The Abdus Salam
International Centre for Theoretical Physics

United Nations
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IAEA
International Atomic Energy Agency

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Summer College on Plasma Physics

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The Power of Plasmas

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The Power of Plasmas

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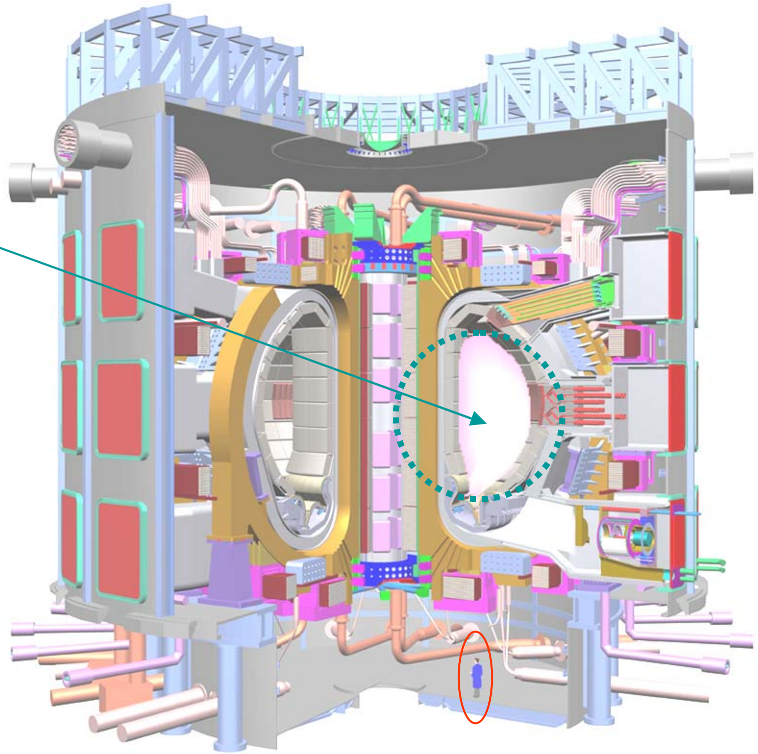
EURATOM Association
Greifswald, Germany

ITER

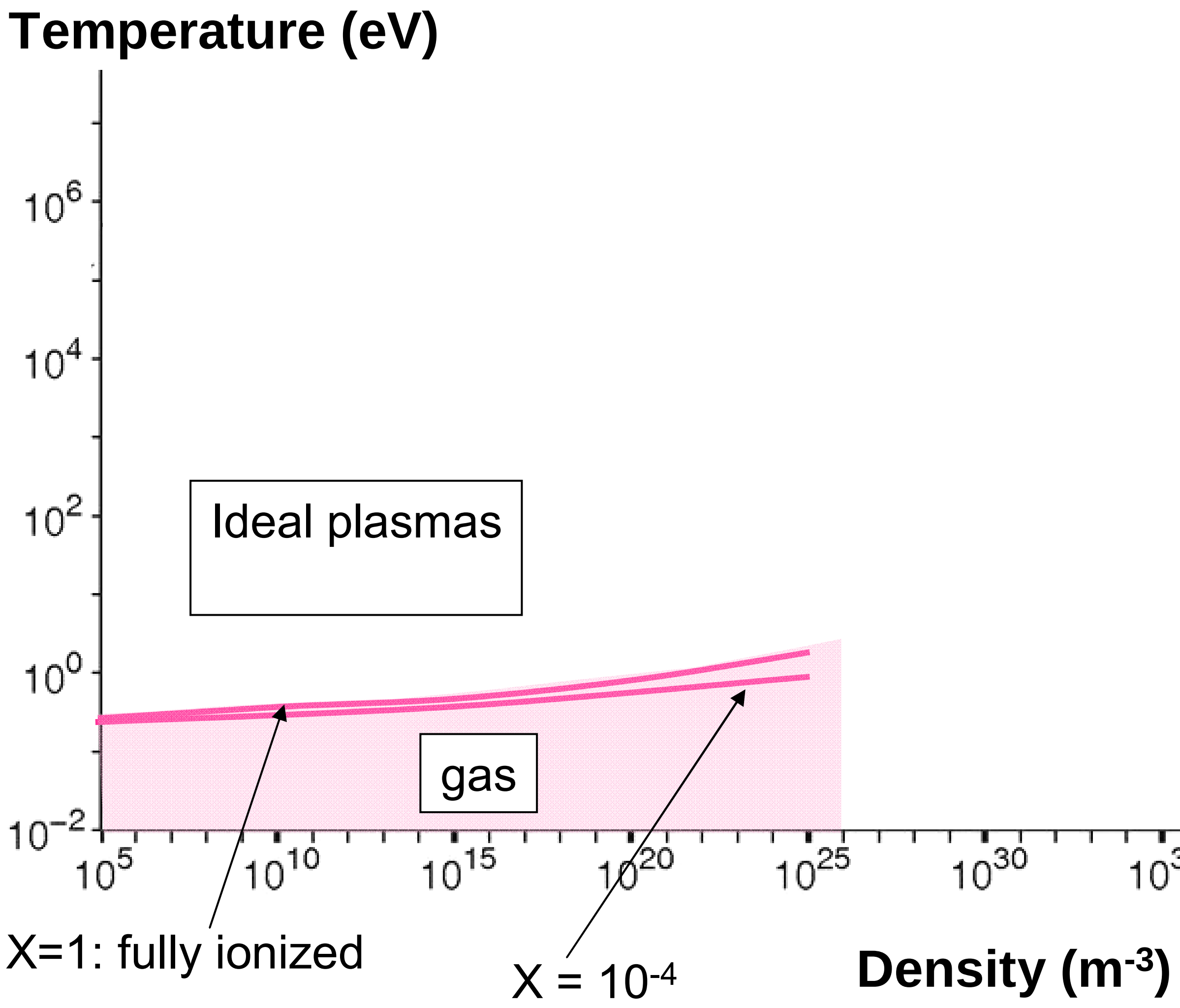
Plasmas
partially ionized
fully ionized

W. Busch

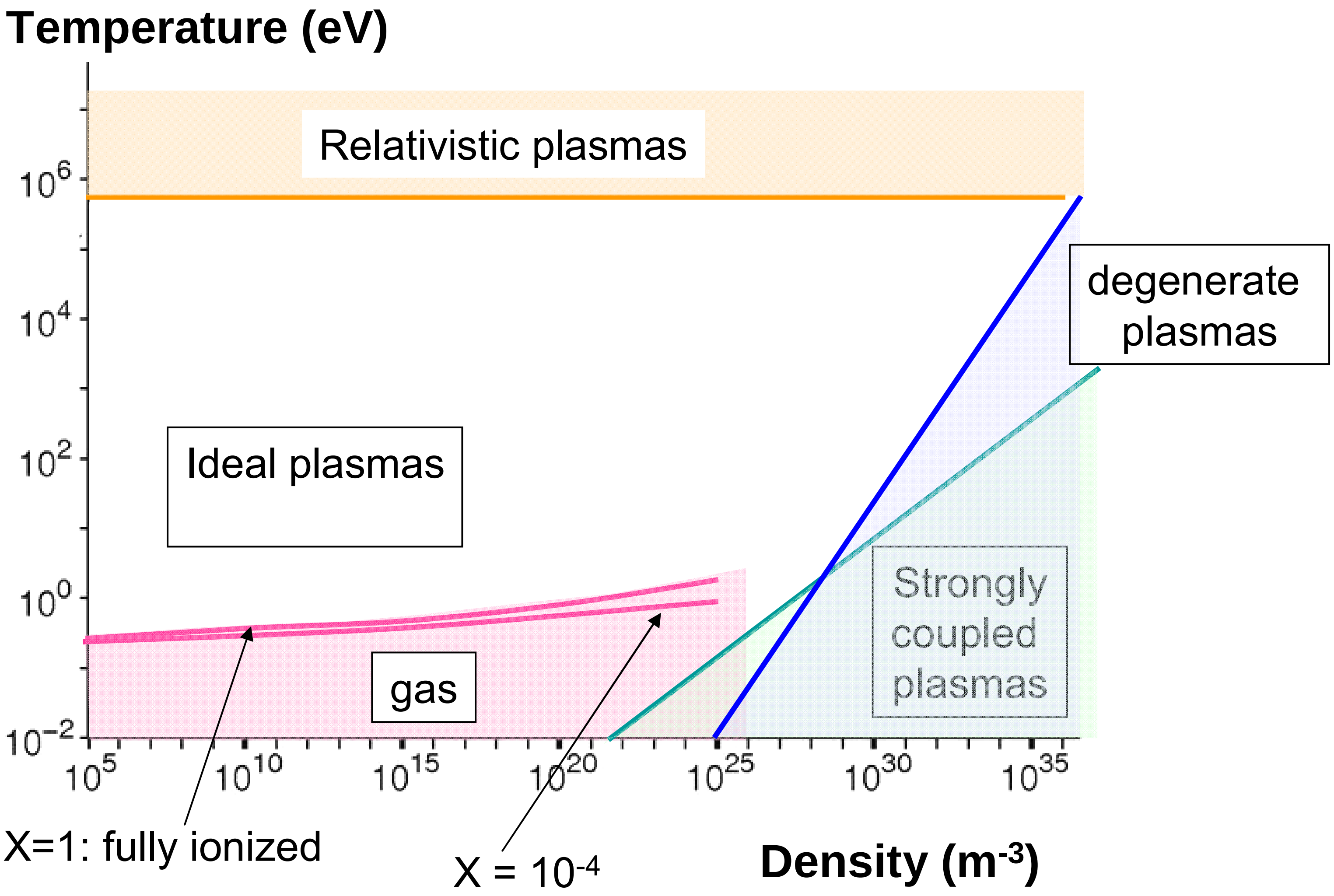


0.5 GW fusion power

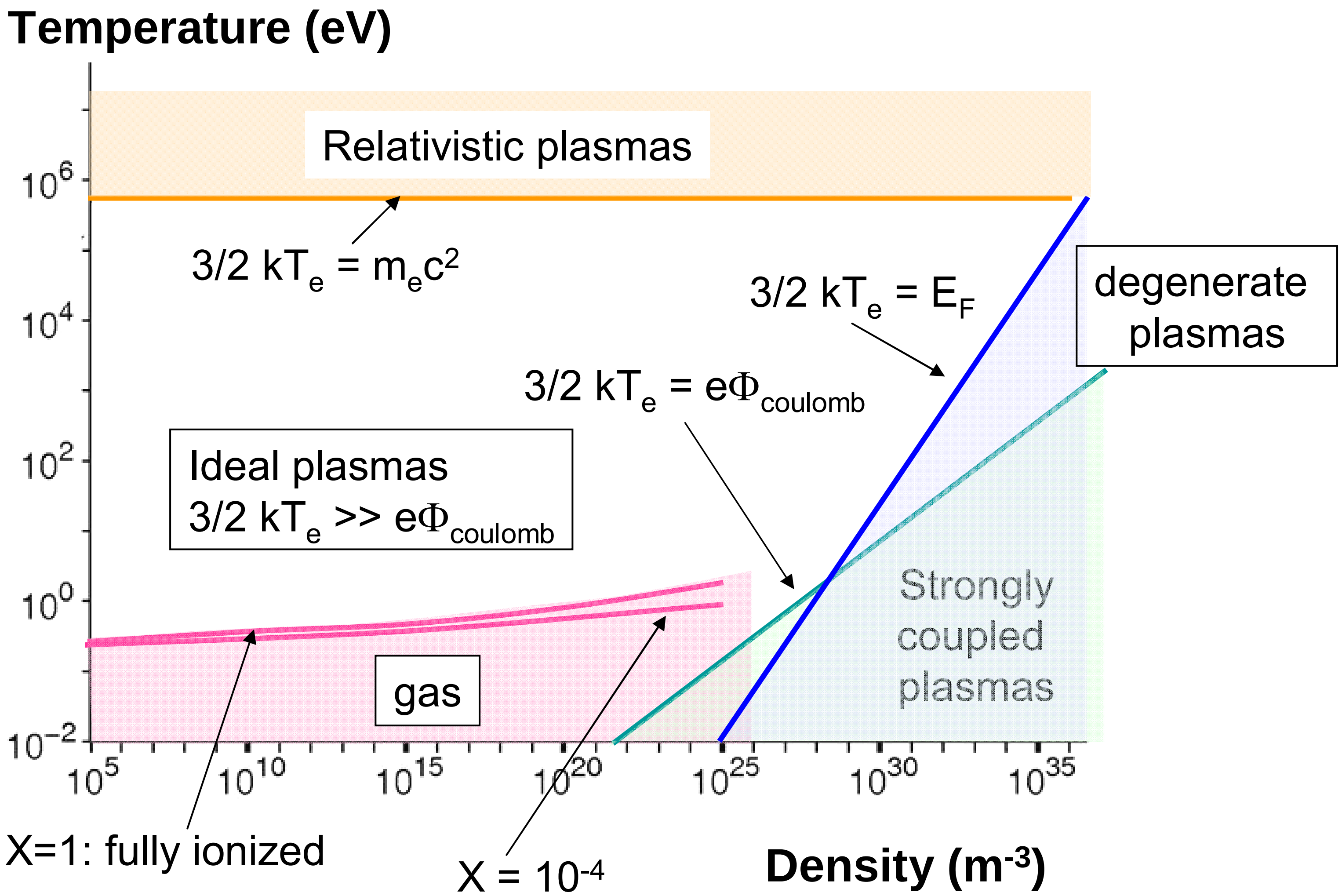
The domain of plasmas



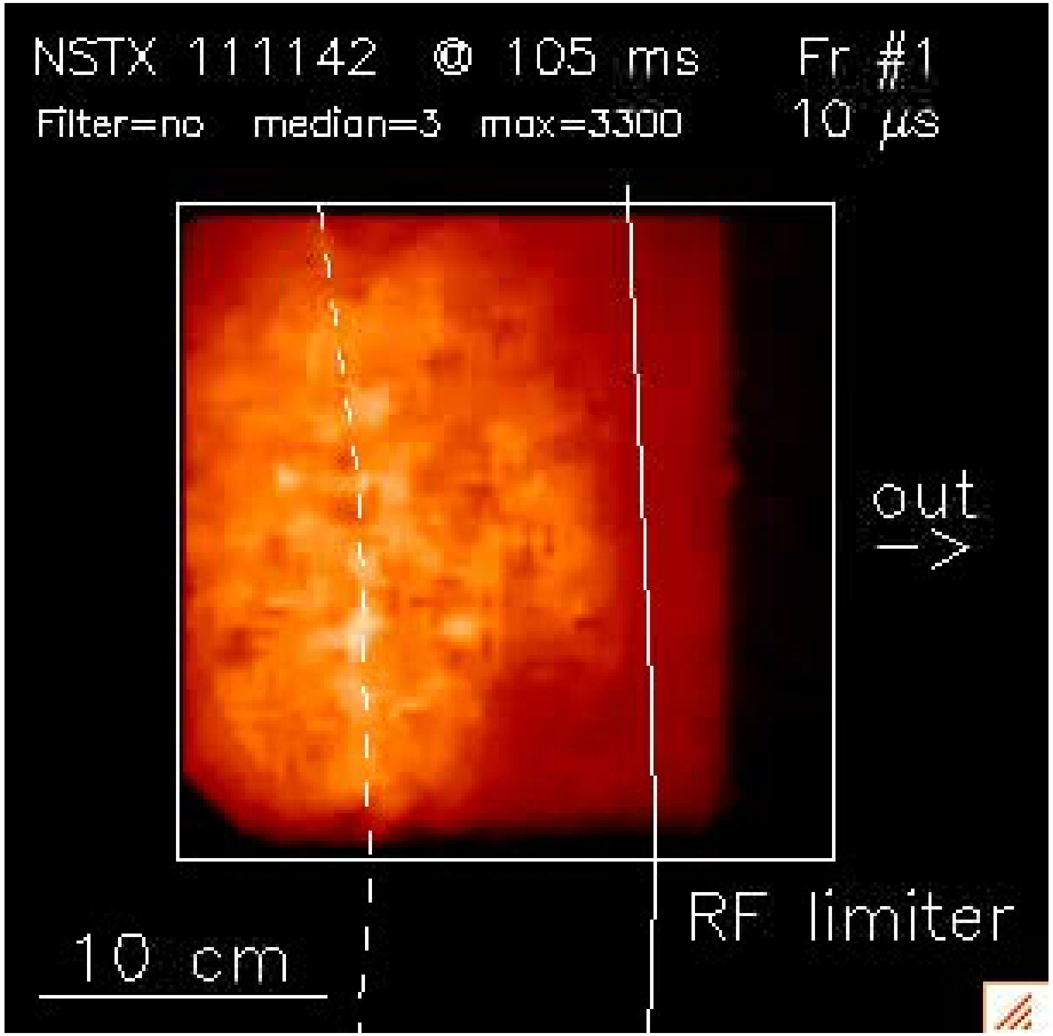
The domain of plasmas



The domain of plasmas



Plasmas are open systems and far from equilibrium:



Plasmas are strongly turbulent.

Transport in magnetically confined systems is mostly caused by turbulence, which can be driven by pressure gradients and which non-linearly evolves.

S.J. Zweben *et al.*,
Phys. Plasmas **9** (2002) 1981

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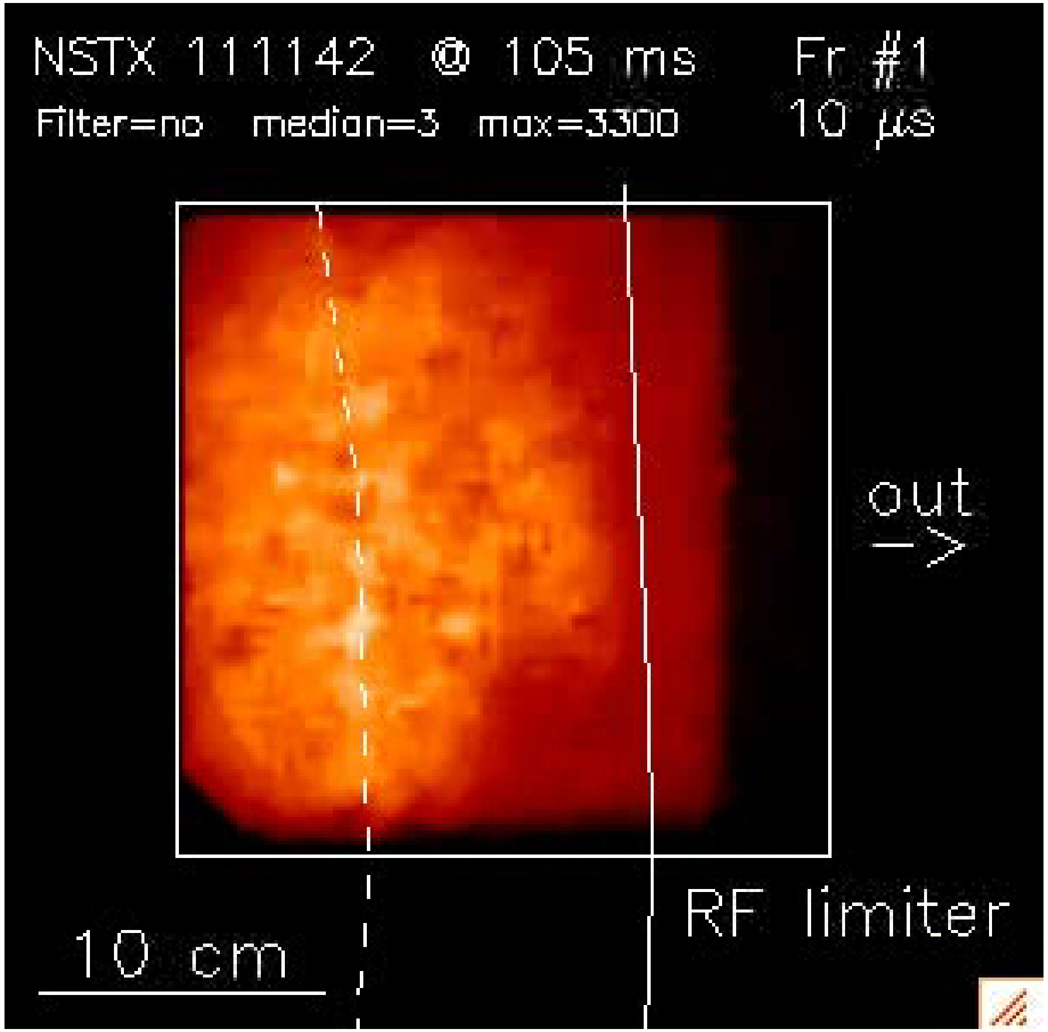

