Oral presentation at 101° Congresso SIF2015, 21-25 Sept 2015, Roma

First experiments with a versatile multiaperture negative ion source

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1) ***Introductory remarks on NBI*** (negative beam injectors)

2) ***NIO1 installation*** (NIO1=Negative Ion Optimization 1)

3) ***NIO1 related works and simulations***

4) ***Experimental results***

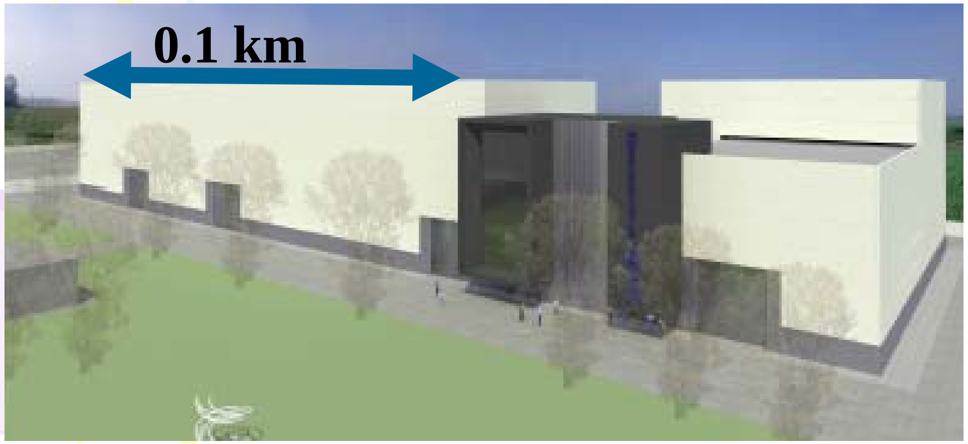
5) ***Conclusions.***

Abstract

Neutral Beam Injectors (NBI) [typical injector MITICA (Megavolt ITer Injector Concept Advancement) specification are 1 MV, 1280 beamlets, total 55 A of D- beam] , which need to be strongly optimized in the perspective of DEMO reactor, request a thorough understanding of the negative ion source used and of the multi-beamlet optics. A relatively compact RF ion source, named NIO1 (Negative Ion Optimization 1), with 9 beam apertures for a total H^- current of 130 mA, 60kV acceleration voltage, was installed at Consorzio RFX, including a high voltage deck and a X-ray shield, to provide a test bench for source optimizations in the framework of the accompanying activities in support to the ITER NBI test facility. NIO1 operation has started in July 2014, at zero extraction voltage. Plasma is heated with a tunable 2 MHz (rf) radiofrequency. NIO1 status and plasma experiments both with air and with hydrogen as filling gas are described, up to a 1.7 kW rf power. Transition to inductively coupled plasma is reported in the case of air and briefly summarized for hydrogen.

1) Introductory remarks on NBI (neutral beam injectors)

For fusion reactors like ITER or DEMO, many (3) neutral beam injectors are needed for: 1) heating; 2) current drive. A test facility is being built in Padua at RFX



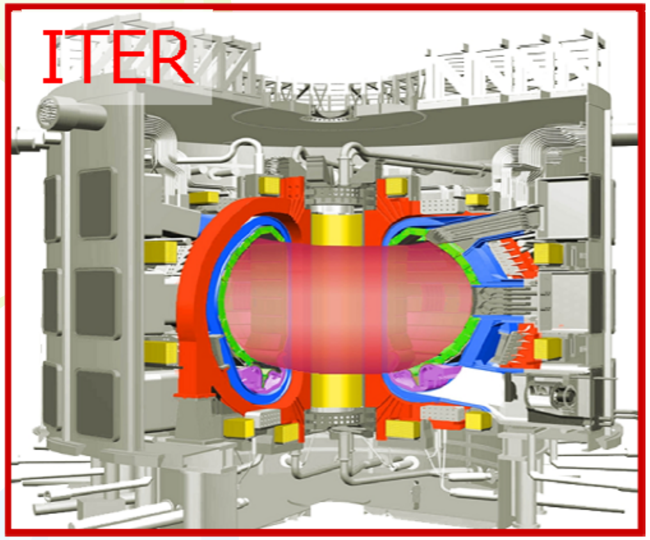
Design of buiding PRIMA-MITICA (from P. Sonato, RFX, 2009) and building view (from V. Toigo, 2015)

