Present and future plans of PROTO-SPHERA
Franco Alladio & PROTO-SPHERA Group, CR-ENEA Frascati

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• PROTO-SPHERA replaces the two central metal conductors of Tokamaks by a Centerpost Discharge (helically wound B lines)

• Magnetic reconnection physics: at ordinary magnetic X-points, a «tear» is operated, followed by a different «mending»

• transferring magnetic flux & electric current

• converting magnetic field energy to plasma temperature

• In Phase-1 (2018) «thin tori», have filled 7% of the total plasma volume.
• In Phase-1.5 (2019, 2020) 6 new PF coils inside an insulating vacuum vessel, spherical tori are planned to fill 70% of the plasma volume.
• In Phase-2 the aim is to fill 95% of the plasma volume.
Ideal MHD stability of PROTO-SPHERA

Tilt instability: toroidal dipole of vertical field overturns plasma current toroidal dipole

But PROTO-SPHERA dipoles:
“Group A” PF compression coils against Plasma dipole
“Group B” PF shaping coils aligned to Plasma dipole
Net result: rigid tilt instability is stabilized

Stability in terms of $\beta = \text{plasma beta} = \frac{\text{kinetic plasma pressure}}{\text{confining magnetic field pressure}}$

ELECTRODE-FACING DISK-SHAPED PLASMA CENTERPOST PROVIDES IDEAL MHD STABILITY

(cutting shorter & shorter the Plasma Centerpost destabilizes the configuration)

$\beta = 1$ is achievable any metal vessel is unneeded
Phase 1.5 Autumn 2019: Tori sustained up to 1 s by new insulating PMMA Vessel (no skin effect: B immediate)

Vacuum as good as with a metal vessel: $5 \times 10^{-5}$ mbar
Operation at $> 10^{-2}$ mbar

The presence of a gas blanket around the plasma cushions the inside of the 9 cm thick PMMA vessel

A further 2 mm thick polycarbonate liner inside the PMMA vessel protects it & screens UV light

Confined plasma can be obtained without a nearby metal wall: the absence of any conducting shell distinguishes PROTO-SPHERA from any spheromak
Phase 1.5 Autumn 2019: 4 refurbished External PF & 6 new Compression (CPF): 18 PF coils, 2 power supplies

«Thick tori» are produced by External PF coils (PFExt) alone

The transparent vessel allows for 3D plasma tomography in visible light

6 cameras around vessel, 600 fps

The 6 compression CPF coils fed by a Supercapacitor bank
«Thin tori» (R/a=7, b/a=4) obtained in PMMA VV same as in 2018 Aluminium VV
• now sustained for 1 sec in static B field!

Vision from 6 cameras rotates to show 3D phenomena

Magnetic reconnections are 3D events around X-point circles:
their intensity is the strongest &
their repetition rate is the highest
at torus formation then both decline
during torus maintenance
«Thin Tori» difficult to produce by pulsing PFExt coils

Supercap power supply pulsed PFExt coils with the right current (compression CPF inactive)

So «Thin torus» formation was attempted on the pre-existing Centerpost discharge: «Thin torus» did not stabilize!

The absence of a toroidal magnet & the torus formation in a magnetostatic field suggest: magnetic confinement devices could be built (in principle) using axisymmetric permanent magnets surrounding a Plasma Arc Discharge.
Stray plasma current paths have been cured during the whole Phase-1.

...but still in Phase-1.5 stray current paths are present around the tori ... curtailing the efficiency of helicity injection!

Argon: currents disconnected from torus connect the electrodes’ rear: 4 kA lost over 10!

In Hydrogen sparks from lower PF2 coil surround the torus.
Argon Tori by PFExt formation, then CPF (Compression coils) or directly in static field (PFExt+CPF together)

The CPF current feedthroughs at first acted as secondary electrodes

Vacuum field without plasma

Reconnections with compressing CPF

Magnetics $I_{\text{torus}} = I_{\text{electrodes}} = 6\ \text{kA}$

Feedthroughs fixed

Vision from 6 cameras rotates to show 3D phenomena

You don’t get what you see ...you don’t see what you get!

