Compact tokamaks as convenient neutron sources for hybrid reactors

Massimo Zucchetti *, **

* Massachusetts Institute of Technology, MIT, Cambridge (MA), USA
** Politecnico di Torino, Italy, zucchett@mit.edu

ICENES 2011 – San Francisco

Introduction

- Future large demand for CO_2-free base load electricity
- May need 10 TW CO_2-free electricity by mid-century
- 20 times more CO_2-free electricity than now
- Only coal and nuclear fission are realistic options
- Coal must solve the sequestration problem - tough job
- Nuclear must solve waste and proliferation problems – and the Japanese syndrome
- Nuclear must also solve the fuel supply problem – only 30 years of proven reserves at 10 TW level

The future for fission

- Mid-century uncertainties
  1. Coal Sequestration
  2. Discovery of new uranium
  3. Opposition to “traditional” nuclear power
- Prudent to have other options
- Problems to be solved:
- *Produce large amounts of fissile fuel*
- *Burn TRU*

so that fission becomes a sustainable source

How are we going to solve the problem?

- Revisit an old idea:

  Use a fission-fusion hybrid to produce fissile fuel and burn TRU

- What has changed to make this old idea interesting?

  1. We may need a lot more uranium than we thought
  2. The fission community is interested and receptive to the idea
  3. No Yucca Mountains are operative anywhere
  4. After Fukushima, “new” ideas are fashionable

The fission-fusion energy park

- One tokamak fusion core
- Surround with a thorium-lithium blanket – produces U-233 plus T
- Separate the U-233 and combine it with U-238 to form fissile fuel for a LWR
- Power gain may reach 8-10
- Burn the resulting Pu and actinides in an onsite fast reactor.
- Store short lived radioactive byproducts on site
- Transmute long lived radioactive byproducts in the hybrid blanket

Why is this good for fusion

- How can fusion make a contribution by mid-century?
  - Fusion electricity is tough from a plasma physics and fusion engineering point of view
- Fissile fuel from fusion is much easier
  - Need Q = 2 -5 for success rather than Q = 50 for electricity
  - Do not need steady state or ultra-high availability
  - Even if fusion electricity is successful, it will likely cost more than a comparable fission reactor
- What about tainting fusion with fission? If we can help fission produce electricity we must do so and collaborate!

Why is this good for fission?

- The fission-fusion hybrid converts fission energy from an intermediate stop-gap energy source into one that is sustainable for over 10,000 years
- Making fissile fuel from a fission-fusion hybrid may be better than alternate options
- It is an innovative reactor concept, going beyond the "GEN-III-IV" pathway, that maybe after Japan accident will have difficulties
- It burns TRU

Comparison of options

- What are the options for producing fissile fuel?

Fuel Source	Cost (cents/kW-hr)
Direct mining of U	0.5
Sea water extraction	1.6
Accelerator production	7.4
Breeder reactor	1.8
Fission-fusion hybrid	1.7

Hybrids and high-energy neutrons

- Whatever in expansion or deep crisis, nuclear power would need a solution to burn the long half-life transuranics (TRU) in the spent nuclear fuel discharged from LWRs.

- Moreover, high-energy neutrons from fusion can be very useful for other processes, such as
  - testing of candidate nuclear materials,
  - production of radioisotopes (for medical applications and research), radiotherapy,
  - detection of specific elements or isotopes in complex environments,
  - alteration of the electrical, optical, or mechanical properties of solids

D-T Hybrids R & D

- D-T fusion neutron sources sufficient to drive sub-critical advanced reactors.
- Such devices could be extrapolated from the current magnetic confinement fusion physics and technology database and deployed within a relatively short timespan.
- A tokamak neutron source could be designed and built soon, extrapolating present designs of fusion tokamaks, paying attention to some additional R&D, such as
  - emphasize quasi-steady state operation,
  - disruption avoidance,
  - component reliability, materials, etc.
  - selected tokamak physics and technology advances.

Compact Tokamak Hybrids?

- Compact high-field tokamaks with short-pulse operation seem at first sight not to be the best candidates for hybrids

- But – as for DT fusion – we must start from an easy-to-build machine and test it as a neutron source and a demonstrative hybrid device

- Proposing as a neutron source for a Hybrid a great big elephant like a brother of ITER can get nervous people ready to build and run 100 GEN-III reactors in the next 20 years

Compact Tokamak Hybrids!

