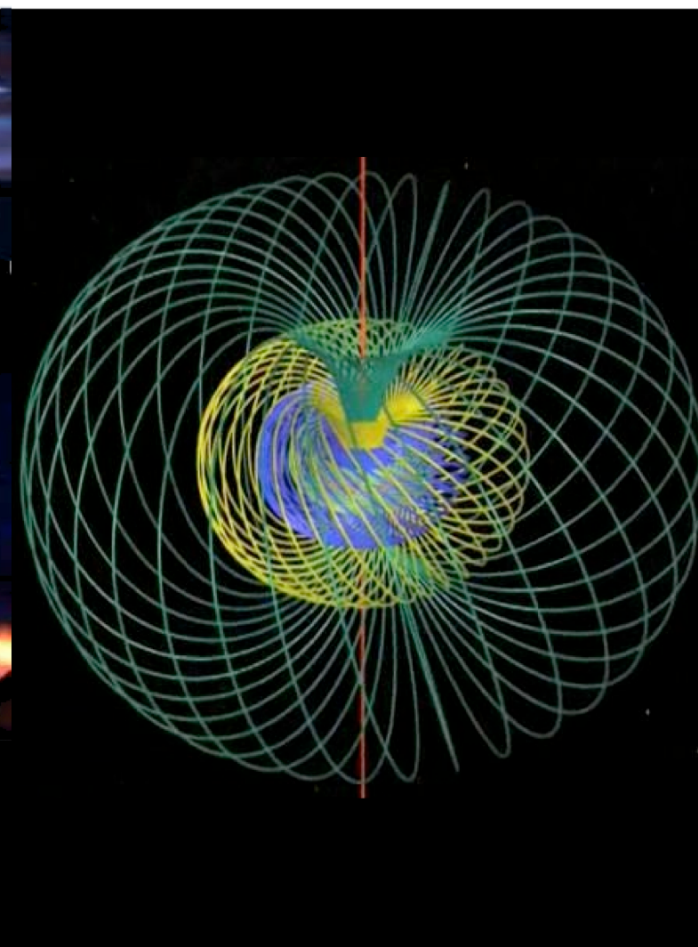


在FRASCATI, PROTO-SPHERA得到了第一根电浆中心柱

F. Alladio, Centro Ricerche ENEA, Frascati C.P. 65 (Roma) franco.alladio@enea.it



概论

- 为什么一个新和不同的磁约束装置? ...**1994年**: 侏罗纪公园!

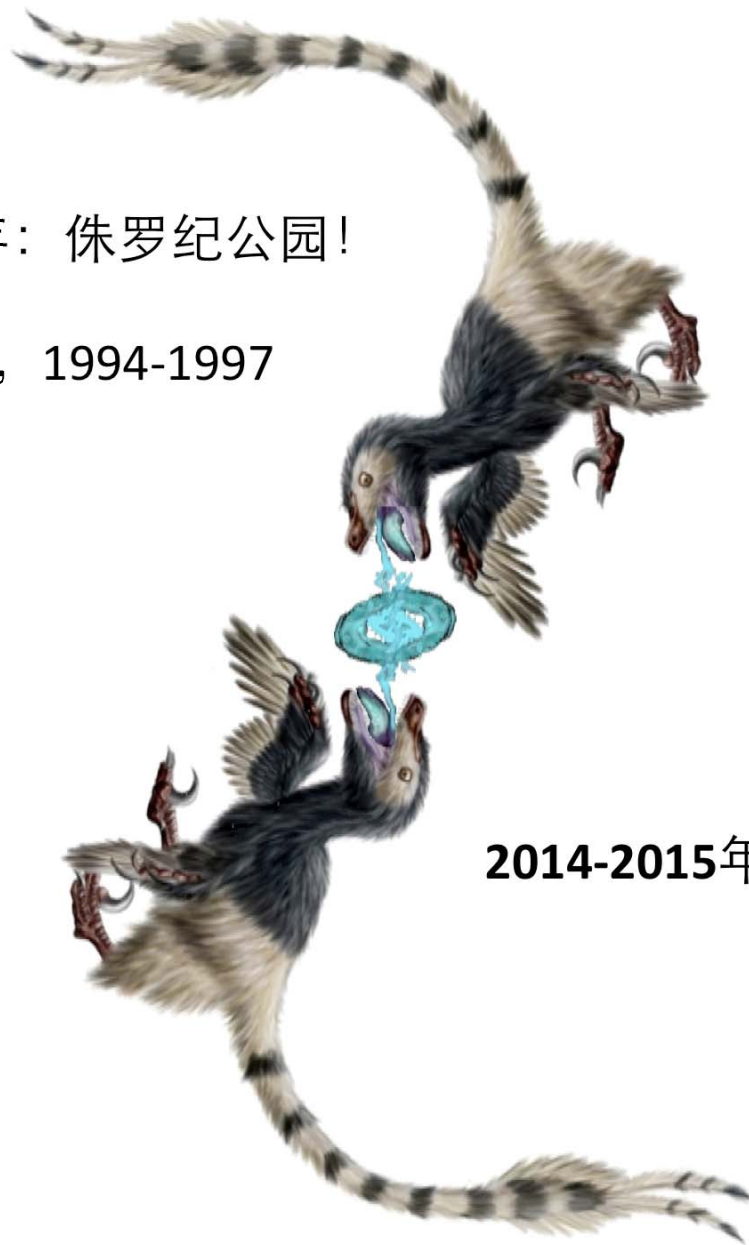
- 如何形成围绕一个双面龙火气息的球环电浆, 1994-1997

- 但建设实验之前还有了两个问题必须解决:
电极可靠性, 理想磁流体稳定性, **1997-2002年**

- 一个古老而光荣的真空室来自英国作为礼物
允许开始实验的建设, **2003-2013年**

- **PROTO-SPHERA**得到了第一根电浆中心柱,

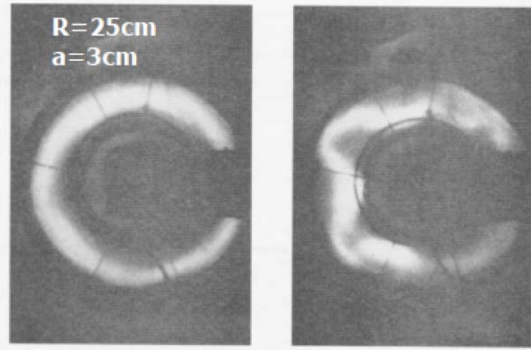
2014-2015年



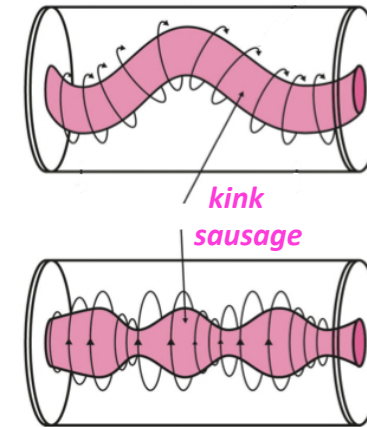
为什么一个新和不同的磁约束装置?

...“电流破裂”

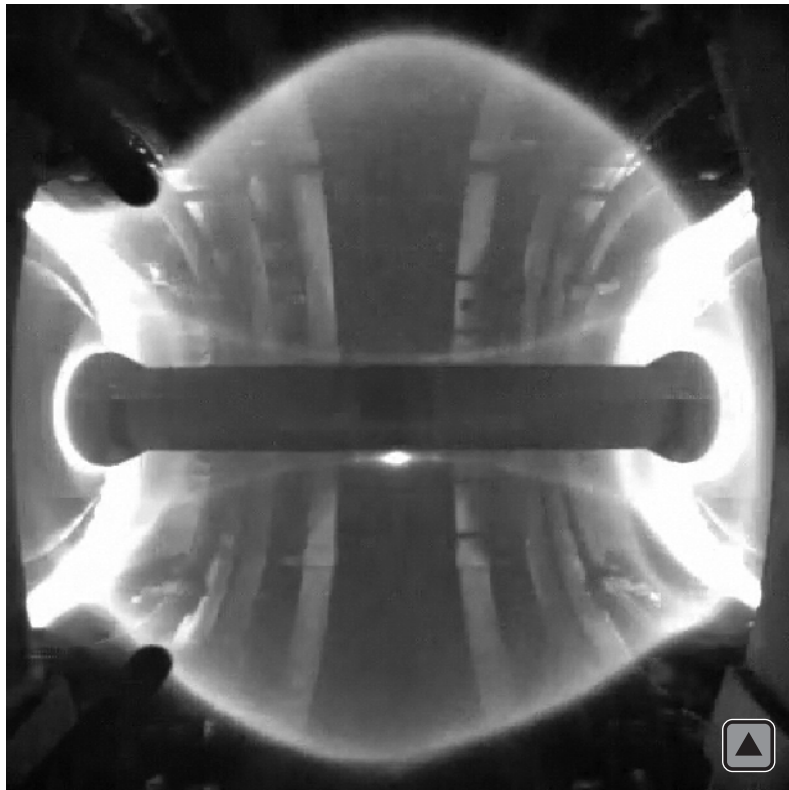
Alan Ware & Thomson
Imperial College 1947.



以来第一些环形磁约束的实验
磁流体不稳定性出现了

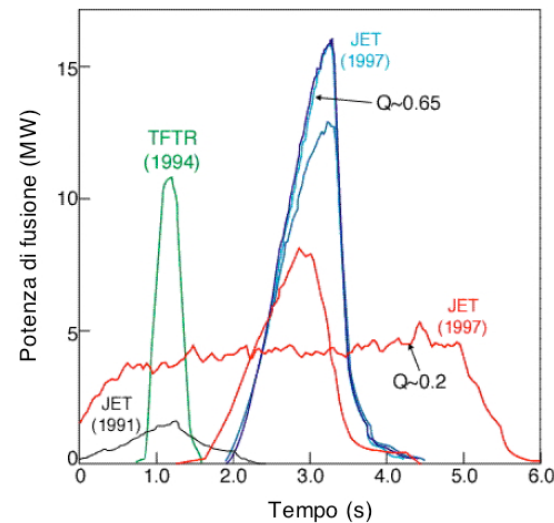


Mast 2004



电流破裂的问题还没有得到解决

...只有仿星配置(不净环形电流)避免这种不便



在氘 - 氚实验:

JET 1991- TFTR 1994

JET 1997

...最高的中子发射
...终止出现了一个
电流破裂

为什么一个新和不同的磁约束装置?

... “ β 的限制”

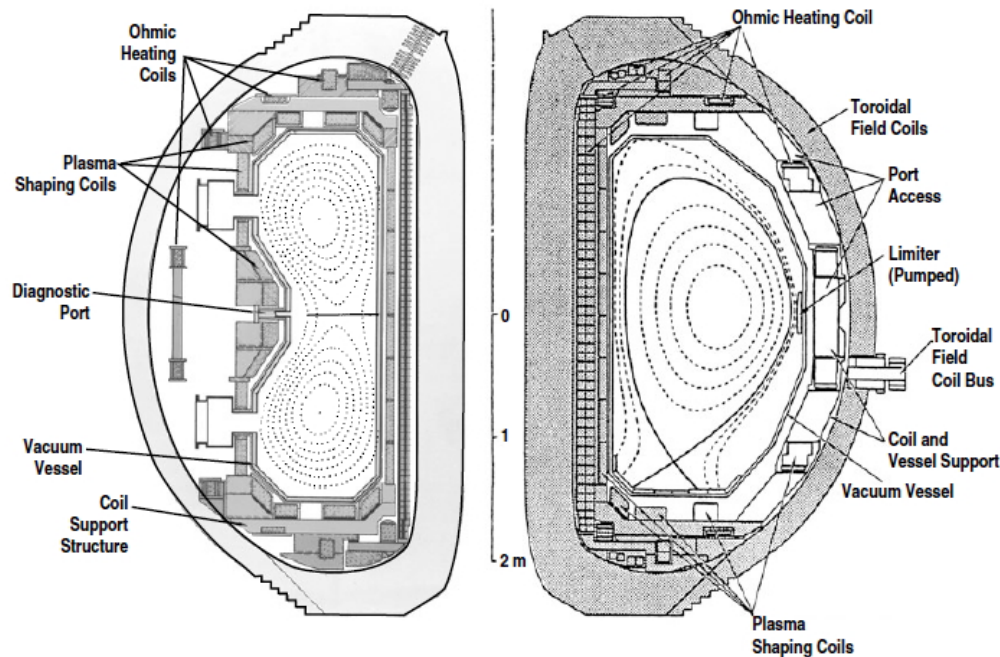
...即使有口头禅喃喃自语托卡马克的物理是完全已知...

$$\beta = \text{plasma beta} = \frac{\text{kinetic plasma pressure}}{\text{confining magnetic field pressure}}$$

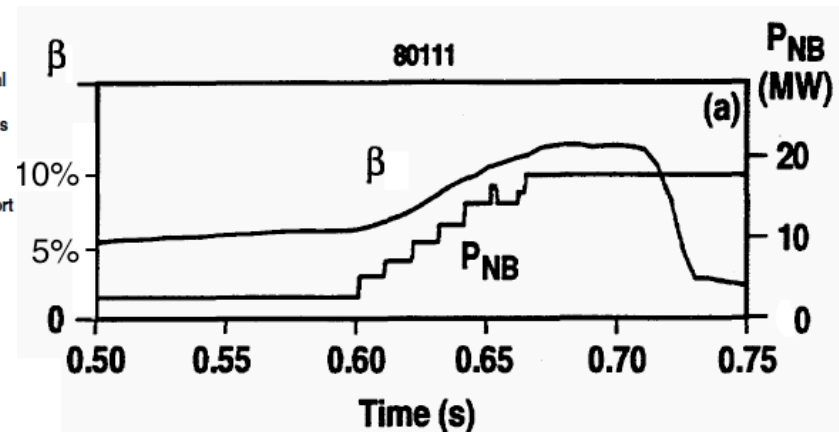
$\beta = 2\mu_0 \int p dV / \int B^2 dV$ 但在托卡马克实验数据的一种经常使用是 β_{T0} 其中,

$\beta_{T0} = 2\mu_0 \int p dV / B_{T0}^2 V$ B_{T0} 是在电浆的轴线的磁真空场

1994年DIII-D达到了最高的 β 值在所有时托卡马克

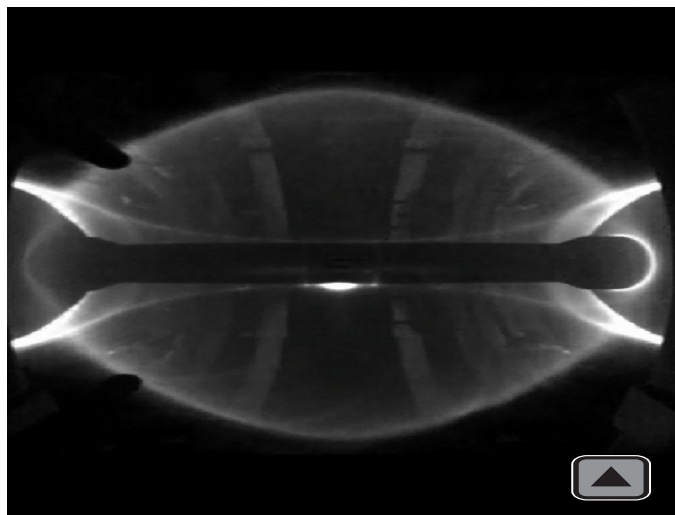


DIII-D达到了 $\beta_{T0} = 12.5\%$,
但 ...有一个电流破裂

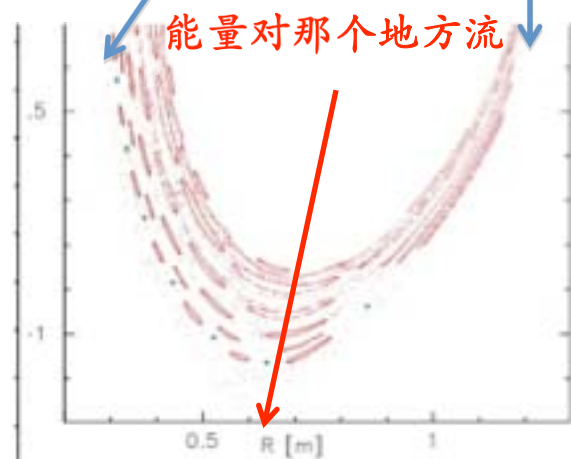
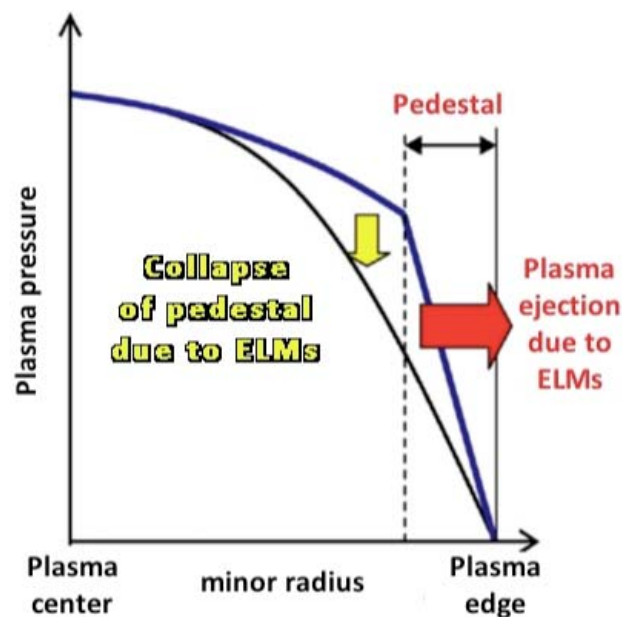


为什么一个新和不同的磁约束装置

边缘本地化不稳定的模式

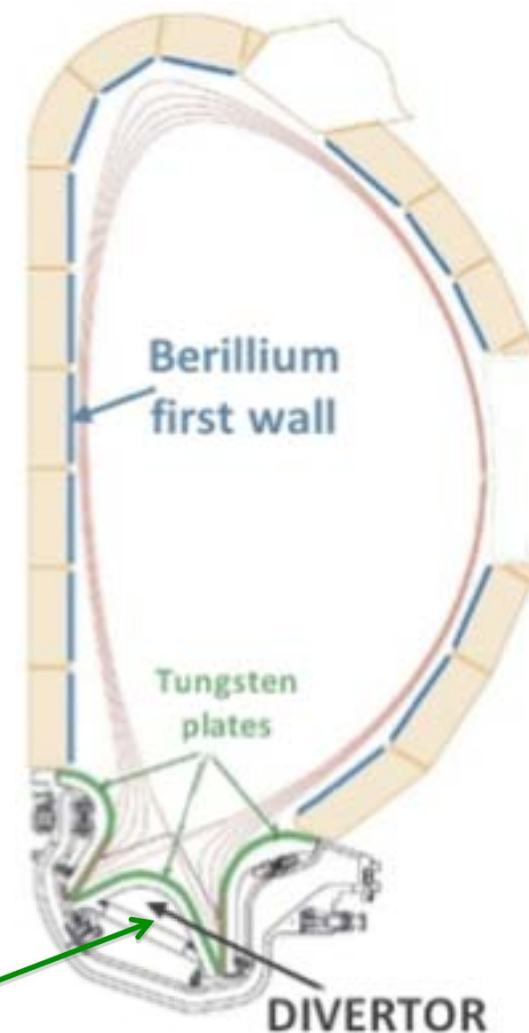


扔在偏滤器上电浆的边缘的能量大一部分



这种情况发生在很短的时间
作为电浆边缘变得遍历
的细丝携带一些非轴对称的电流

关于 的 如果一条细丝携带 % 电浆边缘的能量
这是足以融化或升华偏滤器钨的板



于1994年PROTO-SPHERA是在ITER第一次危机时诞生(作为一个念头)



Paul-Henri Rebut

Rebut设计了JET (1976年至1979年)
然后建设了JET (1979年至1983年)
1991年负责了ITER 的设计

1993年10 G\$: 但成本“爆炸”
Rebut 离开了ITER的领导(1994年5月)

大海航行靠舵手, 所以ITER 停止了: 美国电浆物理社区, 其中包括许多大学教授, 他们所小实验的建设者, 恐怕ITER可以让他们出资金, 并开始攻击 ITER
...于1998年美国国会关闭了最大的US托卡马克(TFTR)和退出了ITER

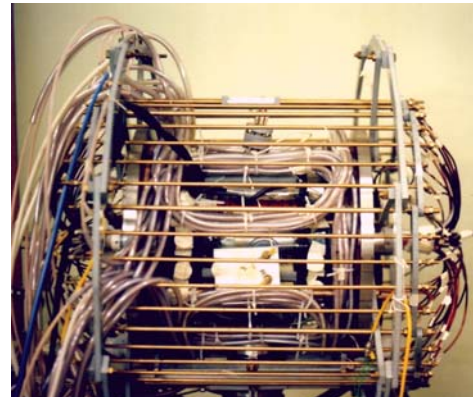
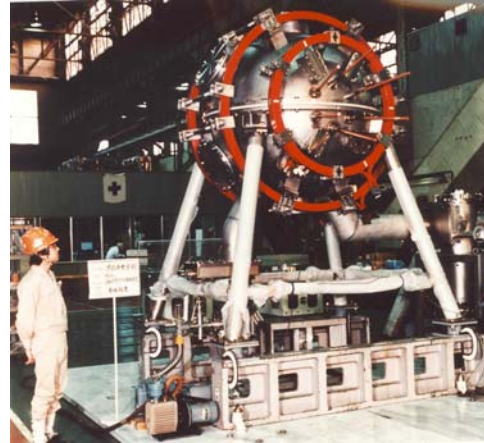
第一个“球形托卡马克研讨会”在OakRidge在1994年7月, 此趋势已经明显了;
它在那里, 美国决定了建设 NSTX, 球形托卡马克

自1994年以来, 至于新的磁约束装置中, 美国和英国只建成球形托卡马克

于1994年 ITER 第一次危机时 ...侏罗纪公园!

ITER关掉了...从他们的笼子以内,自多年以来封闭了,
别的磁约束装置,比“托卡马克”不一样,蹦出来...

Stellarators, Spheromaks, FRCs,
...主要球形托卡马克(ST)

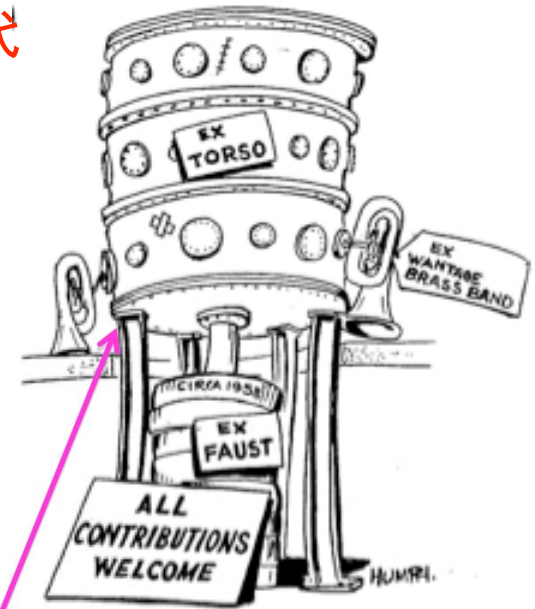
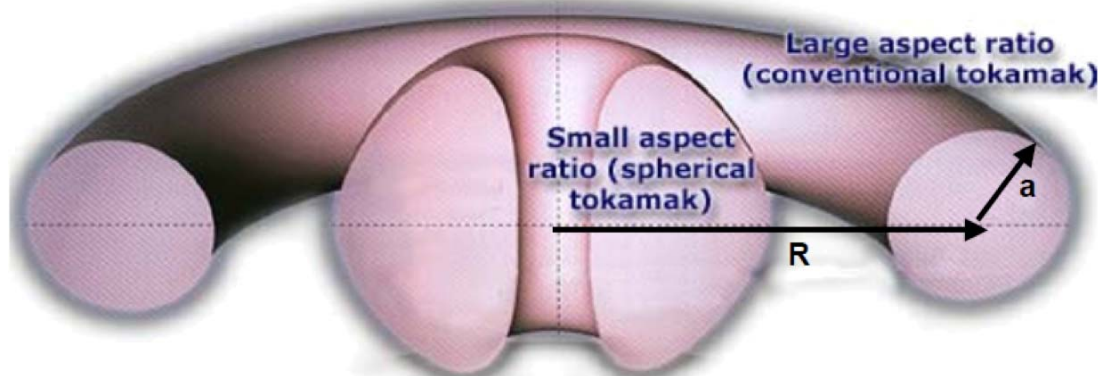


LHD Stellarator (Japan)

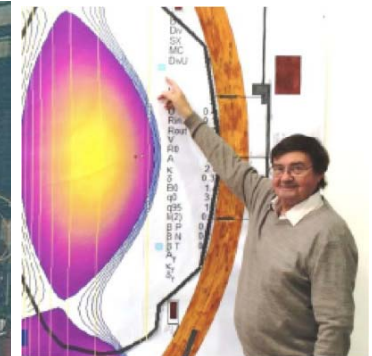
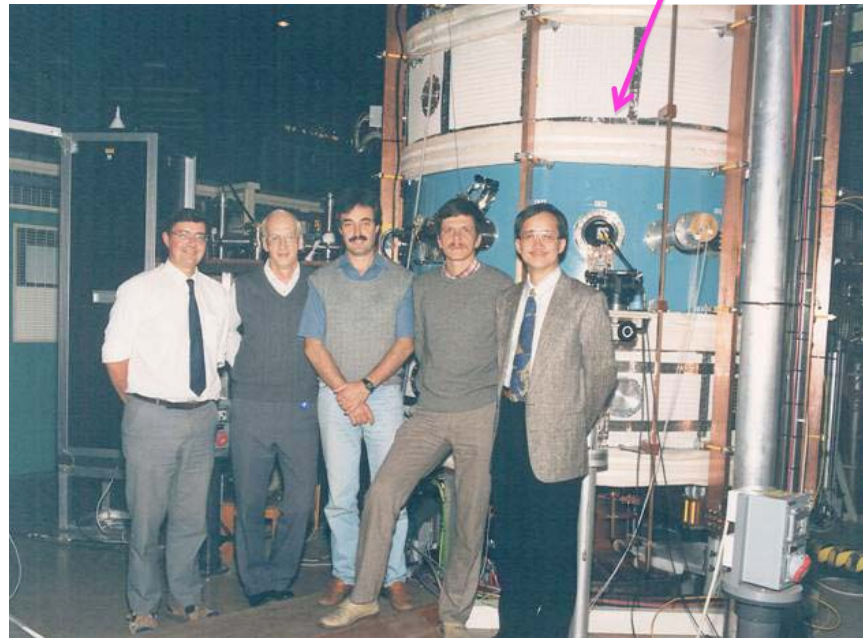
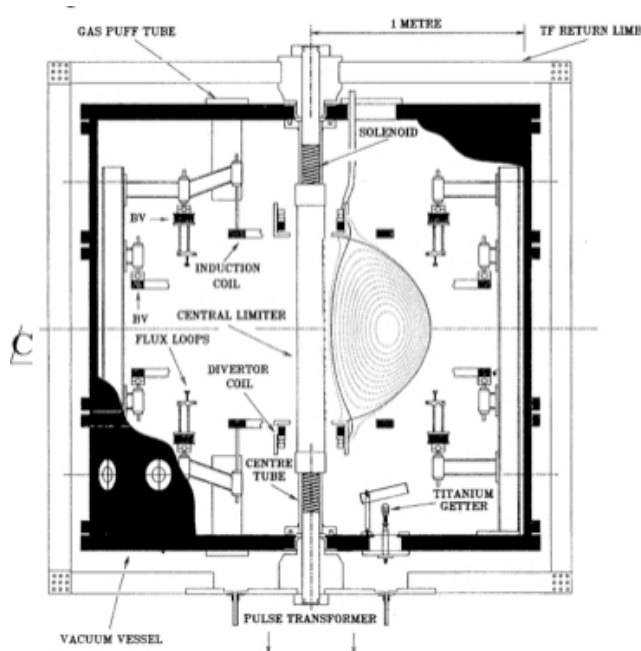


1991 START, 第一个球形托卡马克: 对 Culham(UK) 一新的时代

來自Oak Ridge的 马丁彭(Martin Peng)意识到, 为了提高 β , 托卡马克需要一个球形



Culham建成START球形托卡马克改造一个旧的真空室

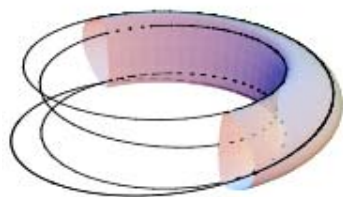


Alan Sykes

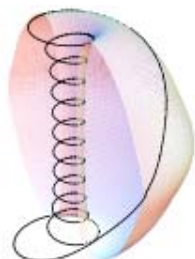
Alan Sykes Dick Colchin Edson Del Bosco Mikhail Gryaznevich Martin Peng

在Culham和Princeton 球形托卡马克

1998年, 从Oak Ridge老NBI 加热系统上安装了后,
START达到了 $\beta_{T0} \sim 40\%$ (比DIII-D三次更高)



常规托卡马克

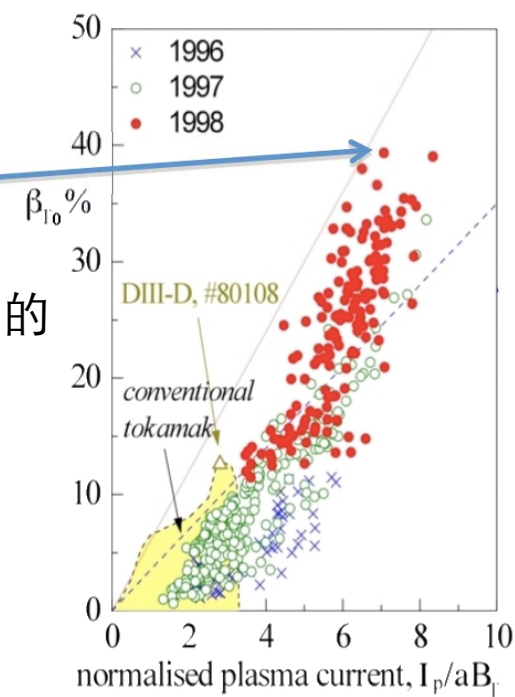


球形托卡马克

球形托卡马克具有有利性质, 因为它的
磁力线从磁面的短程线不太远



马丁彭 *Martin Peng*
球形托卡马克(ST)
的发明家

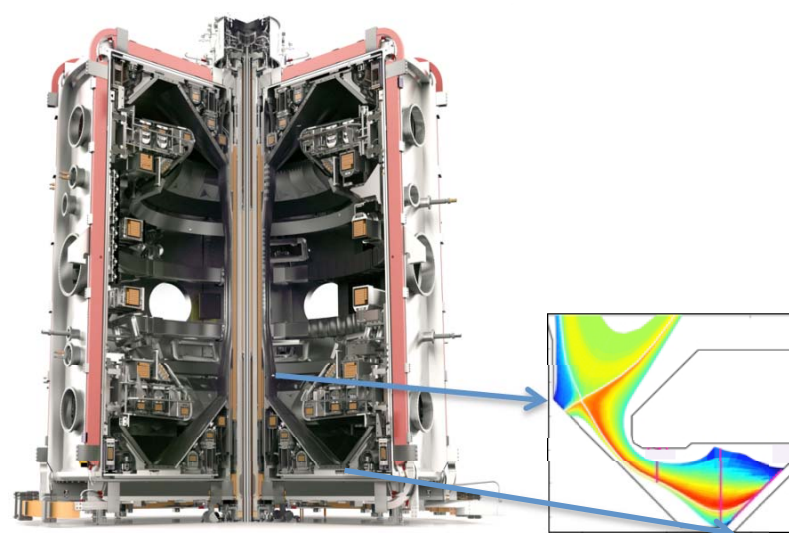
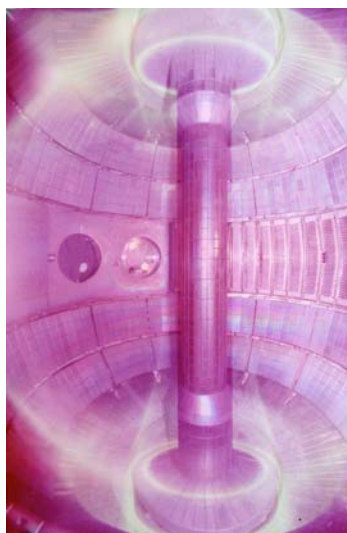


在90年代底, 两个大型球形托卡马克被建成了:

NSTX在Princeton

MAST在Culham (2000)

MAST-Upgrade (2017)

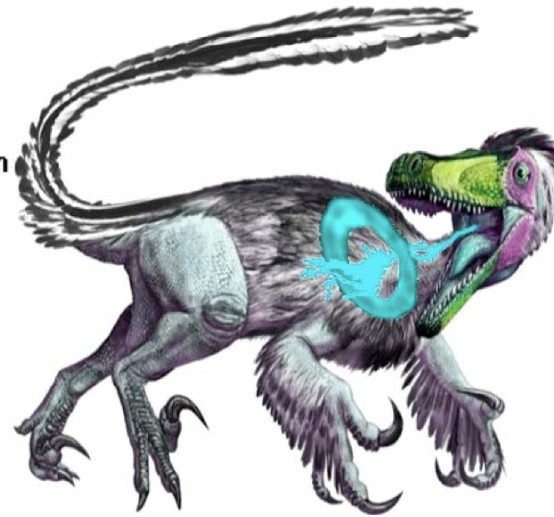
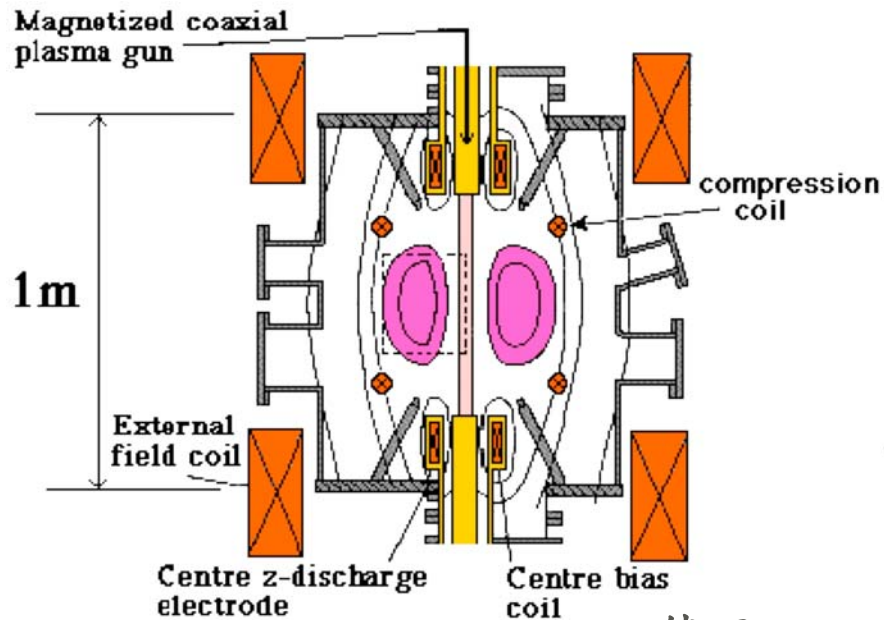
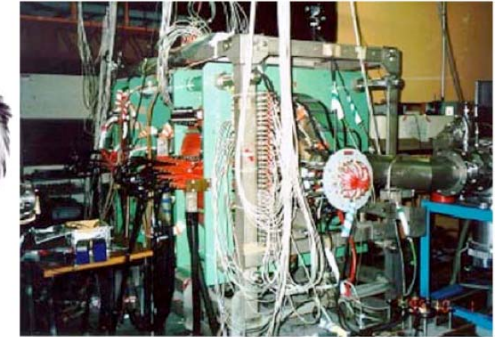


一个可爱的小恐龙突然跳出侏罗纪公园是一个东京大学的实验: TS-3

其研究的题目主要是获得电浆的环形的磁重联围绕一根的金属中心柱



Yasuchi Ono



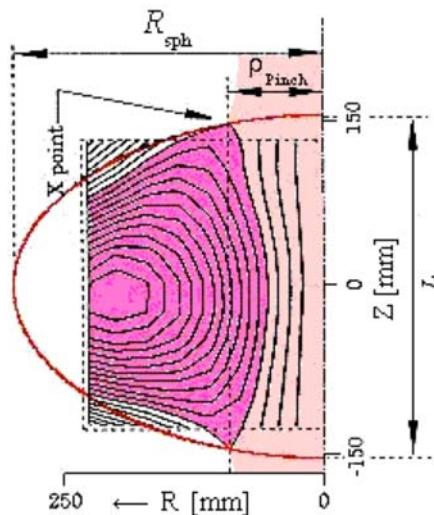
然而1993年TS-3取出了金属中心柱, 两支电浆枪之间施加1kV的电压和产生了 $I_e = 40\text{kA}$ 的"电浆中心柱"

它通过非线性不稳定性, 创作了一个球马克围绕"电浆中心柱": 得到的环形电流 $50\text{kA} < I_{ST} < 100\text{kA}$

形成时间为 $60\mu\text{s}$

维持时间为 $20\mu\text{s}$

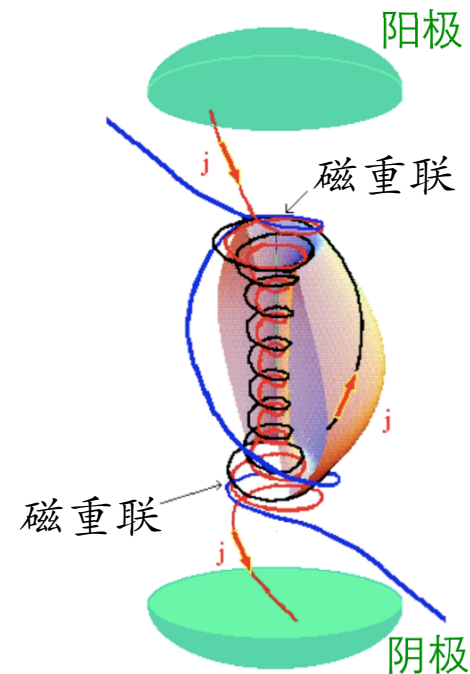
电浆总持续时间为 $80\mu\text{s} \sim 100\tau_{\text{Alfvén}}$



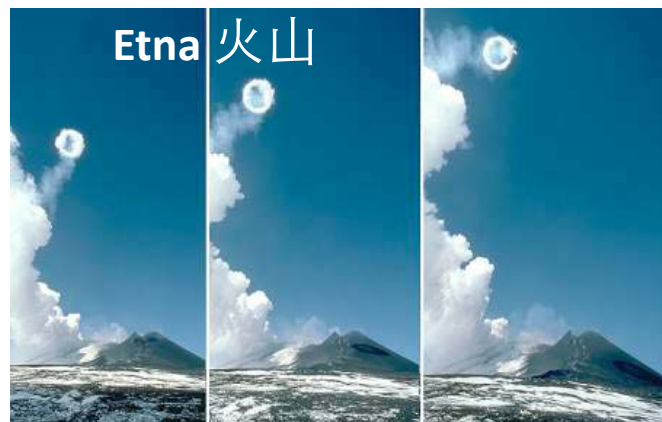
磁螺注射以维持环形的电浆:

电浆中心柱, 经过放松振荡, 驱动球环电浆的形成和维持

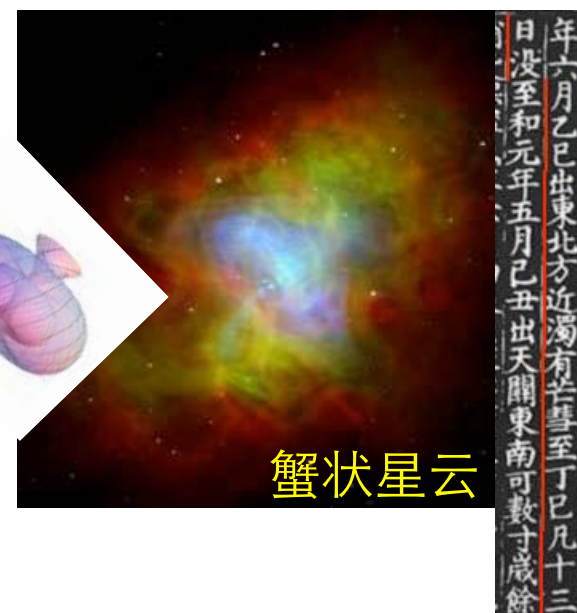
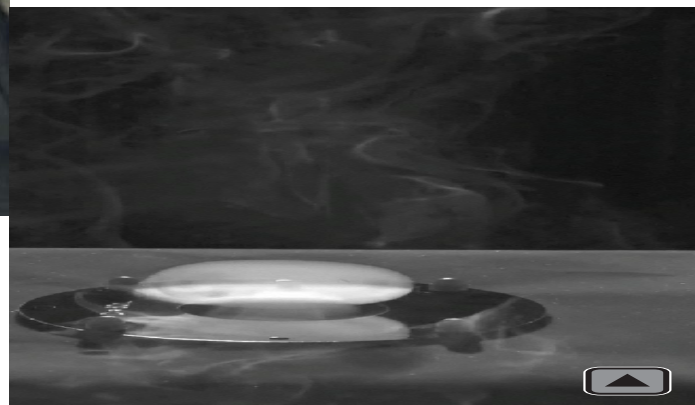
- 在电极的前部的电浆: 磁力线具有开始点和结束点, $\vec{j} \parallel \vec{B}$
- 开放的磁力线也缠绕在环形方向
- 磁重联带去着开放的磁力线($\vec{B}$, $\vec{j}$) 并将其转化为闭合的磁力线($\vec{B}$, $\vec{j}$)



“自组织类似一个烟圈”

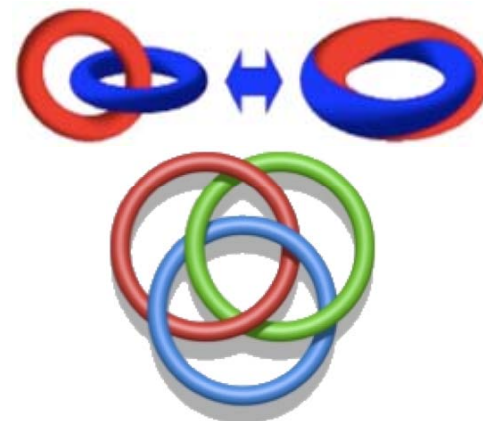


William Irvine-University of Chicago

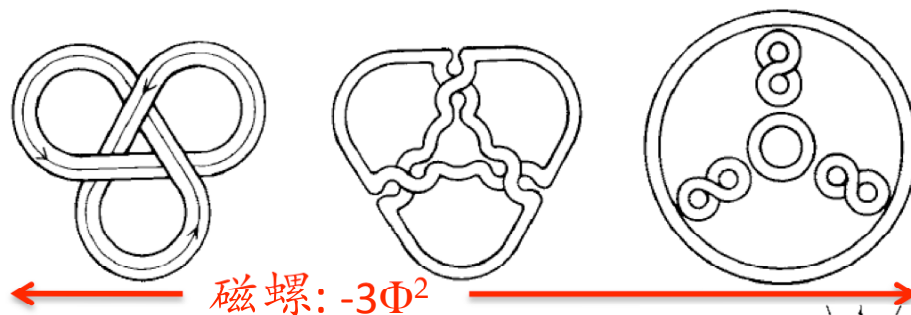


蟹状星云

考虑简单连接的体积, 被一个磁性表面定界磁螺, $\vec{B} \cdot \hat{n} = 0$
 磁螺 $K = \int \vec{A} \cdot \vec{B} dV$ 是一个缓慢衰减的理想MHD不变量
 它衡量多大的磁力线是相通的, 弯曲的或扭结的



磁通量: Φ



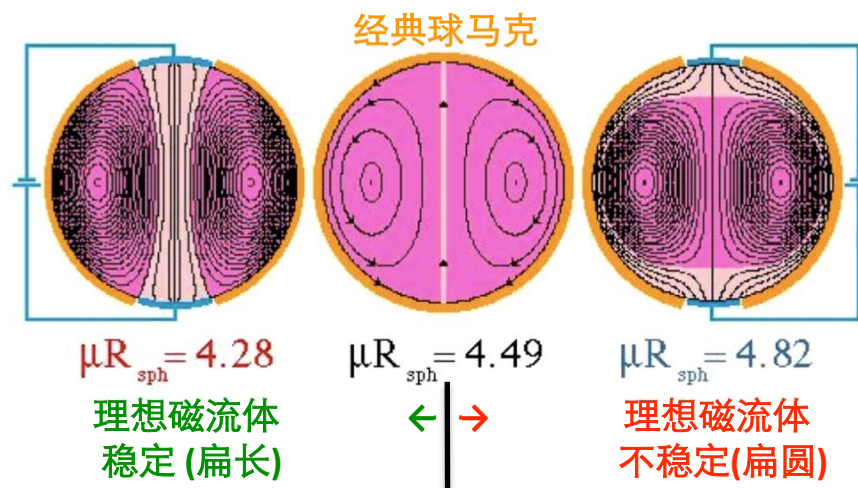
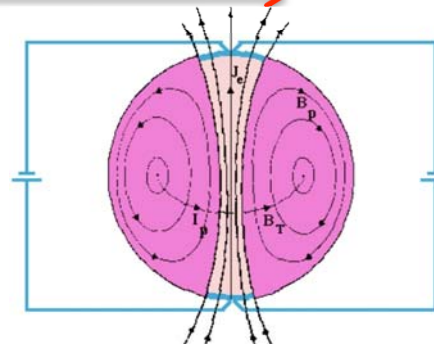
磁螺: $-3\Phi^2$

Flux-core Spheromak 磁通量核心的球马克

放松的状态, $\nabla \wedge \vec{B} = \mu \vec{B}$, $\mu = \text{常数}$,
 被一个理想导体的球面的一部分包围了,
 内部半径 $= R_{\text{sph}}$, 两个极冠的电极维持电浆

不稳定的动向: 磁力线有高旋转变换 χ
 (安全因子 q 的太小了) $q = 1/\chi \leq 1$
 增强“不稳定性的倾斜”

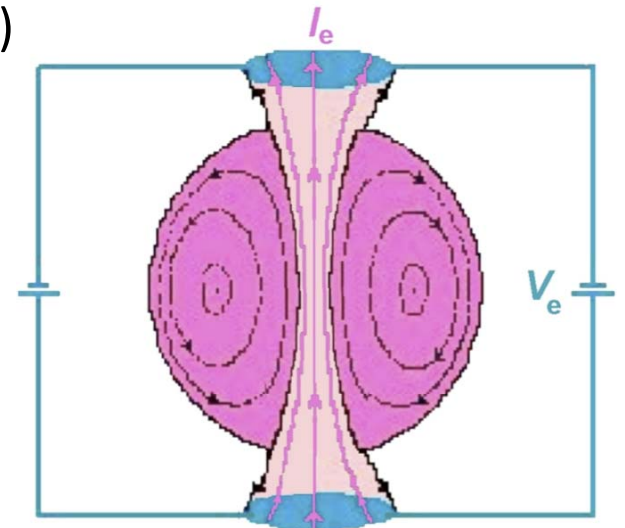
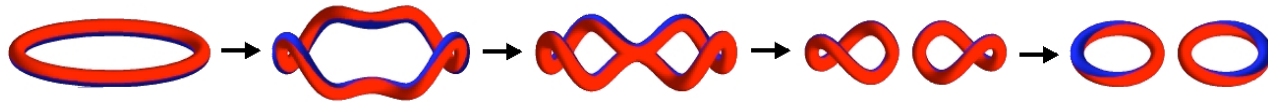
在外部容器中的电流形成一个磁偶极子
 反对着环形电浆电流磁偶极子



如果磁螺源 (即磁通量核心) 从磁螺汇分离(即球形马克)
一个渐变出现在 μ 的放松参数: $\vec{\nabla}\mu = \mu_0 \vec{\nabla} (\mathbf{j} \cdot \mathbf{B} / B^2)$

电阻MHD的不稳定性产生磁螺流
从更大的 μ 到较小的 μ^*

* 在低电阻率电浆, 磁重联再散发磁螺旋波没有消散它



$$\Psi_e = 0.5 \int (\vec{B} \cdot \hat{n}) dS$$



V_e 静电电位

在一个区域以内,磁螺注射的平衡 ($\hat{n}$ 向外导向)

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

• $2 \int V_e (\vec{B} \cdot \hat{n}) dS =$ 直流磁螺注射: $2V_e \cdot \Psi_e$
(极向的静电电位 • 极向的磁通量)

• $2 \int (\vec{A} \wedge \partial \vec{A} / \partial t \cdot \hat{n}) dS =$ 交流电磁螺注射: $2V_t \cdot \Psi_t$
(环形的电压 • 环形的磁通量) V_t 环路的电压
欧姆的磁螺的驱动力

• $2 \int (\vec{E} \cdot \vec{B}) dV =$ 磁螺的总损耗

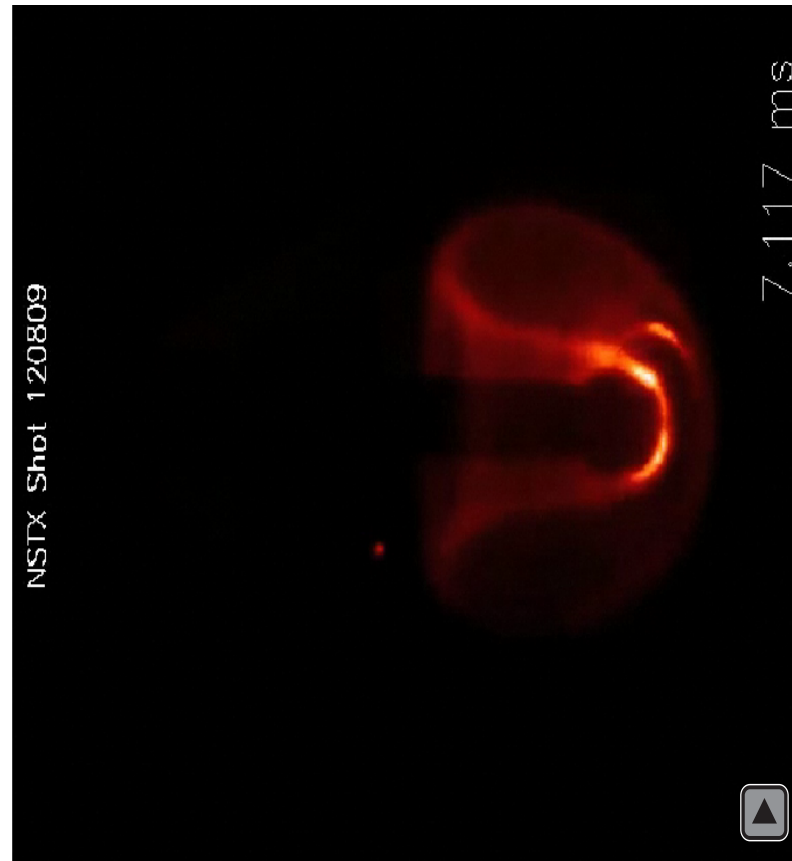
磁通量,电流和磁能量的电浆被注入随着磁螺,但如何有效?