Covered surface 7050 m^2
Heigth 26 m

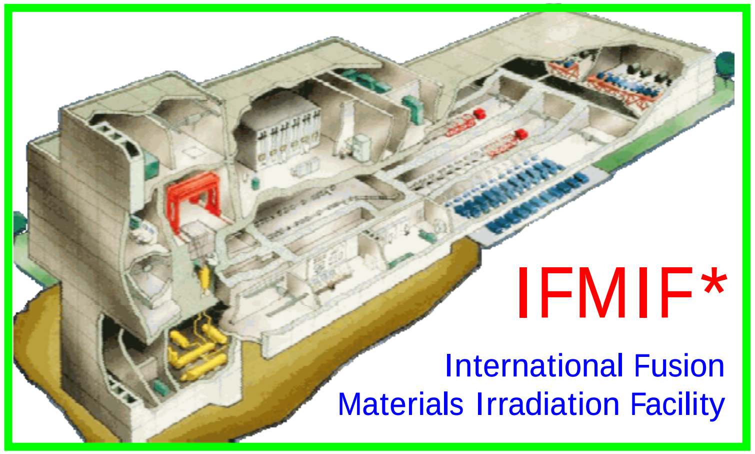
MITICA = 1 MV/40 A beam

SPIDER = 100 kV/55 A system

Many displacement per atom (dpa) expected in DEMO
Advanced Materials are at a critical path



1-3 dpa/lifetime



20-40 dpa/year

[*INFN strongly partecipates to IFMIF, see Pisent, 2010]

< 150 dpa

According to energies of products of

$$D^{+} + T^{+} \rightarrow {}^{4}He^{2+} \ (3.5\ MeV) + n\ (14\ MeV)$$

Material issues are divided into :

plasma facing power load (from α)

neutron irradiation of structures (from primary n and from blanket reaction)

