XXXIX European Cyclotron Progress Meeting

Château de Limelette

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Production of H_2^+ beams for high intensity Cyclotrons: status and perspectives

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INFN LNS

Outline

- **Motivations:**
  The perveance and the space charge limitations;
  The daeδalus and ISODAR experiments;

- **Overview on H_2^+ physics;**
  the state of art;
  the physical problem: limitations and solutions;
  plasma physics and modelling;

- **Experimental set-up and results:**
  The Versatile ion source
  The project for a new plasma chamber
  Extracted current, H_2^+ fraction and emittance measurements;

- **Conclusions and perspectives;**

Ion sources @ INFN-LNS

Proton sources

(1993) Midas

(1997) Midas2

(1999) Trips Ion Source

(2006) P.M. TRIPS

(2007) VIS Ion Source

(2007) Plasma Reactor

(2012) Start of design of PSESS

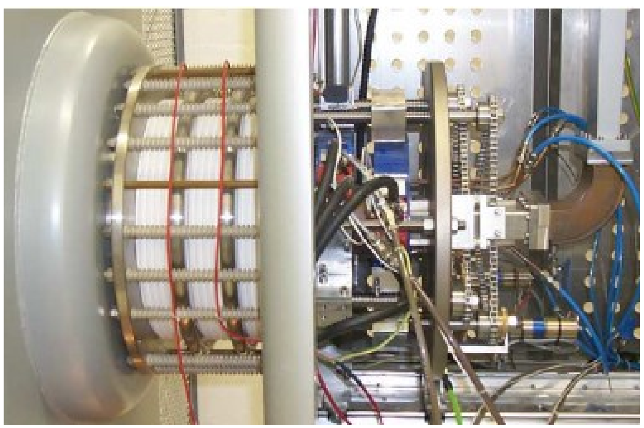
ECRIS for highly charged ion beams

(1999) Caesar

(1998) Serse

(2007) MS eCRIS

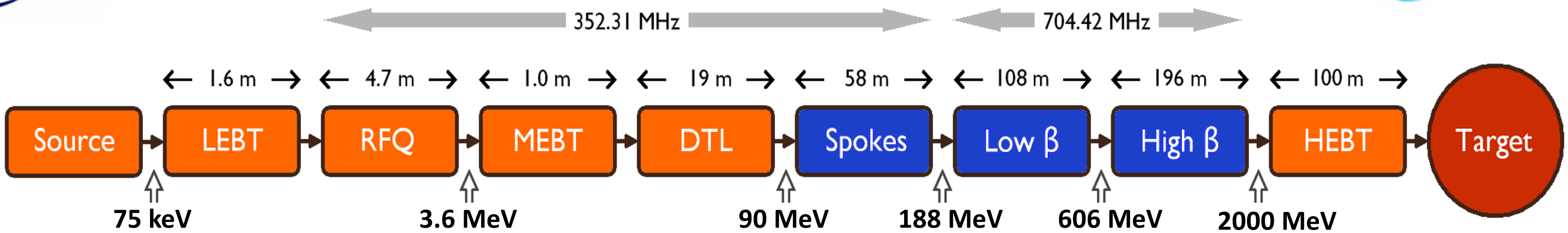
(2013) AiSha



TRIPS

SERSE

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
δI/I (beam ripple)	<2%
Duty factor	4%
Proton current at target [mA]	64
Ion source current [mA]	90
Total linac length [m]	418

100 mA proton current for ESS proton source

DAEδALUS

(Decay At rest Experiment for δ_{CP} At Laboratory for Underground Science)

Physics goal: measuring δ_{CP} using Decay-at-Rest Neutrino Sources

IsoDAR

(ISOtope Decay At Rest)

Searches for light sterile neutrinos with mass 1 eV trough the neutrino oscillations' L/E signature

Requirements

50 mA H_2^+ @ target
by cyclotron acceleration

Space charge limitations

Space charge effects limit **axial injection of proton beams in cyclotrons to 2mA @ 30 keV**

A measure of space charge effects is given by the generalized perveance:

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

Space charge effects decrease with the mass of particles to be accelerated

are H_2^+ molecules an option?

	E_p=30 keV, $E_{H_2^+}$ =30 keV
H^+:10 mA	K_p:1.245 10^{-3}
H_2^+: 5 mA	$K_{H_2^+}$: 0.881 10^{-3}
	$\frac{K_{H_2^+}}{K_p} = 0.707$

	E_p=30 keV, $E_{H_2^+}$=70 keV_{H2}
H^+: 2 mA	K_p: 0.249 10^{-3}
H_2^+: 5 mA	$K_{H_2^+}$: 0.247 10^{-3}
	$\frac{K_{H_2^+}}{K_p} = 0.992$

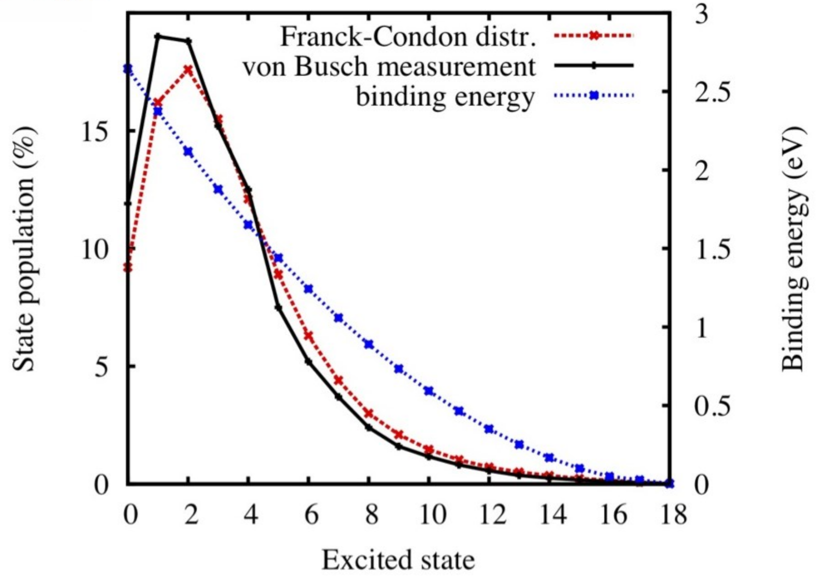
2 mA protons @ 30 keV/amu ⟵ Perveance ⟶ 5 mA H_2^+ @ 35 keV/amu

H_2^+ is then stripped after acceleration into protons

5 mA H_2+ ---------->10 mA protons @target

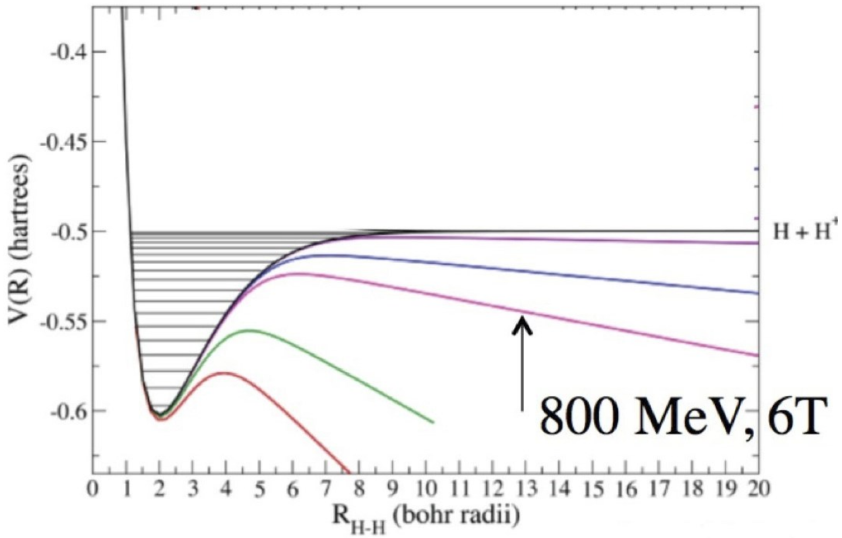
Considering 10% capture, 50 mA H_2+ @35 KeV/amu should be produced

Main drawback



Vibrational States in H_2^+

19 vibrational states
10% with n > 8



Relativistic well distortion leads to unbound upper vibrational states

Upper vibrational states (n>7) should be eliminated to avoid power loss during acceleration

Mitigation possibilities

- In Ion source:

Collisional dissociation of weakly-bound states with noble gases (He, Ne)

$H_2^+ + He \rightarrow HeH^+ + H_0$ exothermic for n > 3

- Lorentz strip in transport line at 60 MeV/amu

10T to dissociate highest vibrational states (a 20T magnetic field should be sufficient to dissociate all the vibrational states)

- Controlled loss at high energy

Selected magnetic bumps to contain lost particles

- **Further ideas are welcome**

Very interesting atomic physics challenges ahead!

(Chupka & Russell, J. Chem Phys 48 (1968) 1518)
Sen et al., J. Phys. B: At. Mol. Phys. **20** (1987) 1509-1515
Kaplan et al., Phys. Rev. Lett. 7, 3 (1961)

State of art (1)

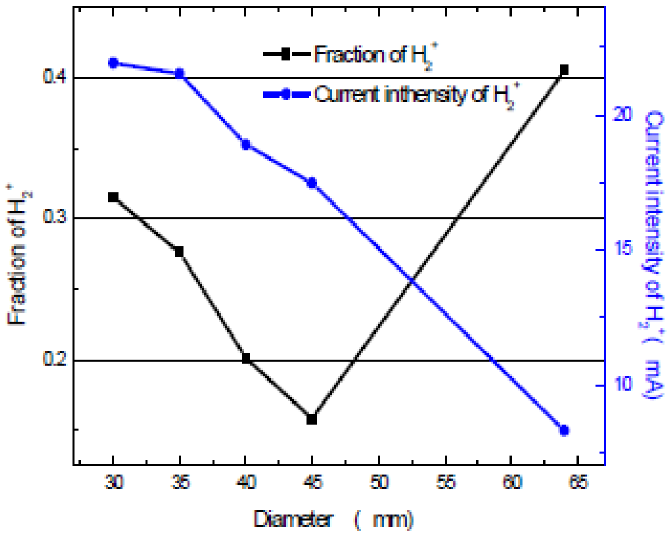
- R. F. King *et al.* proposed a one-dimensional plasma model for a volume arc source, expected to produce up to ***140 mA*** of ion beam with ***73% H_2^+ fraction,*** but it wasn't realized.

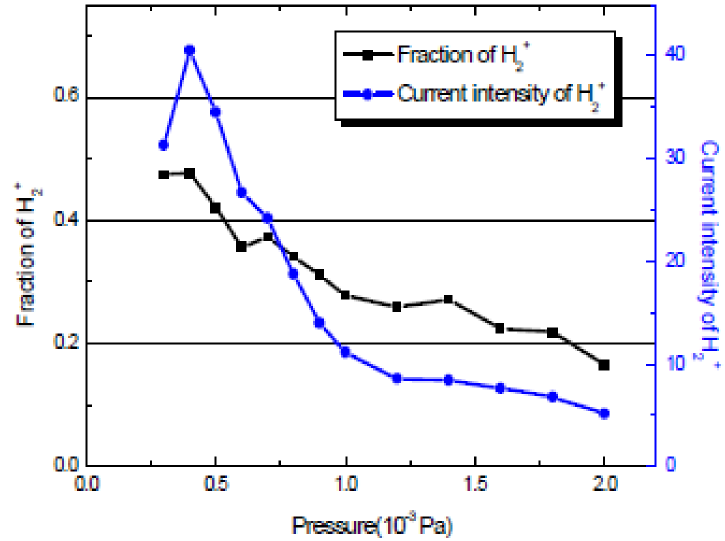
R. F. King, E. Surrey, and A. J. T. Holmes, Fusion Eng. Des. **83**, 1553 (2008).