这是在PROTO-SPHERA实验的主要原因

在PROTO-SPHERA里直流磁螺注射会替代欧姆的驱动力

...试一试摆脱电流破裂...

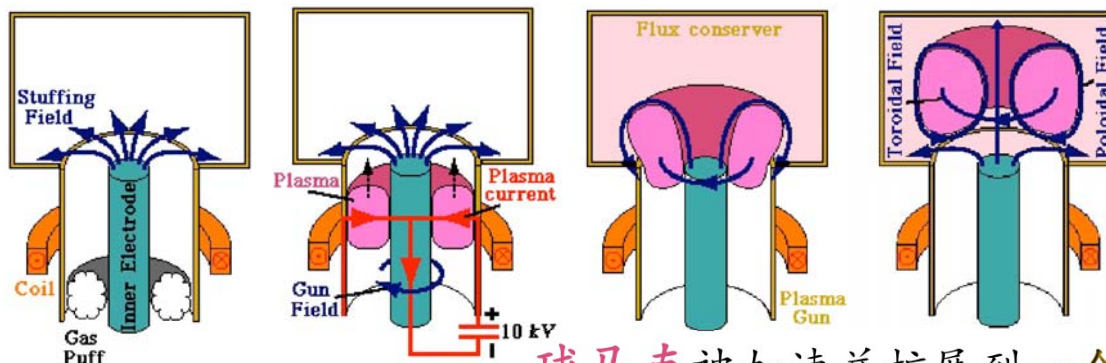
在NSTX 球形托卡马克直流磁螺注射，
常跟欧姆驱动力共存



它已经实现**>300kA**电浆初创和降低了**40%**欧姆驱动力的要求，
尽管在一个金属中心柱的存在，此外等离子体团的“出生和重生”

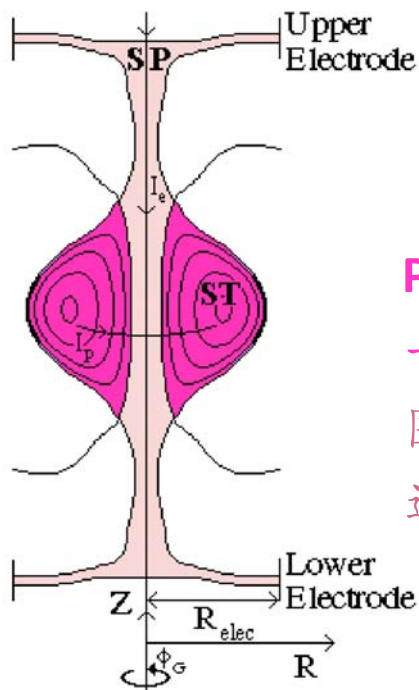
被电浆枪生成的磁通量核心的球马克

电浆的击穿发生在狭小的空间, 具有极高的填充压力和千伏电压
中性物和杂质从电浆枪释放



在形成之后,
球马克被加速并扩展到一个磁通量保存者的真空室
磁力线的错误, 已经存在于电浆枪, 被放大

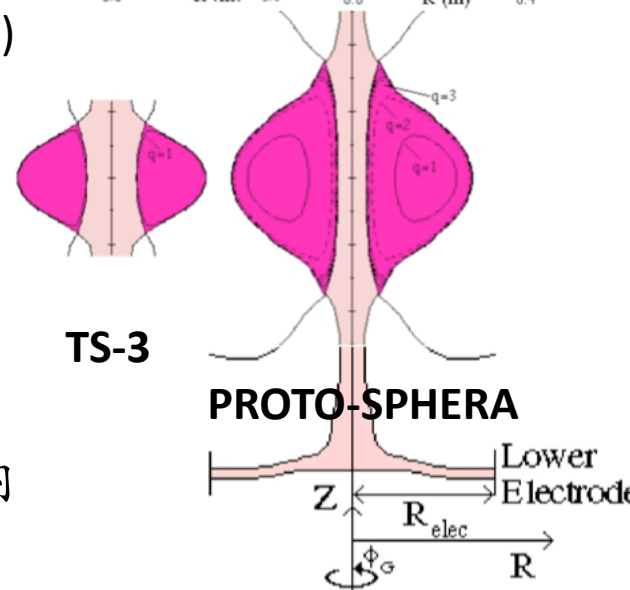
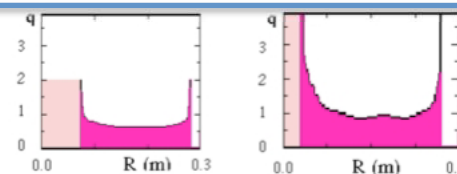
PROTO-SPHERA



将努力让安全因子 q 典型的球形托卡
($q_0 \geq 1$, $q_{edge} \sim 3$)
(环径比 $A=R/a \geq 1.2$, 拉长比 $\kappa=b/a \sim 2.3$)

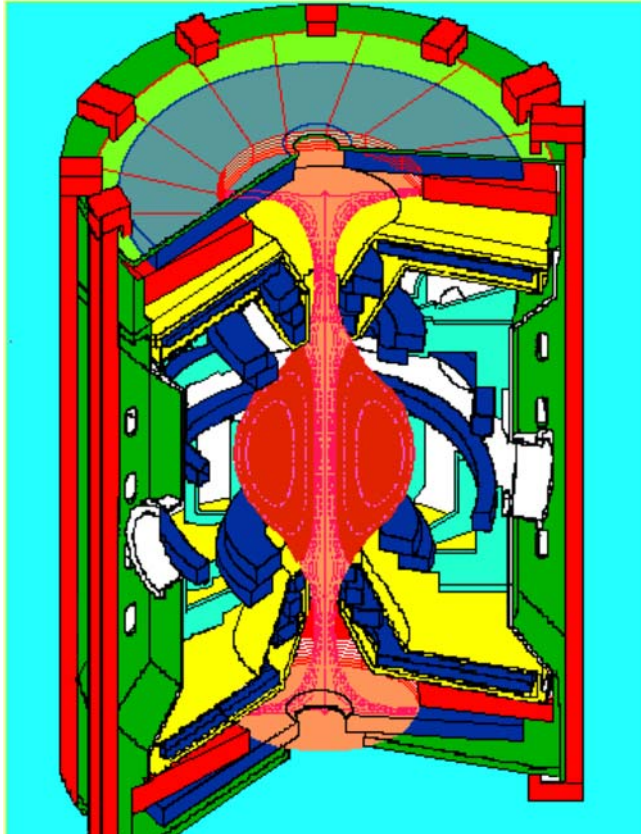
PROTO-SPHERA 被"慢慢"形成
为一个扁长球形托卡马克
围绕先前存在的电浆中心柱,
这是蘑菇状在两个电极的前

需要低电压, 在大真空室以内



SPHERA:

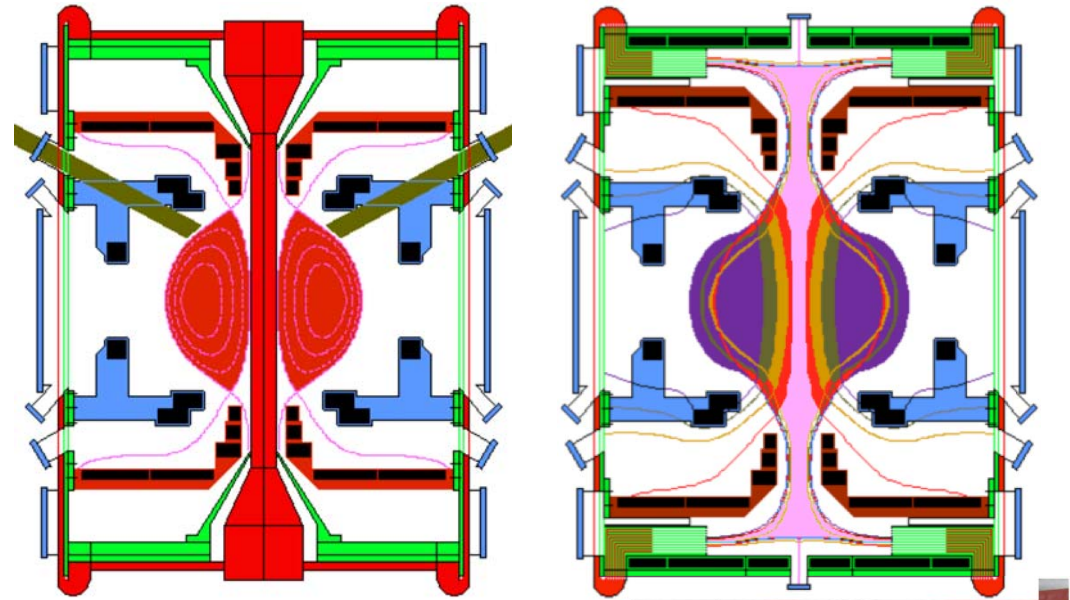
Spherical Plasma for **HE**licity **R**elaxation
Assessment



F. Alladio, G. Angelone, P. Buratti, A. Cardinali, A. Cecchini,
R. Cesario, C. Goullan, L. Lovisetto, A. Mancuso, P. Micozzi,
S. Mantovani, S. Migliori, L. Pieroni, L. Semeraro, A.A. Tuccillo,
F. Valente, V. Zanza

Frascati, March 1997

在1995 - 1996年在 Frascati, SPHERA的提议:
是强磁场的球形托卡马克, $B_{T0} = 2.3T$ $R=0.36m$
有很小环径比 $A = 1.2 \div 1.3$ (没有感应中心螺管)
一间圆柱形真空室以内 高低 $h = 4m$, 径 $\phi = 3m$
也有电浆中心柱的可能性



SPHERA从来没有建成,但它成为了
PROTO-SPHERA的设计的基础

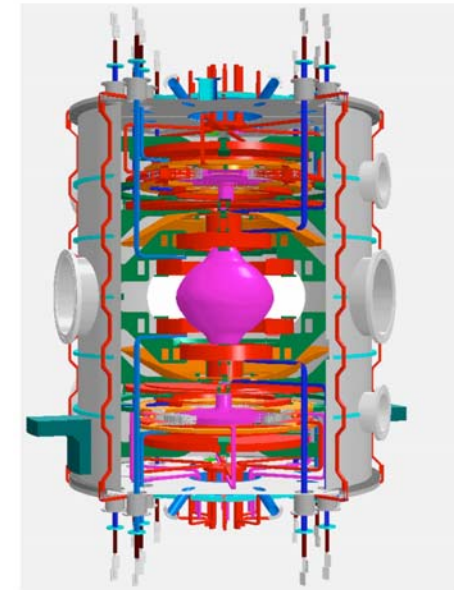


Leonardo Pieroni
1943-2012

Paolo Micozzi ENEA Alessandro Mancuso ENEA

2001年最终的PROTO-SPHERA报告

PROTO-SPHERA



CR-ENEA Frascati, July 2001

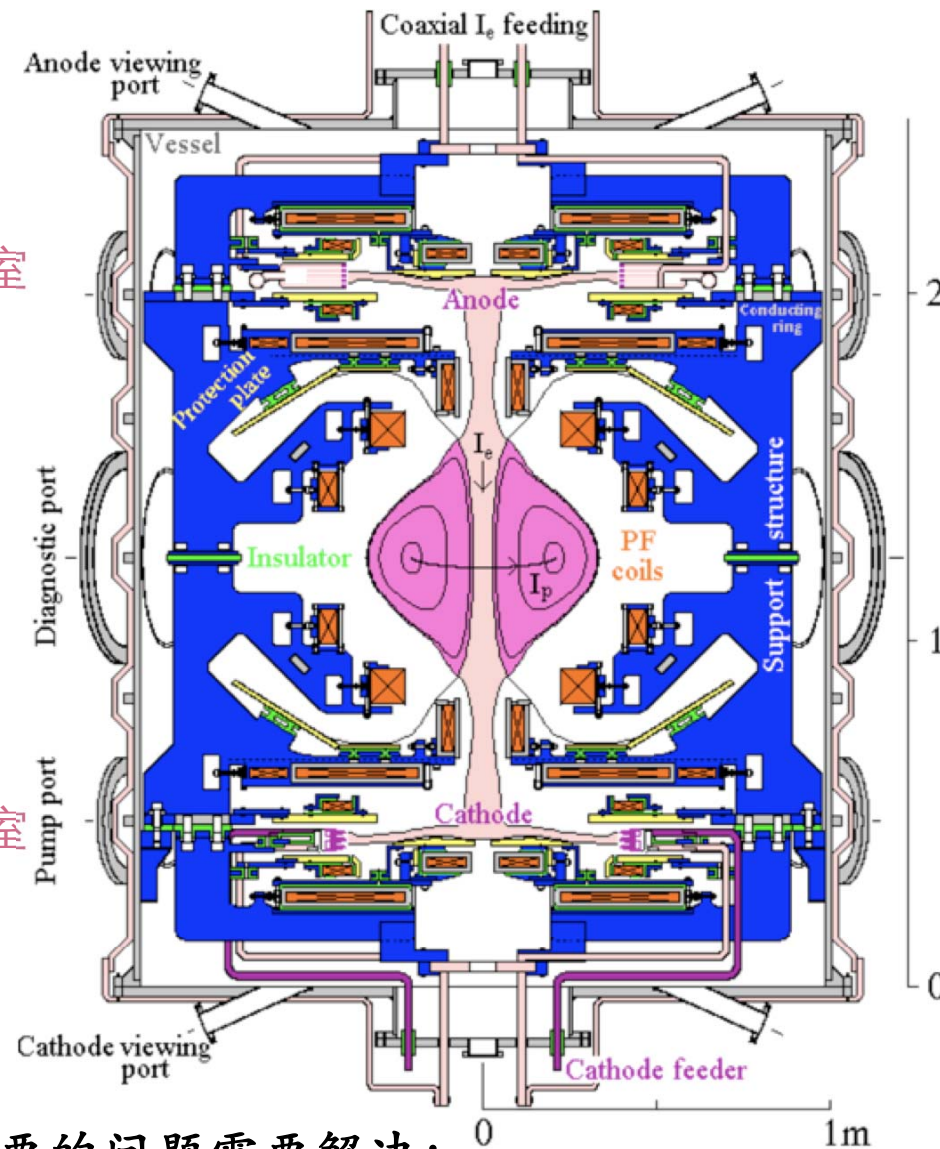
两个电极从主要电浆
被差不多分隔:
大量(18)的极向磁场线圈
(18)PF线圈



阳极准独立的真空室

球形托卡马克的
准独立的真空室

阴极准独立的真空室

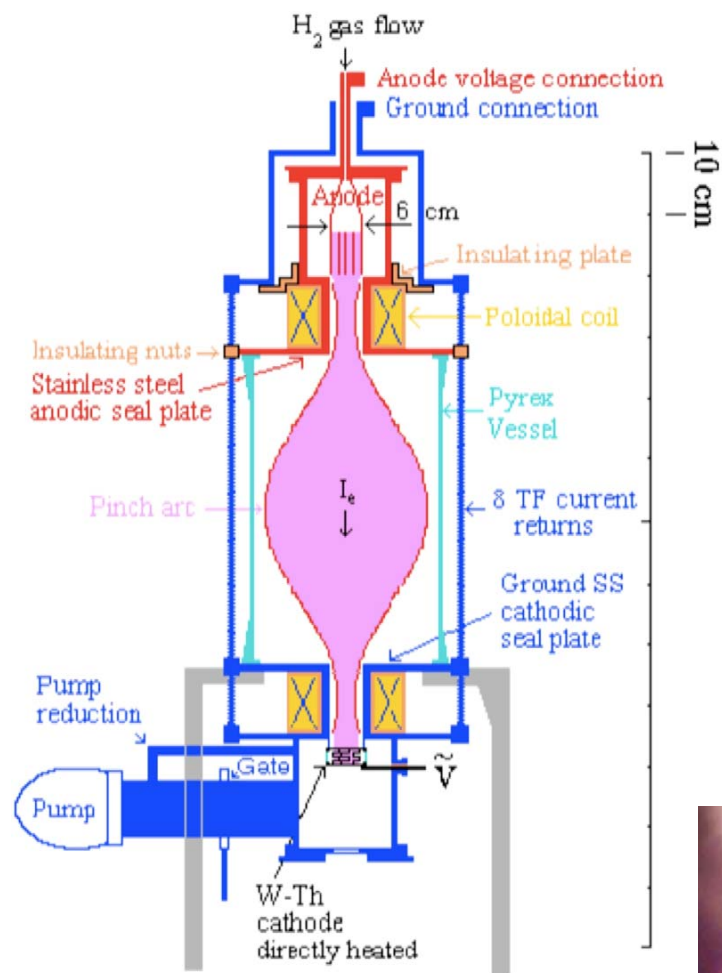


有两个主要的问题需要解决:

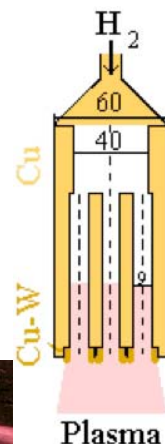
- 建筑耐用电极
- 被理想磁流体稳定性施加的限制

• 建筑耐用电极

PROTO-PINCH 电极测试平台, 建造于1998年,
从1998年底到2000年初的测试平台被操作了



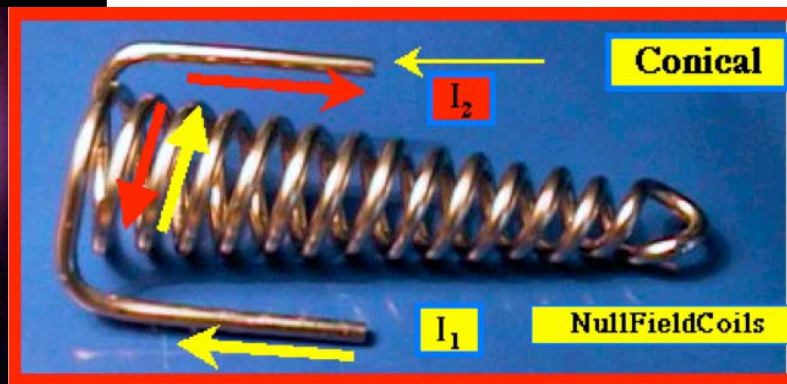
交流电流阴极加热是必需的,
以避免阳极的弧锚固



使用空心气体膨化的阳极(钨铜):
电浆进入孔穴

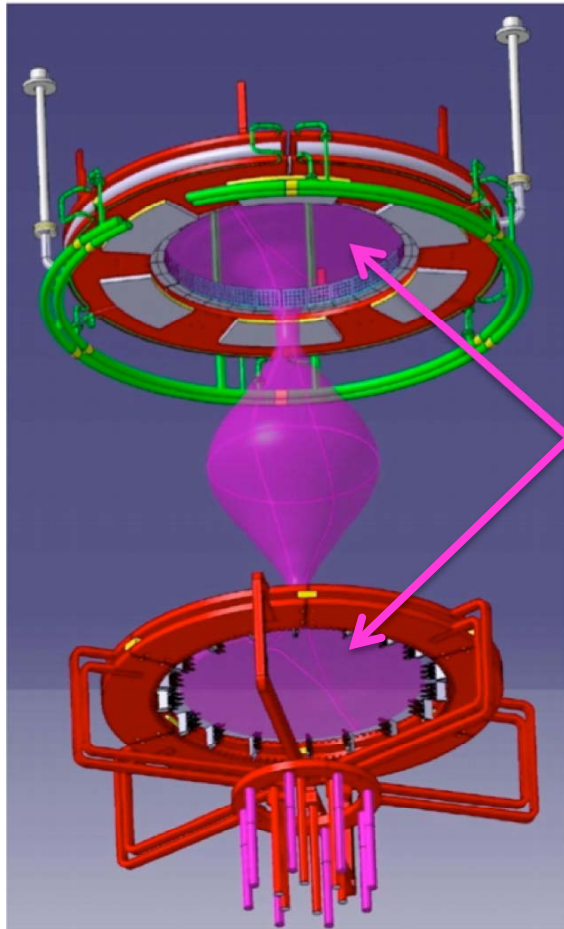
- 一千多的1S的电弧放电
- 电浆电流高达700A
- 电浆击穿~100V, H中
- 电流密度 $j_e = 1 \text{ MA/m}^2$
- 功率密度 $P_e = 20 \text{ MW/m}^2$

W-灯丝(类似于商务的神棍)
直热式阴极



关于PROTO-SPHERA的电极 PROTO-PINCH 测试平台发现了合适的答案

...这个答案可能有一些利益在偏滤器的电流和功率的密度问题上



电极上低的电压(100-200V)

电浆密度跟托卡马克一样

模块化环形电极:

- 使用空心气体膨化的阳极



蘑菇状电浆中心柱
在两个电极的前面

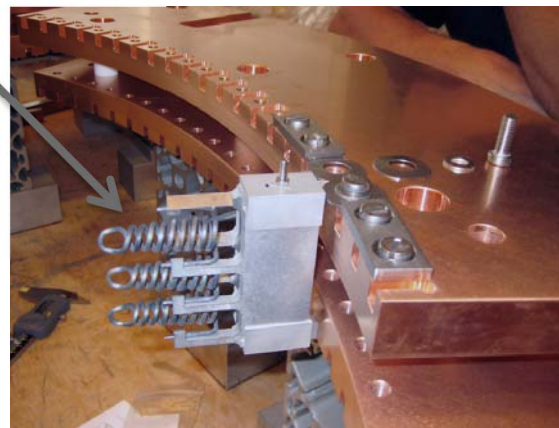
电流密度 $j_e = 1 \text{ MA/m}^2$

功率密度 $P_e = 20 \text{ MW/m}^2$

- W-灯丝直热式的阴极



Alessandro Mancuso ENEA

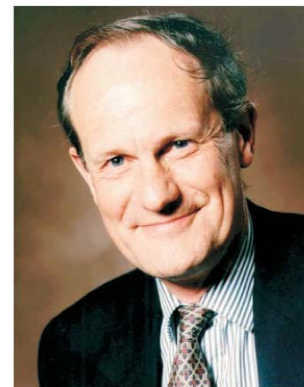


Livio Bettinali ENEA

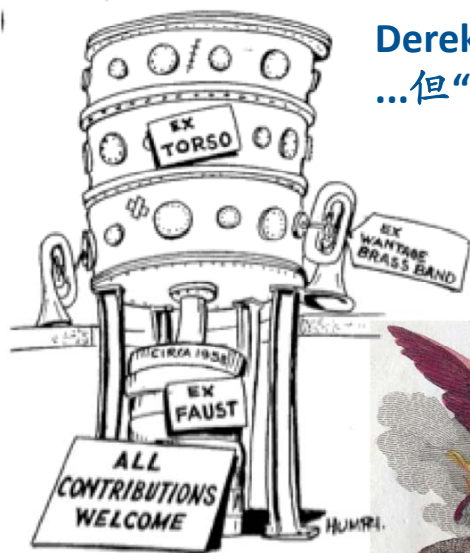
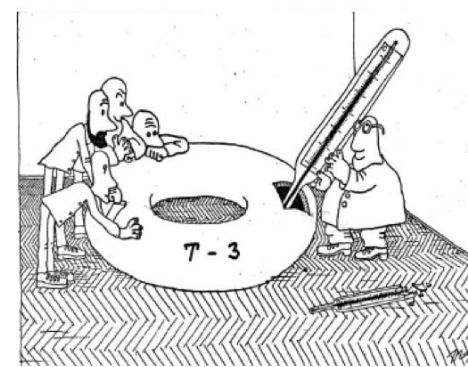
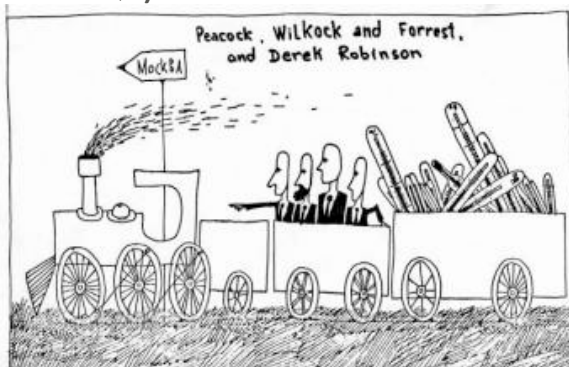


Derek Robinson(从1991年Culham主任)
在**香槟酒瓶**的实验特别感兴趣：
在**1999**年,他建议了,使用着**START**的真空室,
以建成**PROTO-SPHERA**在Culham

Derek Robinson
1941-2002

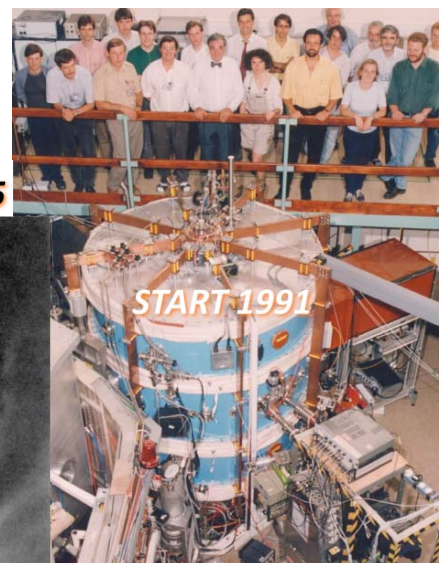
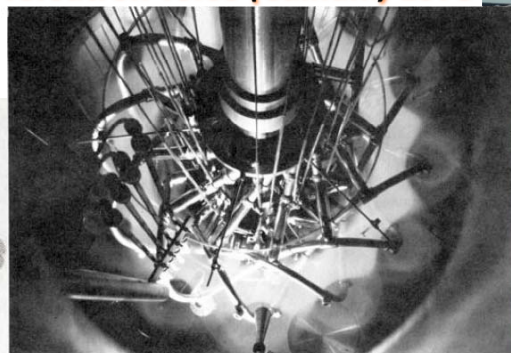


(1969年)Derek Robinson有了主导作用在俄罗斯托卡马克**T3**的温度测量上



Derek Robinson的建议被不幸地不接受了
...但“老而光荣的真空室”
反正找到了自己的路...去罗马

Torsatron Torso (Culham) 1975



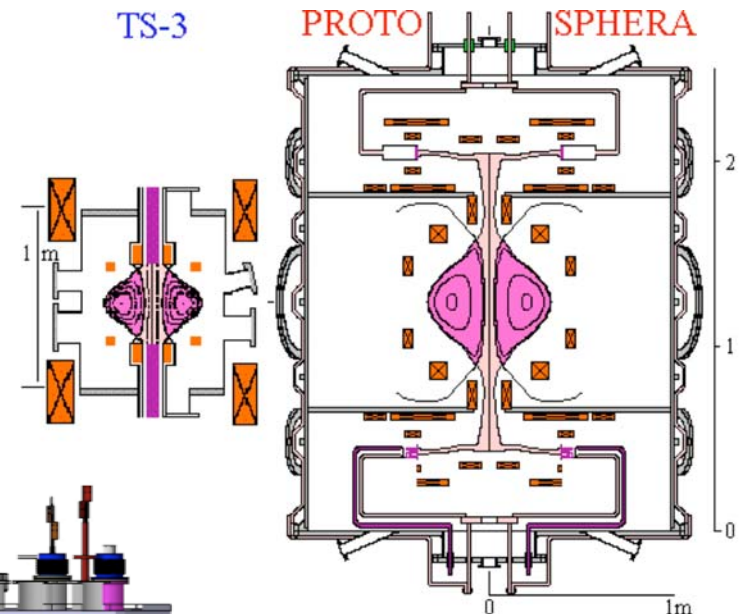
此外Derek Robinson的建议,使用着START的真空室,以建成PROTO-SPHERA在Culham
最终导致参数的选择: 被选择START的大小,而不是TS-3的大小

2002年在Frascati,与Martin Peng为委员长,
一个国际的研讨会举行了;

该委员会批准了实验的建设分两个步骤:

- 第一个阶段要检查“电浆中心柱”的可行性
- 第二个阶段可以然后完成装置使形成球环电浆

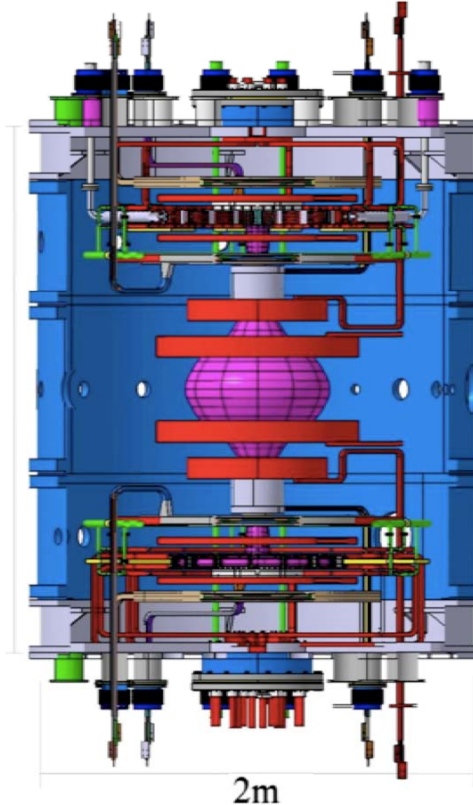
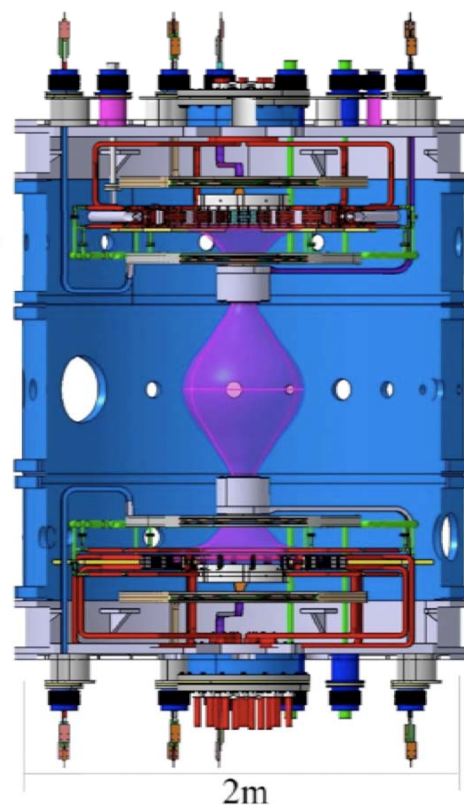
PROTO-SPHERA的计算机辅助设计开始了



第一个阶段:8个
极向磁场线圈



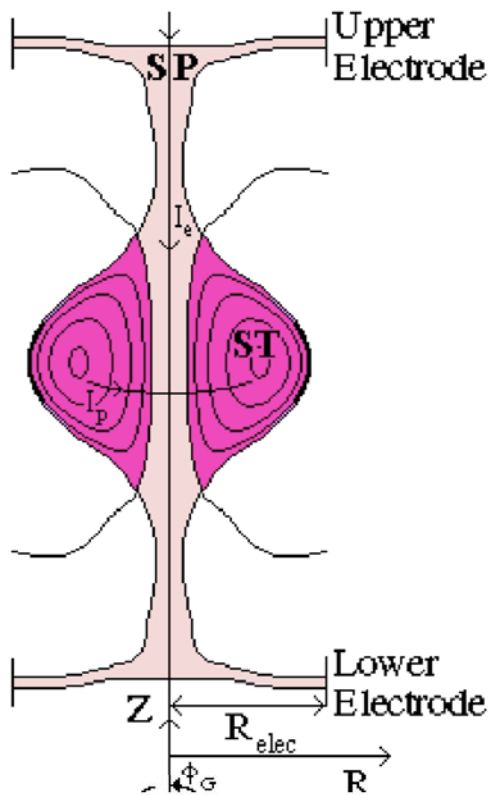
Stamos Papastergiou
Euratom



第二个阶段: 8个线圈
+ 10个极向磁场线圈



Alessandro Mancuso ENEA



PROTO-SPHERA的参数: 电浆中心柱的电流 $I_e = 60\text{kA}$

球环电浆的电流 $I_p = 120 \div 240\text{kA}$

球环电浆的径 $2 R_{\text{sph}} = 0.7\text{m}$

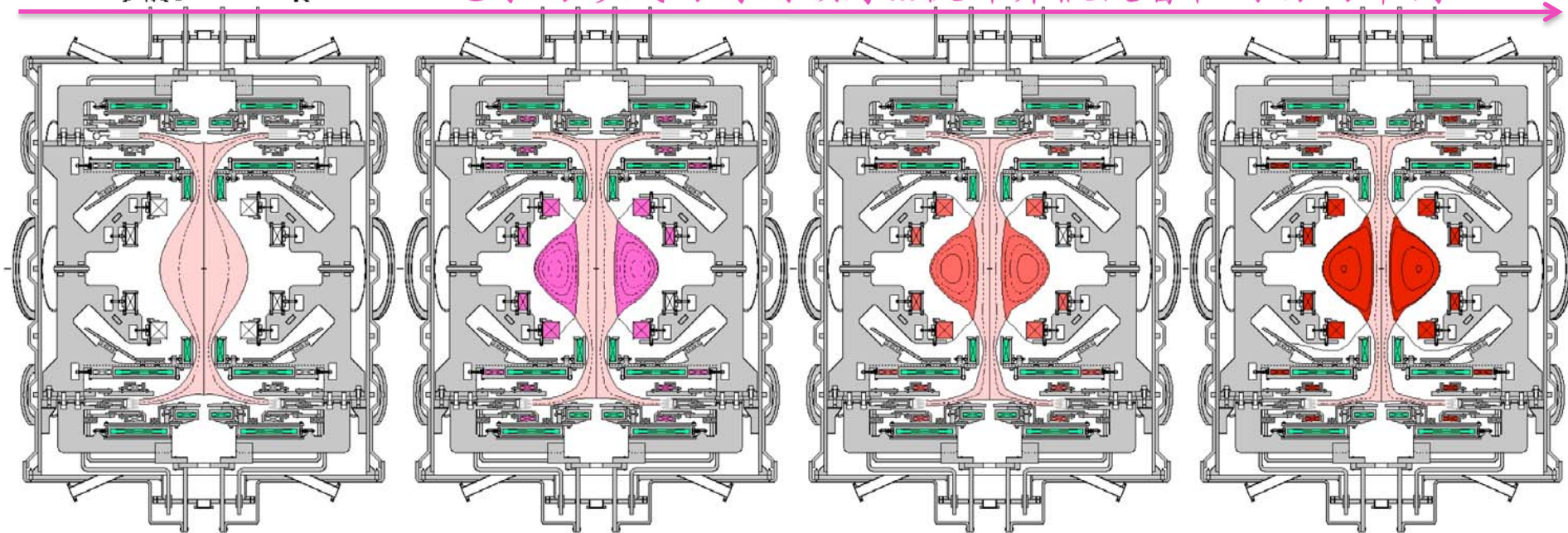
安全因数 $q_0 \geq 1$, $q_{\text{edge}} \sim 3$ “磁通量核心的球形托卡马克”

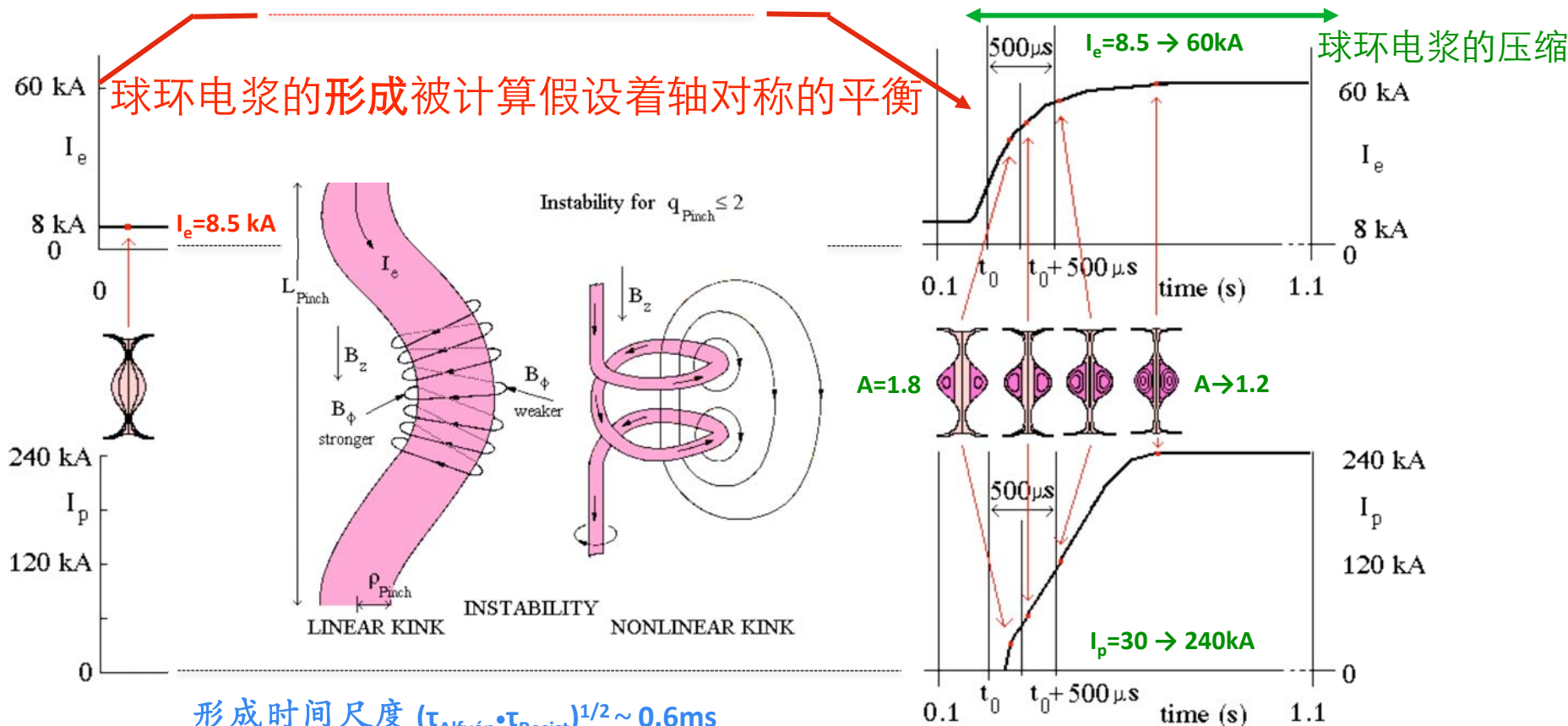
- 稳定性应当改善
- 直流磁螺的驱动力被预计有少破坏性力
比在“磁通量核心的球马克”的情况下

电浆中心柱的电流被迅速增加: $I_e = 8.5 \rightarrow 60\text{kA}$

在为了压缩电浆, PF线圈里每匝电流: $I_A = 0 \rightarrow 1.2\text{kA}$

电浆的形成的时间顺序...被计算假设着轴对称的平衡





形成时间尺度 $(\tau_{\text{Alfvén}} \cdot \tau_{\text{Resist}})^{1/2} \sim 0.6 \text{ ms}$

$\tau_{\text{Alfvén}} \sim 0.5 \mu\text{s}$
 $\tau_{\text{Resist}} \sim 70 \text{ ms}$

电阻性的磁流体的不稳定性可以形成球环电浆

Ricardo Farengo
(ISTW2008 - Frascati)

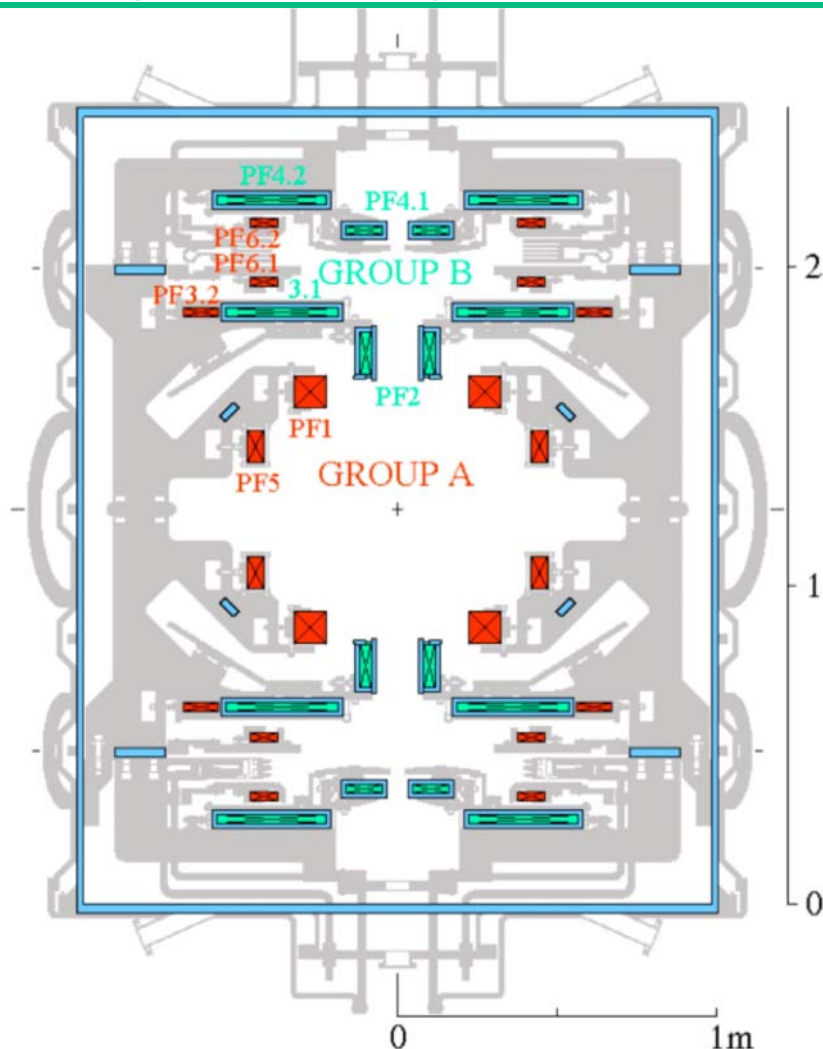


Ricardo Farengo
CNEA Bariloche
(Argentina)

球环电浆的创作被计算非轴对称地

PF线圈被设计了成两个集团, 每个串联连接

B集团(4加4个PF线圈): 电浆中心柱塑造着, 跟厚AISI的外壳($\tau \sim 2\text{ms}$), 现在真空室以内



Antonio Cucchiaro
ENEA

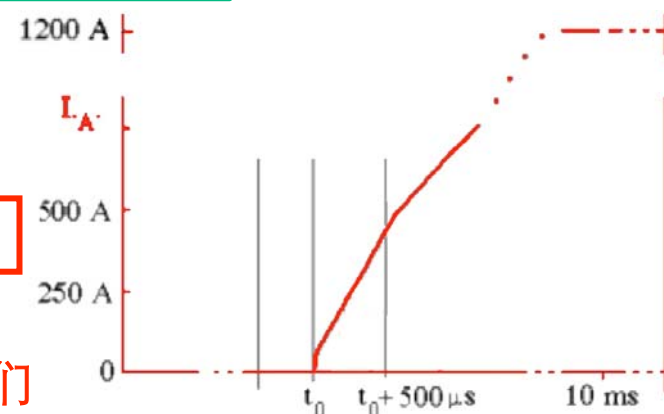
A集团线圈的波形
提供欧姆驱动力
足以到达**120kA**
的电流在球环以内

...范式的逆转:
先欧姆驱动力
然后磁螺注射

A集团(5加5个PF线圈):为了压缩球环的电浆 ...尚未建

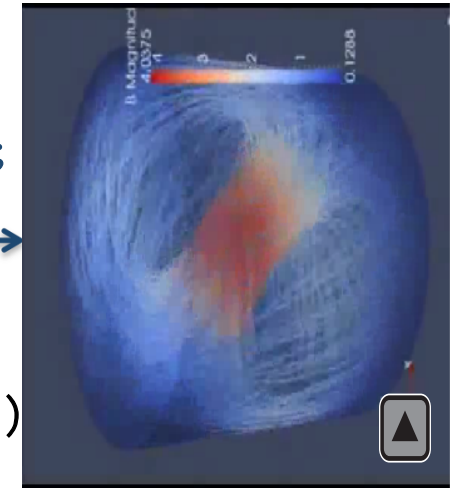
高电压(约20kV绝缘) 快速电流增加(0.5ms)

跟薄'镍铬'合金的外壳, 以便在 $\tau \sim 200\mu\text{s}$ 上磁场扩散通过他们



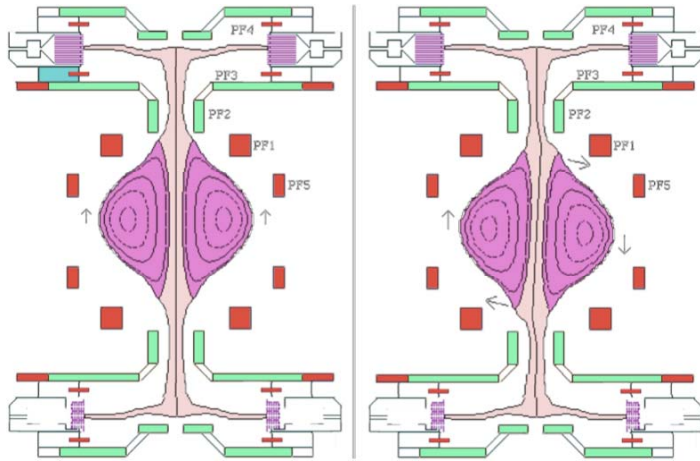
PROTO-SPHERA的理想磁流体稳定性

压缩电浆的外部线圈的磁偶极子是相反到球环电浆电流的磁偶极子;
这是'球马克'倾斜不稳定性的原因



刚体位移

刚体倾斜



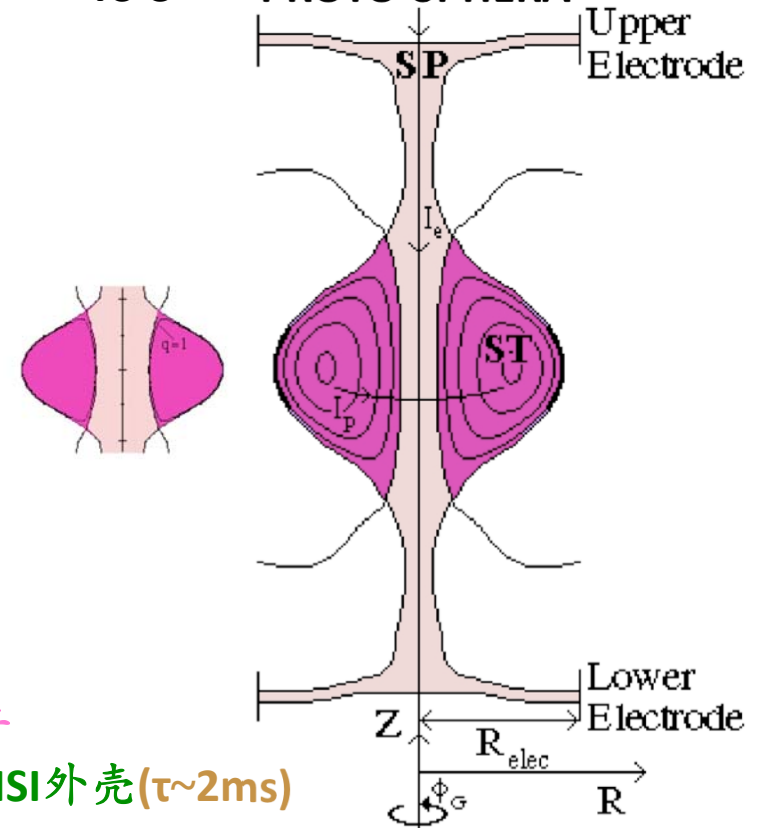
线圈A集团 (是磁场压缩着电浆的)
磁偶极子也是相反的,
但是线圈B集团(是磁场塑造着电浆的)
磁偶极子并不是相对的

$\Delta Z=4\text{ mm}$ 位移	$\Delta\theta=0.5^\circ$ 倾斜
$F_z=+38.9\text{ N}$ 不稳定	$I_p=30\text{ kA}$ $T_y=-2.25\text{ Nm}$ 稳定
$F_z=-9.92\text{ N}$ 通过PF2,3,4的厚外壳 成为稳定 ($t\sim 2\text{ ms}$)	
$F_z=+19.7\text{ N}$ 不稳定	$I_p=60\text{ kA}$ $T_y=-9.22\text{ Nm}$ 稳定
$F_z=-23.5\text{ N}$ 通过PF2,3,4的厚外壳 成为稳定 ($t\sim 2\text{ ms}$)	
$F_z=-6.9\text{ N}$ 稳定	$I_p=120\text{ kA}$ $T_y=-12.0\text{ Nm}$ 稳定
$F_z=-68.1\text{ N}$ 稳定	$I_p=240\text{ kA}$ $T_y=-24.5\text{ Nm}$ 稳定

电浆对刚体倾斜总是稳定由于B集团的线圈的磁偶极子
电浆对刚体位移总是成为稳定由于B集团的线圈的厚AISI外壳($\tau\sim 2\text{ ms}$)

TS-3

PROTO-SPHERA



CKF可能从PROTO-SPHERA概念的一个发生的发展

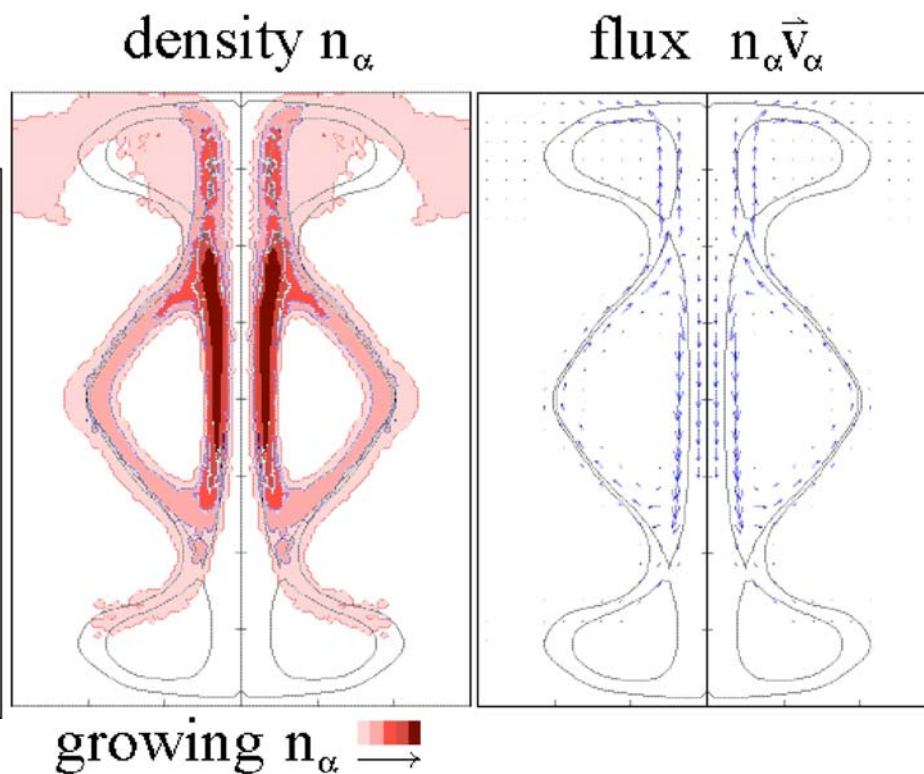
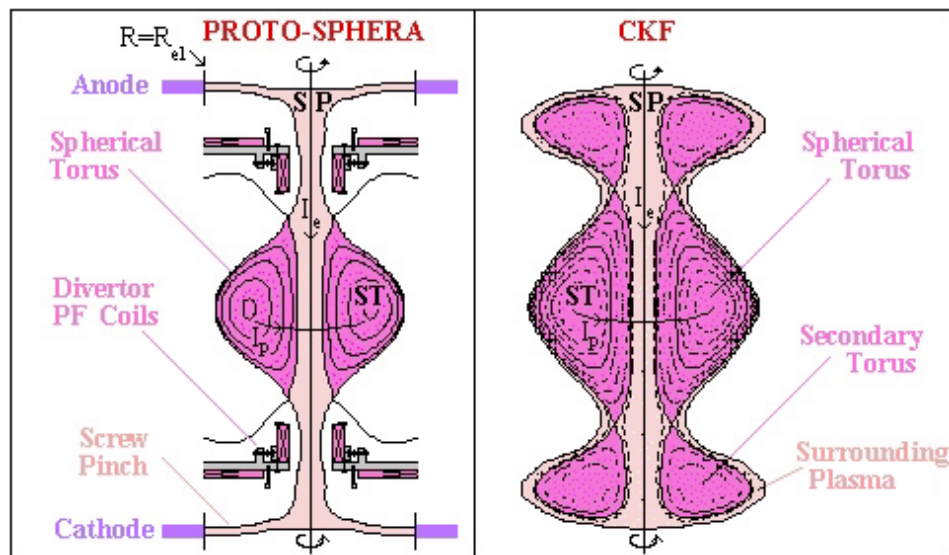
两个简并($B=0$)磁场的X-点存在于顶部和底部电浆里,所以有两个喷嘴



因而如果聚变的条件可以实现在类似
PROTO-SPHERA的一个将来磁约束装置上,
它将直接成为一个空间推进器比化学火箭
一百万次更为强大,每单位质量

n_α 粒子的密度

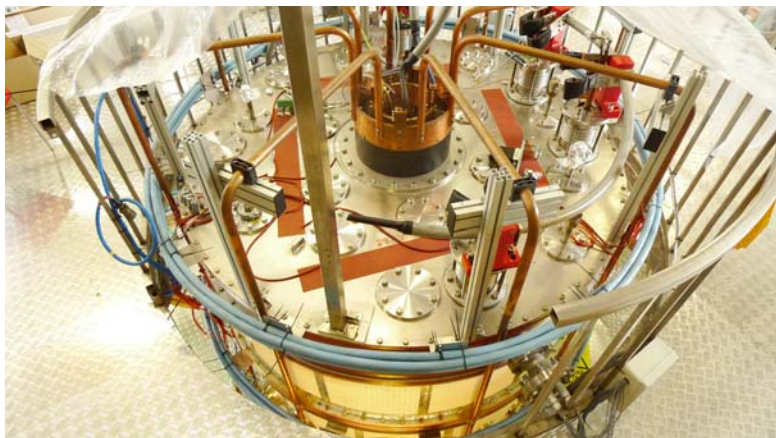
CKF在理想磁流体上被发现是稳定达 $\beta=1$
.....有希望的未来聚变空间的推进器?