- Compact high-field tokamaks can be a candidate for being the neutron source in an experimental fission-fusion hybrid, to be built NOW:
  - Phase 1 – A compact tokamak neutron source for materials irradiation
  - Phase 2 – The same neutron source with a blanket component where TRU transmutation takes place and it is demonstrated
- Small tokamaks have good design characteristics too:
  - Compact dimensions,
  - High magnetic field and neutron-richness,
  - Flexibility of operation
  - Low cost

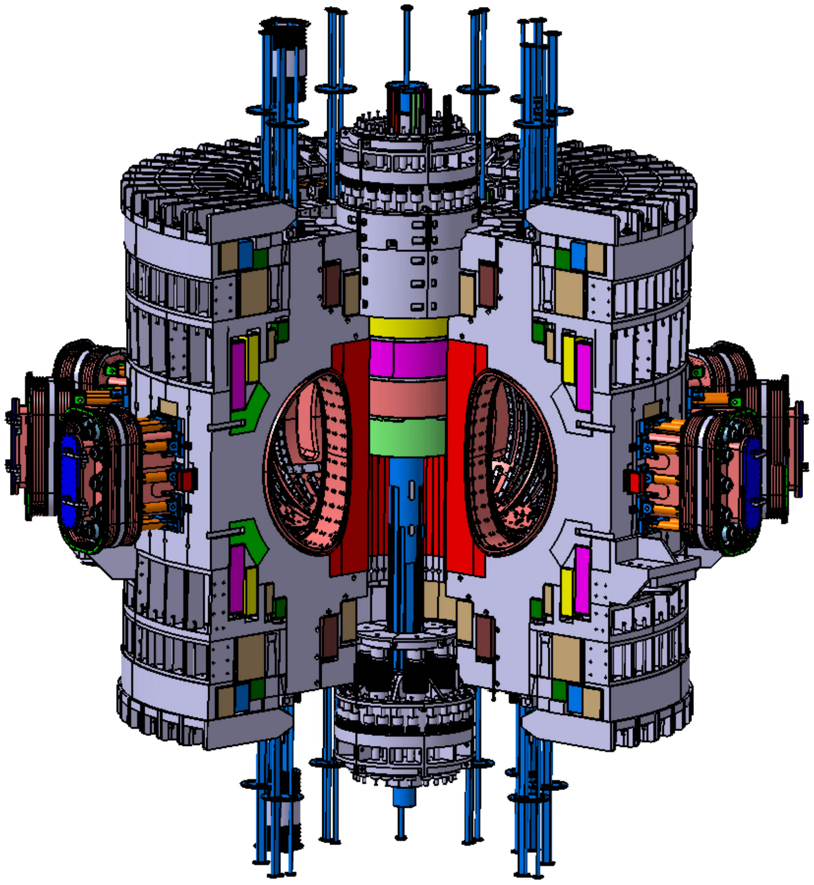
The Ignitor neutron source

- We are studying the development of a tokamak neutron source for a hybrid reactor using Ignitor-based technologies.
- Ignitor is a proposed compact high magnetic field tokamak, aimed at reaching ignition in DT plasmas and at studying them for periods of a few seconds.

