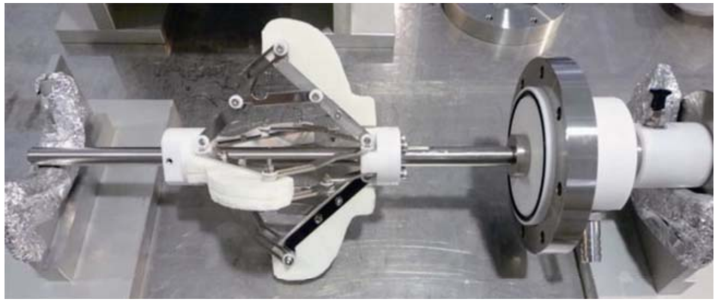
Develop fine EBW, fine EP
and
Develop local grinder
to remove local defects



local grind tool

Remove surface contamination ( 1-2µm size contamination should be removed)

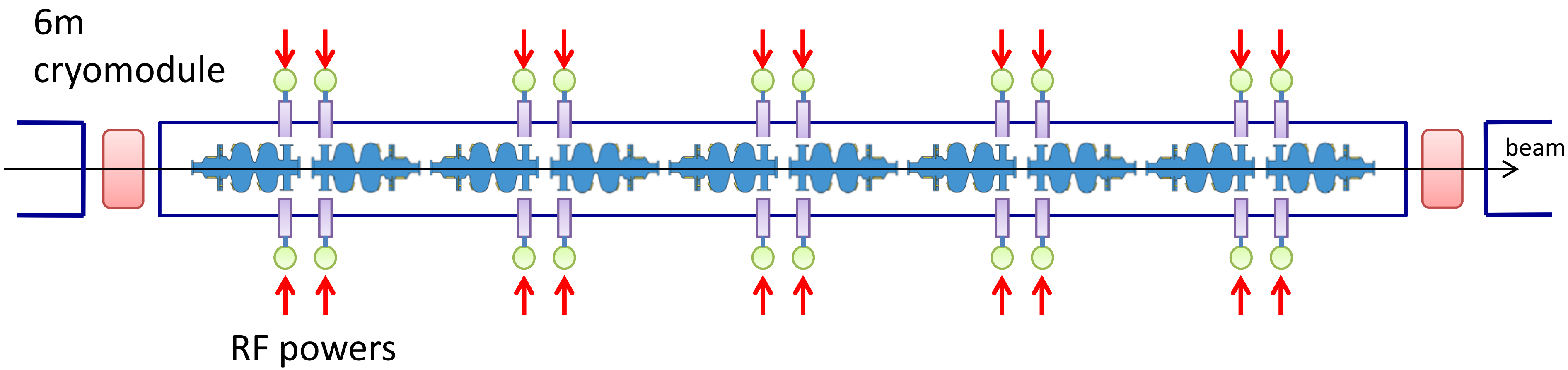
Develop rinse and HPR,
and
Develop sponge wipe rinse

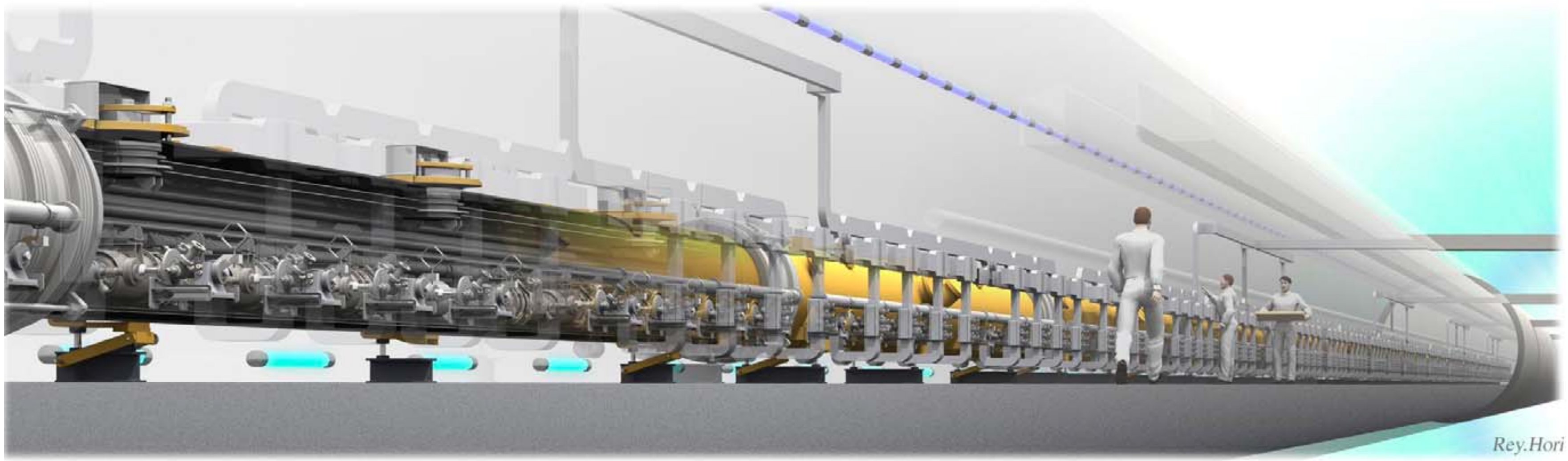


sponge wipe tool
(direct physical cleaning inside of cell)

# Candidate of possible Accelerator in Drawing

High intensity LINAC cryomodule with many RF power feed

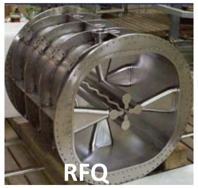



ILC cryomodules for LINAC, as an example

# Brighter Neutron & Neutrino Sources

- superconducting rf technology for proton or ion linac

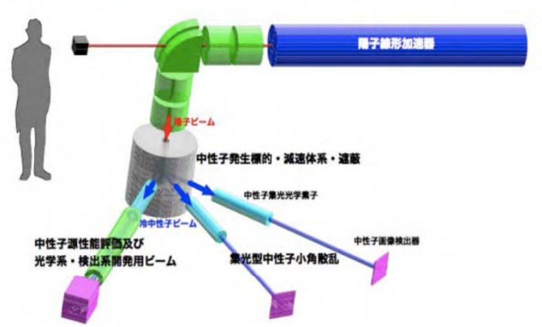



Spoke-type cavity

High β cavity

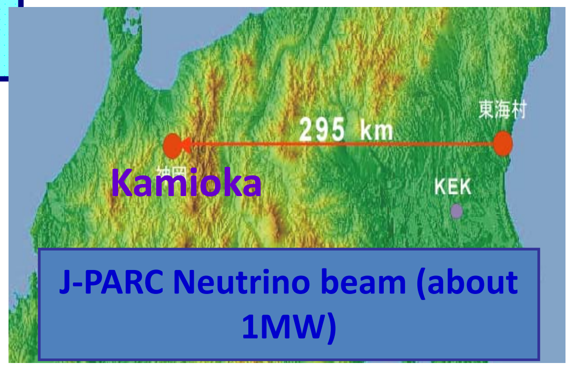

**high gradient -> compact**
**low wall loss -> efficient**
**CW operation -> high beam power**

- **Compact Neutron Source**



**100MW-class proton linac may be feasible; e.g., 5GeV×20mA. It is a single accelerator but not an injector.**

- **Does not need $H^-$ ion source**
- **Less beam loss**
- **Modest peak current**
- **Less requirement for target design**




**J-PARC Neutrino beam (about 1MW)**

Pulsed Mode

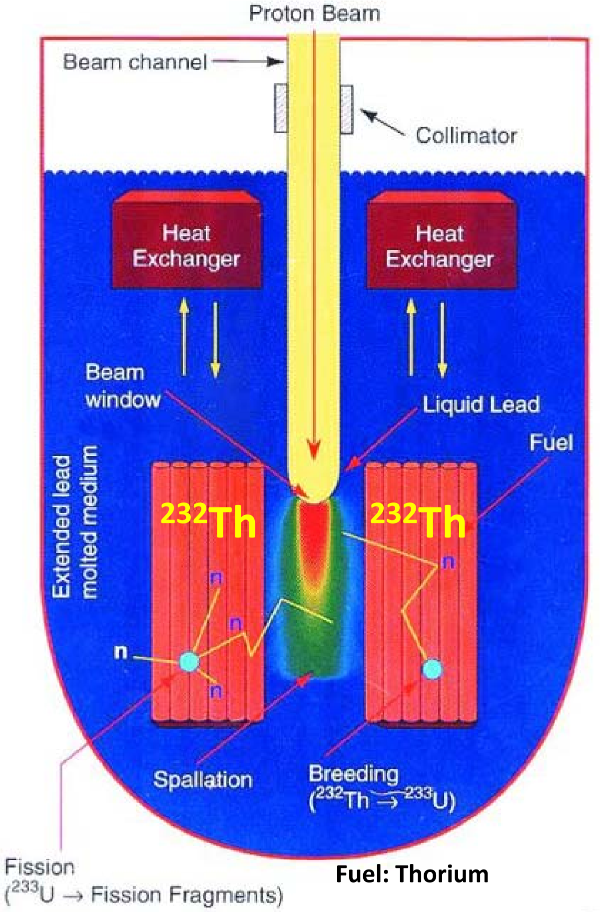
**Very High Power Neutron/Muon Source (> 10 MW)**