PROTO-SPHERA是一个CKF的装置,
所的最外的电浆终止在两个电极上,
而两个次生的电浆环被代替以PF2/PF3磁线圈

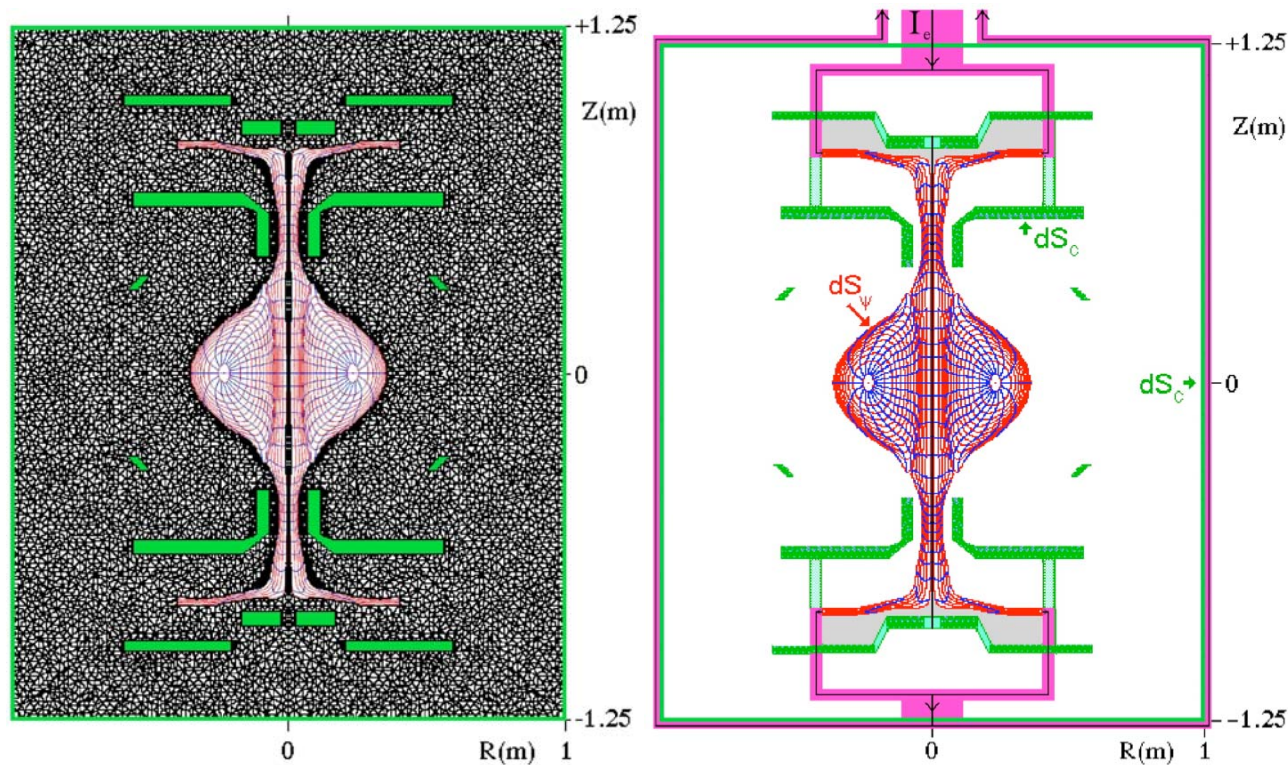
PROTO-SPHERA的理想磁流体稳定性: 真空场的扰动

阳极的电流 I_e 送入在机一内
通过顶部的同轴系统



阴极的电流 I_e 从机的底部返回通过8铜导电棒

二维有限元网格来
计算真空磁场的扰动



PROTO-SPHERA的理想磁流体稳定性: 结果

对于小环形波数 $n=1,2,3$ 为了获得理想的MHD稳定性:

(表示通过参数: $\beta = 2\mu_0 \int p dV / B^2 dV$)

在电浆以内两个电流的比率: I_{ST}/I_e = 电流在球环一内 / 电流在中心柱一内)

- $\beta=21\div26\%$ 以下, $I_{ST}/I_e = 0.5 - 1$ 以下

- $\beta=14\div15\%$ 以下, $I_{ST}/I_e = 2 - 4$ 以下

(表示通过参数: $\beta_{T0} = 2\mu_0 \int p dV / B_{T0}^2 V, I_{ST}/I_e$)

- $\beta_{T0}=28\div29\%$ 以下, $I_{ST}/I_e = 0.5 - 1$ 以下

- $\beta_{T0}=72\div84\%$ 以下, $I_{ST}/I_e = 2 - 4$ 以下

电浆中心柱的电流 $I_e = 60\text{kA}$

球环电浆的电流 $I_{ST} = 120\text{kA}$: $I_{ST}/I_e = 2$

不稳定环形波数限于为 $n=2,3$

在 $\beta=25\%$ 由从动 $q=3/2$ 共振

电浆中心柱的电流 $I_e = 60\text{kA}$

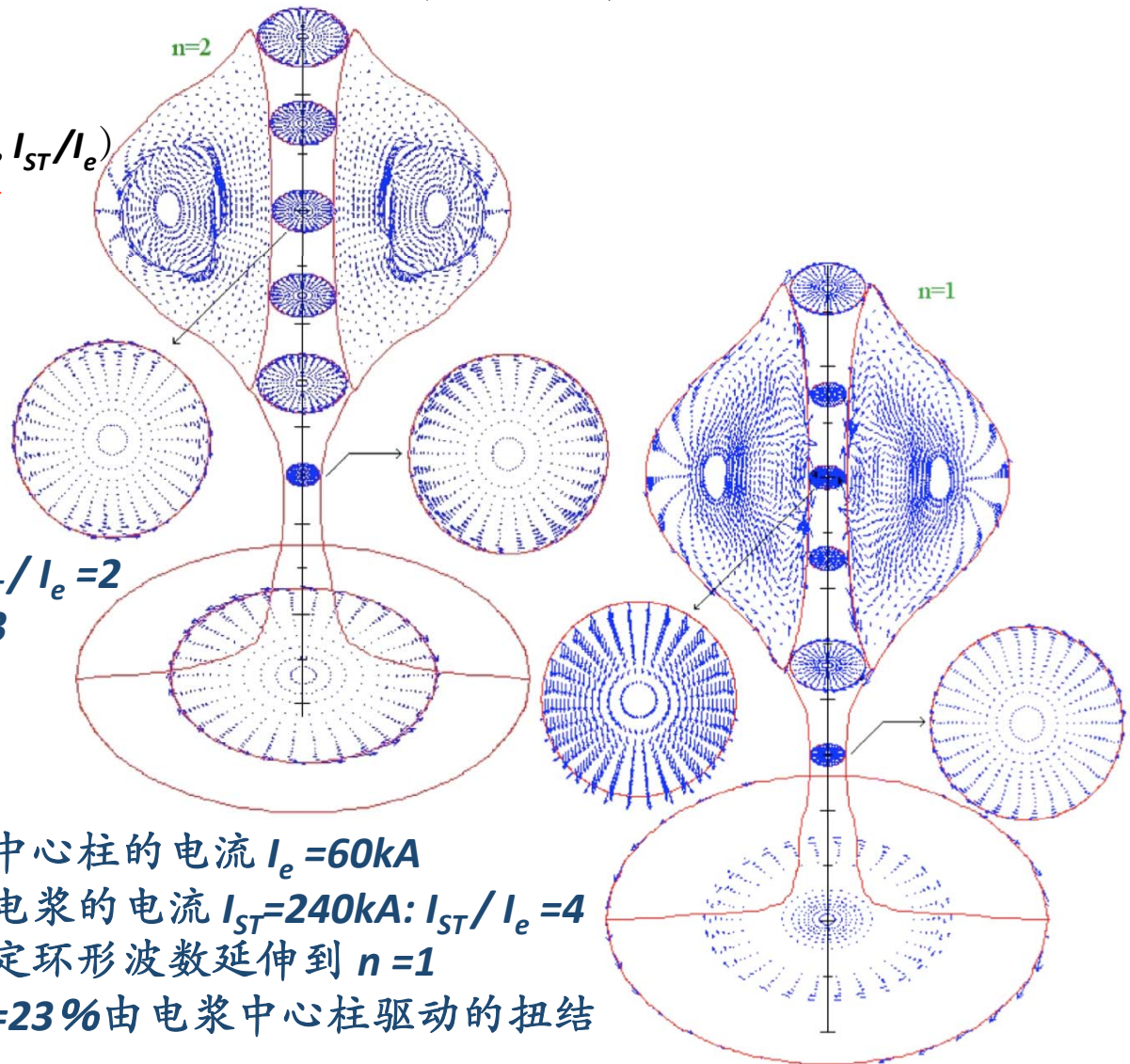
球环电浆的电流 $I_{ST} = 240\text{kA}$: $I_{ST}/I_e = 4$

不稳定环形波数延伸到 $n=1$

在 $\beta=23\%$ 由电浆中心柱驱动的扭结

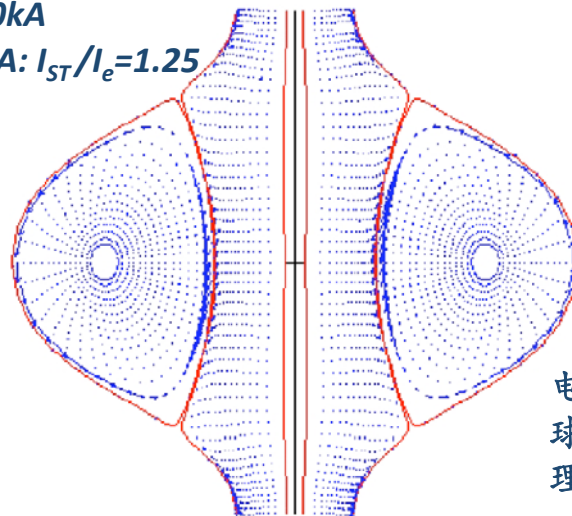
理想的磁流体分析, 以评估 I_{ST}/I_e 和 β 限制

(Micozzi P. et al., 2010 Nucl. Fusion **50** 095004)

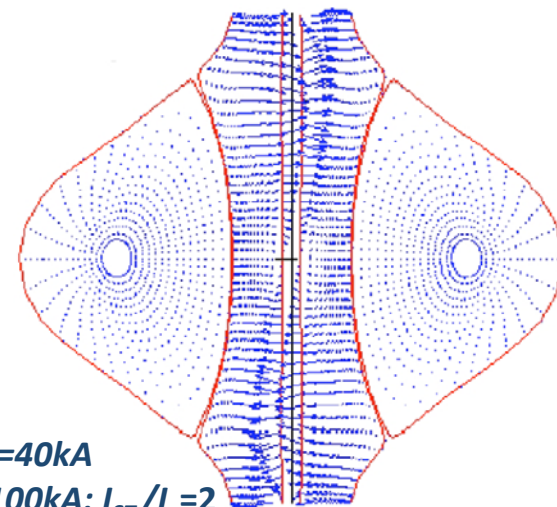


与TS-3实验的结果比较

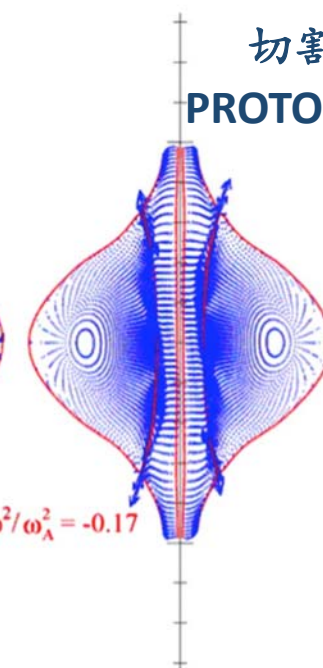
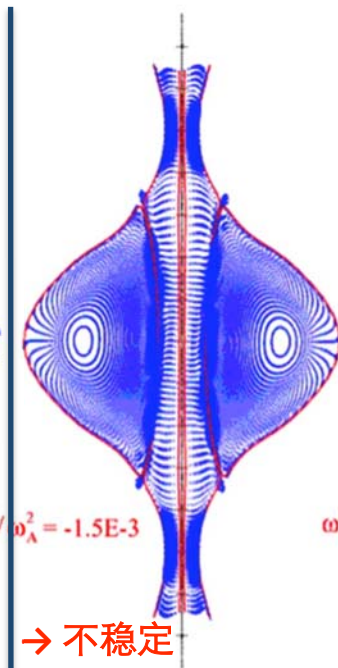
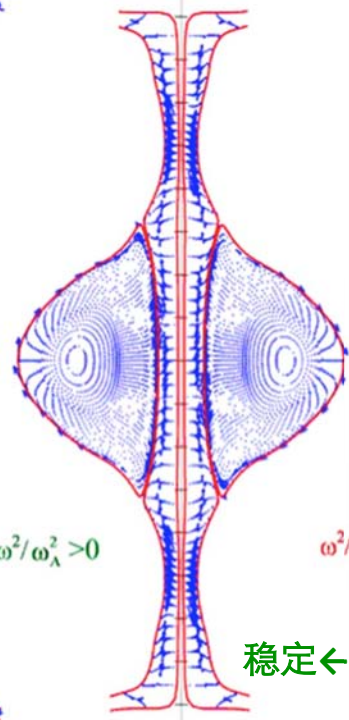
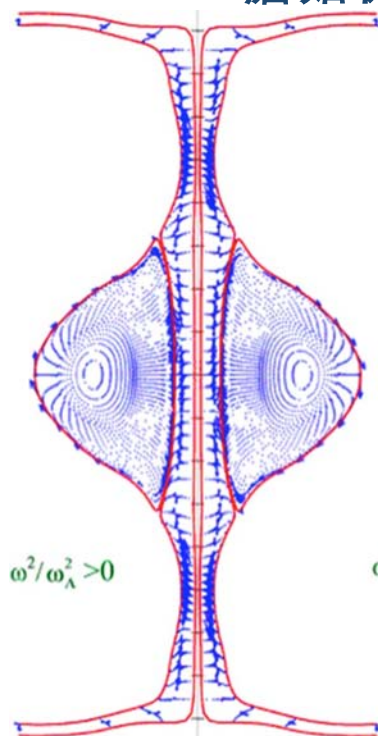
电浆中心柱的电流 $I_e = 40\text{kA}$
 球环电浆的电流 $I_{ST} = 50\text{kA}$: $I_{ST}/I_e = 1.25$
 理想MHD里TS-3稳定的



电浆中心柱的电流 $I_e = 40\text{kA}$
 球环电浆的电流 $I_{ST} = 100\text{kA}$: $I_{ST}/I_e = 2$
 理想MHD里TS-3不稳定的: 电浆中心柱的扭结



蘑菇状电浆面临着两个电极: 对于理想的MHD稳定性很重要



稳定 ← → 不稳定

切割越来越短的电浆中心柱,
 PROTO-SPHERA携带着 $I_{ST} = 120\text{kA}$
 越来越成为不稳定

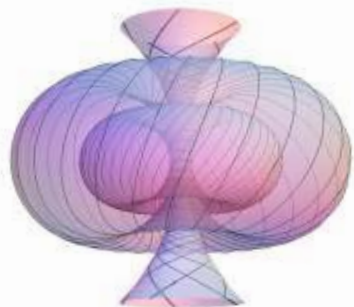


圆柱形的真空室, 属于过START直到1998年, 是由Culham于2004年捐赠

老而光荣的真空室来自Culham找到了自己的路...来了Frascati



PROTO-SPHERA建了(2006- 2009年)由热那亚的ASG超导, 费用的1M€



2004 - 2010年:



...来自概念

...通过详细设计

...到硬质金属

阳极

PF2线圈
的风门

阴极



为了击穿电浆中心柱
3个电源必须被通电

- 阴极加热的电源, 6阶段的转换器: $6 \times (1.7\text{kA}, 25\text{V})\text{RMS}$
- PF线圈的电源: $2\text{kA}, 350\text{V}$
- 电浆中心柱的电源: $10\text{kA}, 350\text{V}$



Giuseppe Maffia Alessandro Lampasi
ENEA



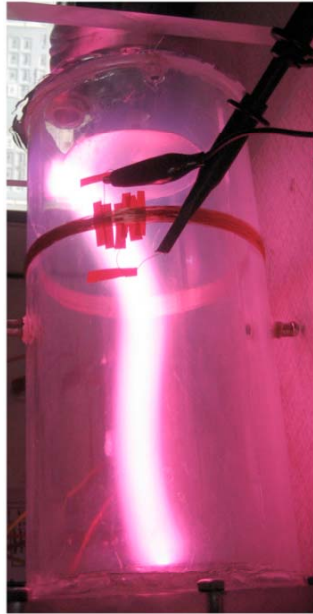
电源被建了由Vicenza的EEI, 费用的0.7M€

2011 - 2014年:



2014年:圆柱形阳极

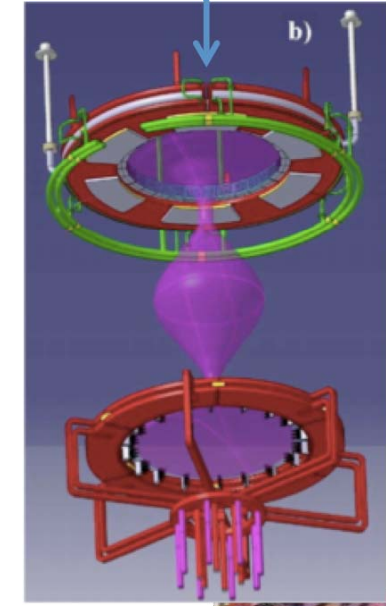
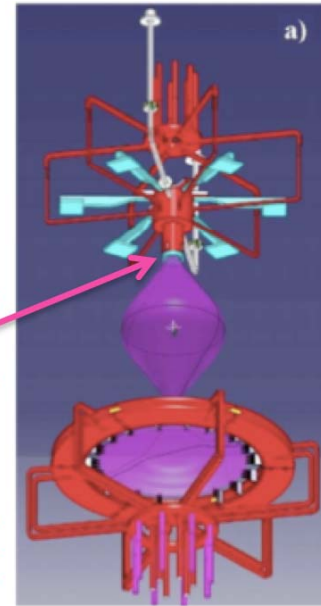
2015年:的环形阳极



生怕阳极的弧锚固，
在电弧放电里经常发生
(氩弧焊，电浆炬)

第一轮实验
有一个简单的圆柱状阳极

击穿被容易地实现，
可是那个圆柱状阳极只是一个烦恼的根源



Vincenzo Zanza
ENEA

圆柱形阳极的结果

氢电浆
击穿电压:170V +10 ms, 500 A +20 ms, 1.5 kA
阳极相机



电浆中心柱相机

2015年4月:的 环形阳极准备



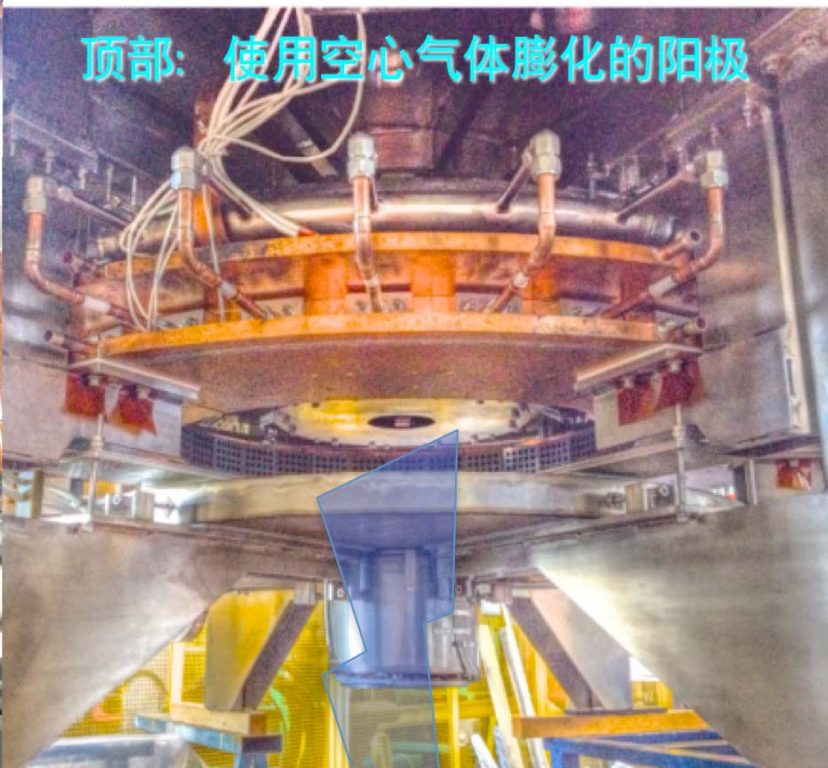
Fabio Crescenzi



Benedetto Tilia Andrea Grosso ENEA



2015年5月: 的环形
阳极被插入
在机上的顶部



顶部: 使用空心气体膨化的阳极



底部: 3000°K加热阴极

现阶段阴极

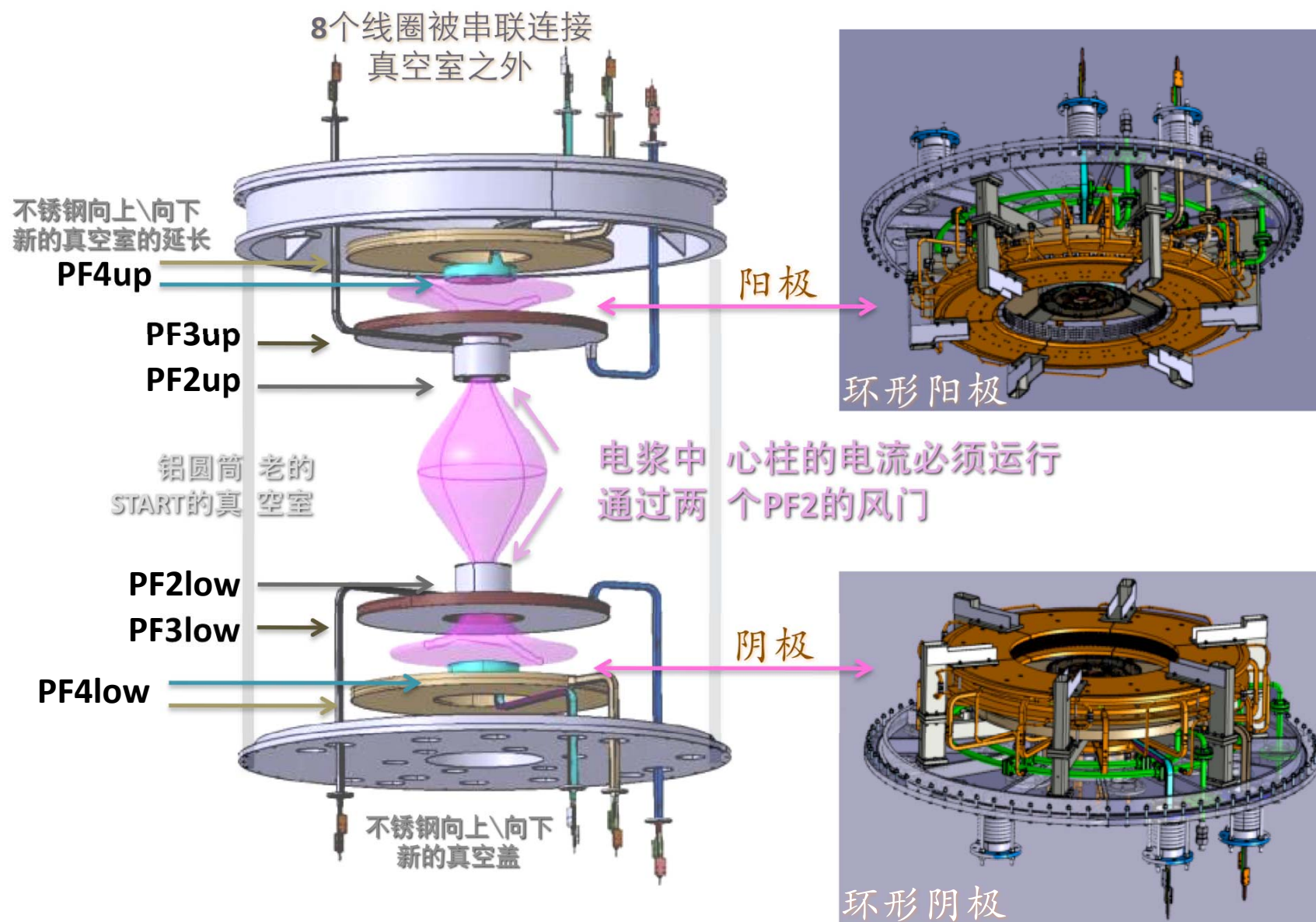
(18×3的发射灯丝): 目标8.5kA

最后阶段阴极, 6 × 现阶段
(108×3的发射灯丝): 目标60kA

类似于“商务的神棍”的发射灯丝
已经存活了一千多的周期



仅为了设置电浆中心柱的PF线圈，已完成了



真空室是接地电势的，

线圈的外壳被建设使得它们的电势是浮动的，
但可以连接它们到一个电势：阳极 +，阴极 -，真空室 0



Federica Causa ENEA

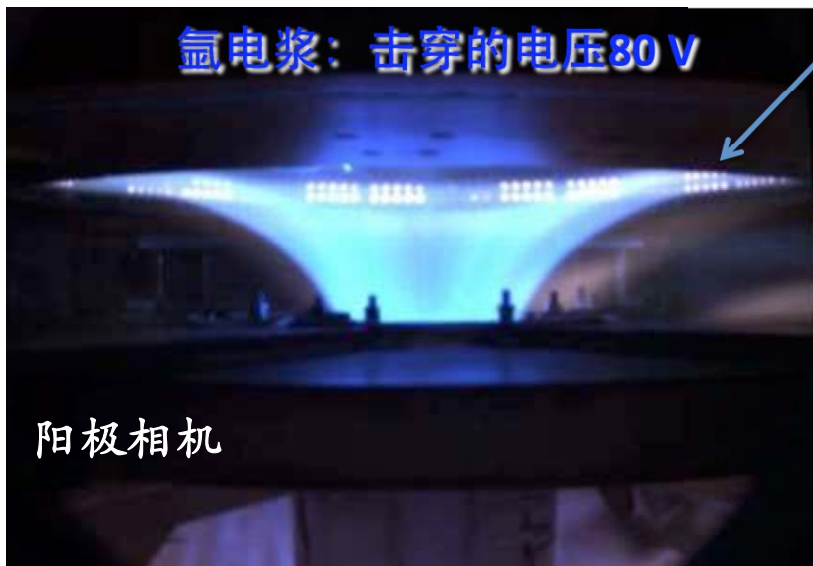


Luca Boncagni ENEA

使用空心气体膨化的阳极是成功的

- 电浆的中心柱贯串通过两个PF2的风门
- 电浆进入了气体膨化的阳极孔穴
- 没有阳极的弧锚固的迹象 ($I < 3.5\text{kA}$)
- 充盈压 10^{-3} - 10^{-2}mbar

氩电浆：击穿电压80 V



阳极相机



阴极相机

环形的阳极从来没表明电浆细丝的迹象
而环形阴极的电浆由细丝组成
(由于稀疏的发射灯丝)

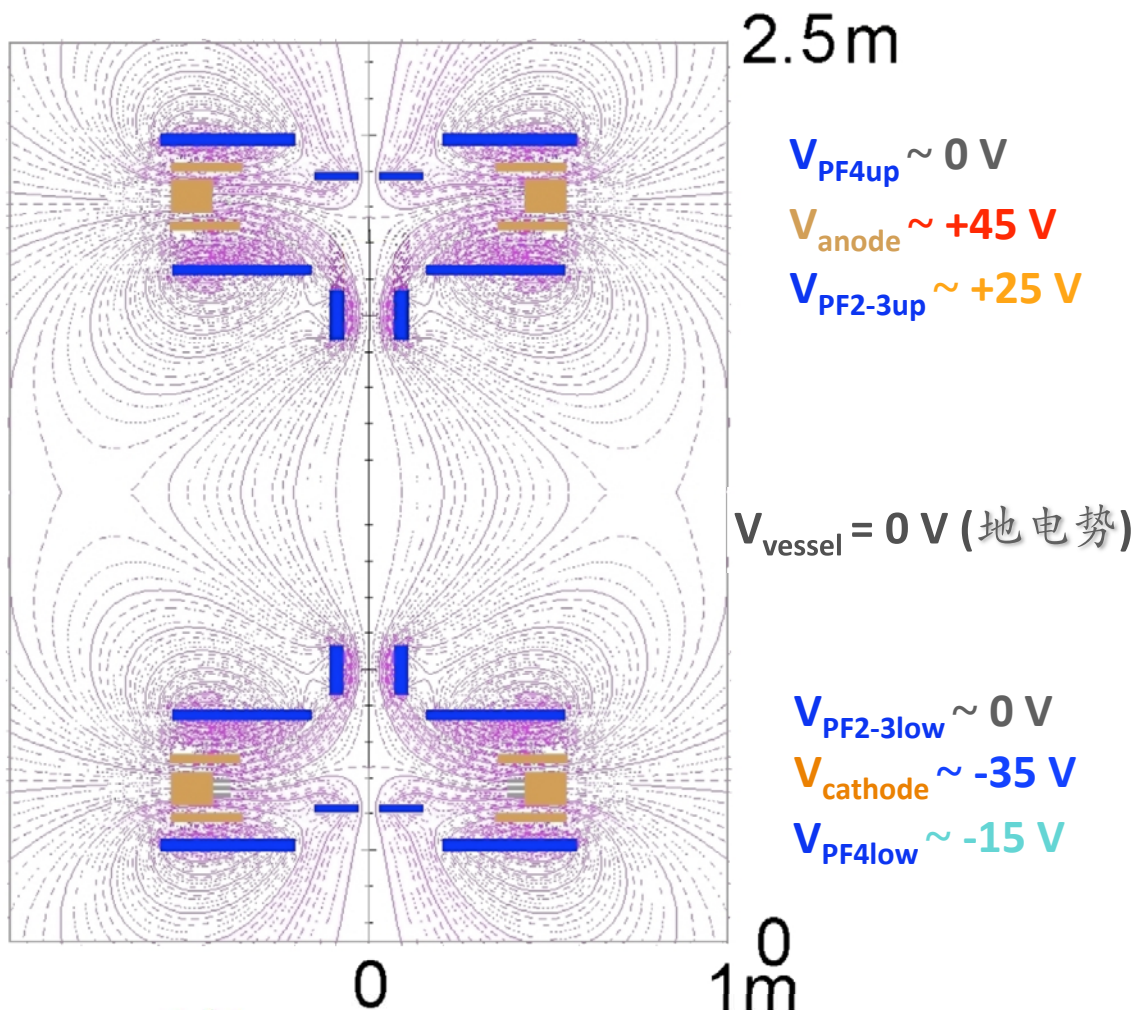


甚至主电浆中心柱显示细丝

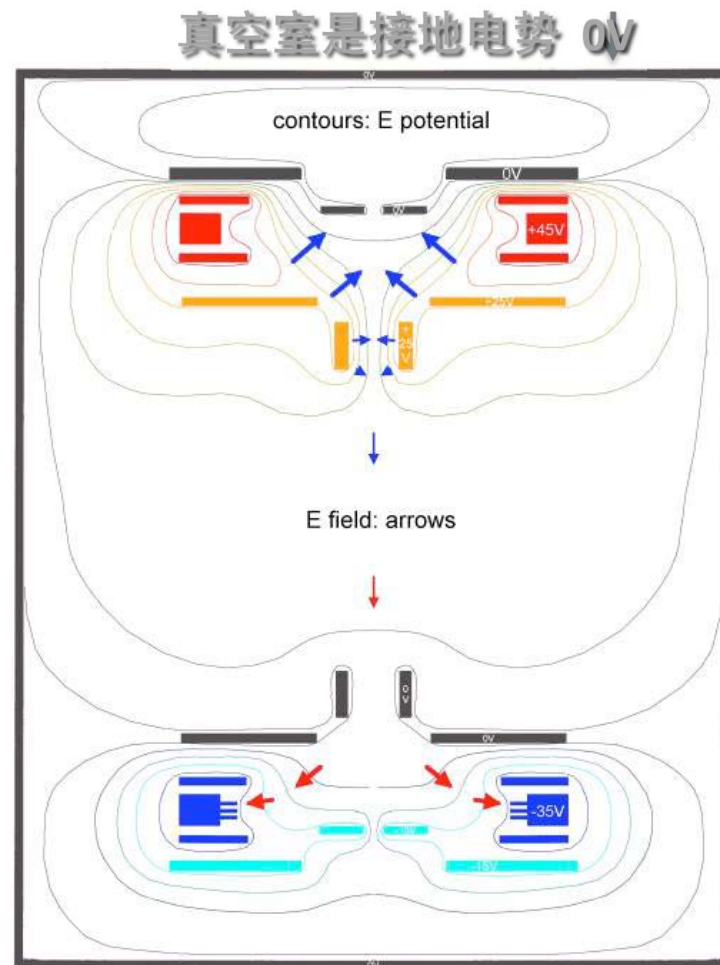
电浆的静电的效果

线圈的外壳有浮动的电势,但可以连接它们到一个电势:
阳极 +, 阴极 -, 真空室 0, 经过 $\sim 0.1 - 1\Omega$ 的电阻

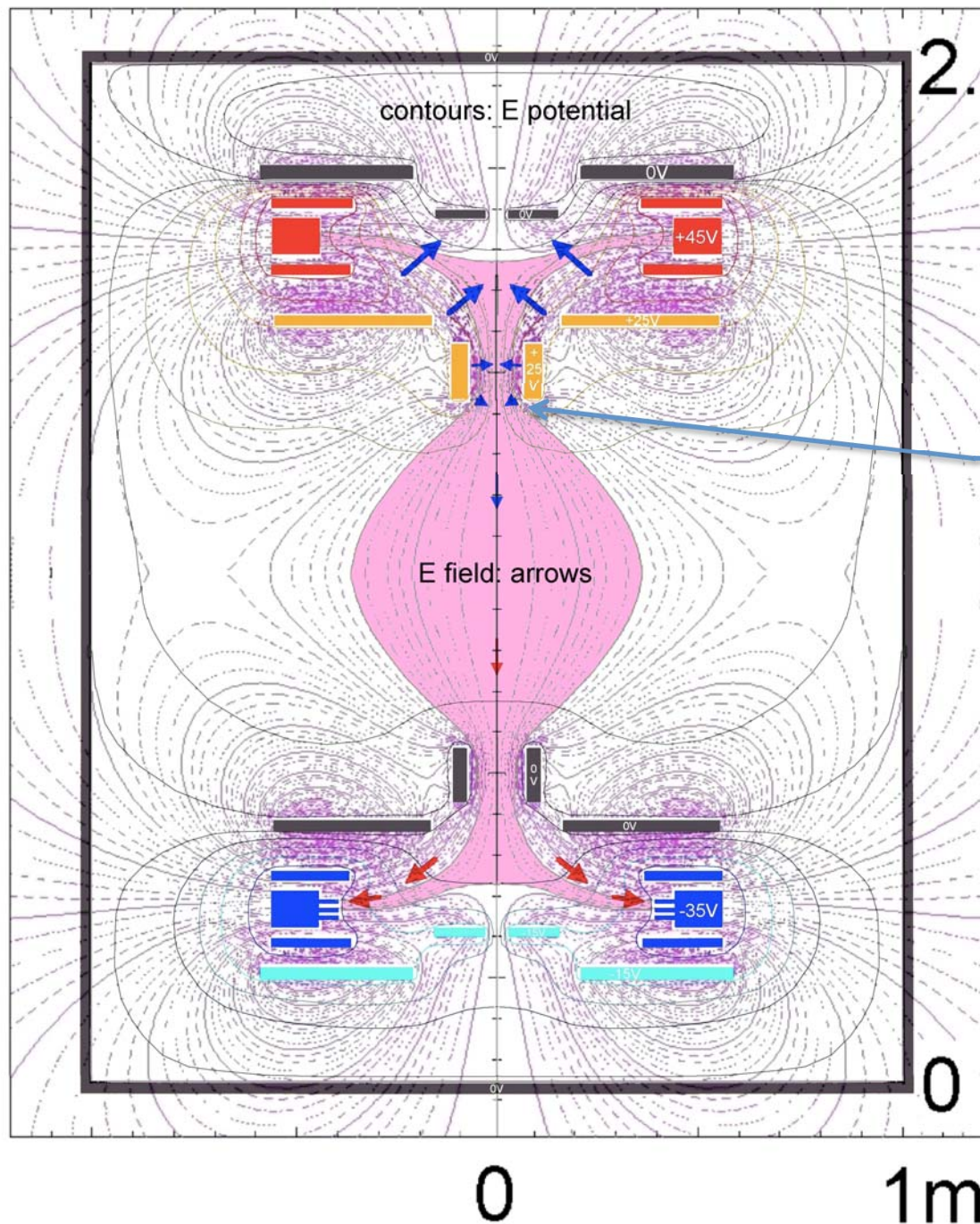
但该静电电势分布是由电浆主导的



虽然**磁场**是上下对称的,



电位的分布不是上下对称的: 既靠近
阳极和阴极, 最上面的线圈的外壳是约接地电势的



电位由电浆诱导:

环形阳极的附近

有E电场的分量垂直于B磁场

... $E \times B$ 漂移旋转了电浆

从附近的PF2up线圈的风门

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

环形阴极的附近:

有E电场平行于B磁场

... 无 $E \times B$ 漂移旋转了电浆

一个电浆的自组织
由环形的电极诱导...

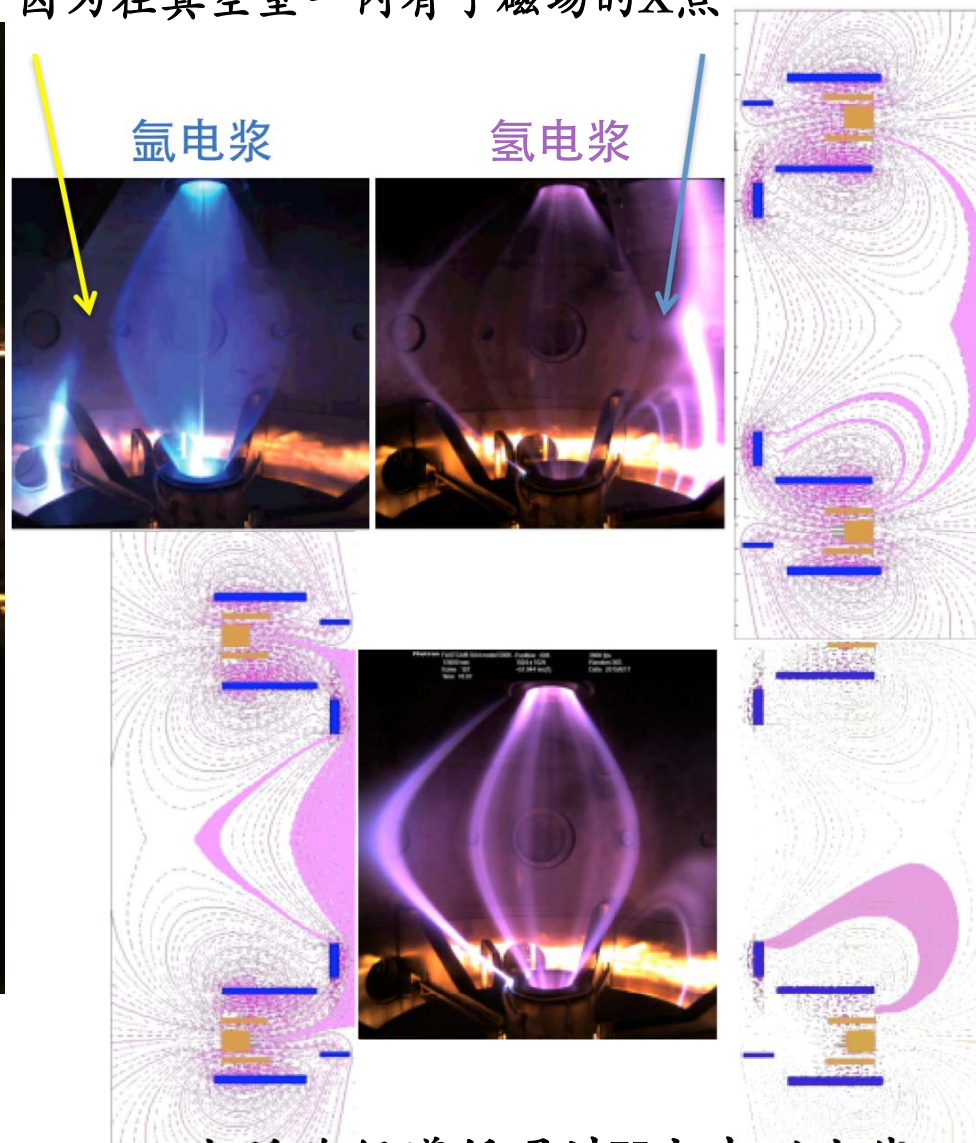


2015年5月第一环形阳极实验
电浆电流的一半 (1kA的2KA)
不通过所打算的路径

因为在真空室一内有了磁场的X点

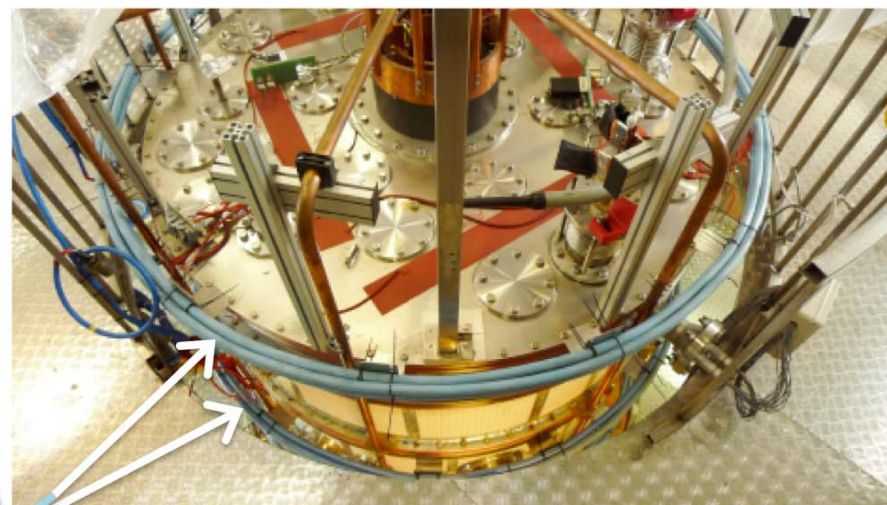
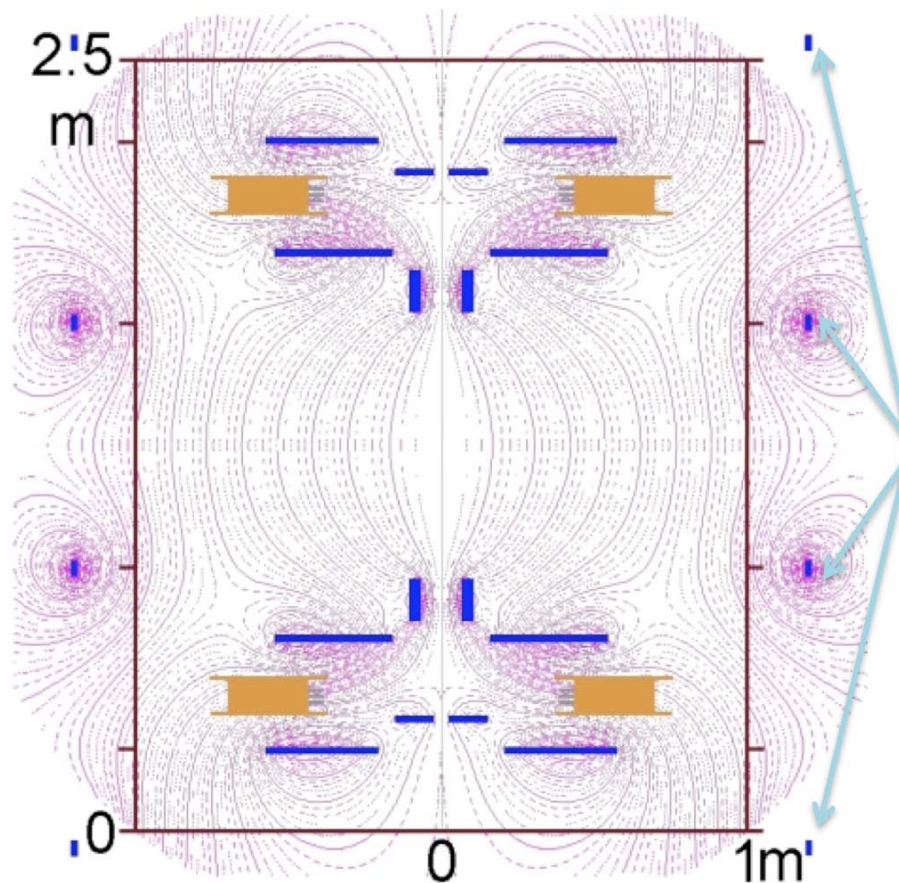