- N. Joshi *et al.* developed a volume type ion source at Frankfurt University, with ***91% H_2^+ fraction***, but ***only 2.84 mA*** were extracted.

N. Joshi M. Droba, O. Meusel and U. Ratzinger, Physics Research A, **606** (2009) 310–313

- In 2013 The *Beijing ion source produced up to* ***40 mA H_2^+ beam*** *and more than* ***50% H_2^+ fraction*** *by using a PM ECRIS*



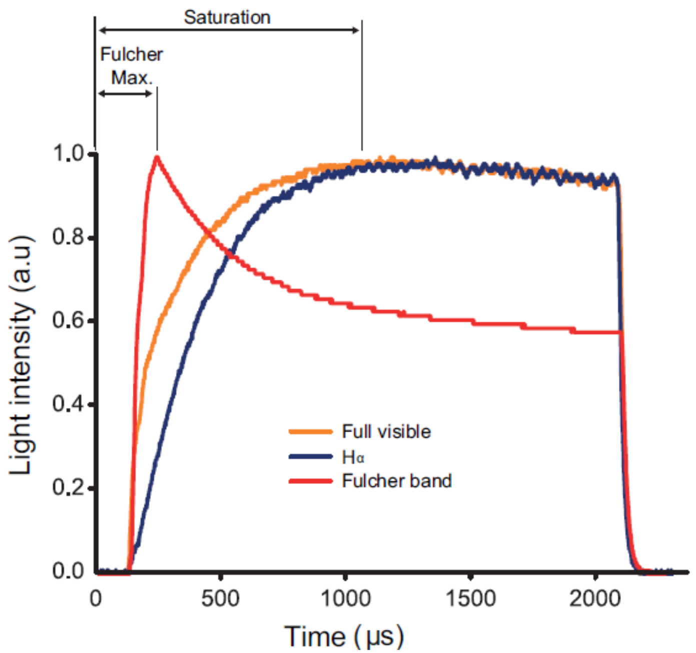


Hu et al. Review of Scientific Instruments **85**, 02A943 (2014);

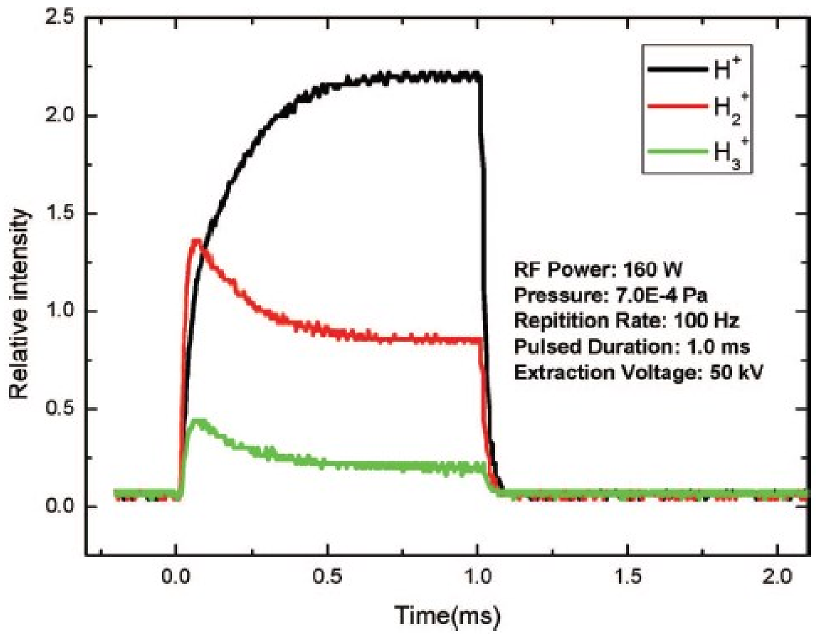
State of art (2)

Chance to intra-plasma diagnotics by means of optical (390–700 nm) spectroscopy:

Balmer-alpha (656.3 nm), Fulcher band (around 600 nm)



Cortazar et al Nucl. Instrum. and Methods A 781 (2015) 50–56



Y. Xu et al. Rev. of Scie. Instrum. **85**, 02A943 (2014);

Room for improvements

Our Approach:
More efforts on plasma physics

Steps of plasma modelling

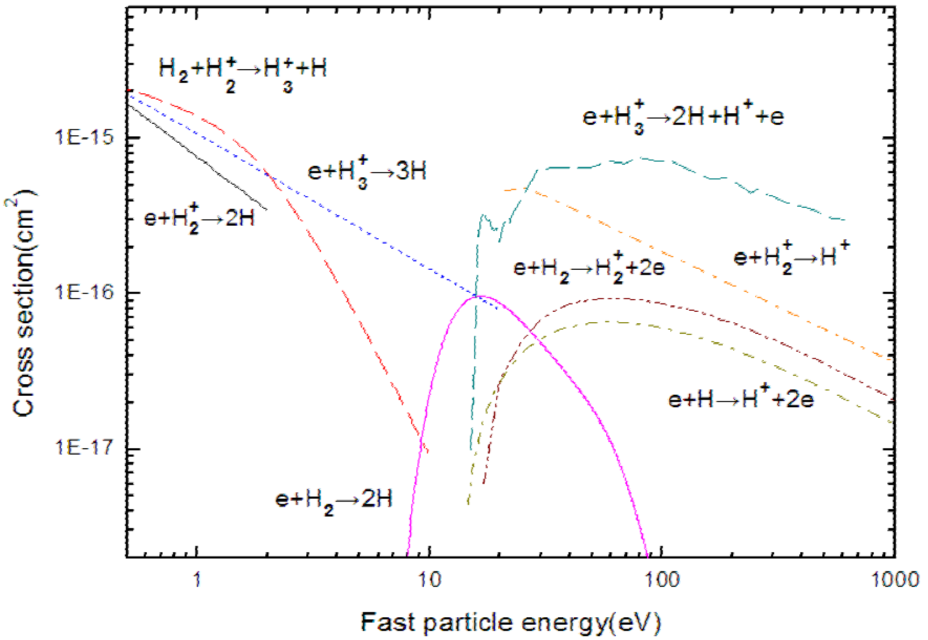
0) Zero- dimensional modelling (solving of balance equations);

1) Single particles modelling (particle motion in superimposed electric field);

2) Full self-consistent modelling (plasma particles motion affect plasma chamber electric field and viceversa);

The balance equations approach

1) $H + e^- \rightarrow H^+ + 2e^-$
2) $H_2 + e^- \rightarrow H + H^+ + 2e^-$
3) $H_2^+ + e^- \rightarrow H + H^+ + e^-$
4) $H_2^+ + e^- \rightarrow H^+ + H^+ + 2e^-$
5) $H_2^+ + H \rightarrow H_2 + H^+$
6) $H_2 + H^+ \rightarrow H_2^+ + H$
7) $H_2 + e^- \rightarrow H_2^+ + 2e^-$
8) $H_3^+ + e^- \rightarrow H_2^+ + H + e^-$
9) $H_2^+ + e^- \rightarrow H^* + H$
10) $H_2^+ + H_2 \rightarrow H_3^+ + H$
11) $H_3^+ + e^- \rightarrow 3H$
12) $H_3^+ + e^- \rightarrow H_2 + H$
13) $H_2 + e^- \rightarrow 2H + e^-$

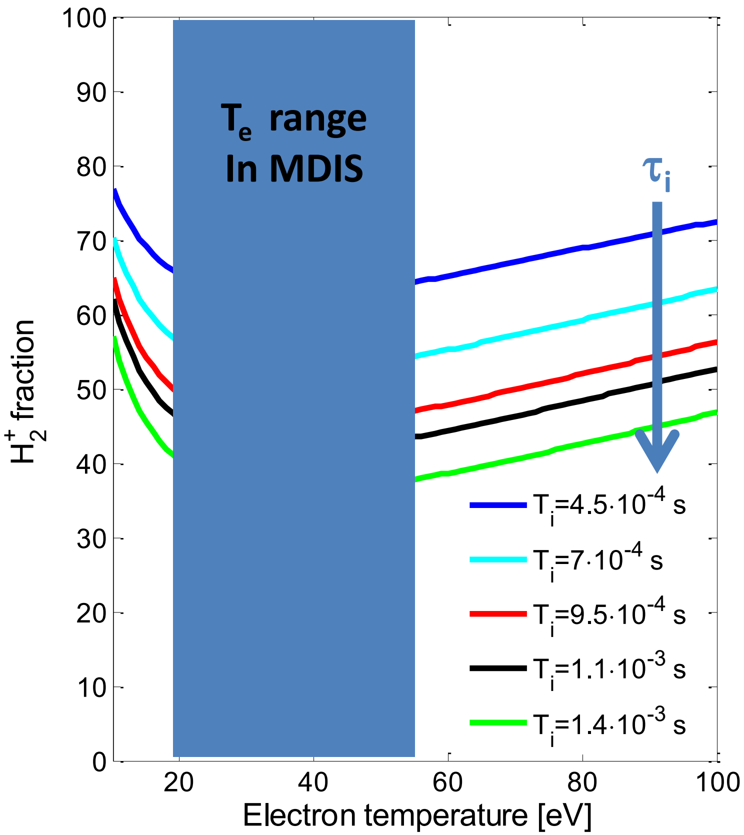


reactions at the walls

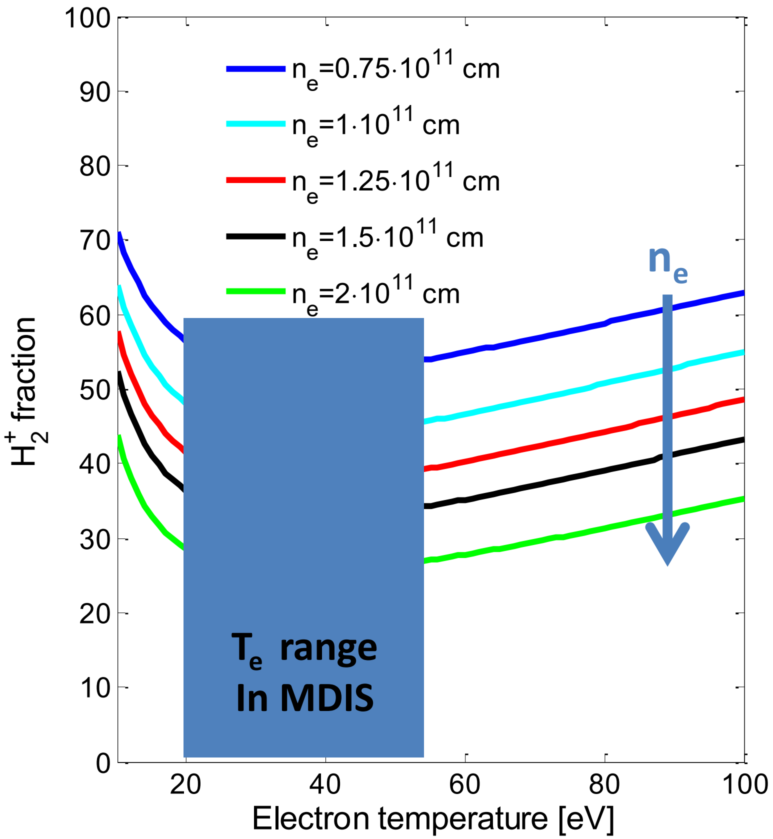
1) $H + \text{walls} \rightarrow H_2$ $\gamma = 0.03$
2) $H^+ + \text{walls} \rightarrow H$ $\gamma = 0.9$
3) $H_3^+ + \text{walls} \rightarrow H_2 + H$ $\gamma = 0.9$

