Synchrotron radiation source configurations for the fast x-ray ignition of inertial confinement fusion (ICF) targets: application to WDM heating

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Workshop on Accelerator-Driven Warm-Dense-Matter Physics
Pleasanton, California February 22-24 2006

OVERVIEW

- Application to ICF heating

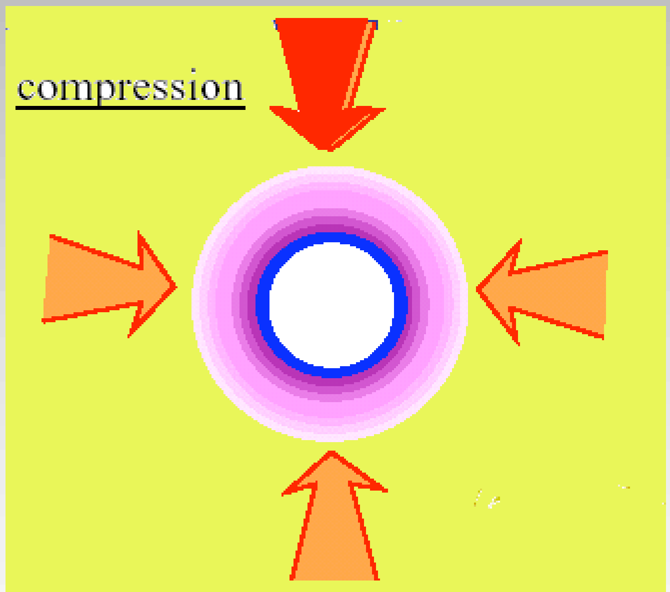
- Application to WDM heating

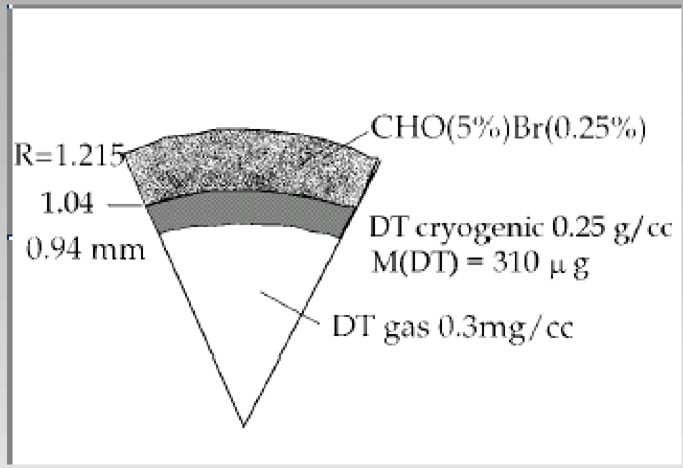
ABSTRACT (ICF)

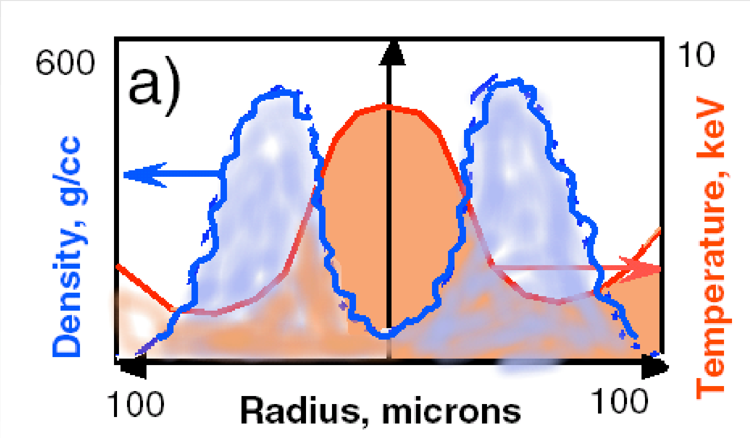
- In contradistinction to the major heating and ignition schemes being developed for Inertial Confinement Fusion (ICF) – in which the heating and ignition are to be driven by the compression of the target wall, the relatively recent concept of Fast Ignition proposes to realize the compression and heating (+ ignition) in two independent steps, permitting either or both to be optimized in ways that could, in principle, substantially reduce the total energy required to achieve net gain. In this paper we report on systematic investigations of the recently proposed concept of rapidly heating and igniting an already-compressed ICF target using x-rays. We discuss a number of the principal advantages of this approach in comparison to alternative Fast Ignition schemes and outline the basic requirements and features of a possible ICF X-ray Igniter configuration based on 4th generation source and optics technologies. Selected concepts for controlling both the target and igniter parameters to optimize net energy yield are described.

‘Conventional’ and Fast Ignition approaches to ICF

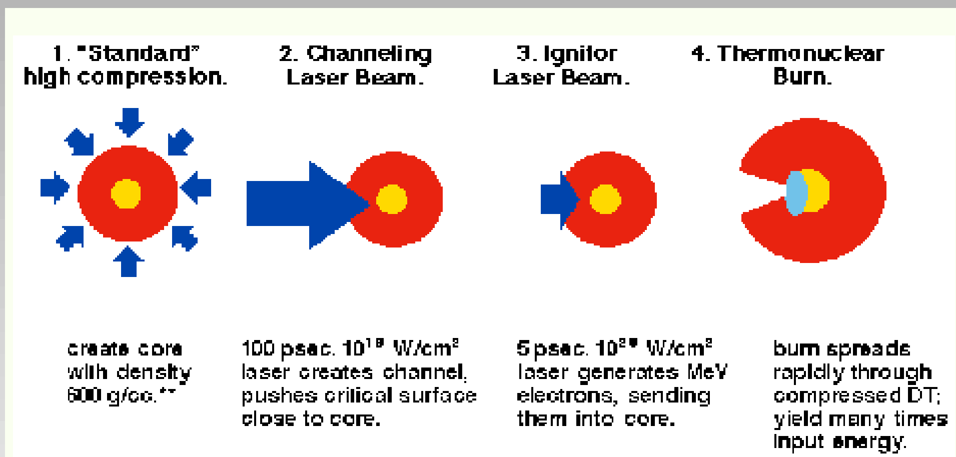
Direct drive



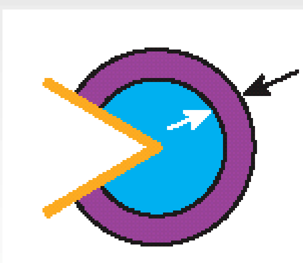


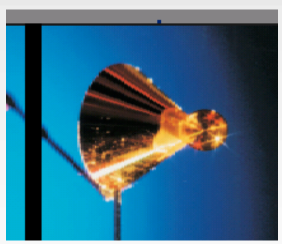


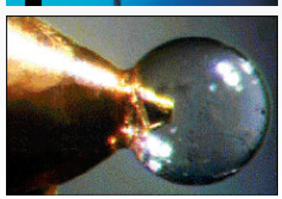
Fast Ignition main approaches : laser beams or proton / light ion / negative ion beams



