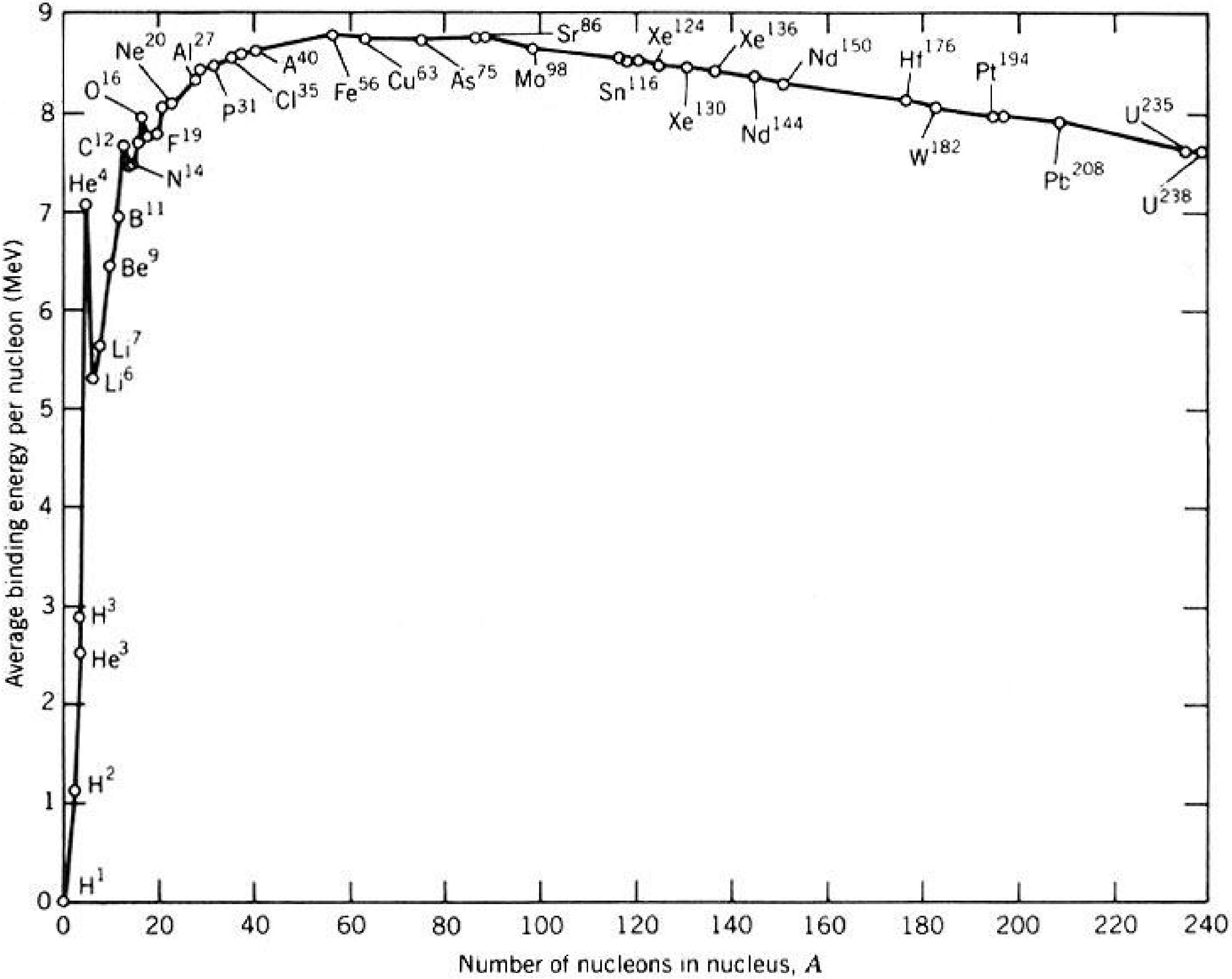
La Fusion Nucléaire

Energies de liaison



Réactions de fusion

- $p+p+p+p \rightarrow \alpha(He_4)+2e^-+2\nu+28$ MeV(4x7) (Interaction faible)
- $p+n \rightarrow D(H_2)+1{,}2$ MeV
- $D+D \rightarrow He_4{}^*(23{,}2\ \text{MeV}) \rightarrow \alpha + (28-4\text{x}1{,}2)$

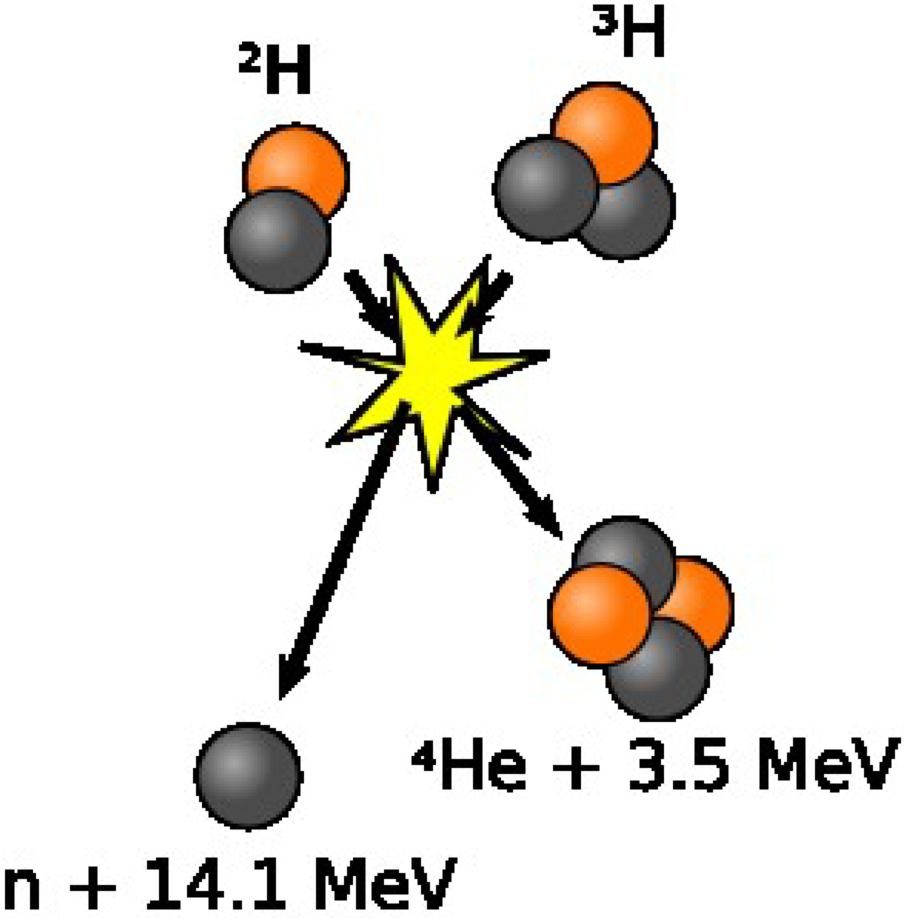
  $\rightarrow He_3 + n + (7{,}5-4{,}2=3{,}3\ \text{MeV})$

  $\rightarrow T\ (H_2)+p+(8{,}2-4{,}2=4{,}0\ \text{MeV})$
- **$D+T \rightarrow He_5{}^* \rightarrow \alpha(He_4)+n+17{,}6$ MeV** **(E/A=3,48)**
- $D+He_3 \rightarrow Li_5{}^* \rightarrow \alpha(He_4)+p+18{,}4$ MeV

Fission

$B_n(238)=7{,}6$ MeV
$B_n(119)=8{,}5$ MeV
$\Delta B_n=0{,}9$ MeV
$\Delta E=238\text{x}0{,}9=215$ MeV (E/A=0,9)

Fusion D+T



Répulsion coulombienne

- Energie de répulsion entre deux noyaux de charges Z_1 et Z_2, masses A_1 et A_2
- Rayons nucléaires (formules approchées)

