Development of an H^- plasma generator for SPL

Formation of H^- ions

SPL is foreseen to operate with an ion source producing **up to 80mA of H^-.**

However, **high brightness H^- beams** are **difficult to achieve** and require a sophisticated ion source !

Possibilities for H^- formation:

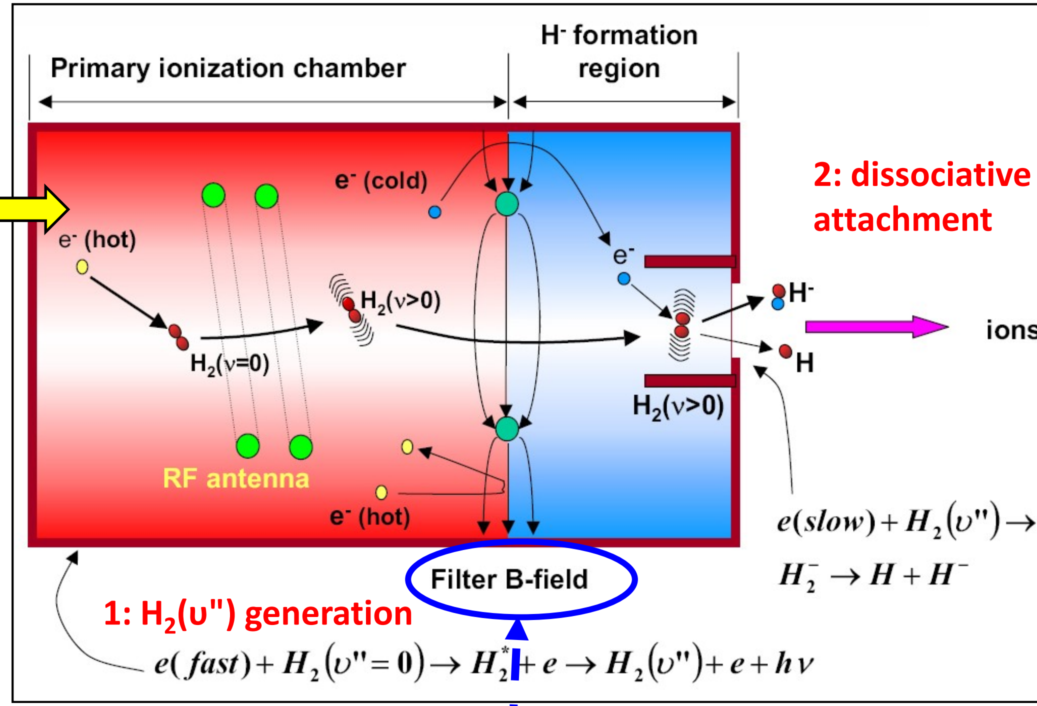
- **Volume production:**
  dissociation of a vibrationally excited H_2 molecule by a slow e^-:

  $H_2(\upsilon''=0) + e^-(fast) \rightarrow H_2(\upsilon''\geq 5) + e^- + h\nu$
  $H_2(\upsilon''\geq 5) + e^-(slow) \rightarrow H + H^-$

- **Surface production:**
  H^- formation by wall collisions of H and H^+:

  $H + e^-(wall) \rightarrow H^-$
  $H^+ + 2e^-(wall) \rightarrow H^-$

  requires surface with low work function (typically Cs-on-metal)



fast e^- cannot migrate into the extraction region

H^- destruction rate: ↓

I_{H-}: ↑

The Linac4 source

Linac4 source = **copy of the DESY-HERA H^- source:**

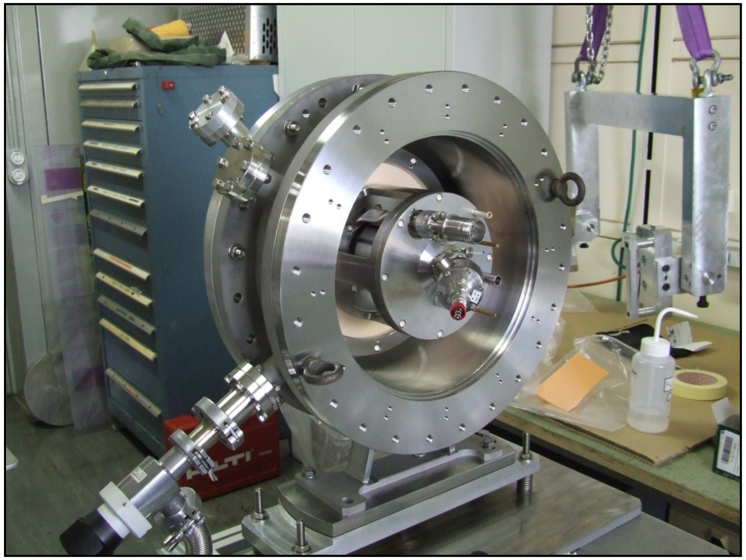
- Volume source
  → **no Cs required**

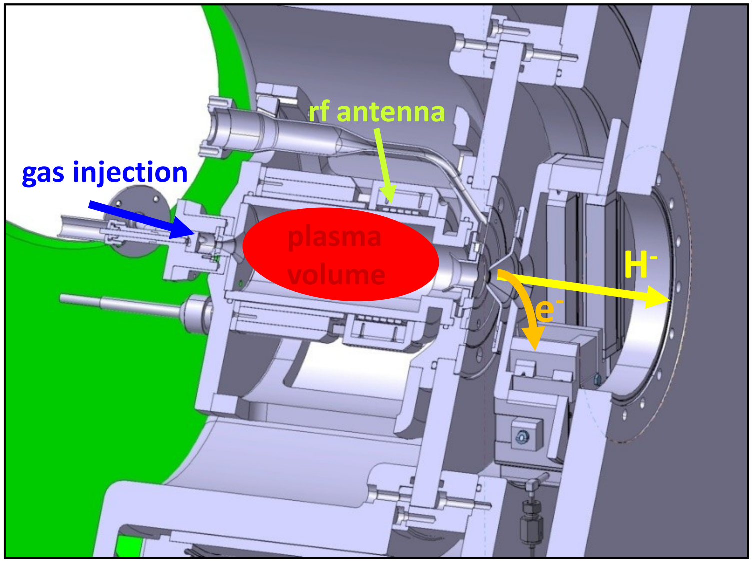
- Plasma heating by an rf discharge with external 2MHz antenna
  → **minimum of downtime**

- **rf coupling** with the plasma **improved by ferrites** surrounding the rf antenna

- co-extracted electrons removed from beam by **magnetic spectrometer**

- I_{H-} typically **≈ 40 mA** measured at DESY
  (Linac4 requirement: 80mA)





Why a new plasma generator for SPL ?

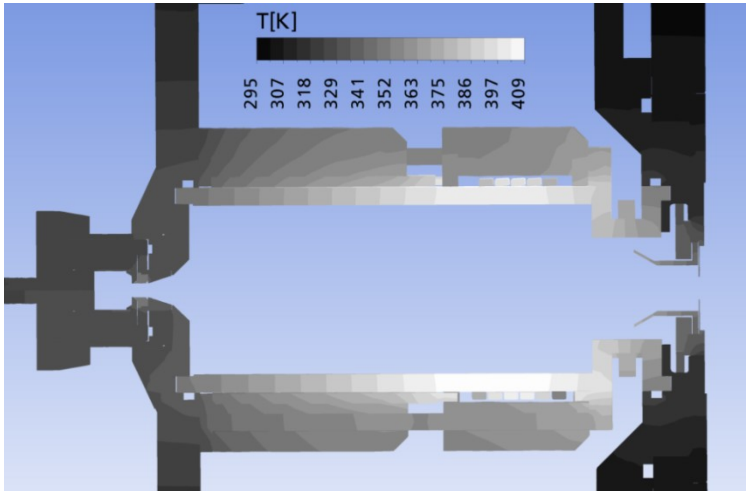
nominal operation parameters: DESY, Linac4 & SPL

