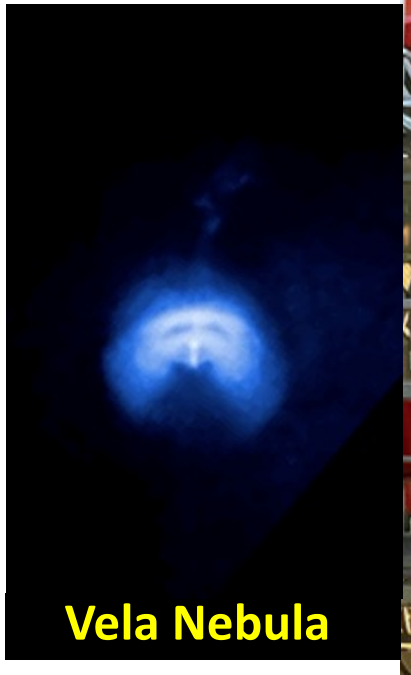
PROTO-SPHERA: a magnetic confinement experiment which emulates the jet + torus astrophysical plasmas

F. Alladio[1] and PROTO-SPHERA Group[2]

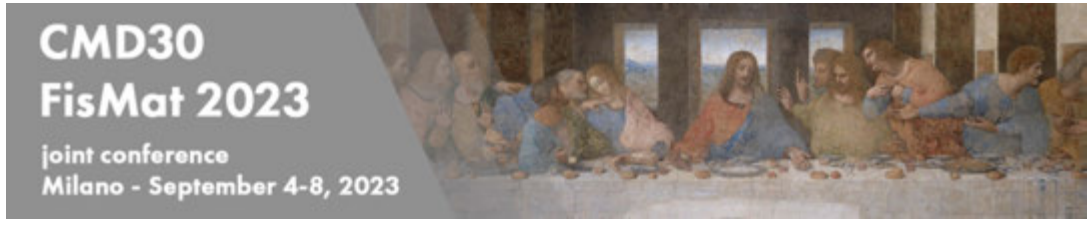
[1]*INAF – IAPS, Via Fosso del Cavaliere 100, 0133 Rome, Italy*

[2] *Centro Ricerche ENEA, Frascati*
[2] *Università Roma1-LaSapienza*
[2] *Gran Sasso Science Institute*
[2] *Pisa University*

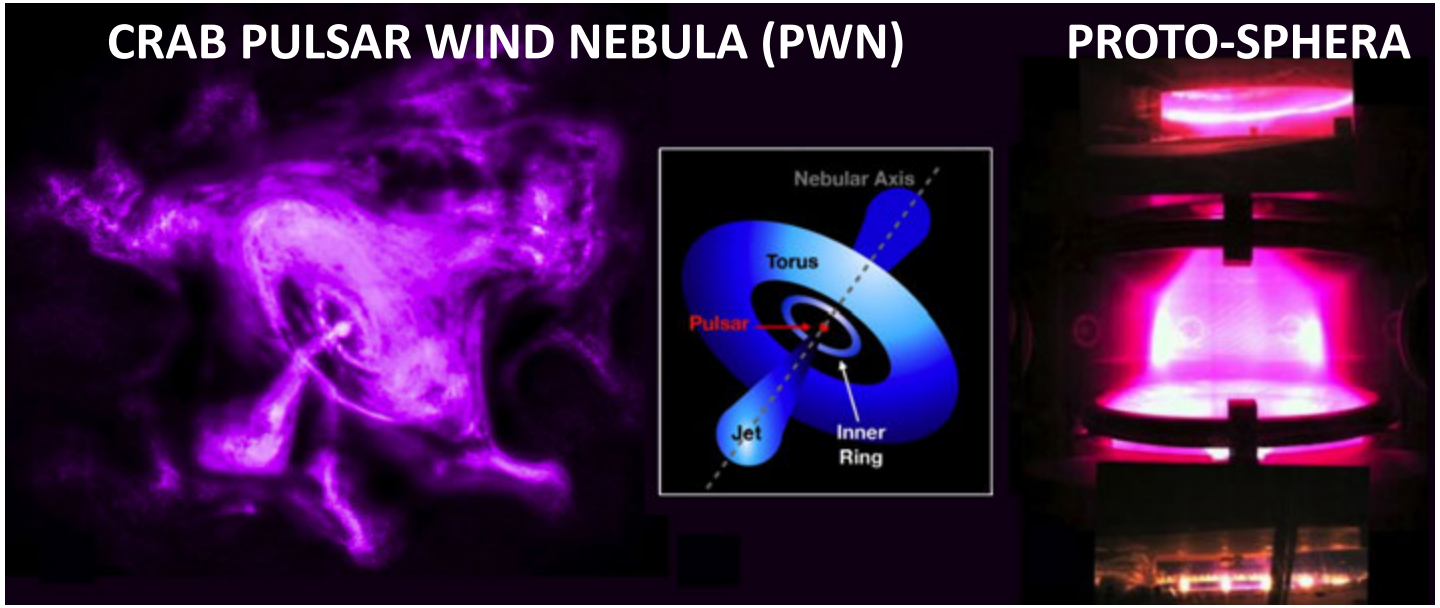
[1]*email: franco.alladio@protosphera.it*


Vela Nebula


PROTO-SPHERA



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



Chandra X-ray image of Crab

Visible light PROTO-SPHERA

SUMMARY

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

Ideal MHD stability of PROTO-SPHERA in theory & in practice

3D Tomography diagnostics of PROTO-SPHERA: sustainment & formation of Torus by Magnetic Reconnections

Force-free model of Double-Torus model for PWNe

Comparison of Double-Torus model with PWNe observations, relevance for acceleration due to reconnections

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

force-free field (fff) models: self-consistent distributions of $\vec{B}$ and $\vec{j}$ with $\vec{j} \wedge \vec{B} = 0$ (excluding $\vec{j} = 0$), this means $\vec{\nabla} \wedge \vec{B} = \mu \vec{B}$

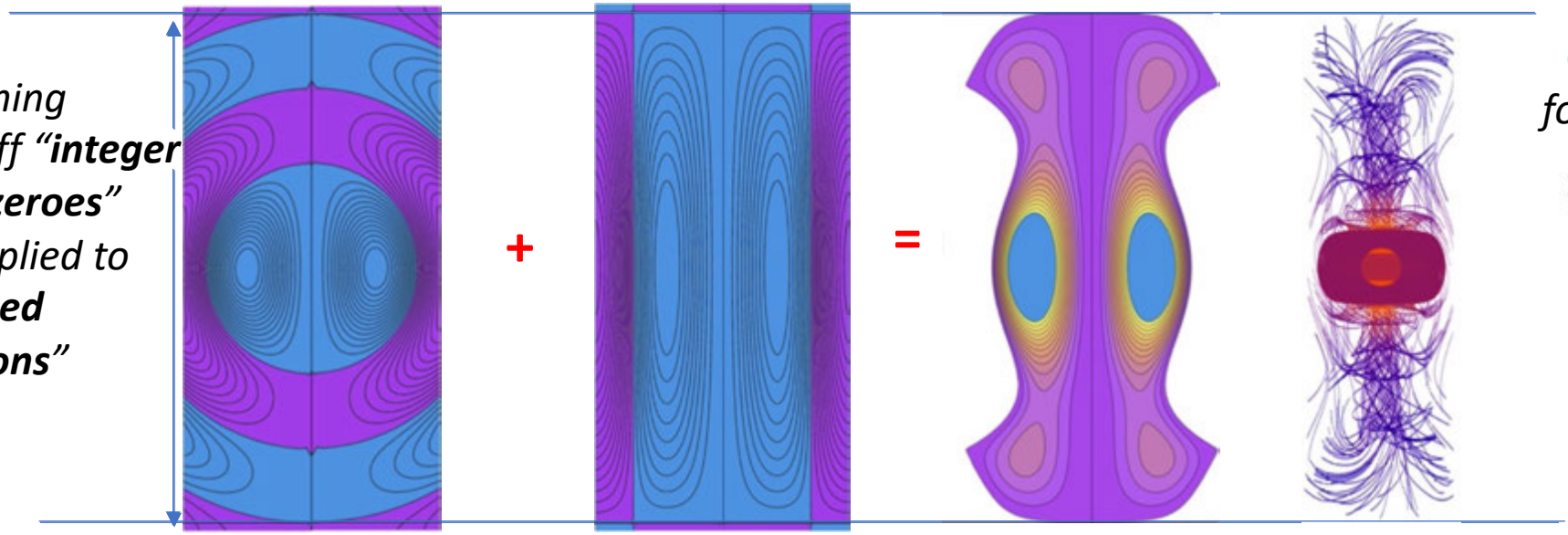
- no Lorentz force upon them
- can decay without causing material fluid motions
- the simplest choice for large scale structures in Astrophysics
- a hint for laboratory plasmas