Initial idea for fast fusion (Tabak et al 1994)







Cone geometry – is another modifications of the same idea

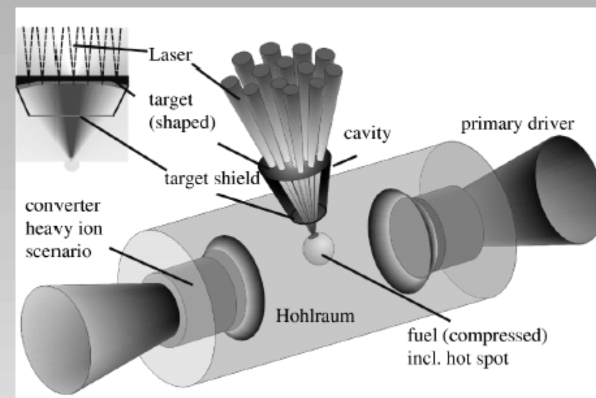
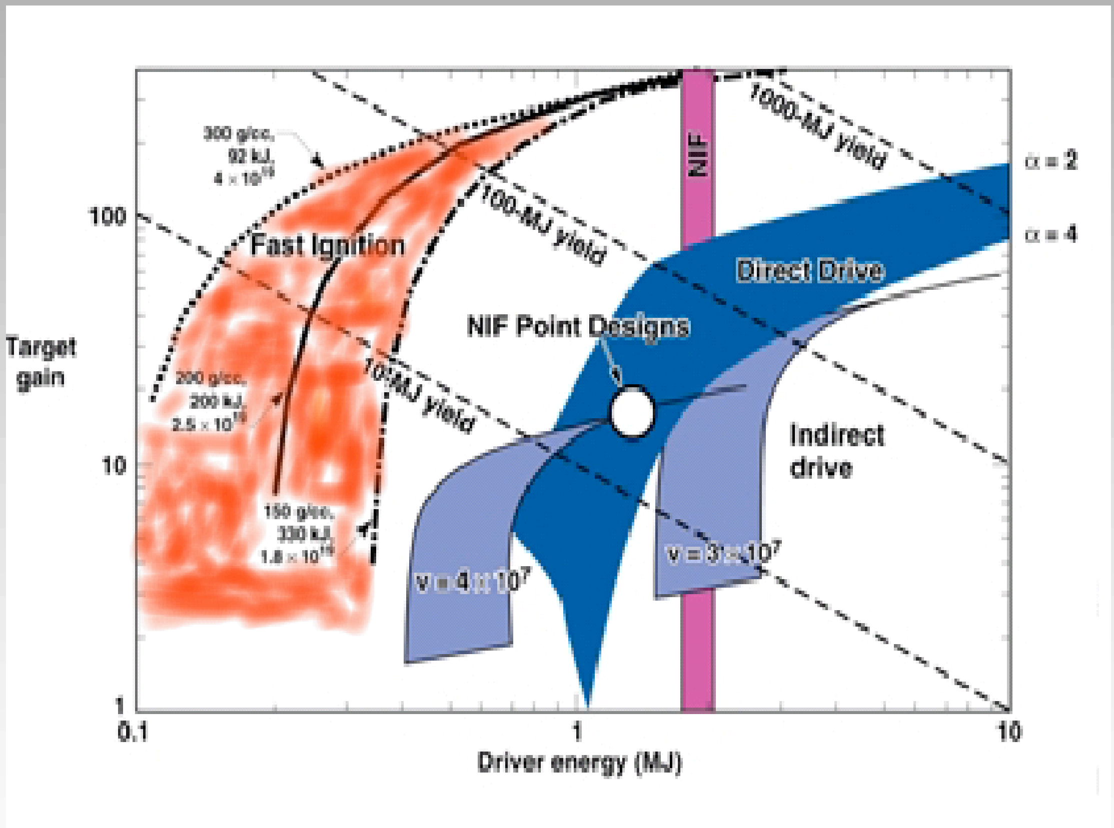


FIG. 1. Indirectly driven fast ignition using a laser accelerated proton beam (not to scale). The rear surface of the laser target is shaped to focus the ion beam into the spark volume.

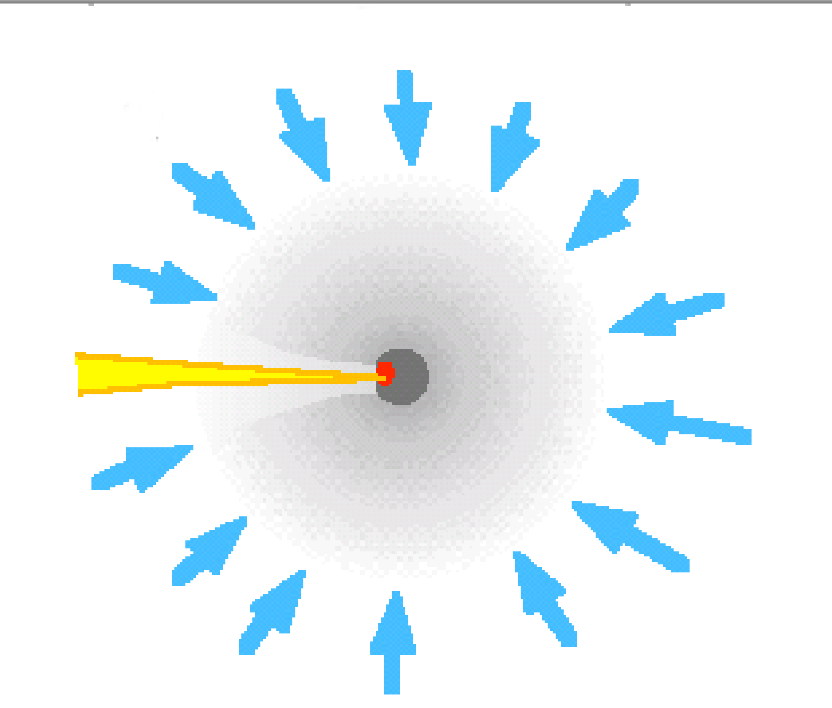
MeV proton beams from laser plasma (do not require hole boring or cone geometry)

Separating compression and ignition phases with Fast Ignition approach promises substantionally lower laser driver requirements and higher gains



R.B.Stephens et al 1999, "The Case for Fast Ignition as an IFE Concept Exploration Program"

Fast ignition with X-ray source



X-rays pass through plasma corona, lower density debris and hohlraum walls and deliver energy exactly at the dense compressed core.