**CW Mode**

**Unprecedentedly High Power CW Neutrino Beam (100 MW)**

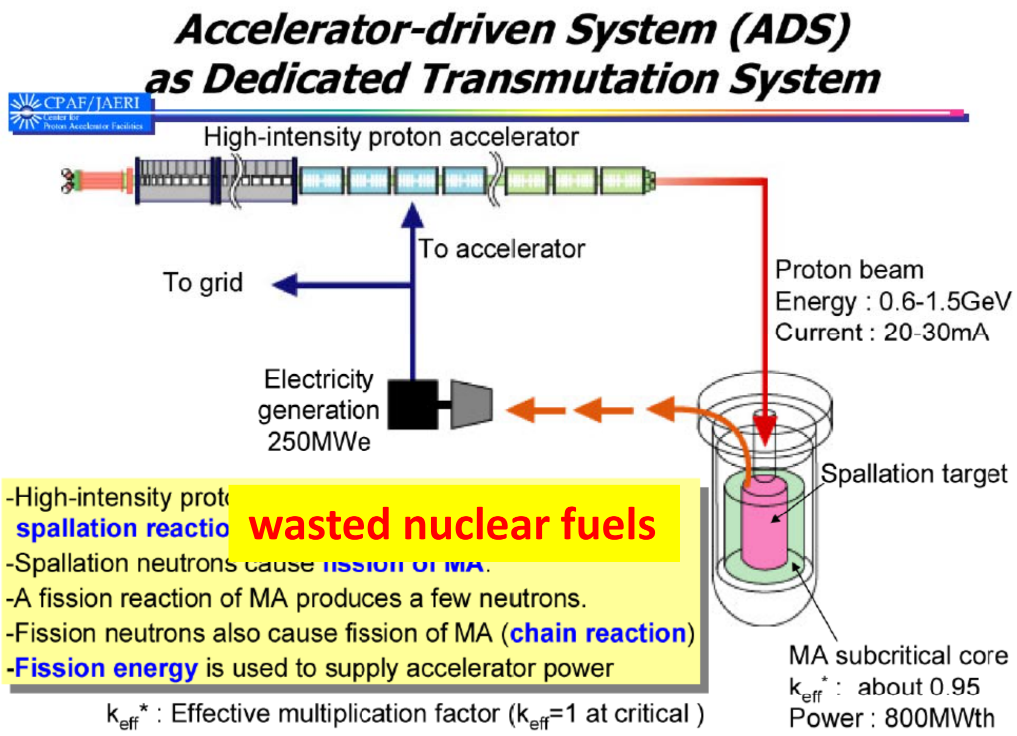
# The dream of realizing accelerator driven (subcritical reactor) system and nuclear waste transmutation system comes true with high power superconducting linacs !

## Subcritical reactor alone




**Fuel: Thorium**

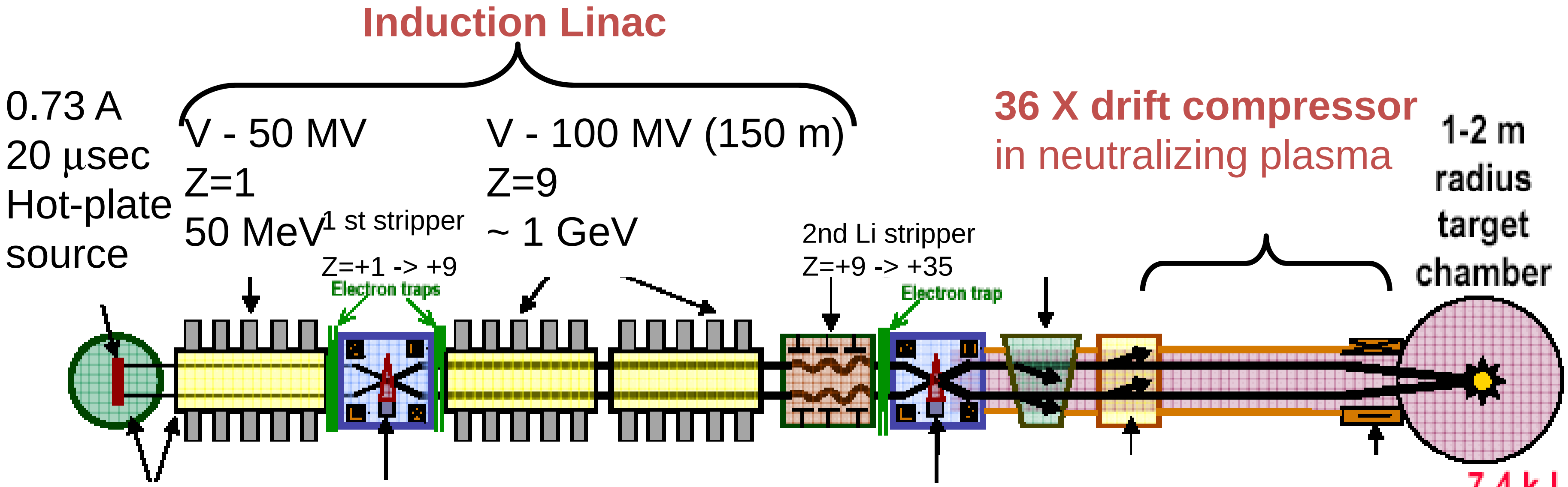
## Electric power generation & nuclear transmutation




**MA: minor actinide**

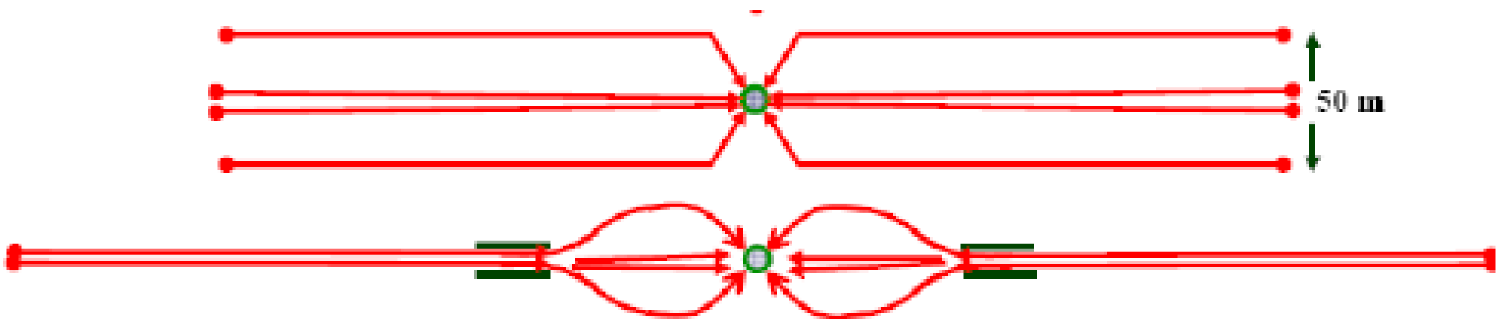
# Idea of Proton Driven Inertial Fusion : Down

