

PROTO-SPHERA: a magnetic confinement experiment which emulates the Jet + Torus astrophysical plasmas

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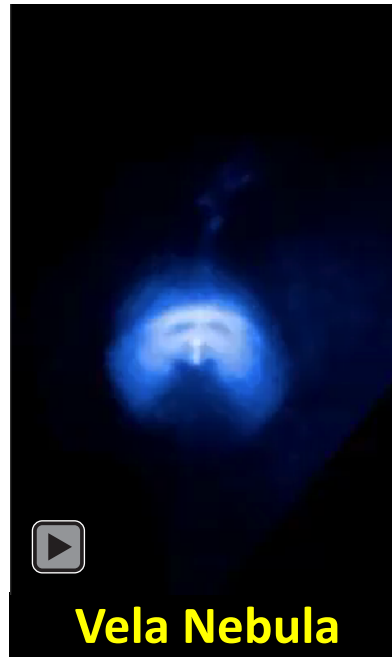
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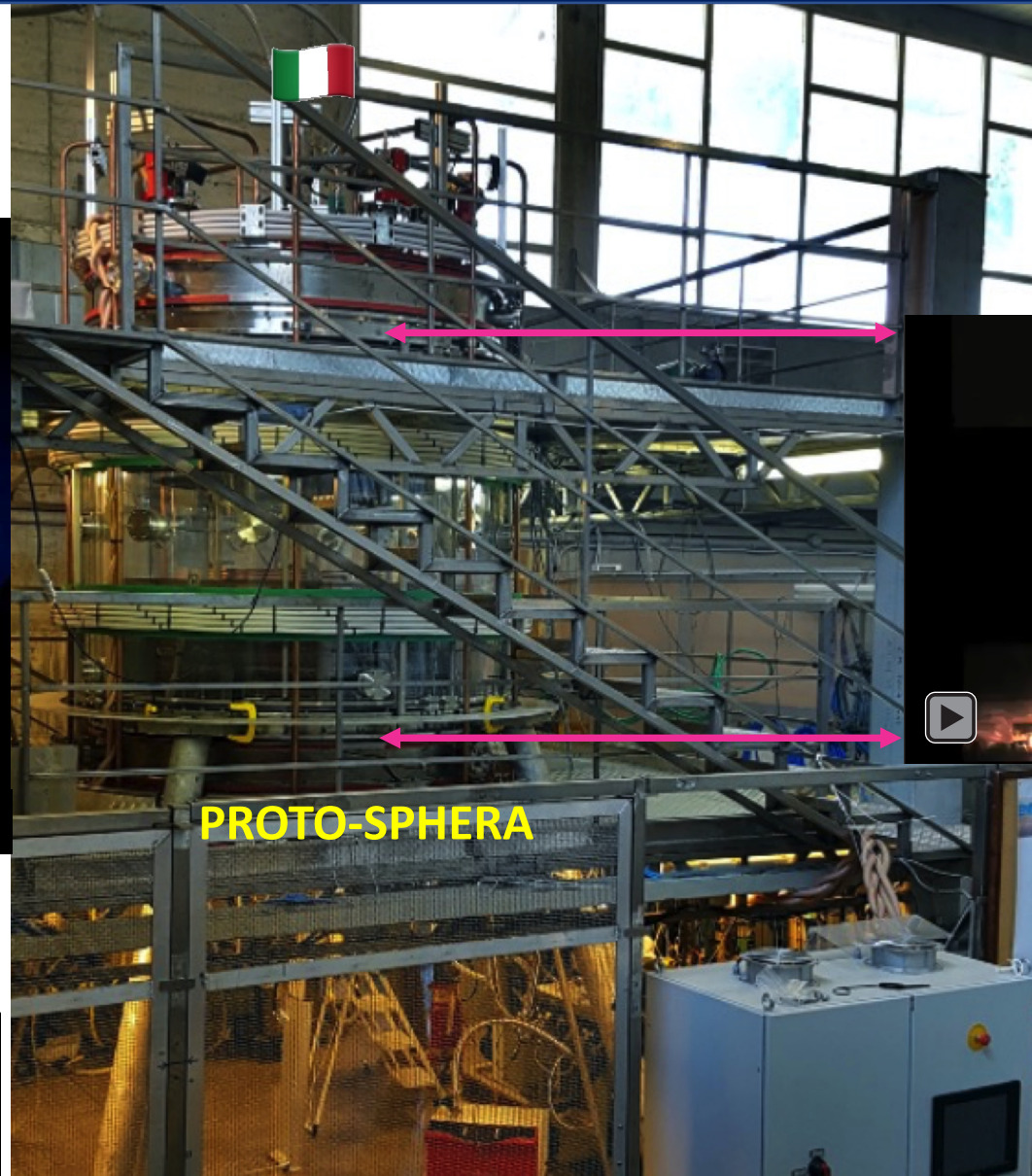
UNIVERSITÀ DI PISA



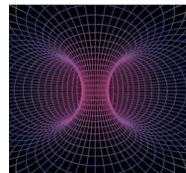
GRAN SASSO
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Vela Nebula



PROTO-SPHERA



ISTW 2024

22ND INTERNATIONAL
SPHERICAL TORUS WORKSHOP

SUMMARY

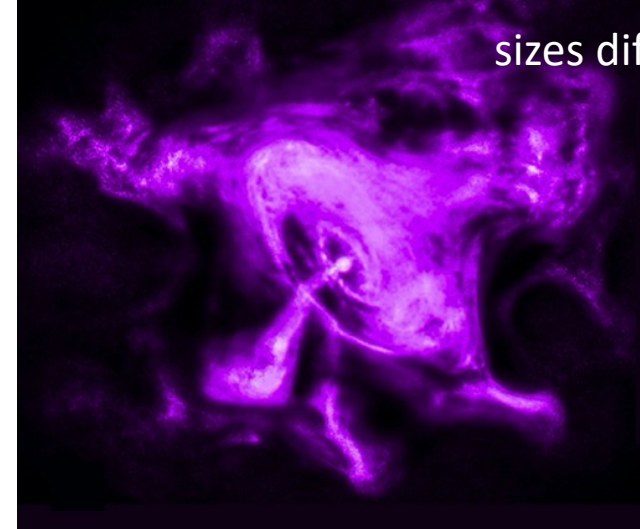
PROTO-SPHERA: 3D Tomography shows magnetic reconnections forming & sustaining the torus

Force-free magnetic field double-torus model for Pulsar Wind Nebulae (PWNe)

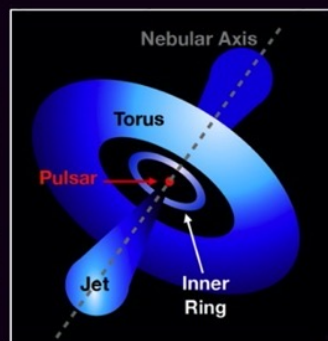
Flow & injection of magnetic helicity in PROTO-SPHERA & comparison with PWNe

Jet + Torus plasmas are produced by self-organization in PWNe & in laboratory

CRAB PULSAR WIND NEBULA (PWN)



sizes differ by a factor of 10^{16} - 10^{17}

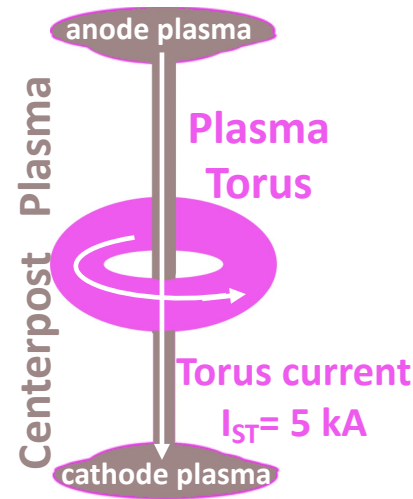


PROTO-SPHERA

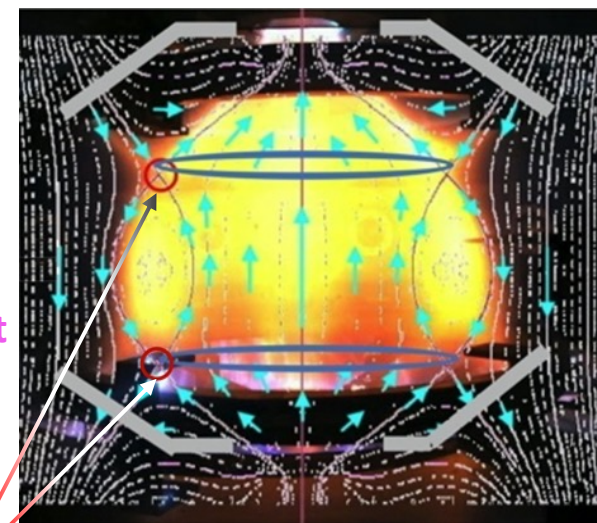


2 main plasma currents

Centerpost current $I_{CP} = 10$ kA



on the 2 sides of torus
opposite B_{pol}



Torus self-organized by magnetic reconnections around **plasma jets (Centerpost)**,
ideal MHD stable & sustained for 1 s, with $\tau_{Alfvén} \sim 0.5 \mu s$, $\tau_{resistive} \sim 10$ ms

without any conducting shell near the plasma

2023 3D tomography: reconstruction of non-plasma objects

6 equally-spaced cameras (600 fps) arranged around transparent vessel equator

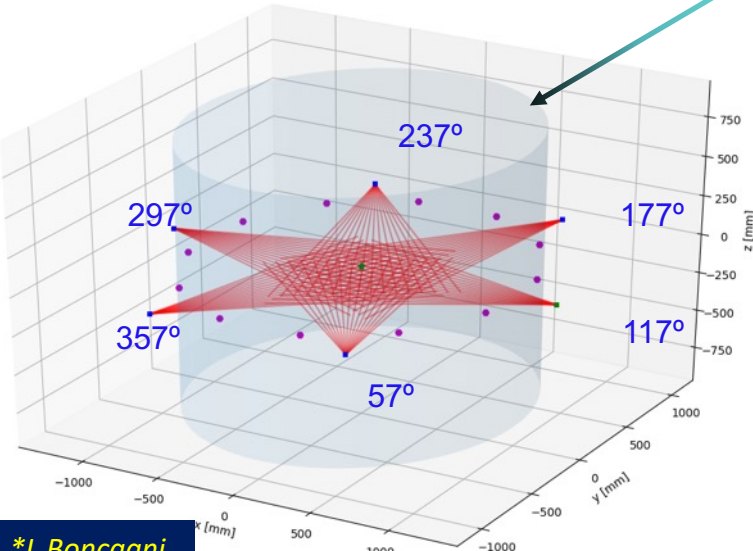
Since 2019: transparent insulating PMMA vacuum vessel & steel conical divertor plates