- 100% absorption right at the dense spot, highest efficiency,
- no hole boring or cone geometry needed.

Absorption of x-ray radiation

$$\alpha \approx 2.44 \times 10^{-37} \frac{\langle Z^2 \rangle n_e n_i}{\sqrt{kT}\,(h\nu)^3}\left[1 - \exp\left(\frac{-h\nu}{kT}\right)\right] \mathrm{cm}^{-1}$$

- absorption of 2 – 4 A radiation in dense hot DT core is well described by classical inverse-bremsstrahlung mechanism.
- the e-fold absorption length of x-ray radiation can easily match the size of its focal spot. At 5 keV, 600 g/cc absorption length of of 2 – 4 A rays is of the order of 10-20 microns. This ensures complete utilization of x-ray source energy
- The electron quiver velocity, for 1-4A x-ray radiation will not exceed several eV even at the fluxes of the order of 10^{20} W/cm^2 ensuring classical absorption, no hot electrons
- all peripheral regions of DT capsule remain transparent for 2-4 A radiation
- **ρ^2 absorption dependence allows "density modulation" schemes for selective energy deposition into precisely located sub-volumes**

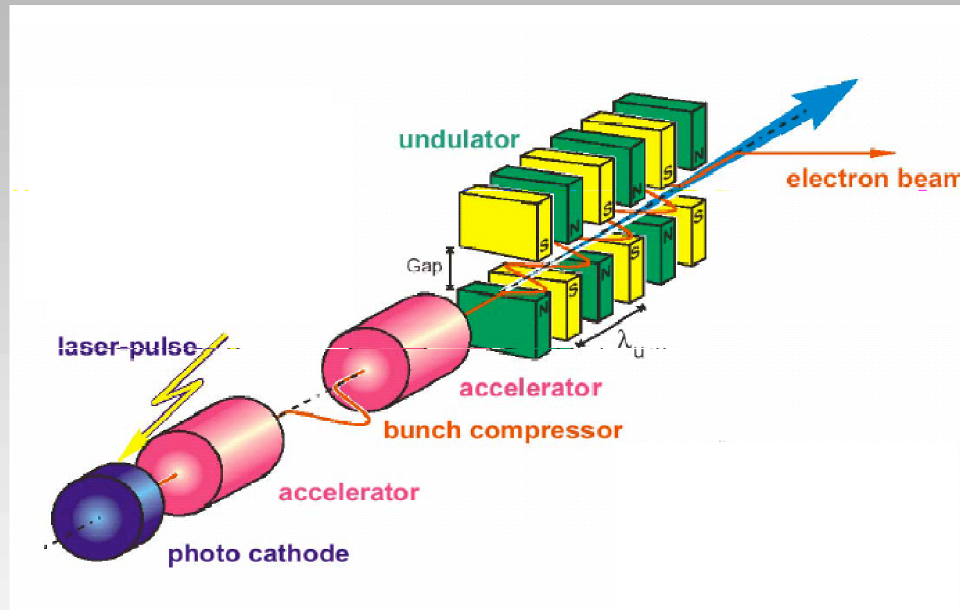
The X-ray source requirements

- The construction of 100-1000J x-ray source whose radiation can be focused into 10 micron spot represents currently extremely challenging problem. Few major candidates for that are powerful accelerator sources, plasma sources and plasma x-ray lasers.
- The broad spectrum from plasmas (K-alpha radiation or thermal radiation from high-Z plasmas) can potentially provide needed energy but in large angle so it is challenging-to-impossible to focus it at all.
- Plasma x-ray lasers are still way off in energy and required wavelengths.

- The X-ray Fast ignition approach does not require **heating x-ray source to be monochromatic or coherent**.
- The broad spectra sources like ones obtained in synchrotrons and wigglers/undulators are well suitable for this concept of fast ignition if they can be scaled to provide required energy.

The LINAC ICF X-Ray source

- **Requirement**: deliver ~ 100 Joule, ~10 ps pulse of 3-10 keV photons into 10-20 micron diameter volume
- **Method:** focus synchronized Energy Recovery Linac (ERL) driven wiggler pulses into target volume
- ERLs using laser-driven photocathode (pc) rf guns can easily produce ~10 ps electron bunches synchronized to ~1 ps.



The electron trajectory and spectrum of Linac X-Ray source

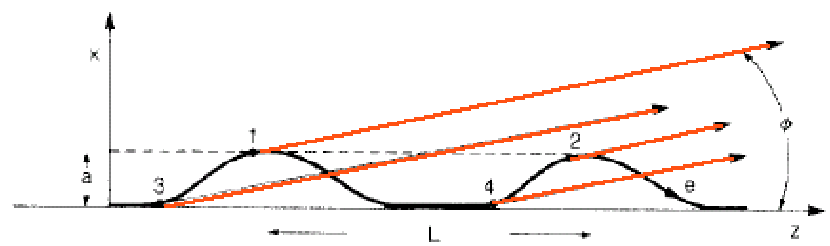


Fig. 1. A schematic representation of the electron trajectory in the interference wiggler. Radiation in the direction ϕ is generated from small segments of the trajectory around the tangent points, marked as 1, 2, 3 and 4.