Shot 78



电弧路径遵循通过X点去磁力线

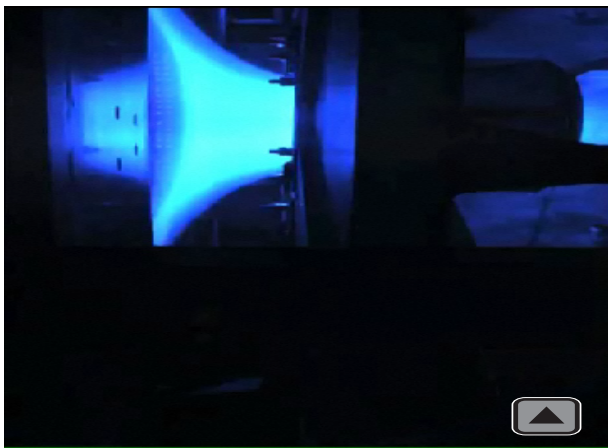
4个外部PF线圈已添加
为了取出赤道的X点从真空室内
...和串联连接的与内部PF线圈



4个外部PF线圈



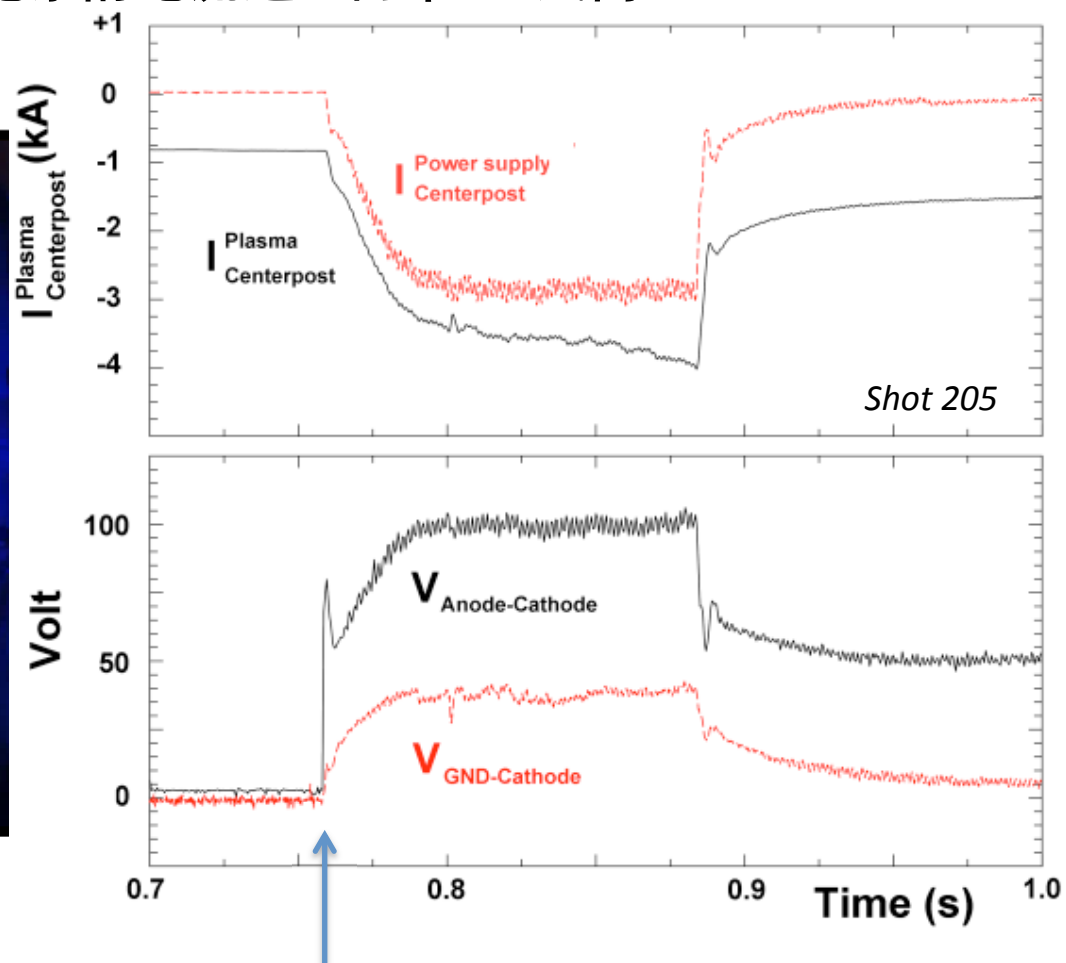
由于电流皮肤效应在铝制真空室和不锈钢盖上,PF线圈电流烧成以后必须等待0.75s, 然后可以获得电离的电浆中心柱



2015年10月实验使用外部PF线圈:

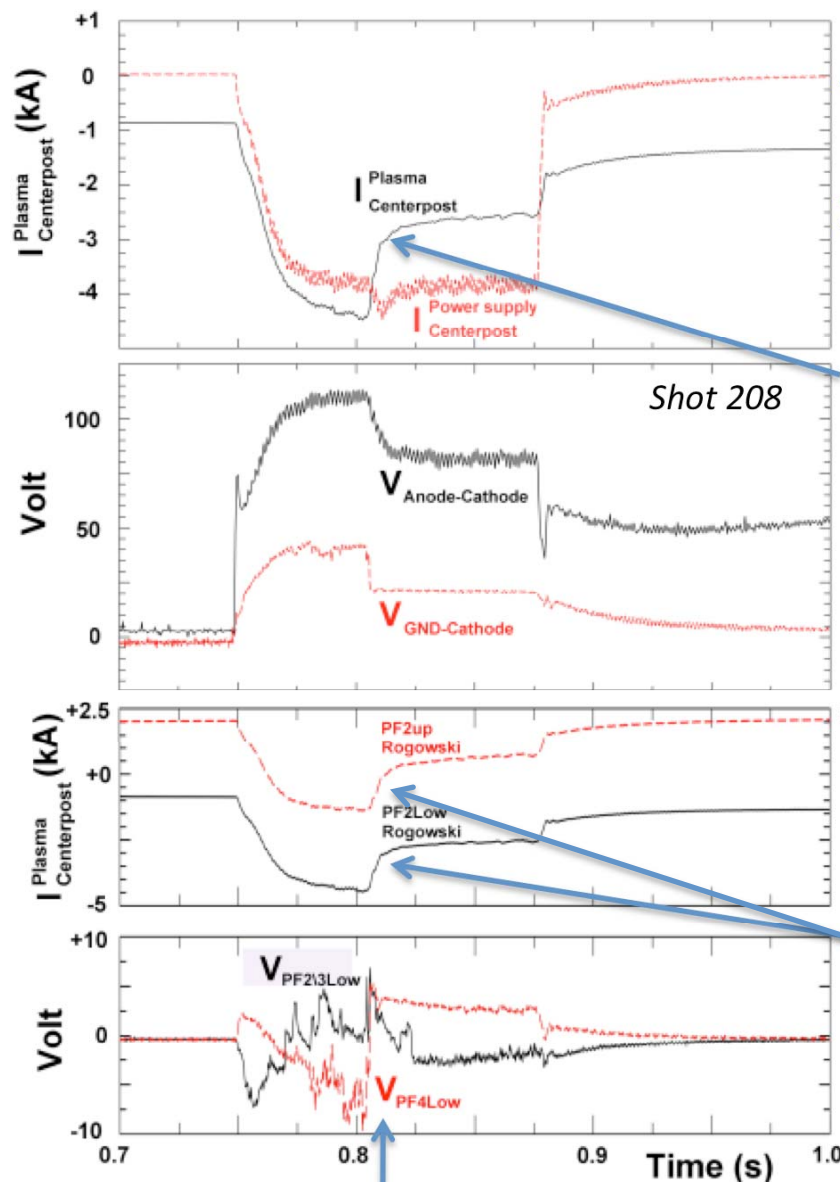
氙电浆的电流达到3kA了, 持续了150 ms的时间

整个电浆的电流通过两个PF2风门



等待0.75s为了获得电离的电浆中心柱
(为了取出赤道的X点从真空室内)

对于**电浆**的电流 $>3.5\text{kA}$ 外部路径仍然是开放的



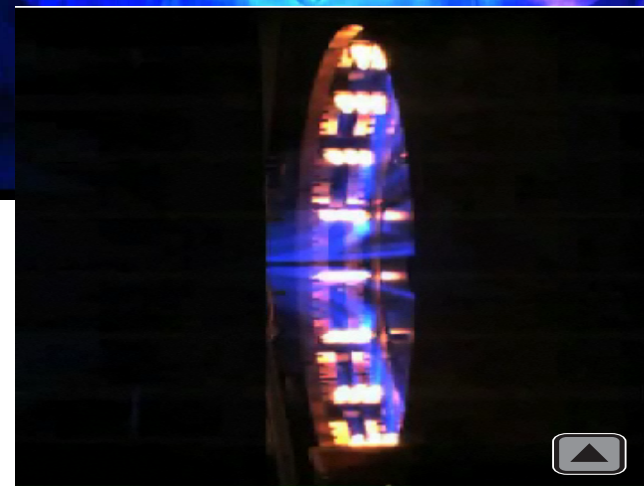
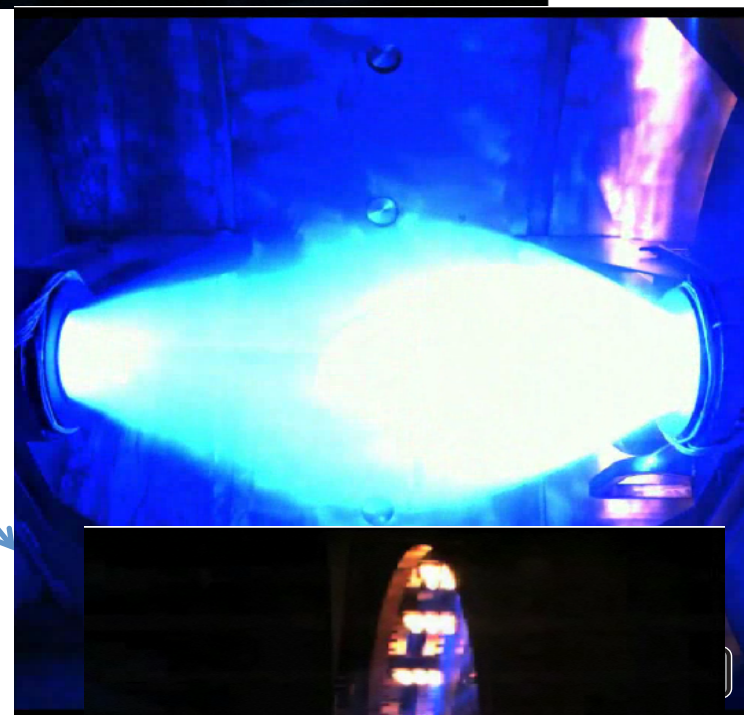
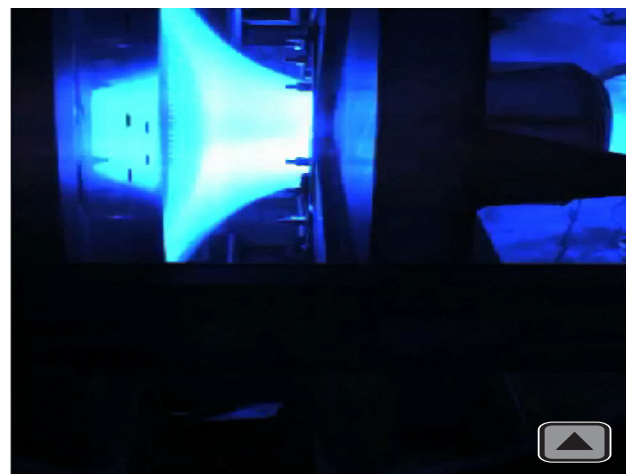
氩电浆:
目标是 4kA
达到 3.5kA

$\sim 1.5\text{kA}$ 丢失
从主电浆

从放电
阴极下来
到底盖\真空室

电浆电流的
路径避免穿过
两个PF2的风门

10V的电压尖峰出现在浮动较低PF线圈
它们与乱真的电流路径相关

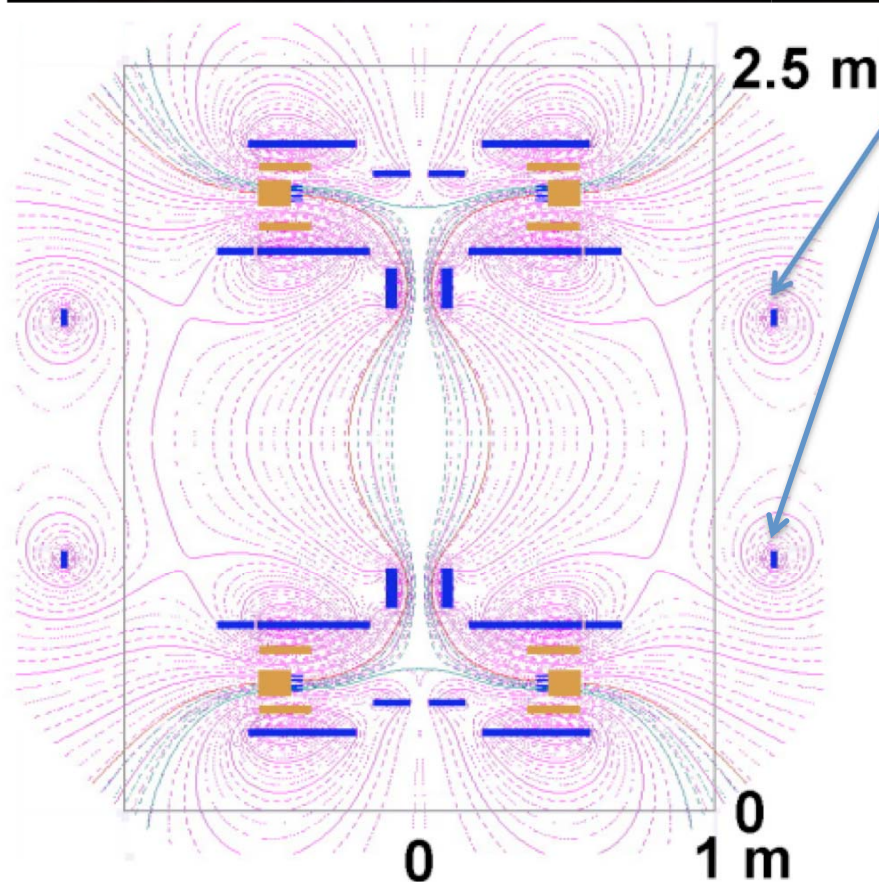


调整磁场允许电浆有更好的电极的填充

当电浆沿着一条寄生的路径流动阴极的发射被减少

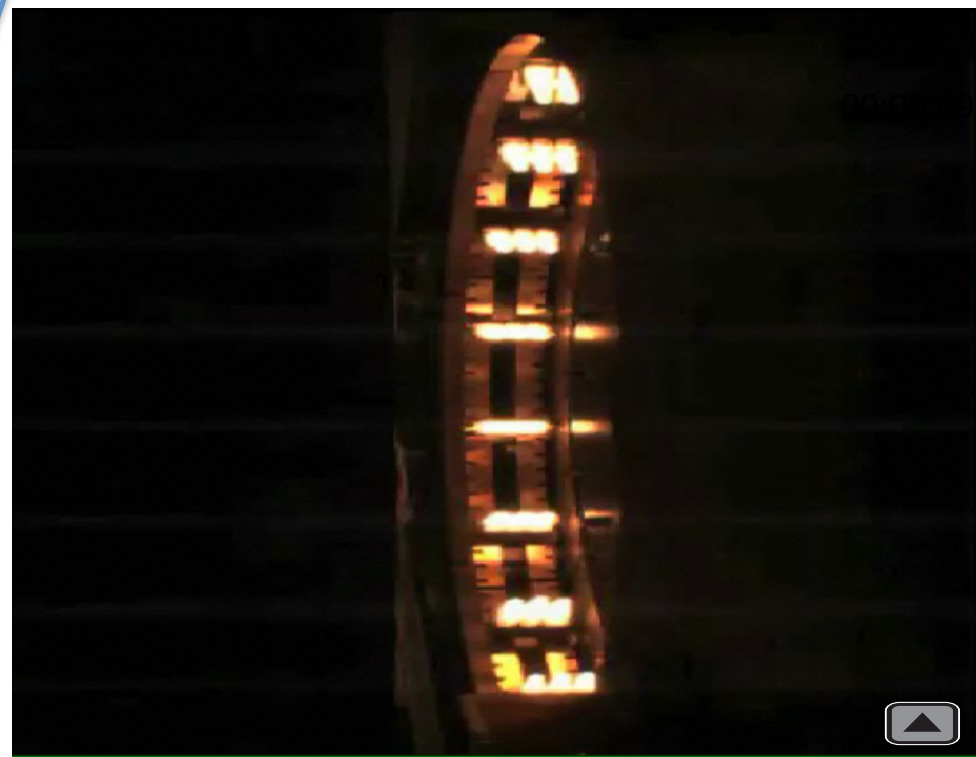
电浆的电流 **3.5kA**

电浆的电流 **2.0kA**, 1.5kA 被丢失



电仅流在赤道附近的外部 线圈

阴极似乎在任何时候通过电浆更好地充满阴极

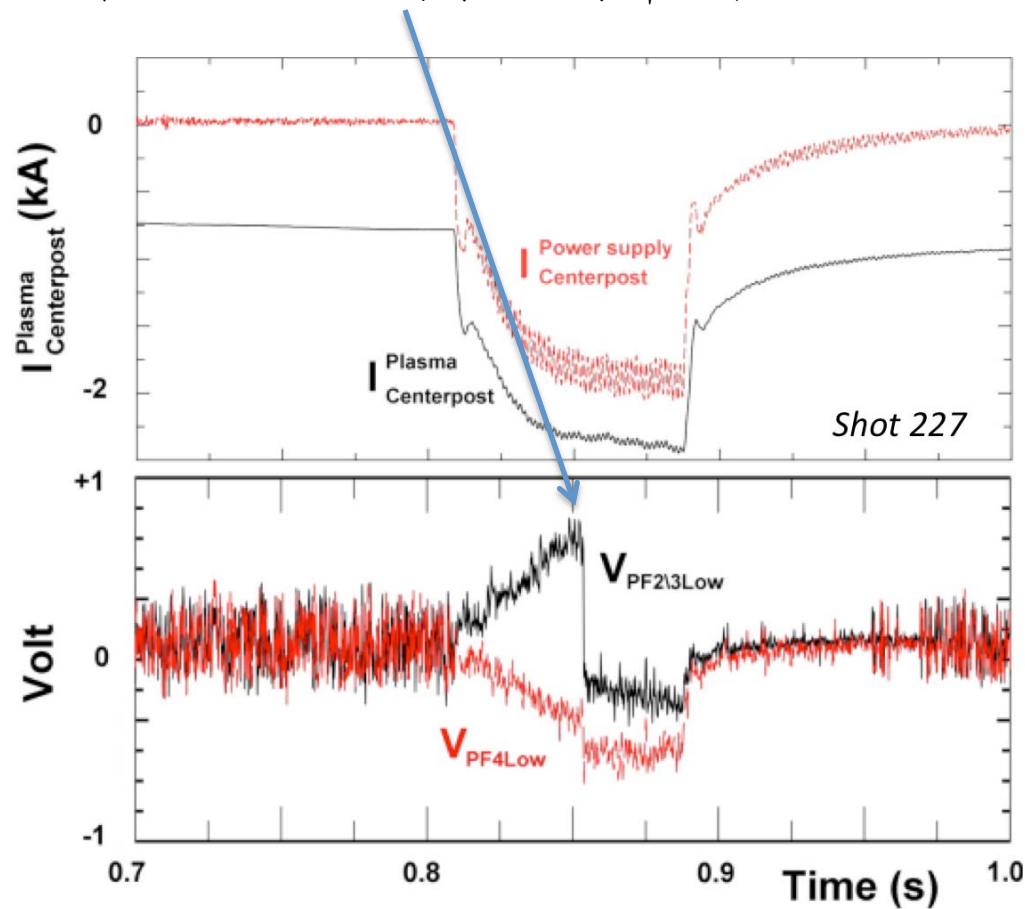


- (一) 电流仅在赤道附近的外部PF线圈
- (二) 最低的PF线圈被短路到地电势:
阴极是由电浆更好地充满

氩电浆 2kA



电压的尖峰已被排除从在底部上的线圈，
在1V的跳后很安静的电浆中心柱电压



行动正在进行中

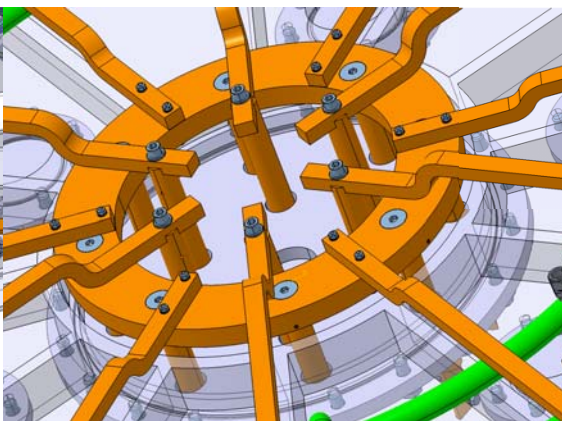
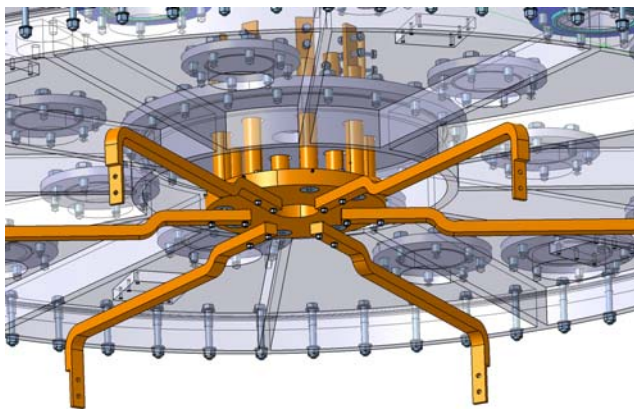
为了实现8.5kA的全电流,有必要除去
电流馈通棒的附近的导电材料,其允许寄生的电浆放电



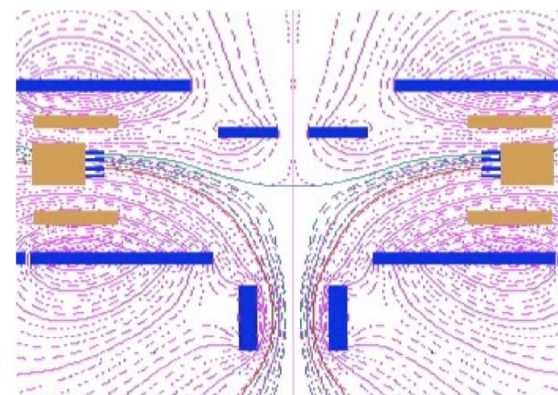
• 电流馈通棒(在阳极的顶部)
从20MΩ到2kΩ的绝缘



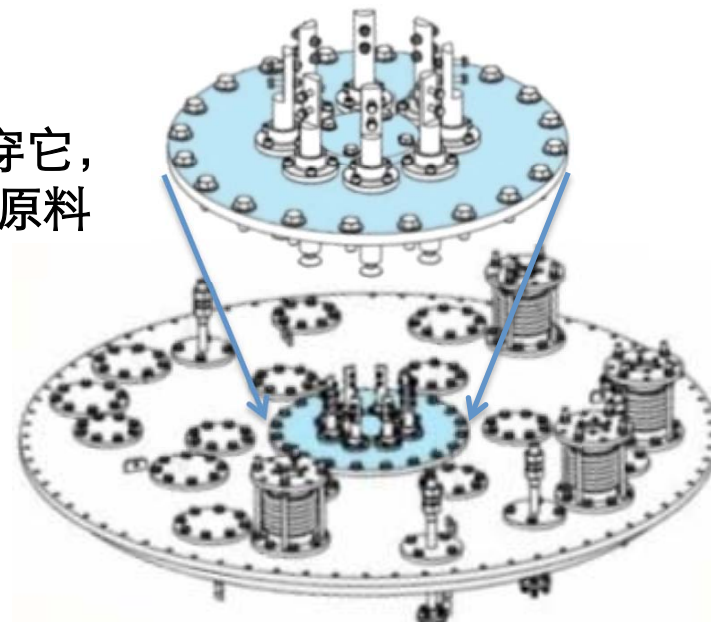
• 电流馈通棒(在阴极的底部)
从20MΩ到40Ω的绝缘



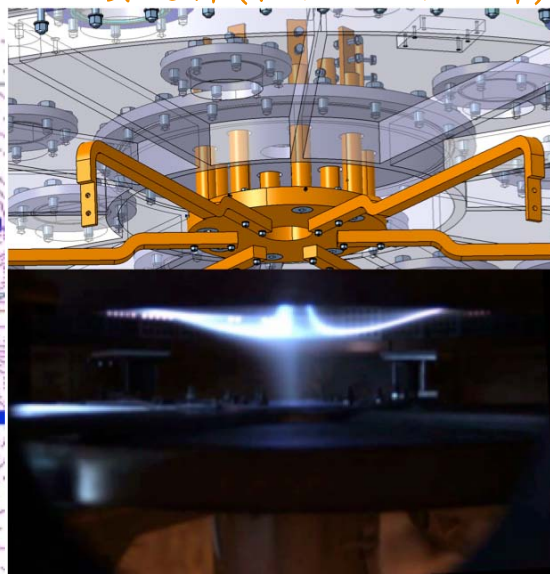
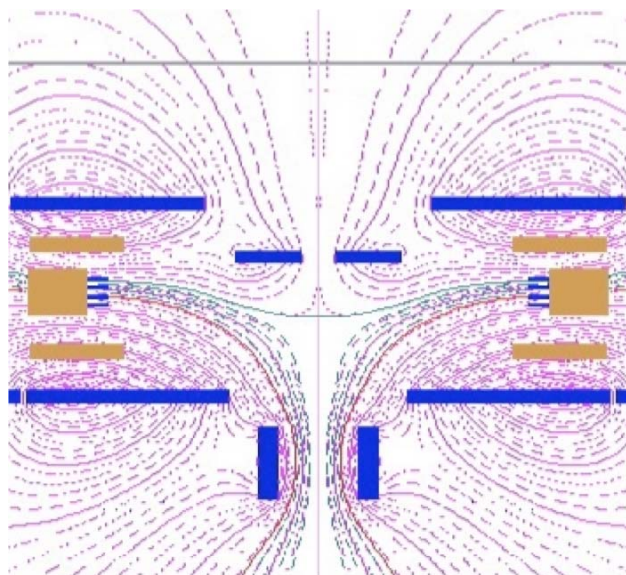
金属化的原因是:
简并($B=0$)磁场的X点存在于顶部
和底部电浆里,它作为一个喷嘴



(一)在顶部上(阳极的附近)有一张的凸缘, 8根馈通刺穿它, 现在凸缘被重建了使用着Polycarbonate(聚碳酸酯)为原料

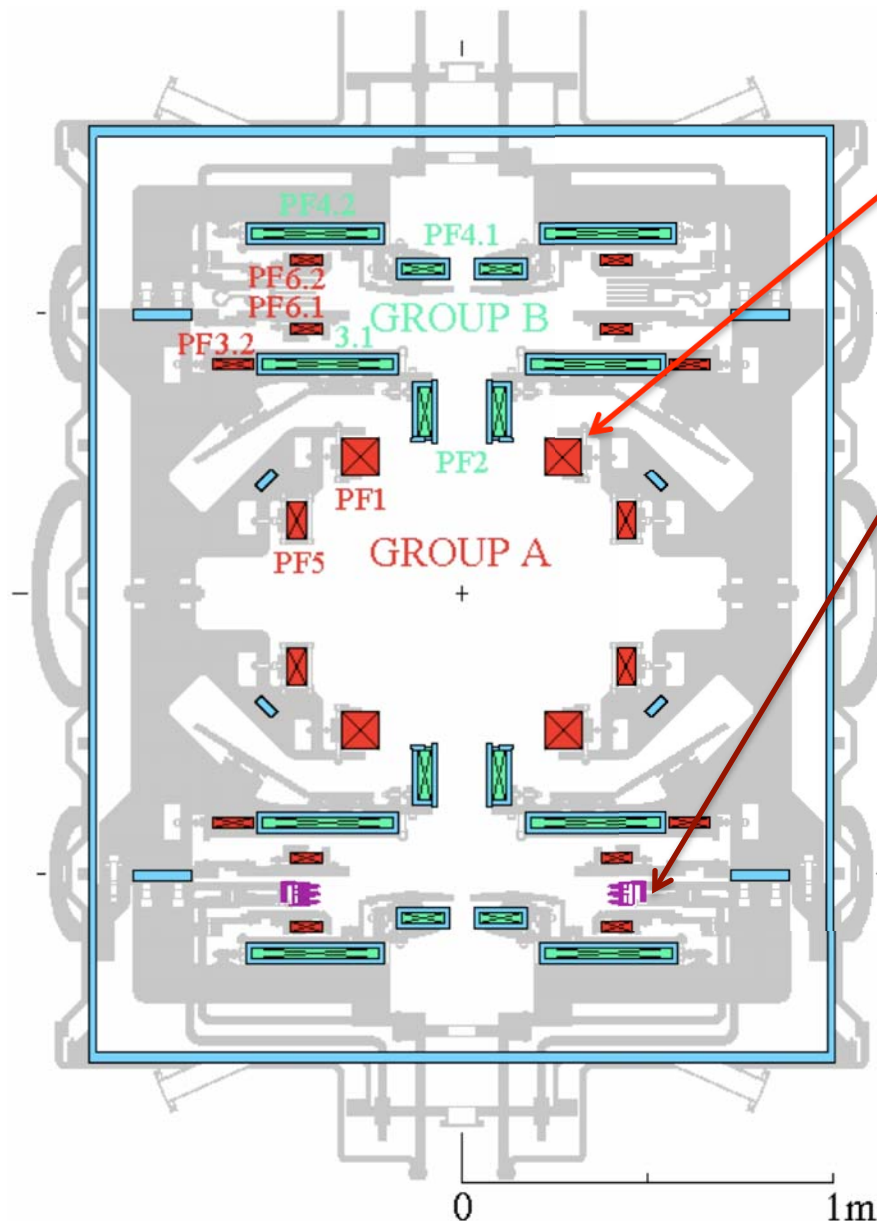


电流馈通棒(在阳极的顶部)



(二)在底部下(阴极的附近)有一张的凸缘, 14根馈通刺穿它, 现在使用Polycarbonate(聚碳酸酯)为原料凸缘被重建了

8.5 kA的电浆中心柱被获得后，什么要建:



5加5个PF线圈:为了压缩球环的电浆

...尚未建, ...但内部真空室准备主办

- 高电压(~20kV绝缘)
- 跟薄镍铬合金的外壳

费用的~0.5M€

钨灯丝的数将增加6倍(54→324)

费用的~0.2M€

第二阶段的电源:

- A集团的线圈的电源 费用的~0.1M€
 - 阴极加热的电源 ($I_{\text{cath}} \rightarrow 60\text{kA}$) 费用的~0.2M€
 - 电浆中心柱的电源 ($I_e \rightarrow 60\text{kA}$) 费用的~0.6M€
- 超级电容器将用于

G. Maffia et al., IEEEIC 2015, Rome

成本到现在为止
成本实验的最后阶段

~ 2.0M€

~ 1.6M€

简述

- **PROTO-SPHERA**正在生产它的第一个电浆中心柱...迟到总比不到好!
- 使用空心气体膨化的阳极是成功的: 没有阳极的弧锚固的迹象
(电浆的静电的效果, $E \times B$ 漂移旋转了电浆)
- 关于设计的电流(8.5 kA):40%已经实现, 3kA持续的氩电浆
- 为了实现8.5kA的完整设计电流, 边界条件必须调整:
 - (一)通过连接PF线圈外壳, 使用电浆的静电的效果
 - (二)通过产生附加磁场由在真空室外面的附加PF线圈
- 在氩的电浆中心柱被驯服(击穿80V)的后, 可以战斗氢电浆中心柱(击穿180 V)
- 如果电浆中心柱的最大的电流(10 kA)被实现和持续只使用(18×3)个电浆发射的稀疏灯丝, 然后全电流(60kA)会更好的实现使用个(108×3)电浆发射的灯丝



PROTO-SPHERA的第一个阶段仅是第一个步骤

...放龙入海!

...give a chance to the dragon to show his endowments into the sea!

透视

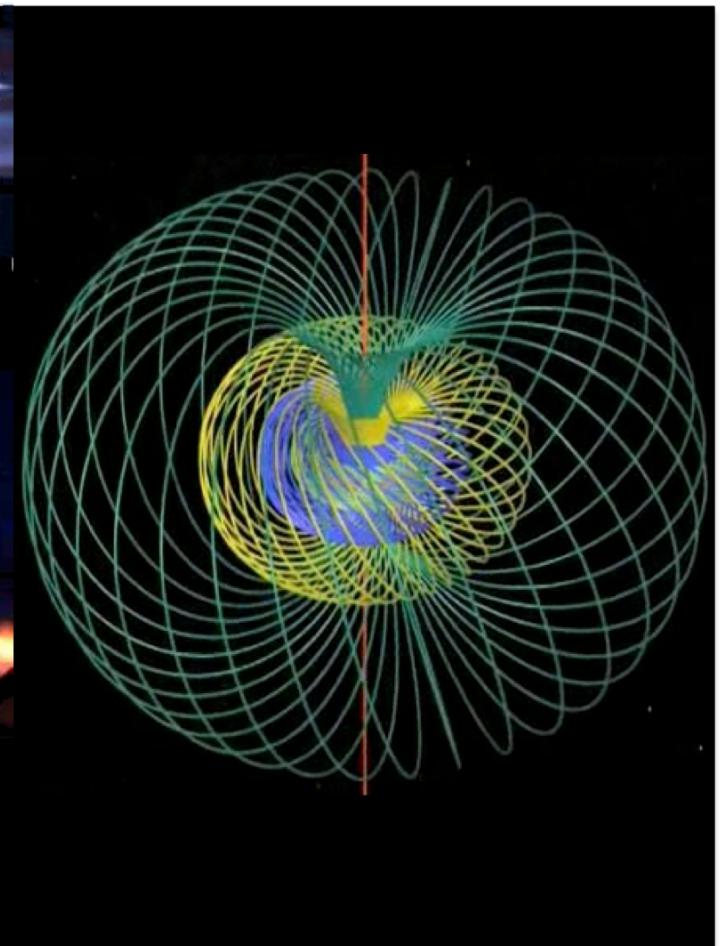
PROTO-SPHERA将评估新的磁约束配置

- 简单连接的一个磁约束装置(更容易建设和维持)
- 具有提高电浆 β 的可能性
- 直流磁螺注射会替代欧姆的驱动力

PROTO-SPHERA可以开发这个科学的节目单:
在低的费用(1.6M€)
以灵活的方式(新的组成部分可方便地添加)

The first plasmas obtained in PROTO-SPHERA at Frascati

F. Alladio, Centro Ricerche ENEA, Frascati C.P. 65 (Roma) franco.alladio@enea.it



OUTLINE

Why a new and different magnetic confinement device?

1994: Jurassic Park!

How to form a Spherical Torus around a Plasma Centerpost:

1994-1997

Before the construction of the experiment

two issues were addressed: 1997-2002

- **reliability of electrodes**
- **ideal MHD stability of the magnetic configuration**

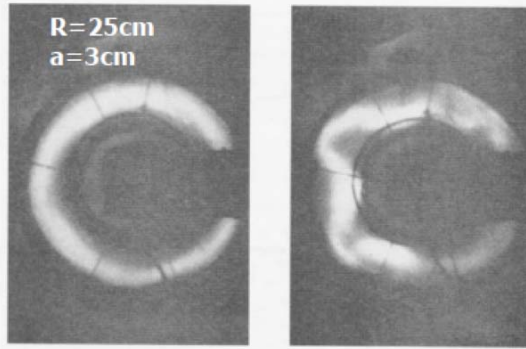
**An old vacuum chamber, as a gift from Great Britain,
started the construction of the experiment: 2003-2013**

- **PROTO-SPHERA got its first plasma centerpost: 2014-2015**

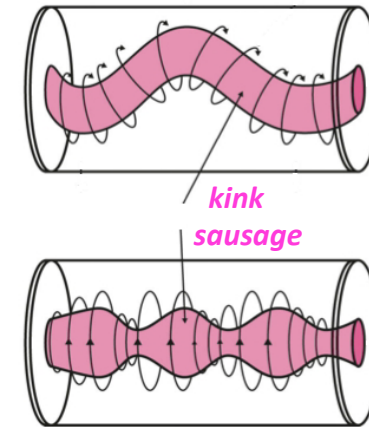


Why a new and different magnetic confinement device? one reason is ... "disruption"

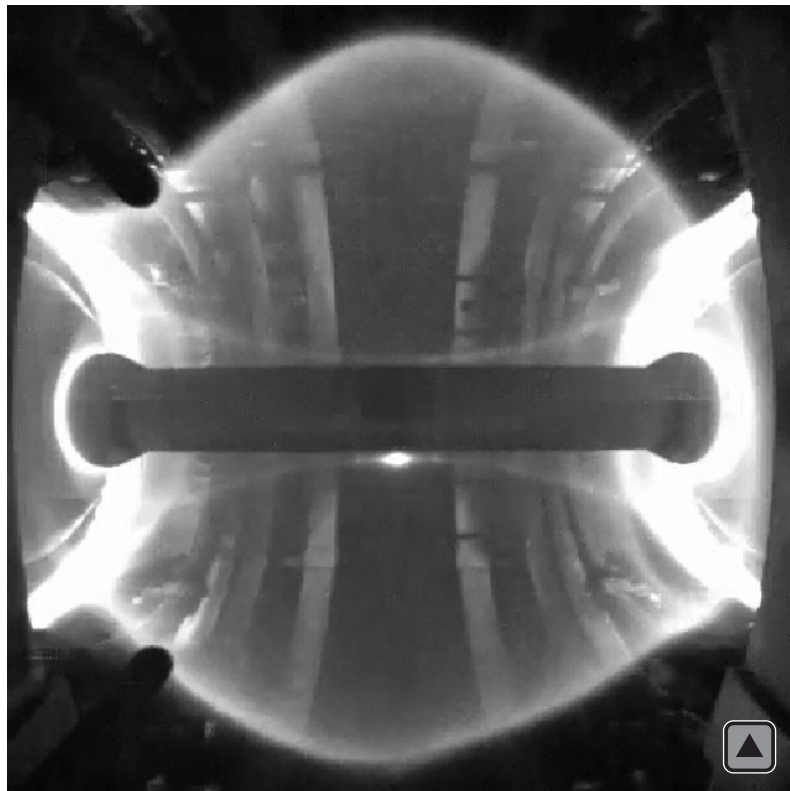
Alan Ware & Thomson
Imperial College 1947.



MHD instabilities appeared since the earliest toroidal magnetic confinement devices

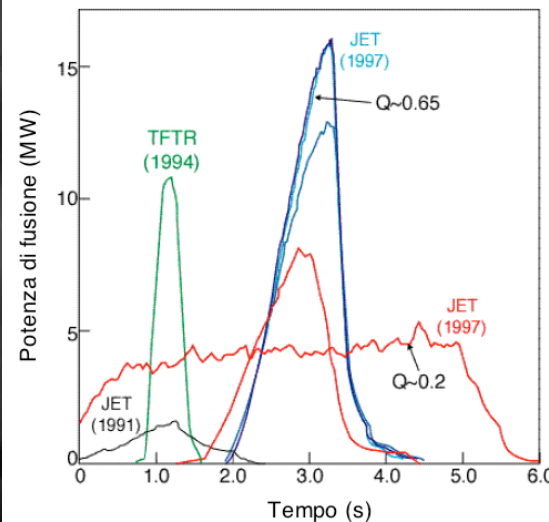


Mast 2004



...the problem of disruption has not yet been solved

... Only Stellarator configurations (without a net toroidal current) can avoid this inconvenience



In D - T experiments:
JET 1991- TFTR 1994
JET 1997

The highest neutron yield
...terminates in a disruption

Why a new and different magnetic confinement device? another reason is ... " β limit"

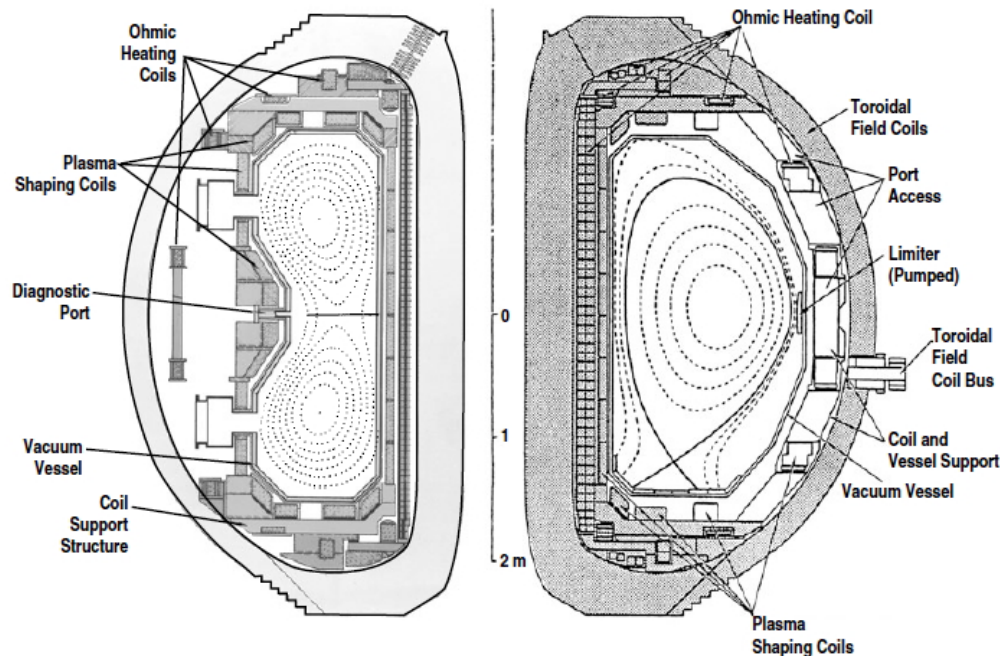
... Even if the muttered mantra is that tokamak physics is perfectly known ...

$$\beta = \text{plasma beta} = \frac{\text{kinetic plasma pressure}}{\text{confining magnetic field pressure}}$$

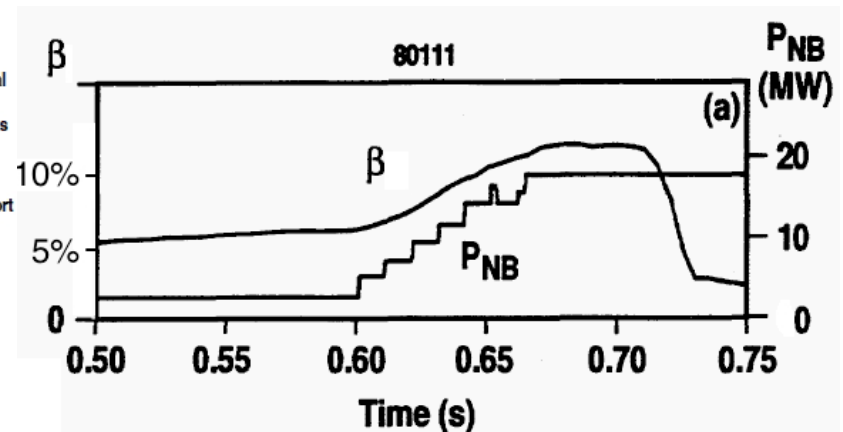
$$\beta = 2\mu_0 \int p dV / \int B^2 dV \quad \text{but in tokamak experimental data one often uses } \beta_{T0}$$

$$\beta_{T0} = 2\mu_0 \int p dV / B_{T0}^2 V \quad \text{where } B_{T0} \text{ is the vacuum field on the axis of the plasma}$$

DIII-D in 1994 reached the highest value of β tokamak at all time



**DIII-D reached $\beta_{T0} = 12.5\%$,
but...the plasma "disrupted"
vanished in ~ 1 msec!**

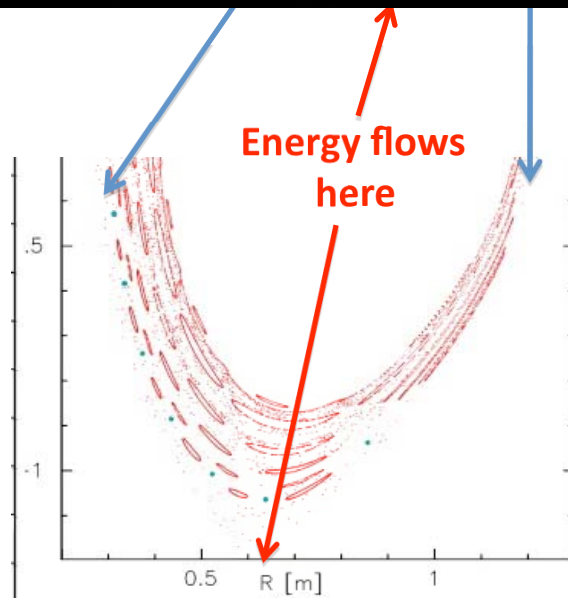
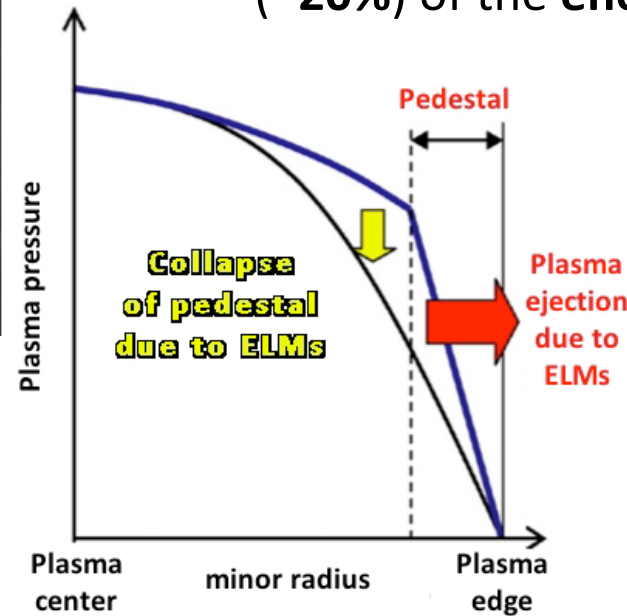
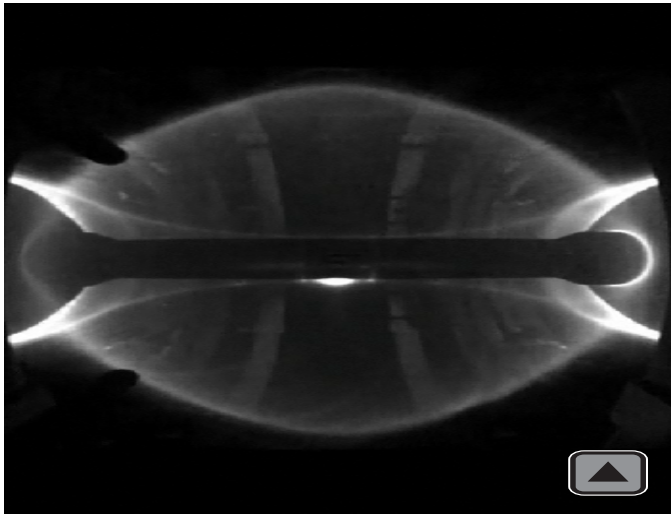


Why a new and different magnetic confinement device?

still another reason is...

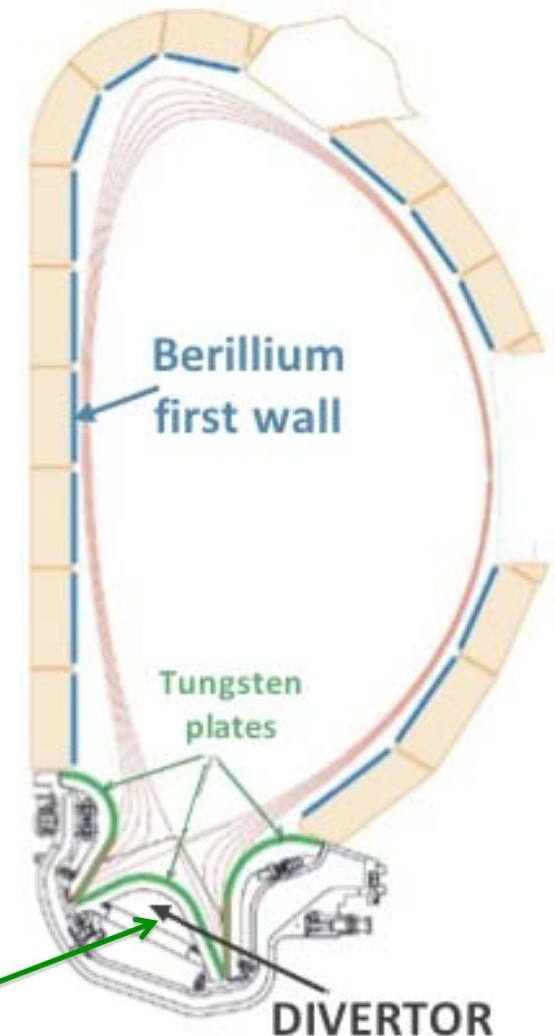
"ELMs" (unstable edge localized modes)

"ELM" mode throw upon the divertor a sizeable portion (~20%) of the energy in the pressure pedestal

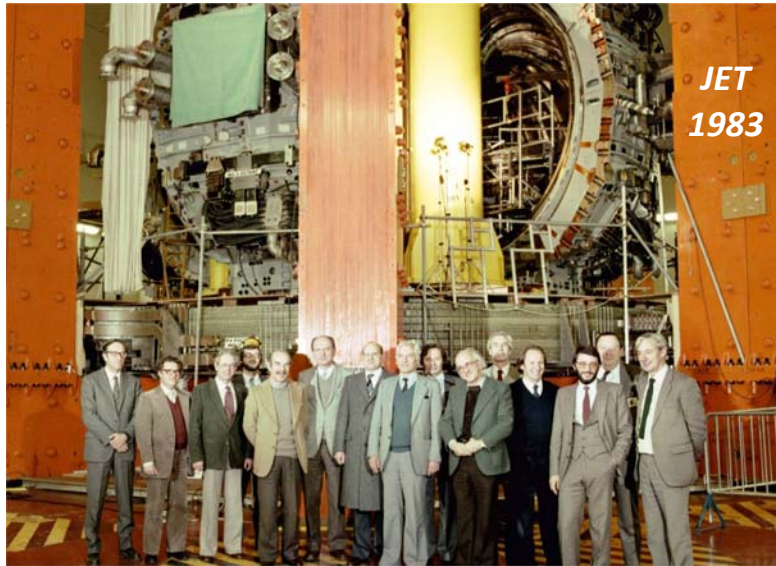


This happens in a very short time (250 μ s) as the plasma edge becomes ergodic (ELM filaments carry current)

On ITER an ELMs carrying >3% of pedestal energy can even melt or sublimate the **Tungsten of the Divertor plates**



PROTO-SPHERA was born (as an idea) in 1994 at the first crisis of ITER



Paul-Henri Rebut

Rebut after having **designed (1976-1979)**
and **built JET (1979-1983)**
in 1991 was in charge of designing ITER

But the cost 'exploded': 10 G\$ in 1993
Rebut left the ITER leadership (May 1994)

*...Sailing the seas depends on the Helmsman... so ITER stalled: US plasma physics community included many university professors, which were builders of small experiments and were afraid that ITER can let them out of research funds and began taking on ITER
... In 1998 the **US Congress** shut down the largest US Tokamak (**TFTR**) and withdrew from ITER*

*During the first “**Spherical Tokamak Workshop**” at **Oak Ridge in July 1994** this trend was already evident; it was there that **US decided to build NSTX, a Spherical Tokamak***

From 1994 onward USA e UK built only Spherical Tokamaks and no more conventional ones

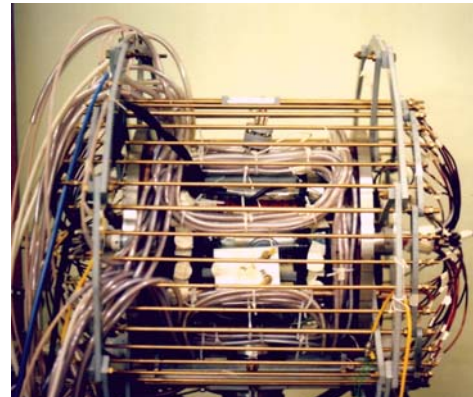
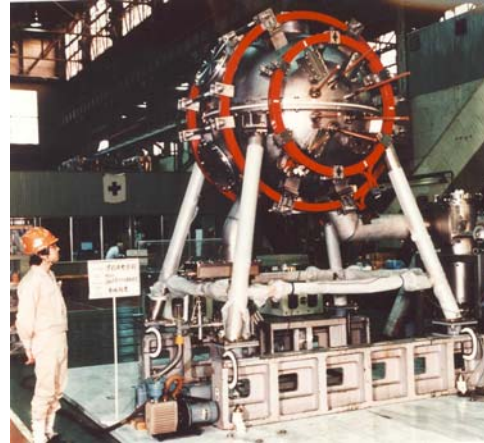
1994

first ITER Crisis

...Jurassic Park!