vertical tomographic section

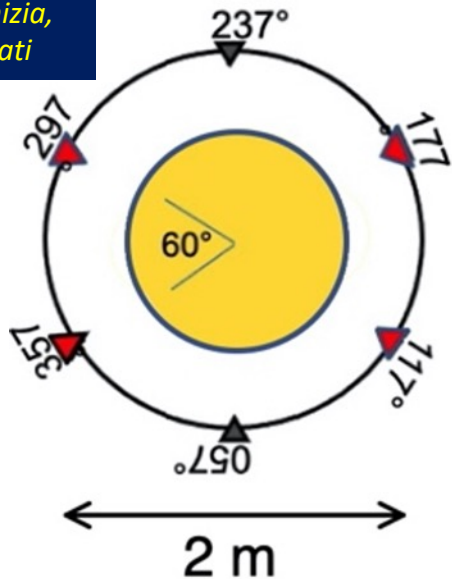
**A Pau, S Naghinajad*

Langmuir probe

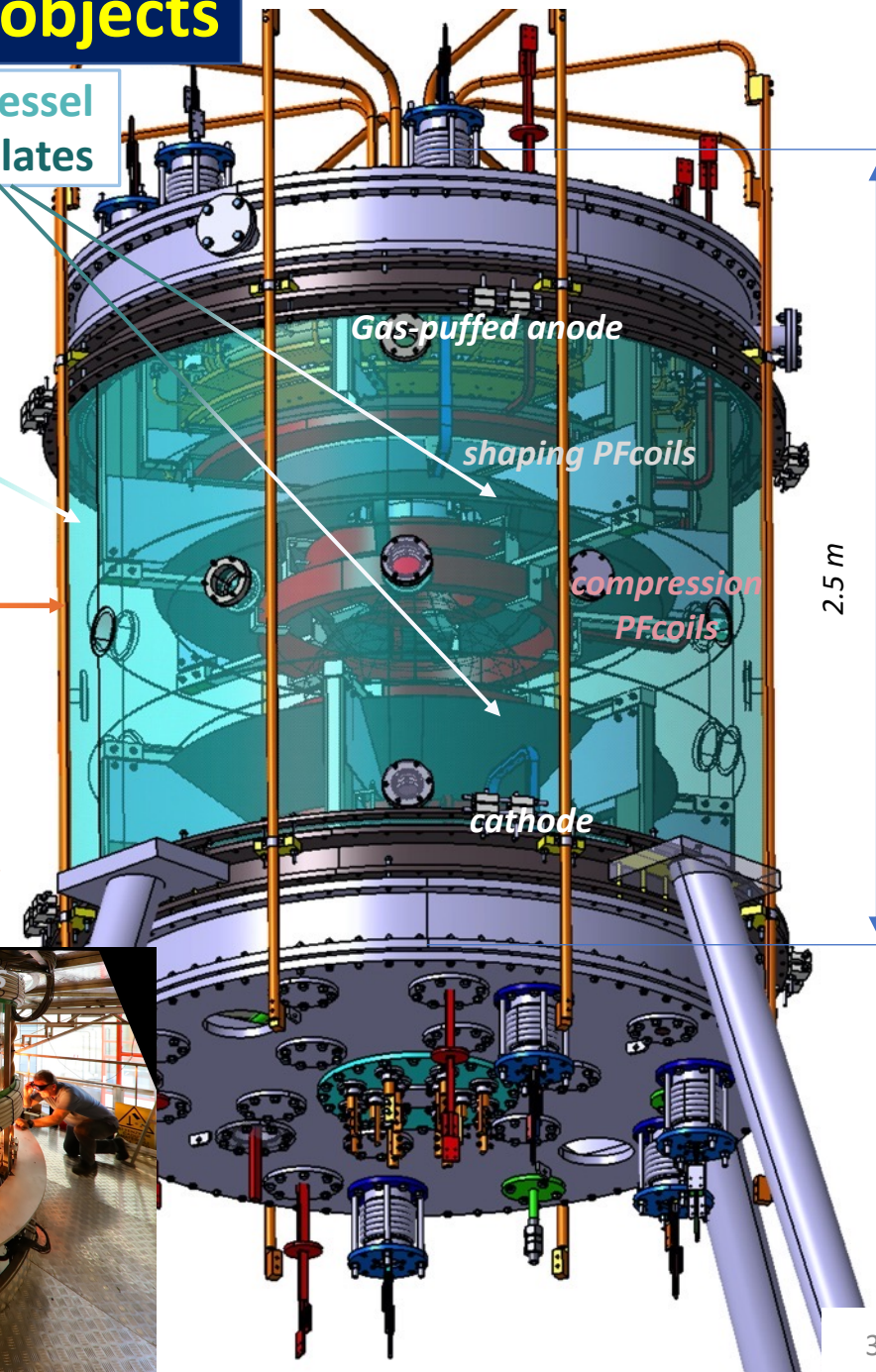
3cm $\varnothing$ copper bars are perfectly reconstructed



**L Boncagni,
Y Damizia,
M Iafrati*

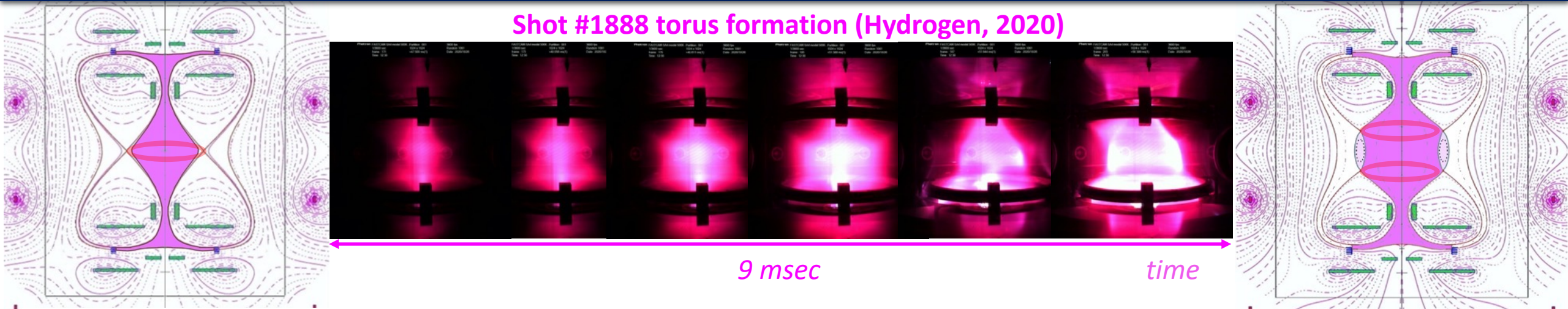


Since 2019: 18 PFcoils
8 shaping PFC internal
6 compression PFC internal
4 PFC external
to the vacuum vessel



2 circles of X-points on top and bottom of the equator indicate that a toroidal current exists

Shot #1888 torus formation (Hydrogen, 2020)



Absence of toroidal current on the equator ($j_{tor} = 0$)
results in single equatorial circle of null points

Presence of toroidal current on the equator ($j_{tor} \neq 0$)
results in 2 circles of null points on the 2 sides of equator

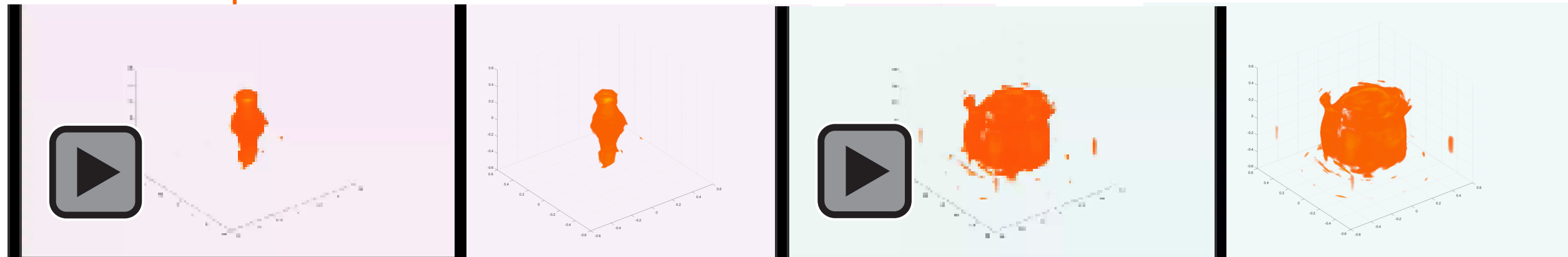
beginning of 3D tomography in visible light – 2023 – torus self-organization *A Pau, S Naghinajad