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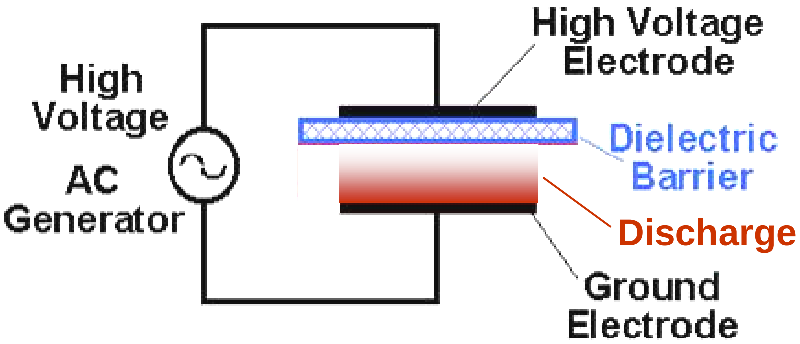
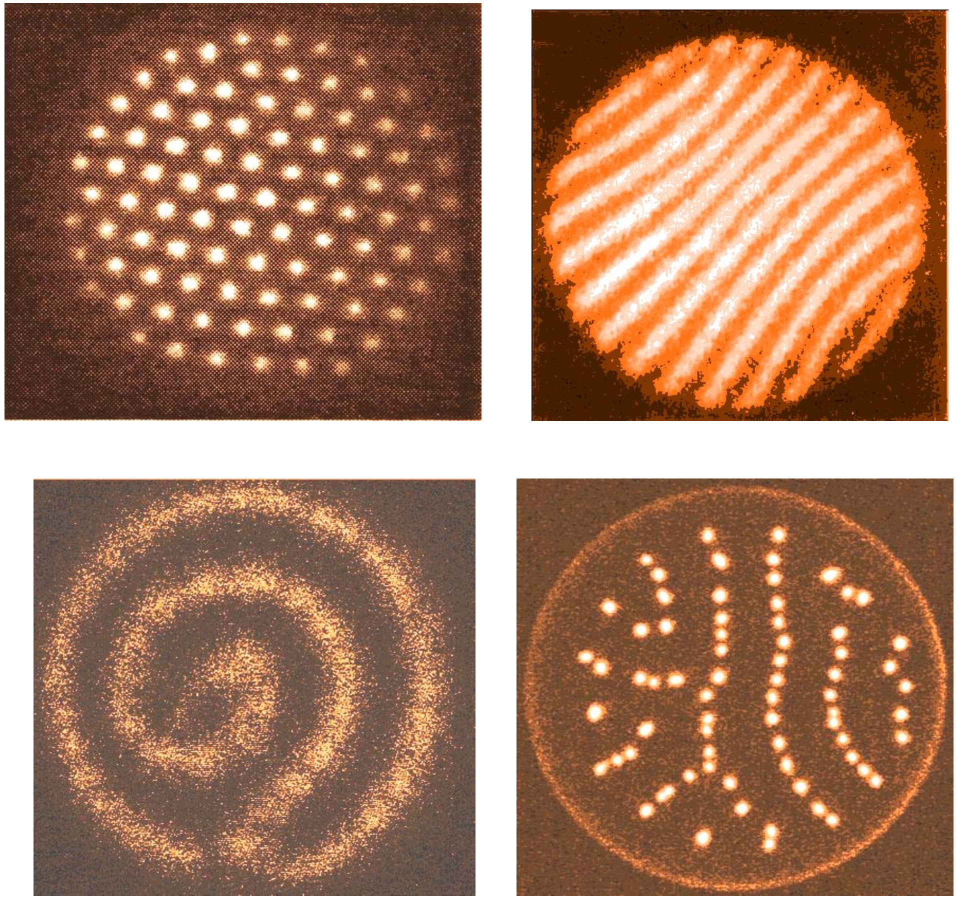
Self-organisation of Plasmas: spatial structures in low temperature plasmas

Simple arrangement for dielectric barrier discharge



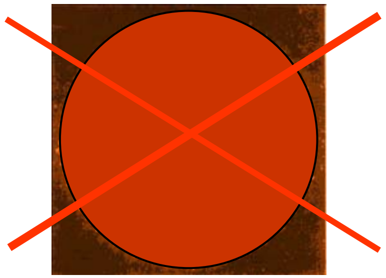
The dielectric barrier prevents arc development

The planar gas-discharge systems self-organises in patterns; control parameter is the current. The non-linear element is the negative conductivity of the discharge



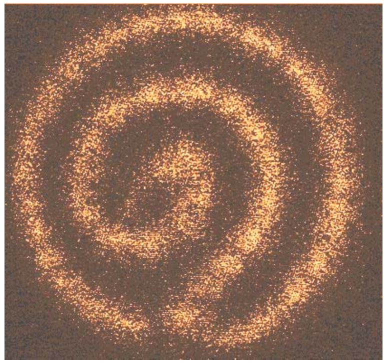
Research Group Purwins, UNI Münster, 2005

The discharge current does not organise itself with homogeneous current density



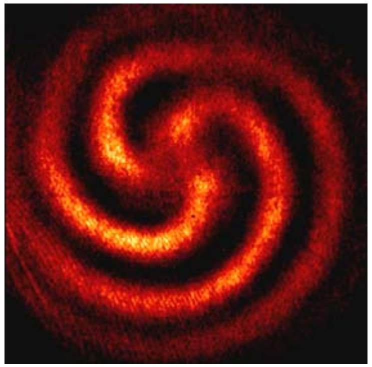
Universal behaviour in spatially self-organized systems

Spirals as examples for pattern formation in nonlinear dissipative systems

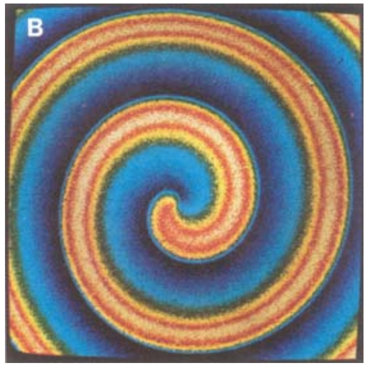


dielectric barrier Discharge
Purwins et al. 2005

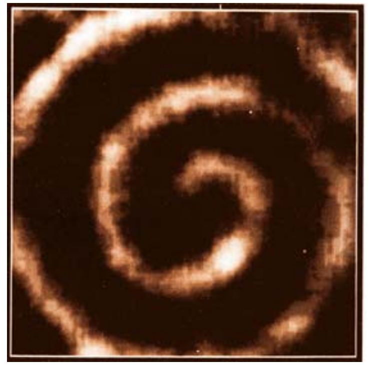
Semi-conductor
Rüfer et al. 1980



Optical system
Huneus et al. 2003



Chemical solution
Müller et al. 1985



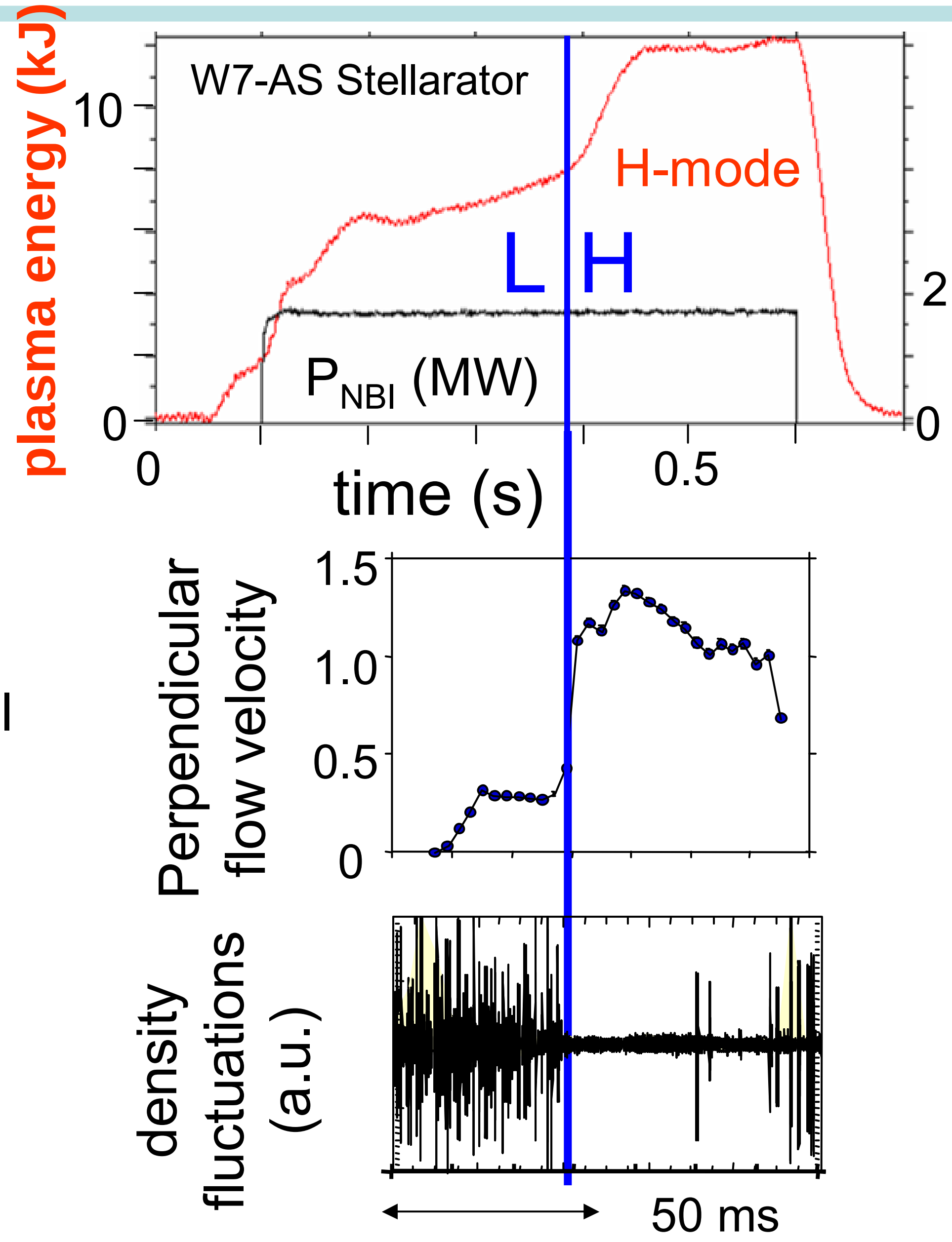
Ca-waves on frog egg
Clapham, in Ball 2001

All cases can be described by complex Ginzburg-Landau equations;
the homogeneous solution is unstable.
It transits by a Hopf-Turing bifurcation into an inhomogeneous state.

Self-organisation of toroidal confinement plasmas

The H-mode transition

Improved confinement regime
develops spontaneously

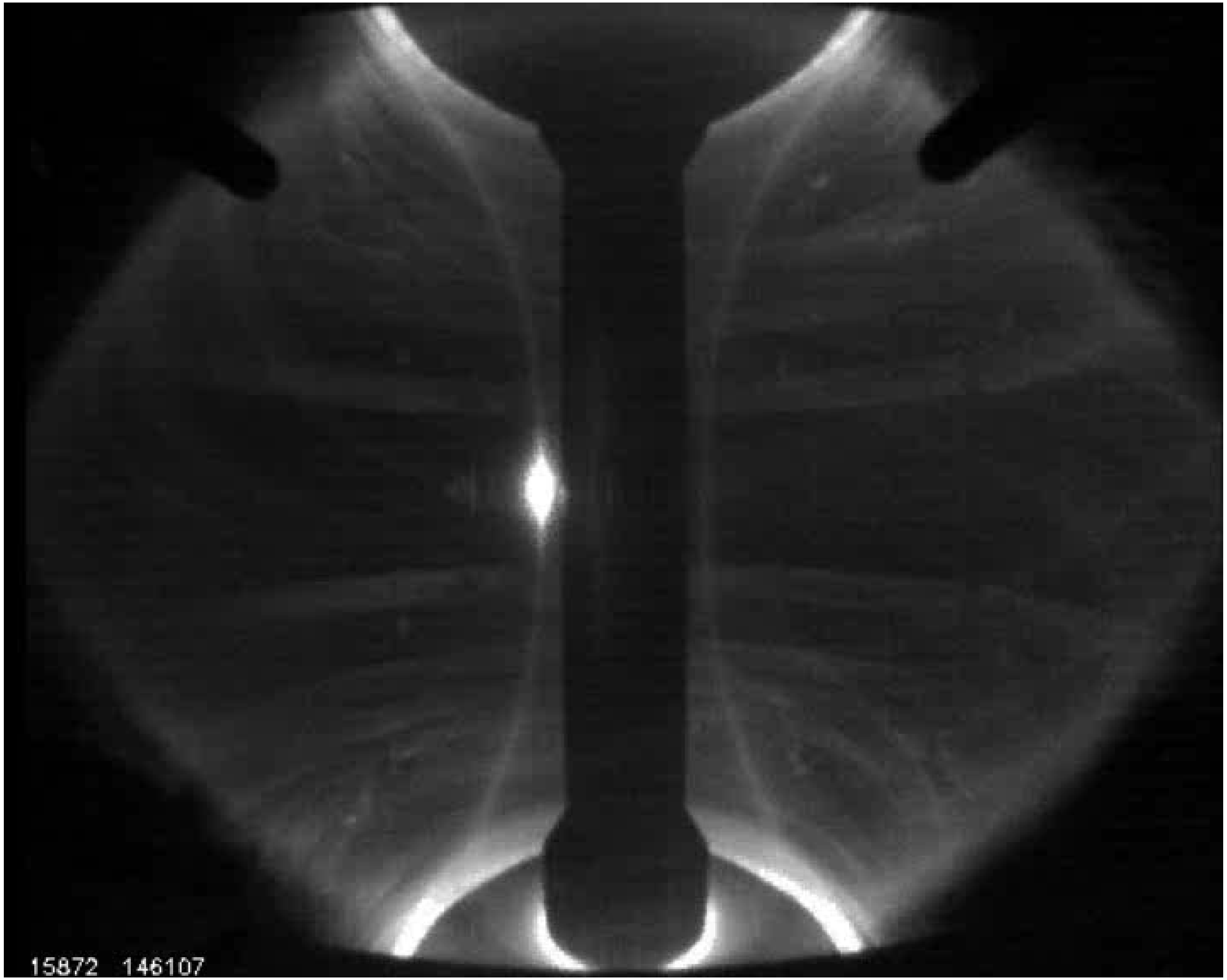


Present understanding:

Plasma turbulence generates poloidal
Flow structures (zonal flows)
These flows are radially sheared.

In the sheared flow, turbulence is
decorrelated and suppressed

Movie of H-mode transition of MAST (UK)



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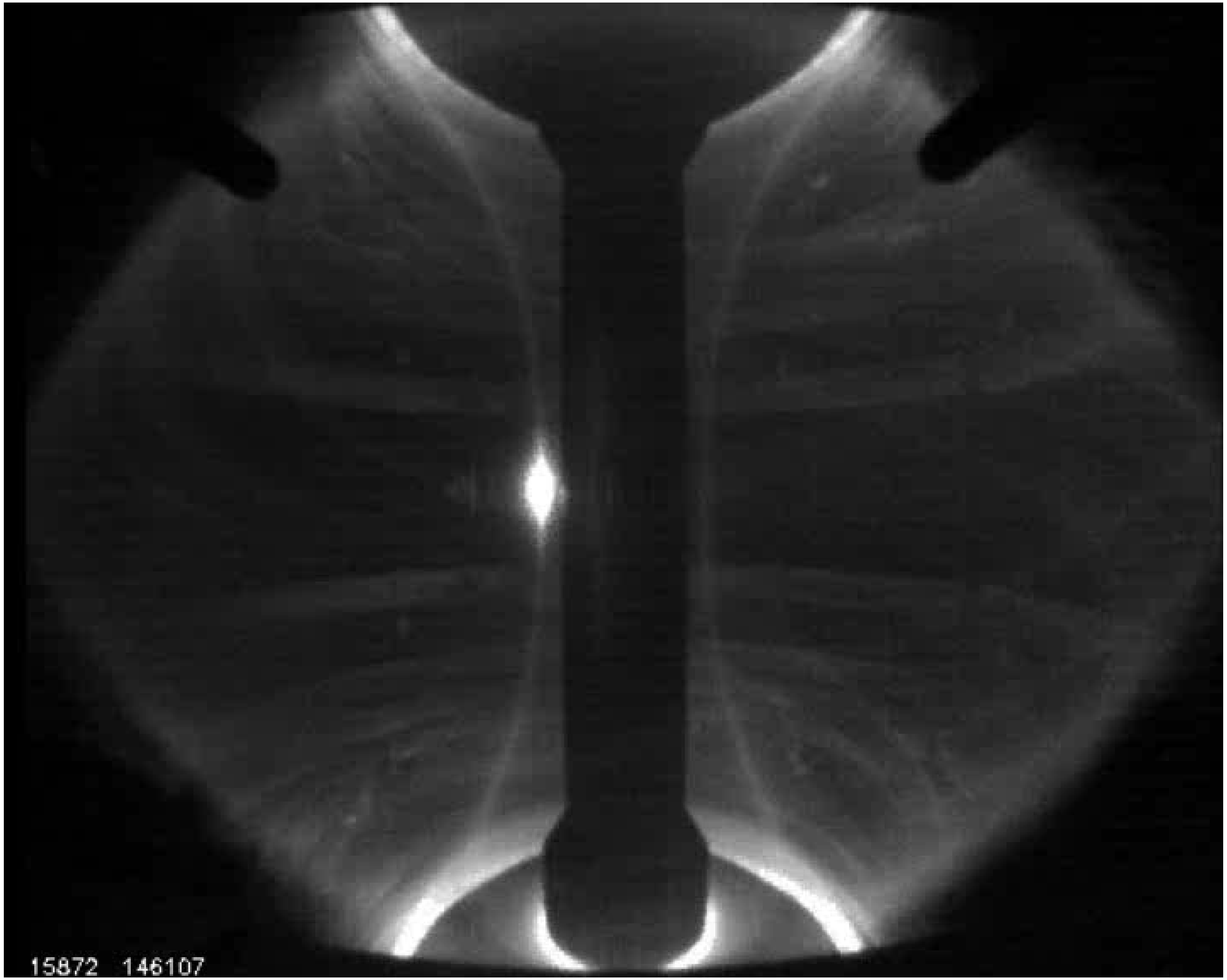
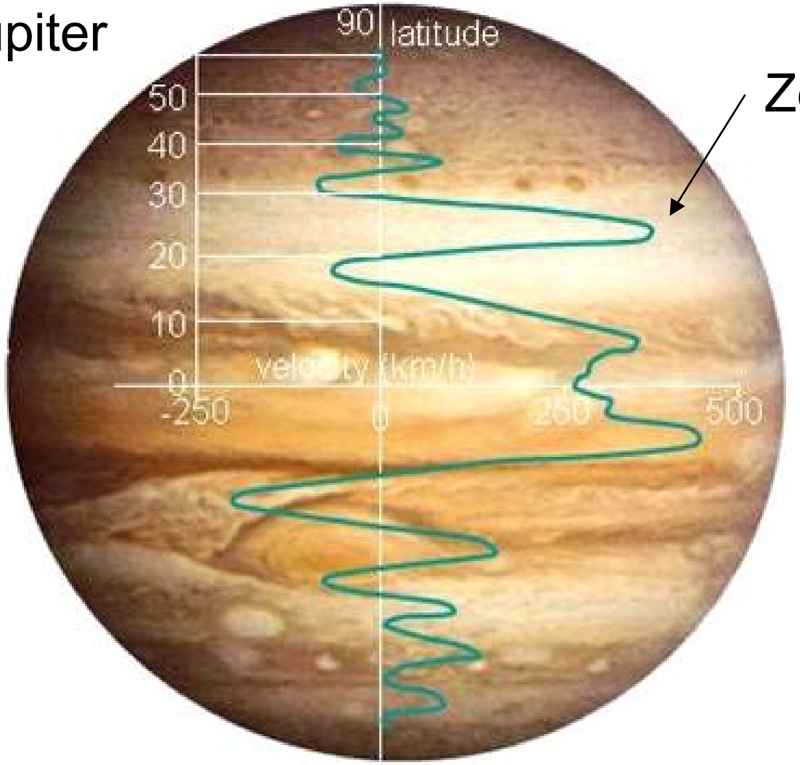
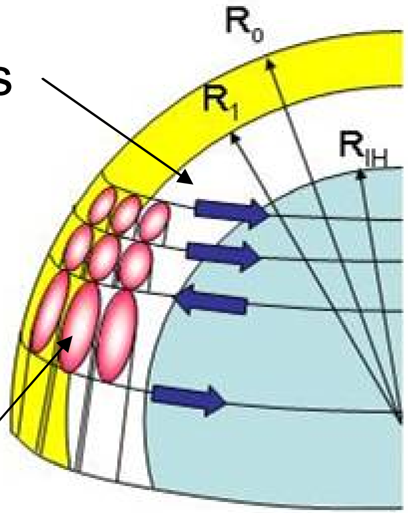