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

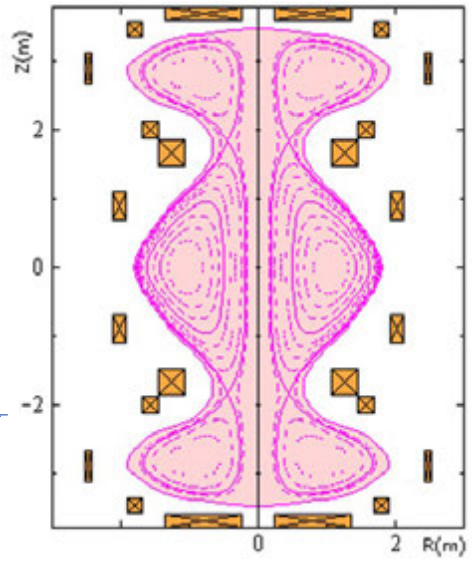
Linear *fff*, with μ= constant in space, are a **linear algebra**: ***fff*** with **same μ can be summed to give another *fff***

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

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



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



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

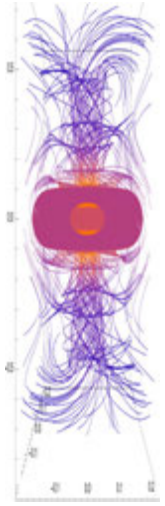
Furth even squared *fff* toroids model a Jet Furth Rev.Sci.Instrum. 28 (1957)

Torus+Jet linear *fff* (CKF) Chandrasekhar-Kendall-Furth

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

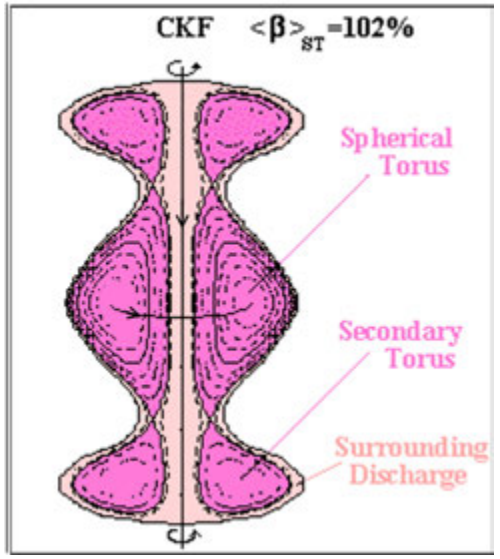
CKF *fff* Stable in Ideal MHD at β= plasma pressure/magnetic pressure ≥ 1 *

fff



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

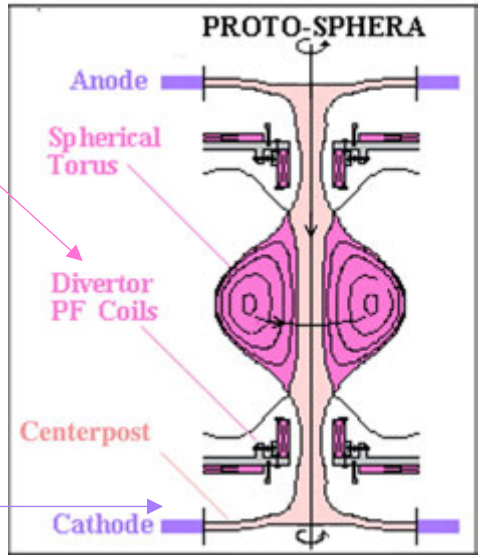
CKF *fff* can be filled up with plasma pressure, maintaining good features, such as ideal MHD stablity



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"

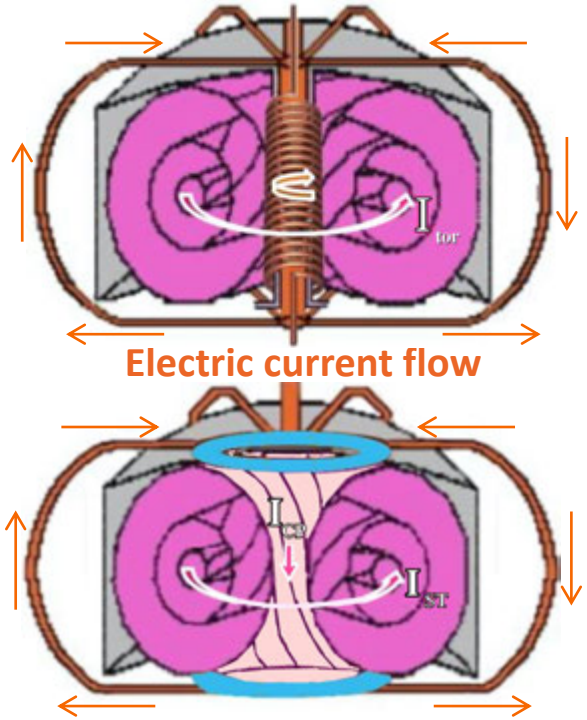
vacuum vessel has a complex toroidal geometry

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

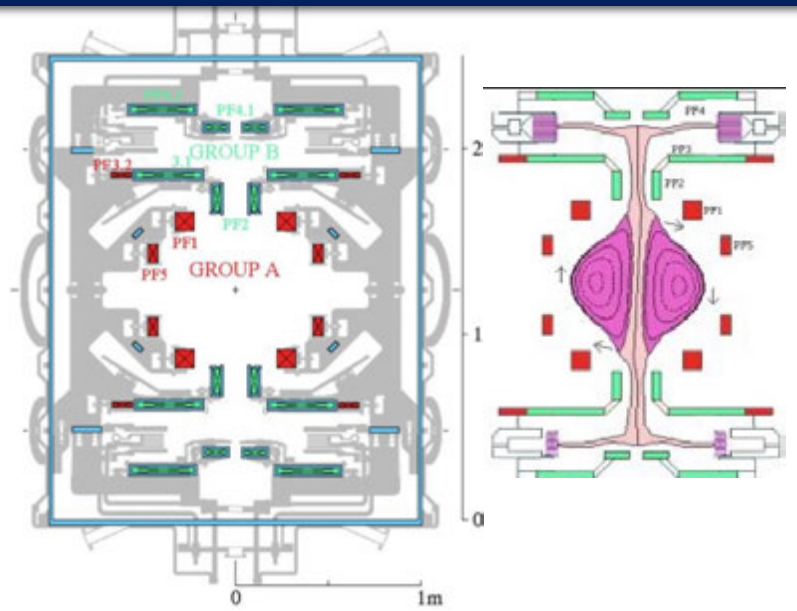
vacuum vessel has a simple geometry

…but electrodes are required inside vacuum feeding

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

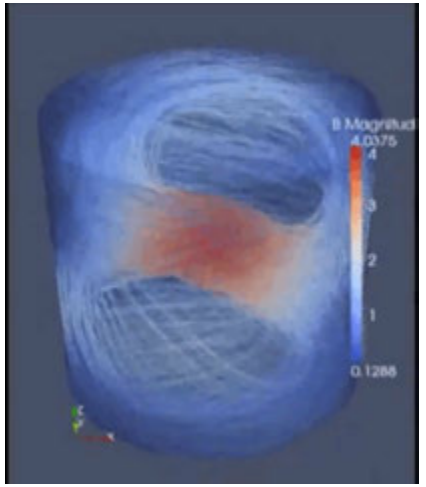


Ideal MHD stability of PROTO-SPHERA remains remarkable



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

Avoids Spheromak tilting instability



But PROTO-SPHERA dipoles:

