ITALIAN NATIONAL AGENCY
FOR NEW TECHNOLOGIES, ENERGY AND
SUSTAINABLE ECONOMIC DEVELOPMENT

The High Density Approach for Fusion

F. Bombarda

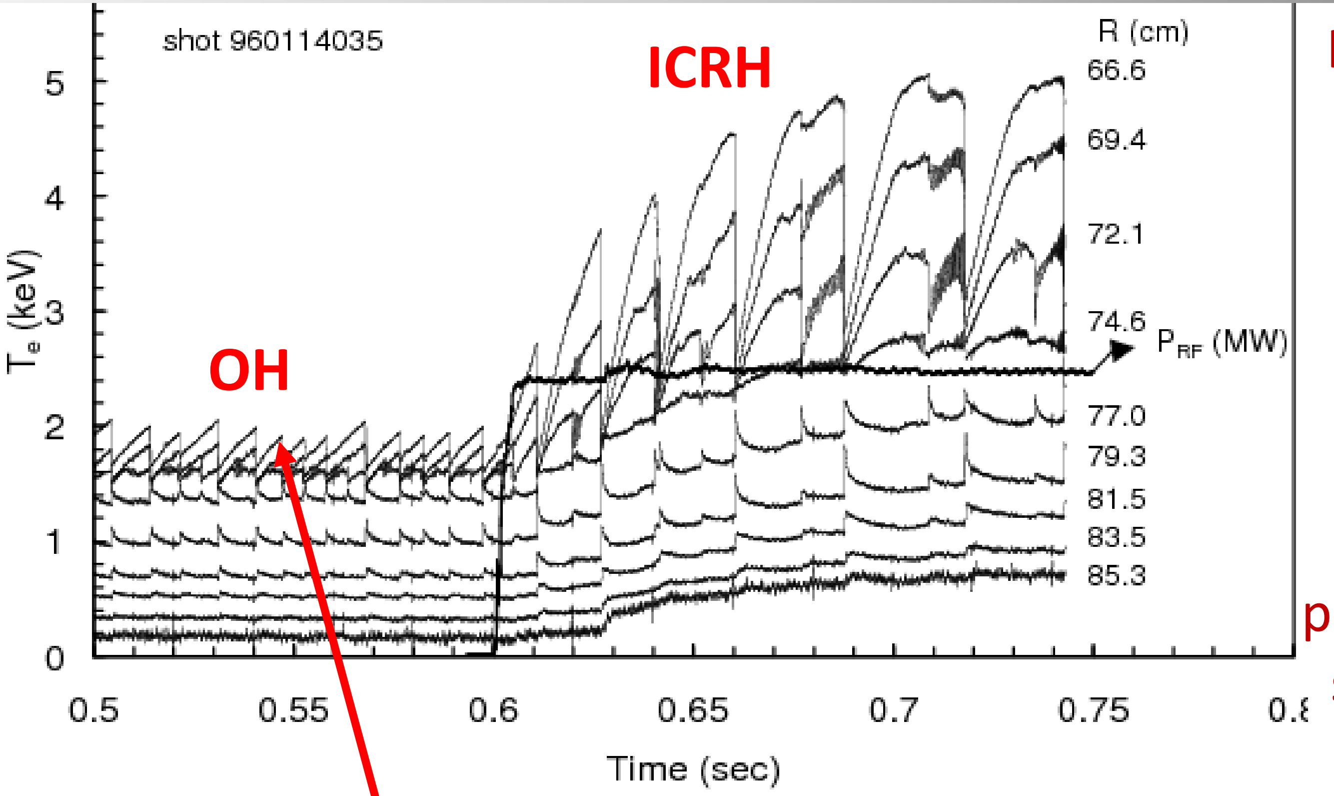
ENEA – FSN, Frascati (Italy)

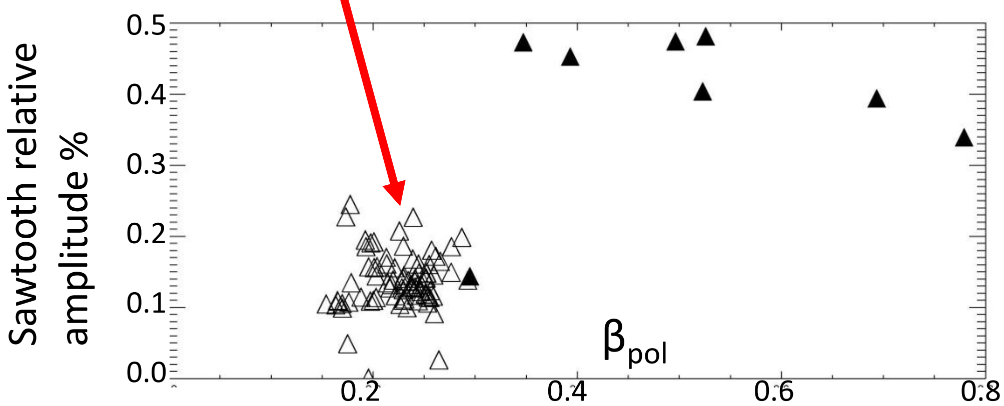
European Plasma Theory Conference, Lisbon, 4-8 October 2015

Outline

- Stability and high fields
- Plasma regimes
- Divertors vs Limiter
- What the future looks like
- The “tilted” coil concept
- Conclusions

Stability Issues





It is difficult to predict the amplitude of the expected sawtooth oscillations without direct experience with meaningful burning plasma regimes.

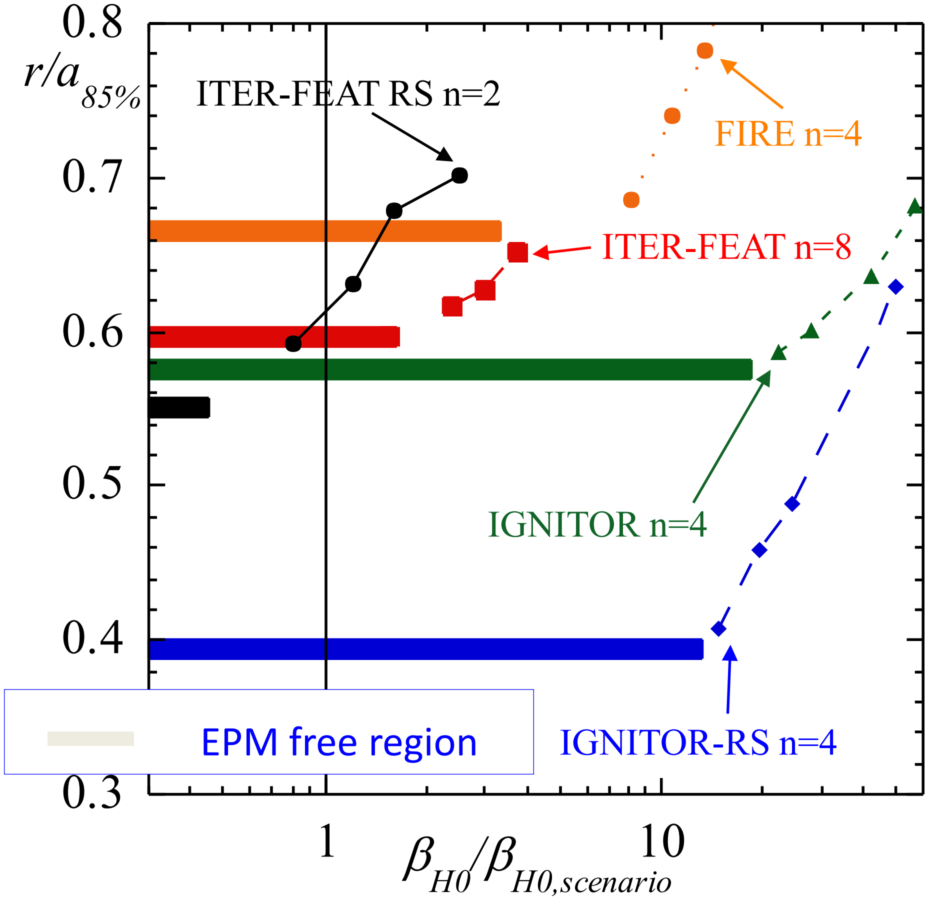
An important protection against large sawteeth is connected to the **low value**s of $\beta_{pol} = 8\pi p/B_p^2$

(See the analysis of plasmas produced by Alcator C-Mod reported in BOMBARDA, F., BONOLI, P., COPPI, B., et al., *Nucl. Fus.* **38** (1998) 1861.

Alpha Particle Transport Induced by Alfvénic Instabilities in Proposed Burning Plasma Scenarios.