## Driver for Heavy Ion Inertial Fusion Program in US-VNL



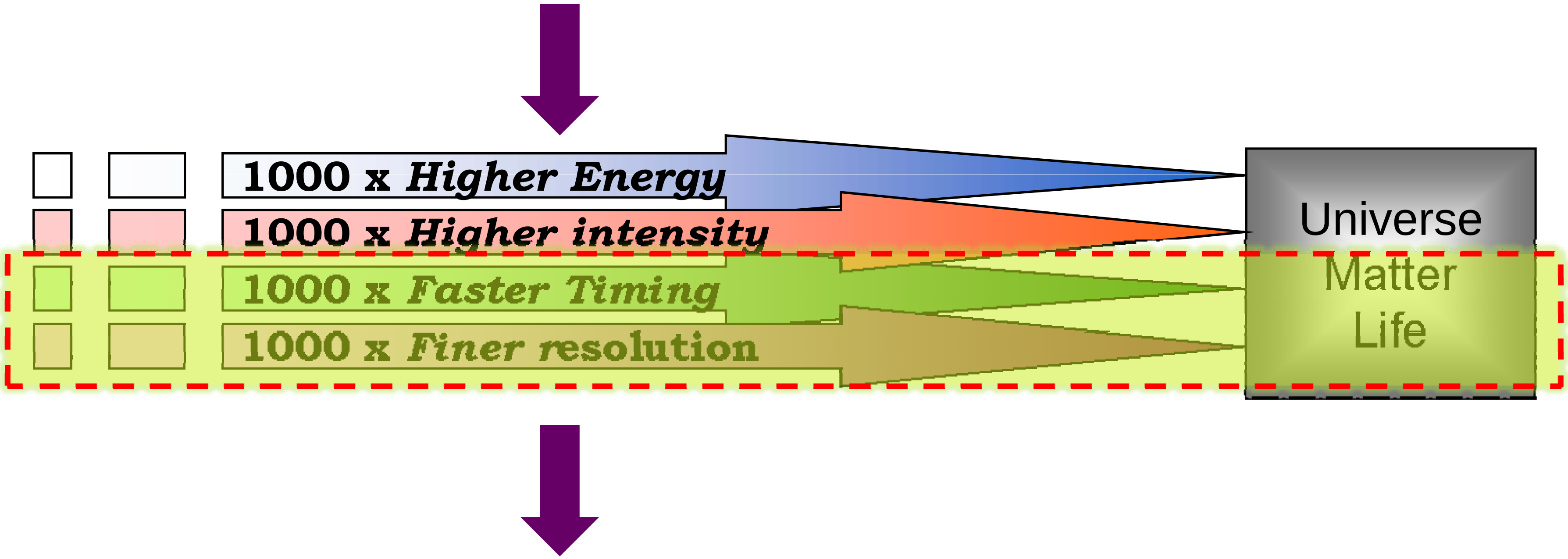

7.4 kJ per beam on target

## Driver configuration (Horizontal)




**G.B.Logan (VNL), presented at HIF2008, Tokyo Japan**

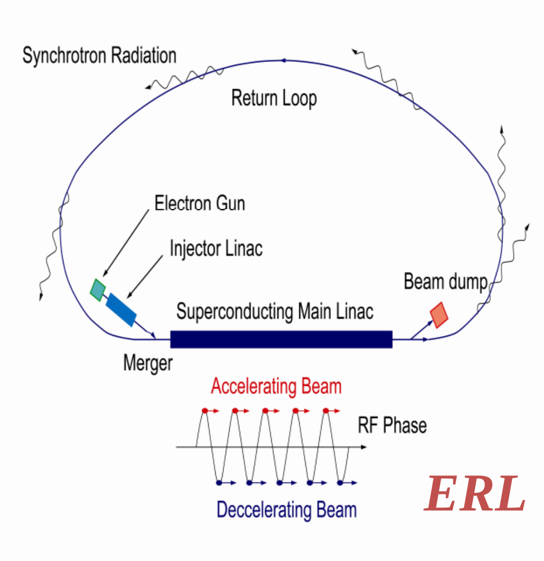
# Future PF Accelerators



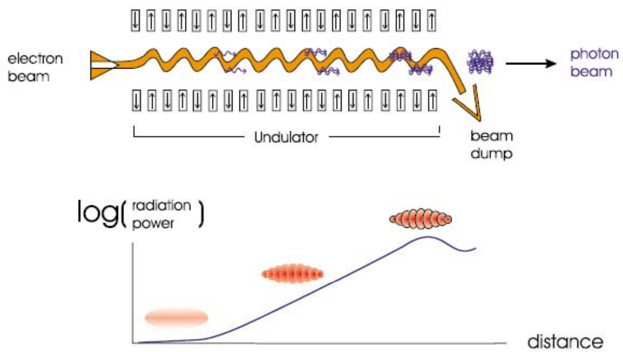

- Ultra – short light pulses : enable to visualize dynamics of molecules and transient phenomena of materials

- Ultra – small size beams : provide powerful tools to probe biological cells or materials with an atomic precision

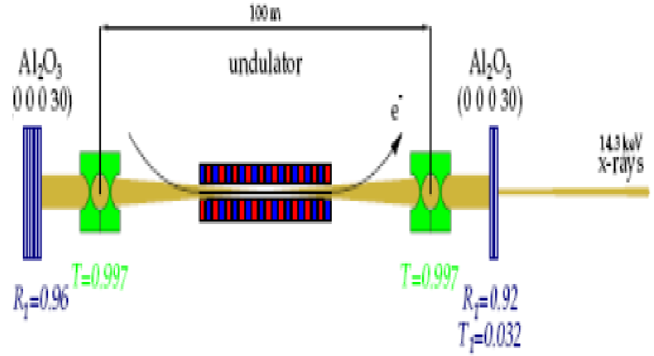
# Functions of ERL, SASE-FEL & XFEL-O




ERL



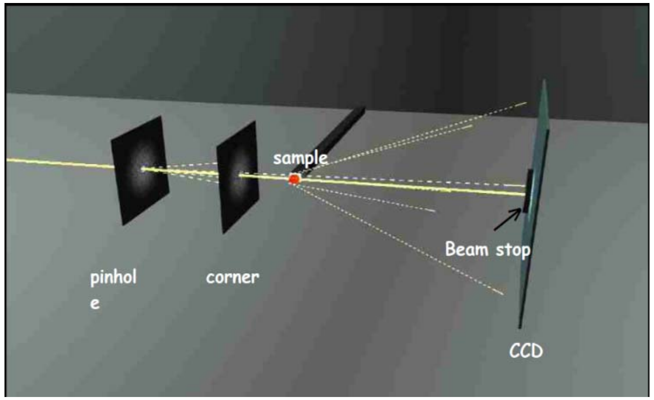

SASE-FEL




XFEL-O

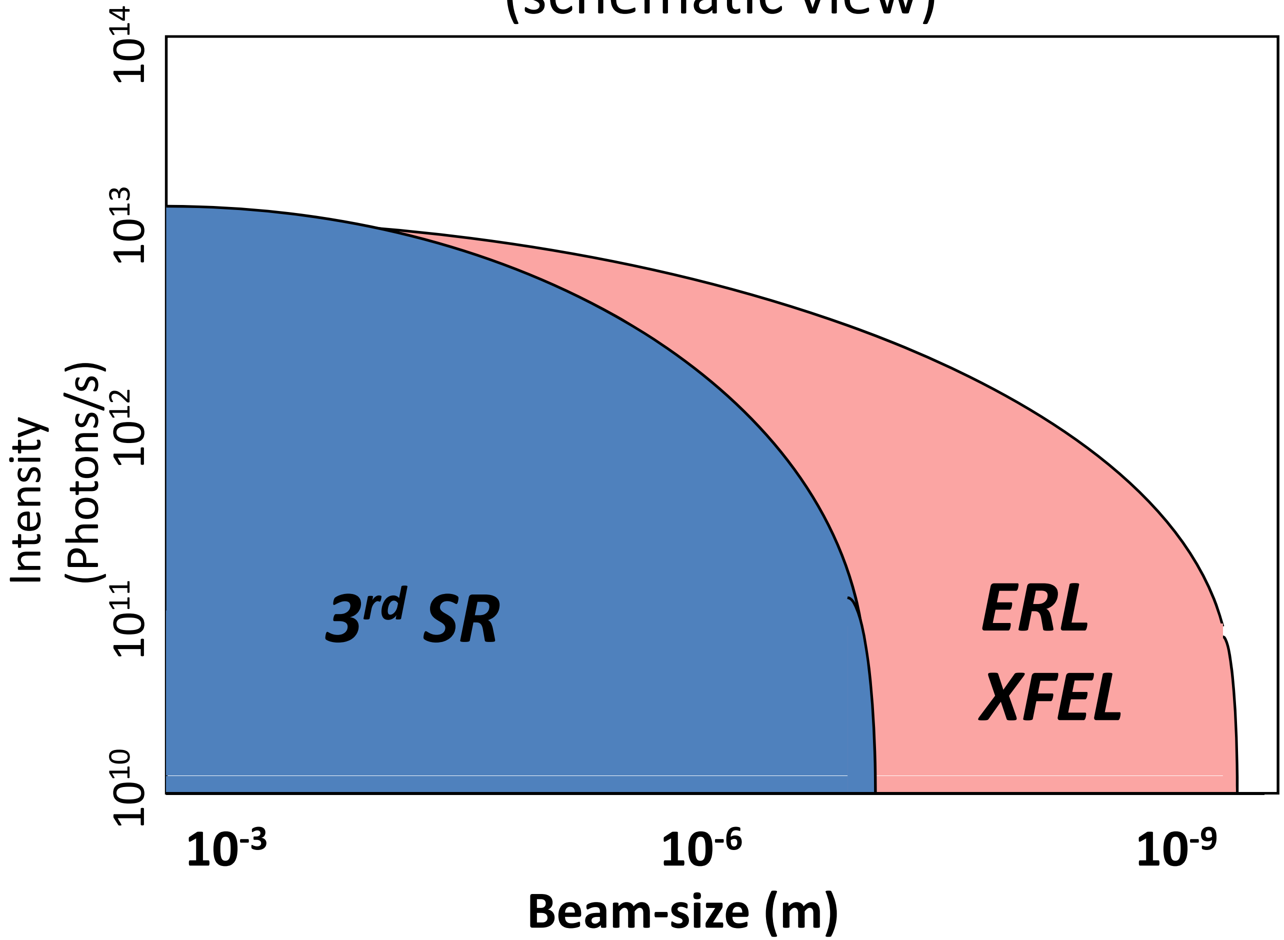
| | average brilliance | peak brilliance | repetition rate (Hz) | coherent fraction | bunch width(ps) | # of BLs | Remark |
|---|---|---|---|---|---|---|---|
| ERL | ~$10^{23}$ | ~$10^{26}$ | 1.3G | ~20% | 0.1~1 | ~30 | Non-perturbed measurement |
| SASE -FEL | ~$10^{22\sim23}$ | ~$10^{33}$ | 100~1K | 100% | 0.1 | ~1 | One-shot measurement |
| XFEL-O ( Option) | ~$10^{27}$ | ~$10^{33}$ | ~1M | 100% | 1 | few | Single mode FEL |