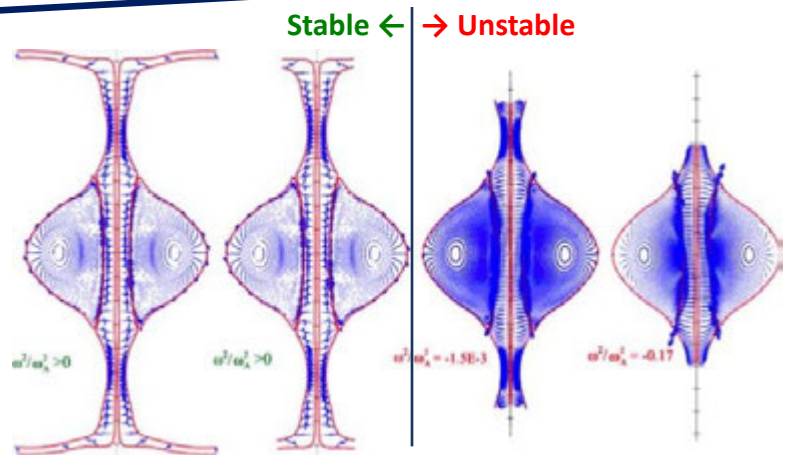
"Group A" PF compression coils against Plasma dipole

"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

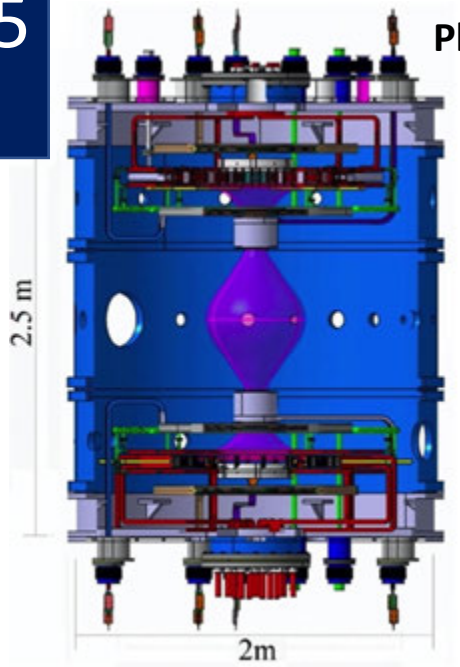
MUSHROOM-SHAPED PLASMA FACING ANNULAR ELECTRODES PROVIDES IDEAL MHD STABILITY

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

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

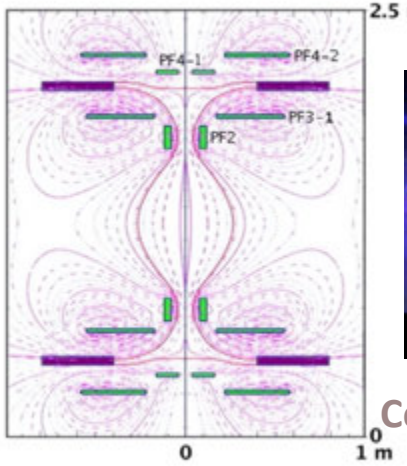
From 2015 Phase-1

Aluminum Vessel of START

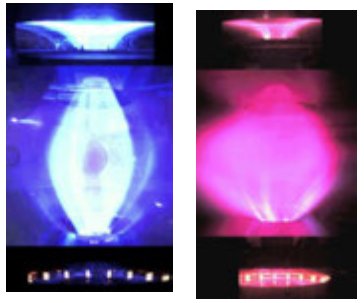


Phase-1: 8 PF coils

Centerpost Plasma duration: 1 sec



Argon Hydrogen



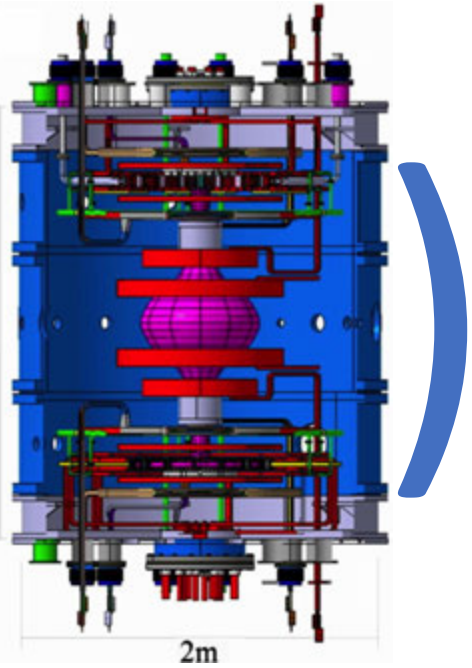
Centerpost I_{CP} = 10 kA

Future

Phase-2: 8 PF + 6 PF

Torus I_{ST}= 280 kA

Centerpost I_{CP} = 70 kA

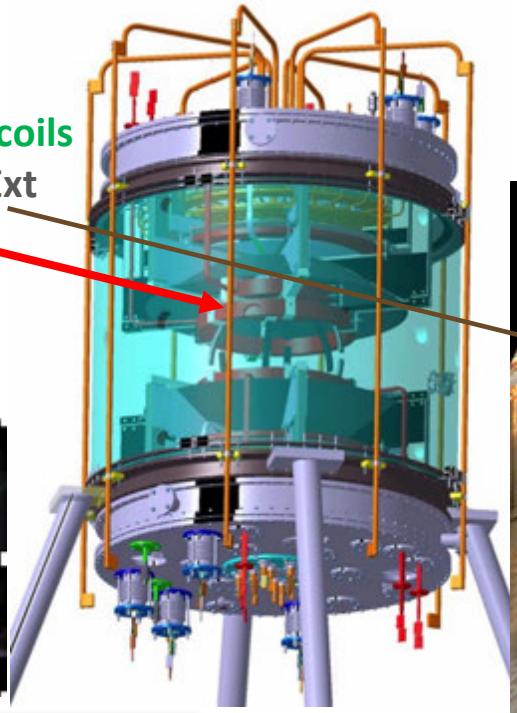


Centerpost I_{CP} = 10 kA

Torus I_{ST}= 5 kA

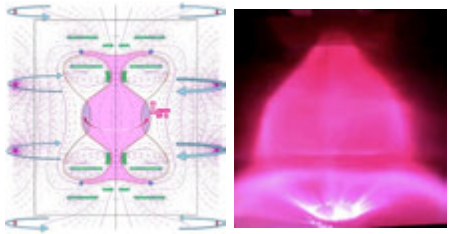
From 2019 Phase-1.5: 18 PF coils new insulating & transparent vessel

