First results of plasma centerpost in PROTO-SPHERA

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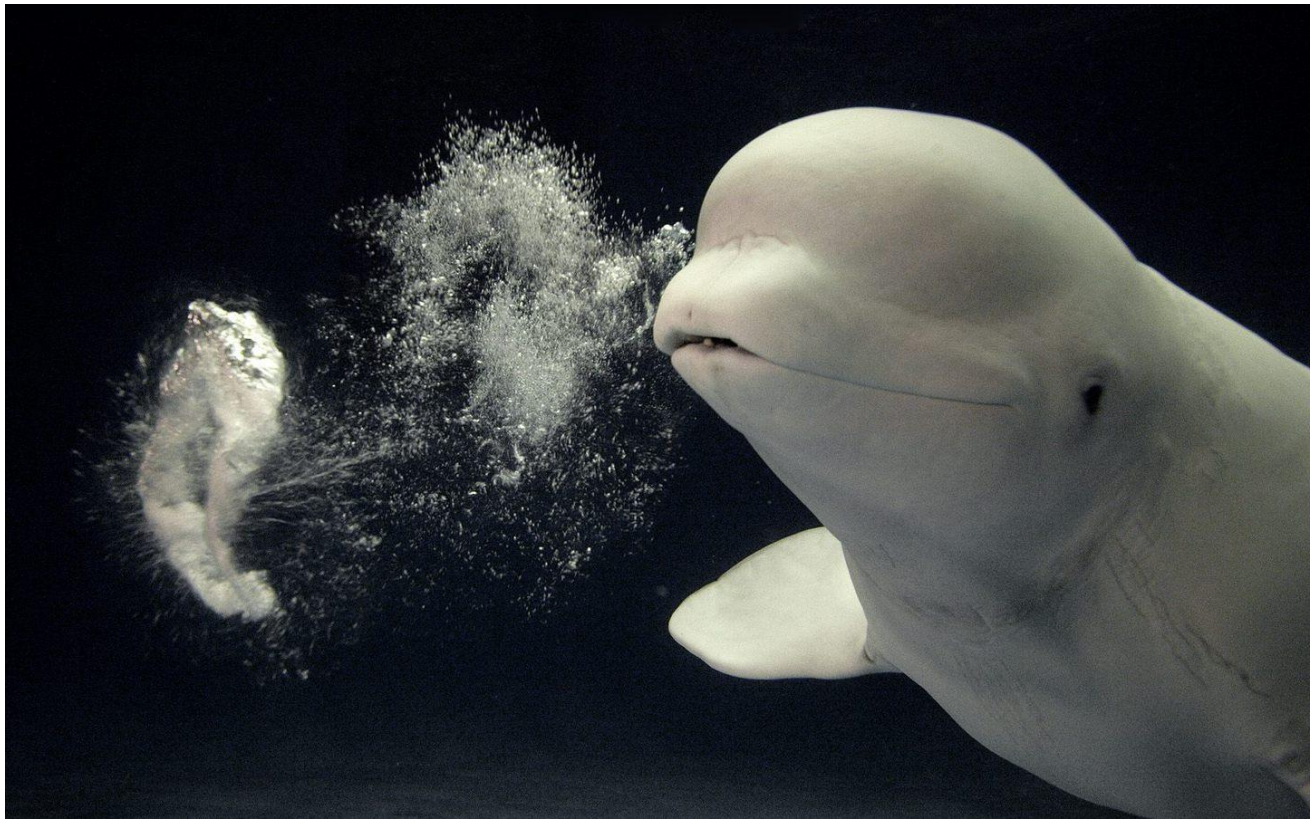


Summary

History of construction of PROTO-SPHERA

Cylindrical anode experiments (2014)

Annular anode experiments (2015)

Absence of anode attachment due to electrostatic potential

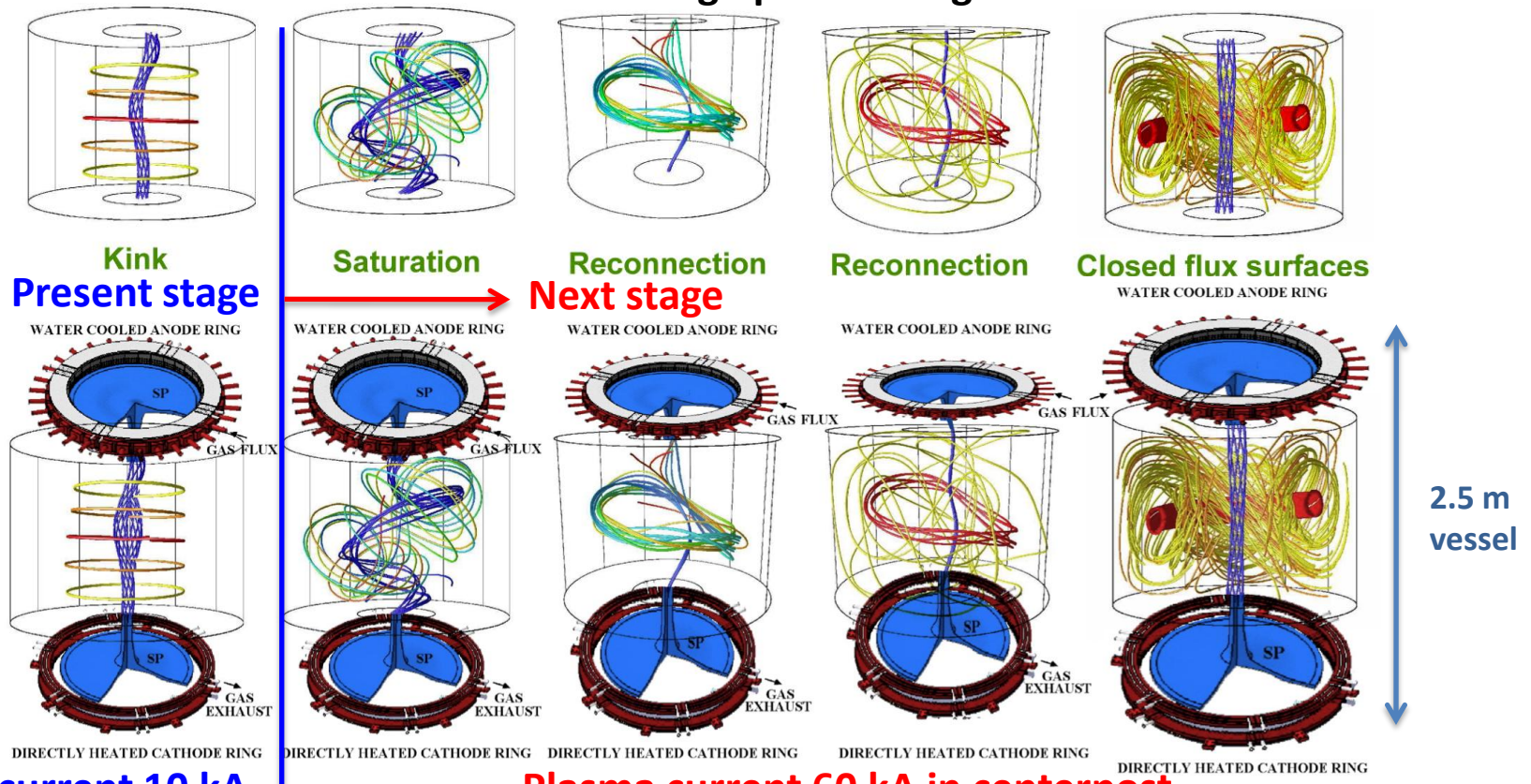
Tailoring of electrostatic potential by connecting PF coils casings, built as floating

Tailoring of magnetic field through additional PF coils external to the vessel

Conclusions

PROTO-SPHERA aim

A spherical tokamak with metal centerpost replaced by a plasma centerpost: anode and cathode needed for setting up the configuration



Plasma current 10 kA in centerpost, no torus

Plasma current 60 kA in centerpost, 240 kA in spherical torus

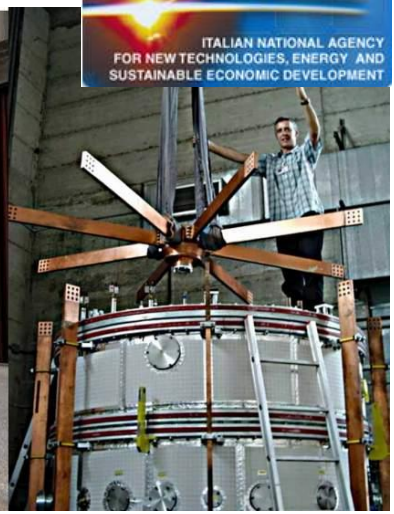
Experiments began in 2014 on plasma centerpost only; aim is 10 kA, 1 s

Years 1995 - 2002: *Idea & design*
1995 - 2nd ST Workshop Princeton
2002 - International Workshop Frascati