G. Vlad, S. Briguglio, G. Fogaccia and F. Zonca, Plasma Phys. Control. Fusion **46** (2004) S81–S93

Hybrid MHD-Gyrokinetic simulations: reduced $O(\varepsilon^3)$ MHD equations coupled with fully nonlinear gyrokinetic Vlasov equation for energetic ("Hot") particles



Radial positions of the surface containing 85% of the alpha-particle energy versus $\beta_{H0}/\beta_{H0,nom}$

Nonlinear results for Energetic Particle driven Modes (EPMs)

Most unstable toroidal mode number n

Define $(r/a)_y$: the radial position of the surface containing a fraction y of the alpha-particle energy:

$$y = \frac{\int_0^{(r/a)_y} x\beta_H(x;t)\,dx}{\int_0^1 x\beta_H(x;t_{relax})\,dx}$$

The high field “theorem” - 1

- For values of q_ψ, β_p, and p compatible with plasma macroscopic stability and burning conditions:

$$\beta_p \equiv \frac{2\mu_0 \langle p \rangle}{\bar{B}_p^2} < \beta_{p,crit} \qquad \bar{B}_p = \frac{\varepsilon B_T G}{q_\psi}$$

$$G \cong 2.5 \ \text{ for } \kappa \cong 1.8$$

$$\varepsilon \equiv a / R \cong 1/3$$

- For q_ψ ~3, $r_{q=1,2}$ are large, therefore $\beta_{p,crit} \lesssim$ 0.3 to keep sawteeth small

$$\Rightarrow \bar{B}_p \ \cong 0.3\, B_T \gtrsim 3\ \mathrm{T} \quad \Rightarrow B_T \gtrsim 10\ \mathrm{T}$$

The high field “theorem” - 2

- High field, compact machines can operate far away from the density limit:

$$n_{\lim} = \frac{I_p}{\pi a^2} \propto \frac{B_T}{R}$$

- A high $q_\psi \sim 5$, the plasma current is lower and therefore much higher confinement times are needed:

$$I_p \propto \frac{5a^2\sqrt{\kappa}B_T}{Rq_\psi G_2} \qquad \tau_E \propto I_p \Rightarrow H > 2$$

Ignition conditions: $P_\alpha = P_L$

$$P_\alpha \propto n^2 T^2$$

for D-T

$$\langle p \rangle \approx 1-4\,\mathrm{MPa}$$

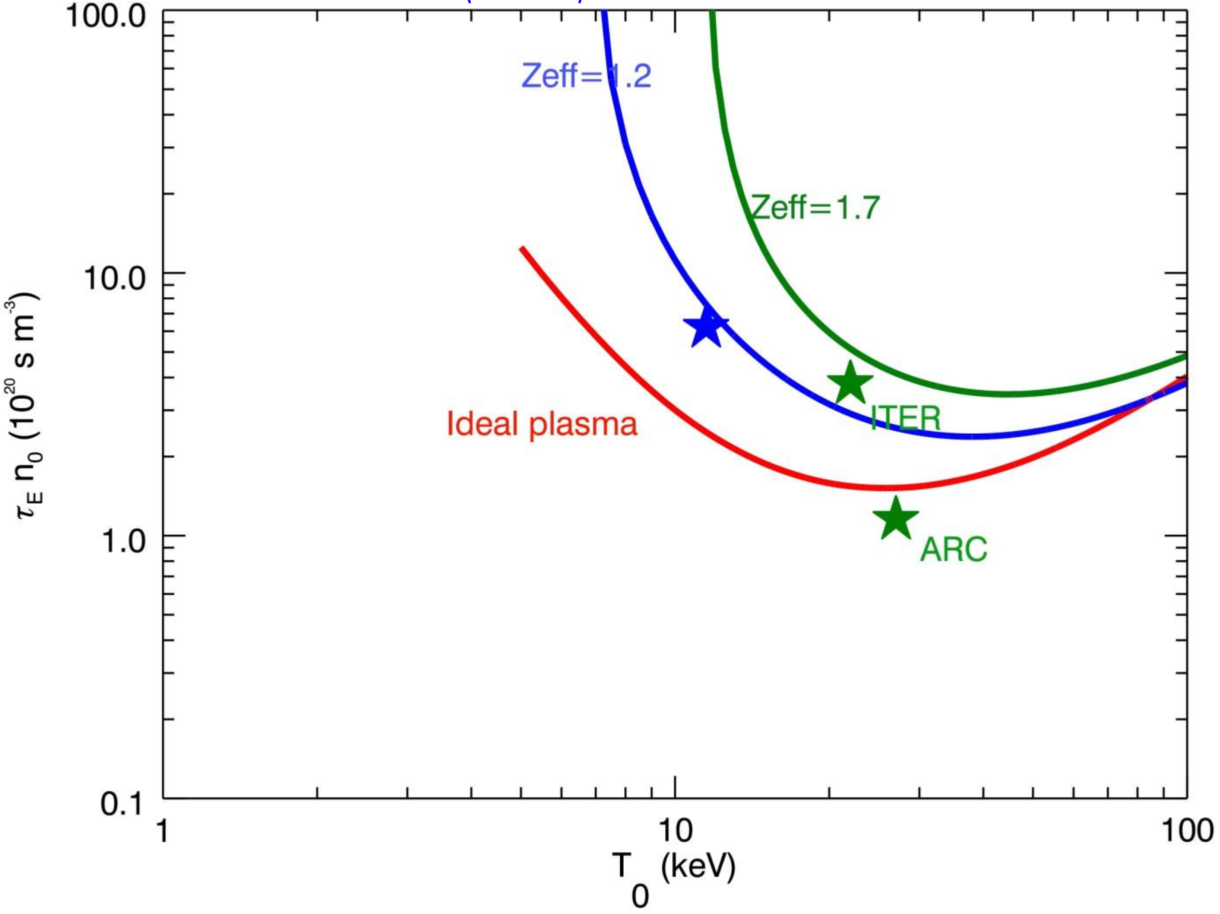
$$\boxed{\Rightarrow P_\alpha \propto B_p^4}$$

Furthermore

$$T_e \sim T_i$$

$$Z_{eff} \sim 1$$

$$\varepsilon_\alpha n^2 \langle \sigma \mathrm{v} \rangle / 4 = 3nT / \tau_E$$



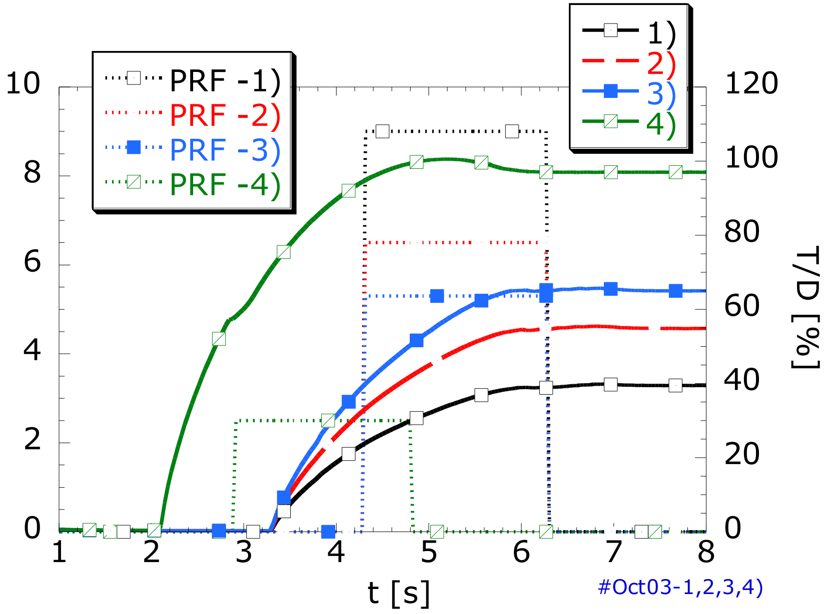
Plasma regimes

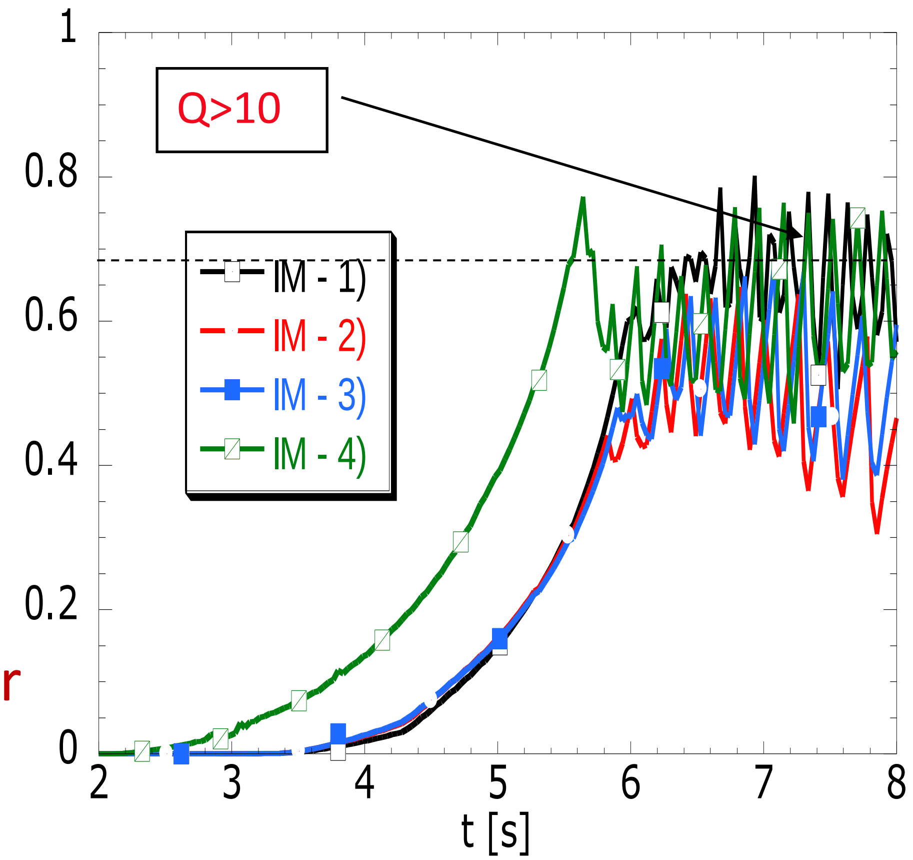
- Until the fundamental physics issues of fusion burning plasmas have been identified and confirmed by experiments, the defining concepts for a fusion reactor will have to remain uncertain
- None of the plasma regimes obtained in present experiments are really suitable for the reactor
- A single burning plasma experiment will NOT be sufficient to fully understand the "reactor physics"

$$K_f = P_f / (5P_L) \lesssim 1 \qquad Q = 5K_f / (1 - K_f) > 50$$

$$Q = 10 \Rightarrow K_f = 2/3$$

Ignition control by means of Tritium and ICRF





With proper timing, the RF power compensates for the unbalanced fuel ratio. As a result, only small differences in the ignition margin are observed.

