

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

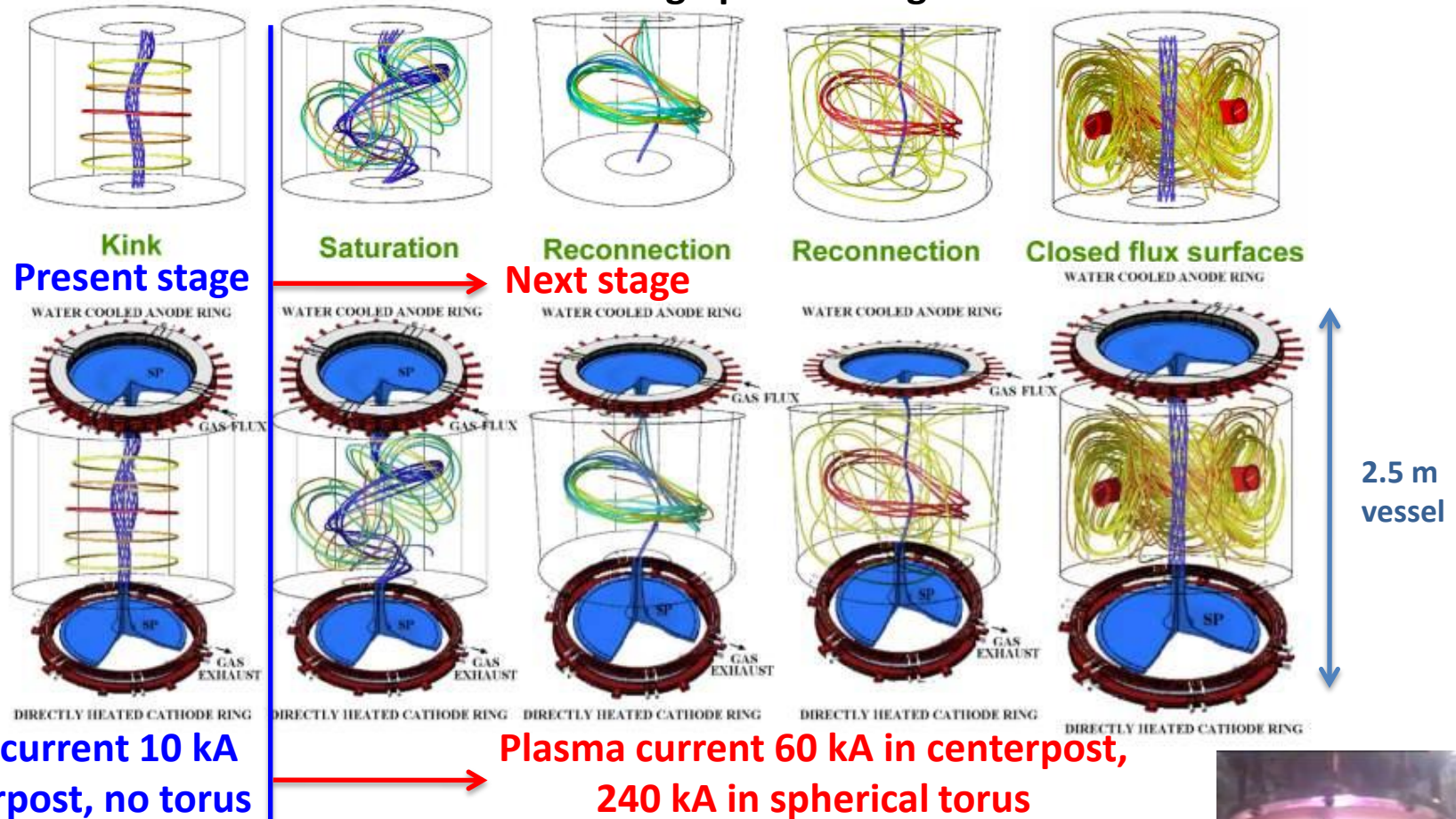
Tailoring of electrostatic potential by connecting PF coils casings, built as floating

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



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



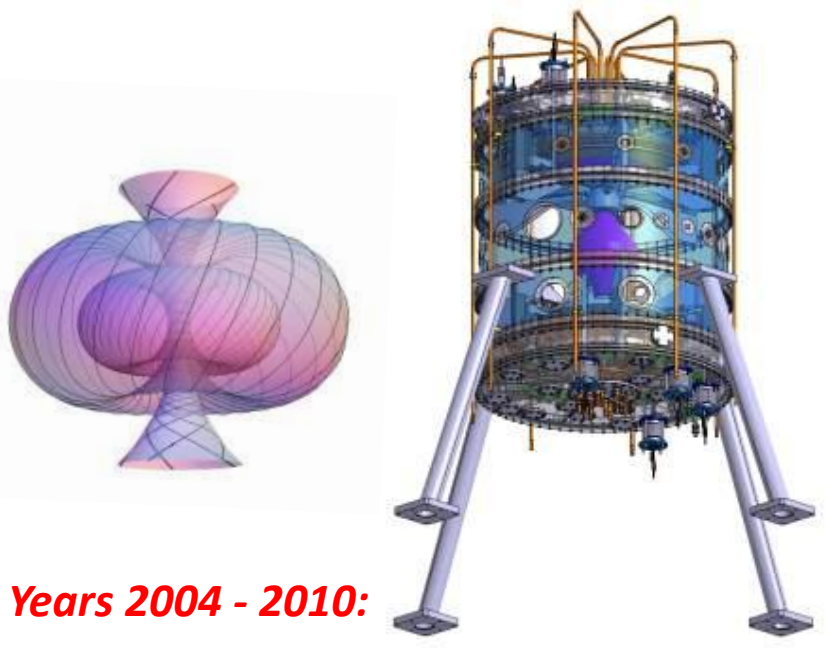
Years 1995 - 2002: Idea & design
1995 - 2nd ST Workshop Princeton
2002 - International Workshop Frascati

