CONSORZIO RFX
Ricerca Formazione Innovazione

Surface coatings for arc prevention between plasma facing components

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8th International Workshop on Mechanisms of Vacuum Arcs

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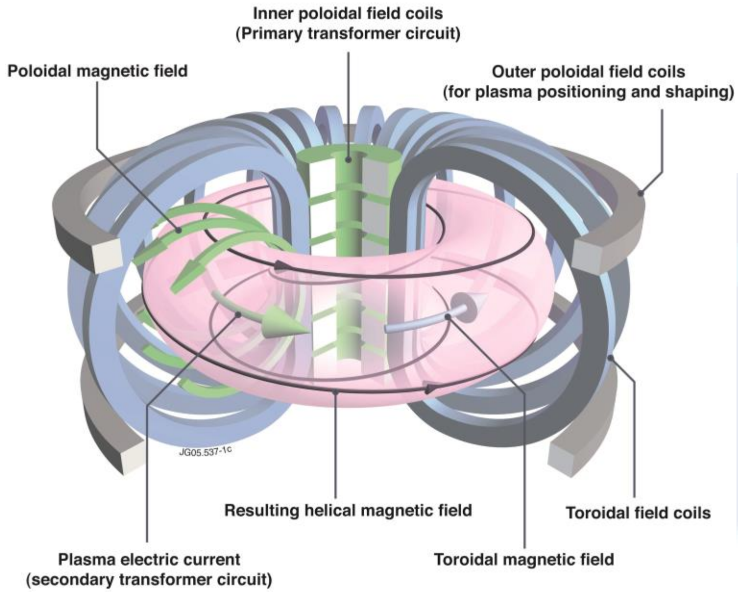
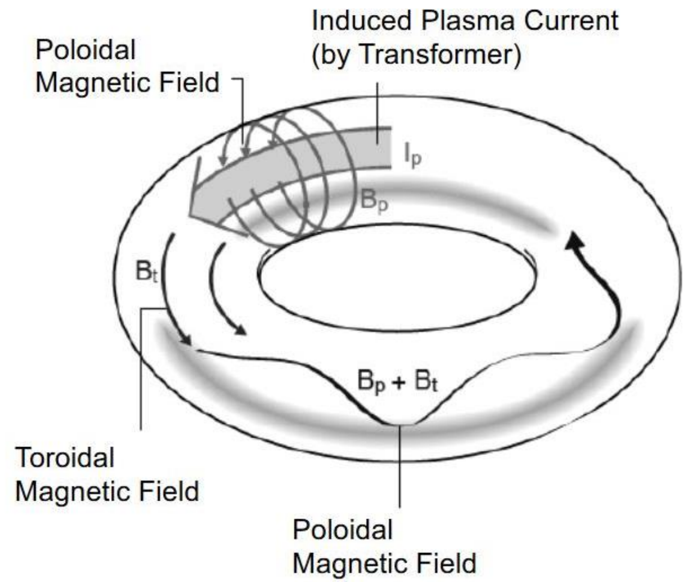
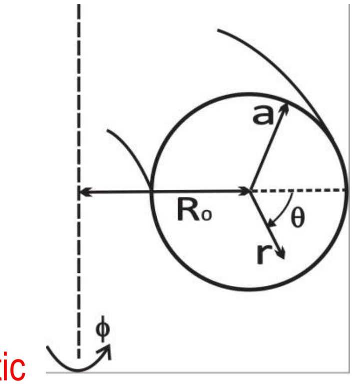
Fusion plasma magnetic confinement





Φ - toroidal direction
Θ - poloidal direction
r - radial direction
R_0 - major radius
a - minor radius



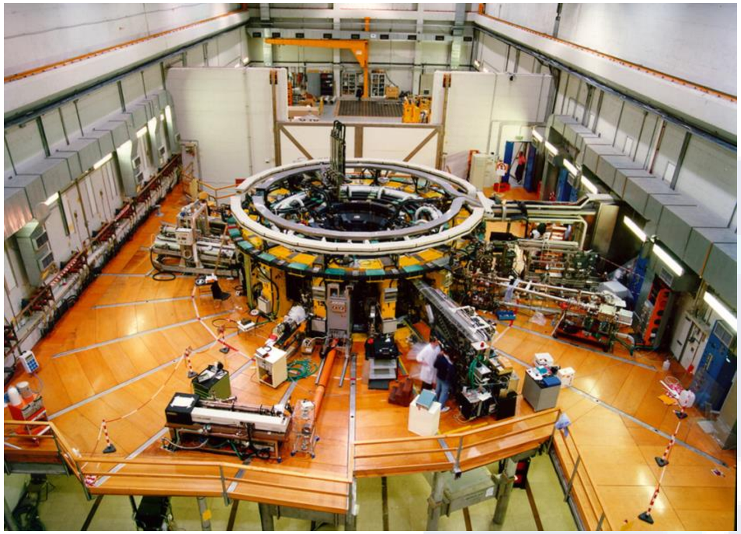
The combination of poloidal and toroidal field components results in a helical magnetic field, necessary for a stable confinement of the plasma in a toroidal configuration.

In Tokamak and Reversed Field Pinch (RFP) the poloidal magnetic field is mainly produced by a toroidal current (plasma current) flowing into the plasma itself

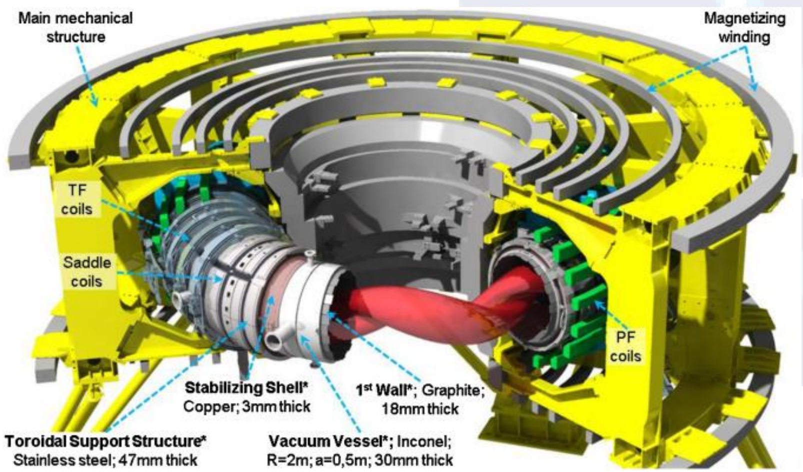
How is plasma current produced and sustained in tokamak and RFP?

