

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

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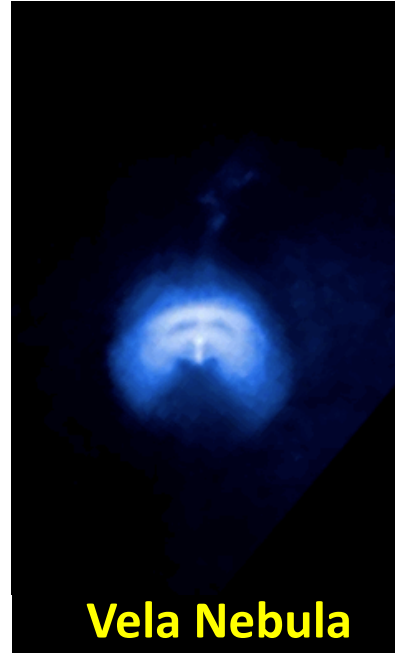
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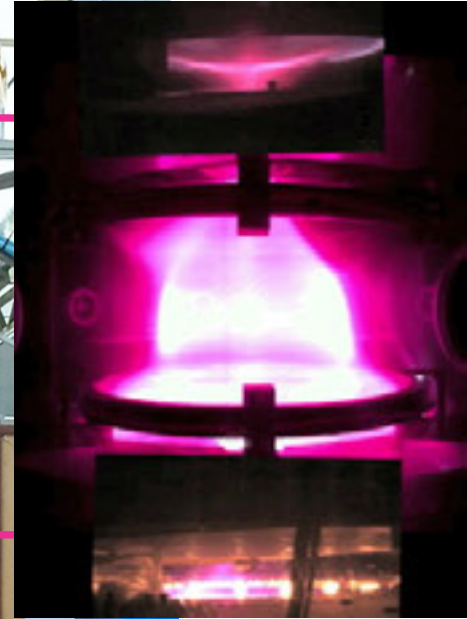
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Vela Nebula



PROTO-SPHERA



UNIVERSITÀ DI PISA

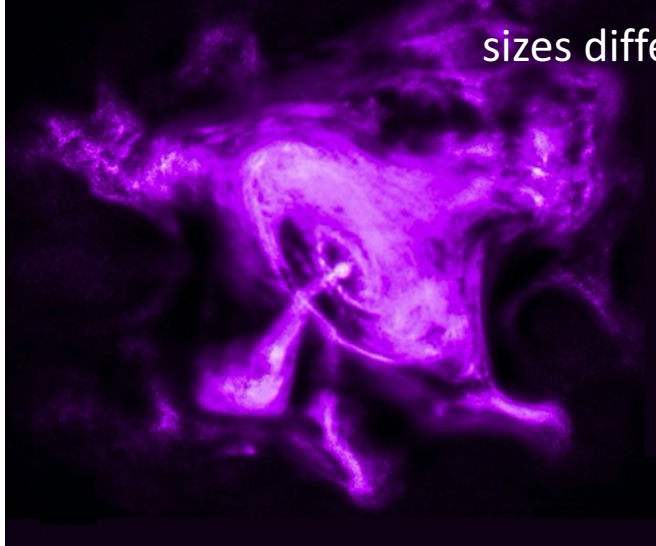


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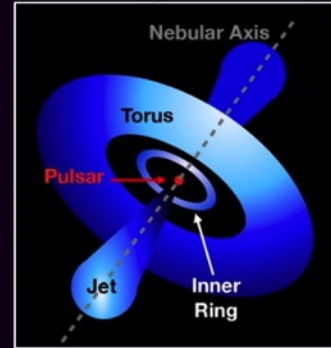
torus + jet plasmas are present in Pulsar Wind Nebula (PWN) objects & are produced in laboratory experiments

Chandra X-ray
image of Crab

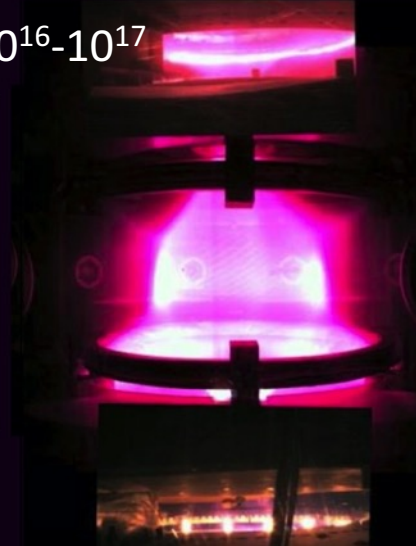
CRAB PULSAR WIND NEBULA (PWN)



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



PROTO-SPHERA



Visible light of
PROTO-SPHERA

SUMMARY

Force-free magnetic 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 magnetic field 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 magnetic field (ffmf) models: self-consistent distributions of $\vec{B}$ and $\vec{j}$, 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

*Lundquist S 1950 *Arkiv Fysik* Bd 2 nr 35

Force-free (excluding $\vec{j} = 0$), for weakly resistive plasma means* $\vec{\nabla} \wedge \vec{B} = \mu \vec{B}$, with $\mu = \mu_0 \vec{j} \cdot \vec{B} / B^2$
Beltrami vector fields* *Beltrami 1889 *Rendiconti del Reale Istituto Lombardo...* Series II, vol. 22

Plasma relaxation: minimize energy with appropriate constraints

J.B. Taylor did show that **force-free fields are the final result of plasma relaxation***

*Taylor J B. 1974 *Phys. Rev. Lett.* 33 1139

*The relaxation of a flexible perfectly conducting wire in viscous medium provides an analogy:
minimize energy $(1/2)LI^2$, with the invariant $LI=\text{constant}$ (L self-inductance) as the constraint*

Plasma relaxation: constraint is Magnetic Helicity

A magnetized plasma resembles a tangle of braided flexible conductors (lines of force):
in presence of perfect conductivity the plasma moves together with the lines of force

In a perfectly conducting plasma around a line of force $\vec{B} = \vec{\nabla}\alpha \wedge \vec{\nabla}\beta$, for every infinitesimal flux tube one constraint: the **Magnetic Helicity*** $K(\alpha, \beta) = \int \vec{A} \cdot \vec{B} dV$ is invariant

*Woltjer L. 1958 *Proc. Nat. Acad. Sciences* 44 (6) 489–491

perfect conductivity ($\eta=0$)
& motion $\vec{v}$

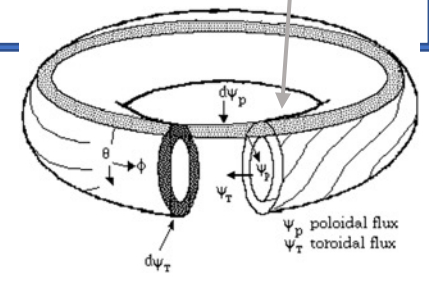
$\vec{A}$ vector potential
 χ arb. gauge

magnetic differential
equation for $\vec{A}_{\parallel}$

gauge χ single-valued if

$$\vec{E} + \vec{v} \wedge \vec{B} = 0 \quad \rightarrow \quad \partial \vec{A} / \partial t = \vec{v} \wedge \vec{B} + \vec{\nabla} \chi \quad \rightarrow \quad \vec{B} \cdot \vec{\nabla} \chi = \vec{B} \cdot \partial \vec{A} / \partial t \quad \rightarrow \quad \begin{cases} \oint \frac{dl}{B} \vec{B} \cdot \frac{\partial \vec{A}}{\partial t} = 0 & \forall \text{ field line } l \\ \oiint \frac{dS}{|\vec{\nabla} \psi_p|} \vec{B} \cdot \frac{\partial \vec{A}}{\partial t} = 0 & \forall \text{ flux surface (pol. flux } \psi_p) \end{cases} \rightarrow$$

$\rightarrow$ for every volume bounded by field lines the quantity $K = \int \vec{A} \cdot \vec{B} dV$ is invariant

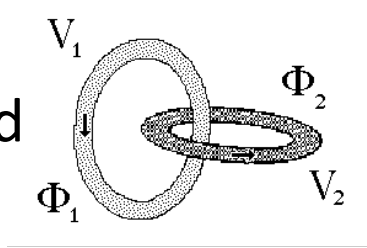


with Magnetic Helicity as constraint Plasma relaxation yields *ffmf*

Magnetic Helicity measures* how much the lines of force are:

*Berger M A. 1984 *J. Fluid Mech.* 147 133

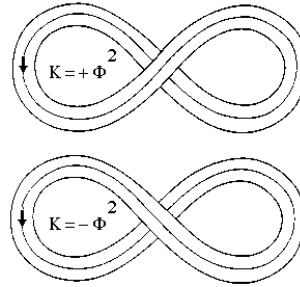
interlinked



Two interlinked flux tubes

$$K = 2\Phi_1\Phi_2$$

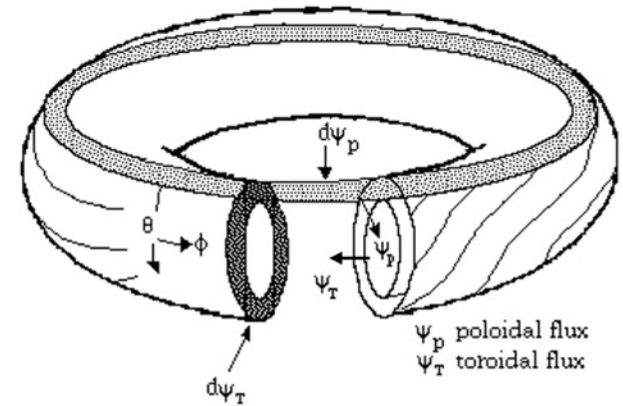
kinked



Sign depends on sign of kinking

$$K = \pm\Phi^2$$

or twisted



χ rotational transform = poloidal turns/toroidal turns

$$K = \chi \psi_T^2$$

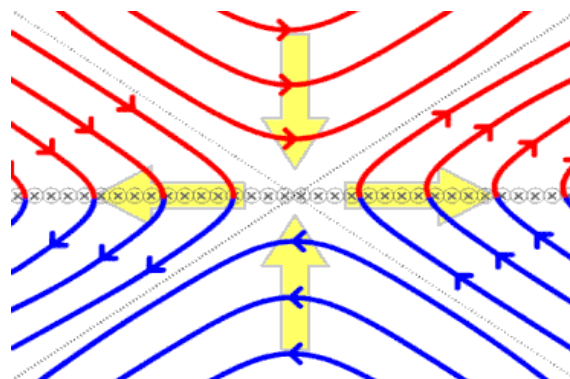
Minimize the energy $W = (1/2\mu_0) \int (\vec{\nabla} \wedge \vec{A})^2 dV$, under the constraint $K = \int \vec{A} \cdot \vec{B} dV = \text{constant}$
 the Euler's equation is obtained: $\vec{\nabla} \wedge \vec{B} = \mu(\alpha, \beta) \vec{B}$, $\vec{B} \cdot \vec{\nabla} \mu = 0$: a force-free magnetic field

→ This is why the **coefficient** $\mu = \mu_0 \vec{j} \cdot \vec{B} / B^2$ takes the name of **relaxation parameter**

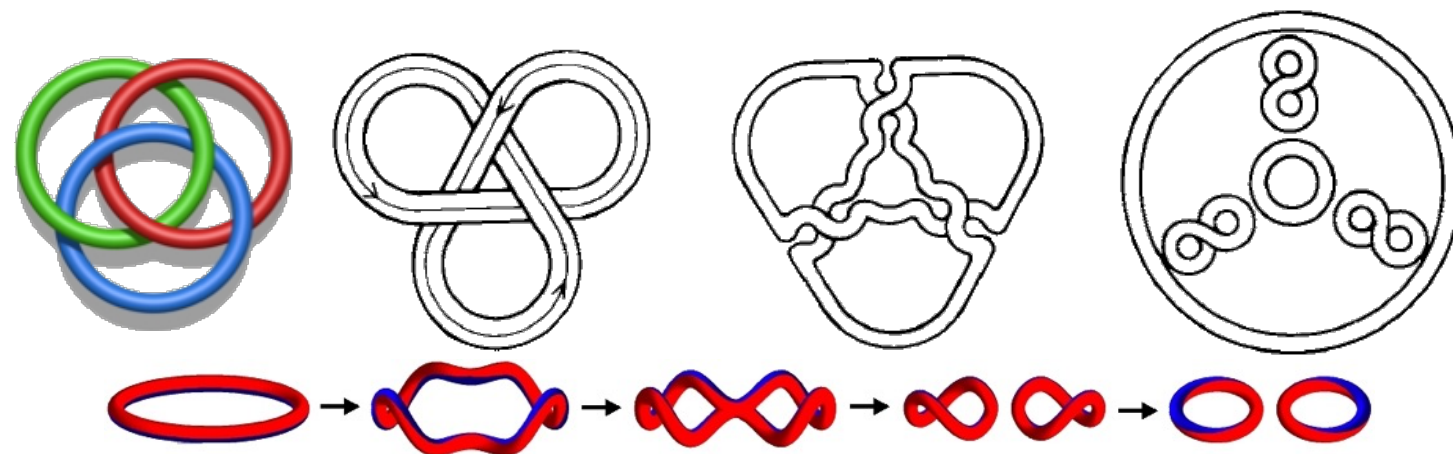
But the constraint is one for any field line (α, β) ...just too much!

Magnetic Reconnections redistribute Magnetic Helicity

Real plasmas are never perfectly conducting, lines of force break & re-join in reconnections



Magnetic Reconnections redistribute the Magnetic Helicity without destroying it*



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

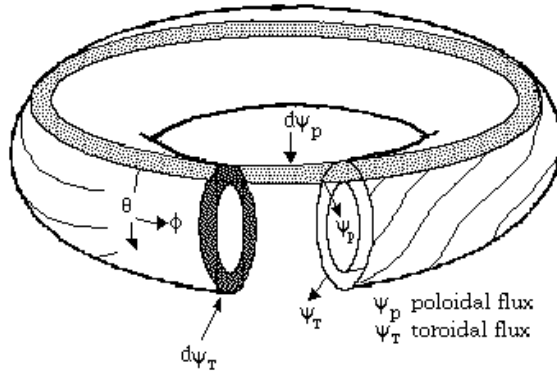
**reconnections
preserve Helicity!**

magnetic reconnections transfer magnetic flux and electric current
between magnetic field regions that in ideal MHD would remain disconnected

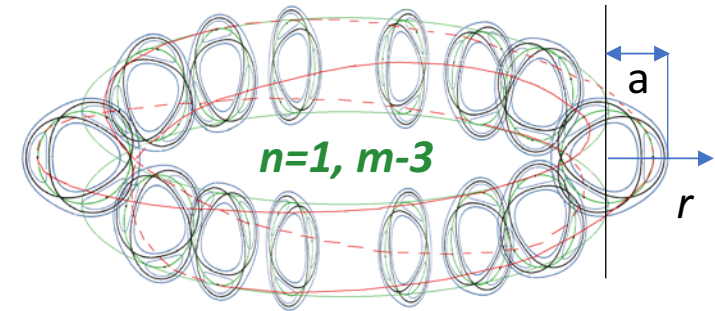
Magnetic Reconnections and in-homogeneous *ffmf*

resonant B-line closes after m times toroidally, n times poloidally on $\psi_{p,nm}$: $\chi(\psi_{p,nm})=n/m$
 if a resonant perturbation $\tilde{\psi}_{p,mn}$ on $\psi_{p,nm}$ is unstable a reconnection will occur

$$\psi_p = \bar{\psi}_p + \tilde{\psi}_{p,mn} \cos(n\varphi - m\theta)$$



magnetic reconnection
 forms an n/m island,
 which mixes plasma
 over its width



around $\psi_{p,nm}$ pressure will be flattened: $\vec{\nabla}_p = 0 \rightarrow \boxed{\vec{j} \wedge \vec{B} = \vec{\nabla}_p = 0} :$

$$\vec{\nabla}_p(\psi_{p,nm}) = 0 \rightarrow \vec{j} = (\mu(\psi_{p,nm}) / \mu_0) \vec{B}$$

MHD equilibrium

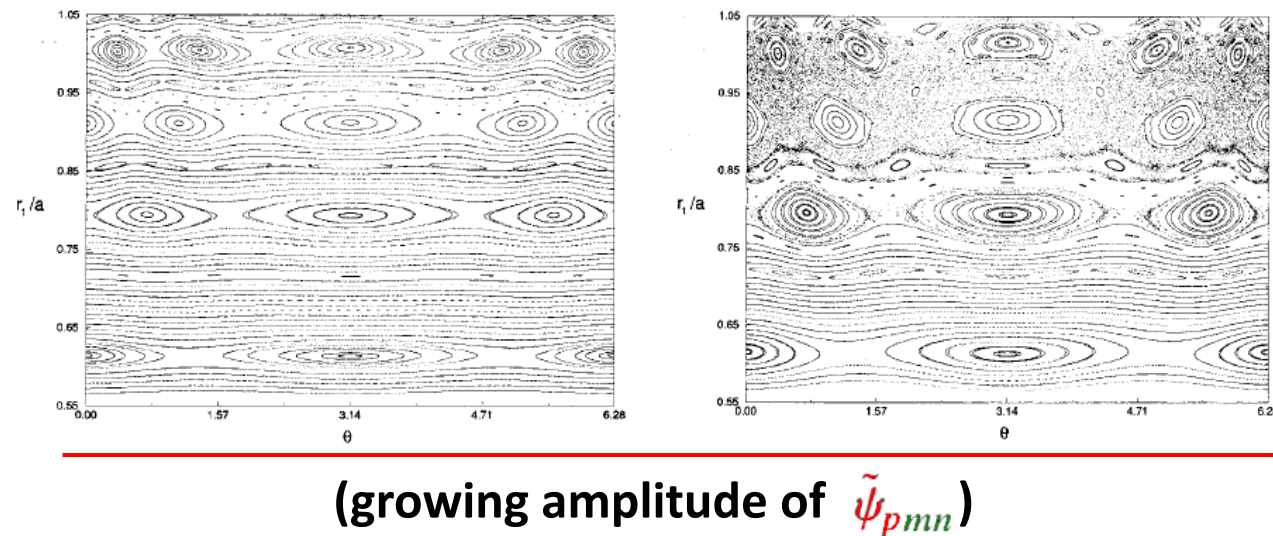
a **in-homogeneous** (or non-linear) **force-free magnetic field**, with $\mu = \mu(\psi_p)$,

is achieved locally: $\vec{\nabla} \wedge \vec{B} = \mu(\psi_p) \vec{B}$

Magnetic Reconnections and homogeneous *ffmf*

in presence of multiple (m,n) helicity **unstable perturbations**: $\psi_p = \bar{\psi}_p + \sum_{mn} (\tilde{\psi}_p)_{mn} \cos(n\varphi - m\theta)$
where many B-line close after m times toroidally, n times poloidally chaotic **B** is produced
Chirikov criterion: half-widths of island overlap $\rightarrow$ **onset of chaos**

Poincaré plots



If too many flux surfaces reconnect across the cross section, the whole plasma will become a **homogeneous *ffmf***: $\vec{\nabla} \wedge \vec{B} = \mu \vec{B}$ with $\mu = \text{constant}$ everywhere (aka a **completely relaxed state**)

Certainly field ergodicity $\rightarrow$ plasma relaxation

...but (hopefully) plasma relaxation $\nrightarrow$ field ergodicity

Homogeneous *ffmf* are linear as well (often analytical): Chandrasekhar-Kendall-Furth

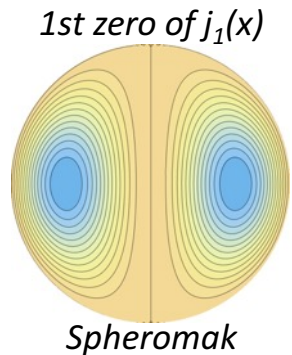
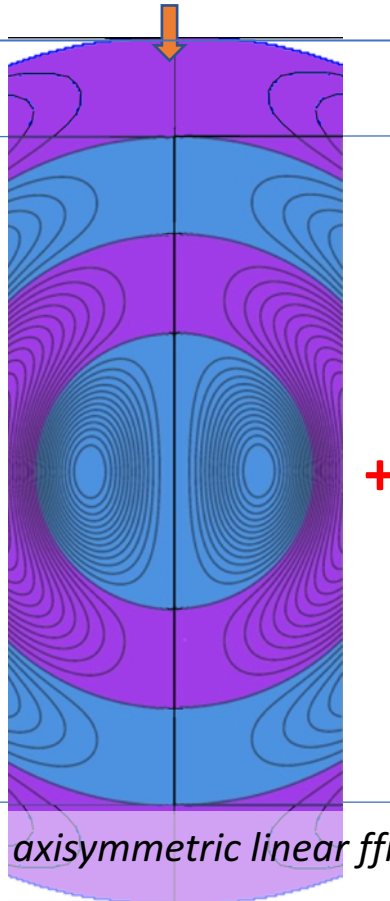
homogeneous *ffmf*, with $\mu = \mu_0 \vec{j} \cdot \vec{B} / B^2 = \text{constant everywhere}$, are called also **linear *ffmf*** as they are a **linear space**: linear *ffmf* with same μ can be summed to give another *ffmf*

Chandrasekhar-Kendall even *ffmf* model a torus

Chandrasekhar 1957 *ApJ* 126

$$\psi_{\mu}^{CK, \text{even}}(R, Z) = -\mu R j_1(\mu \sqrt{R^2 + Z^2}) P_1^1(Z / \sqrt{R^2 + Z^2})$$

$\mu = x_{1,4} = 14.066$ 1
4th zero of $j_1(x)$
 $x_{1,3}/x_{1,4} = 0.775$

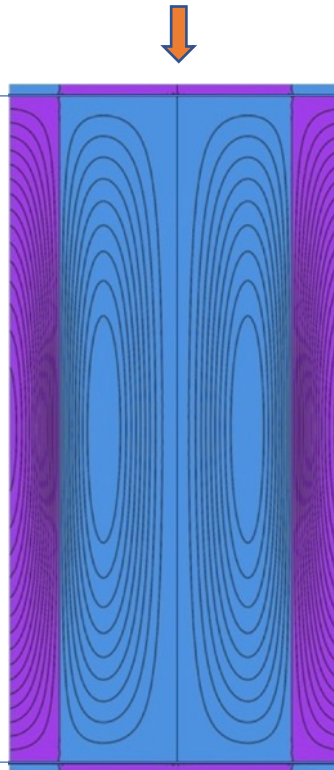


$\lambda = 2.0263$, so that at
 $R=0, Z=x_{1,3}/x_{1,4}=0.775$
the zeroes of $\psi_{\mu\lambda}^{F, \text{even}}$
and of $\psi_{\mu}^{CK, \text{even}}$ coincide