A. Airoldi, G. Cenacchi, B. Coppi, APS-DPP 2003 *RP1.042*

See also:
A. Cardinali, G. Sonnino
Eur. Phys. J. **D** (2015) 69:194

Issues with present regimes

1. L-mode	Confinement not good enough
2. H-mode	Impurity accumulation, steep edge gradients, ELMS…
3. EDA H-mode, I-mode	Better, but so far essentially unique to a single experiment
4. NI Steady-State	Unstable, low density, expensive

Critical issues in plasma-wall interactions:

- Control of impurity production at the boundary between plasma and material surfaces
- Screening of impurities
- Dispersal of power exhausted from the main plasma
- Ash removal

At the same time:

1. Good energy confinement time
2. High core plasma density (for reactivity)
3. Clean core plasma ($Z_{eff} = 1$)

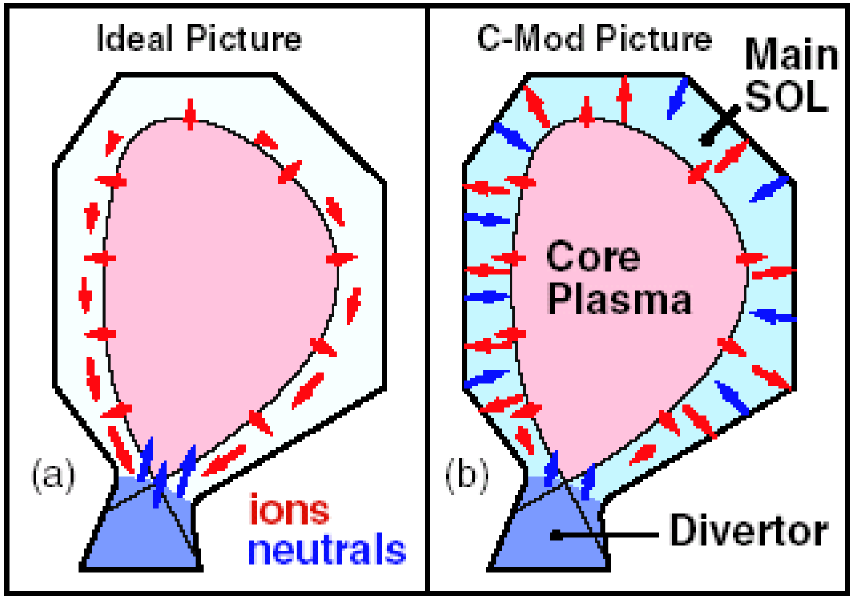
Possible solutions:

a) Divertors (good to decrease impurity levels in low density plasmas)

b) Limiters with high radiating edge (high density plasmas)

Divertors

- Divertor machines do not produce “cleaner” plasmas than limiter, high density devices.
- In high density regimes ($>10^{20}$ m^{-3}), particle recycling from the main chamber and cross-field diffusion can challenge the picture of the divertor as the sole power and particle sink.

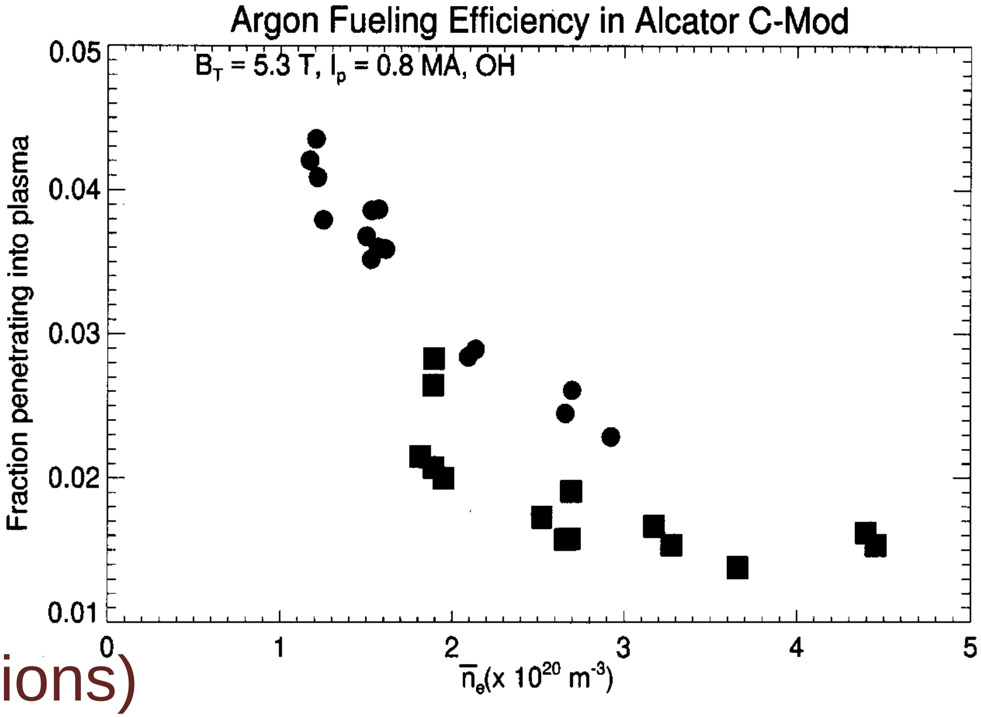


LABOMBARD, et al.,
Nucl. Fusion 40 (2000) 2041.

Divertors reduce the usable volume inside the magnet cavity thus limiting, on a given device, the achievable plasma performances.

Impurity Screening

- At high density, lower temperatures reduce sputtering from the wall; medium/high Z impurities are effectively screened from the main plasma.
- All-metal limiter machines could turn out the best solution for the requirements of plasma-wall interaction control in high density, reactor relevant plasmas.



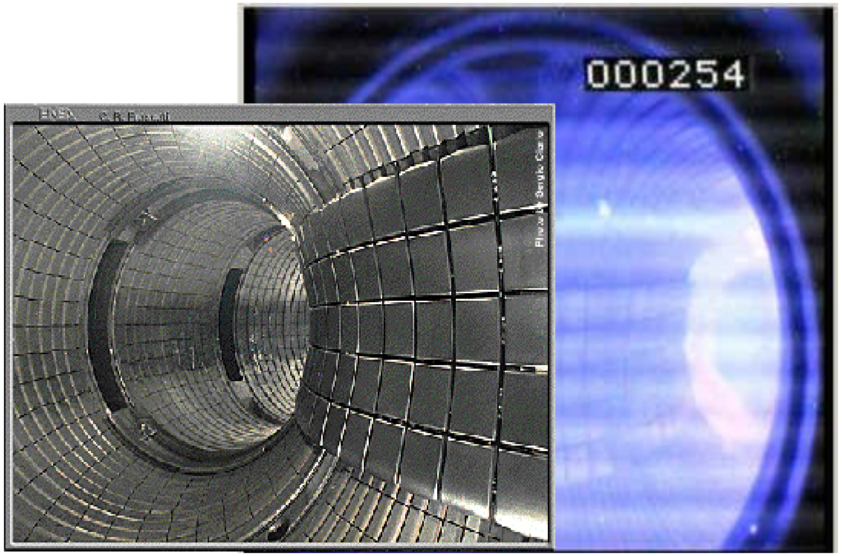
⇒ “High Recycling Regime” (ions)

⇒ “Edge Radiative Regime” (electrons)

The high density approach avoids the need for divertors to manage impurities!