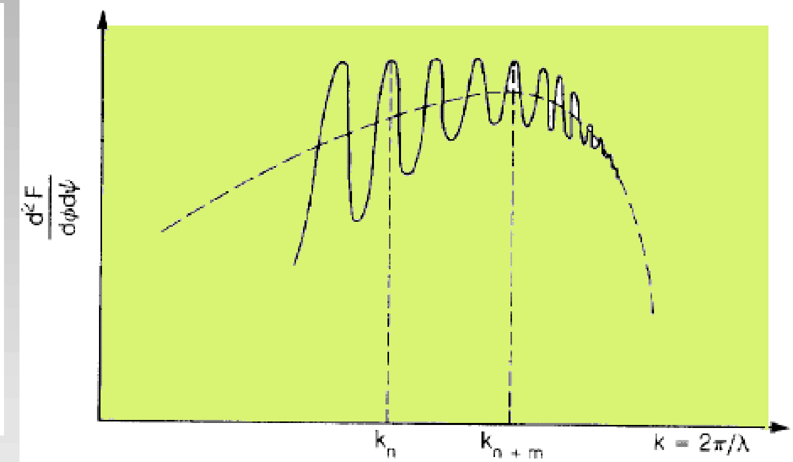
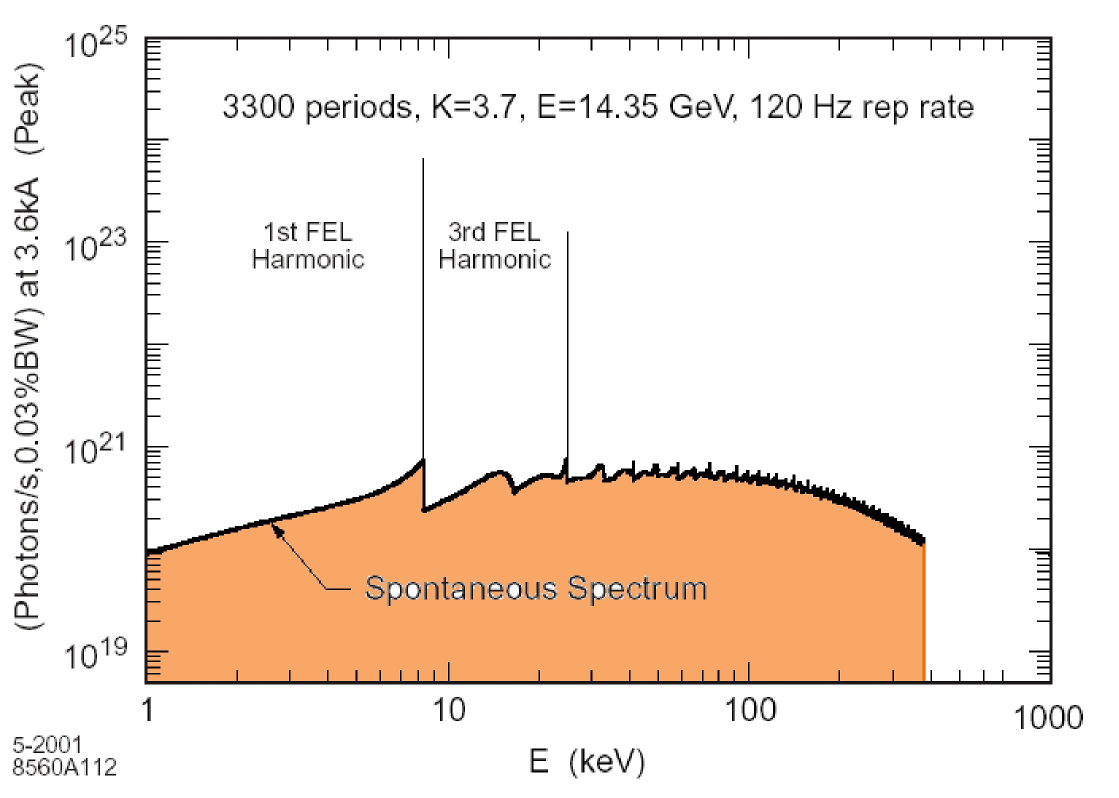


Fig. 2. A schematic representation of the spectrum from the interference wiggler. The solid line shows the modulated spectrum while the dotted line represents the smooth background due to radiation from individual wigglers. For the examples considered in the paper, hundreds of peaks would appear in the operating spectrum range.

- Divergence of spontaneous radiation of relativistic electron K / $\gamma \sim 5 / 2600 \sim 2$ mrad

The typical spectrum of LCLS X-Ray source



LCLS peak flux spectrum with FEL radiation saturated at first harmonic 1.5 A

- **The main idea of x-ray source is to utilize spontaneous radiation of wiggler which is typically order(s) of magnitude larger than coherent radiation in first saturated harmonics. Net extraction efficiencies of ~1%-2% feasible.**

- **(N.B., continuing development of tapered-period FELs may improve net extraction efficiency by ~ 10x)**

The X-ray source

Defining η the ratio of energy radiated by a wiggler bunch to its kinetic energy

Kinetic energy of the electron bunch is

$$\varepsilon_B = EI_p\sigma_\tau = EQ_B$$

Radiated energy of the electrons is defined by Larmour formula for radiation of relativistic electron

$$\varepsilon_{RB} = 6.33\times 10^{-16}E^2B^2L_wI_p\sigma_\tau = 6.33\times 10^{-16}E^2B^2L_wQ_B$$

$$\eta \cong 6.329\times 10^{-16}EB^2L_w$$

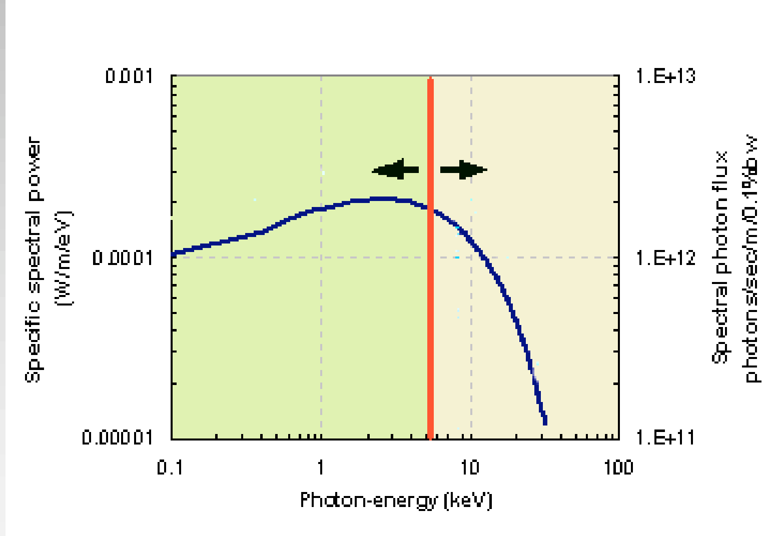
The X-ray source

Electron energy for transverse wiggler is defined by critical energy ε and magnetic field B