Phase-1.5: 8 PF coils + 6 PF + 2 PFExt

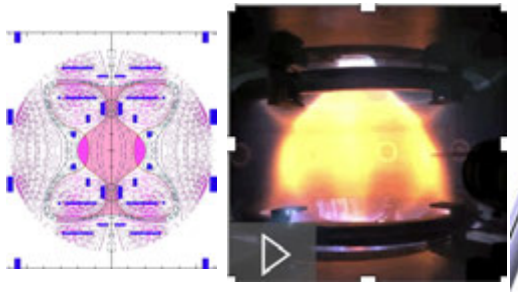


Torus Plasma duration: 1 sec

2018
2.5 MW



2022
3.5 MW



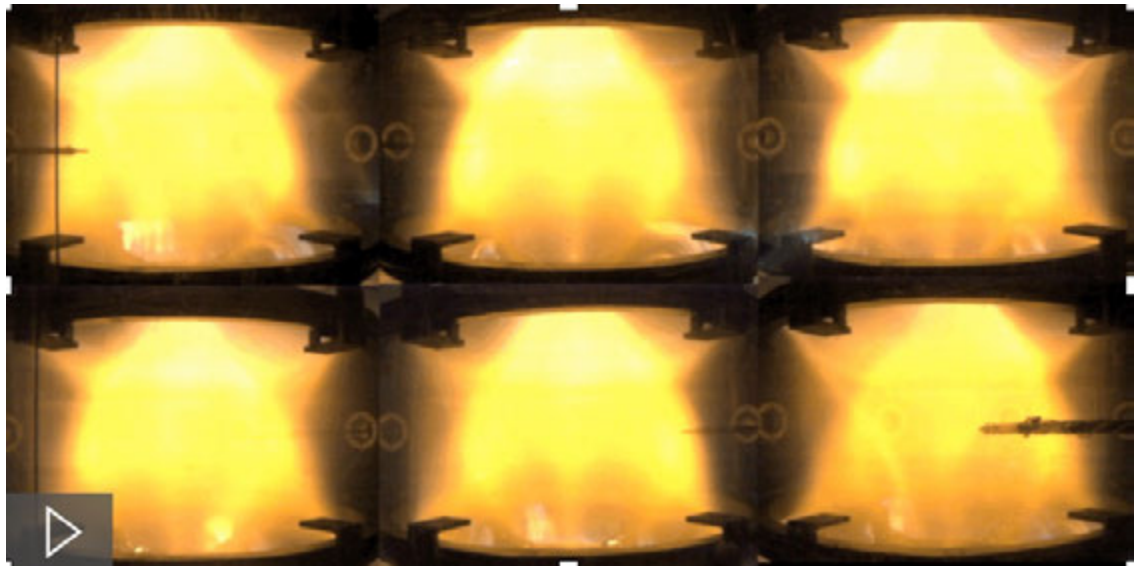
Remarkable ideal MHD stability without any near conducting shell

Vacuum Vessel in PMMA

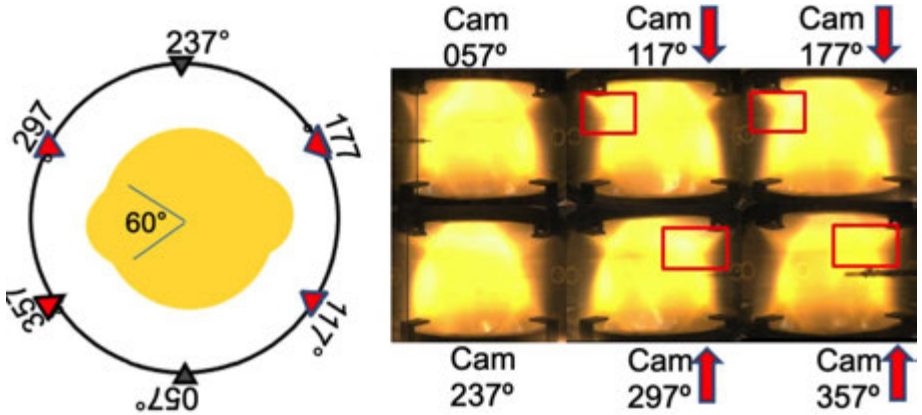
Torus sustained: magnetic reconnections break axisymmetry

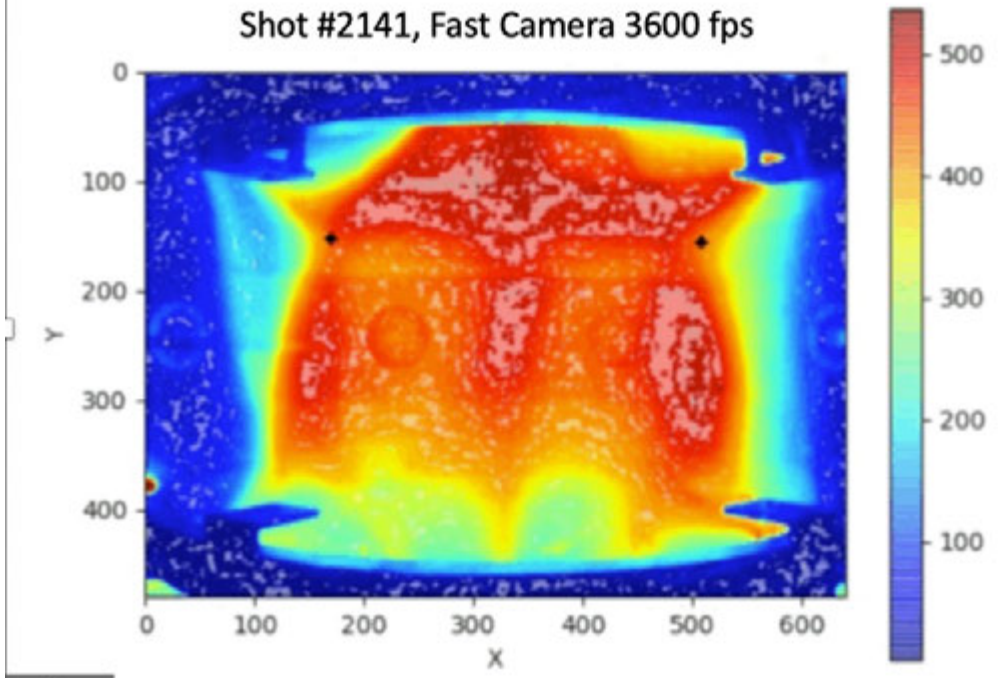
Breaking of axisymmetry is required in order to inject current into the torus (Cowling anti-dynamo theorem)

Transparent vessel: *6 cameras (600 fps)* ***around equator***



Surprise:
PROTO-SPHERA plasma spontaneous toroidal rotation ~600 rad/s





light intensity contours & upper X-points positions

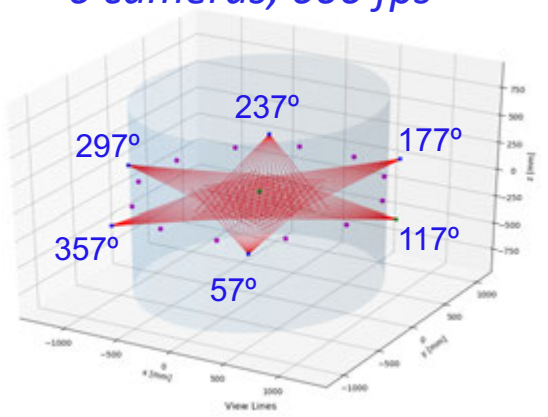
- **Plasma brightenings of divertor tails**
- **Deformation of plasma in the area of the X points**