Universal behaviour in dynamically self-organized systems

Jupiter



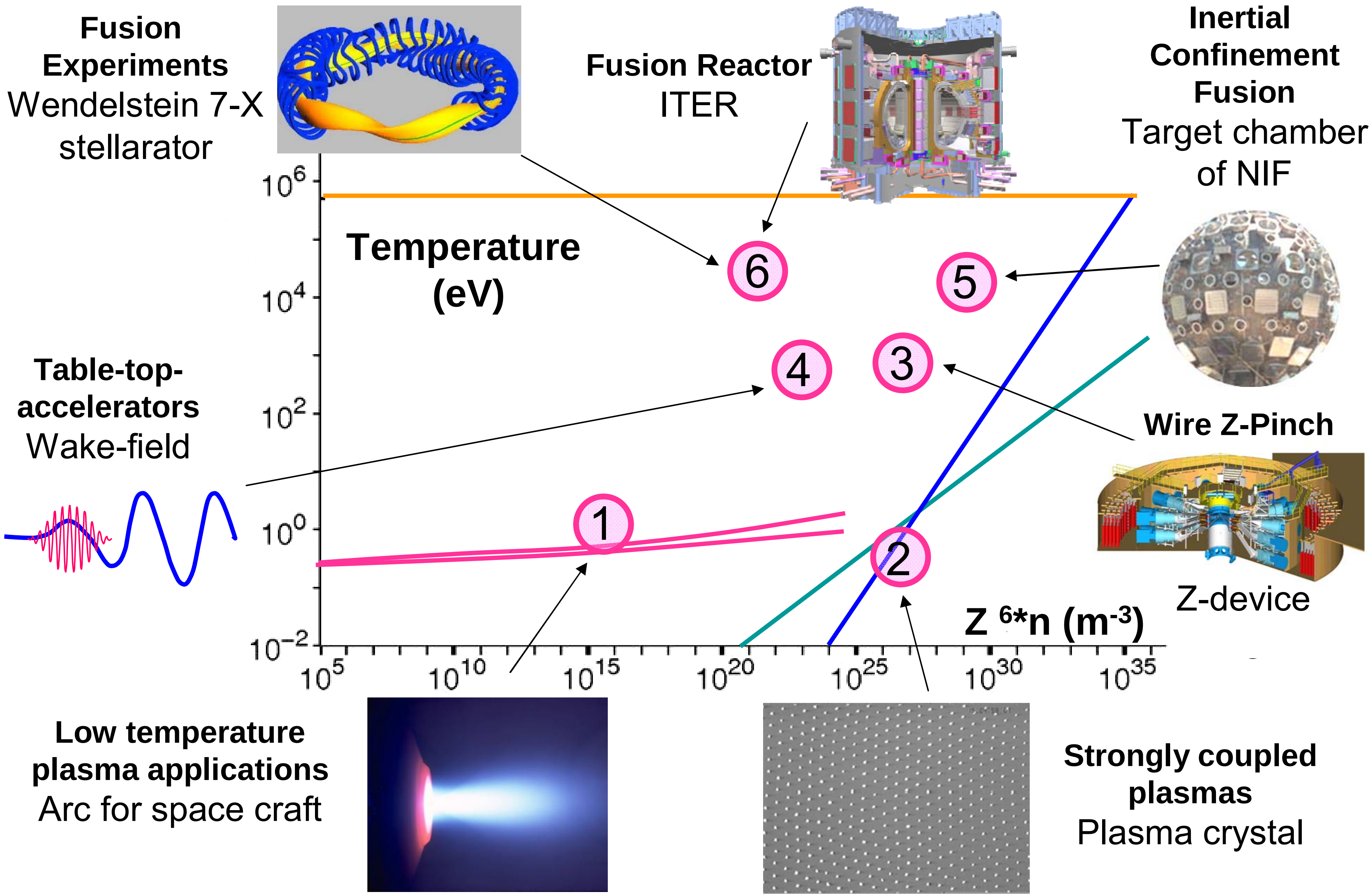
Zonal flows



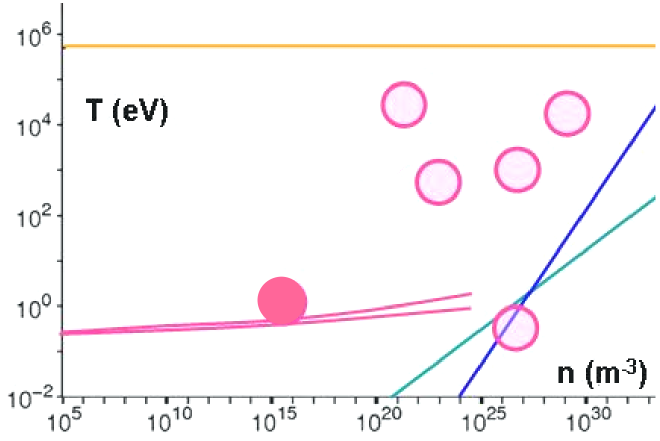
convective cells drive ZFs
via Reynolds stress

Formation of large-scale flows from turbulence via RS
in laboratory experiments,
the sonic wind in gases,
meandering flows in oceans, Jet stream, in the ionosphere
e.g. Rossby waves (Coriolis force instead of Lorentz force)
in the sun

Application potential of plasmas



1. Topic: Low-temperature plasmas

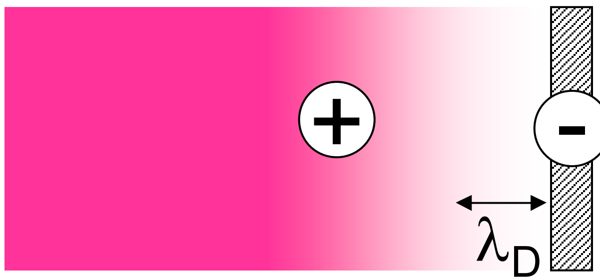


Topics and issues:

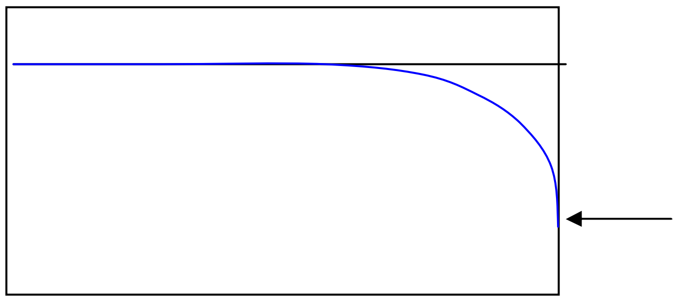
surface cleaning
surface structuring and etching
surface depositions
chemistry with non-thermal electron distributions
light emission
functional surfaces, bio-functional surfaces
plasma de-contamination

Physics

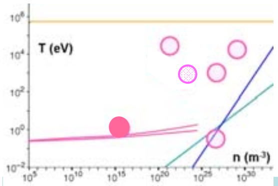
The plasma boundary



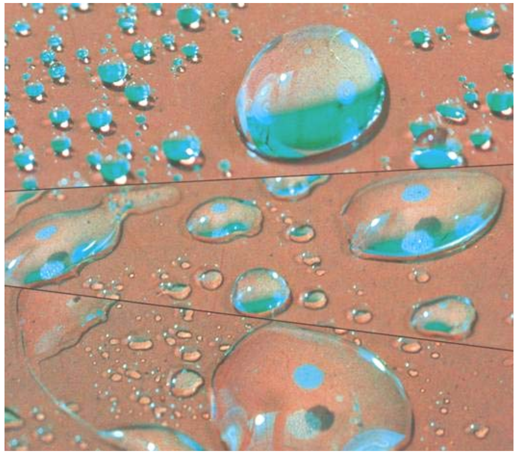
Perpendicularly impinging energetic ions



$e\Phi_{floating} \sim -4\,T_e$



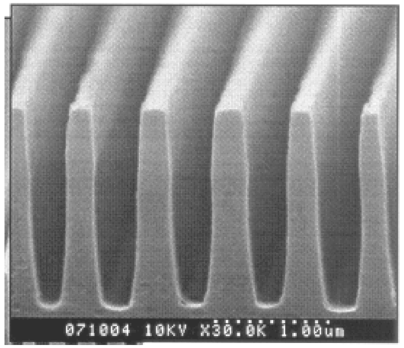
Low-temperature plasma applications



hydrophobic treated textiles
(photo: fmt Wuppertal)

PVD coated gas turbine blade
photo: RWTH Aachen

Coating of tools by plasma vapour deposition (photo: Metaplas Ionon)

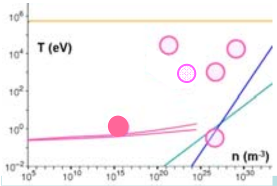


1 μm

Silicon etching

High-power light sources

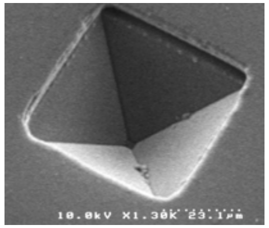
Low power plasma screen

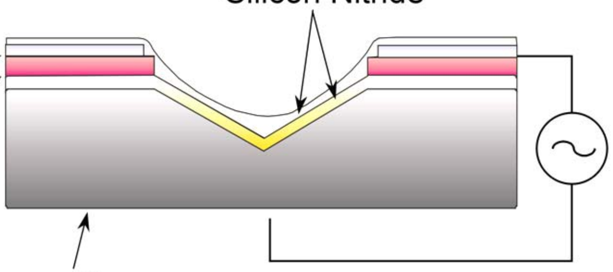


New trends: plasmas interfaced with semiconductors

Micro-cavity plasma devices and arrays

Pyramidial Microcavities

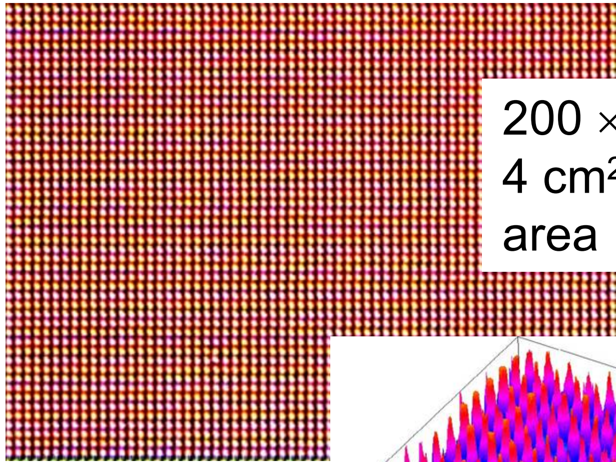




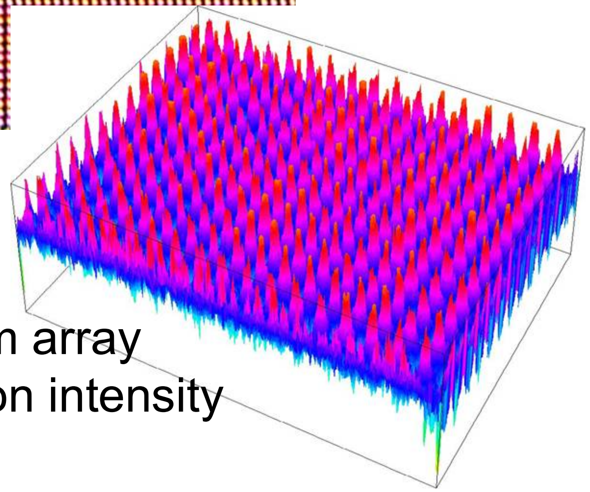
-Glow discharges confined to mesoscopic dimensions (< 10 ~ 100 μm)

-A variety of atomic and molecular emitters are available (VUV ~ IR)

-Array can be operated continuously at normal gas pressures at power loadings exceeding 100 kW/cm^2



200 $\times$ 200 array; 4 cm^2 of active area



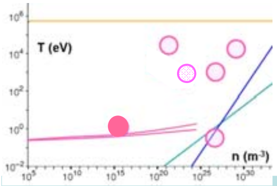
Uniform array radiation intensity

New developments:

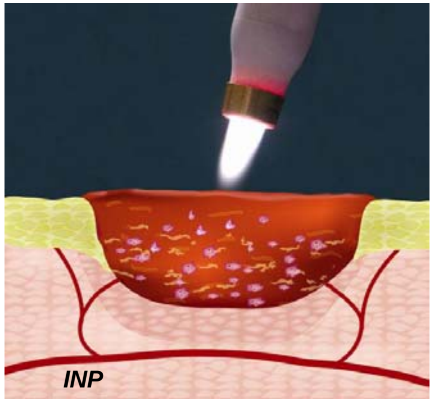
-Ability to interface plasma with electron-hole plasma in a semiconductor

-Microcavities of dimension λ_D using nanotubes for small scales

J. G. Eden, University of Illinois

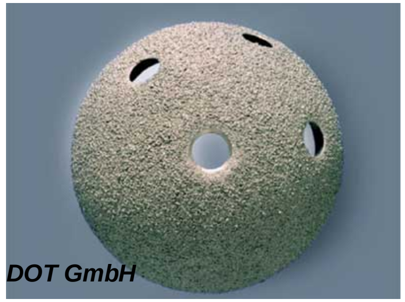


New trends: plasma techniques at the interface to medicine



plasma medicine

- tissue treatment
- wound healing
- skin disease treatment



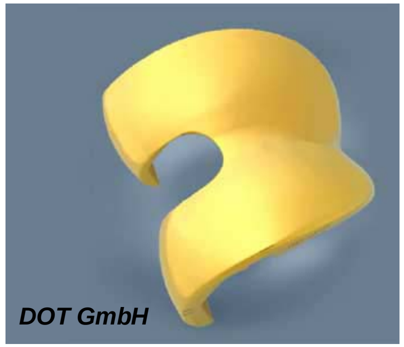
biofunctional surfaces

- bone implants (joints, teeth)
- tendons and ligaments
- vascular grafts
- stents
- heart valves

INP

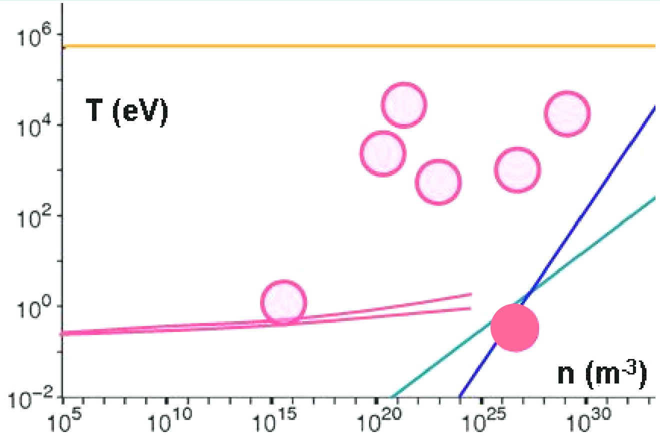
plasma decontamination

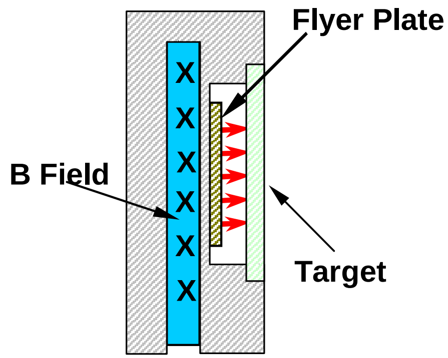
- packaging materials
- medical devices
- powders, pharmaceutics



K.-D. Weltmann, INP Greifswald e.V.

2. Topic: Strongly coupled plasmas





Topics and issues:

Production of high pressures (100 Mbar) with gas-guns or magnetic flyer plates

Pressure induced „cold“ ionisation
($r_{WS} < a_0$; density >> solid-state density)

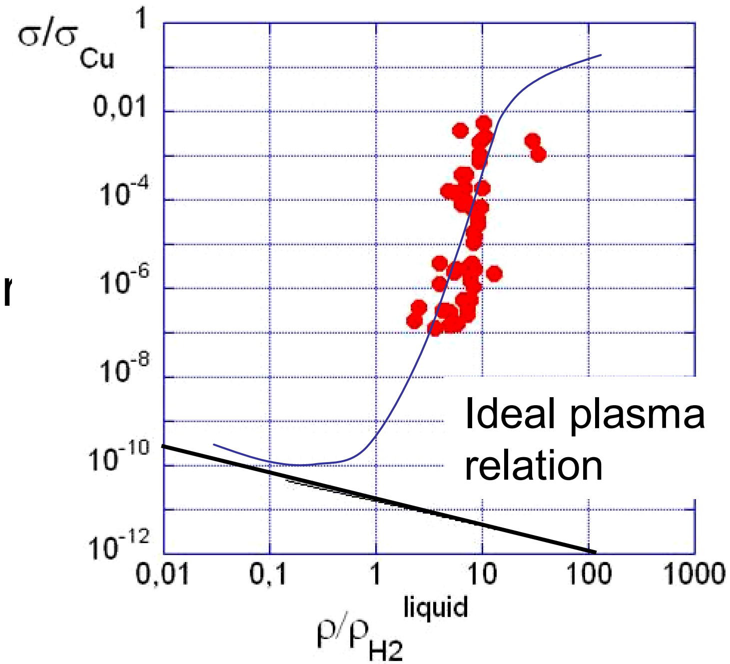
Determination of the equation of state (EOS) for extreme material conditions at high pressure

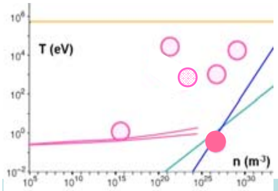
Transition of insulators into metallic state

Transition of metals into plasma state

Metallic and superconducting hydrogen

Electrical conductivity of hydrogen under strong pressure (V. Fortov)





Another strongly coupled system: Dusty plasmas

Topics and issues:

Dust particles, μm-size, suspended in a plasma

$T_e \sim$ eV

$n_e \sim 10^{19}$ m^{-3}

Dust charges up to 10^4 e^-

Experimental set-up

Electrode

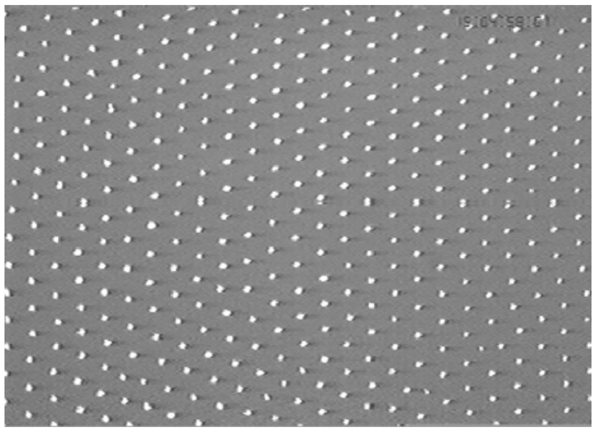
Physics:

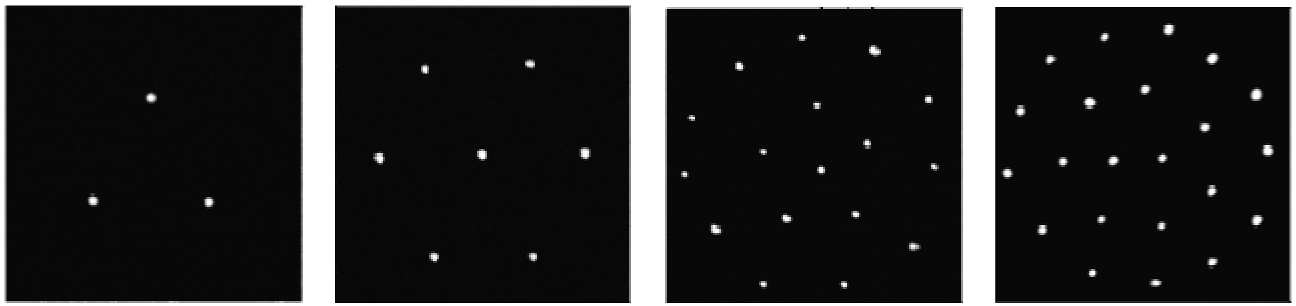
Wigner crystal for

$\Gamma >$ few x 100

Lattice constant < mm

dust lattice at different occupation numbers

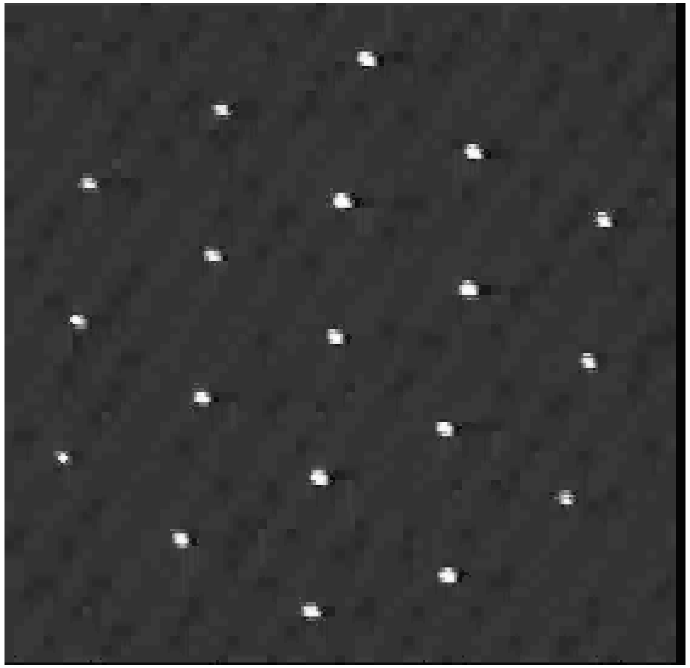




3 7 (1,6) 17 (1,5,11) 22 (2,7,13)