$$E[GeV] = 1.23\sqrt{\frac{\varepsilon_c[keV]}{B[T]}}$$

Hence η is

$$\eta = 7.81\times 10^{-7}\sqrt{\varepsilon_c B^3} L_w$$



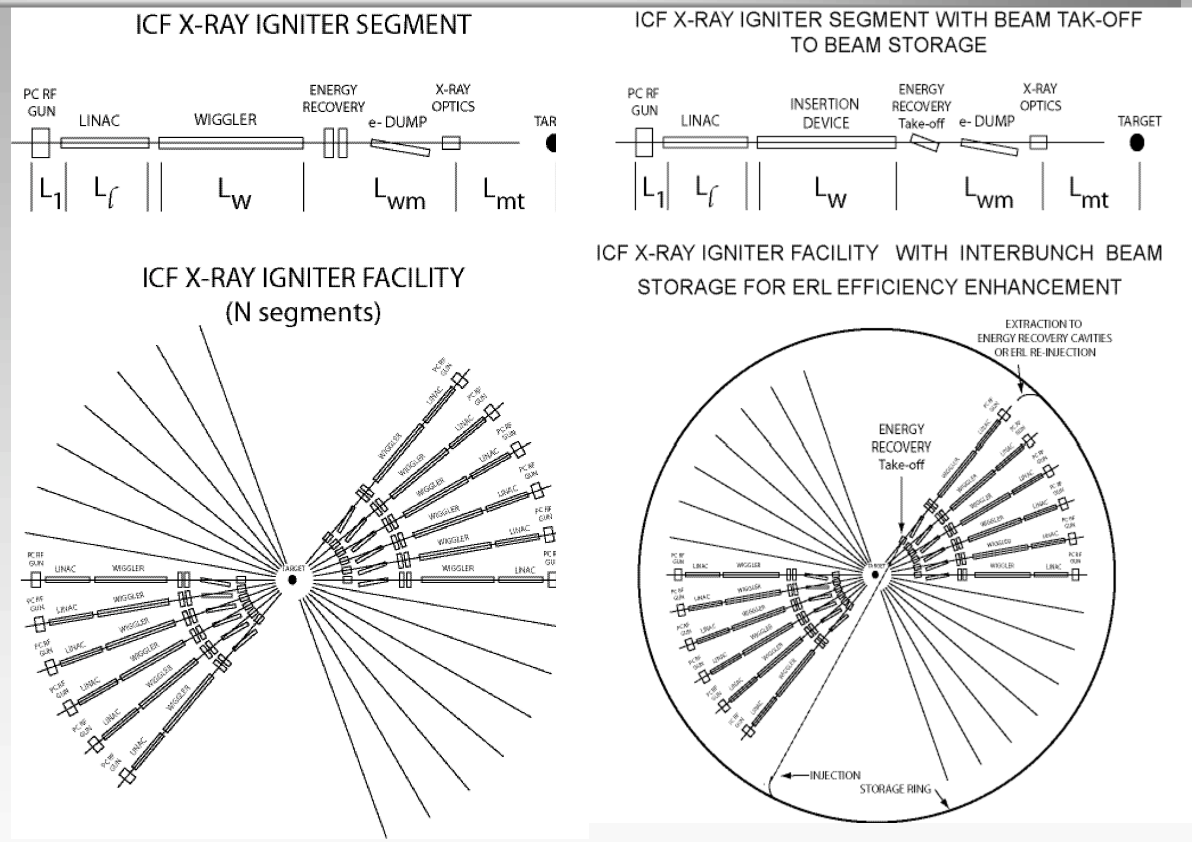
therefore the number N of ERLs required to produce E_{IG} Joules is, in terms of ERL and wiggler parameters:

$$N = \frac{E_{IG}[J]}{\eta E[GeV] Q_B[nC]} \cong \frac{E_{IG}[J]}{\varepsilon_c[keV]\, B[T]\, L_w[km]\, Q_B[\mu C]}$$

The X-ray source

- The required energy can be obtained by multiplexing ERLs
- Extraction-enhanced (tapered) FELs may offer prder-of-magnitude higher energy (>5 kJ)

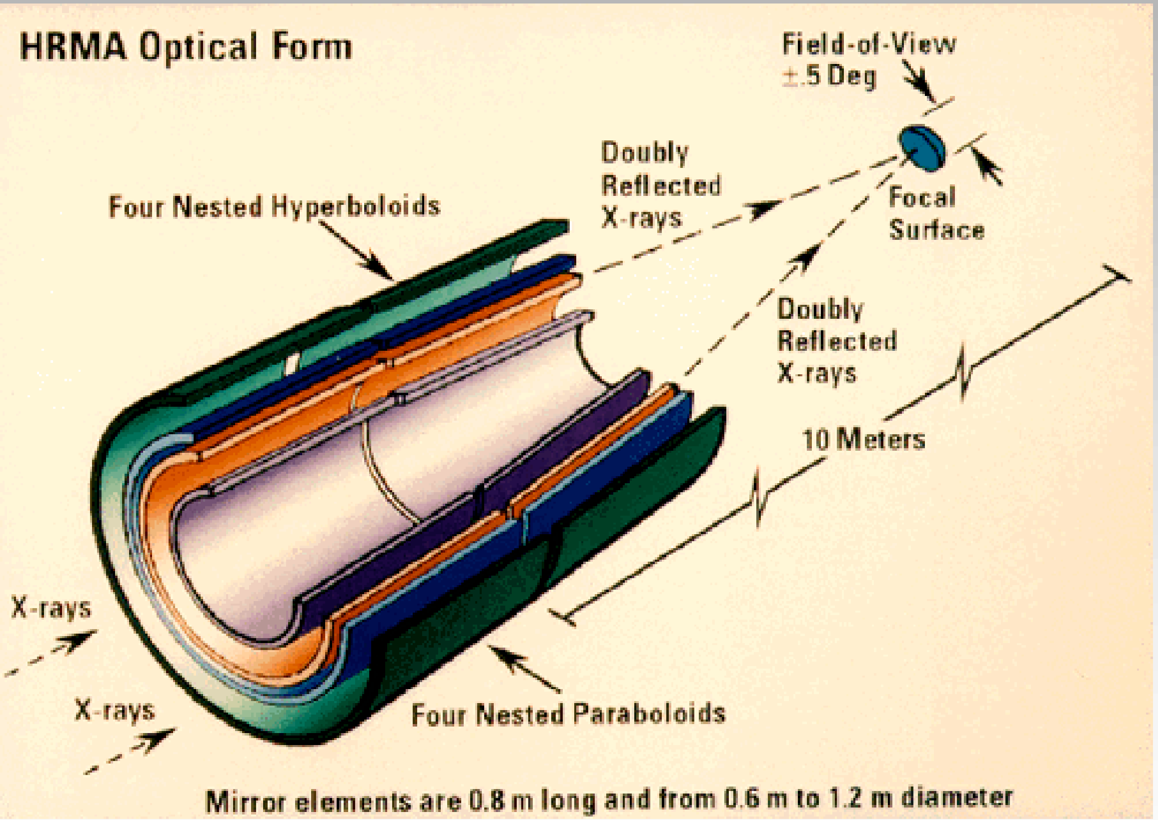
$$N \cong \frac{E_{IG}[J]}{\eta_{FEL} E[GeV] Q_B^2[nC]}$$