ITER temporarily switched off ... from the cages,
were they were confined since many years,
all concepts different from tokamaks popped out...

Stellarators, Spheromaks, FRCs, ...
and mainly Spherical Tokamas

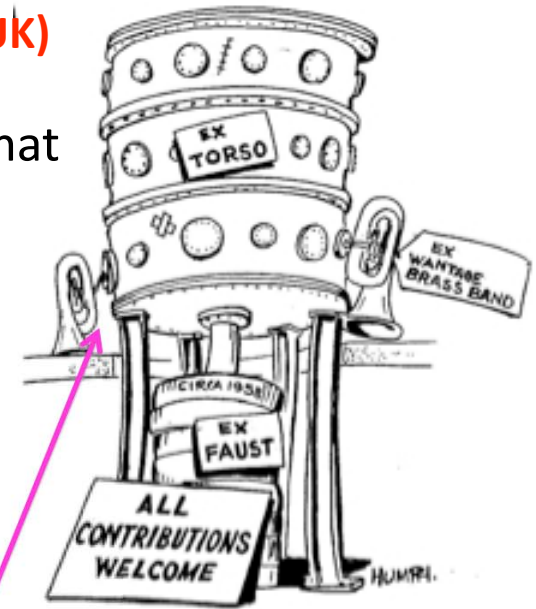
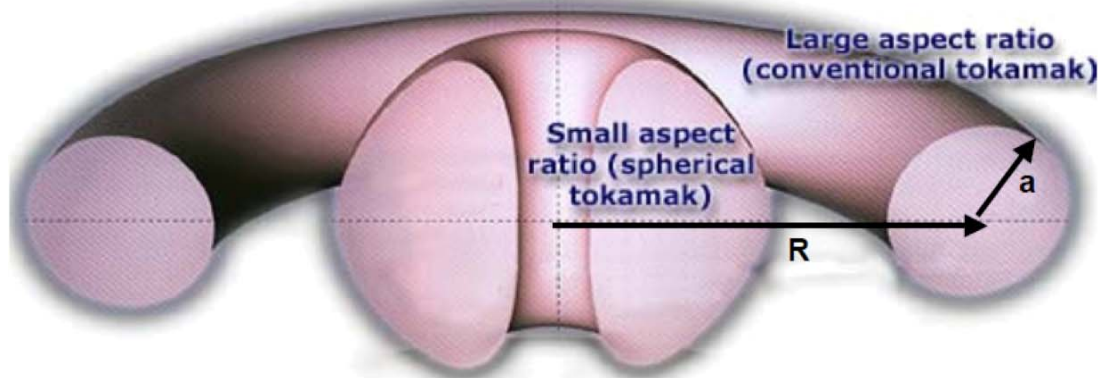


LHD Stellarator (Japan)

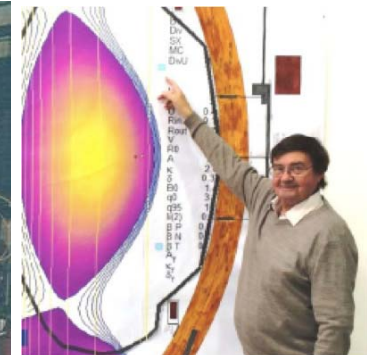
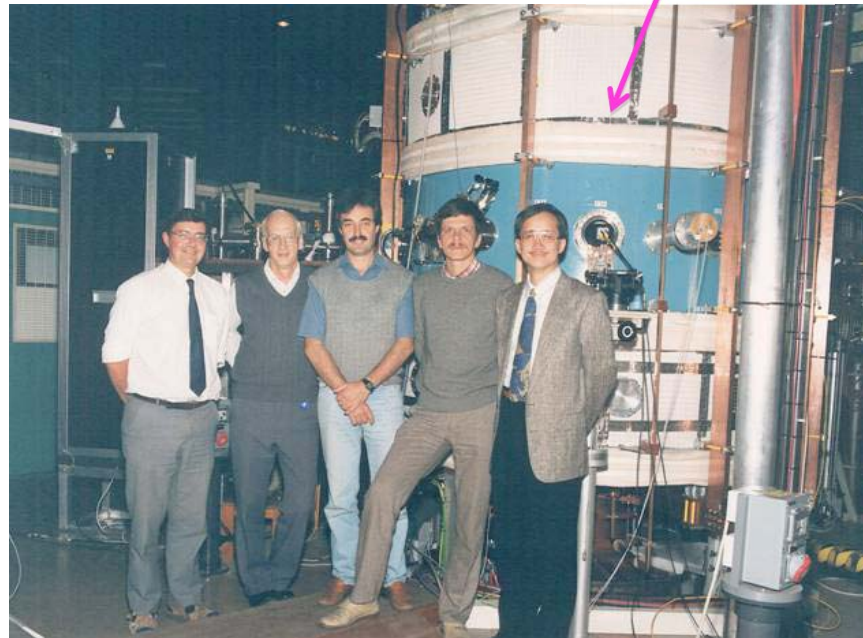
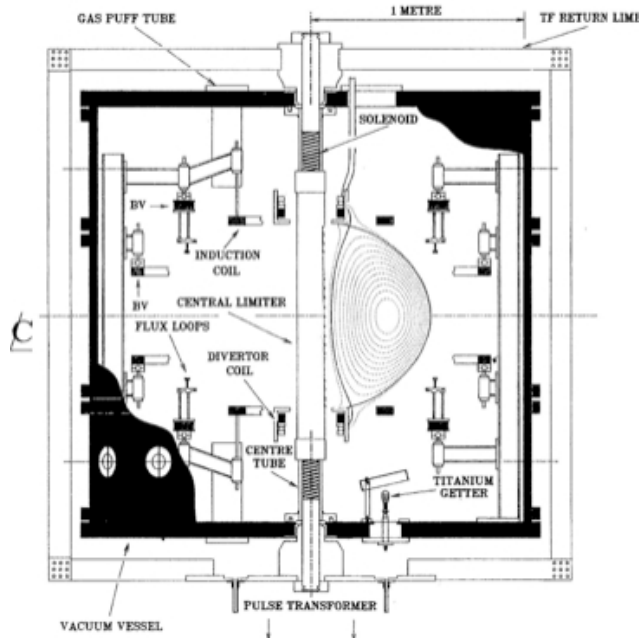


1991 START The first Spherical Tokamak – A new era for Culham (UK)

Martin Peng of Oak Ridge Nat. Lab. (Tennessee, USA) realized that in order to increase β the Tokamak needed a spherical shape



Culham built the START Spherical Tokamak revamping an *old vacuum vessel*

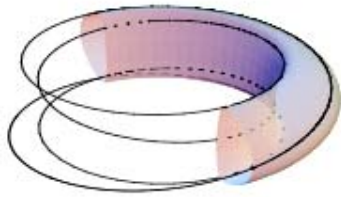


Alan Sykes

Alan Sykes Dick Colchin Edson Del Bosco Mikhail Gryaznevich Martin Peng

From 1991 Spherical Tokamaks at Culham and Princeton

Once endowed with an old Oak Ridge NBI heating
START reached $\beta_{To} \sim 40\%$ (3 x DIII-D)



Conventional Tokamak

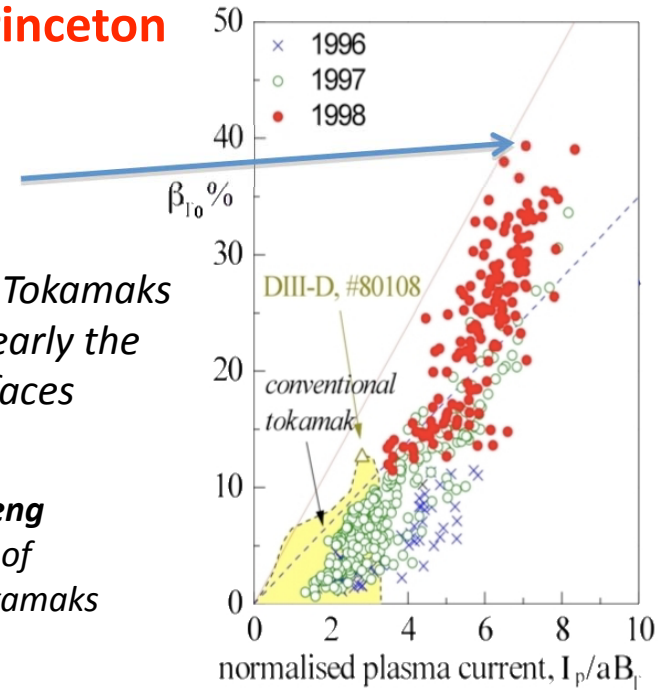


Spherical Tokamak

Favourable properties of Spherical Tokamaks are due to lines of force that are nearly the geodesic lines of the magnetic surfaces



Martin Peng
inventor of
Spherical Tokamaks

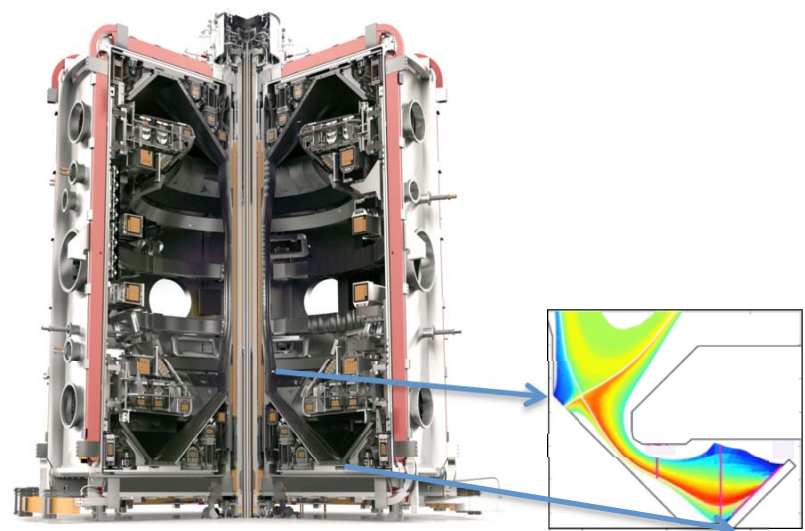
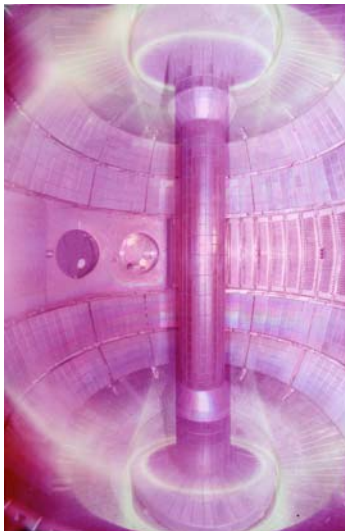


At the end of '90 two large Spherical Tokamaks were built:

NSTX a Princeton

MAST a Culham (2000)

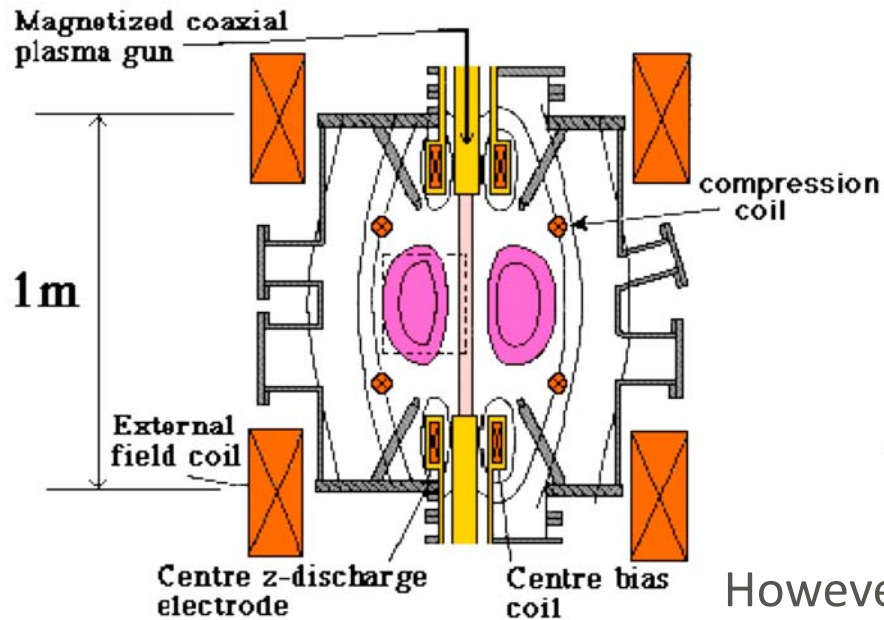
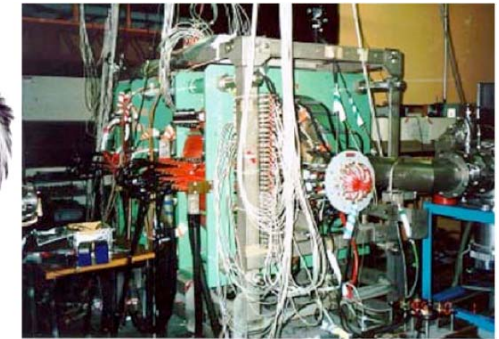
MAST-Upgrade (2017)



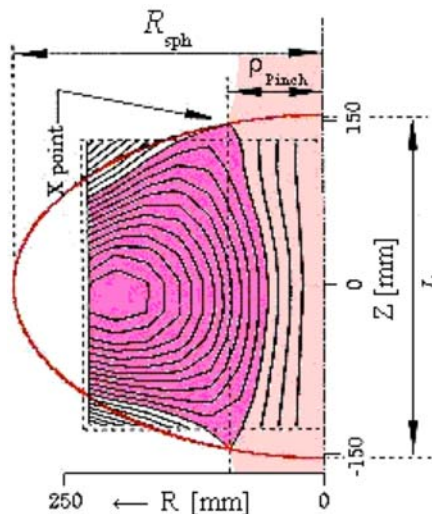
A small dinosaur out of Jurassic Park was the TS-3 experiment at the Tokyo University: it studied **magnetic reconnection** of **plasma toroids** around a **metal centerpost**



Yasuchi Ono



However in 1993 TS-3 **removed the metal centerpost**, between two plasma guns; applied **1kV** and produced a "**Plasma Centerpost**" carrying a plasma current $I_e = 40 \text{ kA}$, which through non-linear "kink" instability engendered around itself a **Spherical Torus** carrying a toroidal plasma current $50 \text{ kA} < I_{ST} < 100 \text{ kA}$



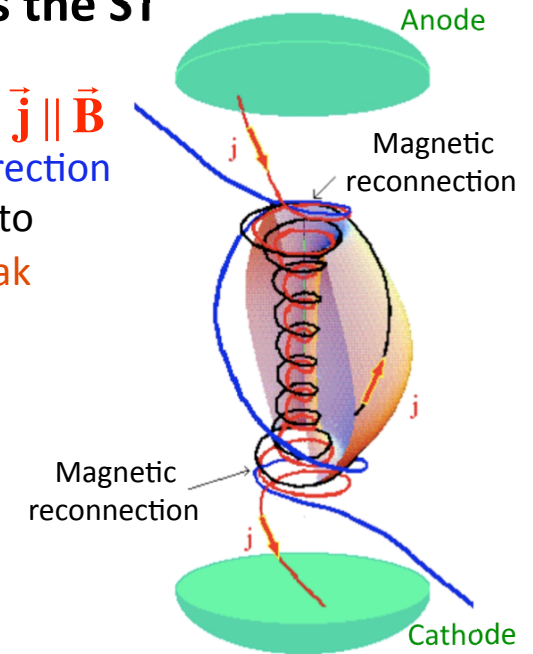
60 μs formation

20 μs sustainment

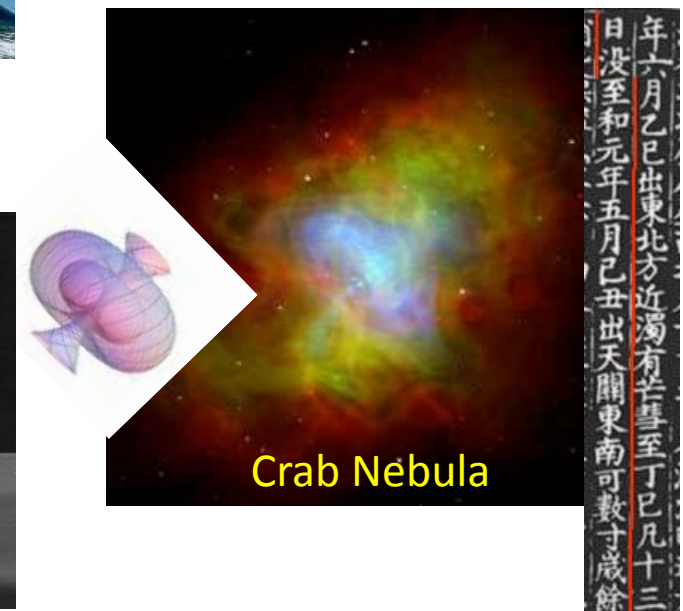
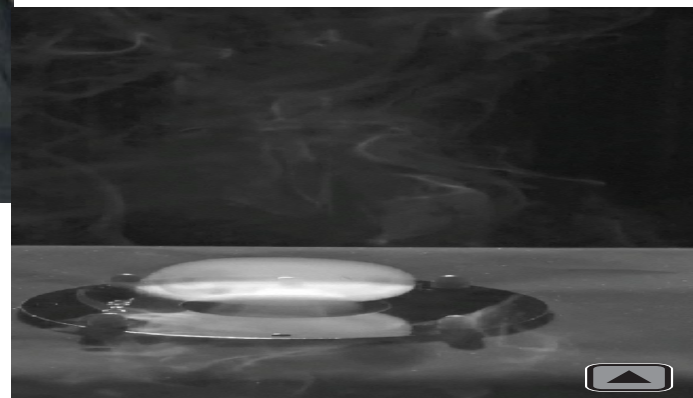
total duration **80 μs $\sim$ 100 $\tau_{\text{Alfvén}}$**

Helicity injection to sustain the plasma torus: driven relaxation of Plasma Centerpost forms & sustains the ST

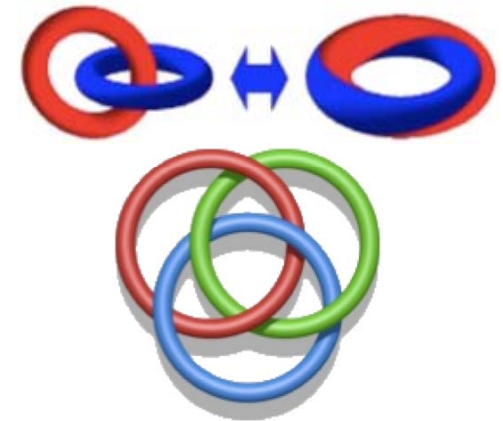
- In front of the electrodes: open magnetic field lines, $\vec{j} \parallel \vec{B}$
- open magnetic field lines are wound in a circular direction
- **Magnetic reconnections** convert open $\vec{B}$, $\vec{j}$ lines into closed $\vec{B}$, $\vec{j}$ lines wrapped around a spherical tokamak



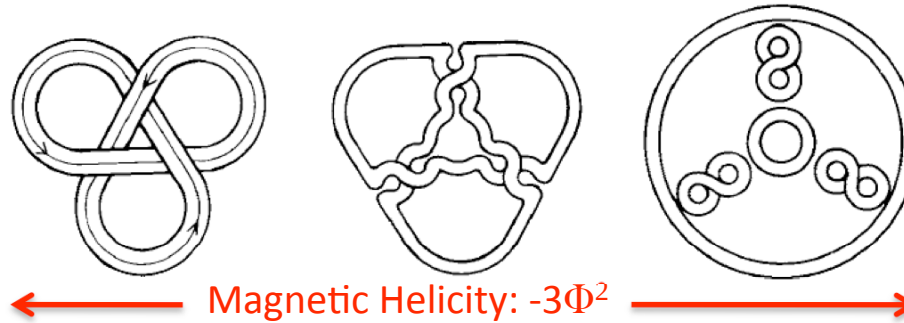
William Irvine-University of Chicago



For a simply connected volume bounded by a magnetic surface $\vec{B} \cdot \hat{n} = 0$ the **Magnetic Helicity** $K = \int \vec{A} \cdot \vec{B} dV$ is a slowly decaying ideal MHD invariant which measures how much the lines of force are **kinked**, **twisted** or **interlinked**

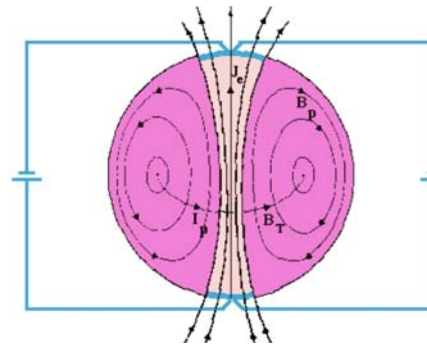


Magnetic
flux: Φ



Flux-core Spheromak

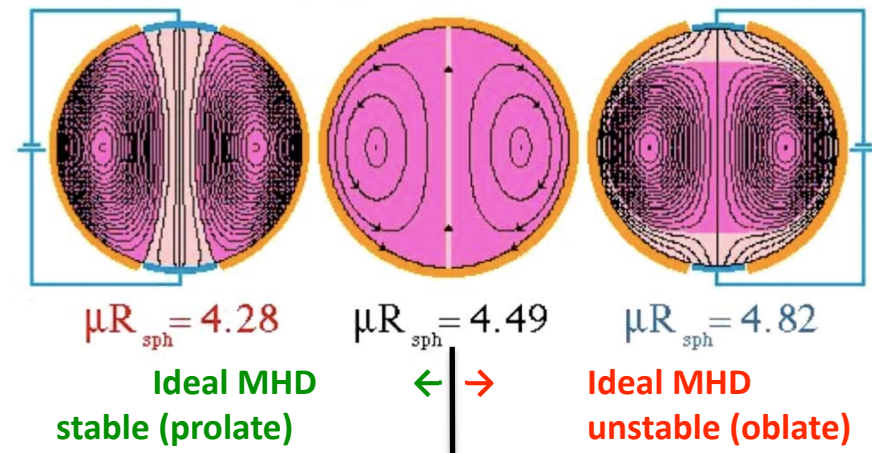
Relaxed state: $\nabla \wedge \mathbf{B} = \mu \mathbf{B}$, $\mu = \mu_0 (\mathbf{j} \cdot \mathbf{B} / B^2) = \text{constant}$
all over the plasma, **enclosed within a perfectly**
conducting portion of sphere of radius R_{sph} ,
fed by electrodes upon polar caps



Instability-prone: high inverse rotational transform χ
of the lines of force
(low MHD safety factor $q = 1/\chi \leq 1$)
enhances “tilt instability”:

Current in the external container has a magnetic dipole
opposite to toroidal plasma current dipole

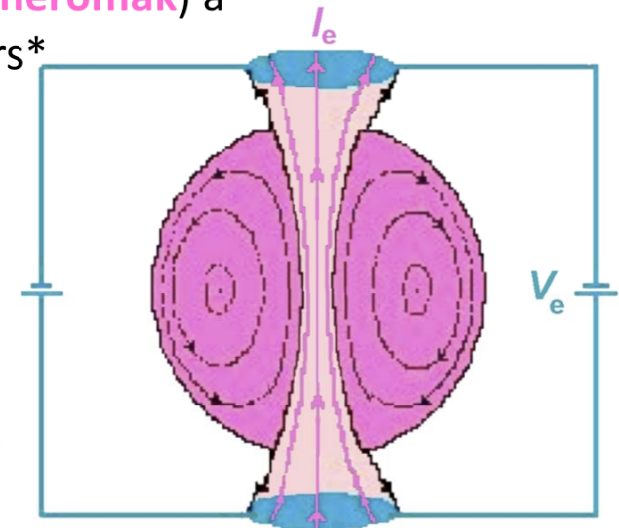
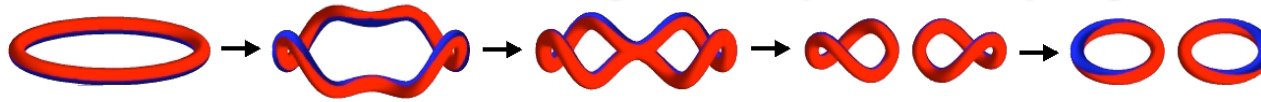
Classical Spheromak



If helicity source (eg. **Flux-core**) is separated from helicity sink (**Spheromak**) a gradient in the relaxation parameter $\vec{\nabla}\mu = \mu_0 \vec{\nabla} (\vec{j} \cdot \vec{B} / B^2)$ appears*

resistive MHD instabilities produce **helicity flow**
from **larger μ** to **smaller μ** regions*

***This corresponds to the fact that, in low resistivity plasma, the magnetic reconnections redistribute the Magnetic Helicity without dissipating it**



$$\Psi_e = 0.5 \int (\vec{B} \cdot \hat{n}) dS$$

Injection of magnetic helicity in a domain, ($\hat{n}$ outwards)

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

- $2 \int V_e (\vec{B} \cdot \hat{n}) dS$ = **DC helicity injection:** $2V_e \cdot \Psi_e$ V_e electrostatic potential
(poloidal voltage • poloidal cross section flux)
- $2 \int (\vec{A} \wedge \partial \vec{A} / \partial t \cdot \hat{n}) dS$ = **AC helicity injection:** $2V_t \cdot \Psi_t$ V_t toroidal loop voltage
(toroidal voltage • toroidal cross section flux): ohmic Helicity drive
- $2 \int (\vec{E} \cdot \vec{B}) dV$ = **total helicity dissipation**

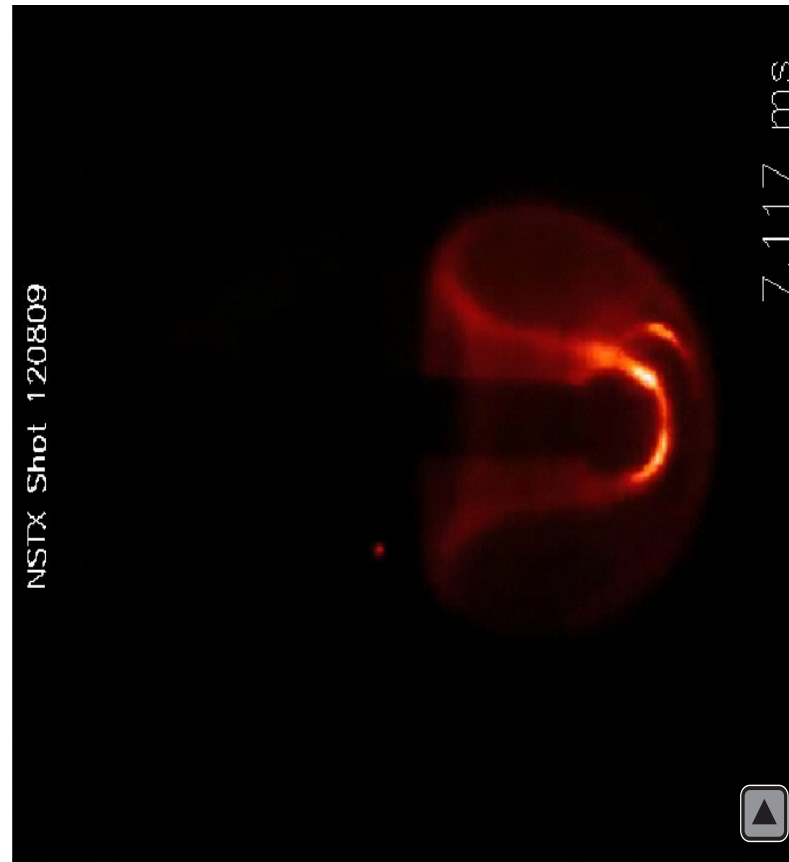
Magnetic flux, plasma current and magnetic energy injected along with magnetic helicity

...but how efficiently?

This is the main reason for the PROTO-SPHERA experiment

Attempt of replacing **ohmic drive** with **DC helicity injection**,
... trying to get rid of “**disruptions**”?

DC helicity injection in NSTX (Princeton) Spherical Tokamak
often followed by or coexisting with **ohmic drive**

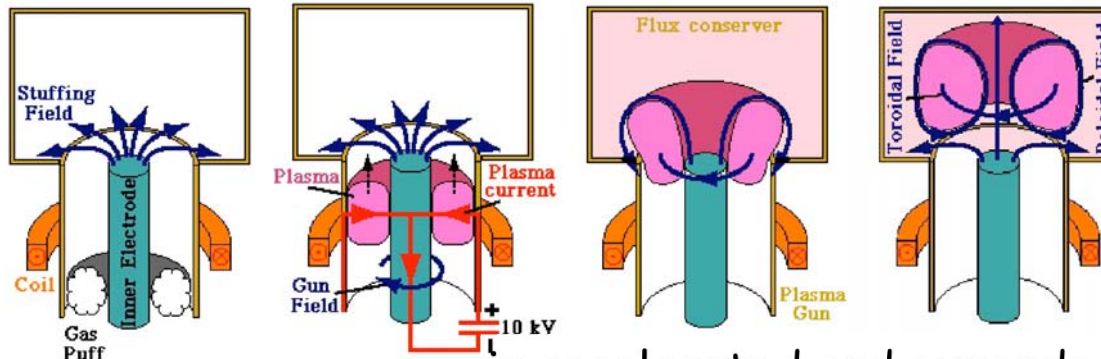


has achieved >300kA plasma start-up & lowered by 40% ohmic drive requirements
albeit in presence of a metal centerpost, furthermore **plasmoids** are “**born & reborn**”

GUN INJECTED FLUX-CORE-SPHEROMAKS

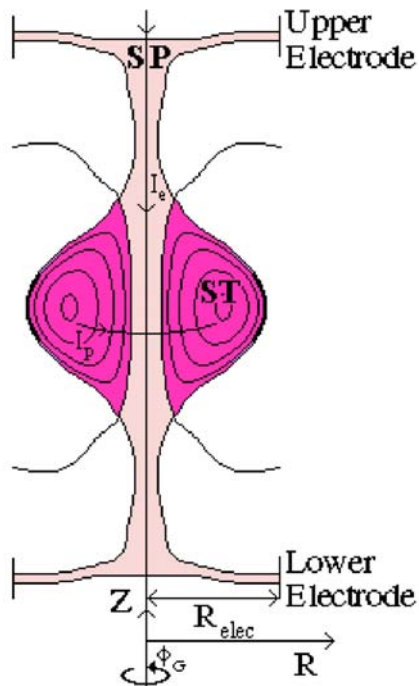
Breakdown in small spaces, with extremely high filling pressures and kV voltages

Neutrals and impurities are released from the gun



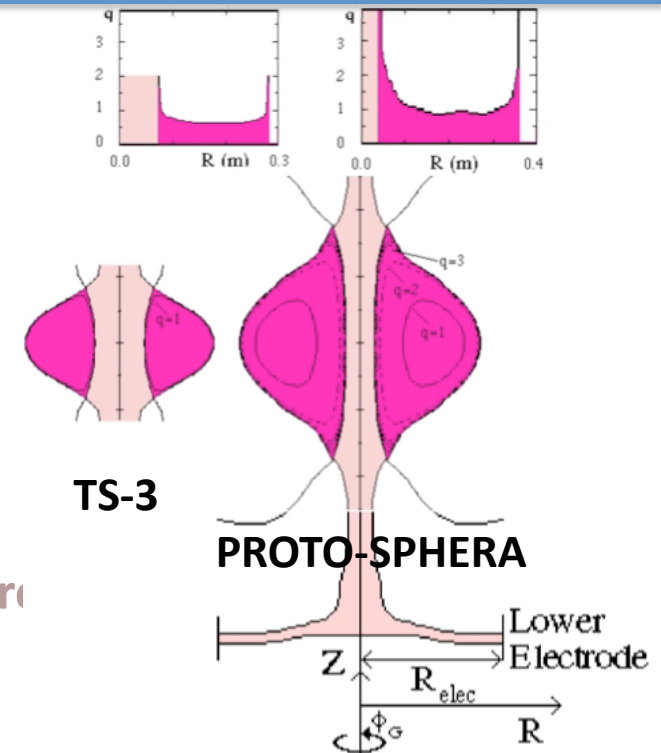
After the formation, the **Spheromak** is accelerated and expanded into a **flux conserver** field errors already present in the gun are amplified

PROTO-SPHERA



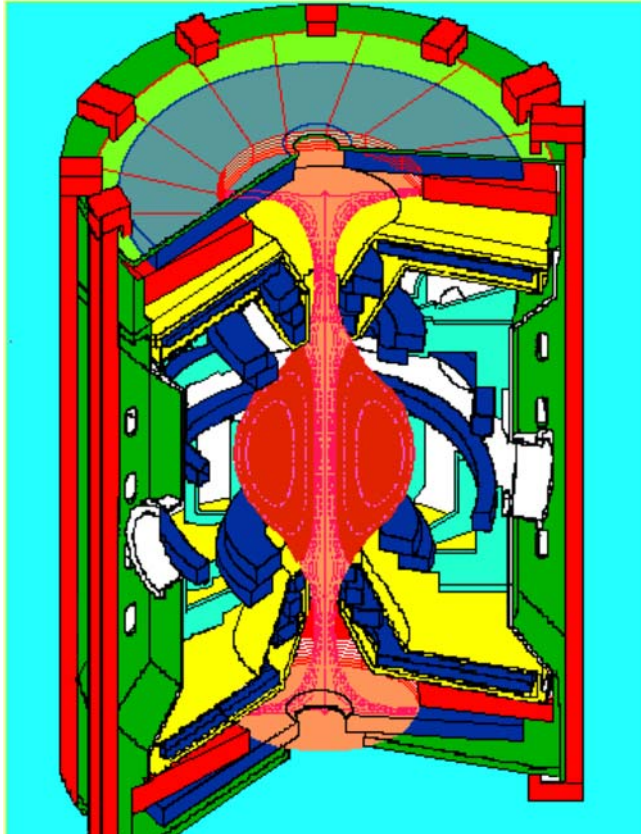
Designed to get a Tokamak-like MHD safety factor ($q_0 \geq 1$, $q_{\text{edge}} \sim 3$) ($A=R/a \geq 1.2$, $\kappa=b/a \sim 2.3$)

PROTO-SPHERA formed “slowly” as a **Prolated low aspect ratio Spherical Torus** from the preexisting **plasma centerpost mushroom-shaped** in front of electrode at low voltage, inside big vessel



SPHERA:

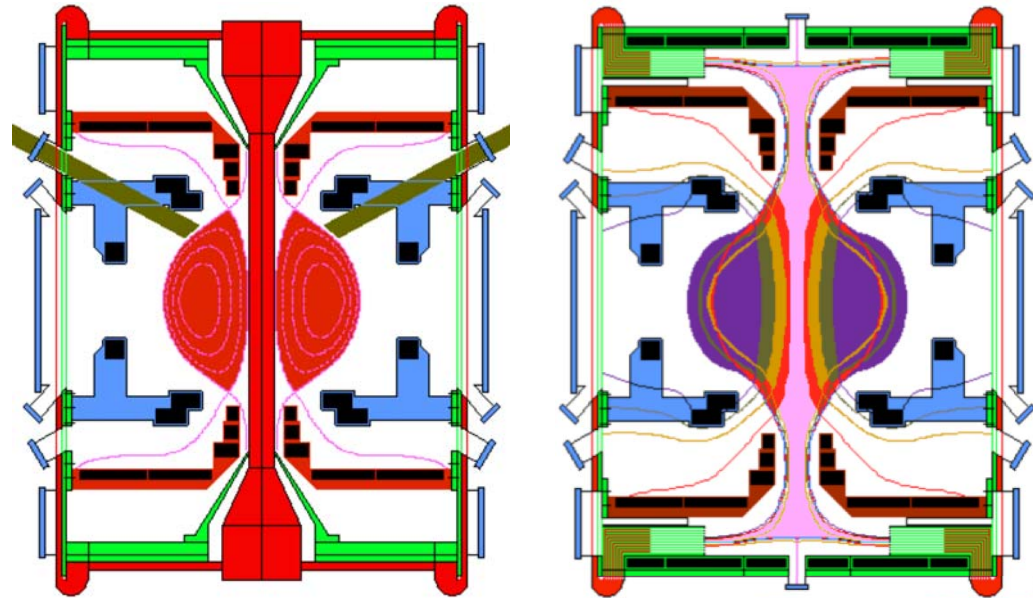
Spherical Plasma for **HE**licity **R**elaxation
Assessment



*F. Alladio, G. Angelone, P. Buratti, A. Cardinali, A. Cecchini,
R. Cesario, C. Goullan, L. Lovisetto, A. Mancuso, P. Micozzi,
S. Mantovani, S. Migliori, L. Pieroni, L. Semeraro, A.A. Tuccillo,
F. Valente, V. Zanza*

Frascati, March 1997

1995-1996 in Frascati the SPHERA proposal:
a Spherical Tokamak at very low aspect ratio $A=1.2\div 1.3$
(no induction central solenoid)
inside a cylindrical vessel $h=4$ m, $\varnothing$ 3 m
...also the possibility of plasma centerpost



SPHERA was never built, but became
the design basis of PROTO-SPHERA



Leonardo Pieroni
1943-2012



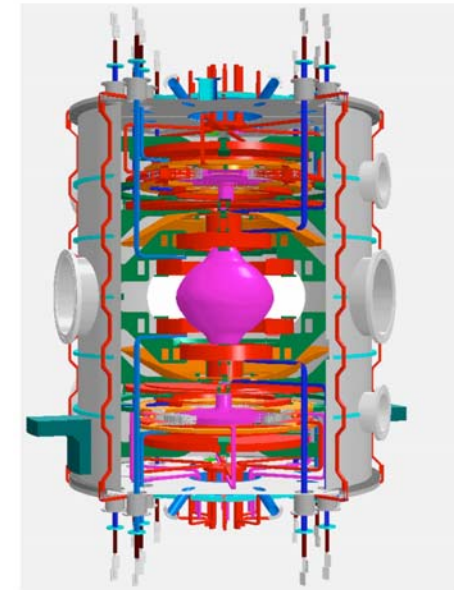
Paolo Micozzi ENEA



Alessandro Mancuso ENEA

2001 PROTO-SPHERA final design report

PROTO-SPHERA

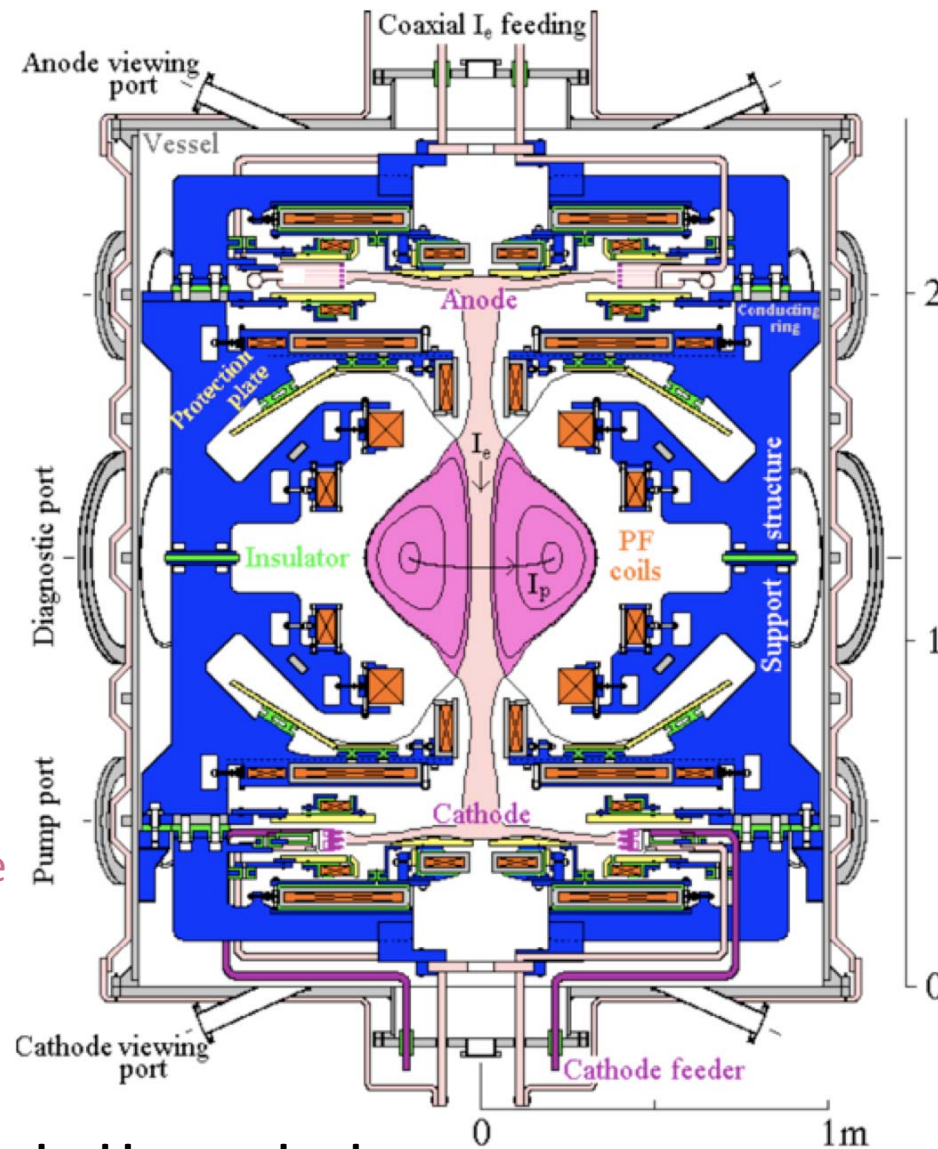


CR-ENEA Frascati, July 2001

Quasi-separate
chamber for anode

Spherical Torus
chamber

Quasi-separate
chamber for cathode



Electrode plasmas quasi
separated from main
plasma:

large number (18) of PF
(poloidal field) coils

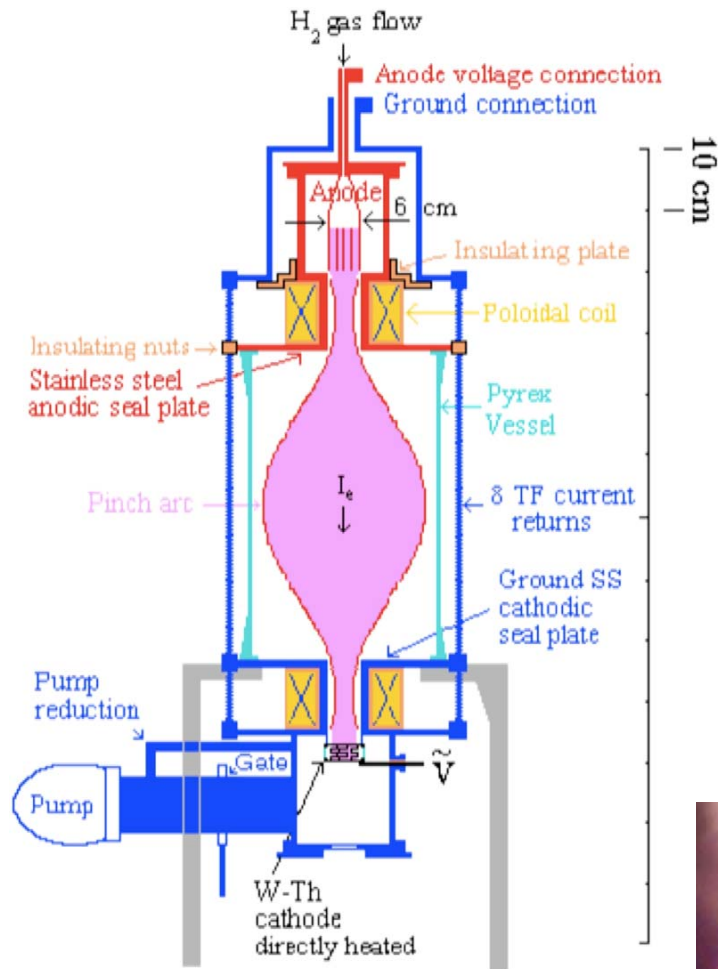


Two main problems had been solved:

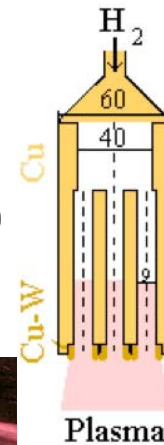
- building durable electrodes
- restrictions imposed by the ideal MHD stability

- **Building durable electrodes**

PROTO-PINCH Electrodes testbench, built 1998
experiments from end of 1998 to beginning 2000



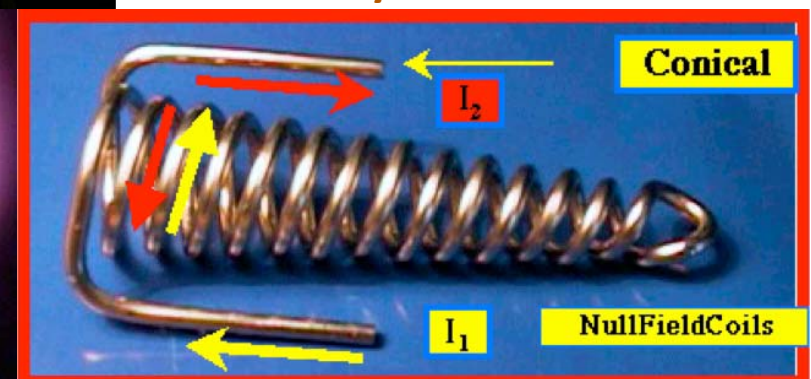
AC current required
on cathodes for avoiding
anode arc anchoring



Hollow gas-puffed anode (W-Cu):
plasma enters holes

- Thousand 1s discharges
- Plasma current up to 700 A
- Breakdown ~ 100 V in H
- **Current density $j_e = 1$ MA/m²**
- **Power density $P_e = 20$ MW/m²**

W-Filaments (Caduceus shaped)
directly heated cathode



PROTO-PINCH testbench found a solution for the electrodes that works on PROTO-SPHERA
at a current and power density that is relevant for a **Biased Divertor of a reactor-grade plasma**

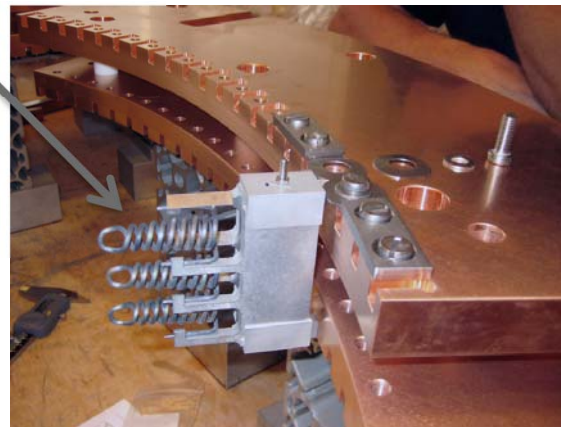
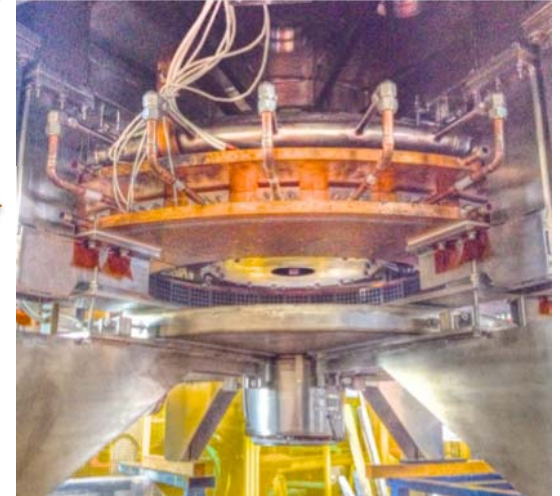
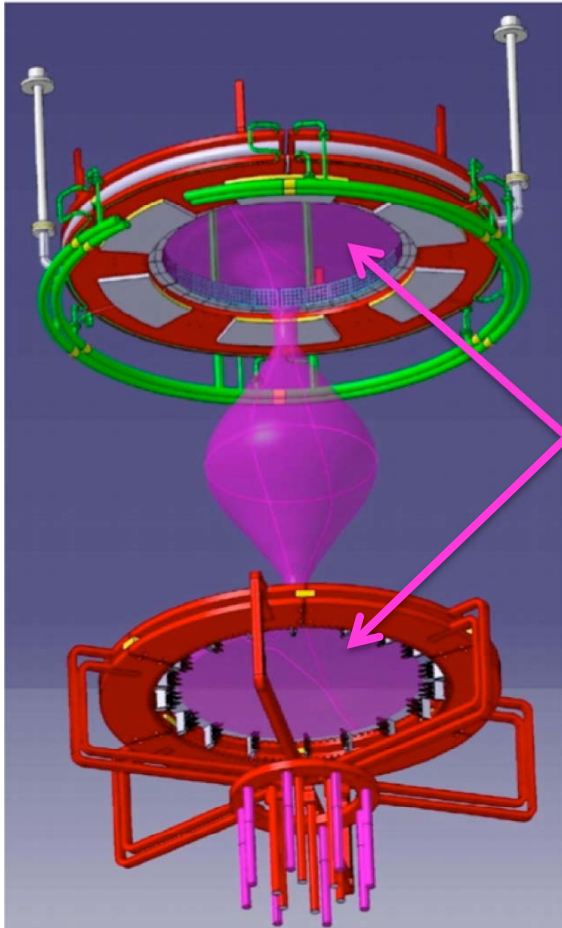
- low (100-200 V) voltage on electrodes
- tokamak-like density

Modular annular electrodes:
Gas puffed hollow anode →

Plasma centerpost at electrode
interfaces mushroom-shaped

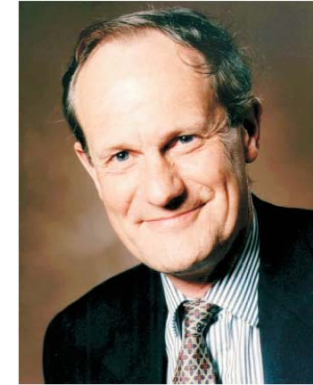
Plasma current density $j_e = 1 \text{ MA/m}^2$
Power density $P_e = 20 \div 30 \text{ MW/m}^2$

W-Th directly heated cathode →



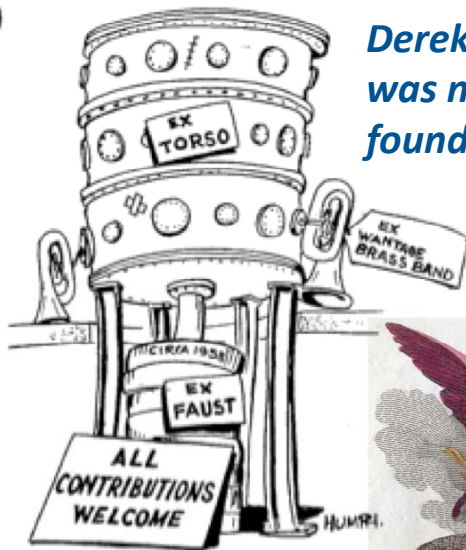
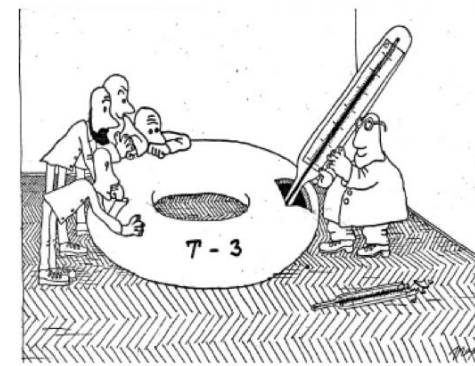
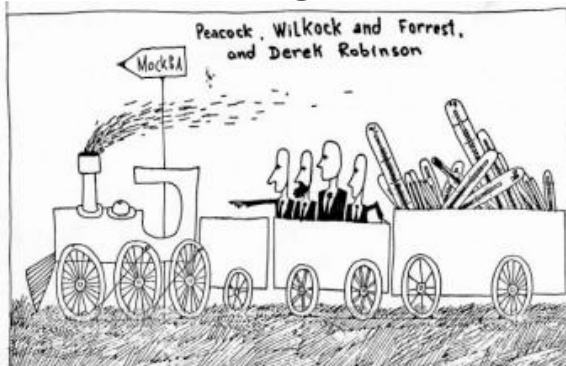


Derek Robinson
1941-2002



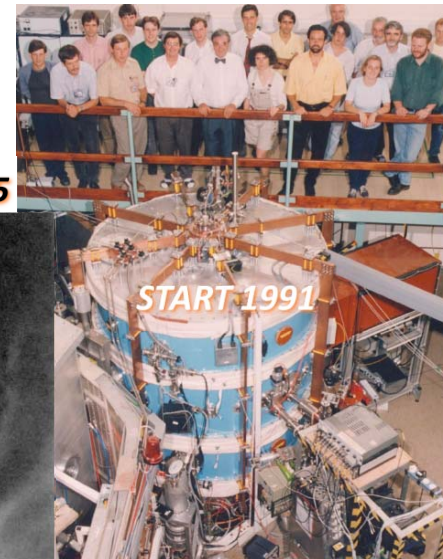
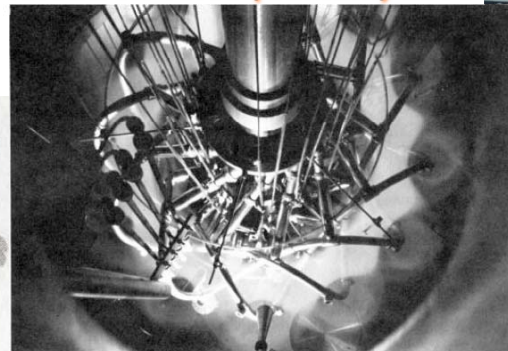
Derek Robinson (director of Culham from 1991) was very interested in the “Champagne bottle” experiment: in 1999 he proposed to build at Culham PROTO-SPHERA inside the START vessel

Derek Robinson had a leading role in the historical temperature measurements on Russian Tokamak T3 (1969)



Derek Robinson's proposal unfortunately was not accepted... but the “Old Vessel” found anyway its way ...to Rome!