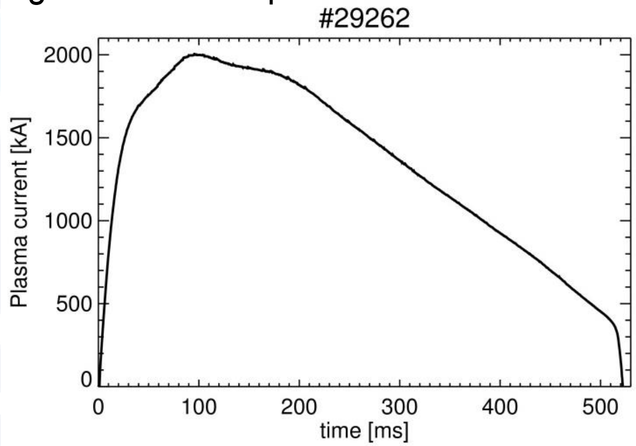
- a time-varying current in the central solenoid produces a flux variation that induces a toroidal current.
- the plasma constitutes the secondary circuit of a transformer, the primary coils representing the primary circuit.
- The current heats plasma by Ohmic heating

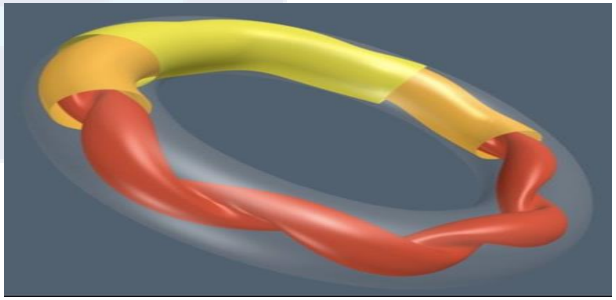
RFX-mod



- Magnetic confinement of fusion plasmas
- Largest Reversed Field Pinch (RFP)
- Other configurations accessible: Tokamak, Ulq
- R_0 = 2m; a = 0,459 m
- Plasma current up to 2 MA
- Advanced system for active control of MHD instabilities
- Self-organized helical plasma

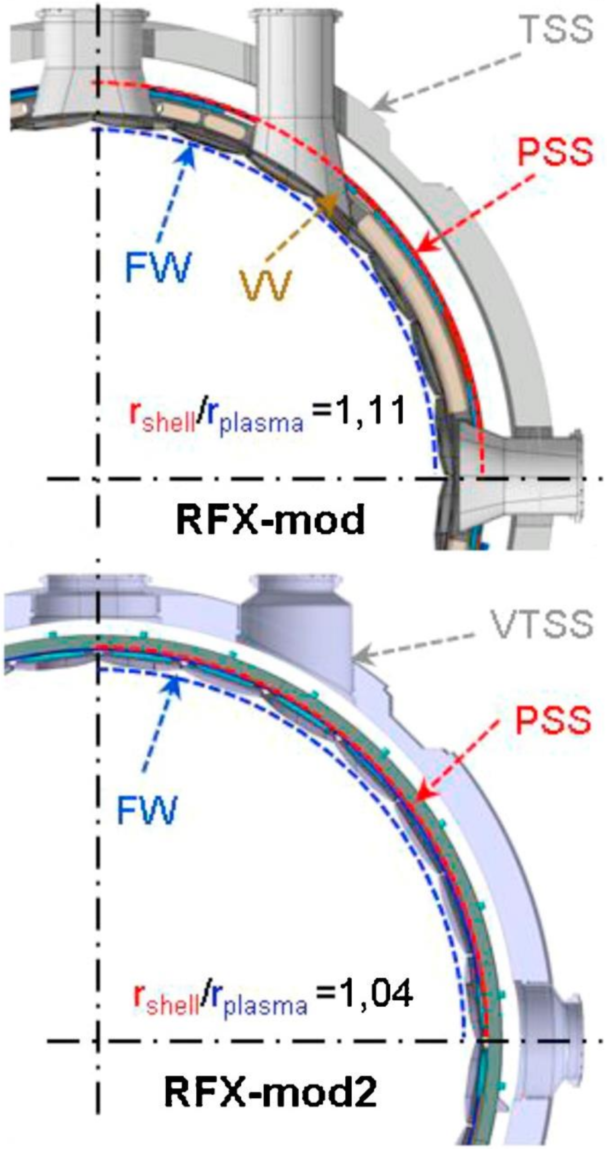






Lorenzini R. et al, Nature Physics 5, 570–574 (2009)

RFX-mod ⟶ RFX-mod2



- The upgrade of the RFX-mod device is presently under design
- The enhancement of the 'plasma-shell proximity' is required

Main changes of 'load assembly' will involve:

- **First Wall (FW)** - made of graphite tiles
  - withstand high thermal loads
- Vacuum Vessel (VV) - 30 mm thick Inconel
- Passive Stabilizing Shell (PSS) - 3 mm thick copper
  - passive control of magnetic instabilities
  - allows penetration of externally induced magnetic fields
- Toroidal Support Structure (TSS) - 47 mm stainless steel
  - mechanical support to the enclosed structures

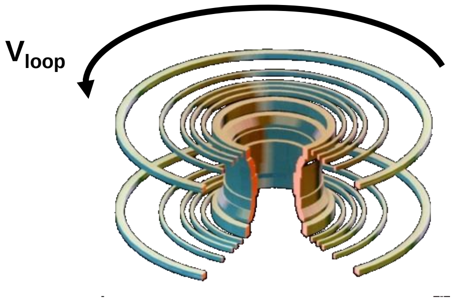
Main modifications:

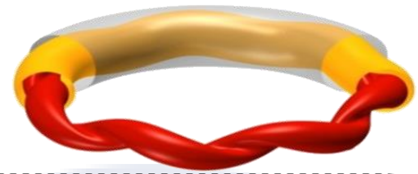
- Removal of the current Vacuum Vessel
- fastening of new first wall to the PSS
- Transfer of vacuum barrier at the TSS:

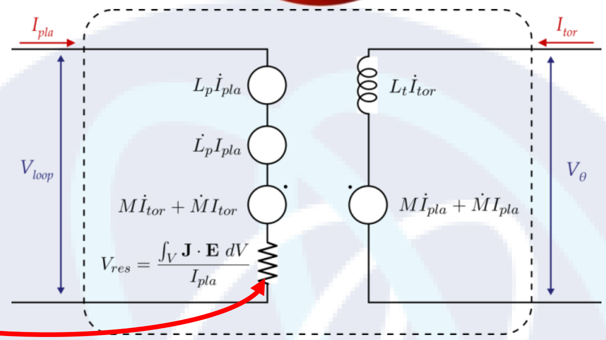
Vacuum Tight Support Structure (VTSS)

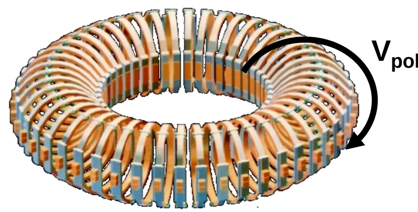
Peruzzo S. et al, Fusion Engineering and Design 123 (2017) 59-62