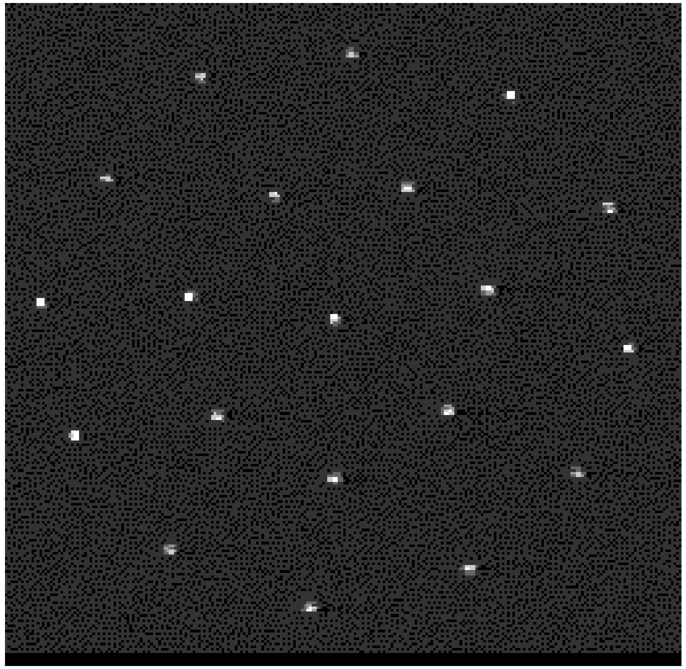
Rotation of crystals

Rigid rotation when
occupation number fits

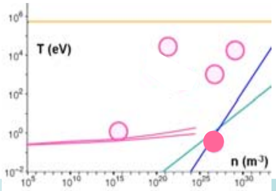


1, 6, 12

sheared rotation when
occupation number does not fit



1, 7, 12



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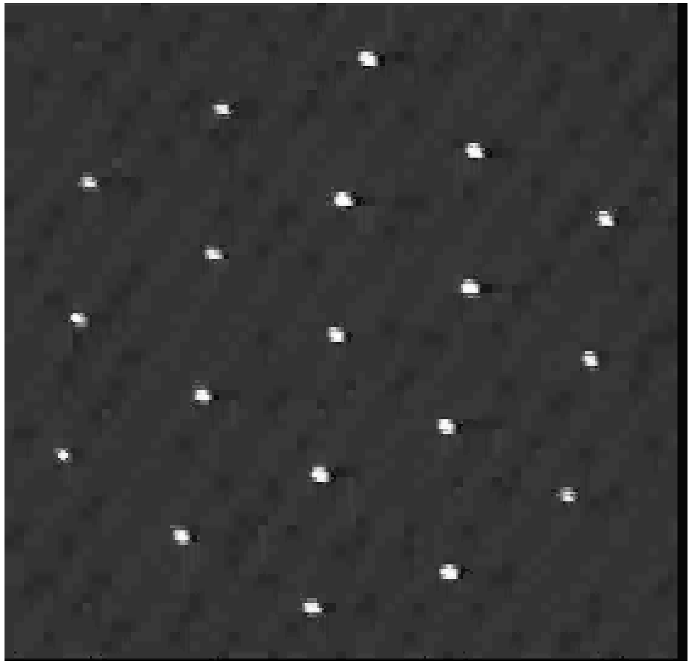

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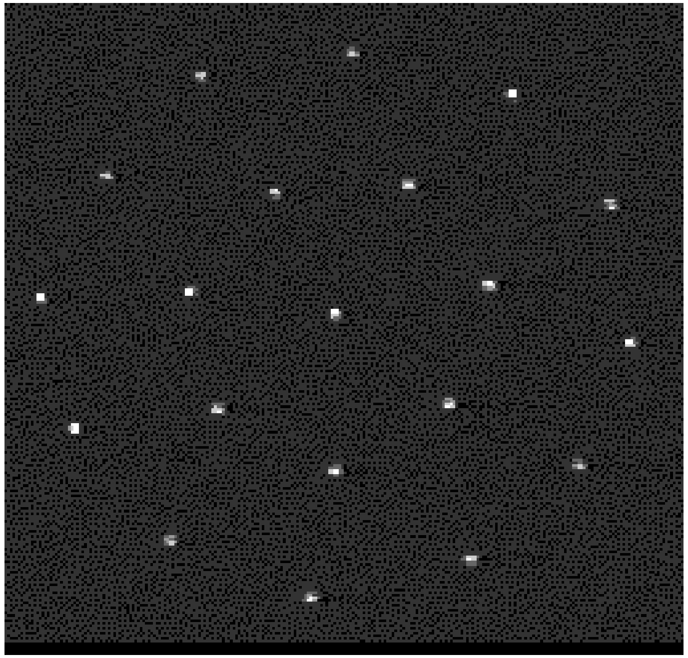
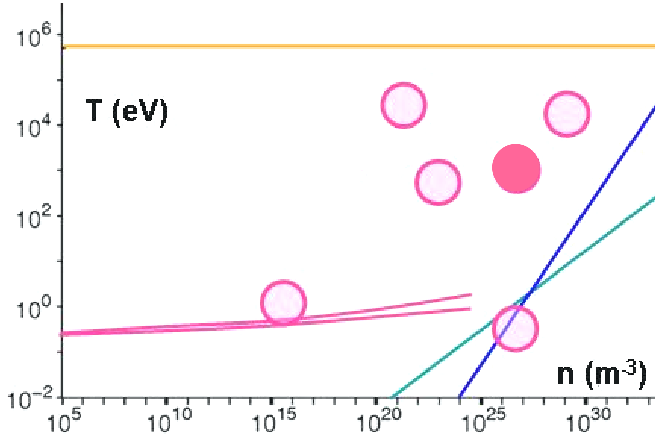
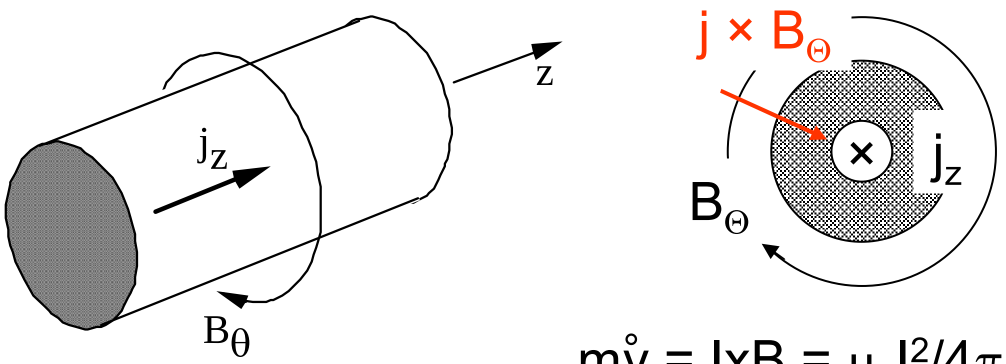


1, 7, 12

3. Topic: Z-pinch as ICF driver and X-ray source

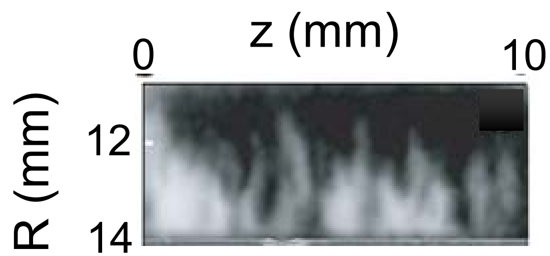


Principle of the conventional Z-pinch

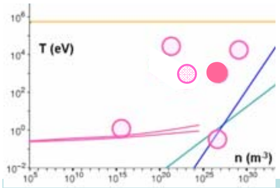


$m\mathring{v} = IxB = \mu_0 I^2/4\pi r$

No direct fusion potential:
Rayleigh-Taylor instabilities easily develop because the heavy fluid (plasma) is accelerated by the light fluid (field)



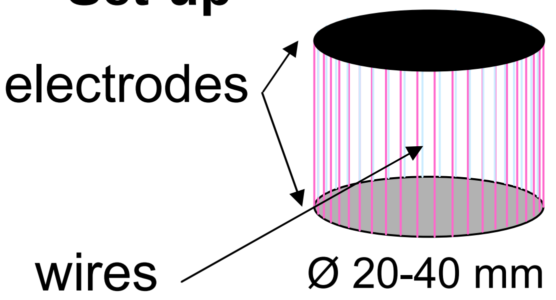
T W L Sanford, Sandia



New concept: The fast wire-array Z-pinch

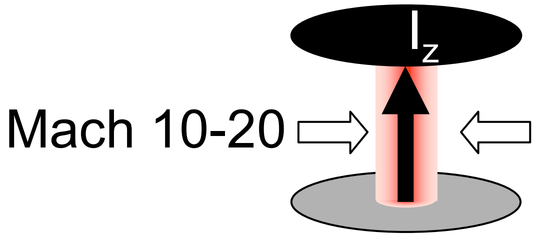
Topic: To built a powerful X-ray source for various applications

Set-up



~ 240 thin (7.5 μm) tungsten wires to stabilize implosion
A fast rising current (20 MA in 100 ns) is applied
The outer surface of the wires is turned into a plasma

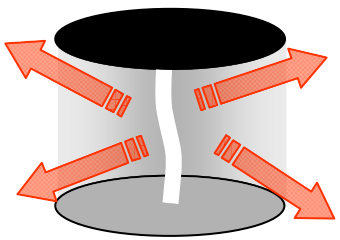
By the jxB force the plasma is compressed on axis (mm Ø)



electrical energy into kin. energy

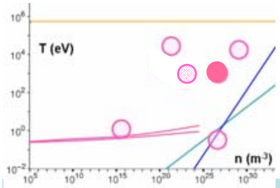
Compression in 2 stages:

(1) slow ablation of wire; radial density re-distribution
(2) rapid implosion (snow-plough)

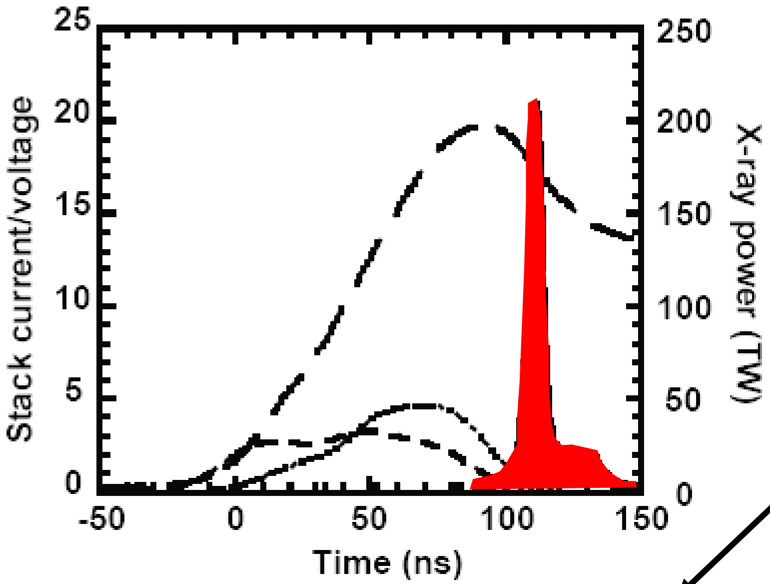


Shock energy into radiation

On stagnation, short, intense soft x-ray pulse of ~290 TW, 1.8MJ, in 4 ns from the Z-device at Sandia => strongest X-ray source

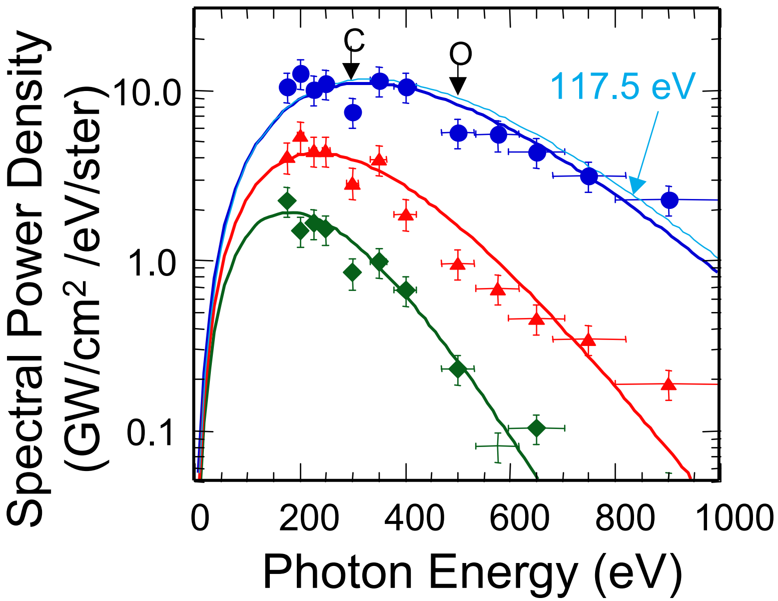


Results from the Z-device (Sandia)

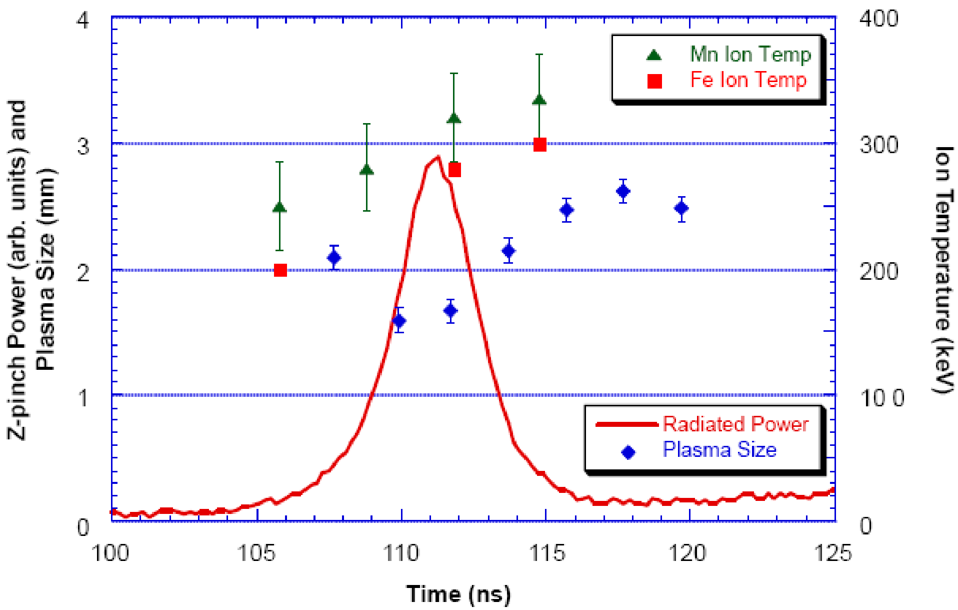


Pulse traces of an imploding tungsten wire array Z-pinch

X-ray spectra
black-body radiation



Ion temperatures



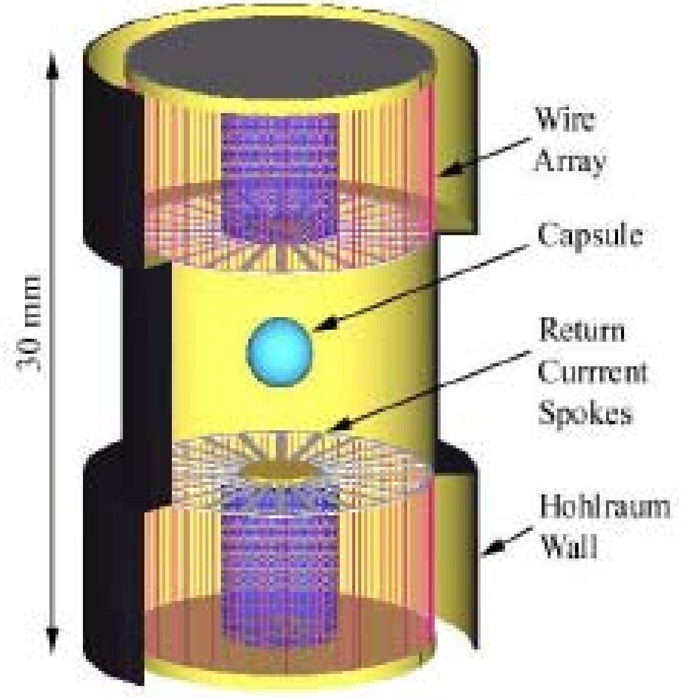
Application as ICF driver

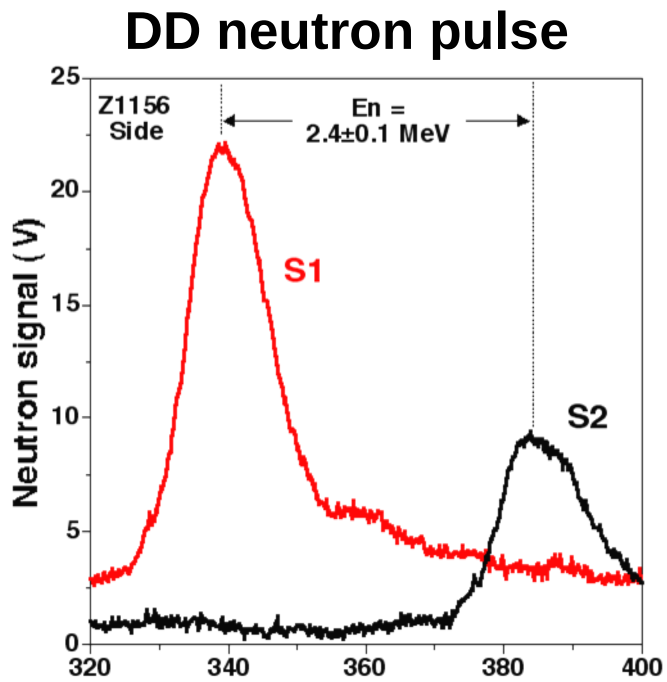
Double-ended

Z-pinch driven

Hohlraum

With pellet

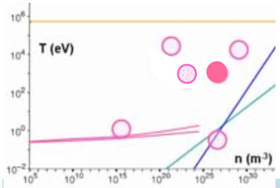




World record neutron yield from D_2 capsule:

3.4×10^{10} thermonuclear neutrons

M.K. Matzen et al. PPCF 41, A175, 1999

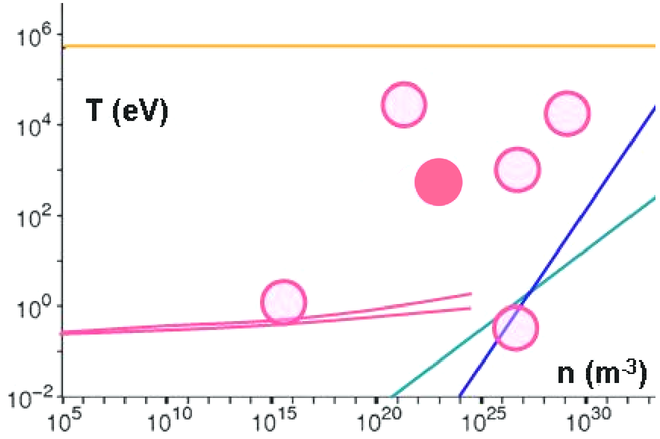


Applications and questions

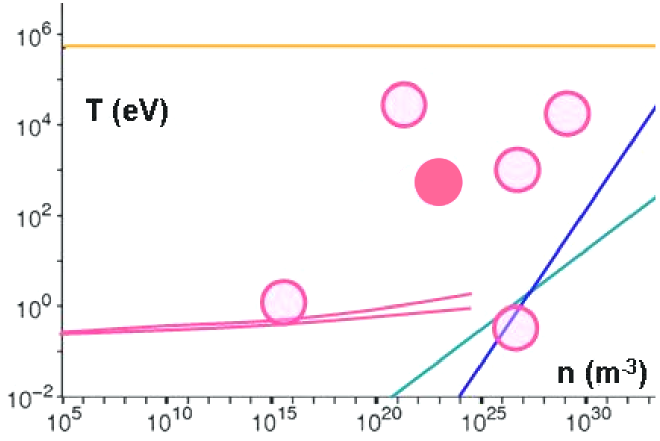
Applications:
SX source as driver for ICF
Powerful radiation source for X-radiogrphy
EOS studies at dense plasmas
Laboratory astro-physics e.g. mimicking axial jets at high Mach numbers

Open issues
Power balance: radiation power “too” large
Equilibrium: The state is long-lived facing the balance of kinetic and magnetic pressure
High ion temperatures: What is the heating mechanism (viscous heating due to m=0 turbulence ?)