	DESY	Linac4	LP-SPL	HP-SPL
I_{H^-}	40	80	80	40-80
ε_n [π mm·mrad]	0.25	0.25	0.25	0.25
$q_{RF,peak}$ [kW]	30	100	100	100
f [Hz]	3	2	2	50
Pulse length [ms]	0.15	0.4	0.9	0.4 – 0.8
Duty factor [%]	0.045	0.08	0.18	2 – 4
$q_{RF,avg}$ [W]	**13.5**	**80**	**180**	**2k-4k**

6x

150-300x

Linac4 source temperature distribution, P_{avg} = 80W



→ Linac4 magnet cage, magnets & ferrites reach **limit of operation at P_{avg} = 80W**

→ Further extrapolation shows **failure of all source components at P_{avg} = 2kW**

→ Development of a new plasma generator necessary

SPL Plasma Generator

In view of these results, it was aimed to develop a new plasma generator for SPL **(sLHC 7.1).**

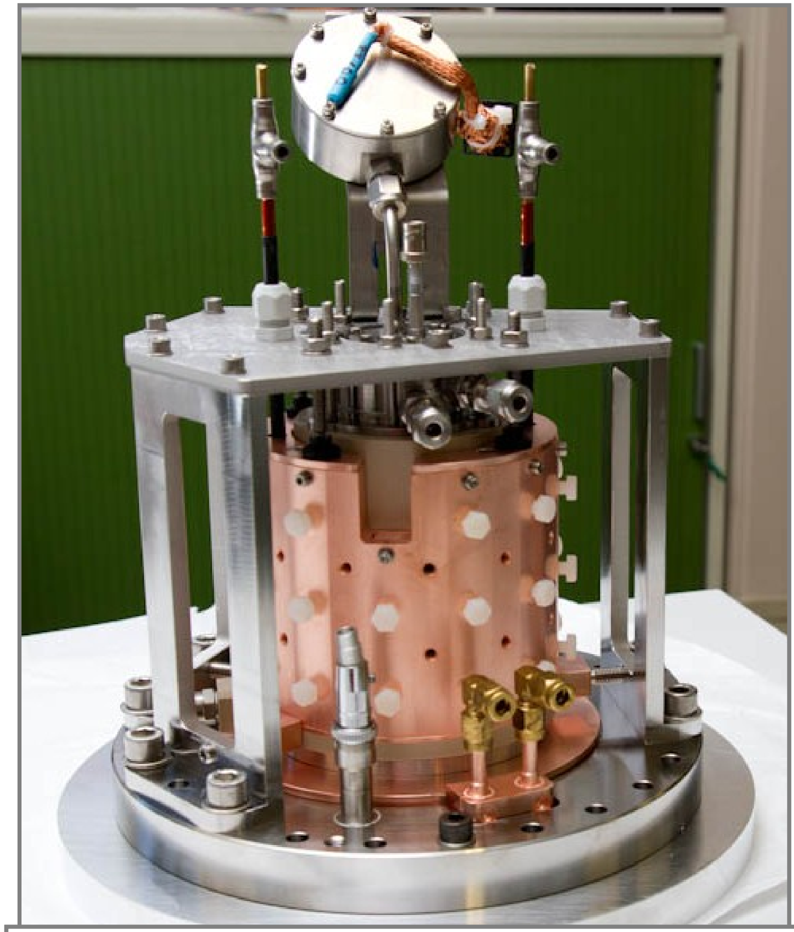
Design strategy:

- preserve excellent performance of DESY/Linac4 source

  → **minimize changes in plasma region**

- Adaptation to operation at high average power:
  - Use of **high thermal conductivity materials (Mo, AlN, ...)**
  - **Optimize design** for an efficient heat flow
  - Implementation of **cooling circuits** to remove incident heat load
  - **Minimization of ohmic losses** to protect ferromagnetic materials

Project start: 01. April 2008
Project end: 31. March 2011

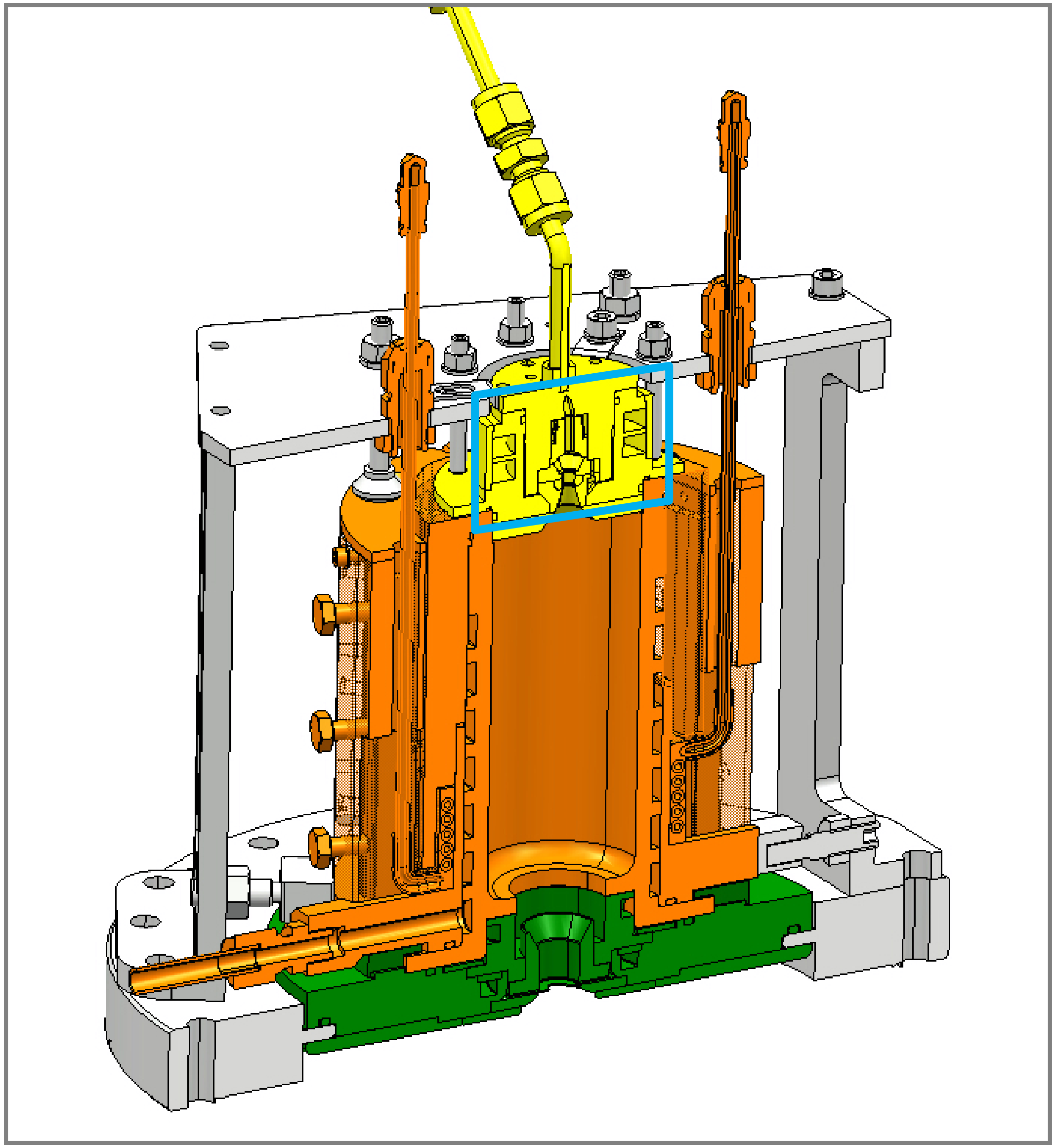


Production of prototype finished 09/2010
(in line with project schedule!)