a kinked centerpost

forms the torus

& a kinked state

lets the torus to be re-born

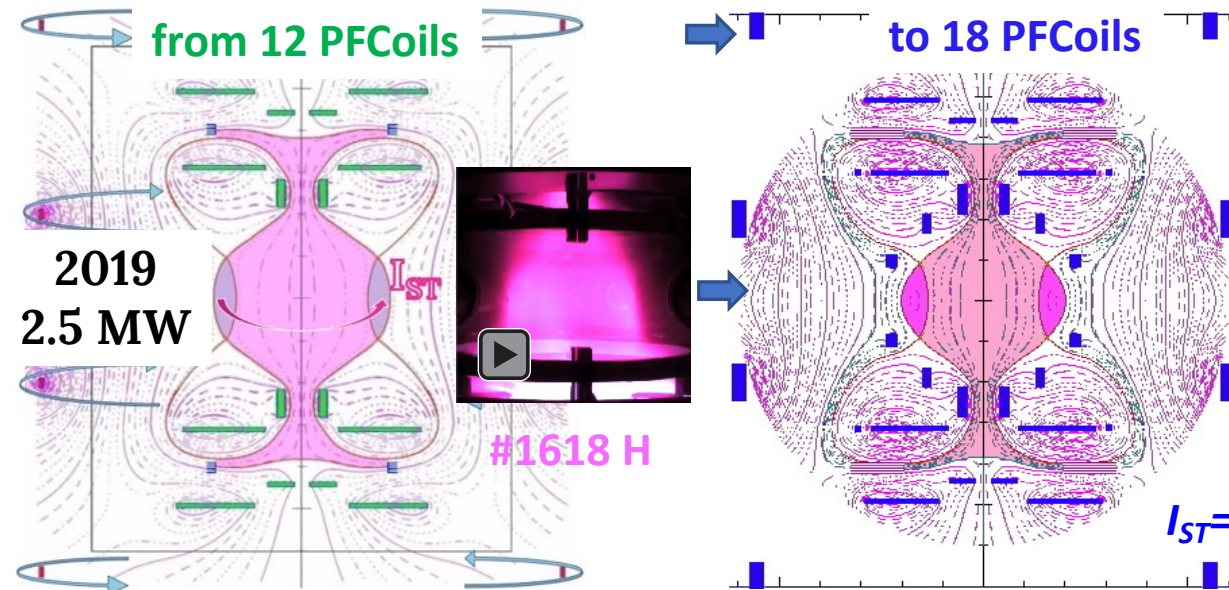


#2141 He, false colours

formation time <10 msec

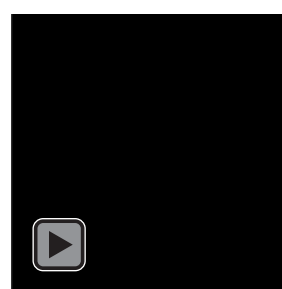
re-birth cycle <10 msec

Surprise: torus forms in pre-existing purely magnetostatic B field



2019 to 2024, evolution of torus up to 1 sec

2022, 3.5 MW
poor divertor
plate insulation
0.3 s tori always
produced



#2126 He

2024, 1 s, better
divertor plate
insulation
but tori not
always produced

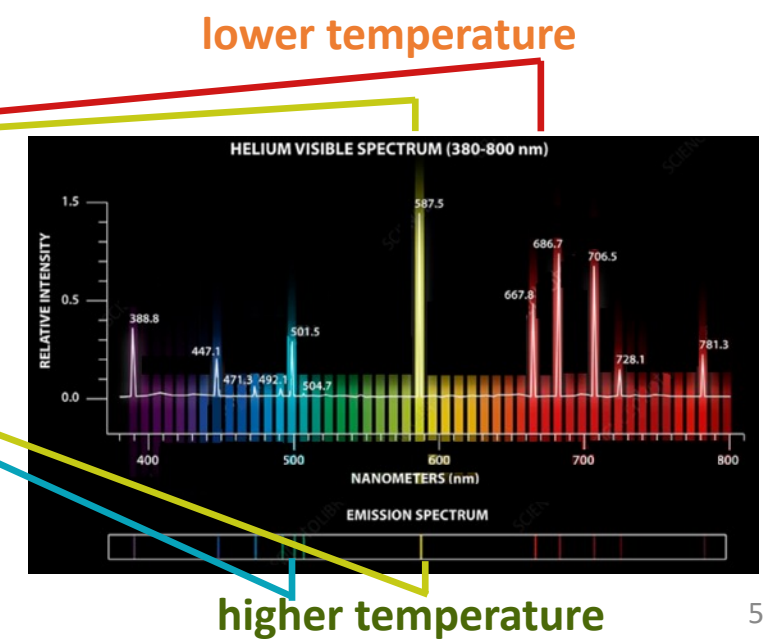
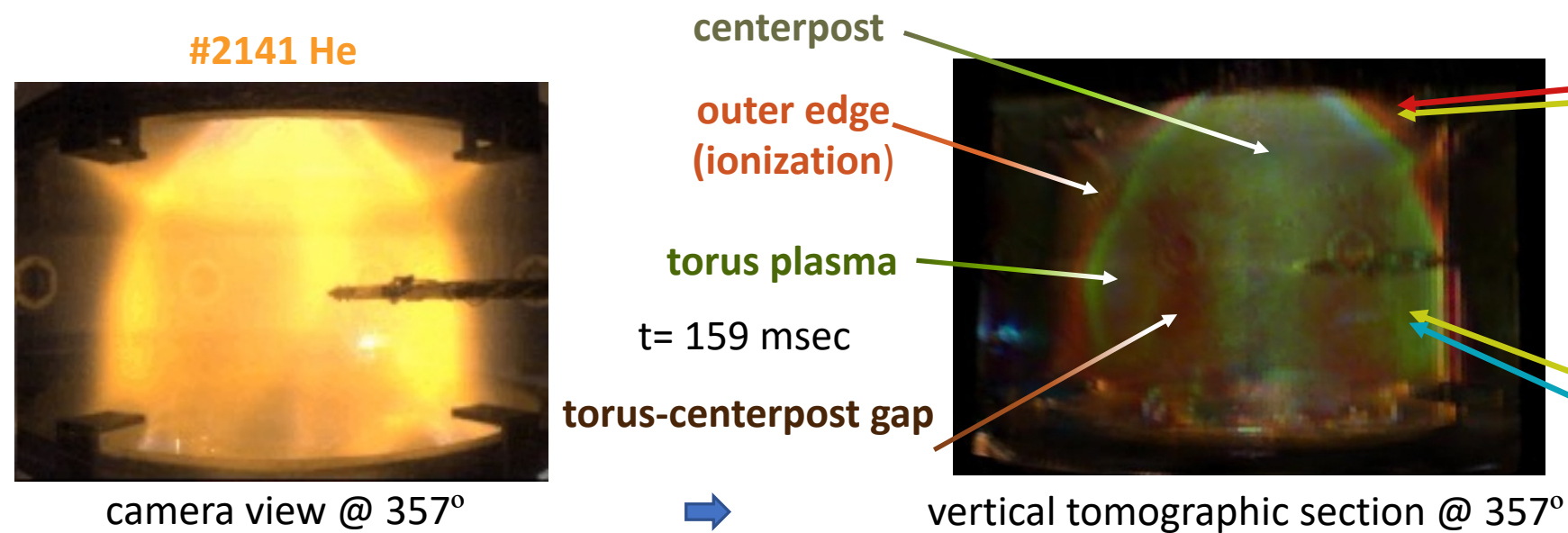


#2460 He

$I_{ST}=5$ kA tori: anode-cathode ΔV grows by 20-30 Volts (10% of 200 V)

2023 - 3D tomography allows to steal a glance inside the plasma cross-section

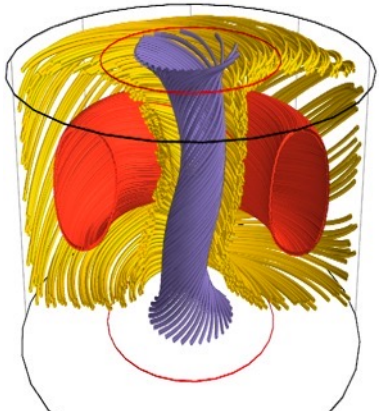
Surprise from 3D tomography: PROTO-SPHERA Helium plasmas are technicolor!



looking inside an Helium discharge: a restless, still enduring plasma

vertical tomographic cross section @ 357°

#2141 He



- kinked plasma centerpost

Farengo 2018 *Physics of Plasmas* 25



surprise: PROTO-SPHERA
plasma spontaneous
toroidal rotation ~ 600 rad/s
(clockwise from top)

oblique rotator

torus shaken by
continuous
unrest

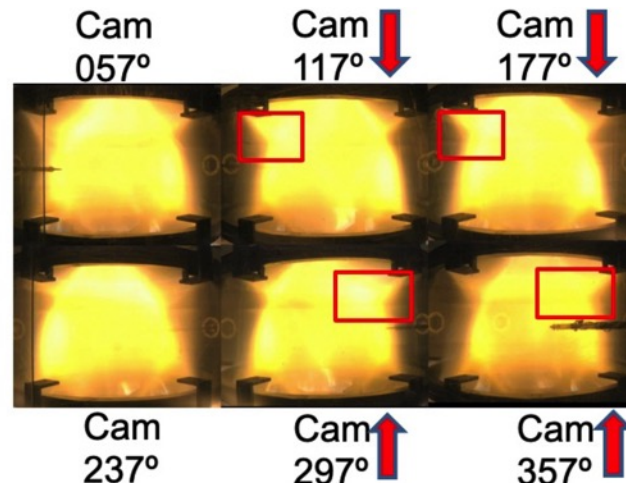
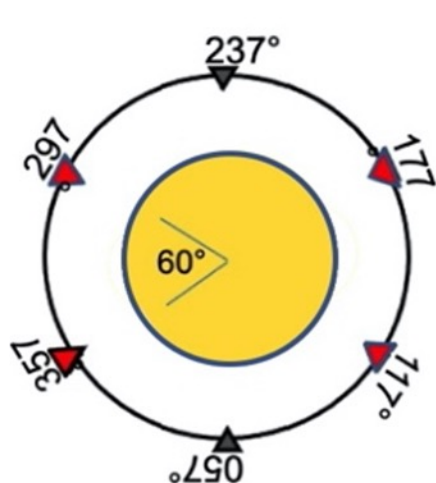
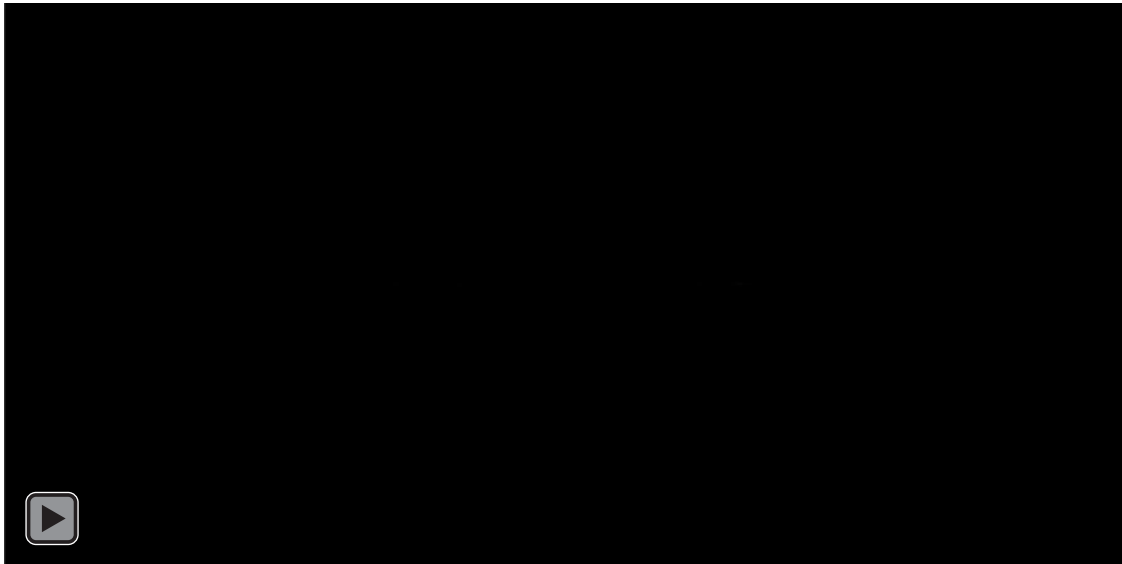
centerpost plasma in continuous turmoil