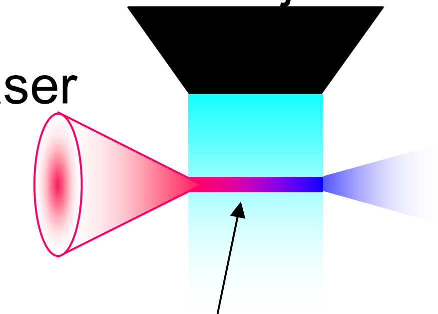
4. Topic: Table top plasma accelerators



4. Topic: Table top plasma accelerators



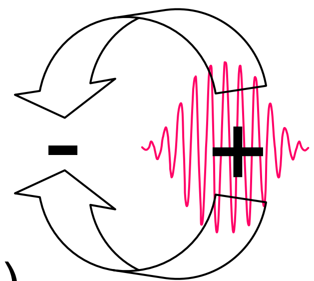
Experimental set-up



Topic and issues:

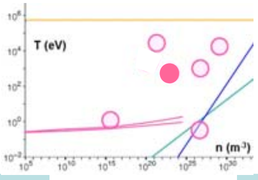
Excitation of plasma wave => longitudinal E-field

- by charged particle beam (electrons, positrons)
- by intense laser (ponderomotive force: $F_p \sim e^2\nabla E^2/m_e\omega^2$)



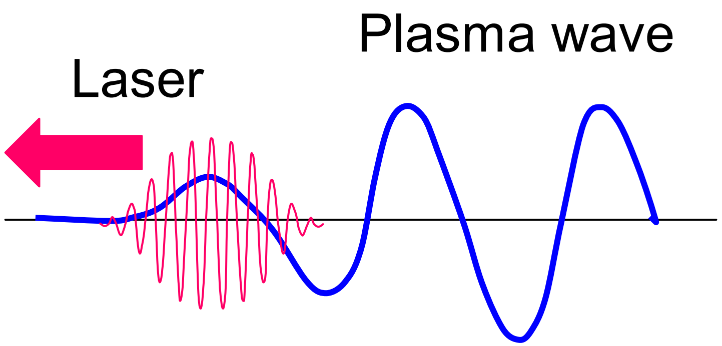
Large electric field gradients develop which accelerate charged particles

Relativistic plasma wave: $v_{phase} \sim c \Rightarrow v_{particle}$



Physics of laser-plasma accelerators

Plasma wakefield



like behind a ship

acceleration

Laser interaction with electrons: $a = eA/mc^2$ = normalized laser amplitude; $A=-\dot{c}E$)

non-relativistic: $a < 1$

laser

electron

relativistic: $a > 1$

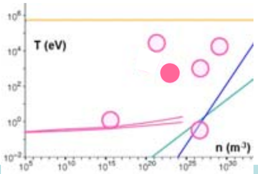
electron

beam generation: $v_{electron} \longrightarrow c$

$a=1$ ($\lambda_L = 1\mu m$) -> $I_L = 10^{18}$ W/cm^2

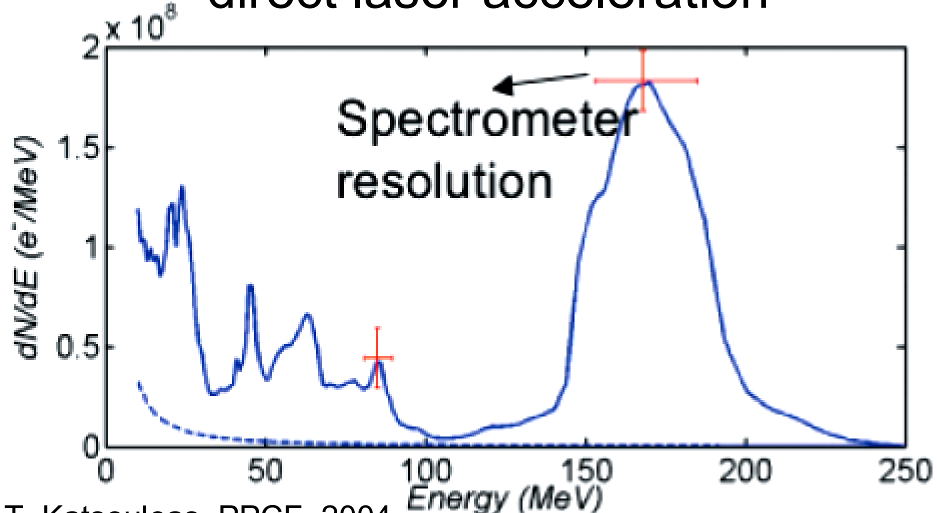
$n_e=10^{22}$ m^{-3} -> $E=10^{10-12}$ V/m; acceleration => 300 GeV/m

conventional: <100 MeV/m; 1km -> 1m -> table-top accelerator



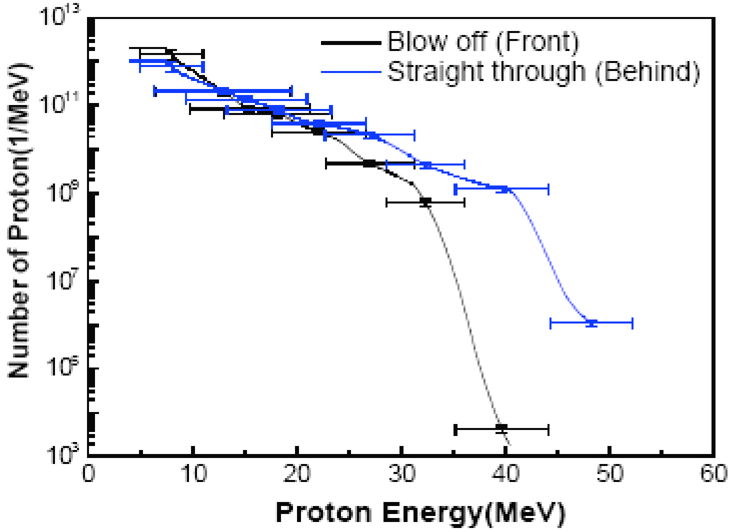
Status of particle acceleration

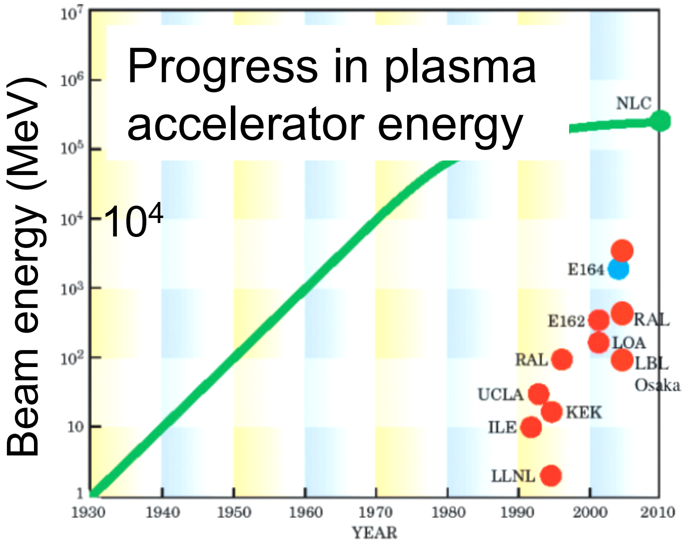
Electron energy spectrum from direct laser acceleration



T. Katsouleas, PPCF, 2004

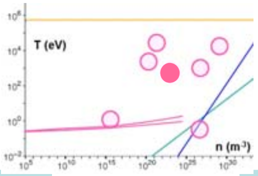
Proton energy spectrum





Proton acceleration: beam onto foil => makes E-field gradient stationary => proton interaction

Applications:
production of neutrons, positrons,
coherent, incoherent X-rays
photo-nuclear physics,
generation of isotopes, medical applications,
injection for conventional accelerators,

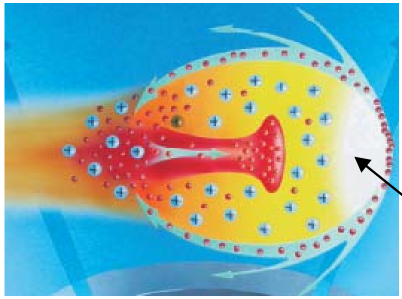


Progress: optimisation via geometry

$\Delta L_{Laser} \sim \lambda_{plasma}/2$ focus $\sim \lambda_{plasma}$

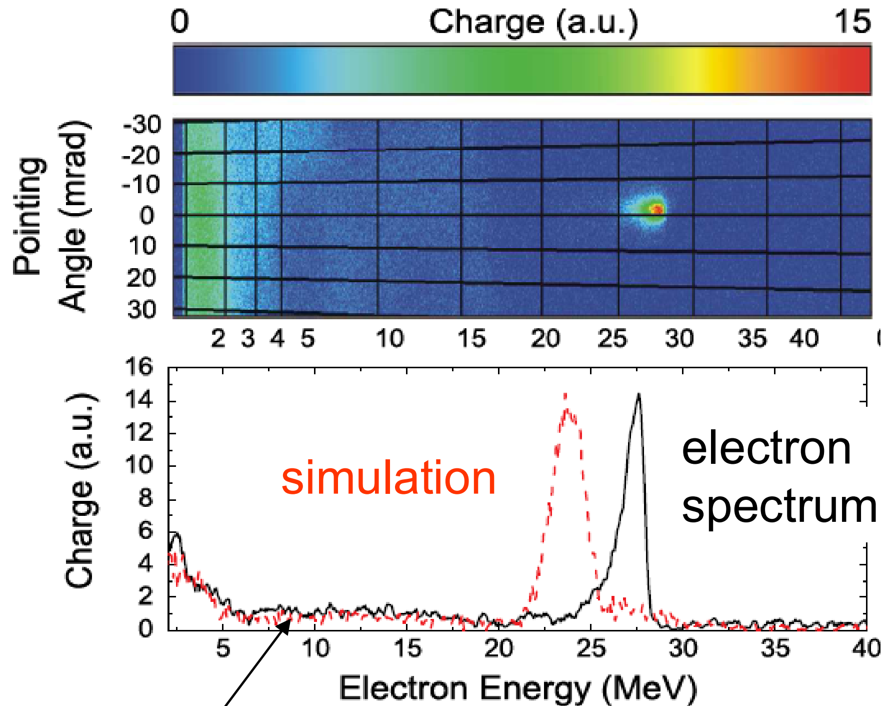
More monoenergetic electrons, less thermal background

Strongly reduced secondary radiation

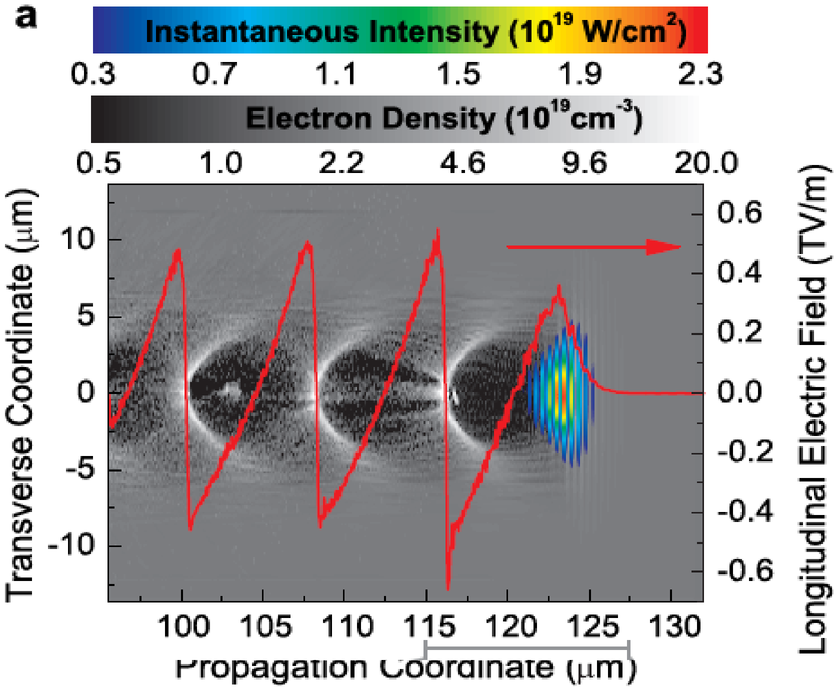


Bubble

Laser pulse

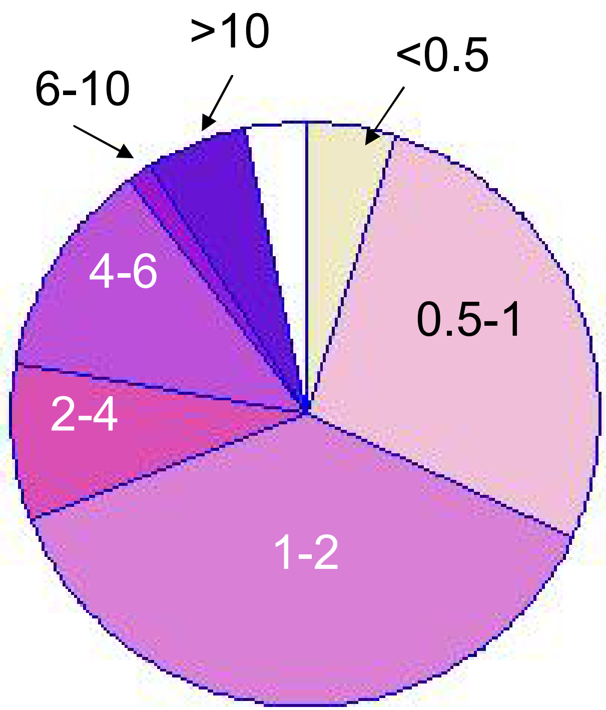


No thermal background

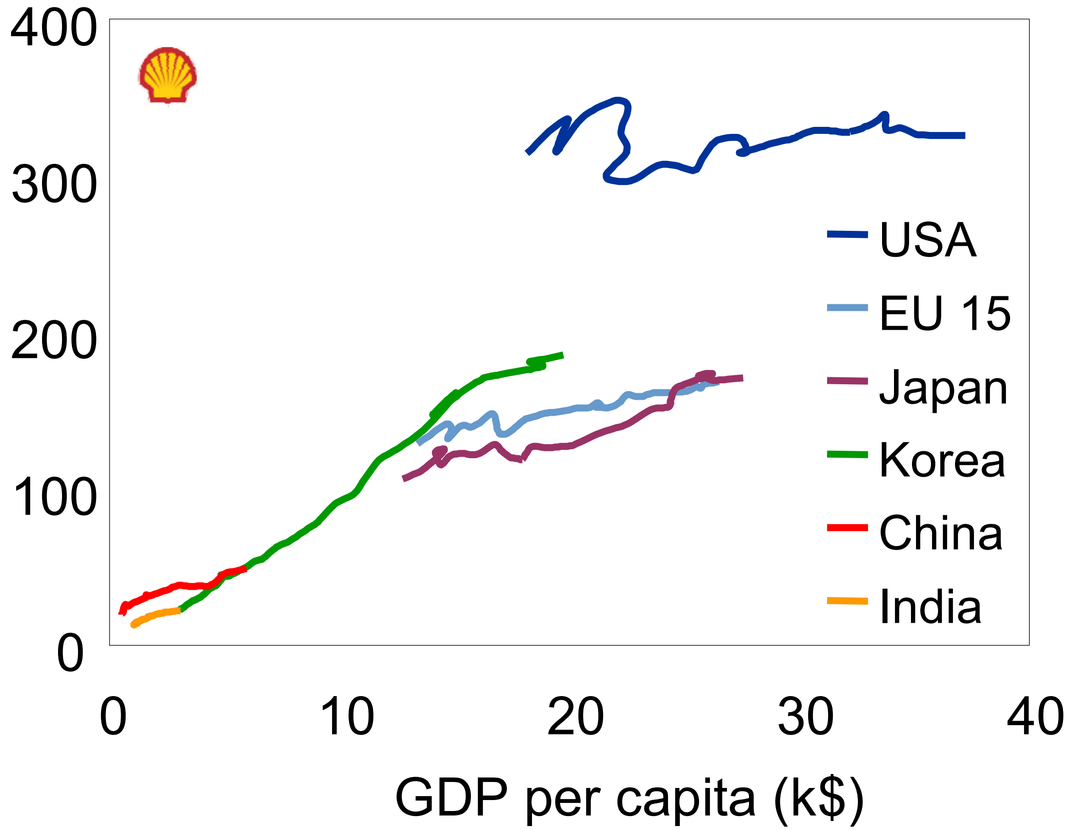


The need for new energy sources

Global distribution of energy demand (kW/person)

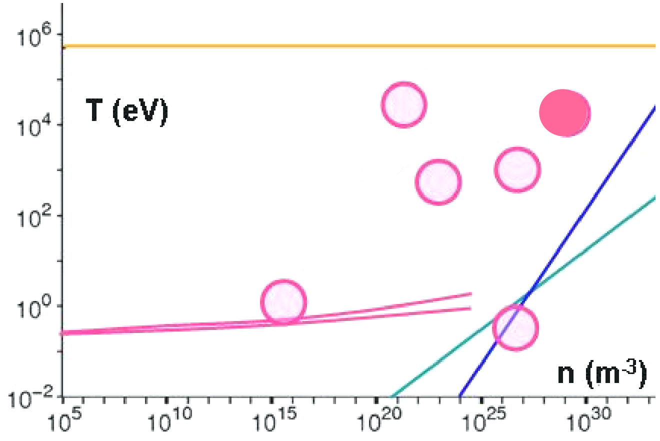


per capita primary energy (GJ)

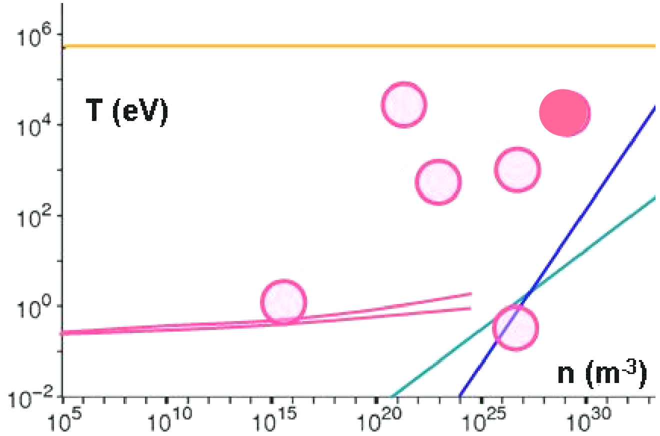


Electricity consumption
2030: + 50%; 2050: + 100%

5. Topic: Inertial confinement fusion (ICF)



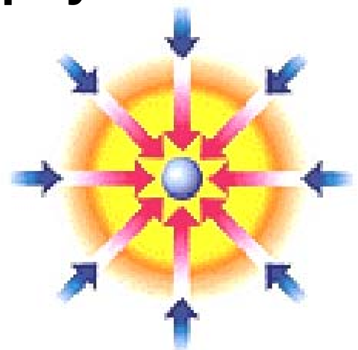
5. Topic: Inertial confinement fusion (ICF)



Topics and issues:

To compress and heat a small (R_o~2mm) solid D –T pellet by lasers, beams, or X-rays from a Z-pinch such that they ignite and deliver fusion energy.

The physics of the conventional approach: Ignition via central hot-spot formation

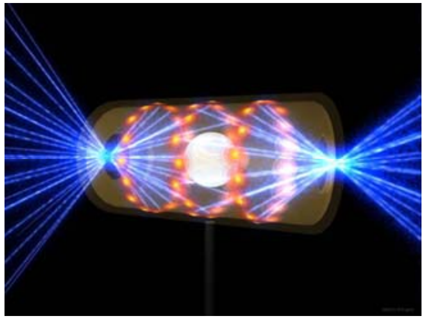


Hot-spot development
pressure: 250 Gbar
p_{therm}/p_{degen} ~ 5

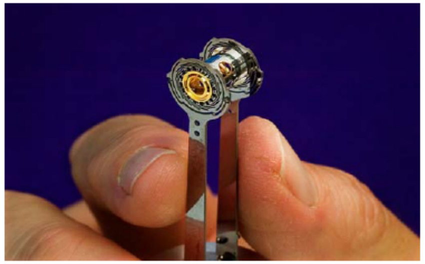
Core heating by confined α-particles

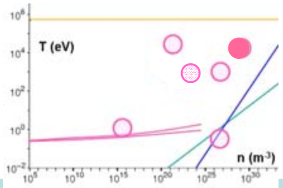
Burn wave propagates outward into shell of high n

Indirect drive



target





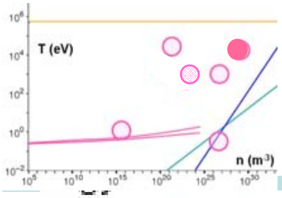
NIF and LMJ facilities

Recent photos from NIF: amplifier section

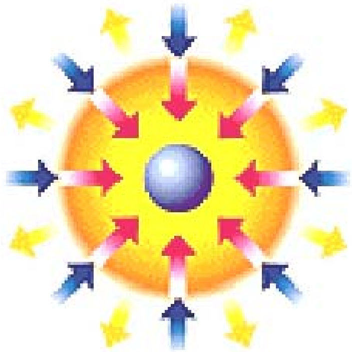
https://lasers.llnl.gov/multimedia/photo_gallery

NIF
Target chamber

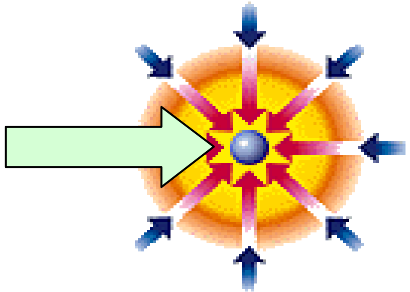
LMJ:
240 lasers
3^{rd} harmonic of Nd-Yag
1.8 MJ -> 20 MJ thermonuclear yield
550 TW



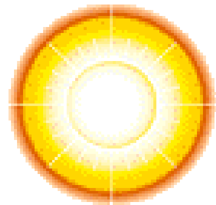
New concept: Fast ignition



Compression without hot spot



PW laser pulse creates a channel to the core and produces MeV electrons



relativistic electrons heat the core creating a fusion burn wave.