Furth even squared *ffmf* toroids model a jet

for any value of $\lambda < \mu$ Furth 1957 *Rev.Sci.Instrum.* 28

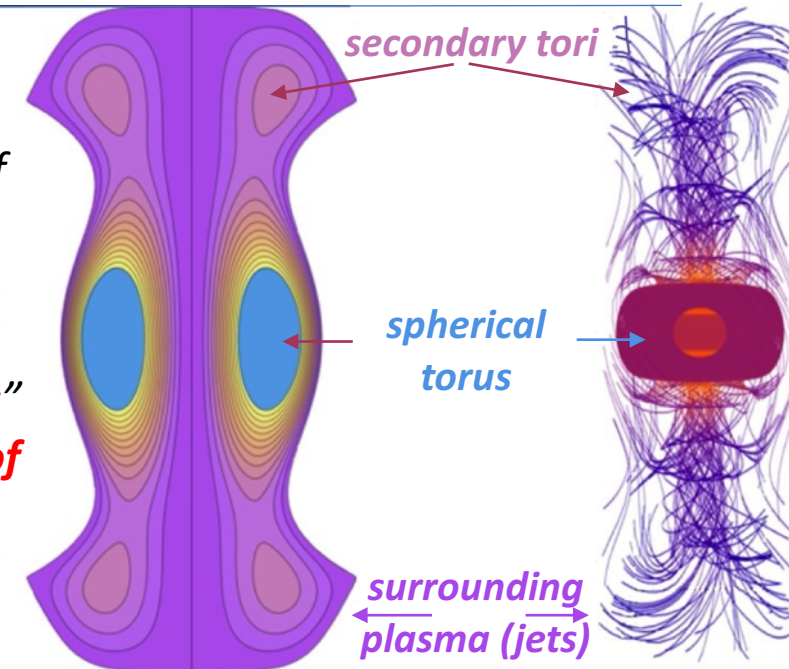
$$\psi_{\mu\lambda}^{F, \text{even}}(R, Z) = \gamma \sqrt{\mu^2 - \lambda^2} R J_1(\sqrt{\mu^2 - \lambda^2} R) \cos(\lambda Z)$$



linear *ffmf* (CKF) model torus+jet

Chandrasekhar-Kendall-Furth

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



summing same- μ *ffmf*
“**number of zeroes**”
rules allow to obtain
= “**simply connected-
closed configurations**”
with **same direction of**
 j_{ϕ} & B_{ϕ} (say >0)

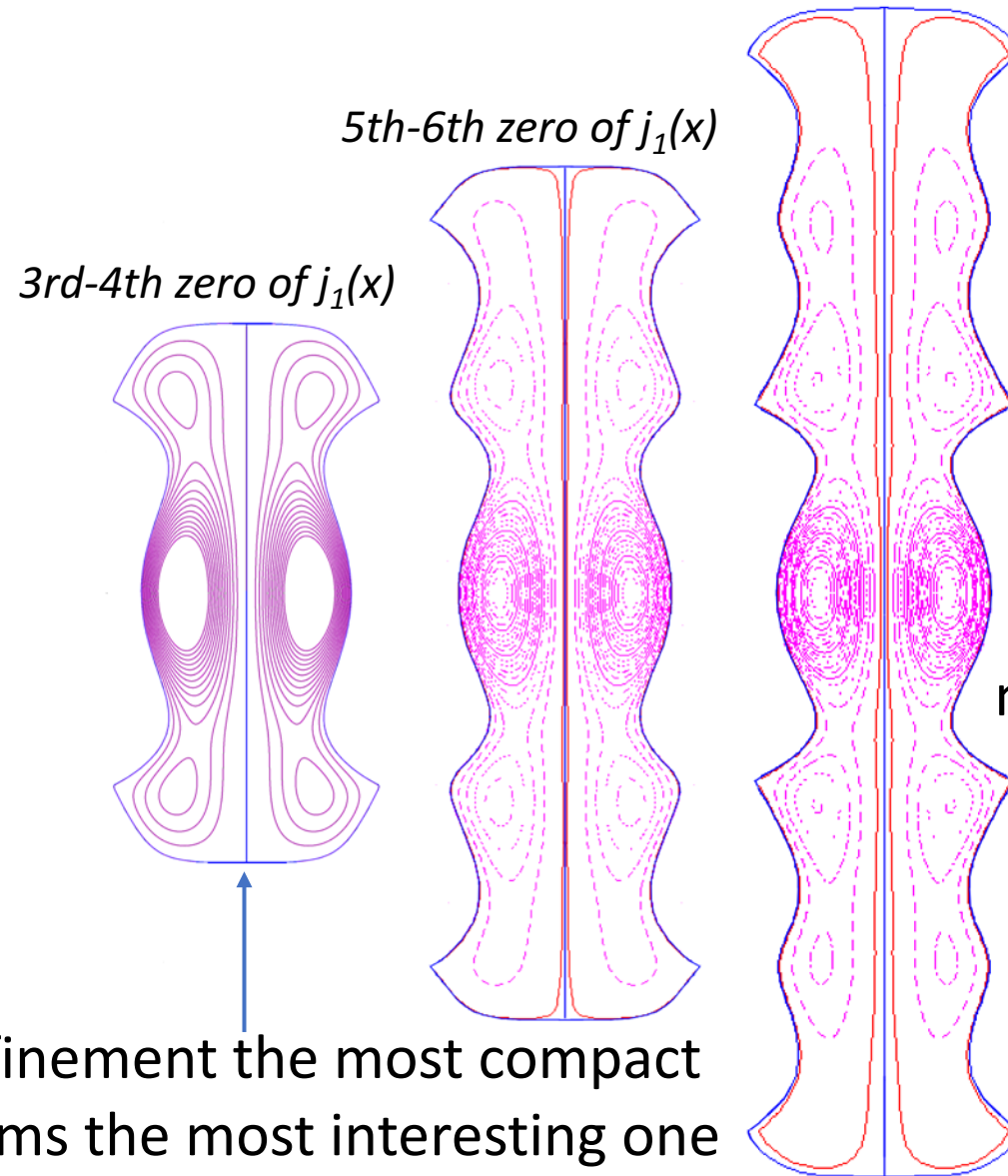
axisymmetric linear *ffmf* shown as cross sections of magnetic flux surfaces

by flux surfaces

by field line tracing

CKF as a variety of different elongation of jets with respect to torus diameter

shown as cross sections of magnetic flux surfaces 7th-8th zero of $j_1(x)$

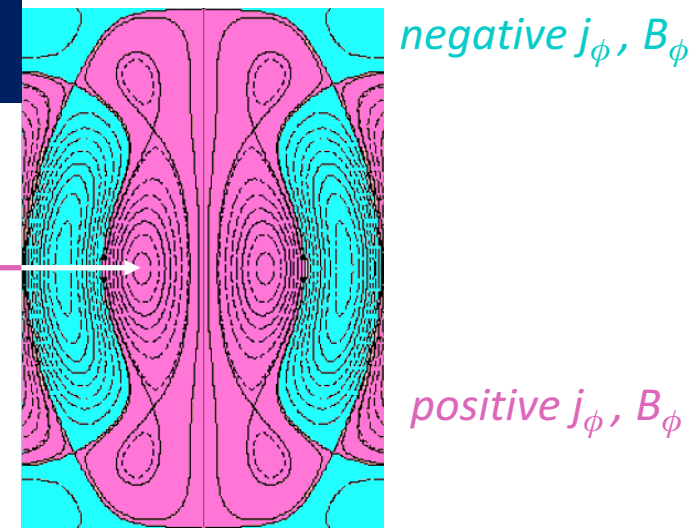


choosing odd-even zeroes in increasing sequence: 3rd-4th, 5th-6th, 7th-8th, ... more & more extended jets are obtained

for magnetic confinement the most compact configuration seems the most interesting one

Ideal MHD stability of Chandrasekhar-Kendall-Furth *ffmf*

CKF *ffmf*s are non-localized equilibria: plasma regions with both signs of j_ϕ & B_ϕ extend to the whole 3D space beyond closed configuration

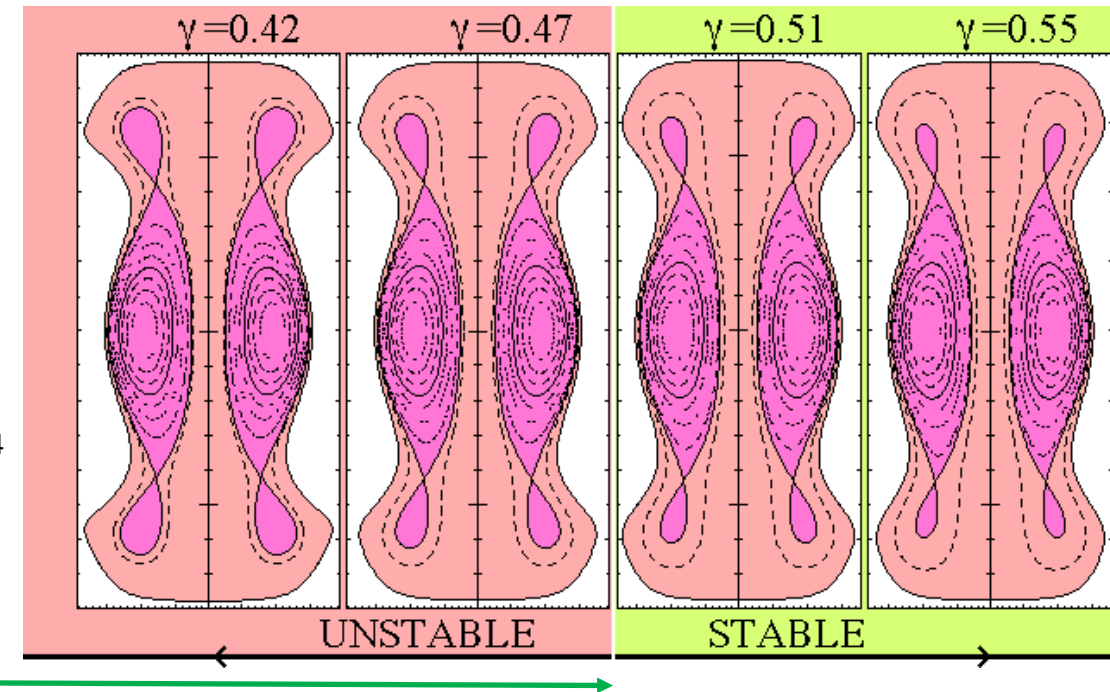


MHD equilibrium with $\vec{\nabla} p = 0$ all over the plasma exists due to unlimited set of alternating $j_\phi, B_\phi > 0, j_\phi, B_\phi < 0$

Ideal (plasma & field move together) MHD stability of the CKF *ffmf* studied solving* the eigenvalue problem $\vec{W} \cdot \vec{\xi} = \omega^2 \vec{K} \cdot \vec{\xi}$, where $\vec{W}$ is the plasma perturbed potential energy and $\vec{K}$ is the plasma perturbed kinetic energy, associated to perturbed plasma displacement $\vec{\xi}$

code was home-produced *Micozzi P 2010 Nucl. Fusion 50 095004

Stability depends upon superposition parameter γ
torus is stable if jet is "strong enough": $\gamma > 0.5$



Ideal MHD stability of CKF *ffmf* studied in **fixed boundary only**: $\xi_{\perp, edge} = 0$, as their free-boundary ideal MHD stability is meaningless: they do not exist as localized equilibria

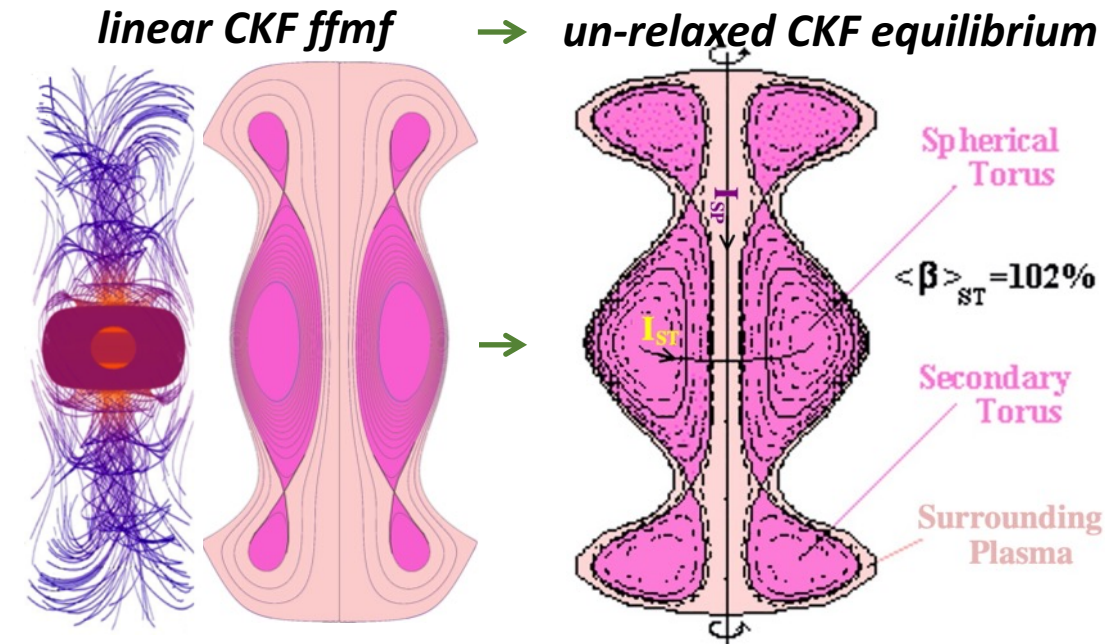
torus + jet CKF *ffmf* can be filled-up with pressure, up to $\beta \geq 1$ *

*Rogier F 2003 AIP Conference Proceedings 669

β = plasma pressure/magnetic pressure

CKF *ffmf* can be filled up with plasma pressure, keeping features such as ideal MHD stability, yielding un-relaxed equilibria*: $\vec{\nabla} p \neq 0, \vec{j} \wedge \vec{B} \neq 0$ if ratio of currents $I_{ST}/I_{SP} < 4$ (jets strong enough)
 β limit > 1 in free-boundary conditions $\vec{\xi}_{edge} \neq 0$
free perturbed plasma displacement everywhere
($\beta \sim$ few % for other confinement schemes)

still home-made code *Alladio F 1997 Nucl. Fus. 37 1759

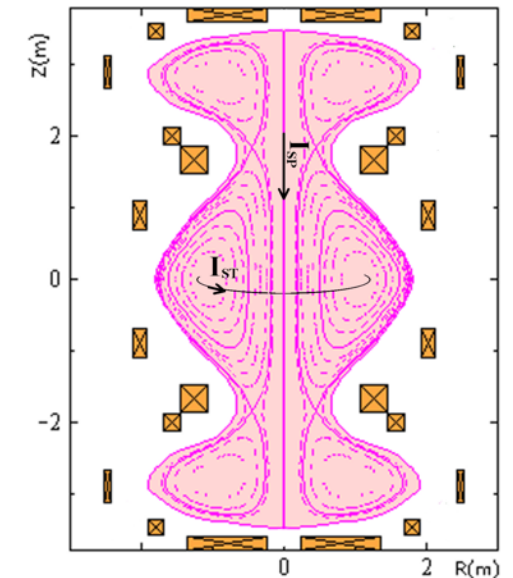


In the case of "localized configurations"

Virial Theorem requires **Gravity** or **External Coils** for containment

un-relaxed CKF equilibria are localized:
ideal MHD stability must so be studied
in free-boundary conditions: $\vec{\xi}_{edge} \neq 0$

contained by **Compressing External Coils**, whose total current is $\sim I_{ST}$ total toroidal current flowing in the main spherical torus

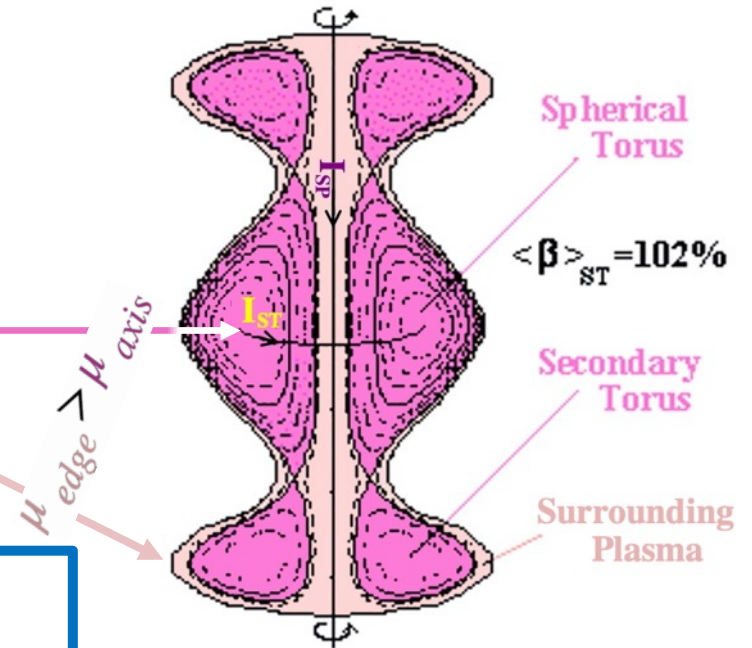


un-relaxed CKF and flow of Magnetic Helicity

In un-relaxed CKF equilibria μ value not anymore constant on flux surfaces, but surface averaged value $\langle \mu \rangle = \mu_0 \langle \vec{j} \cdot \vec{B} / B^2 \rangle$ still relevant:

diffusion toward the axis of the torus $\psi = \psi_{axis}$
of the helicity injected from the boundary $\psi = \psi_{edge} = 0$

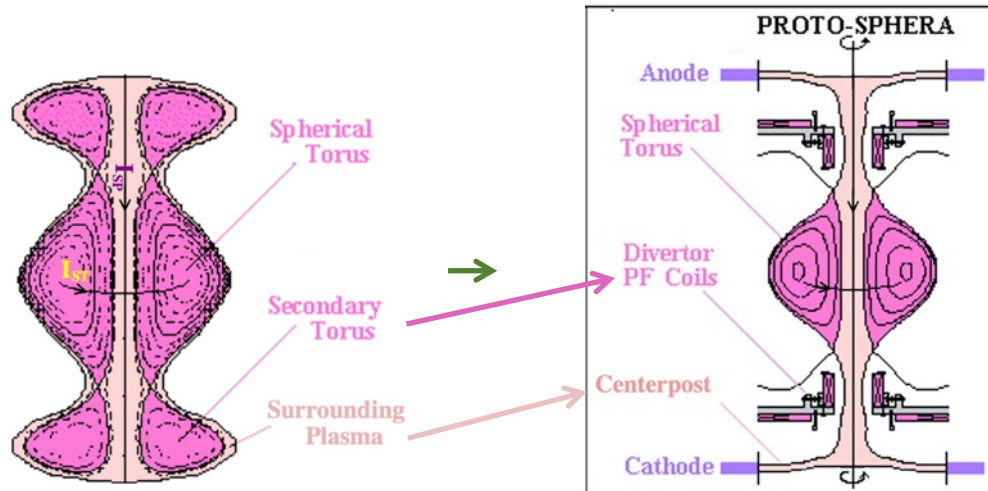
the ratio between the change of magnetic energy ΔW and of Helicity ΔK in a relaxed state: $d(\Delta W) / d(\Delta K) = \mu / 2\mu_0$
shows that **Helicity flows from higher to lower μ values: $\mu_{edge} > \mu_{axis}$**



as dimensionally $\mu [L^{-1}]$ Helicity (relaxation parameter) flows from **smaller** to **larger** scales
(an example of inverse cascade)

Helicity has the capability of forming large magnetic structure in nature...

Torus + Jet CKF *ffmf* are the model for PROTO-SPHERA with open field lines



How to create a *CKF ffmf* in laboratory?

How to set up Secondary Torus & Surrounding Plasma?

