PROTO-SPHERA: a magnetic confinement experiment which emulates the jet + torus astrophysical plasmas

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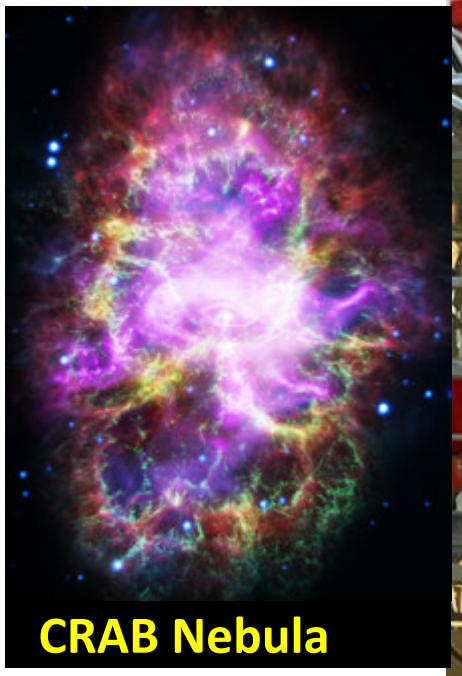

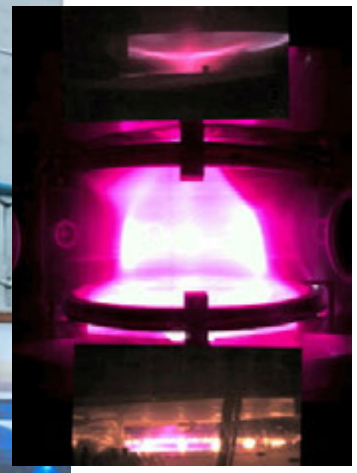

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OUTLINE

Force-free fields model for Astrophysical plasma & as foundation of the PROTO-SPHERA experiment

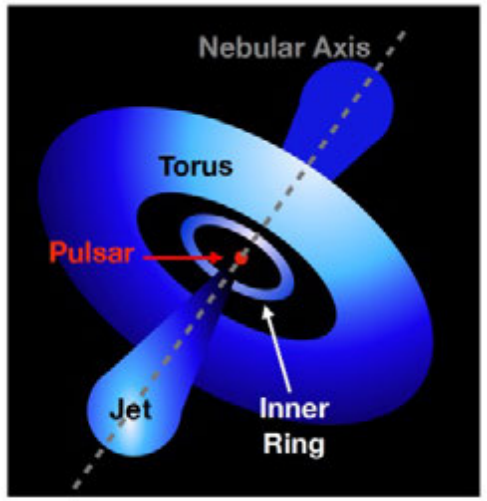
Torus + Jet configurations in Laboratory and Pulsar Wind Nebulae (PWNe), but
- **in PROTO-SPHERA, jet electric current has even parity on the equator**
- **in PWNe , jet electric current has odd parity on the equator**

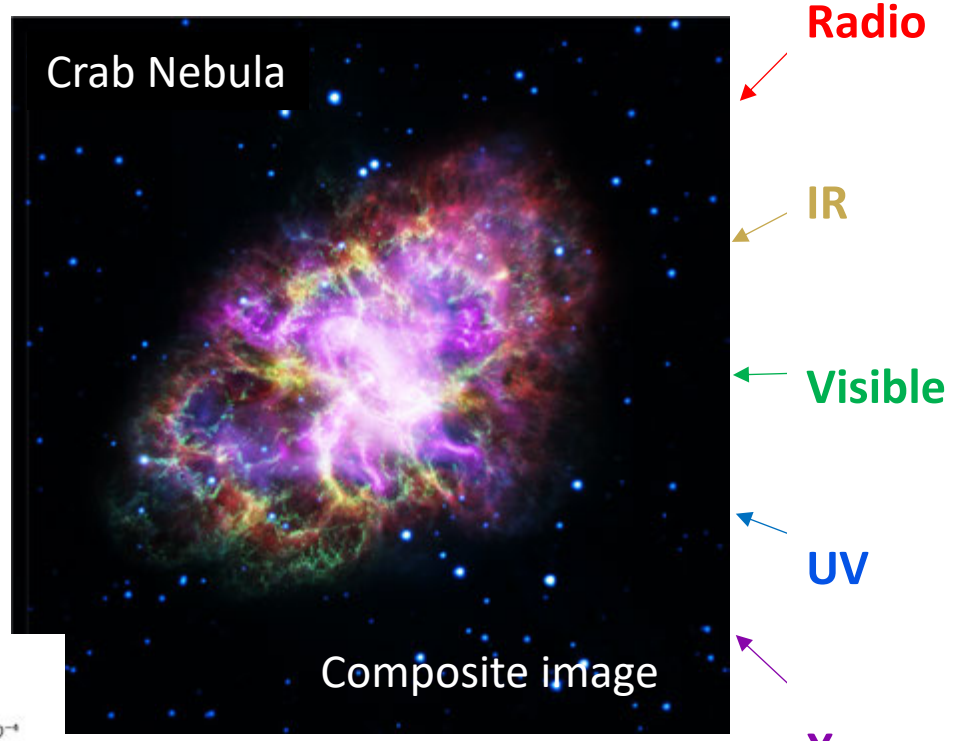
Ideas about magnetic reconnection in PWN and the role of the equator of PWNe
The "quiet" formation of the torus in PROTO-SPHERA

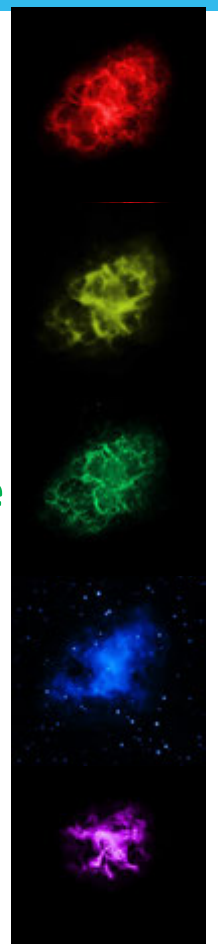
Symmetry breakings in PROTO-SPHERA plasma:
- **Rotation and electrostatic field symmetry breaking**
- **Magnetic Reconnections (with their first thermal effects) and breaking of axisymmetry**

Both plasma configurations are oblique rotators

Torus + Jet plasmas are present in Pulsar Wind Nebulae and are produced in laboratory experiments







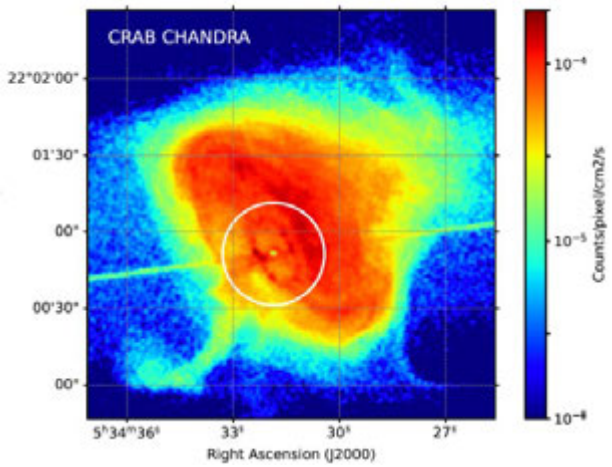
Radio

IR

Visible

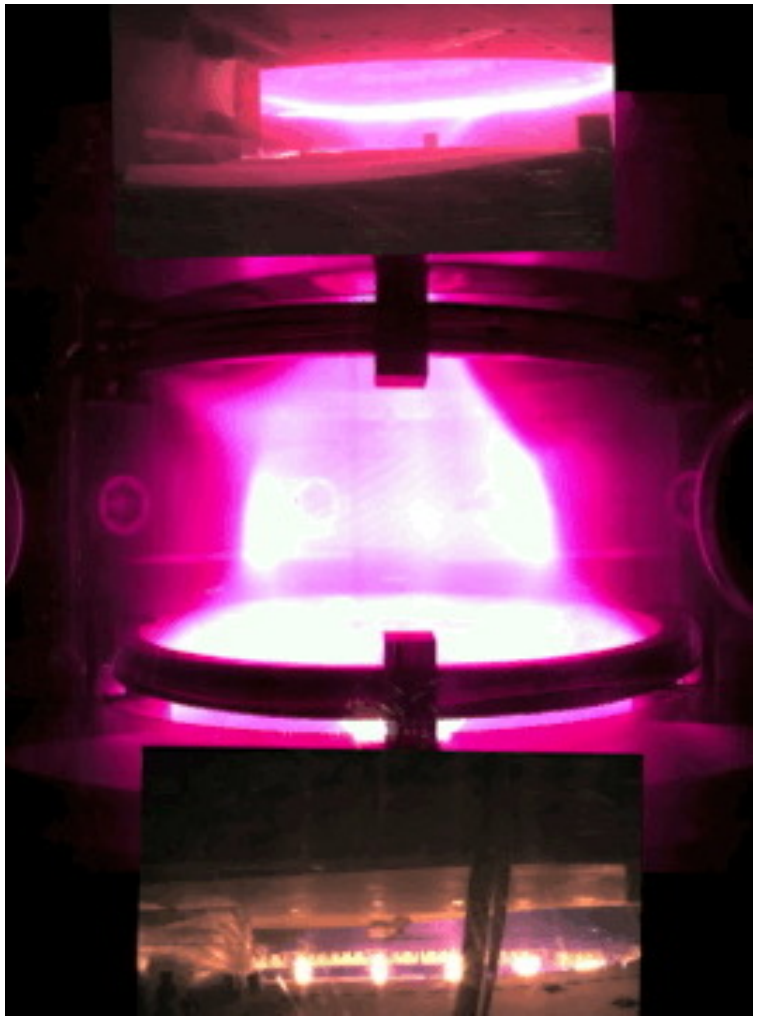
UV

X-ray



…the Torus of the Pulsar Wind Nebula is best seen in the high-energy part of the e.m. spectrum (Chandra image)

PROTO-SPHERA



Torus + Jet plasmas as force-free fields - if currents are unavoidable, let them flow along fields!