The X-ray optics

The x-ray optics suitable for focusing of powerful radiation if XFI is based on well developed technology of grazing incidence mirrors.

Dimensions of mirrors needed for it though are several times larger



The X-ray source

current nominal vs. projected parameters

	current	projected
Q_B [μC]	0.1 - 0.01	0.05
E [Gev]	1-10	1-10
B [T]	2-6(SC)	2-6(SC)
L_W [km]	0.1-0.33	0.5-1.0
E_{IG} [J]	100	?
ε_c [keV]	3-6	3-10
L_1 [m]	100-200	50 (SC) -200
X-ray Optics Aperture [m]	<1	2-10

- With optimal technology, rough rule of thumb appears to be ~1 ERL / Joule
- probable cost of ~$25M-$50M/ERL

The advantages of X-ray fast ignitor approach

- **Almost complete utilization of x-ray source energy for photons in 2-4 A range, 1-2 orders smaller source energy requirements** as opposed to regular approach to fast ignition which supposed to produce multi-MeV electrons which have small absorption crossection and pass through dense core almost without interaction.

- **Very directional deposition of heating energy exactly at the dense spot.** The keV x-ray photons are absorbed exactly at high compression core while all other material on the pass are almost completely transparent. Surrounding areas are transparent for x-rays due to N^2 density dependence of absorption coefficient. **No hot electrons, self-focusing and filamentation problems.**

- Both the electron and ion mean free paths in hot spot are much smaller than spot dimension, at 5keV they are of the order of 100 A, which means **high locality of x-ray energy deposition** (electron collision time of thermal electrons is very short, less than 10-15 fsec) which assures **high predictability and reliability of modeling of this concept. The interaction of x-ray radiation with plasma and hydrodynamics remain classical** hence simplifying many aspects of physical and numerical models.

- **Potentially high focusability of X-ray source radiation into small focal spot** of required dimensions ~10 microns.

- **All other advantages of fast ignitor concept are valid** (smaller and cheaper laser driver for initial compression, less symmetry constraints, instabilities and turbulences are much less influence).

Comparable-scale project: the TESLA X-RAY FEL

TESLA Technical
Design Report

PART V

THE X-RAY FREE
ELECTRON LASER
March 2001

Editors: G. Materlik,
Th. Tschentscher

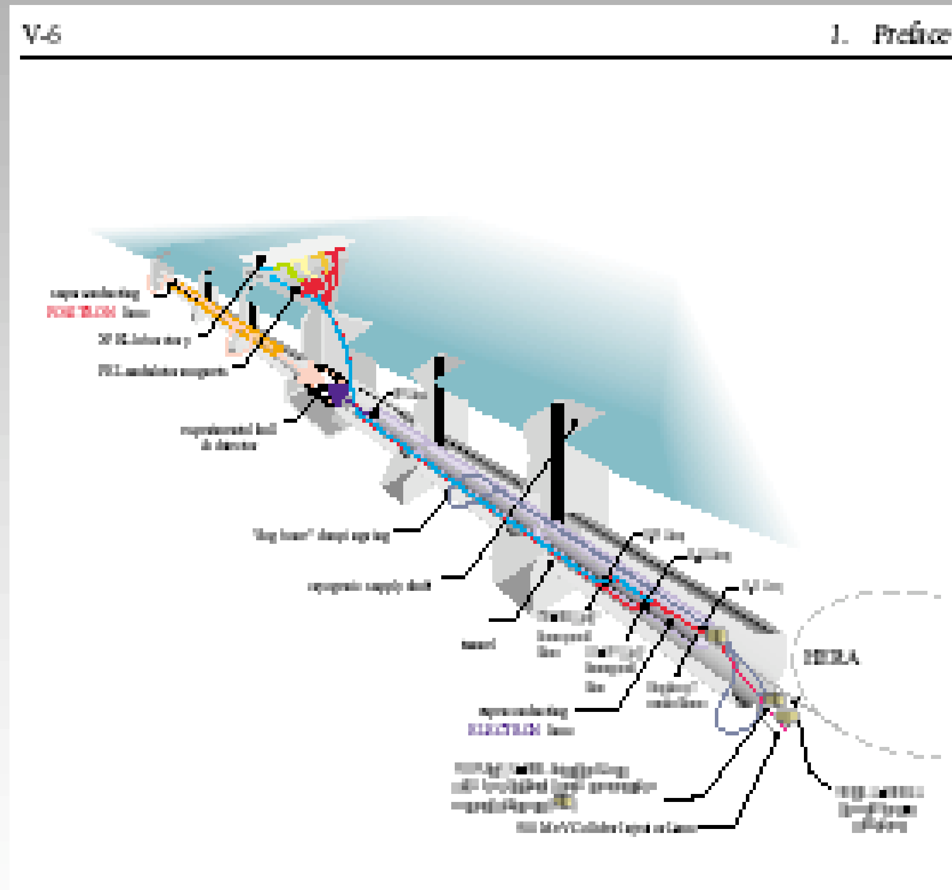


Figure 1.0.4.: Schematic presentation of the whole TESLA facility

WDM HEATING: We performed hydro and atomic calculations for two photon energies: 200 eV (DESY-FEL) and 8 keV (LCLS, TESLA FEL)