→ Substitute the *Secondary Torus* with *Divertor PF Coils*

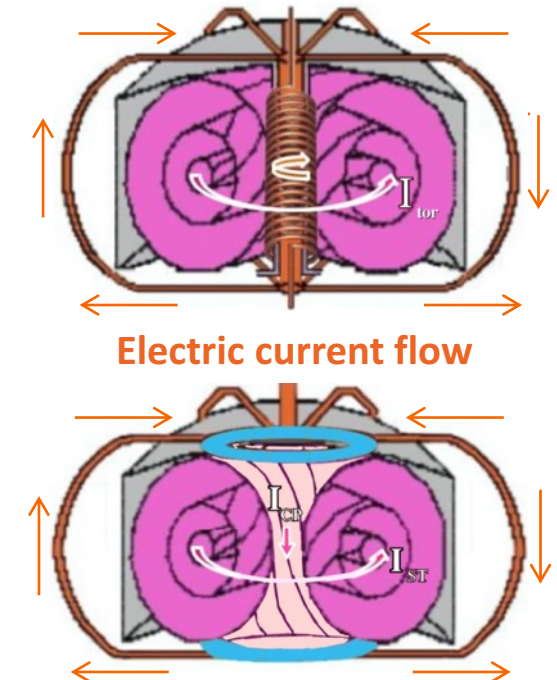
→ Cut short the *Surrounding Plasma* into a *Centerpost Plasma* impinging on *annular electrodes: anode on top, cathode on bottom*

Relation of PROTO-SPHERA to Tokamaks

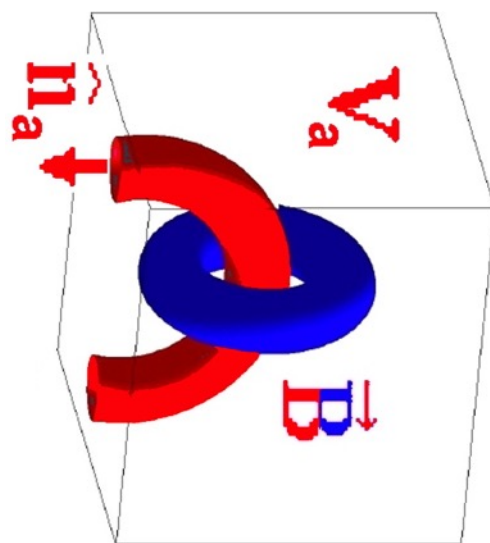
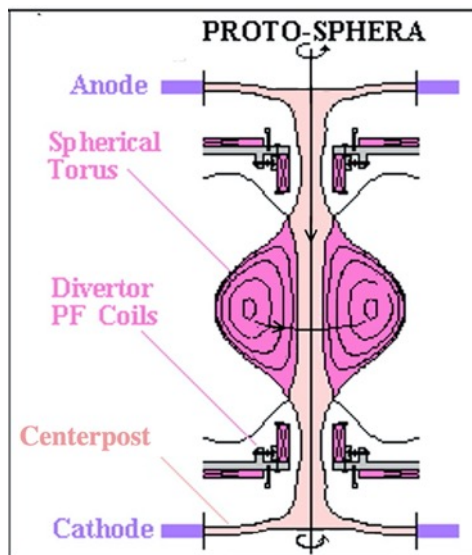
Tokamak: *toroidal plasma* I_{tor} surrounds a “*Metal Centerpost*”
vacuum vessel has a complex toroidal geometry

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}

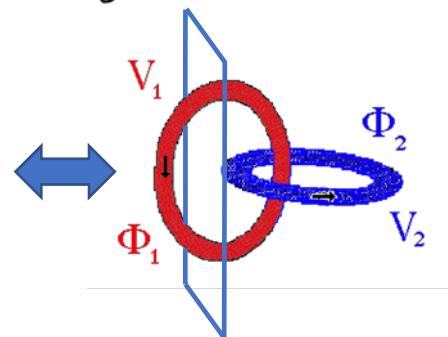


PROTO-SPHERA: on open field lines Helicity & relaxation parameter still rule



With open field lines, ending on electrodes

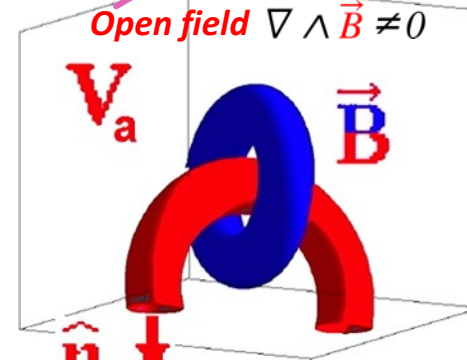
$$K = \int \vec{A} \cdot \vec{B} dV \text{ not any more invariant to gauge transf.: } \vec{A}' = \vec{A} + \vec{\nabla} \chi$$



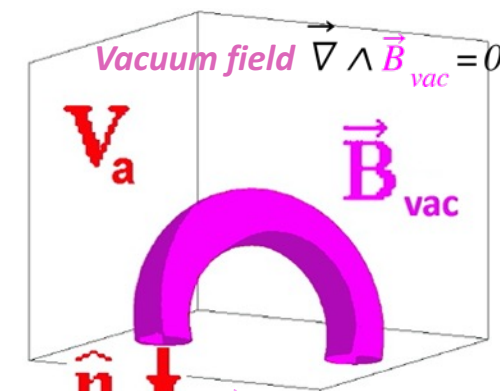
Relative Magnetic Helicity ΔK replaces K introducing an open vacuum field $\vec{B}_{vac}$ with same boundary conditions

$$\Delta K = \int_{V_a} (\vec{A} + \vec{A}_{vac}) \cdot (\vec{B} - \vec{B}_{vac}) dV$$

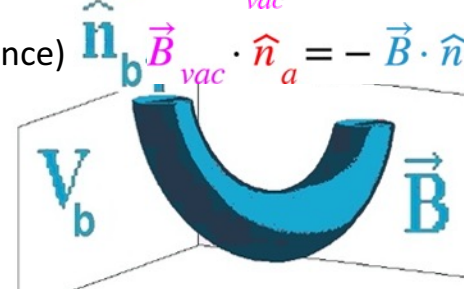
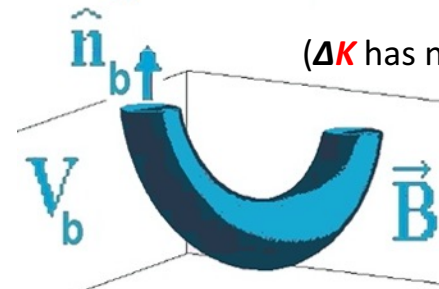
Closed field $\vec{\nabla} \wedge \vec{B} \neq 0$
Open field $\vec{\nabla} \wedge \vec{B} = 0$



ΔK



(ΔK has no V_b dependence)



$\vec{B}_{vac}$ has zero Helicity

$$\vec{B}_{vac} \cdot \hat{n}_a = -\vec{B} \cdot \hat{n}_b$$

DC Helicity injection: a steady state replacement of transient Ohmic drive

Helicity source (Centerpost Plasma) & Helicity sink (Spherical Torus)

a gradient in the relaxation parameter $\vec{\nabla}_\mu = \mu_0 \vec{\nabla}(\vec{j} \cdot \vec{B}/B^2)$ appears

Helicity flow from **larger μ** to **smaller μ** regions
through Magnetic Reconnection on the X points
converting part of the magnetic energy into kinetic plasma energy

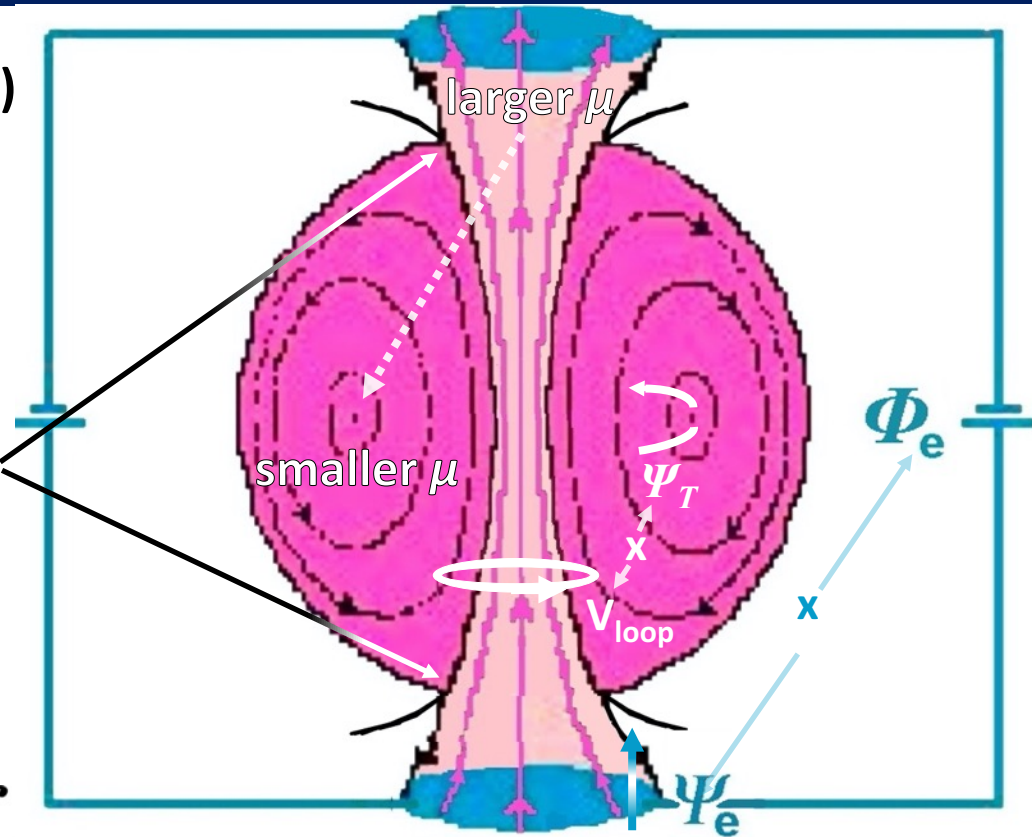
injection of magnetic helicity in an open domain, ($\hat{n}$ outwards)

$$d(\Delta \mathbf{K}) / dt = 2 \int \Phi_e (\vec{B} \cdot \hat{n}) dS - 2 \int (\vec{A} \wedge \partial \vec{A} / \partial t \cdot \hat{n}) dS - 2 \int (E \cdot B) dV$$

- $2 \int \Phi_e (\vec{B} \cdot \hat{n}) dS$ = DC Helicity injection : $2\Phi_e \Psi_e$ (Φ_e poloidal voltage; Ψ_e poloidal flux)

- $-2 \int (\vec{A} \wedge \partial \vec{A} / \partial t \cdot \hat{n}) dS =$ **AC Helicity injection = Ohmic drive** : $2V_{loop}\Psi_T$ (V_{loop} toroidal voltage; Ψ_T toroidal flux)

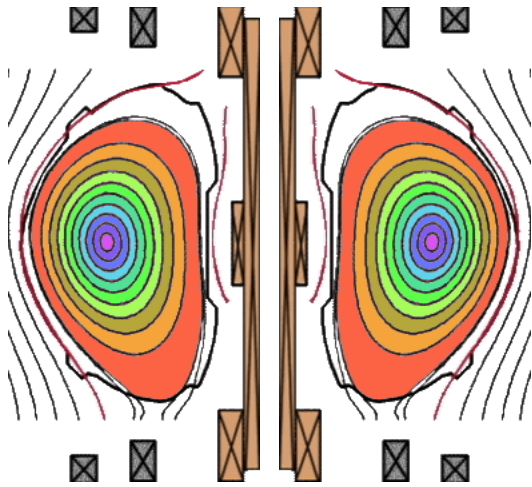
- $-2 \int (\vec{E} \cdot \vec{B}) dV$ = **total Helicity dissipation**



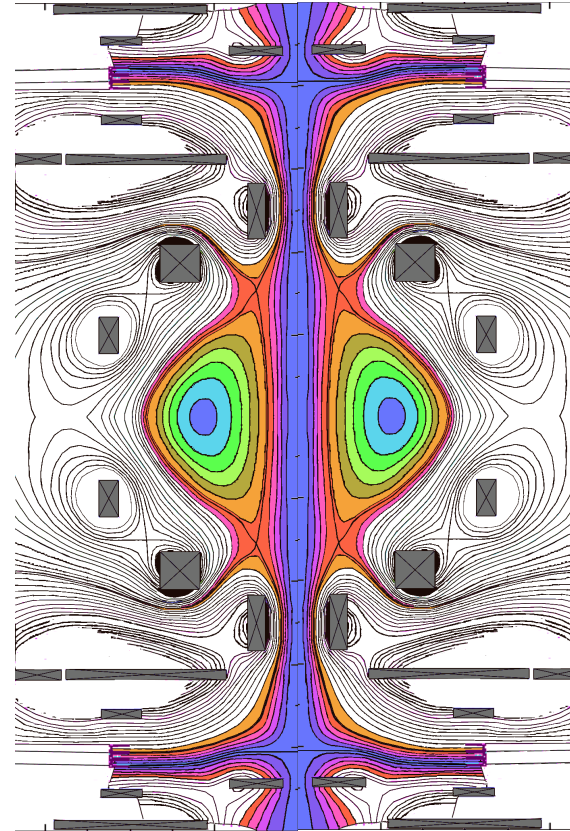
Magnetic reconnections provide: formation, sustainment and heating

PROTO-SPHERA: DC Helicity drive by magnetic reconnections, the price is payed by **DC voltage between electrodes**, sustainment is steady-state

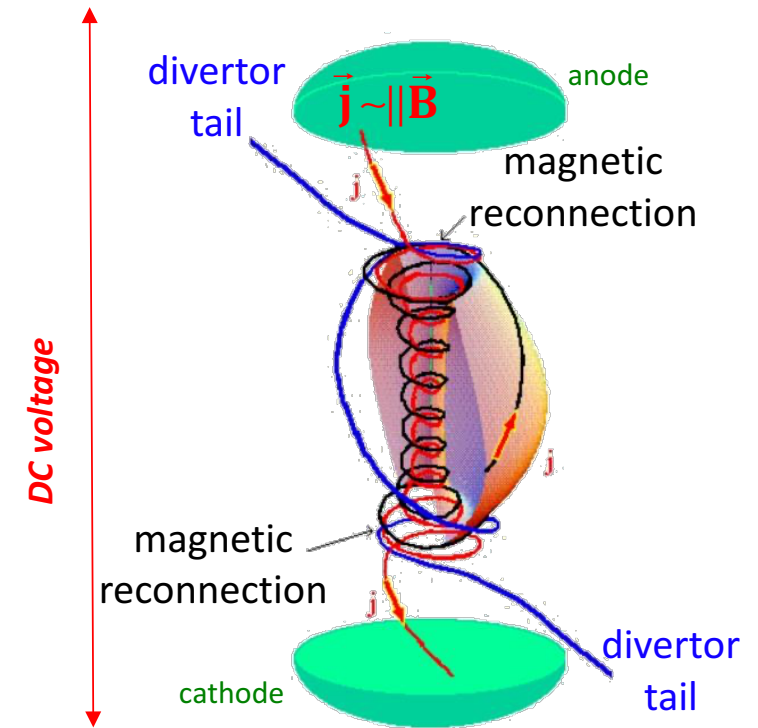
Tokamak: induction drive by **central solenoid**
the price is payed by **current variation**
sustaiment of torus is transient



flux surfaces enter from the central solenoid
into the torus & are dissipated inside it

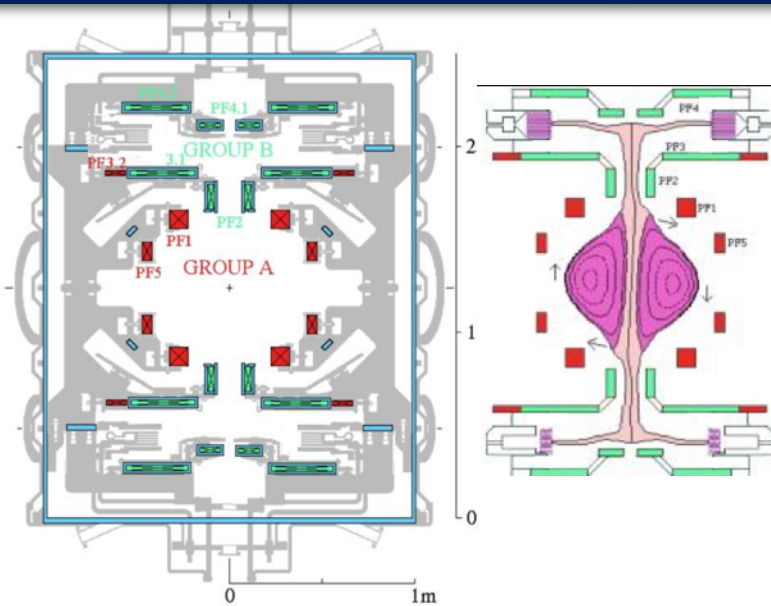


flux surfaces enter from the centerpost plasma into the Torus & are
dissipated inside it; other flux surfaces are **expelled into the divertor tails**



try and unify into a single machine all requirements for magnetic confinement: formation, sustainment & heating

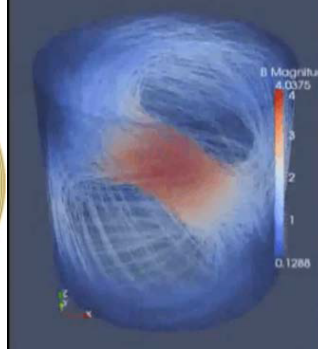
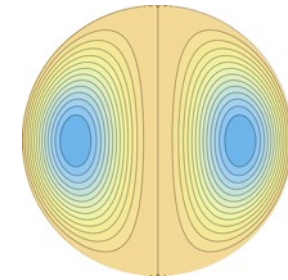
Ideal MHD stability of PROTO-SPHERA not far from CKF



Spheromak tilt instability: toroidal dipole of vertical field overturns plasma current toroidal dipole

But PROTO-SPHERA dipoles:

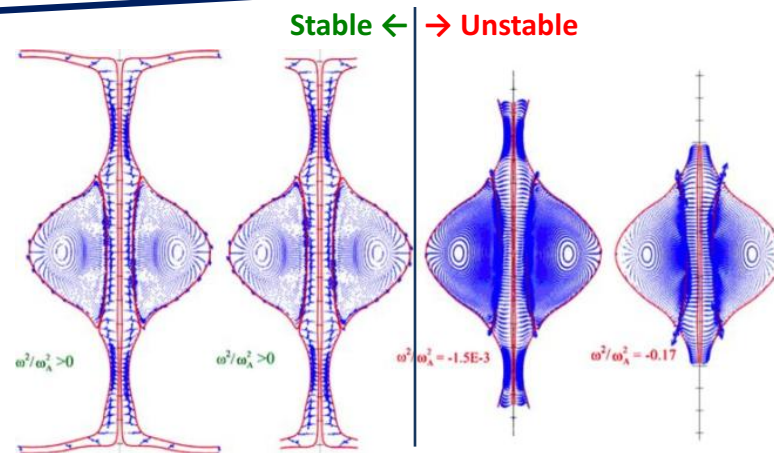
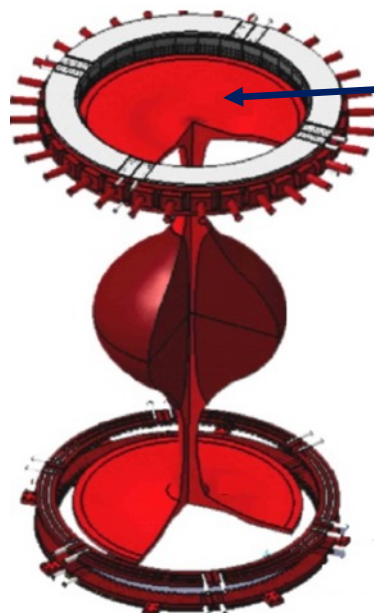
“Group A” PF compression coils against Plasma dipole
 “Group B” PF shaping coils aligned to Plasma dipole
 result: rigid tilt instability is stabilized without any stabilizing shell around the plasma (as Spheromaks do)



Spheromak tilt instability avoided by PROTO-SPHERA

The stability was confirmed by full Ideal MHD calculations*

*Micozzi P Nucl. Fusion 50 (2010)



Ideal MHD stability calculations

MUSHROOM-SHAPED PLASMA FACING ANNULAR ELECTRODES PROVIDES IDEAL MHD STABILITY

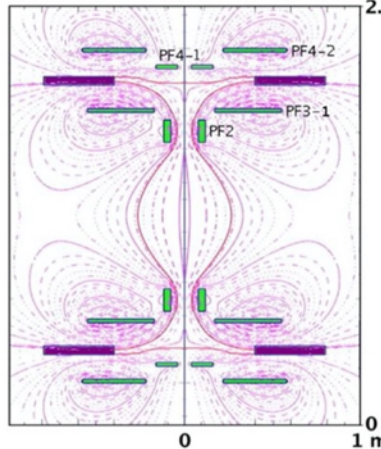
(cutting shorter & shorter the Plasma Centerpost destabilizes the configuration)

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

2015 to 2018 Phase-1 successful: $I_{CP}=10$ kA (max of power supply), 1 sec plasma limited diagnostics: magnetics, 2-color interferometer, fast camera

Centerpost Plasma duration: 1 sec

Phase-1: 8 PF-B coils



Argon



Hydrogen

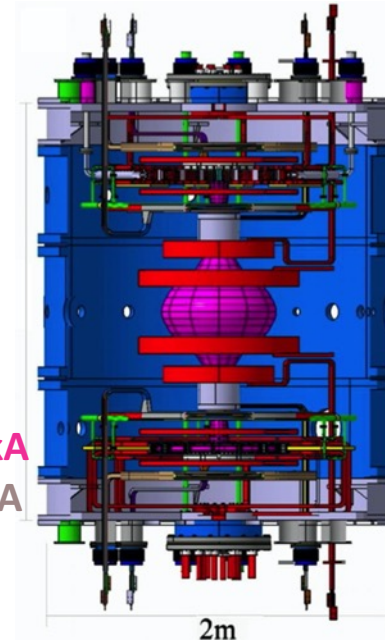


Future

Phase-2: 8 PF + 6 PF

Torus $I_{ST} = 280$ kA
Centerpost $I_{CP} = 70$ kA

Centerpost $I_{CP} = 10$ kA



2015 to 2019
Aluminum Vessel
of START (Culham)



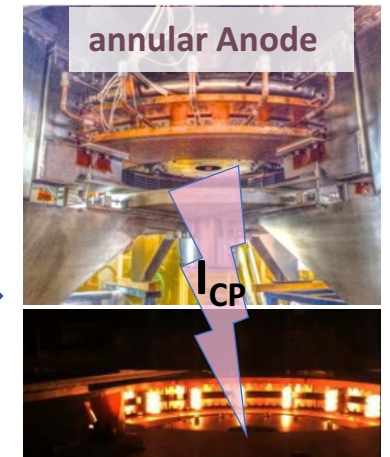
*easy access did
allow to eliminate
spurious plasma
paths step-by-step*

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

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

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

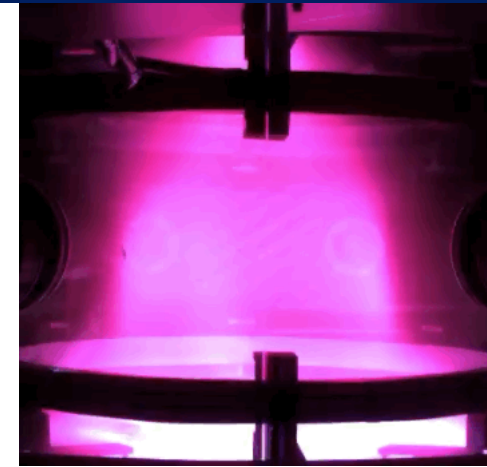
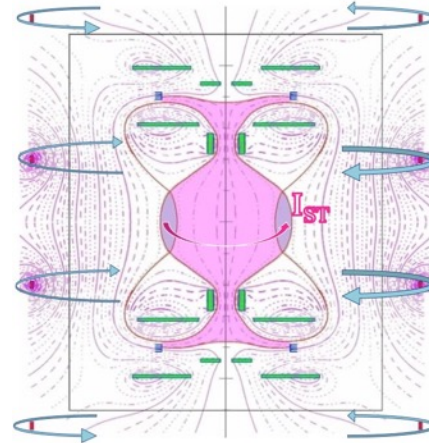
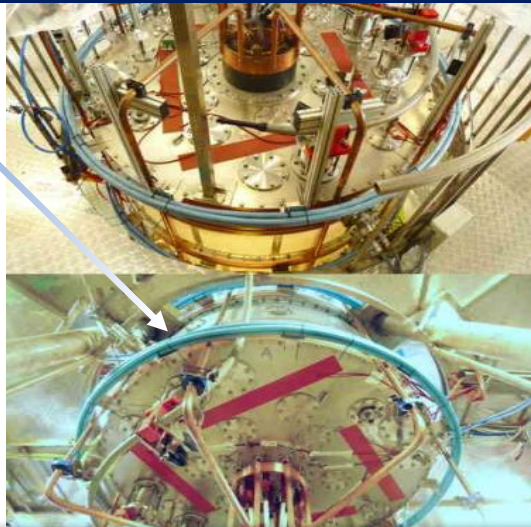
Anode-Cathode ΔV : 320 V at break-down,
~220 V at 10 kA flat-top



2900 °C hot Cathode

2018 the first tori ($I_{ST}=5\text{kA}$, with $I_{CP}=10\text{ kA}$) were immediately produced, as soon as External compression PF coils added & fed on equator with currents opposite to plasma ones

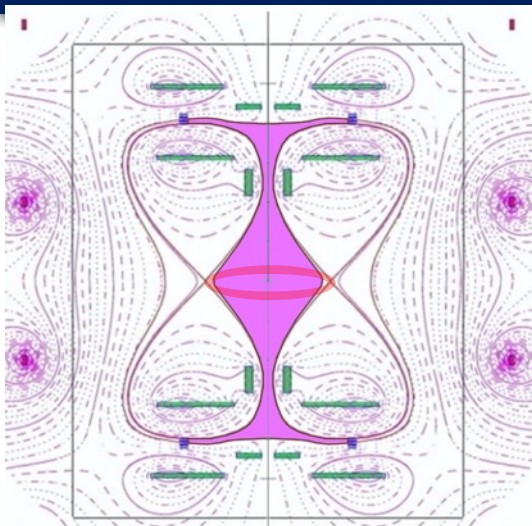
2018 still Aluminum Vessel, skin current delay: 0.6 s were lost