SPL Plasma Generator: Cooling circuits

Efficient heat removal assured by four independent, fully integrated **cooling circuits**:

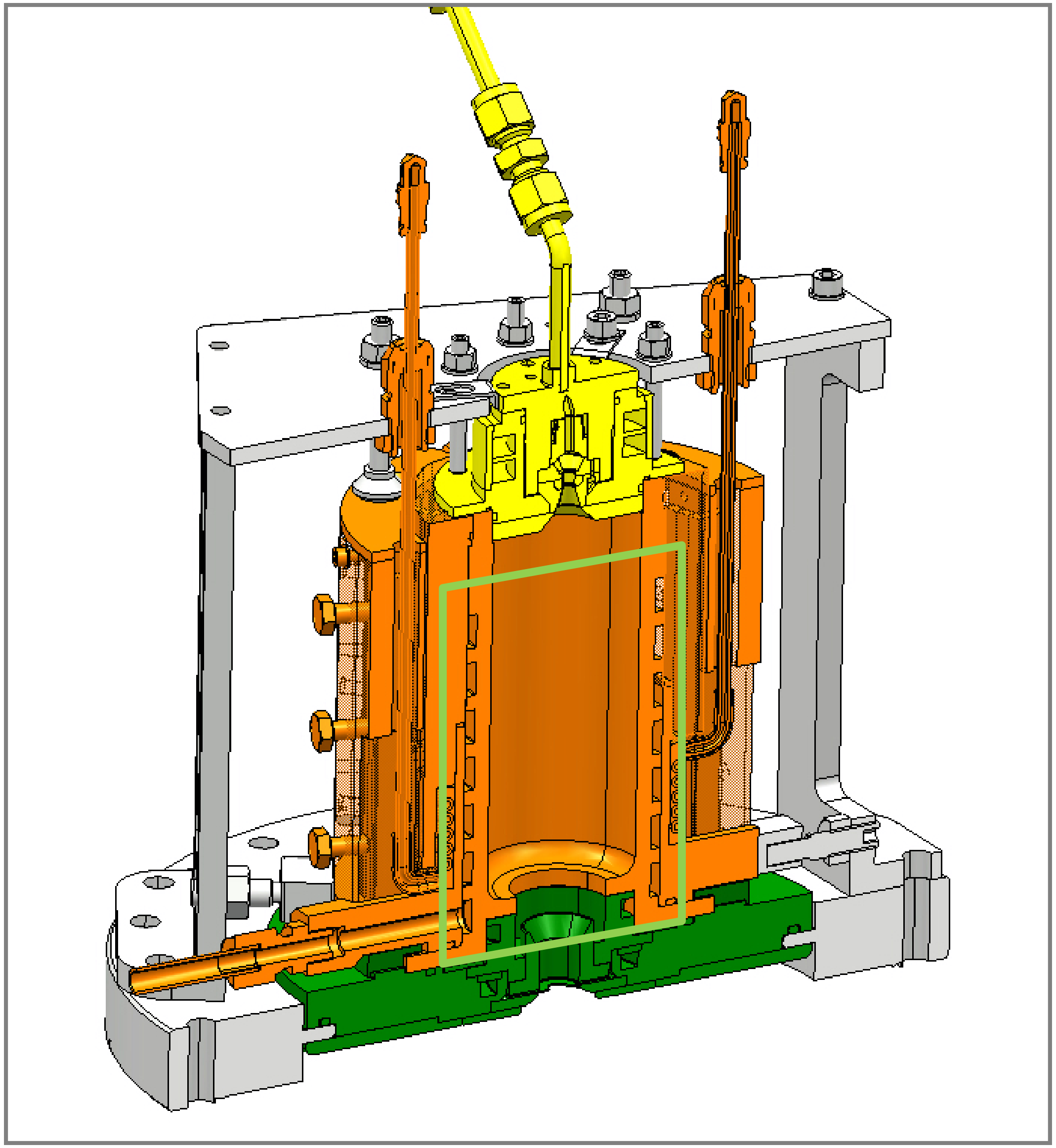
- **ignition region** (0.5l/min)



SPL Plasma Generator: Cooling circuits

Efficient heat removal assured by four independent, fully integrated **cooling circuits**:

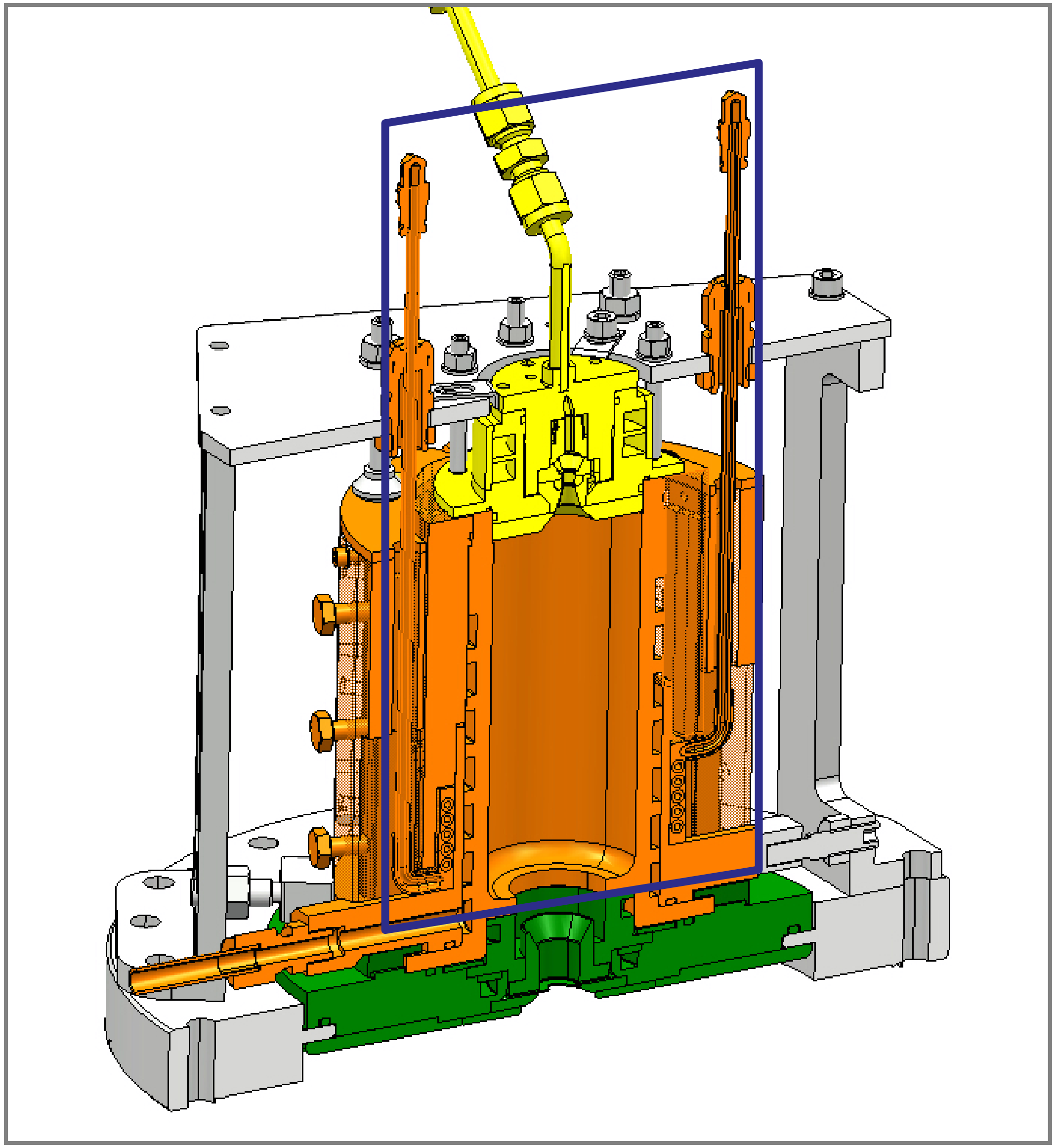
- **ignition region** (0.5l/min)
- **plasma chamber** (3 l/min)



SPL Plasma Generator: Cooling circuits

Efficient heat removal assured by four independent, fully integrated **cooling circuits**:

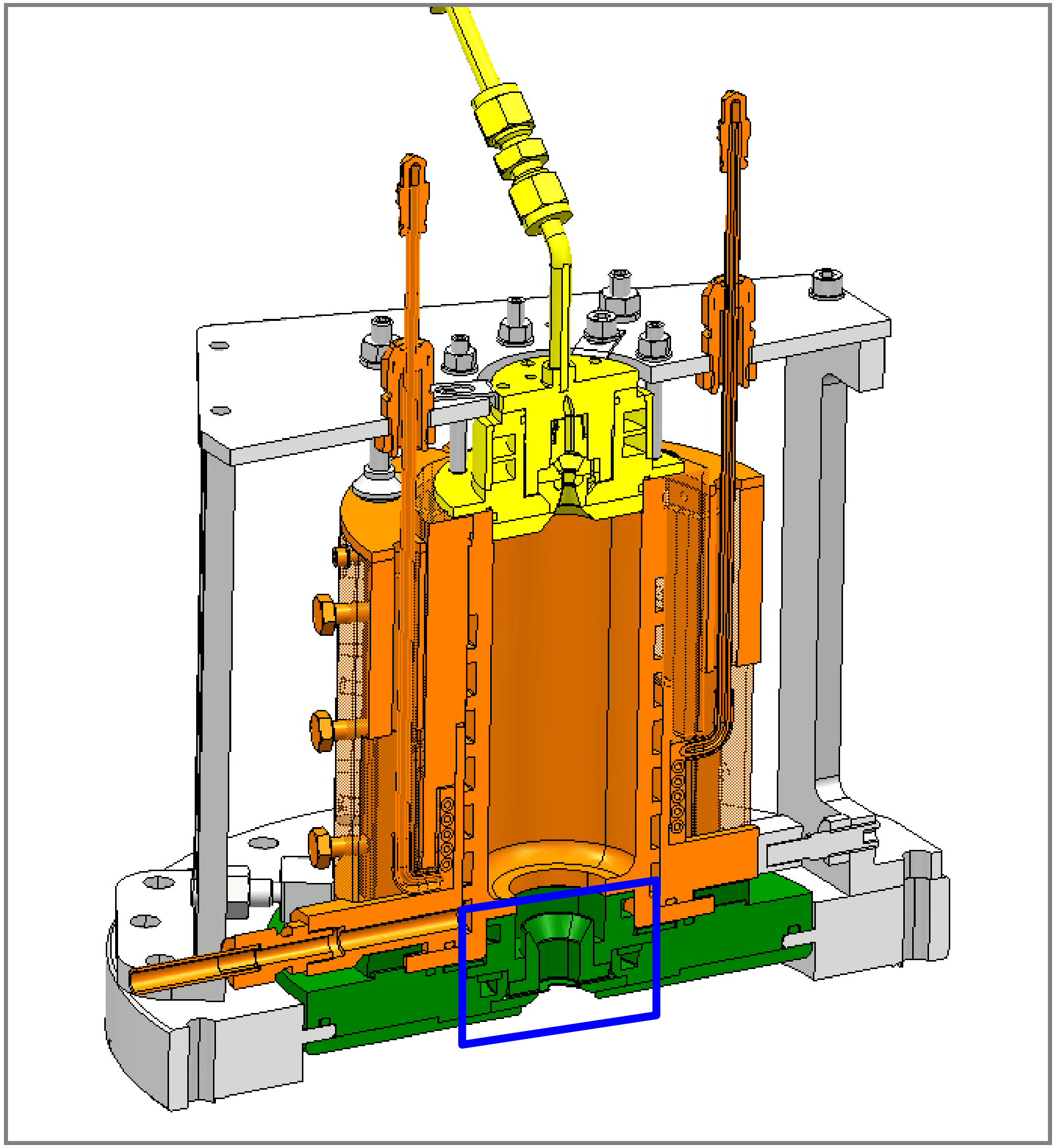
- **ignition region** (0.5l/min)
- **plasma chamber** (3 l/min)
- **rf antenna** (0.5 l/min)



SPL Plasma Generator: Cooling circuits

Efficient heat removal assured by four independent, fully integrated **cooling circuits**:

- **ignition region** (0.5l/min)
- **plasma chamber** (3 l/min)
- **rf antenna** (0.5 l/min)
- **extraction region** (2l/min)

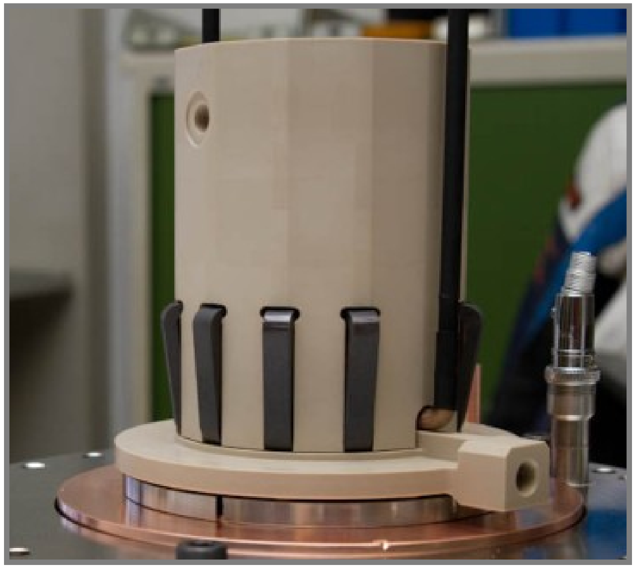


SPL Plasma Generator: Ceramic plasma chamber

Ceramic plasma chamber:

receives > 90% of the total heat load

→ **efficient removal of heat required** to avoid failure due to thermal stresses

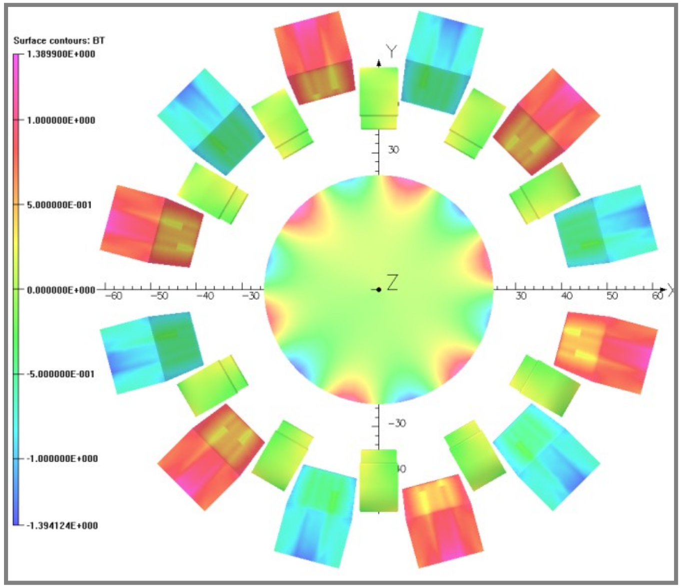


Solution:

- Material changed from Al_2O_3 to **AlN** (high thermal conductivity!)
- Integrated **spiral cooling channel** assures optimum cooling during operation
- **PEEK sleeve** confines cooling channel on the outside and serves also as support for antenna & ferrites

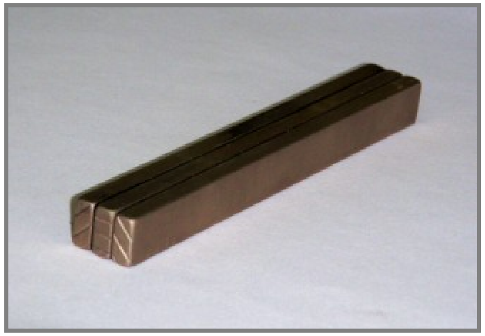
SPL Plasma Generator: Cusp Configuration & Magnet Cage

The SPL plasma generator comprises a dodecapole **magnetic cusp configu-ration** for plasma confinement and minimization of wall losses