Generation of H_2^+ in hydrogen discharge

Fixed density: $n_e=1\cdot10^{11}\ cm^{-3}$



Fixed ion lifetime: $\tau_i=1\cdot10^{-3}$ s



In the MDIS range, Electron temperature is a less important parameter w.r.t. ion lifetime and electron density for H_2^+ fraction determination

Generation of H_2^+ in hydrogen discharge

Decrease of electron density:

Decrease of ion lifetime:

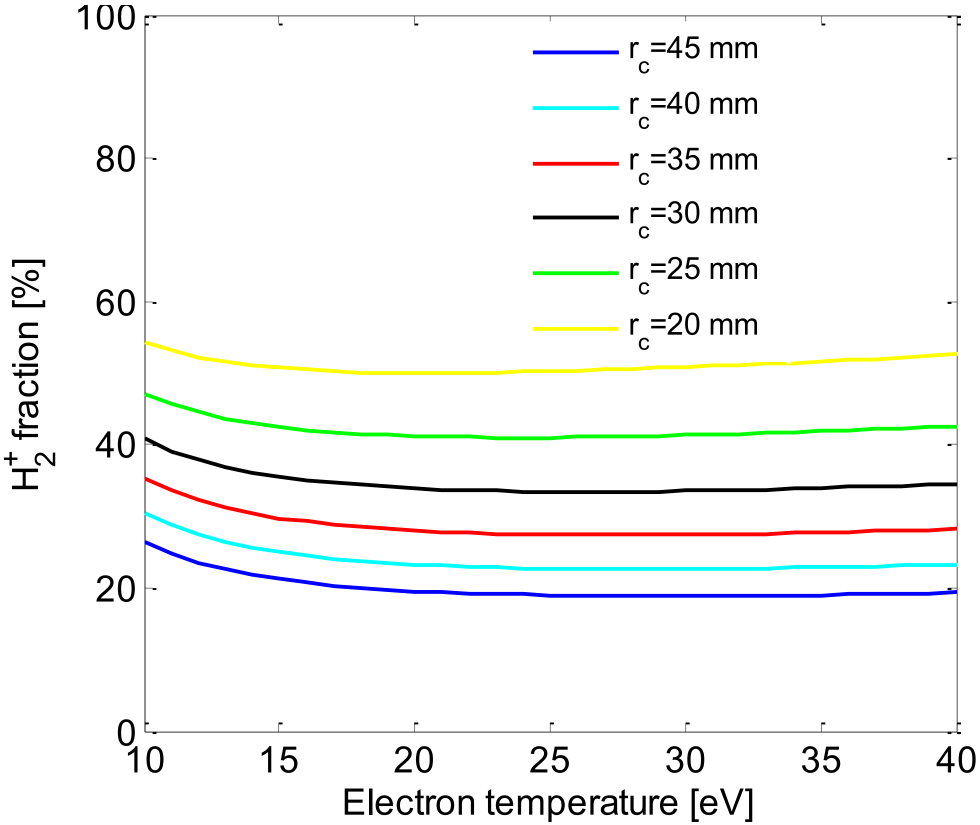
Generation of H_2^+ in hydrogen discharge

Decrease of electron de

Decrease of ion lifetime:

Influence of chamber radius on ion lifetime

n_e=1·10^{11} cm^{-3}
t_i = 0.500 ms (estimated by experimental results)
L=100 mm



Simulated **H_2^+ fraction** increase with the **chamber radius decrease**.

A **Smaller plasma chamber radius** enables **higher H_2^+ currents**

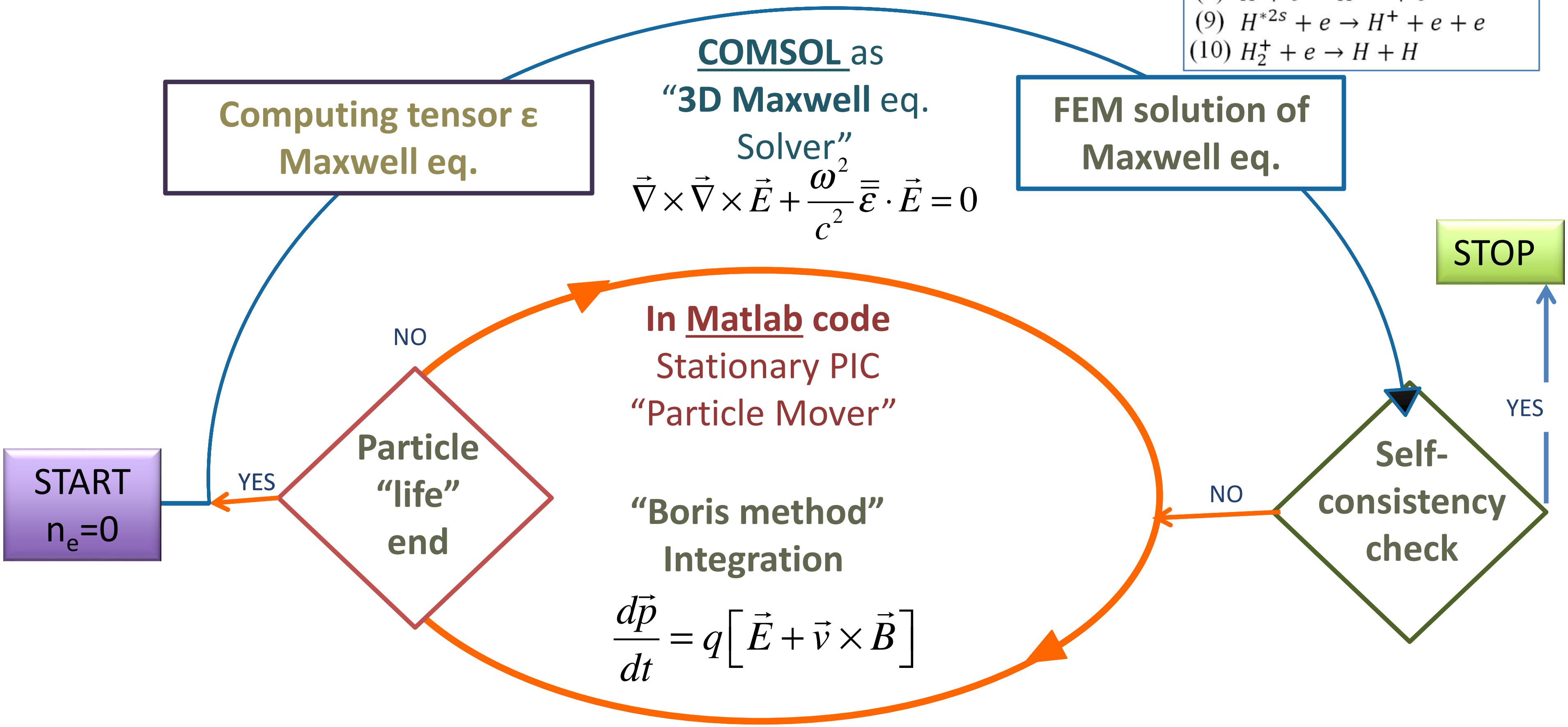
Steps of plasma modelling

1) Single particles modelling (particle motion in superimposed electric field);

2) Full self-consistent modelling (plasma particles motion affect plasma chamber electric field and viceversa);

Diagram showing our “Stationary” PIC strategy

(1) $H_2 + e \rightarrow H + H + e$
(2) $H_2 + e \rightarrow H_2^+ + e + e$
(3) $H_2 + e \rightarrow H^+ + H + e + e$
(4) $H_2^+ + e \rightarrow H^+ + H + e$
(5) $H_2^+ + e \rightarrow H^+ + H^+ + e + e$
(6) $H + e \rightarrow H^+ + e + e$
(7) $H + e \rightarrow H^{*2p} + e$
(8) $H + e \rightarrow H^{*2s} + e$
(9) $H^{*2s} + e \rightarrow H^+ + e + e$
(10) $H_2^+ + e \rightarrow H + H$



Ionizations and neutralizations 3-D distribution inside the plasma chamber

Creation: Protons , Electrons , H_2^+

Distruction: Electrons , H_2^+

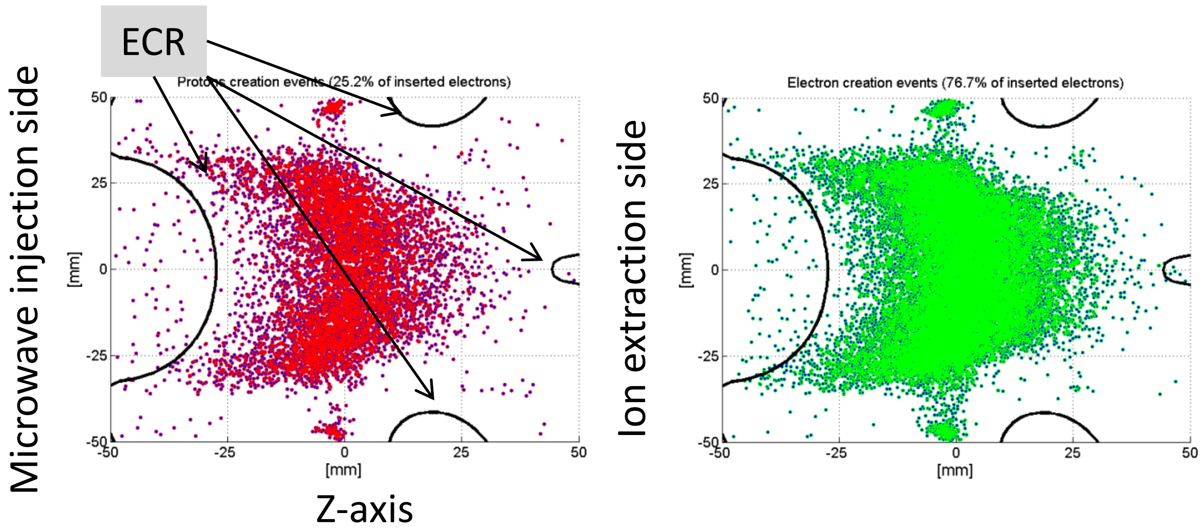
Preliminary results!!