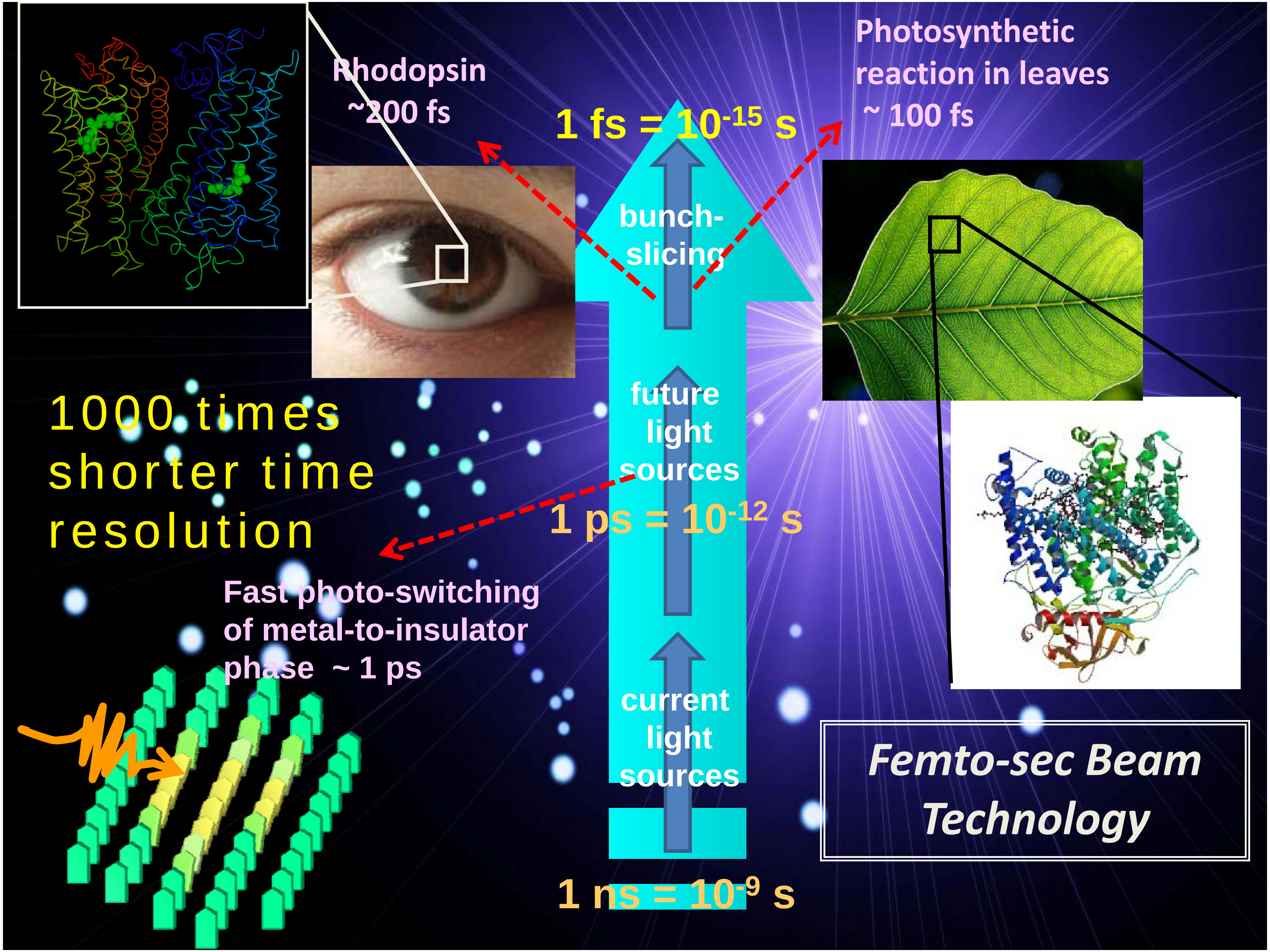
(brilliance : photons/mm$^2$/mrad$^2$/0.1%/s @ 10 keV)




# Intensity vs. Beam-size

(schematic view)

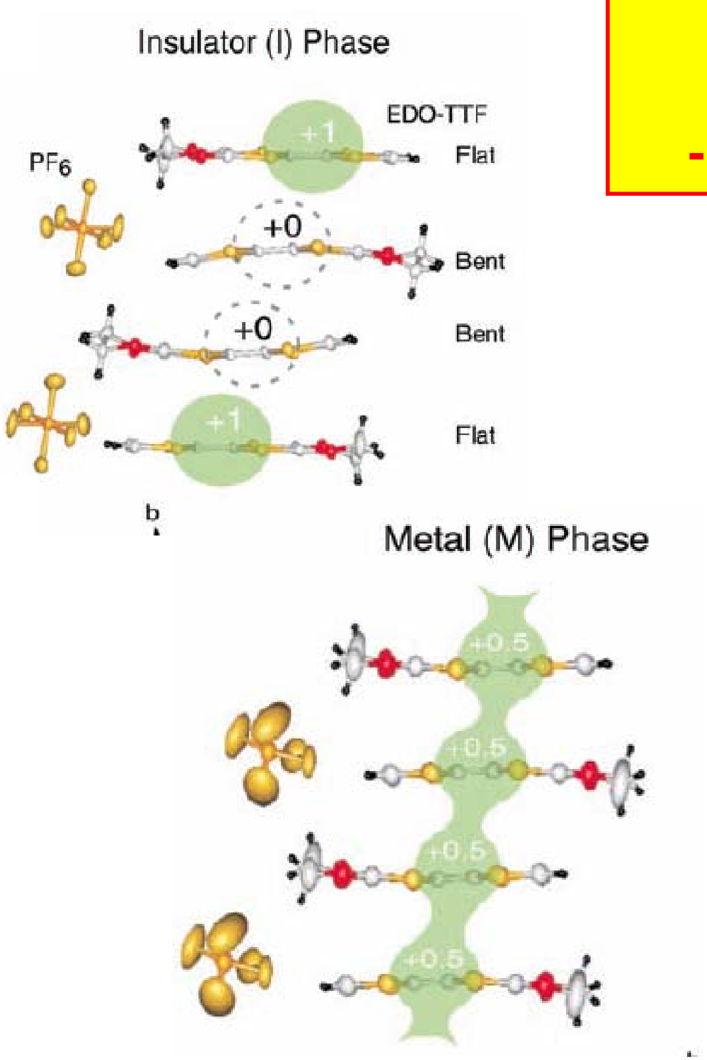




Rhodopsin
~200 fs
1 fs = 10-15 s
Photosynthetic
reaction in leaves
~ 100 fs
bunch-
slicing
future
light
sources
1000 times
shorter time
resolution
1 ps = 10-12 s
Fast photo-switching
of metal-to-insulator
phase ~ 1 ps
current
light
sources
Femto-sec Beam
Technology
1 ns = 10-9 s