  $R(\text{Fermis}=10^{-13}\text{cm})=r_0A^{1/3}$ $r_0=1{,}45$

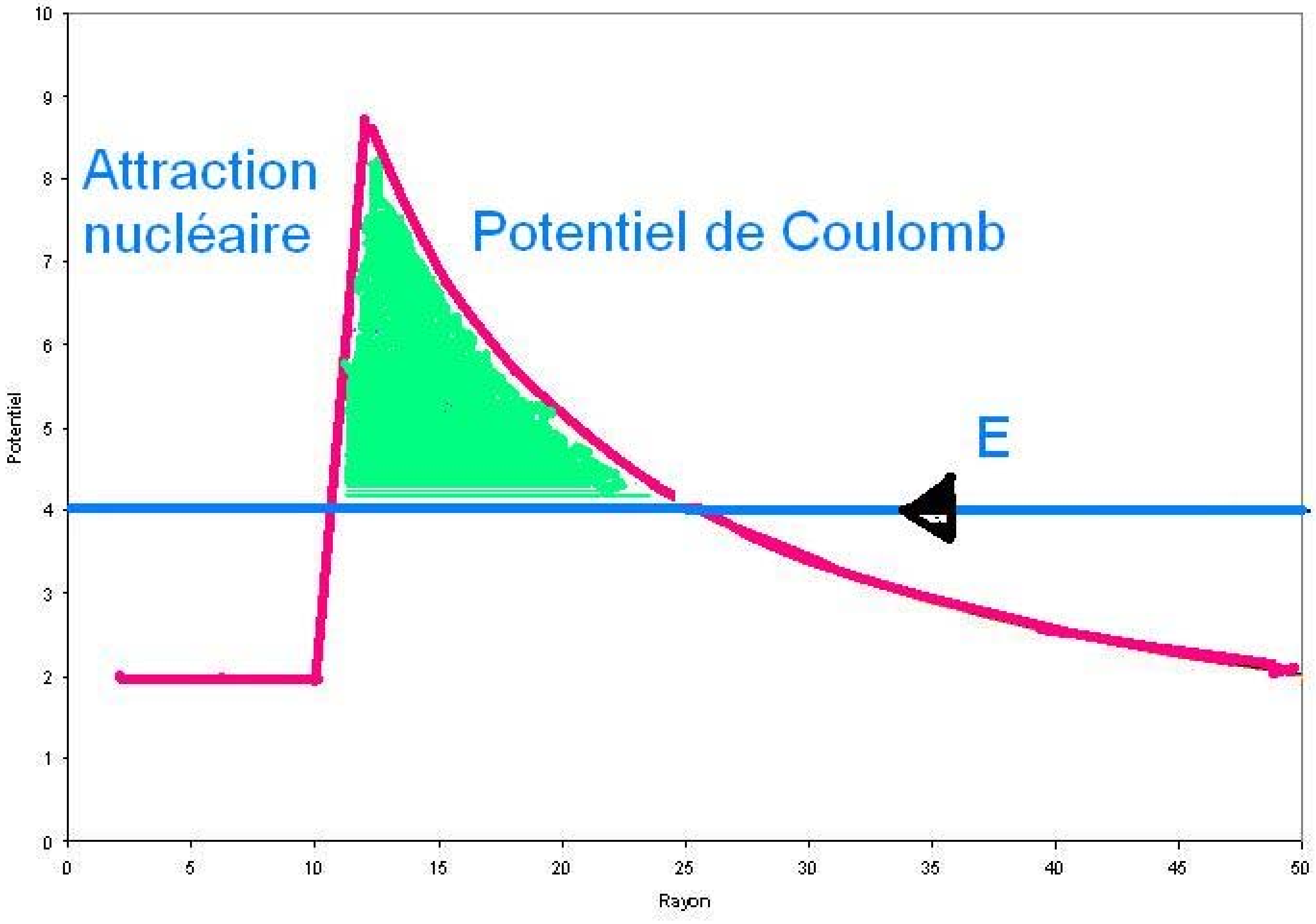
  R(deuton)=1,85 R(tritium)=2,1

$$V_{Coulomb}=1{,}44*\frac{Z_1Z_2}{1{,}45*\left(A_1^{1/3}+A_2^{1/3}\right)}$$

- $V_C(d+d)=0{,}394$ MeV
- $V_C(d+t)=0{,}367$ MeV

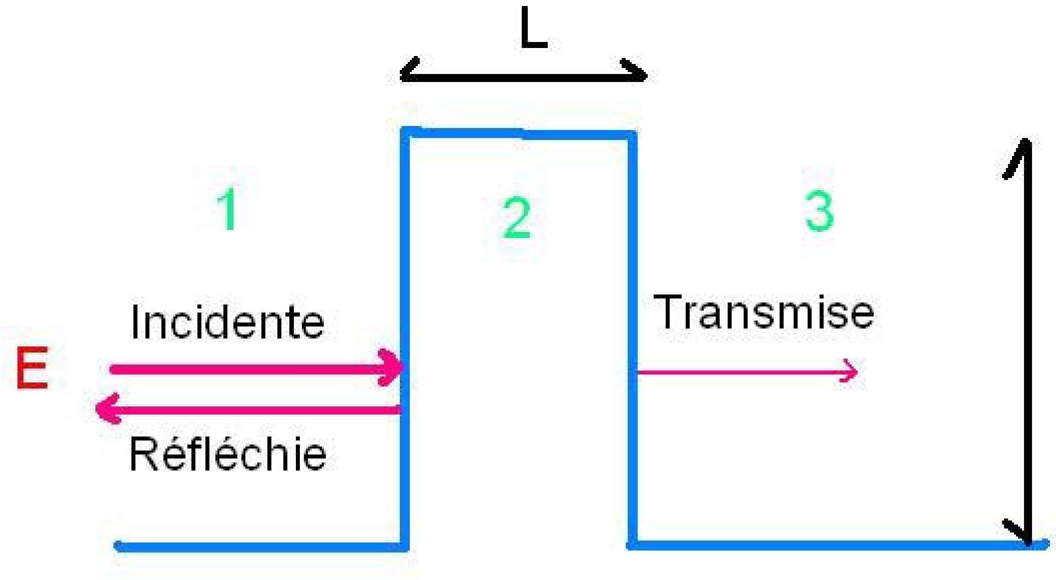
1 MeV=12 milliards de degrés K !!!

Barrière de fusion



Transmission de la barrière: effet quantique

Effet tunnel



$\Delta p.\Delta x > \hbar$ $\quad \Delta p > \frac{\hbar}{L}$ $\quad E' = \frac{(p+\Delta p)^2}{2m} = E + \frac{p\Delta p}{m} + \frac{\Delta p^2}{2m} \approx E + \frac{p\Delta p}{m}$

$$\Delta E > \frac{p\Delta p}{m} = v\frac{\hbar}{L}$$

Approximations

Distance d'approche: $r_c = \frac{Z_1 Z_2 e^2}{E}$

Section efficace: $\sigma_{Fusion} = \pi r_c^2 \theta = \pi \frac{Z_1^2 Z_2^2 e^2}{E^2} \theta$

Transmission de
la barrière (carrée):

$$\theta = \exp - \left(\frac{2L}{197} \sqrt{2Mc^2V\left(1 - \frac{E}{V}\right)} \right)$$

M est la masse réduite : collision de deux noyaux de masses M1 et M2:

$$M = \frac{M1M2}{M1+M2} \qquad M_i c^2 \approx 930 A_i$$

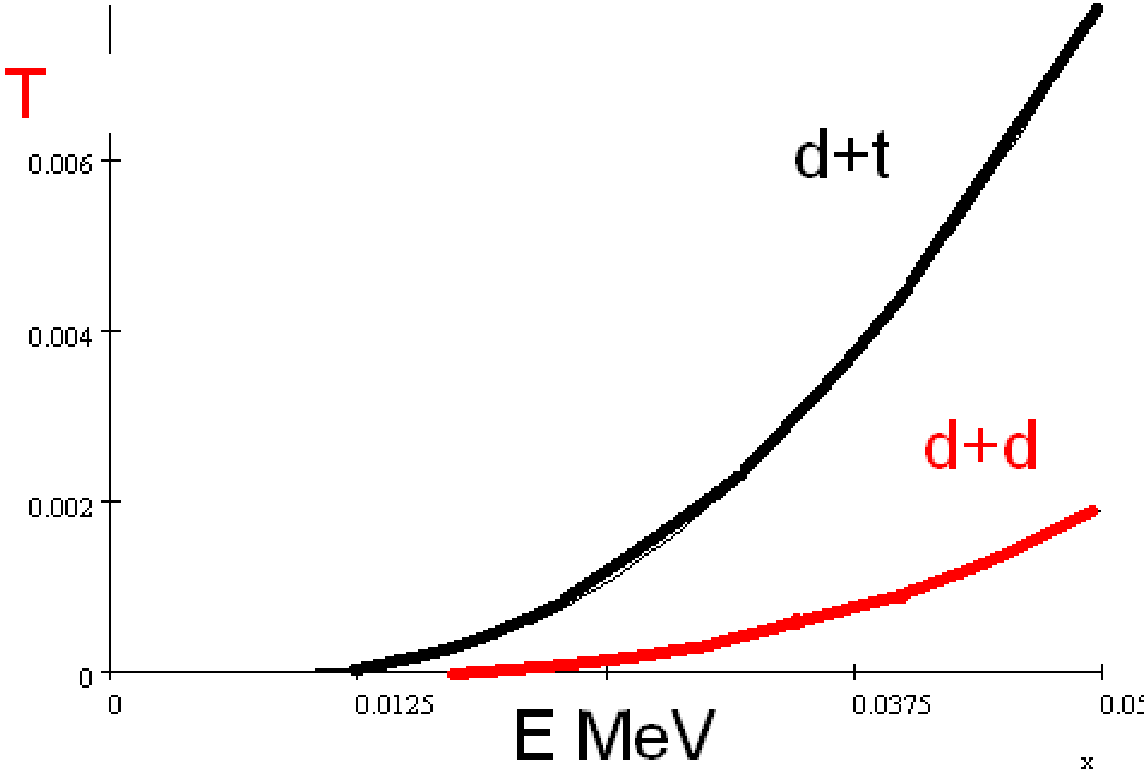
Barrière de Coulomb
(Gamow)

$$\theta = \exp - \left(\frac{1{,}44 * 2\pi * Z1 * Z2 \sqrt{M}}{197\sqrt{E}} \right)$$