torus sustained: magnetic reconnections break axisymmetry

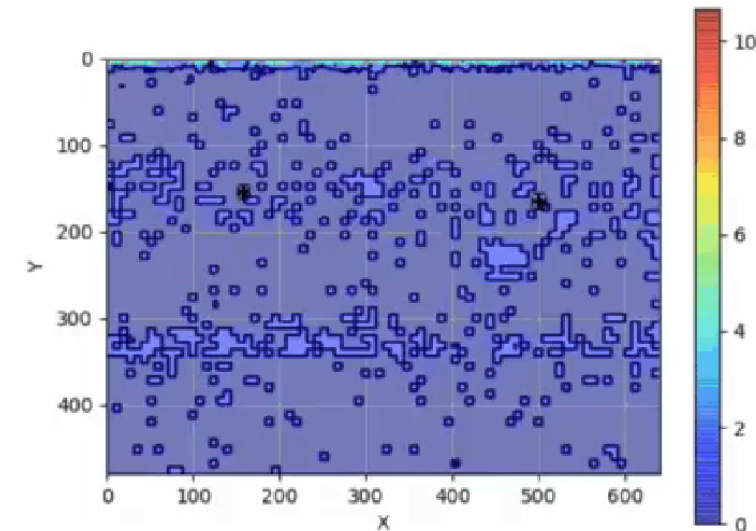
S Macera

breaking of axisymmetry* is required in order to inject current into the torus **Cowling anti-dynamo theorem*

6 cameras (600 fps, 640x480 pix) around vessel equator



Shot #2141, Ultra-fast Camera, 3600 fps, 1024x1024 pix

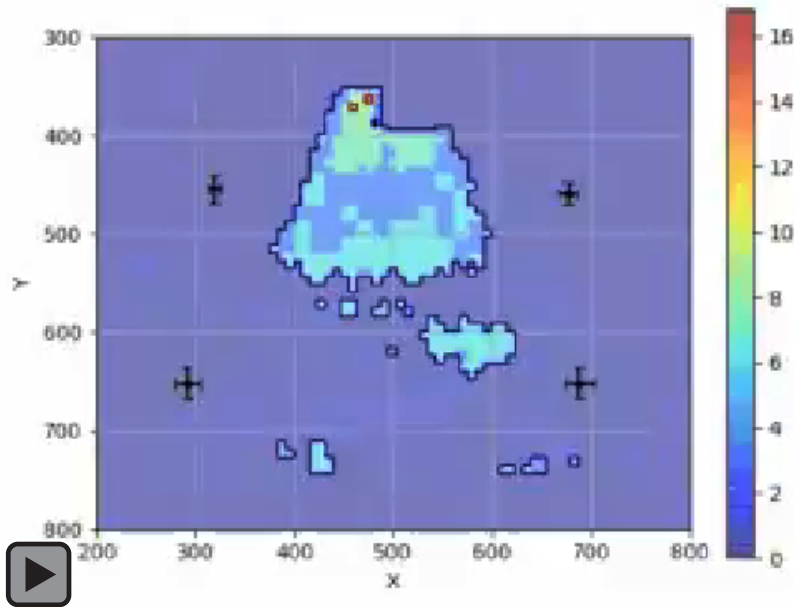


light intensity contours & upper X-points positions

- **plasma brightenings of divertor tails**
 - **deformation of plasma in the area of the X points**
- both phenomena localized within $\sim 60^\circ$ azimuthal angle

only **2 toroidally contiguous cameras** observe brightening and deformation (**& also the 2 opposite ones**)
but the other 2 cameras do not see anything

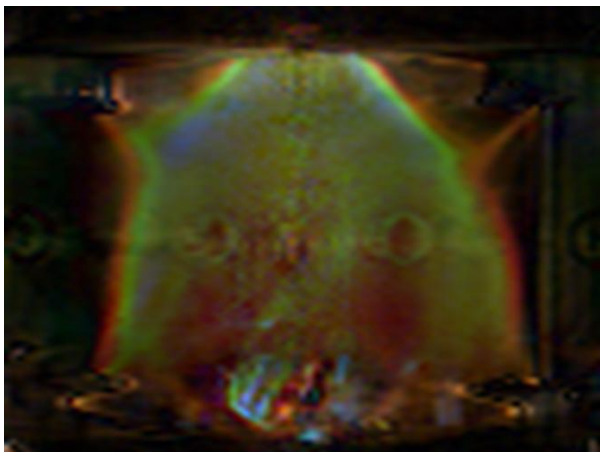
notwithstanding symmetry breaking, fair integrity of toroidal surfaces



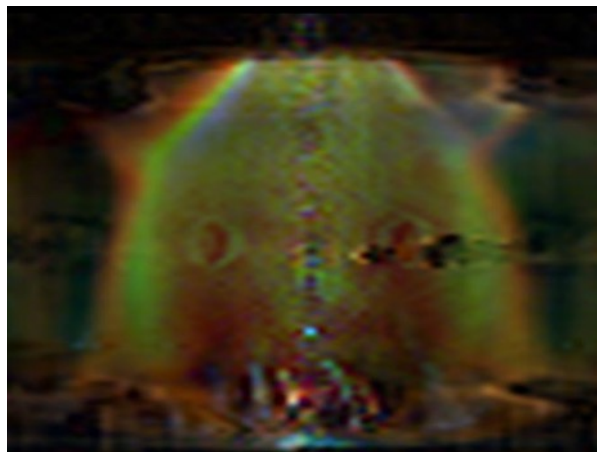
#2029 He Ultra-fast Camera, 3600 fps, 1024x1024 pix

- notwithstanding X-points position oscillations
- nested & closed light intensity contours inside the torus

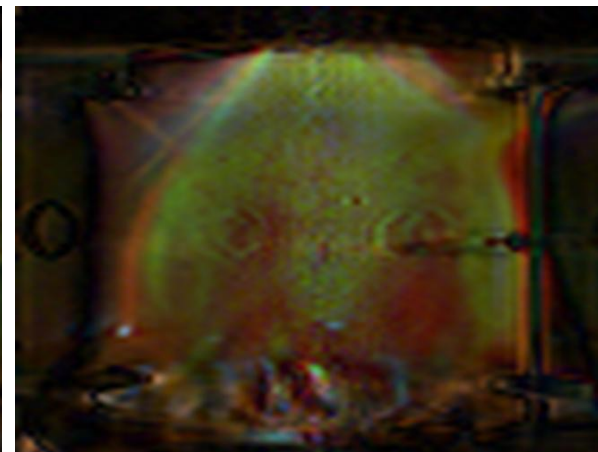
3D tomography vertical cross sections at various angles suggest fair axisymmetry of torus, apart from oblique rotation



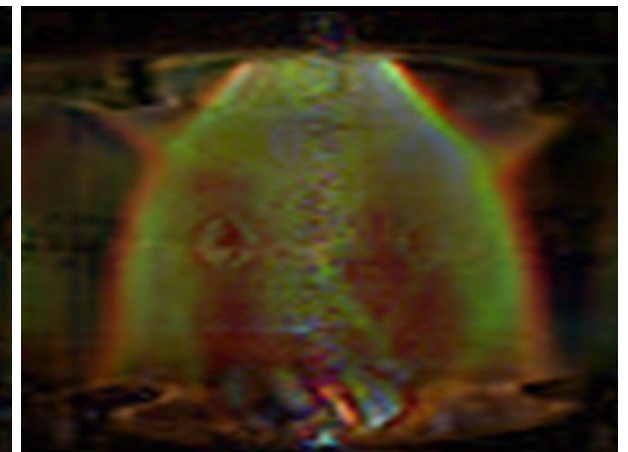
vertical section @ 0° azimuth



vertical section @ 45°

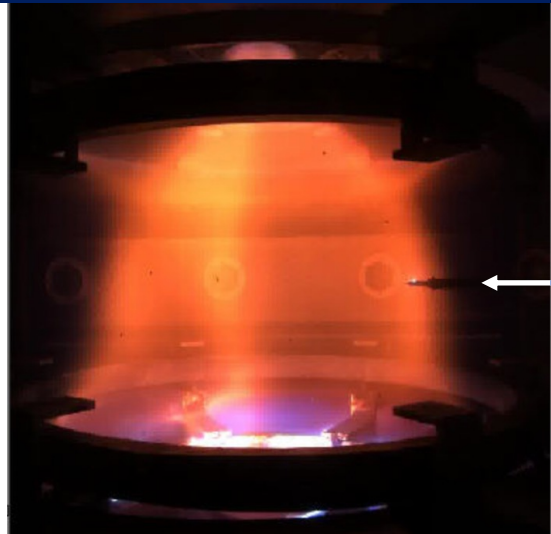


vertical section @ 90°



vertical section @ 135° azimuth

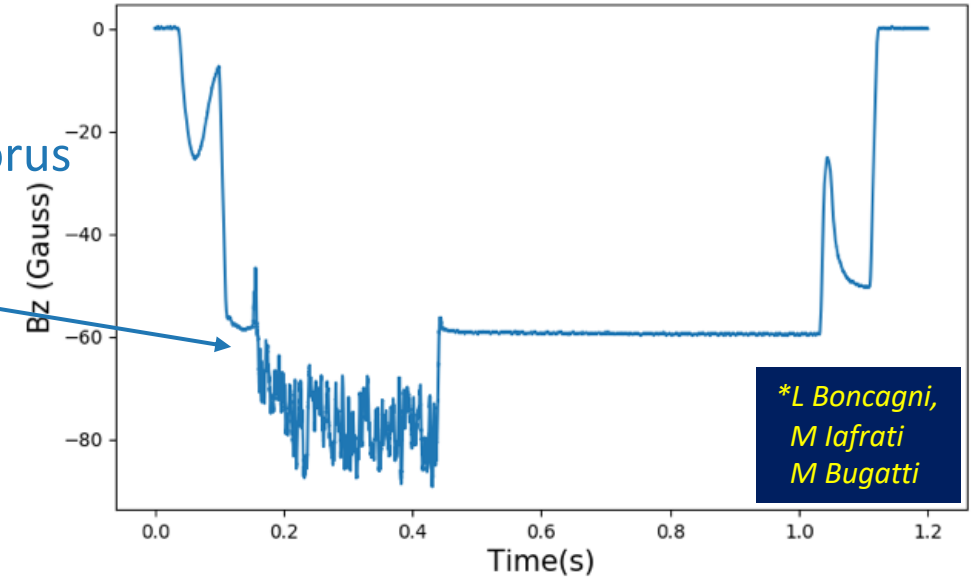
magnetic reconnections: plasma temperature and/or particle acceleration