Simulation of RFX-mod fast termination



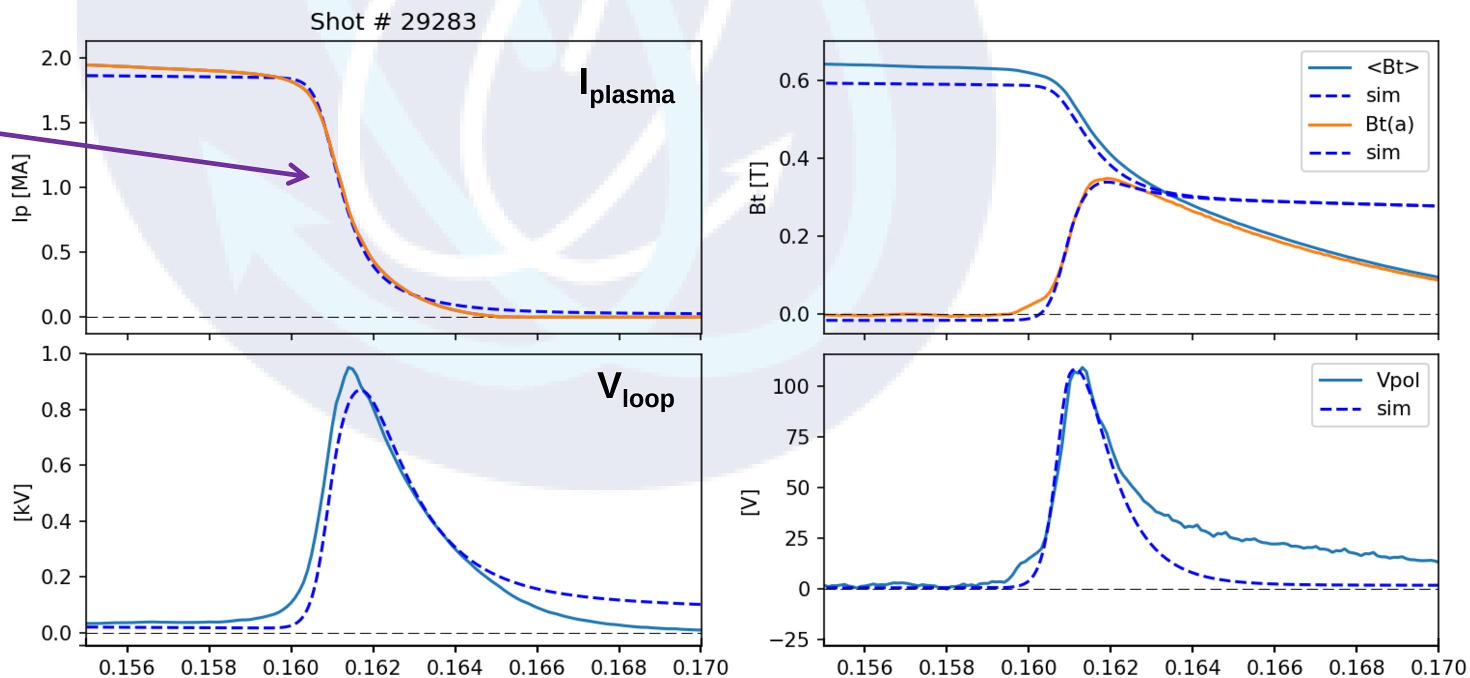




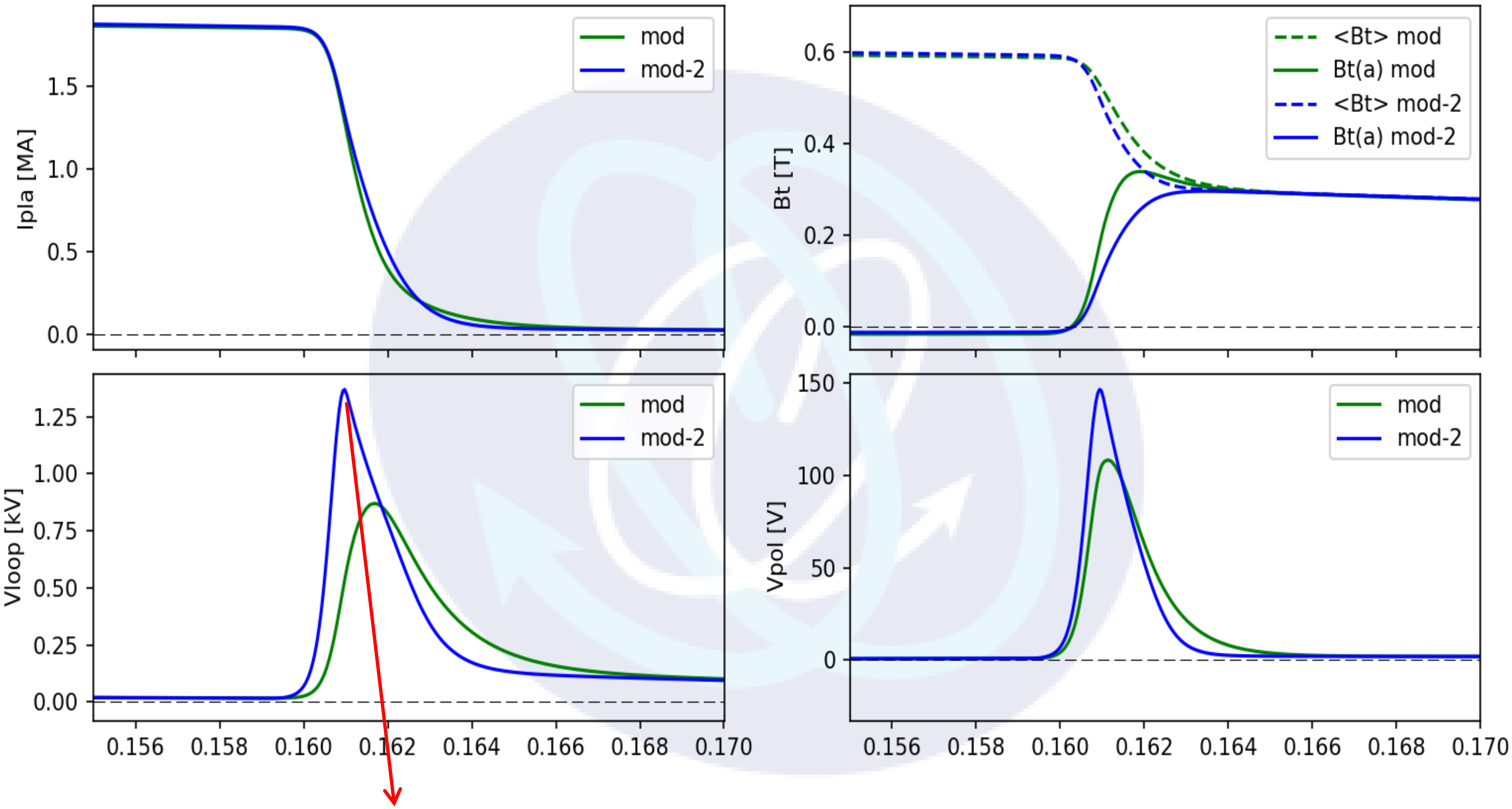


Rp: 15µΩ → 4 mΩ

Worst operating condition:
2MA current quench in ~ 3ms

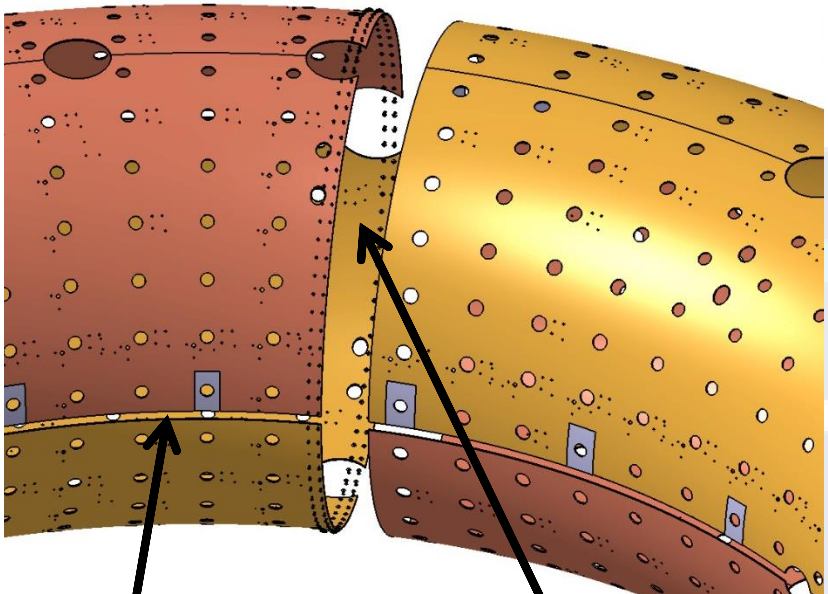


Simulation of RFX-mod2 fast termination

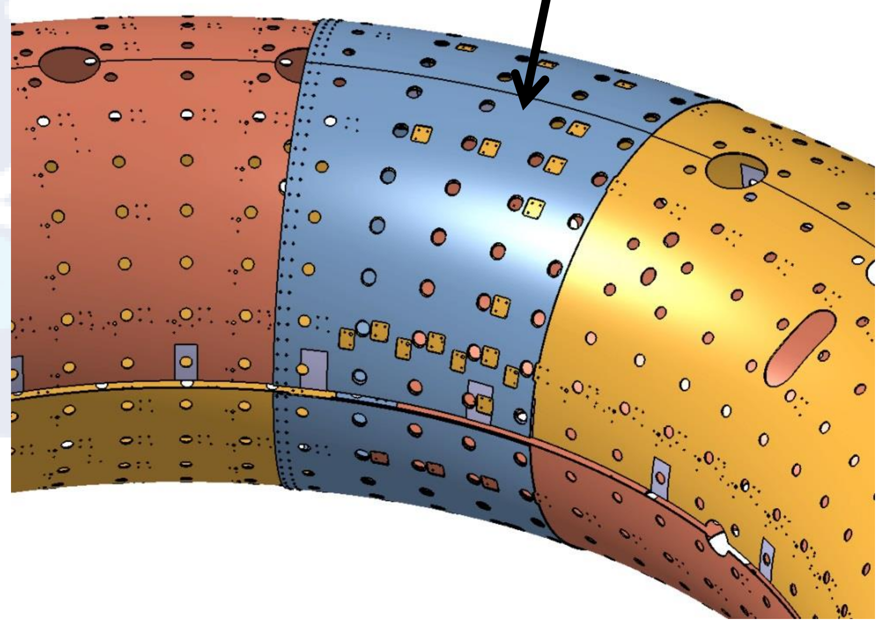


~ 1.5 kV toroidal loop voltage!

In-vacuum passive stabilizing shell design