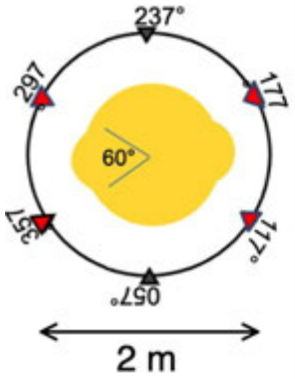
Both phenomena localized within ~ 60º azimuthal angle
only **2 toroidally contiguous cameras** see the brightening and the deformation (& **also the opposite ones**)
but the other 2 cameras do not see anything

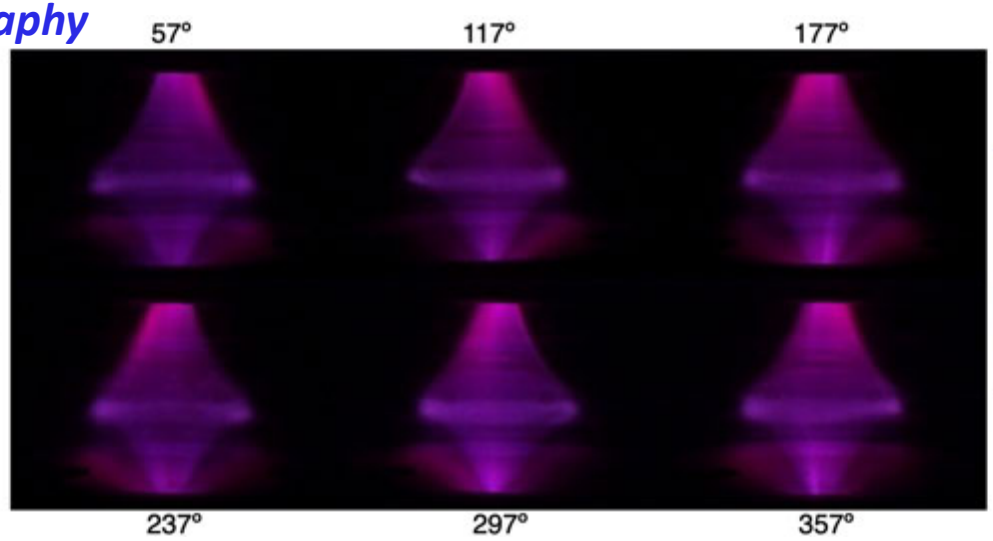
Torus formation: magnetic reconnections break axisymmetry

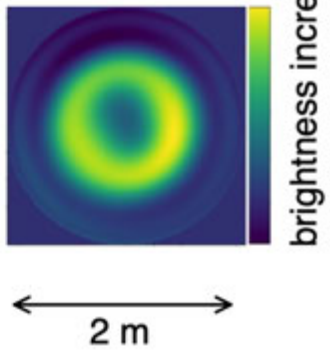
Transparent vessel → visible light tomography

6 cameras, 600 fps





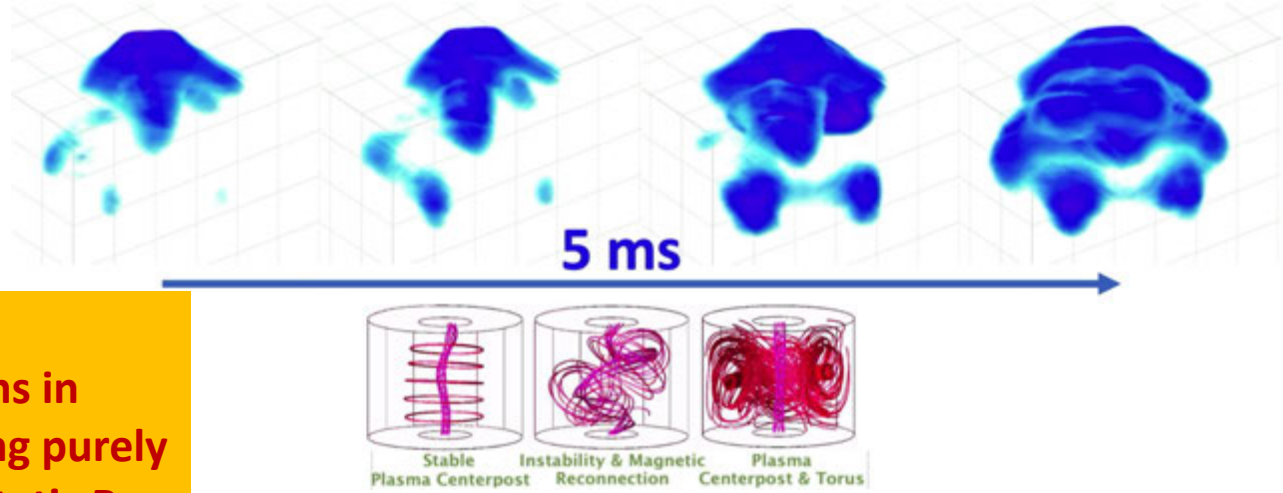




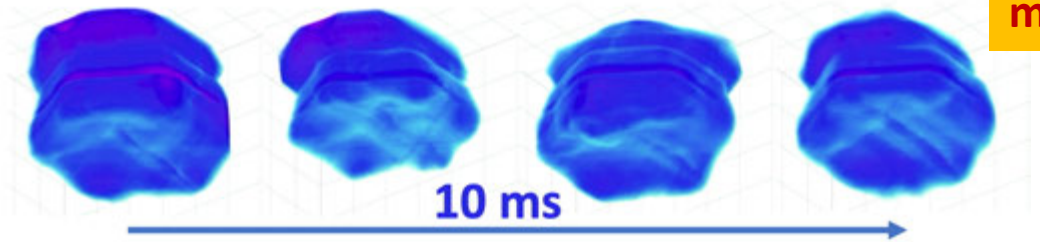
Tomography on equatorial plane 2019

First 3D tomography results 2023: Torus formation

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



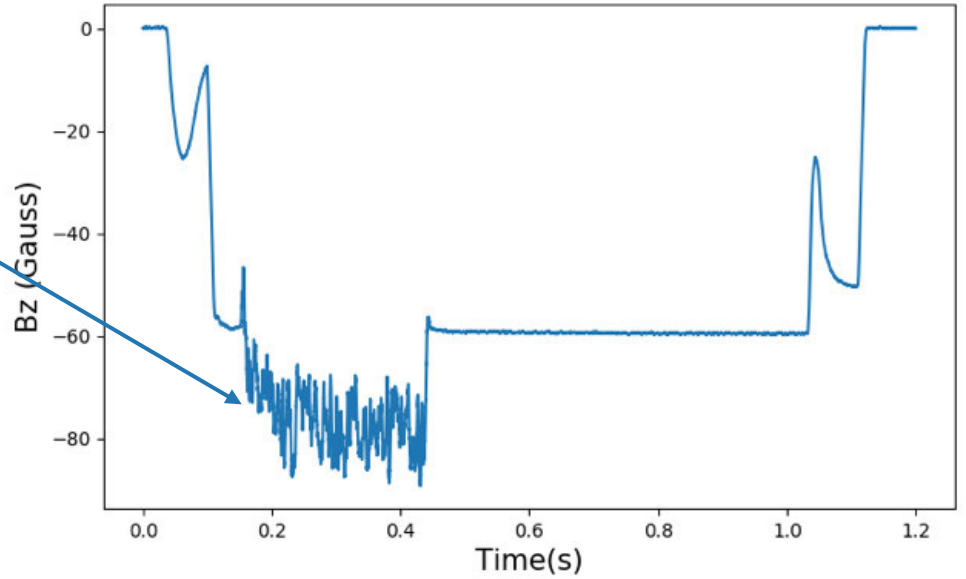
Surprise:
Torus forms in pre-existing purely magnetostatic B