Comparaison d+d, d+t Transmission

	10 keV 120 Md°K	5 keV 60 Md°K
d+d	$8.\ 10^{-7}$	$2{,}5\ 10^{-9}$
d+t	$2.\ 10^{-5}$	$2.\ 10^{-7}$

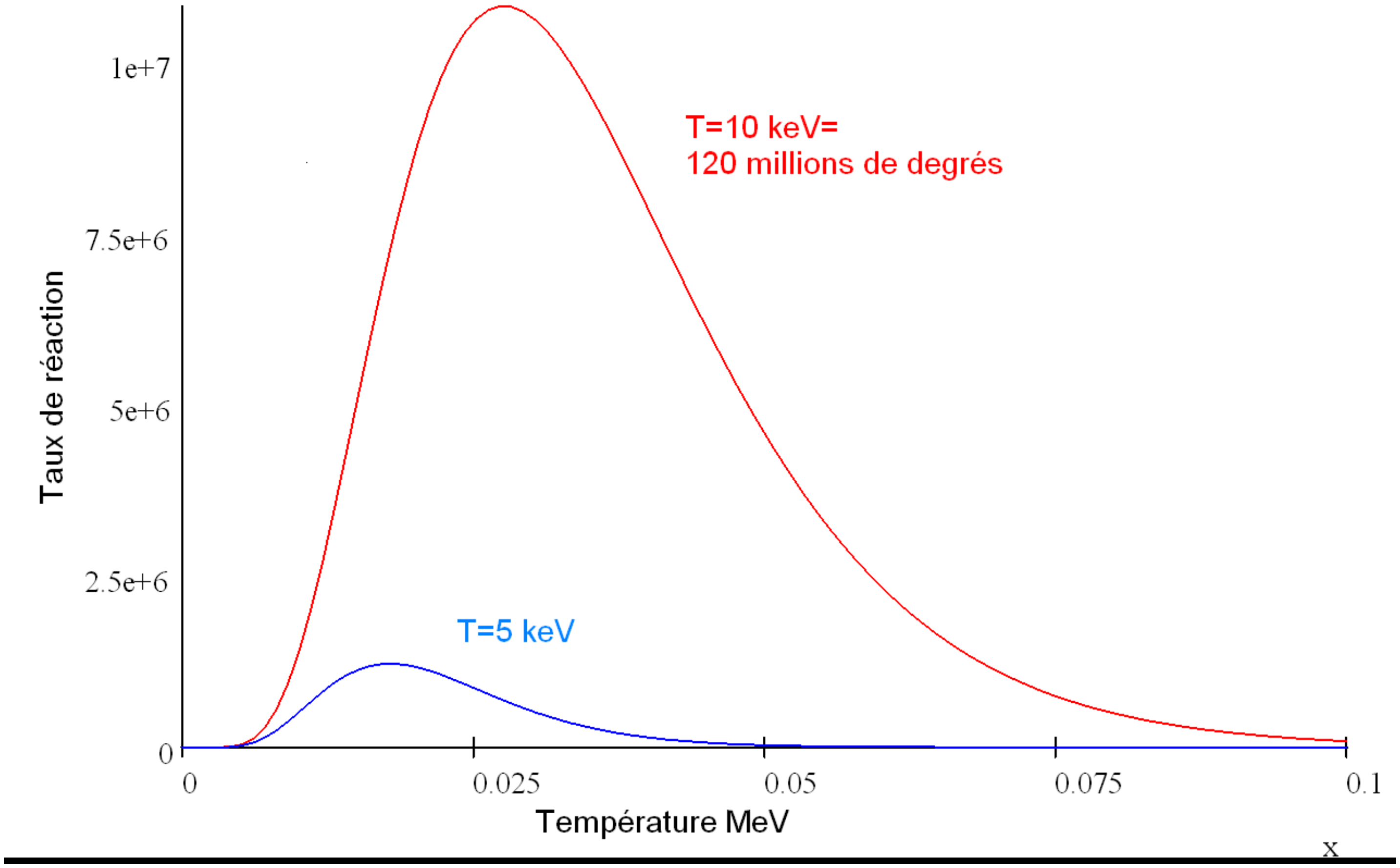
d+d vs d+t courbes



Taux de réaction

$$R(E) = \left(\frac{E}{\sqrt{2\pi m T}}\right)\exp\left(-\frac{E}{T}\right)\sigma_{fus}(E)$$

Pic astrophysique

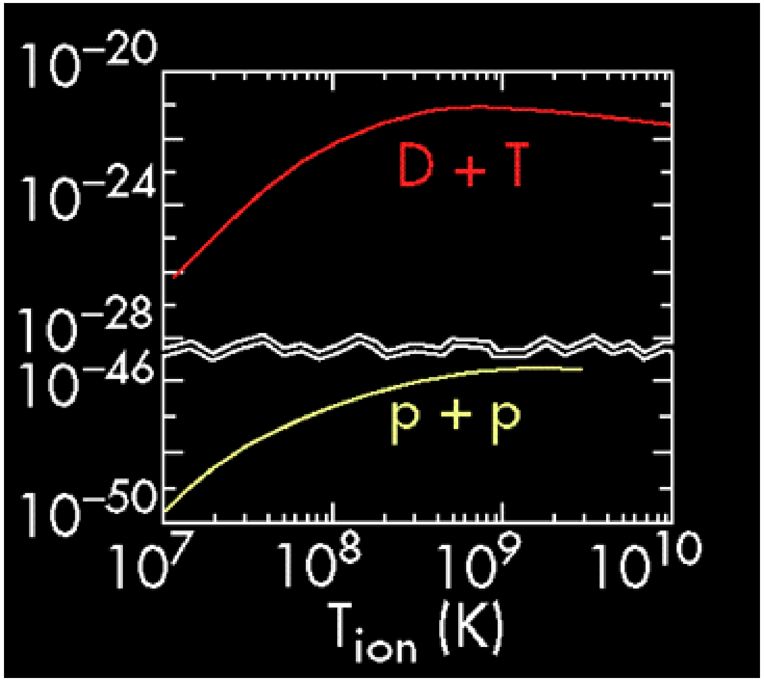


Taux(T)

(1 MeV=1.2 10^{10} d°K)

$$R_M(T) \approx 3.67 \times 10^{-20} \exp\left(-\frac{2}{T^{1/3}}\right)$$

Unité: m^3/s



Le plasma

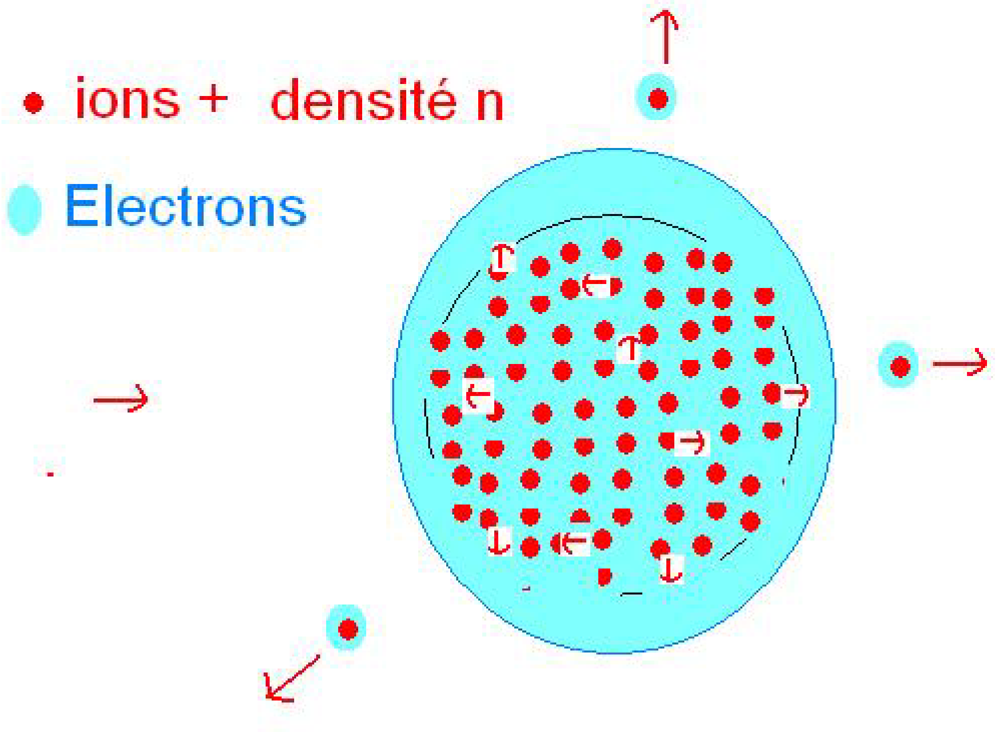
Mélange ions et électrons. Charge moyenne nulle