First Wall Limiter vs. Divertor

“FWL” (eg, FTU, Frascati)

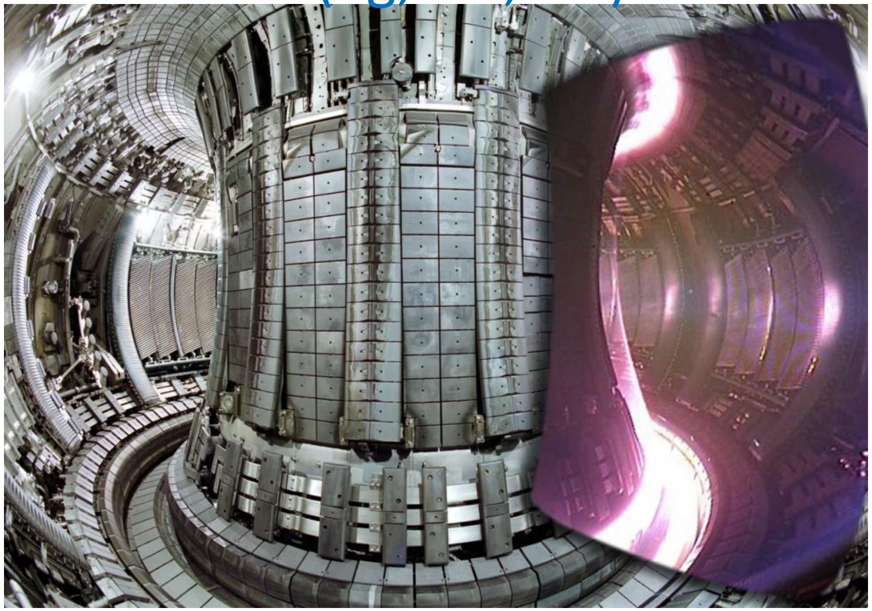


PWI (ideally) spread over the wall

Adopted on circular machines

Vanishing B incidence to (part of the) wall

Divertor (eg, JET, UK)

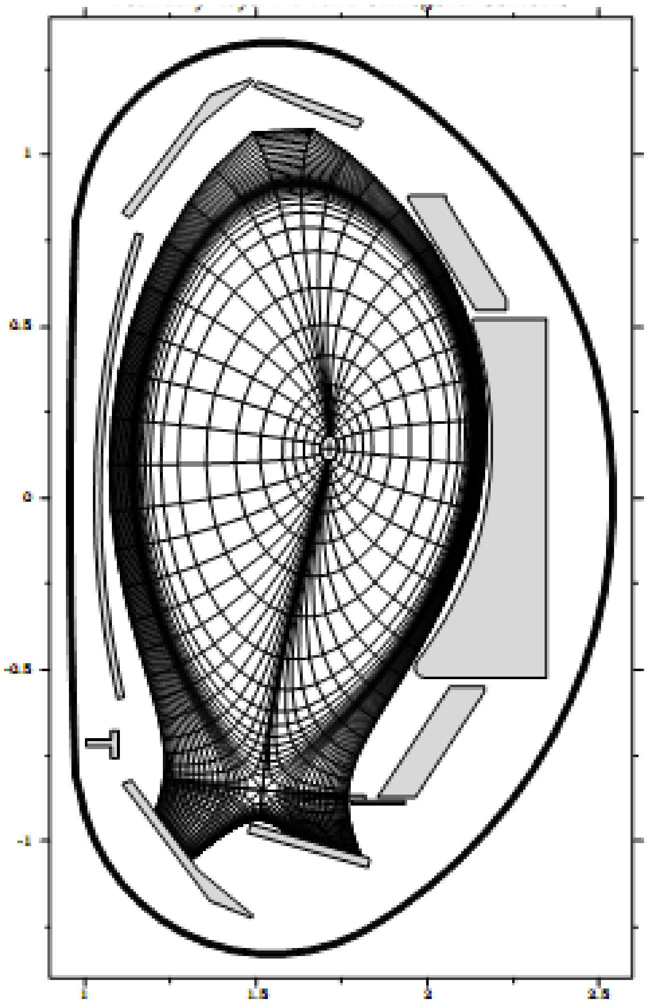


PWI (ideally) concentrated in the divertor

Most often adopted in large, medium-to-low field /density machines

Finite B incidence to wall

Traditional SOL/Edge Modeling



Ref. B2/SOLPS code [B. Braams, et al.]

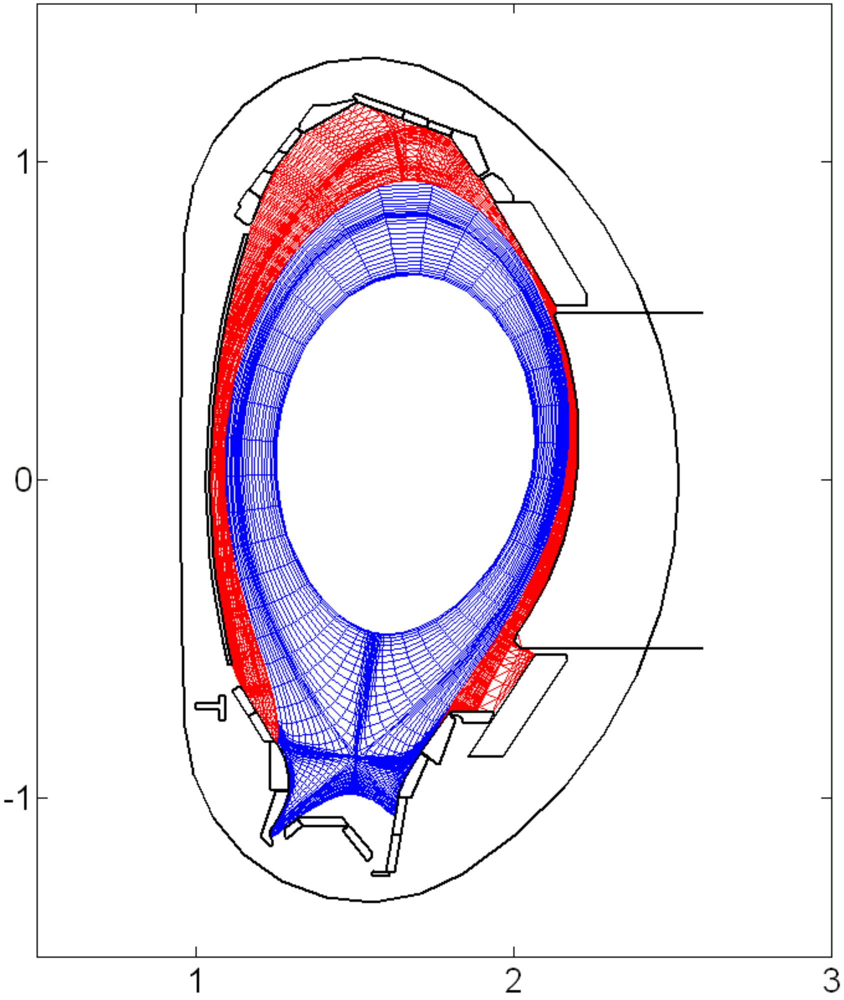
- Quadrilateral FV grid optimized for DIVERTOR (easy for coding)
- Grid strictly aligned: every cell has two sides parallel to B_θ (accurate $\partial/\partial\theta$ discretization)
- Well established target boundary conditions (Bohm criterion)

BUT

- Cannot be extended up to the FW
- Introduces artificial “outer” boundary (conditions?!)

[R. Schneider, et al. Contrib. Plasma Physics, (2006)]

FWL SOL/Edge Modeling



Ref. ASPOEL code (developed at PoliTo & first validated against AUG data)

- Triangular CVFE grid optimized to be extended up to the outer wall (both LIMITER and DIVERTOR)
- Keep strict alignment (one side/triangle aligned with B_θ)

BUT

- Physics model (much) simpler at present
- Limited mesh flexibility at present

[F. Subba, et al., *Comp. Phys. Commun.*, 179 (2008)]