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

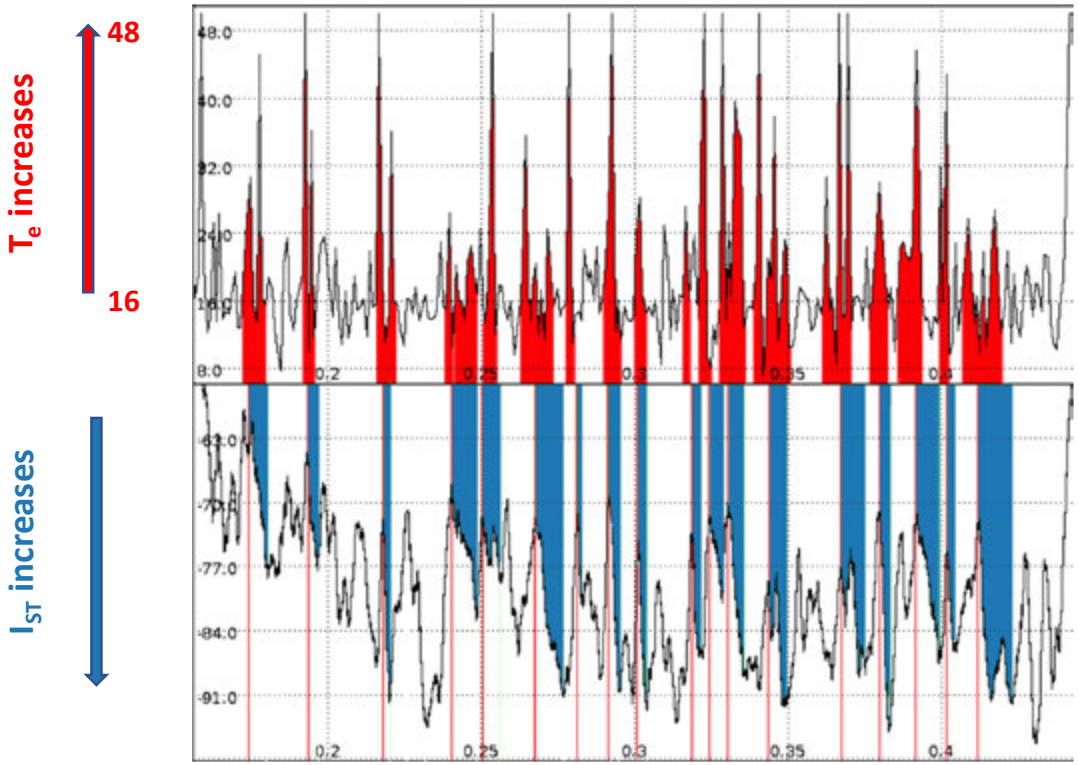
Magnetic reconnection on plasma temperature and/or particle acceleration

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



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

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



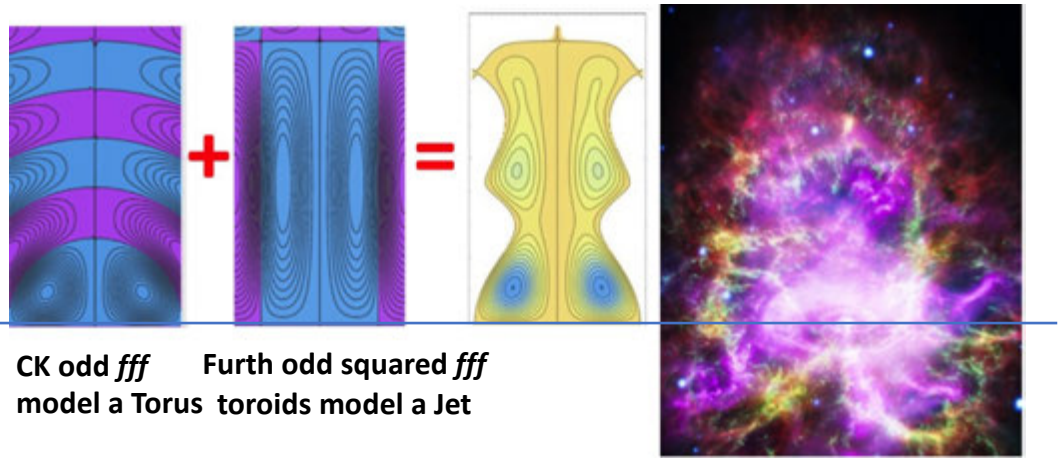
α toroidal current in the torus (Gauss)

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)

Torus + Jet : *fff* double tori model for Pulsar Wind Nebulae (PWN)

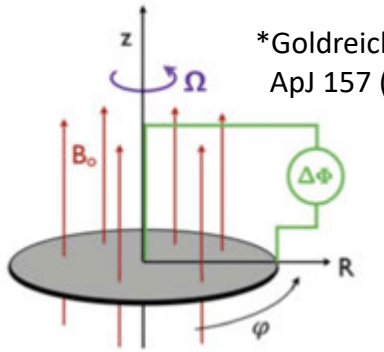


CK odd *fff* model a Torus

Furth odd squared *fff* toroids model a Jet

Crab Nebula

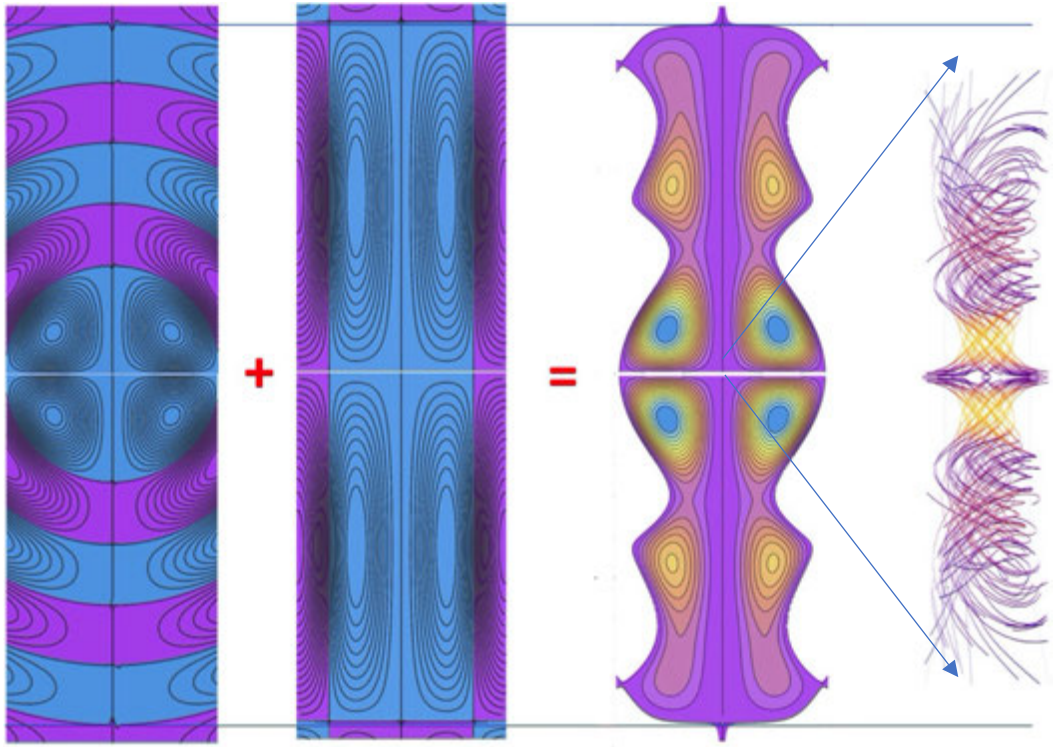
But **Even-Symmetry of $B_{vertical}$** on the 2 emispheres, legacy of **B** of the Neutron star; Faraday disk effect gives **Odd-Symmetry $j_{vertical}$** on the 2 emispheres*



