Reliable Injectors for High Power Accelerators

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LNL 14/04/2014

Workshop on Accelerator based Neutron Production ABNP 2014

Outline

Midas - 1993 Midas2 -1997

(1999) **Trips ion source**
- Magnetic field shape
- Space charge compensation studies

(20065 **P.M. TRIPS**

(2007) **VIS ion source**
- The effectiveness of Alumina and BN coating
- High intensity He^+ beam generation
- The influence of magnetic field on the proton fraction

(2007): **Plasma reactor**
- Overcoming the density cut-off: EBW heating and modal conversion

(2012) **Start of design of the ESS proton source**
- The project of PSESS and LEBT
- The chopper and space charge compensation in the LEBT

(2013) **The VIS source for ISODAR and Daeδalus projects**
- Toward smaller plasma chambers for H_2^+ generation
- The new injection system

(2013) **The Flexible Plasma Trap (FPT) – (not yet tested)**

MIDAS

Microwave Discharge Ion Source: easy operation of the plasma generator at 2.45 GHz, fast assembly, reliability not acceptable

- *Goal:*
  High Ionization Efficiency
- *Current:*
  Less than 0.5 mA from 1 mm hole
- *Species:*
  Any

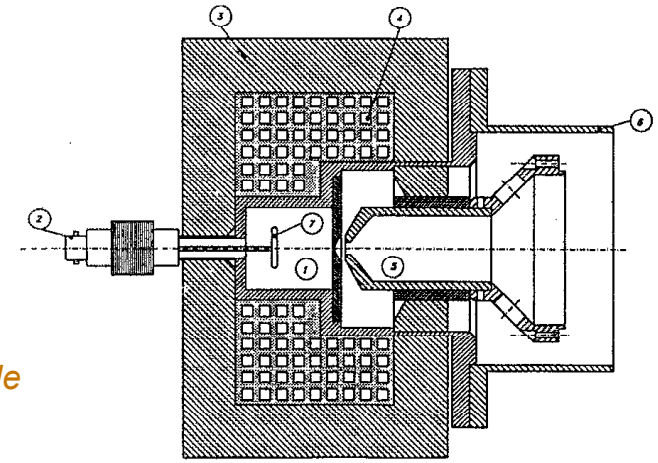
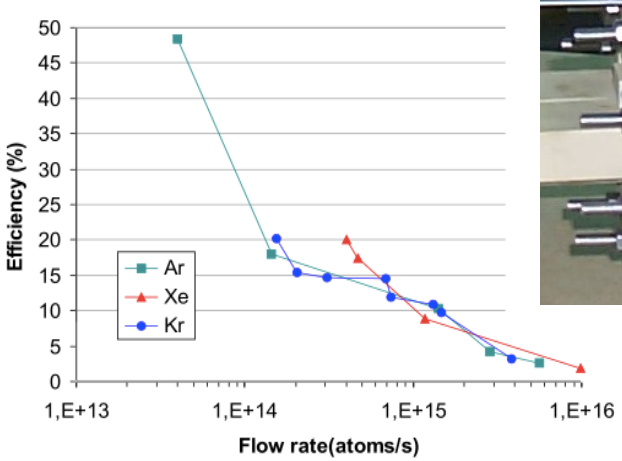


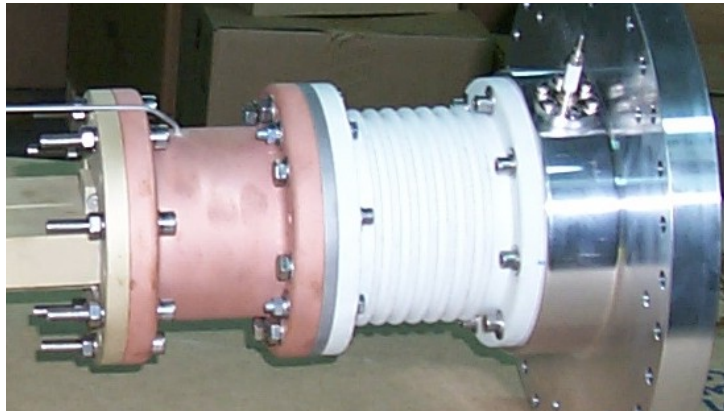
FIG. 1. A schematic design of MIDAS. (1) plasma chamber; (2) microwave input; (3) iron yoke; (4) coil; (5) 20-kV extraction system; (6) 20-kV insulation; and (7) antenna.

Problems with sparks and grounding

MIDAS and MIDAS 2

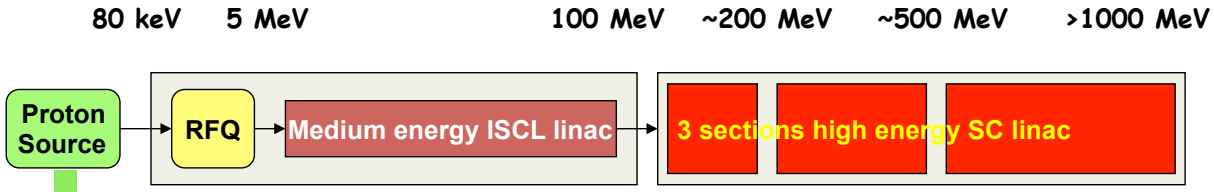
- *Goal:*
  High Ionization Efficiency





Improved magnetic field
Improved grounding
Above 1 mA from 1 mm hole

The TRASCO linac (1 GeV, 30 mA)

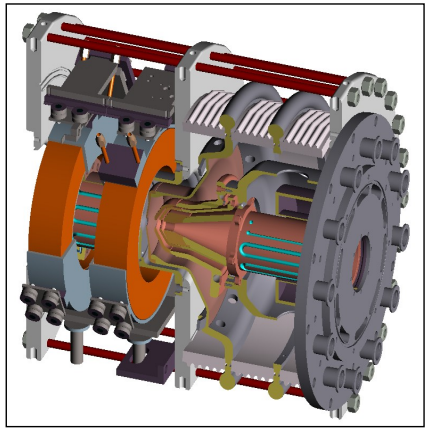


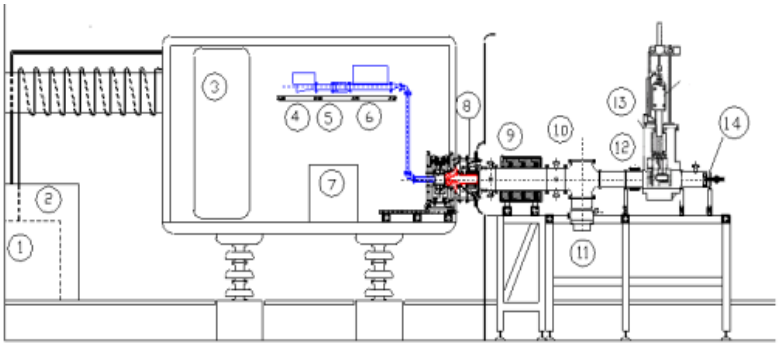
Proton beam current: *35 mA dc*
Beam Energy: *80 keV*
Beam emittance: $\varepsilon_{RMS} \leq 0.2\ \pi$ *mm mrad*
Reliability: *close to 100%*

TRIPS (TRasco Intense Proton Sources) requirements

	Requirement
Beam energy	80 keV
Proton current	35 mA
Proton fraction	>70%
RF power, Frequency	2 kW (max) @2.45 GHz
Axial magnetic field	875-1000 G
Duty factor	100% (dc)
Extraction aperture	8 mm
Reliability	≈100%
Beam emittance at RFQ entrance	≤0.2 πmmmrad

TRIPS (TRasco Intense Proton Source)



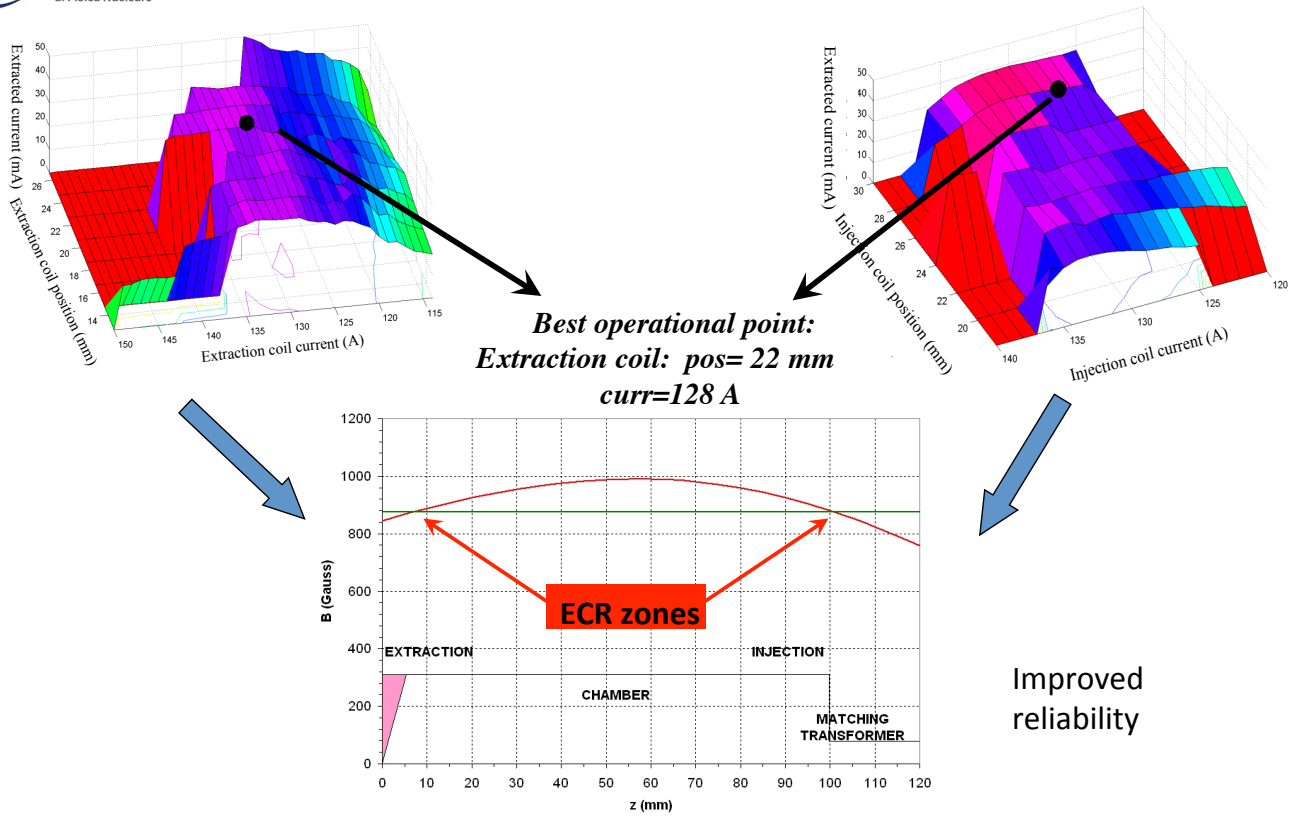


A layout of the whole set-up at INFN-LNS:
1- Demineralizer; 2- 120 kV insulating transformer; 3- 19" Rack for the power supplies and for the remote control system; 4- Magnetron and circulator; 5- Directional coupler; 6 – Automatic Tuning Unit; 7- Gas Box; 8- DCCT 1; 9- Solenoid; 10 – Four sector ring; 11- Turbomolecular pump; 12- DCCT 2; 13- EMU ; 14- Beam stop.