Hydrogen plasma

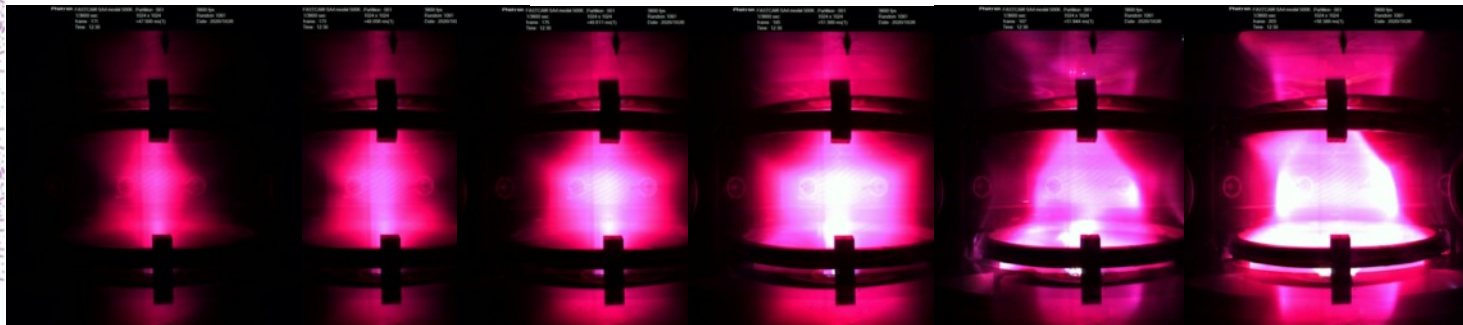
Ultrafast camera 3600 fps
1024x1024 pix

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

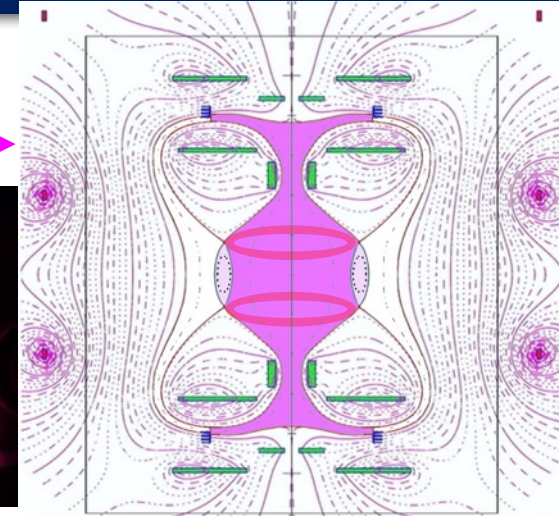


vacuum field ($\vec{j} = 0$) shows
single equatorial circle of null points

9 msec



Shot #1888 torus formation (Hydrogen)



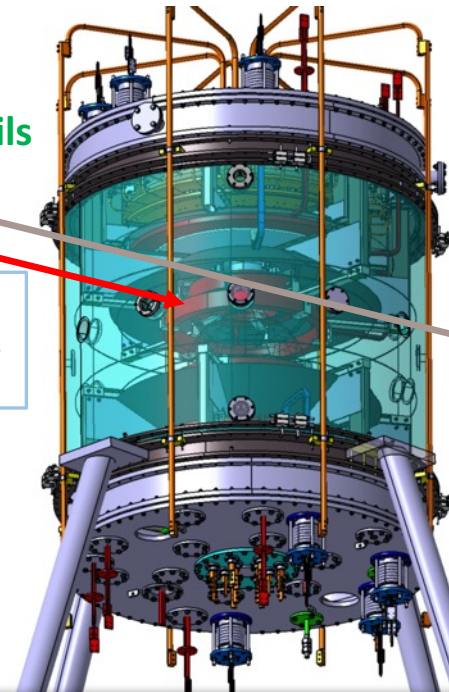
plasma field ($j_{tor} \neq 0$) shows
2 circles of null points out of equator

From 2019 Phase-1.5:
18 PF coils*; new insulating
& transparent vessel*;
new super-cap power supply*

*A Grosso, G Rocchi, A Sibio, P Micozzi, A Lampasi

Phase-1.5: 8 PF-B coils
+ 6 PF-A + 4 PFExt

transparent &
insulating PMMA
vacuum vessel



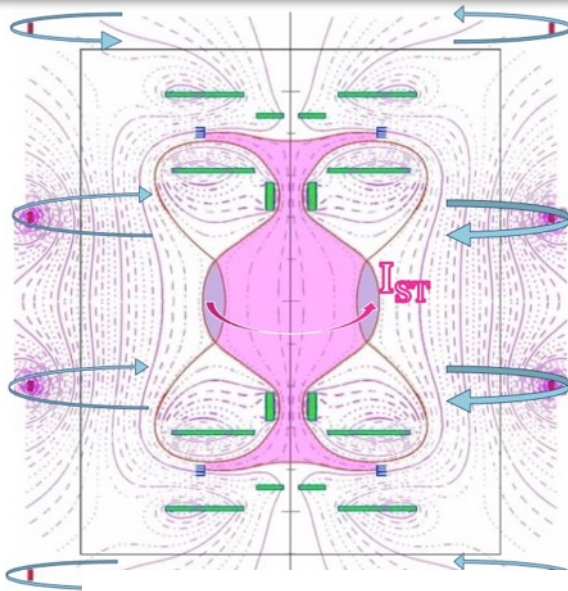
Centerpost $I_{CP} = 10$ kA
Torus $I_{ST} = 5$ kA



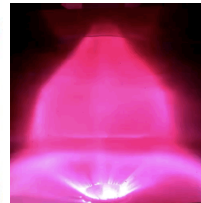
duration of plasma torus: 1 sec

remarkable Ideal MHD stability without any surrounding conducting shell

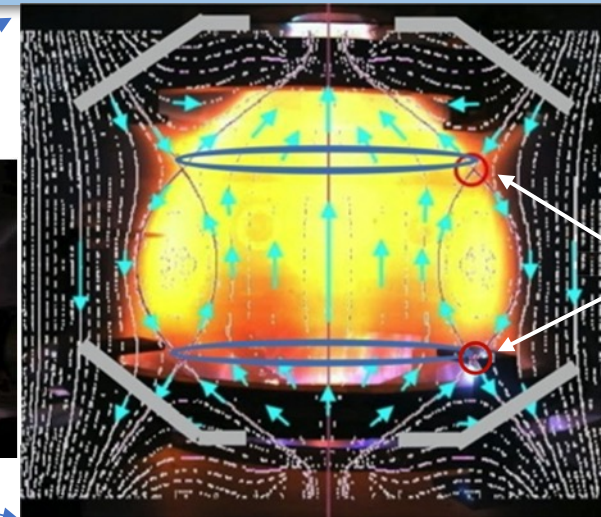
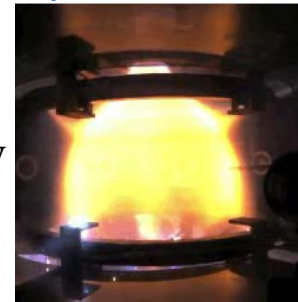
2018
2.5 MW



Ultrafast camera 3600 fps



2022
3.5 MW



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

Shot #2126 (Helium)

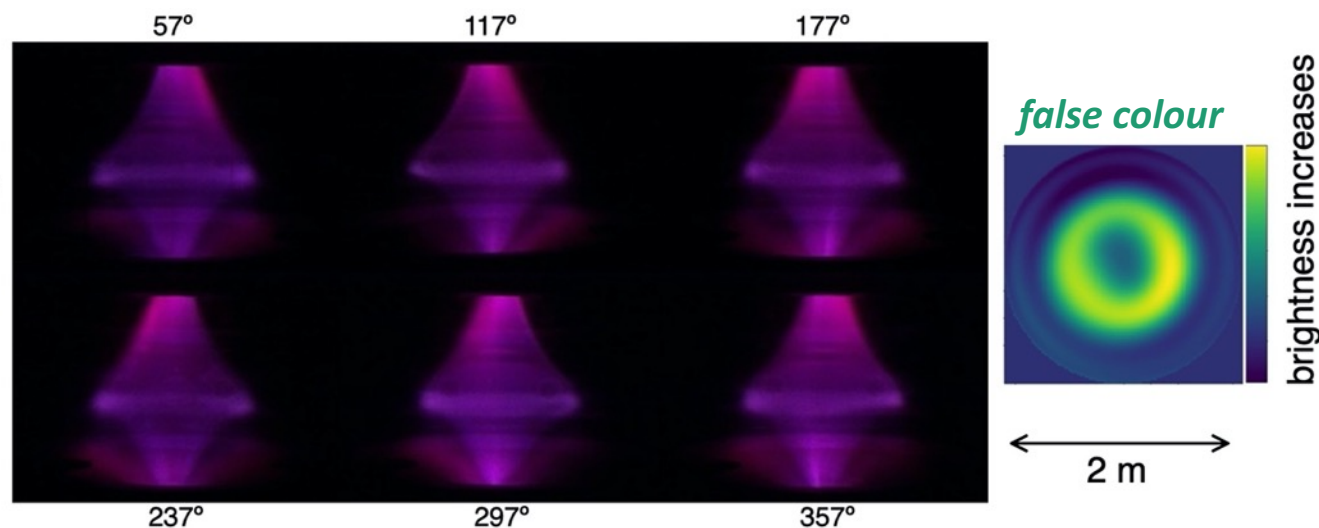
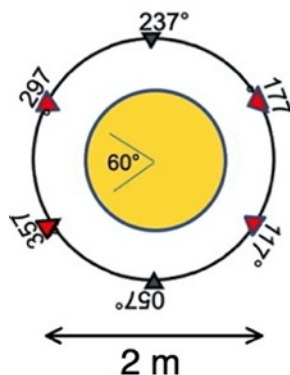
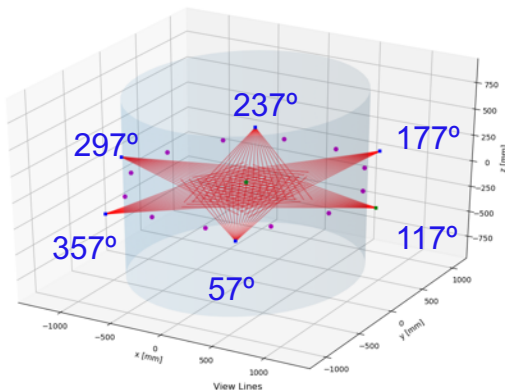
price for 5 kA plasma torus sustainment: Anode-Cathode ΔV increases by 20-30 Volts (on top of ~ 200 V)

2019 first visible light planar tomography* limited to equatorial plane

transparent vessel → visible light tomography

6 cameras, RGB, 600 fps, 640x480 pix

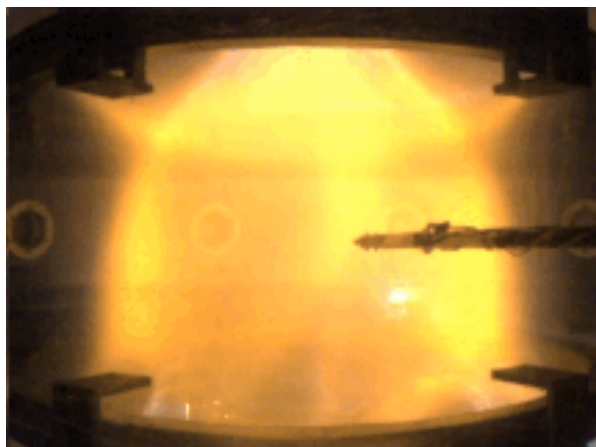
*L Boncagni,
Y Damizia,
M Iafrati



2023 beginning of 3D tomography* in visible light

*A Pau, S Naghinajad

camera view from 357°



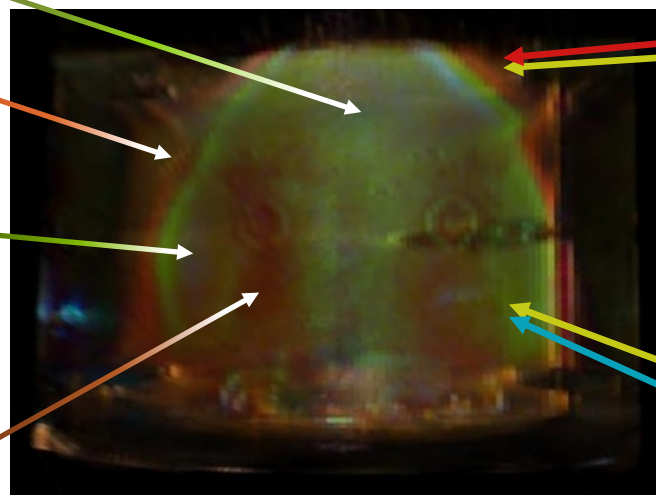
centerpost vertical tomographic section from 357°

outer edge (ionization)

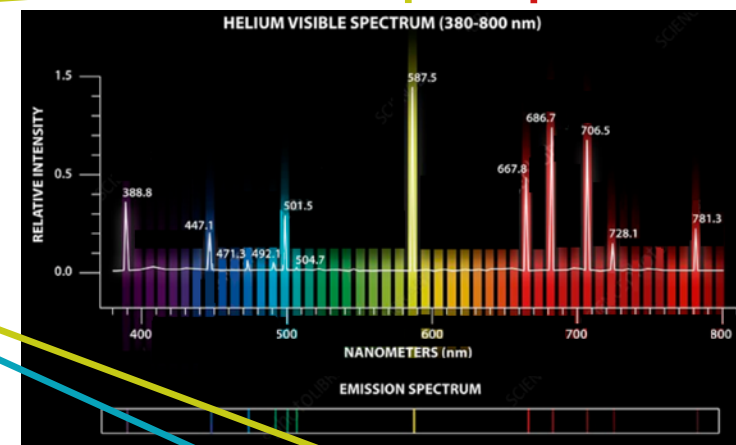
torus plasma

t= 159 msec

torus-centerpost gap



lower temperature

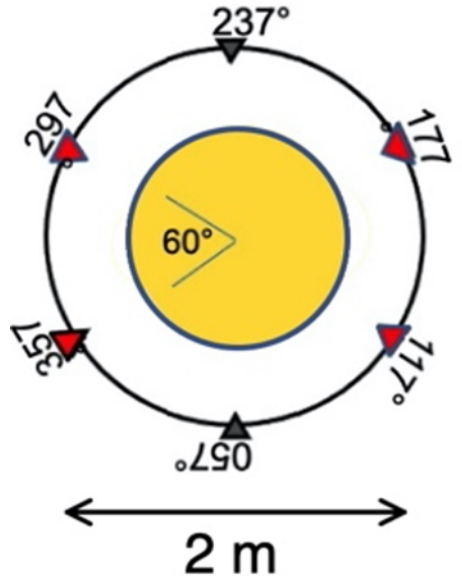
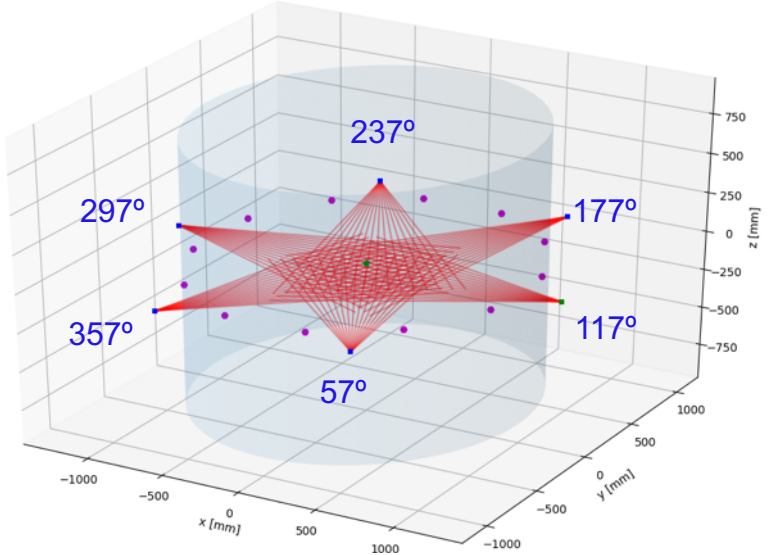


higher temperature

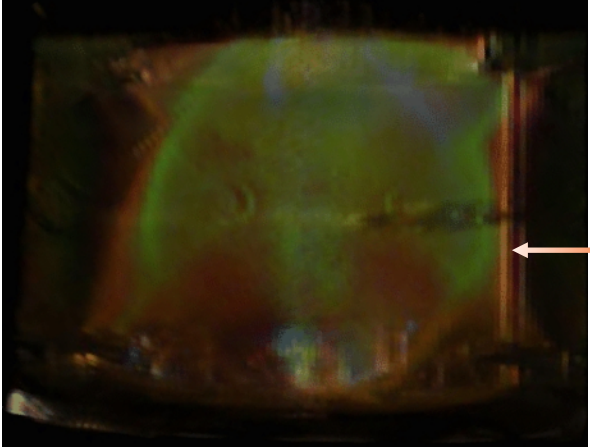
#2141, He, 297 msec total

surprise: PROTO-SPHERA Helium plasma is technicolor!

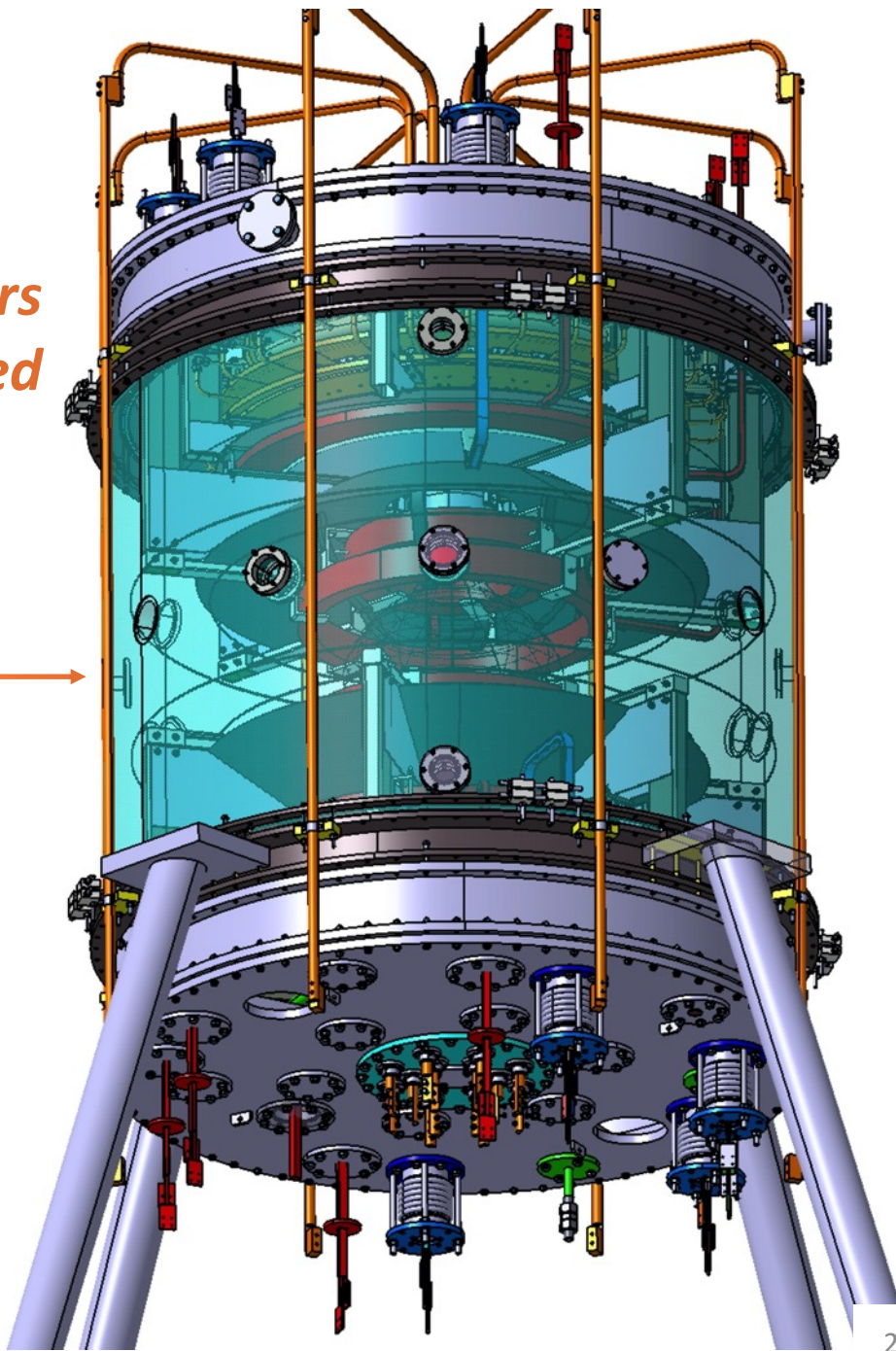
2023 3D tomography very accurate
in reconstructing non-plasma objects



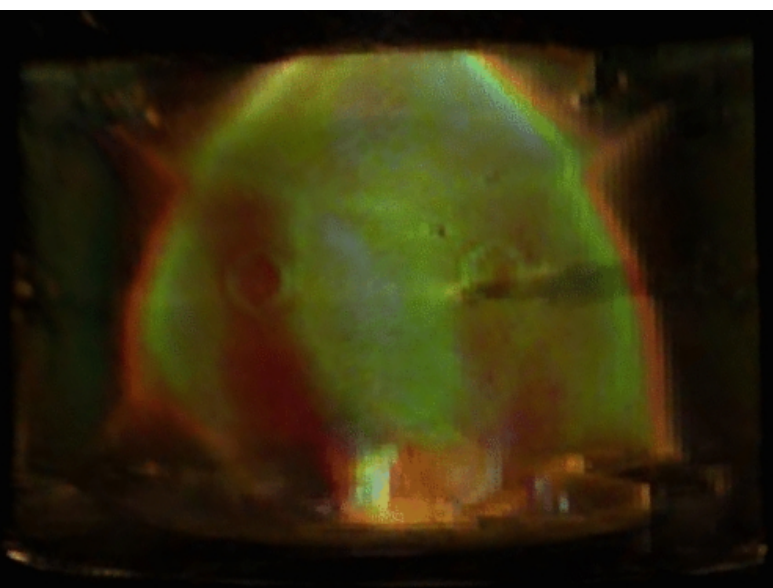
*3cm ø copper bars
are perfectly reconstructed*