From Thomas Tschentscher, 29/03/2001

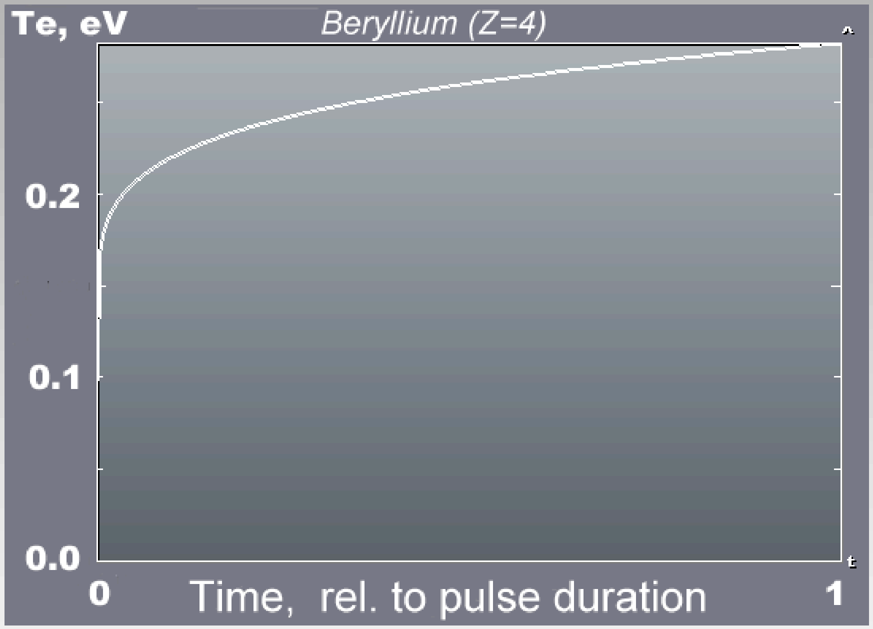
Parameters of plasma X-ray lasers in comparison with the DESY VUV-FEL and the proposed TESLA XFEL

Source Parameter	unit	Plasma XRL	VUV-FEL	VUV-FEL	VUV-FEL	X-ray FEL	X-ray FEL	X-ray FEL
Electron energy	GeV	-	0.3	~ 0.5	1	23	23	25
Photon energy	eV	100	20	60	200	500	1.24×10^{3}	1.24×10^{4}
Pht. wavelength	nm	12	60	20	6	2.5	1	0.1
Pulse duration	fs	(200)-3000	100	100	100	100	100	100
Bandwidth	%	~ 0.1	0.6	0.6	0.6	0.6	~ 0.5	0.1
Peak brilliance	**	10^{24}-(10^{28})	1×10^{28}	1×10^{29}	2×10^{30}	3×10^{32}	5×10^{32}	8.7×10^{33}
Peak power	GW	0.01	3	3	3	220	~150	37
Pht. source size	µm	< 100	150	150	150	75	~ 75	110
Beam divergence	µrad	(100)-3000	200	~ 60	20	13	< 10	0.8
Exp. to source	m	-	60	60	60	1000	1000	1000
Demagnification	-	100-(1000)	100	100	100	75	75	100
Focusing eff.	-	0.5	0.5	0.8	0.8	0.5	0.5	0.2
Focal spot size	µm	3-(0.03)	1.5	1.5	1.5	1	1	1
Power density	W/cm²	10^{13}-(10^{18})	6.7×10^{16}	1×10^{17}	1×10^{17}	1×10^{19}	7.5×10^{18}	7.4×10^{17}
Start operation	-	2002-2005	2004	2004	2005	2011	2011	2011

** units of peak brilliance are phts/(s mm² mrad² 0.1% bandwidth) scaled to a length of the pulse of 100 fs

*The present schedule for the TESLA Test Facility (TTF), resp. the VUV-FEL foresees FEL operation of TTF until spring 2002. Due to non-optimized components it is not clear what performance we can expect during this period. Thereafter the machine will be reconfigured. FEL operation shall resume in the beginning of 2004. Then experiments will be in the experimental hall, whereas until 2002 only a very small area inside the accelerator tunnel is available. Two setups, for ablation studies and cluster physics, can be installed here.

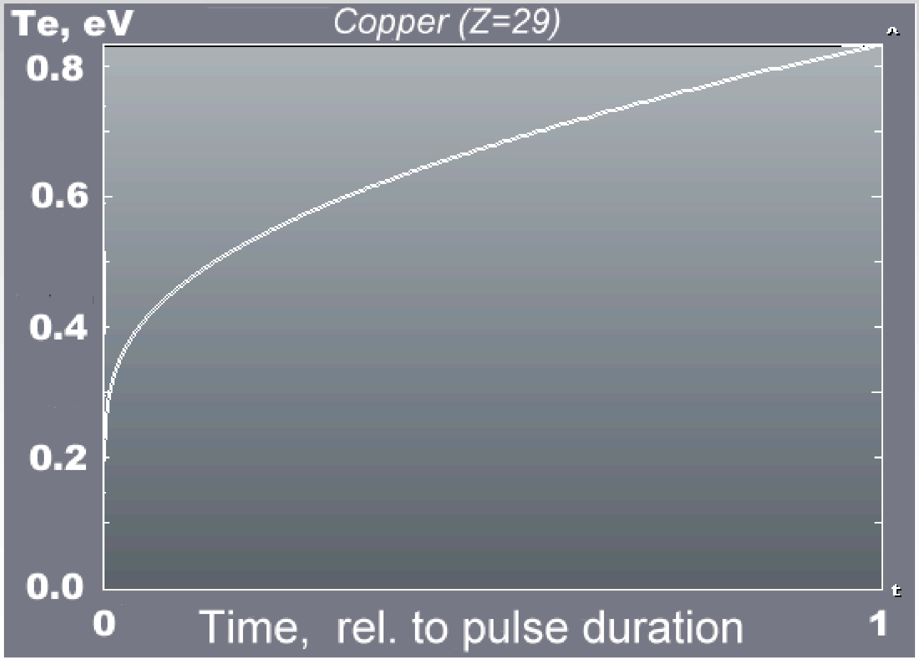
WDM HEATING: At 1 mJ pulse energy and almost unfocused 100 micron spot size the electron temperatures reach 0.2-0.3 eV for small-Z materials, 0.8 eV for middle-Z, and 1-2 eV for high-Z materials