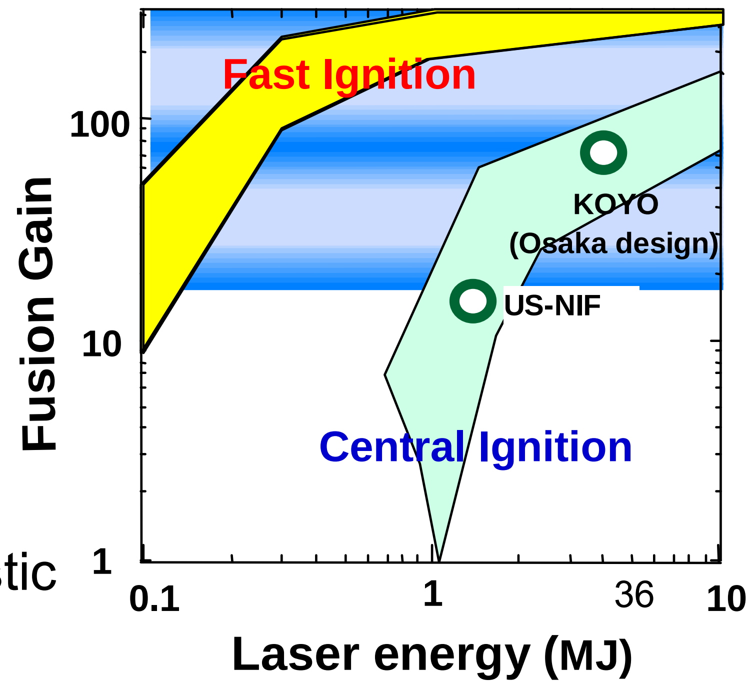
Topics and issues:

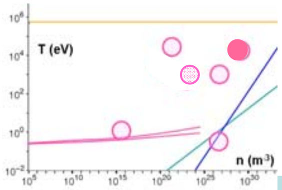
Much lower laser energy possible (200 kJ instead of 1.5 MJ)

Less critical for Rayleigh-Taylor instabilities

Lower requirements to homogeneity of driver

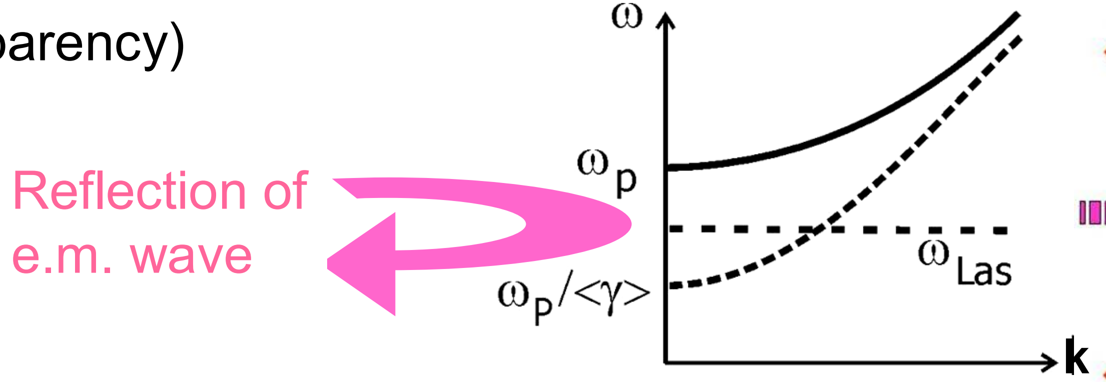
Picosecond laser necessary because of relativistic electron dynamics

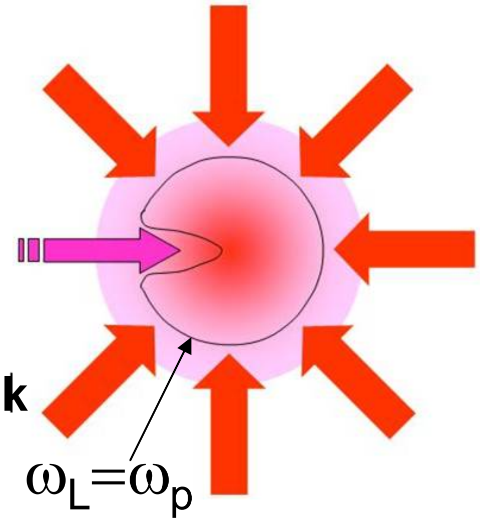




Physics of fast ignition

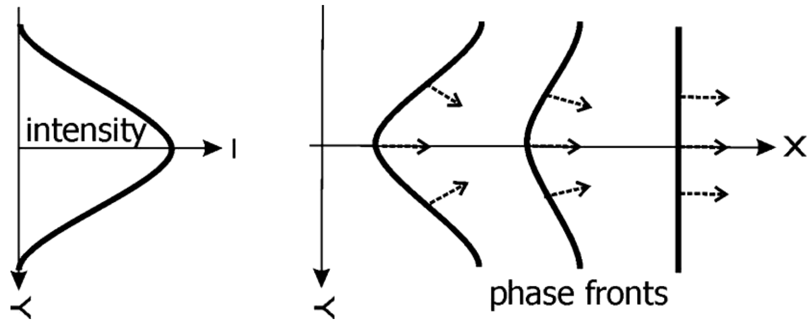
The PW laser pulse propagates through overdense plasma (induced transparency)

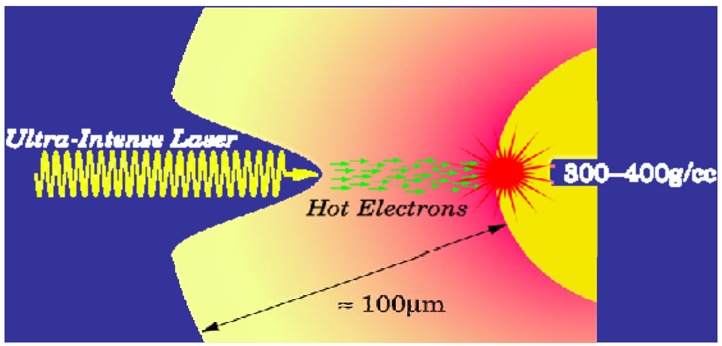




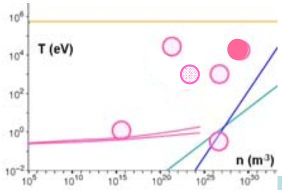
self-focussing (via relativistically modified index of refraction)

$$n_R = (1 - \omega_{po}^2 / \gamma\omega_L^2)^{1/2}$$





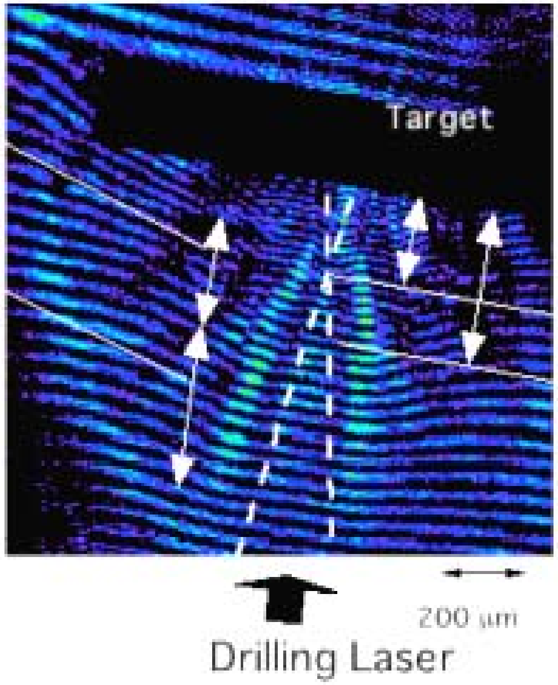
Laser intensity 10^{20}W/cm^2; radiation pressure: 30 Gbar
relativistic electrons 5 MeV, 100 MA/cm^2
heat the core, creating a fusion burn wave.



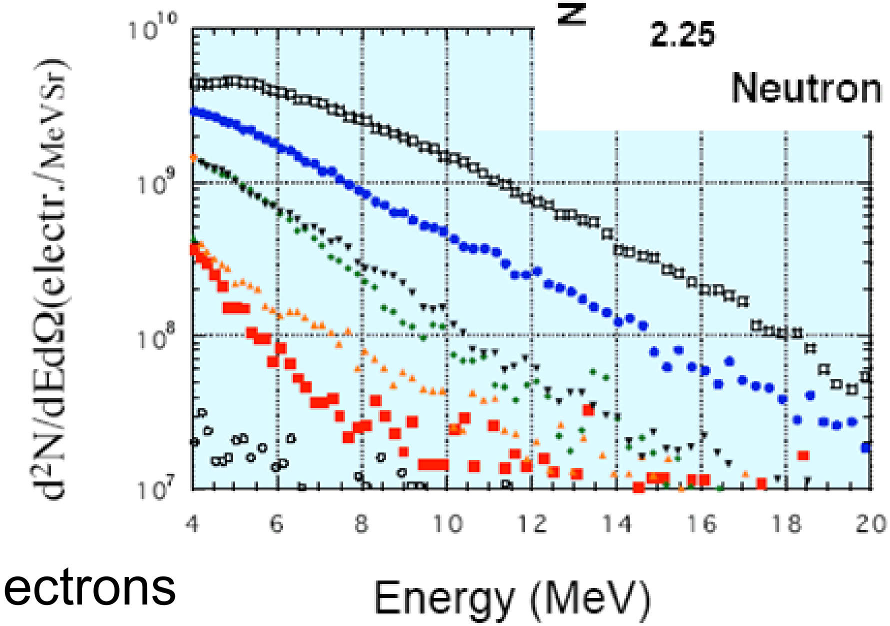
Fast ignition: results

...of a macroscopically relativistic plasma

Evidence for self-focussing
Interferogram

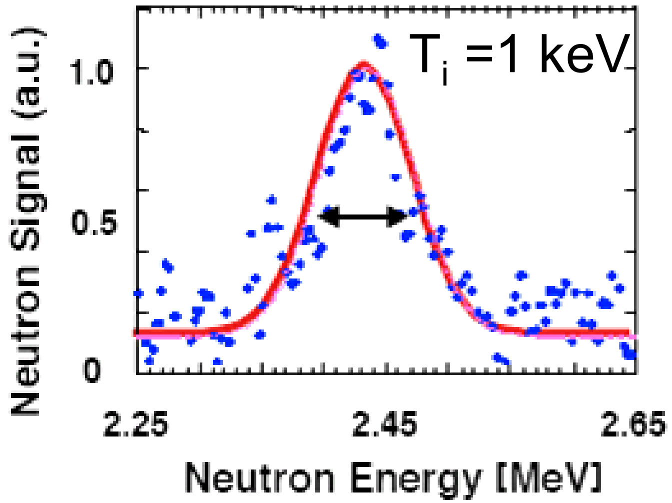


Electron spectra depending on laser intensity



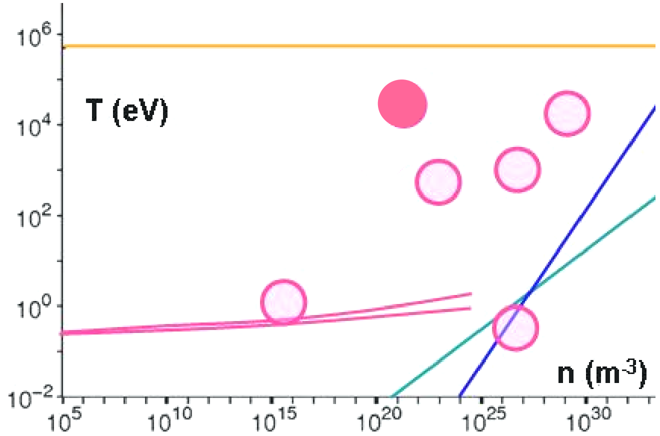
Energetic electrons up to $E/m_ec^2 \sim 80$

Thermal neutron spectra (DD) with fast ignition



Kodama et al. Nature 418, 933 (2002)

6. Topic: Fusion and magnetic confinement



Fusion reaction:

D + T → ^{4}He + n + 17.6 MeV

0.08 g D und 0.2 g Li

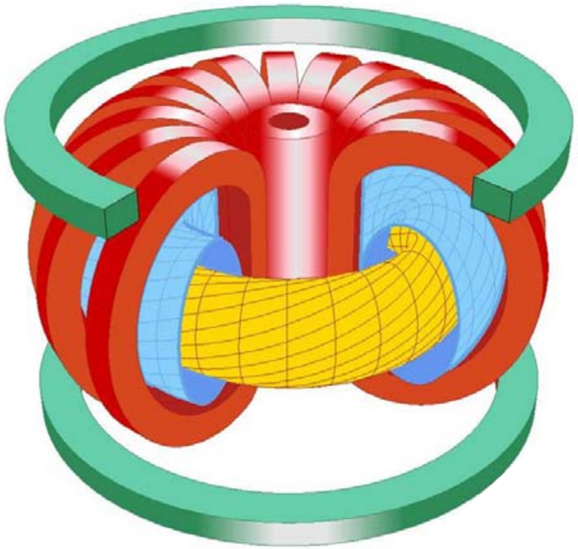
U. Samm, FZJ

Magnetic confinement

in toroidal systems

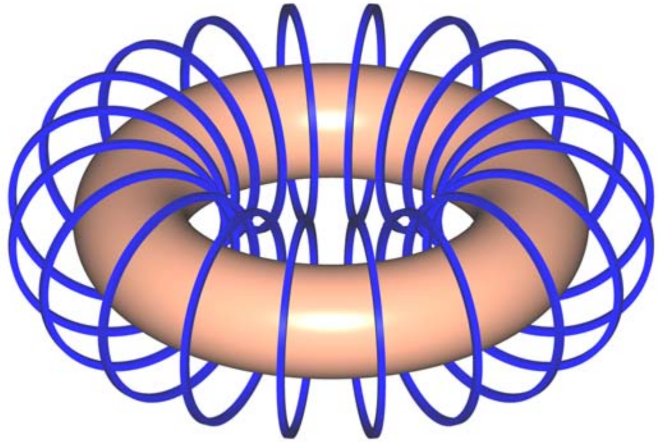
⊥ confinement: gyration

II confinement: torus geometry



Tokamak

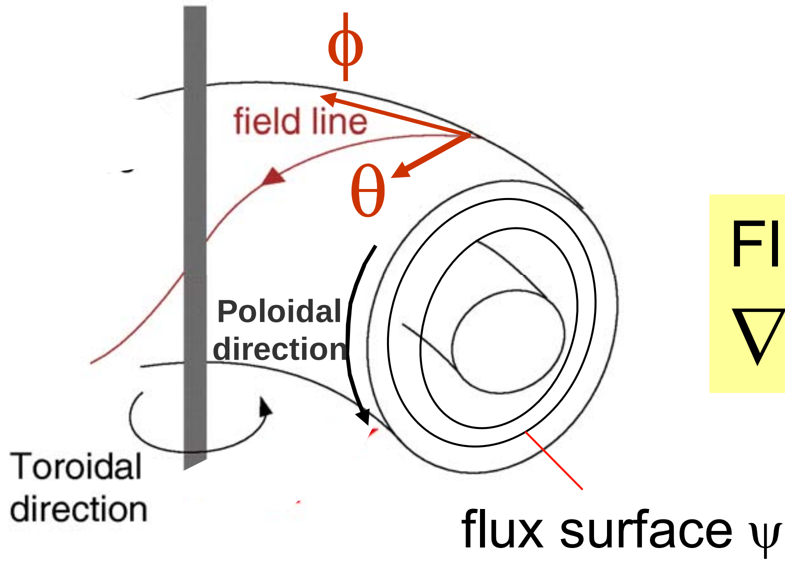
The basis of toroidal confinement



Toroidal geometry: no end losses
BUT
Vertical drift of particles in inhomogeneous field: $B \sim 1/R$

Helical magnetic field line:

- B_Φ: toroidal field (external)
- B_Θ: poloidal field (external, internal)

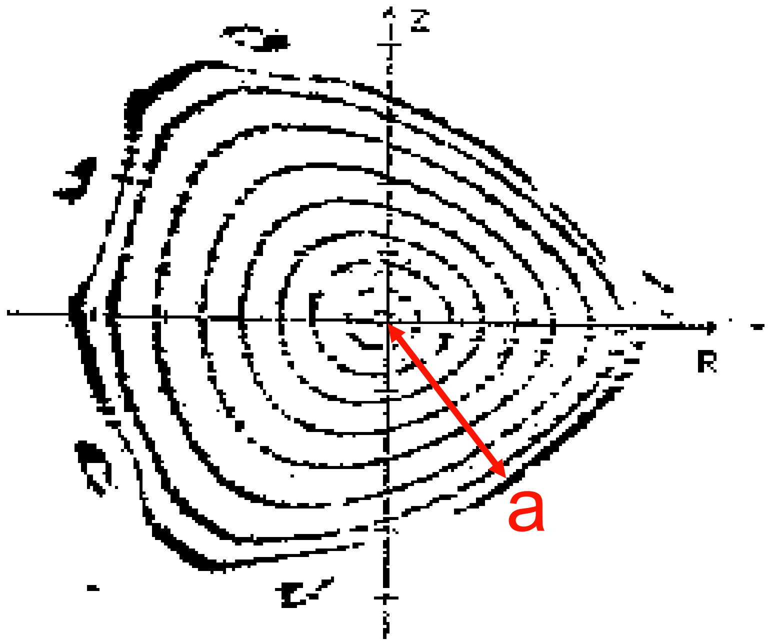


Flux surfaces:

$\nabla\psi \cdot \mathbf{B} = 0$

Equilibrium of toroidal systems

The nested flux surfaces provide confinement
Measured flux surfaces from
W7-AS Stellarator



Poloidal cross section

Rough estimate of collisional transport in magnetised plasmas

$D = \Delta x^2 / 2\Delta t$

$\parallel B$: $D_{\parallel} \sim \lambda^2/\tau_{cb}$
$\perp B$: $D_{\perp} \sim \rho_L{}^2/\tau_{cb}$

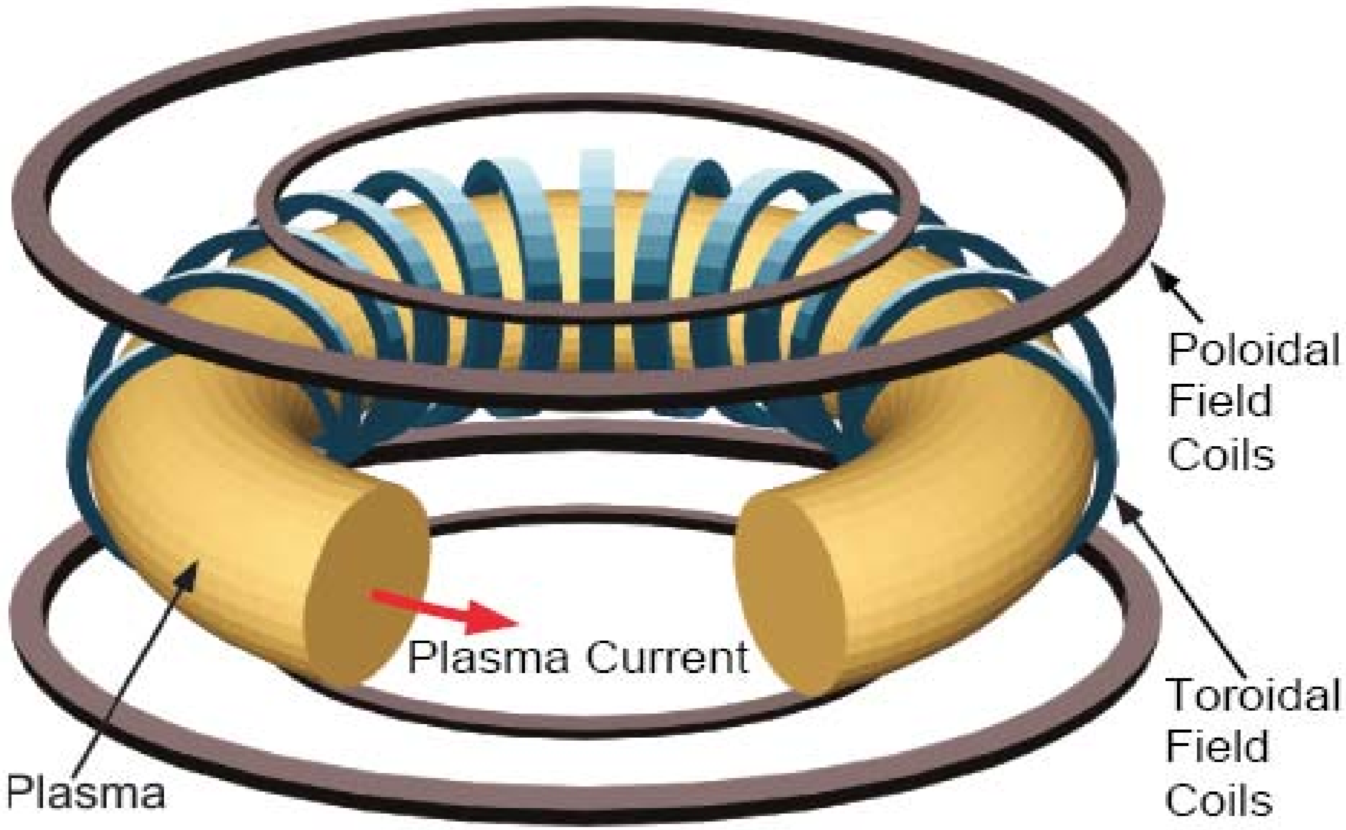
$D_{\parallel} \sim 10^{10}\, D_{\perp}$