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

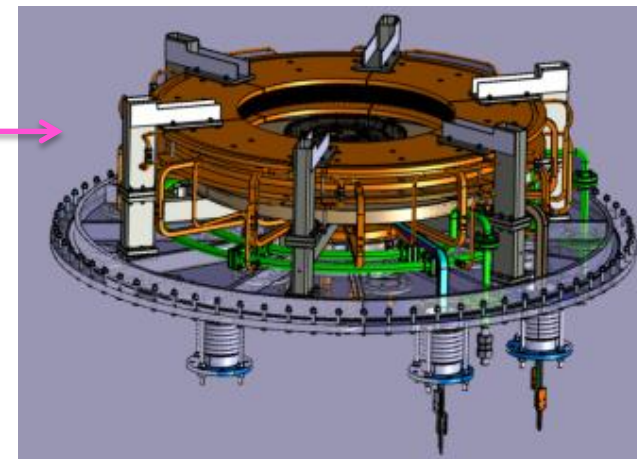
annular anode



anode

plasma current must run through both PF2 throttles

cathode



annular cathode

8 PF coils in series inside the machine

Stainless steel up\down new extensions

PF4up

PF3up

PF2up

Aluminium cylindrical vessel
START

PF2low

PF3low

PF4low

Stainless steel up\down new lids

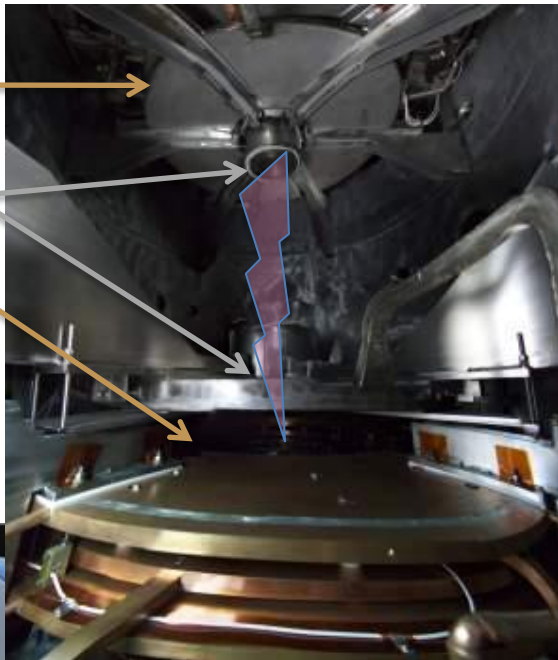
vacuum vessel is GND potential

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

Anode

PF coils

Cathode



To fire the plasma centerpost
3 Power supplies are required

- Cathode heating, rotating 6-phase: $6 \times (1.7 \text{ kA}, 25 \text{ V})_{\text{rms}}$
- PF coils: $2 \text{ kA}, 350 \text{ V}$
- Plasma centerpost: $10 \text{ kA}, 350 \text{ V}$



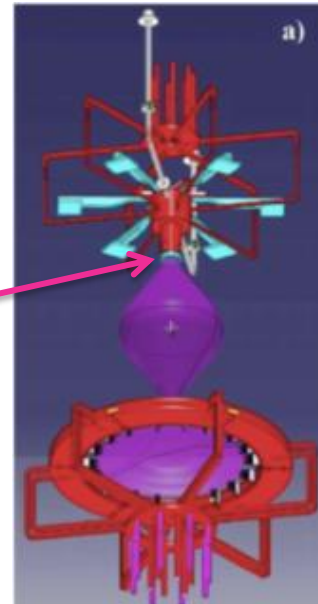
Electrical power supplies built by EEI of Vicenza, cost 0.7 M€

Years 2011 - 2014:

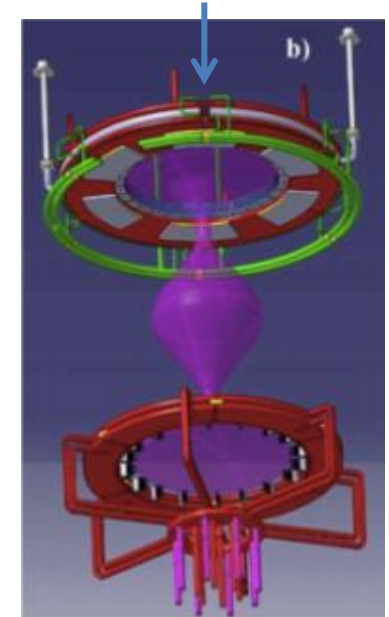




2014 cylindrical anode



2015 annular anode



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 cylindrical anode
was just a source of troubles

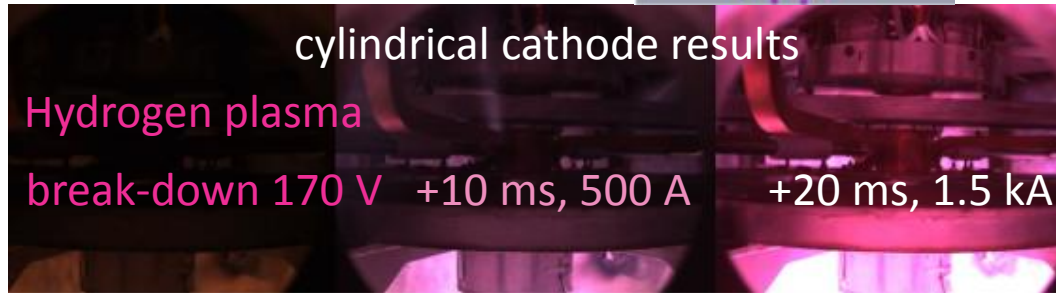
cylindrical cathode results

Hydrogen plasma

break-down 170 V +10 ms, 500 A

+20 ms, 1.5 kA

anode camera



centerpost camera



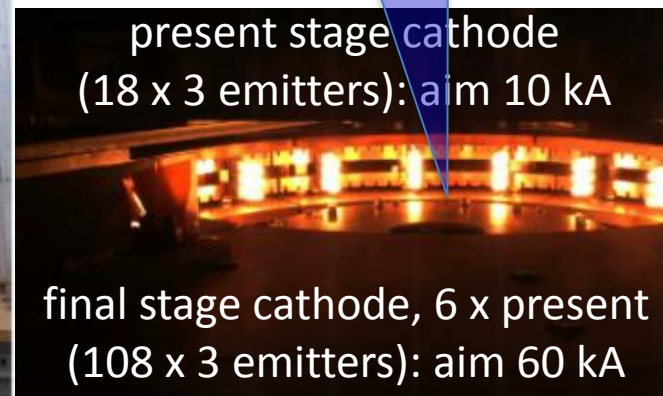
May 2015 annular
anode lowered
on top of machine





up: hollow gas-puffed anode

down: 3000° K heated cathode
present stage cathode
(18 x 3 emitters): aim 10 kA



final stage cathode, 6 x present
(108 x 3 emitters): aim 60 kA
“Caduceus”-like emitting spirals
have survived ~ 1000 cycles