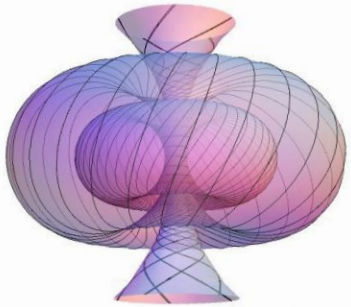
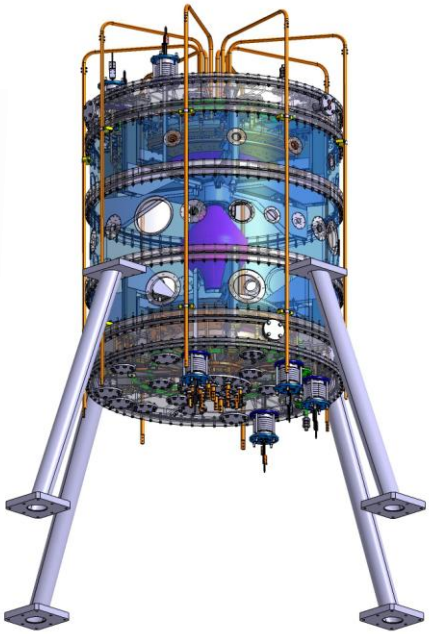
Years 1997 - 2000: *Test of electrodes in "Champagne bottle experiment" (late Derek Robinson, Prague EPS98)*

Cylindrical vacuum vessel was START vacuum vessel, donated by Culham in 2004





PROTO-SPHERA was built (2006-2009) by ASG Superconductors of Genoa, cost 1 M€.


Years 2004 - 2010:

…from ideas *…to detailed design* *…to hard metal*

Only the PF coils necessary for setting up the plasma centerpost have been built

8 PF coils in series inside the machine

Stainless steel up\down new extensions

PF4up

PF3up

PF2up

Aluminium cylindrical START vessel

PF2low

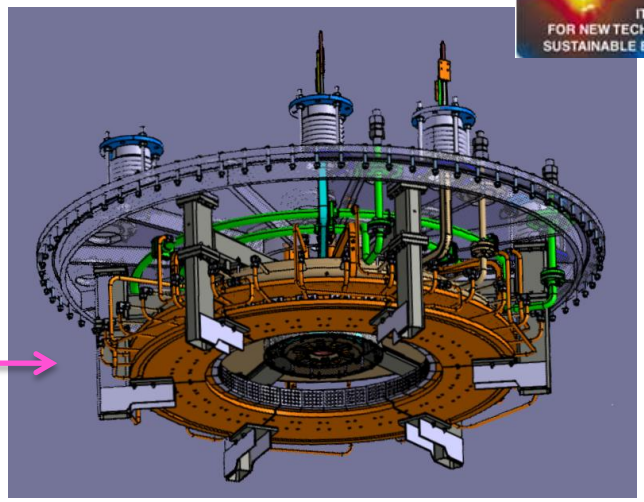
PF3low

PF4low

Stainless steel up\down new lids

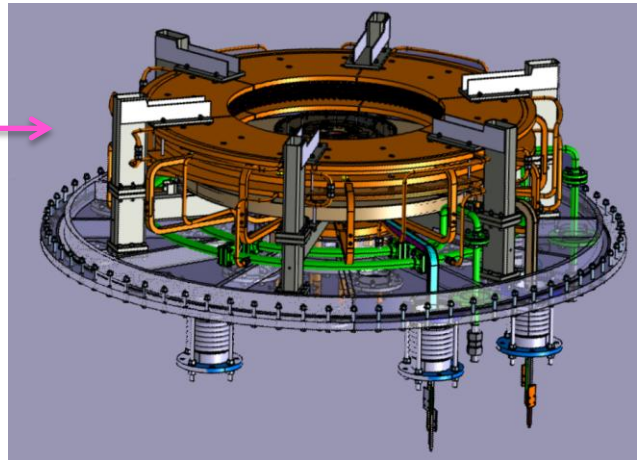
anode

annular anode



plasma current must run through both PF2 throttles

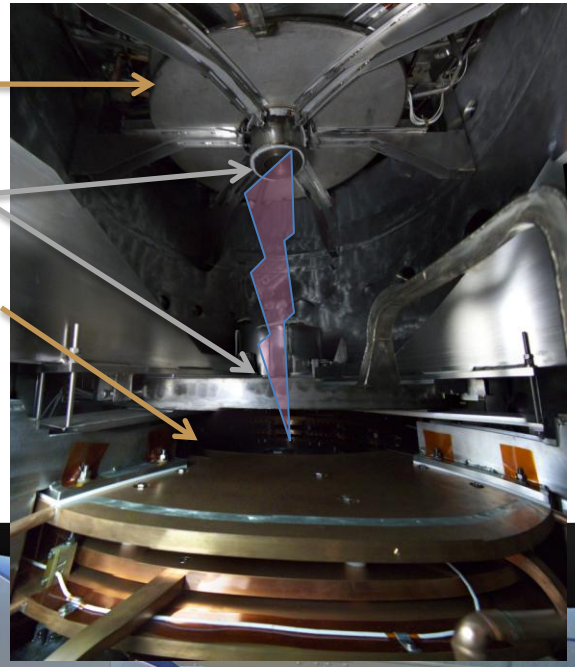
cathode



annular cathode

vacuum vessel is GND potential

PF coils casings built as floating, can be connected to potentials: **anode +**, **cathode -**, **vessel 0**



To fire the plasma centerpost
3 Power supplies are required

- Cathode heating, rotating 6-phase: 6 x(1.7 kA,25 V)rms
- PF coils: 2kA, 350 V
- Plasma centerpost: 10 kA, 350 V

Electrical power supplies built by EEI of Vicenza, cost 0.7 M€

Years 2011 - 2014:

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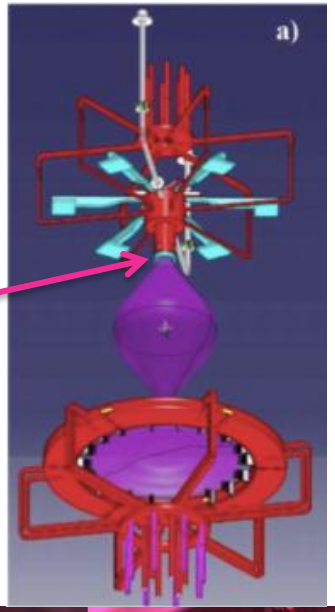
Being afraid of anode attachment, often observed in arc discharges (arc welding, plasma torches)

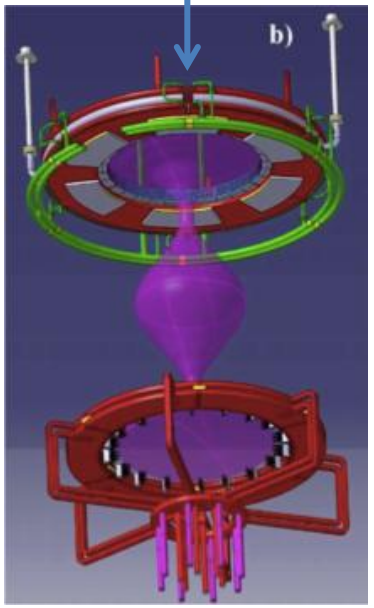
the first rounds of experiments had a simple cylindrical anode

break-down was easily achieved, apart from this the cylidrical anode was just a source of troubles