Why force-free field (fff) models? They are distributions of $\vec{B}$ and $\vec{j}$ such that $\vec{j} \wedge \vec{B} = 0$ (apart from $\vec{j} = 0$), this usually means $\nabla \wedge \vec{B} = \mu \vec{B}$: field & currents are aligned inside the plasma

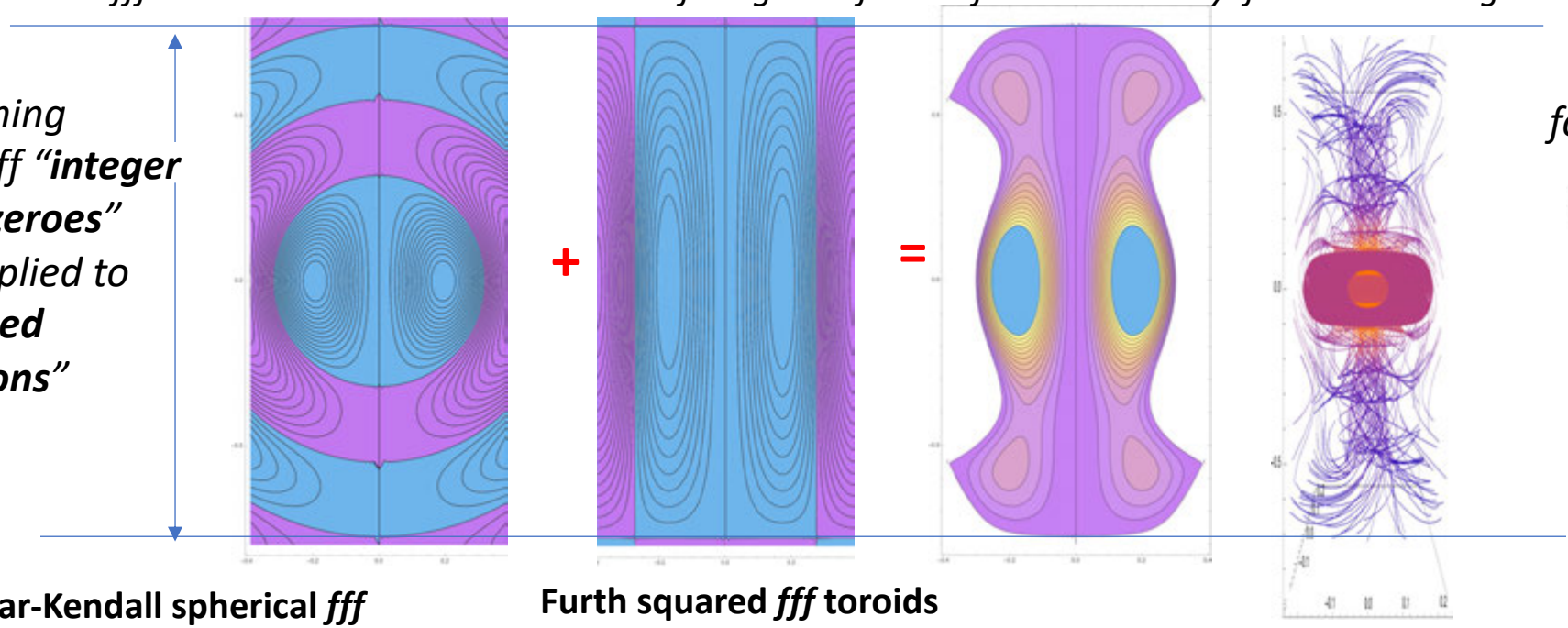
- no Lorentz force upon them
- can decay without causing material fluid motions
- the simplest choice for large scale structures in Astrophysics
- a hint for laboratory plasmas

The proportionality coefficients ***μ*** takes the name of **relaxation parameter**: $\mu = \mu_0 \vec{j} \cdot \vec{B} / B^2$

If μ= constant (in space) **linear *fff*** become a **linear algebra**: ***fff*** with **same *μ* can be freely summed to give a *fff***

Axisymmetric linear fff shown as: *cross sections of magnetic flux surface* *& by field line tracing*

*When summing up same μ fff "**integer number of zeroes**" rules are applied to obtain "**closed configurations**"*

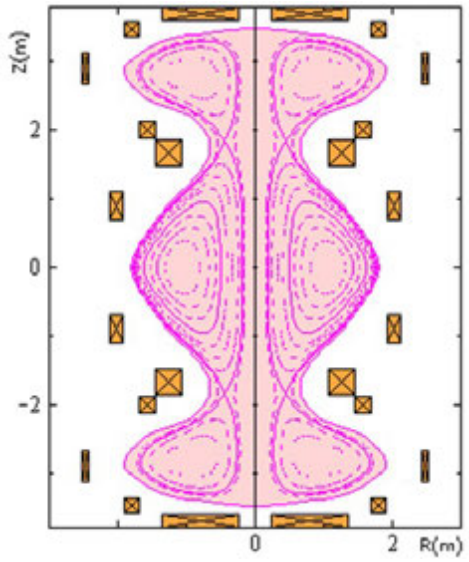


Chandrasekhar-Kendall spherical *fff* model a Torus Chandrasekhar, ApJ 126 (1957)

Furth squared *fff* toroids model a Jet Furth Rev.Sci.Instrum. 28 (1957)

Torus+Jet linear *fff* (CKF)

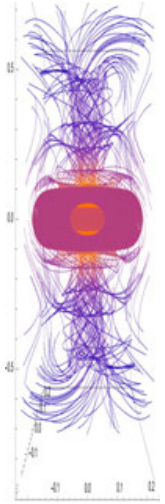
*Virial theorem requires **Gravity** or **External Coils** for "**closed configurations**"*



Torus + Jet *fff* plasmas have been the model for PROTO-SPHERA experiment

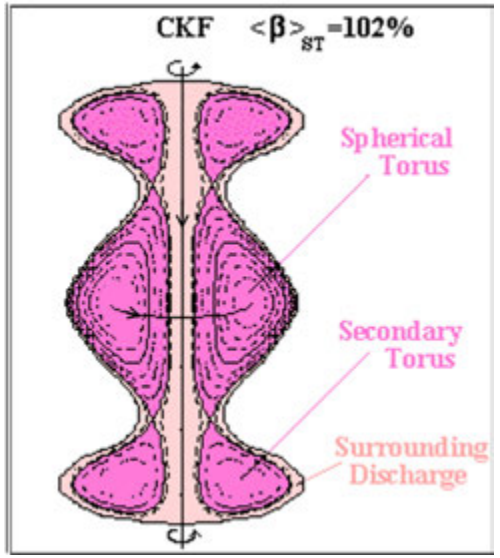
CKF *fff* Stable in Ideal MHD at β= plasma pressure/magnetic pressure ≥ 1 *

fff



*Rogier, *AIP Conference Proceedings* 669 (2003)

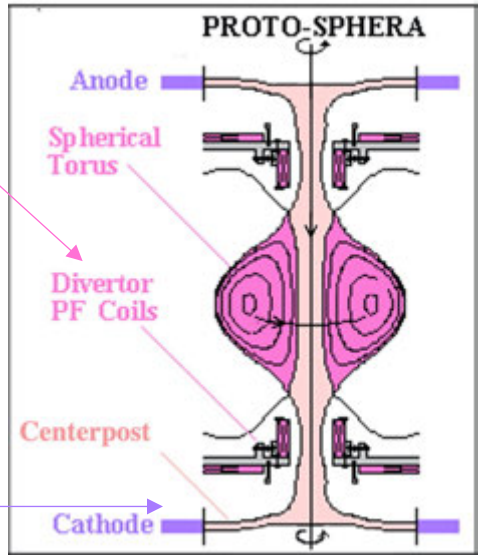
CKF *fff* can be filled up with plasma pressure, maintaining good features, such as ideal MHD stablity



But how to create a *CKF fff* in laboratory?

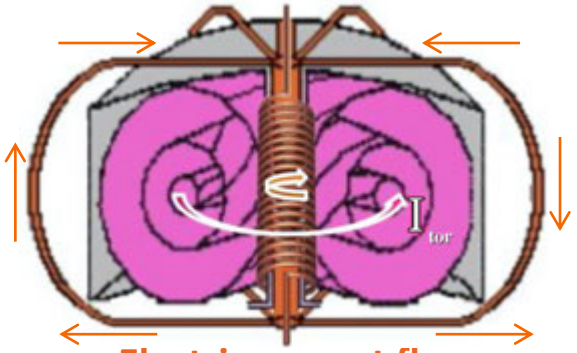
Substitute the secondary torus with divertor coils

Cut short the enveloping plasma making the Centerpost plasma to impinge on annular electrodes



Tokamak: toroidal plasma I_{tor} surrounds a "Metal Centerpost"

Vacuum vessel has a complex toroidal geometry

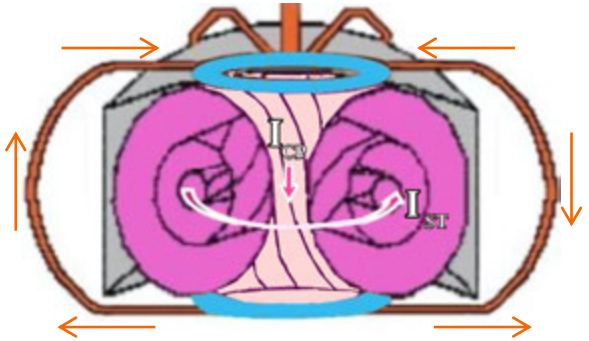


Electric current flow

PROTO-SPHERA: toroidal plasma I_{ST} around a "Plasma Centerpost I_{CP}"

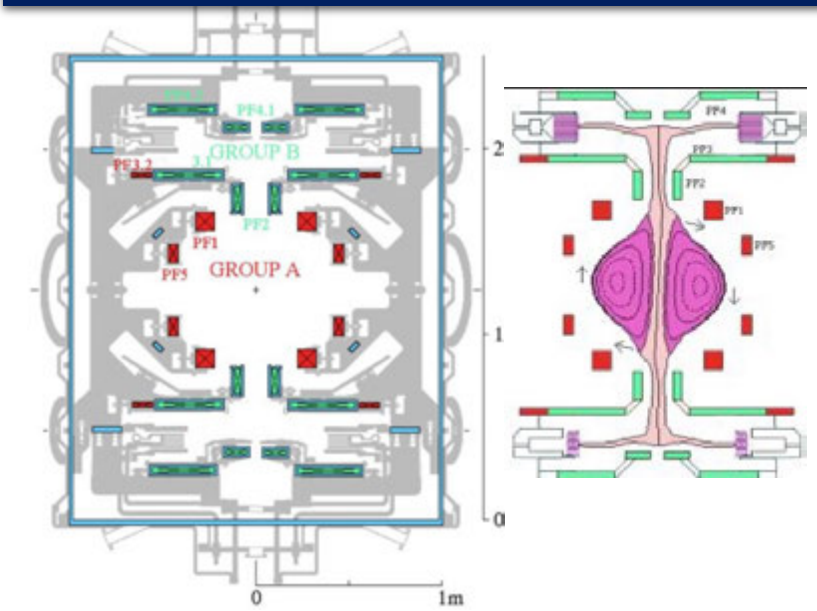
Vacuum vessel has a simple geometry

…but electrodes are required inside vacuum feeding



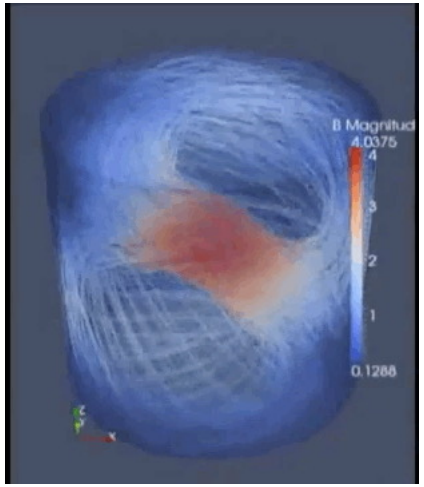
a Centerpost current I_{CP} surrounded by a Spherical Torus with toroidal current I_{ST}

Ideal MHD stability of PROTO-SPHERA remains remarkable



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

Avoids Spheromak tilting instability



But PROTO-SPHERA dipoles:

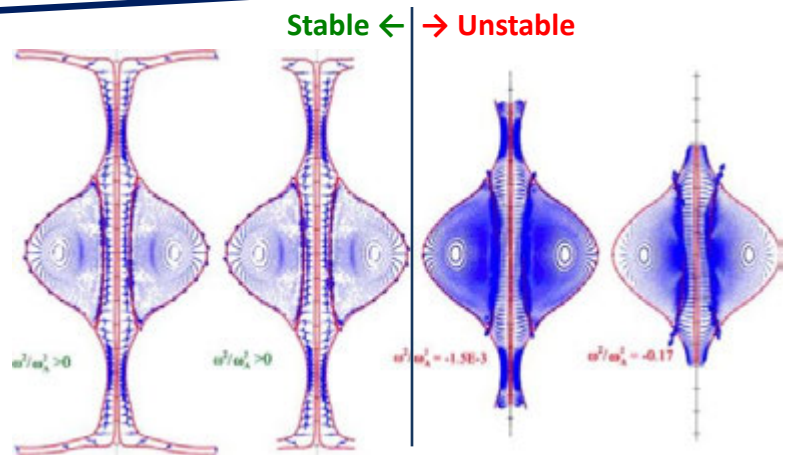
"Group A" PF compression coils against Plasma dipole