Densités n_e et n_i $Z_i n_i - n_e = 0$.

$$v_{e,i} = \sqrt{\frac{2T}{m_{e,i}}}$$

$$m_i >> m_e \qquad v_e >> v_i$$

Nuage
Électronique
Longueur de
Debye



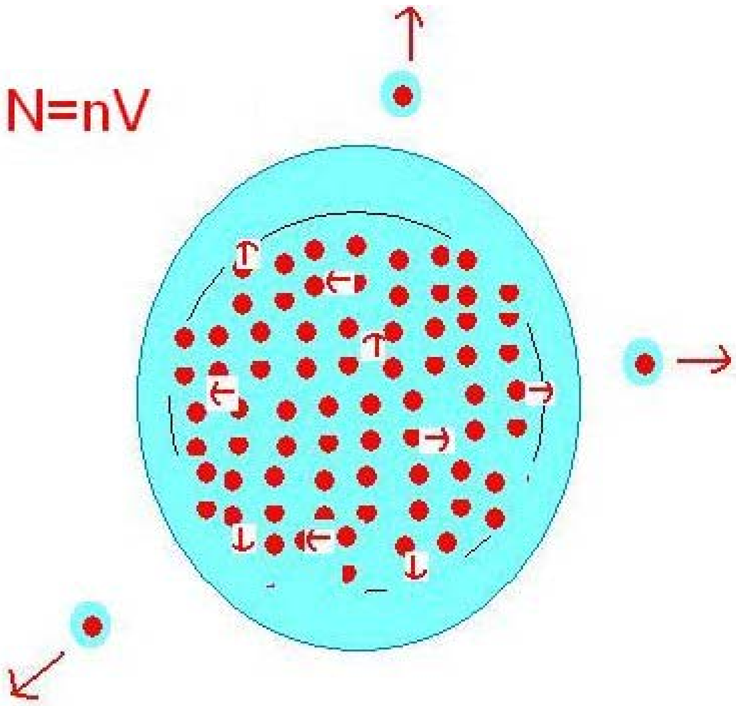
Temps de vie

Volume V du plasma, surface S

$$\frac{dN}{dt} = -\lambda N = -\frac{N}{\tau}$$

$$\frac{dN_i}{dt} = -\theta n_i v_i S = -\theta \frac{N_i}{V} \sqrt{\frac{2T}{m_i}} S$$

$$\lambda = \frac{S}{V} \theta \sqrt{\frac{2T}{m_i}}$$



Condition d'entretien

Nombre de réactions par cm^3: $n\sigma\phi$

Q énergie par interaction

$$W = (nv)(n\sigma(v))VQ = nNQR_M(T)$$

Perte d'énergie: $$Pertes = \frac{dN}{dt}T$$

Equilibre: $$W = Pertes$$

$$nQR_M(T) = \lambda T \qquad n\tau = \frac{T}{QR_M(T)}$$

Critère de Lawson

Unité: n/(m3/s)

$$n\tau = \frac{T}{QR_M(T)} = 0.27*10^{20}\frac{T}{Q}\exp\left(\frac{2}{T^{1/3}}\right)$$

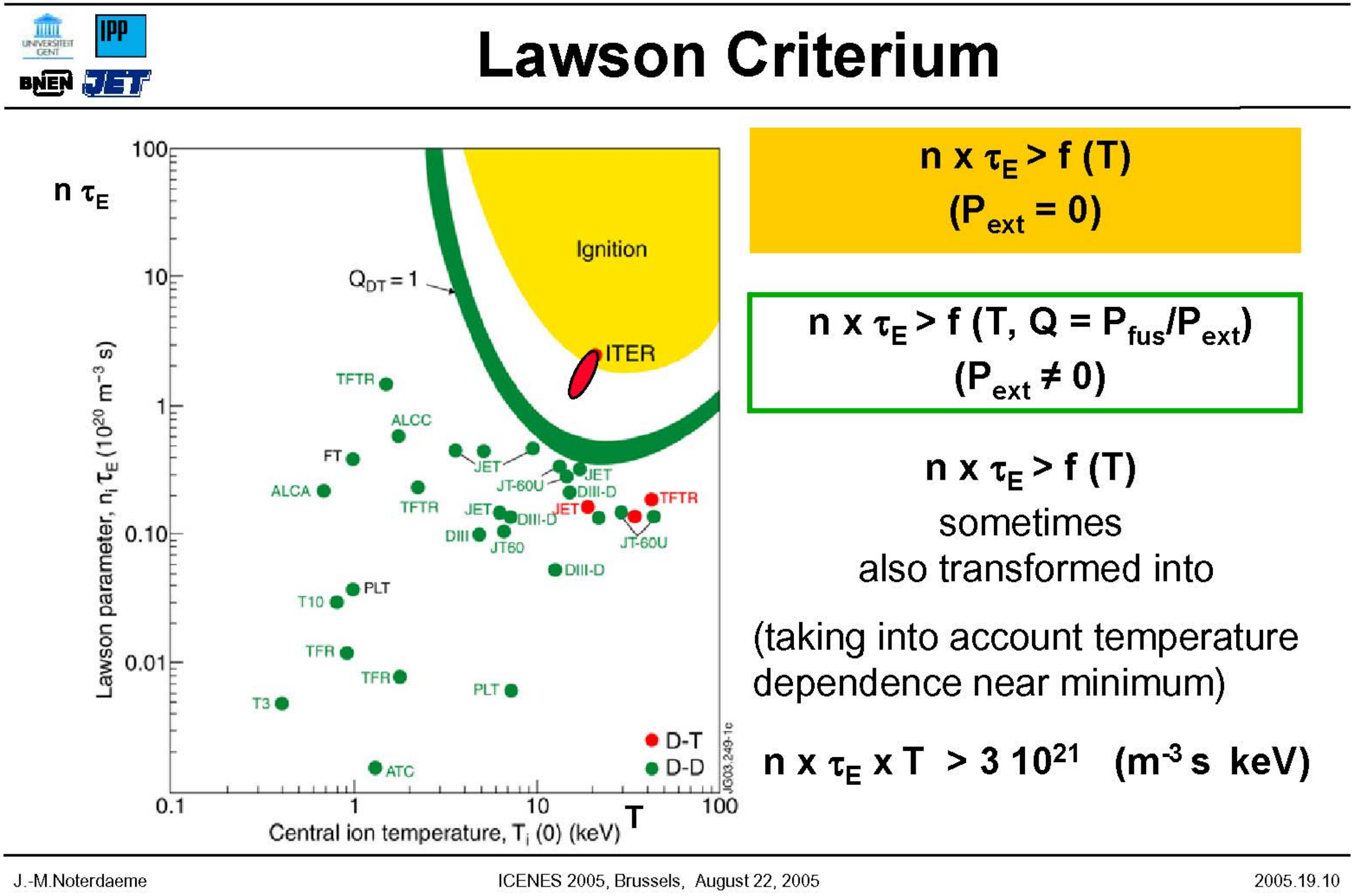
Unité: n/(cm3/s)

$$n\tau = \frac{T}{QR_M(T)} = 0.27*10^{14}\frac{T}{Q}\exp\left(\frac{2}{T^{1/3}}\right)$$

Pour T=10 keV (120 millions de d°).
Q=20 MeV

$n\tau = 1,43*10^{14}$ cm^{-3}.s

Réalisation de machines



Lawson Criterium

$n \times \tau_E > f(T)$

$(P_{ext} = 0)$

$n \times \tau_E > f(T, Q = P_{fus}/P_{ext})$

$(P_{ext} \neq 0)$

$n \times \tau_E > f(T)$

sometimes

also transformed into

(taking into account temperature dependence near minimum)