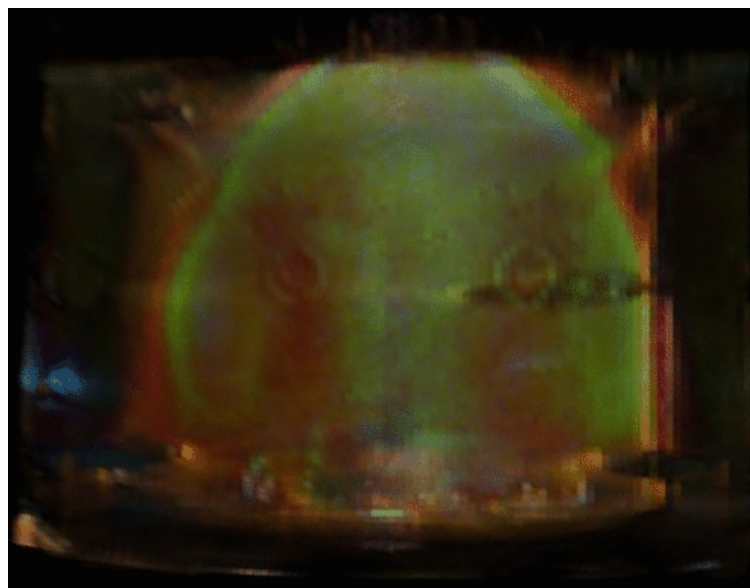
vertical tomographic section



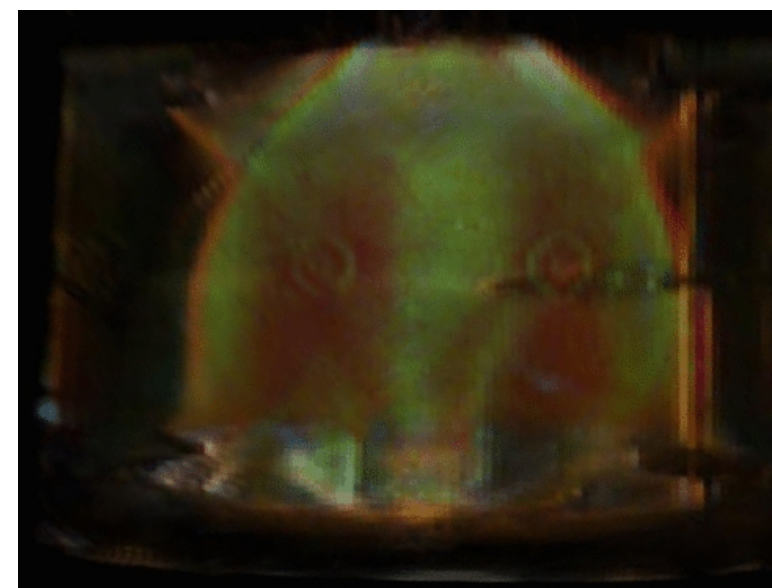
2023 - 3D tomography allows to steal a glance inside the plasma cross-sections



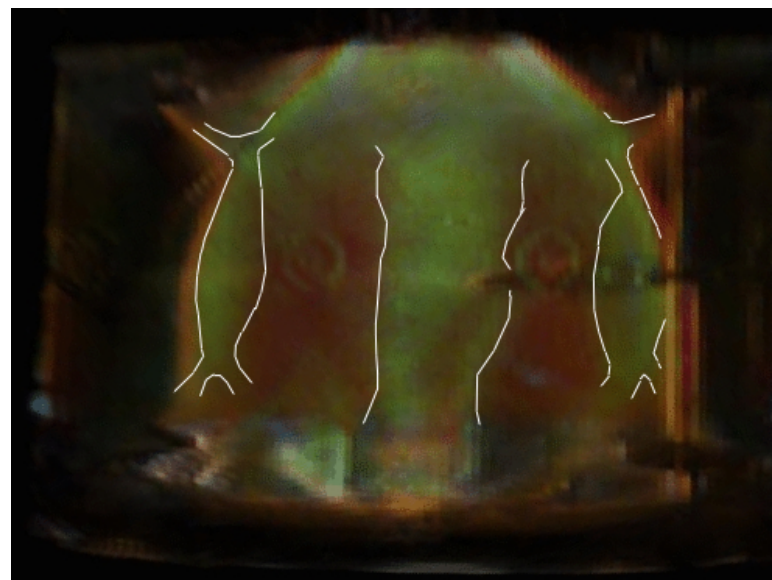
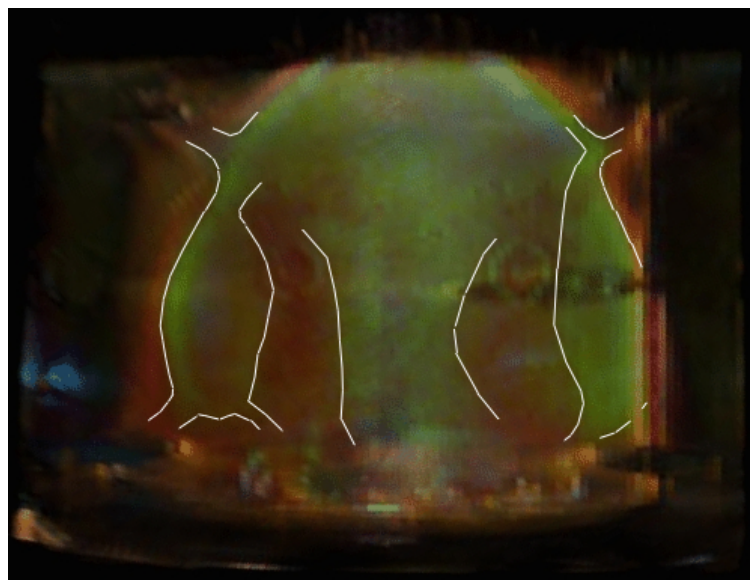
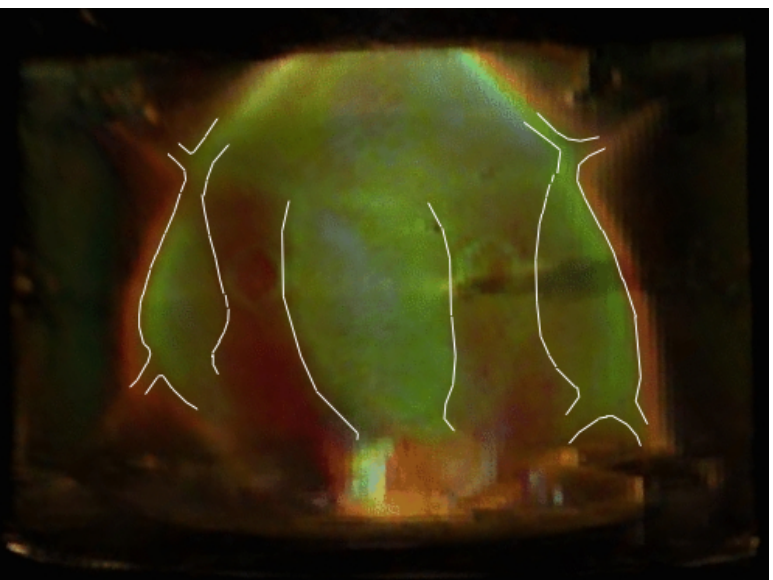
32 msec



159 msec



256 msec



it is possible to distinguish the torus inner edge as a transition from **higher** to **lower** temperature plasma

beginning of 3D tomography in visible light – 2022 – torus self-organization

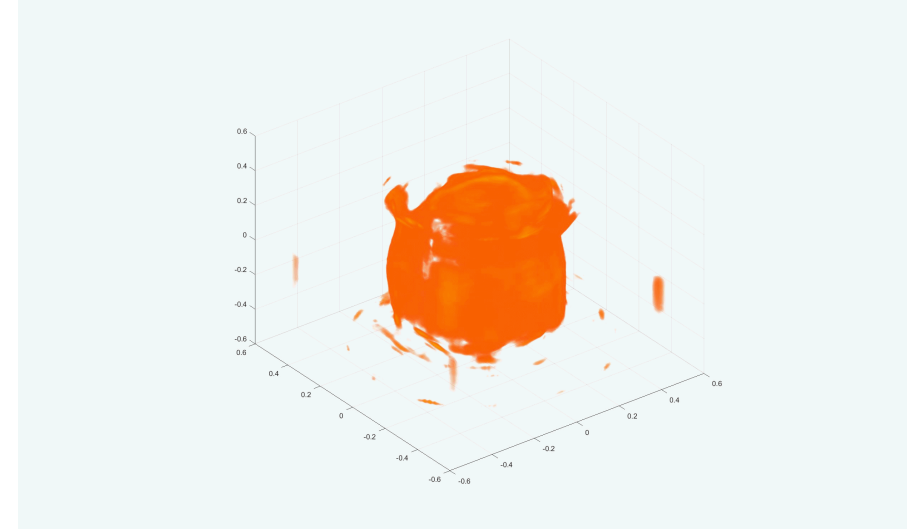
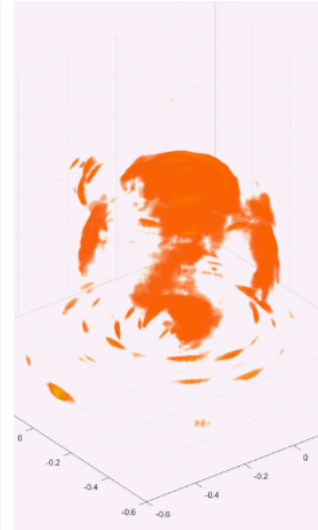
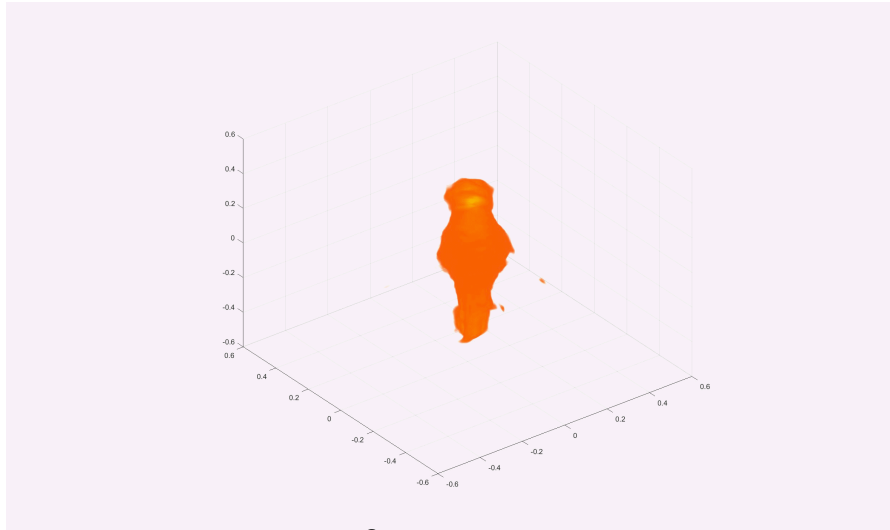
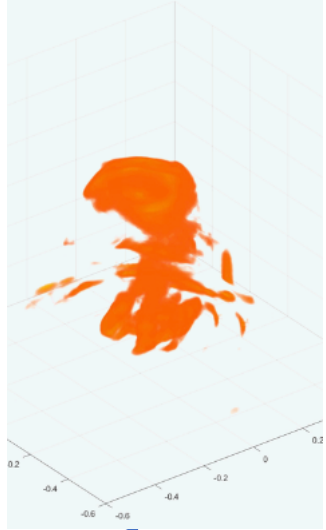
PROTO-SPHERA plasma torus forms in < 10 ms, while Plasma Centerpost current I_{CP} still grows - 3D tomography

a kinked centerpost

forms the torus

& a kinked state

lets the torus to be re-born

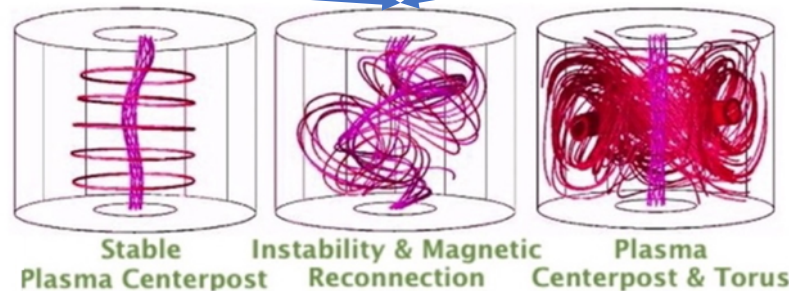


formation time < 10 msec

re-birth cycle < 10 msec

in accordance with scenario
computed by R. Farengo*

*Farengo R. 2014 *Phys. Plasmas* **21** 122511



torus after almost vanishing, is always re-born
undergoes serial relaxation changing its size

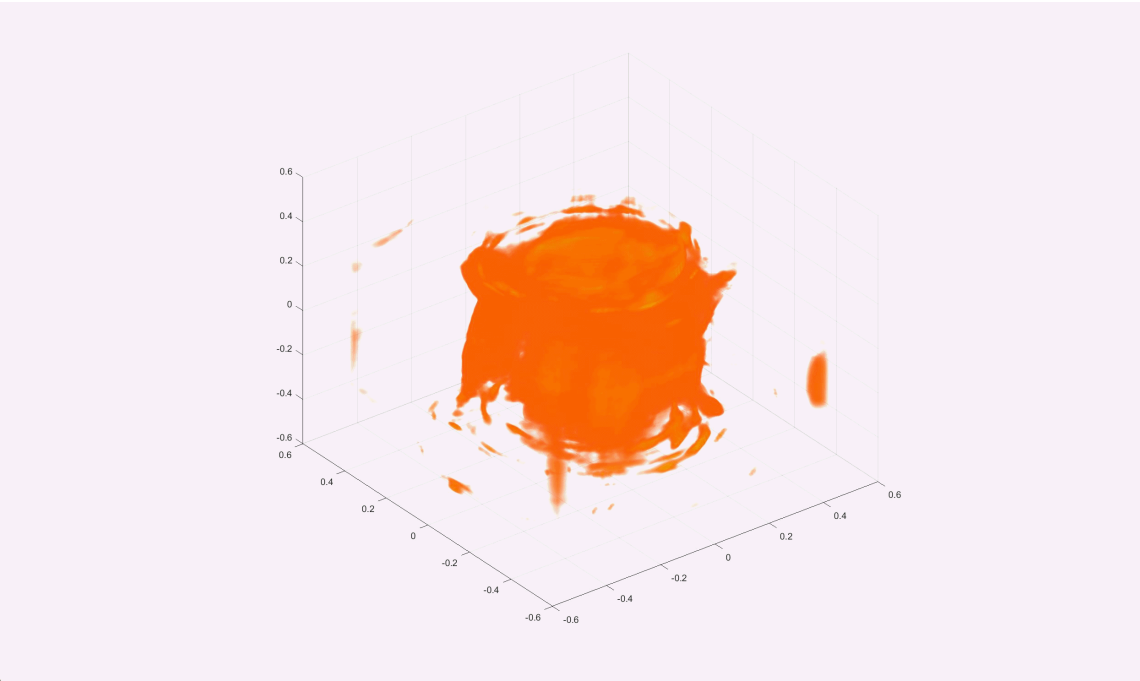
plasma terminations (disruptions)
never ever arised

surprise: formation happens inside a stationary pre-existing purely magnetostatic field:

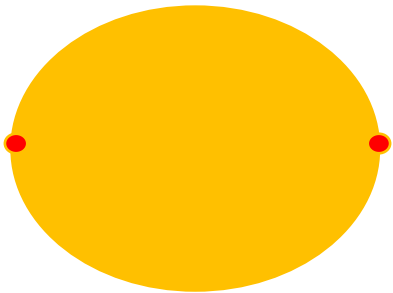
→ a toroidal axisymmetric plasma formed & maintained in steady-state, surrounding it by permanent magnets only?

Plasma oblique rotation

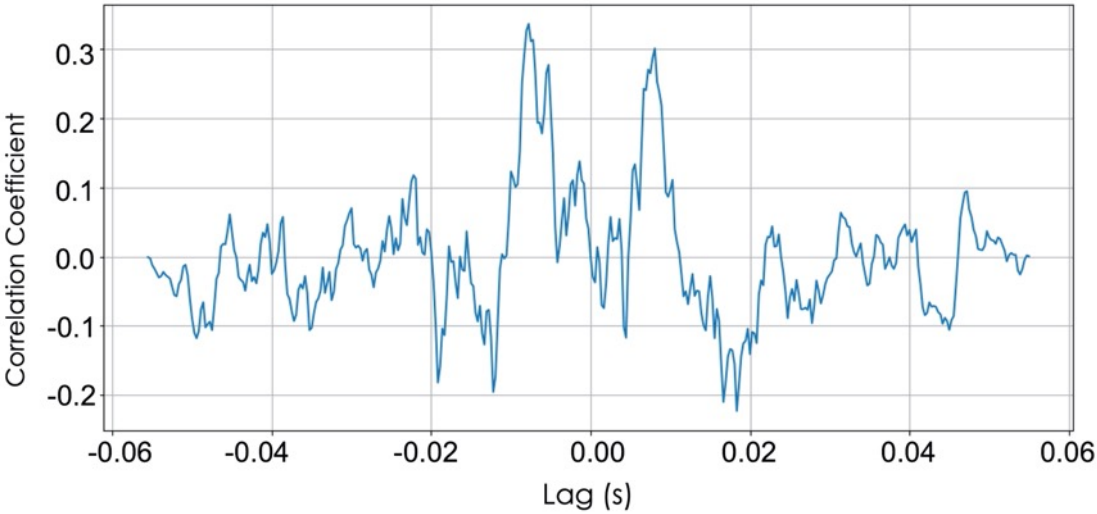
surprise: PROTO-SPHERA plasma spontaneous toroidal rotation ~ 600 rad/s (anti-clockwise from top)



plasma seems slightly oval in azimuth (oblique rotation)



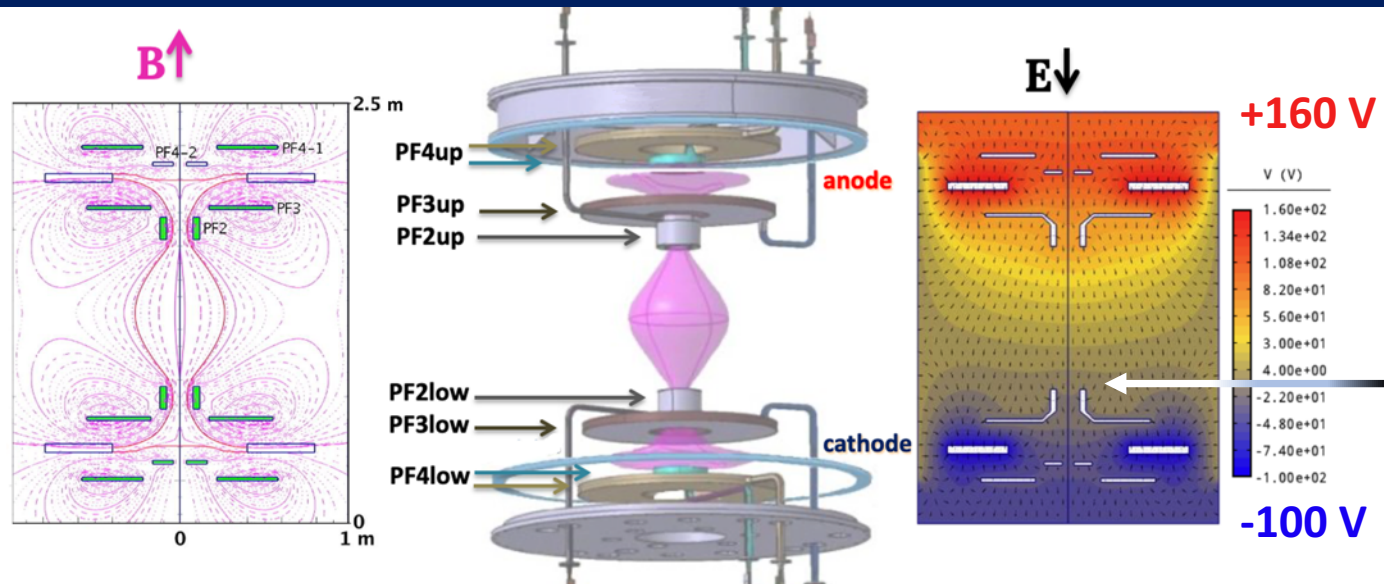
all cameras see a double correlation peak (ovalization) between brilliance and diameter



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

plasma rotation due to up/down anti-symmetry breaking of electric field

although magnetic field **B** is up/down symmetric



E... electrostatic field* is not up/down anti-symmetric

**E Giovannozzi*

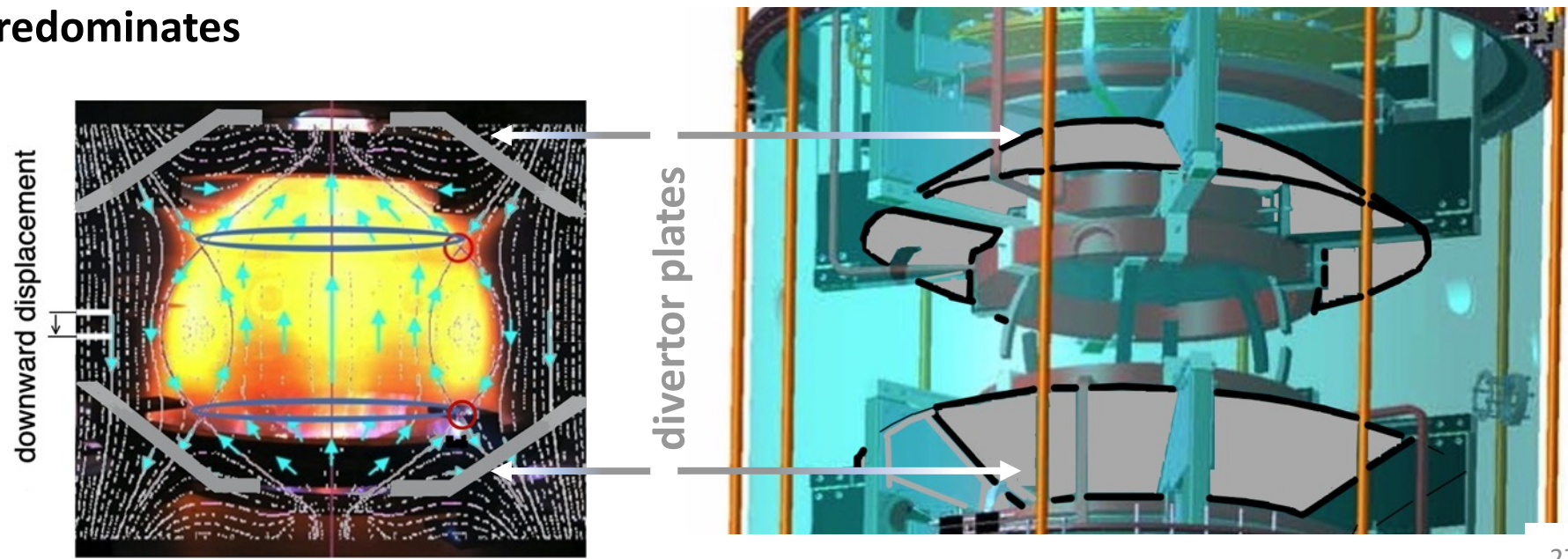
predominant anodic potential

zero potential near lower mirror coil PF2low

the plasma charges all nearby conductors:
anodic direction of $\vec{E} \wedge \vec{B}$ predominates
in the main plasma region:
anti-clockwise (from top)
plasma rotation