2014 cylindrical anode



2015 annular anode



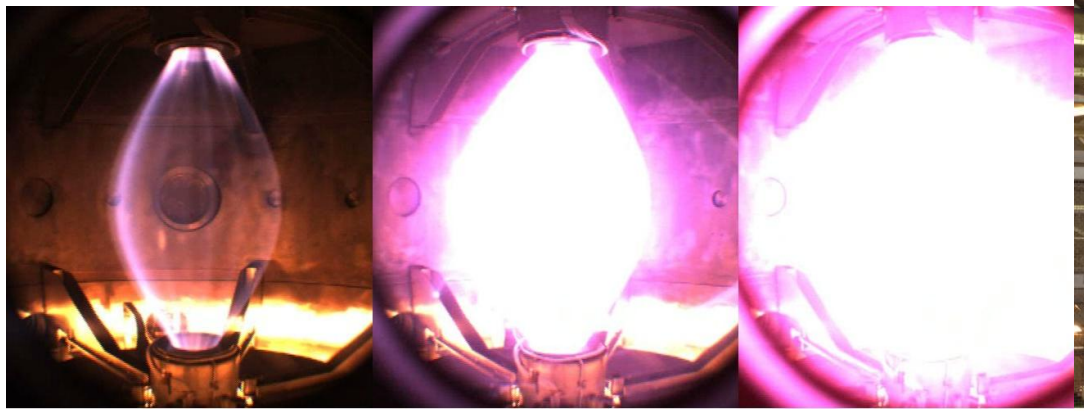
cylindrical cathode results

Hydrogen plasma

break-down 170 V +10 ms, 500 A +20 ms, 1.5 kA

anode camera

centerpost camera



May 2015 annular anode lowered on top of machine

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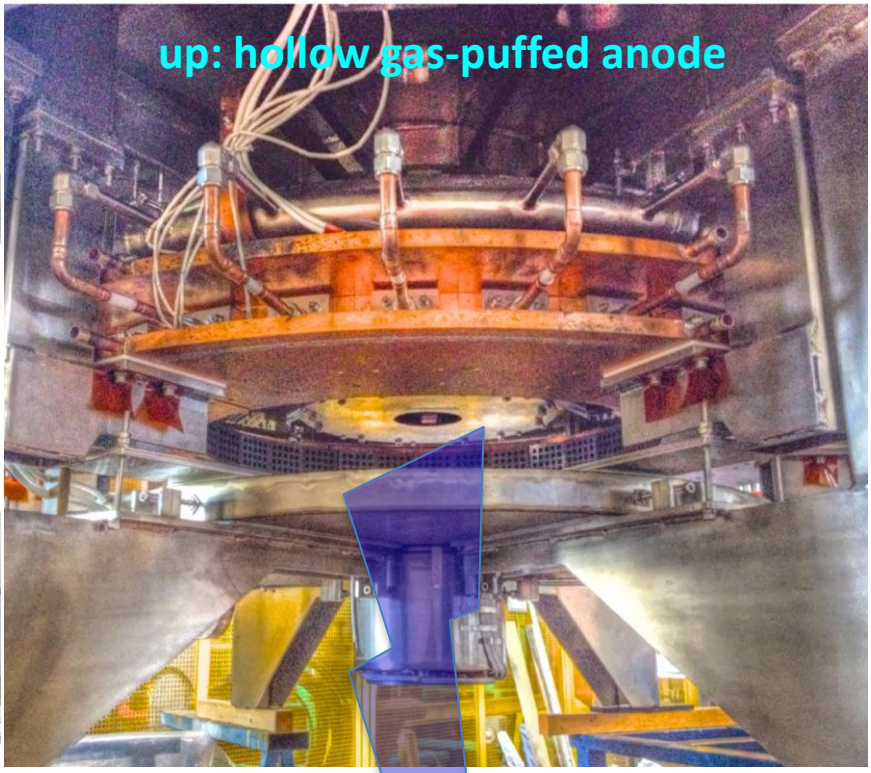
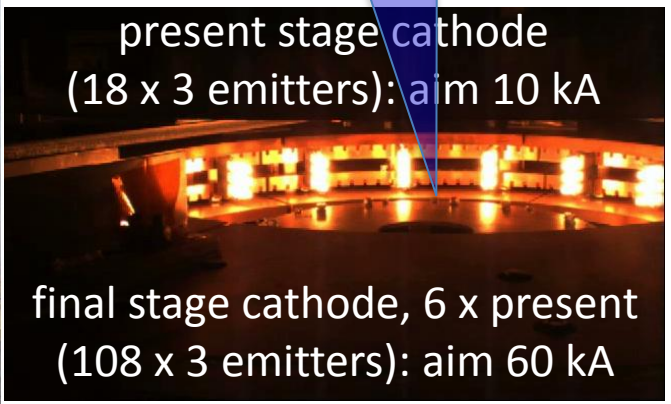
PROTO-SPHERA CR-ENEA Frascati



down: 3000º K heated cathode



“Caduceus”-like emitting spirals have survived ~ 1000 cycles

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hollow annular anode performs

- plasma goes through both PF2 throttles
- plasma enters anode gas-puffing holes
- no sign ($I < 3.5$ kA) of anode attachment
- filling pressure 10^{-3} - 10^{-2} mbar

annular anode plasma is never filamented

whereas annular catode plasma (sparse emitters) and even plasma centerpost are filamented

Electrostatic plasma effects

vacuum vessel at GND →

PF coil casings can either be at floating potential or can be connected to:

anode +, cathode -, vessel 0

through ~ 1 Ω resistors

but the electric potential distribution is dominated by the plasma

PF2\3up to anode (1 Ω)\PF4up cathode (10 Ω)

V_{PF4up} ~ 0 V

V_{anode} ~ +45 V

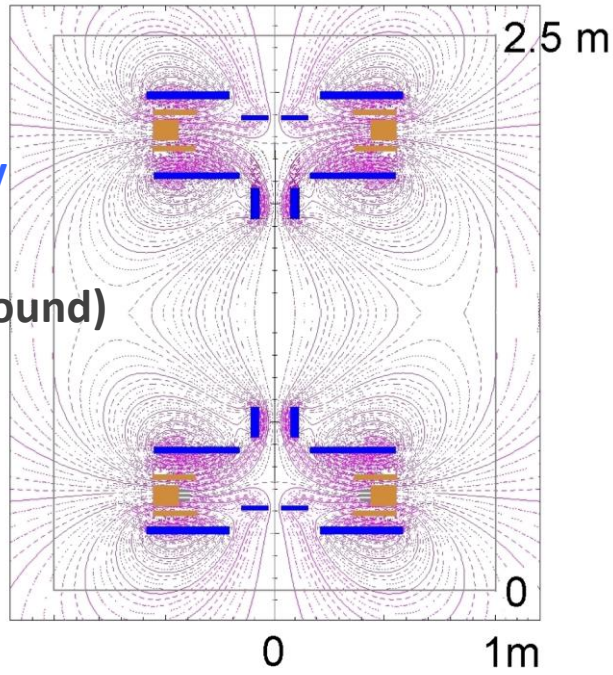
$V_{PF2\text{-}3up}$ ~ +25 V

V_{vessel} = 0 V (ground)