Torsatron Torso (Culham) 1975



Furthermore Derek Robinson's proposal to build PROTO-SPHERA at Culham inside START led to the final parametrers' choice, the **START** size and not the **TS-3** one was chosen

In **2002** at Frascati an **International Workshop** was held, chaired by **Martin Peng**, it advised to build the machine in two steps:

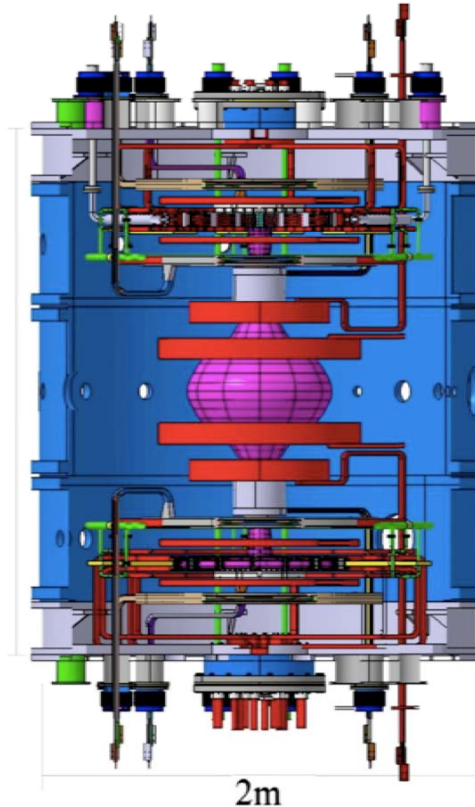
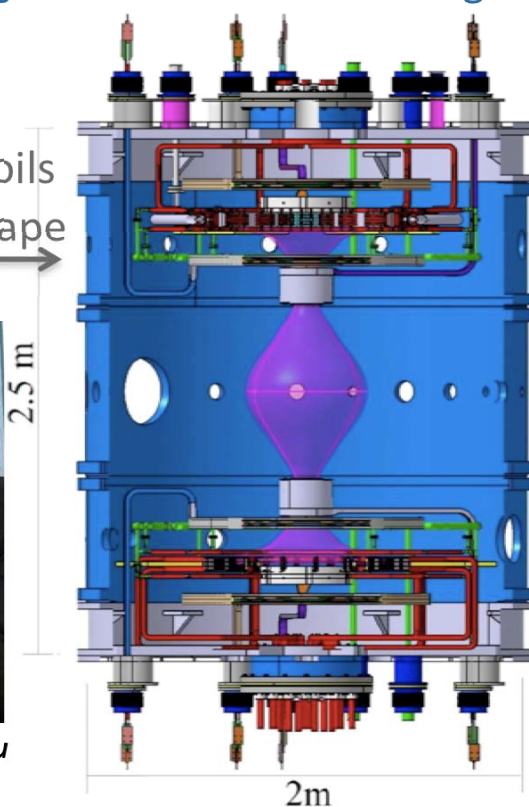
- first step: check Plasma Centerpost's feasibility
- second step: the machine would have been completed such as to produce the Spherical Torus

The CAD design of PROTO-SPHERA began

Phase1: 8 PFcoils
Centerpost shape



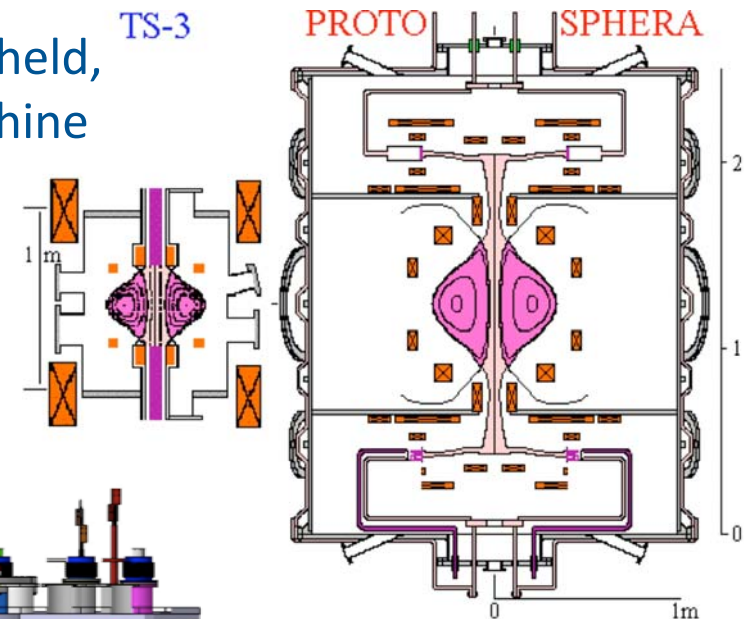
Stamos Papastergiou
Euratom

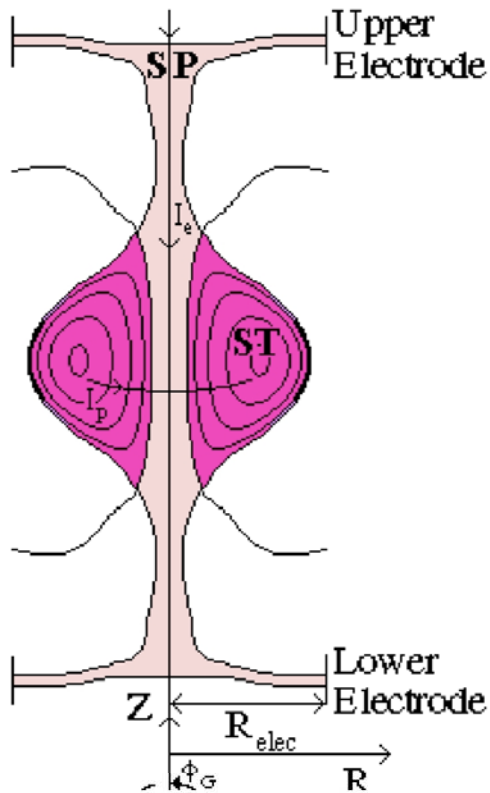


Phase 2: 8 PF shaping coils
+ 10 PF compressing coils



Alessandro Mancuso ENEA





PROTO-SPHERA parameters:

SP centerpost current

$$I_e = 60 \text{ kA}$$

ST toroidal current

$$I_p = 120 \div 240 \text{ kA}$$

ST diameter

$$2R_{sph} = 0.7 \text{ m}$$

MHD safety factor

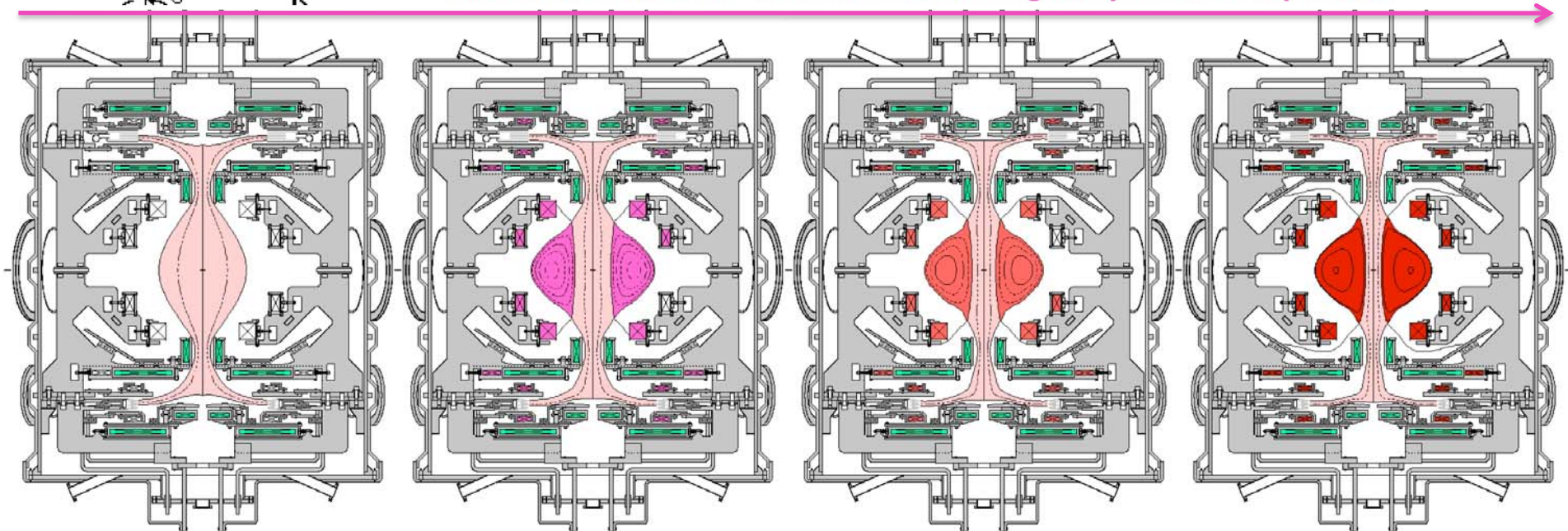
$$q_0 \geq 1, q_{edge} \sim 3 \text{ (Tokamak-like)}$$

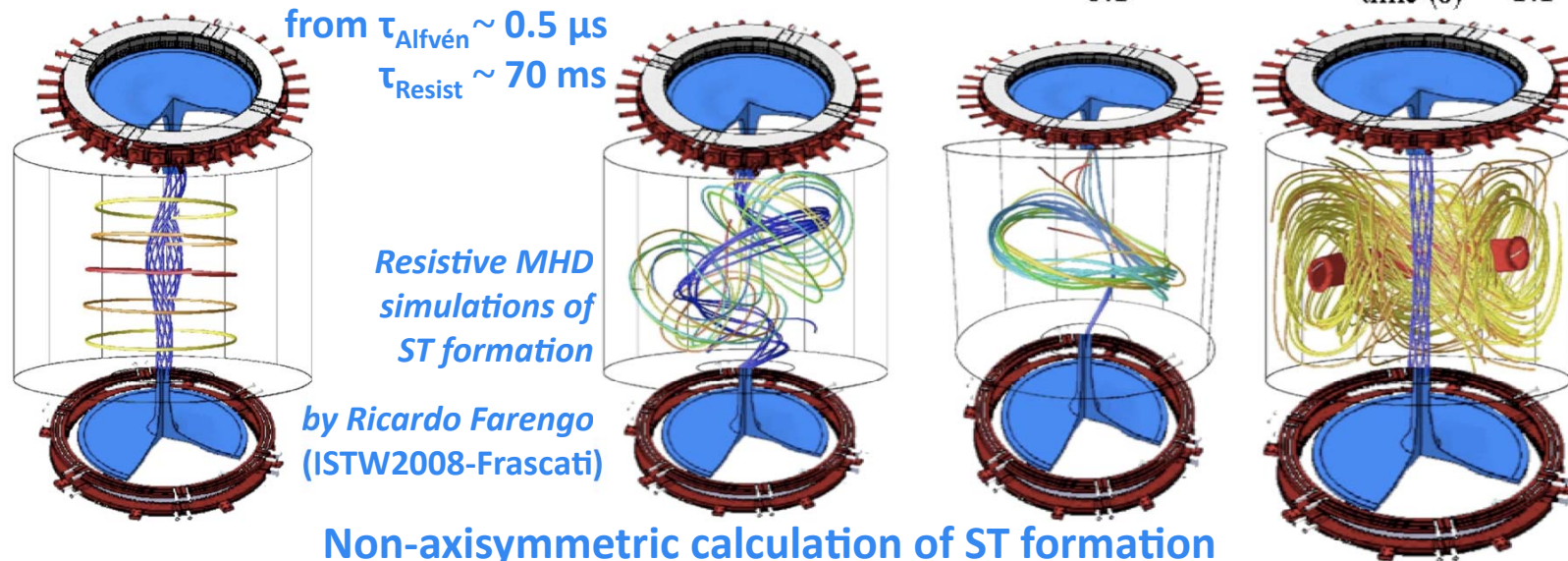
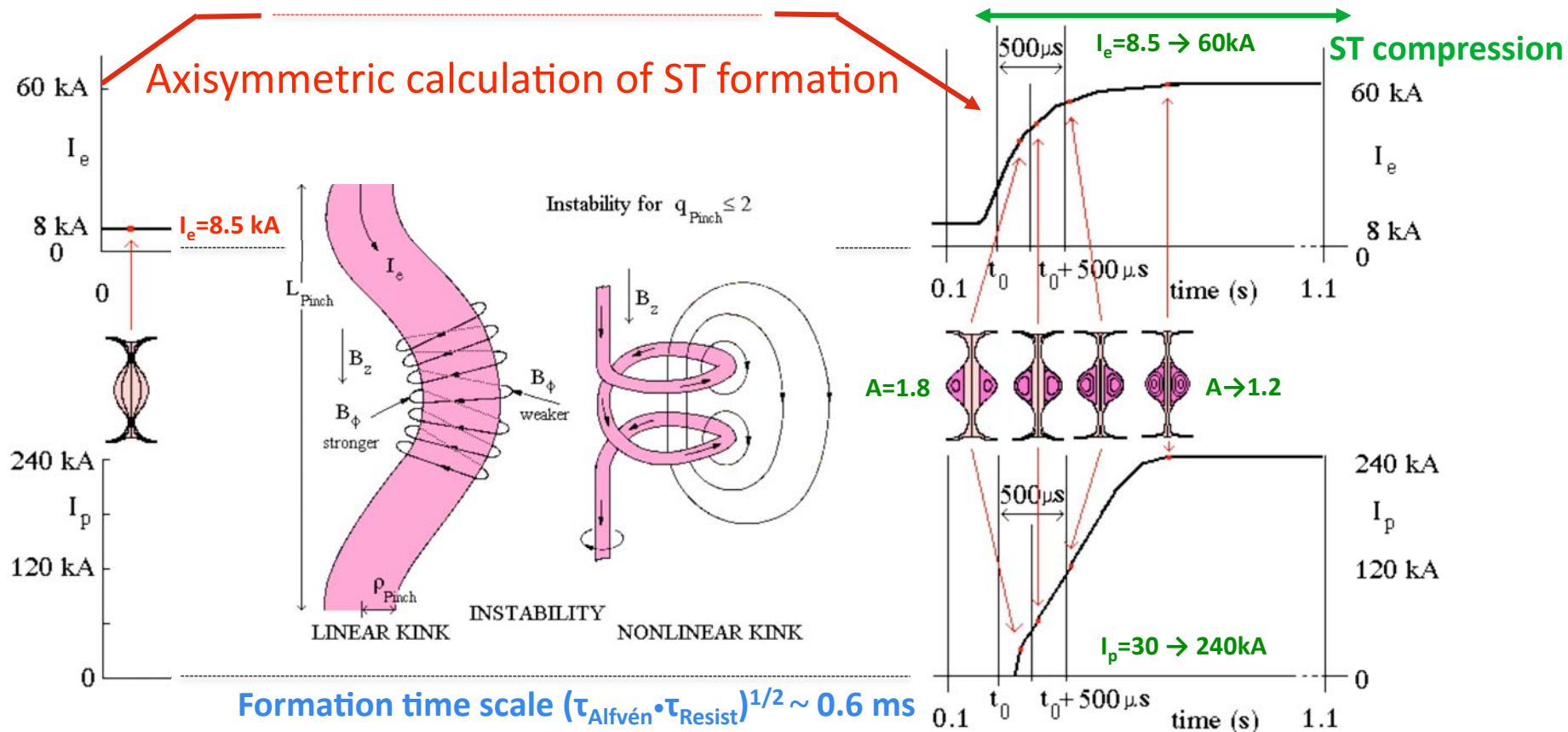
Stability should be improved and Helicity drive expected to be less disruptive than in conventional Flux-Core-Spheromak

Current plasma center column is rapidly increasing: $I_e = 8.5 \rightarrow 60 \text{ kA}$

To compress the plasma, PF coil current in each turn: $I_A = 0 \rightarrow 1.2 \text{ kA}$

Plasma formation ... Calculated assuming axisymmetric equilibria

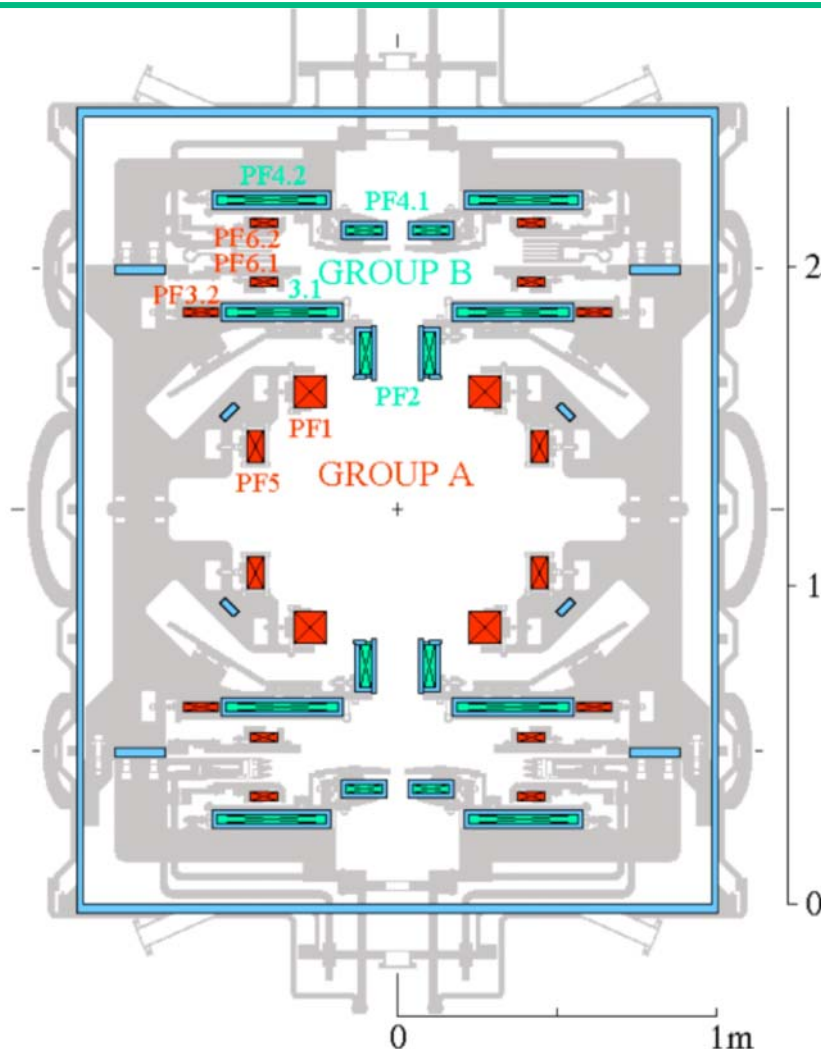




Ricardo Farengo
CNEA Bariloche
(Argentina)

The PF coils have been designed as two sets, each connected in series

Group B (4+4 coils): Centerpost shaping PF coils ...thick AISI casings ($\tau \sim 2\text{ms}$), *now inside machine*



Antonio Cucchiaro
ENEA



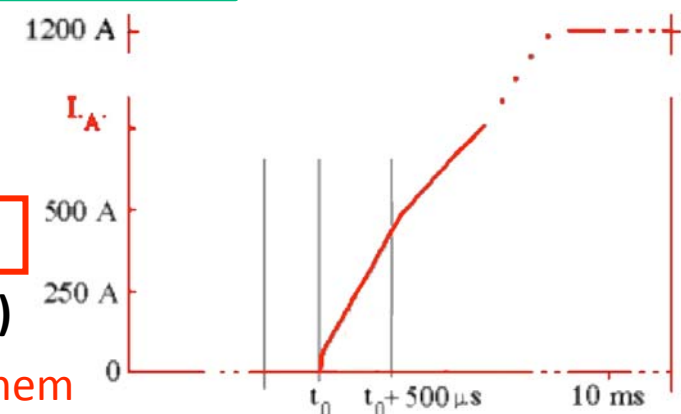
...waveform of **Group A** provides ohmic drive to torus up to 120 kA

Paradigm reversal:
ohmic drive followed
by Helicity Injection

Group A (5+5 coils): ST compression PF coils ...*not yet built*

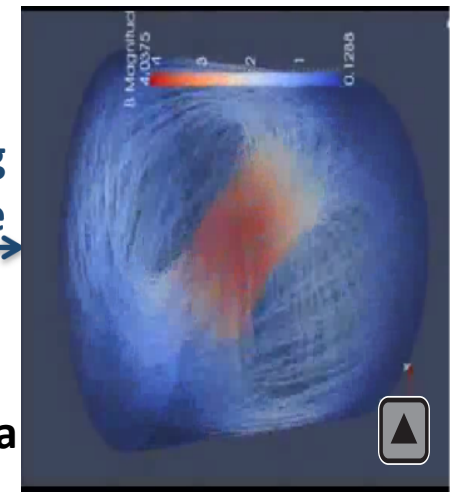
high voltage ($\sim 20\text{ kV}$) insulation: **fast current increase (0.5 ms)**

thin Inconel casings allow for **B diffusion** in $\tau \sim 200\text{ }\mu\text{s}$ across them



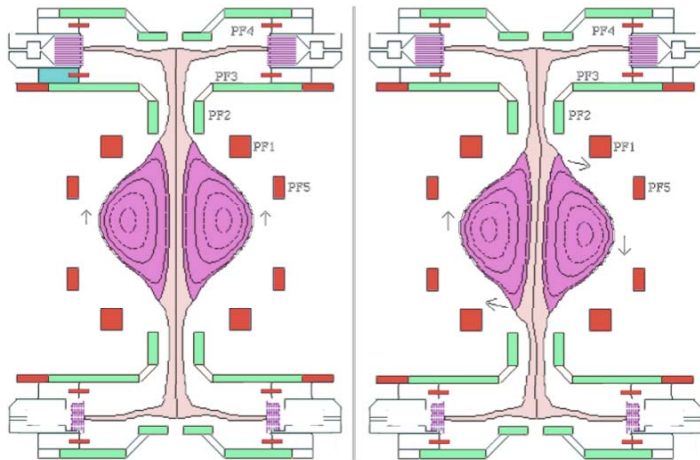
IDEAL MHD STABILITY of PROTO-SPHERA

Spheromak tilt instability is due dipole of containing field opposite to toroidal plasma current dipole



Rigid shift

Rigid tilt



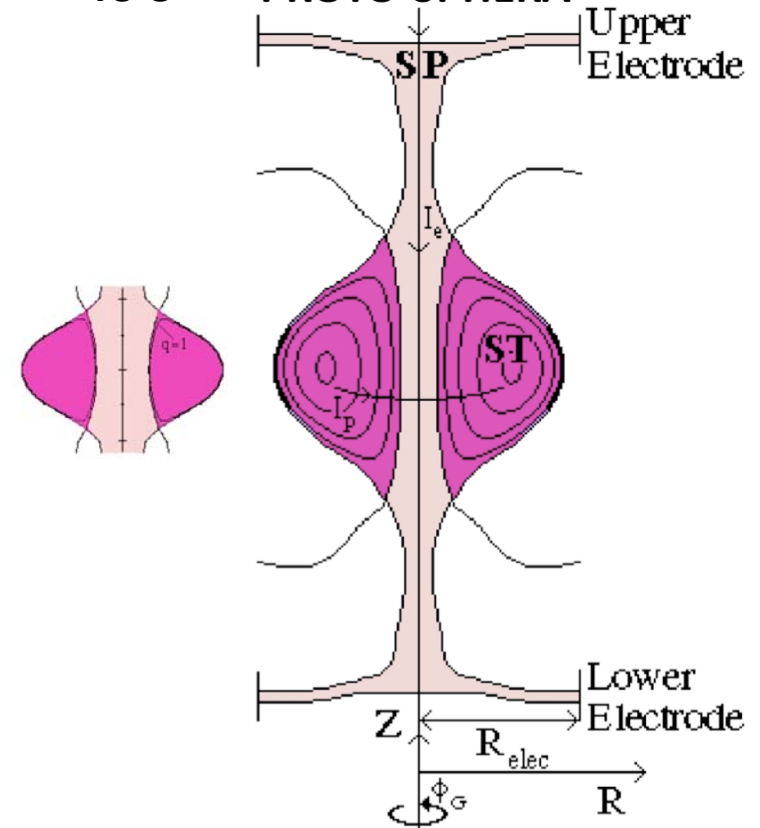
Group A PF coils (compression coils) has dipole moment opposite to Plasma but **Group B PF coils (shaping coils)** has dipole moment aligned to Plasma

Shift $\Delta Z=4$ mm		Tilt $\Delta\theta=0.5^\circ$	
$F_z=+38.9$ N	Unstable	$I_p=30$ kA	$T_y=-2.25$ Nm Stable
$F_z=-9.92$ N	Stabilized ($t<2$ ms) by thick metal casings of PF2,3,4		
$F_z=+19.7$ N	Unstable	$I_p=60$ kA	$T_y=-9.22$ Nm Stable
$F_z=-23.5$ N	Stabilized ($t<2$ ms) by thick metal casings of PF2,3,4		
$F_z=-6.9$ N	Stable	$I_p=120$ kA	$T_y=-12.0$ Nm Stable
$F_z=-68.1$ N	Stable	$I_p=240$ kA	$T_y=-24.5$ Nm Stable

Rigid tilt of Spherical Torus is always stabilized by aligned dipole moment of **Group B shaping PF coils**
Rigid vertical shift of Spherical Torus is always stabilized by thick AISI casings of **Group B shaping PF coils** ($\tau\sim 2$ ms)

TS-3

PROTO-SPHERA



CKF configuration is a possible evolution of the Proto-Sphera concept

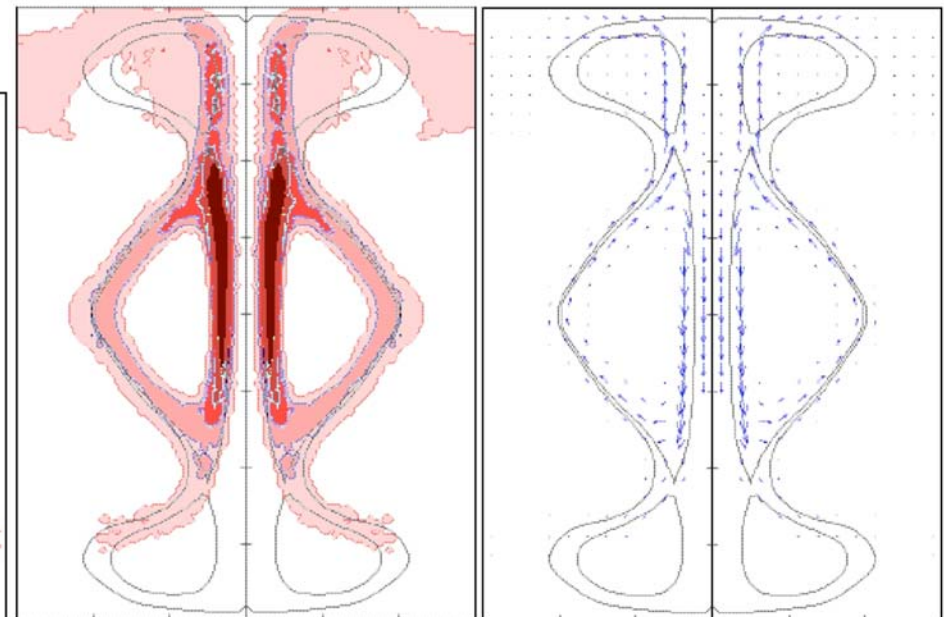
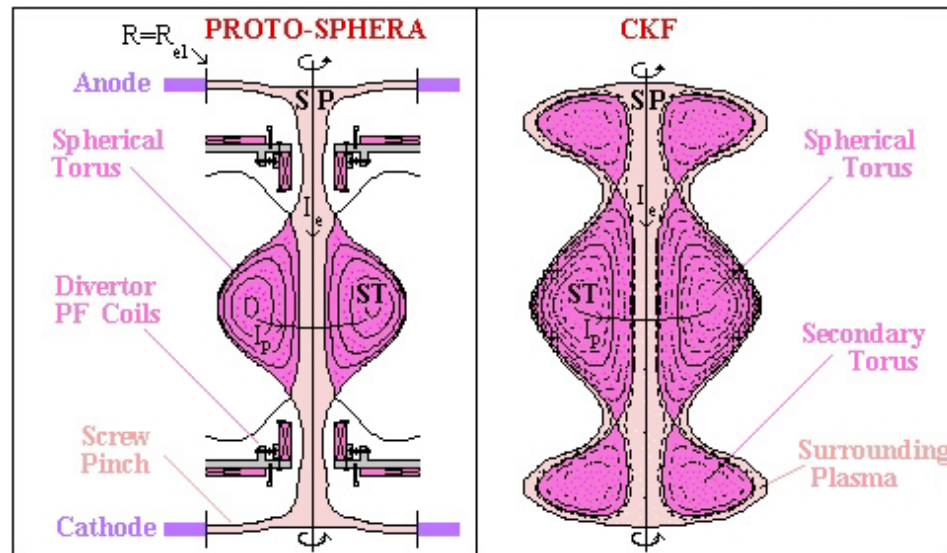
Degenerate X-points on Proto-Sphera anode (and cathode) are nozzles



Different orbits of co- & counter-circulating charged fusion products:
...preferential thrust through only one of the two degenerate X-points

n_α charged fusion product density
density n_α flux $n_\alpha \vec{v}_\alpha$

CKF found to be ideally MHD stable up to $\beta=1$
...promising for future fusion thrusters?

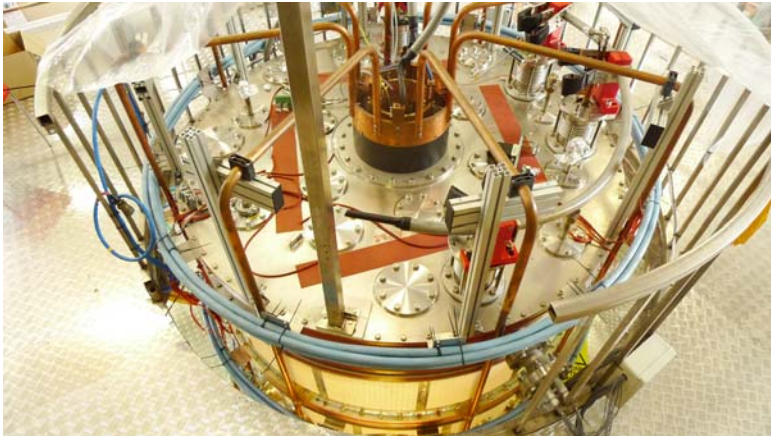


growing $n_\alpha \rightarrow$

Proto-Sphera: a CKF whose
surrounding Plasma terminates upon electrodes
and whose Secondary Tori are substituted by PF2/3 coils

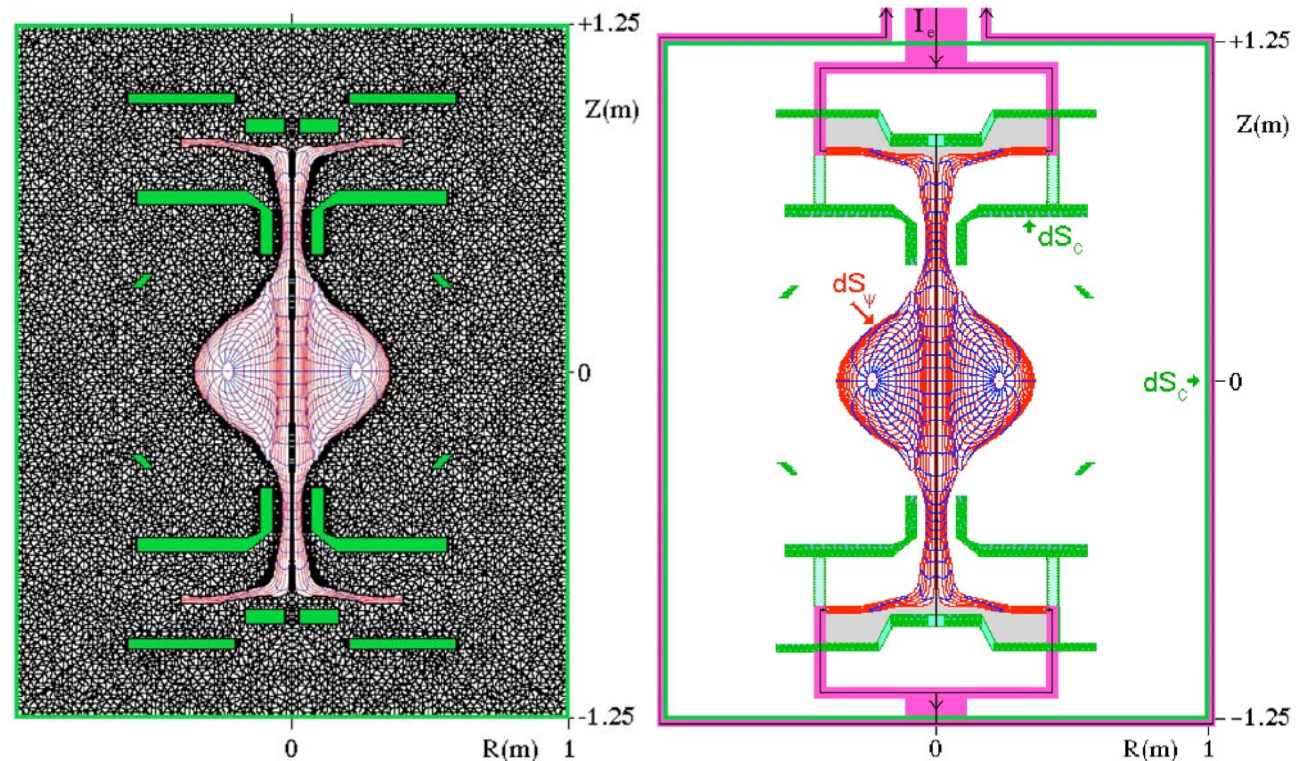
IDEAL MHD STABILITY of PROTO-SPHERA: the vacuum perturbations

Electrode plasma current I_e fed to anode inside machine by coaxial system on top



I_e current returns from the cathode through 8 bars: their circuit inside the machine affects vacuum terms

2D finite element mesh to calculate the perturbed vacuum field



IDEAL MHD STABILITY of PROTO-SPHERA: the results

For low toroidal numbers $n=1, 2$ & 3

ideal MHD stability obtained

expressed with $\beta = 2\mu_0 \int p dV / B^2 dV$

ratio of the two plasma currents I_{ST}/I_e = toroidal ST current/centerpost current

• up to $\beta = 21 \div 26\%$, $I_{ST}/I_e = 0.5 - 1$

• up to $\beta = 14 \div 15\%$, $I_{ST}/I_e = 2-4$

expressed with $\beta_{To} = 2\mu_0 \int p dV / B_{To}^2 V$

• up to $\beta_{To} = 28 \div 29\%$, $I_{ST}/I_e = 0.5 - 1$

• up to $\beta_{To} = 72 \div 84\%$, $I_{ST}/I_e = 2-4$

Centerpost current $I_e = 60$ kA

and ST current $I_{ST} = 120$ kA: $I_{ST}/I_e = 2$

The instability is limited to $n=2, 3$

driven by $q=3/2$ resonance at $\beta = 25\%$

Centerpost current $I_e = 60$ kA

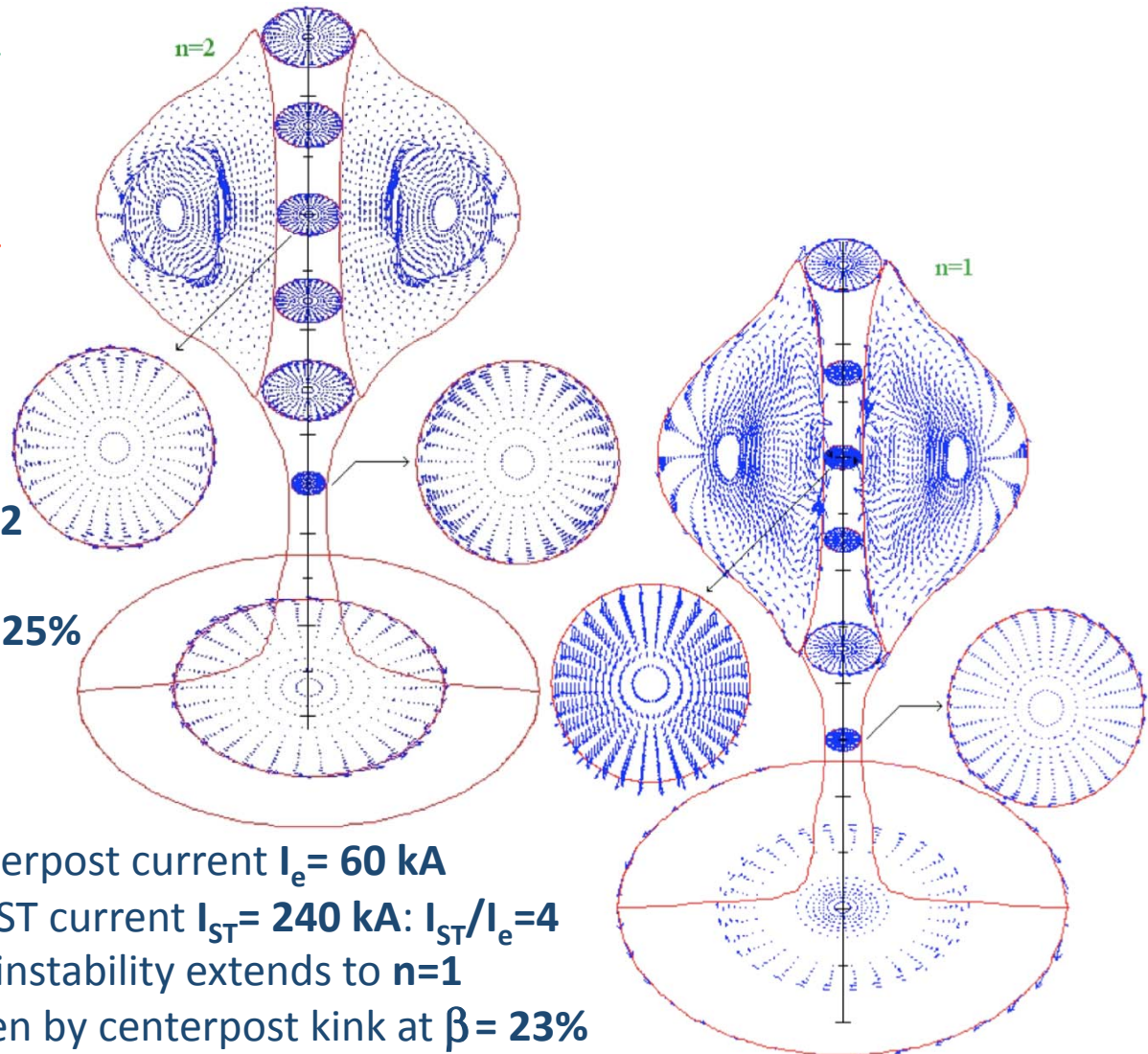
and ST current $I_{ST} = 240$ kA: $I_{ST}/I_e = 4$

The instability extends to $n=1$

driven by centerpost kink at $\beta = 23\%$

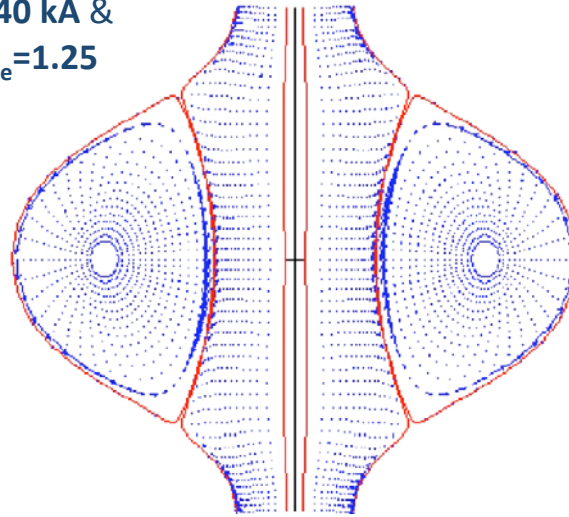
Ideal MHD analysis to assess I_p/I_e & β limits

(Micozzi P. et al., 2010 Nucl. Fusion **50** 095004)

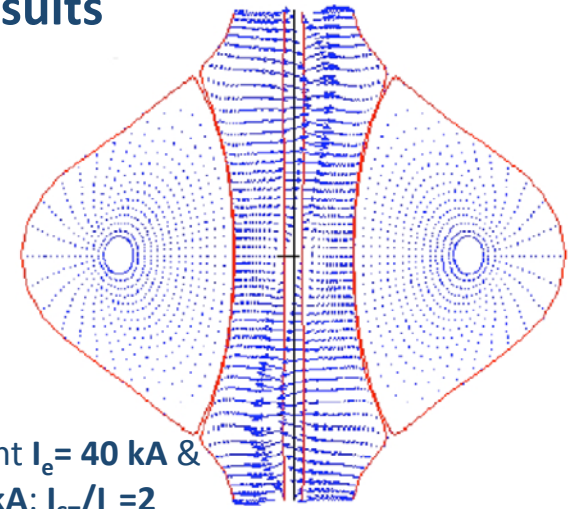


Comparison with TS-3 experimental results

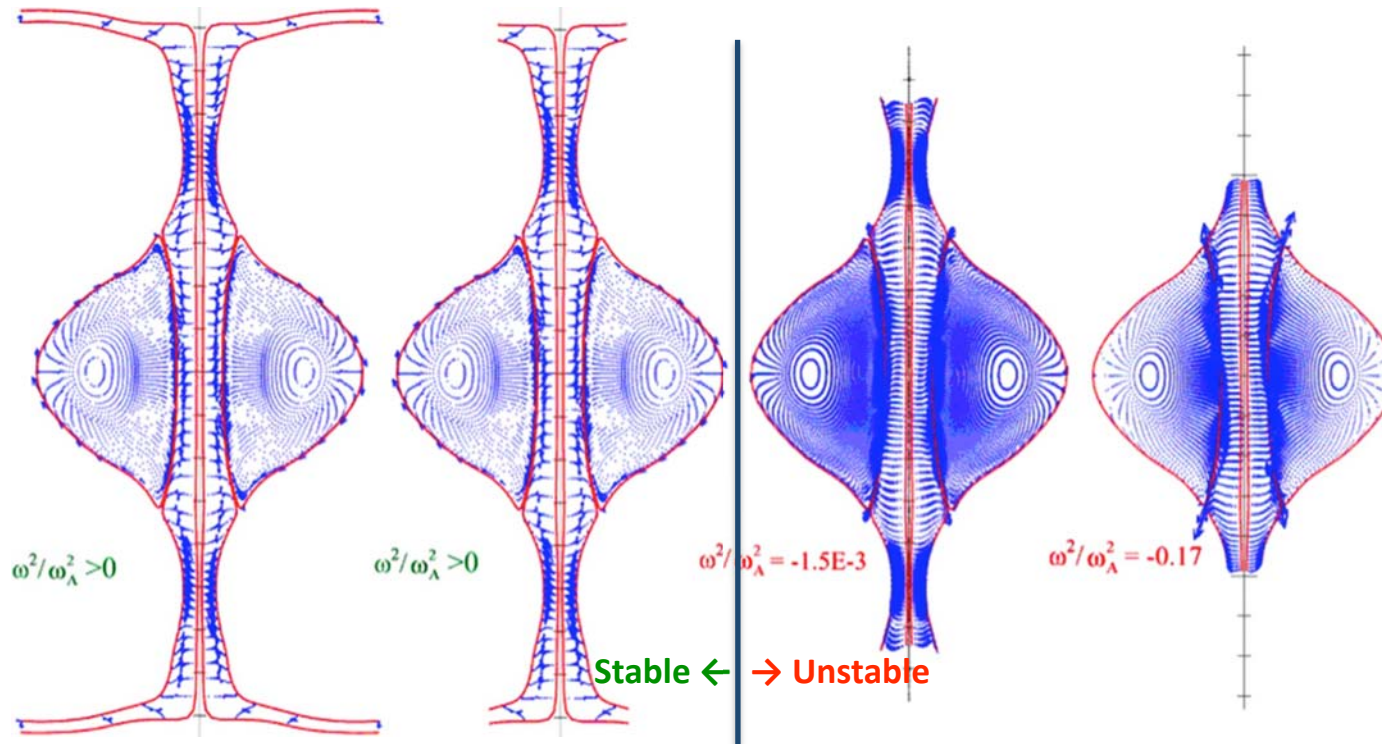
At centerpost current $I_e = 40$ kA &
ST current $I_{ST} = 50$ kA: $I_{ST}/I_e = 1.25$
TS-3 is **ideal MHD stable**