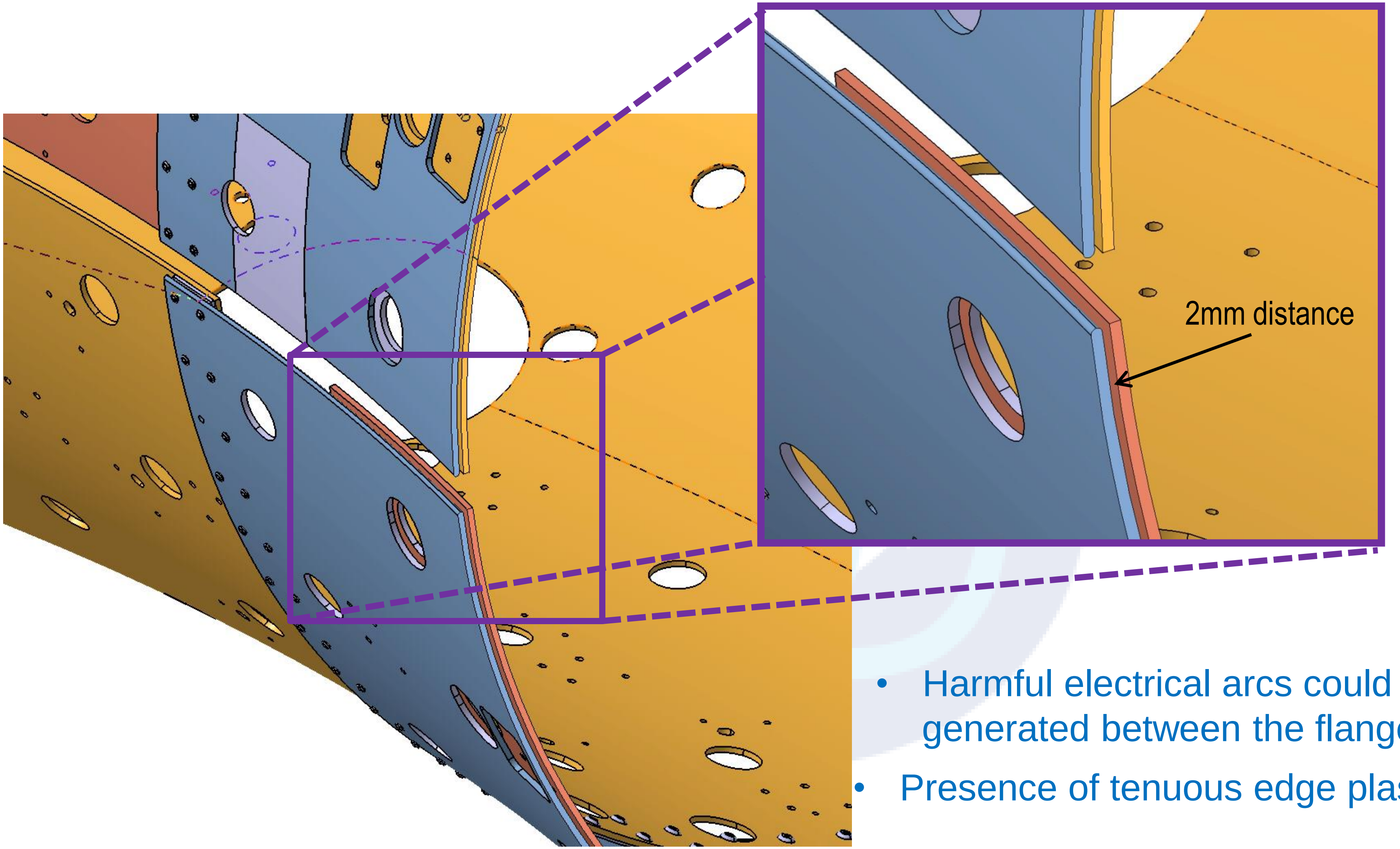


- 3 mm thick copper shell
- Two gaps (electrical discontinuity) to allow penetration of externally induced magnetic fields
- Gaps avoid loop currents in both directions



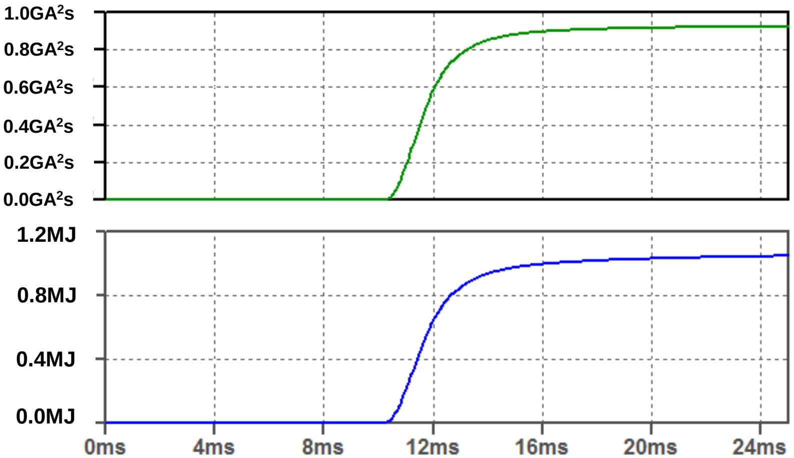
- An overlap spanning ~ 30° in toroidal direction is necessary to minimize magnetic error fields
  - 2 mm overlap distance