PROTO-SPHERA CR-ENEA Frascati

10/20/2014

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

Argon plasma: break-down 80 V



annular anode plasma is never filamented



**whereas annular cathode 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 $\sim 1 \Omega$ resistors

but the electric potential distribution is dominated by the plasma

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

$V_{PF4up} \sim 0 \text{ V}$

$V_{anode} \sim +45 \text{ V}$

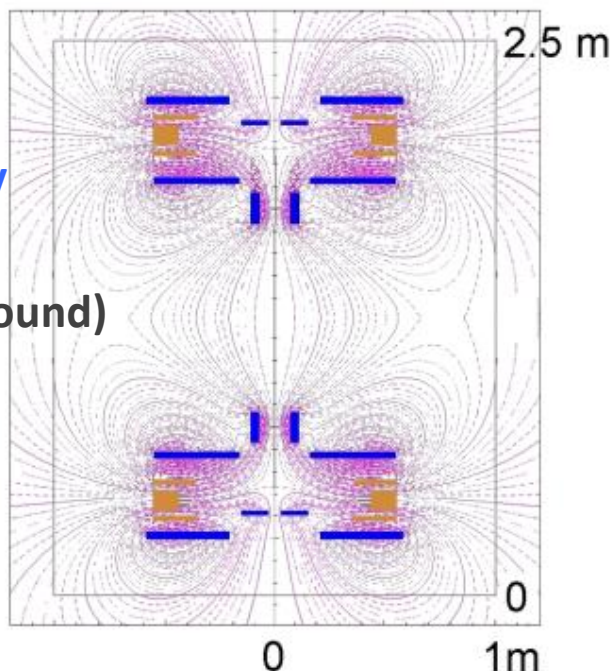
$V_{PF2-3up} \sim +25 \text{ V}$

$V_{vessel} = 0 \text{ V (ground)}$

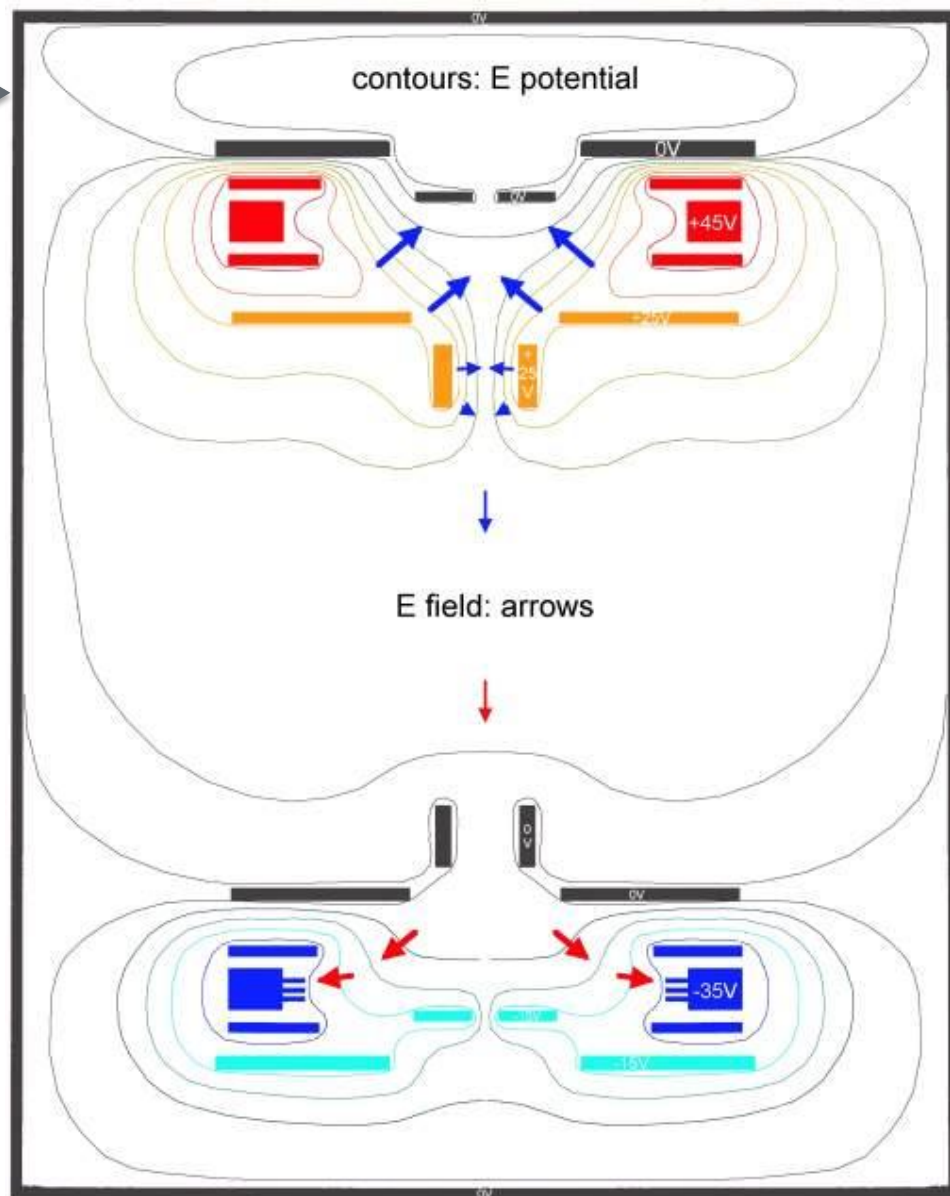
$V_{PF2-3low} \sim 0 \text{ V}$

$V_{cathode} \sim -35 \text{ V}$

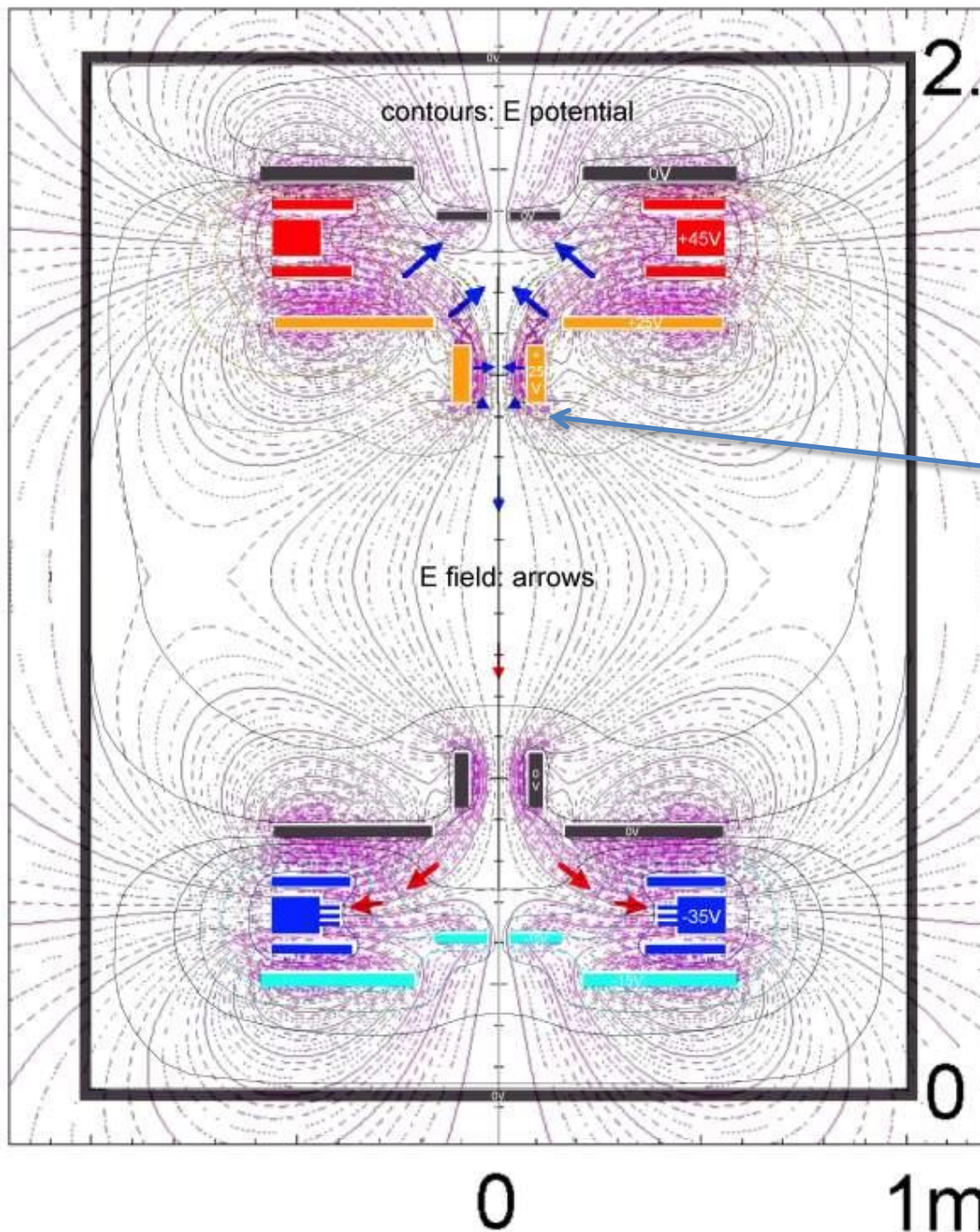
$V_{PF4low} \sim -15 \text{ V}$



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



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**
... **$E \times B$** **azimuthal plasma rotation**
...starting from PF2up throttle