"Group B" PF shaping coils aligned to Plasma dipole

Net result: rigid tilt instability is stabilized without any stabilizing shell around the plasma (as Spheromaks do)

The stability was confirmed by full ideal MHD calculations*

*Micozzi, Nucl. Fusion 50 (2010)



Ideal MHD stability calculations

MUSHROOM SHAPED PLASMA FACING ANNULAR ELECTRODES PROVIDES IDEAL MHD STABILITY

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

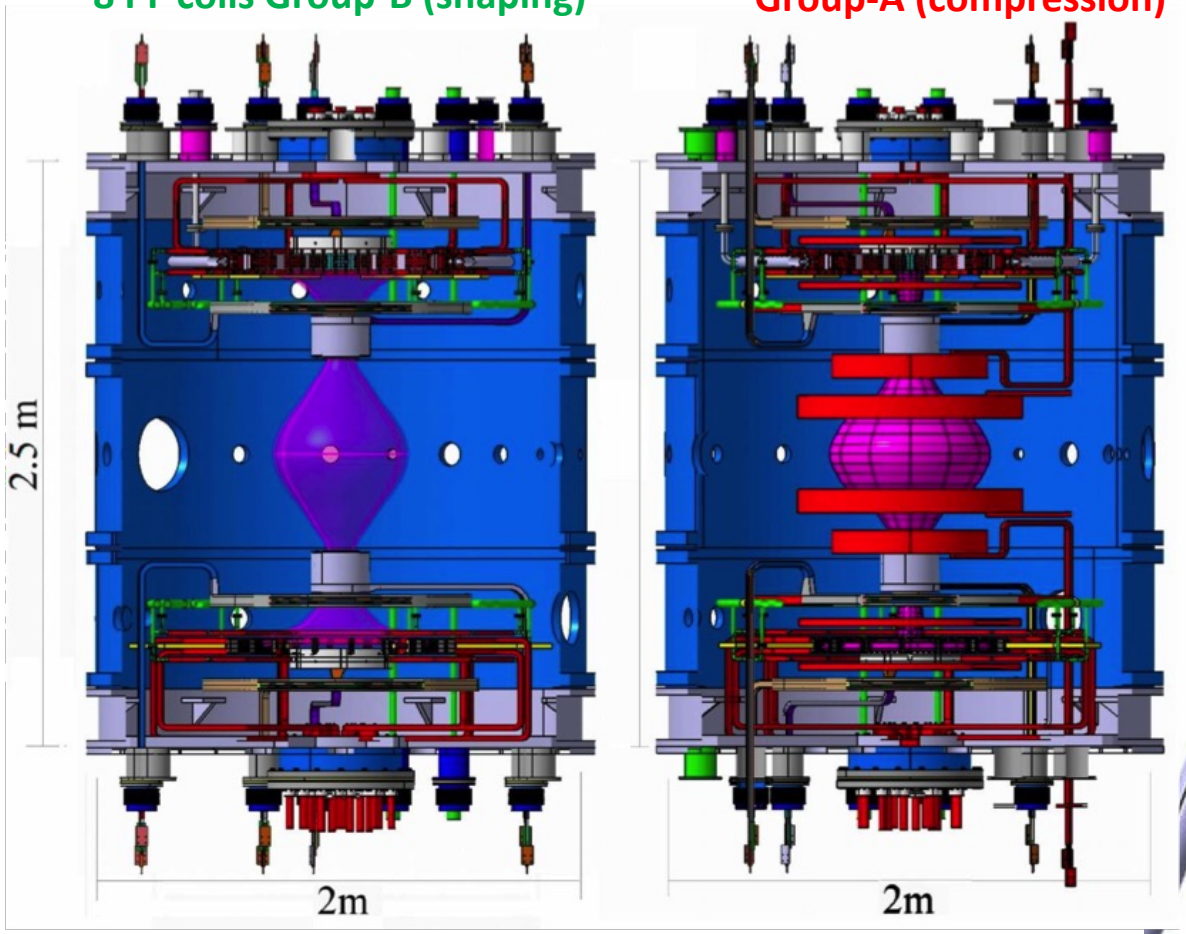
$\beta = 1$ is achievable
no nearby metal shell is required

PROTO-SPHERA: built 2015 (Phase-1) in ENEA, modified 2020 to Phase-1.5: new insulating vessel; from 8 to 18 poloidal coils, some fed by superCaps

Aluminum Vacuum Vessel of START (Culham)

Phase-1:
8 PF coils Group-B (shaping)

Phase-2: 8 PF coils + 6 PF Group-A (compression)



Phase-1.5

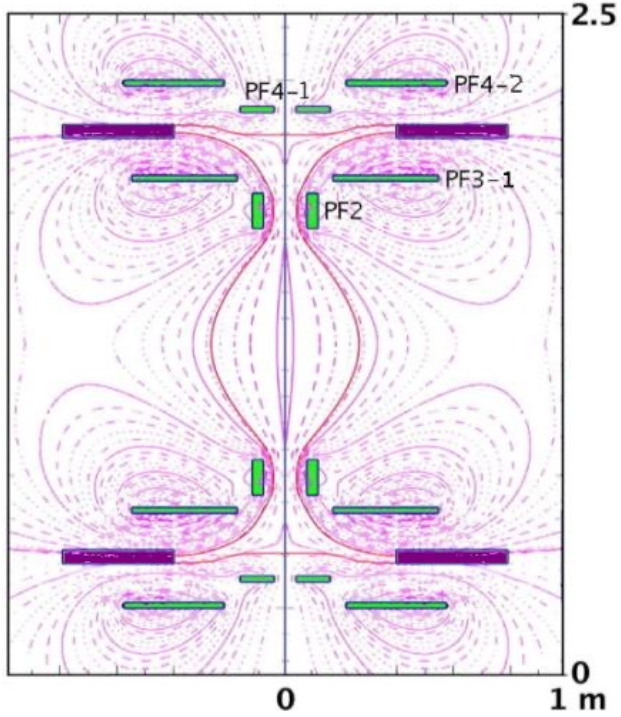
Plasma currents: **Phase-1** **Phase-2**

Centerpost I_{CP} = 10 kA Centerpost I_{CP} = 70 kA

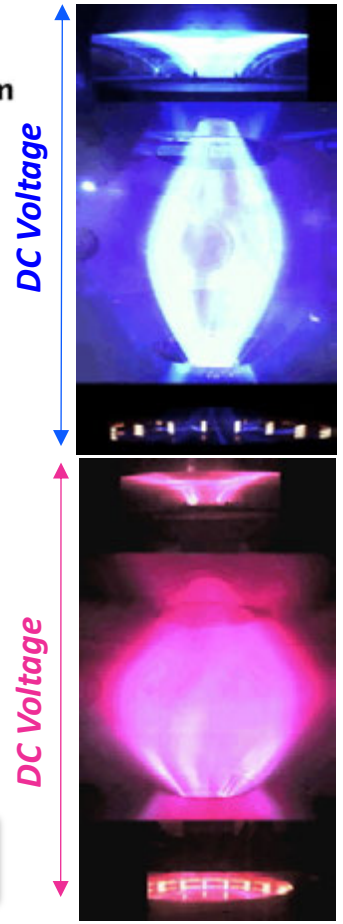
Spherical Torus I_{ST}= 5 kA…! Spherical Torus I_{ST}= 280 kA

PROTO-SPHERA: in 2018 Phase-1 was completed with success I_{CP}=10 kA, 1s
Diagnostics: magnetics, 2-color interpherometer, fast camera

Since the commissioning, one problem: to avoid spurious plasma discharges, but the simple cylindrical geometry of the vessel allowed for an easy access & the boundary conditions of the experiment were improved step-by-step



Pulse duration: 1 sec

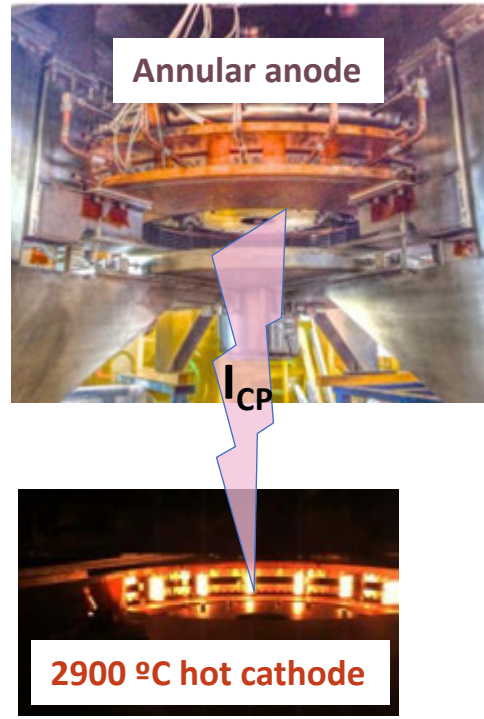


Anode-Cathode: 90 V at break-down, ~200 V at 10 kA flat-top

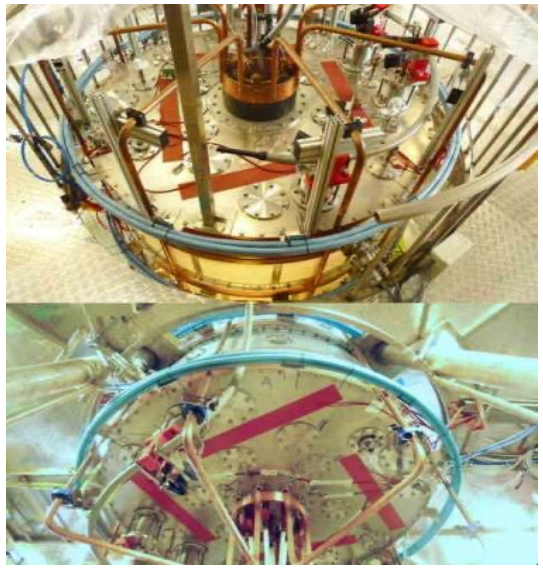
Argon line-averaged electron density: $\langle n_e \rangle \propto I_e$ $\langle n_e \rangle = 4 \bullet 10^{20}$ m^{-3} at I_{CP}= 10 kA

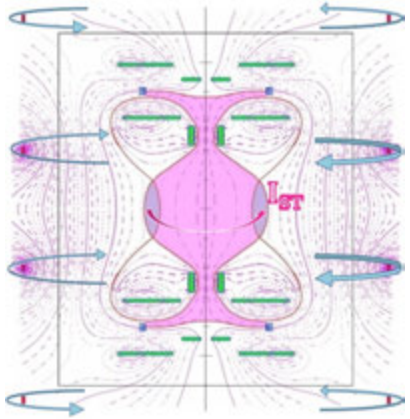
Anode-Cathode: 320 V at break-down, ~220 V at 10 kA flat-top