Shell design



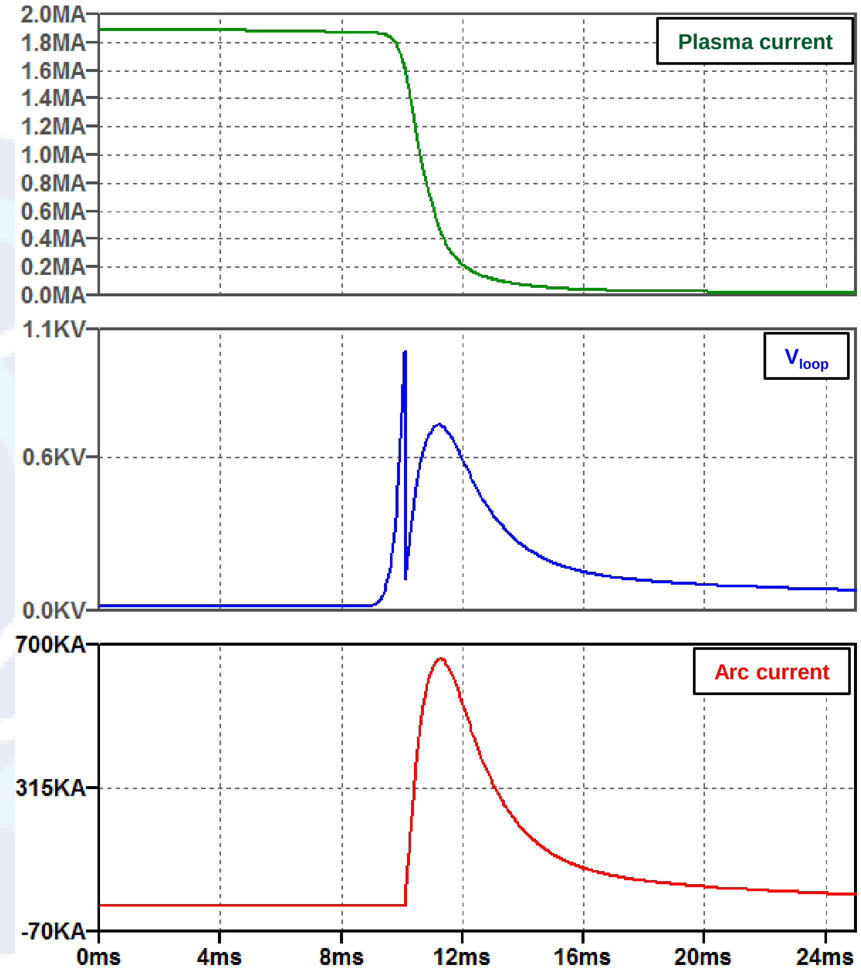
- Harmful electrical arcs could be generated between the flanges!
- Presence of tenuous edge plasma

Worst case: arching at the shell



$I^2t \approx 10^9\ A^2s$

$E \approx 1$ MJ



- ~ 1 MJ stored energy can be delivered to the arc in the worst scenario!
- 700kA current could circulate in the PSS
- A cage of supporting rings and steel plates is designed to withstand mechanical forces
- Protection necessary to avoid damage caused by large localized thermal loads

Arching at shell: possible solution

- Shell cover with insulating material
  - Arc formation prevention
  - Thin insulating material due to geometrical constraints
  - High vacuum compatible
  - Low Z impurities
  - Thermo-Mechanical constraints

+

- Multiple vertical gaps
  - Reduction of electric field at each gap
  - Reduction of simultaneous arcing probability
  - Geometrical constraints (diagnostic access, cables, mechanical structures,…)
  - Costs

Alumina coating

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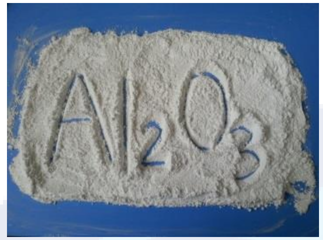
Aluminum Oxide Al_2O_3



- Ceramic
- High thermal conductivity
- Poor electrical conductivity
- Hard, wear-resistant
- Vacuum compatible

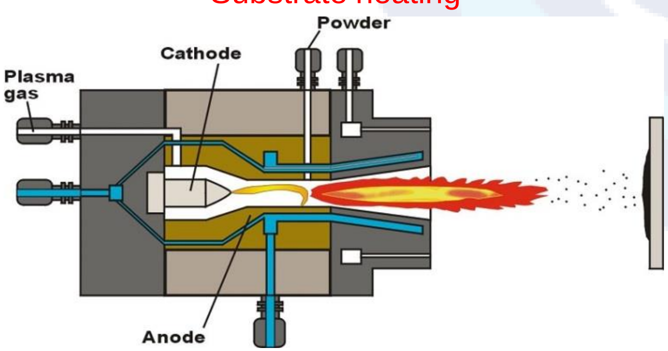
Coating Method:

Atmospheric Thermal Spraying

- Semi-molten or solid particles are deposited on substrate
- Spraying technique generates a 'stream' of such particles
- Coating is generated if particles can plastically deform at impact
- Several techniques, differing for:
  - Temperature
  - Deposition rate
  - Materials
  - Particle velocity
  - Bond strength
  - Coating treatment

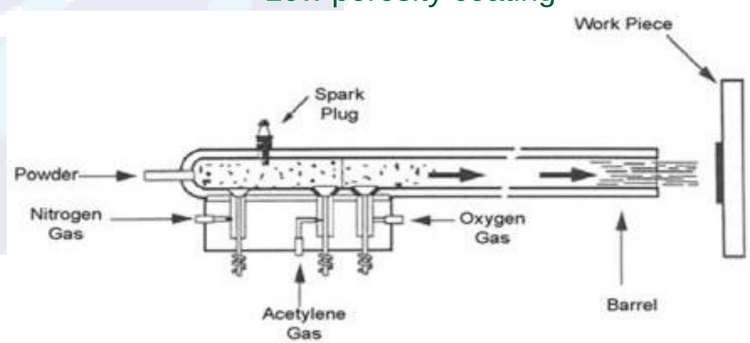
Plasma Spray

- Plasma expands in air, producing a jet
- Powder injected into the jet
- Particles are melted and accelerated in jet
- Particles impact the substrate and form coating
- Easy tool handling
- Continuous process
- Substrate heating



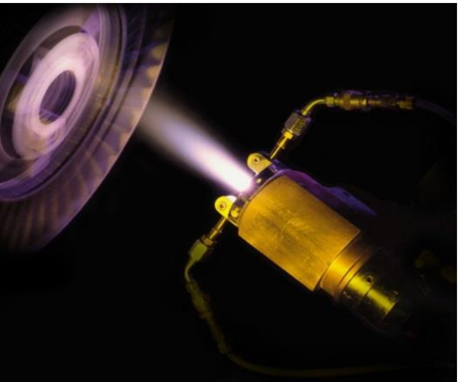
Detonation Gun Spray

- Powder injected into the barrel
- Oxygen and acetylene ignited by a spark
- Detonation wave accelerates the particles
- Particles impact the substrate and form coating
- Poor handling
- Discontinuous process (frequency up to 15 Hz)
- Low porosity coating



Insulation test: samples

- 3mm thick copper plates covered with alumina
- 100x30 mm^2
- 120x120 mm^2
- 100:150 μm alumina coating