*Goldreich & Julian, ApJ 157 (1969)

*Superposition of **2 fff fields with opposite μ:** **μ>0 on upper and μ<0 on lower emisphere***

* Kumar, Phys of Plasmas 20 (2013)



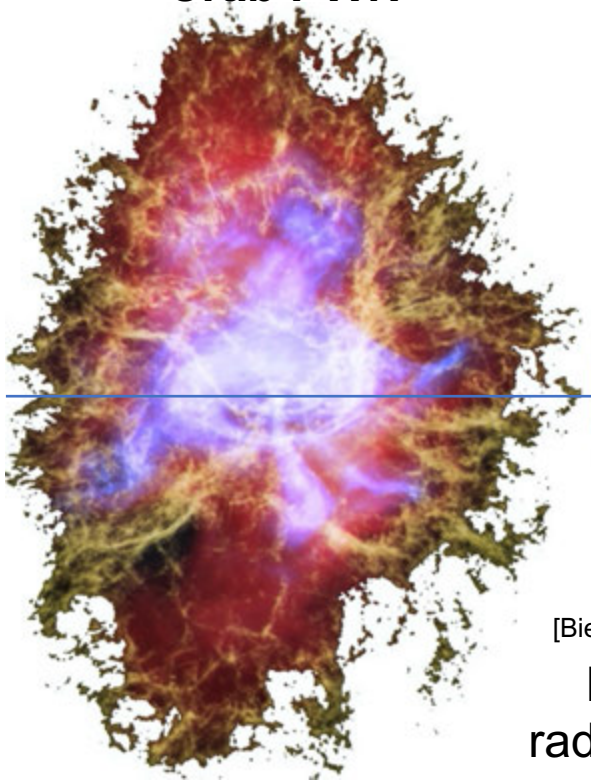
which gives rise to a **B_{radial} discontinuity** and implies a **singular j_{tor} current layer on the equator of the PWN**

PWN double tori *fff* model is a generalization of well-known split-monopole *fff* model

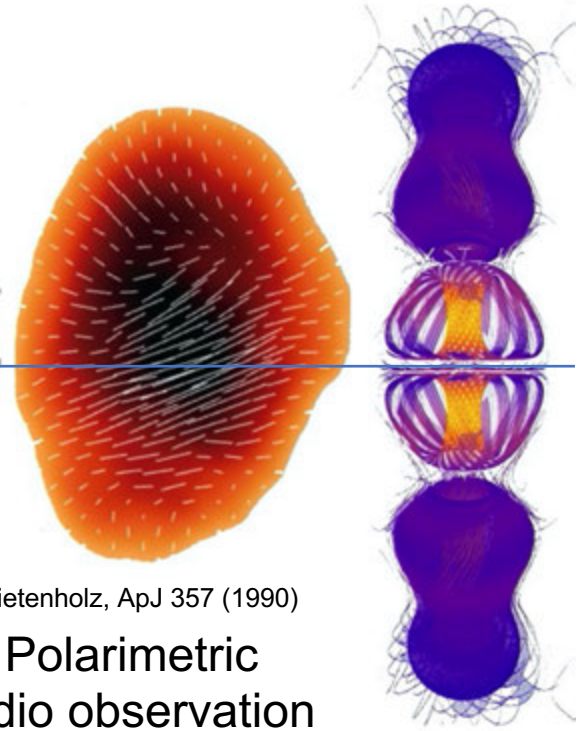
shown by magnetic flux surface & by enlarged field-line-tracing

Double tori PWN model compared with observations (Crab & Vela)

combined wavelength
Crab PWN



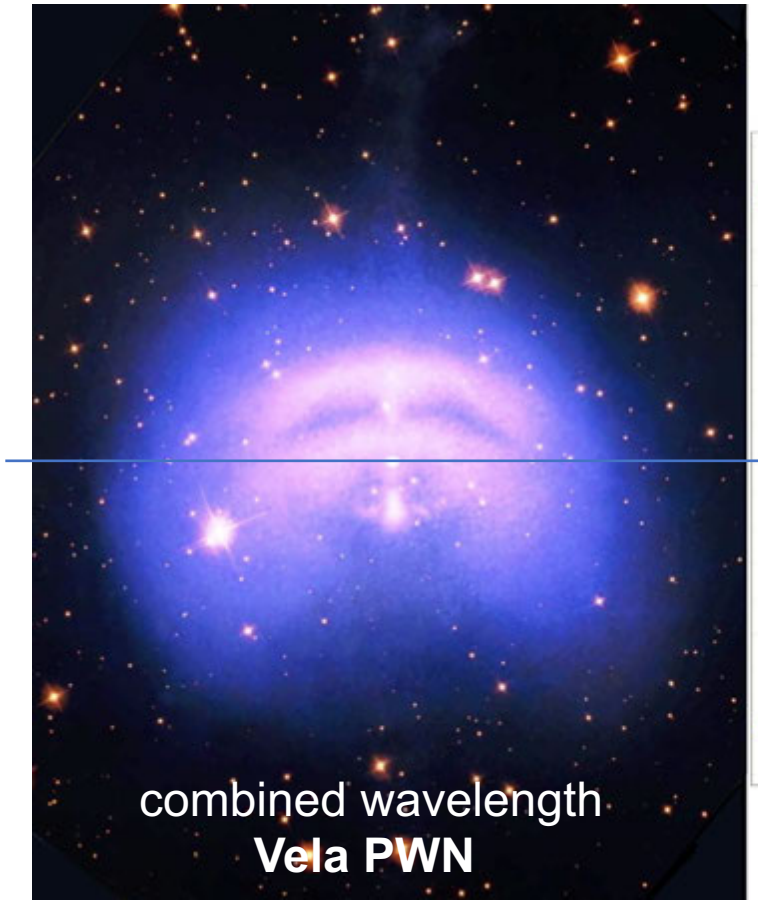
PWN double tori *fff* model
by field-line tracing



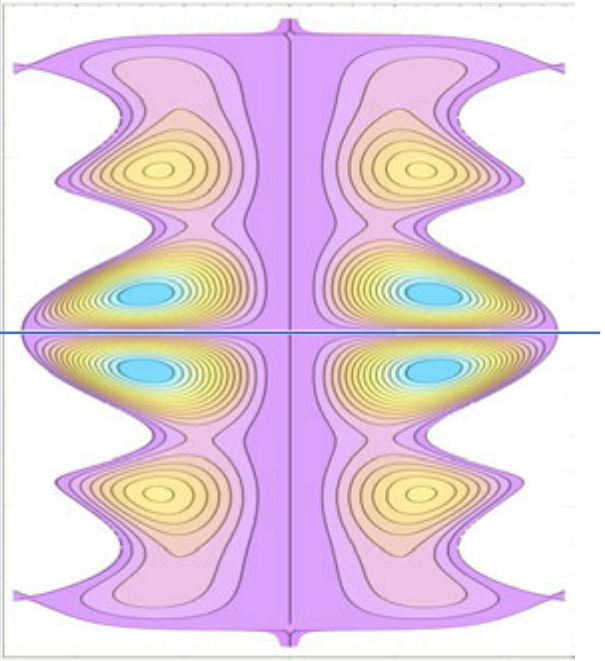
[Bietenholz, ApJ 357 (1990)