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

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

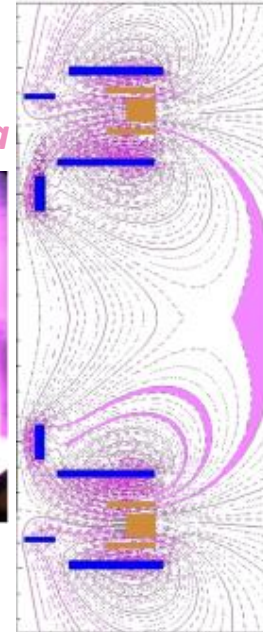
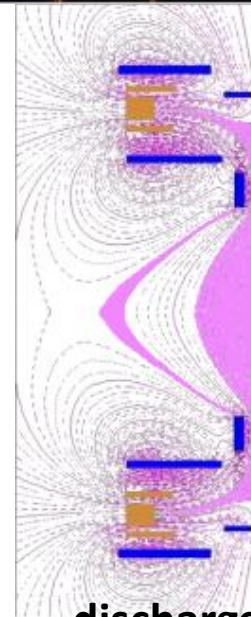
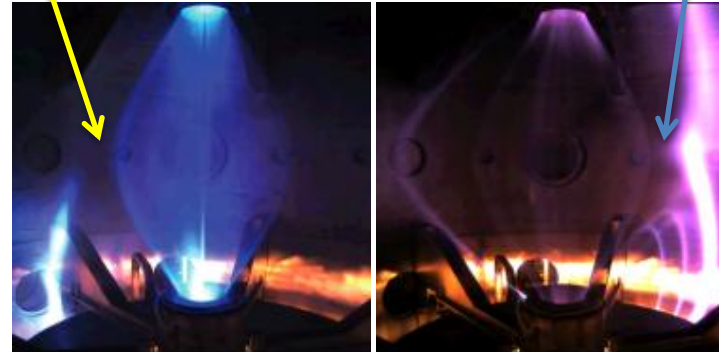
E-field is parallel to **B-field**
...no $E \times B$ plasma rotation

*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

Argon plasma *Hydrogen plasma*



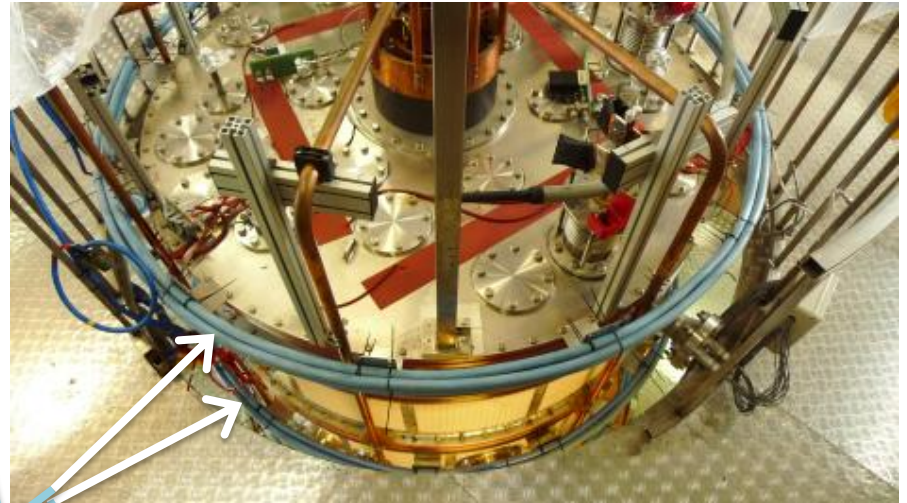
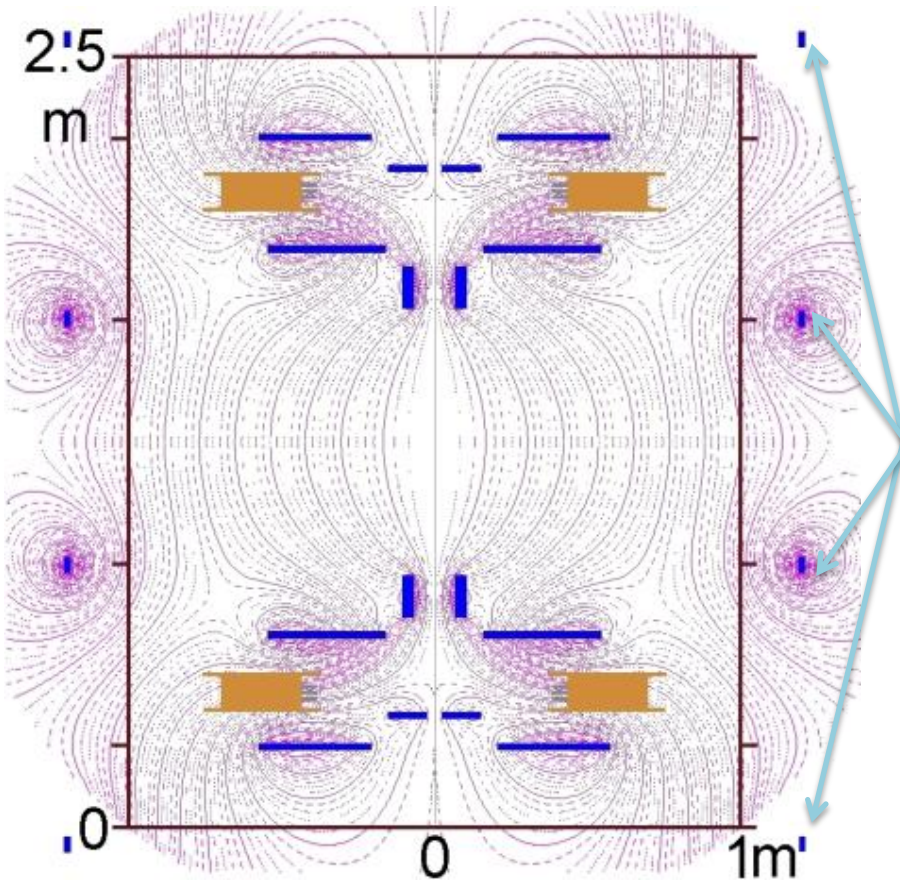
Shot 78

discharges along field lines near X-point



Photron FASTCAM SA4 model 500K_Partition : 006
1/3600 sec 1024 x 1024 3600 fps
frame : 138 1024 x 1024 Random 363
Time : 16.07 +38.333 ms(1) Date : 2015/6/17