$\tau_E \sim a^2/D_{\perp}$

size or thermal insulation

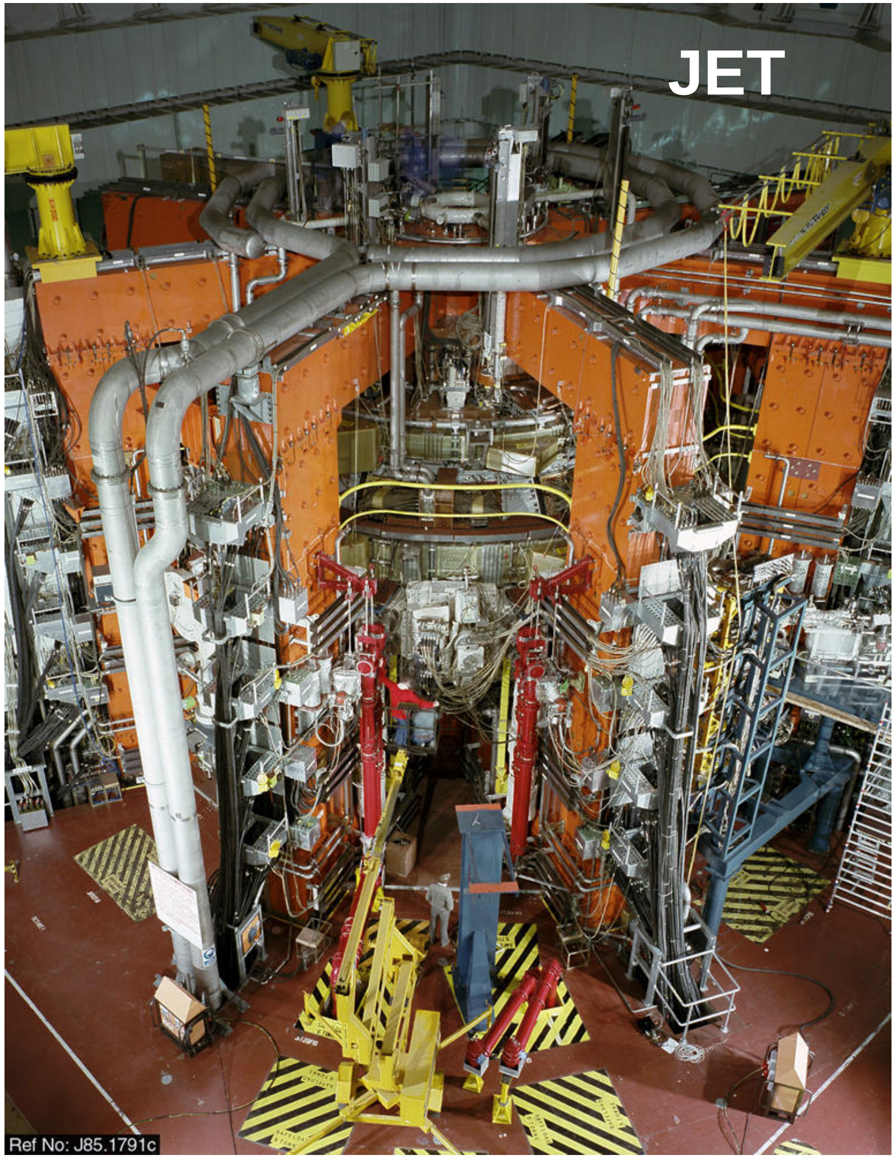
Two toroidal confinement systems

1. Tokamak

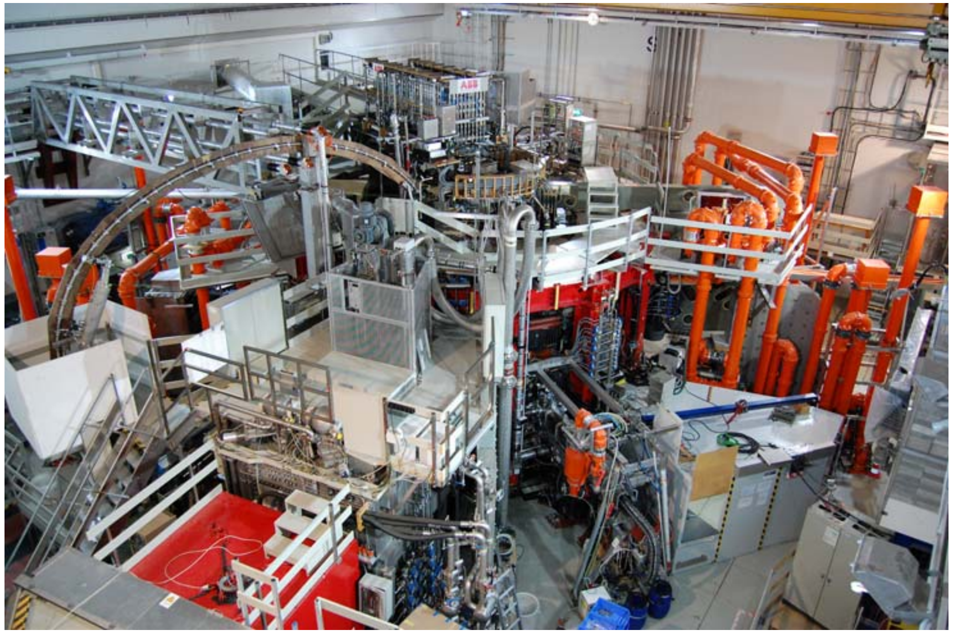


I_p induced (by transformer)

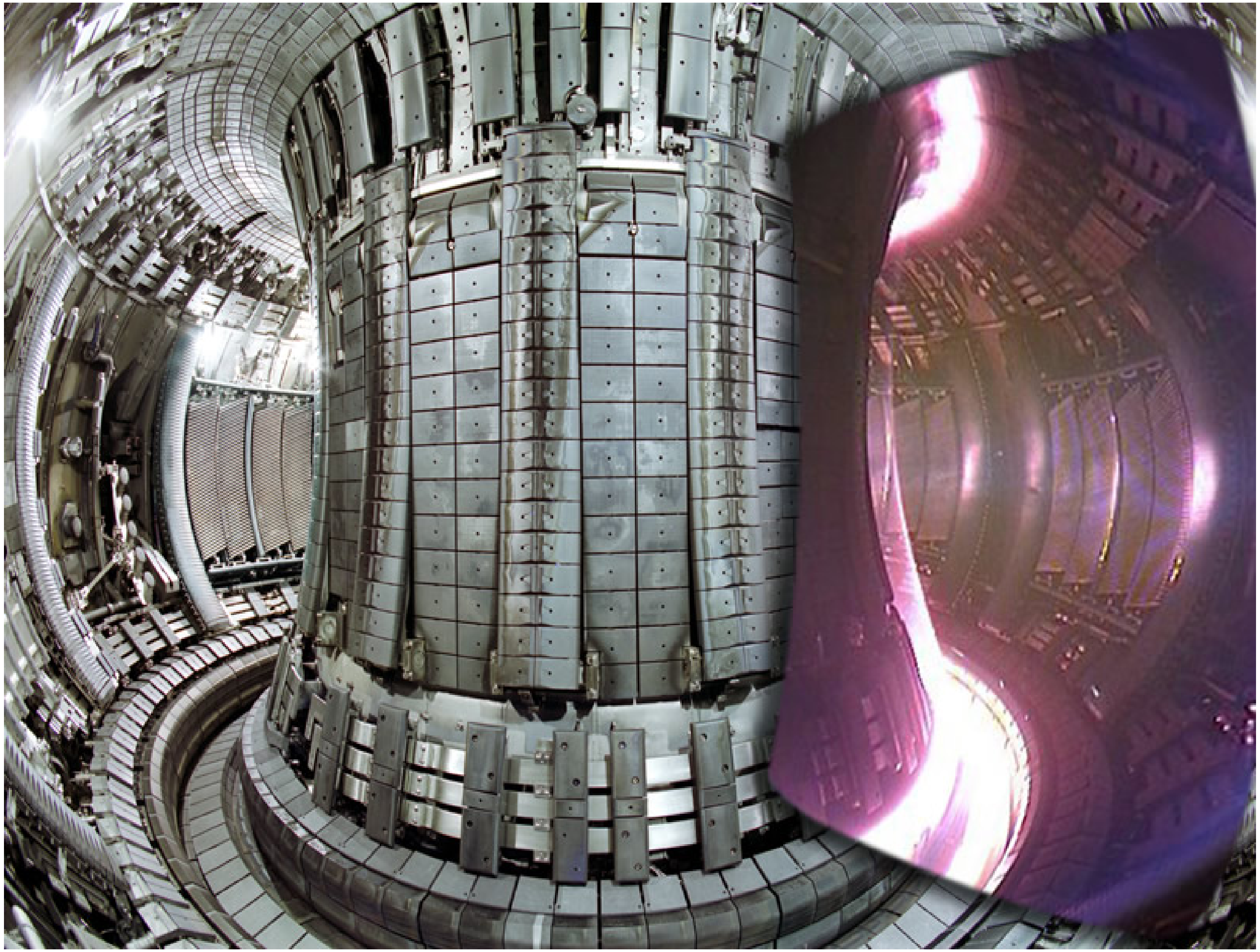
The JET and ASDEX-Up tokamaks

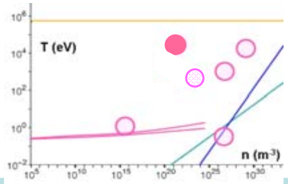


ASDEX-Upgrade
IPP Garching

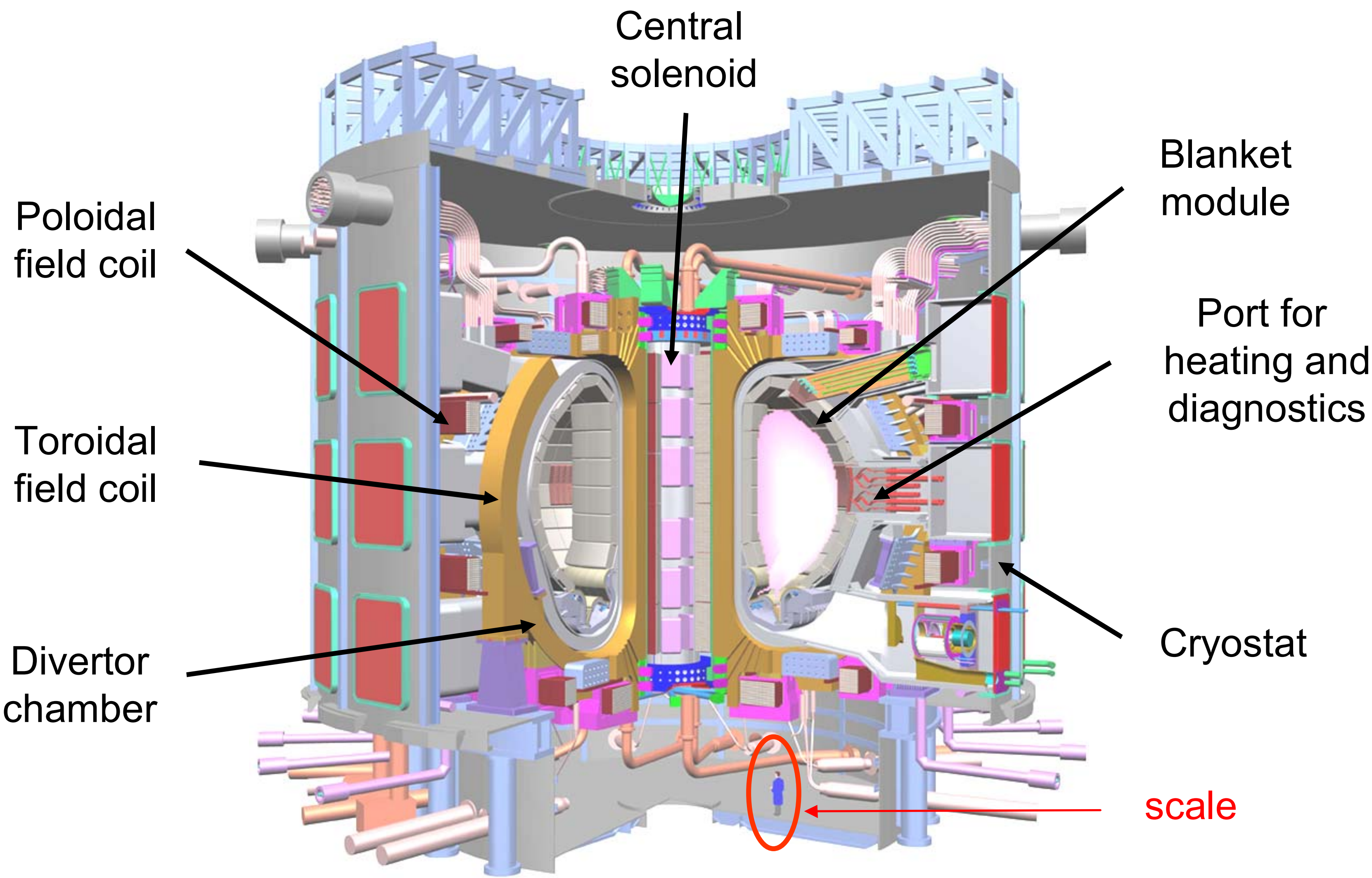


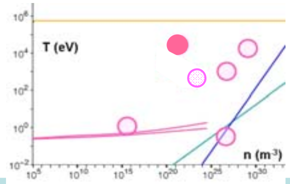
The JET tokamak (inside)




T (eV)
n (m-3)

ITER


Central solenoid
Poloidal field coil
Toroidal field coil
Divertor chamber
Blanket module
Port for heating and diagnostics
Cryostat
scale



ITER: The 1st experimental power reactor

A fusion plasma has to fulfil many physics requirements simultaneously:
equilibrium, stability, „tamed“ turbulence (H-mode operation), cleanliness, exhaust of helium, heating to 15 keV, steady-state operation...

ITER design elaborated by an international partnership:

Europe, Russia, Japan, Korea, China, USA, India

ITER will produce 500 MW of fusion power for 30 min; Q ≥ 10

ITER will provide fusion technology:

Nb_3Ti-superconductivity, T-breeding, high-heatflux components, heating technology...

ITER will clarify remaining open physics issues:

transport and stability with 3.5 MeV α-particles, He exhaust, burn control...

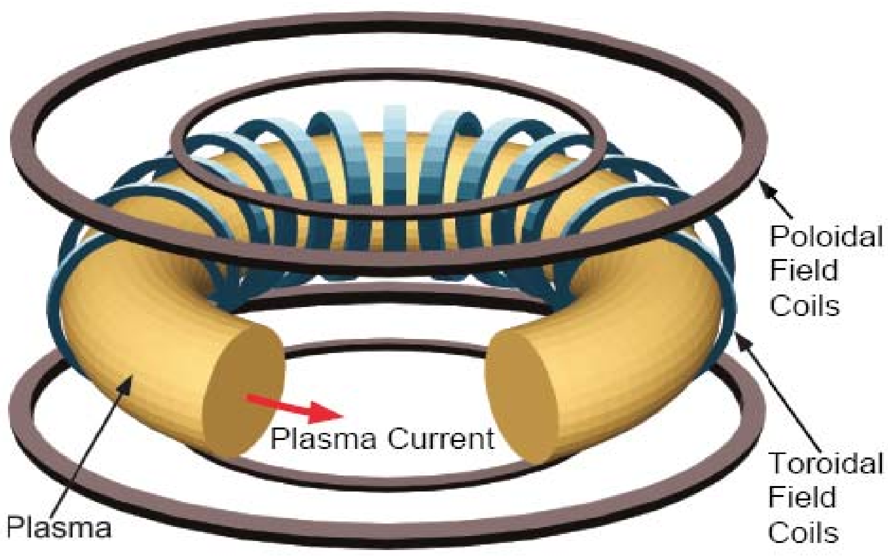
ITER operation will start around 2018

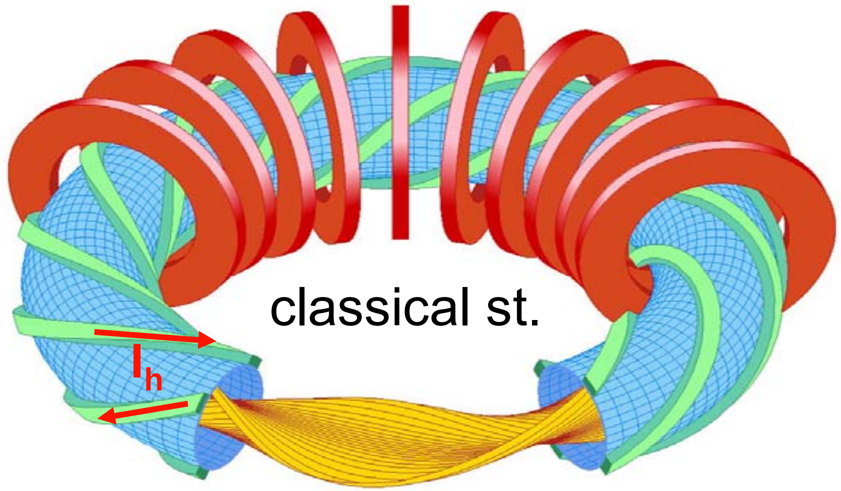
The ITER site – as it once will be

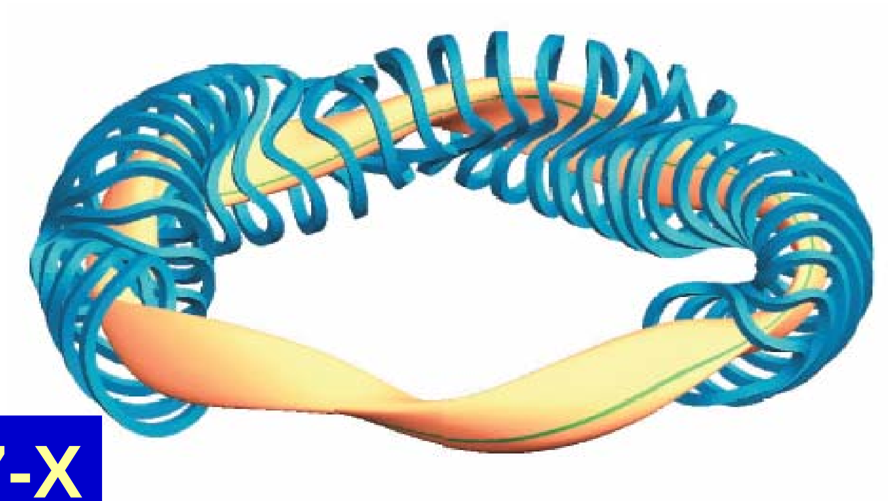
Two toroidal confinement systems

2. Stellarator

Tokamak





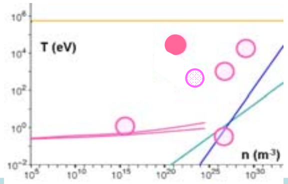


Wendelstein 7-X

Why stellarators ?