Revision of Ignitor parameters

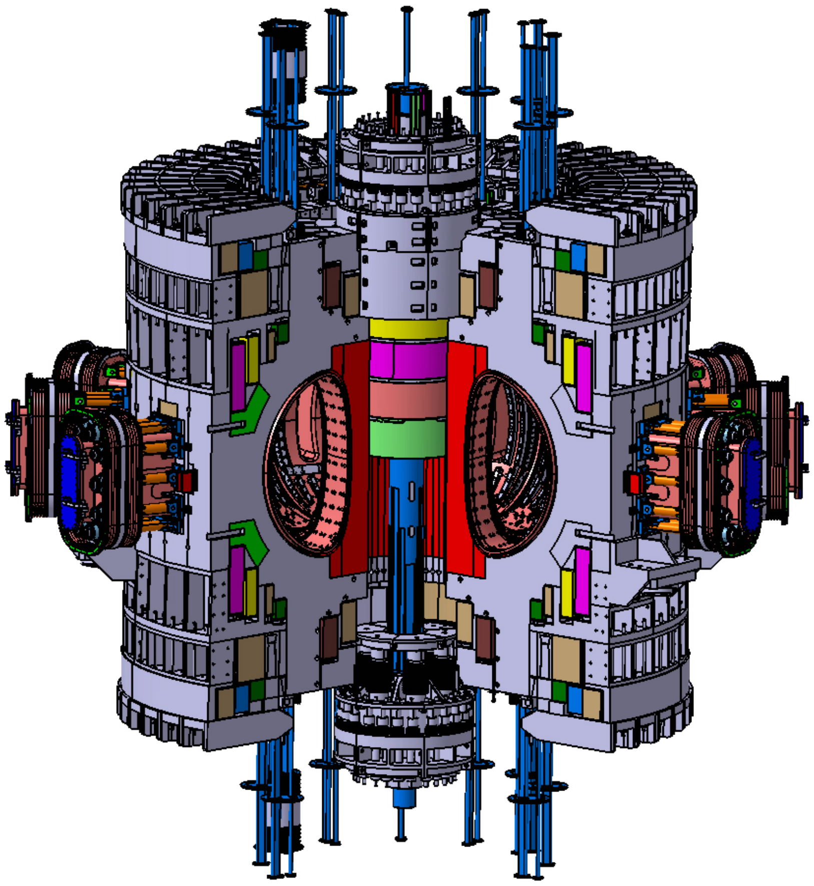
- Revision of Ignitor operating parameters in order to act a as a suitable neutron source in a hybrid reactor is being undertaken within a collaboration among MIT, Politecnico di Torino (Italy) and Kurchatov Institute (Russia)
- New operating scenarios are proposed.
- The Ignitor-based tokamak source has a longer plasma discharge length, operates at lower magnetic field values, and does not reach ignition: however, its neutron production is estimated to be fully sufficient for an experimental hybrid demonstration device.

The Ignitor Tokamak



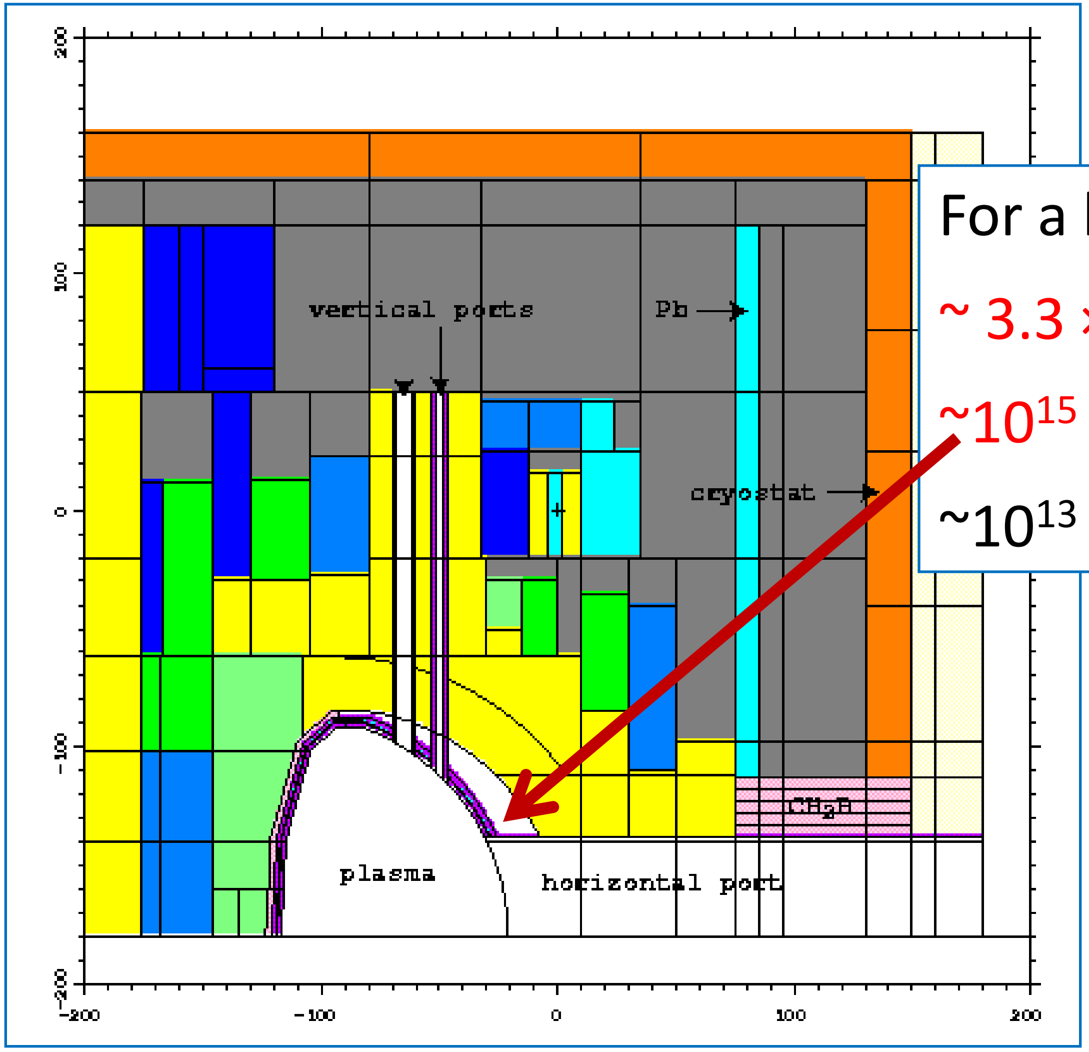
R	1.32 m
a	0.47 m
κ	1.83
δ	0.4
V	10 m^3
S	36 m^2