...not yet a spherical torus

Magnetics (currents in PFC & separatrix position) gives $I_{\text{torus}}/I_{\text{electrodes}} = 6\ \text{kA}/6\ \text{kA} = 1$
Hydrogen Tori by CPF (Compression coils) alone

Vacuum field without plasma

Magnetics $I_{\text{torus}} = 3 \text{ kA}$
$I_{\text{electrodes}} = 10 \text{ kA}$

Plasma surrounds both PF5

Vision from 6 cameras rotates to show 3D phenomena

Sparks from PF2 flow around torus

...far from a spherical torus
Magnetics (currents in PFC & separatrix position) gives $I_{\text{Torus}}/I_{\text{electrodes}} = 3 \text{ kA}/10 \text{ kA} = 1/3$
Planned escalation of performances

2018-2019
2.5 MW power to overall plasma

From Phase-1

$I_e = 10 \text{ kA}$
$I_{ST} = 7 \text{ kA}$

2019-2020
up to 3.5 MW overall

to Phase-1.5

$I_e = 10 \text{ kA}$
$20-40 \text{ kA}$

end 2021
up to ~ 20 MW overall

to Phase-2

$I_e = 70 \text{ kA}$
$I_{ST} = 0.28 \text{ MA}$

From 7% Torus/Sphere volume
7% of Power Input to Torus

to 70% Torus/Sphere volume
? of Power Input to Torus

to 95% Torus/Sphere volume
? of Power Input to Torus

No additional heating systems? (reconnection heating)

$\beta \sim 1 \Rightarrow$ cost is 1% of a Tokamak ($\beta \sim 1\%$), with same power input into plasma
To be built to achieve 1/3 MA Spherical Torus (Phase-2 2021)

**Group A: compression coils** (3+3 in series)
- Electric power supplies based on *Super-Caps*
  - Compression Group A (fit up to $I_{ST}=0.5$ MA)
  - Cathode ($I_{cath} 10 \rightarrow 70$ kA)
  - Centerpost ($I_e 10 \rightarrow 70$ kA)

**Already built, for Phase 1.5, June 2019**
- PFExt 8+12+12+8, 240 mm$^2$
- PMMA Vacuum vessel
- W cathode Filaments (54→378) (still 54 now)

**To be built, at the end of Phase 1.5**
- Cost incurred so far (2019) ~ 2.5 M€
- Cost for completion (Phase-2) ~ 1.5 M€
Last Confinement Surface spherical, but Tori inside

Poincare’ “Hairy-ball theorem”: no continuous field tangent to a sphere
there is at least upon one point $\vec{B} = 0$ and $\vec{\nabla} p = 0$
null or degenerate X-point

a hairy torus can be combed
a hairy sphere cannot!

One of the “tufts” of the sphere is predominant
in expelling charged fusion products

Space-thruster forerunner?

Magnetic nozzle observed in PROTO-SPHERA experiment (2015)
Remarks:

• The machine does not aim at refining previously achieved results, but to be ground-breaking.

• Until now the physics ideas seem sound: tori were sustained until $I_{\text{Torus}}/I_{\text{electrodes}} = 1$.

• Technically it can achieve Phase-2 without design uncertainties, with limited corrections.

• Until now these corrections have dealt with boundary conditions (magnetic & electrostatic).

• The progress of the machine must follow a step by step path: no hazards, …single steps. …btw: complete successfully Phase-1.5 before moving to Phase-2 PF coils & Power Supplies.

• Successfull Phase-1.5 requires a spherical torus with $I_{\text{Torus}}/I_{\text{electrodes}} > 2$ in Hydrogen.

• Fusion might be a dream, but magnetic reconnections studies must aim at excellence. …& must accommodate experiments of astrophysical interest.

• But there’s a dream: a permanent magnets confined arc discharge as ultimate fusion machine.

Part II - 10 Fusion Concepts for the future - Ultimate Fusion pag. 413 ...the very end of the book.

One hundred years from now, what will a fusion reactor look like?
They may look like those of the Chandrasekhar–Kendall–Furth force-free configuration shown in Fig. 10.56.
The exterior regions above and below the divertor necks can be expanded like those of an axisymmetric mirror.
High-energy alpha particles leaving the divertors can be channeled into direct converters to generate high-voltage DC directly. The central core can be slid up or down continuously to be refreshed without a shutdown.
This is a dream, but we can hope.