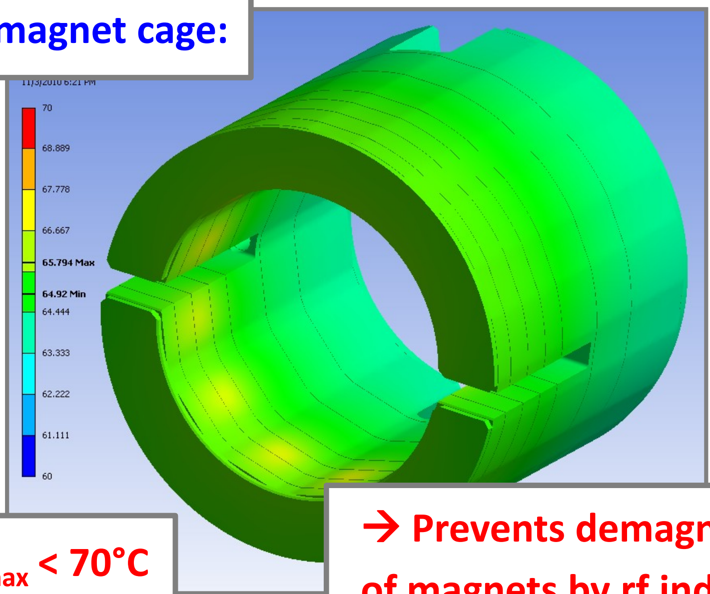


Wall losses & confinement improve with field strength in plasma region

→ use of **offset Halbach elements** instead of N-S magnets **(+40% field at plasma chamber wall!)**



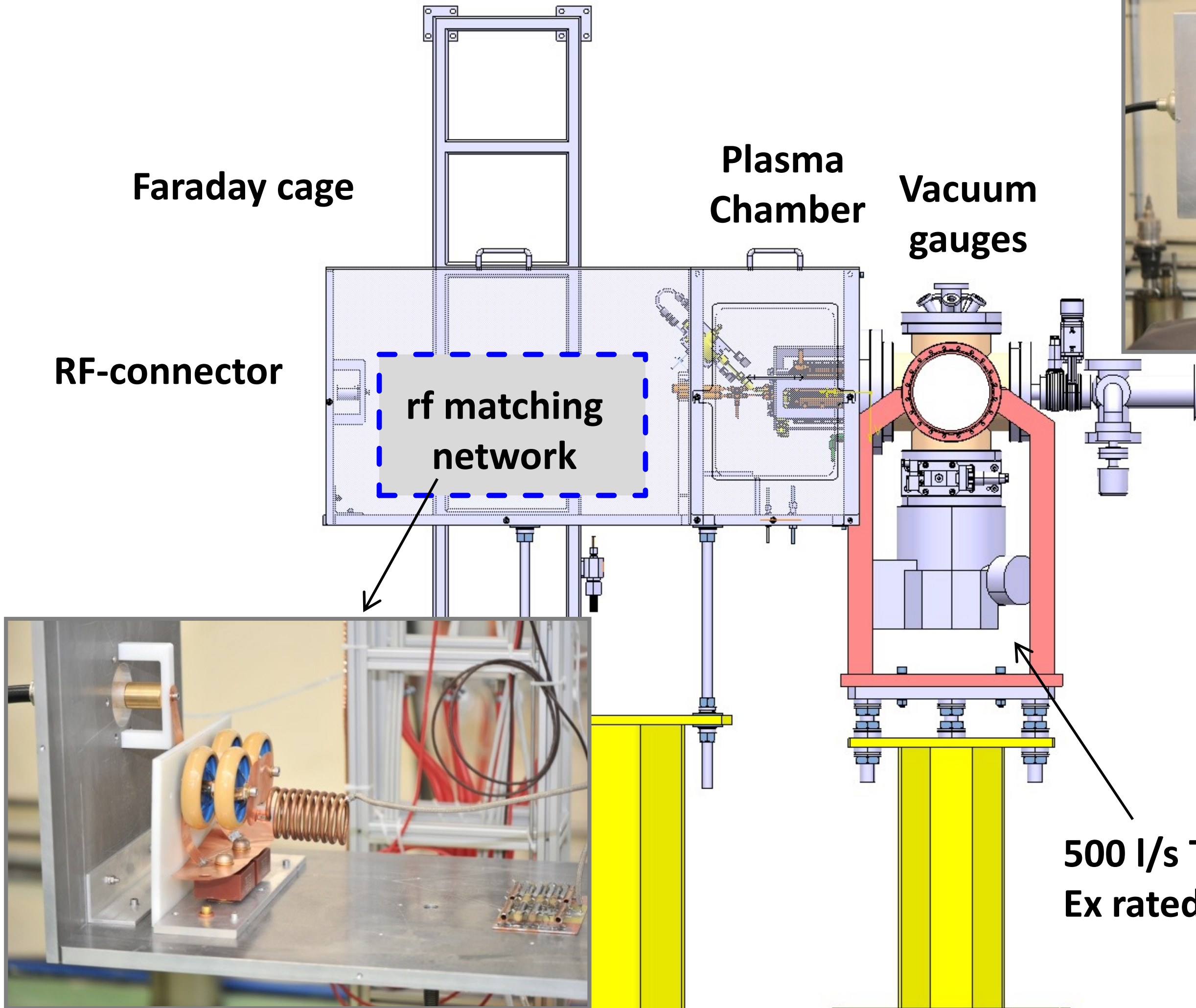
Cu magnet cage:

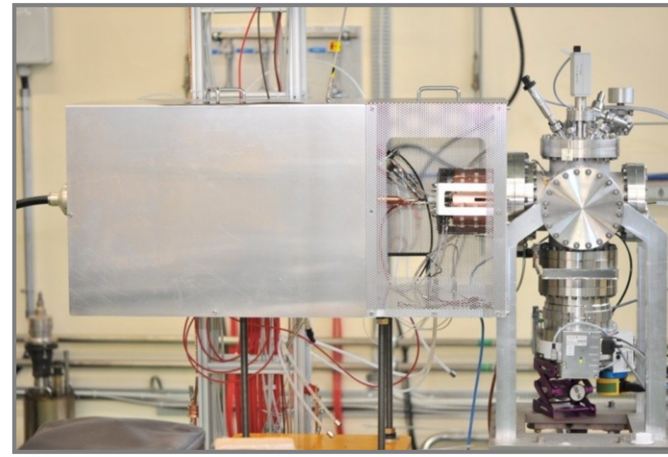


T_{max} < 70°C

→ Prevents demagnetization of magnets by rf induced ohmic heating!