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

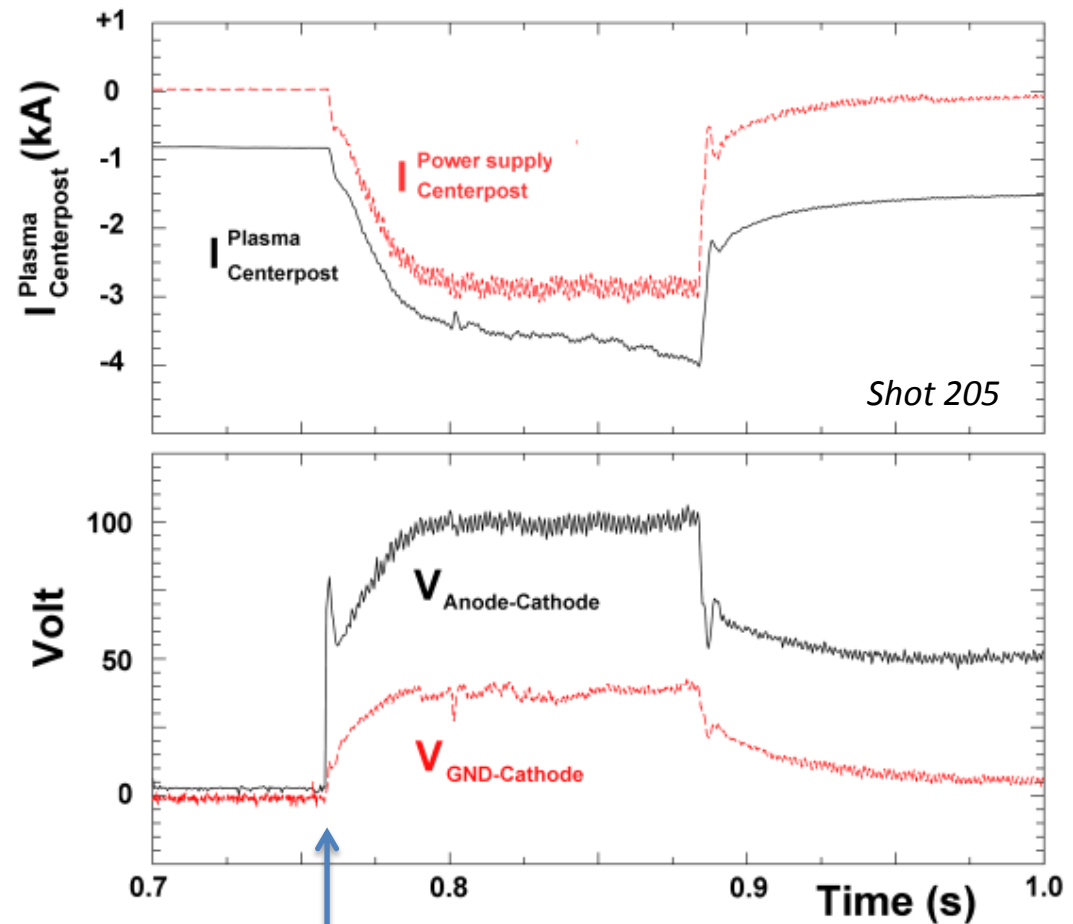


plasma fired after 0.75 s of PF current to allow for skin current diffusion in Al vessel and SS lids

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)