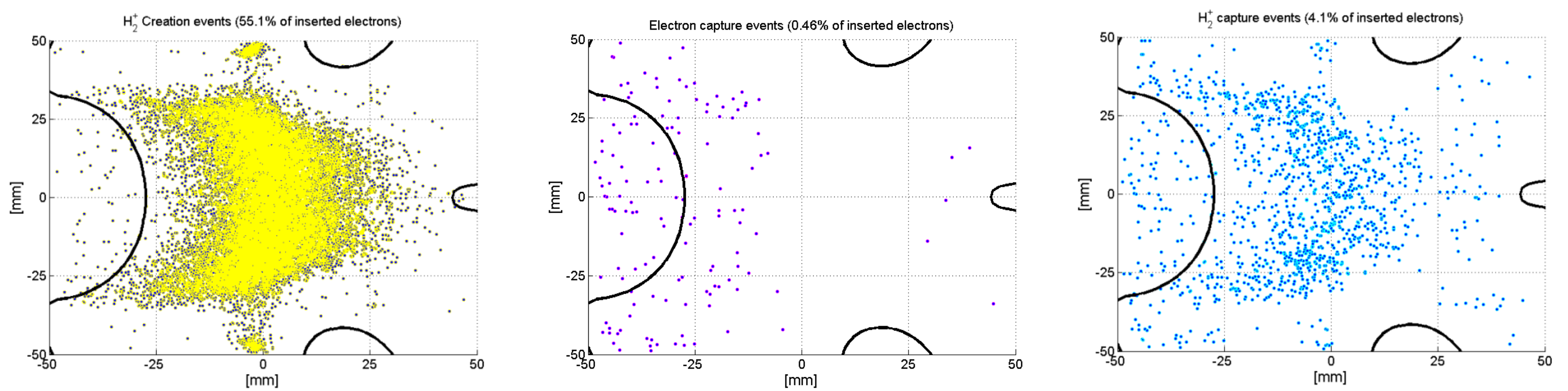
TABLE I. Counts for the reactions taken into account.

ID	1	2	3	4	5
Counts	8766	16521	710	1069	24
ID	6	7	8	9	10
Counts	5757	7014	858	0	138

TABLE II. Production of particles.

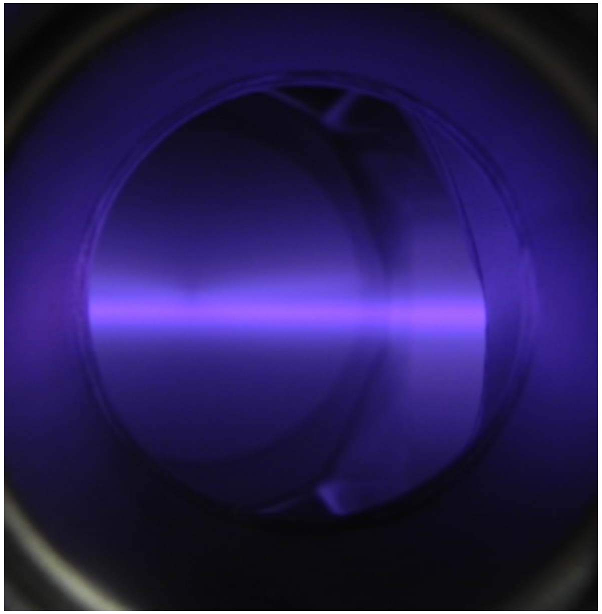
ID	H	H_2	H^+	e^-	H_2^+
Counts	5958	-25997	7584	22874	15290





Neri et. Al., Recent progress in plasma modelling at INFN-LNS, accepted for publication on Rev. of Scie. Instrum.

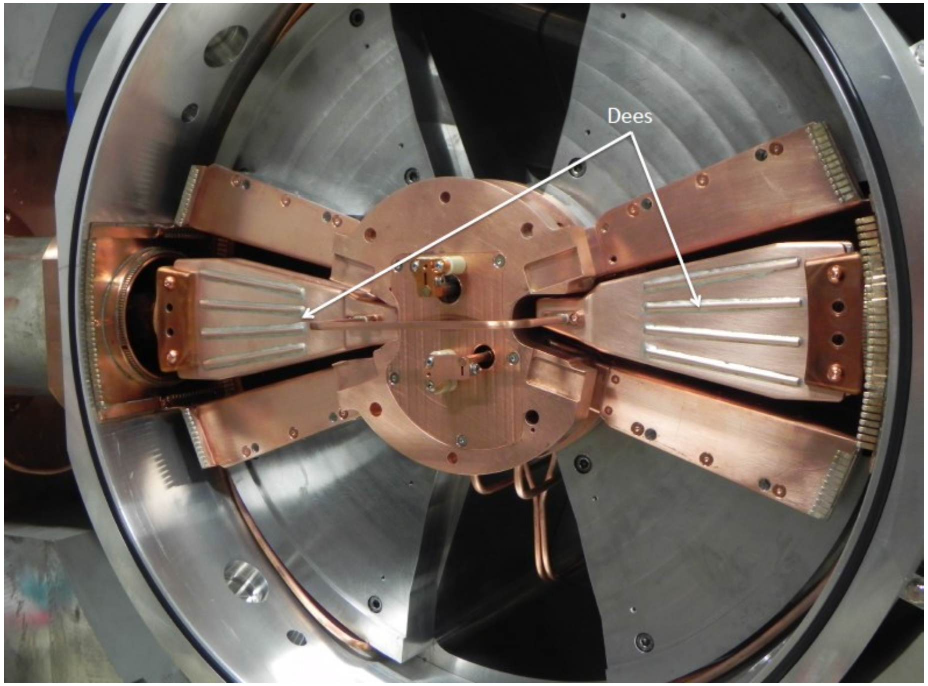
From theory and models to experimental results



Proof of principle tests @ BEST- Vancouver

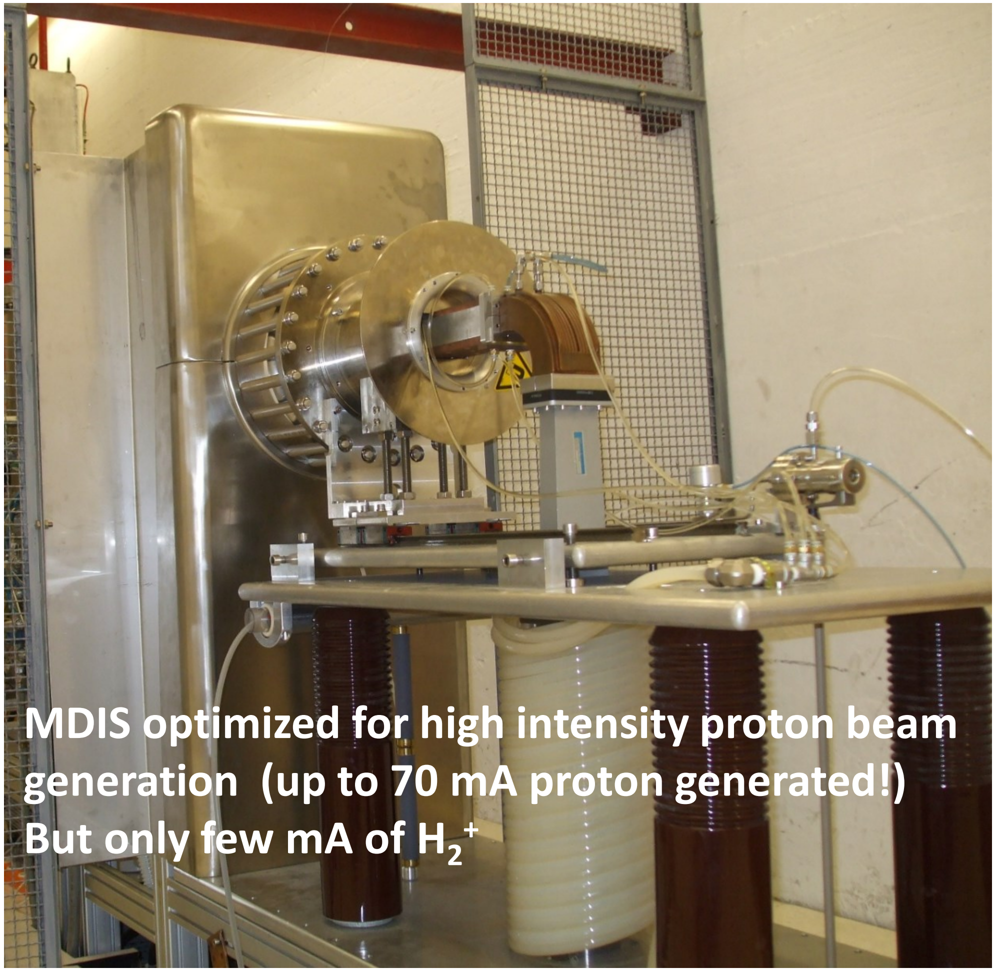
10-15 mA needed for proof-of-principle injection tests:

Electrostatic Spiral Inflector and Central region to be tested



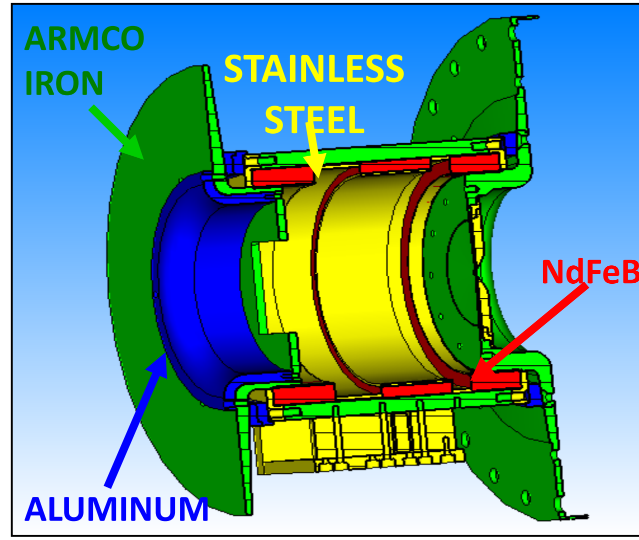
INFN-LNS Ion source group has been involved by BEST for high power H_2^+ beam generation for tests

The Versatile Ion Source

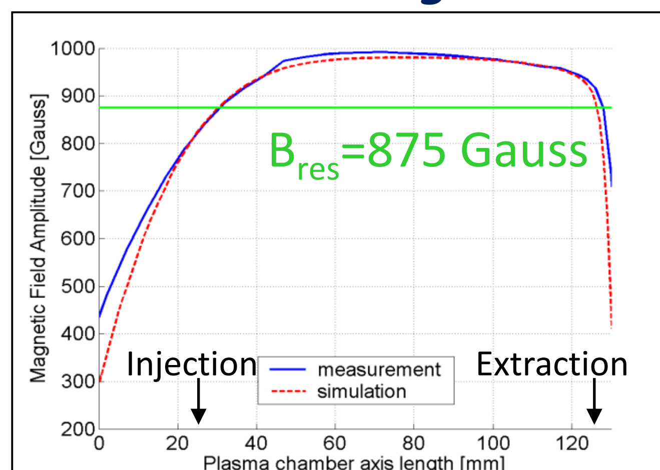


MDIS optimized for high intensity proton beam generation (up to 70 mA proton generated!)
But only few mA of H_2^+