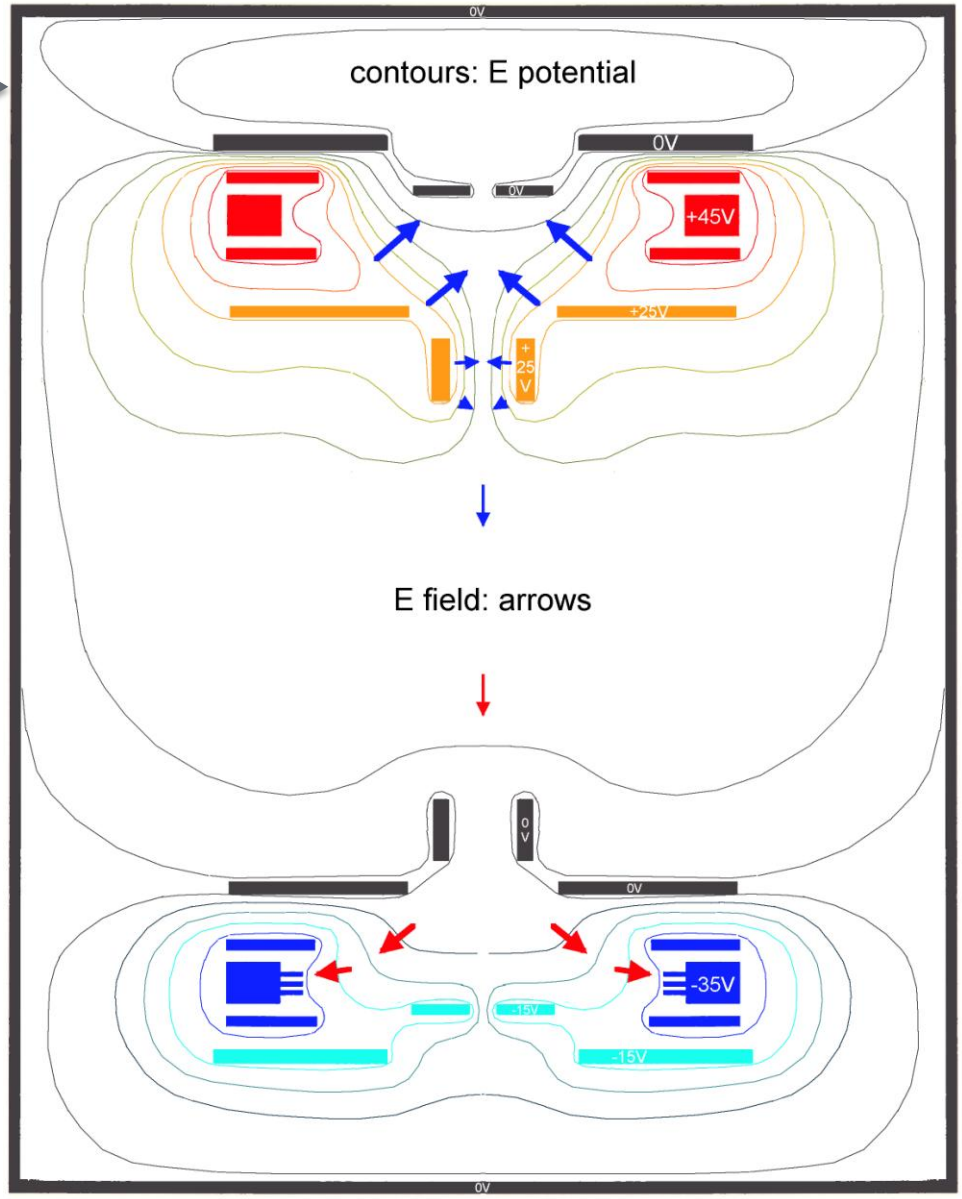
$V_{PF2\text{-}3low}$ ~ 0 V

$V_{cathode}$ ~ -35 V

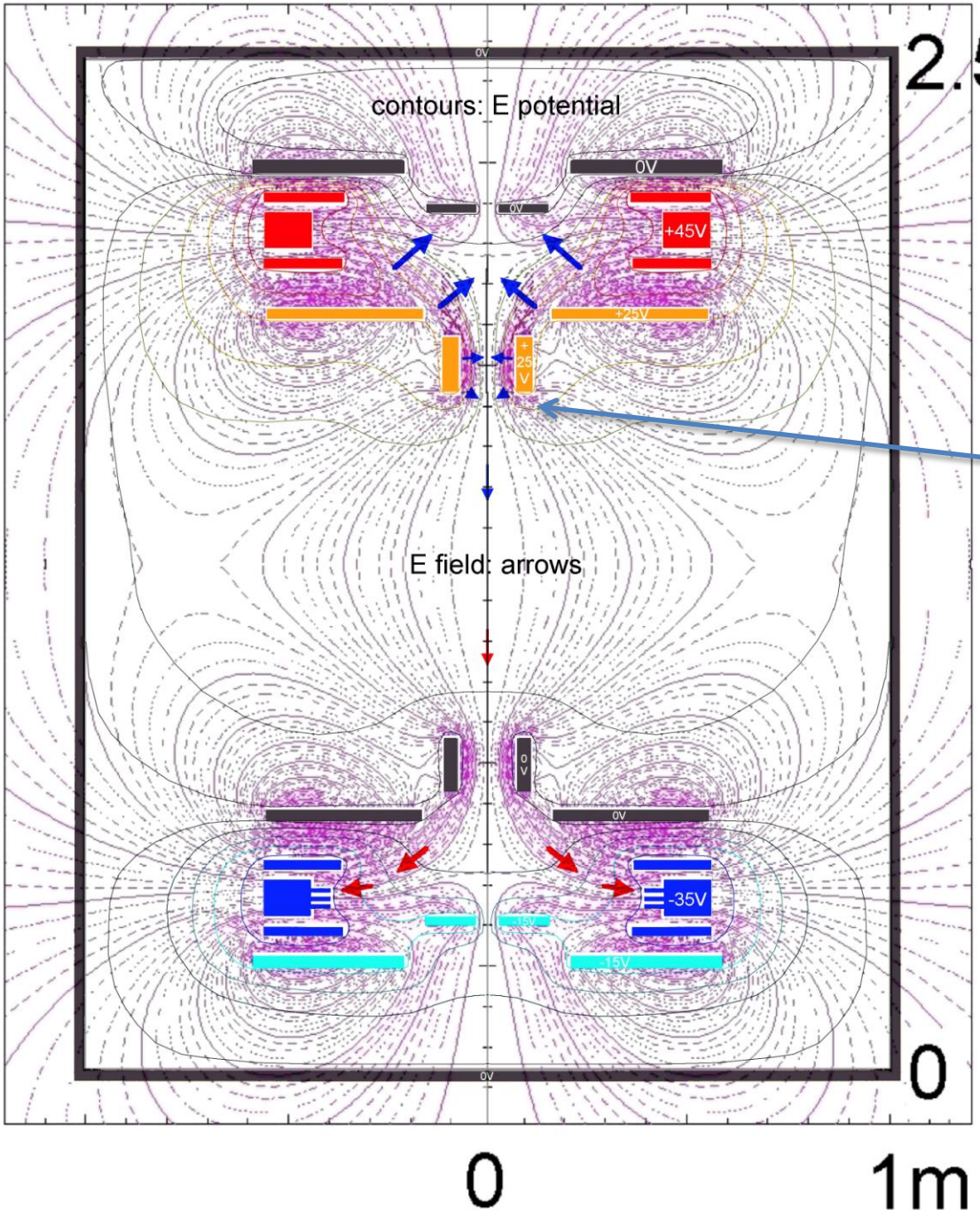
V_{PF4low} ~ -15 V



PF2\3low to GND (1 Ω)\PF4low cathode (0.5 Ω)



distribution of **electric potential** is not up-down symmetric: near both anode and cathode the uppermost PF coil casings is at GND



plasma-induced **electric potential** near the **annular anode** :

E-field is perpendicular to B-field
…E x B azimuthal plasma rotation
…starting from PF2up throttle

$v_{ExB}=(E/B) \sim 10^4$ m/s ~ $v_{drift} \sim v_{thi}$

plasma-induced **electric potential** near the **annular cathode:**

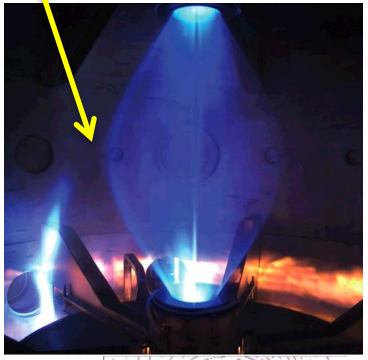
E-field is parallel to B-field
…no E x B plasma rotation

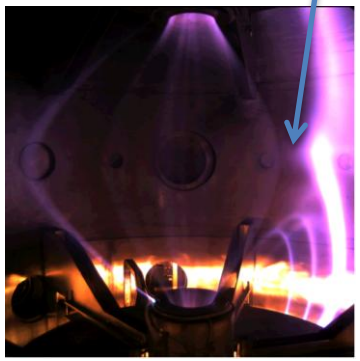
self-organization at work inside annular electrodes plasma…

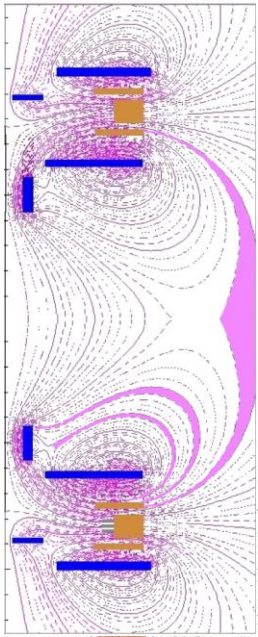
May 2015 annular anode experiment
half of the plasma current: (1kA\2kA)
was going around the required path due to
equatorial X-point inside the vessel