Proton beam current:
35 mA dc
Beam Energy:
80 keV
Beam emittance:
$\varepsilon_{RMS} \leq 0.2\ \pi$ ***mm mrad***
Reliability:
close to 100%

Based on CRNL-LANL-CEA design
MANY INNOVATIONS

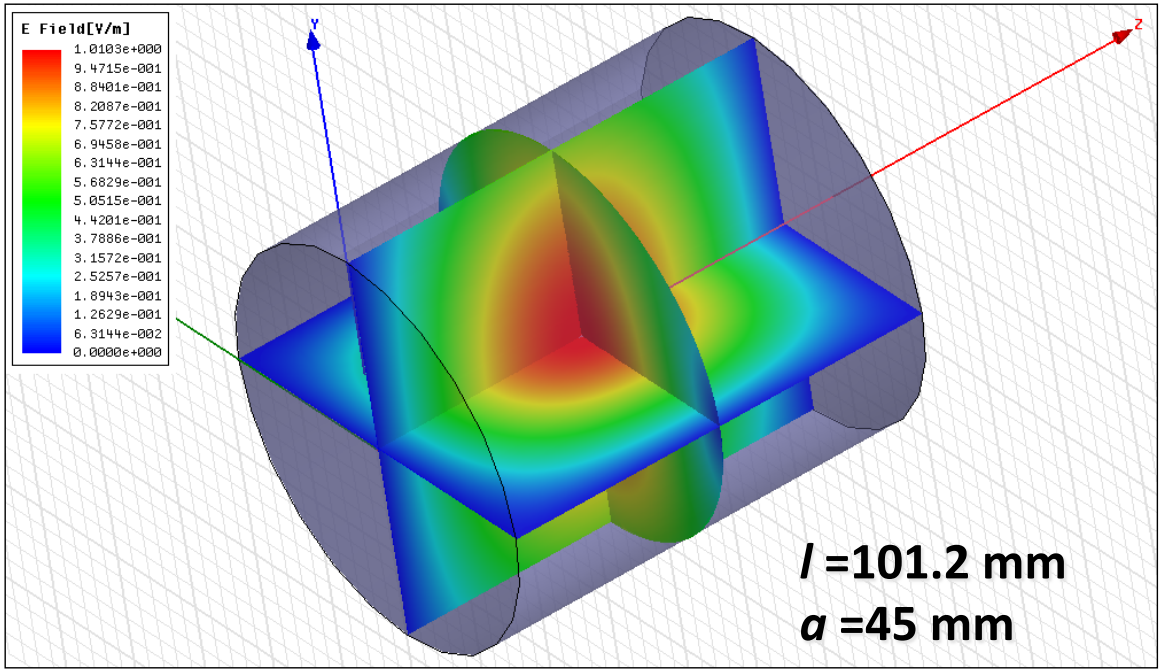
Optimum magnetic field profile



Improved reliability

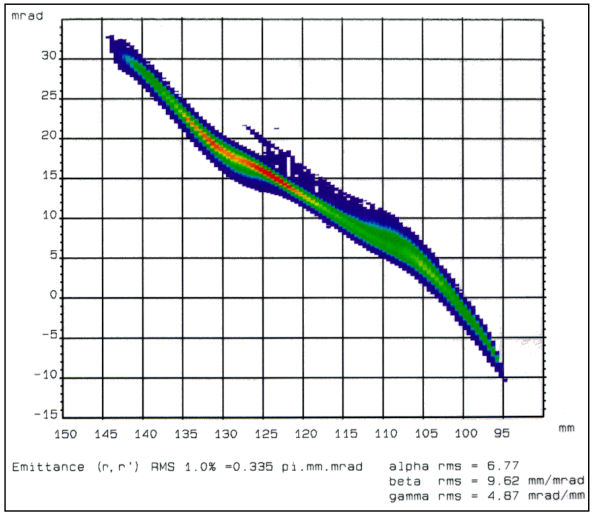
Plasma chamber optimization

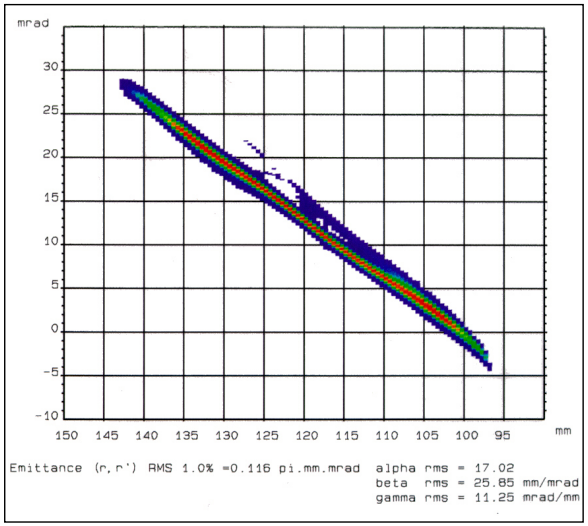
PARAMETRICAL ANALYSIS RESULTS-TE_{111} MODE



TE_{111} ELECTRIC FIELD DISTIBUTION INSIDE THE CYLINDRICAL RESONANCE CAVITY

Space charge compensation with ^{84}Kr





Emittance plot (99%) **without injecting** gas in the beam line:

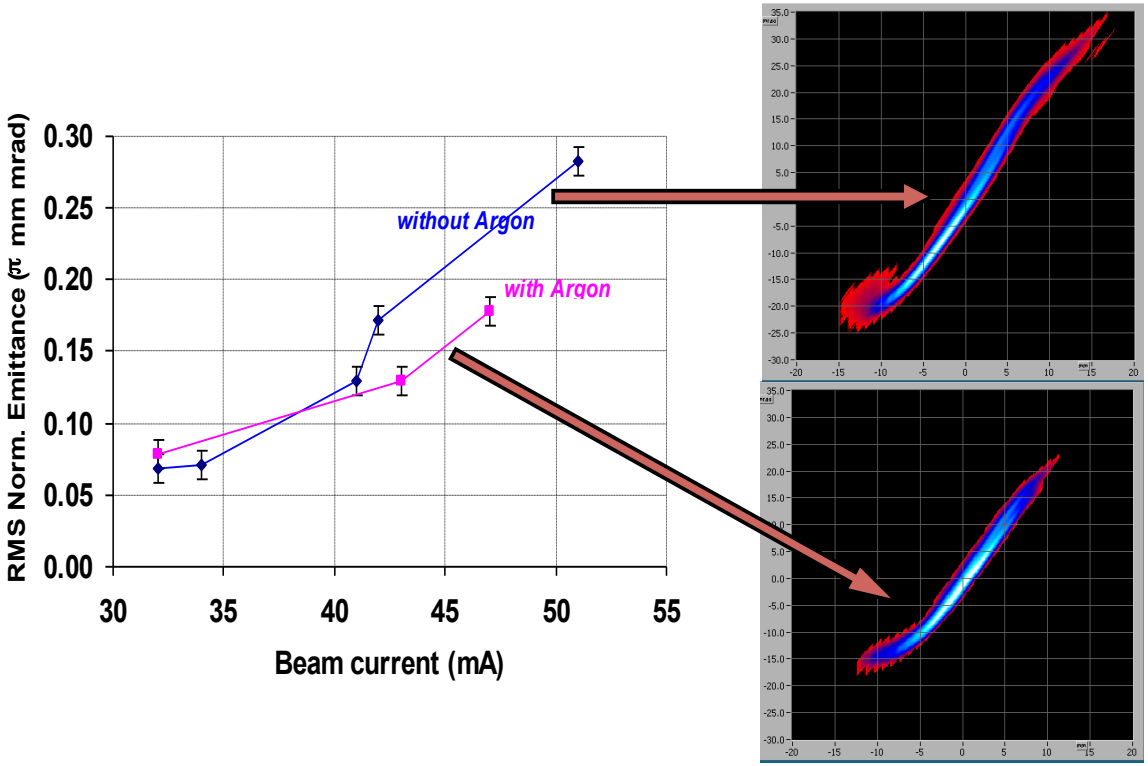
$p=1.8\cdot10^{-5}$ T⇒ **ε_{RMS}=0.335 π mm mrad**

Emittance plot (99%) **injecting** ^{84}Kr in the beam line:

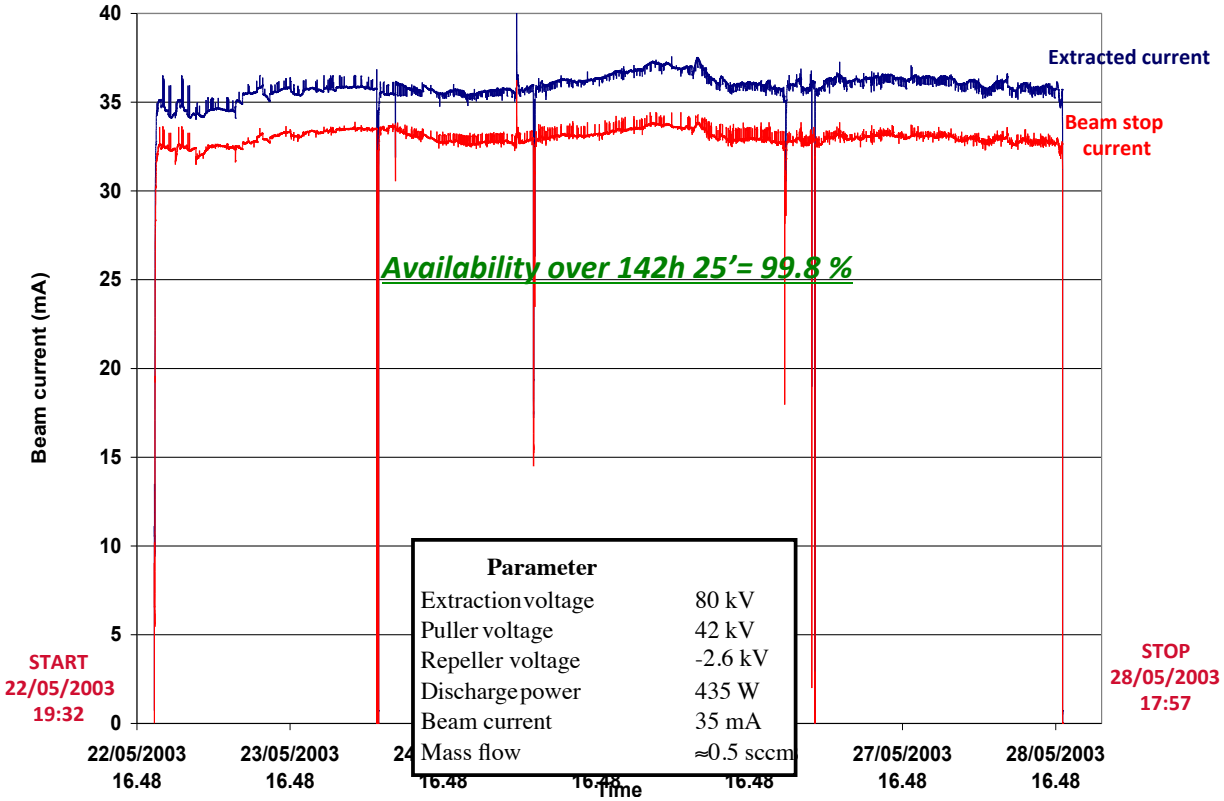
$p=3.0\cdot10^{-5}$ T⇒ **ε_{RMS}=0.116 π mm mrad**

R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino, Rev.Sci.Instr. 70(6),(1999), 2652