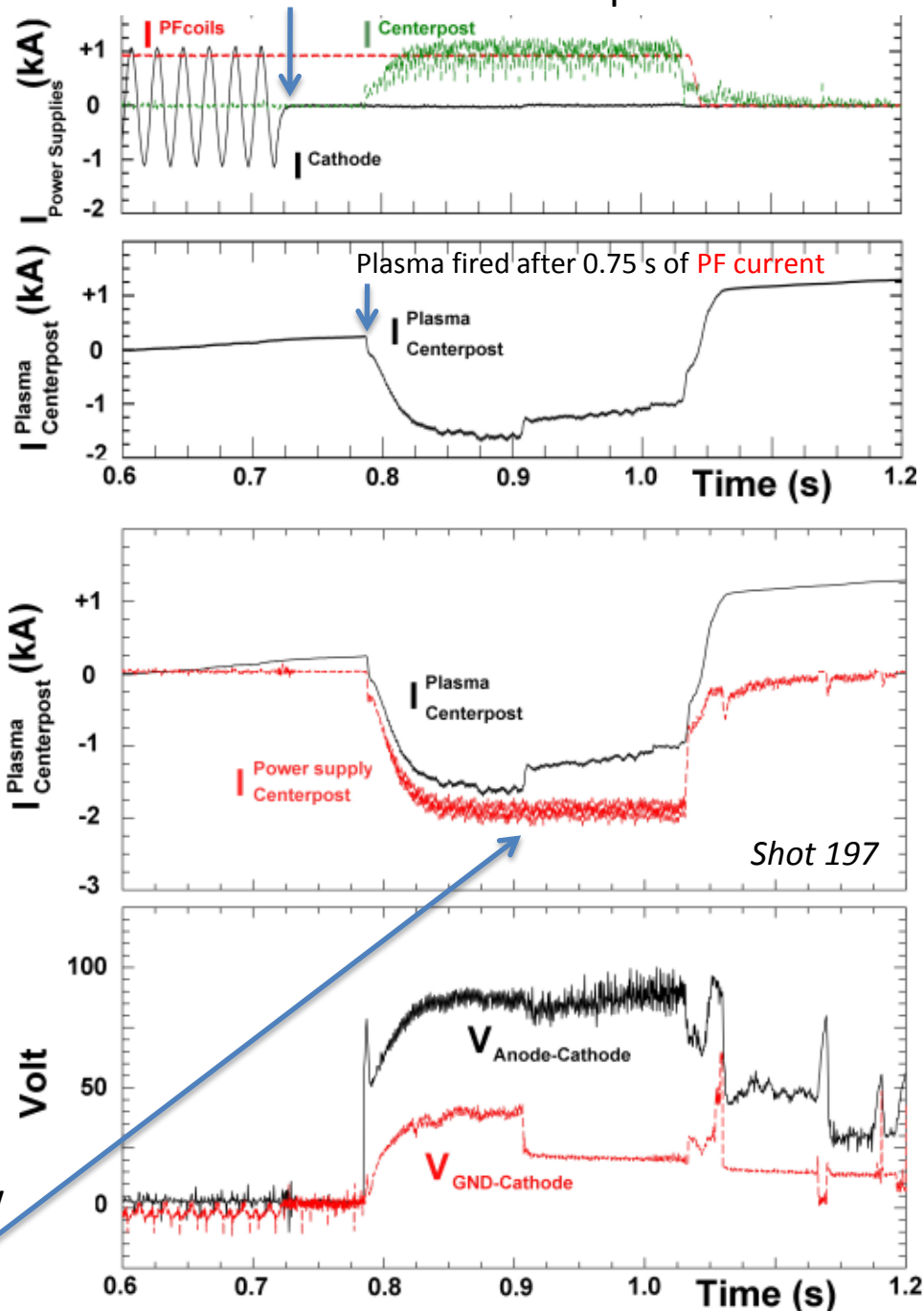


October 2015, external PF

Argon discharge sustained at 2 kA for ~ 0.3 s



cathode is switched off < 0.1 s before plasma current

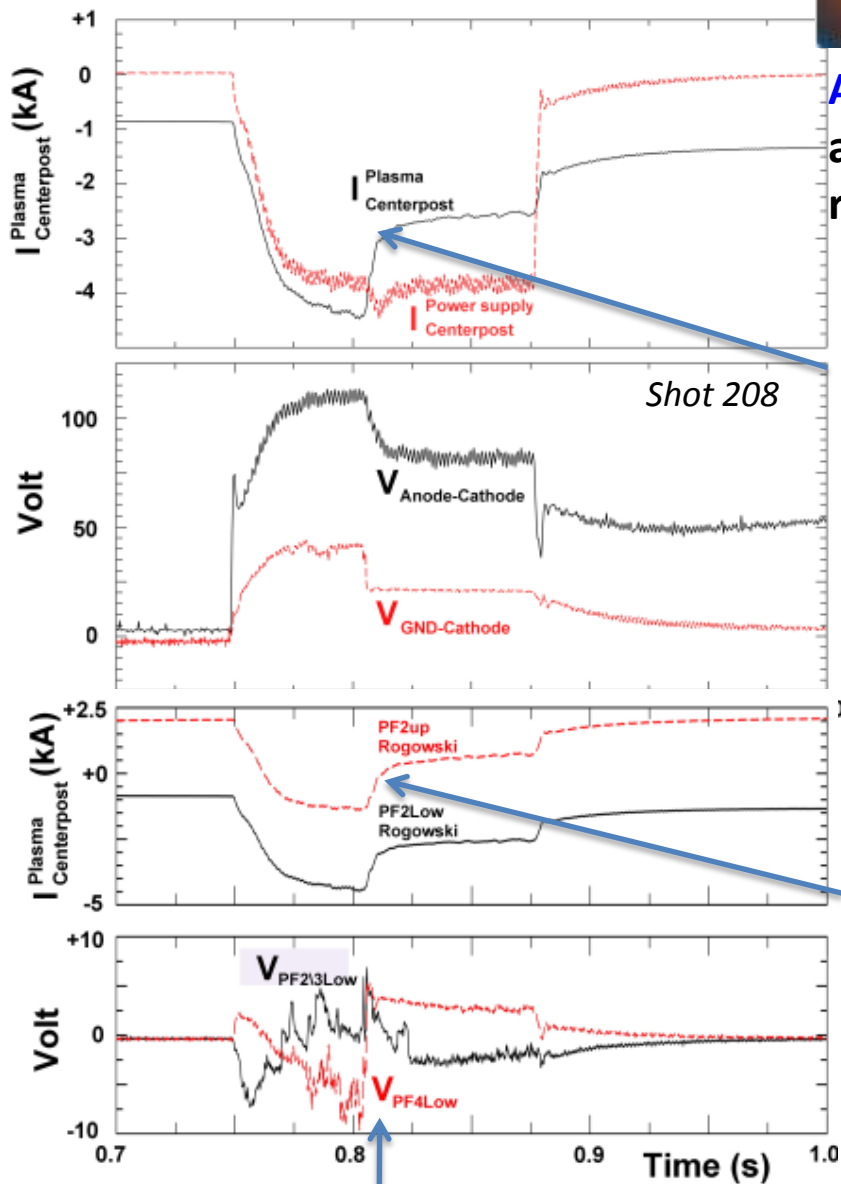


however **equatorial hot spots** appear and a few hundreds Ampere are lost from main plasma

Plasma current outer paths for $I > 3$ kA



Argon plasma
aiming to 4 kA
reaches 3.5 kA



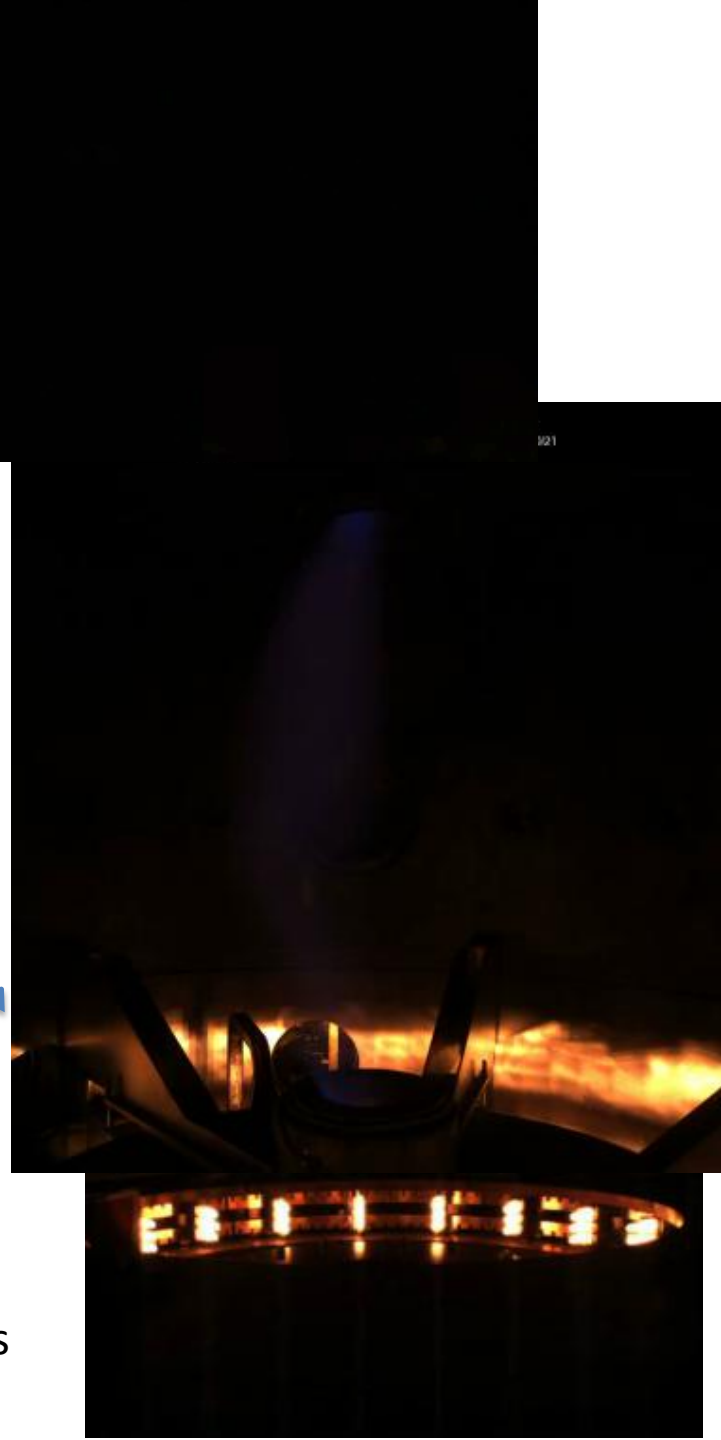
Shot 208

~ 1.5 kA lost
from main plasma

in discharge from
cathode down to
lid\ vessel

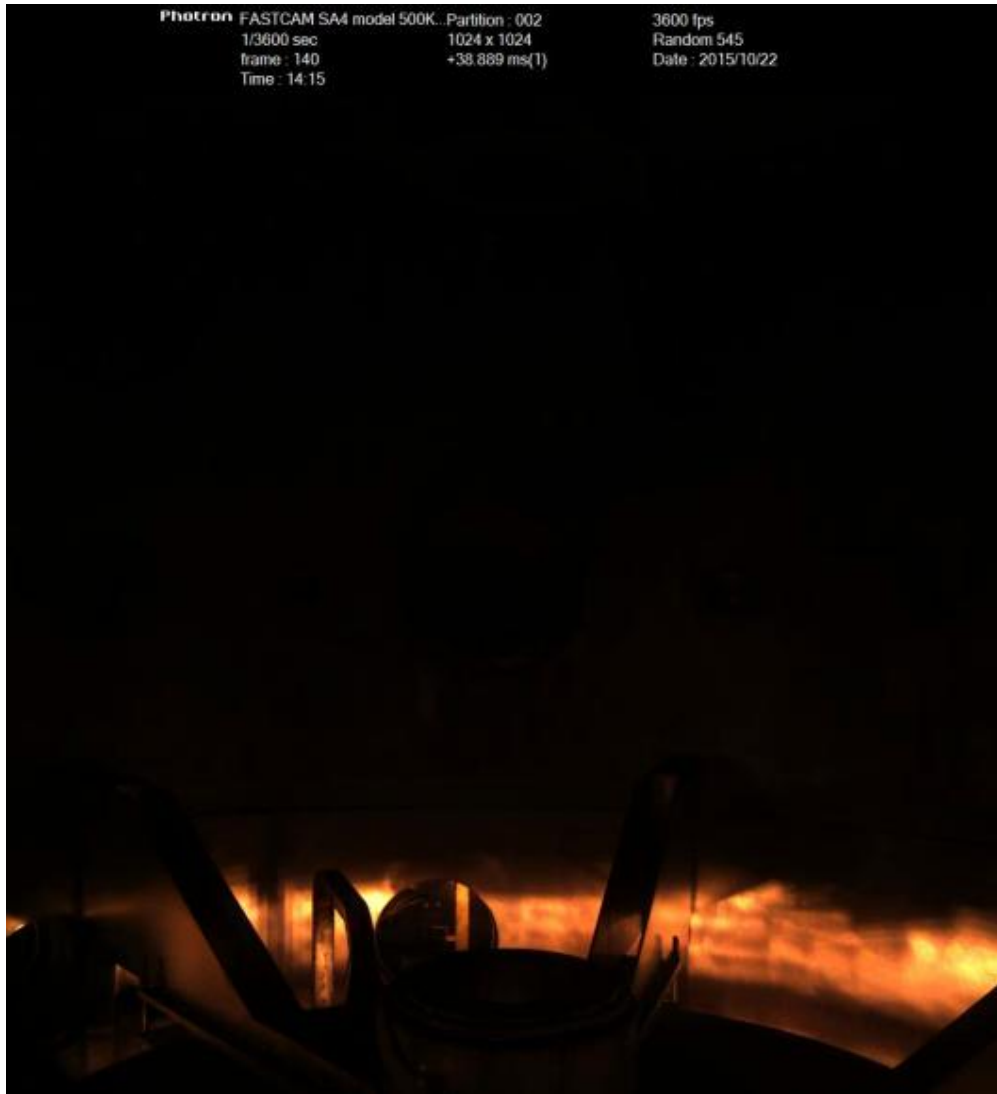
plasma current
lost on both
PF2 throttles