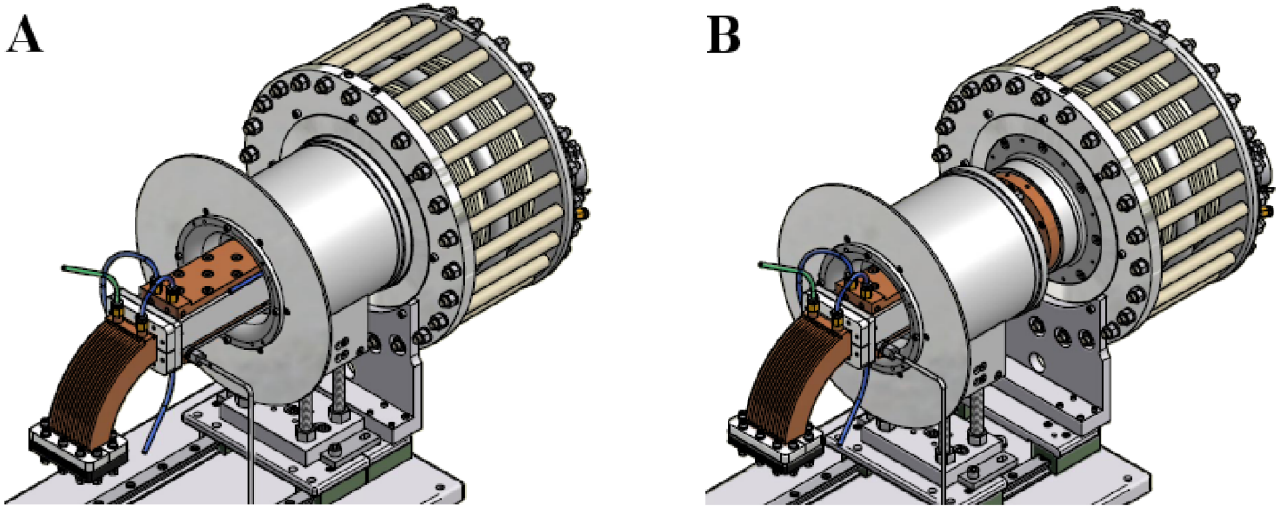
Test-bench for studies towards PS-ESS source moved to Vancouver in late 2013

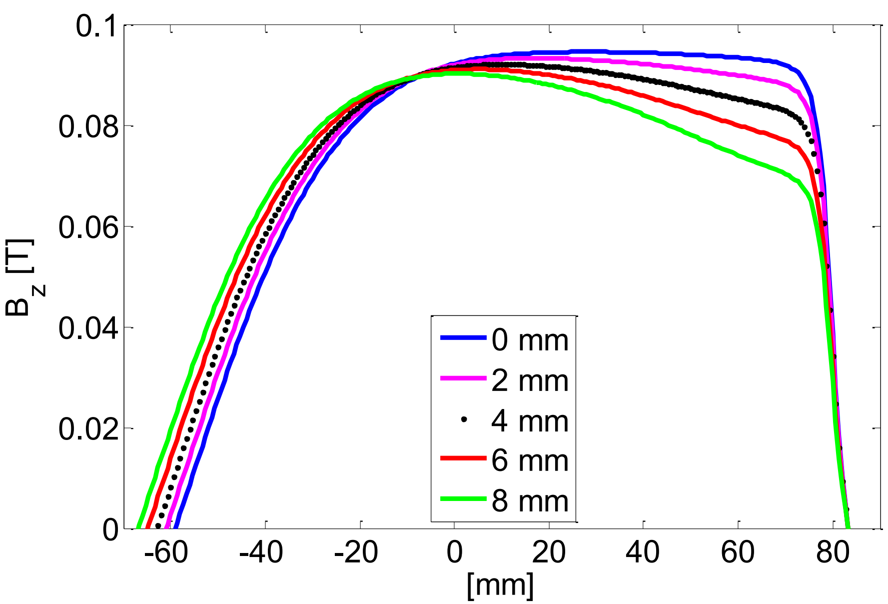


Permanent magnets



The shift of permanent magnets

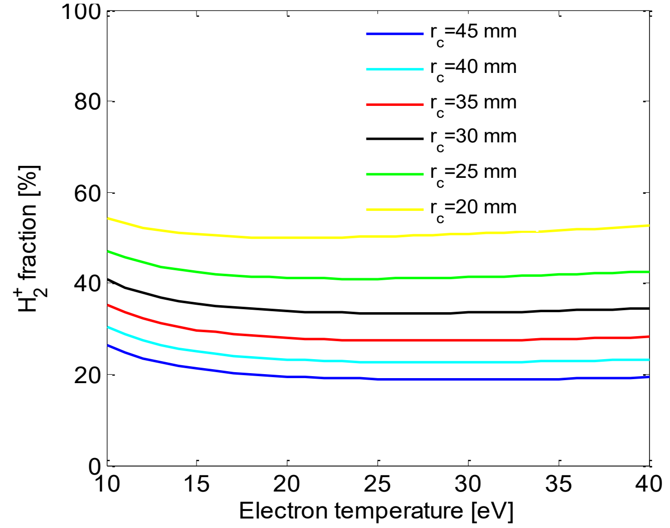




The new plasma chamber

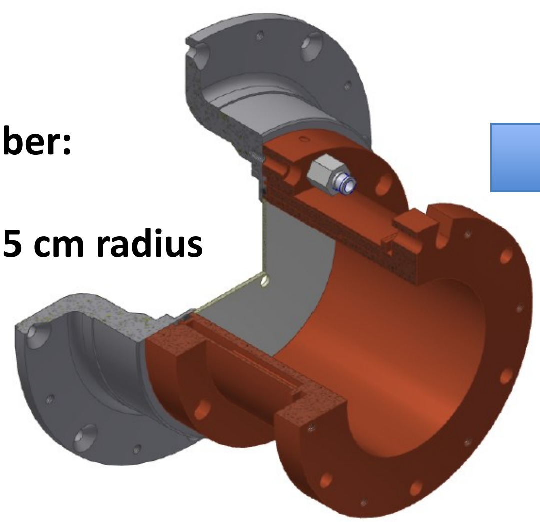
- Physical constraints impede to modifiy magnetic field shape or extraction electrodes

- Results from zero-dimension modelling suggested that a lower plasma chamber radius could allow higher H_2^+ fraction



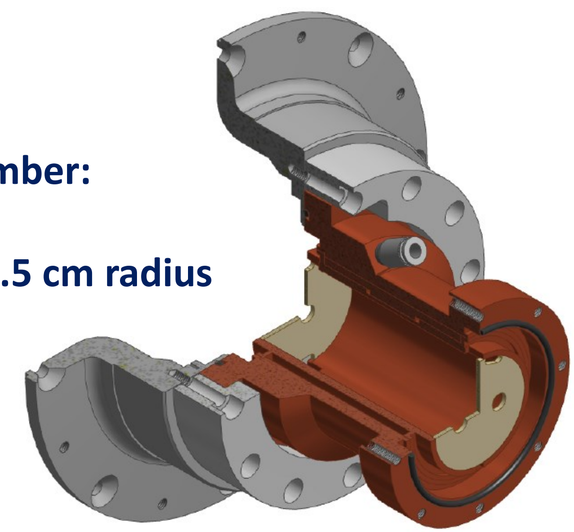
Standard chamber:

10 cm length x 5 cm radius



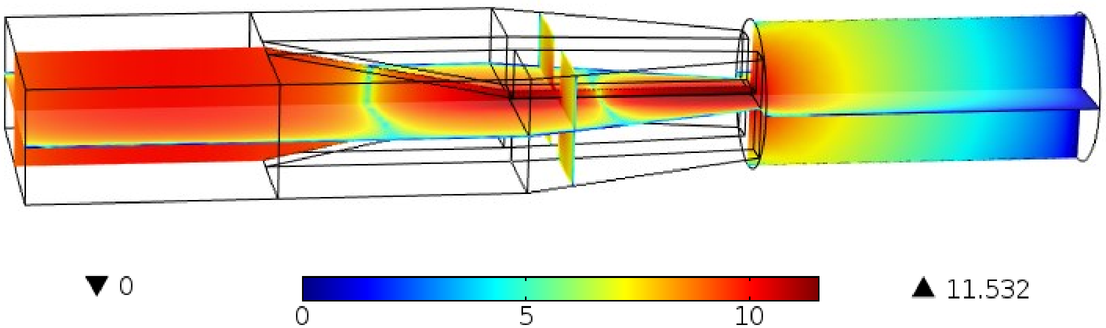
New chamber:

10 cm length x 2.5 cm radius

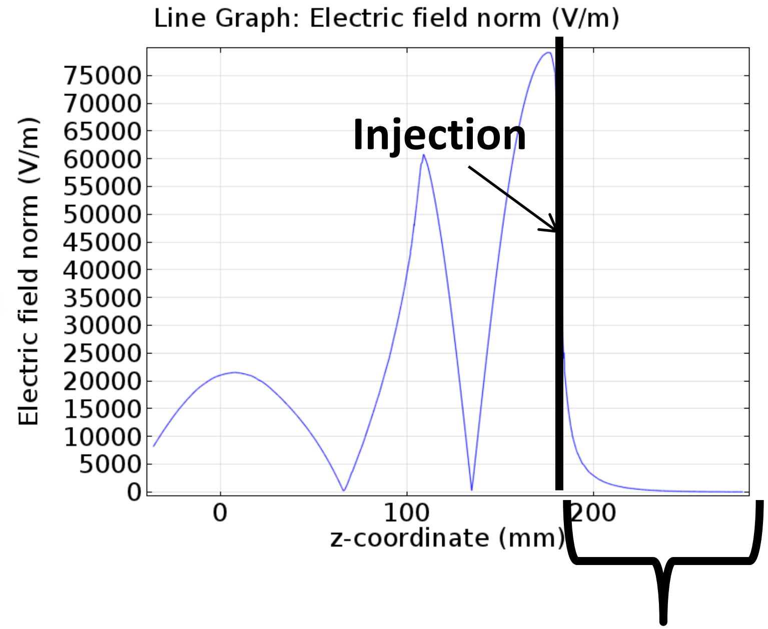


Toward a smaller chamber radius: new waveguide for E.M coupling with plasma chamber

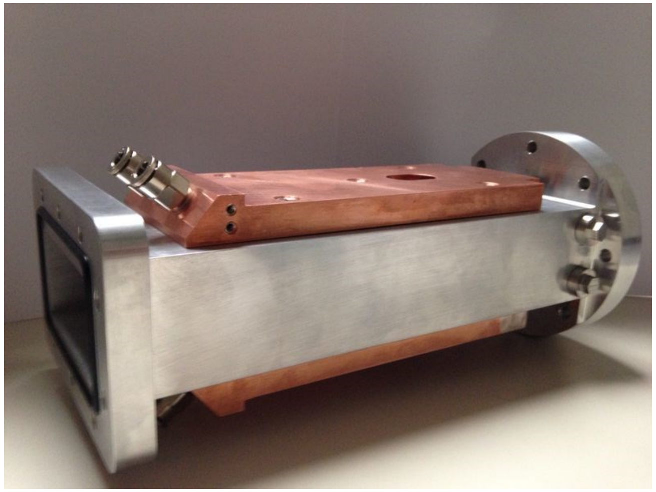
The new 2.45 Ghz plasma source with 25 mm radius chamber was simulated and tested.



|E| Electric field on a multislice (log scale)