Emittance measurements



TRIPS reliability test: 35mA @ 80kV

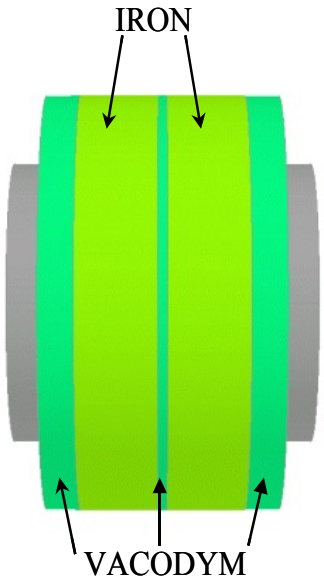


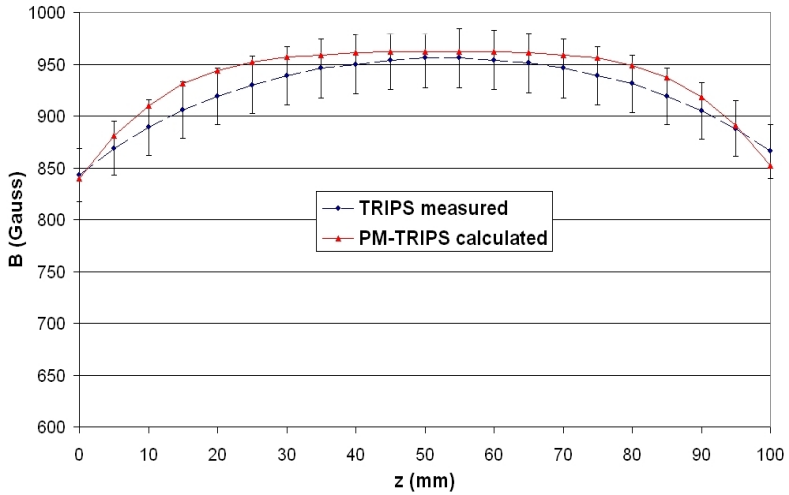
Parameter	
Extraction voltage	80 kV
Puller voltage	42 kV
Repeller voltage	-2.6 kV
Discharge power	435 W
Beam current	35 mA
Mass flow	≈0.5 sccm

TRIPS ---------> PM TRIPS

TRIPS ---------> PM TRIPS

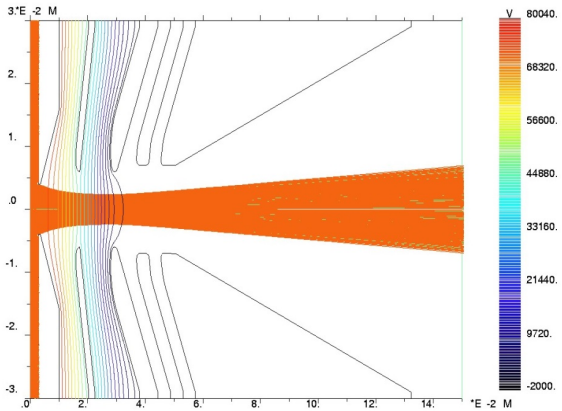
In TRIPS the large number of control devices placed at high potential affected the reliability requirement.
PM TRIPS is the **permanent magnets version** of TRIPS, designed to increase the reliability of the whole source.





PM-TRIPS extraction system

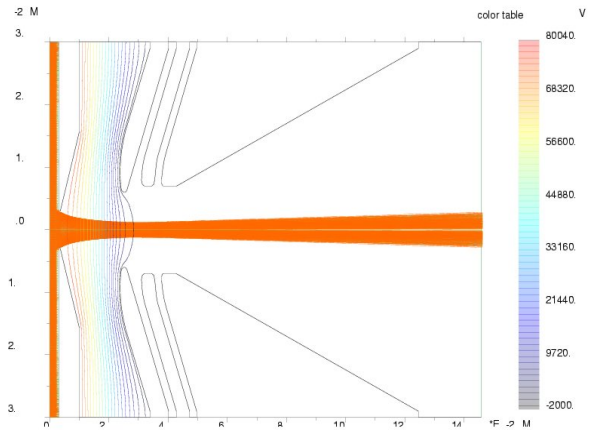
TRIPS



Five-electrode topology

- on-line optimisation of the extracted beam
- wide range of operations (10-80 mA)

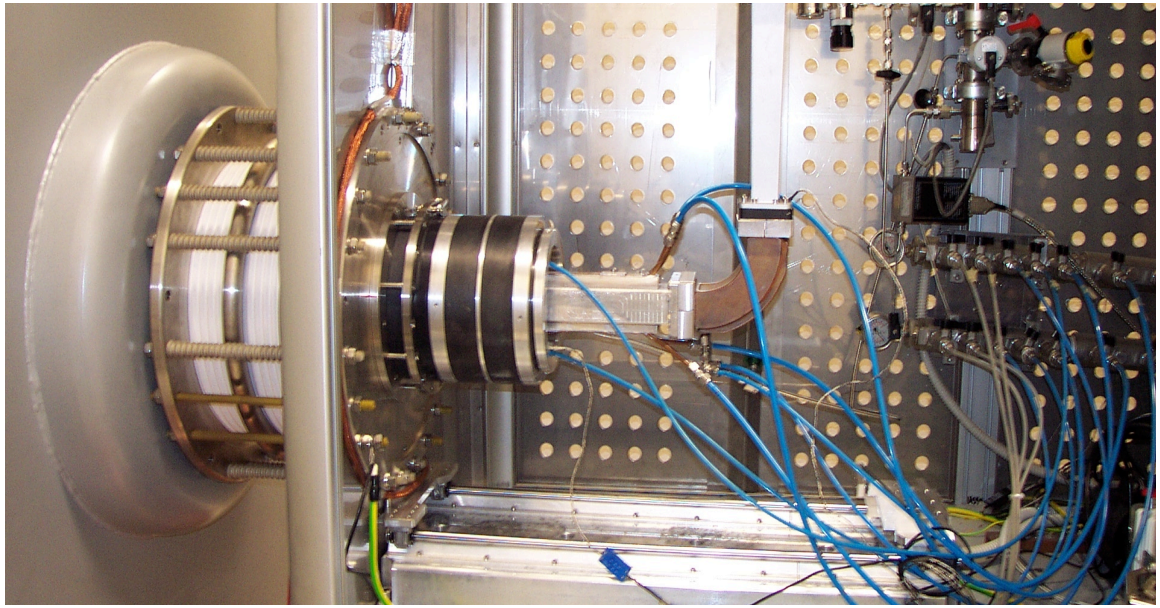
PM-TRIPS



Four-electrode topology

- optimized for a 40 mA beam (90% proton, 10% H_2^+)

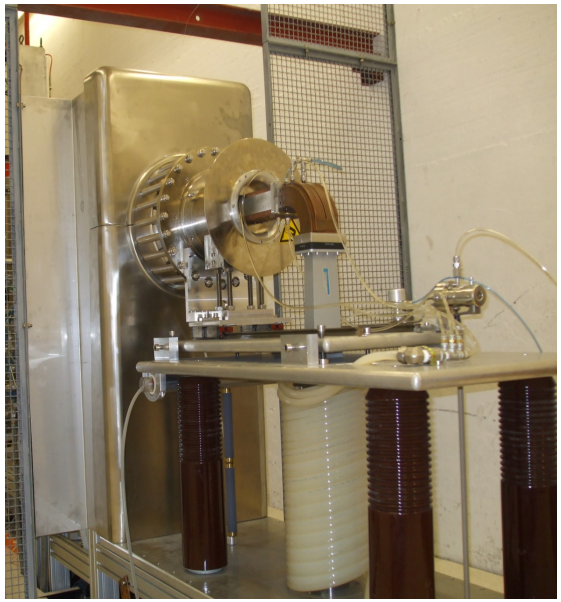
Operations were limited to 40 kV because of HV discharge at extraction due to poor vacuum conductance in presence of stray magnetic field

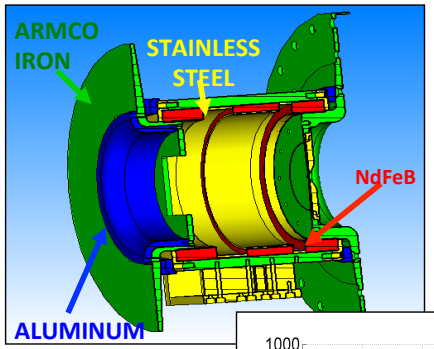


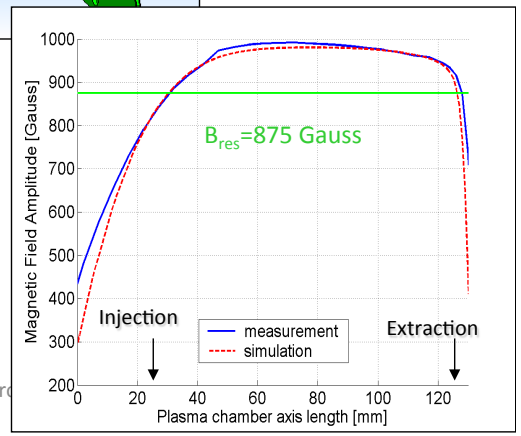
PM TRIPS ---------> VIS

PM TRIPS ---------> VIS

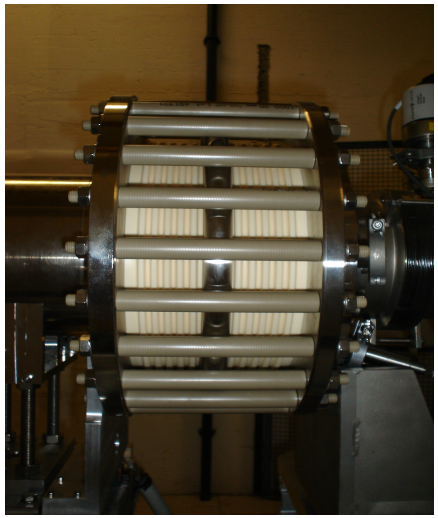
A new magnetic system has been designed by using **OPERA,** to get rid of the Penning discharges in the extraction region.



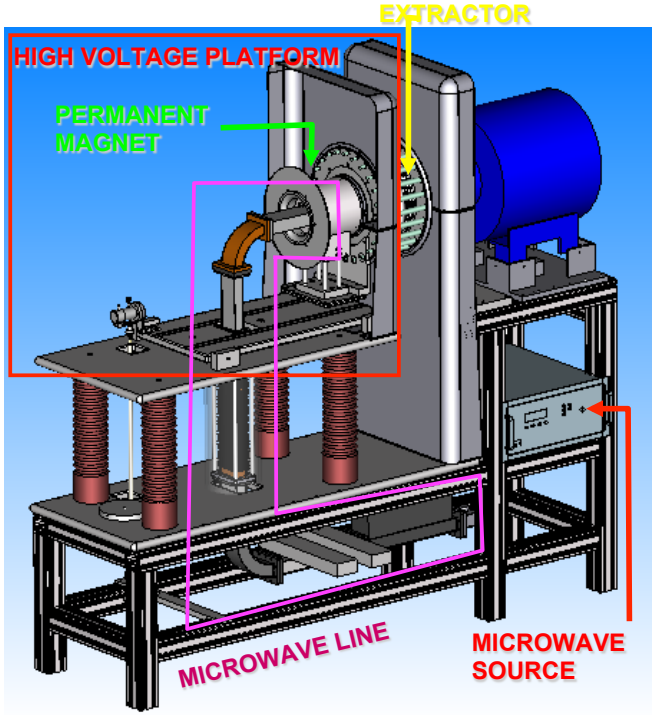




VIS description



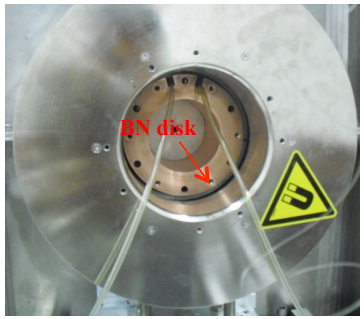
80 kV Extraction voltage



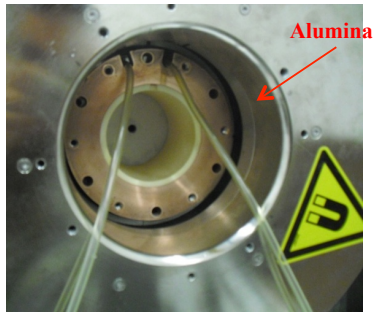
The Dc break permits to maintain the microwave generator at ground.