$n \times \tau_E \times T > 3\ 10^{21}$ $(m^{-3}\ s\ keV)$

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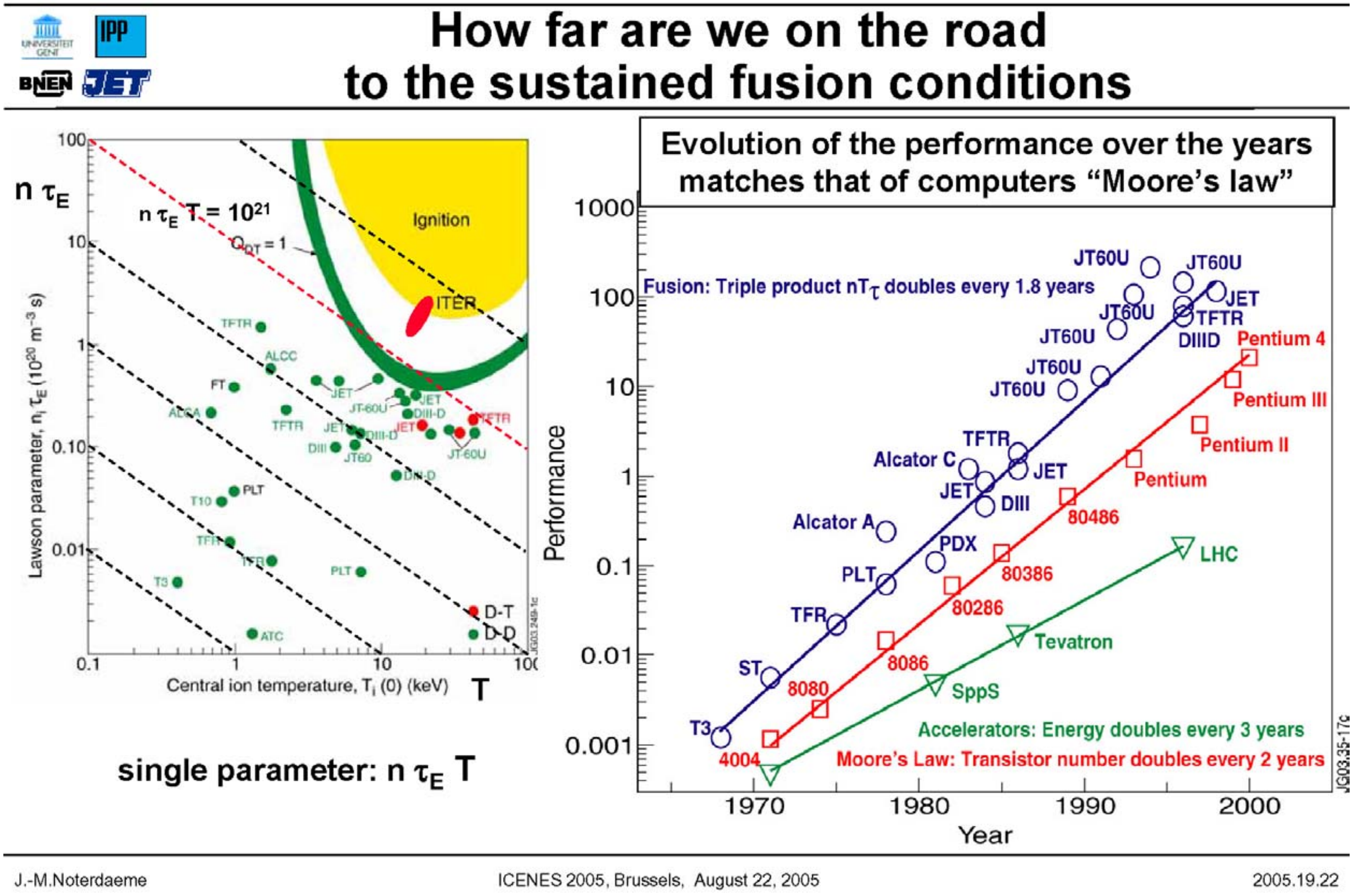
Evolution des performances

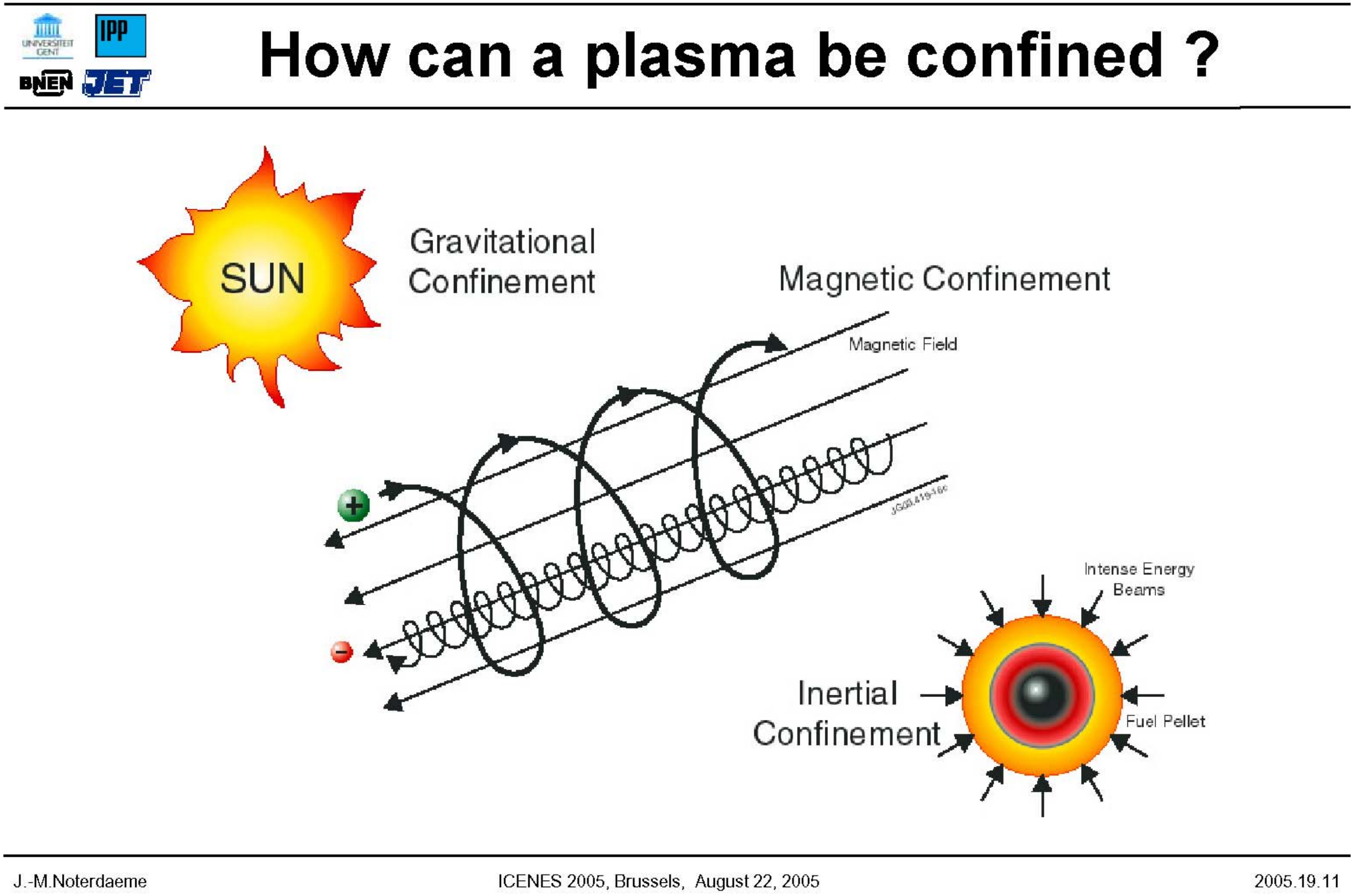


How far are we on the road to the sustained fusion conditions

Evolution of the performance over the years matches that of computers "Moore's law"

single parameter: n τ_E T

Principe de confinement



How can a plasma be confined ?

