Status of the Proto-Sphera Load Assembly

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Talk Outline

1) PROTO-SPHERA: (Experiment)³
2) PROTO-SPHERA Engineering Design and Analysis
3) Anode & Cathode Concept
4) Timetable
5) Conclusions
Results of the PROTO-SPHERA Panel held in Frascati on March 2002

Interesting Concept Exploration Experiment, adequate size & useful contribution to magnetic fusion programs.

• ....

• Are the PROTO-PINCH electrode experiments a sufficient technical basis for a reliable electrode operation in PROTO-SPHERA?

YES, BUT… are not yet adequate for reliable multi-electrode operation...
START -> 3D Modelling -> Real 3D

Start Arrival
May 2004

ProtoSphera Panel
March 2002: OK

Project & Design
Anode & Cathode
Construction
2004-2008

Coils: June 2005/Dec. 2007
A way to build a complex Experiment

- More conventional items:
  - 3D CATIA Modelling (ENEA)
  - Exec.Design, Building & Assembly (ASG Superconductors)

- Less conventional items:
  - Cathode, Filaments, Molybdenum Modules
  - Anode, W-Cu interfaces to the arc

(All designed and supplied by ENEA)
Main Breakdown features

- **Screw pinch (SP) formed by a hot cathode breakdown**
- **Filling pressure** $p_H \sim 10^{-3} \div 10^{-2}$ mbar
- **Cathode filaments heated to** 2700 °C
- **$V_c \sim 100$ V applied on the anode**
- **Electrode arc current limited to** $I_e \sim 10$ kA
Design Philosophy

- Simplicity, symmetry, conservatism.
- Viewing capability and good access to electrodes.
- All connections to PF coils from top and bottom flanges, external to the Machine.
- Bellows in coil feedthroughs for adjustment.
- Operation and disruption (but no fault) conditions considered.
Design Aims

- Easy handling, Reliability, Repairability of Machine.
- Reliability of electrodes and avoidance of arc anchoring.
- Minimise Technological Risks: provide appropriate electrical insulation, avoid local coil overheating (>100°C) due to hot anode and cathode (12MJ, 2700°C).
- Minimise electromagnetic stresses (Filaments).
- Accurate insulation study to avoid arc anchoring & flexibility to realize future Helicity Injection.
Operating conditions

Temperature 20°C

Vacuum < 1\times 10^{-7} \text{ mbar}

(predicted outgassing rate: \sim 3 \times 10^{-5} \text{ mbar} \cdot \text{l/s})

Baking

80-90°C

Adequate for water removal, coil protection; compatible to Viton O-rings

Possibility of N_2 1 mbar contact gas
## Machine Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical Torus (ST) diameter</td>
<td>0.7 m</td>
</tr>
<tr>
<td>Longitudinal Screw Pinch current</td>
<td>Phase I&amp;II 10kA, III 60 kA</td>
</tr>
<tr>
<td>Toroidal ST current</td>
<td>120÷240 kA</td>
</tr>
<tr>
<td>Plasma pulse duration</td>
<td>1 s</td>
</tr>
<tr>
<td>Minimum time between two pulses</td>
<td>5 min.</td>
</tr>
<tr>
<td>Maximum heat loads on first wall components in divertor region</td>
<td>2 MW/m², for 1 ms</td>
</tr>
<tr>
<td>Maximum current density on the plasma-electrode interface</td>
<td>1 MA/m²</td>
</tr>
</tbody>
</table>
Load Assembly 4-Groups

- Easy Accessibility
Proto-Sphera
Phase I & II & III

Phase I: Axial Anode

Phase II: Radial Anode

Phase III: Shaping Coils & PSU
Puffed Anode Design Capability:
ProtoPinch\textsubscript{Tested} = 30 MW/m\textsuperscript{2} ProtoSphera\textsubscript{Max} = 30 MW/m\textsuperscript{2}
Anode

- $P_{W_{\text{Anode}}} = 2/3 \times (670 \ 120) \text{ KW} \rightarrow 56 \text{ KW (module)}$
- $A_{\text{surface}} = 1.8 \times 10^{-3} \text{ m}^2$
- $D_{pw} = P_w / A_{\text{surface}} \rightarrow 30 \text{ MW/m}^2$
- anode arc anchoring with Cathode DC heated (a)
- No Anode anchoring with AC cathode heating (b)

- No Damages after 1000 discharge
- Material W 90% Cu10%.
- Scheme: Puffed Hollow Anode

PROTO-SPHERA Workshop - Frascati, 18-
ANODE PHASE 2 - ASSEMBLY

- ELECTRICAL CONDUCTORS
- Cu
- WCu
- WATER

Associazione Euratom-ENEA sulla Fusione Frascati, 8 February 2010
Anode Phase II Assembled
CATHODE - CROSS SECTION