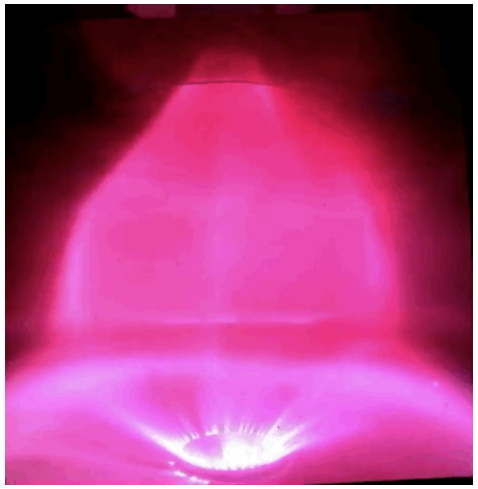
Hydrogen, line-averaged electron density: $\langle n_e \rangle \sim 1.5 \bullet 10^{20}$ m^{-3} at I_{CP}= 10 kA



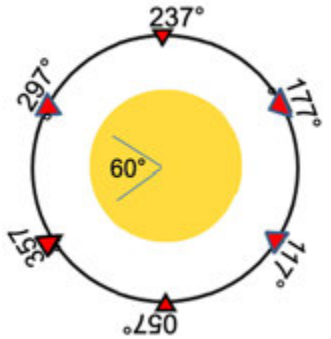
External compression PF coils were added in 2018 around the vessel: the first Tori (I_{ST}=5kA, with I_{CP}=10 kA) were immediately produced



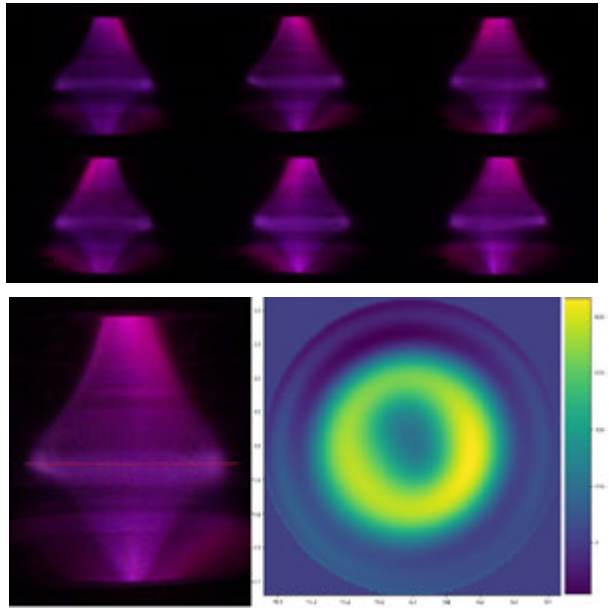




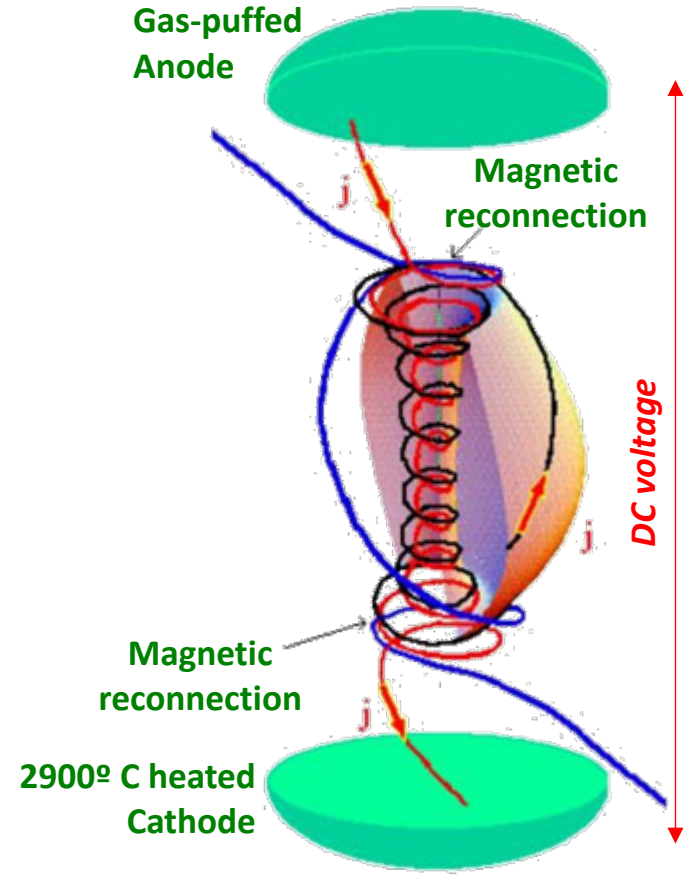
Boundary conditions were fine for Centerpost *but became not anymore adequate in presence of Torus*, in 2019 this led to the changes of Phase-1.5 *…now still working on Torus Boundary Conditions*



Since 2019, 6 cameras (600 fps) around the plasma, produced the first tomography on the equator

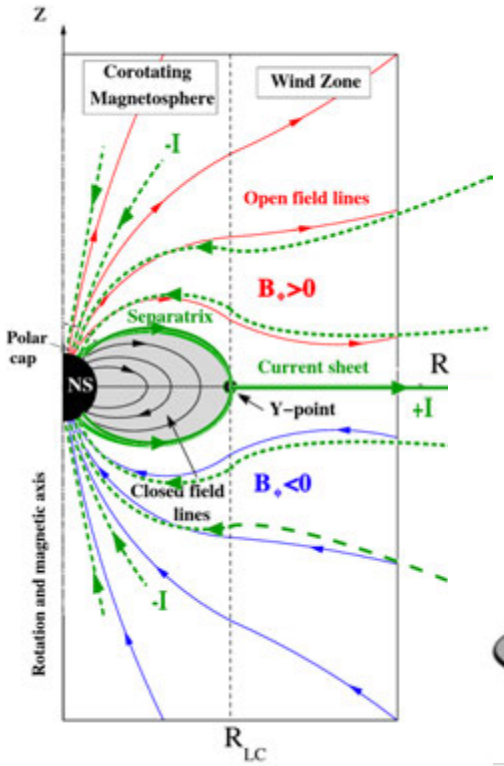


confirming the presence of the Torus

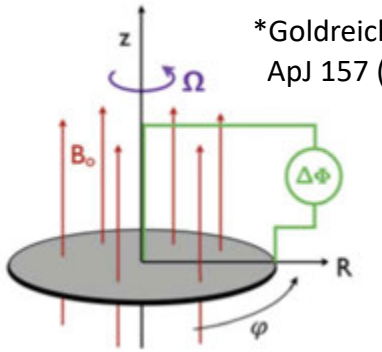


DC voltage from anode to cathode SUSTAINS THE TOROIDAL CURRENT by Magnetic Reconnections

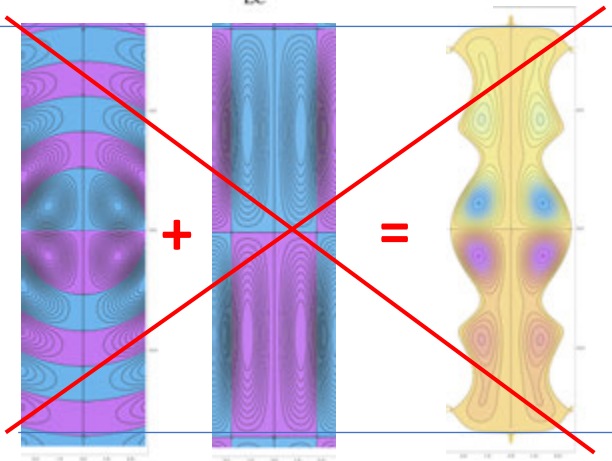
Torus + Jet plasmas: force-free fields for Pulsar Wind Nebulae (PWN)



Even symmetry of $B_{vertical}$ on the 2 emispheres, legacy of **B** of the Neutron star: Faraday disk effect gives **opposite $j_{vertical}$** on the 2 emispheres*



*Goldreich & Julian, ApJ 157 (1969)



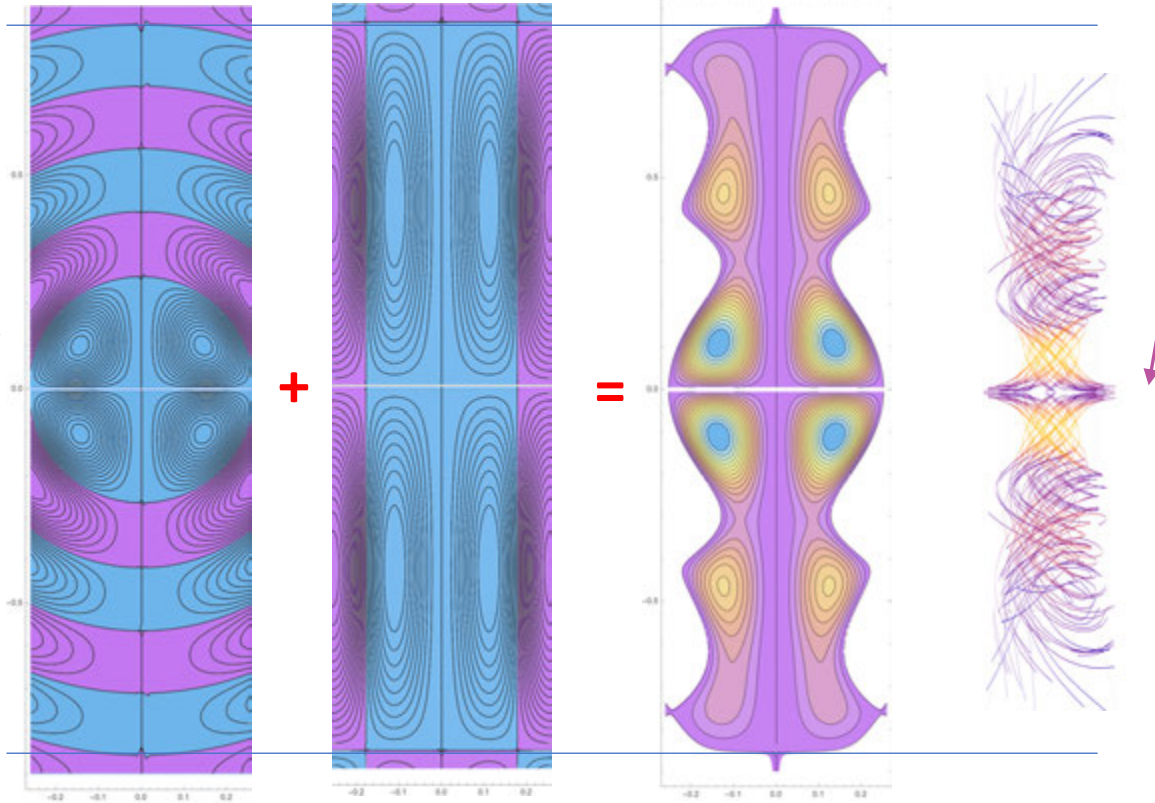
magnetic flux surfaces

Summing 2 odd-parity CK + F *fff* with the same *μ*… would give opposite **$B_{vertical}$** on the 2 emispheres, which is not right!