Polarimetric
radio observation

Whereas the **Crab PWN** does not exhibit an evident double torus, the polarimetric radio & X-ray observations show a dominant toroidal field direction



PWN double tori *fff* model
by flux surfaces



(*Elongation reduced by ~2*
to correct perspective)

The observation of the **Vela PWN** gives instead the most clear observation of a **double torus**

Polarimetric X-ray observations from IXPE show a dominant toroidal field, which extends beyond the brightest X-ray emission region

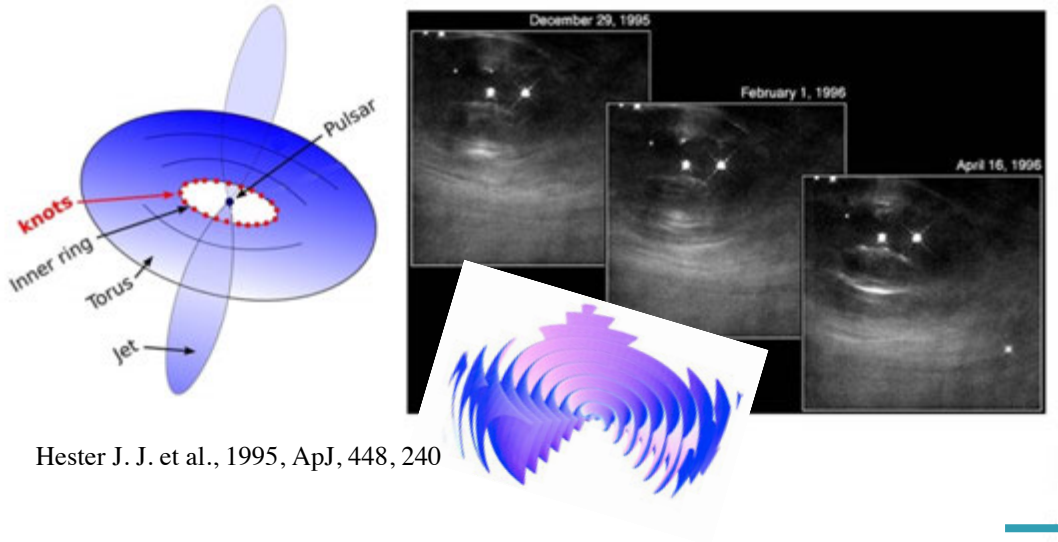
Acceleration & Reconnections in PWN

Most efficient accelerators in the Galaxy are the PWNe
>25% of their released power is emitted in radiation
• spectrum of e.m. emission extends beyond PeV (10^{15} eV)

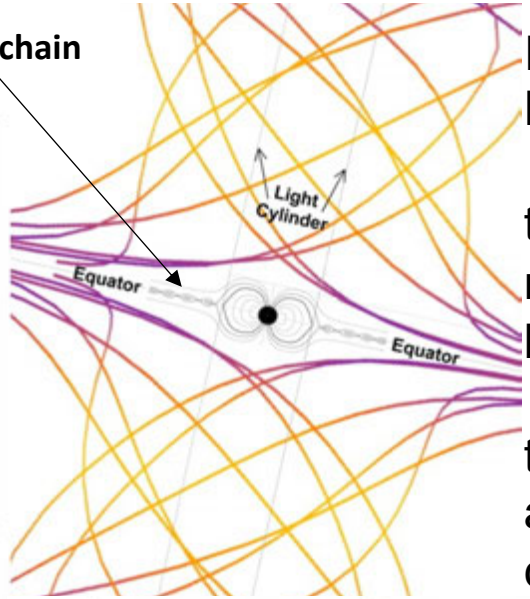
The question of the origin of the acceleration of particles in the PWN remains unsettled, the main competitors are:
1) Fermi-type acceleration in shockwaves; 2) magnetic reconnections

reconnecting plasmoid chain

Do the fast moving "knots" (~c/2) coincide with such plasmoids?



Hester J. J. et al., 1995, ApJ, 448, 240

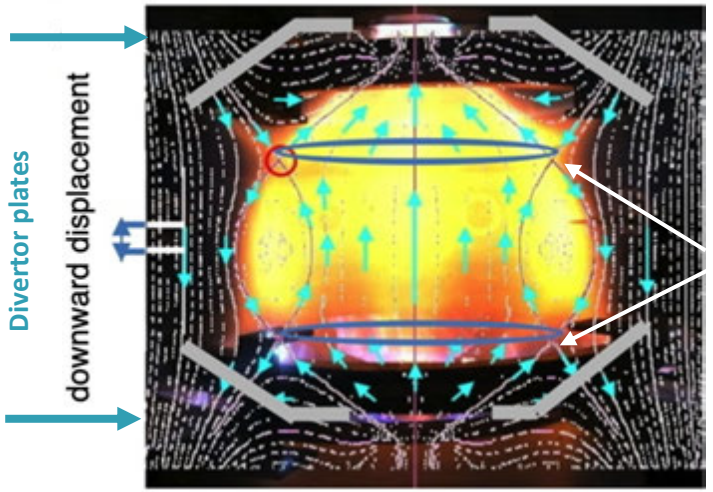


If reconnections responsible for acceleration, PWN double tori model indicates their place:

the equatorial region, where radial & toroidal magnetic field magnetic fields are opposite between the 2 emispheres

the two neighboring tori would be attracted against each other: they have toroidal currents in same direction (B_{tor} opposite)

Reconnections occur in PROTO-SPHERA in a completely different location: 2 circles of X-points removed from equator



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

CONCLUSIONS

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

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

Very good agreement of Ideal MHD stability with design (without any conducting shell near the plasma), but unpredictable good surprises:
- **The plasma rotates in toroidal direction, acting as an oblique rotator, just as PWNe**
- **The torus is formed in a purely magnetostatic field**

Magnetic Reconnections observed, not axisymmetrical & showing thermal effects

The Double-Torus *fff* model of PWNe provides what could an impressive reconnection machine: reconnections would be on the equator, between the two tori, where bright fast-moving knots are observed

The 2 cases (laboratory and Astrophysics) are distinct: • number of tori (1 vs. 2)
• location of magnetic reconnections (circles of ordinary X points vs. equator between the 2 Tori)

The possibility of building a PWN-like reconnection machine in the laboratory is been investigated, through a modification of PROTO-SPHERA able to do so

PROTO-SPHERA Group

INAF – IAPS, Via Fosso del Cavaliere 100, 0133 Rome, Italy
Franco Alladio

FSN Department, CR-ENEA Frascati
Paolo Micozzi, Luca Boncagni, Paolo Buratti, Alessandro Mancuso[retired], Vincenzo Zanza[retired], Gerarda Apruzzese, Francesca Bombarda[retired], Alessandro Fassina, Francesco Filippi, Donatella Fiorucci, Giuseppe Galatola Teka, Edmondo Giovannozzi, Luigi Andrea Grosso[retired], Matteo Iafrati, Alessandro Lampasi, Violeta Lazic, Simone Magagnino, Simone Mannori, Francesco Napoli, Valerio Piergotti, Giuliano Rocchi, Alessandro Sibio, Benedetto Tilia[retired], Onofrio Tudisco

GSSI, Viale Francesco Crispi 7, 67100 L'Aquila, Italy
Samanta Macera

Pisa University, Lungarno Pacinotti 43, 56126 Pisa, Italy
Francesco Giammanco[retired], Paolo Marsili

Università di Roma-1 La Sapienza
Annamaria Pau, Shayesteh Naghinajad Mohammadkhanlou, Yacopo Damizia