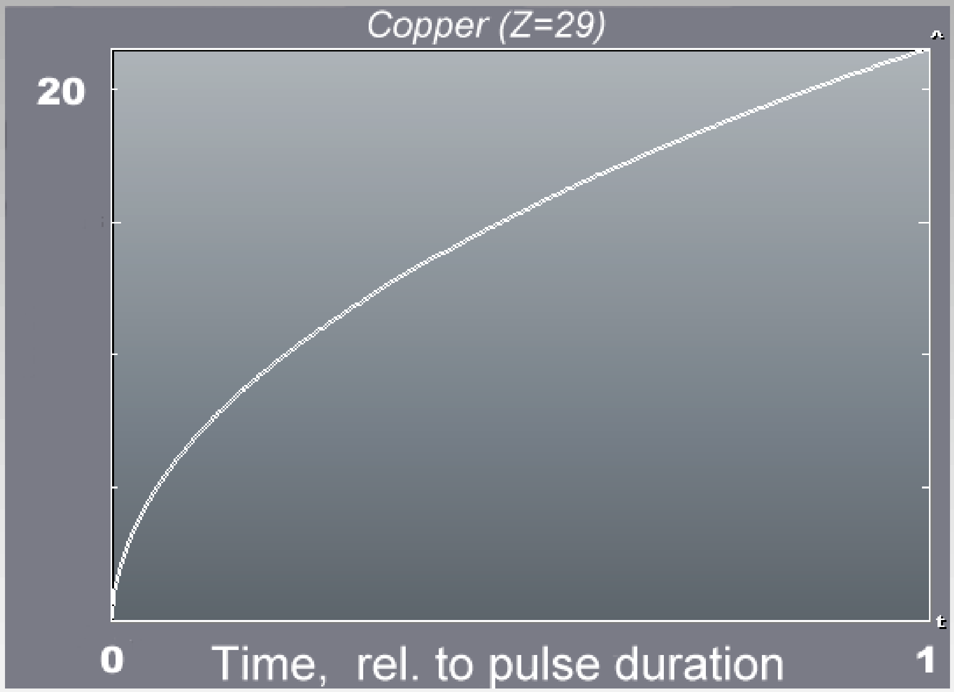
Case of 8 keV photon energy

Included are

- **Transient ionization**
- **Activation (atomization) of materials**
- **Electron-ion relaxation**
- **Photo- and bremsstrahlung absorption**



WDM HEATING: In the same case (1 mJ pulse energy, almost unfocused 100 micron spot size) but with 200 eV (60 A) photon energy temperatures are an order higher



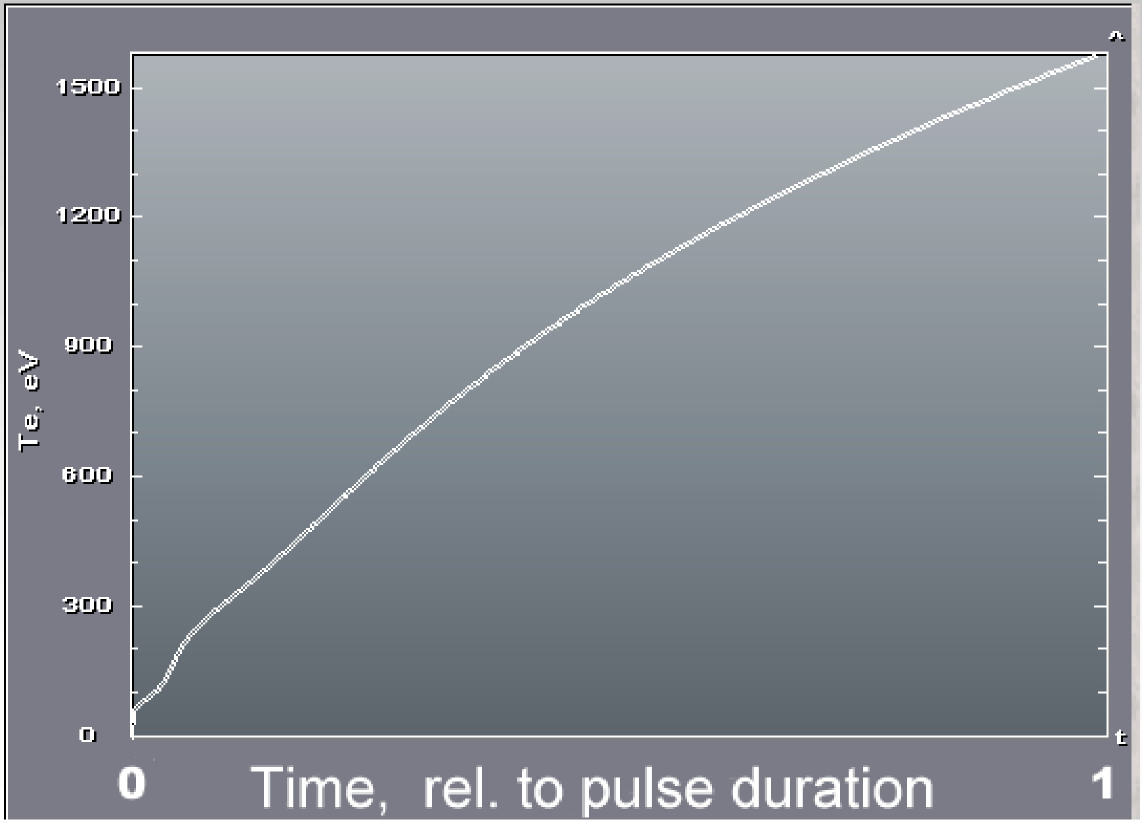
In the case of 200 eV photons the temperatures can reach 20-50 eV due to larger photoabsorption

In mid- and high-Z elements

- **Ionization is strongly non-equilibrium during the 200 fs pulse**
- **Ion temperature remains small, it has ps, not fs time scale**
- **Bremsstrahlung absorption is small compared to photoabsorption**

WDM HEATING: 1 mJ pulse energy focused to 1 micron spot size can bring 4 orders of magnitude higher irradiation fluxes, and up to 2 orders higher temperatures

Te to reach 100 eV (for 8 keV photons) and 1000 eV (for 200 eV photons)



- **Copper (Z=29)**