The only possible choice is a superposition of 2 ff fields with opposite μ, ***μ>0 on upper and μ<0 on lower emisphere*** …a feasible choice*,

which gives rise to a **B_{radial} discontinuity** and implies a **singular j_{tor} current layer on the equator of the PWN**

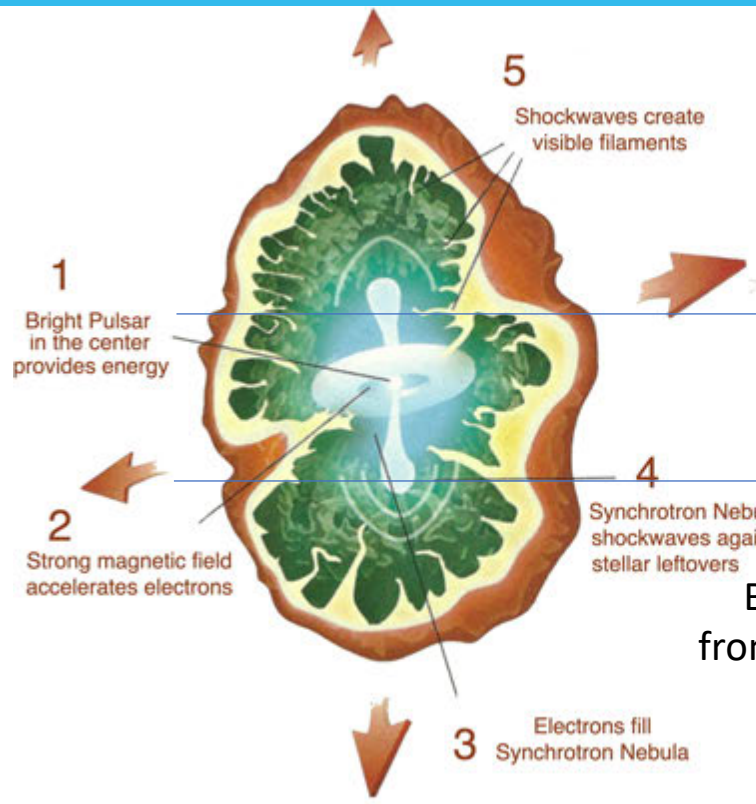
This implies **opposite $B_{toroidal}$** and even symmetry **of $j_{toroidal}$** on the 2 emispheres*



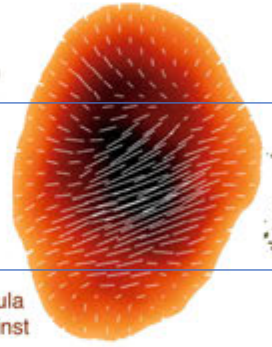
shown as cross sections of magnetic flux surface & by field line tracing

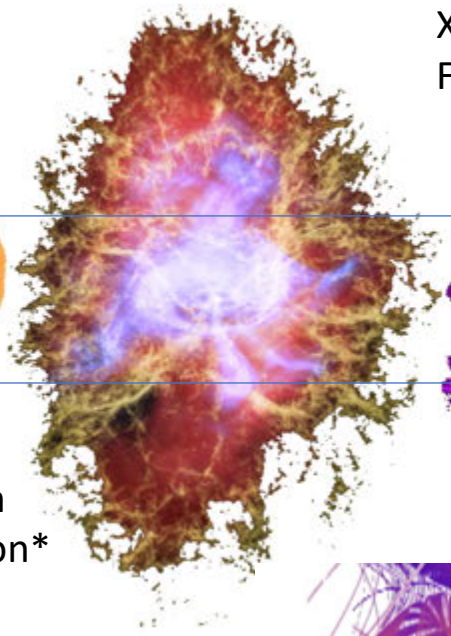
* Kumar, Phys of Plasmas 20 (2013)

Crab nebula & observed direction of B (radio to X-ray emission): polarized X-ray come from region with B toroidal & from equatorial j layer



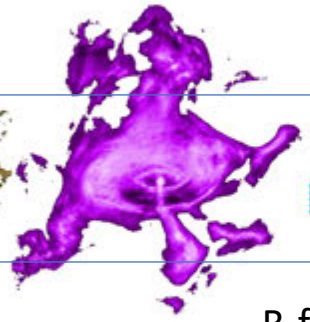
*Bietenholz, ApJ 357 (1990)





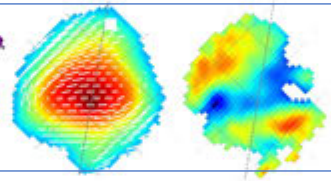
B-field direction from radio emission*

X-ray emission From Chandra



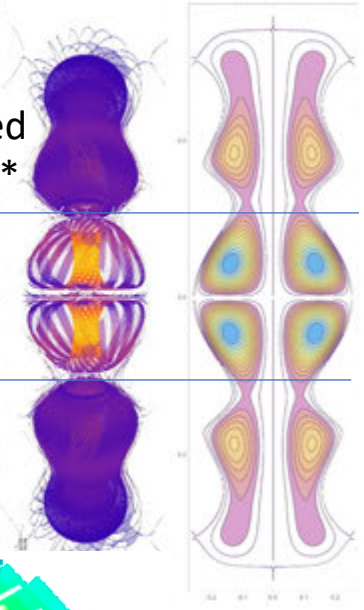
*Bucciantini, *Nat Astron* (2023)

X-ray polarized fraction IXPE*

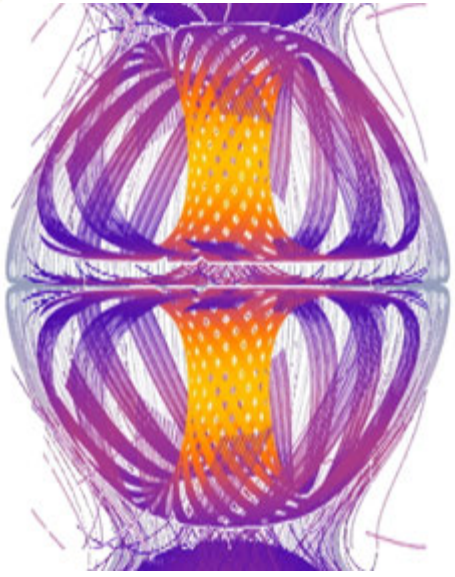


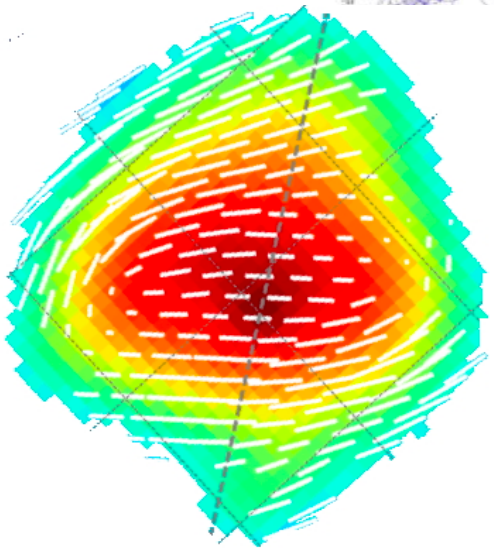
B-field direction From x-Ray IXPE*

Force-free model

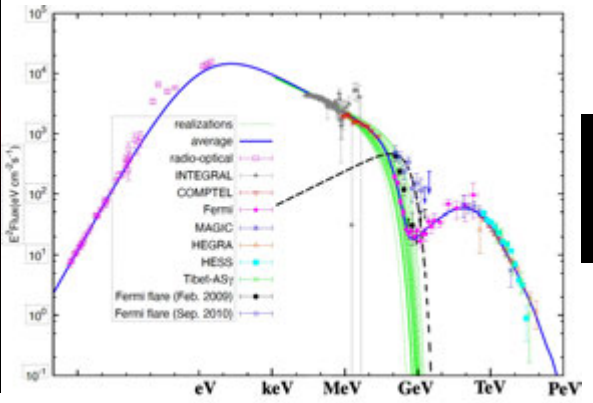


fff model toroidal field mainly in equatorial region just near the singular current layer



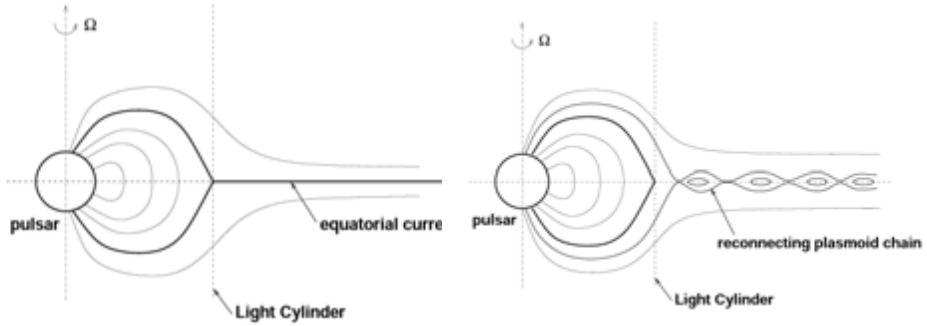


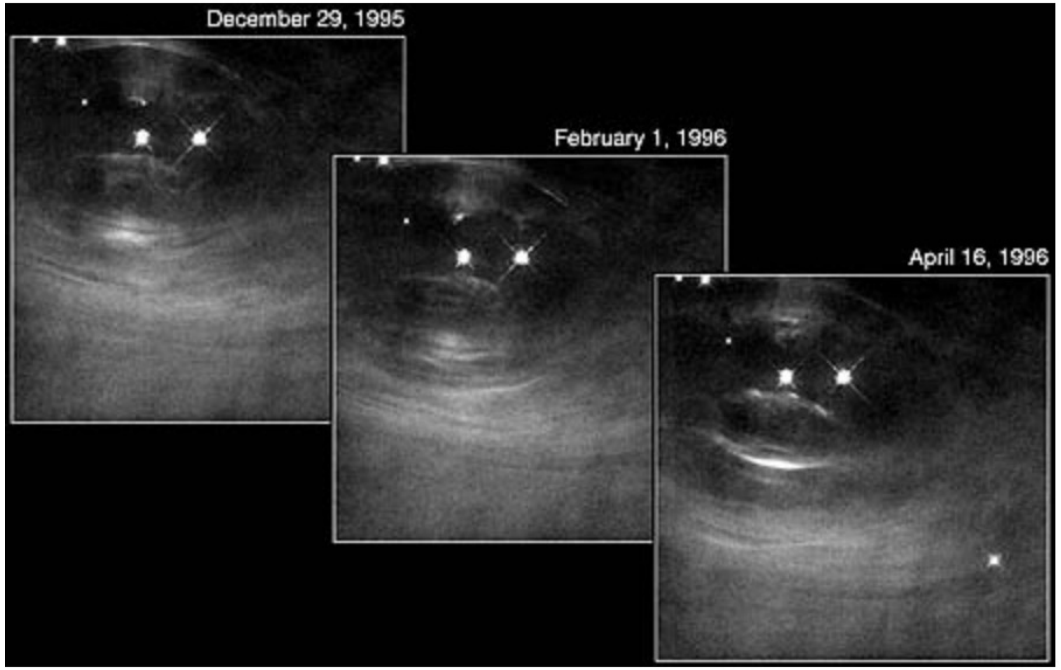
Do magnetic reconnections accelerate particle Acceleration in PWNe?