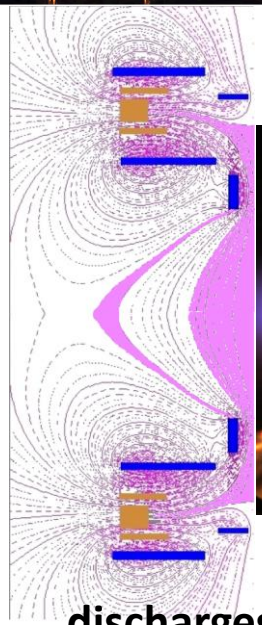
Shot 78

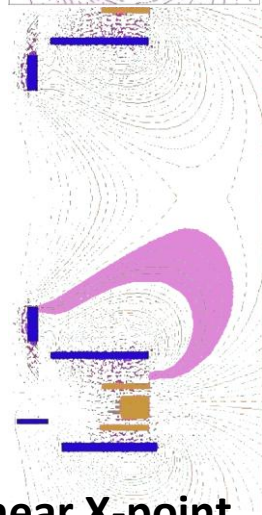
Argon plasma ***Hydrogen plasma***









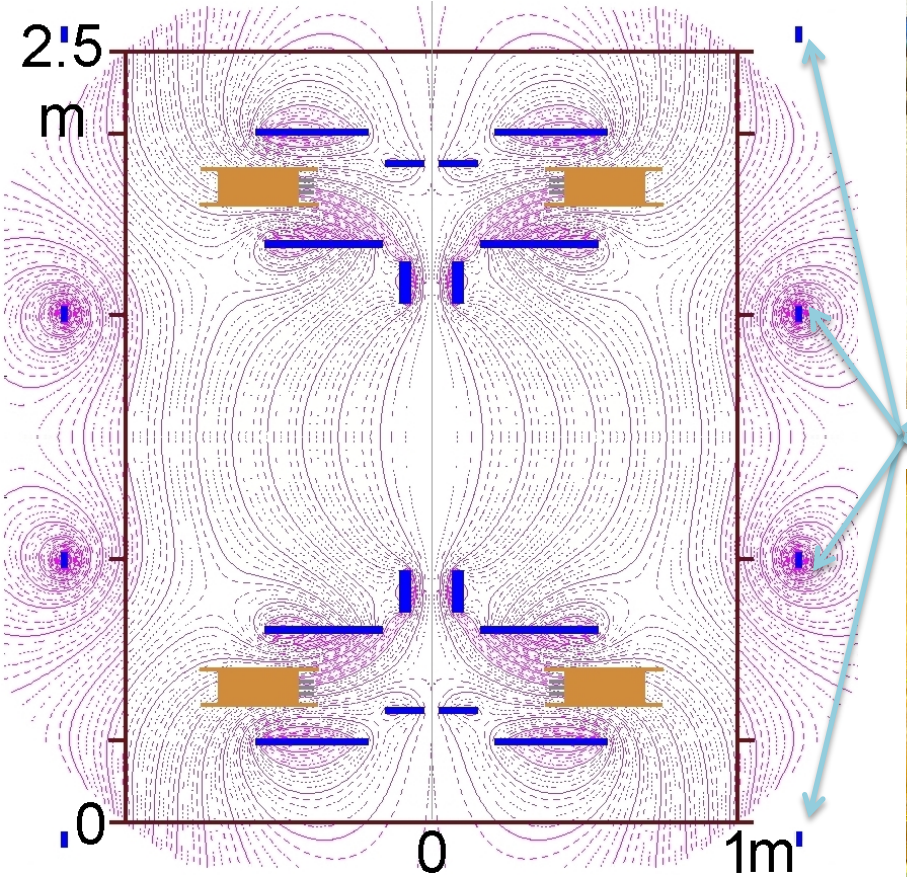


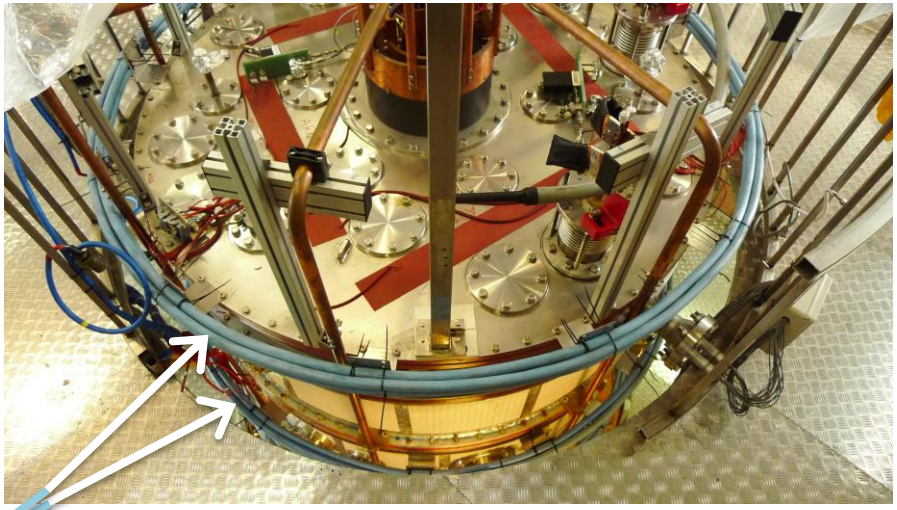
discharges along field lines near X-point

The equatorial X –point has been removed from inside the vessel

4 external PF coils have been added (home-made from spare connection cables)

…and **fed in series with the internal PF coils** (PF coils power supply has sufficient margin)