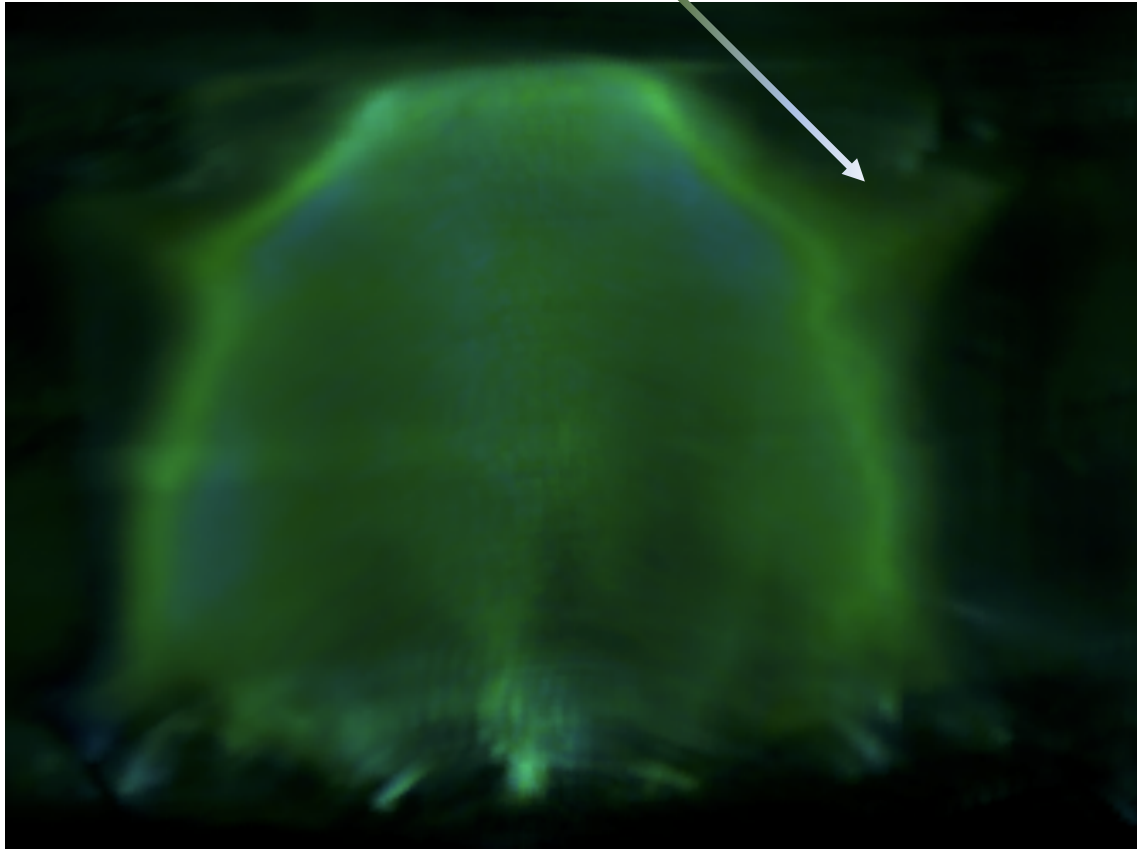
also downward displacement
of plasma torus is
presumably due to same
anti-symmetry breaking

PF coils & divertor plates inside the vacuum vessel

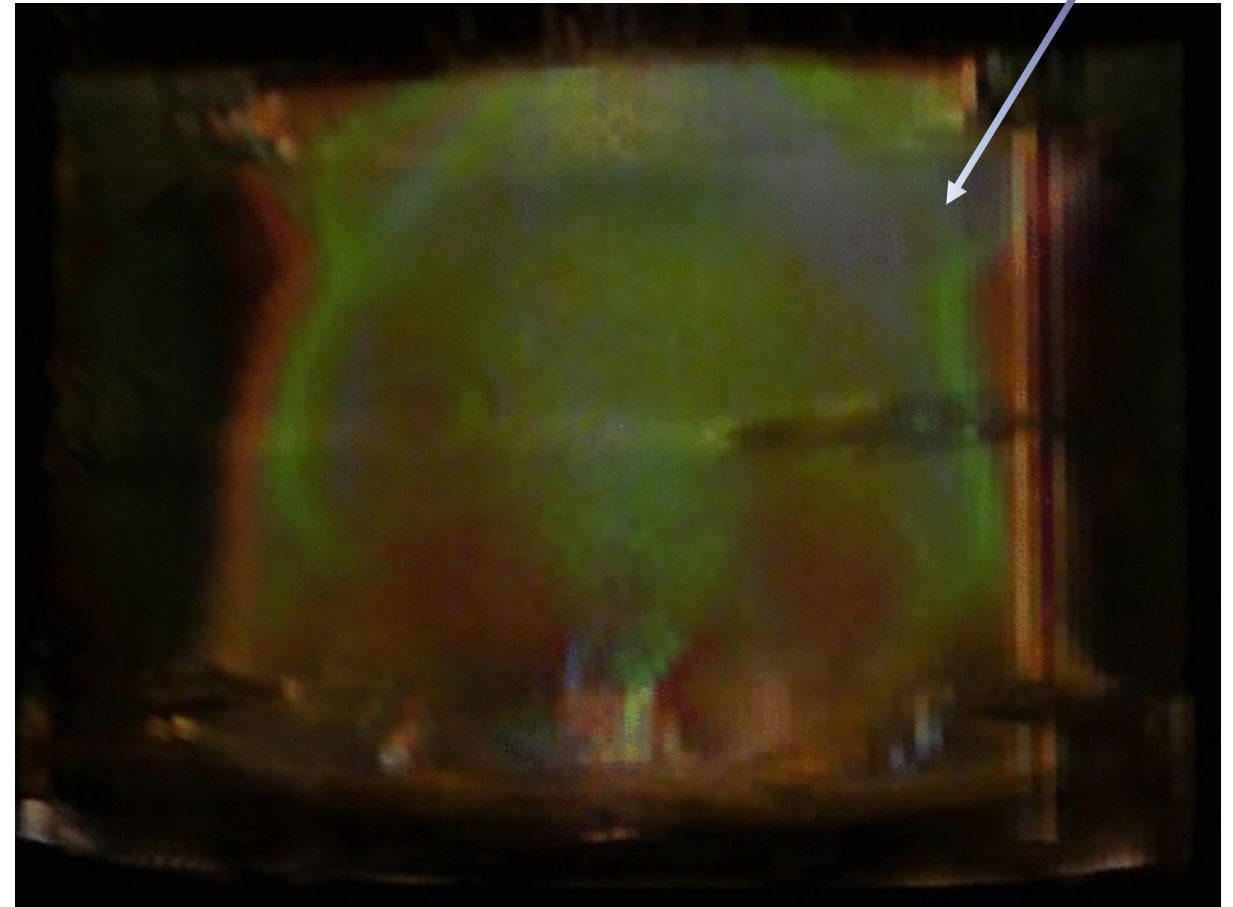


2023 3D tomography & thermal effects of magnetic reconnections

when torus protrudes near X-points

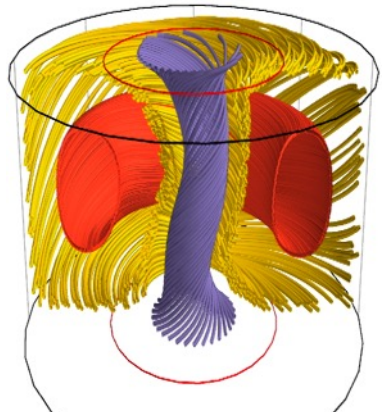


green plasma takes a blue nuance



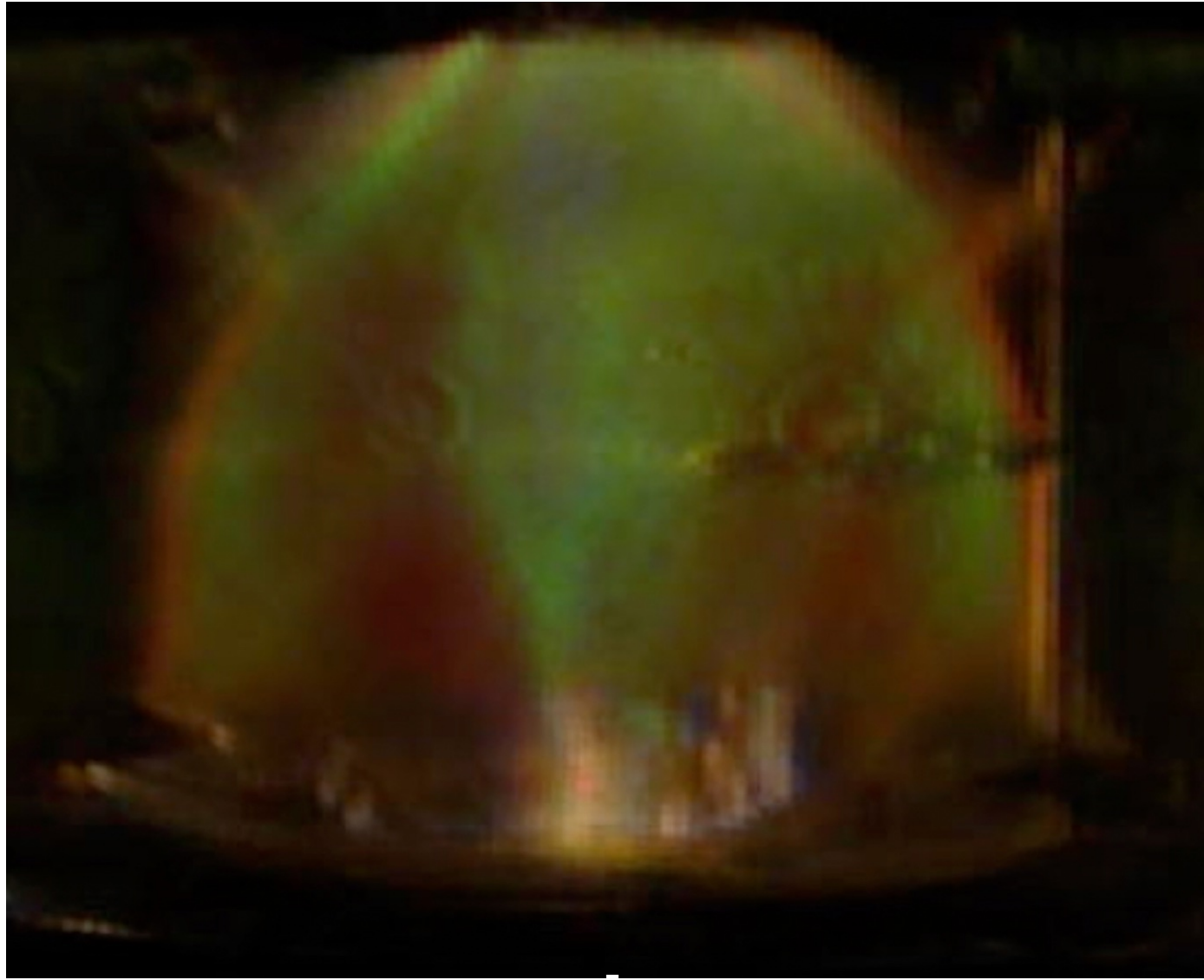
vertical tomographic section at 77 msec

looking inside a 300 msec Helium discharge: blue storms on upper X-points



- kinked plasma centerpost

Farengo 2018 *Physics of Plasmas* 25



stormy blue
upper X-points

torus shaken
by continuous
unrest

lower X-points
interact too strongly
with lower divertor plate:
spurious blu lights

vertical tomographic cross section

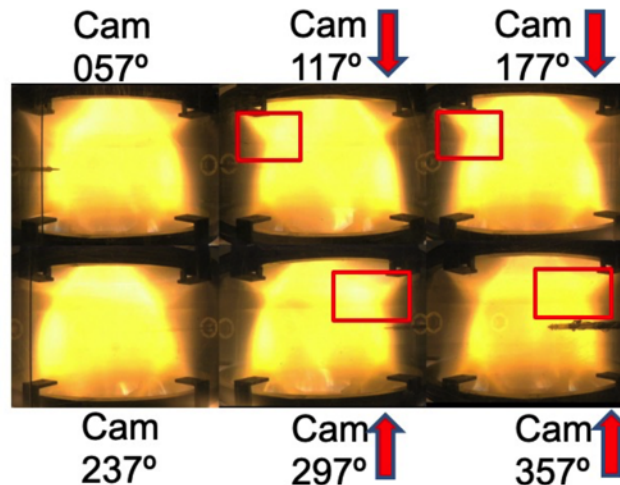
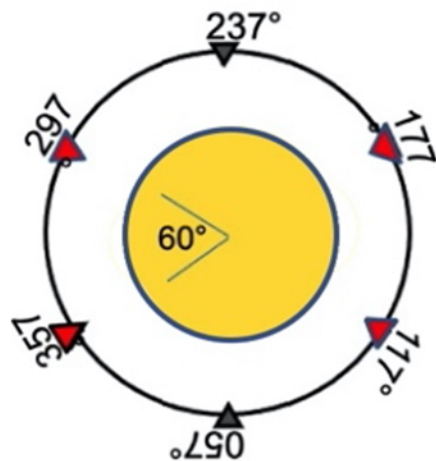
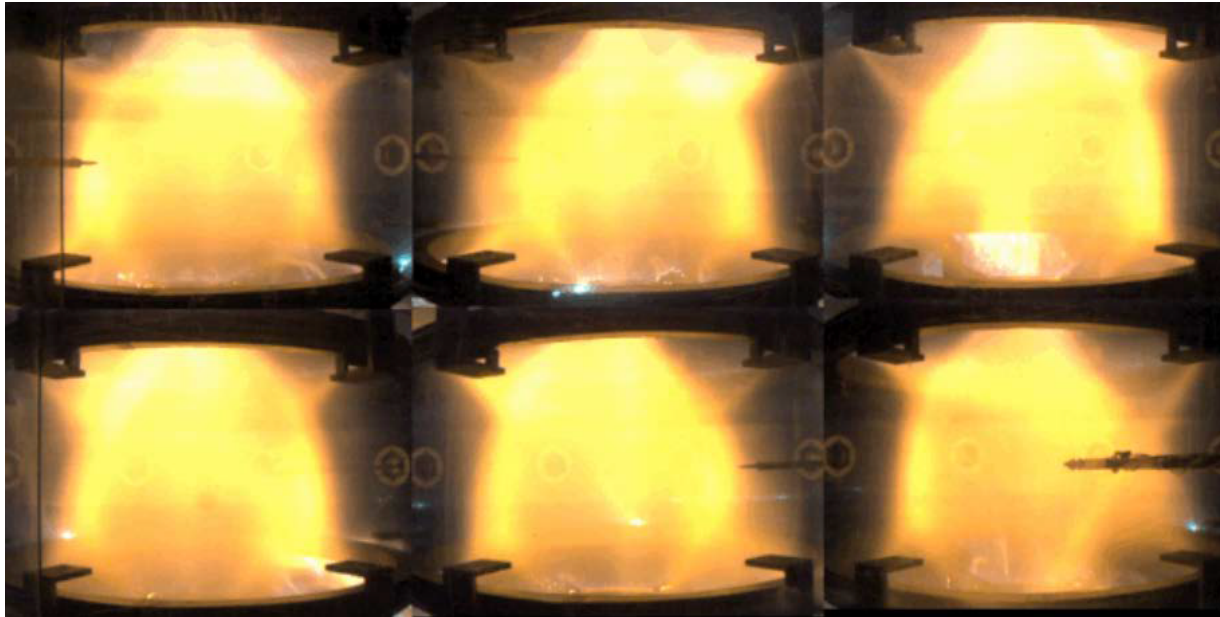
centerpost plasma in continuous turmoil

torus sustained: magnetic reconnections break axisymmetry*

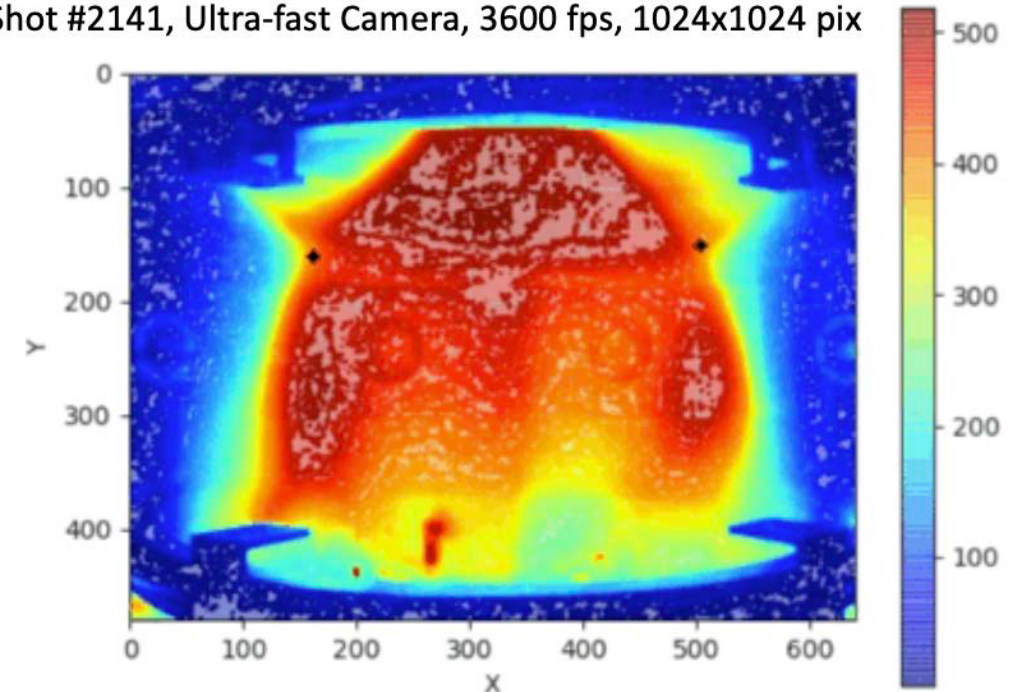
*S Macera

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



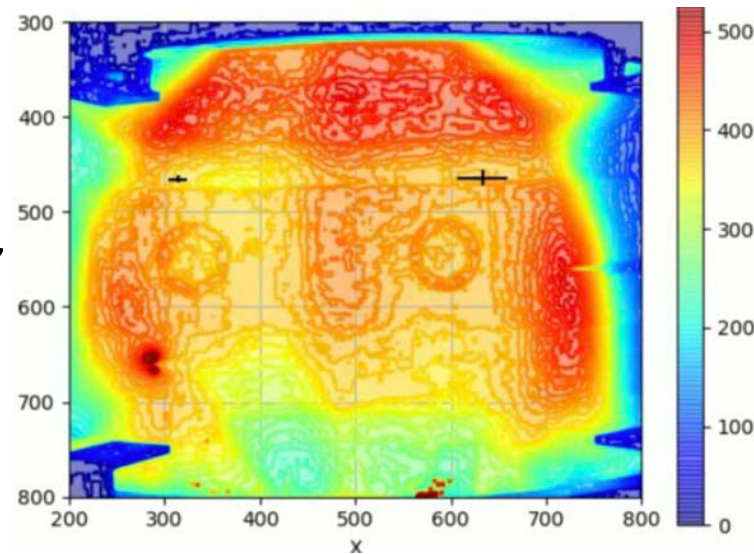
light intensity contours & upper X-points positions

- **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** see the brightening
and the deformation (& **also the opposite ones**)
but the other 2 cameras do not see anything

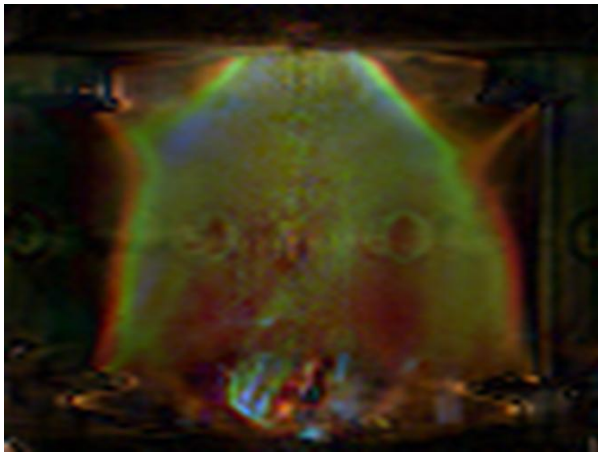
notwithstanding symmetry breaking, fair integrity of toroidal surfaces

*ultra-fast camera 3600 fps,
1024x1024 pix*

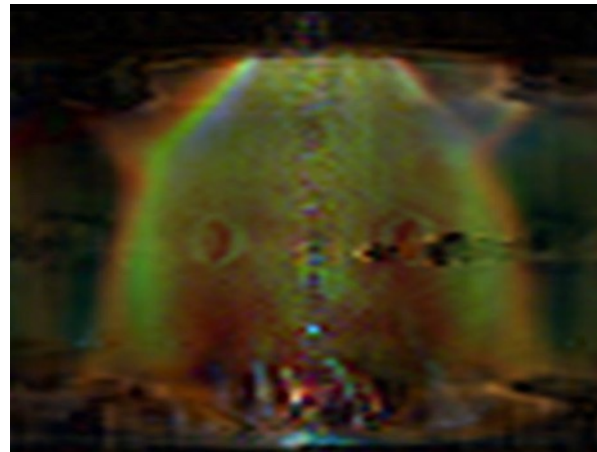


- notwithstanding X-points position oscillations
- nested & closed light intensity contours inside the torus

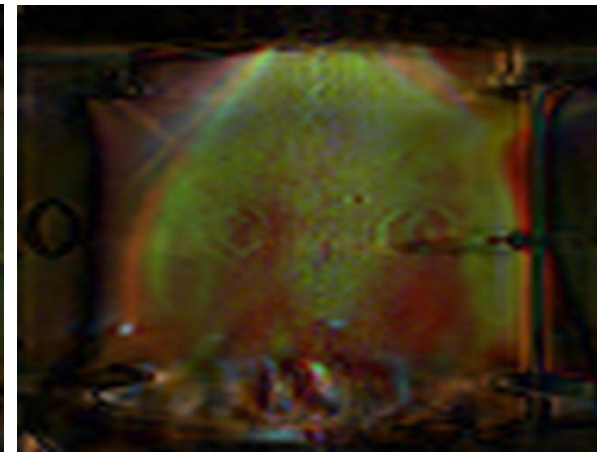
3D tomography vertical cross sections at various angles suggest reasonable axisymmetry of torus, apart from obliquity