Passive method to increase and to improve the intensity of the ion beam

BN disk and wall coating effects

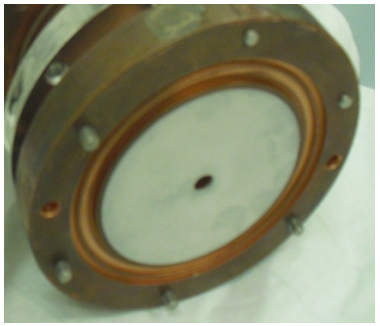


Configuration with BN disk and alumina



Configuration with BN disk and no alumina

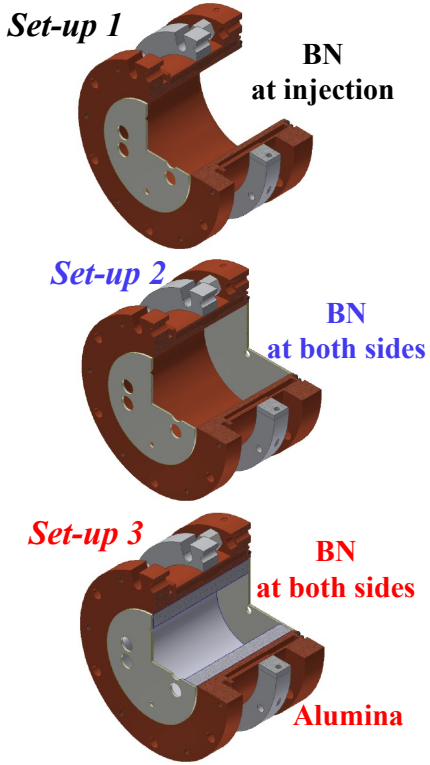
AL_2O_3
- Inner diameter: 79 mm.
- Outer diameter: 89.5 mm.
- Length: 95 mm.

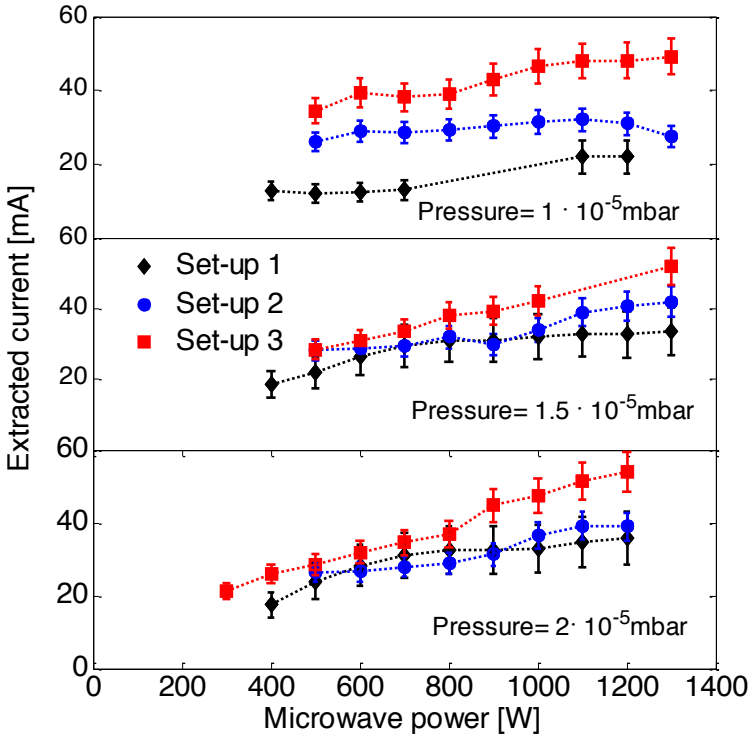


BN
- Inner diameter: 7.8 mm.
- Outer diameter: 89.5 mm.

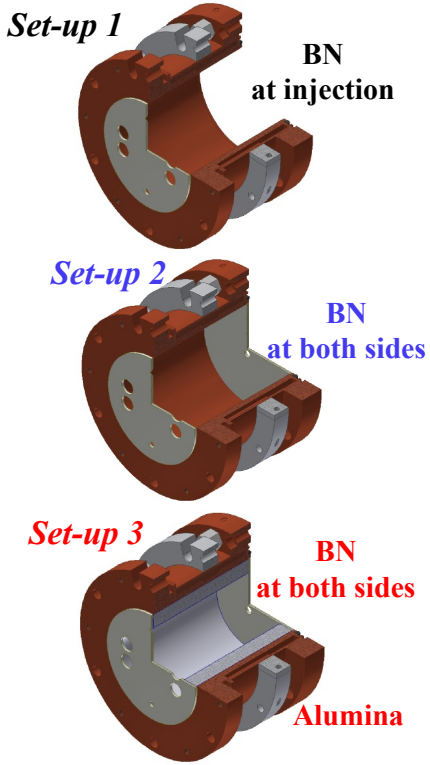
thick **BN plates** are located at two extremities of the plasma chamber.
Al_2O_3 tube is nested within the plasma chamber, it **covers the entire walls** from one side to other

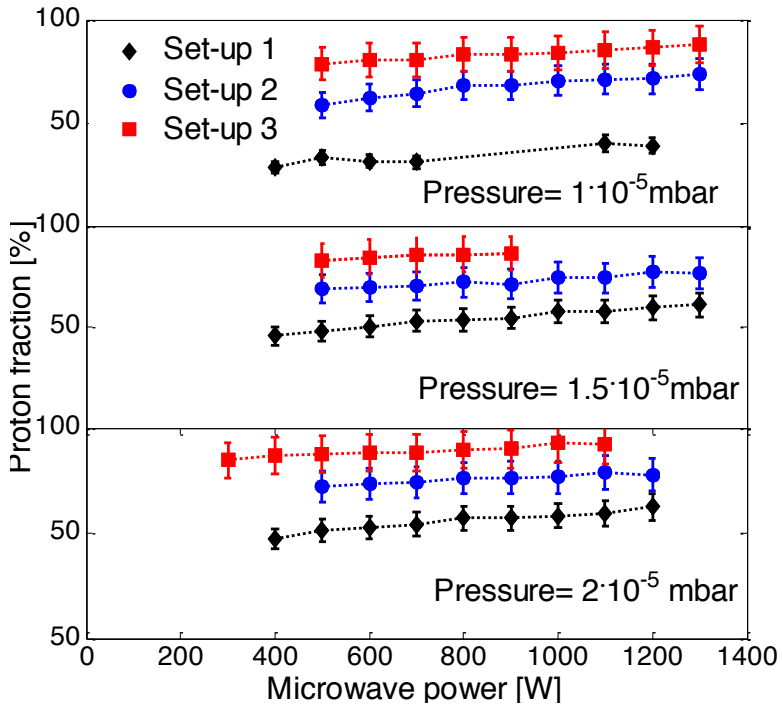
BN disk and wall coating effects





BN disk and wall coating effects

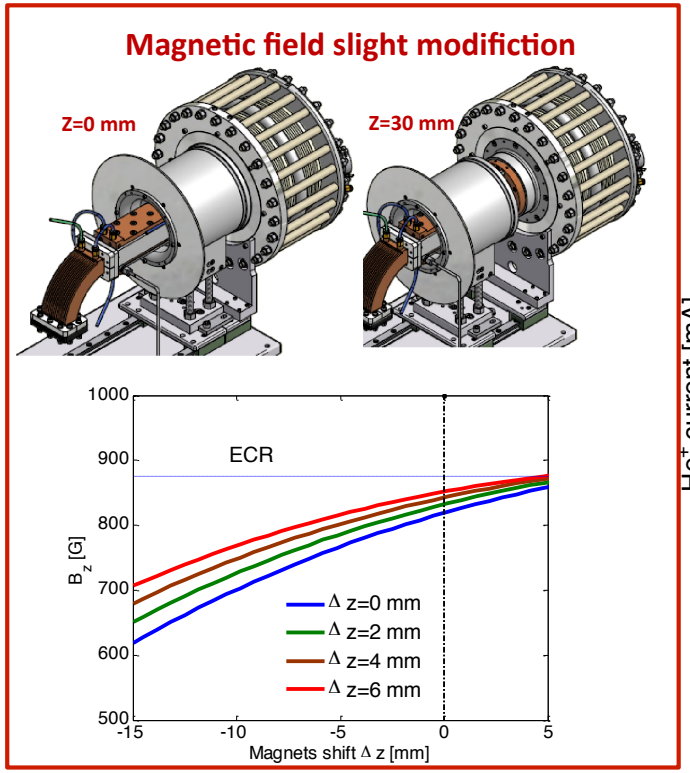




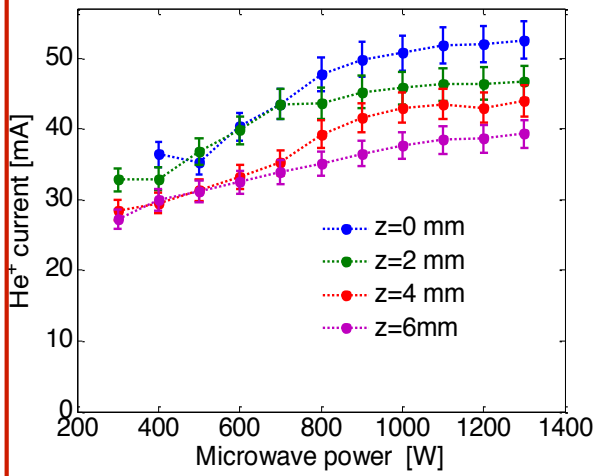
Not only the **Alumina cylinder** improved the intensity, but also the beam ripple was decreased and the sparks became less frequent.