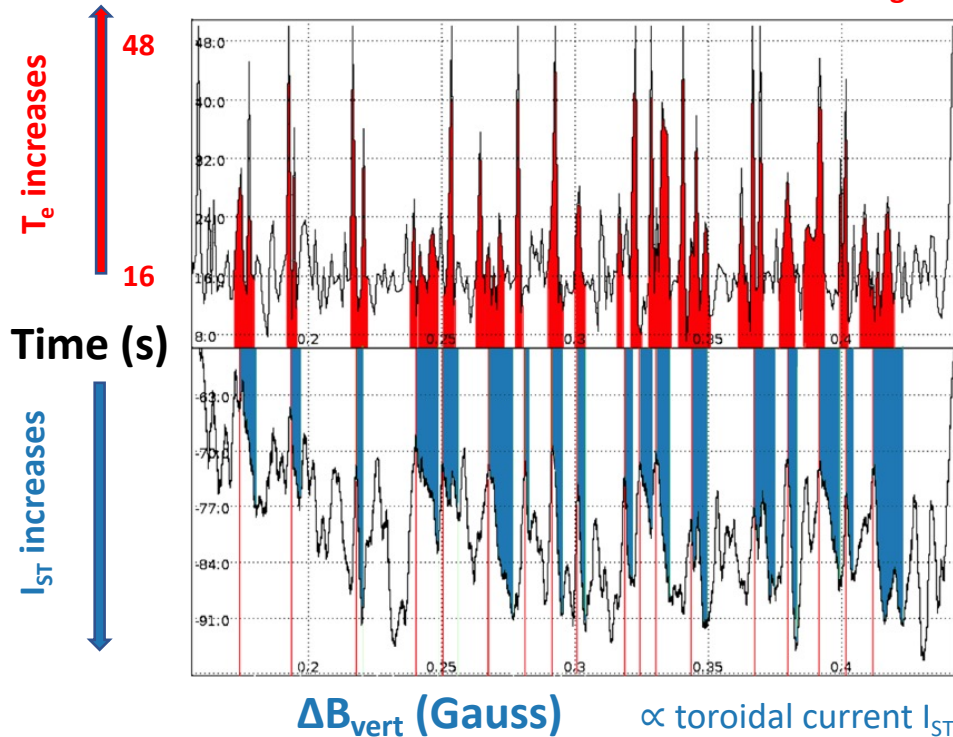
#2141 He

Hall probes* at torus edge ($B_{Z\text{-vertical}}$):
 ΔB_{vert} bursts (toroidal current ΔI_{ST}) into torus

Langmuir probes*: T_e spikes
coincide with the toroidal bursts ΔI_{ST}



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



reconnections T_e spikes 20 eV $\rightarrow$ 50 eV (heating?/acceleration?)

followed by

toroidal current bursts $\Delta I_{\text{ST}} \sim 1\text{-}1.5$ kA injected into torus ($I_{\text{ST}} \sim 5\text{ kA}$)

Jet + Torus plasmas can be modelled as force-free fields

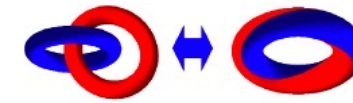
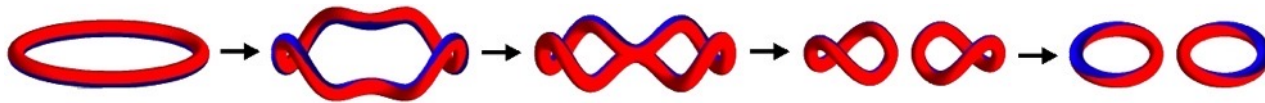
Force-free magnetic field (ffmf) models: self-consistent distributions of $\vec{B}$ & $\vec{j}$, with $\vec{j} \wedge \vec{B} = 0$

- no Lorentz force upon them
- can decay without material fluid motions, with e-folding times $\gg$ Lorentz motion time-scale
- the simplest choice for large scale, long duration magnetic structures in Astrophysics

- in a perfectly conducting plasma, for every flux tube (α, β) : $\vec{B} = \vec{\nabla} \wedge \vec{A} = \vec{\nabla} \alpha \wedge \vec{\nabla} \beta$,
the Magnetic Helicity* of the tube $K(\alpha, \beta) = \int \vec{A} \cdot \vec{B} dV$ is invariant *Woltjer L. 1958 Proc. Nat. Acad. Sciences 44 (6) 489–491

K measures how much the lines of force are interlinked, kinked or twisted

- in a resistive plasma, magnetic reconnections redistribute K over the volume $K = \int \vec{A} \cdot \vec{B} dV$



Plasma relaxation: minimize energy $W = (1/2\mu_0) \int (\vec{\nabla} \wedge \vec{A})^2 dV$, with $K = \int \vec{A} \cdot \vec{B} dV = \text{constant}$

yields* a Beltrami vector field*: $\vec{\nabla} \wedge \vec{B} = \mu \vec{B}$, $\vec{B} \cdot \vec{\nabla} \mu = 0 \Rightarrow$ a ffmf

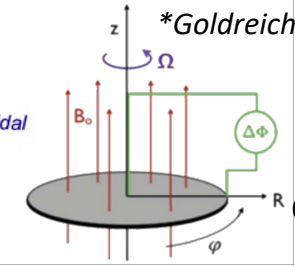
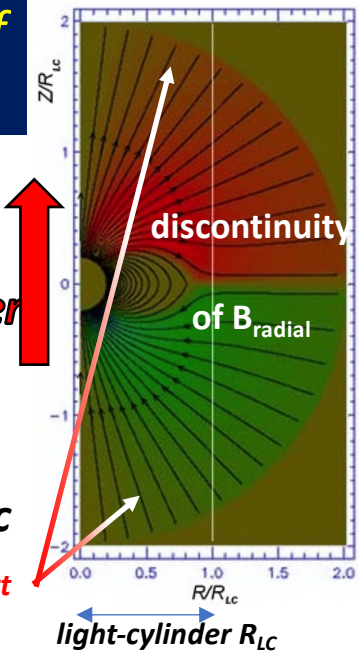
*Taylor J B. 1986 Rev. Mod. Phys 58 741

*Beltrami E. 1889 Rendiconti Reale Istituto Lombardo

if relaxation parameter $\mu = \mu_0 \vec{j} \cdot \vec{B} / B^2 = \text{constant everywhere}$ the relaxed state is a linear ffmf
linear ff with same μ can be summed & give another linear ffmf

split-monopole *ffmf* model* for PWNe

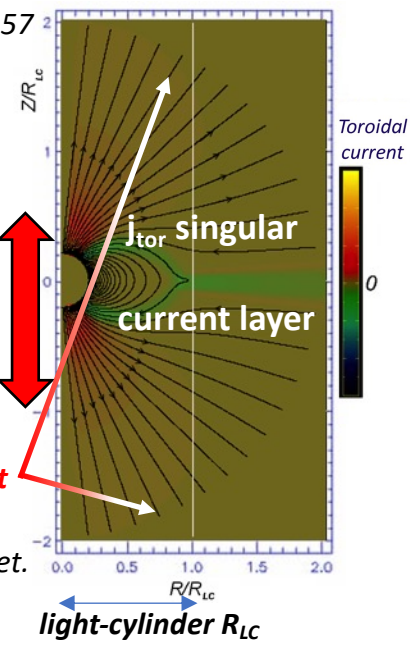
B of Pulsar yields:
 single direction **B_{vert}**
 even-symmetric
 emispherical **B_{vert}**



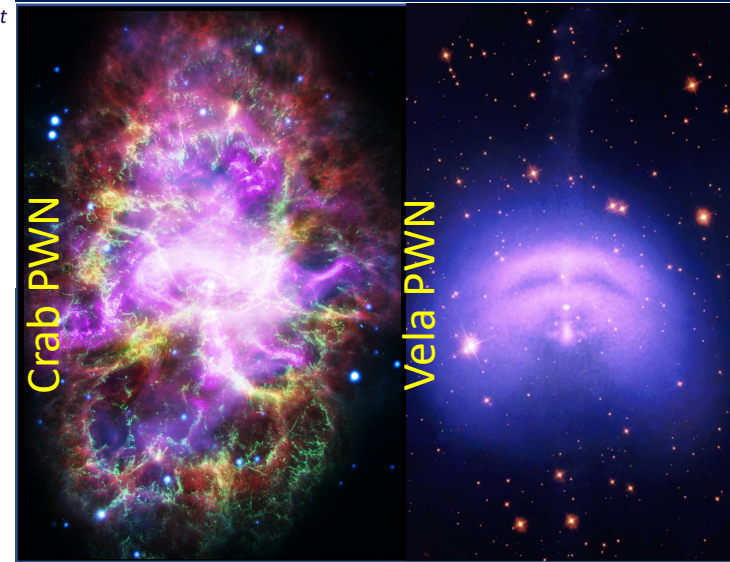
Faraday disk effect* yields:

bi-directional current **j_{vert}**
 odd-symmetric
 emispherical **j_{vert}**

*Michel 1991 Theory of Neutron Star Magnet. University of Chicago Press



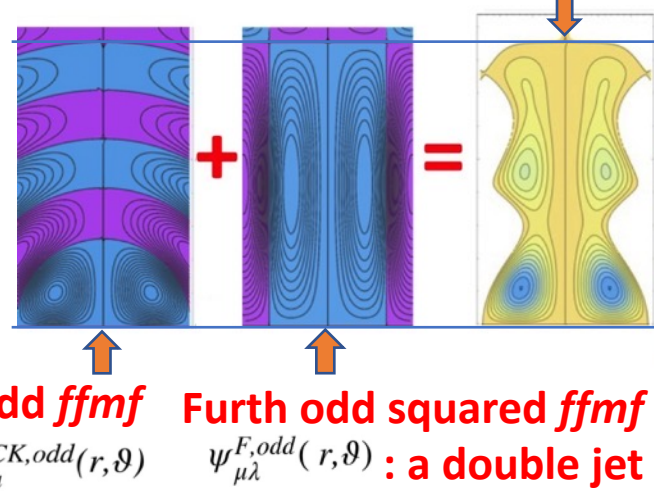
but observed PWNe are composed by Jets & Tori