What the future looks like

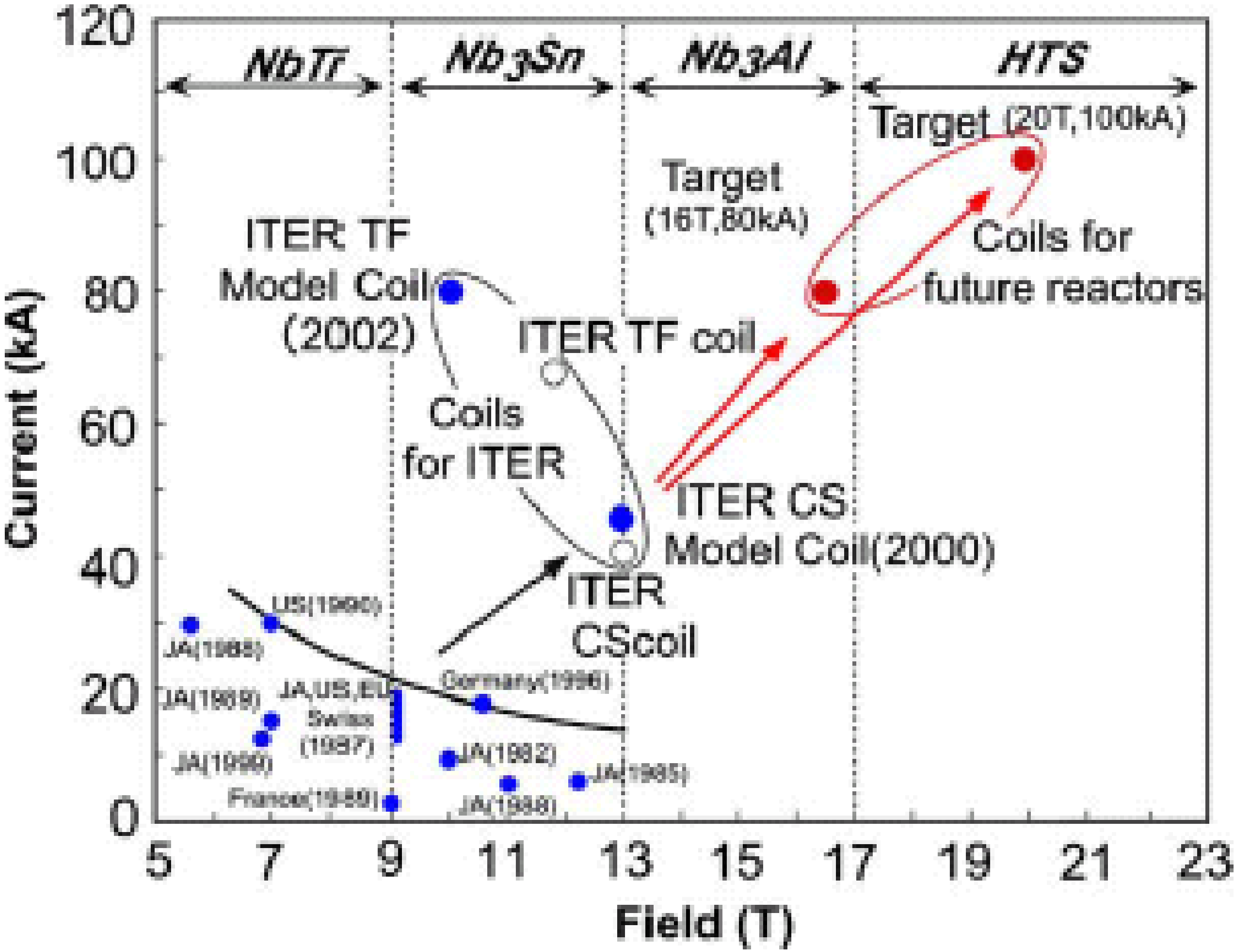
	DEMO	**ITER**	**ARC**	**IGNITOR**
B_T (T)	5.6	5.3	9.2	13
I_p (MA)	21.6	15	7.8	11
$B_p{}^*$	1.2	1.05	0.93	3.5
R (m)	7.5	6.2	3.3	1.32
B/R (T/m)	0.75	0.85	2.8	10.
T_0 (keV)	34.7	22.	27.	11.
n_0 (10^{20} m^{-3})	1.2	0.9	1.8	5.
Material	Nb3Sn	Nb3Sn	REBCO	Cu
Fusion Power (MW)	~3255	500	525	100
Fusion Gain Q_{plasma}	<10*	10	13.6	∞

* Estimated

From JET to the reactor

P.H. Rebut, Alfvèn Prize Lecture, 33rd EPS Conference, Rome (2006)
http://eps2006.frascati.enea.it/invited/post.htm

- In a reactor, the energy produced by fusion reactions only matters, not the record on some of the non dimensional parameters.
- The real gain has to be proven in tritium operation.
- Having superconducting coils adds to the complexity and the cost of a machine; in my opinion it was premature to do it on ITER on the program leading machine which is still far from a reactor.
- Taking into account the **efficiency of the conversion** from heat to electricity, and the **efficiency of the auxiliary heating** and **plasma control**, a **Q of 50** for the fusion reactor is required
- To achieve such a Q of 10, ITER must operate in the **H mode**, The H mode appears in presence of a divertor, over a power threshold. It is not possible to **maintain** it for a **long time**.

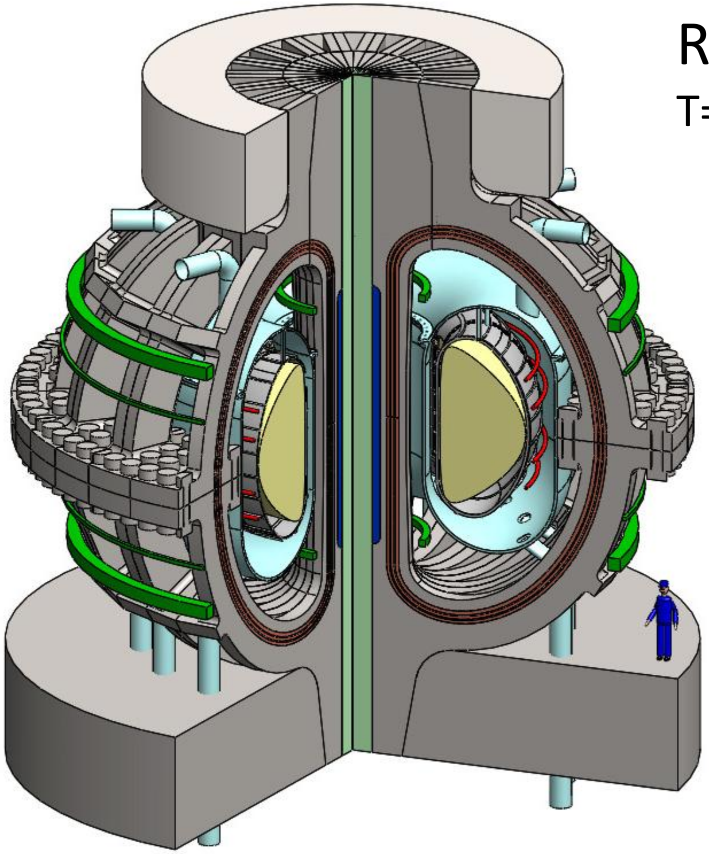


From: Ingegneria dei sistemi elettromagnetici per la fusione termonucleare controllata
Scuola di Dottorato in Ingegneria Industriale
Università degli Studi di Bologna - 2009

ARC

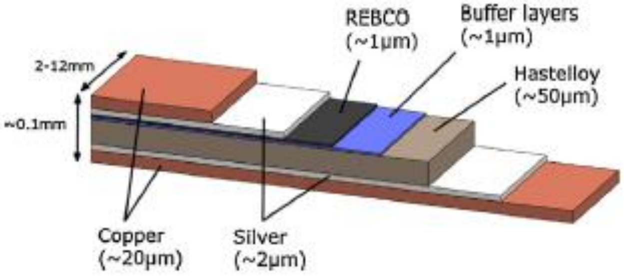
“A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets”

B.N. Sorbom, et al., *Fusion Engineering & Design*, in press
http://dx.doi.org/10.1016/j.fusengdes.2015.07.008



REBCO: Rare Earth Barium Copper Oxide

T=20 K, 5730 km, <36 $/m



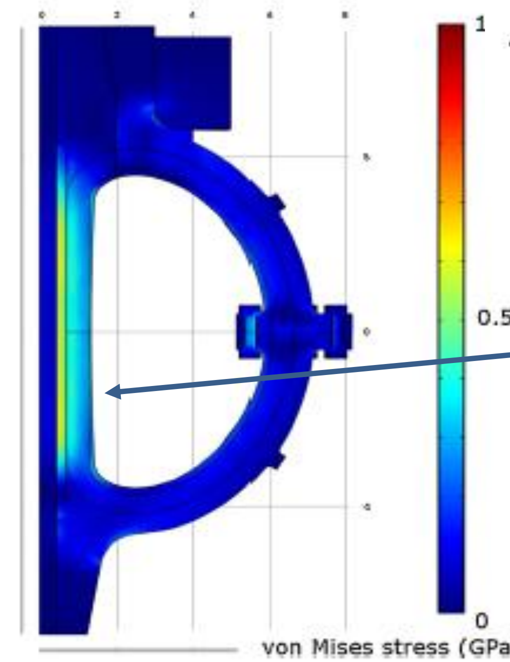


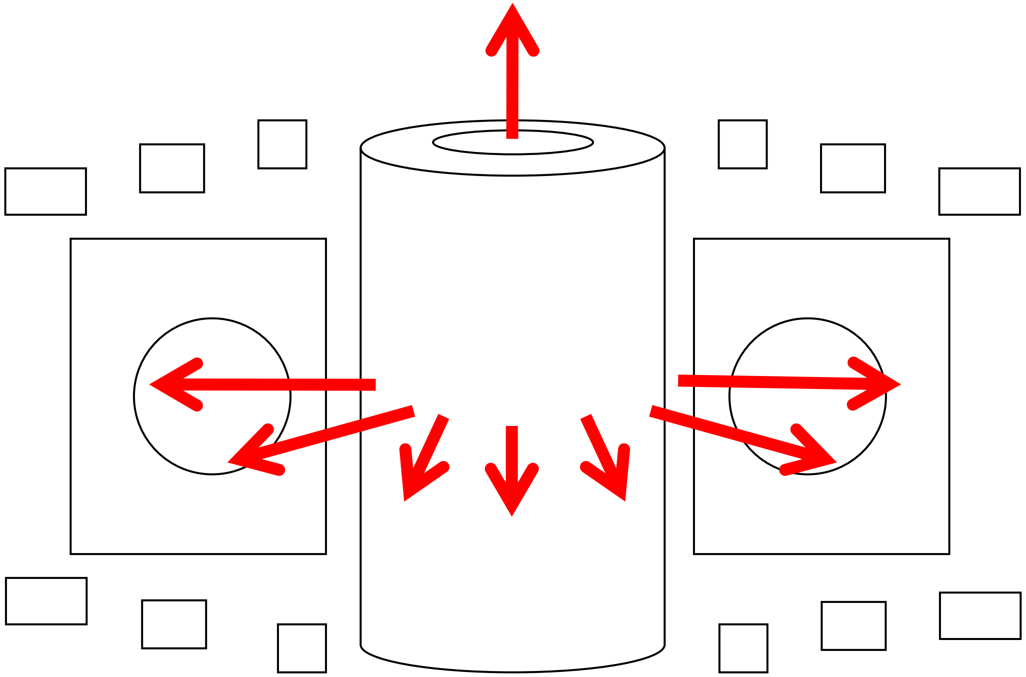
Fig. 24. Results of stress simulations in the TF coils. The maximum stress in the stainless steel 316LN structure is 660 MPa, which gives safety margin of approximately 65%.