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

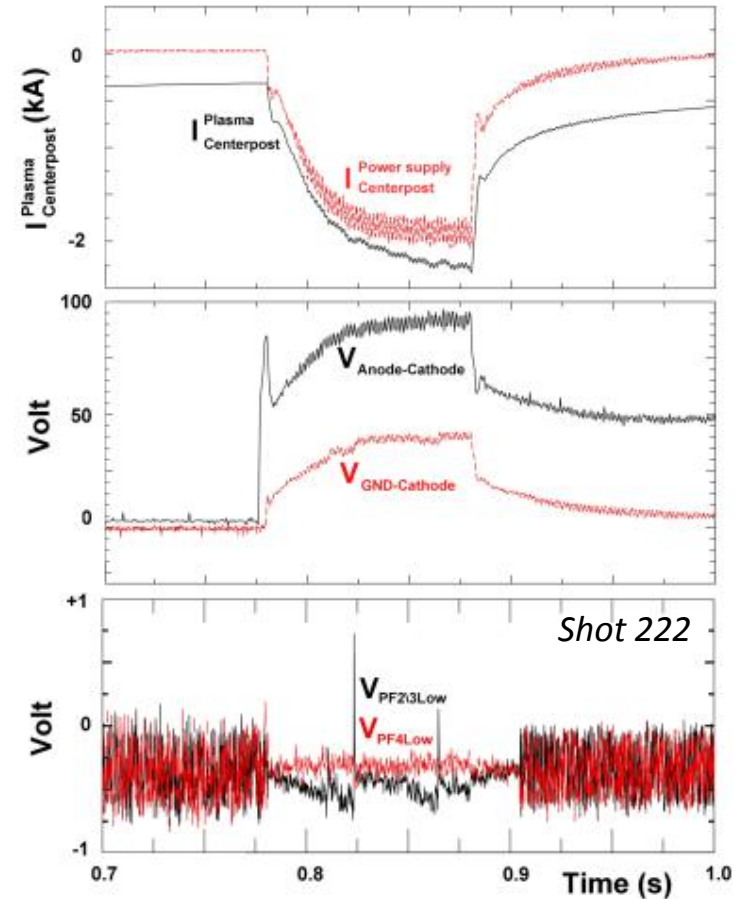


Removal of equatorial hot spots through straighter grounding of low PF coils

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

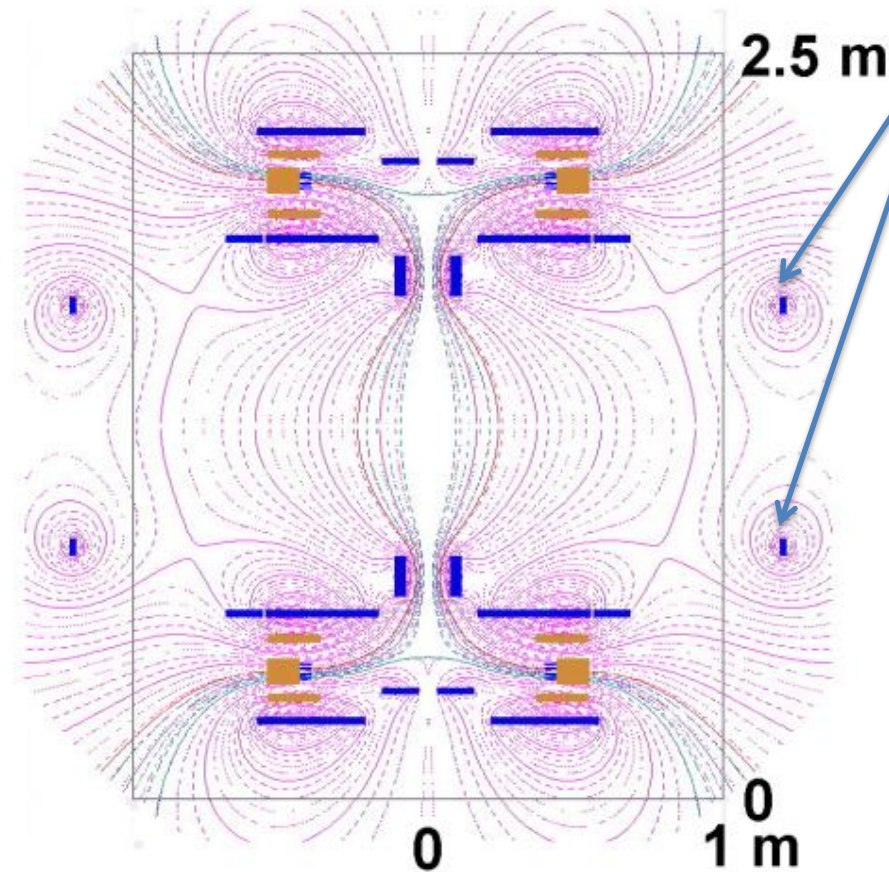
Magnetic tailoring in order to have a better filling of electrodes