Test stand outline

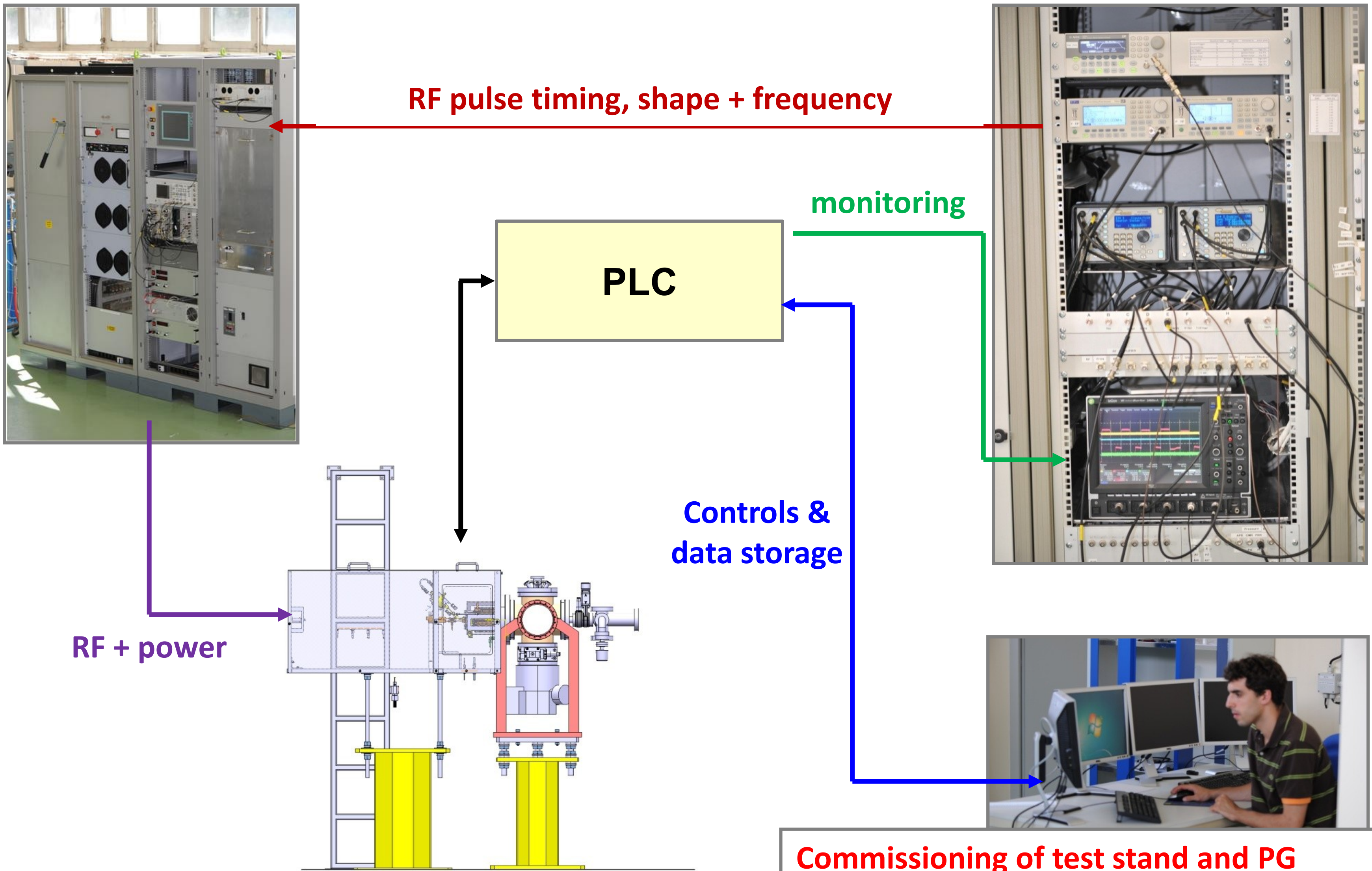




Measurement systems:

- Rest Gas Analyzer
- Optical spectrometer
- Ge + Quartz window for optical & IR imaging
- Langmuir gauge
- ...

Test stand outline

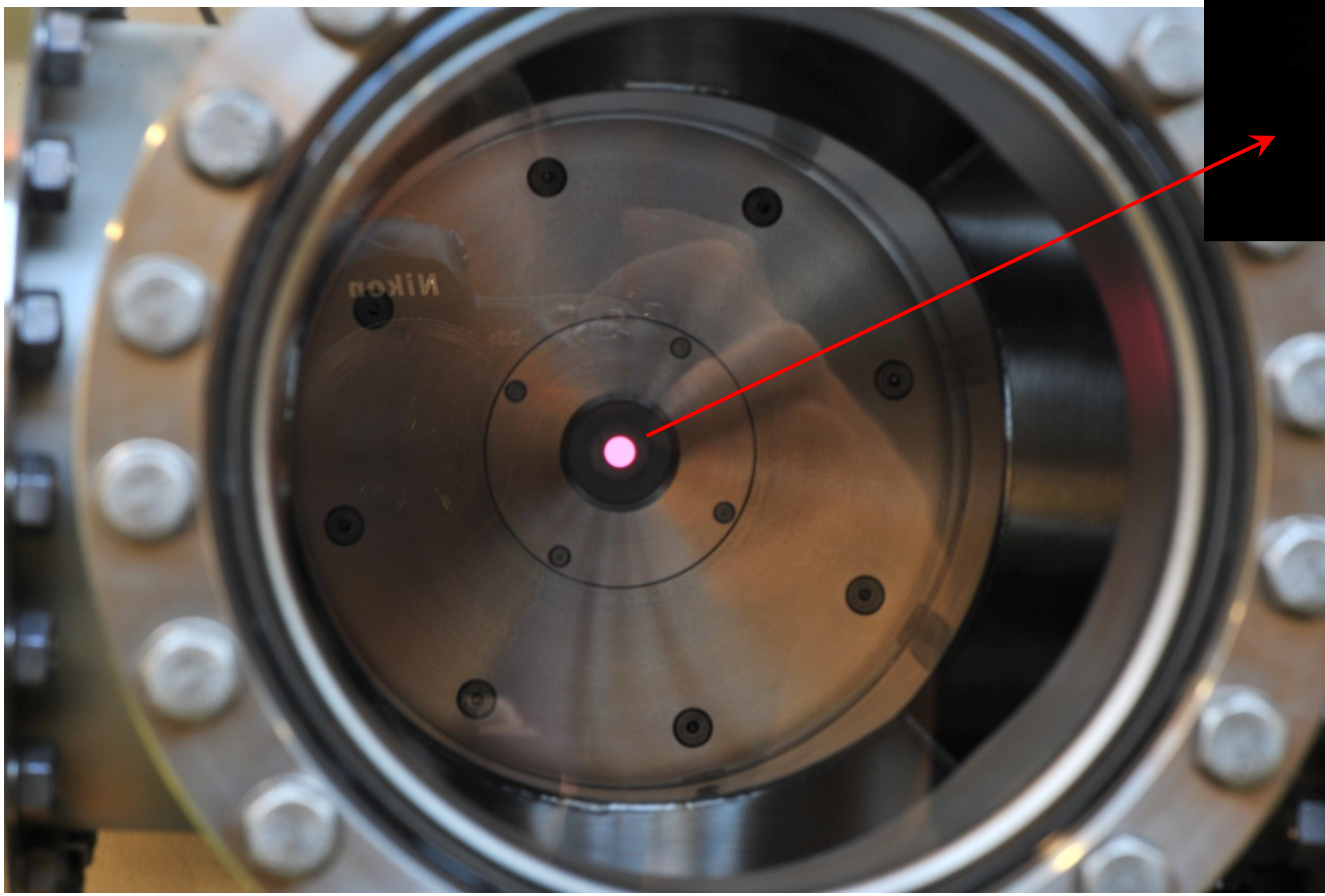


Commissioning of test stand and PG finished, ready for 100 kW, 50 Hz, 1.2 ms pulse testing !

First results

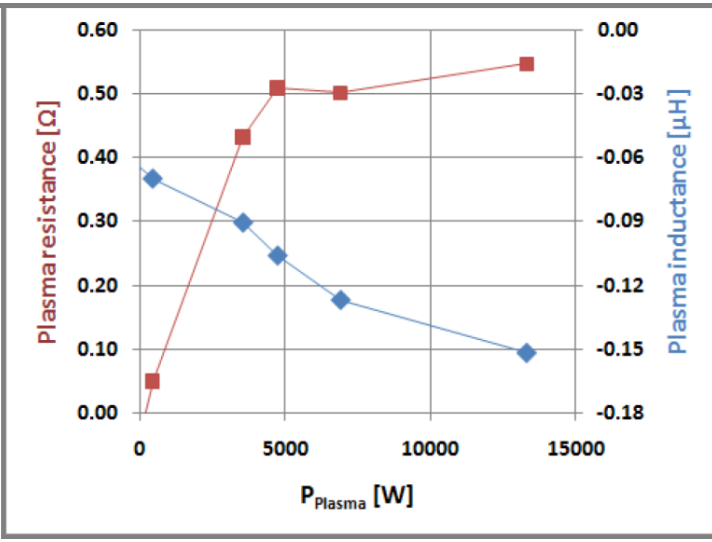
1st November 2010:

First plasma ...