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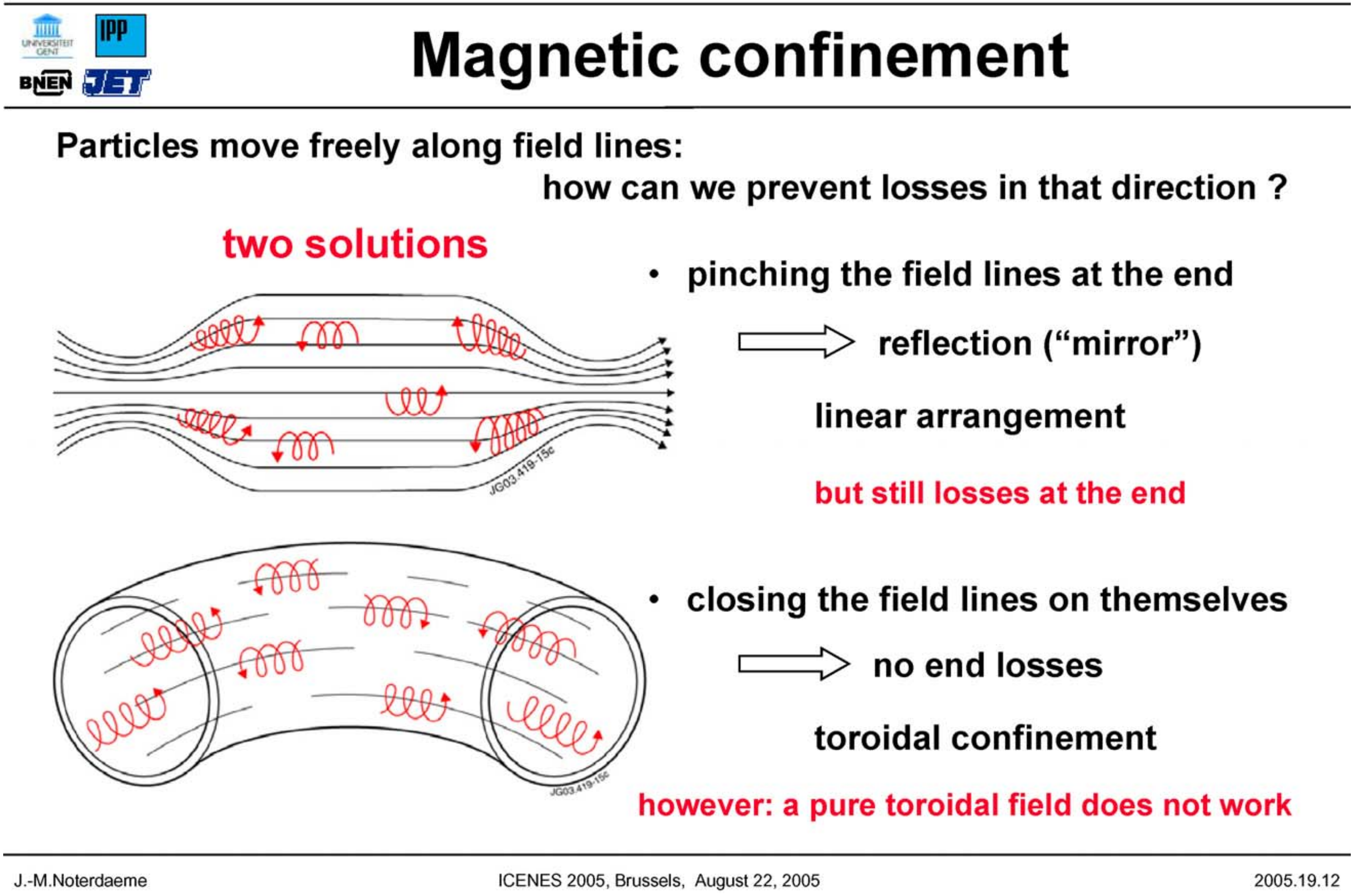
Principaux concepts



Magnetic confinement

Particles move freely along field lines:

how can we prevent losses in that direction ?

two solutions

- **pinching the field lines at the end**

⇨ **reflection ("mirror")**

linear arrangement

but still losses at the end

- **closing the field lines on themselves**

⇨ **no end losses**

toroidal confinement

however: a pure toroidal field does not work

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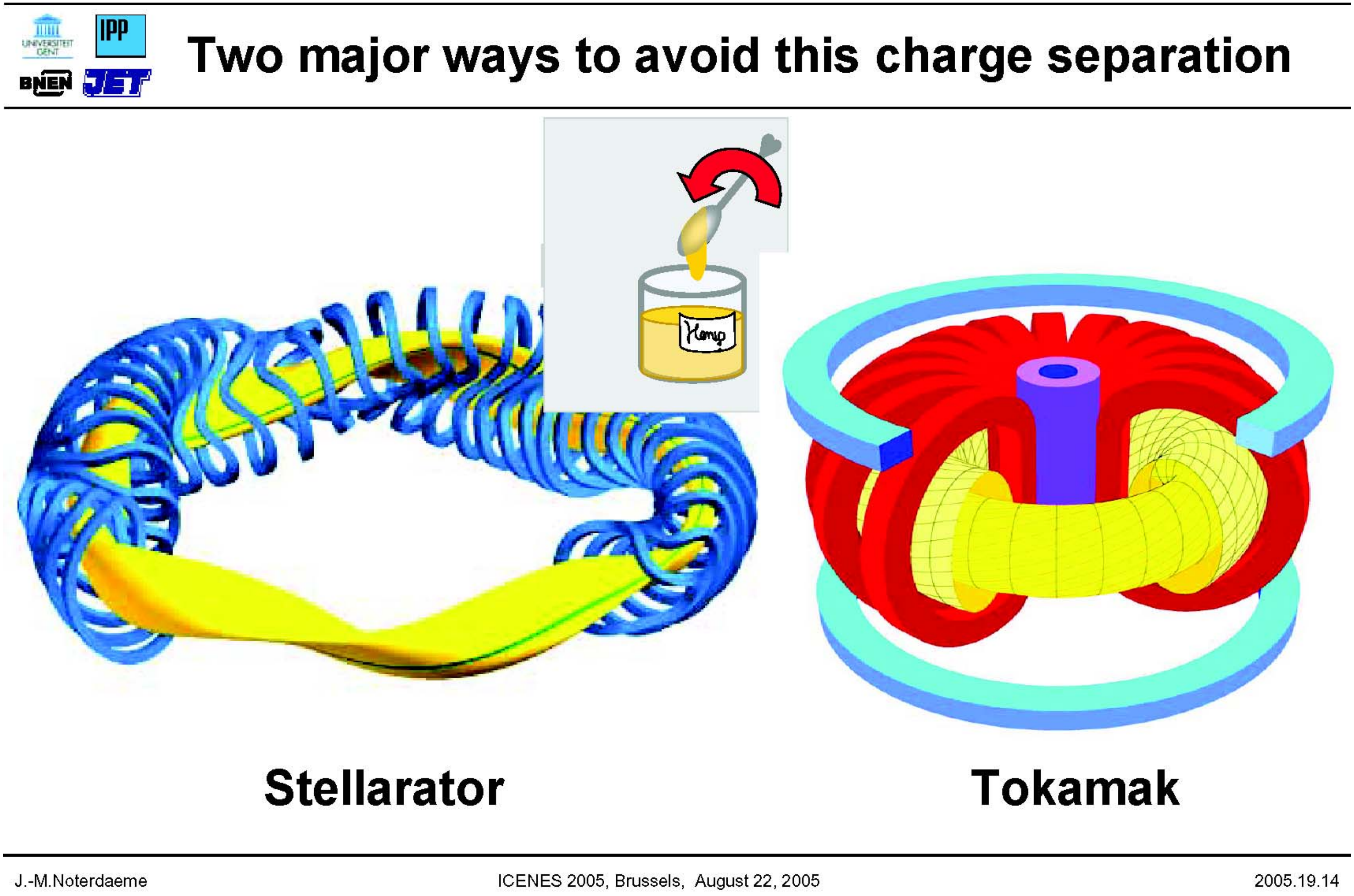
Machines circulaires



Two major ways to avoid this charge separation

Stellarator

Tokamak

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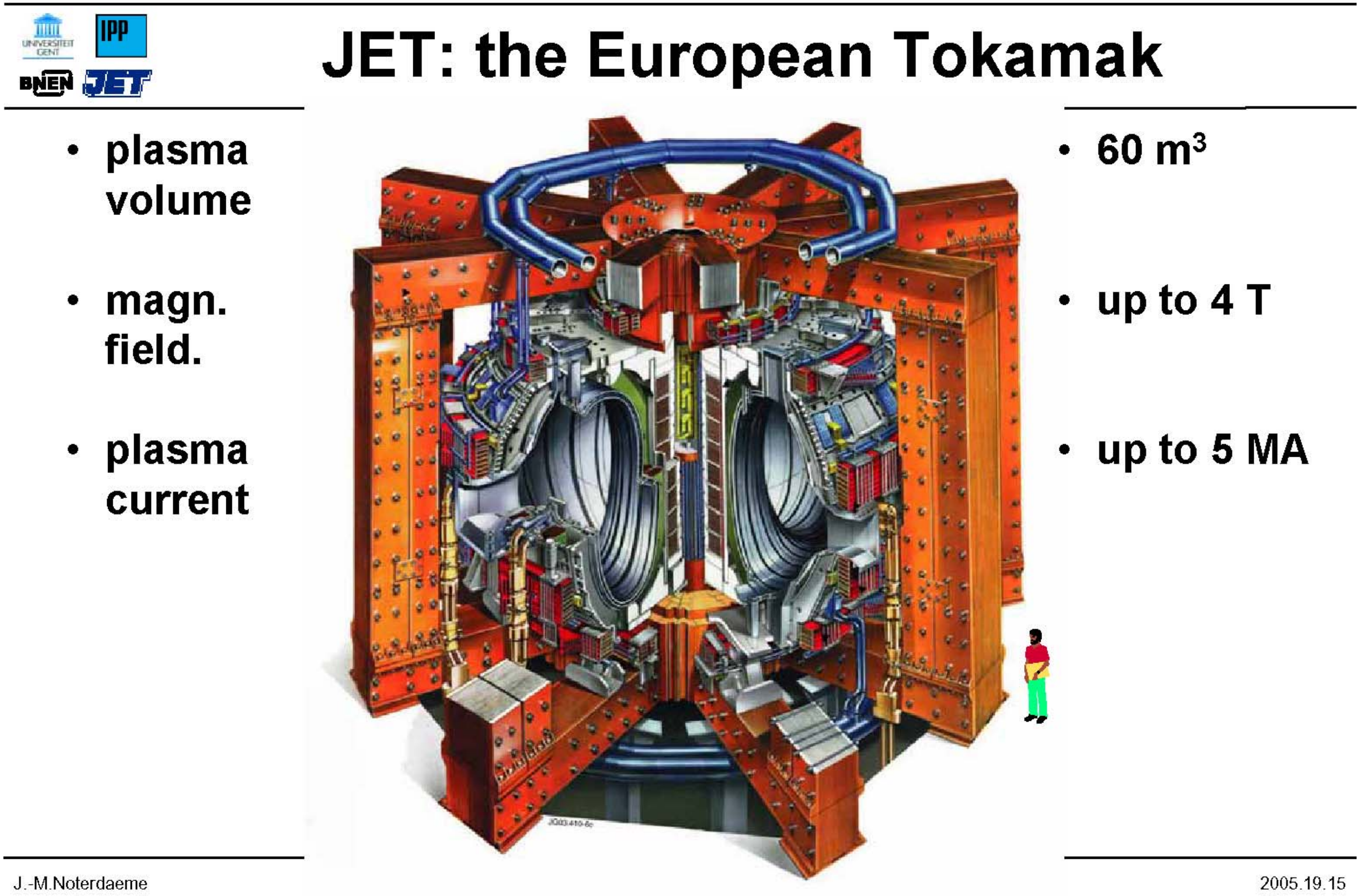
JET