- Cu
- Mo
- W

WATER COOLED PROTECTION PLATES
Multi-Pinch Cathode

• Limited number of cathode filaments (54 vs. 378)

• Coils will drive a total limited current (10 kA vs. 60 kA)
  Each coil will be capable of delivering the design current (150 A).
HeliConical Coil

- Null Field
- Optimize Temperature Distribution
- Optimize Weight Distribution
- $I_e = 167 \text{ A}$ (each coil)

- Wire (1 Out 4)
- Conical Wire Terminal & Clamp
- Tantalum Column
- Alumina Insulator

- Molybdenum Plates
- $T \approx 2600 \degree C$
- $\text{Emis} = 6.7 \text{ A/cm}^2$
- Ground $I = 150 \text{ A}$
- $D_{\text{wire}} = 0.2 \text{ cm}$
- $L_{\text{wire}} = 37 \text{ cm}$
- Zero Field
- Double Winding
- $D_{\text{coil}}^{\text{max}} = 1.4 \text{ cm}$
- AC Power $V = 14.5 \text{ V}$
MultiPinch Coils Delivery: June/2007

EURATOM, ENEA & ASG Personnell
SECTION OF PF2
ProtoSphera Timetable

I. Delivery of Load Assembly * December 2009
II. Power Supplies International Tender Action * March 2010
III. Delivery of Power Supplies * June 2011
IV. Site Preparation * February 2010
V. Services (Vacuum, Electricity, Diagnostics) * June 2010
VI. Commissioning * September 2011
VII. ProtoSphera Fase I Start * September 2011
CONCLUSIONS

• The ProtoSphera Phase I&II design & construction has been properly done.

• There are medium/good probability to be able to avoid Filamente low lifetime & arc anchoring.

• There is high degree of confidence that the formation and the stability of the PROTO-SPHERA initial arc will be achieved.

• First Plasma can be obtained in September 2011.

• PROTO-SPHERA Phase III can be obtained by simply adding PF coils to current configuration.

• Finally, the LoadAssembly was a heavy task but ..
Load Assembly Heavy but Happy End

- Help to share load:
  HeartlyWelcomed

- Subscription list:
  Opened
**Structural Analysis**

- Max VonMises Stress 0.16 Kg/mm²
- Max Displacement 42.9 μm
- Coil Safety Factor = 5.3

*W - Bending Proof Strength vs Temperature*
Electromagnetic Forces and Stresses

\[ B = 50 \text{T/s} \quad B = 500 \text{G} \quad t \leq 1 \text{ ms} \]

Subdivision of Cu and 304LN plates to achieve \( \leq 100 \text{ MPa} \) of eddy current stresses.

Unaccounted skin effects (\( t \sim 1 \text{ms} \)) significant. Conservative prediction of eddy current effects.

Electromagnetic forces in the coils (\( \sim x10 \text{ weight} \)) require to be sustained.
Predicted and Permitted Stresses

**ASME III - NB 3221 Stainless Steel**

Allowable $S_m$ for 304LN $100^\circ$C : 200MPa [304L $S_m$~150MPa]

Predicted e-m stresses : 320MPa

Thermal local stresses : 320 MPa (2 MW/m$^2$ ,1s)

- Criterion 1 : $100 < 200 \times 1.5$
- Criterion 2 : $100 + 320 < 200 \times 3$

**Copper**

Minimum required allowable at $100^\circ$C> 70 MPa (100MPa<70x1.5)

Thus $\sigma_y > 115$ Mpa and $\sigma_u > 230$ MPa at 20$^\circ$C i.e. Cu hardened
Thermal and Heat transfer Behaviour

• **Solution:**

1. Use of Cu components to collect or reflect the heat away from coils. Conservative (but symmetrical) design for the anode. Thermal mass of these components results in operational temperature $< 100^\circ C$. Water cooled! Optimum design; i.e. one circuit/component, $D \sim 10-15\text{mm}$, $v \sim 2\text{m/s}$, duty cycle 5min.

2. Use of thermocouples in no water cooled components to avoid $>100^\circ C$ with frequent pulses; every 5min.

3. Use of 10mm divertor AISI 304LN plates. $2\text{ MW/m}^2$ for 1 s gives $\Delta T \sim 120^\circ C$, $\sigma_{\text{th}} \sim 320\text{MPa}$

4. Use of optical diagnostics to view the electrodes which are relatively easily accessible.
Protection Components

- **Thermal and Heat Transfer Behaviour**

  **Philosophy:** collect the heat (via radiation) from the electrodes to black resilient componenet and then conduct or radiate it away in a controlled way. Hot spots are thus avoided.
  (Will be done in ProtoSphera with black copper oxidization)

  **Danger:** the hot cathode (less the anode) radiates at 2750°C with ~3.5MW/m² and even a 10mm thick coil casing cannot sustain this power density for more than 0.5s without exceeding 100°C