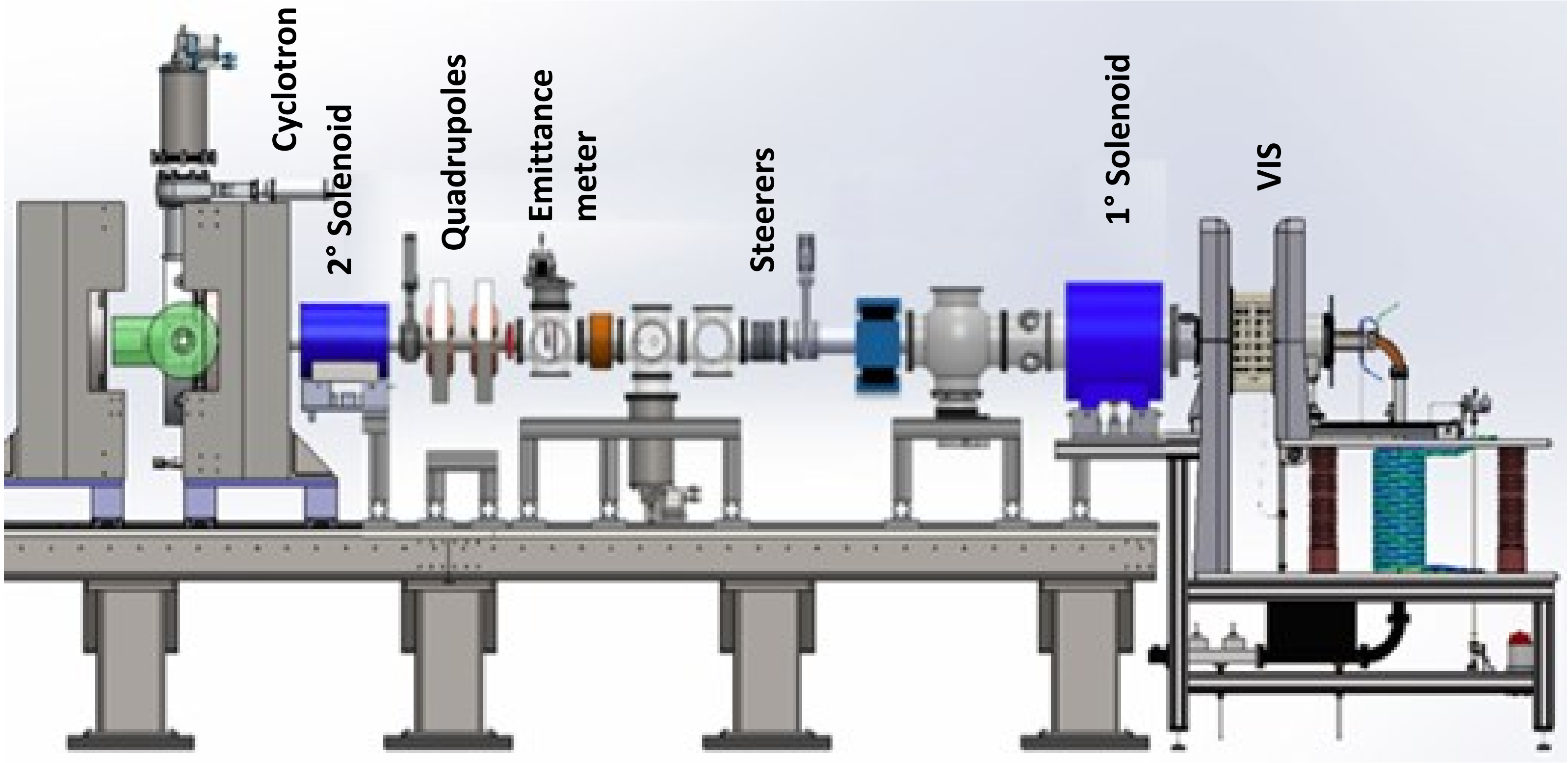
Plasma chamber



No resonant mode inside the plasma chamber because the **fundamental mode TE_{111}** (3.8 GHz) > RF signal (2.45 GHz)

EM-ES coupling and plasma injection?

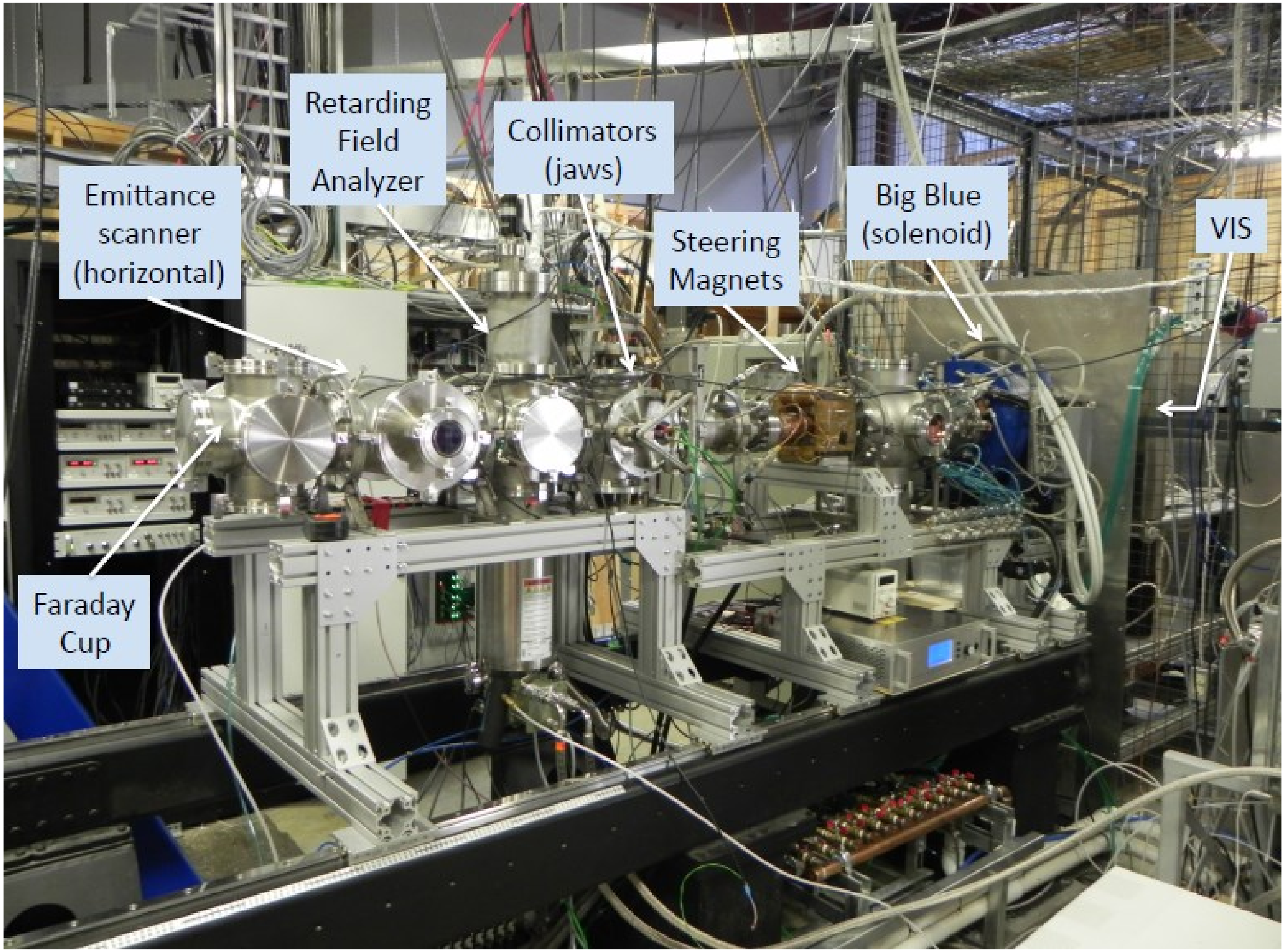
BEST-company testbench



Work configuration

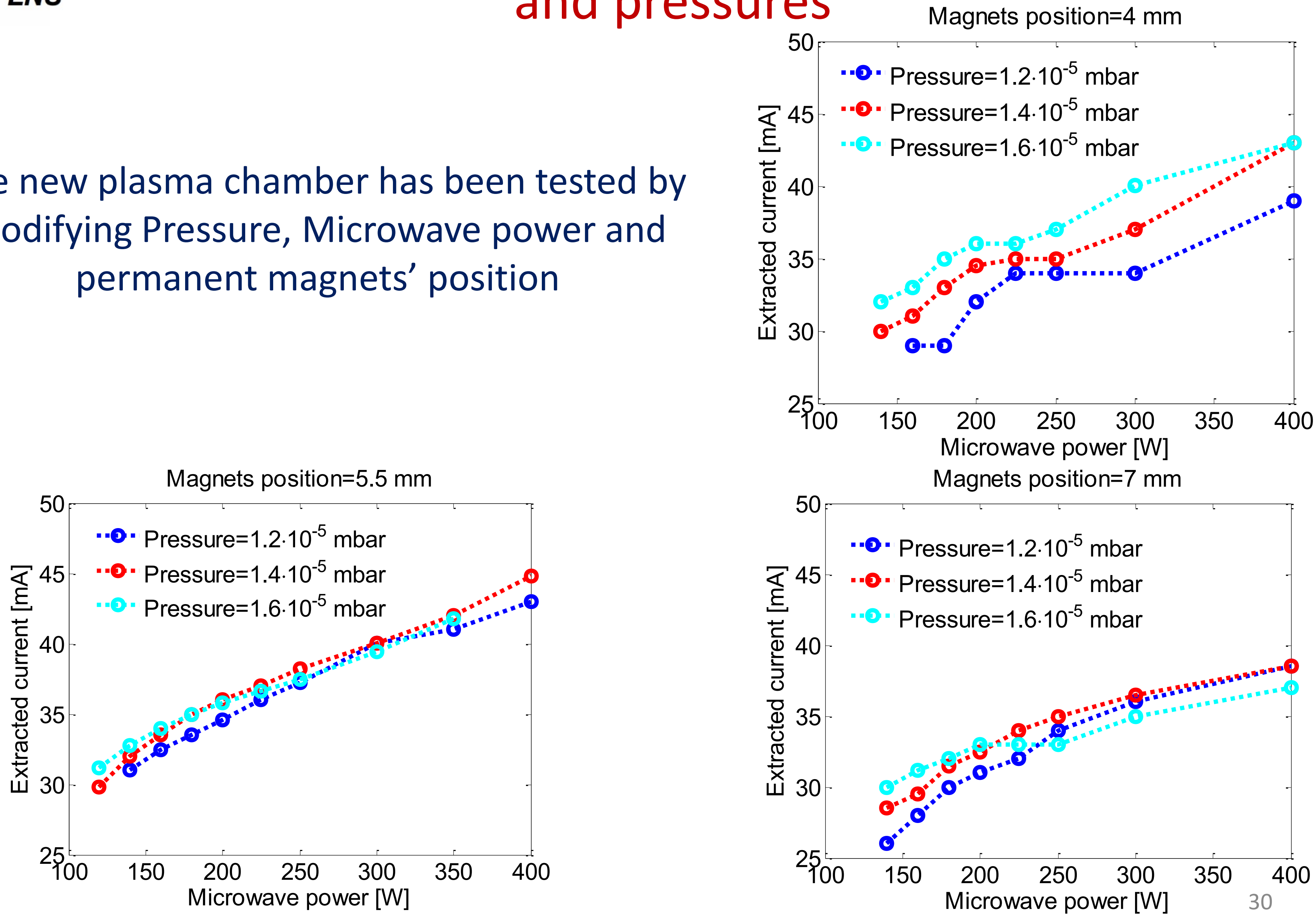
Alonso et al., The IsoDaR High intensity H_2^+ Transport and Injection tests, submitted to Journal of Instrumentation (2015)