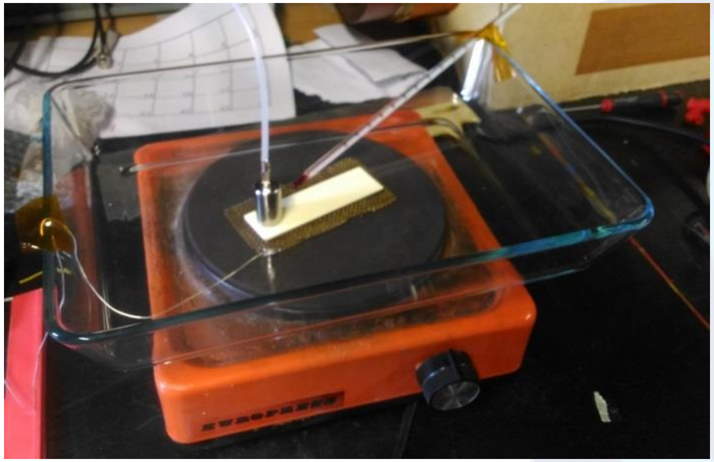


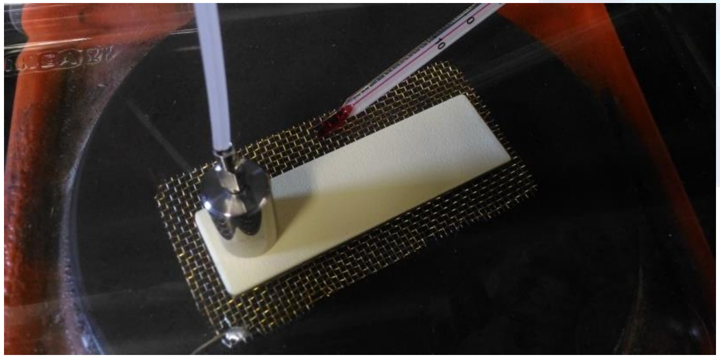
Tests to be performed:

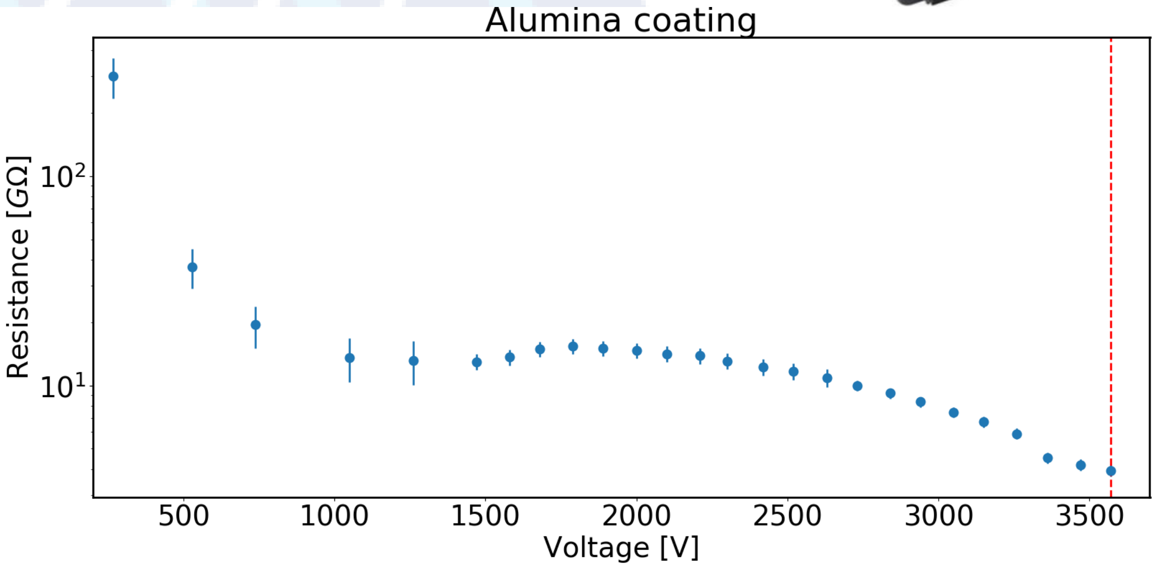
- Insulation tests in air
- Insulation tests in vacuum with a weakly ionized plasma
- Mechanical stress
- Thermal stress

Insulation test in air

- Insulation tests carried out in by means of Hioki High Voltage Insulation Tester IR3455
- Samples kept at temperature T> 75 °C to reduce humidity







- Electrical discharges identified V ≥ 3.5 kV

Insulation test: weakly ionized plasma

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- The presence of RFX-mod2 edge plasma ($n_e \approx 10^{16} \div 10^{18}$ m^{-3}, $T_e \approx$ few eV) can create the appropriate conditions for dangerous arc formation
- It is crucial to know what happens with pulsed voltages in the kV range in a weakly ionized plasma

Insulation test: weakly ionized plasma

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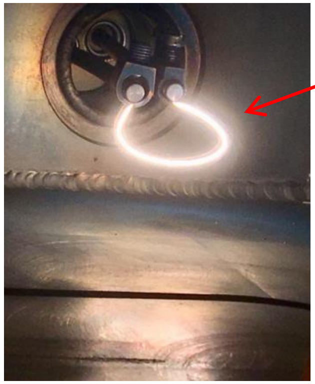
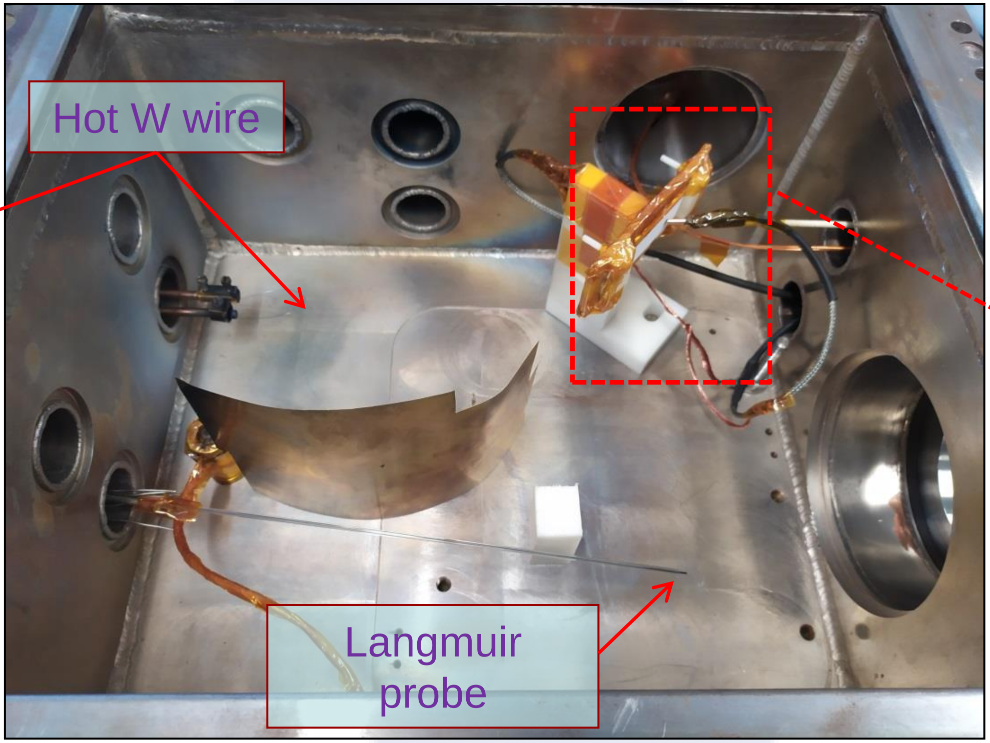
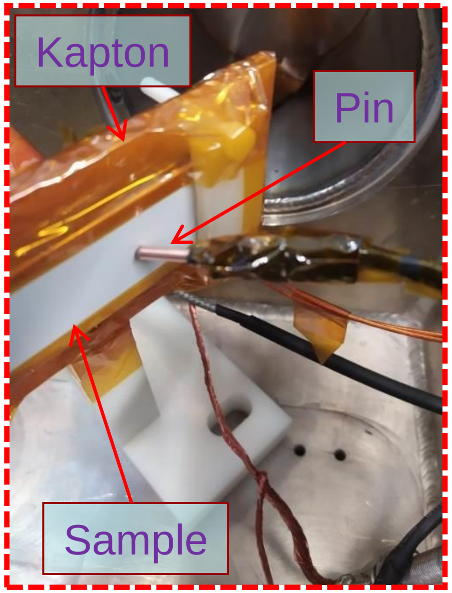
Experimental setup