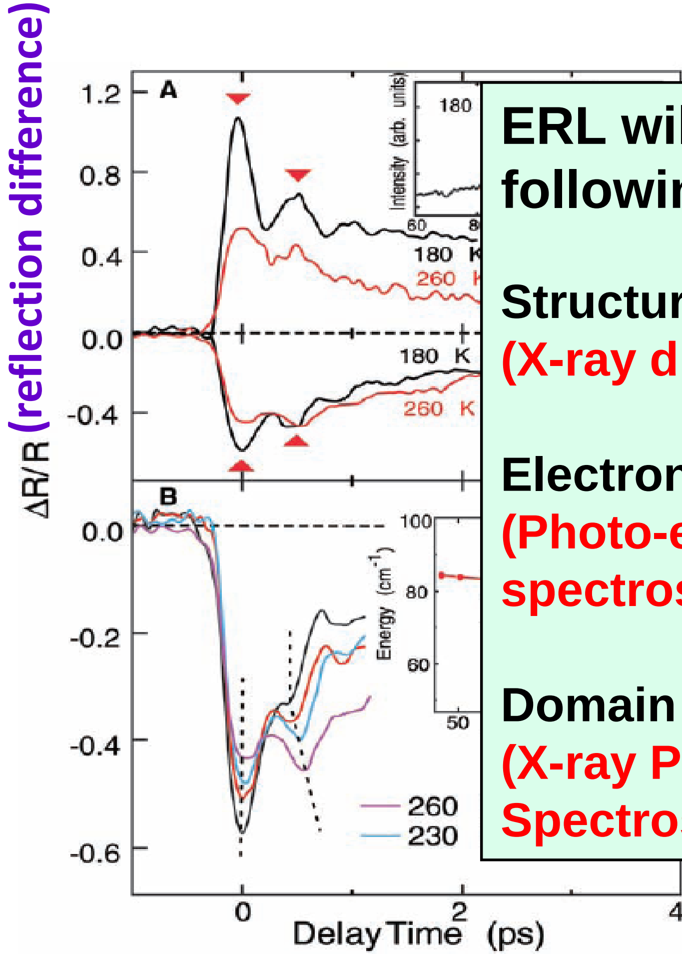
# Photo-induced phase transition

## (Strongly-Correlated Electron Systems)




Chollet et al. (2005) Science 307, 86

**Sub-pico-second photo-induced metal-insulator phase transition - Application for a THz-switching device -**




**ERL will provide us following information!!**

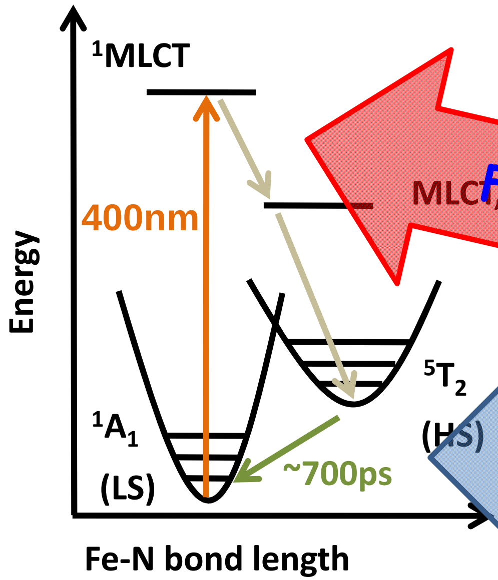
**Structure?**
**(X-ray diffraction)**

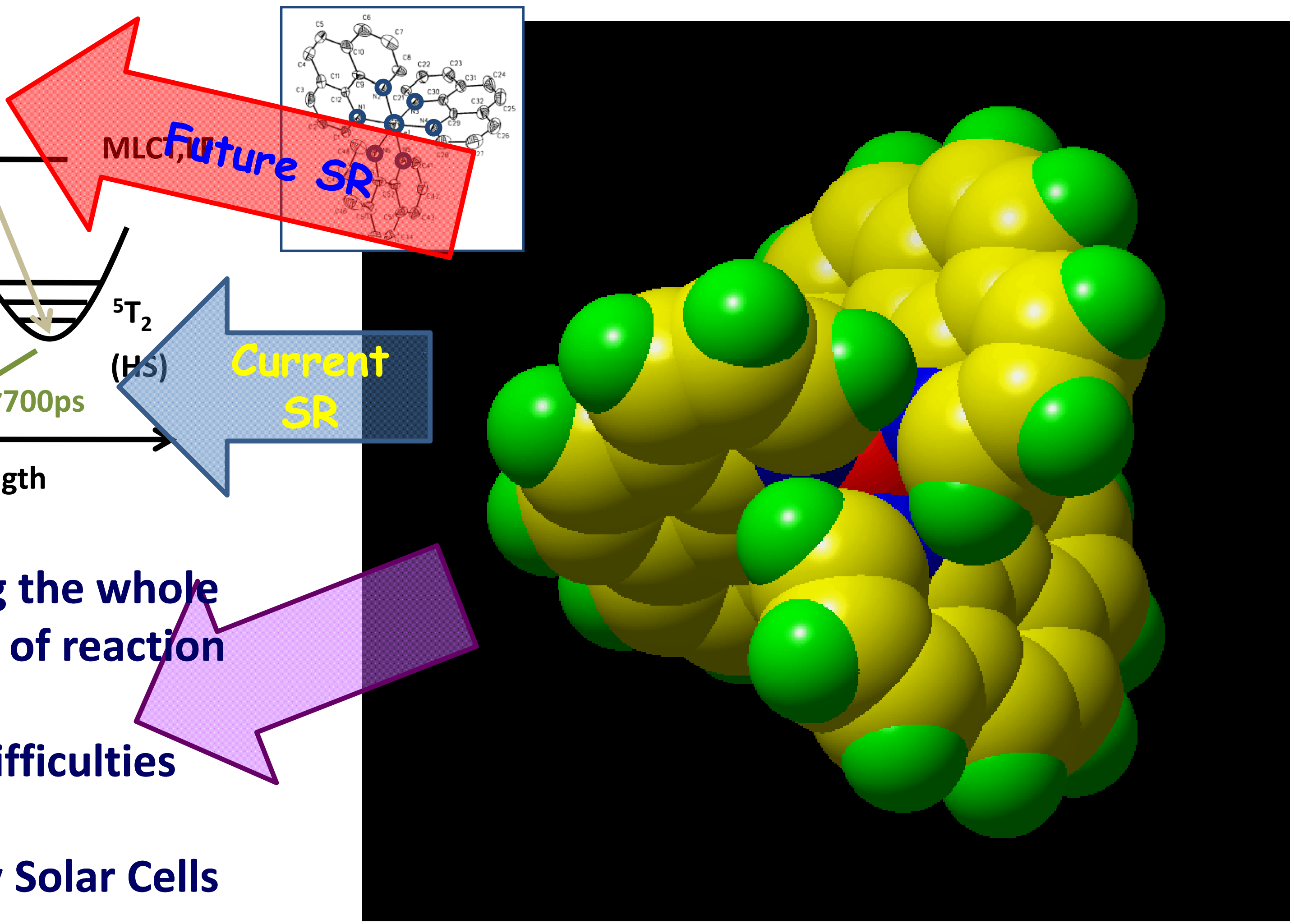
**Electronic state?**
**(Photo-emission spectroscopy)**