Spectrum of e.m. emission extends beyond PeV

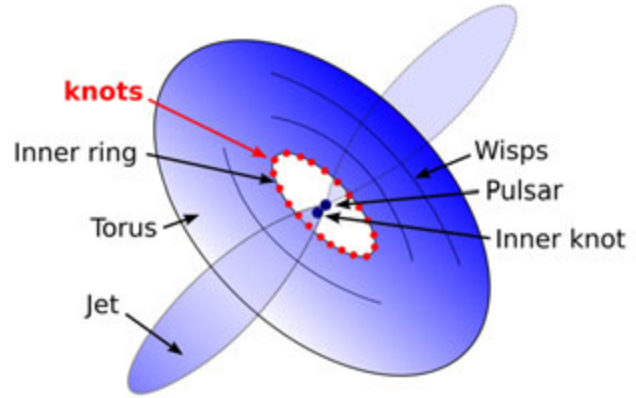
TheCrab Nebula is the best accelerator in the Galaxy! PeV = 10^{15} eV, & very efficient too: >25% of the released rotational power is emitted





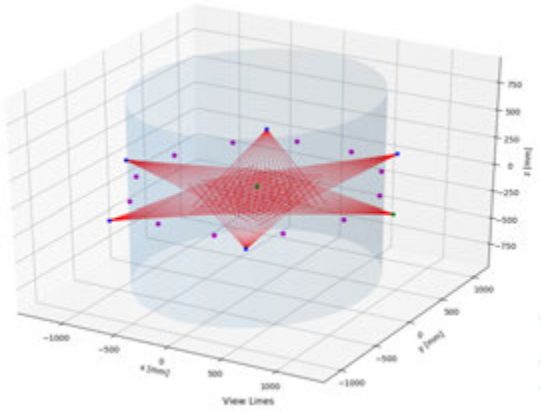
Singular current layer on the equatorial plane, where B_{tor} and B_{rad} change sign, can give rise to to plasmoids moving at large fractions of the speed of light: Relativistic Magnetic Reconnections can occurr

Do such plasmoids coincide with the fast moving “knots”?*



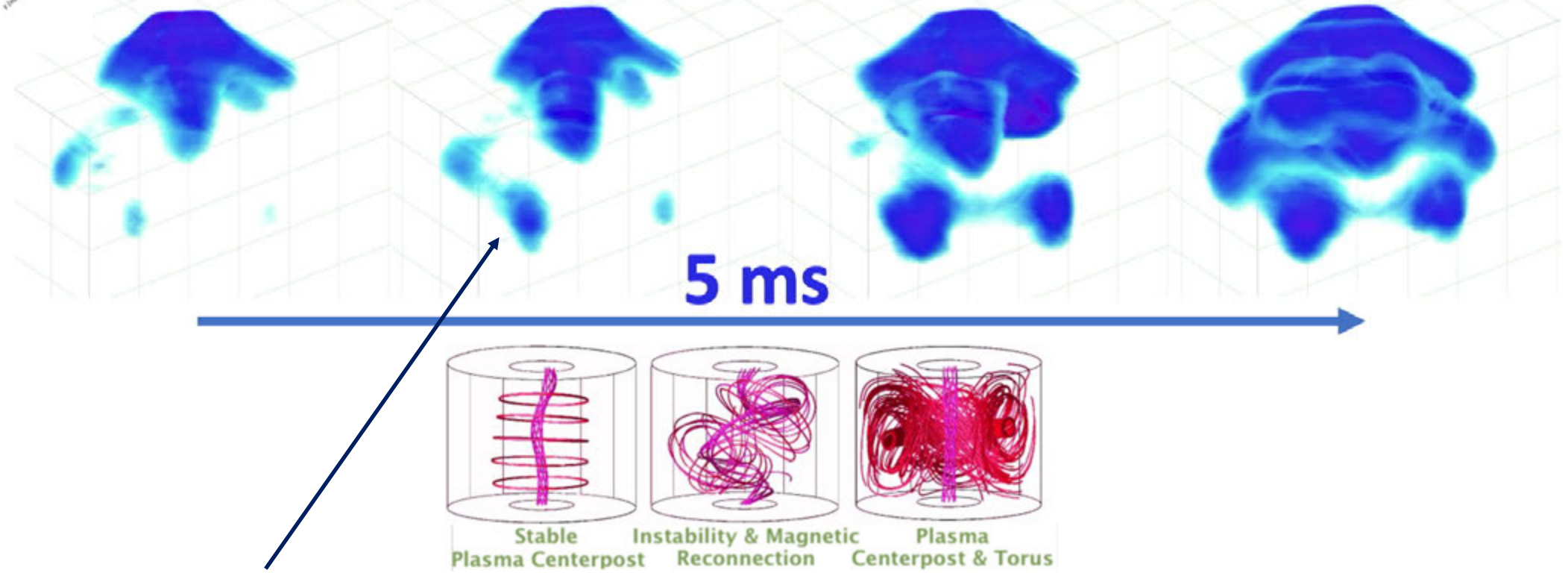
*Schaller, ApJ 123 (2002)

Beginning of 3D tomography in visible light – 2022 – Torus self-organization



The transparent cylindrical vacuum vessel allows for 3D plasma tomography in visible light, 6 cameras around vessel, 600 fps

PROTO-SPHERA plasma torus forms in 5 ms, when Plasma Centerpost current I_{CP} still grows preliminary (still with some artifacts) 3D tomographic reconstruction from the 6 cameras

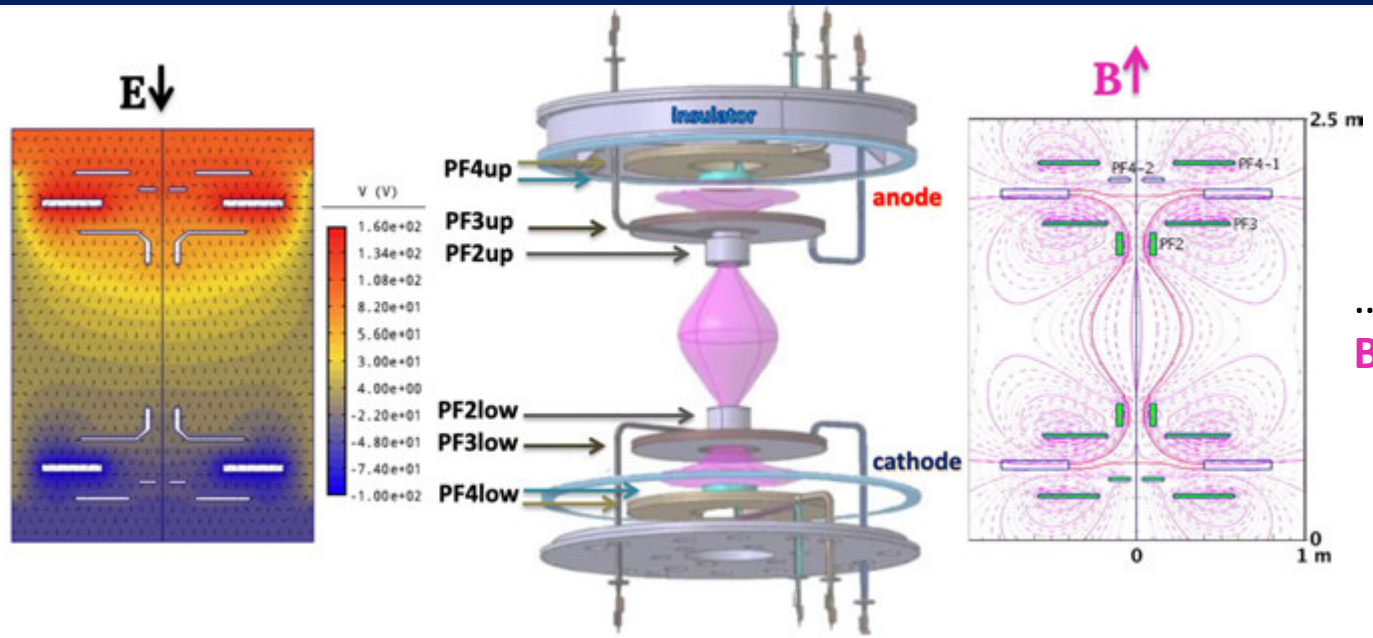


The Plasma Torus grows from a kinked filament, & forms inside a pre-existing purely Magnetostatic Field: → a toroidal axisymmetric confined plasma could be formed & maintained steady-state by permanent magnets only

Symmetry breakings: rotation due to electrostatic field symmetry breaking

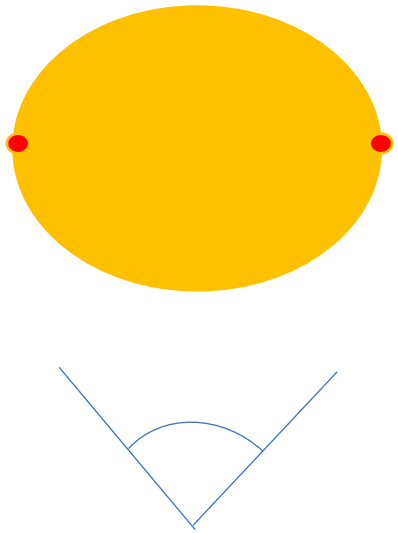
The plasma charges all conductors (PF coils, divertor plates) present inside the vacuum vessel

Rotation of PROTO-SPHERA is due to up/down symmetry breaking of electrostatic field **E…**

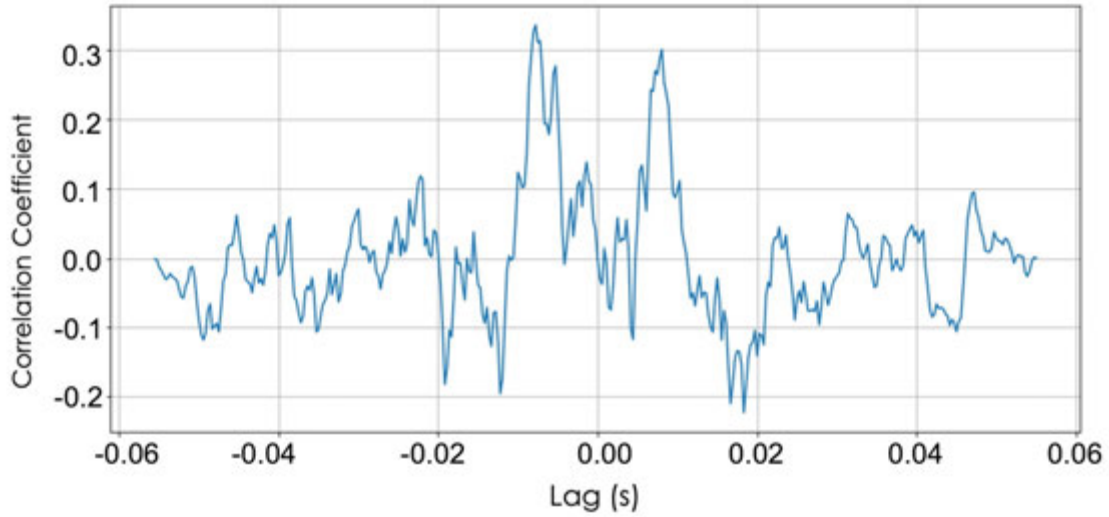


…albeit magnetic field **B** is up/down symmetric

Plasma is slightly oval in azimuth



All cameras see a double correlation peak (ovalization) between brilliance and diameter

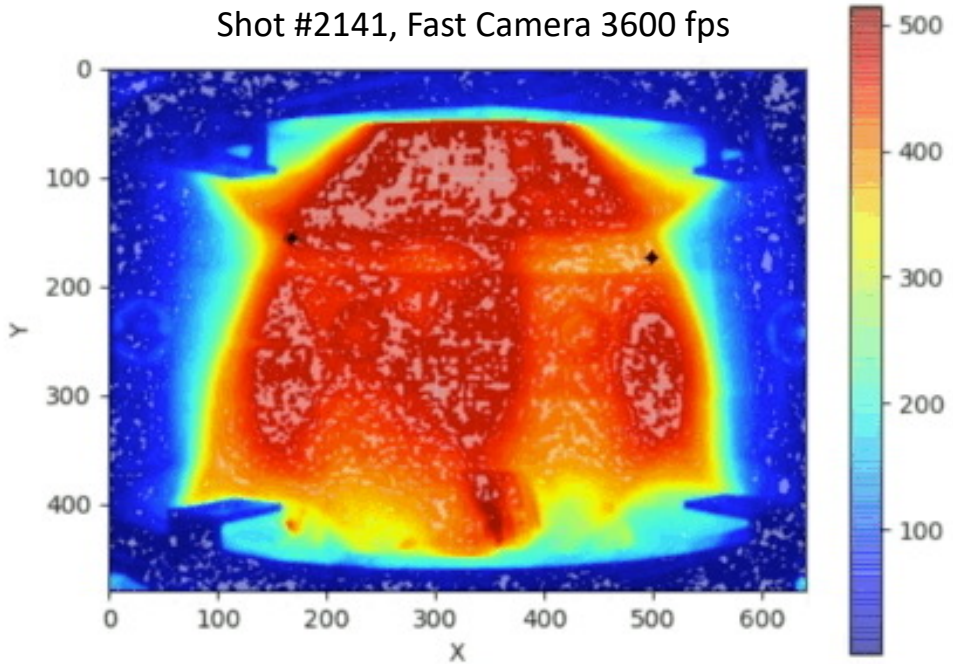


Plasma rotates at about 100 turns/s, it always did so, even when it was a plasma Centerpost only, in Phase-1