- Weak plasma
- Helium
- $n_e \sim 10^{15}$ m-3

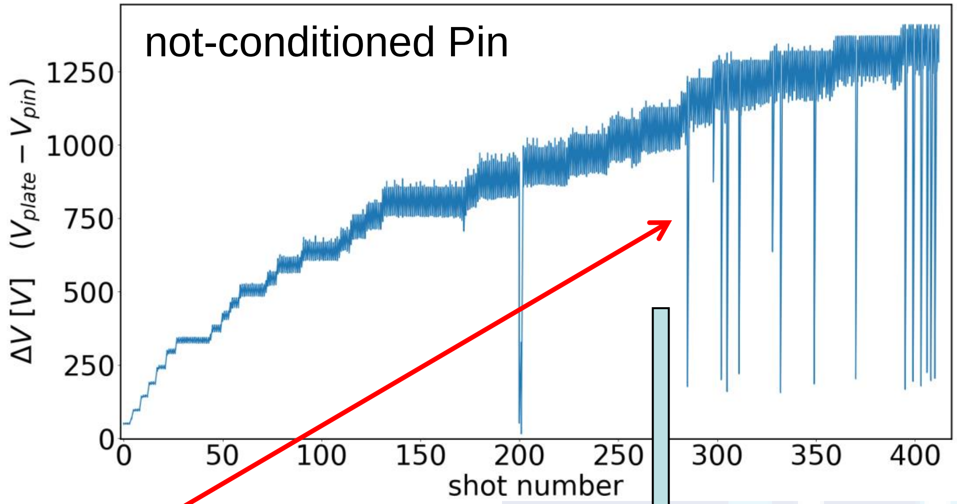


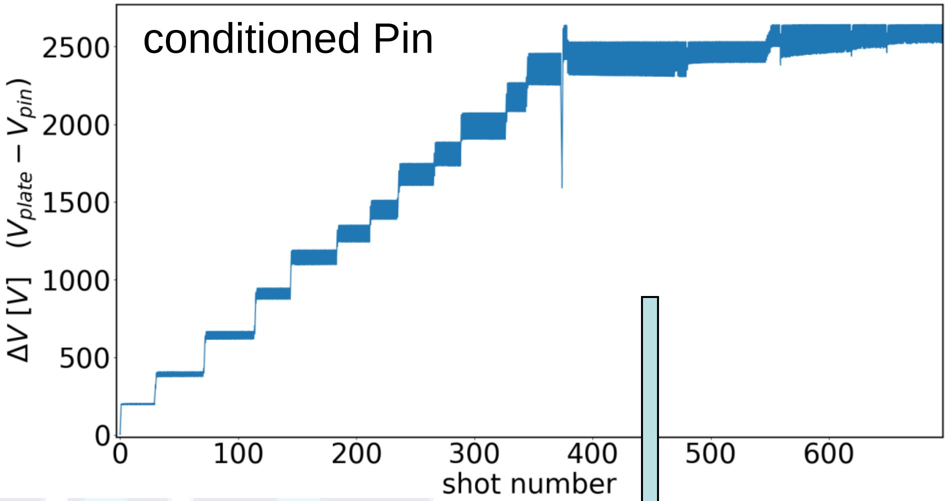
- Langmuir probe negatively biased to collect ion saturation current



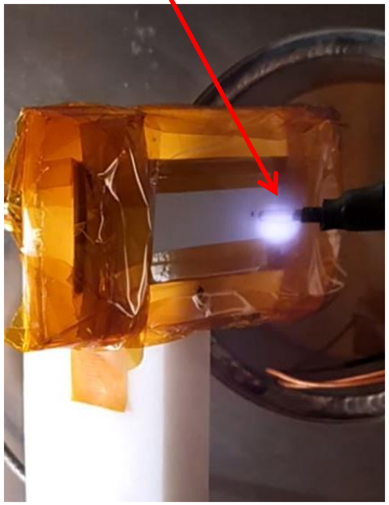
- Floating electrodes (sample and a copper pin)
- Biased by a small capacitor bank (0.3÷2 μF)
- Voltage pulses 200 ms long
- 1Hz repetion rate
- Sample-pin distance in range 0 - 4 mm

Insulation test: weakly ionized plasma





Arcs



- Arcs observed at pin
- No dielectric breaking

- No arcs observed
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- Voltage pulses up to 2.7 kV

Insulation test: weakly ionized plasma

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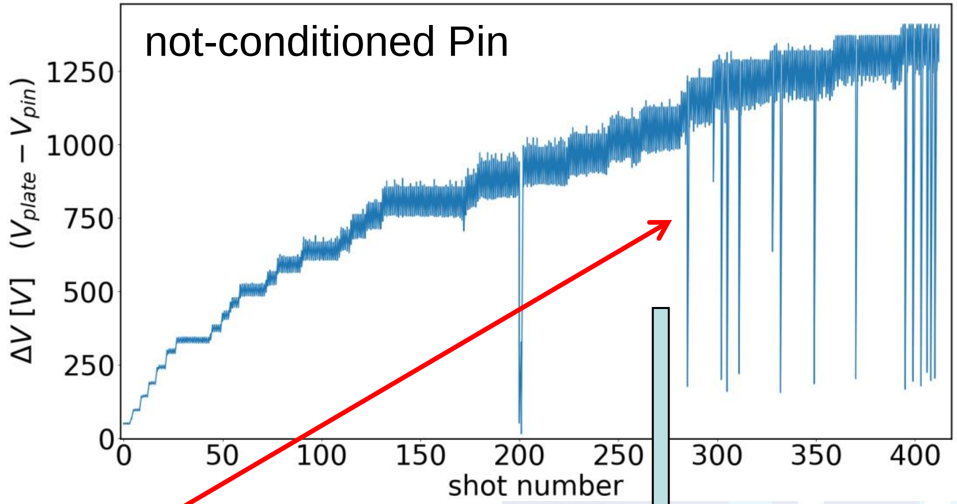

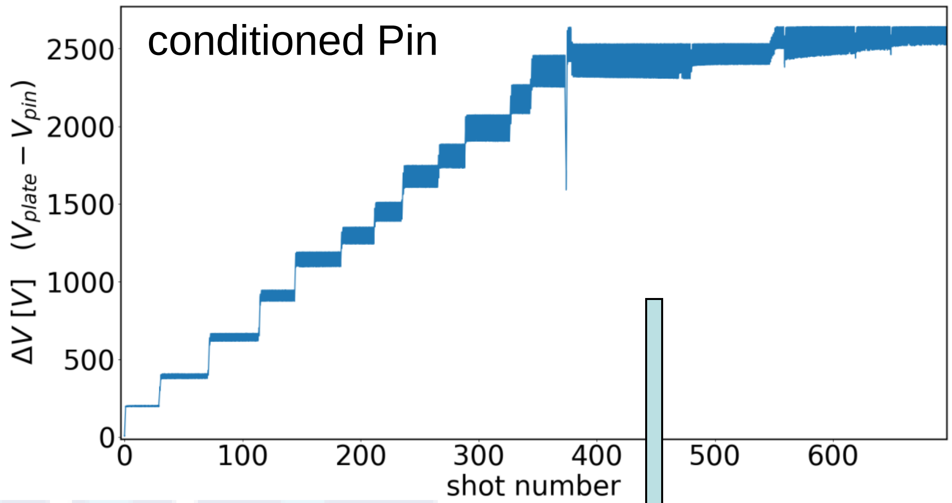

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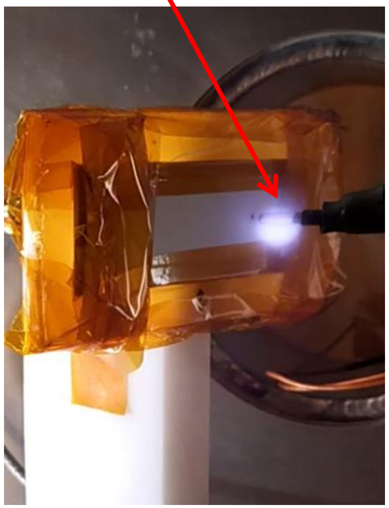