Soon after, the tests carried out to improve the current of He^+ beams put in evidence that the ***magnetic field shape*** *plays a major role in EEDF formation as well as in reliability of the source and stability of the beam.*

Generation of High intensity He^+ beam



Pressure: $6 \cdot 10^{-5}$ mbar
Extraction hole: 10 mm
Alumina and BN nested in plasma chamber



More than 50 mA He^+ have been obtained at z=0 position

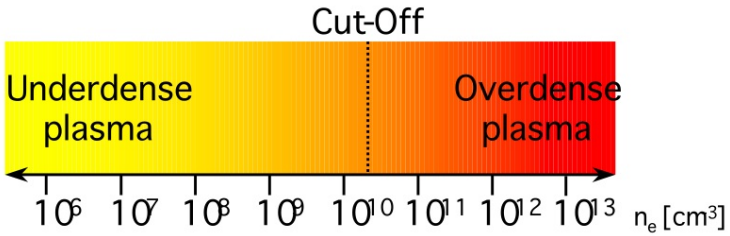
The Plasma Reactor

Overcoming the current limits

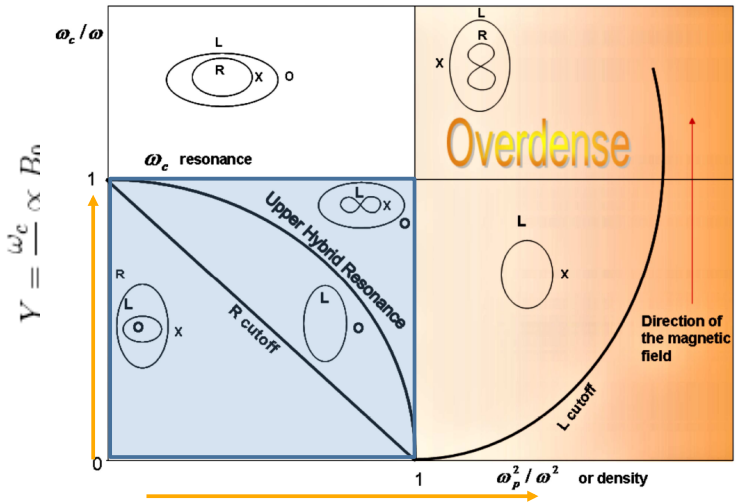
Current ~ 100 **mA** for protons and other monocharged species will be required in the next years.

$$I \sim n_e / \tau_i$$

Larger density is required



E.M. Wave propagation in a magnetized plasma



$$X = \frac{\omega_p^2}{\omega^2} \propto n_e$$

Normalized density

$$Y = \frac{\omega_c}{\omega} \propto B_0$$

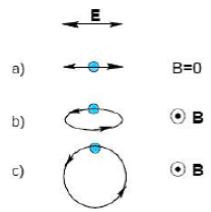
Normalized magnetic field

$$X = \frac{\omega_p^2}{\omega^2} \propto n_e \qquad X<1 \longrightarrow n_e < \frac{\epsilon_0 m_e}{e^2}\omega^2 = n_{cutoff}$$

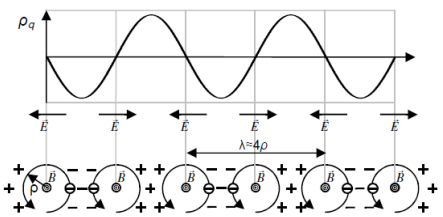
E.M waves can not produce plasmas, whose density overcomes the so-called density cut-off n_{cutoff}

Bernstein waves

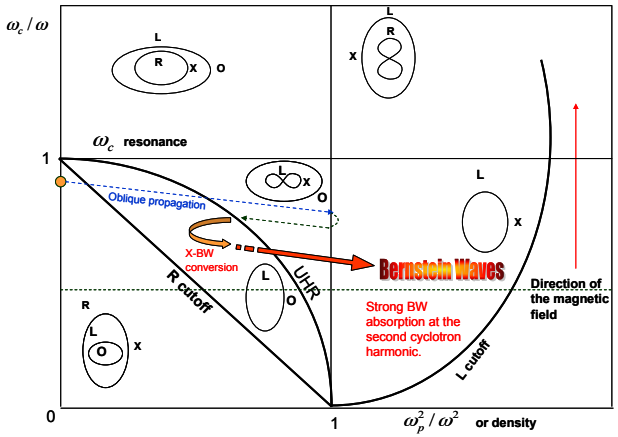
EBWs consist in a phase bunching due to both cyclotron motion and plasma oscillations. Electrons form net charge accumulation-rarefaction which propagate in a warm plasma.



$$\boldsymbol{k} \downarrow \boldsymbol{EBW}, \boldsymbol{E} \downarrow \boldsymbol{EBW} \perp \boldsymbol{B}$$



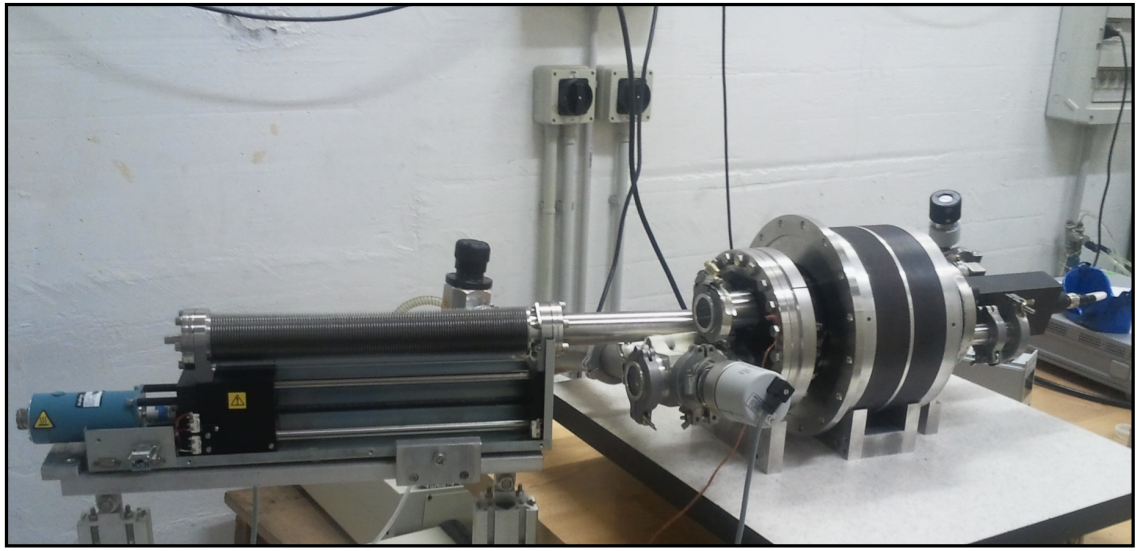
No Density cutoff



Modal conversion from X to Bernstein wave at UHR

The Plasma Reactor

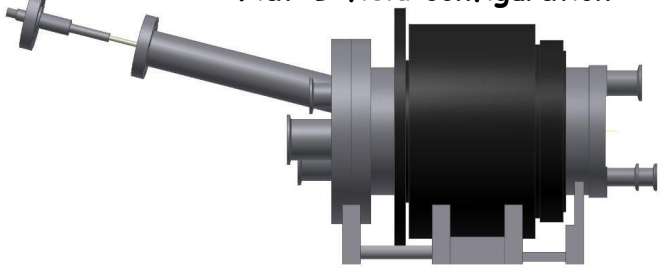
The Plasma Reactor is a test-bench for studies on **plasma physics** and **new** mechanisms of **plasma heating**



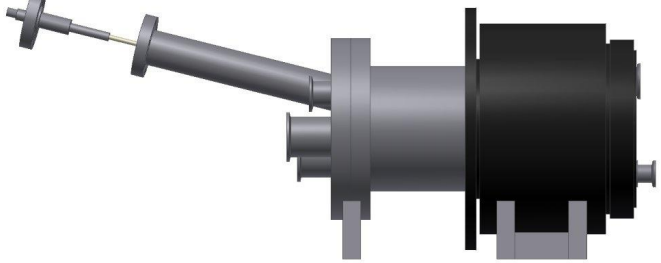
It is possible to have **larger brightness** and **stability**, **less ripple** in overdense conditions?

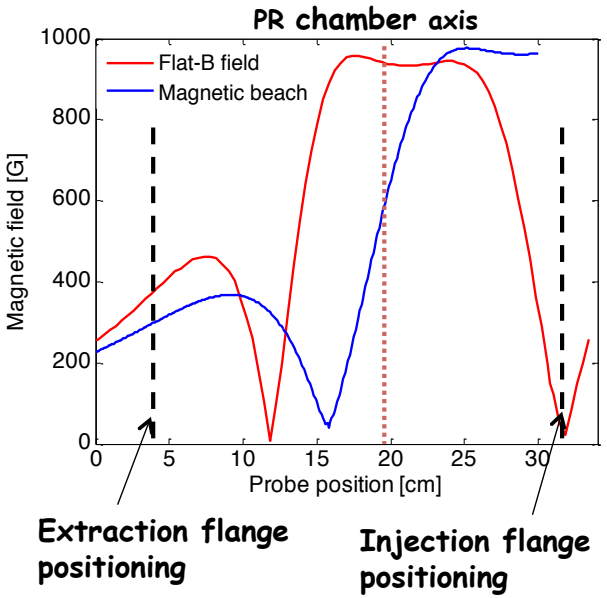
Magnetic configurations

Flat-B field configuration



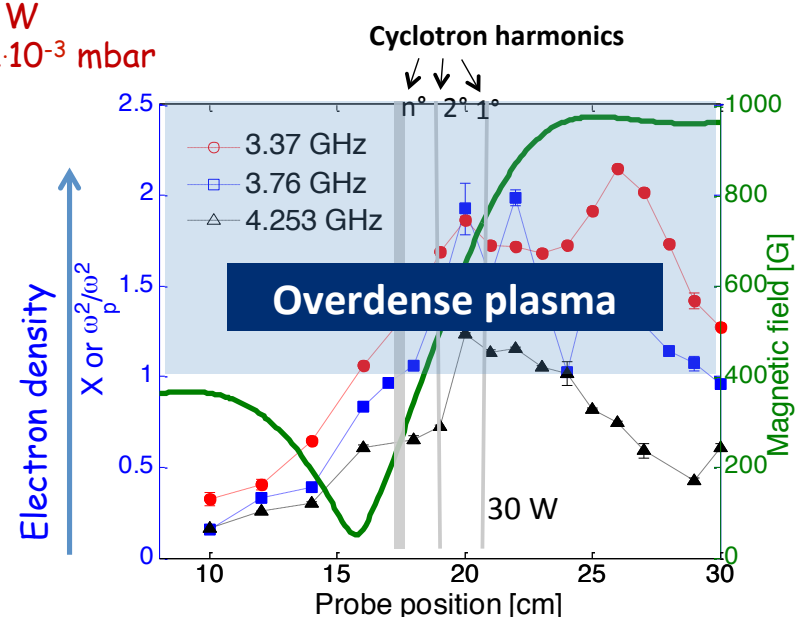
Magnetic beach configuration





The magnetic beach configuration

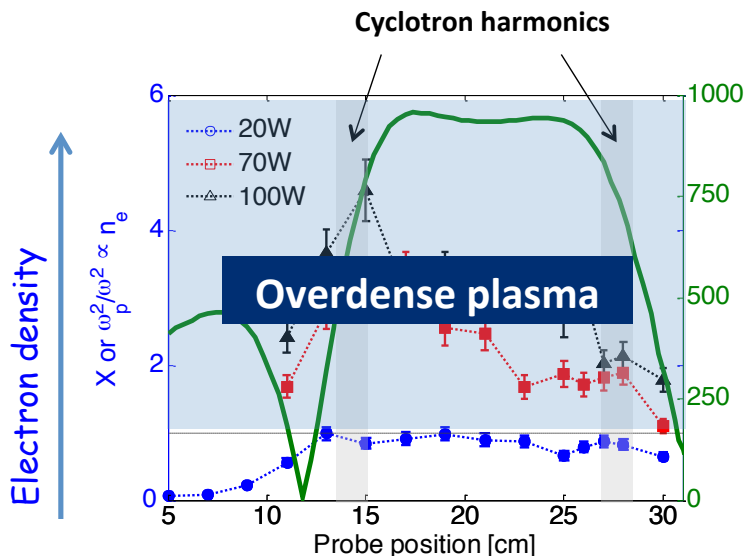
$P_{forward}$:30 W
Pressure:$1 \cdot 10^{-3}$ mbar



At 3.37 GHz and 3.76 Ghz an overdense plasma is obtained with only 30 W forward power!!!