**Domain formation?**
**(X-ray Photon Correlation Spectroscopy)**

# Solar Cells and Photon-Catalysts

- How do molecules act after absorbing photons ? -




**Understanding the whole time sequence of reaction**

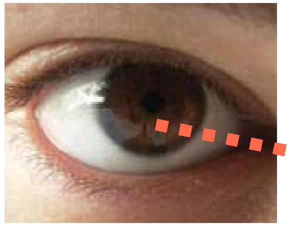
↓

**solves the difficulties**

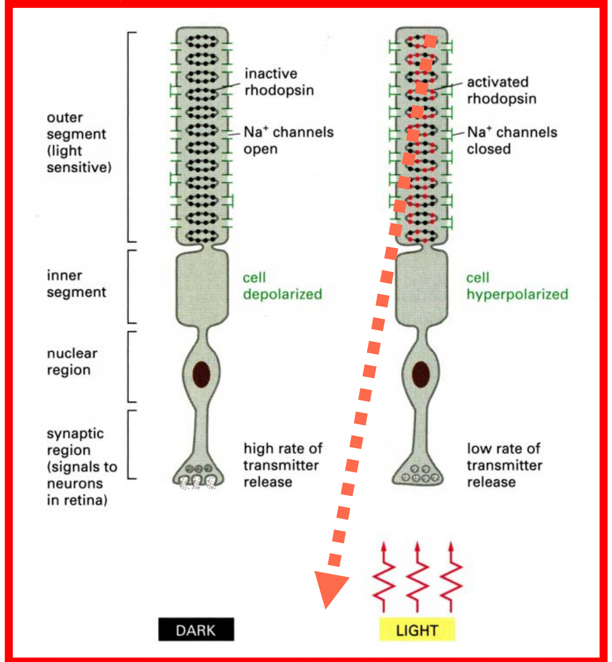
↓

**High Efficiency Solar Cells**

# Visual Sensing and Photosynthesis



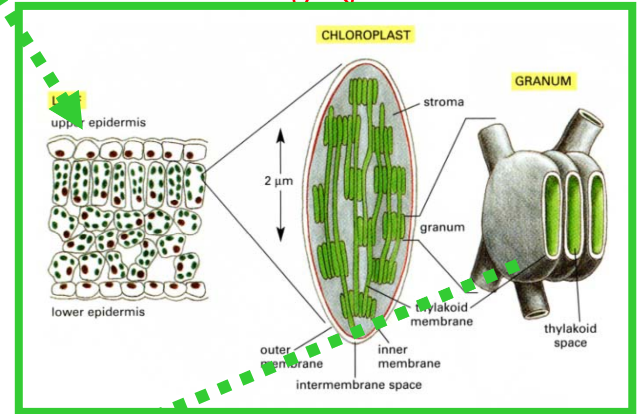
200 fs



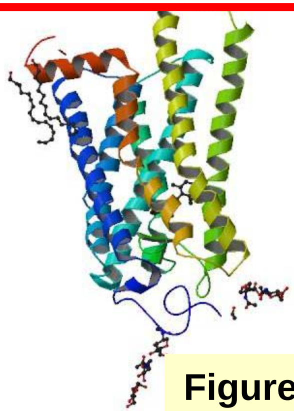

**Visual Sensing Cascade**

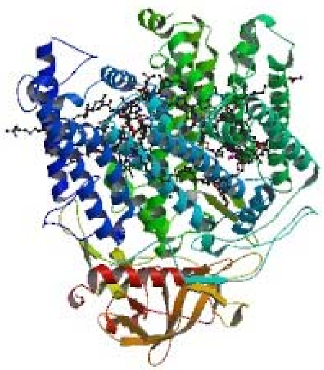
**Leaf, Chloroplast and Granum**

100 fs



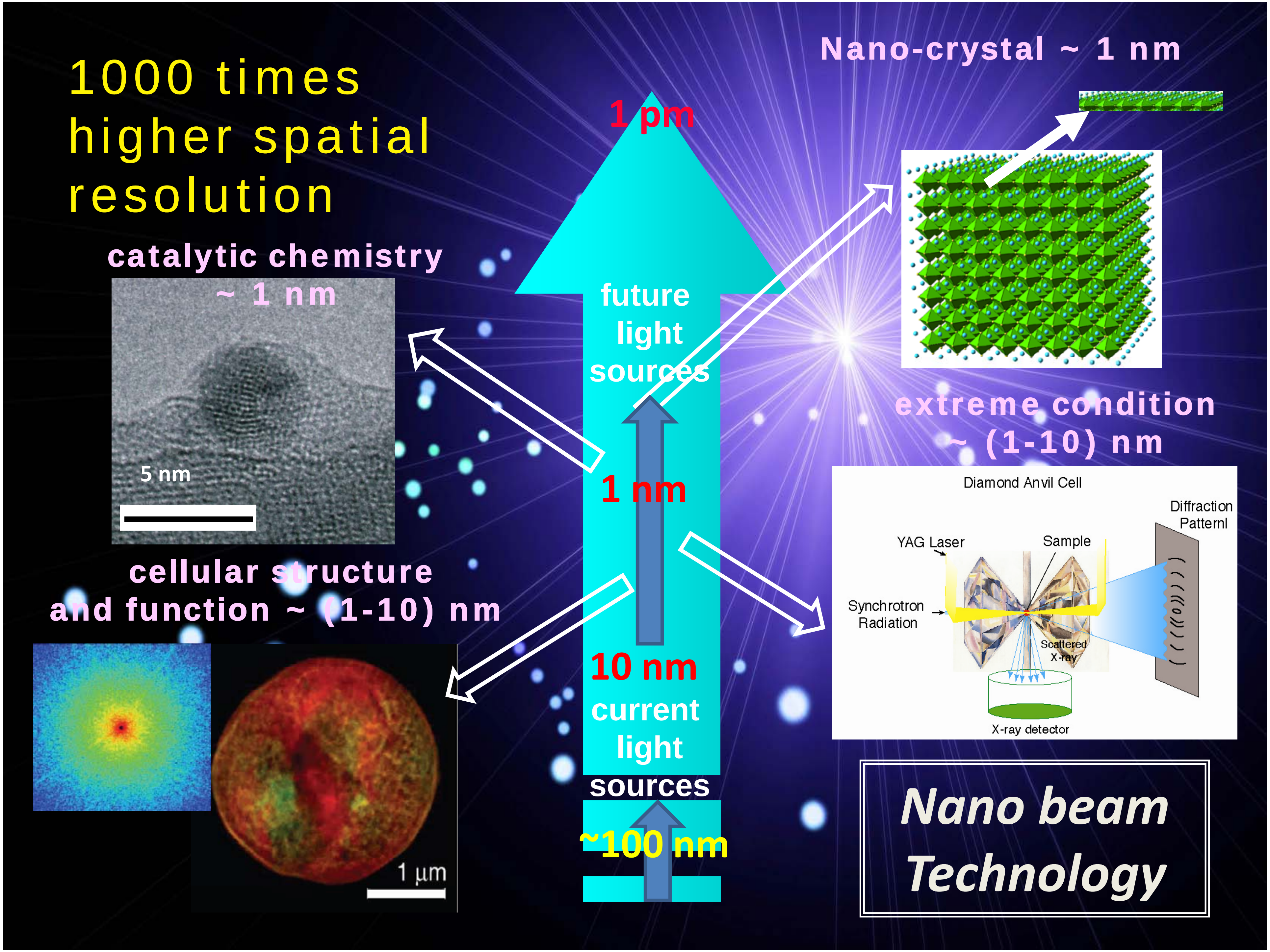

**Rhodopsin absorbs light in ~ 200 fs in eye, and transmits visual information to brain in ms order.**



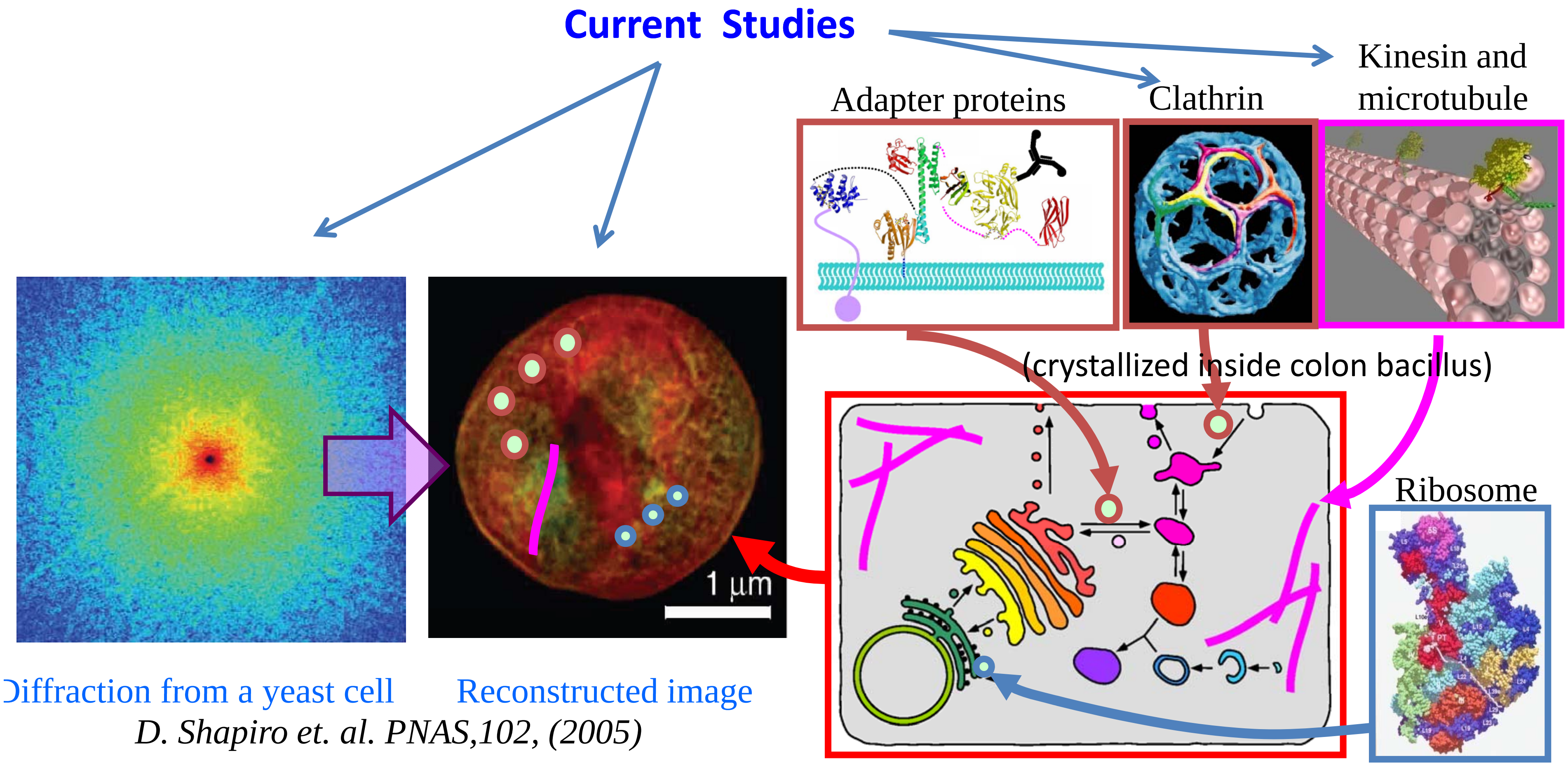


**Photochemical reaction center absorbs light in ~ 100 fs, and converts light to chemical energy.**

**Figures from THE CELL (4th edition)**


1000 times higher spatial resolution
Nano-crystal ~ 1 nm
1 pm
catalytic chemistry ~ 1 nm
5 nm
future light sources
extreme condition ~ (1-10) nm
1 nm
Diamond Anvil Cell
Diffraction Patternl
YAG Laser
Sample
Synchrotron Radiation
Scattered X-ray
X-ray detector