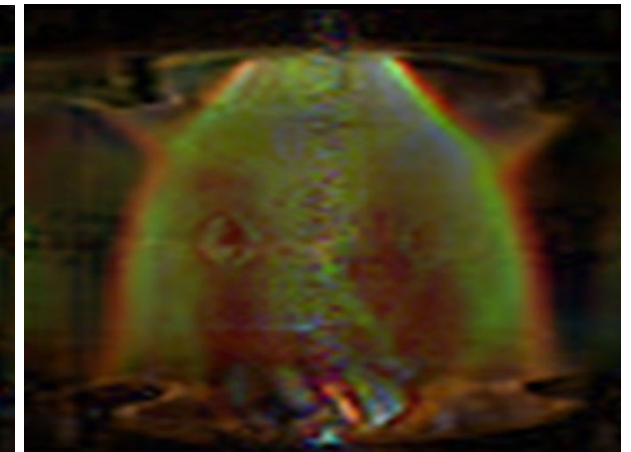
vertical section $\perp 0^\circ$



vertical section $\perp 45^\circ$



vertical section $\perp 90^\circ$



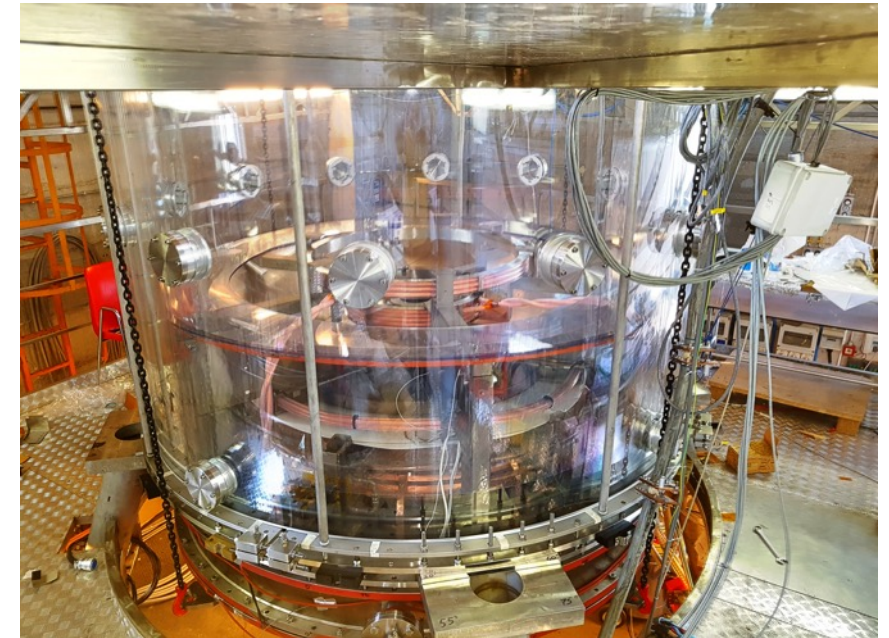
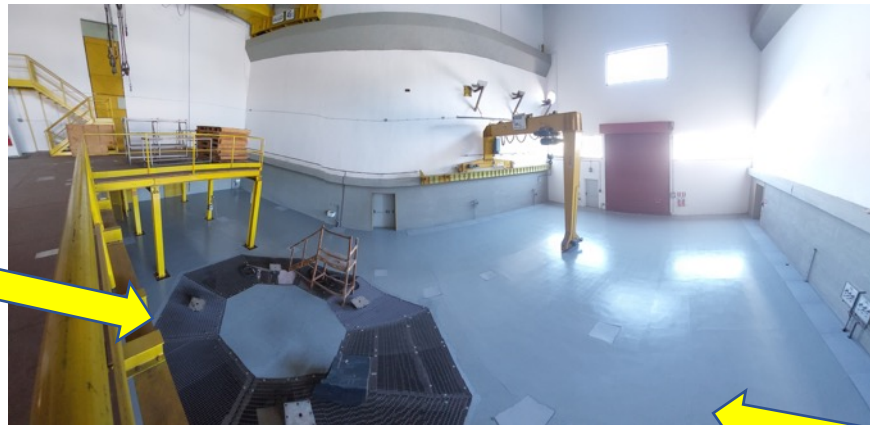
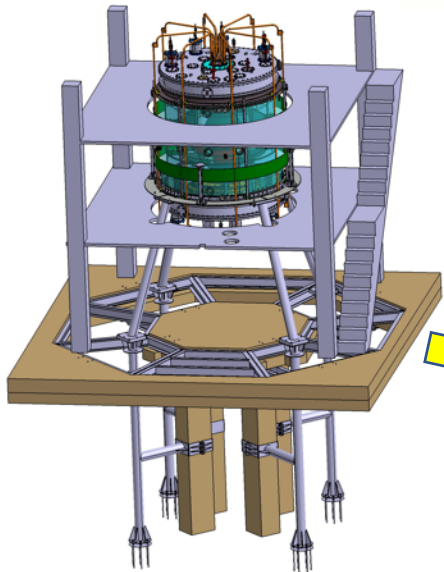
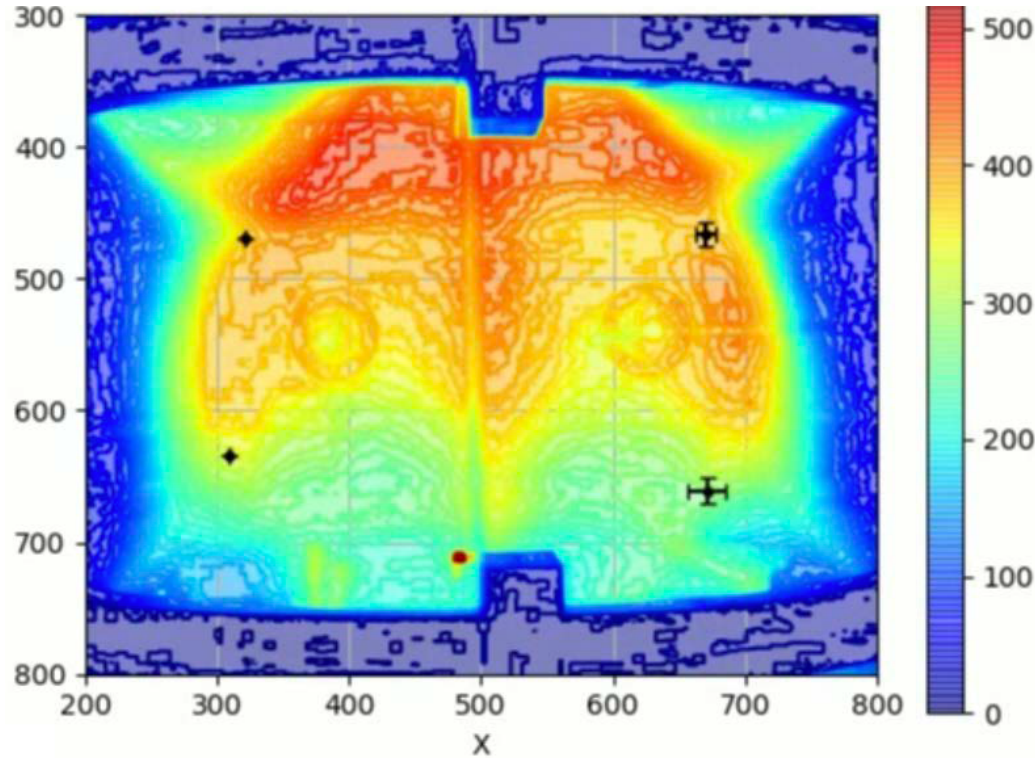
vertical section $\perp 135^\circ$

time frame 222 msec

up/down symmetry breaking makes lower X-points difficult to observe

shot # 2092, He
ultra-fast Camera
3600 fps, 1024x1024 pix

lower X-points
barely detectable
& with large
uncertainty



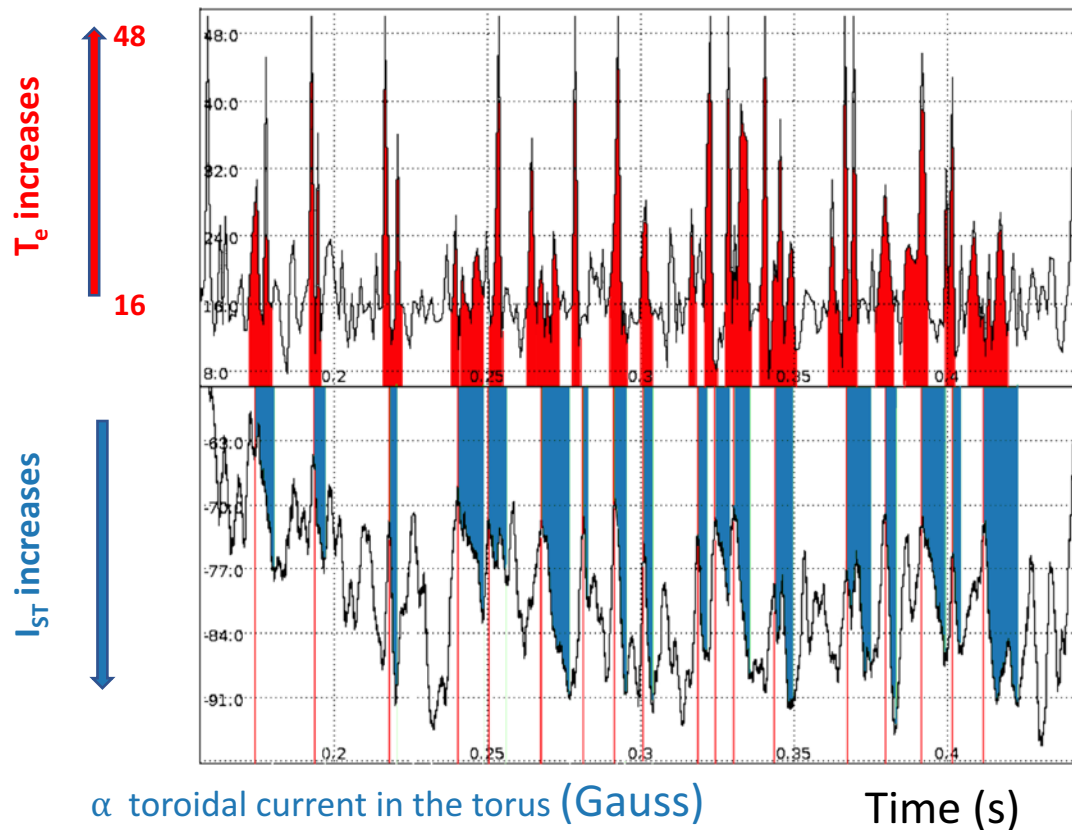
adjustment of boundary conditions & insulation
of lower (cathodic) part has to be improved
before moving to new experimental hall

magnetic reconnection on plasma temperature and/or particle acceleration

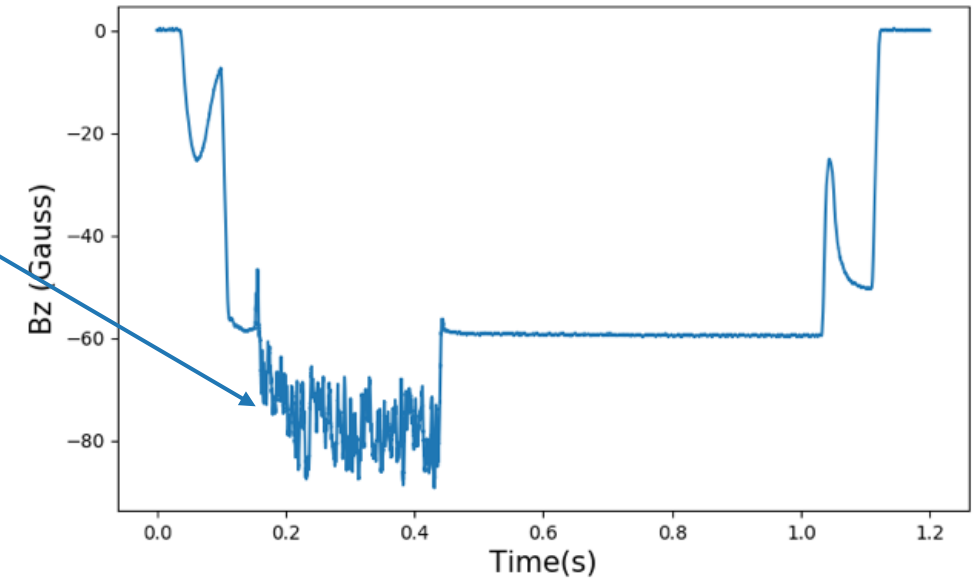
Hall probes* near the plasma edge (measuring $B_{Z\text{-vertical}}$) show bursts of B_z ($\propto$ toroidal current ΔI_{ST}) entering the torus

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)



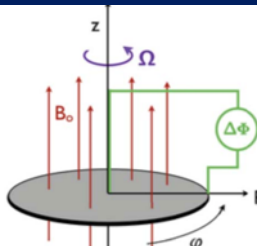
*L Boncagni,
M Iafrati



magnetic reconnections T_e spikes 20 eV $\rightarrow$ 50 eV (heating? suprathermal acceleration?), followed by

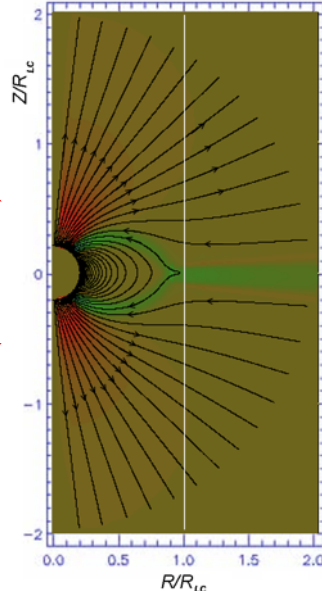
toroidal current bursts $\Delta I_{ST} \sim 1\text{-}1.5$ kA injected into the torus ($I_{ST} \sim 5\text{kA}$)

torus + jet : split-monopoles *ffmf* model for Pulsar Wind Nebulae (PWN)

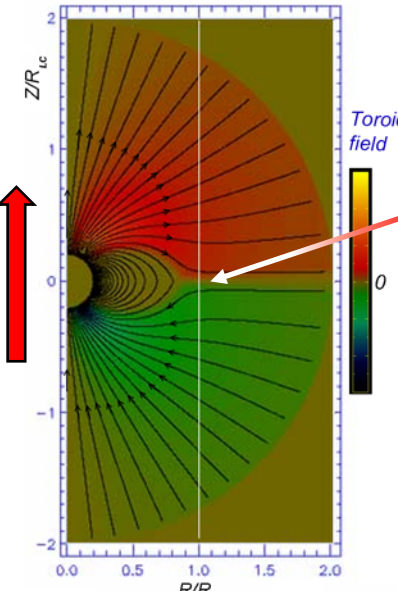


bidirectional Jet :
 Faraday disk effect gives
odd-symmetric j_{vert}
 on the 2 emispheres*

**Goldreich & Julian, 1969 ApJ 157*



even-symmetric
emispherical B_{vert}
 legacy of B of star
single direction B



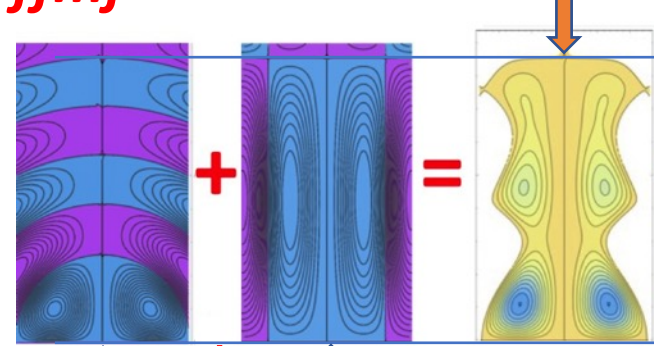
split-monopole *ffmf**, then
 rotation & obliquity added

** Michel 1991 Theory of Neutron Star Magnetospheres
 University of Chicago Press*

double jets are described
but no torus is present

describe by an odd *ffmf*
 the 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* model a double torus

Furth odd squared *ffmf* model a double jet for any value of $\lambda < \mu$



Crab Nebula

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

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

$\lambda = 3.6736$, so that at
 $R=0, Z=x_{2,5}/x_{2,6} = 0.85518$
 the zeroes of $\psi_{\mu\lambda}^{F,odd}$
 and of $\psi_{\mu}^{CK,odd}$ coincide

however, under the equatorial rug...

$$\psi_{\mu}^{CK,odd}(r,\vartheta) = -(\mu r) j_2(\mu r) \sin\vartheta P_2^1(\cos\vartheta)$$

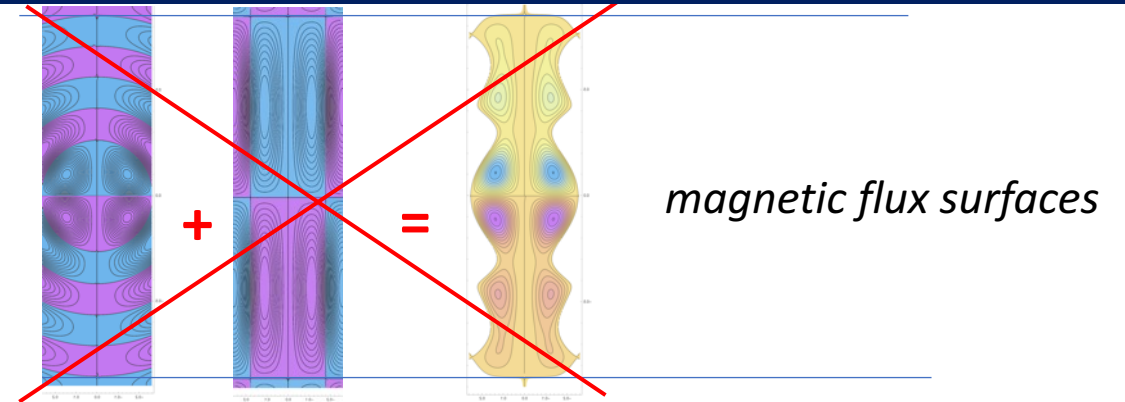
$$\psi_{\mu\lambda}^{F,odd}(r,\vartheta) = \sqrt{\mu^2 - \lambda^2} r \sin\vartheta J_1(\sqrt{\mu^2 - \lambda^2} r \sin\vartheta) \sin(\lambda r \cos\vartheta)$$

jet+torus model requires 2 *ffmf* with opposite μ on the 2 sides of equator

looking under the rug of the equator...

summing 2 odd-parity CK + F *ffmf* with the same μ ...

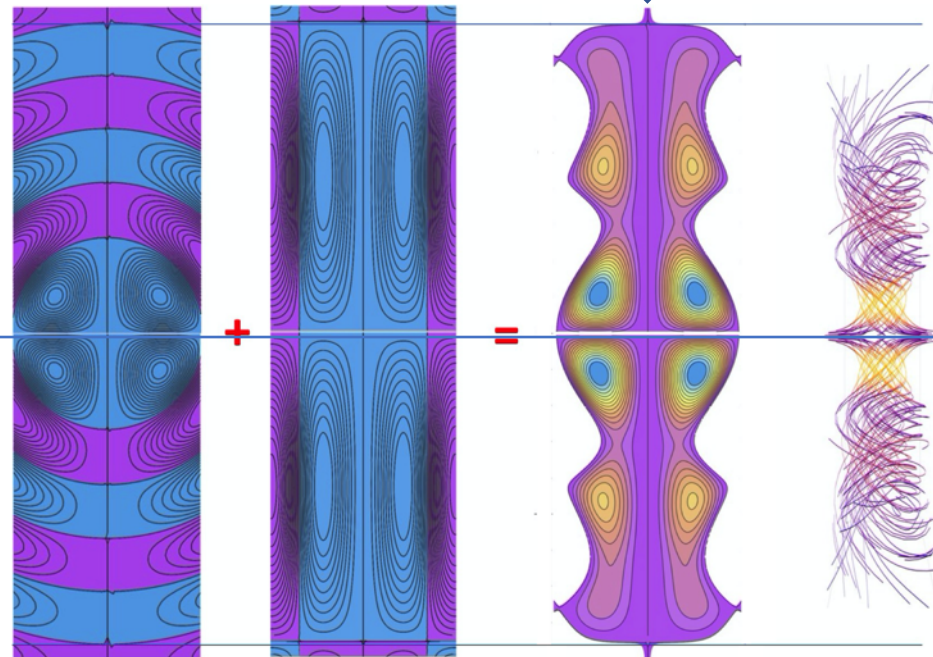
gives opposite $\mathbf{B}_{\text{vertical}}$ on the 2 emispheres, not right!