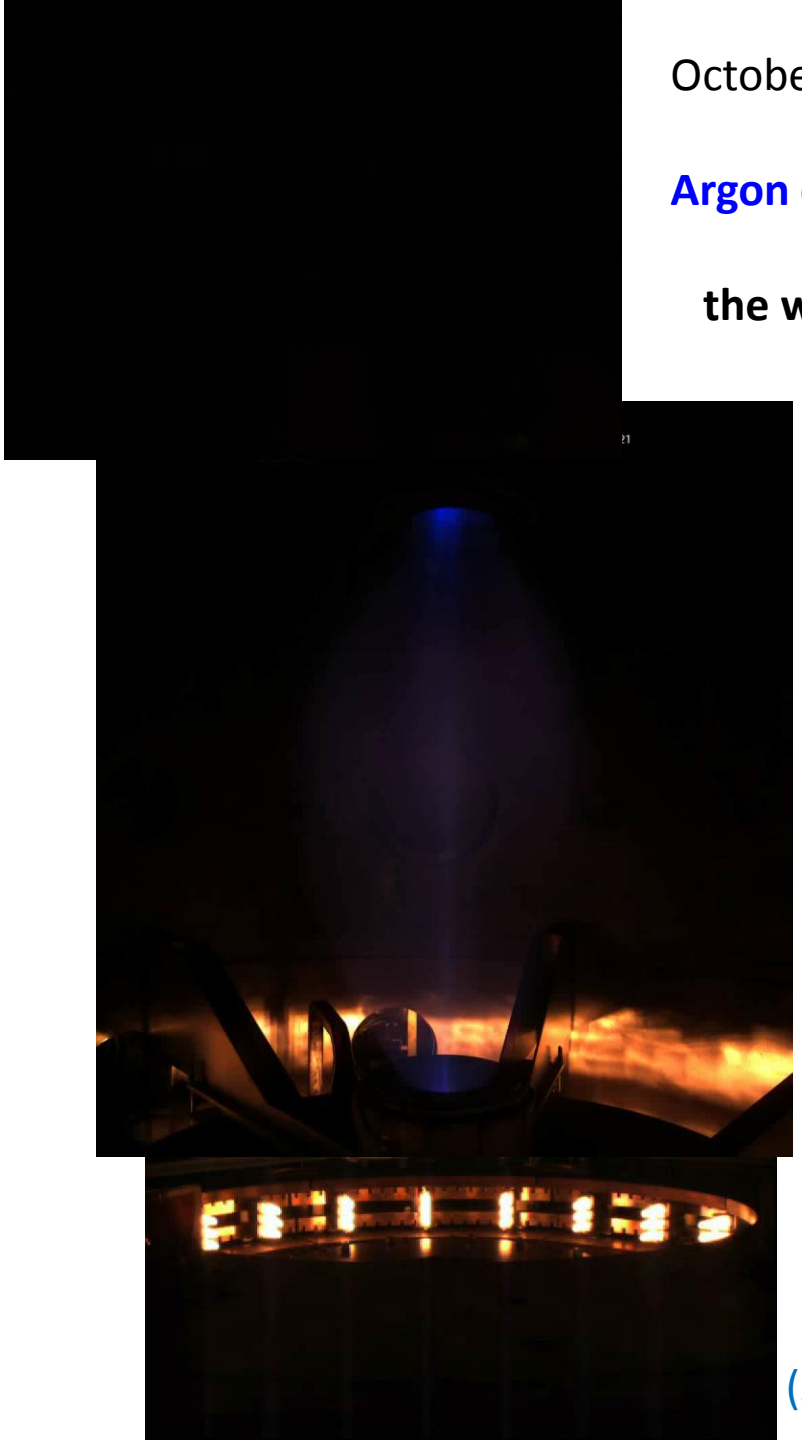
4 additional external PF coils

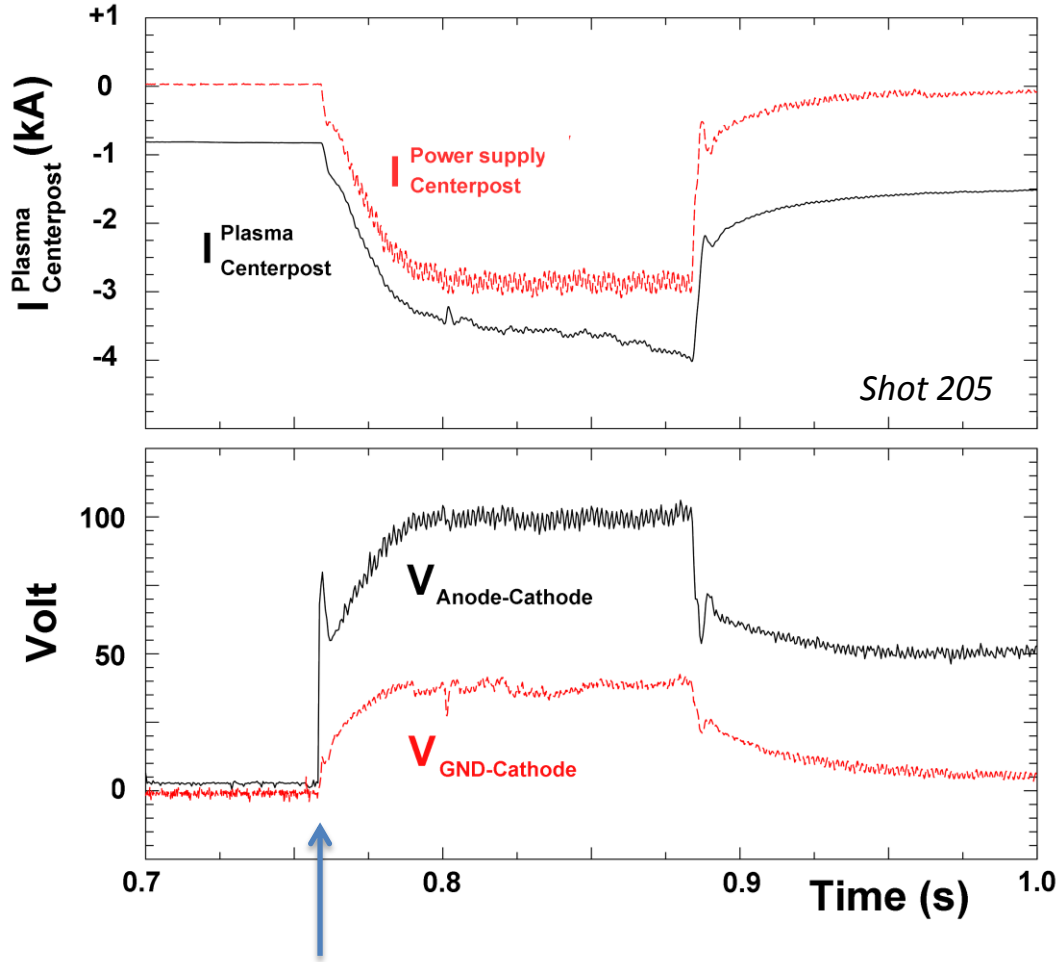
plasma fired after 0.75 s of PF current to allow for skin currente diffusion in Al vessel and SS lids

October 2015 experiments with external PF:

Argon discharge reaching 3 kA for 0.15 s

the whole plasma current runs through both PF2 throttles





plasma fired after 0.75 s of PF current
(skin current time to remove X-point from inside vessel)

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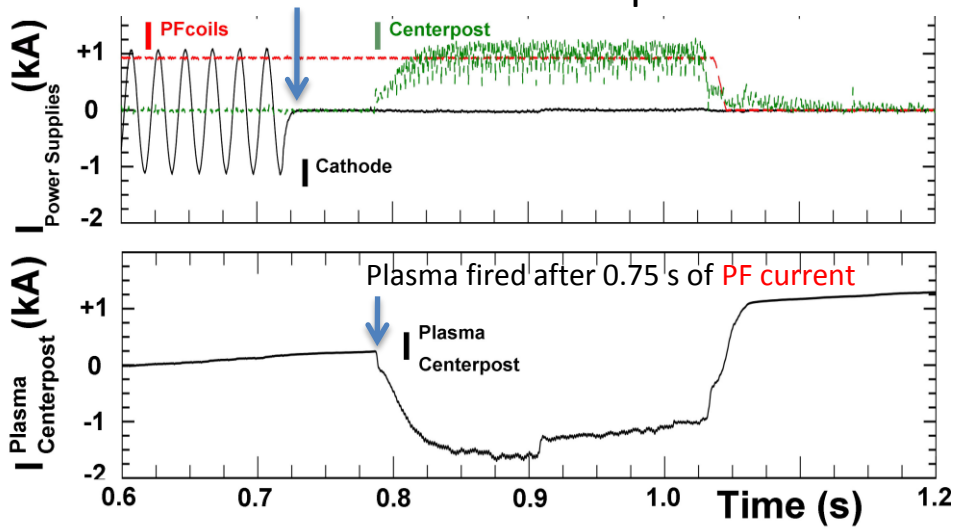
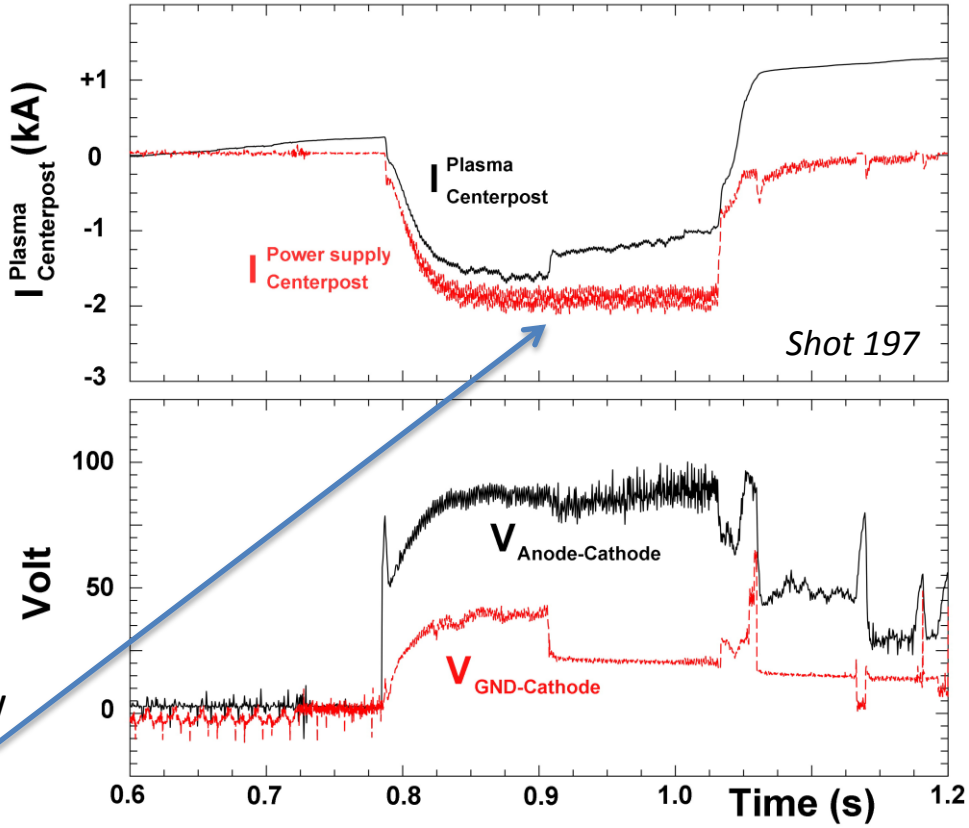
October 2015, external PF

Argon discharge sustained at 2 kA for ~ 0.3 s

however **equatorial hot spots** appear and a few hundreds Ampere are lost from main plasma

cathode is switched off < 0.1 s before plasma current





Plasma current outer paths for I > 3 kA

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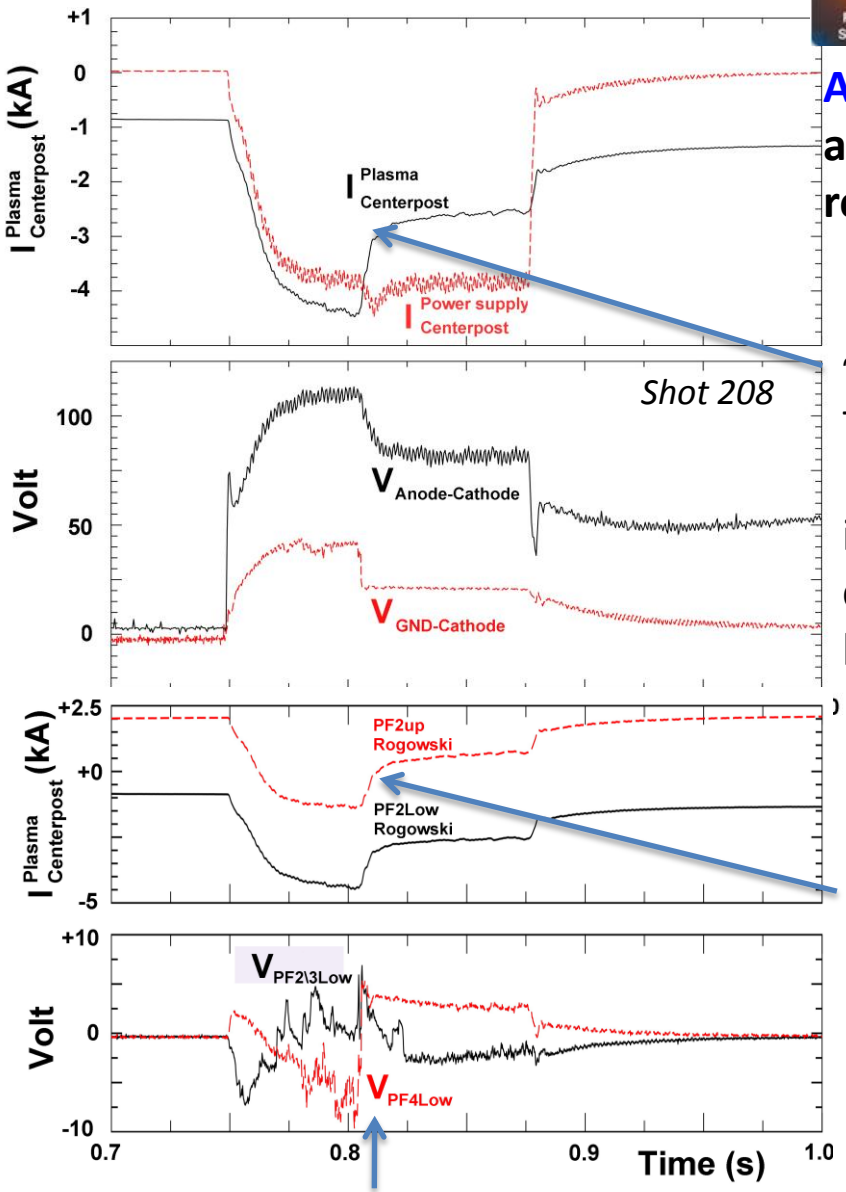