cellular structure and function ~ (1-10) nm
10 nm
current light sources
~100 nm
1 µm
Nano beam Technology

# Cellular and sub-cellular imaging & elementary mapping inside cells
# :
# New Insights on Real Cell Functions



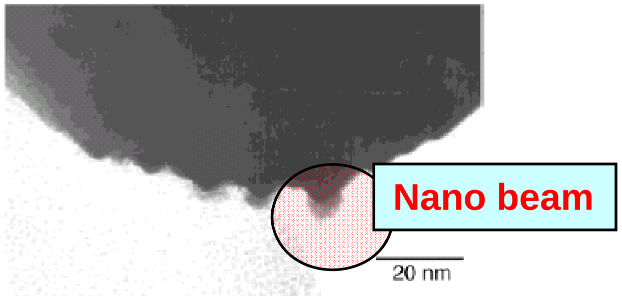

*D. Shapiro et. al. PNAS,102, (2005)*

# Catalysis Chemistry

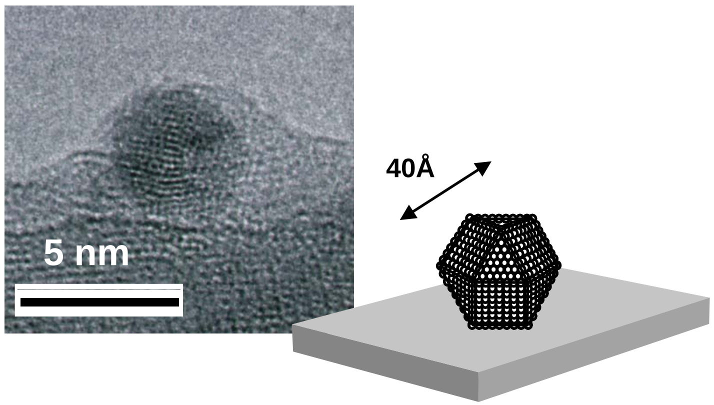
**in situ observation of active site (species) itself using nano beam**

**active site (species) of catalysts**

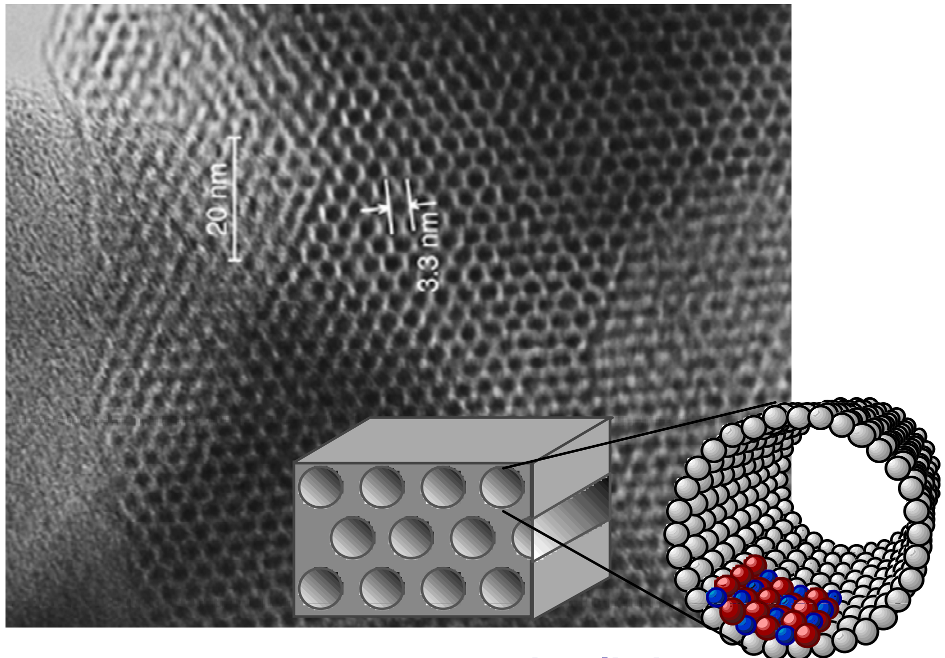
**Nano beams enable to evaluate local structure and electronic state of active site (species) for various catalysts**




**$NaTaO_3$:La + NiO catalyst**
**A. Kudo, *et al. J. Am. Chem. Soc.* (2003)**

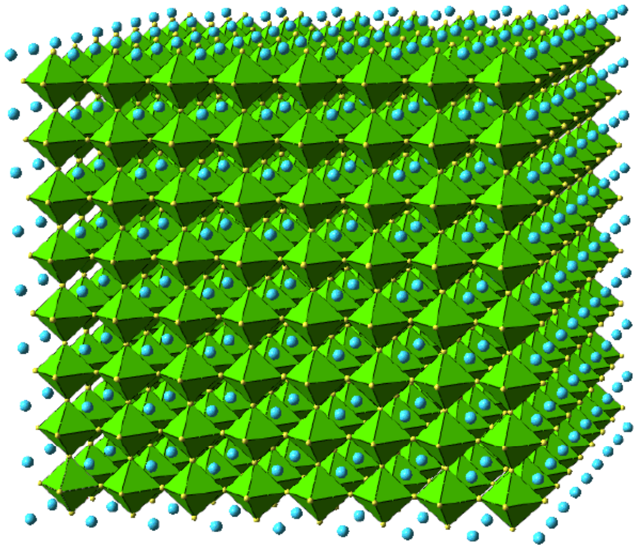



**Pd nanocluster**
**K. Kaneda, *et al. J. Am. Chem. Soc.* (2002)**
***J. Am. Chem. Soc.* (2004)**




**MCM-41 (zeolite)**
**N. *Ichikuni et al.* (2005)**

# Nano-Beam : Charge, Spin and Orbital States of Single Layer or Single Nano-Crystal

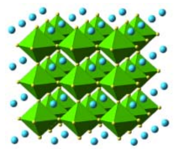


Current SR

Surface & Interface

Laser MBE

Nano-size



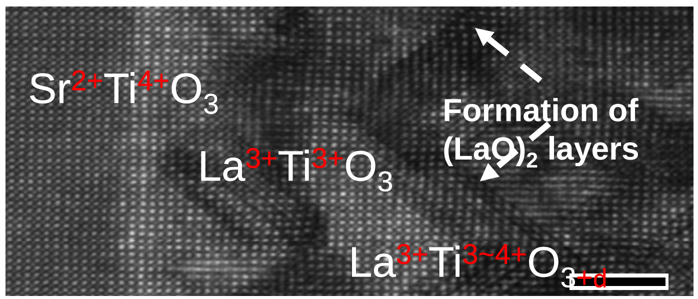
Nano Crystal of $(3nm)^3$

---> 60%: Surface

Expectations of Novel Electronic State!