30 W << 800-900 W (typical power rate used for MDIS)

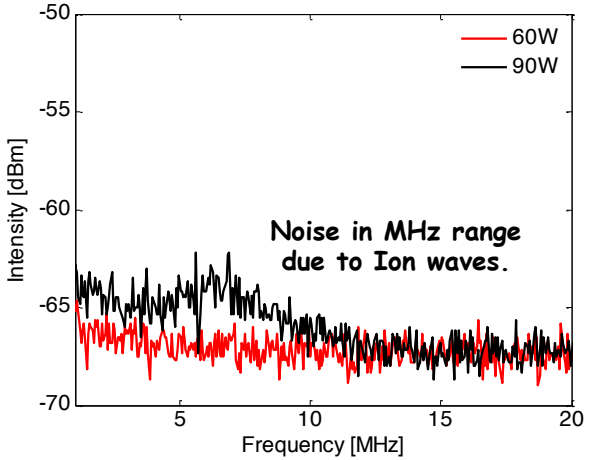
The Flat- B field configuration



At 70 and 100 W **plasma is overdense** everywhere along the LP axis!!!!

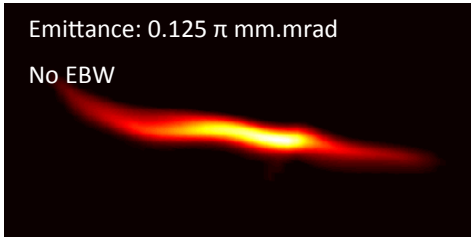
At 13 cm (first harmonics) ion density reaches up to **$5n_{cut-off}$!!!!**
Obtained with only 100 W forward power

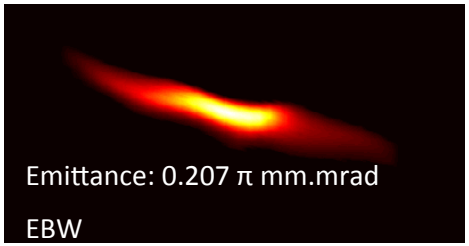
Possible limits of EBW heating



Generation of overdense plasmas by EBW heating is accompanied by the ancillary generation of ion acoustic waves .

Ion waves damping can cause an increase of ion temperature and then of the emittance.





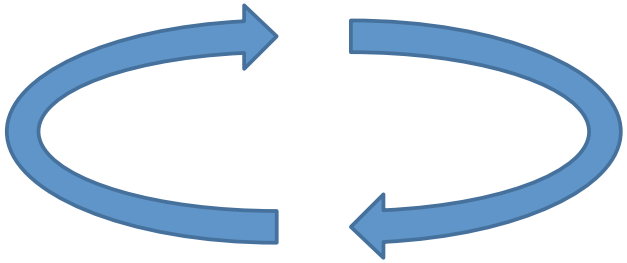
Measured @ VIS testbench

- The **brillance** parameter $B=I/\varepsilon$ must be evaluated;

A new code to characterize the **extracted beam** from **plasma parameter** is in preparation

Stairway to heaven

Tests and measurements



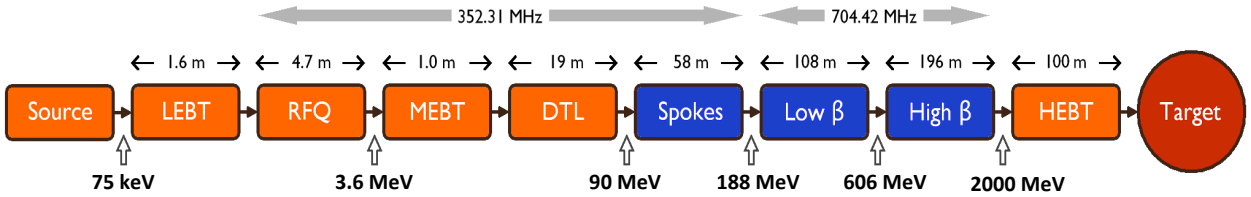
Simulations and modelling

Goal

Plasma parameters (n_e, τ_e) → **B field, P_{rf}, Pressure** → **Beam parameters parameters ($I_{ext.}$, ε)**

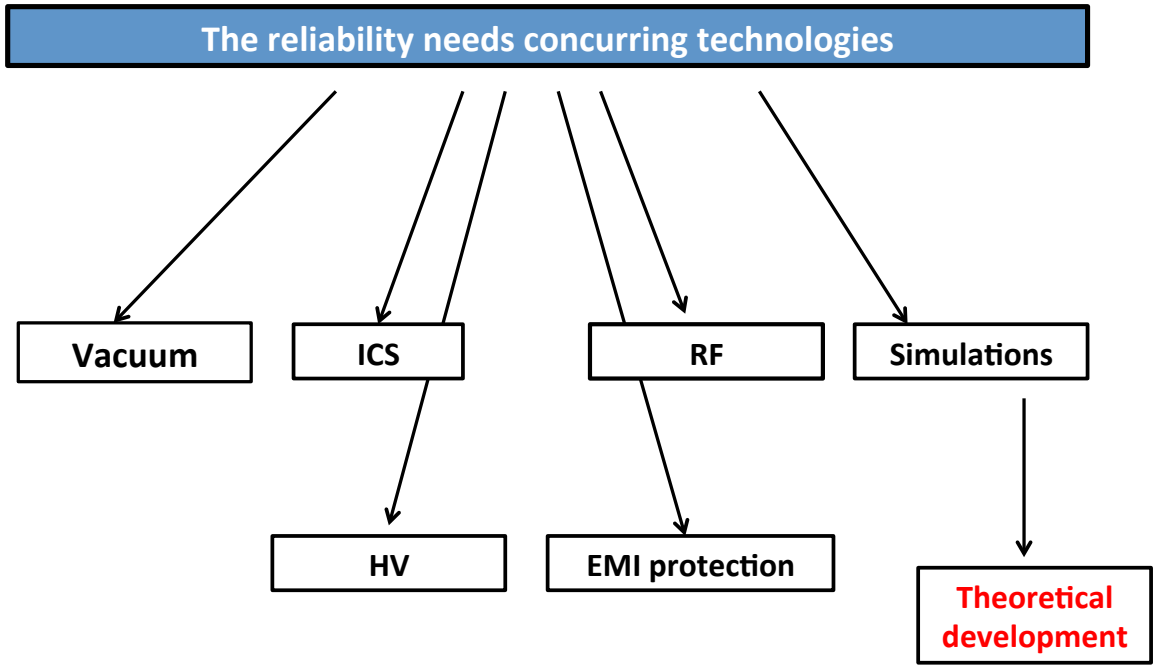
The European Spallation Source (ESS)

The European spallation source

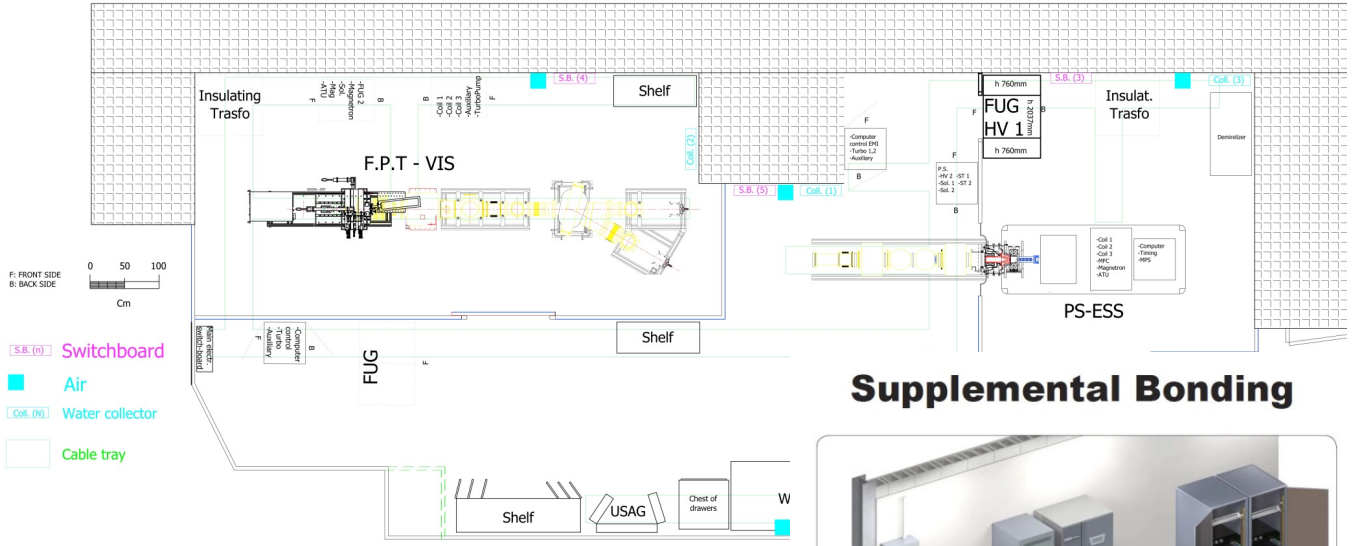


Beam parameters	requirement
Average beam power [MW]	5.0
Macro-pulse length [ms]	2.86
Pulse repetition rate [Hz]	14
Proton kinetic energy [GeV]	2
Beam ripple	Less than +/-2.5%
Duty factor	4%
Proton current at target [mA]	62.5
Ion source current [mA]	90
Total linac length [m]	418
beam pulse rise and fall time	As small as possible