Argon plasma aiming to 4 kA reaches 3.5 kA

~ 1.5 kA lost from main plasma

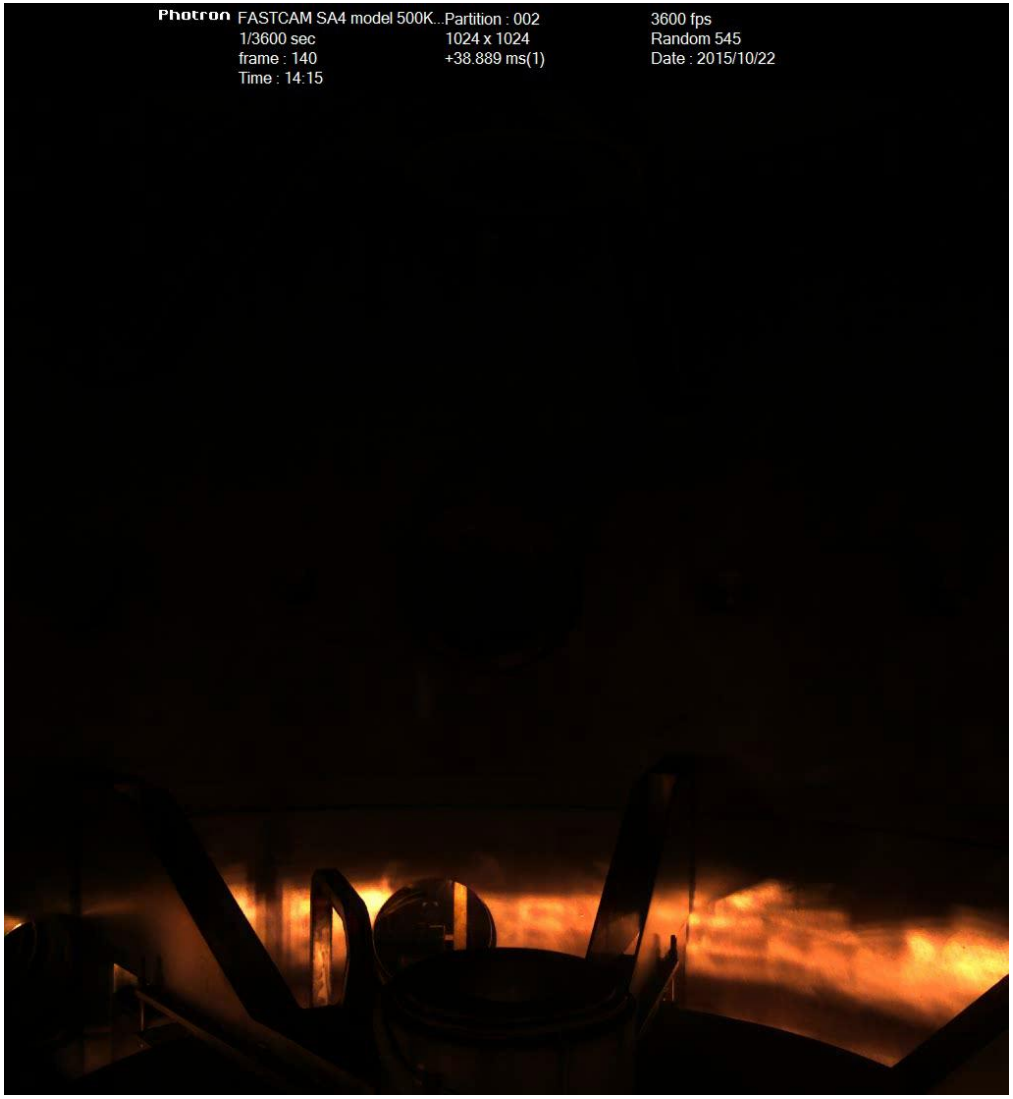
in discharge from cathode down to lid\vessel

plasma current lost on both PF2 throttles

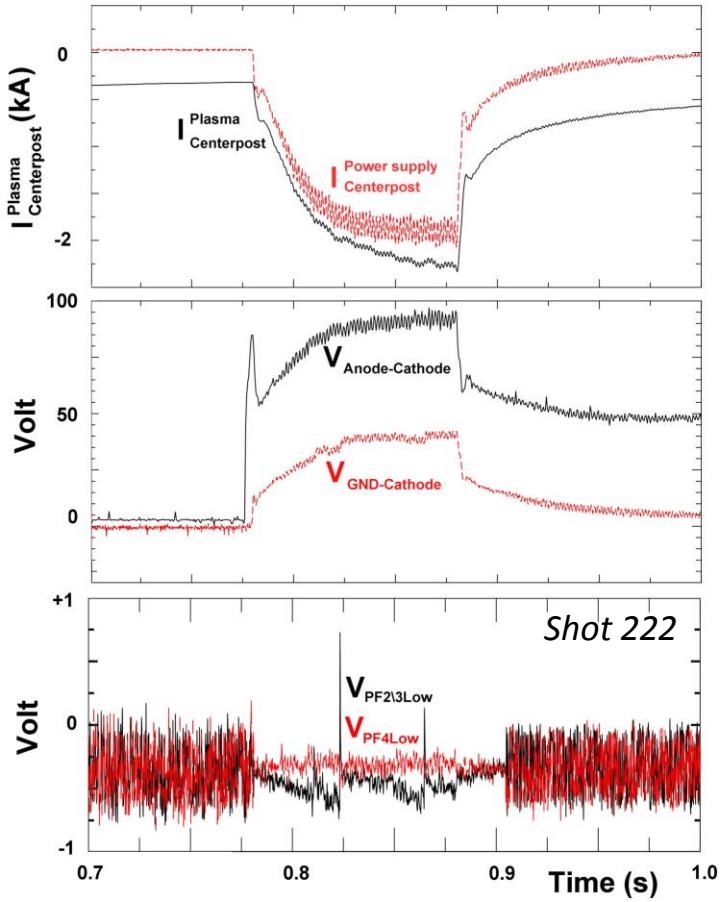
10 V spikes appearing on floating voltages on lower PF coils are associated with plasma current outer path

Removal of equatorial hot spots through straighter grounding of low PF coils

Argon discharge at 2 kA



to avoid voltage spikes on low PF coils
PF2\3low + PF4low connected to GND
through much smaller (16 mΩ) resistors



Equatorial hot spot eliminated, voltage spikes have been reduced to 1 V amplitude on PF2/3low
only small sparks from PF2/3low remain in correspondence to 1V PF2/3low spikes