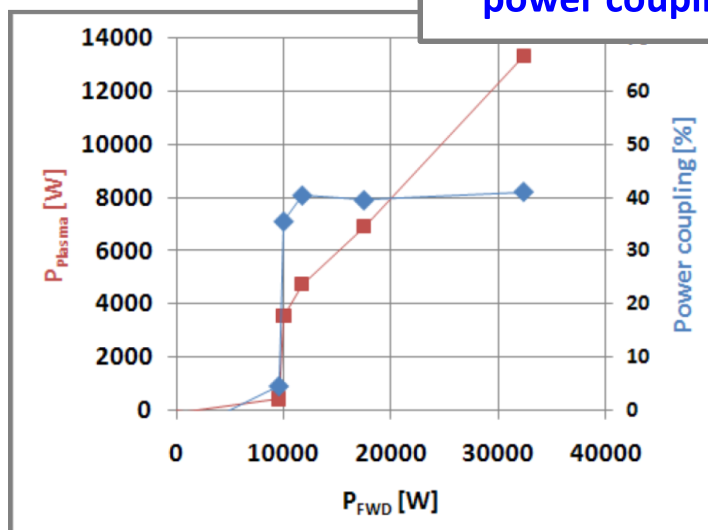
First results: rf measurements

equivalent plasma resistance & inductance:



- determined from **phase shift, forward and reflected power**
- **Ω_{plasma}**: increase with P_{plasma}
  L_{plasma}: decrease

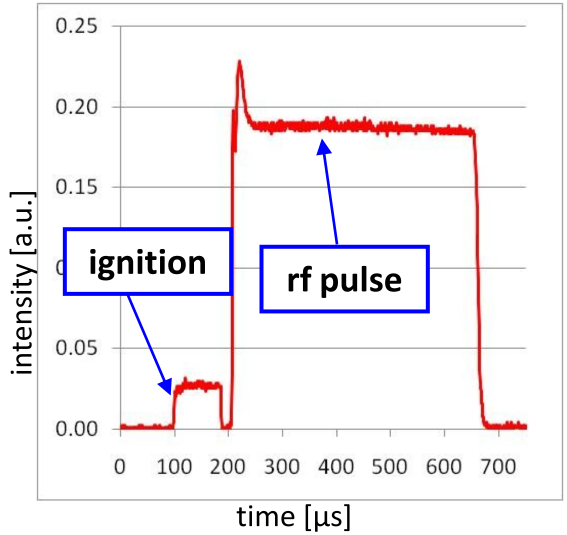
Plasma formation & power coupling:



- plasma formation only at $P_{fwd} \approx$ 10 kW → **strong increase of P_{plasma} when formation starts**
- rf power coupling efficiency ≈ 40%
  → **lower than in Linac4 (70%)**
  → **to be investigated ...**

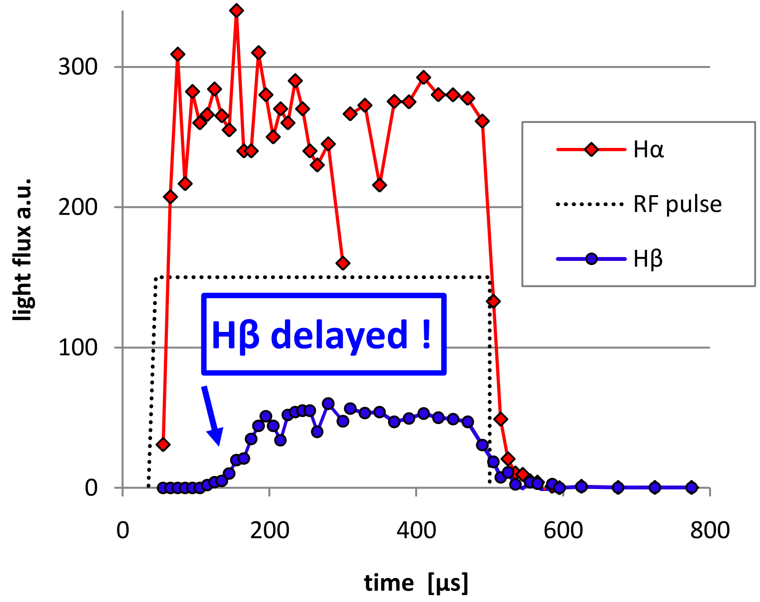
First results: optical emission measurements

light pulse measurements:



- ignition and rf pulse **well resolved**
- **overshoot** at start of rf pulse probably due to **very fast electrons** (avalanche!)

Spectral analysis of plasma light:

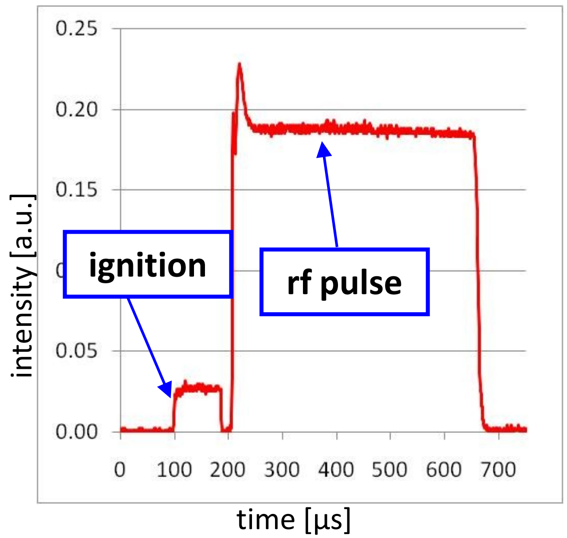


Intensities of Hydrogen Balmer lines (Hα, Hβ and Hγ) depend on **T_{e-}, n_{e-} and n_{H-}**

- **possibility to characterise plasma**
- **allow comparison with Linac4 source!**
- **plasma formation can be assessed** by time-resolved measurements

First results: optical emission measurements

light pulse measurements:



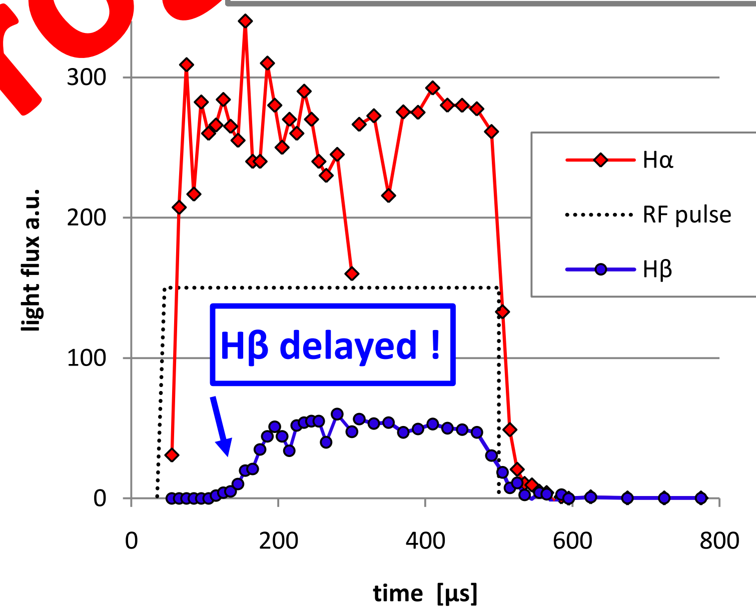
- ignition and rf pulse **well resolved**
- **overshoot** at start of rf pulse probably due to **very fast electrons** (avalanche!)

work in progress…

Intensities of Hydrogen Balmer lines (Hα, Hβ and Hγ) depend on T_{e-}, n_{e-} and n_{H-}

- **possibility to characterise plasma**
- **allow comparison with Linac4 source!**
- **plasma formation can be assessed** by time-resolved measurements

Spectral analysis of plasma light:



Summary and Outlook

Summary:

- SPL plasma generator prototype is **well on schedule**
- **Test stand and plasma generator commissioning completed** at low rep rate
- **1st plasma** created November 2010
- **plasma resistance, inductance** and **rf power coupling** studied for different forward rf power; coupling efficiency lower than in Linac4 !
- **optical emission** from plasma allows direct comparison with Linac4 source performance

to be done:

- Verification of **thermal model**, test of **cooling systems**
- **mitigate problems** identified during commissioning and testing (antenna sparks, gas ignition, ...)
- optimize **gas pulsing + pressure** and **power coupling**
- **Final goal: Operate plasma generator at 100 kW, 50 Hz and 1.2 ms pulse length!**