2 *ffmf* fields contiguous with opposite μ : $\mu > 0$ on upper and $\mu < 0$ on lower emisphere:

$$\psi_{\mu\lambda}^{PWN}(R, Z) = \frac{RZ}{|Z|} \left[-|\mu| j_2(|\mu|r) P_2^1(Z/\sqrt{R^2 + Z^2}) + |\gamma| \sqrt{\mu^2 - \lambda^2} J_1(\sqrt{\mu^2 - \lambda^2} R) \sin(\lambda Z) \right]$$

by cross-sections of flux surfaces



by enlarged field-line-tracing

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

PWN double tori *ffmf* model

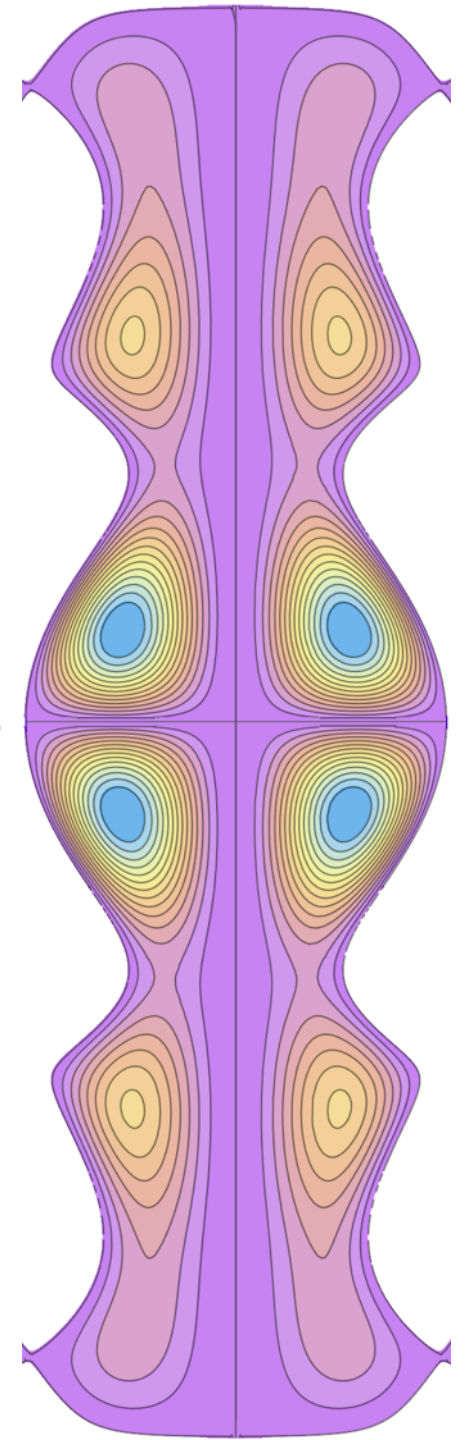
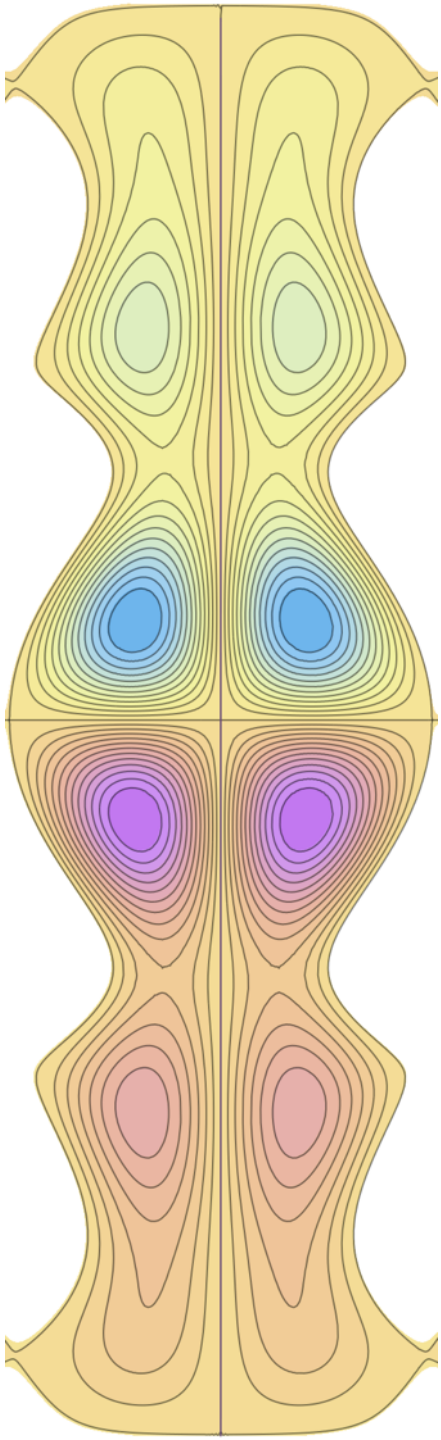
can generalize the split-monopole *ffmf* model

symmetries & anti-symmetries on the 2 sides of equator

B_φ

- the 2 hemisphere have:
- opposite toroidal fields
 - aligned toroidal currents

j_φ



PWN double tori *ffmf* varying elongation of jets with respect to torus diameter

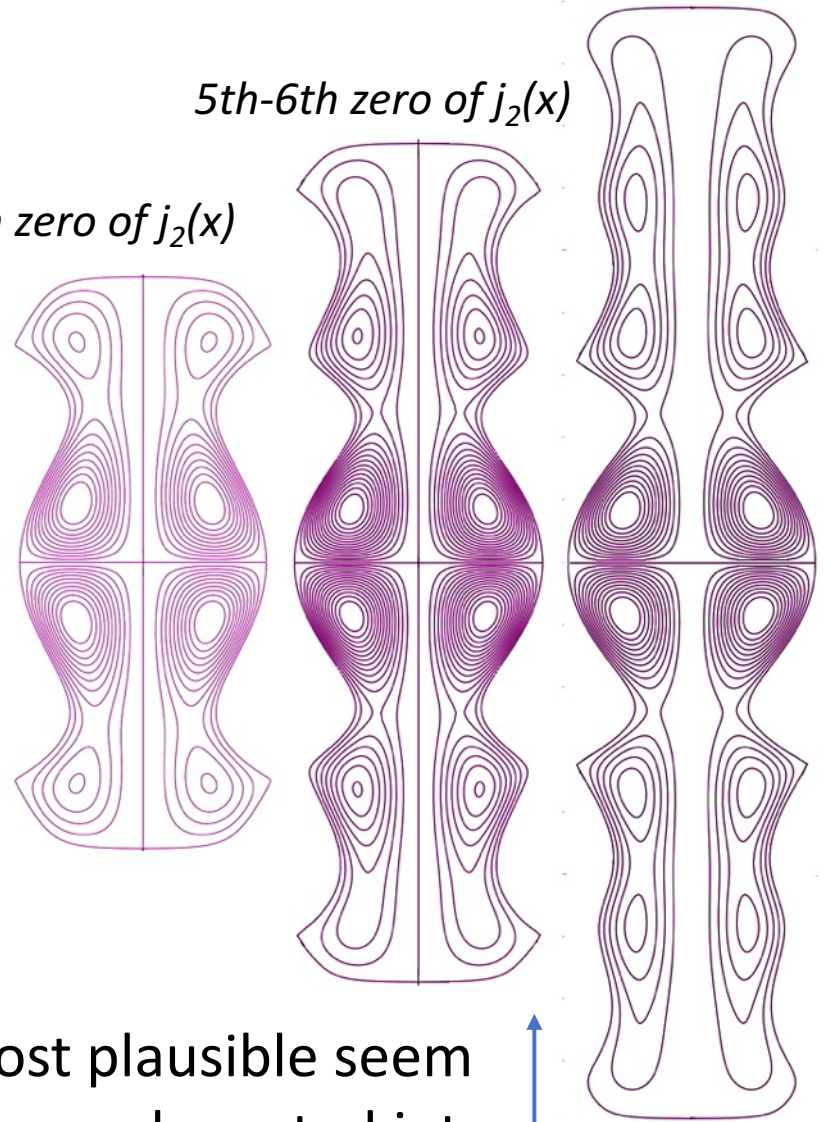
shown as cross sections of magnetic flux surfaces

7th-8th zero of $j_2(x)$



3rd-4th zero of $j_2(x)$

5th-6th zero of $j_2(x)$



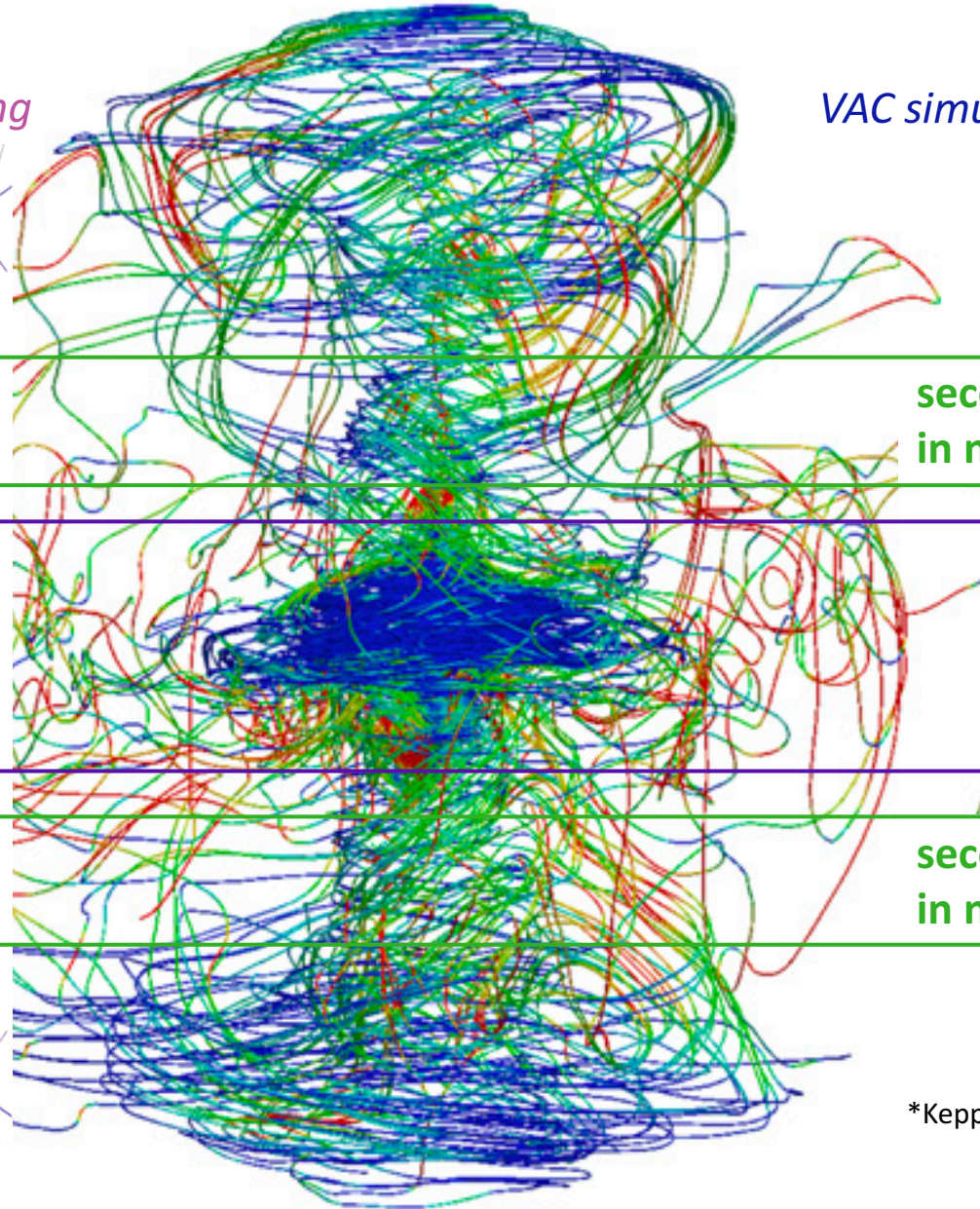
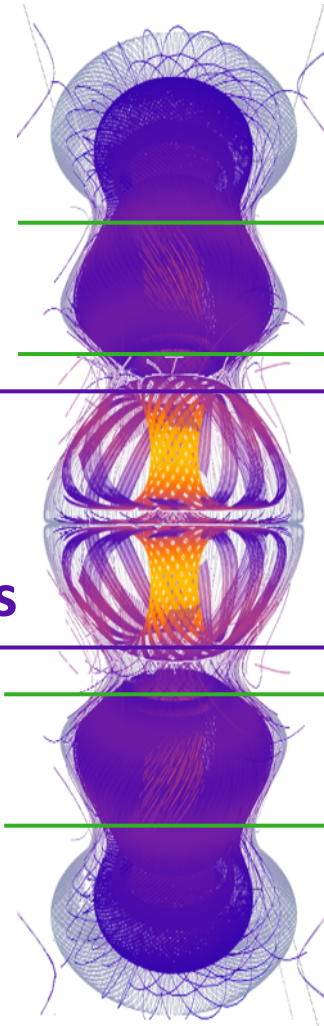
Choosing odd-even zeroes in increasing sequence: 3rd-4th, 5th-6th, 7th-8th, ... more & more extended jets are obtained

For PWN the most plausible seem the ones with more elongated jets

PWN double tori *ffmf* compared to simulations by Versatile Advection Code*

PWN double tori fmf model by field-line-tracing

VAC simulation



Double tori have:

- opposite toroidal fields
- aligned toroidal currents

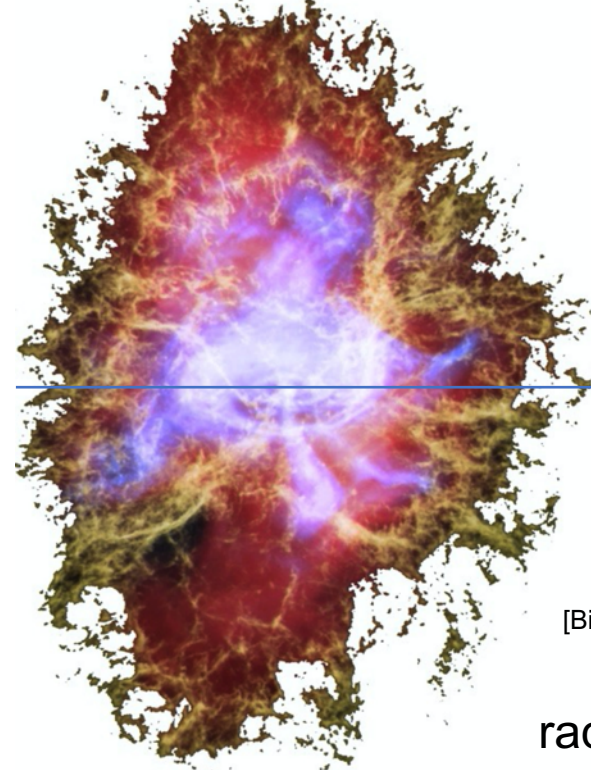
secondary tori show up
in numerical simulations

secondary tori show up
in numerical simulations

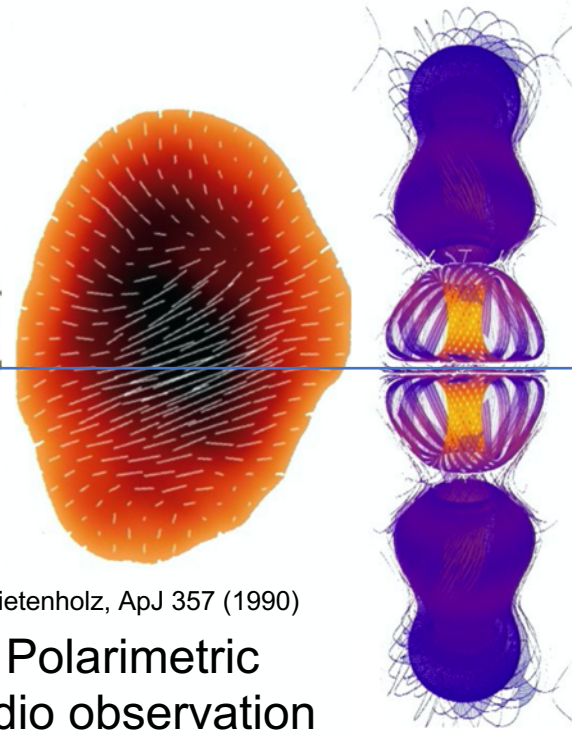
*Keppens 2014 MNRAS 438 278

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

combined wavelength
Crab PWN



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



[Bietenholz, ApJ 357 (1990)]

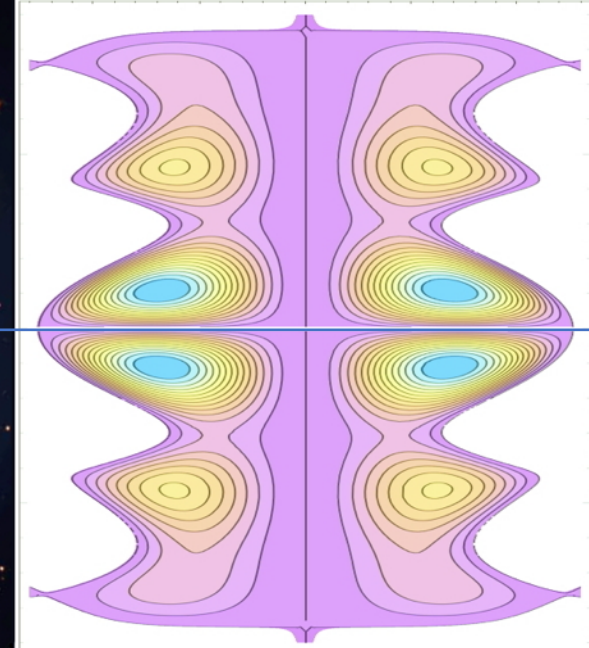
Polarimetric
radio observation

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



combined wavelength
Vela PWN

PWN double tori *ffmf*
model by flux surfaces



(elongation reduced by ~ 2
to correct perspective)

the observation of the **Vela PWN** gives instead one of 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

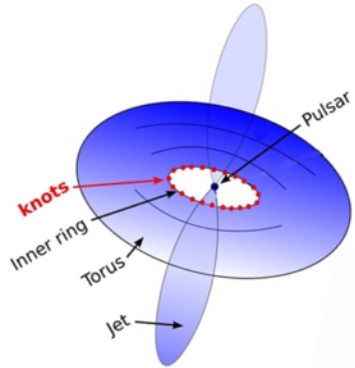
most efficient accelerators in the Galaxy are the PWNe

>25% of their released power is emitted in radiation

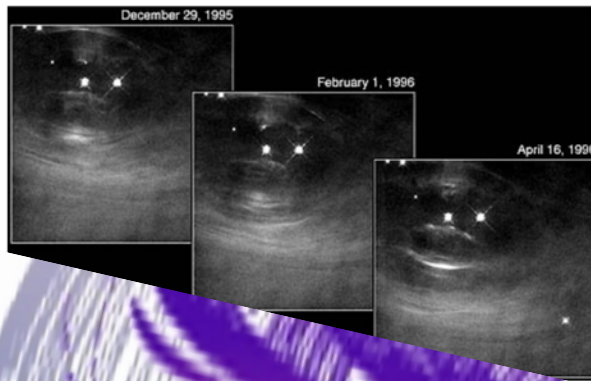
- spectrum of e.m. emission extends beyond PeV (10^{15} eV)

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

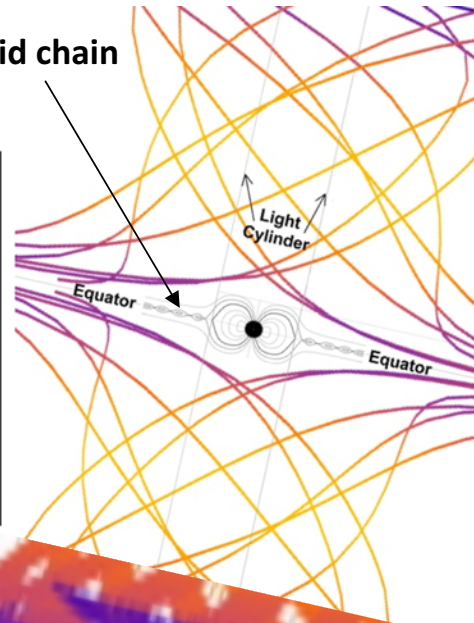
do the fast moving “**knots**” ($\sim c/2$) coincide with such plasmoids?



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

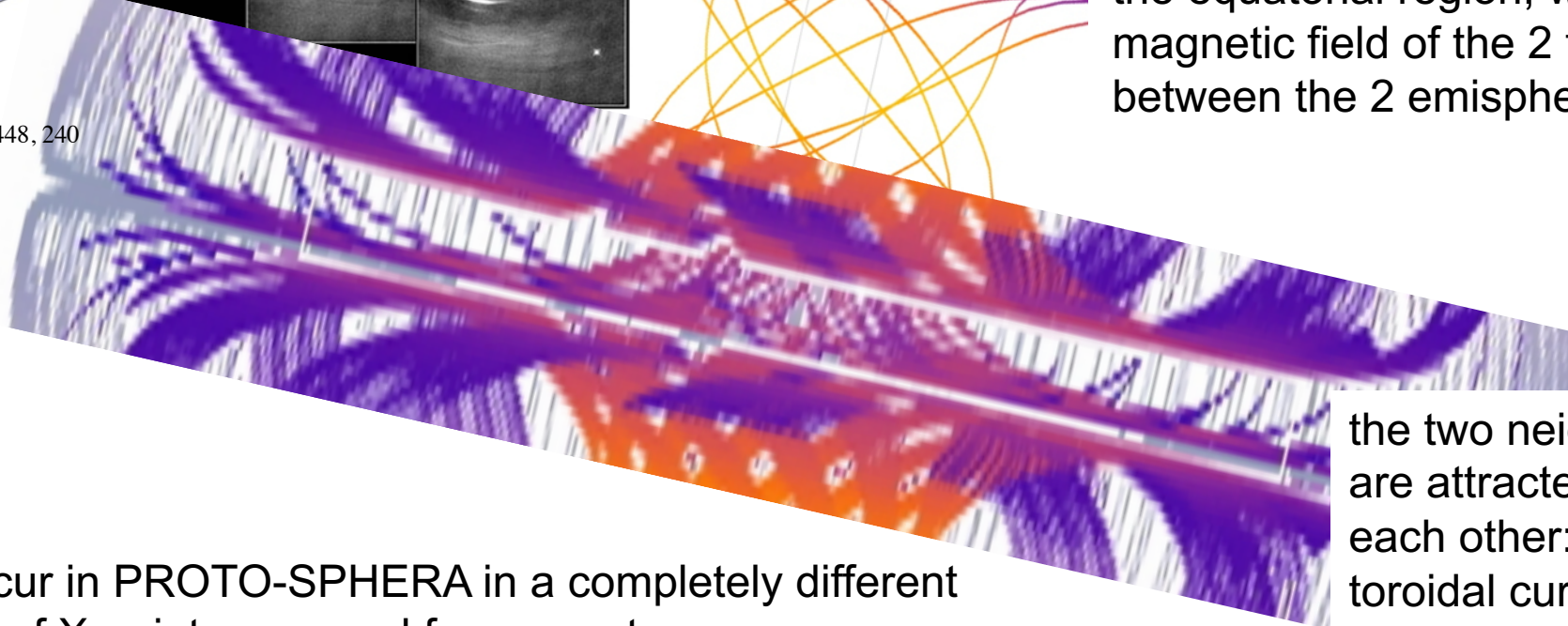


reconnecting plasmoid chain



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

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



the two neighboring tori are 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

CONCLUSIONS

Torus + Jet force-free magnetic fields (*ffmf*) helpful for laboratory **experiments**, can describe PWNe as well?

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

Very good agreement of Ideal MHD stability with design (without any conducting shell near the plasma), furthermore 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 *ffmf* model of PWNe, if applicable, describes 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 being investigated, through a modification of PROTO-SPHERA able to do so

The future:

Although the machine has reached, at low plasma currents (1/7th of final), almost all its aims:

- formation & maintenance of current carrying tori by self-organization
- ideal MHD stability in absence of any surrounding conducting shell
- clear signs of magnetic reconnections and of plasma heating/acceleration due to them
- fair axisymmetry of tori, even if shaken by continuous unrest and turmoiling centerpost

The future is quite uncertain: organizational problems not addressed up to now could remain unsolved

- an almost underground experiment, never fully accepted by ENEA management
- a crippled program manager, the lack of steady funding, the exclusion from European funding
- the vanishing of expert technical personnel (a much more general problem in ENEA-Frascati)

If the experiment does not evolve to Phase-2 ($I_{CP}=70$ kA, $I_{ST}=280$ kA, cost 2 M€) it will soon be dead

- experiment must move to Phase-2; technical problems for $I_{CP}=70$ kA be addressed before moving to new hall
 - to be back in 2025 (in the new hall) to the same plasma discharges of 2020 will spell ruin

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