JET: the European Tokamak

- plasma volume
- magn. field.
- plasma current

- 60 m^3
- up to 4 T
- up to 5 MA

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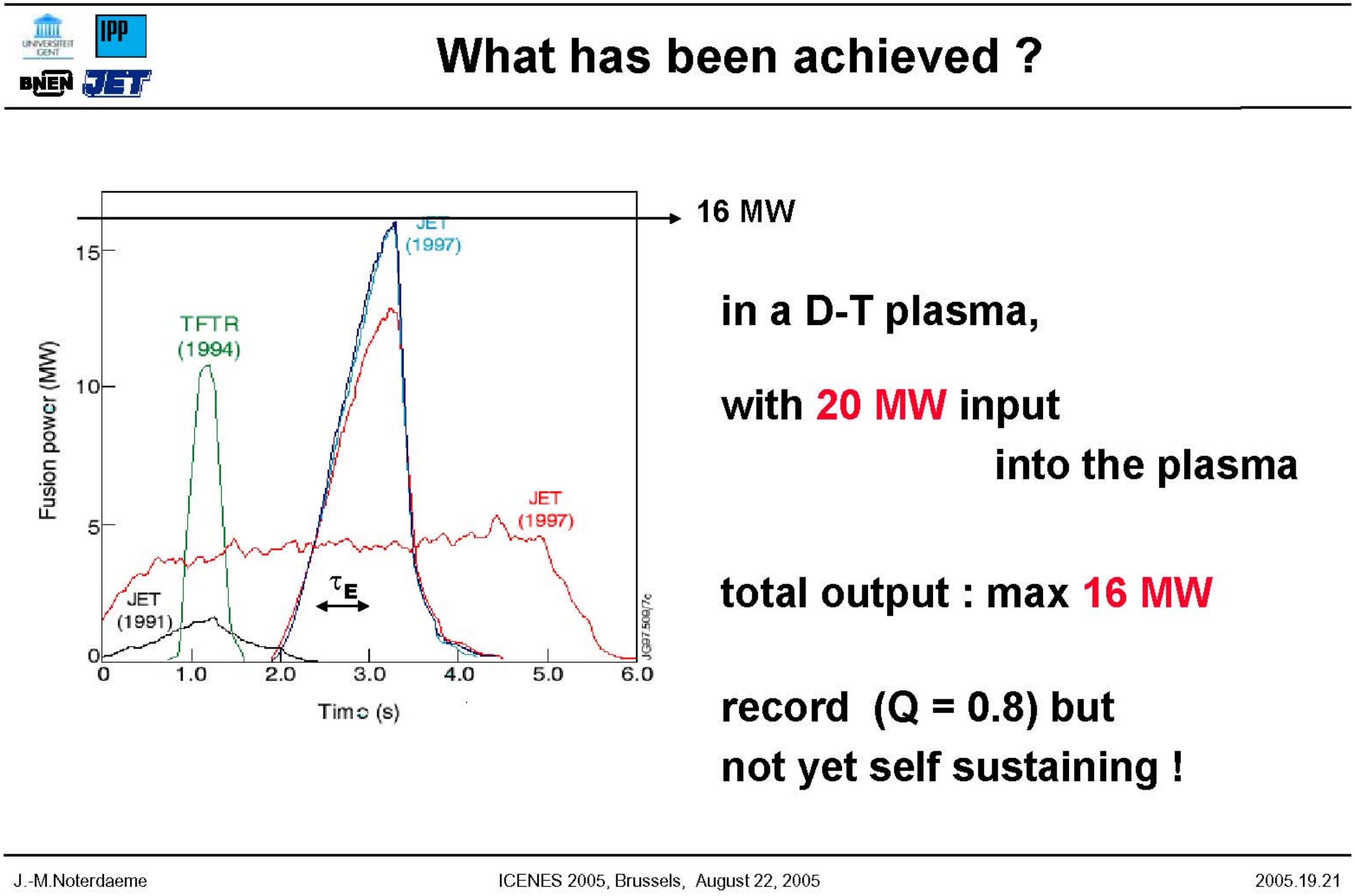
Performances JET



What has been achieved ?

in a D-T plasma,

with 20 MW input
into the plasma

total output : max 16 MW

record (Q = 0.8) but
not yet self sustaining !

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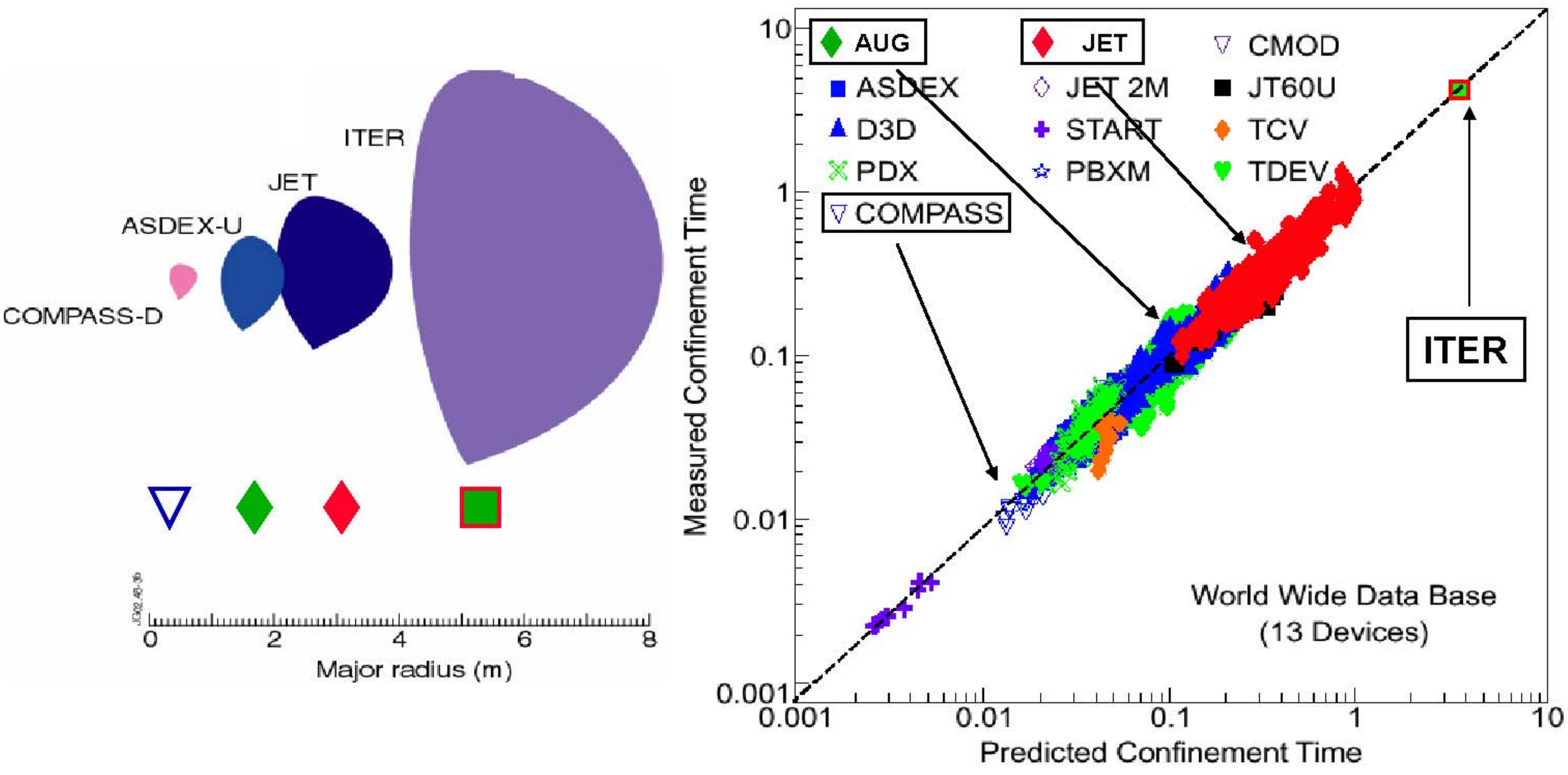
Loi d'échelle