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OBSERVATIONS

- In-chamber n_e (~ 10^{15} m^{-3}) << edge RFX-mod2 n_e (~ $10^{16} \div 10^{18}$ m^{-3})
- Careful coverage of the plate bare copper is required (to avoid electrical arcs even at low voltage)
- Electrical conditioning of conductive structures faced to plasma is necessary

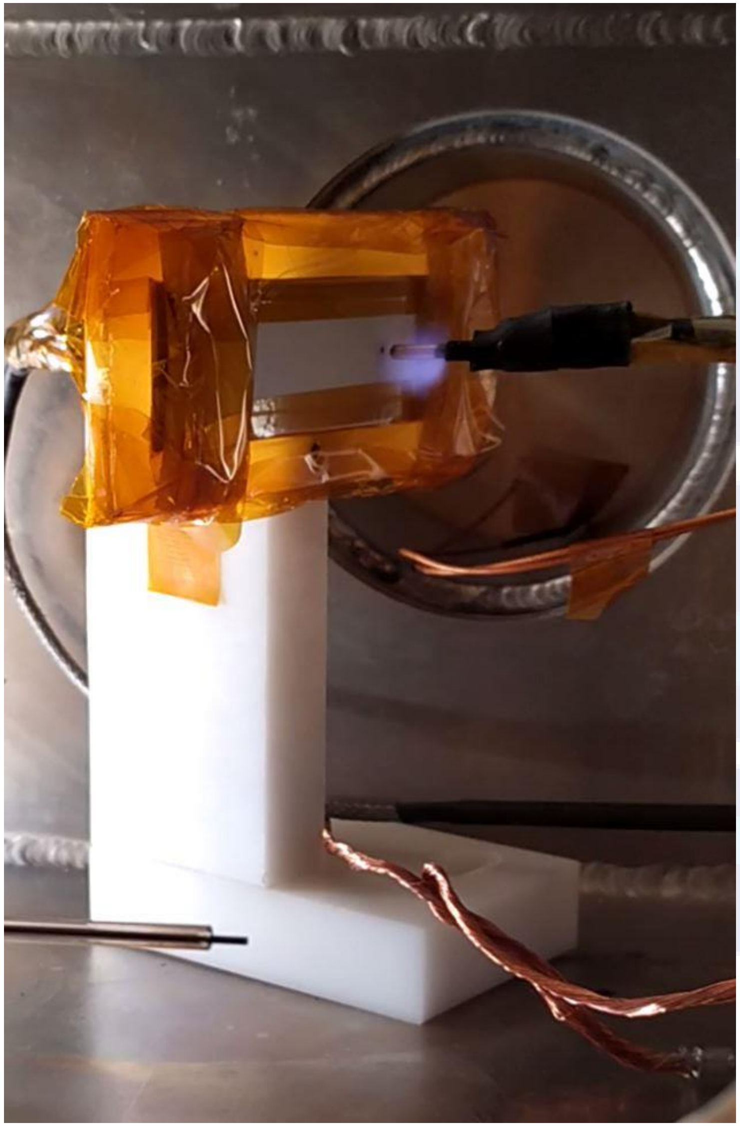
→ R. Cavazzana, Electrode conditioning for prevention of DC arc formation in presence of cold plasma background, Poster session

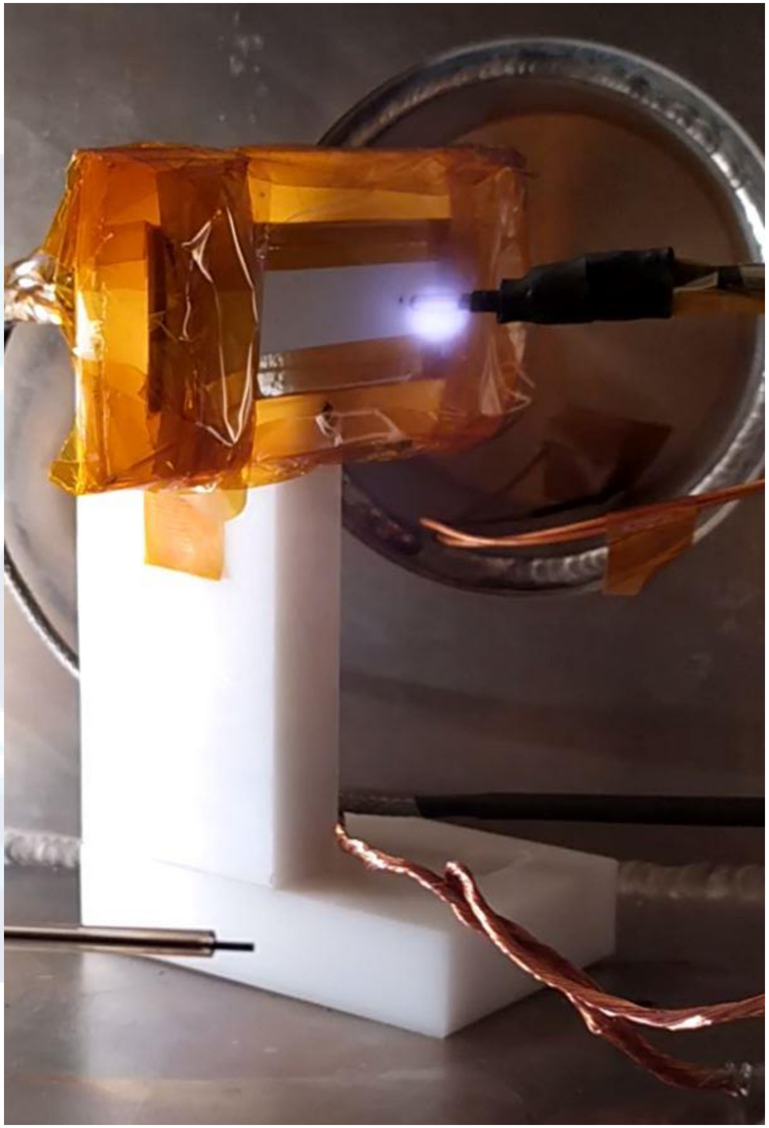
Conclusions

- The upgrade of the RFX-mod device is under design
- In the case of rapid terminations, damaging electric arcs could occur on the passive stabilization shell
- The presence of tenuous plasma can create the appropriate conditions for dangerous arc formation even at relatively low voltage
- The feasibility of coating material such as alumina is being evaluated
- First positive insulation tests performed
- D-Gun coating is going to be evaluated
- Thermo-mechanical stress tests are going to be performed

Spare slide

Spare slide





Capacitor bank discharge