The Ignitor Tokamak



Plasma Current I_P	11 MA
Toroidal Field B_T	13 T
Poloidal Current I_θ	8 MA
Average Pol. Field $\langle B_p \rangle$	3.5 T
Edge Safety factor q_ψ	3.5
Pulse length	4+4 s
RF Heating P_{icrh}	<12 MW

Ignitor, a powerful neutron source



For a high performance shot

~ 3.3 × 10^{19} n/s

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

~10^{13} n/(cm^2 s) @ port flange

Neutron requirements for 10 DPA/year

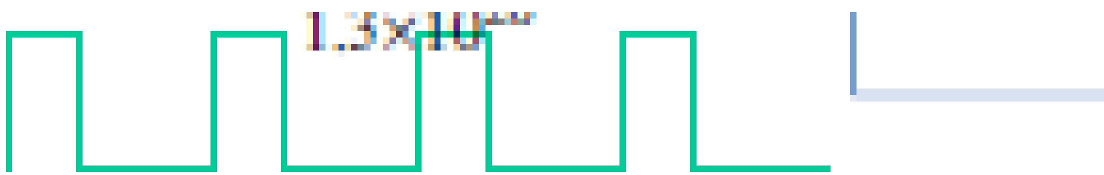
$$N = \frac{10[\text{DPA}]}{3.22\times10^{-26}[\text{DPA/n}]} = 3.1\times10^{26} \text{ neutrons/yr}$$

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

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

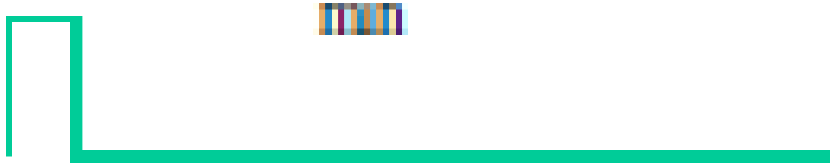
8760 pulses /yr
Irradiation volume
~ 1 m³ = 1000 l
Tritium burn-up
= 1.6 Kg/yr

4 mo



@ 1 pulse / hour : T_{pulse}= 1200 sec = 20 min, T_{cool} = 40 min

1 mo



@ 1 pulse / hour: T_{pulse}= 300 sec = 5 min, T_{cool} = 55 min

Conclusions

- Either in crisis or expansion, fission should explore the possibility of:
  - Burning TRU
  - Developing alternatives to GEN III-IV mainstream, such as hybrids
- Fusion could shortcut its deployment as an energy source
- Tokamaks are a candidate for being the neutron source in a hybrid fission-fusion device
- Compact tokamaks, derived for instance from the Ignitor project, are a good candidate for:
  - Testing tokamaks as neutron soucres
  - Testing TRU transmutation
- Italian and Russian Governments have agreed and relevantly financed the construction of the machine in Russia, Troitsk site