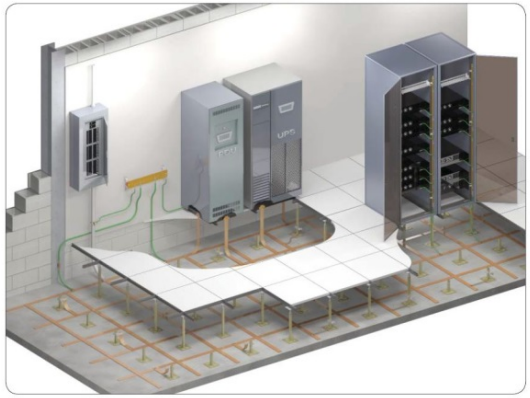
The reliability requirement



PS-ESS area at LNS

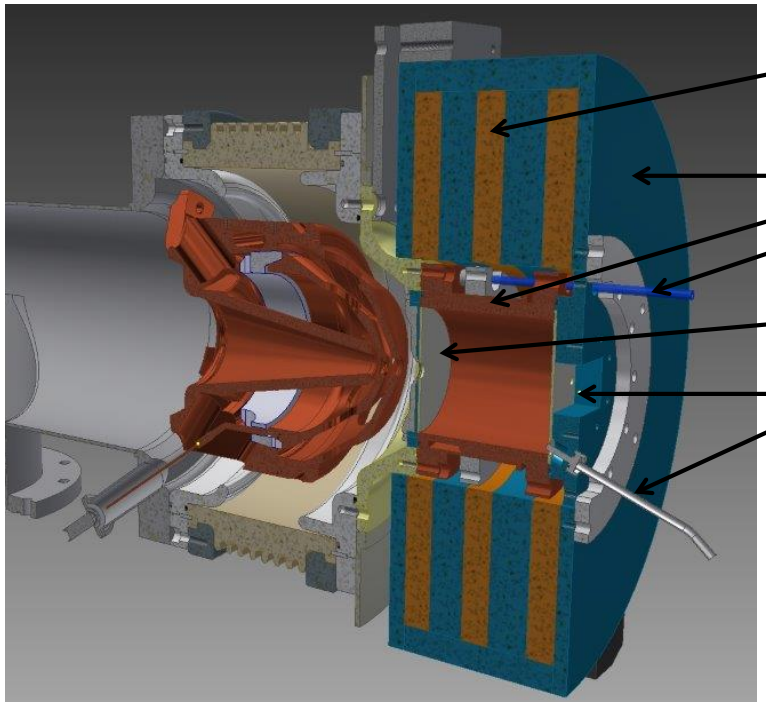


Supplemental Bonding



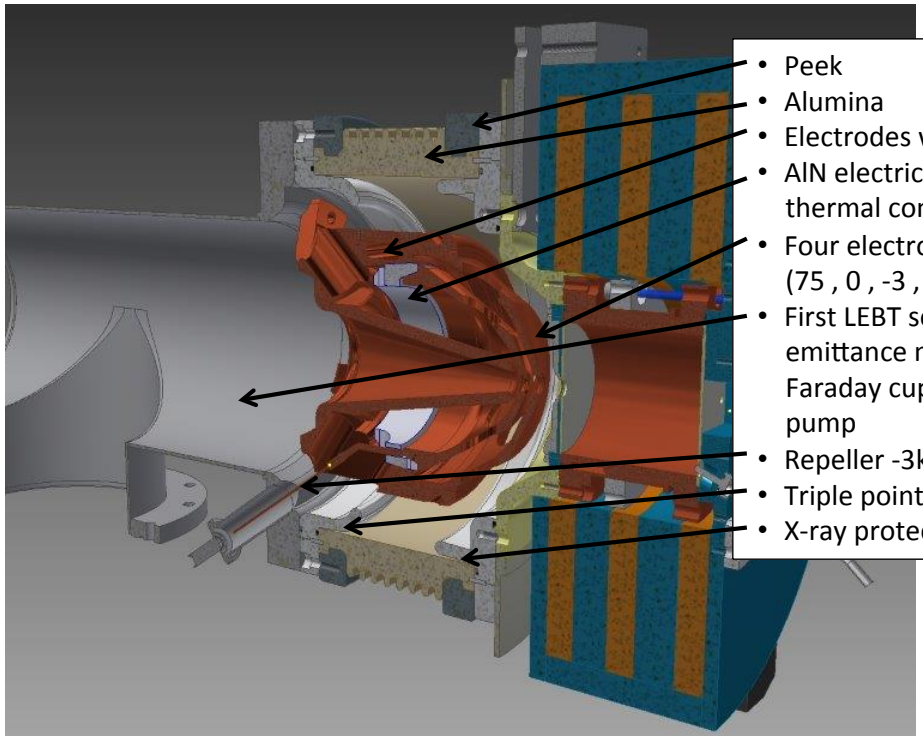
High Frequency Bonding for H.V. sparks

PS-ESS



- Three coils magnetic system to test new plasma heating mechanism
- ARMCO magnetic shielding
- Copper plasma chamber
- Water cooling for plasma chamber
- Two plasma chamber ends with BN disks
- Microwave injection
- Gas injection

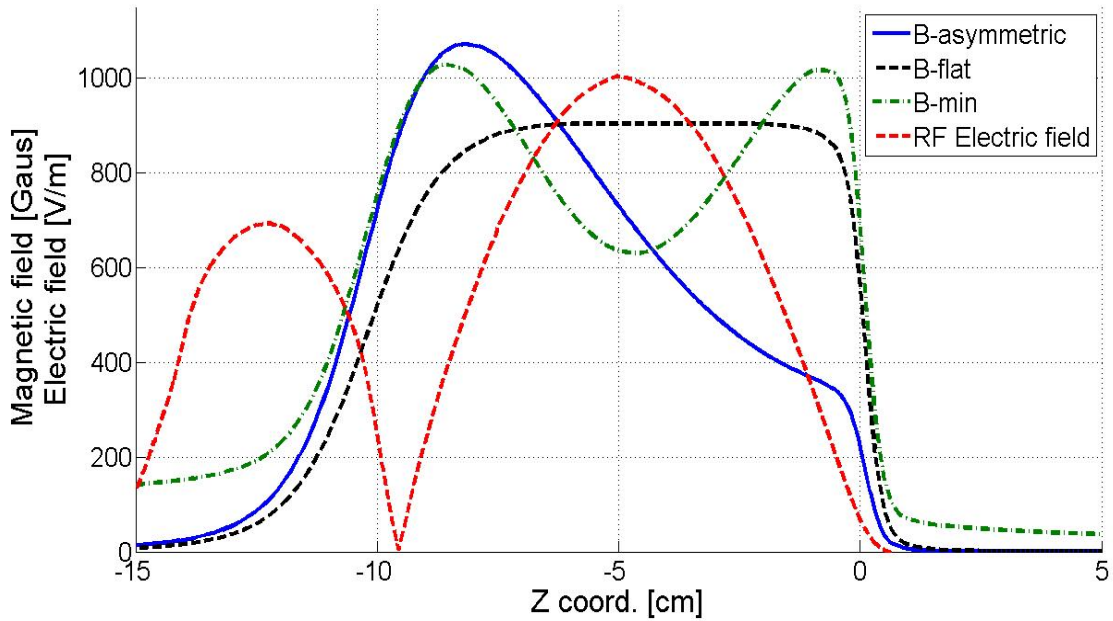
PS-ESS



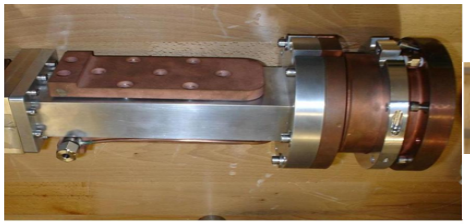
- Peek
- Alumina
- Electrodes water cooling
- AlN electric insulator with high thermal conductivity
- Four electrodes extraction system (75 , 0 , -3 , 0 [kV])
- First LEBT segment with two emittance measurements, a Faraday cup and a turbo molecular pump
- Repeller -3kV connection
- Triple point new geometry
- X-ray protection

PS-ESS magnetic field

The **PS-ESS magnetic field** has been developed on the basis of the **know-how** acquired with the **TRIPS**, **VIS source** and with **plasma reactor**