Symmetry breakings: magnetic reconnections break axisymmetry

Breaking of axisymmetry is required in order to inject current into the torus (Cowling anti-dynamo theorem)

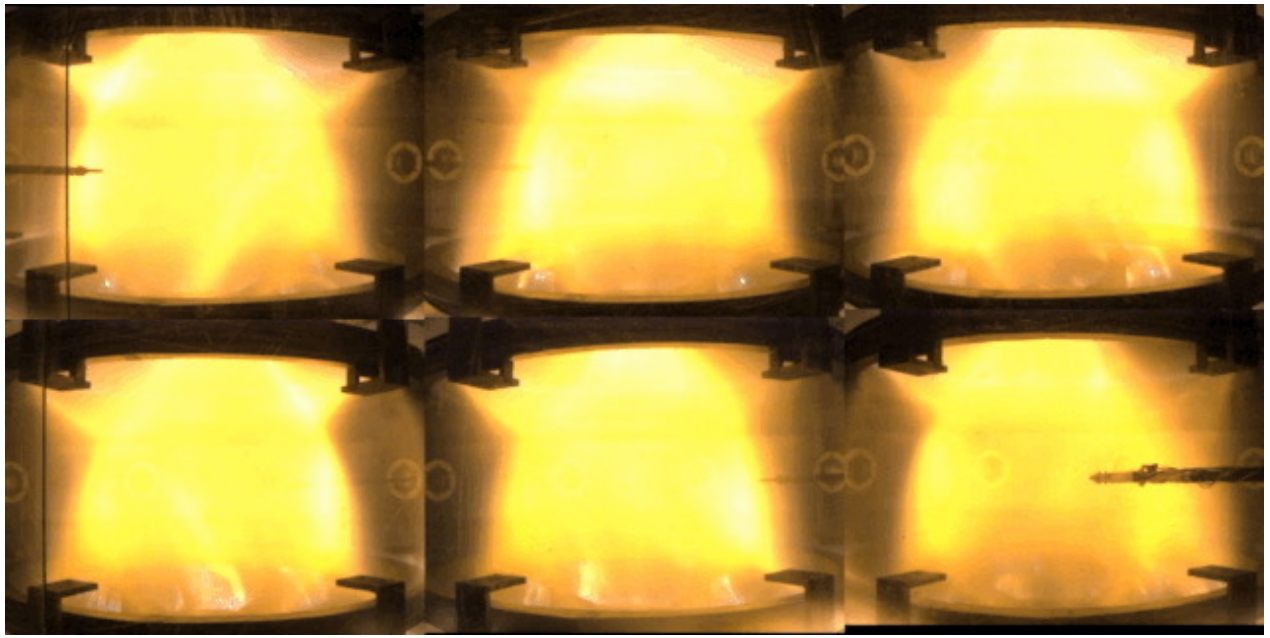
Shot #2141, Fast Camera 3600 fps

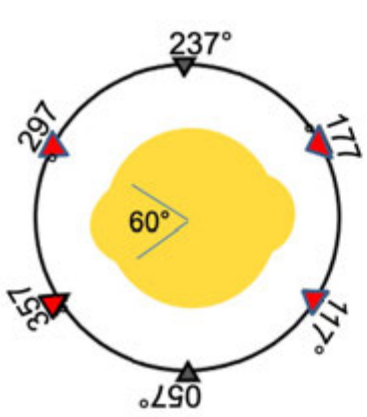


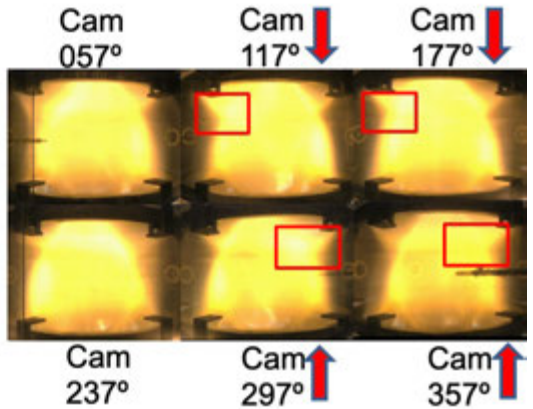
light intensity contours & upper X-points positions

- Plasma brightenings of divertor tails
- Deformation of plasma in the area of the X points

Shot #2141, 6 cameras 600 fps



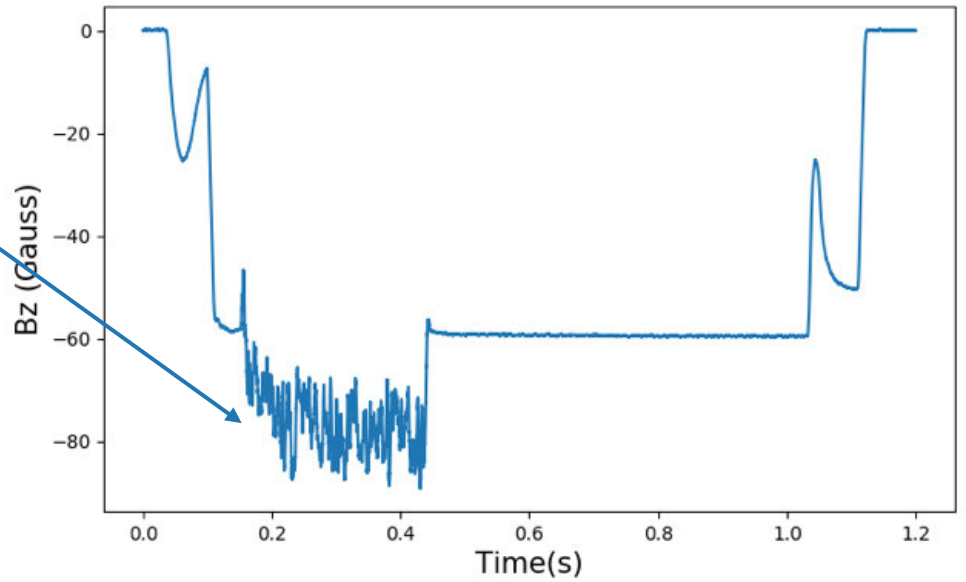




Both phenomena localized within ~ 60º azimuthal angle
only 2 toroidally contiguous cameras see the brightening
and the deformation (& also the opposite ones)
but the other 2 cameras do not see anything

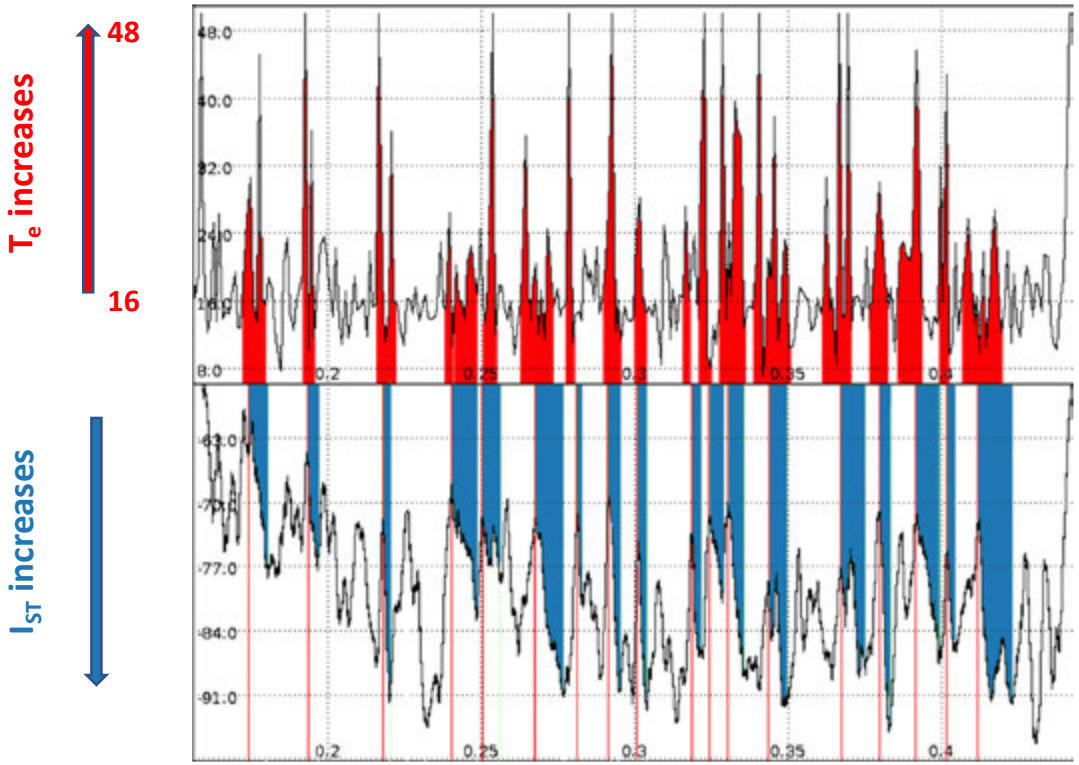
Magnetic reconnection on plasma temperature and/or particle acceleration

Hall probes near the plasma edge (measuring $B_{Z\text{-vertical}}$) show bursts of BZ (α toroidal current ΔI_{ST}) entering the torus



Langmuir probes, always near the plasma edge, see **T_e spikes** in coincidence with the bursts

electron temperature at outer equatorial torus edge **$T_{e\text{-edge}}$ (eV)**



α toroidal current in the torus (Gauss)

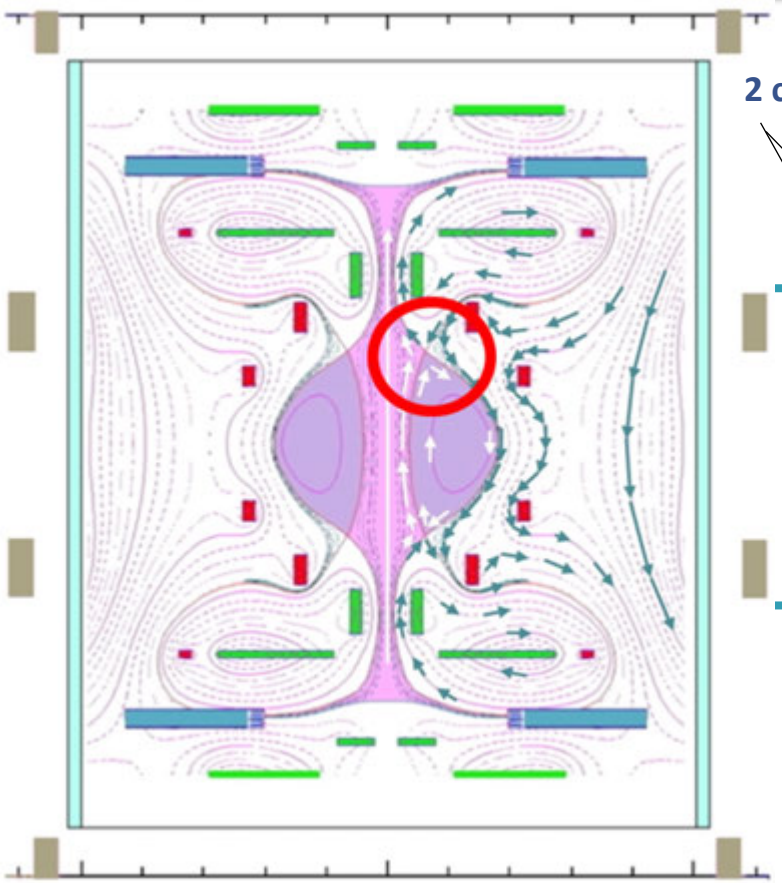
Time (s)