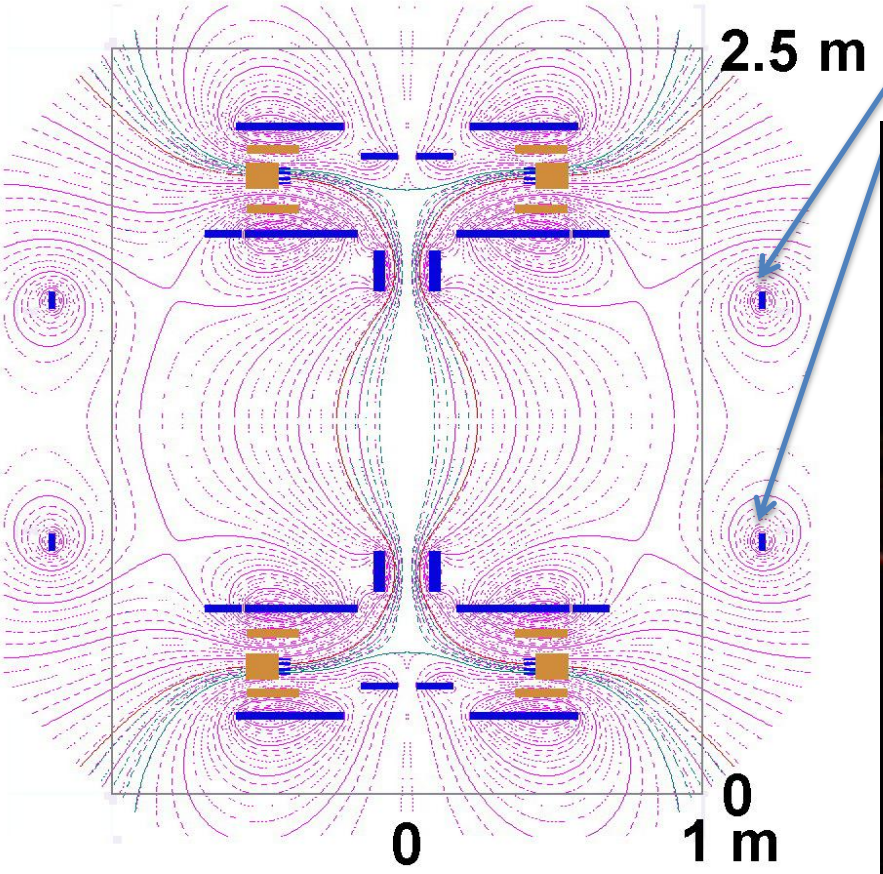
Magnetic tayloring in order to have a better filling of electrodes

when plasma current takes outer path cathode seems less emitting

plasma current 3.5 kA

plasma current 2kA, 1.5 kA lost

Shot 208



current flows only in external PF near equator

cathode seems better filled at all times

Shot 227

Straighter grounding of lower PF coils and better filling of cathode flowing current only in the two external PF coils nearer to equator

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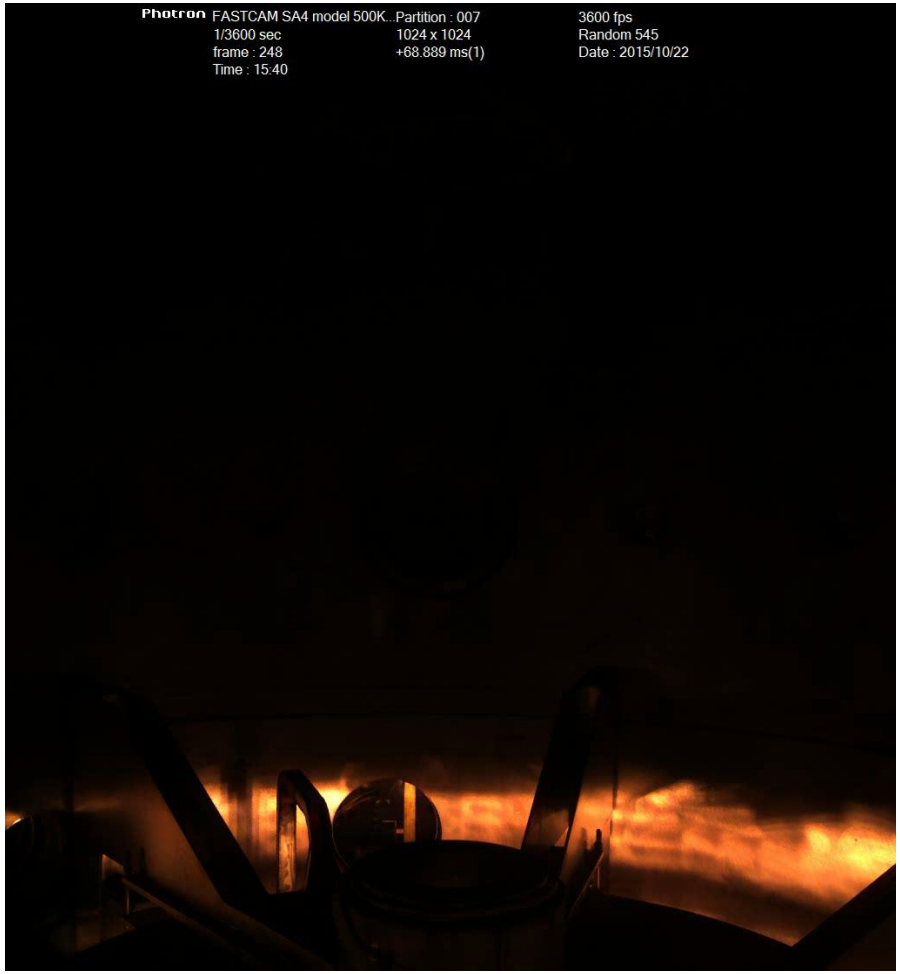
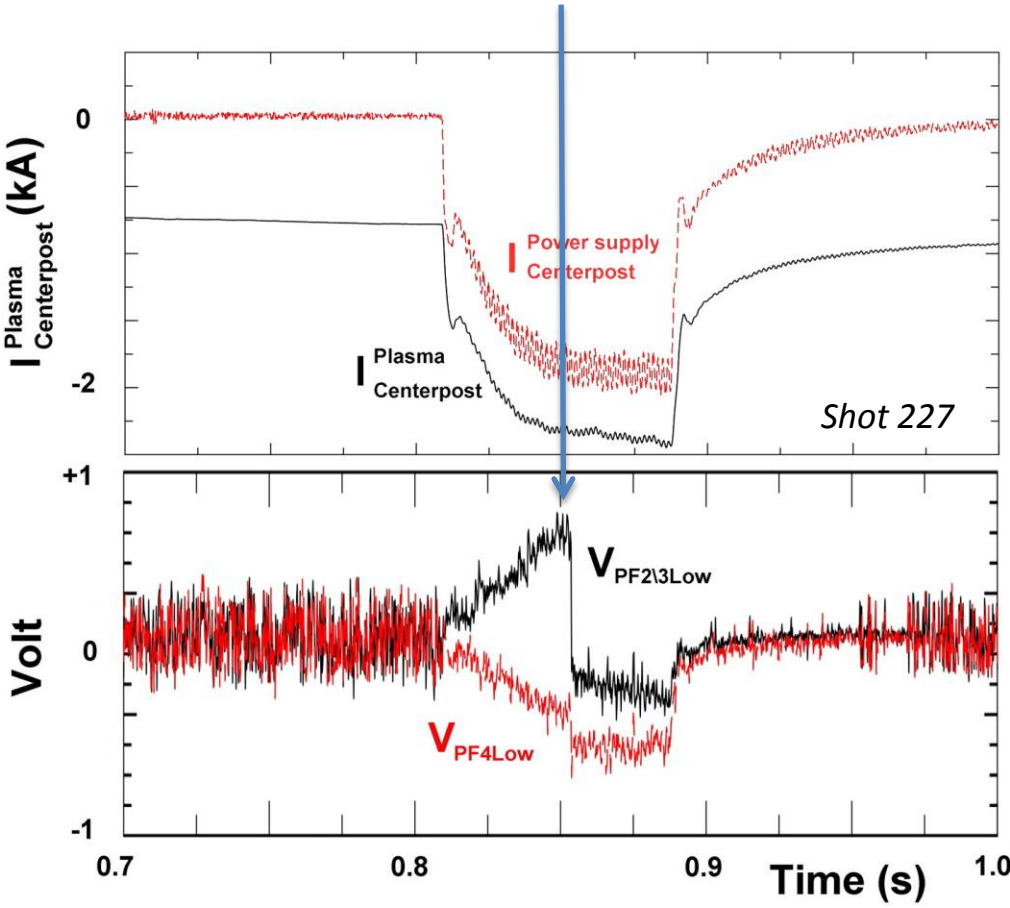
voltage spikes have been eliminated on PF2/3low, after 1 V amplitude jump even small sparks vanish

Argon discharge at 2 kA



voltage jump does not lose plasma current
very quiet plasma at 2 kA after voltage jump



Conclusions

20 years after 2nd ST Workshop – Princeton (1995) the "aggressive proposal" PROTO-SPHERA is producing its first centerpost plasmas *…better late than never! …迟到总比不到好!*

Hollow anode surprise, no anode arc attachment (electrostatic potential, E x B plasma rotation)

(1/3) of the due current (10 kA) achieved, 3 kA sustained in Argon plasma

To achieve full current of 10 kA requires patient learning of how to tailor boundary conditions:
- electrostatic potential by connecting PF coils casings, built floating with respect to the vessel
- magnetic field by additional coils external to the vessel

After Argon centerpost is tamed (80 V breakdown), start fight with Hydrogen centerpost (180 V)

If full current of plasma centerpost(10 kA) is achieved and sustained with 54 sparcely spaced emitting filaments, then full current (60 kA) will be even better achieved with 324 filaments

First stage of PROTO-SPHERA is only an appetizer for the production of the Spherical Torus

…放龙入海! …give a chance to the dragon to show his endowments into the sea!