ERL

XFEL

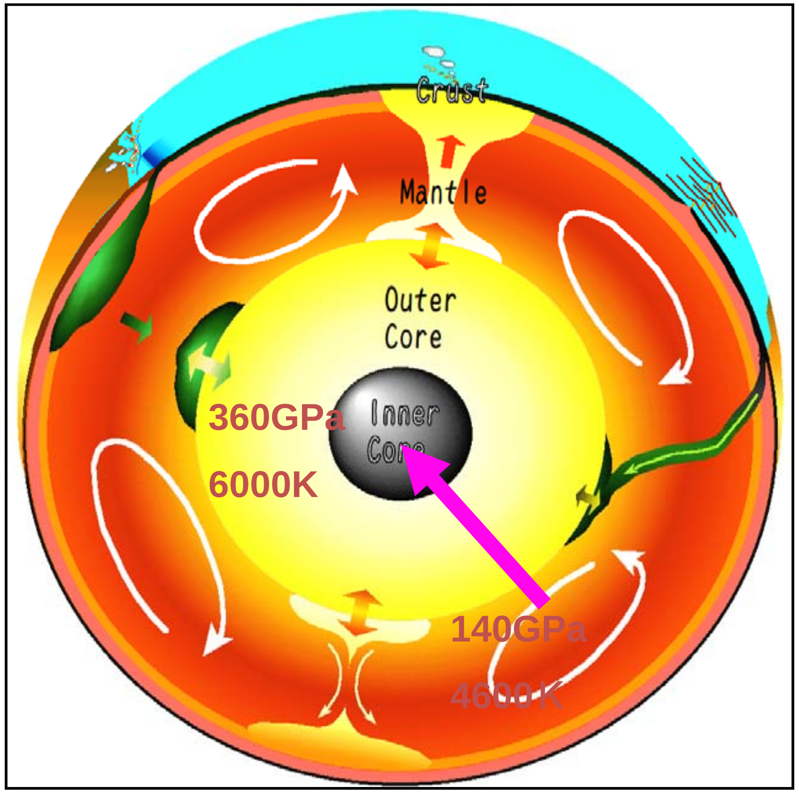


# Application to the Earth & Planetary Science

**High intense sub-micron focused beam gives information on the center of the earth.**

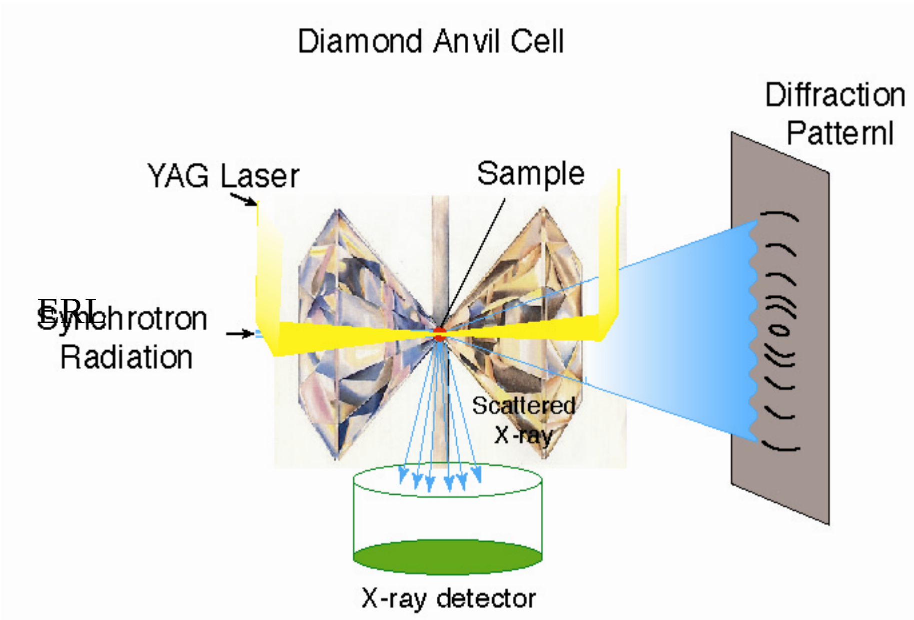
***Exploration of Earth's Core***

**Lower mantle: 140GPa and 4600K**
**Center of the earth: 360GPa and 6000 K**

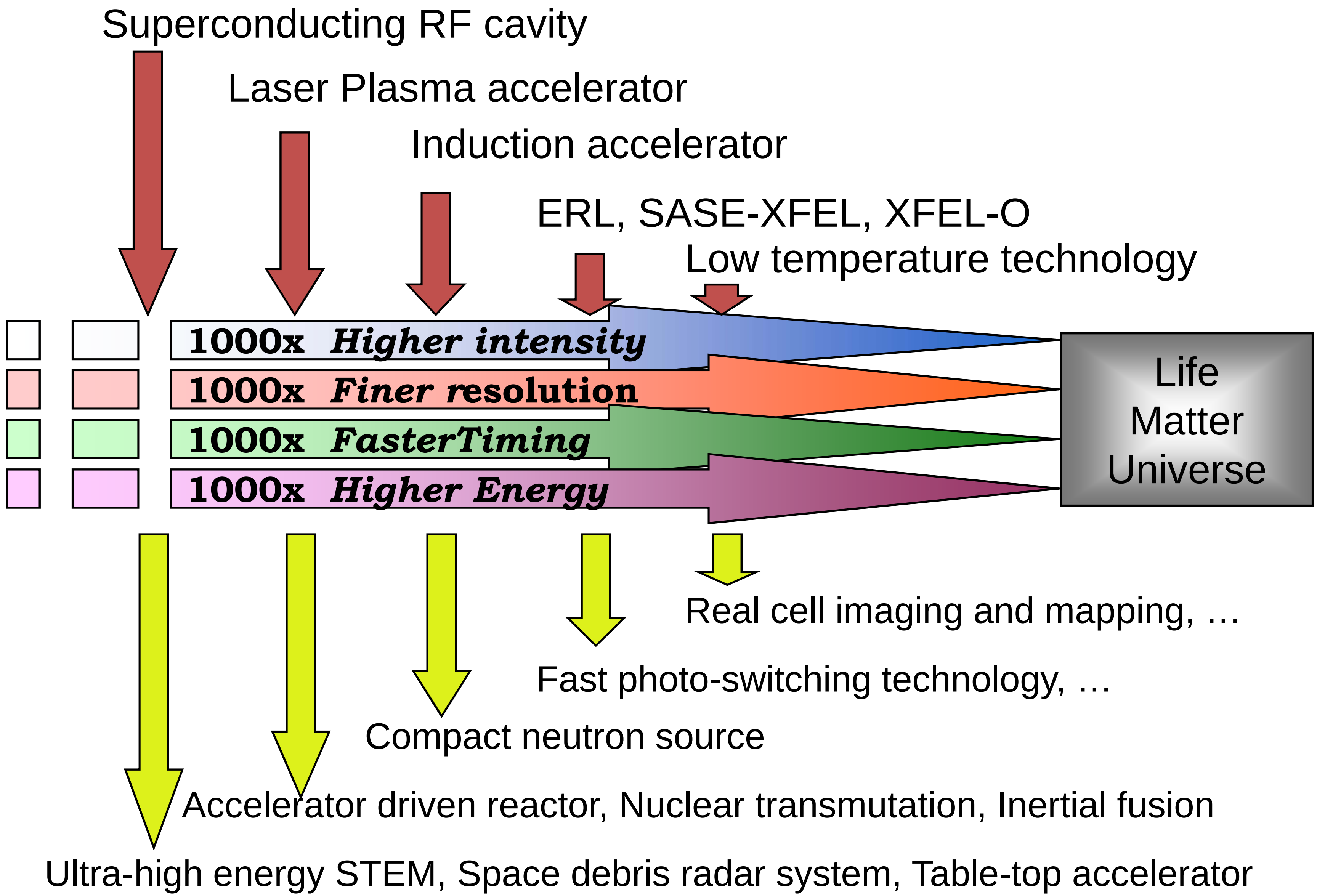



**High temperature and high pressure states like the Earth core in small size of materials at laboratory**

**Information on atomic, electric and magnetic structures**



# Conclusions



**As the size of accelerator science projects grows bigger and bigger and the time span of each project becomes longer and longer, we can never conduct such research programs, unless we have the strong support of taxpayers, and active contributions from researchers to society in general.**

**Now it is time for us to make a serious commitment to solving various societal issues such as energy and environmental problems through cooperation with industry and technology transfer to society, in addition to producing the highest level research outcomes.**