VIS test configuration



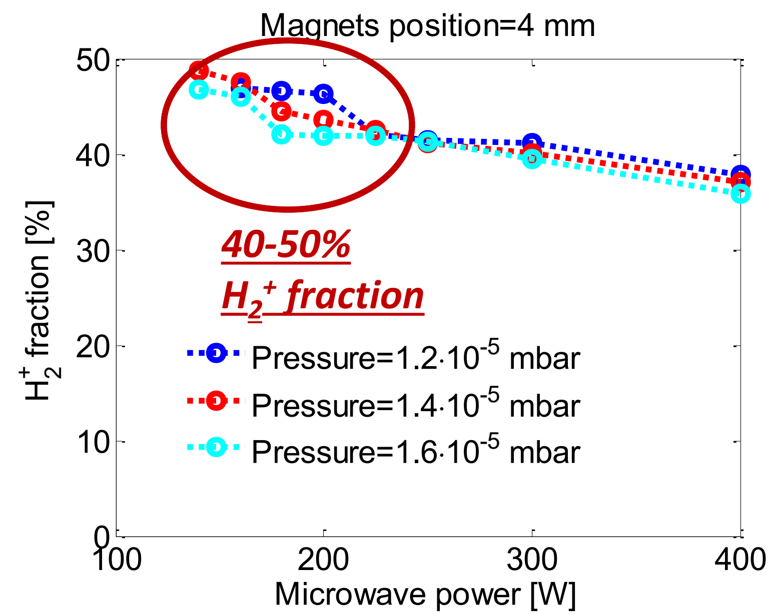
Total currents @ F.C. for different magnets positions and pressures

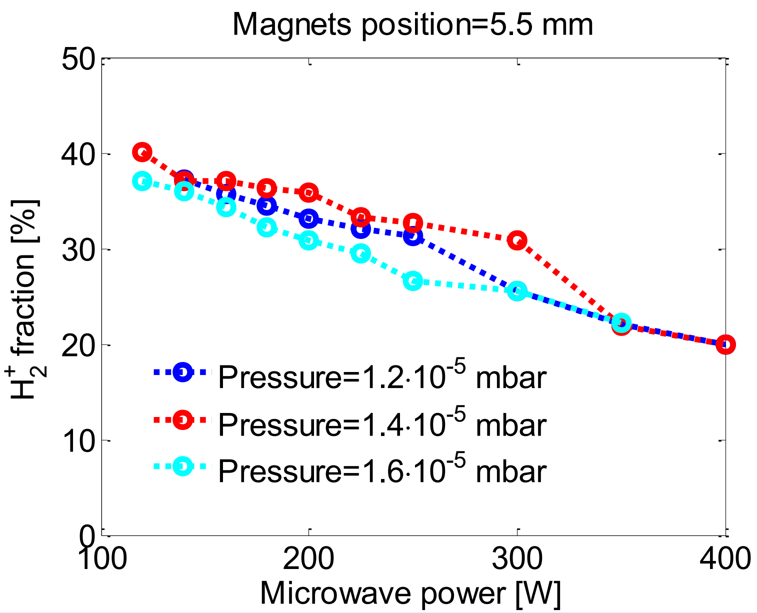
The new plasma chamber has been tested by modifying Pressure, Microwave power and permanent magnets' position

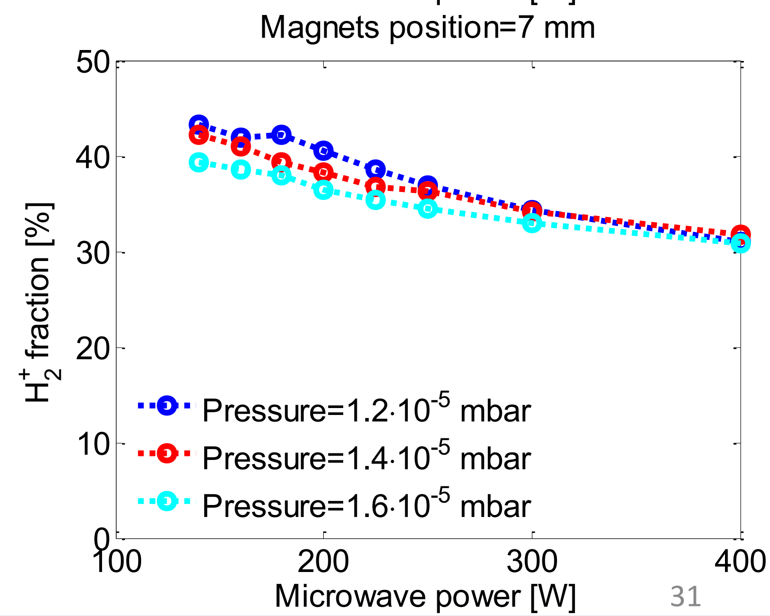


H_2^+ fraction for different magnets’ positions and pressures

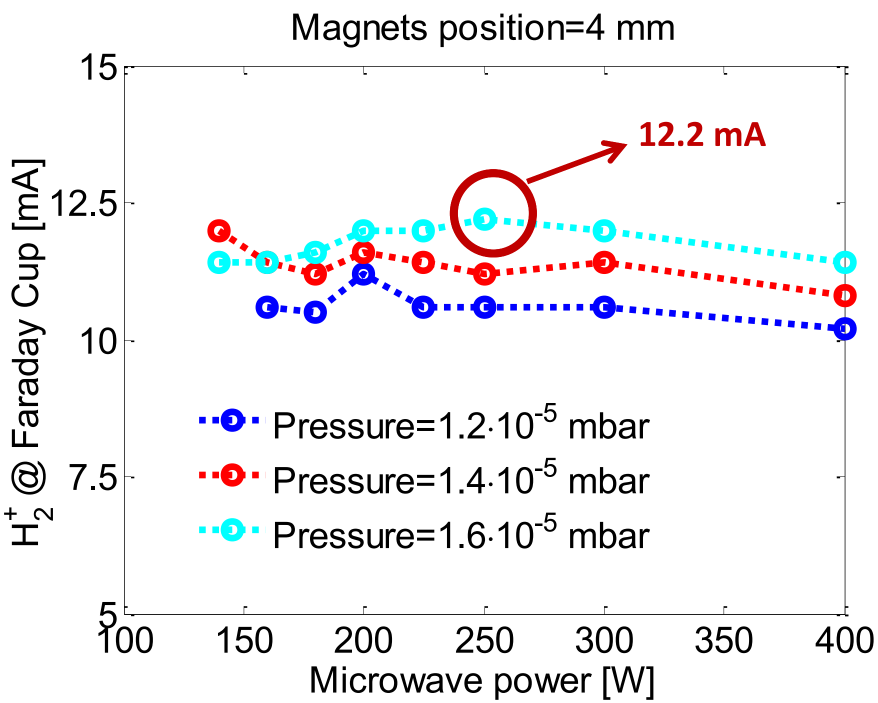
- Magnets’ position strongly affects H_2^+ fraction!
- 40-50% H_2^+ fraction obtained at 4 mm magnets’ shift







Vancouver Test Results



9 mA: best results obtained by standard plasma chamber

- **9 ------>12.2 mA H_2^+ @F.C.**
- **(+ 35% improvement w.r.t. standard chamber)**
- **75% transmission factor implies that source generates >16 mA H_2^+ beam**

12.2 mA H_2^+ @ F.C. absolute maximum obtained during tests

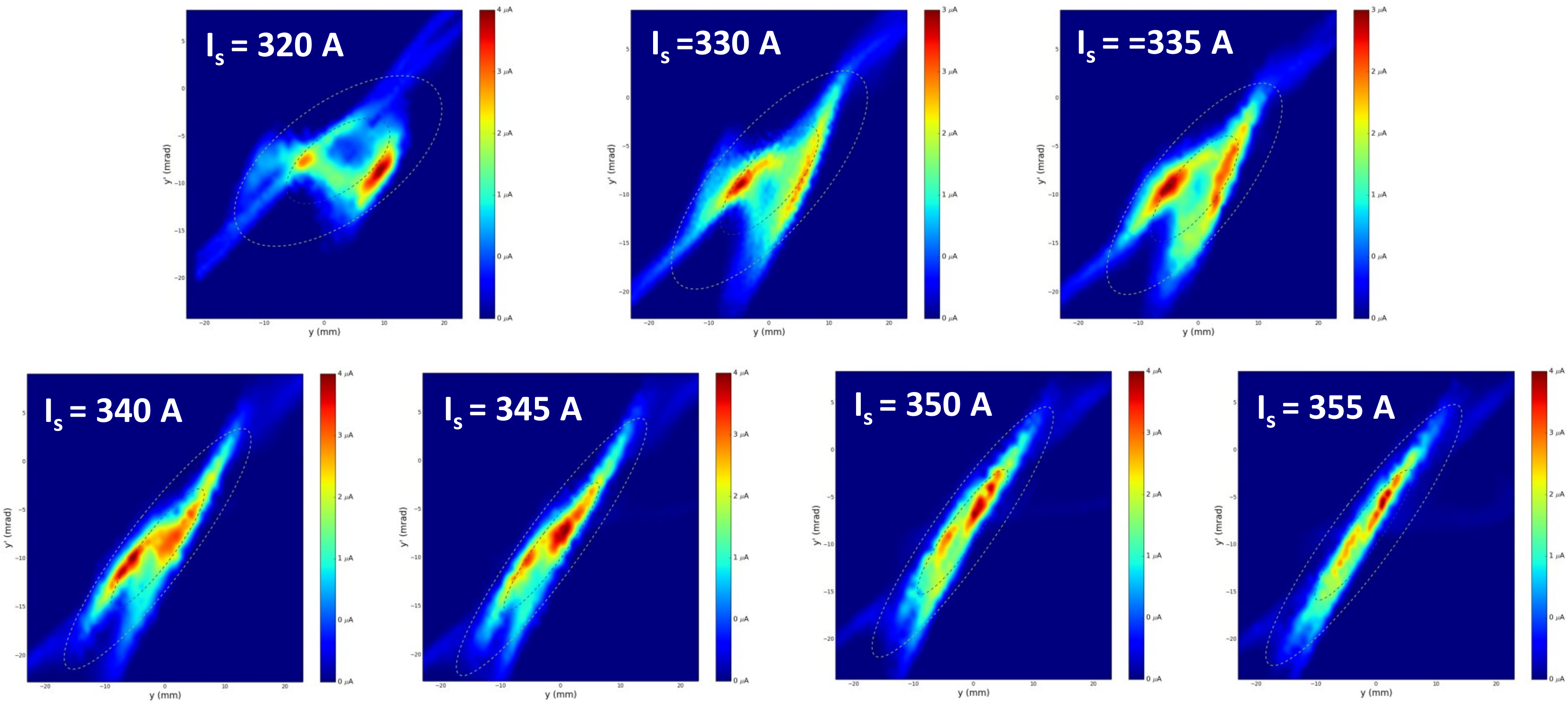
Castro et al., A new H_2^+ source: conceptual study and experimental test of an upgraded version of the VIS - Versatile Ion Source, submitted to Phis. Rev. STAB (2015)