Field at magnet interface: 23 T

Max stress: 660 MPa

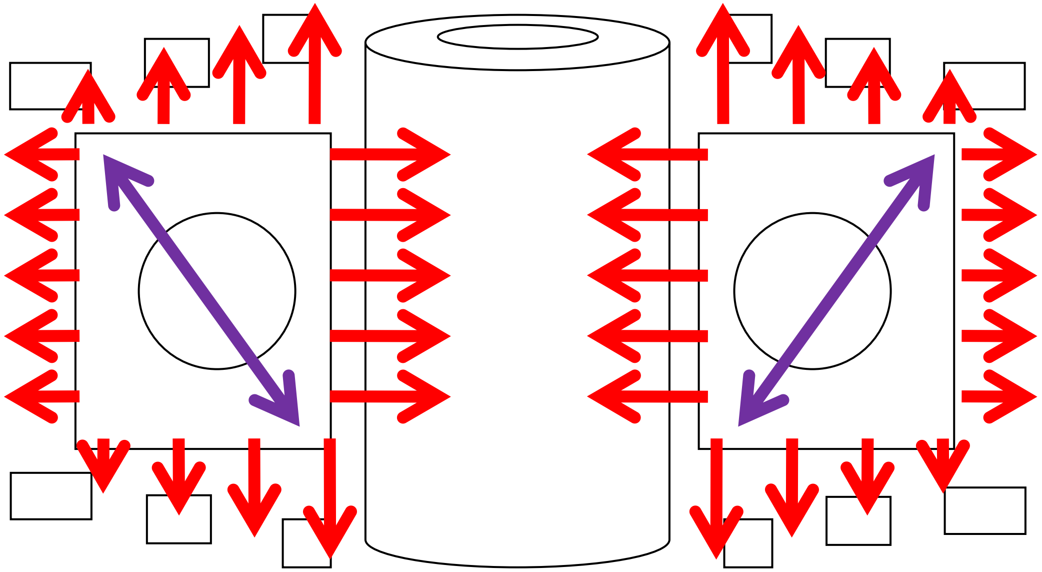
P_{fusion}=525 MW
$P_{elect,\ net}$ =190 MW
Cost: < 5.6 B$

EM Forces in the Central Solenoid



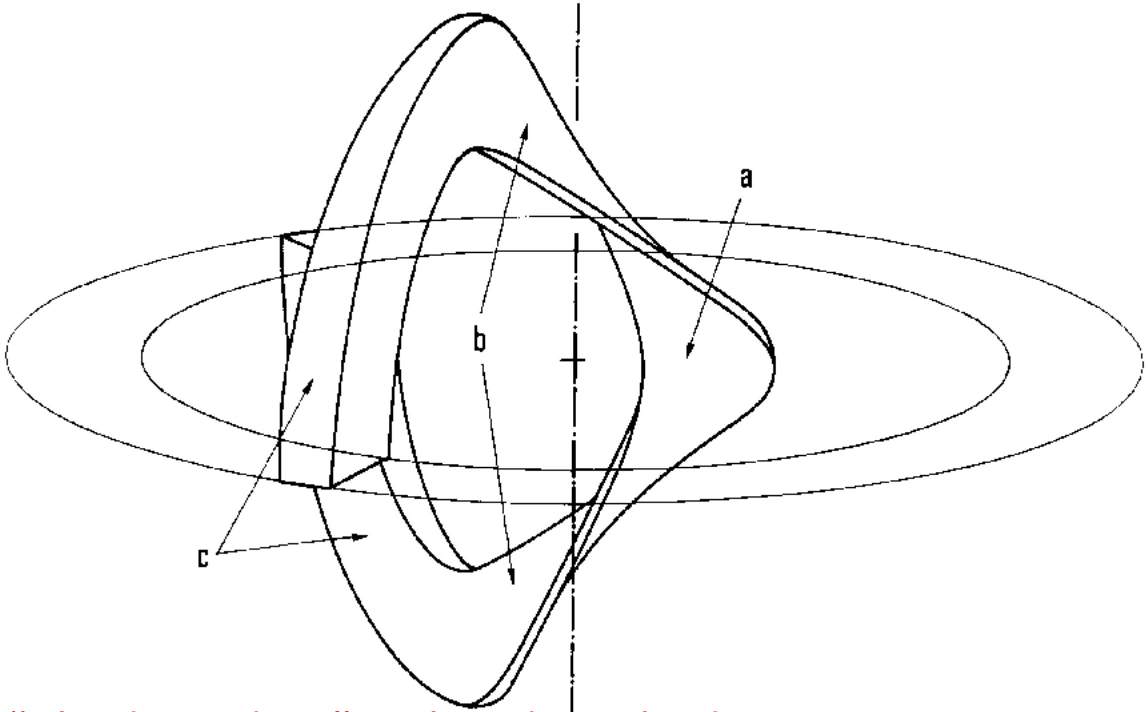
EM Forces in the Toroidal Magnet

Forces at the magnet interfaces is the B limiting factor in both superconducting “low field” and conventional “high field machines

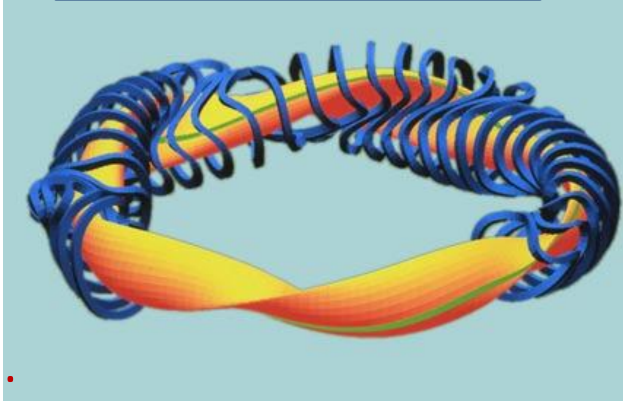


The interaction of the magnet current with the poloidal field produces out-of-plane stresses (in purple).

The “tilted coil” concept



NOT a Stellarator!

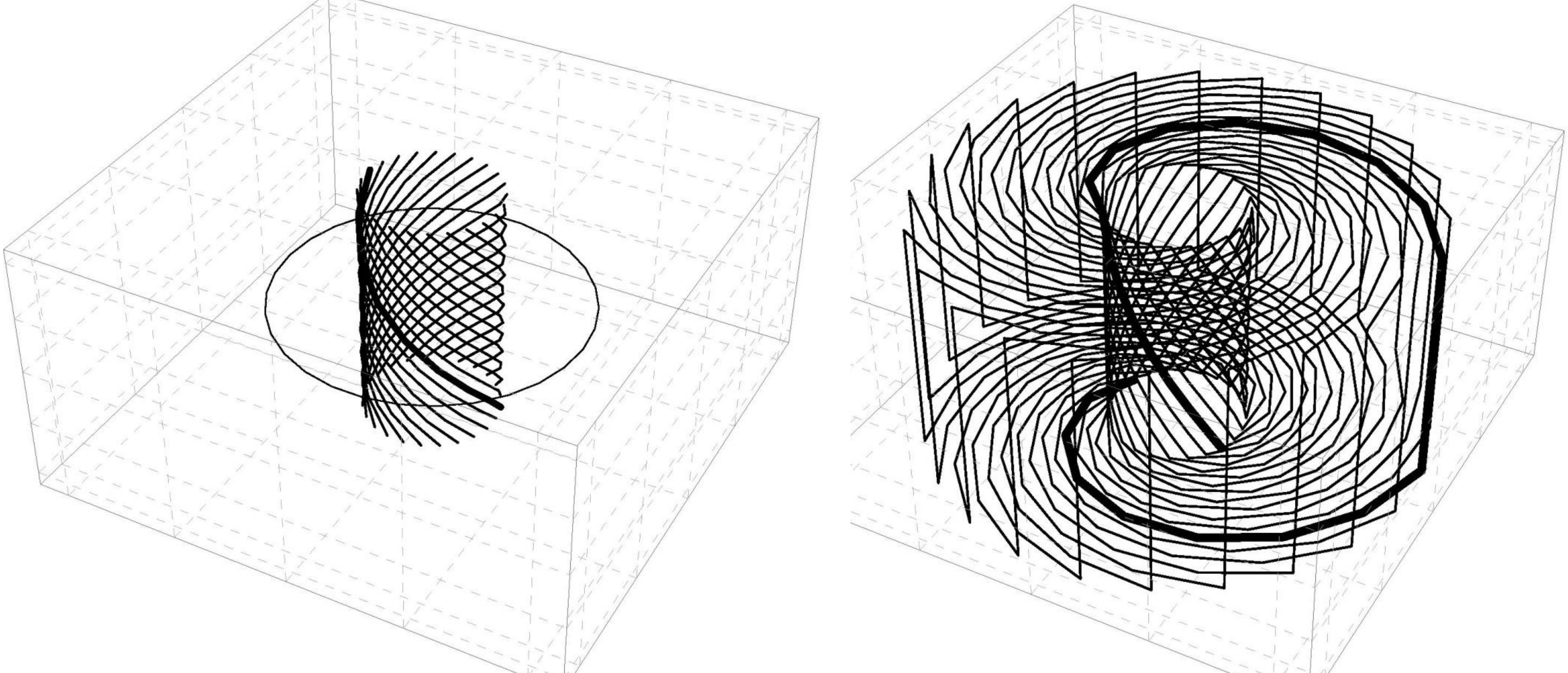


The “tilted-winding” coil as described in: A. Sestero, *Comm. Plasma Phys. Controlled Fusion* **11**, 27(1987).
Legend: a: inner region; b: transition region; c: outer region.