when plasma current takes outer path cathode seems less emitting

plasma current 3.5 kA

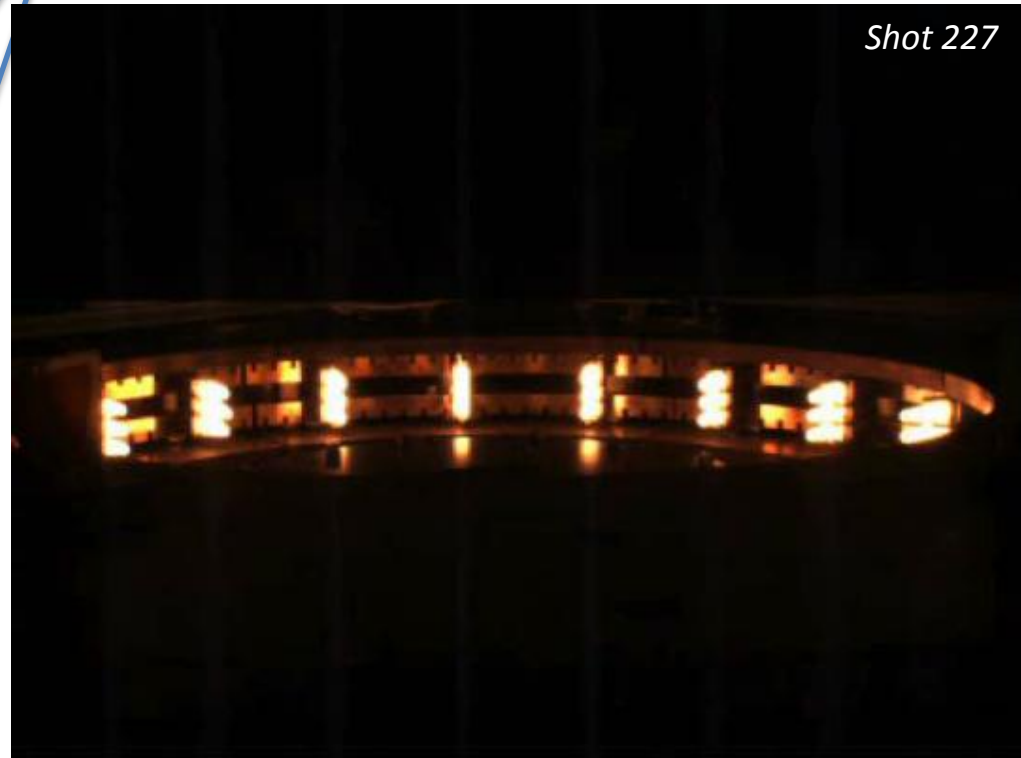
plasma current 2kA, 1.5 kA lost

Shot 208



current flows only in external PF near equator
cathode seems better filled at all times

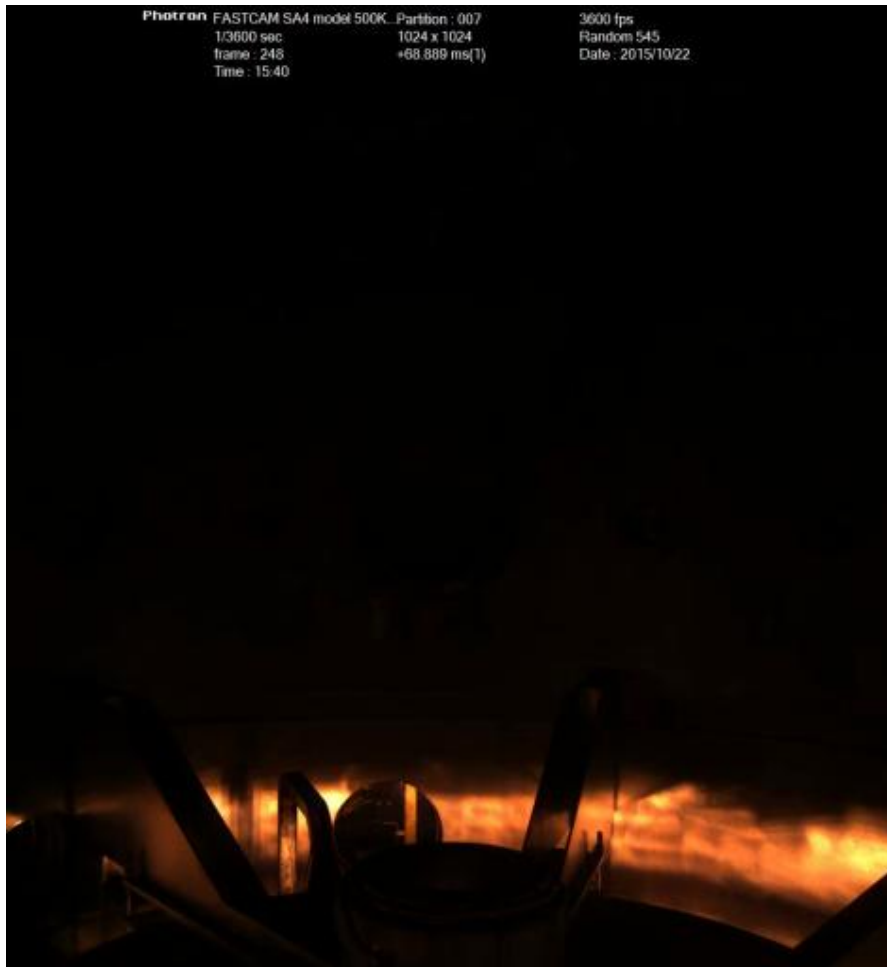
Shot 227



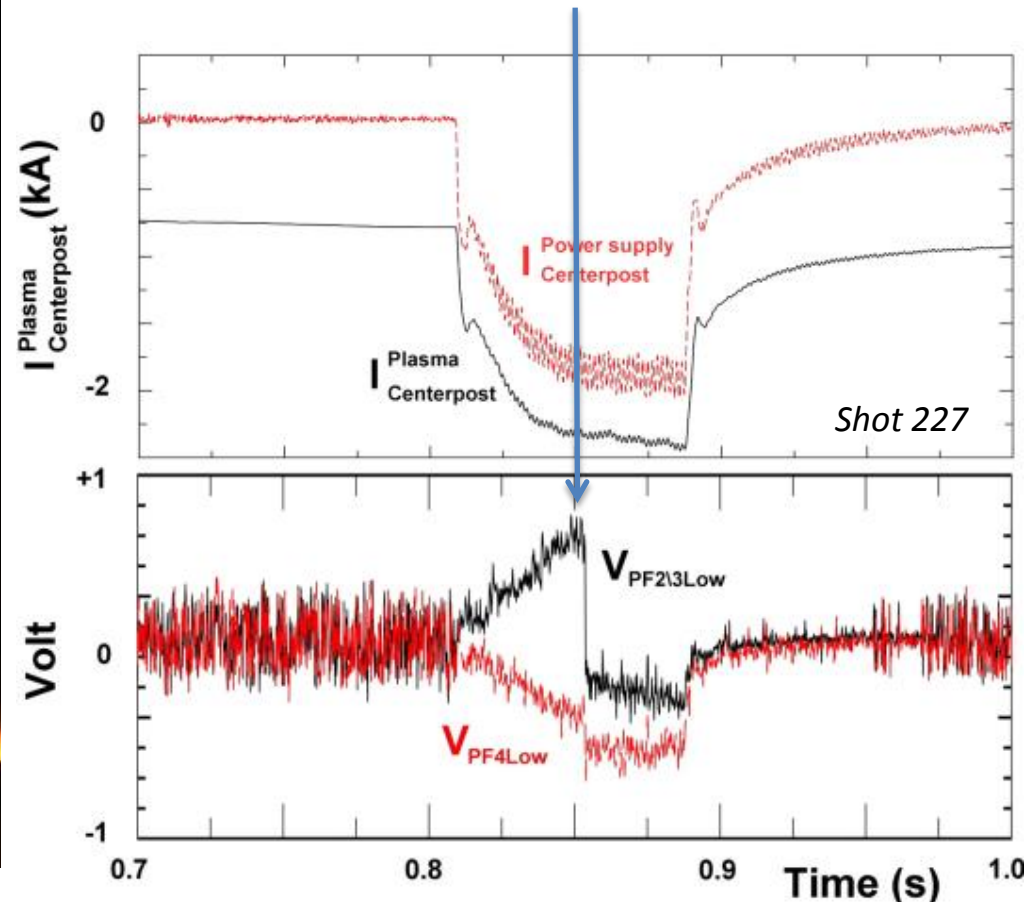
Straighter grounding of lower PF coils and better filling of cathode flowing current only in the two external PF coils nearer to equator

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, $E \times B$ 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 sparsely 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!*