At centerpost current $I_e = 40$ kA &
ST current $I_{ST} = 100$ kA: $I_{ST}/I_e = 2$
TS-3 is **ideal MHD unstable: tilt of SP**



DISK-SHAPED SP PLASMA: IMPORTANT FOR THE IDEAL MHD STABILITY



Cutting shorter & shorter
the plasma centerpost
PROTO-SPHERA at 120 kA
gets destabilized

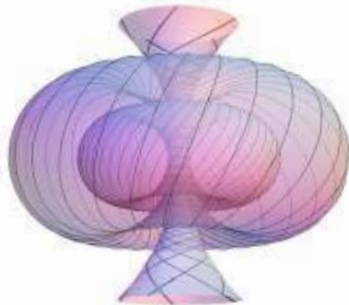


Cylindrical vacuum vessel was START vacuum vessel, donated by Culham in 2004

From **Culham** the old vacuum vessel found its way to **Frascati**



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

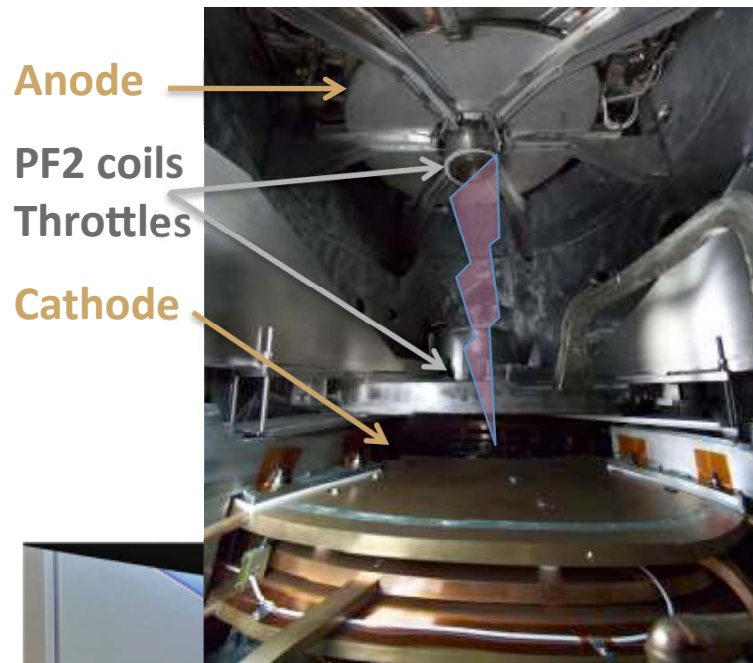


Years 2004 - 2010:

...from ideas

...to detailed design

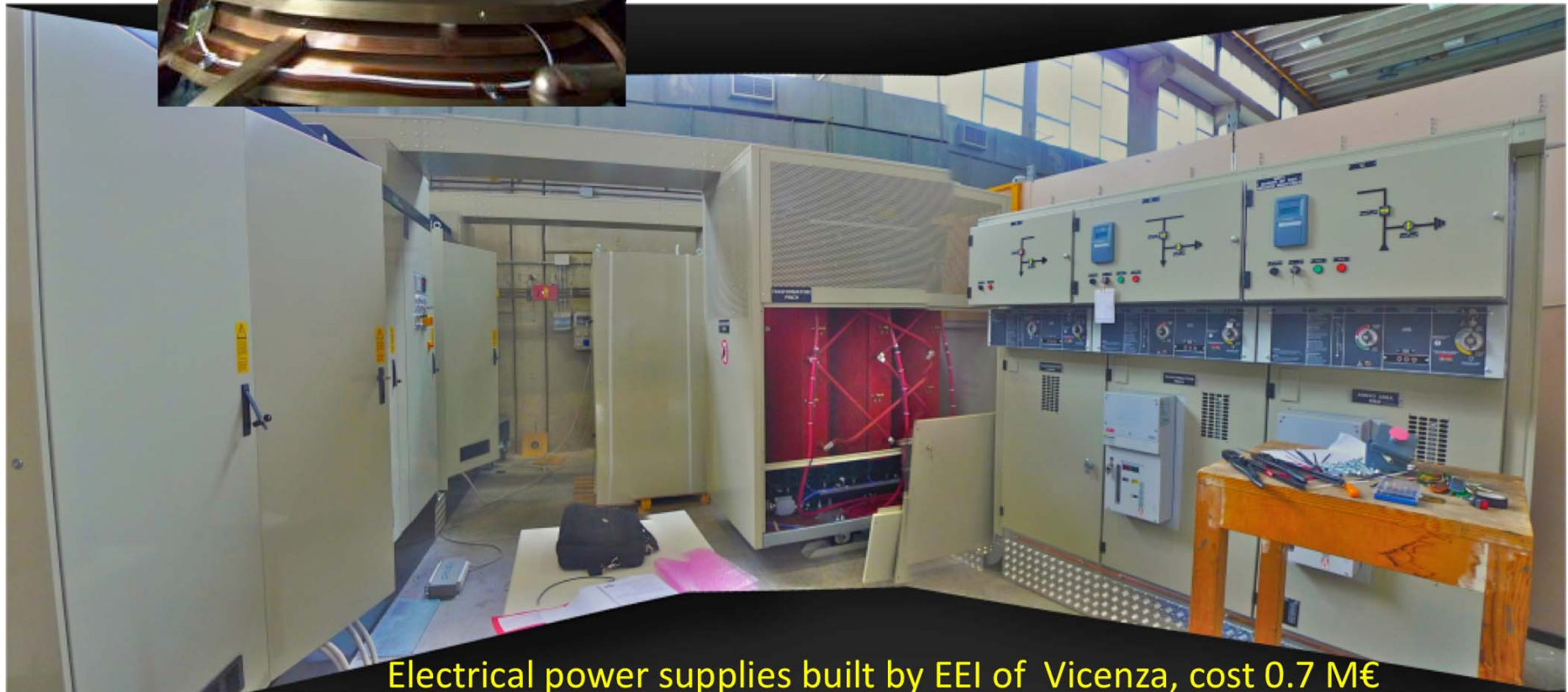
...to hard metal



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:



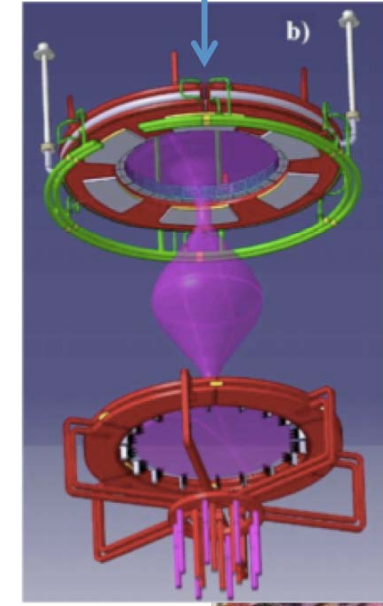
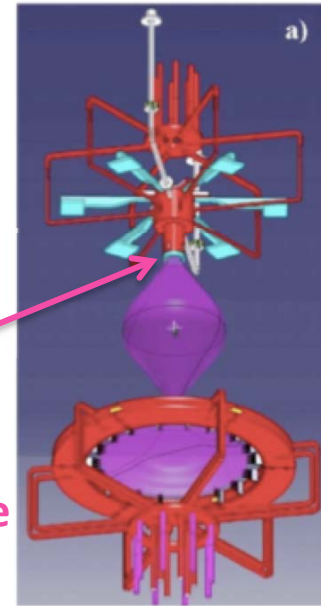
2014 cylindrical anode

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



Vincenzo Zanza
ENEA

Cylindrical cathode results

Hydrogen plasma

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

anode camera



centerpost camera

April 2015
annular anode
installed



Fabio Crescenzi



Benedetto Tilia Andrea Grosso ENEA

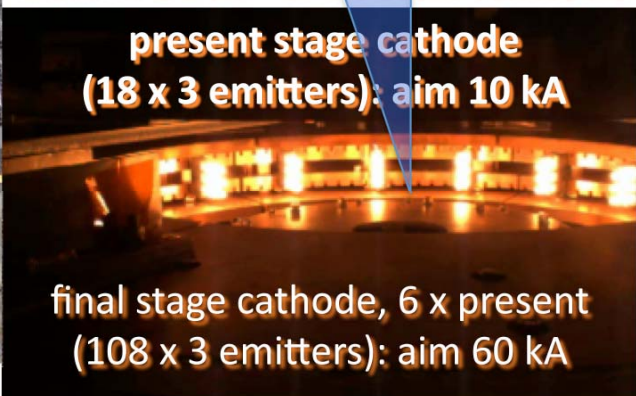


May 2015 annular
anode lowered
on top of machine



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 now survived > 1000 cycles



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

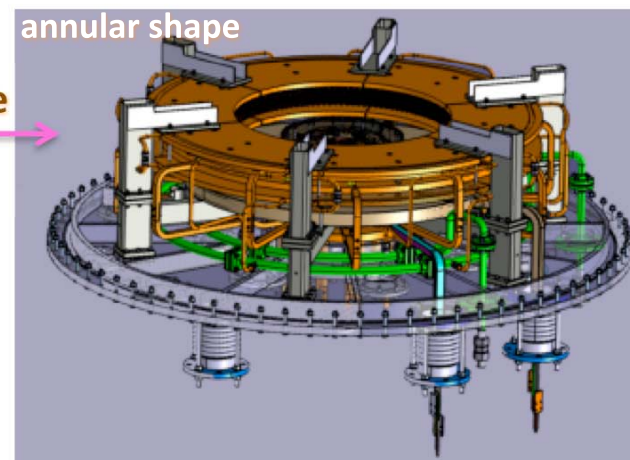
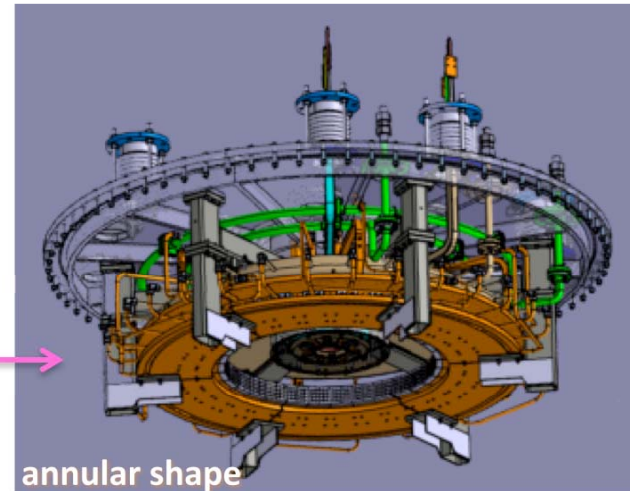
PF4low

Stainless steel
up\down new lids

anode

Plasma current must run
through both PF2 throttles

cathode



vacuum vessel is GND potential

can be connected to potentials: **anode +**, **cathode -**, vessel 0



Federica Causa ENEA

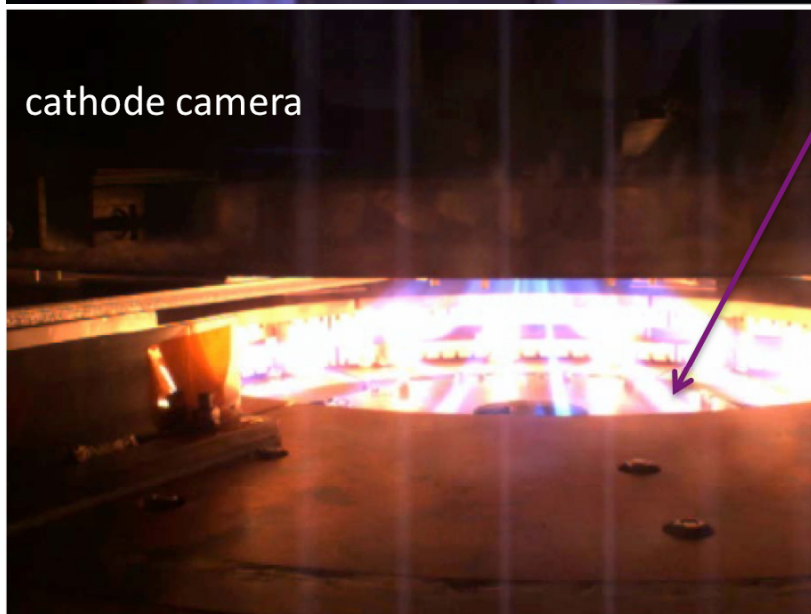


Luca Boncagni ENEA

Argon plasma: break-down 80 V



anode camera



cathode camera

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 cathode plasma is filamented (due to sparse emitters)

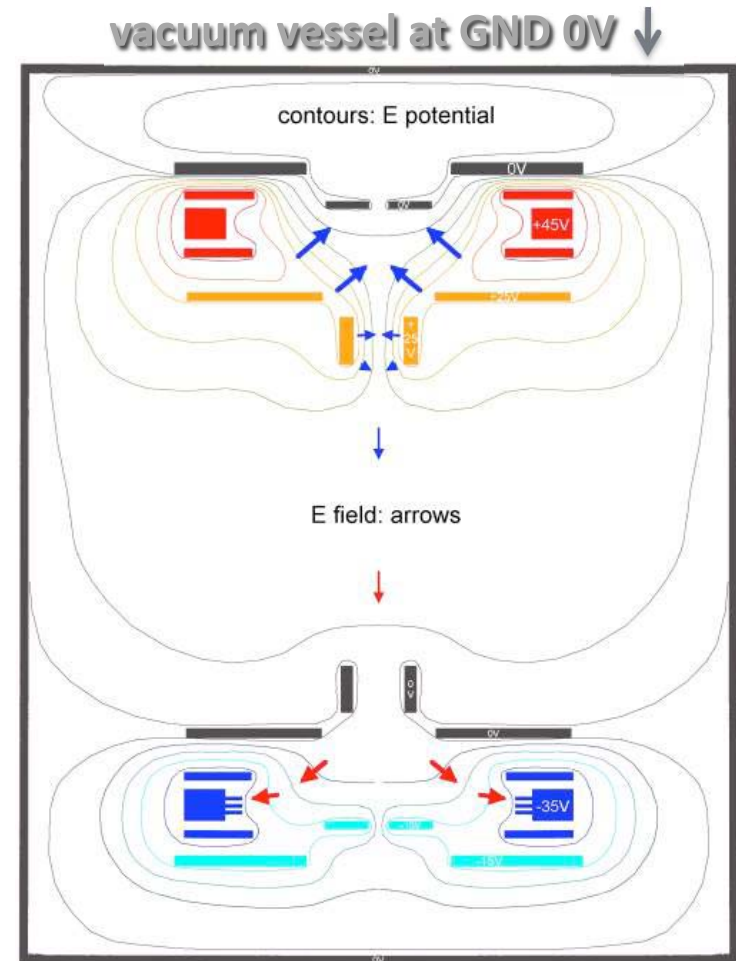
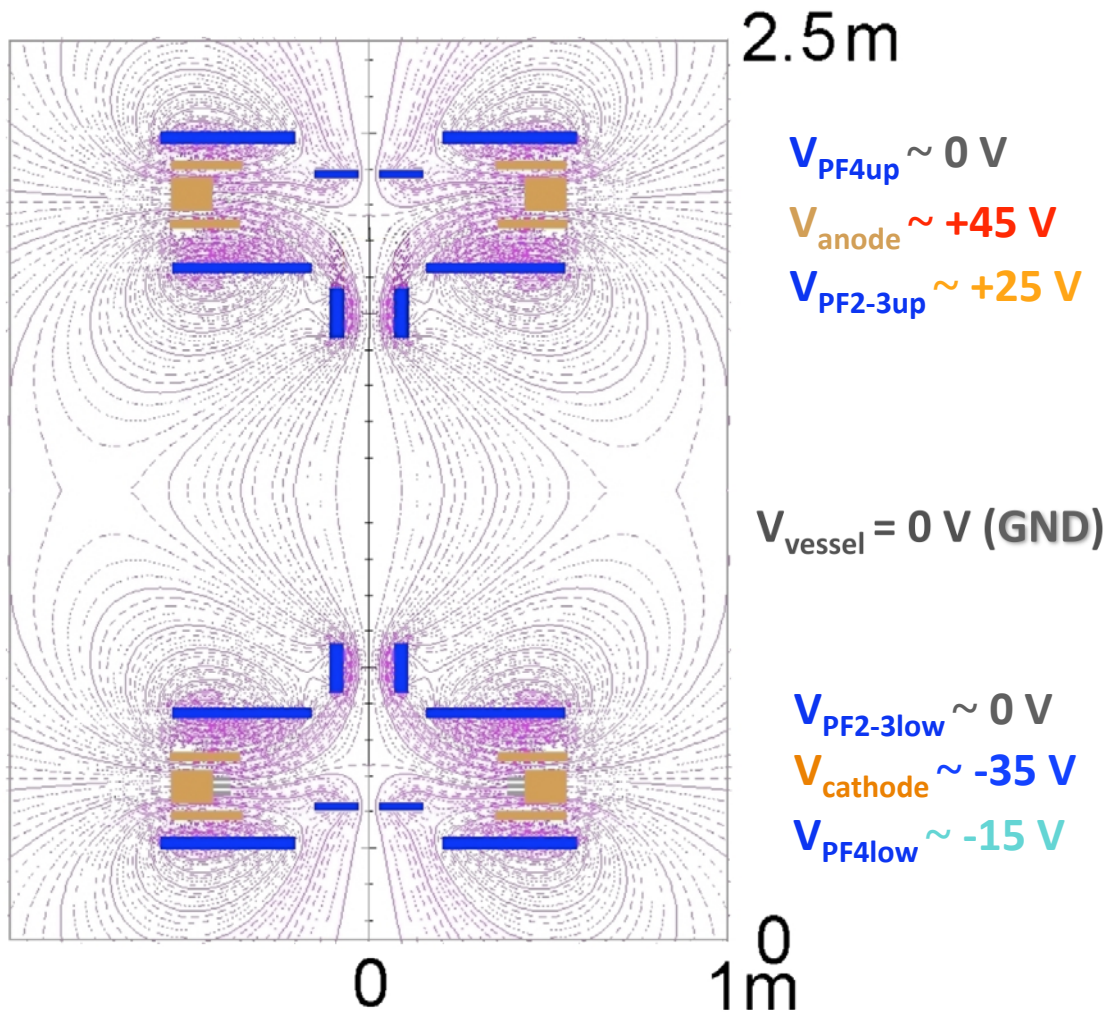


even plasma centerpost is in part filamented

Electrostatic plasma effects

However, the electrostatic potential distribution is dominated by the plasma

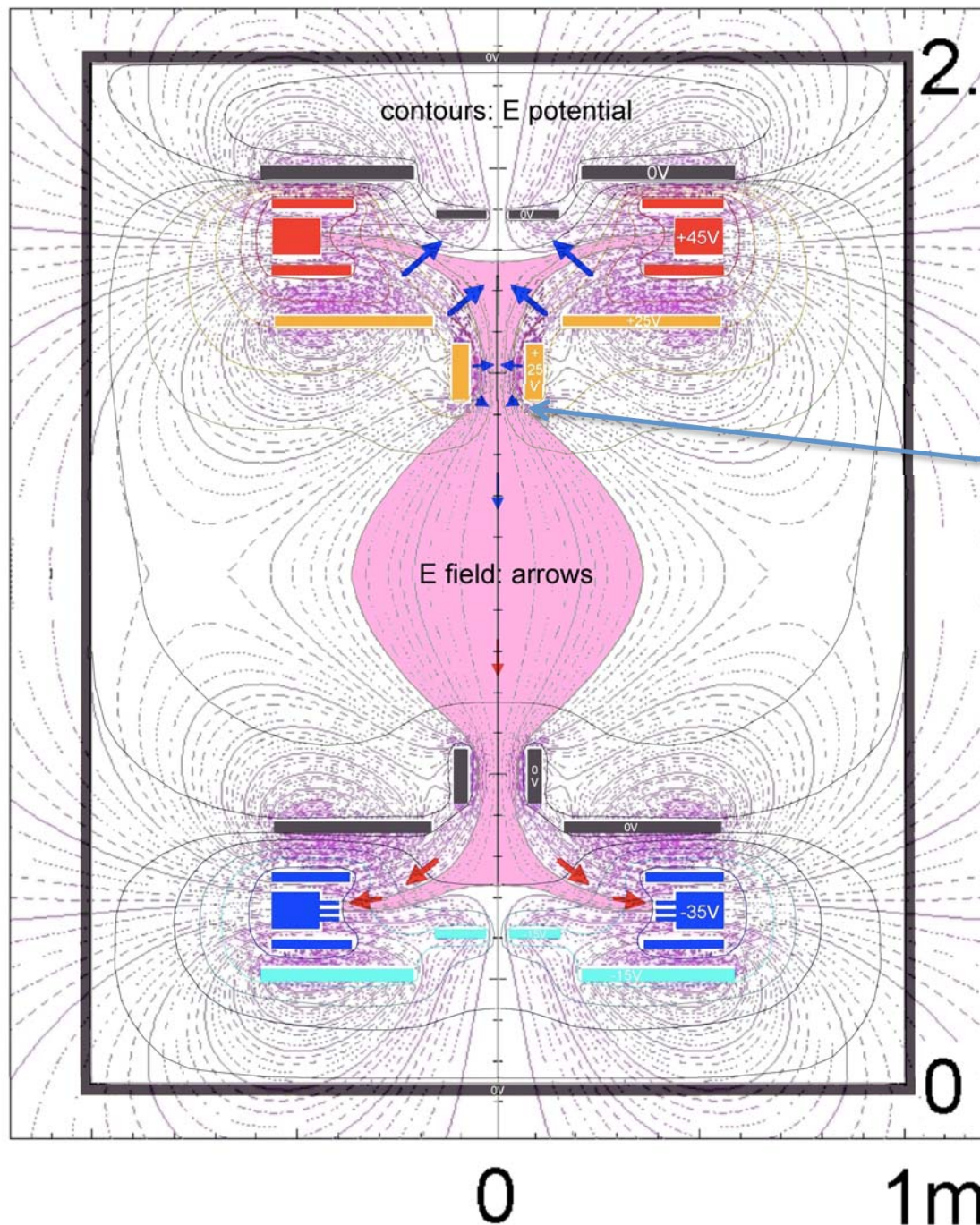
PF coils casings built as floating, can be connected to potentials: **anode +**, **cathode -**, vessel 0 through $\sim 0.1 - 1\Omega$ resistors



the magnetic field is up\down symmetric

near either the anode or the cathode, the topmost coil casing is approximately at ground potential

but the electrostatic field is not up\down symmetric



Plasma-induced electric potential:

near the annular anode
the **E** field is in part perpendicular
to the **B** field

... **E** X **B** azimuthal plasma rotation

... starting from PF2up throttle

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

near the annular cathode

the **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

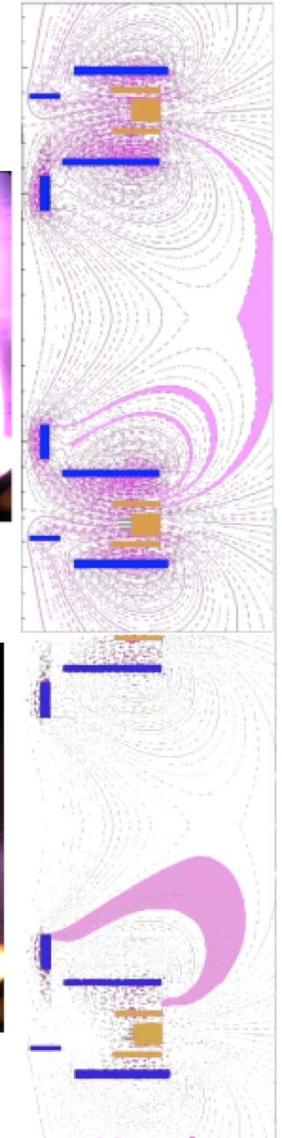
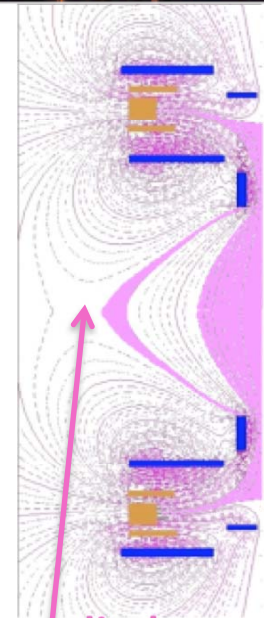
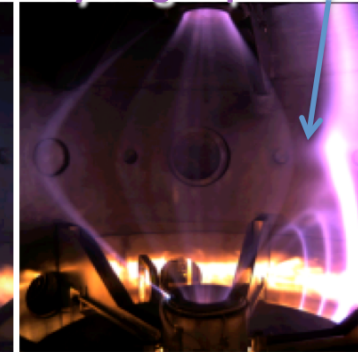


Shot 78

Argon plasma



Hydrogen plasma

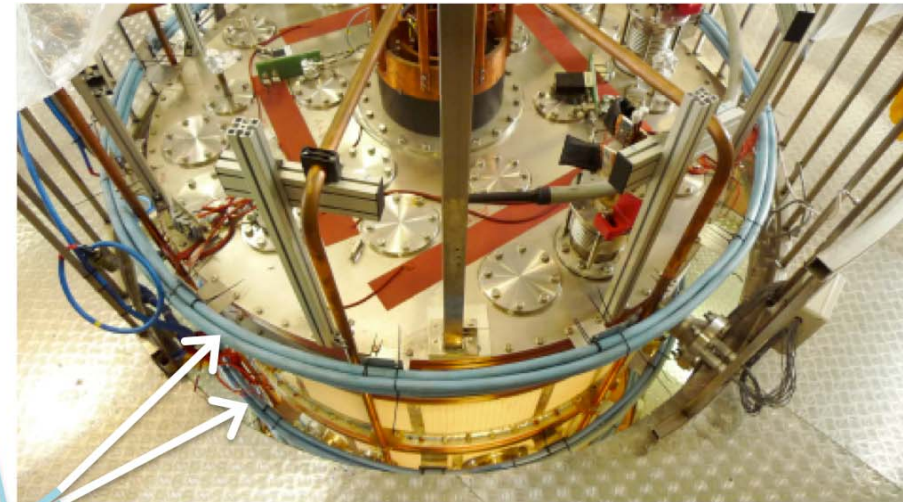
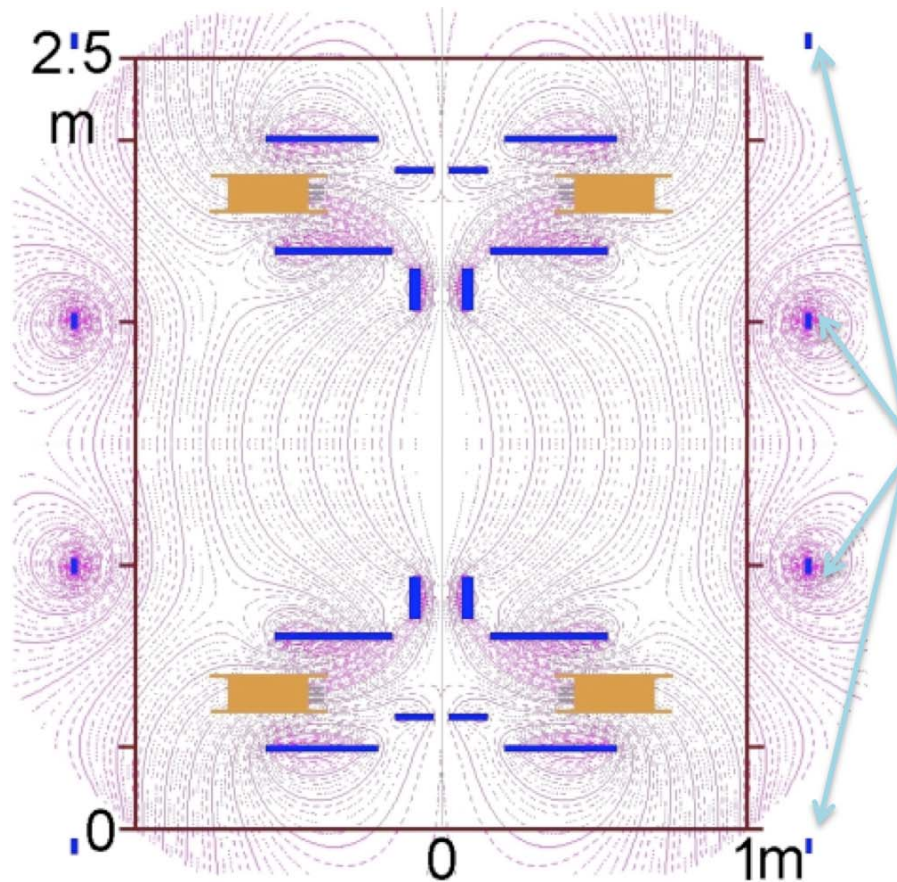


discharges along field lines near X-point

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

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

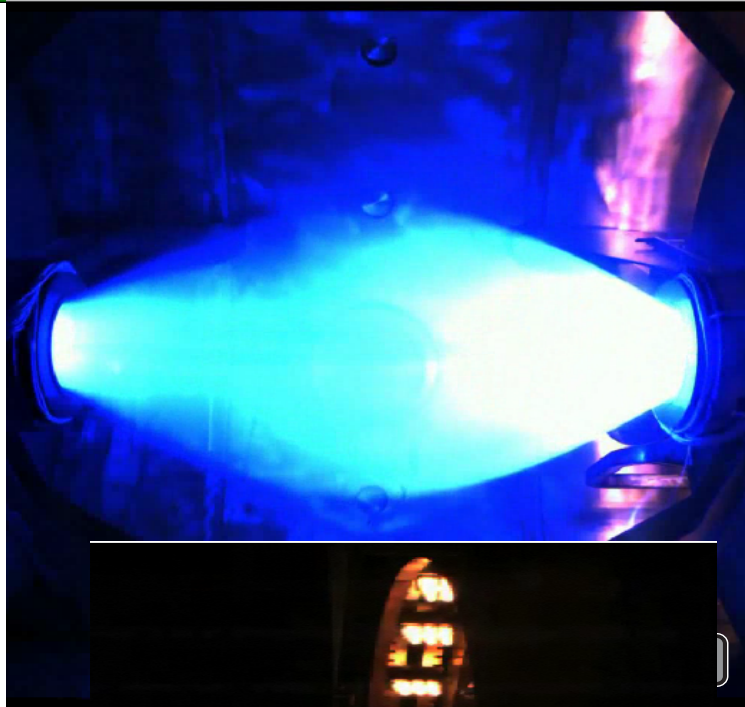
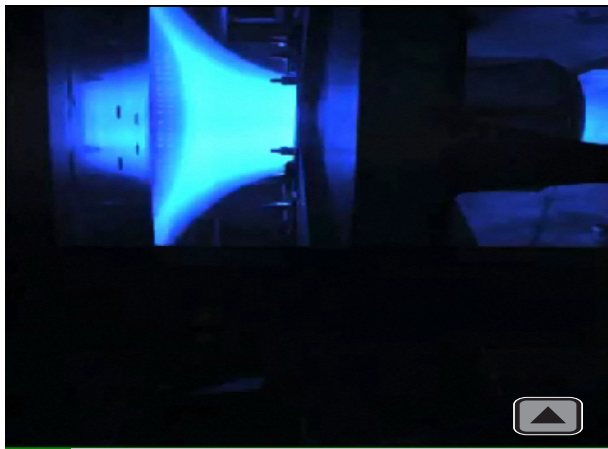
...and fed in series with the internal PF coils (PF coils power supply has sufficient margin)



4 external PF coils



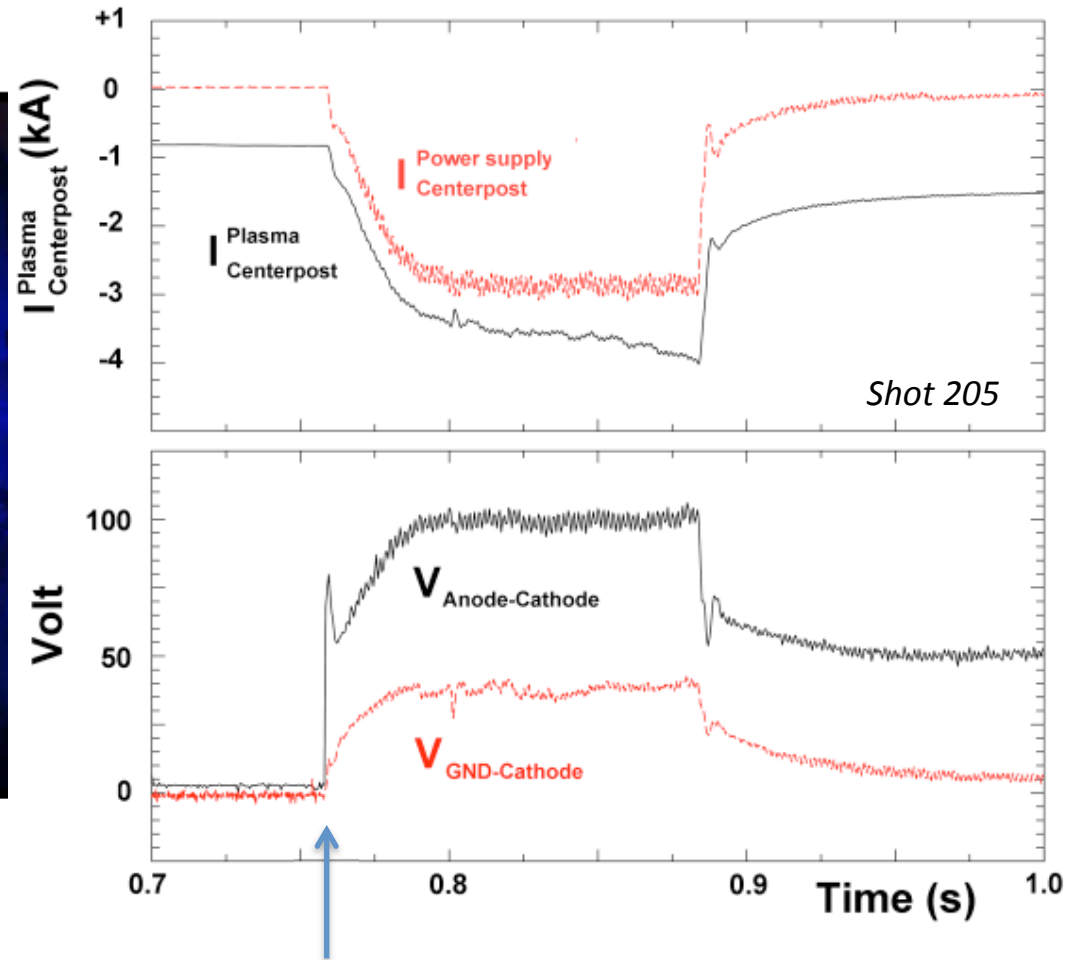
plasma fired after 0.75 s of PF current to allow for skin current diffusion in Al vessel and SS lids



October 2015 experiments with external PF coils:

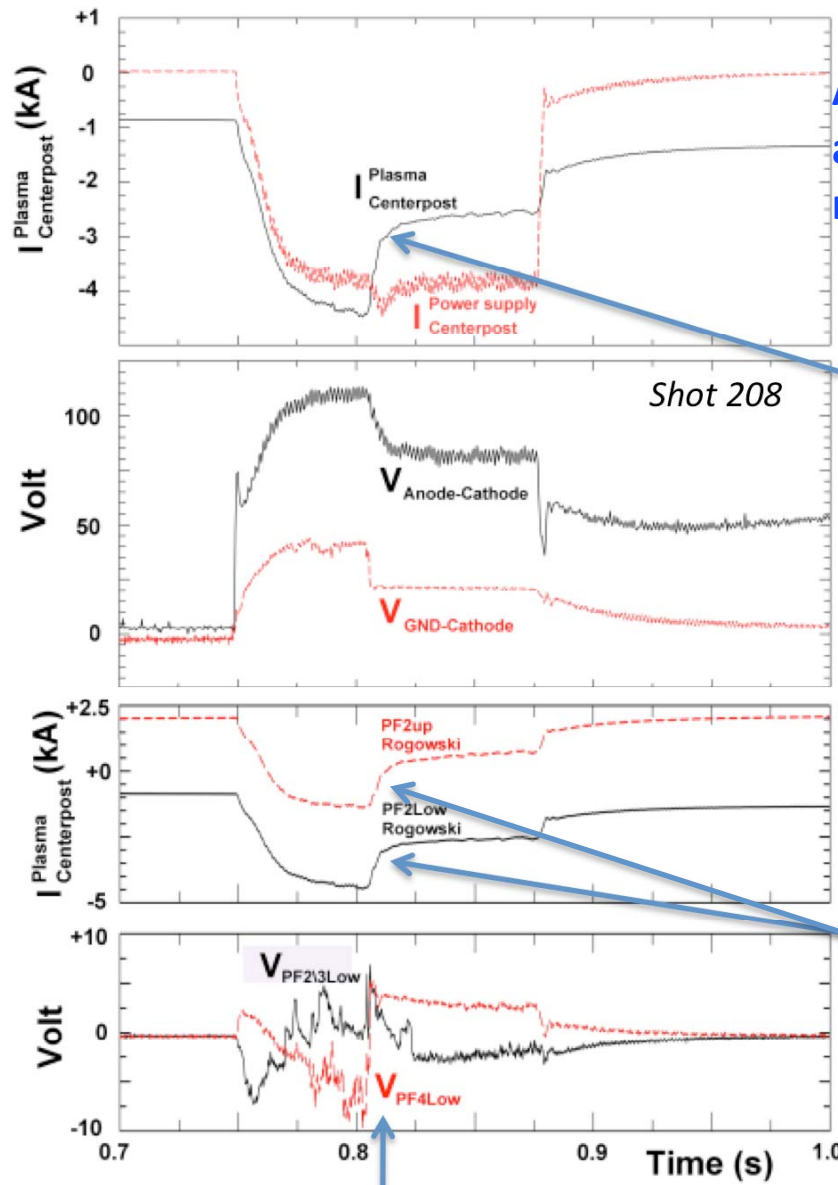
Argon discharge reaching 3 kA for 0.15 s

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)

Plasma current outer paths for $I > 3.5$ kA



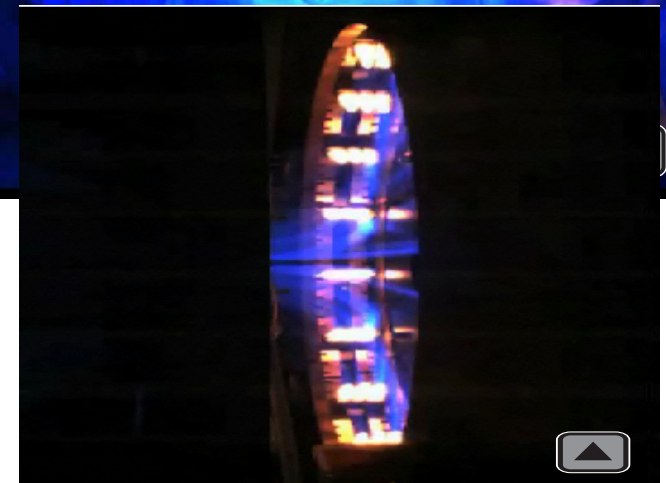
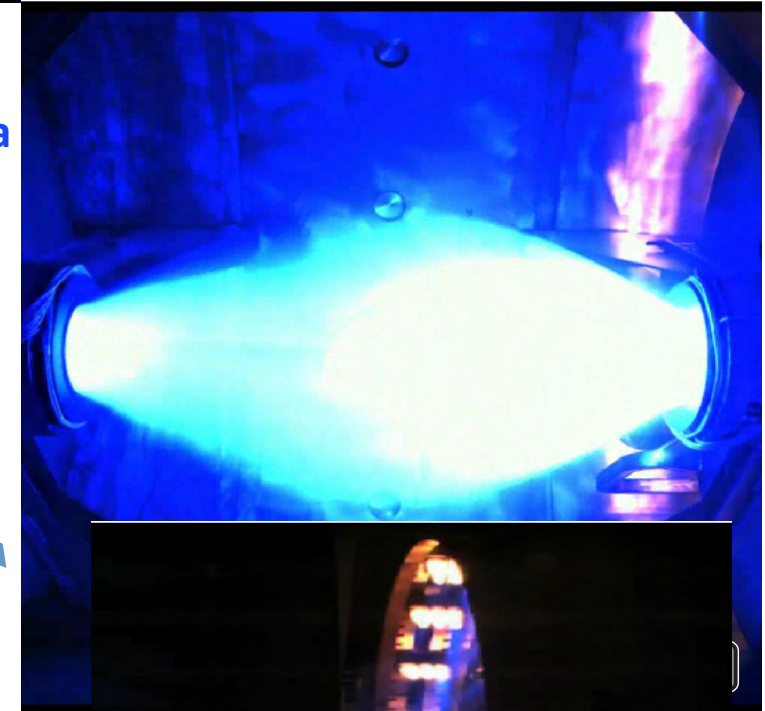
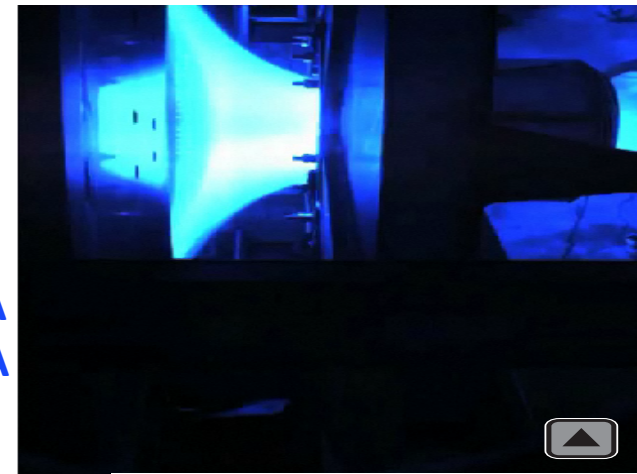
Argon plasma aiming to 4 kA reaches 3.5 kA

~ 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



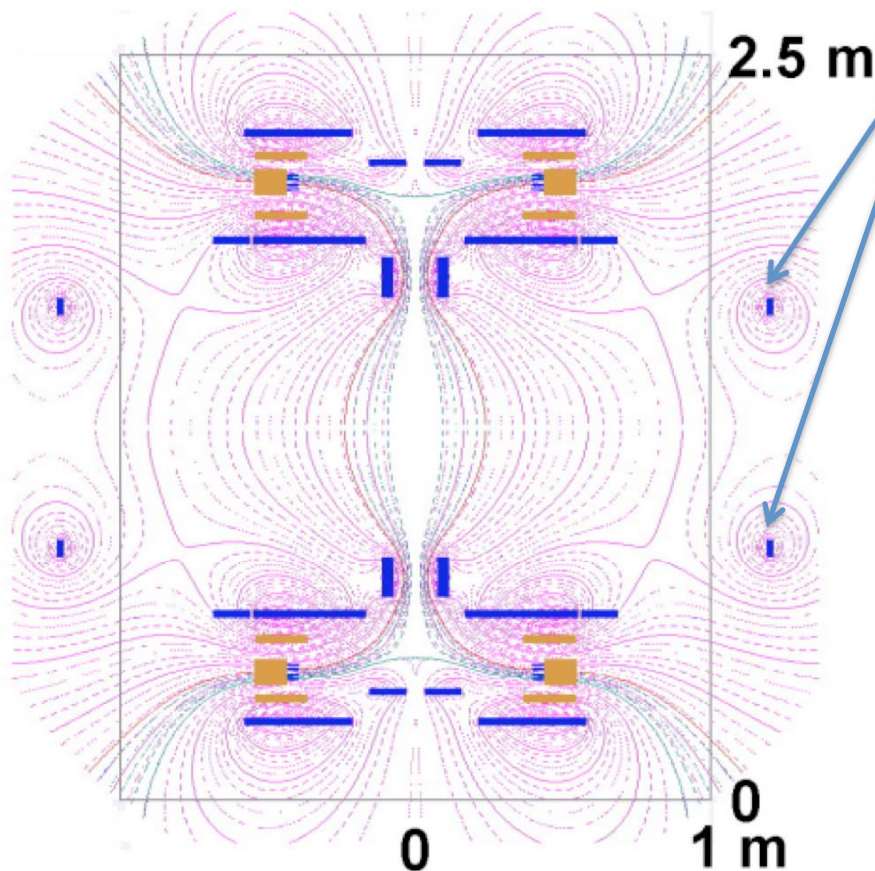
Magnetic tailoring in order to have a better filling of electrodes

when plasma current takes outer path cathode is 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

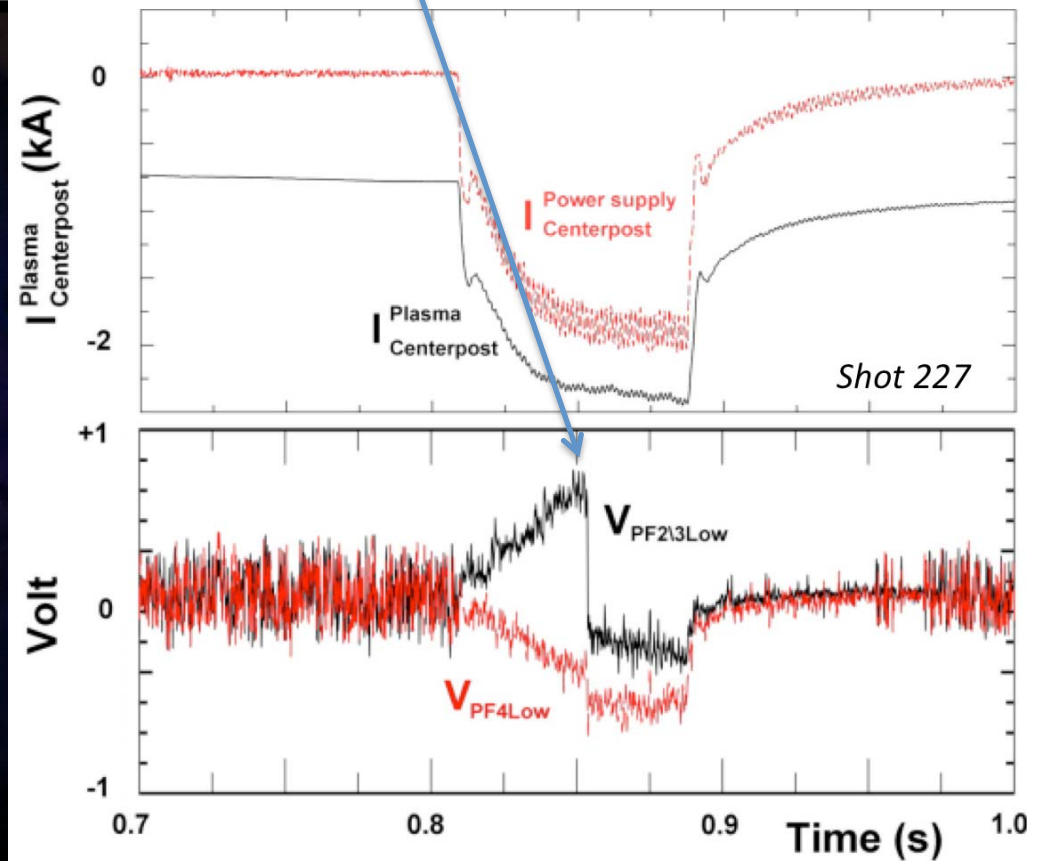


- straighter grounding of lower PF coils
- flowing current only in the two external PF coils nearer to equator

Allows for and better filling of cathode

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

Argon plasma 2kA



What is going on at this moment

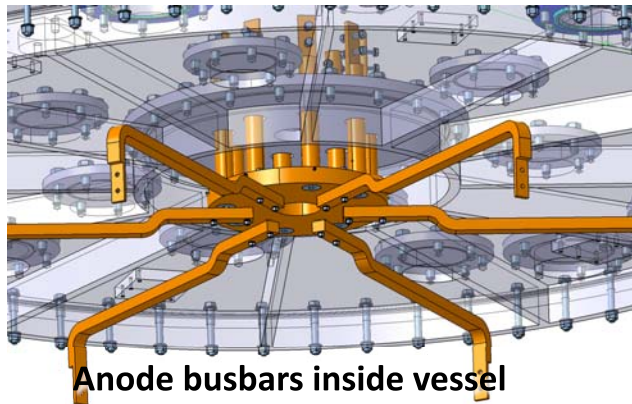
To achieve the full design current 8.5kA to remove the electrically conductive material near the current copper busbars, which allow the **parasitic plasma discharges**