See also:
A.Sestero, S. Briguglio, *Fus. Eng. Des.* **6**, 281 (1988)
B.Coppi, L. Lanzavecchia, *Comm. Plasma Phys. Controlled Fusion* **11**, 61 (1987)

The tilted coil concept for advanced tokamak devices

F. Bombarda, R. Gatto, RT/2015/12/ENEA

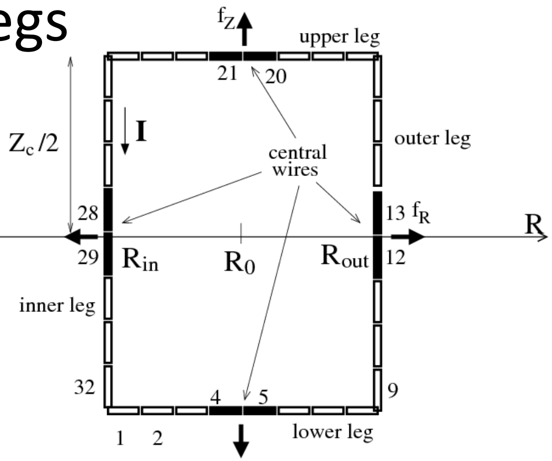


A) The central solenoid is generated by the tilted inner legs (the circle denotes the $R = R_0$ location). One inner leg is shown in bold.

B) While descending, the tilted leg goes around the torus with an angle of approximately 205°. The poloidal flux generated by the tilted inner legs inside the plasma region is equal to 23.32 Wb

Optimized tilting angles (Γ) and force reduction factors (RF) for the R_0=1.32, A_c=0.88 system with tilted legs

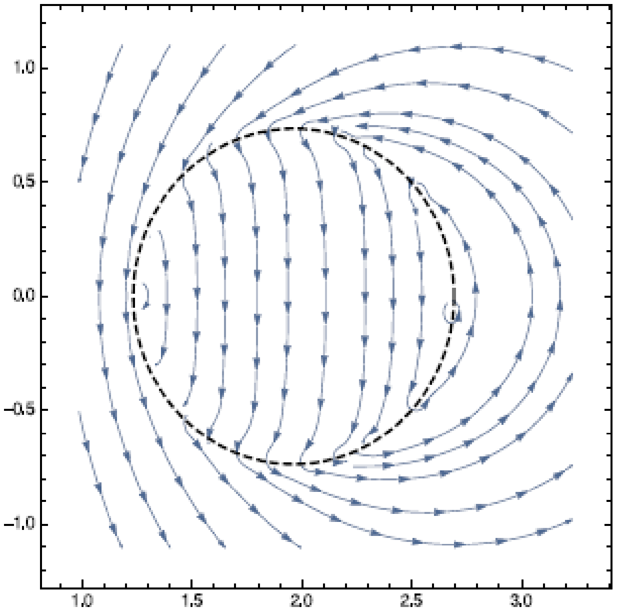
Leg	Γ_f	Γ_l	RF_R	RF_ϕ	RF_Z
Lower	86.6°	83.2°	f_R/f_Z^0=-0.83	f_ϕ/f_Z^0=0.28	**f_Z/f_Z^0=0**
Outer	0	0	**f_R/f_R^0=1**	**f_ϕ/f_R^0~0**	f_Z/f_R^0=0
Upper	83.2°	86.6°	f_R/f_Z^0=0.83	f_ϕ/f_Z^0=0.28	**f_Z/f_Z^0=0**
Inner	30.1°	30.1°	**f_R/f_R^0=0**	**f_ϕ/f_R^0~0**	f_Z/f_R^0=0

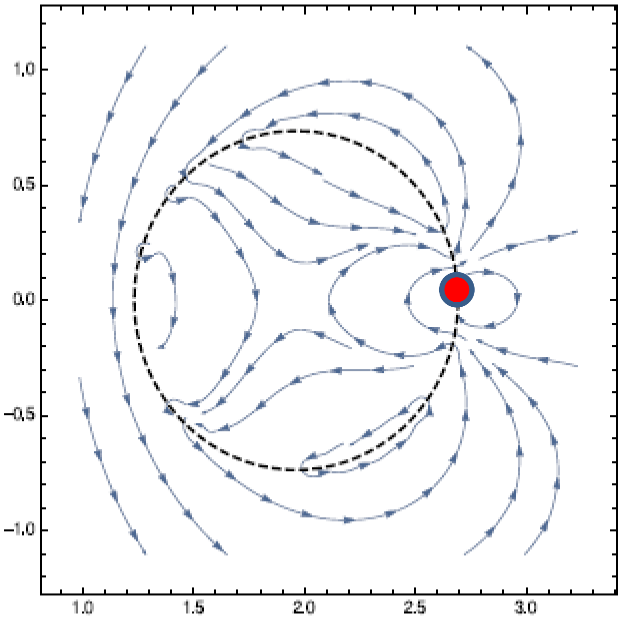


- Stresses in the inner leg of the toroidal field (TF) magnet are relieved, and the heavy steel structure could be considerably reduced.
- Coils could be made of ribbons of HT superconductors, which have rather poor structural properties but can withstand high magnetic fields, combined with IT MgB_2.
- Mechanically unloading the TFC makes it easier to generate the fields required to approach ignition conditions at higher density and relatively lower temperatures .

Flux saving

- The flux swing for generating the plasma (which represents most of the V-s consumption) can be provided by the TFC with the “tilted coil” solution, and the discharge may be sustained for longer times.
- Long pulses are needed mostly to avoid material fatigue and improve gain, not so much for steady state power supply.

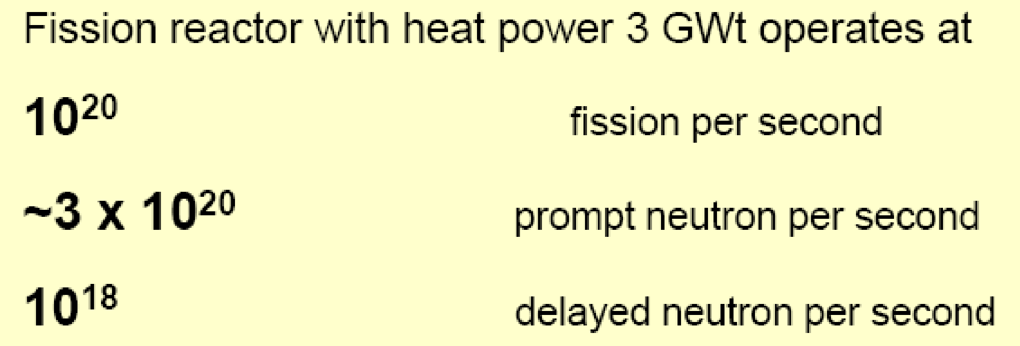




R. Gatto

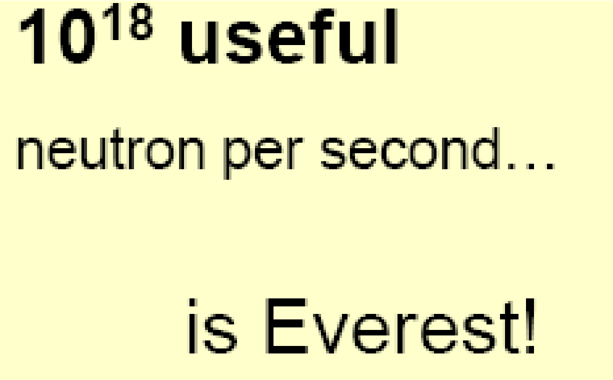
The High Field Approach for Neutron Sources

- Fusion creates more neutrons per energy released than fission or spallation, therefore DT fusion facilities have the potential to become the most intense sources of neutrons for material testing. A compact, high field, high density machine could be envisaged for this purpose making full use of the intense neutron flux that it can generate, without reaching ignition.



Fission reactor with heat power 3 GWt operates at

10^{20}	fission per second
~3×10^{20}	prompt neutron per second
10^{18}	delayed neutron per second



10^{18} useful

neutron per second…

is Everest!