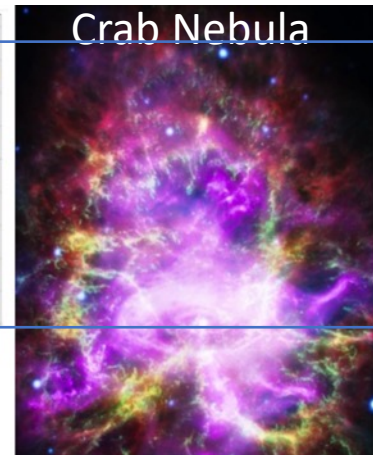
PWNe plasma including double jets & tori can be modelled by homogeneous (linear) *ffmf*

odd linear *ffmf* models a double jet + double torus

$$\psi_{\mu\lambda}^{CKF,odd}(r,\vartheta) = \psi_{\mu}^{CK,odd} + \gamma \psi_{\mu\lambda}^{F,odd}, \quad \gamma \text{ superposition parameter}$$



Chandrasekhar-Kendall odd *ffmf* for a double torus: $\psi_{\mu}^{CK,odd}(r,\vartheta)$
 Furth odd squared *ffmf* : a double jet $\psi_{\mu\lambda}^{F,odd}(r,\vartheta)$



Crab Nebula

$0.85518 = x_{2,5}/x_{2,6}$
 $\mu = x_{2,6} = 21.8539$ 6th zero of $j_2(x)$

"number of zeroes" rules allow to obtain "simply connected-closed configurations" with same direction of j_{ϕ} & B_{ϕ}

$\lambda = 3.6736$, so that zeroes of $\psi_{\mu}^{CK,odd}$ and of $\psi_{\mu\lambda}^{F,odd}$ coincide

however...

Jet + Torus model requires 2 *ffmf* with opposite μ on the 2 sides of equator

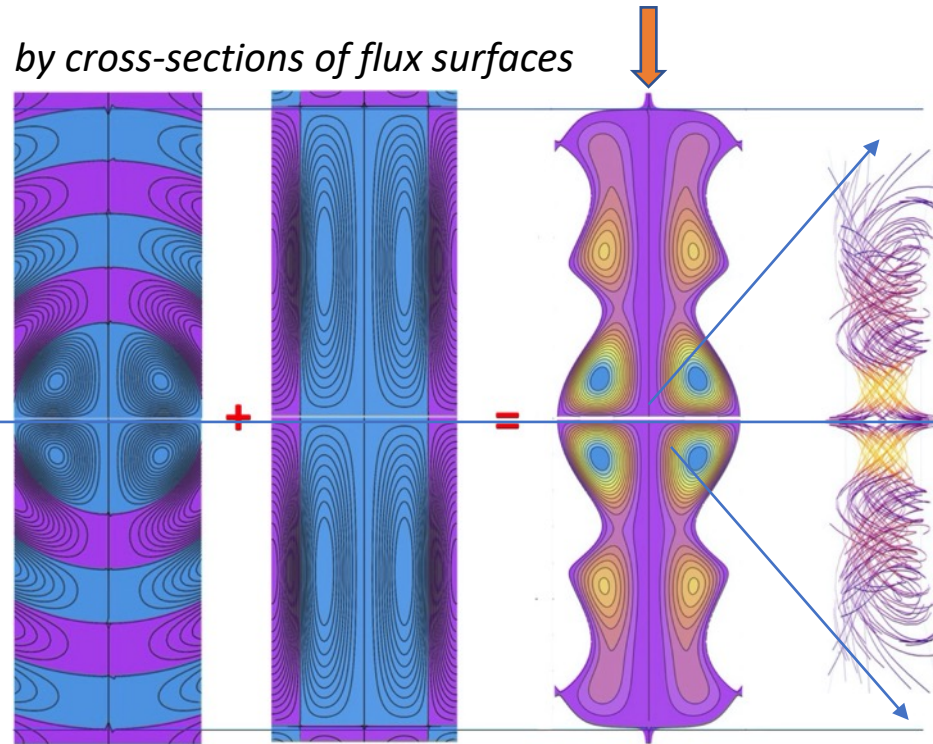
Two *linear ffmf*, contiguous with opposite μ : $\mu > 0$ on upper and $\mu < 0$ on lower emisphere:

Upper emisphere, $Z > 0$

$$\psi_{\mu\lambda}^{PSW}(R, Z) = \frac{Z}{|Z|} [\psi_{\mu}^{CK, odd} + \gamma \psi_{\mu\lambda}^{F, odd}]$$

Lower emisphere, $Z < 0$

$$\psi_{\mu\lambda}^{PSW}(R, Z) = \frac{Z}{|Z|} [\psi_{-\mu}^{CK, odd} - \gamma \psi_{-\mu\lambda}^{F, odd}]$$



by enlarged field-line-tracing

double-torus for PWN separated by a discontinuity on the equator of B_{radial} & a singular j_{tor} current layer

PWN double-torus *ffmf* model
can generalize the split-monopole *ffmf* model

PWN model: symmetries & anti-symmetries on the 2 sides of nebula's equator

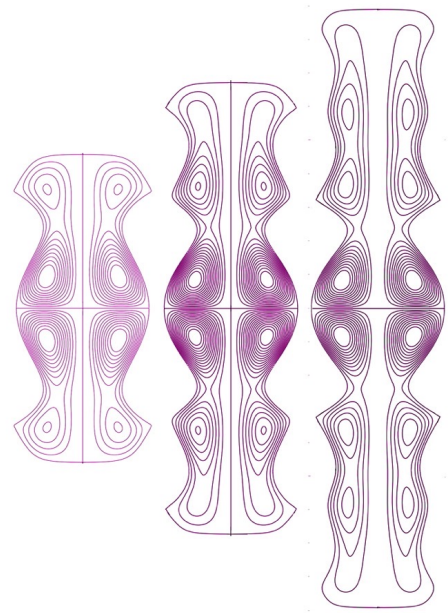
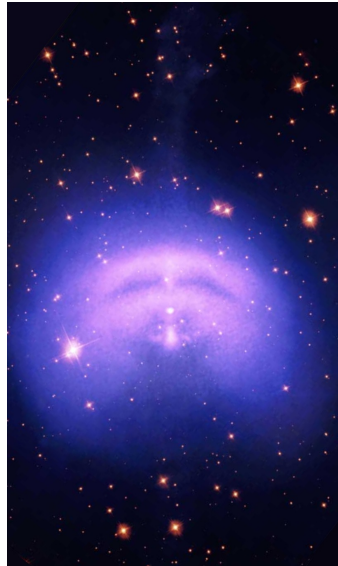
B_ϕ

the 2 hemisphere have:

- opposite toroidal fields
- aligned toroidal currents

j_ϕ

Vela PWN



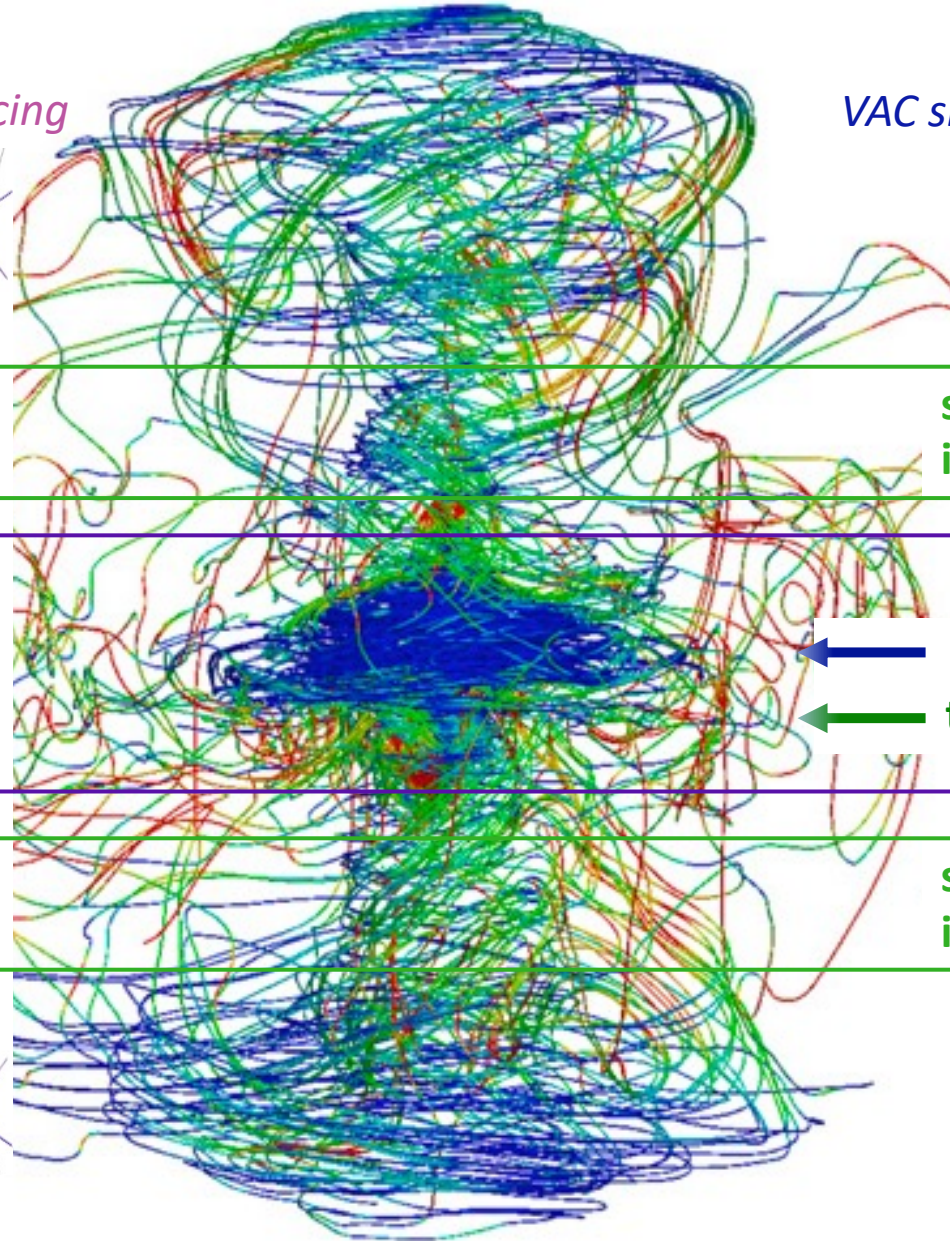
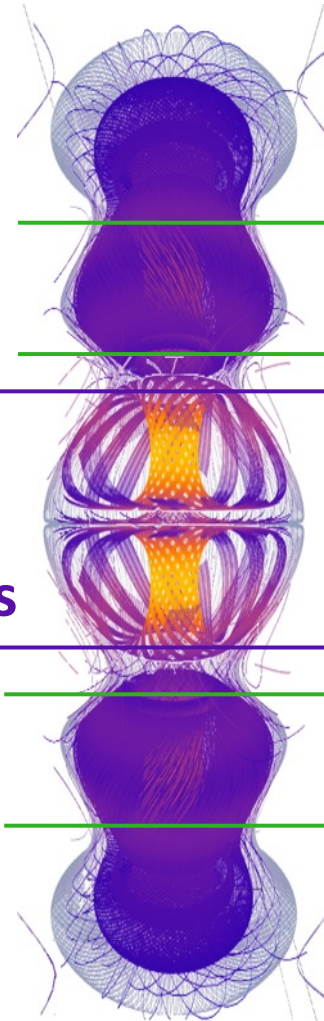
Different length of filaments can be chosen in the model