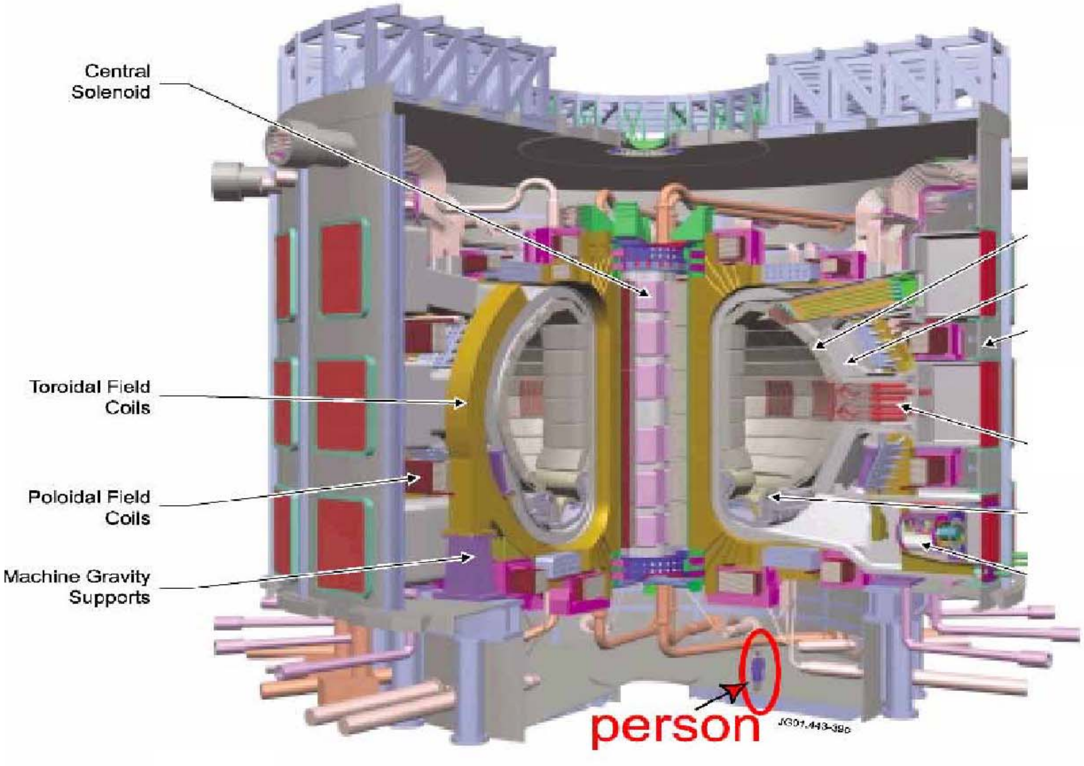
Size from scaling laws

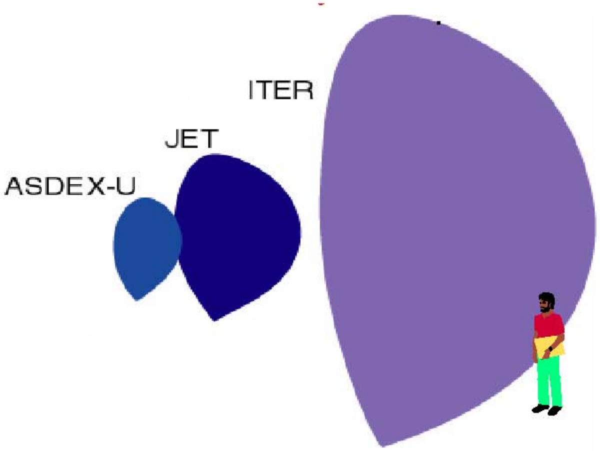


ITER

ITER

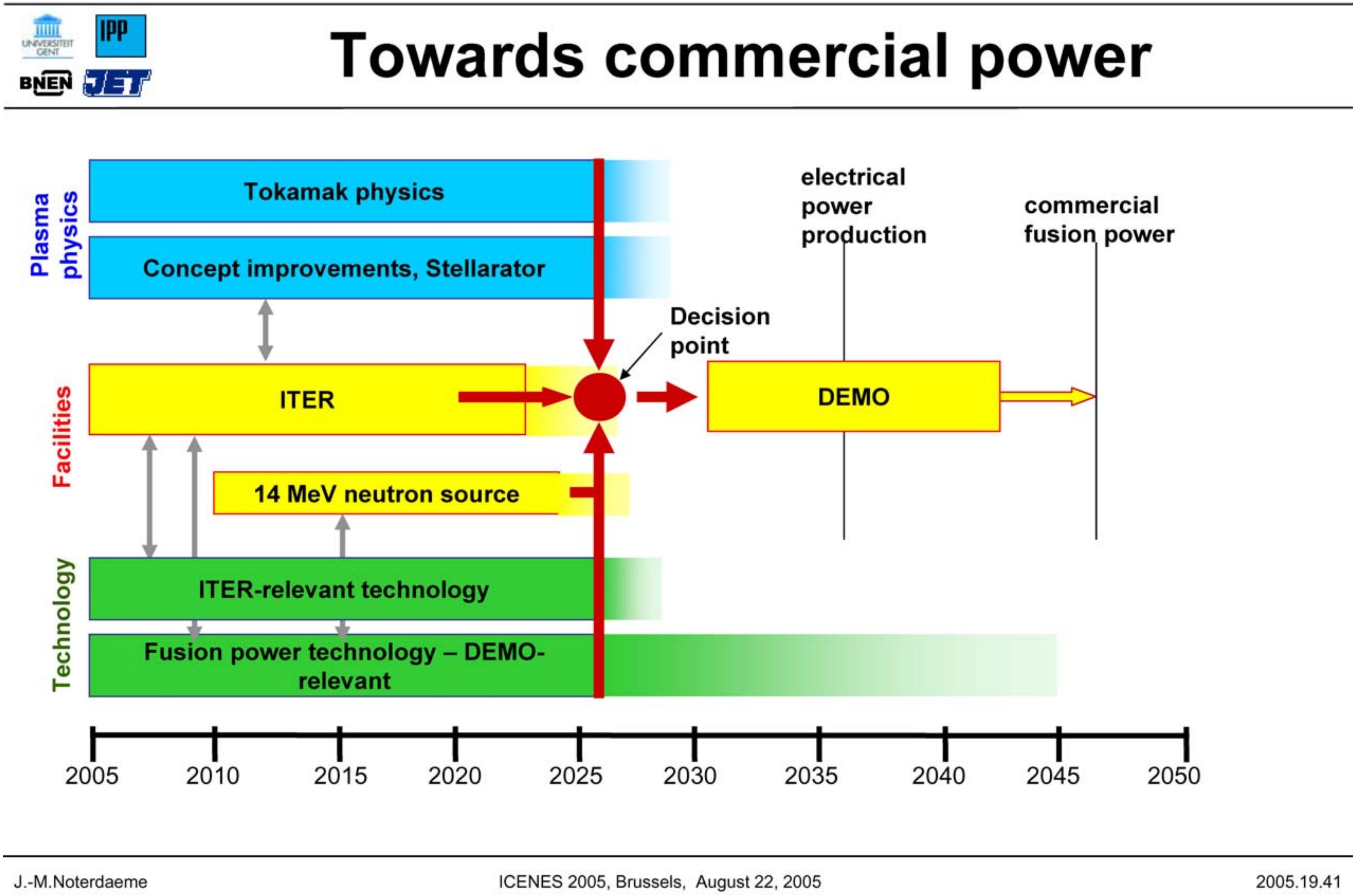
$R = 6.2$ m, $a = 2$ m, $\tau_E = 3$ s





Volume	850 m^3
Current	15 MA
Magnetic field	5.3 T
Fusion power	400 MW
Heating power	40- 90 MW
Q	10

Le futur



Towards commercial power

Plasma physics

Tokamak physics

Concept improvements, Stellarator

Facilities

ITER

Decision point

DEMO

14 MeV neutron source

Technology

ITER-relevant technology

Fusion power technology – DEMO-relevant

electrical power production

commercial fusion power

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