A high performance pulse in Ignitor:

~ 3.3×10^{19} n/s

~10^{15} n/(s cm^2) @ First Wall

IFMIF:

Irradiation volume 0.5 l for 10^{14} n/s cm^2 (20 dpa/year)

Neutron requirements for material testing (10 DPA/yr)

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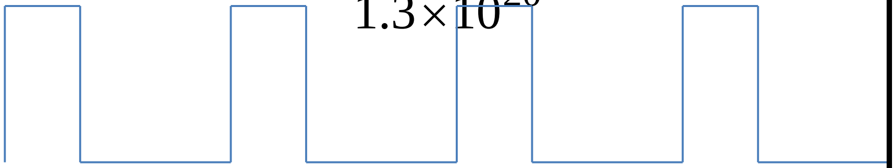
$$N=\frac{10[\text{DPA}]}{3.22\times10^{-26}[\text{DPA/n}]}=3.1\times10^{26}\text{ neutrons/yr}$$

$$=10^{19}\text{ neutrons/s}\times1\text{ yr}$$

$$@\,3.3\times10^{19}\text{ n/s: }\frac{10^{19}}{3.3\times10^{19}}=\tfrac{1}{3}\text{ yr}=4\,\text{mo}$$

$$@\,1.3\times10^{20}\text{ n/s (x2T): }\frac{10^{19}}{1.3\times10^{20}}=1\text{ mo}$$

4 mo



@ 1 pulse / hour :T_{pulse}= 20 min, T_{cool} = 40 min

1 mo

@ 1 pulse / hour: T_{pulse}= 5 min, T_{cool} = 55 min

8760 pulses /yr, Irradiation volume ~ 1 m³ :
Tritium burn-up = 1.6 Kg/yr

- Longer pulse, fewer cycles:
- Limits are driven by:
  - Magnet Heating
  - Available flux swing
- ➢ “Hybrid” superconducting coils
- ➢ “Tilted” coils
- ➢ RF heating to boost plasma temperature and CD
- ➢ Increase dimensions
- Lowering the toroidal field may not be an option

F. Bombarda, M. Zucchetti, Z. Hartwig, *Fus. Eng. Des.* **86**, 2632 (2011)

Fusion Research has provided valuable contributions to basic plasma science …

- Understanding the Physics of High Energy Plasmas
- Physics of Plasma-Material Interactions
- Atomic Physics
- Diagnostic Systems

…and to other fields, such as astrophysics, advanced technologies, etc.

…but so far it has failed miserably in providing a new source of clean, unlimited energy

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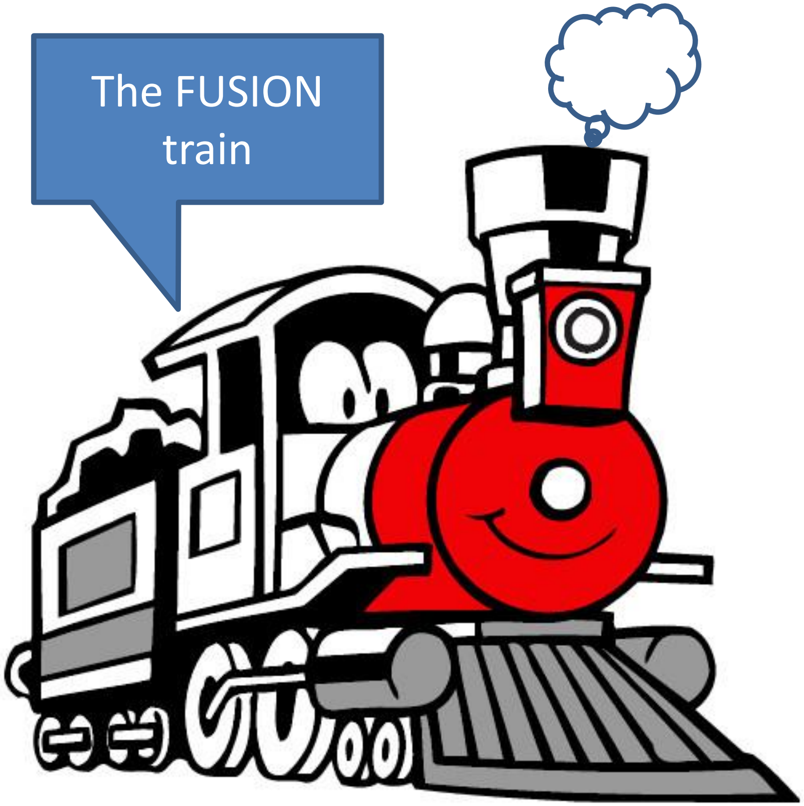
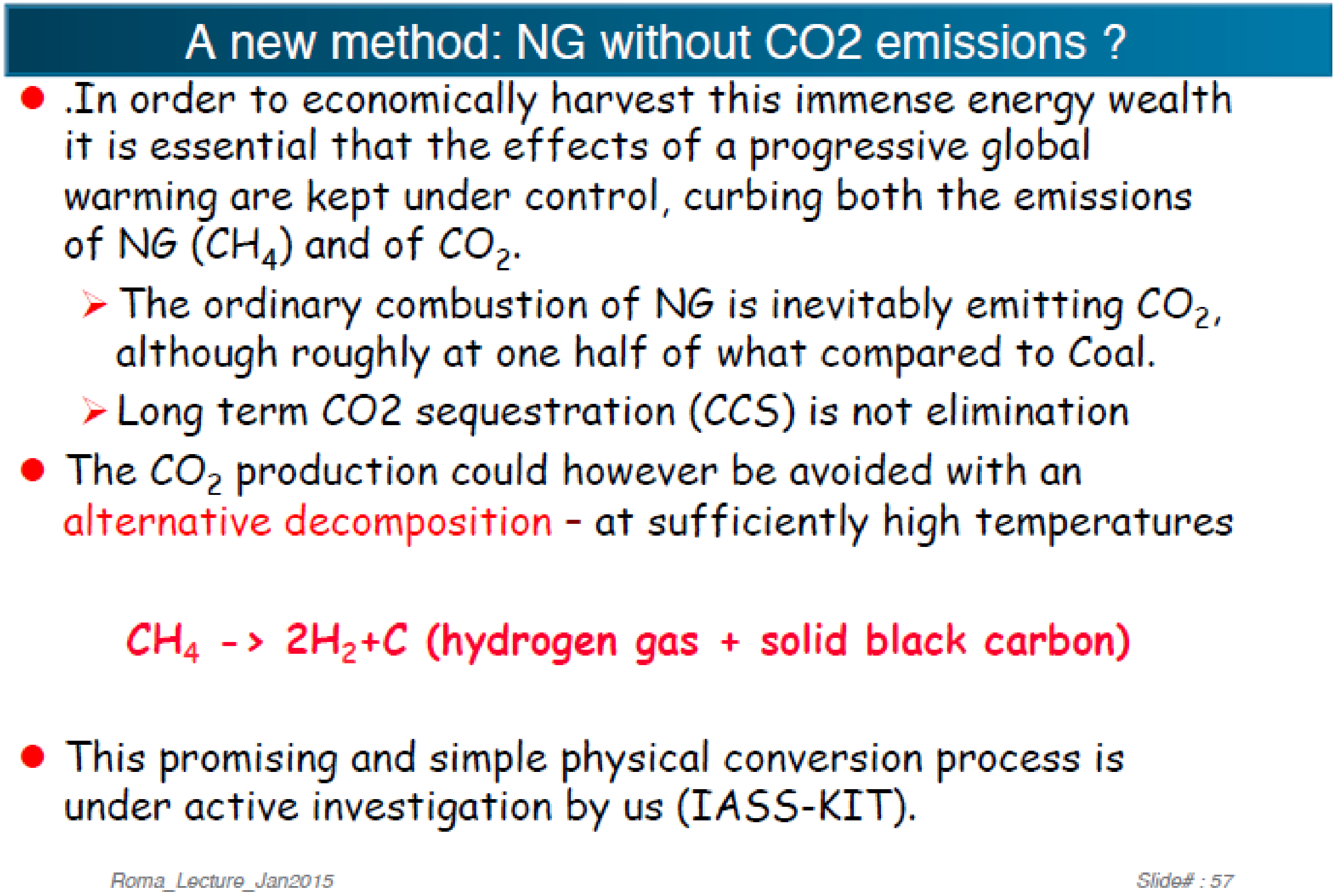


The FUSION train

The WORLD TGV

The Future of Energy

Carlo Rubbia



A new method: NG without CO2 emissions ?

- .In order to economically harvest this immense energy wealth it is essential that the effects of a progressive global warming are kept under control, curbing both the emissions of NG (CH_4) and of CO_2.
  - The ordinary combustion of NG is inevitably emitting CO_2, although roughly at one half of what compared to Coal.
  - Long term CO2 sequestration (CCS) is not elimination
- The CO_2 production could however be avoided with an alternative decomposition - at sufficiently high temperatures

CH_4 -> $2H_2$+C (hydrogen gas + solid black carbon)

- This promising and simple physical conversion process is under active investigation by us (IASS-KIT).

Roma, Accademia dei Lincei, January 2015

Conclusions

- Progress in HTSC magnet technology allows higher fields and more compact devices to be conceived also for reactors;
- Higher fields, higher densities → more attractive plasma regimes (no ELMS, possibly no divertor);
- A more diversified program, both experimental and theoretical, is needed to advance fusion:

→ transport and stability studies in “low” beta regimes

→ edge modeling for “limiter” configurations

→ optimization of magnet shaping and plasma start-ups with ramping I,B