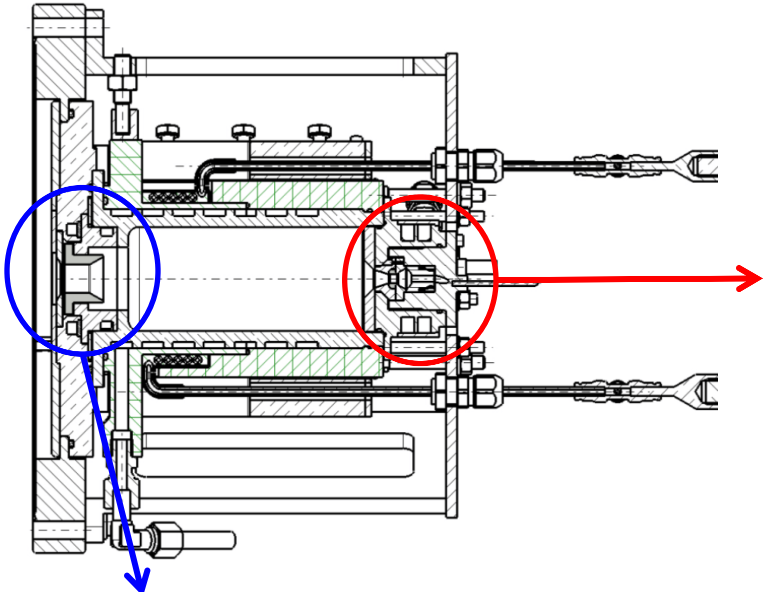
Thank you for your attention !

Backup slides

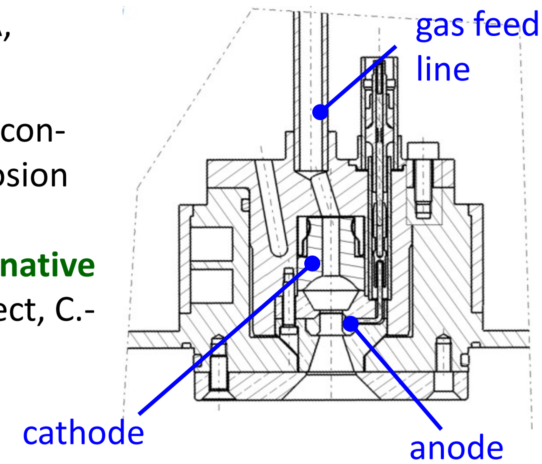
SLHC-7.1: Schedule & Deliverables

- **Project Start:** 1 April 2008
- ✓ 31 March 2009: Report - *Finite element thermal study of the Linac 4 design source at the final duty factor* – **Completed**
  - **determination of thermally critically components in the Linac4 plasma generator**
- ✓ 31 May 2009: Report - *List of required improvements for the design of the high duty factor plasma generator to function at a high duty factor* – **Completed**
  - **development of a design strategy in order to arrive at a plasma generator for SPL**
- ✓ 30 September 2009: Report - *Design of a high duty factor plasma generator* – **Completed**
  - **1st design of the SPL plasma generator prototype**
- ✓ 30 September 2010: Demonstrator - *Construction of the plasma generator and sub-systems* (e.g. 2Hz RF generator, hydrogen gas injection and pumping) – **Completed**
  - **presentation of built plasma generator prototype & test stand**
- **31 March 2011:** Final Report - *Plasma generation and study of the thermal and vacuum conditions* **- tbd**

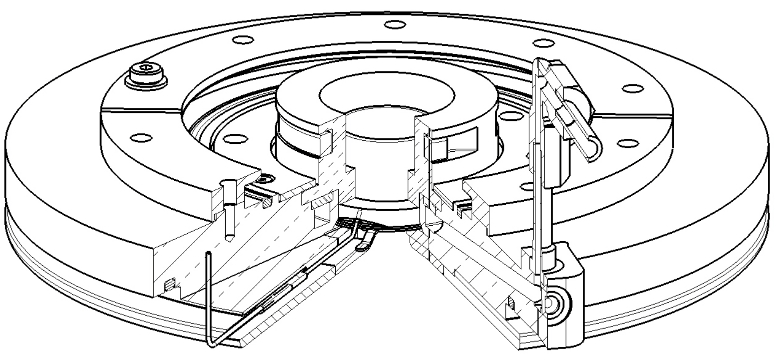
SPL Plasma Generator: Ignition & Extraction Region



- **Plasma ignition** by 5A, 600V, <100µs spark
- **Problem:** high power consumption, electro erosion of materials
  → **Evaluation of alternative solutions** (thesis project, C.-S. Schmitzer)

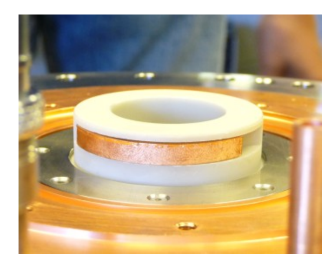


Extraction region includes **filter magnets + plasma electrodes** for optimization of H^- production and extraction

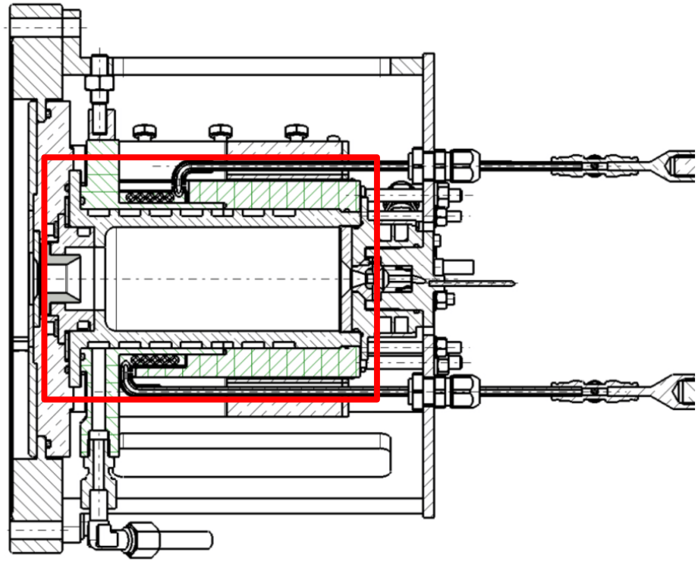


- **Electrode assembly:** Optimized heat transport by **brazing of conductors on insulators**

- **filter magnets:**
  - positioning by **AlN support**
  - minimization of ohmic heating by **laser-welded 0.5mm Cu boxes**



SPL Plasma Generator: Plasma chamber + antenna

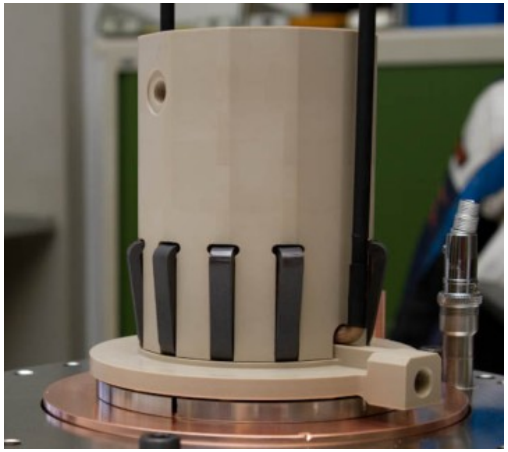


Plasma chamber:

- receives > 90% of the total heat load
  → efficient removal of heat required
- **Solution:**
  - **Material = AlN** (high thermal conductivity!)
  - Efficient heat removal by **spiral cooling channel**
  - **PEEK sleeve** confining cooling channel on the outside

Antenna:

- **5 ½ windings**
- **hollow-tube Cu** for internal water cooling
- insulation by **molded epoxy, Kapton foil and shrink tubes**
- rf coupling with plasma enhanced by **ferrites**



rf system & matching network