Emittance plots

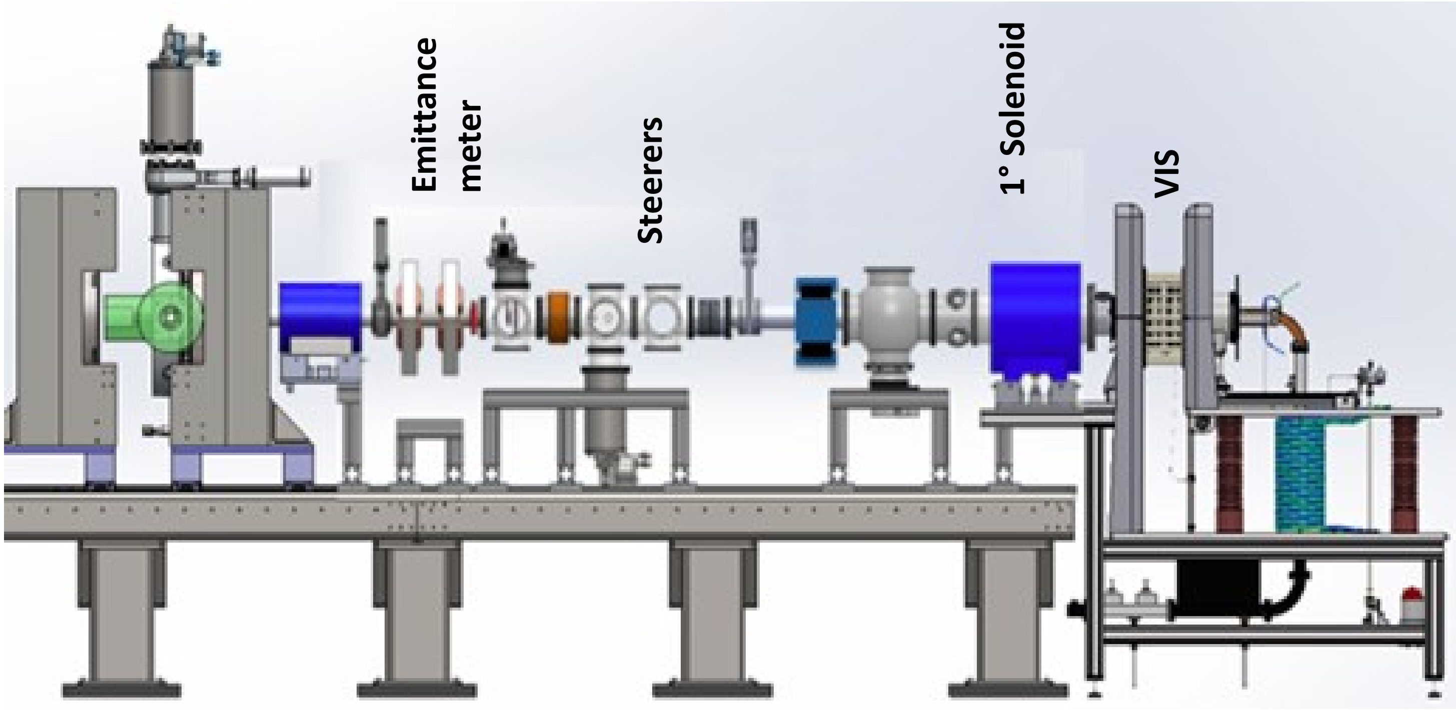
Measurements has been carried out in best experimental conditions:

Emittance < 0.2 π mm.mrad

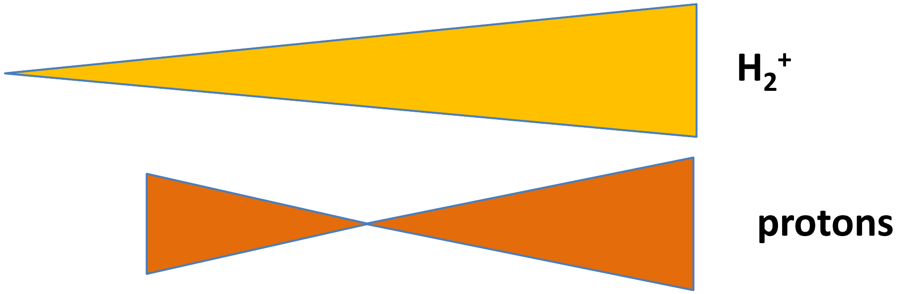
Evidence of Hollow beam!



Causes of hollow beam



Over focalized protons generate large space charge affecting H_2^+ beam



Bending Magnet needed!

Room for improvement in beam transport

How to increase further H_2^+ current?

1) Real time modification of ion lifetime:
   Flexible magnetic field needed!

2) Capability to favor reactions leading to H_2^+ production:
   ability to modify ion lifetime and EEDF through different heating mechanisms;

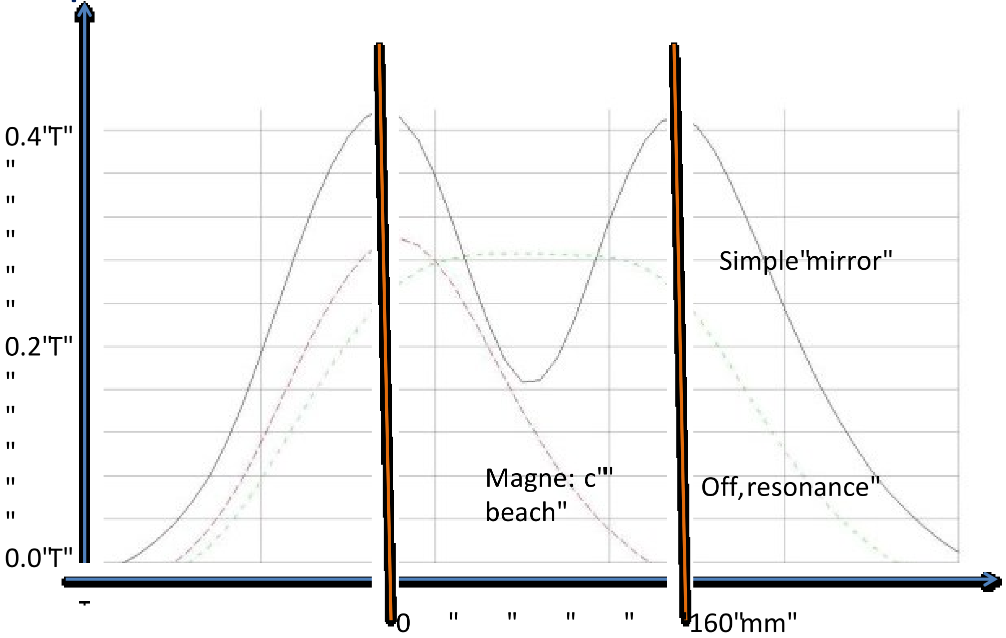
3) Development of an **extraction system** focused on H_2^+ beam;

4) More and more efforts on **plasma diagnostics!**

The Flexible plasma trap

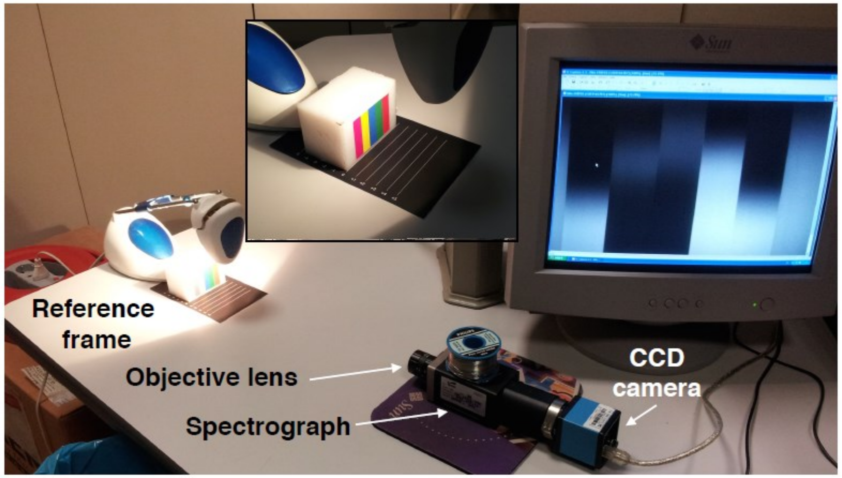
Flexible magnetic field!

Different heating mechanisms can be provided to affect EEDF

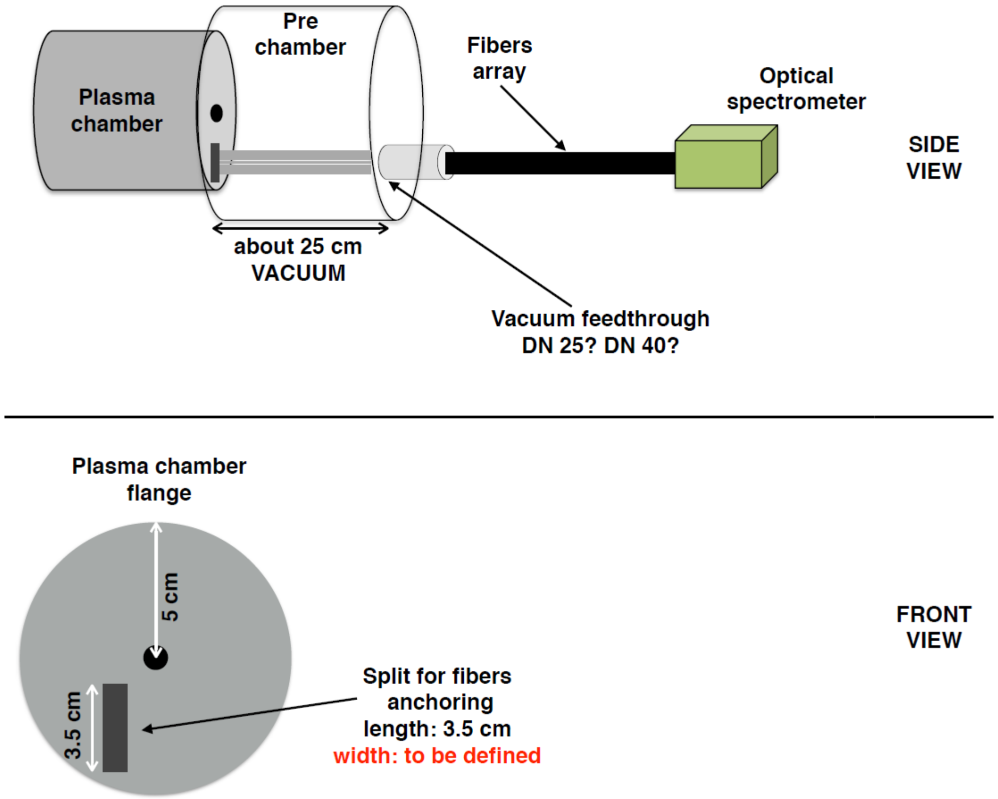


Room for R&D of new sources for generating 50 mA of H_2^+

Optical spectroscopy for plasma diagnostics



Courtesy of D. Nicolosi



Intra-plasma determination of expected values of

H^+ and H_2^+ concentration:

Conclusions

- The demand for H_2^+ sources is rapidly growing;
- Different approaches are ongoing to improve the performances of H_2^+ sources;
- Numerical modelling (from zero dimensional balance equation towards the self-consistency) is an option to describe the hydrogen plasma environment;
- VIS performances have been upgraded from 9 to 12.2 mA H_2^+ beam @F.C. Considering 75% transmission, 16 mA are generated by VIS
- Bending magnet needed to separate protons from H_2^+
- Further studies and diagnostics about the cooling of the H_2^+ vibrational excited states are needed;

perspectives

- A new testbench for studies on fundamental plasma physics is being commissioned at LNS: the Flexible Plasma Trap;
- Self-consistent numerical models could represent a fundamental tool to describe and develop new source devoted to H_2^+ generation;
- Plasma diagnostic will play a fundamental role in future upgrades, in particular Optical Spectroscopy;
- By coupling the FPT to the VIS LEBT, in future will be possible to extract higher H_2^+ current;
- Much room for improvements;

Thank You
for Your attention