Magnetic reconnections T_e spikes 20 eV→50 eV

(heating? suprathermal acceleration?), followed by

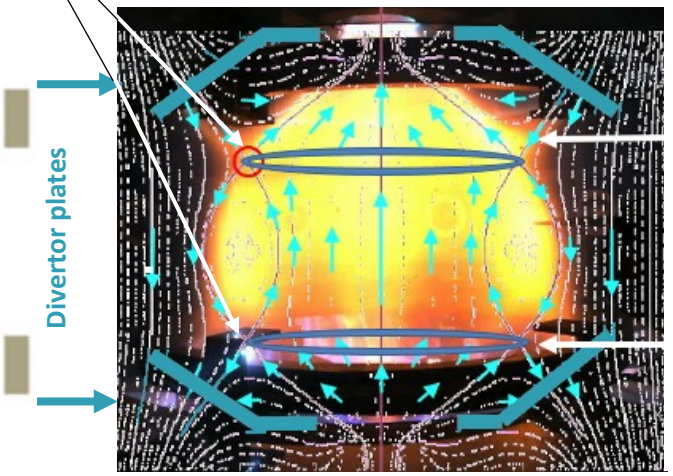
toroidal current bursts ΔI_{ST}~1-1.5 kA injected into the Torus (I_{ST}~ 5kA)

RECONNECTIONS IN PROTO-SPHERA Phase-1.5: Tori sustained for 1 sec



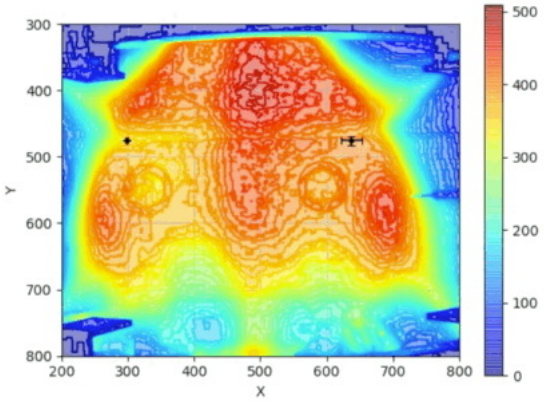
Predictive equilibrium calculation

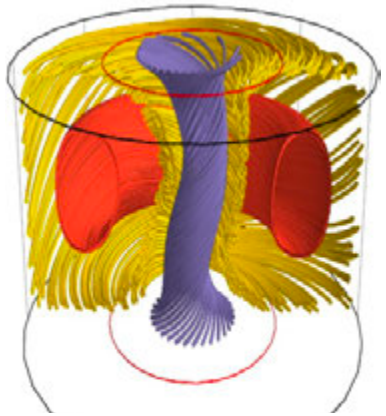
2 circles ordinary X-points ($B_{tor} \neq 0$)
& "divertor tails" top & bottom



2020 Results

Observation of ordinary magnetic X-points by fast camera (3600 fps)

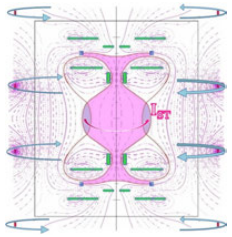


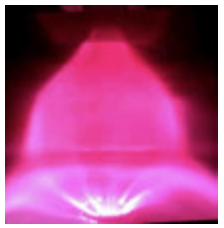


- Nested & closed light intensity contours inside the torus
- X-points position oscillates
- Kinked plasma centerpost

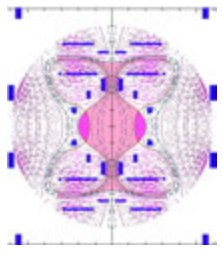
Lampugnani, Garcia, Farengo
Physics of Plasmas, 25 (2018)

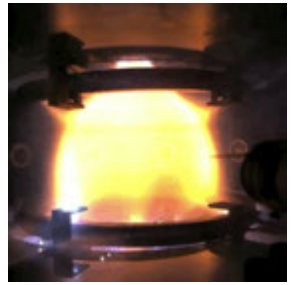
2018
2.5 MW



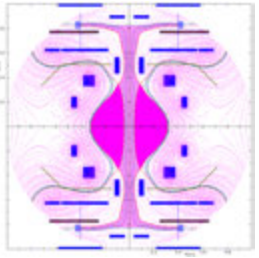


→ **2022**
3.5 MW



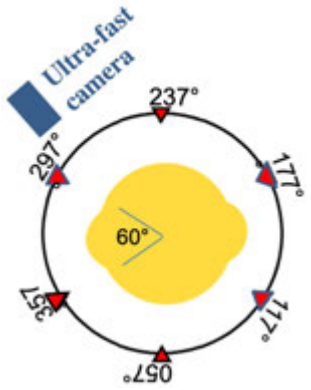


→ **Phase-2**
>20 MW

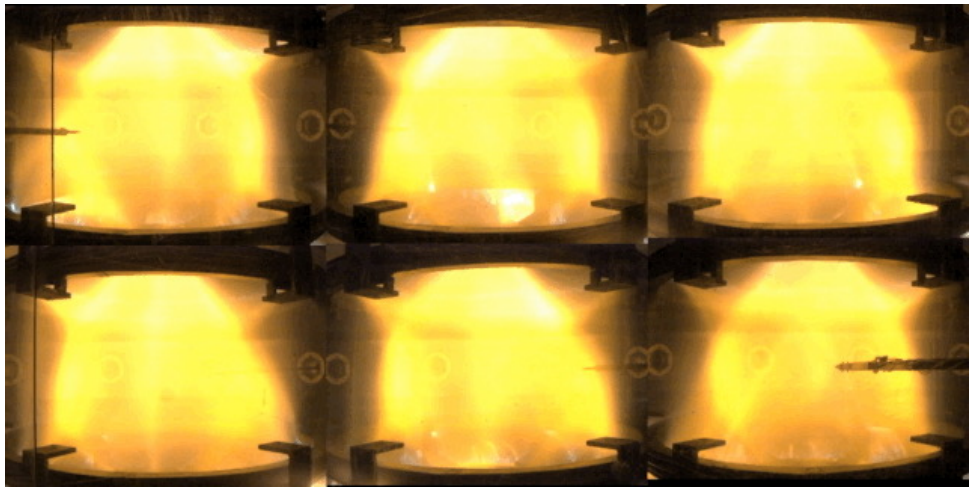


from Phase-1 slim Tori to larger Tori in Phase-15 experiment, how much larger Tori in Phase-2?

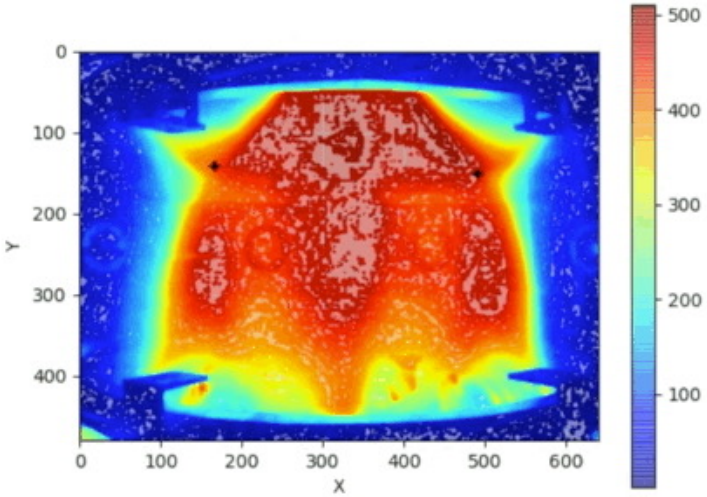
PROTO-SPHERA a slightly oblique rotator (azimuthal rotation)

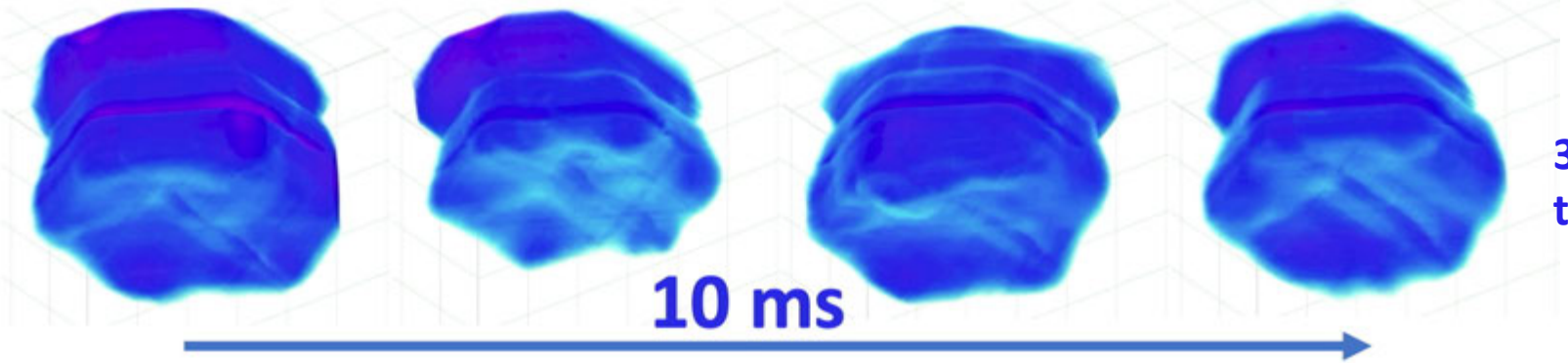


Shot #2141, 6 cameras, 600 fps



Shot #2141, fast camera 3600 fps





3D tomographic reconstructions indicate the Plasma Torus as a slightly oblique rotator

Further analogy to Pulsar Wind Nebulae : Pulsars, born spinning, provide energy as braked oblique rotators

CONCLUSIONS

Torus + Jet linear force-free fields (*fff*) can describe PWNe and laboratory experiments

PROTO-SPHERA has been built as a Torus + Jet *fff,* feasible in the laboratory

Its plasma shows a very good agreement with what was possible to calculate in its design phase
It is quite stable, in absence of any conducting shell near the plasma

But unpredictable good surprises have appeared:
- **The plasma rotates in toroidal direction, certainly a stabilizing feature**
- **The torus is formed in a magnetostatic field (magnetic confinement traps with permanent magnets only?)**

Magnetic Reconnections are there, they are not axisymmetrical & have shown their first thermal effects (how efficient will they be, when the plasma currents will be increased?)

The PROTO-SPHERA plasma is an oblique rotator, just as the plasma of PWNe