PWN double-torus *ffmf* compared to results of VAC* (Versatile Advection Code)

*Keppens 2014 MNRAS 438 278

PWN double-torus fmf model by field-line-tracing

VAC simulation



The 2 main tori have:

- opposite toroidal fields
- aligned toroidal currents

secondary tori show up
in numerical simulations

2 main tori with opposite
toroidal field in simulation

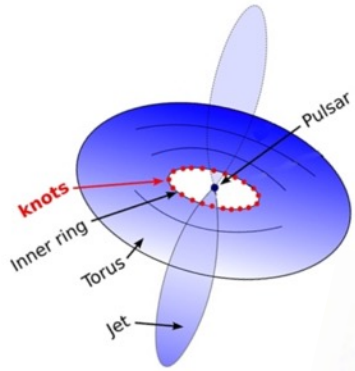
secondary tori show up
in numerical simulations

acceleration & reconnections in PWN

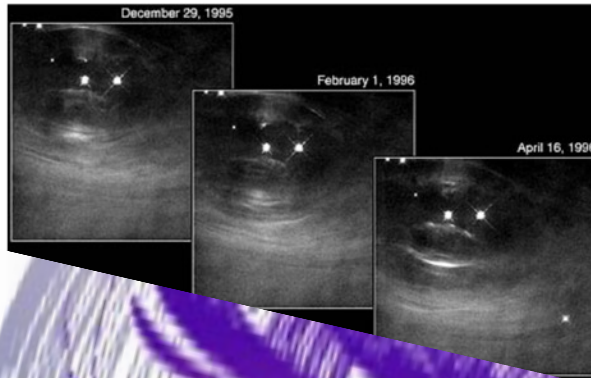
- most efficient accelerators in the Galaxy are the PWNe
>25% of their released power is emitted in radiation
• spectrum of e.m. emission extends beyond PeV (10^{15} eV)

acceleration of particles in PWN is open question: 1) Fermi acceleration in shockwaves; 2) magnetic reconnections

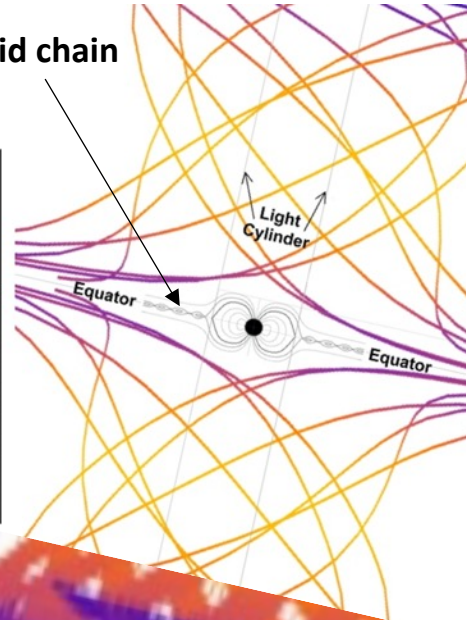
do the fast moving “**knots**” ($\sim c/2$) coincide with such plasmoids?



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



reconnecting plasmoid chain



if reconnections responsible for acceleration, PWN double-torus model indicates their place:

the nebula's equator, where radial & toroidal magnetic field of the 2 tori are opposite between the 2 emispheres, a j_{tor} current layer between the two tori with $\mu > 0$ & $\mu < 0$

the two neighboring tori are attracted against each other: they have toroidal currents in same direction

flow & injection of Magnetic Helicity, as from PROTO-SPHERA design

Ratio between change of magnetic energy ΔW and of Helicity ΔK in a relaxed state: $d(\Delta W) / d(\Delta K) = |\mu| / 2\mu_0$
shows that **Helicity flows from higher to lower $|\mu|$ values: $|\mu|_{edge} > |\mu|_{axis}$**

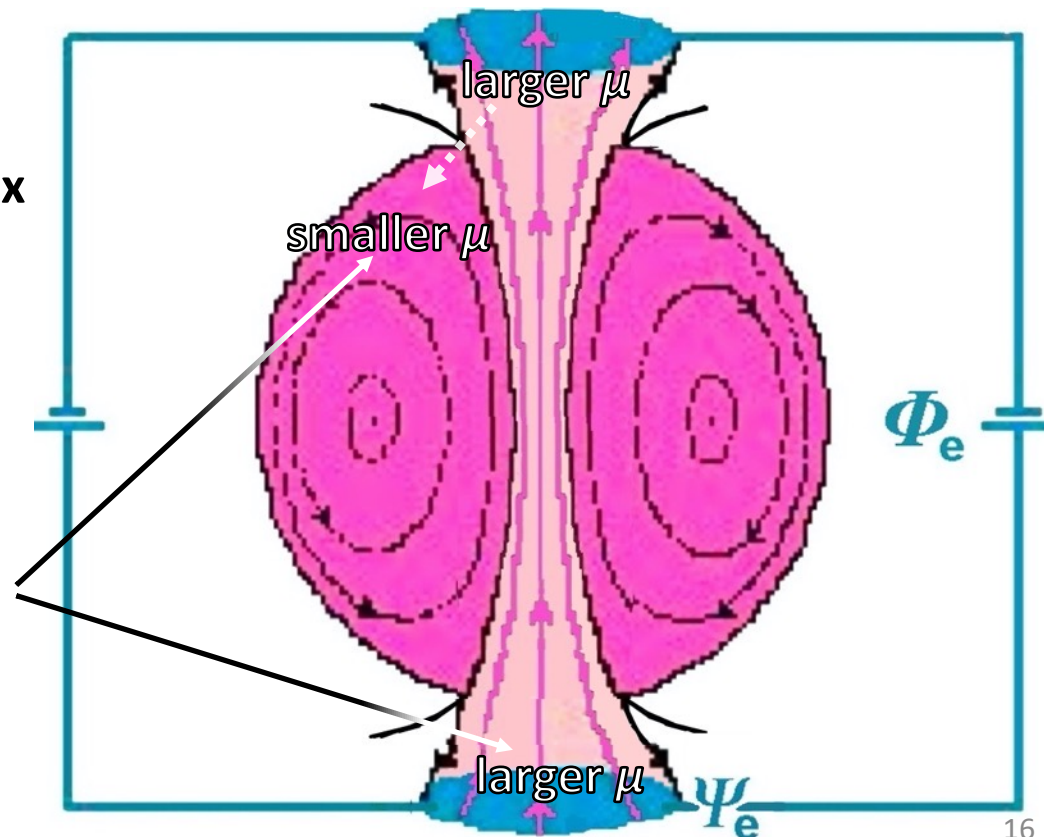
as dimensionally $\mu [L^{-1}]$ Helicity (relaxation parameter) flows from **smaller** to **larger** scales
(*inverse cascade*) Helicity can form large magnetic structure in nature...

nonlinear ffmf: μ can be a function of the flux surface $\mu = \mu(\psi)$

un-relaxed equilibria: $\mu \neq \mu(\psi)$ but the relaxation parameter if flux surface-averaged $\langle \mu \rangle(\psi) = \mu_0 \langle \vec{j} \cdot \vec{B} / B^2 \rangle$ is still relevant:

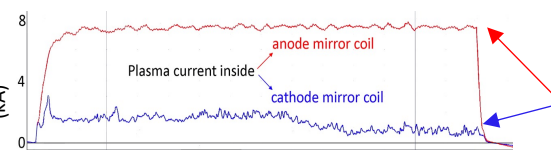
gradient of $\langle \mu \rangle(\psi)$: $\nabla |\langle \mu \rangle(\psi)| = \mu_0 \nabla |\langle \vec{j} \cdot \vec{B} / B^2 \rangle|$
 μ decreases from Helicity source (**Centerpost**) to sink (**Torus**)

magnetic helicity flows from **larger μ** to **smaller μ** regions
by magnetic reconnections on the X points converting
part of the magnetic energy into kinetic plasma energy