Tokamak and stellarator are complementary

- in the tokamak, the current flows in the plasma
- in the stellarator, it flows in the coils
- the tokamak is pulsed
- the stellarator is for steady-state operation
- the tokamak can develop detrimental instabilities
- the stellarator is not 2-dimensional

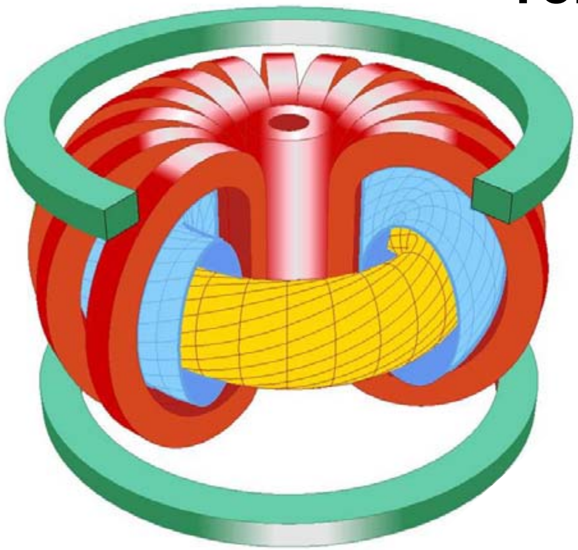


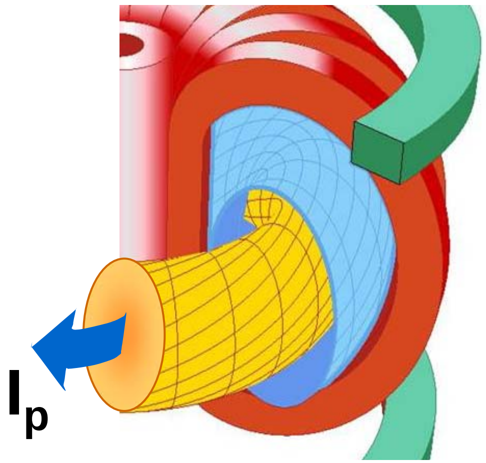
Concept improvement: the stellarator

Magnetic equilibrium by twisted magnetic field lines

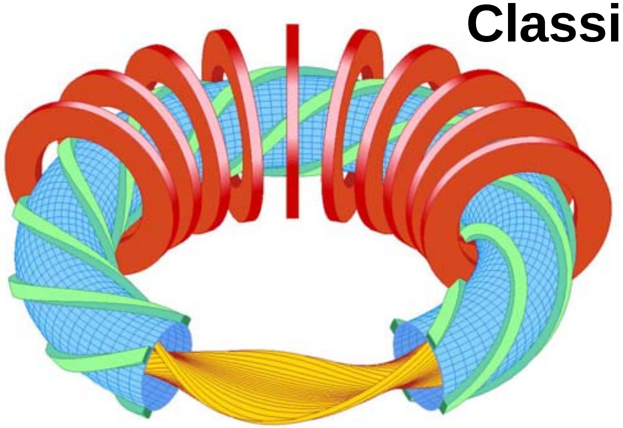
Two possibilities:

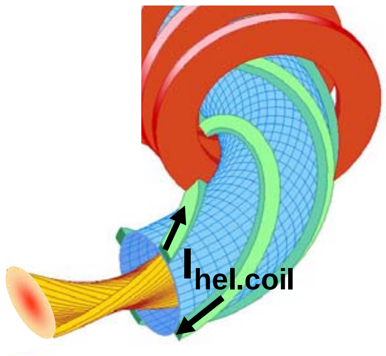
Tokamak





Classical Stellarator





Ampere´s law

Tokamak: **curl B = μ_0j**

→ 2D

sufficient confinement

BUT:

difficult to operate under steady-state (transformer)

current driven instabilities

Stellarator: **curl B = 0**

→ 3D

steady-state operation

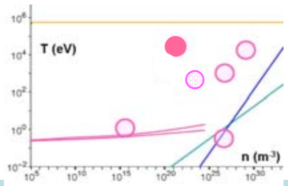
quiescent nature

BUT:

no continuous symmetry

no associated constant of motion

insufficient confinement



The Wendelstein 7-X stellarator

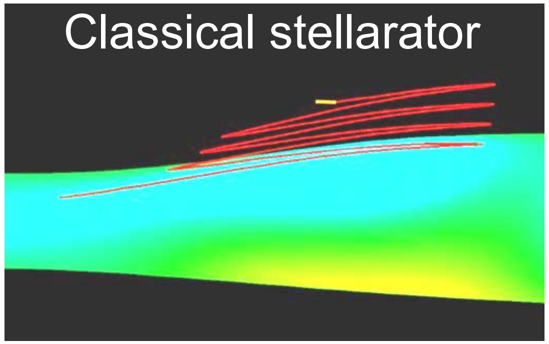
Optimisation of a 3D toroidal system: A manifestation of computational physics

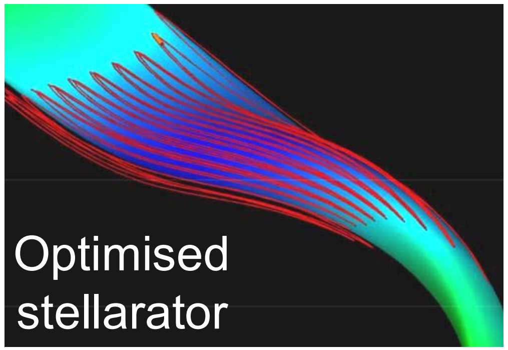
Goal: Improvement of particle and energy confinement (+ 6 other criteria)

Method: Plasma description in magnetic coordinates (field lines appear straight)

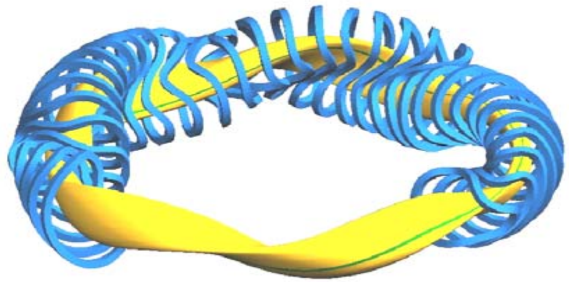
Recognition: The particle guiding centres depend on **|B|** only

Discovery: **|B|** can be made 2D in 3D geometry -> quasi-symmetric systems


Classical stellarator


Optimised stellarator

The modular coil system of W7-X



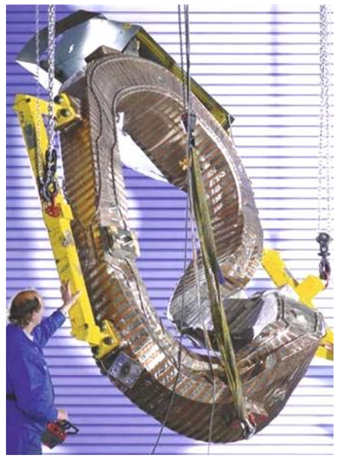
The freedom of 3-d

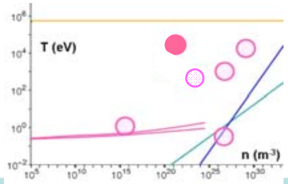
Presentation of desired field properties in combination of spatial Fourier coefficients B_{mn}

Improvement of confinement: $B_{01} \sim -(B_{10} + B_{11})$

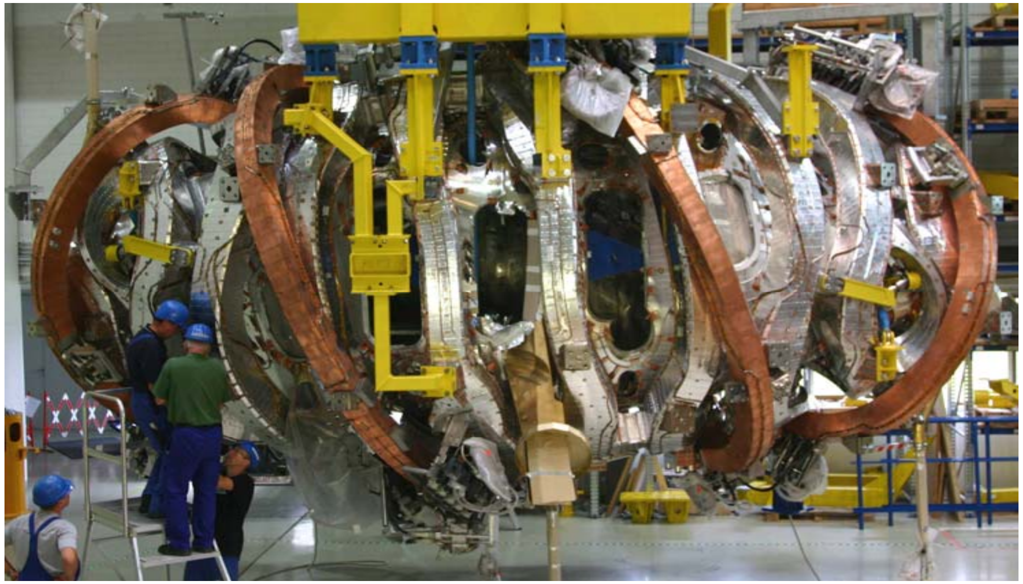
No bootstrap current: $B_{10} = 0.5\ B_{11}$

B_{10} = toroidal-, B_{11}= helical-, B_{01} = mirror field component


W7-X coil

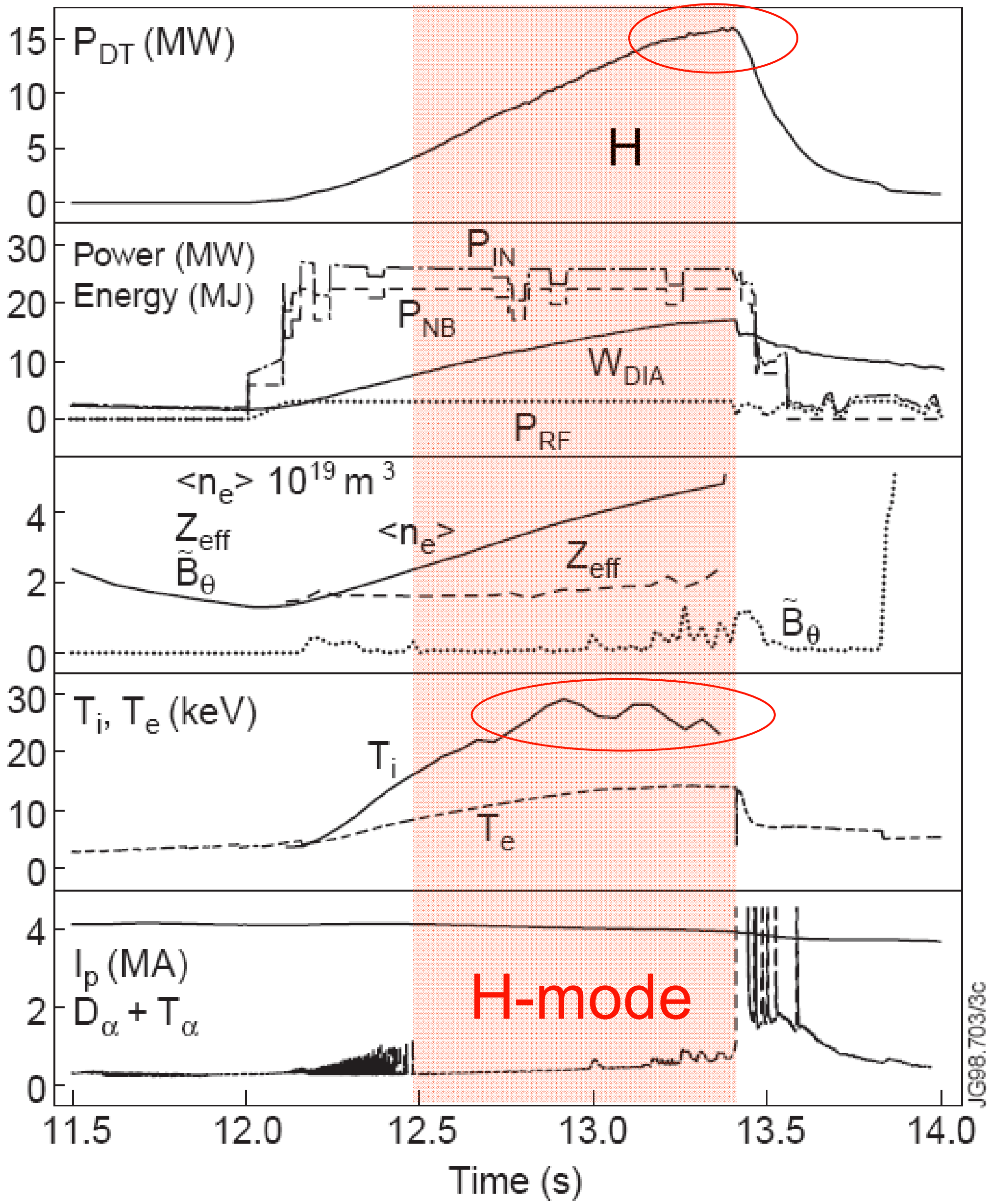


Assembly status of W7-X



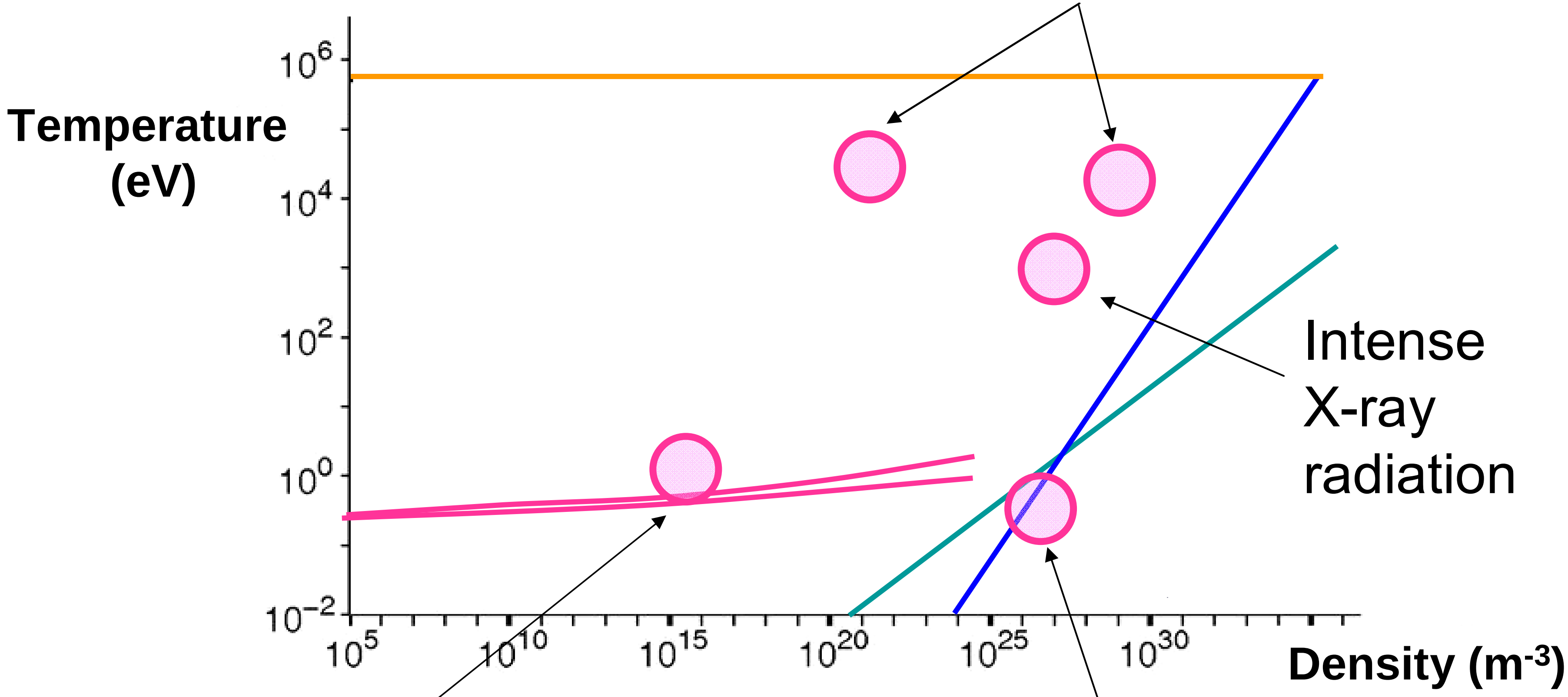
Achievements in magnetic confinement

The 16.1 MW DT discharge of JET



Summary

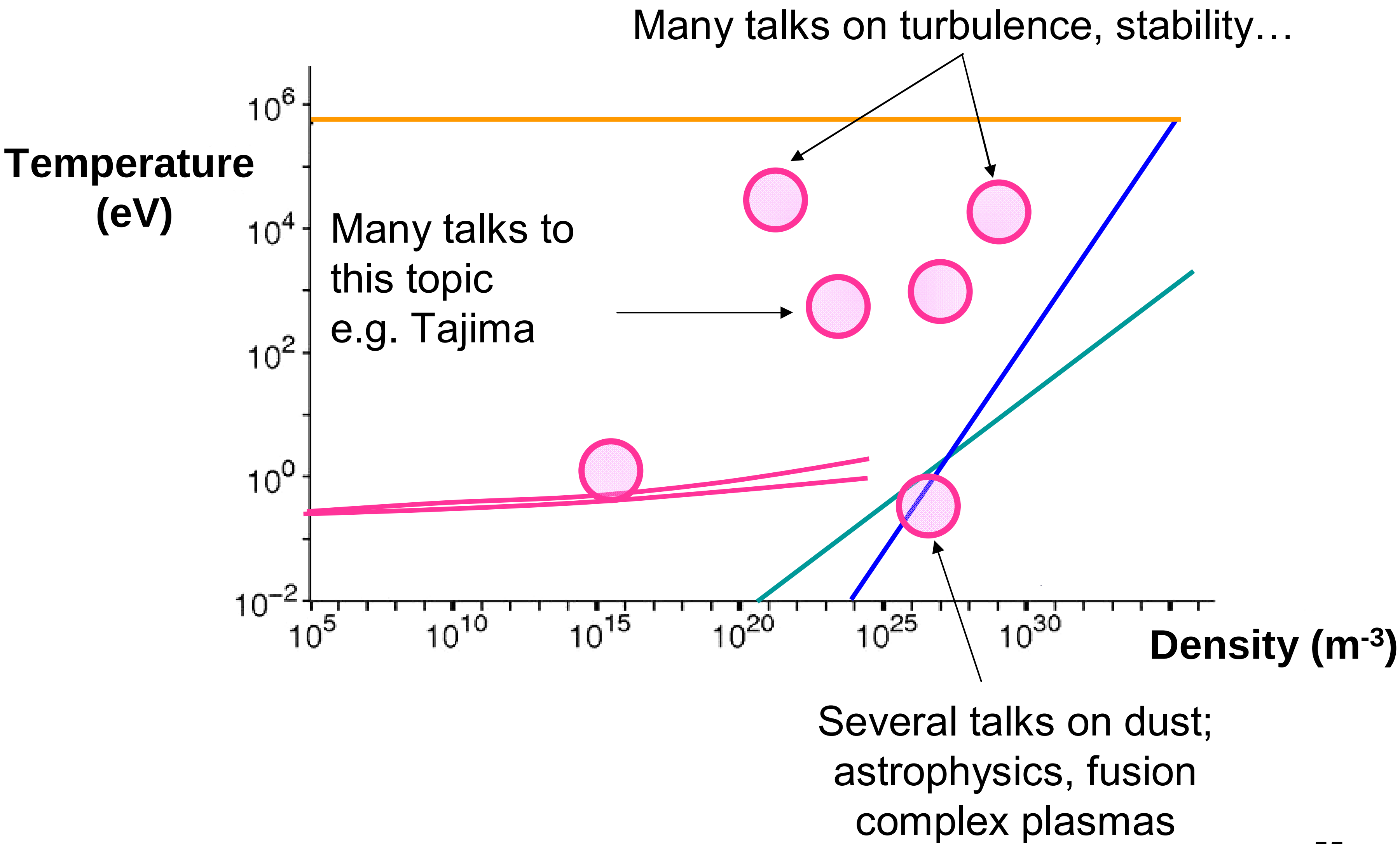
Energy production; ITER, NIF, LMJ



Light, IT, medical application and self-organisation physics

EOS
Links to phase transitions low-dimensionality systems

Summary



Many talks on turbulence, stability…
Temperature (eV)
10^6
10^4
10^2
10^0
10^{-2}
Many talks to this topic e.g. Tajima
10^5
10^{10}
10^{15}
10^{20}
10^{25}
10^{30}
Density (m^{-3})
Several talks on dust; astrophysics, fusion complex plasmas

End + Thanks

Low temperature plasmas:
- G. Kroesen, Uni Eindhoven
- K.-D. Weltmann, INP, Greifswald
- H.G. Purwins, UNI Münster

Laser Plasmas:
- J. Meyer-ter-Vehn, MPQ, Garching
- V. Tikhonchuk, LMI, Bordeau

Strongly coupled plasmas:
- A. Melzer, EMAU, Greifswald