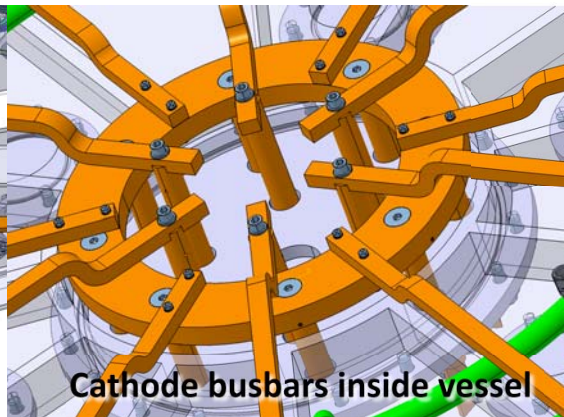
busbars (top-anode) from 20M Ω to 2k Ω resistance



busbars (bottom-cathode) from 20M Ω to 40 Ω resistance



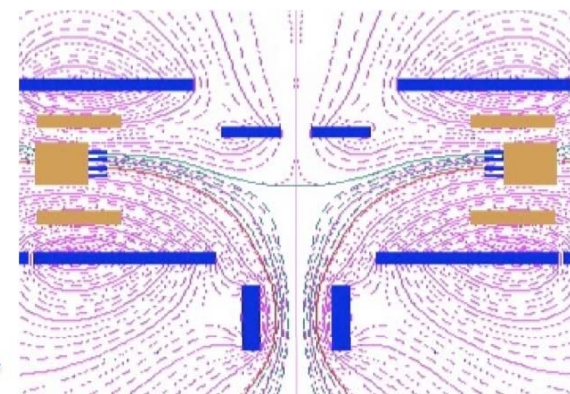
Anode busbars inside vessel



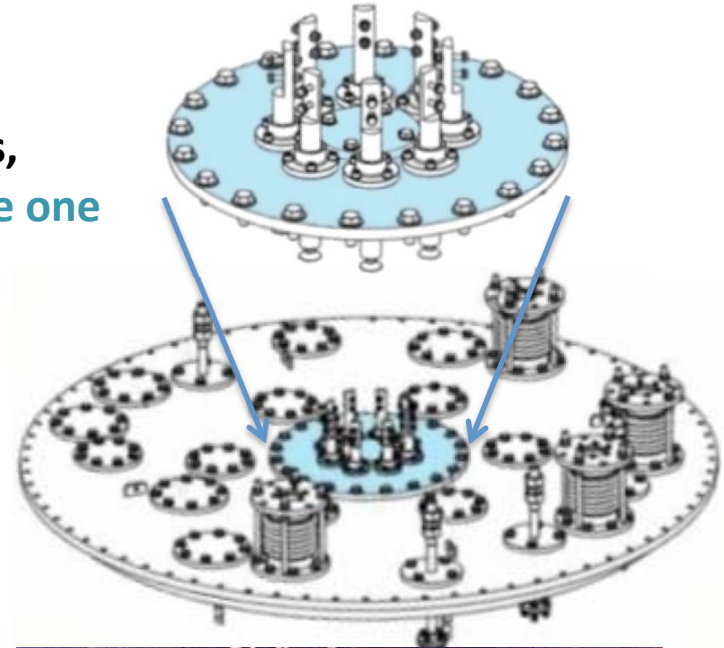
Cathode busbars inside vessel



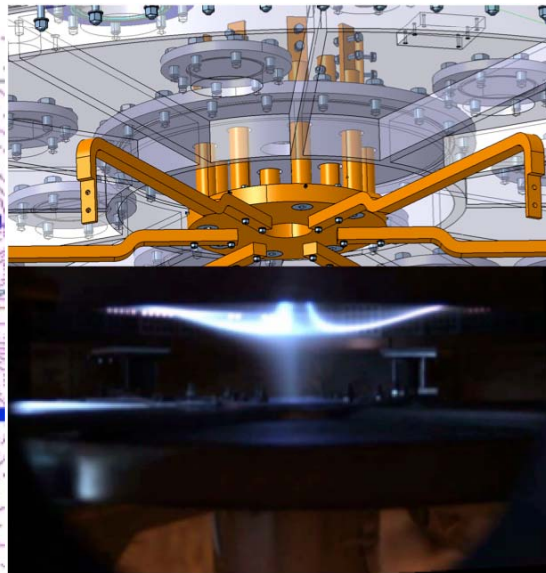
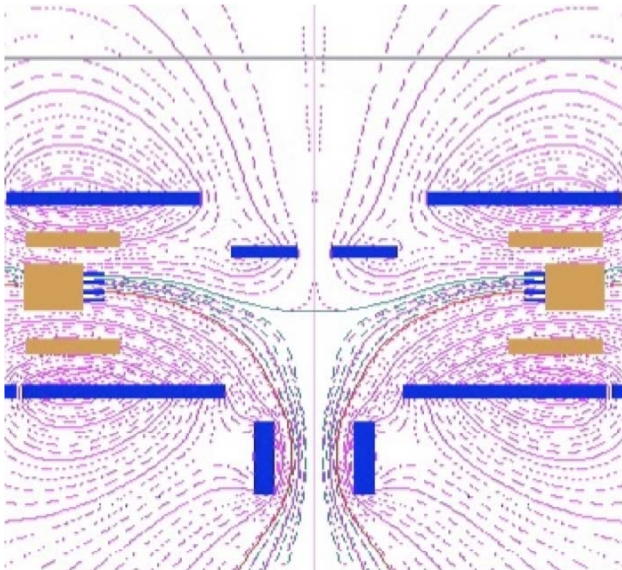
Cause of metallization:
degenerate (B=0) X-points over anode (up) and below cathode (down) act as plasma nozzles



On the top (near anode) a SS flange, pierced by 8 busbars, such a flange is now being substituted by a **Polycarbonate one**

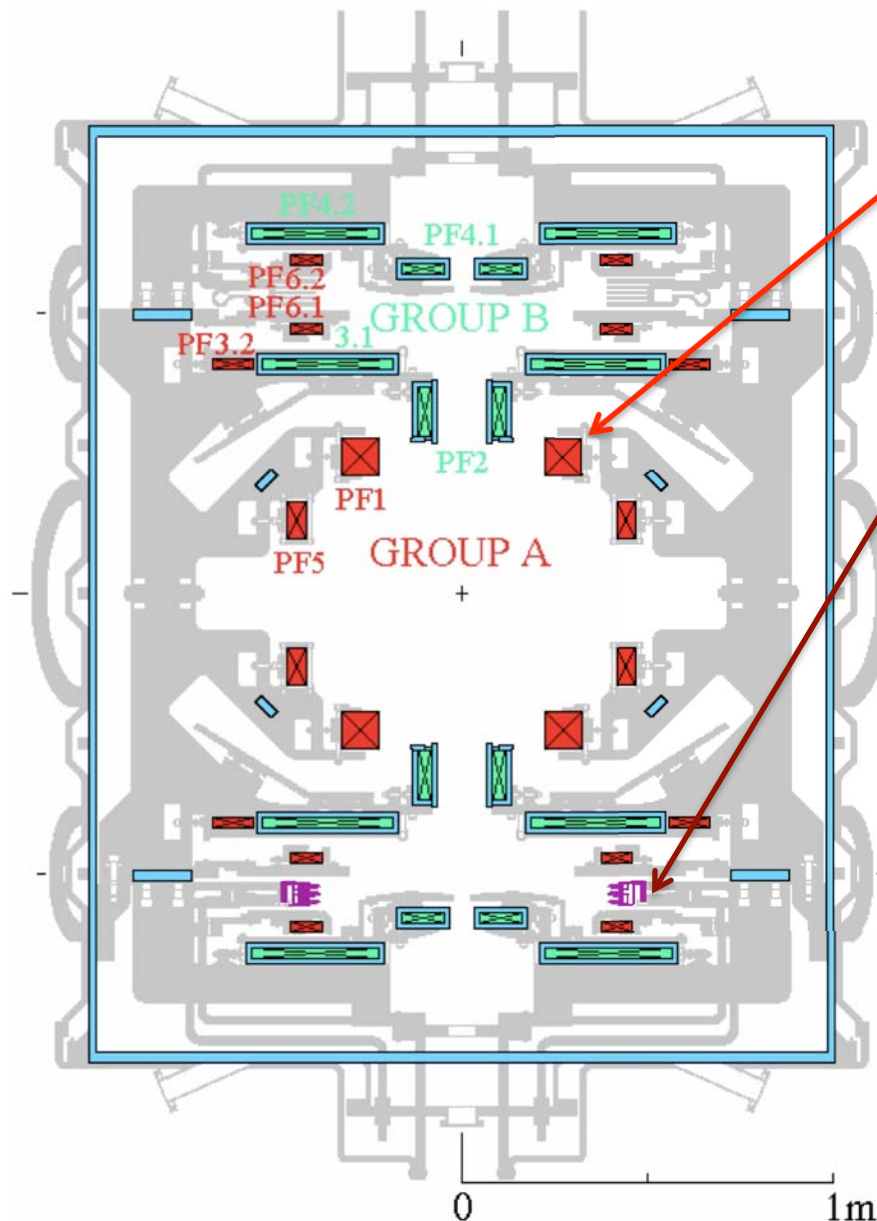


Busbars (top-anode)



At the bottom (near cathode) a SS flange, pierced by 14 busbars, such a flange is now being substituted by a **Polycarbonate one**

To be build after 10 kA plasma centerpost routinely achieved



Group A: ST compression coils (5+5 series)

Not yet built, but inner vessel ready to host

- high voltage (~ 20 kV) insulation
 - thin Inconel casings
- cost ~ 0.5 M€

Tungsten filaments (54 $\rightarrow$ 324) cost ~ 0.2 M€

Final Power Supplies for:

- 1) Group A PF coils cost ~ 0.1 M€
- 2) Cathode (current 10 $\rightarrow$ 60 kA) cost ~ 0.2 M€
- 3) Screw Pinch (I_e 10 $\rightarrow$ 60 kA) cost ~ 0.6 M€

SuperCapacitors will be used

Cost up to now ~ 2.0 M€

Cost for final stage of experiment ~ 1.6 M€

Status

PROTO-SPHERA is producing its first centerpost plasmas ...*better late than never!*

Hollow gas puffed anode is a success, no any anode arc attachment
(plasma induced electrostatic effect, $E \times B$ drift rotation of the plasma)

Target 8.5kA in plasma centerpost: 3.5 kA = 40% has been sustained in Argon plasma

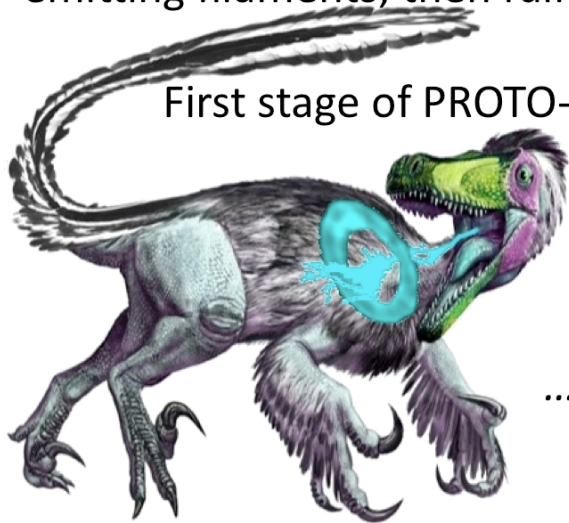
To achieve full current of 8.5 kA boundary conditions must be adjusted:

- electrostatically by connecting PF coils casings, built floating with respect to the vessel
- magnetically by additional PF coils external to the vacuum 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 only a first step



...放龙入海!

...*give a chance to the dragon to show his endowments into the sea!*

Perspective

Proto-Sphera will assess a new magnetic confinement configuration

- simply connected (easier construction & maintenance)
- with high plasma β capability
- sustained by magnetic helicity injection instead of ohmic drive

Proto-Sphera can develop this program:

at very low costs ($\sim 1.6\text{M€} + 2\text{M€}$ already spent)

in a flexible way (new components can be easily added)



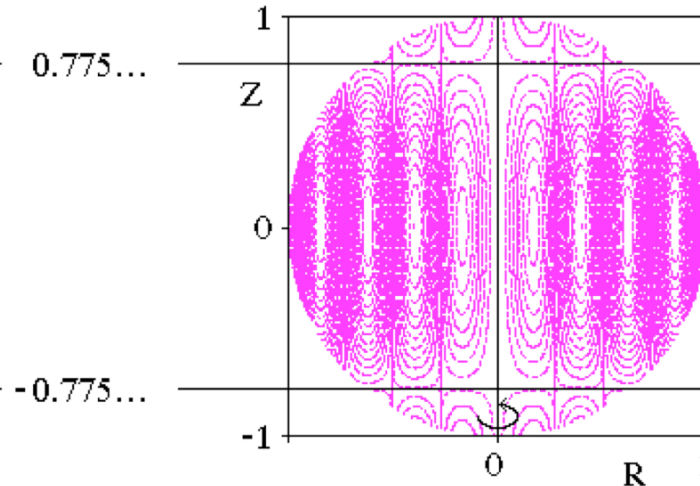
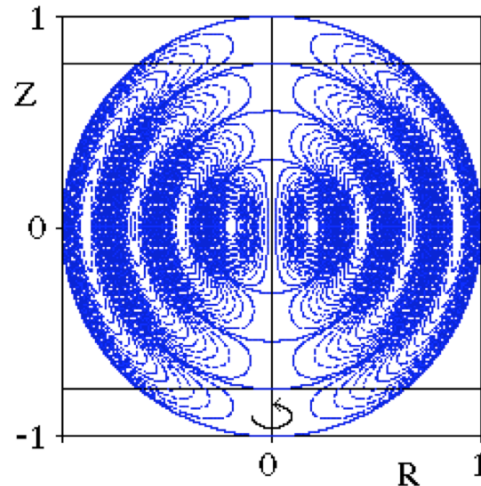
*Other authors
(~all of them)*

Superposition of 2 force-free fields $\nabla \wedge \mathbf{B} = \mu \mathbf{B}$, same relaxation parameter $\mu = \mu_0 \mathbf{j} \cdot \mathbf{B} / B^2 = 14.066\dots$

Chandrasekhar-Kendall (in unitary sphere) Furth square-toroids

$$\psi_{\mu,1}^{CK}(r,\vartheta) = -(\mu r) j_1(\mu r) \sin \vartheta P_1^1(\cos \vartheta)$$

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



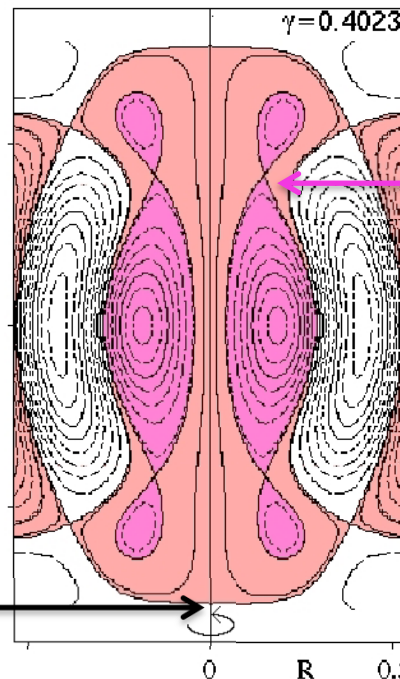
Coincidence of zero of $\psi_{\mu,1}^{CK}$ and of $\psi_{\mu,\lambda}^F$ at $R=0$, $Z=x_{1,3}/x_{1,4}=0.775$ fixes $\lambda = x_{1,4}\pi/2x_{1,3}=2.026\dots$

$$\psi(r,\vartheta) = \psi_{\mu,1}^{CK} + \gamma \psi_{\mu,\lambda}^F$$

**Chandrasekhar-Kendall-Furth
force-free field (CKF)**

For $\gamma \geq 0.402\dots$ in a simply connected region
the toroidal current density j_ϕ has same sign

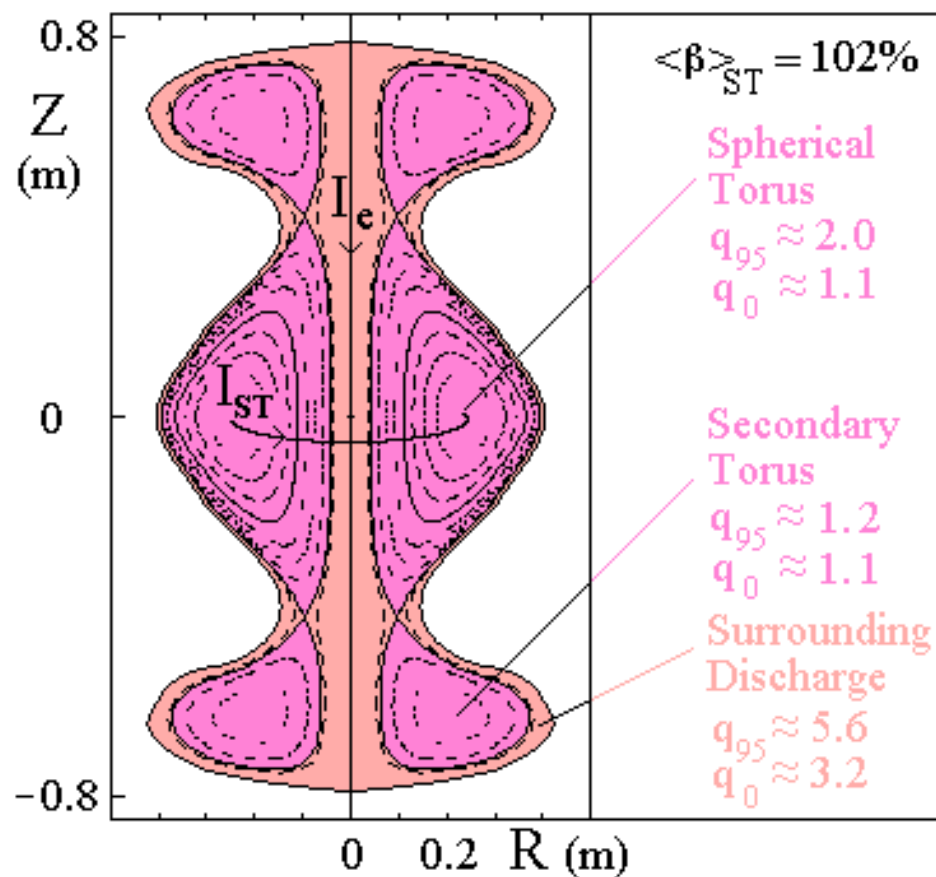
Degenerate X-points ($B=0$) present
(top/bottom) on the symmetry axis



**A magnetic separatrix with
ordinary X-points ($B \neq 0$) divides:
a main spherical torus (ST)
2 secondary tori (SC)
& a surrounding plasma (P)**

UNRELAXED Chandrasekhar-Kendall-Furth CONFIGURATIONS

However CKF force-free fields ($\nabla p=0$) are unable to confine plasmas of fusion interest
 MHD free boundary equilibria of unrelaxed ($\nabla \mu \neq 0$, $\nabla p \neq 0$) CKF configurations



$$\mu = \mu_0 \frac{\vec{j} \cdot \vec{B}}{B^2} = \mu_{\text{edge}}$$

constant at the plasma edge

Main parameters of equilibrium:

$$I_{ST} / I_e = \frac{\text{toroidal current in ST}}{\text{poloidal current in P}}$$

determines q_{95} at ST edge

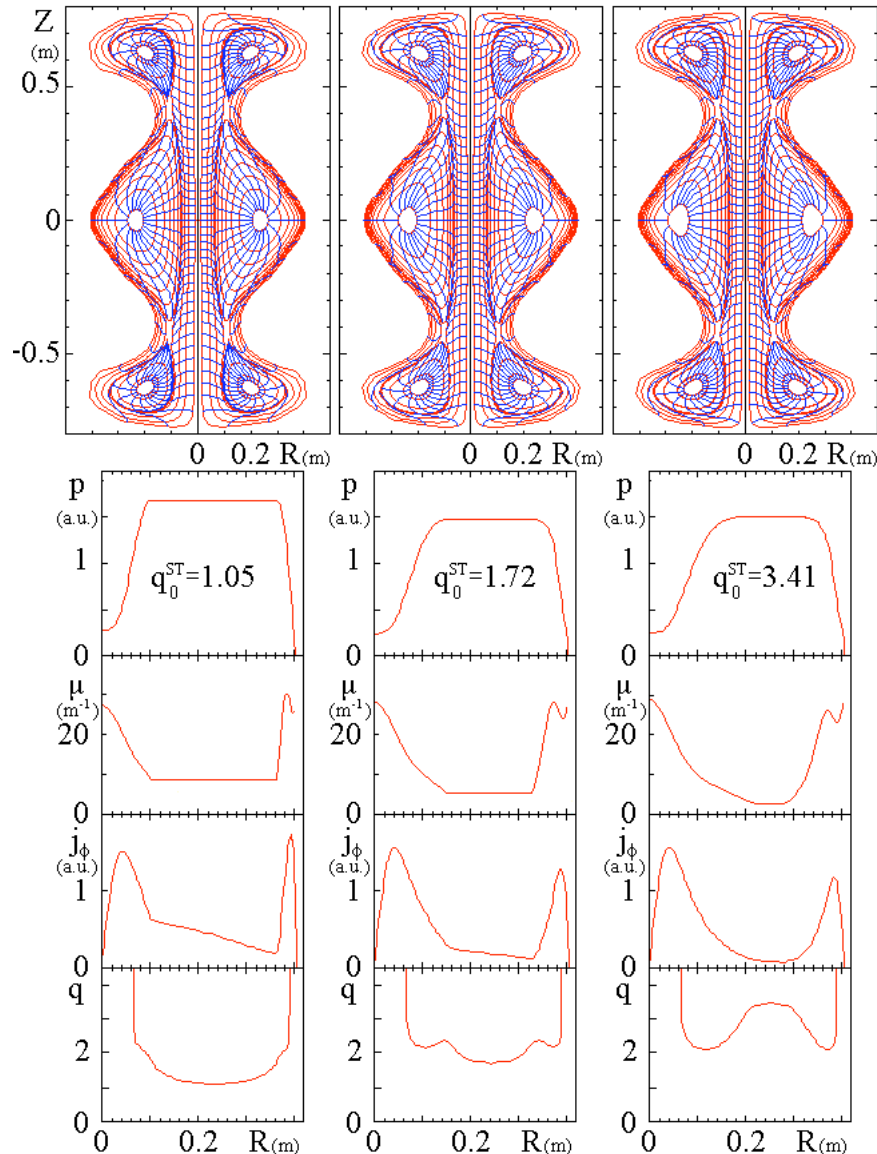
$$\Delta \tilde{\mu} = 14.066 \cdot (\mu_{\text{edge}} - \mu_{\text{axis}}) / \mu_{\text{edge}}$$

normalized jump of μ between edge of P and axis of ST
 given the value of I_{ST} / I_e
 determines q_0 at ST axis

MHD EQUILIBRIA of UNRELAXED CKF

Same edge shape $\Rightarrow$ same total toroidal current I_{CKF}

Boozer coordinates (ψ_T -toroidal flux, θ -poloidal angle, ϕ -toroidal angle; $\sqrt{g} \propto 1/B^2$) for $\beta=1$, $I_{ST}/I_e=3$



If current flow is sustained in surrounding discharge, magnetic helicity is injected into the ST (X-points), flowing down $\nabla \langle \mu \rangle$:

∇p is concentrated in same region

Equatorial profiles of:

$\Leftarrow$ pressure p

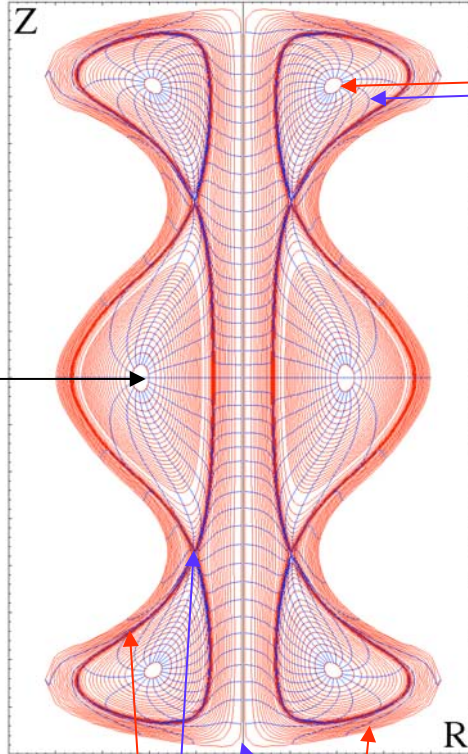
$\Leftarrow$ relaxation parameter μ

$\Leftarrow$ toroidal current density j_ϕ

$\Leftarrow$ ST winding number $q = 2\pi/\iota =$ inverse rotational transform of $\mathbf{B}$ lines of force

MAGNETIC COORDINATES of UNRELAXED CKF

From equilibrium (CKF)



in Boozer coordinates* (ψ_T, θ)

*non orthogonal with $\sqrt{g} \propto 1/B^2$

$$\begin{cases} \psi = \psi_{max} & \text{-poloidal flux} \\ \psi_T = 0 & \text{-toroidal flux} \end{cases}$$

Ideal MHD stability influenced by:
plasma pressure: $p(\psi_T)$
& field lines rotational transform:
 $\iota(\psi_T) = -(d\psi/d\psi_T)/2\pi$

Embedded magnetic separatrix:

$$(\psi = \psi_{max}) \quad \psi_T = \psi_T^X$$

$\vec{\nabla}\theta$ diverges near regular X-point
 θ angles converge on reg. X-point

Edge magnetic separatrix:

$$\psi_T = \psi_T^{\max} \quad (\psi = 0)$$

$\vec{\nabla}\theta$ vanishes near singular X-point
 θ angles don't converge on sing. X-point

Fit numerical ι by poloidal flux distance from separatrix ($\psi - \psi_X$)

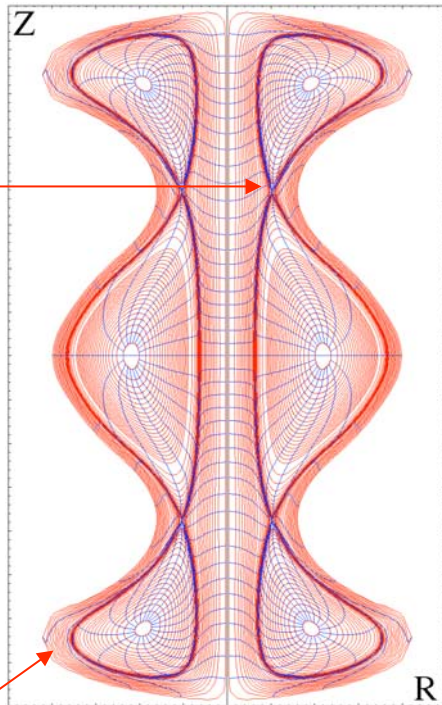
$$\iota^{SP}(\psi) \propto -\frac{1}{\ln|C_{SP}(\psi - \psi_X)|} \quad \iota^{ST}(\psi) \propto -\frac{1}{\ln|C_{ST}(\psi - \psi_X)|}$$

DIVERGENCES OF METRIC COEFFICIENTS NEAR SEPARATRICES

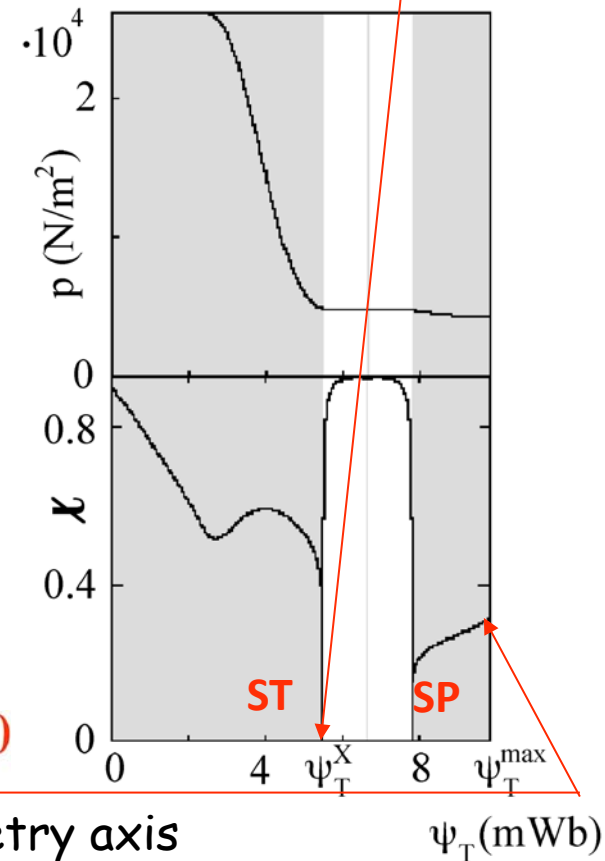
At embedded magnetic separatrix: $\psi_T = \psi_T^X$, logarithmically vanishing ι

- $\vec{\nabla}\psi_T$ vanishes at regular X-point but diverges far from it
- Integrated residual shear $\gamma_* = \vec{\nabla}\psi_T \cdot (\vec{\nabla}\theta - \iota \vec{\nabla}\phi) / |\vec{\nabla}\psi_T|^2$

$$\gamma_* \propto 1/|\vec{\nabla}\psi_T|^2$$



CKF equilibrium



Edge magnetic separatrix: $\psi_T = \psi_T^{\max}$, $\iota_{\text{symm}} \neq 0$

- $\vec{\nabla}\psi_T$ vanishes at singular X-point and symmetry axis
- $\gamma_*(\psi_T, \theta)$ diverges at singular X-points

IDEAL MHD STABILITY of UNRELAXED CKF

François Rogier
ONERA-Toulouse



Perturbed plasma displacement $\vec{\xi}$ for low toroidal number n

Fourier expanded in poloidal angle θ : $\vec{\xi} = \sum_{\ell} \vec{\xi}_{\ell}^{\{c\}}(\psi_T) \frac{\sin(m_{\ell}\theta - n\phi)}{\cos(m_{\ell}\theta - n\phi)}$

1D radial finite element method for normal mode equation:

$$\delta W_p(\vec{\xi}^*, \vec{\xi}) = \omega^2 \delta W_k(\vec{\xi}^*, \vec{\xi}) \quad W_p \text{ potential, } W_k \text{ kinetic energy}$$

REGULARITY of DISPLACEMENT at EMBEDDED MAGNETIC SEPARATRIX

- Normal component vanishes far from and near the regular X-point (except $n=0$)

$$\lim_{\substack{\psi_T \rightarrow \psi_T^X \\ |\theta - \theta_x| \rightarrow \pi/2}} \left| \vec{\xi} \cdot \frac{\vec{\nabla} \psi_T}{|\vec{\nabla} \psi_T|} \right| < O \left(\frac{\sqrt{|\psi_T^X - \psi_T|}}{|\ln |\psi_T^X - \psi_T||^{3/2}} \right)$$

$$\lim_{\substack{\psi_T \rightarrow \psi_T^X \\ \theta \rightarrow \theta_x}} \left| \vec{\xi} \cdot \frac{\vec{\nabla} \psi_T}{|\vec{\nabla} \psi_T|} \right| < O \left(\frac{1}{|\ln |\psi_T^X - \psi_T||} \right)$$

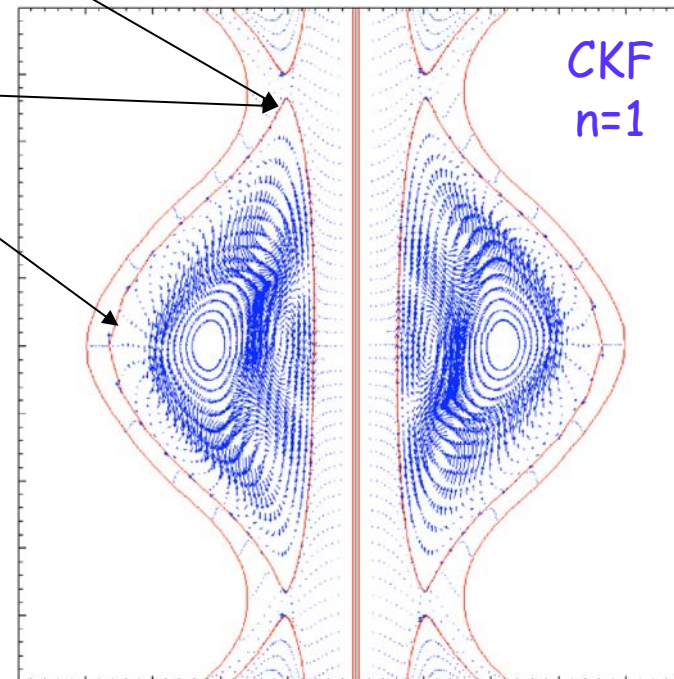
- Binormal component vanishes near but is regular far from the regular X-point

$$\lim_{\substack{\psi_T \rightarrow \psi_T^X \\ \theta \rightarrow \theta_x}} \left| \vec{\xi} \cdot \frac{\vec{B} \wedge \vec{\nabla} \psi_T}{|\vec{\nabla} \psi_T| B} \right| \leq O \left(\frac{1}{|\ln |\psi_T^X - \psi_T||} \right)$$

$$\lim_{\substack{\psi_T \rightarrow \psi_T^X \\ |\theta - \theta_x| \rightarrow \pi/2}} \left| \vec{\xi} \cdot \frac{\vec{B} \wedge \vec{\nabla} \psi_T}{|\vec{\nabla} \psi_T| B} \right| = O(1)$$

- Parallel component regular everywhere

$$\lim_{\psi_T \rightarrow \psi_T^X} \vec{\xi} \cdot (\vec{B}/B) \leq O(1)$$

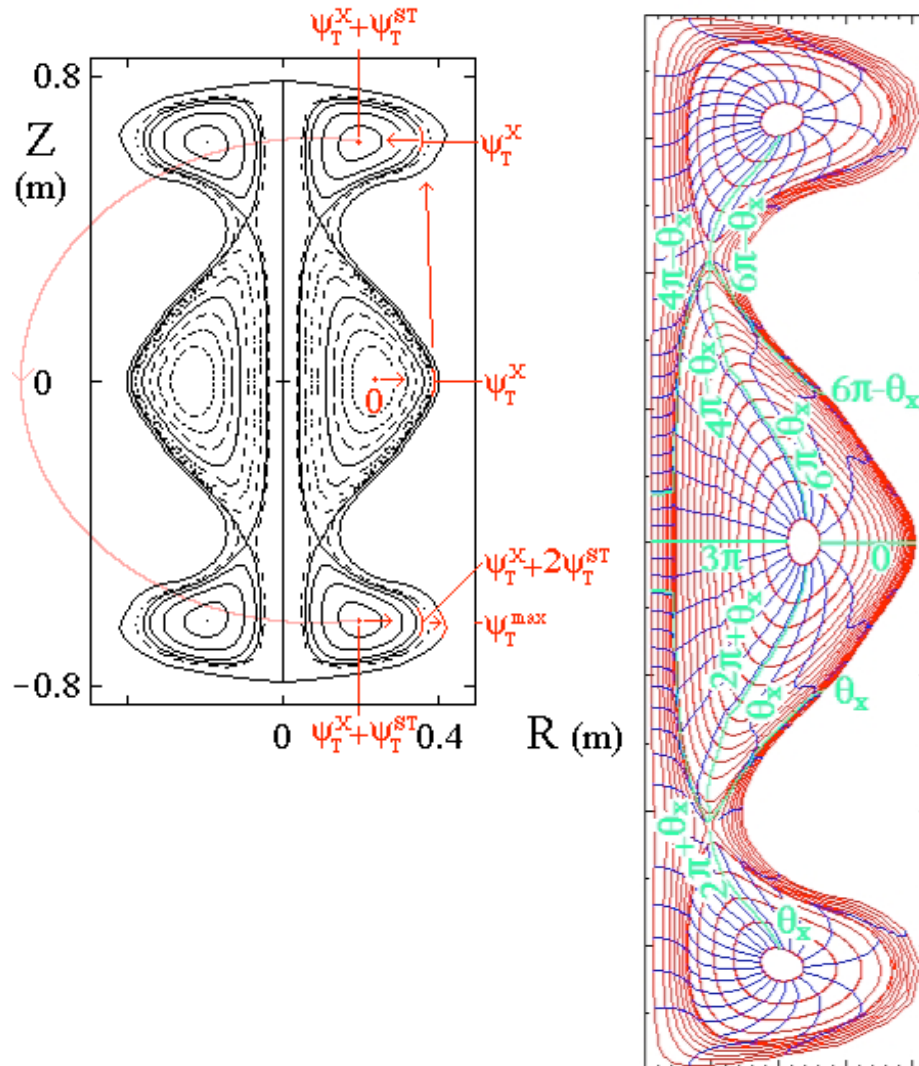


JOINING of PERTURBED DISPLACEMENTS at SEPARATRIX

Displacements: normal $\xi^\psi = \xi \cdot \nabla \psi_T$, binormal $\eta^\psi = \xi \cdot (\nabla \theta - \nabla \phi / q)$, tangential $v = -\sqrt{g} \xi \cdot \nabla \phi$

The code contains a number of innovative features:

- **!Ordering of ψ_T accounts for multiple magnetic axes**



Ideal MHD conditions at separatrix

Normal displacement: $\xi = \xi \cdot \nabla \psi_T / R^2$ continuous

Other jump: $\eta = \xi \cdot (\nabla \theta - \nabla \phi / q) / B$, $v = -\sqrt{g} \xi \cdot \nabla \phi$

Inside Tori:

$$\xi = \sum_{\ell} \xi_{\ell}(\psi_T) \sin(m_{\ell} \theta - n \phi)$$

$$\eta = \sum_{\ell} \eta_{\ell}(\psi_T) \cos(m_{\ell} \theta - n \phi),$$

$$v = \sum_{\ell} v_{\ell}(\psi_T) \cos(m_{\ell} \theta - n \phi)$$

Surrounding coupled mode:

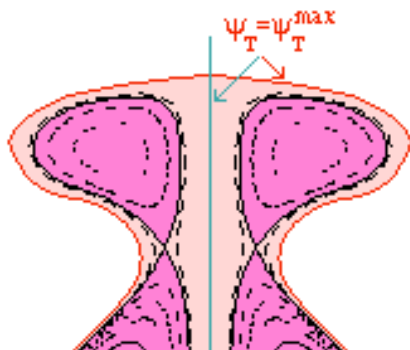
$$\xi = \sum_{\ell} \xi_{\ell}(\psi_T) \sin(m_{\ell} 3\theta - n \phi),$$

$$\eta = \sum_{\ell} \eta_{\ell}(\psi_T) \cos(m_{\ell} 3\theta - n \phi),$$

$$v = \sum_{\ell} v_{\ell}(\psi_T) \cos(m_{\ell} 3\theta - n \phi)$$

TREATMENT of VACUUM ENERGY TERM & of SYMMETRY AXIS

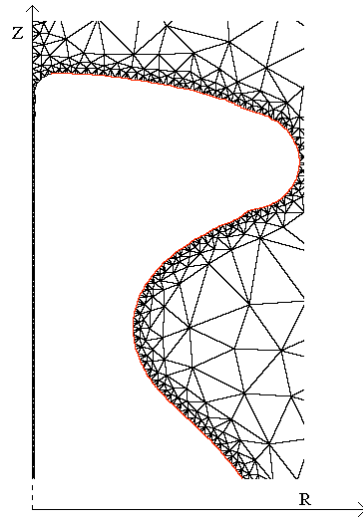
- ! Presence of plasma on the symmetry axis

$$\begin{array}{ll}
 R \neq 0: & \Rightarrow \bar{\nabla} \psi_T \neq 0 \\
 R = 0: & \lim_{R \rightarrow 0} \bar{\nabla} \psi_T = 0
 \end{array}$$


$$\begin{array}{ll}
 \xi^\psi(\psi_T^{max}, \theta, \phi) \neq 0 & \text{(fixed-boundary)} \\
 \xi^\psi(\psi_T^{max}, \theta, \phi) = 0 & \text{(W divergences)}
 \end{array}$$

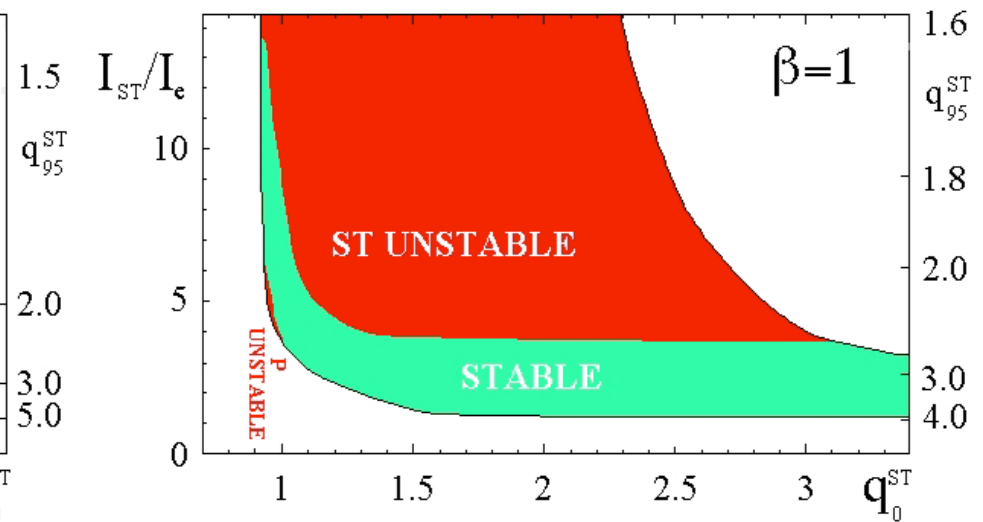
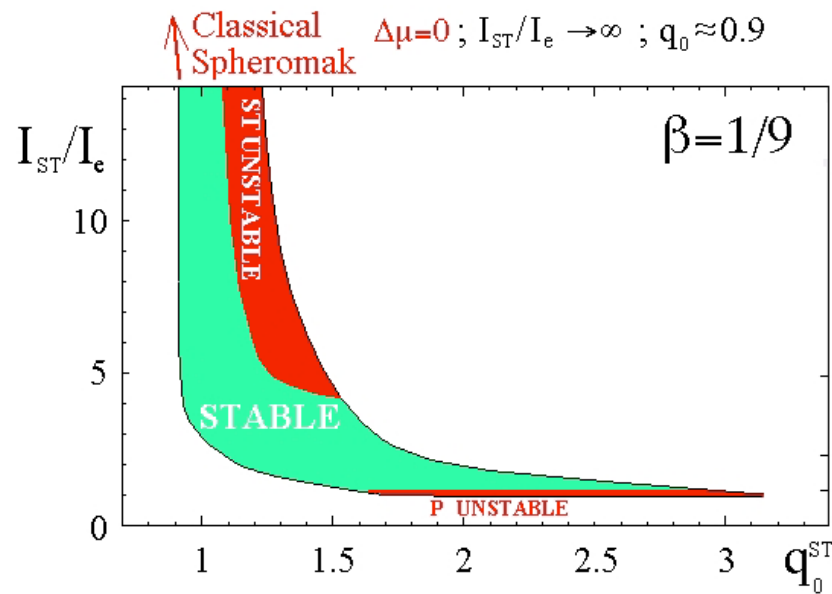
$\Rightarrow!$ New variables: $\xi = \xi \cdot \nabla \psi_T / R^2$, $\eta = \xi \cdot (\nabla \theta - \nabla \phi / q) / B$

- ! 2D finite element method for the vacuum energy



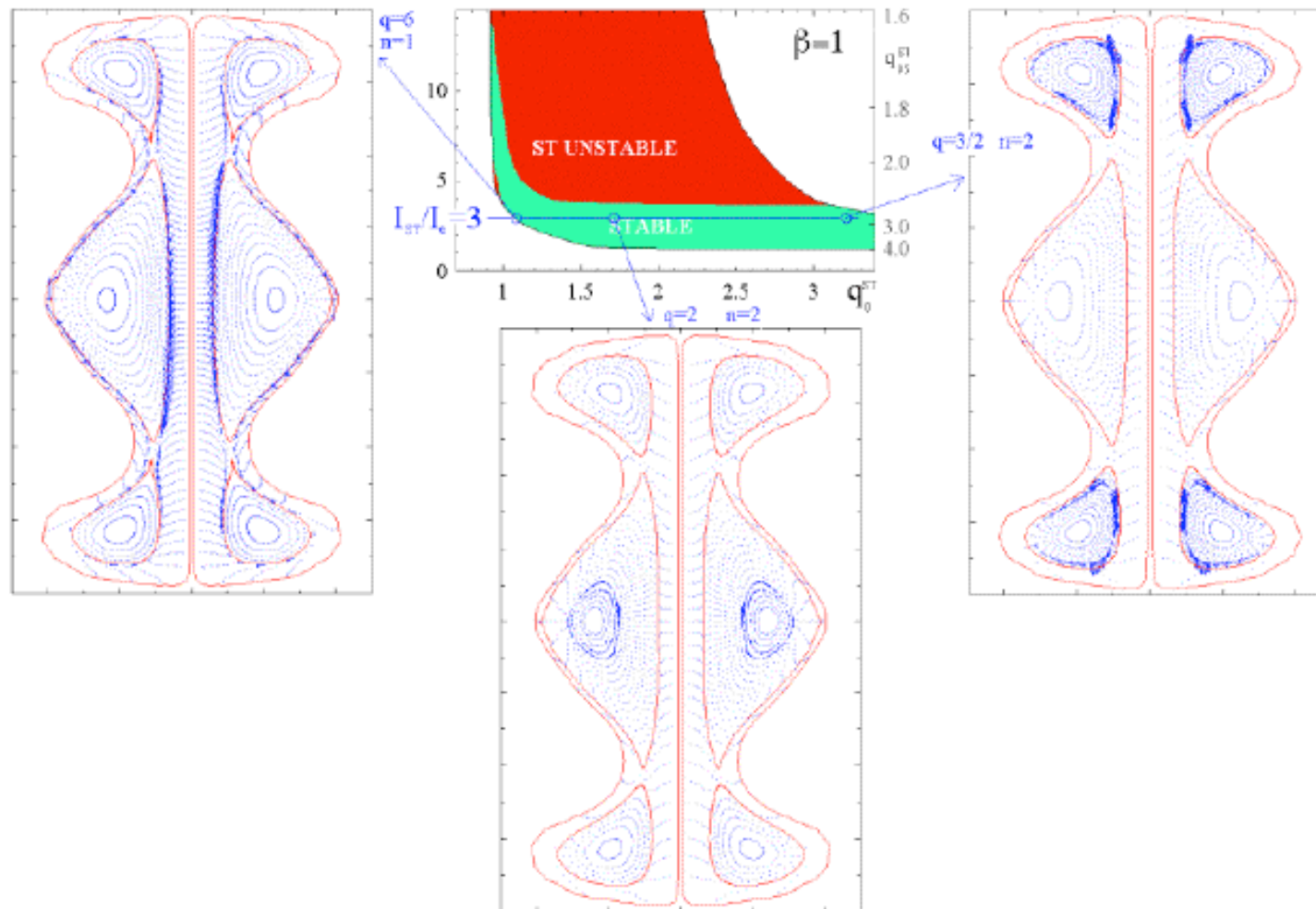
conducting shells of any shape

IDEAL MHD STABILITY RESULTS (wall at $R \rightarrow \infty$)

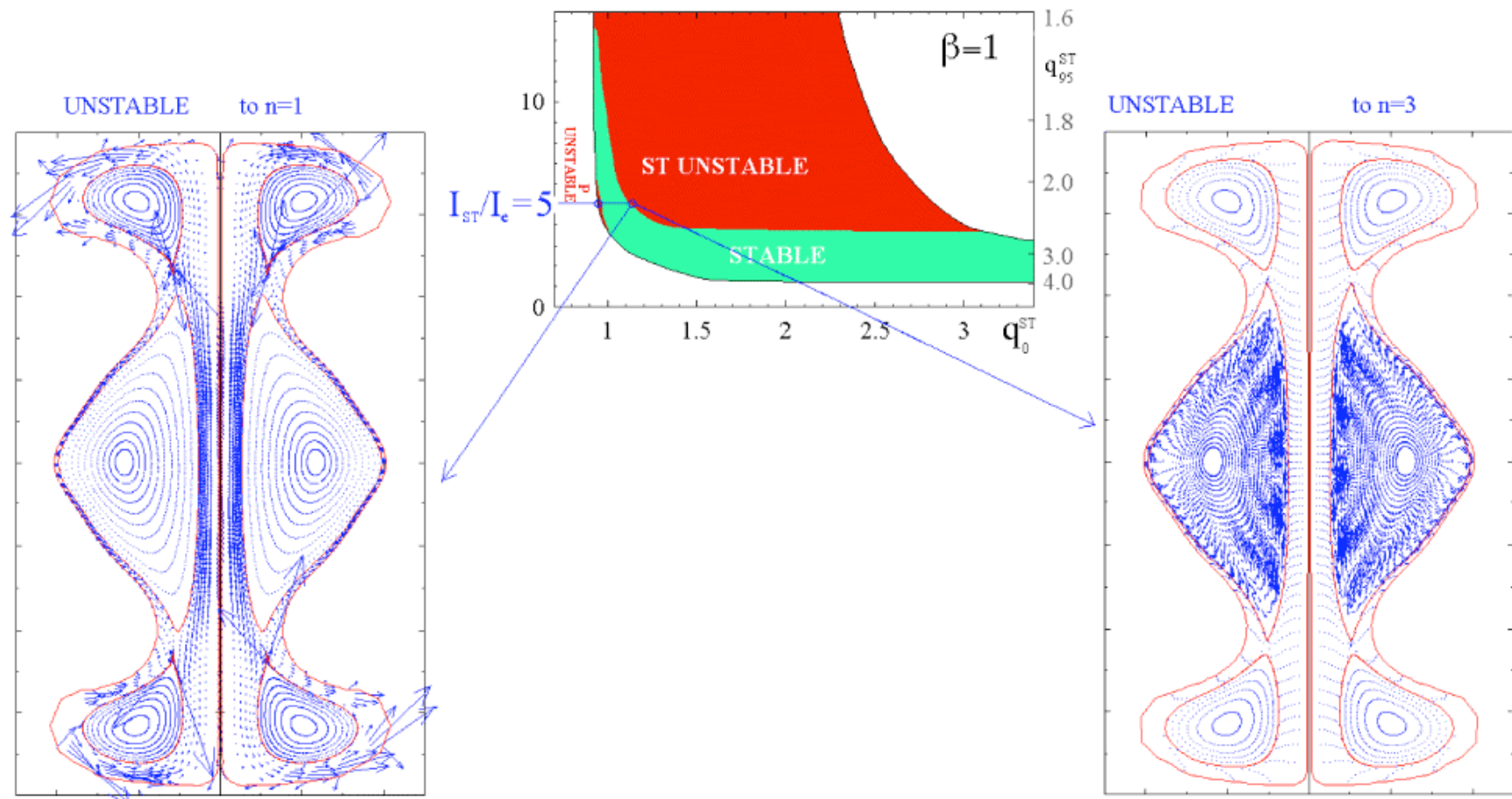


Stability in absence of any conducting shell around the plasma at $\beta=1$

ARROW PLOTS of STABLE OSCILLATION on integer- q , $\beta=1$, $I_{ST}/I_e=5$



ARROW PLOTS of GLOBAL UNSTABLE MODES at $\beta=1$, $I_{ST}/I_e=5$



Low q_0^{ST} : $\Uparrow$ surrounding plasma tilts

High q_0^{ST} : $\Uparrow$ unstable ST

ARROW PLOTS of UNSTABLE MODES LIMITED TO SURROUNDING PLASMA at $\beta=0$ & $1/3$, $I_{ST}/I_e=1$: too large ratio I_e/I_{ST}