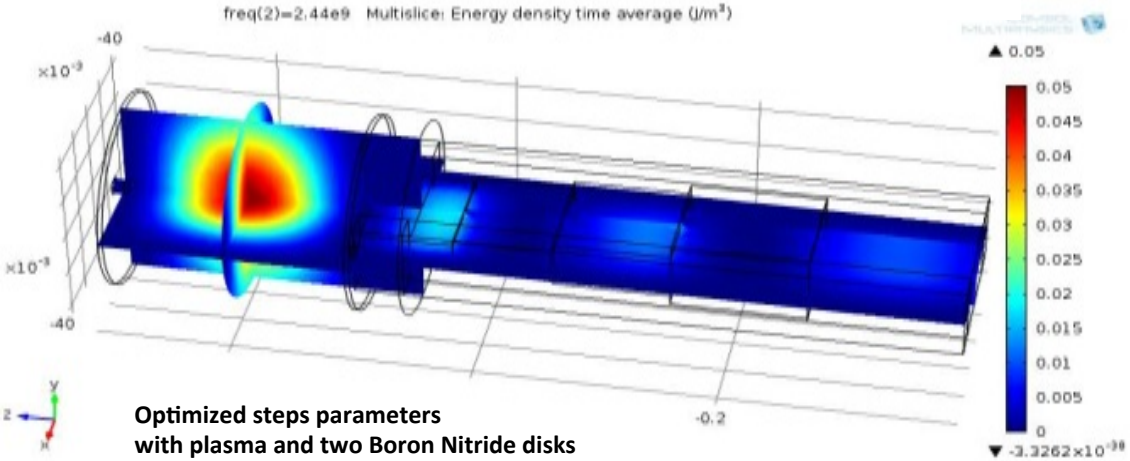


PS-ESS injection



Matching transformer coupled to the plasma chamber

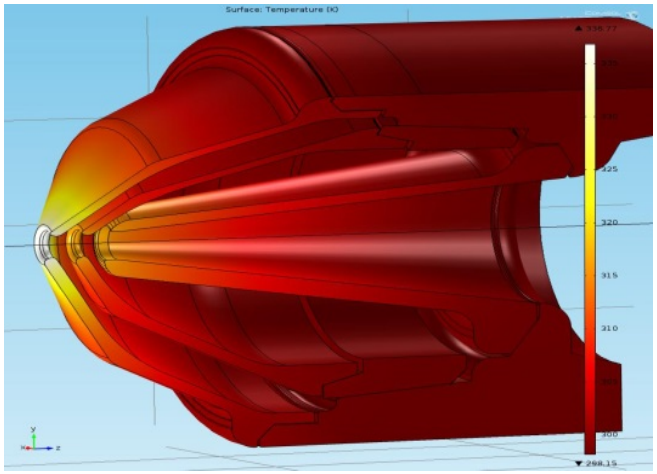
Four step double ridges

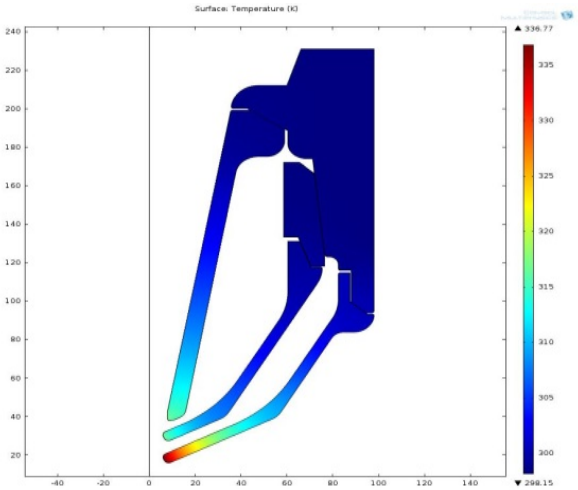


Optimized steps parameters with plasma and two Boron Nitride disks

Extraction system thermal calculation

All the electrodes are cooled, also the repeller by using AlN insulator



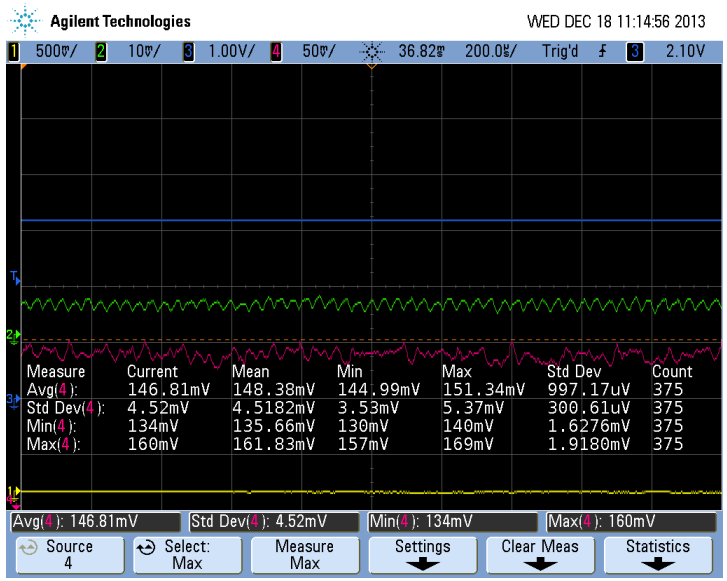


Beam ripple in 2 ms window

Variation of averaged current between different pulses : +1.99% and -2.28%

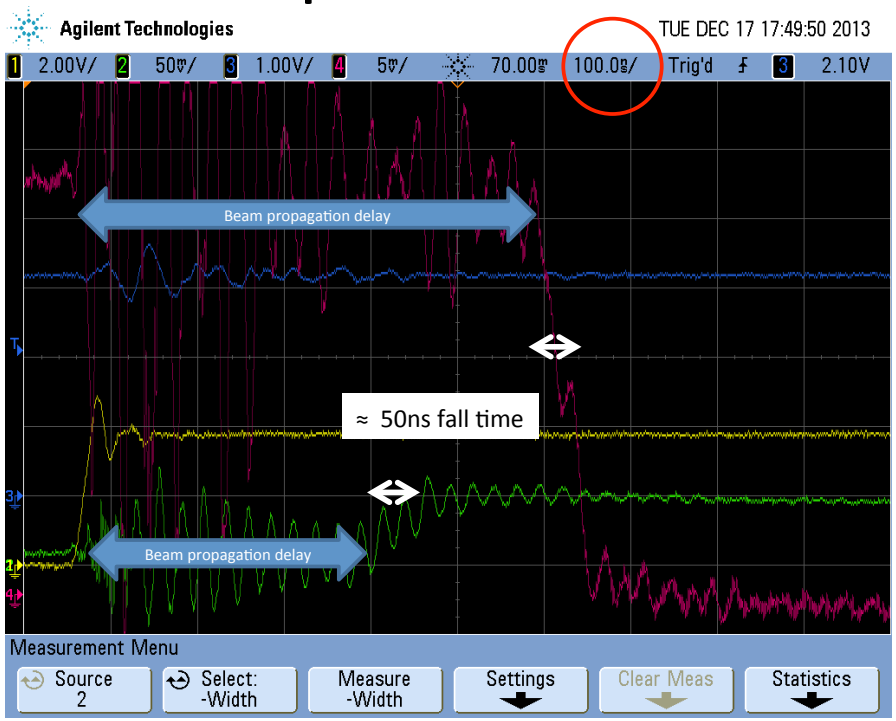
Standard deviation inside a single pulse: between 2,38% and 3.62%

Maximum peak deviation from avaraged current inside a single pulse: -8,57% and +9,06%



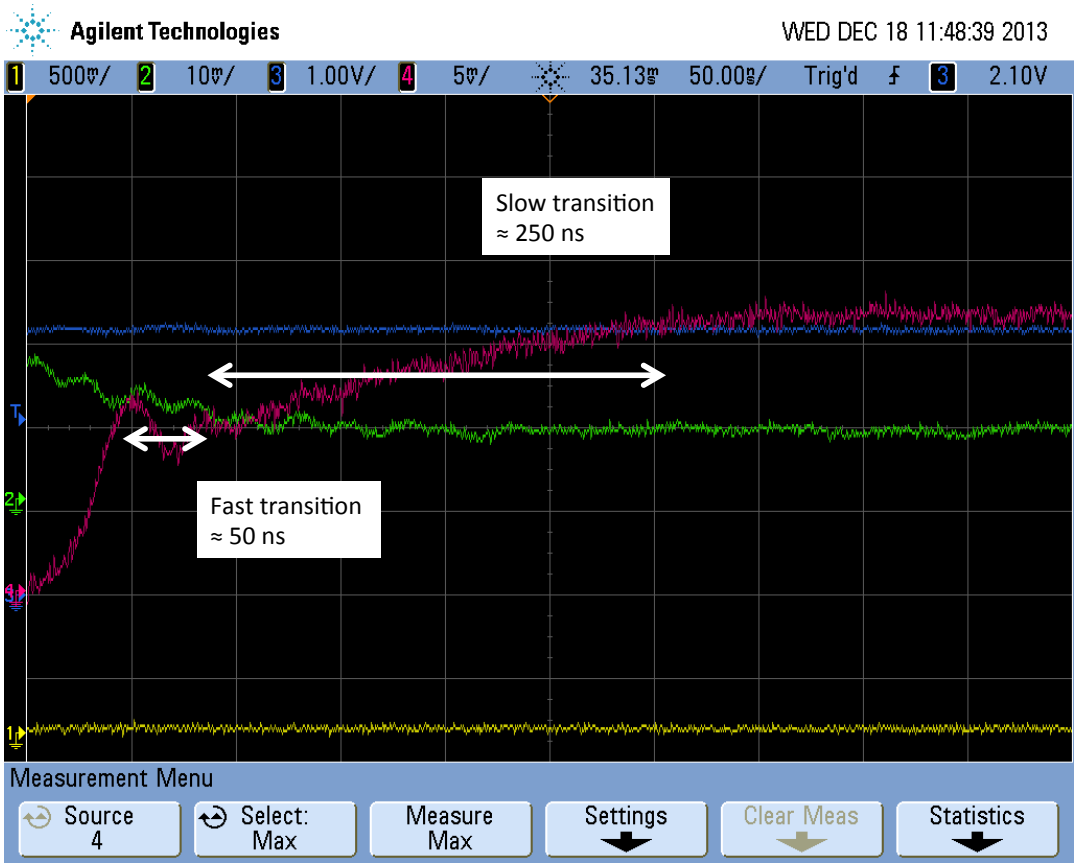
Chopper tests in March 2014 : successful.

Beam pulse fall time



Ch4: Beam Stop (Rτ = 5,5 ohm; C = 183 pf ; Rτ * C = 1 ns)
Ch2: Collimatore (Rτ = 5,5 ohm; C = 534 pf ; Rτ * C = 2,9 ns)

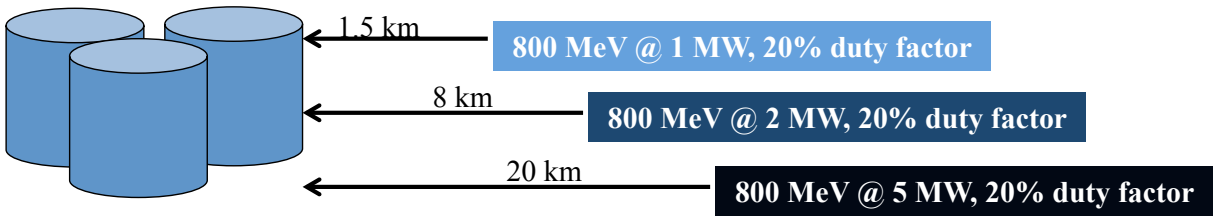
Beam pulse rise time



Next actions:
ISODAR and DAEδALUS

High intensity H_2^+ beams are needed for neutrino physics

The ISODAR e daeδlus experiments



The use of **H_2^+ is key point** for different experiments, like **Daealus and IsoDAR**, which need high intensity proton beams. The use of H_2^+ instead of protons, allows to **decrease** the **generalized perveance** k, the parameter which measures the space charge effect:

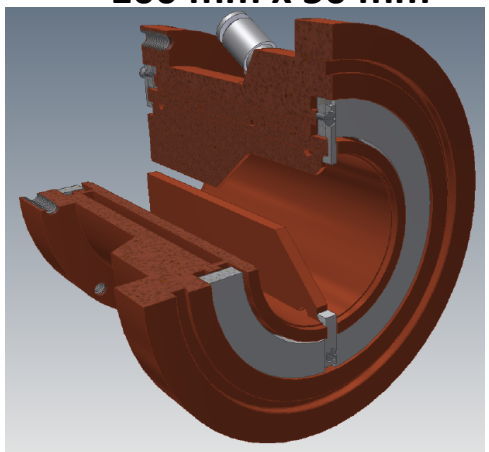
$$K = \frac{qI}{2\pi\varepsilon_0 m\gamma^3\beta^3}$$

Decrease of the chamber dimensions is an option to match ISODAR beam current requirements (50 mA H_2^+)

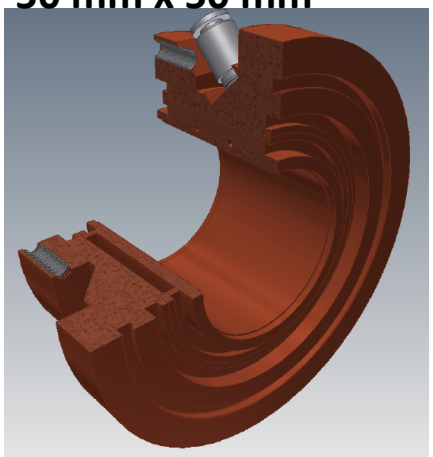
Two new VIS plasma chambers are to be built for BEST test-bench at Vancouver

Old VIS chamber (100 mm x 90 mm)

100 mm x 50 mm



50 mm x 50 mm



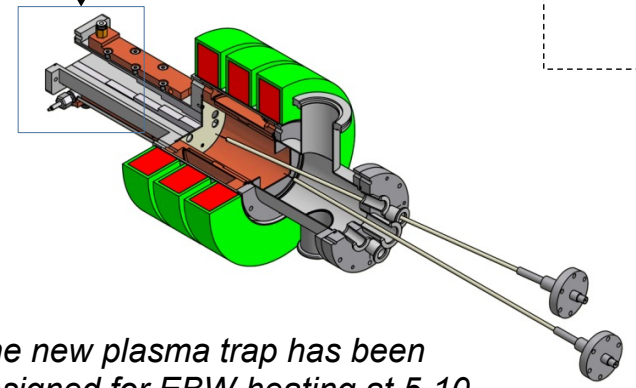
To be tested in next summer

Next actions:

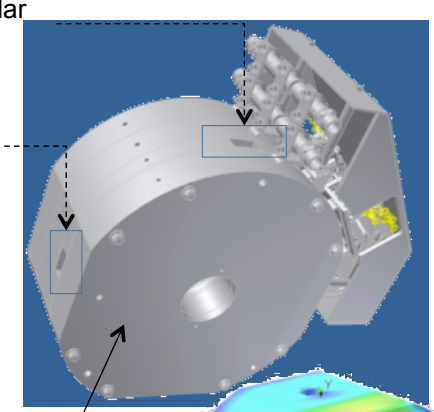
PLASMA TRAP with versatile B-field

PLASMA TRAP with versatile B-field

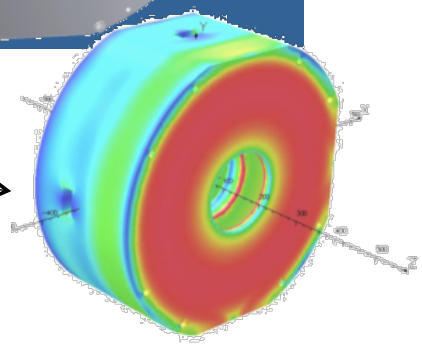
Investigation of EBW-heating under different magnetic field configurations



Parallel and perpendicular launching of EM waves



B-field magnets and structure



The new plasma trap has been designed for EBW-heating at 5-10 GHz:

Simulations on expected plasma density give a factor 10^3 of X-ray flux enhancement

Conclusions

- Larger current, larger brightness, better reliability seem to be achievable in few years' term
- There are 'billion $' projects leading the run (ESS, ISODAR, Daealus IFMIF for p,d as it is SNS for H^-)
- Studies on plasma physics may help to increase output current
- Study of pulsed operation (2 ms-20 Hz) needs more insights
- Looking for short pulse rise time (100 ns)
- Plasma chamber dimensions would modify proton fraction.
- The insertion of insulators may help
- Microwave coupling may improve the brightness
- Plasma physics knowledge may be the key to improve the sources performances

Thank you
for your attention