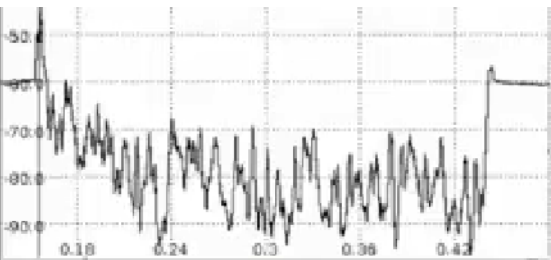


flow & injection of Magnetic Helicity, as from PROTO-SPHERA experiment

#2141 He (2020, lower divertor plate acted as cathode) →



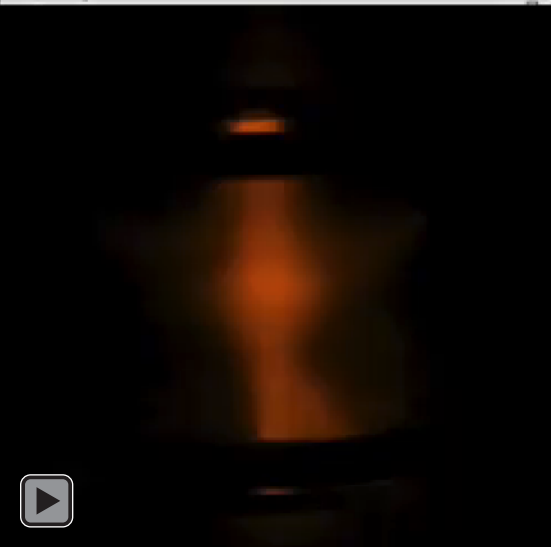
upper & lower plasma centerpost currents were unbalanced @ mirrorPF coils



Hall probe @ Torus edge
 $\Delta B_{Z\text{-vertical}} \sim 30$ gauss

torus formed & sustained

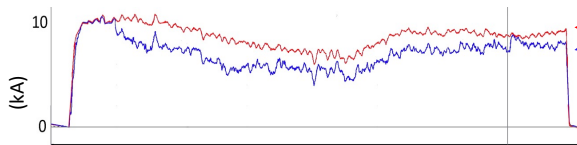
seconds



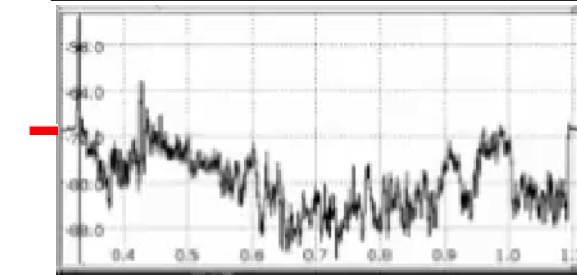
plasma centerpost current intercepts lower divertor plate



#2477 He (2024, after improving divertor plate insulations)



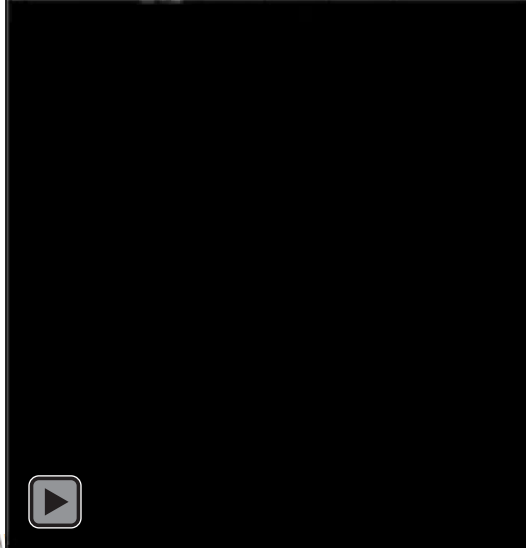
upper & lower plasma, in shots when centerpost plasma currents were well balanced @ mirrorPF coils



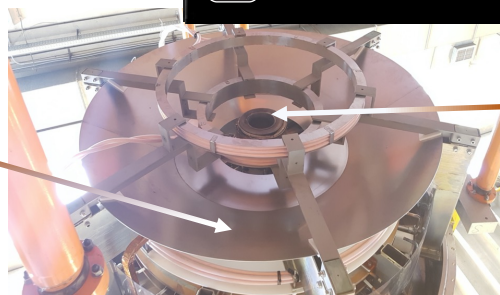
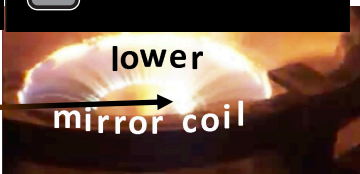
Hall probe @ Torus edge
 $\Delta B_{Z\text{-vertical}} \sim 10$ gauss

kink prevails, no torus*

seconds



plasma centerpost current flows into lower mirror coil



*but in 2024 shots where plasma currents were unbalanced @ mirror PFcoils, tori lasted 1 sec

flow & injection of Magnetic Helicity in Phase-2 of PROTO-SPHERA

- 1) proper cathode's operation requires (2022) balancing the **plasma centerpost current** in the **2 mirror PF coils**
- 2) but proper formation & sustainment of the torus requires (2024) **a current j flowing outside the torus**

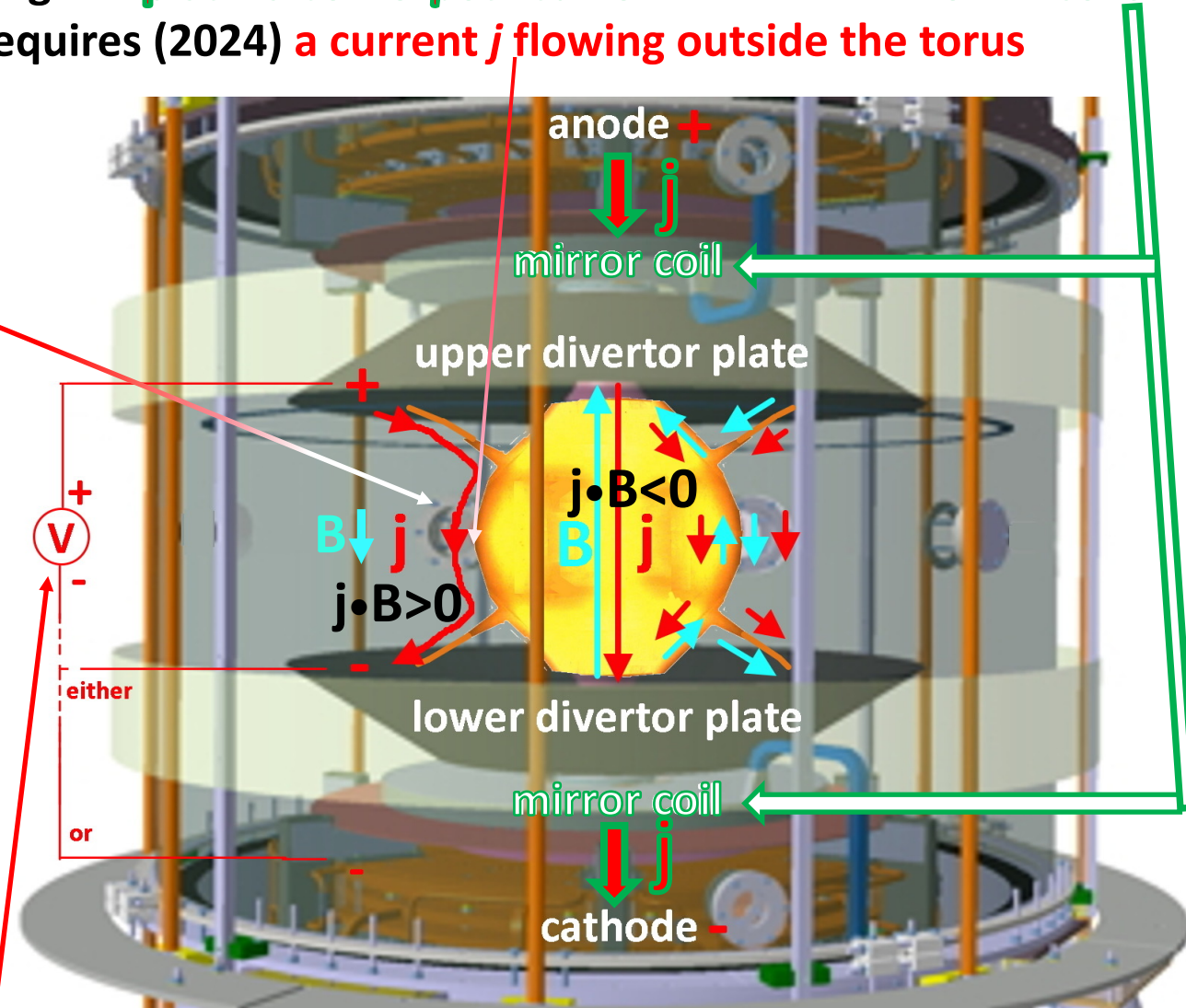
- magnetic field B_{pol} reverses sign at torus edge
- B_{tor} retains the same sign
- plasma current density j flows from top to bottom
(as voltages on all metal surfaces in vessel impose)

The value of $\mu = \mu_0 (\vec{j} \cdot \vec{B}) / B^2$, being $\mu < 0$ inside centerpost and torus, becomes $\mu > 0$ for the plasma current flowing outside the torus, or vice versa

in PROTO-SPHERA reconnections occur at the X-points between inner/outer plasmas with opposite signs of μ

in PWNe model, reconnections occur at the nebula's equator between the 2 tori with opposite signs of μ

between upper divertor plate (+) and either lower plate or cathode (-) a new power supply must be introduced



CONCLUSIONS

Design of PROTO-SPHERA was inspired by astrophysical examples and produced self-organized tori: a successful gamble to sustain for 1 s a self-organized torus, with Alfvén time $0.5 \mu\text{s}$, resistive time $>10 \text{ ms}$

In Laboratory:

- very good ideal MHD stability (without any conducting shell near the plasma),
- the torus is formed in a purely magnetostatic field
- He plasma viewed by 3D tomography shows different colors (torus+centerpost: green, edge: orange-brown)
- the plasma rotates in toroidal direction, acting as an oblique rotator, just as PWNe
- magnetic reconnections observed: not axisymmetrical & evidencing thermal/acceleration effects
- notwithstanding (slight) axisymmetry breaking, fair integrity of toroidal flux surfaces

In Astrophysics:

- the Double-Torus *ffmf* model of PWNe describes an impressive reconnection machine on nebula's equator
- the 2 cases (**Laboratory** and **Astrophysics**) are distinct: • number of tori (**1** vs. **2**)
- location of magnetic reconnections (**circles of ordinary X points** vs. **nebula's equator between the 2 tori**)
- in both cases reconnections between plasmas endowed with opposite sign relaxation parameter $\mu > 0$ & $\mu < 0$

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