Beam current D^- 40 A

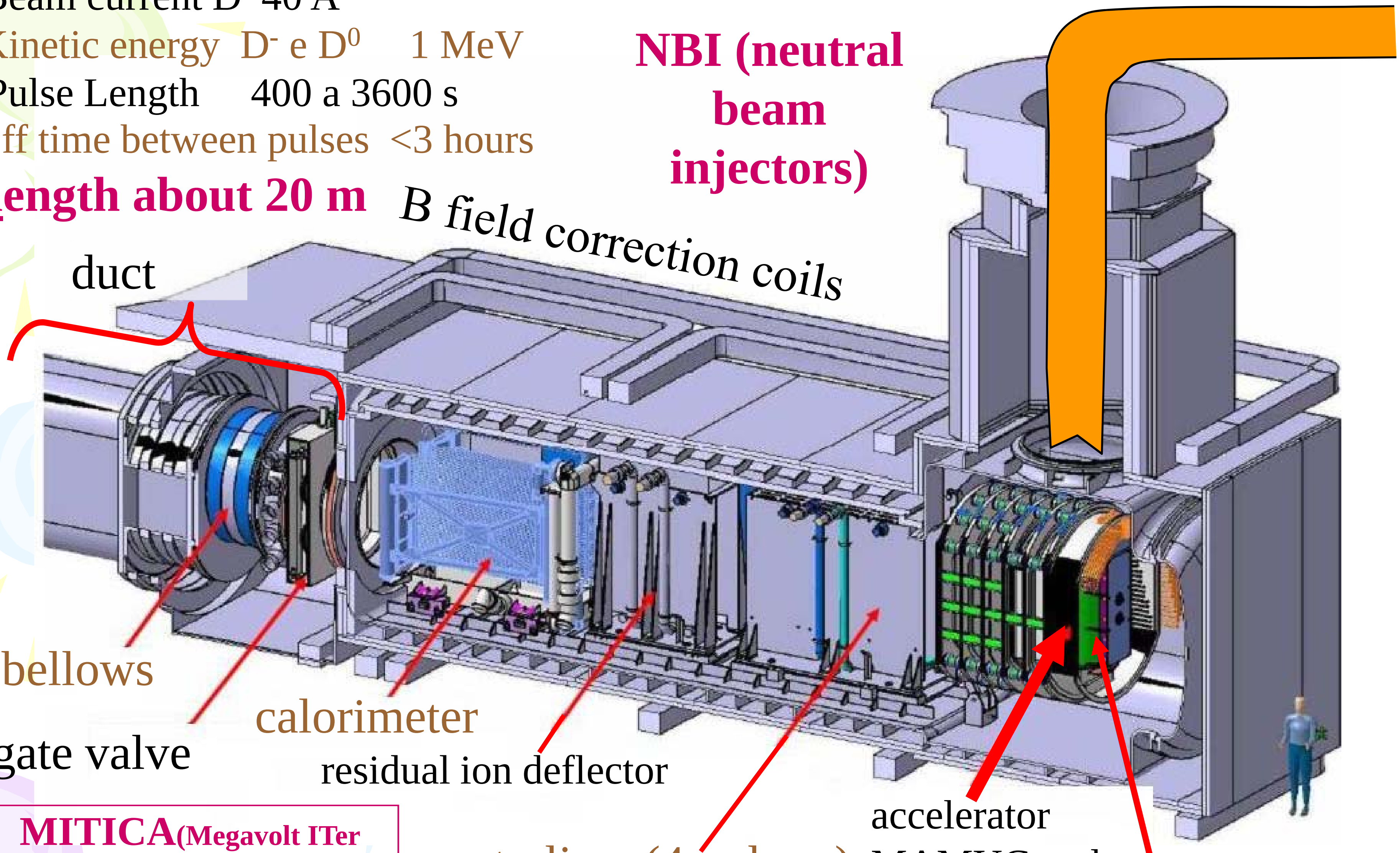
Kinetic energy D^- e D^0 1 MeV

Pulse Length 400 a 3600 s

off time between pulses <3 hours

length about 20 m

NBI (neutral beam injectors)



MITICA (Megavolt ITer Injector Concept Advancement)

3D view of a neutral ion injector [adapted from P.Sonato, RFX, 2009]; MAMUG = MultiAperture MUlti Grid.

Negative ion sources

Understanding of Negative Ion Sources is progressively refining:

1) Source have two plasmas at different temperatures

2) H- are produced in low temperature region by 3 mechanisms:

- **2a) volume production**
- **2b) surface conversion of 'fast' atom H^0 (2 eV)**
- **2c) surface conversion of faster H^+ ions (30 eV)**

What next? Difficult to say; to list a few topics

- **3a) Cesium dynamics and/or cesium free**
- **3b) rf driver detailed simulation/optimization**
- **3c) Low pressure operation**

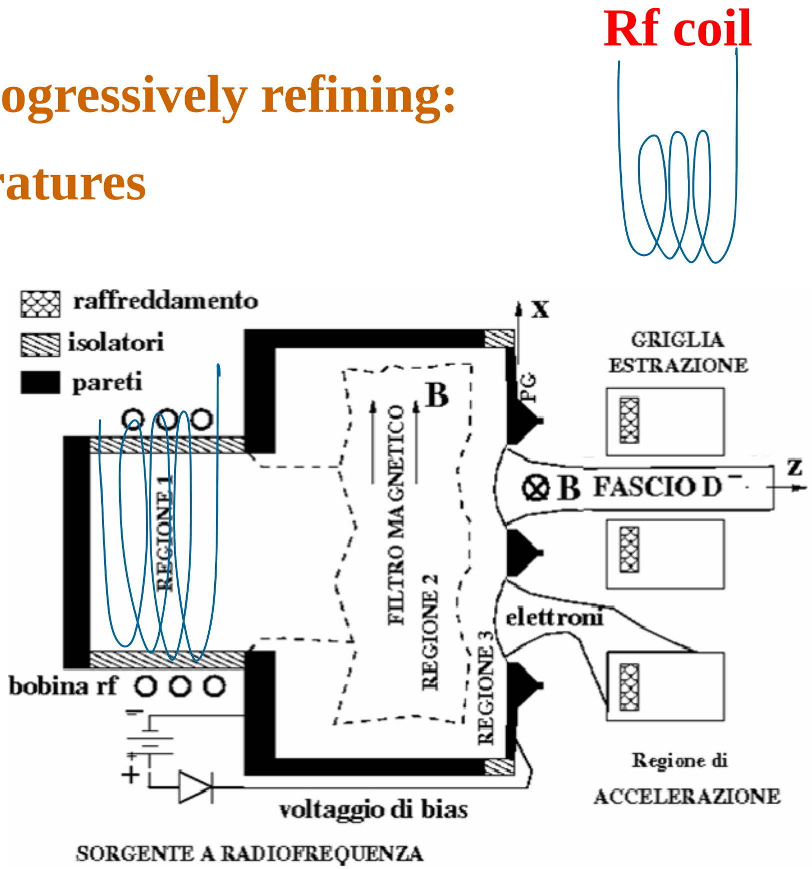


Figure: scheme of an rf driven negative ion source; region 3 (sheath) thickness exaggerated for visibility

So we need versatile ion sources to test new concepts

But versatile ion sources have also disadvantages

- **smaller scale makes construction more difficult**
- **still not negligible cost and manpower needed**
- **....**

2) NIO1 experimental set-up

NIO1 source (0.5 m diameter, 60 kV, nominal beam power 8 kW) delivered to RFX in May 2013

Vacuum tightness improved (with ceramic cleaning) in November 2013

Source support completed in December 2013 and aligned in January

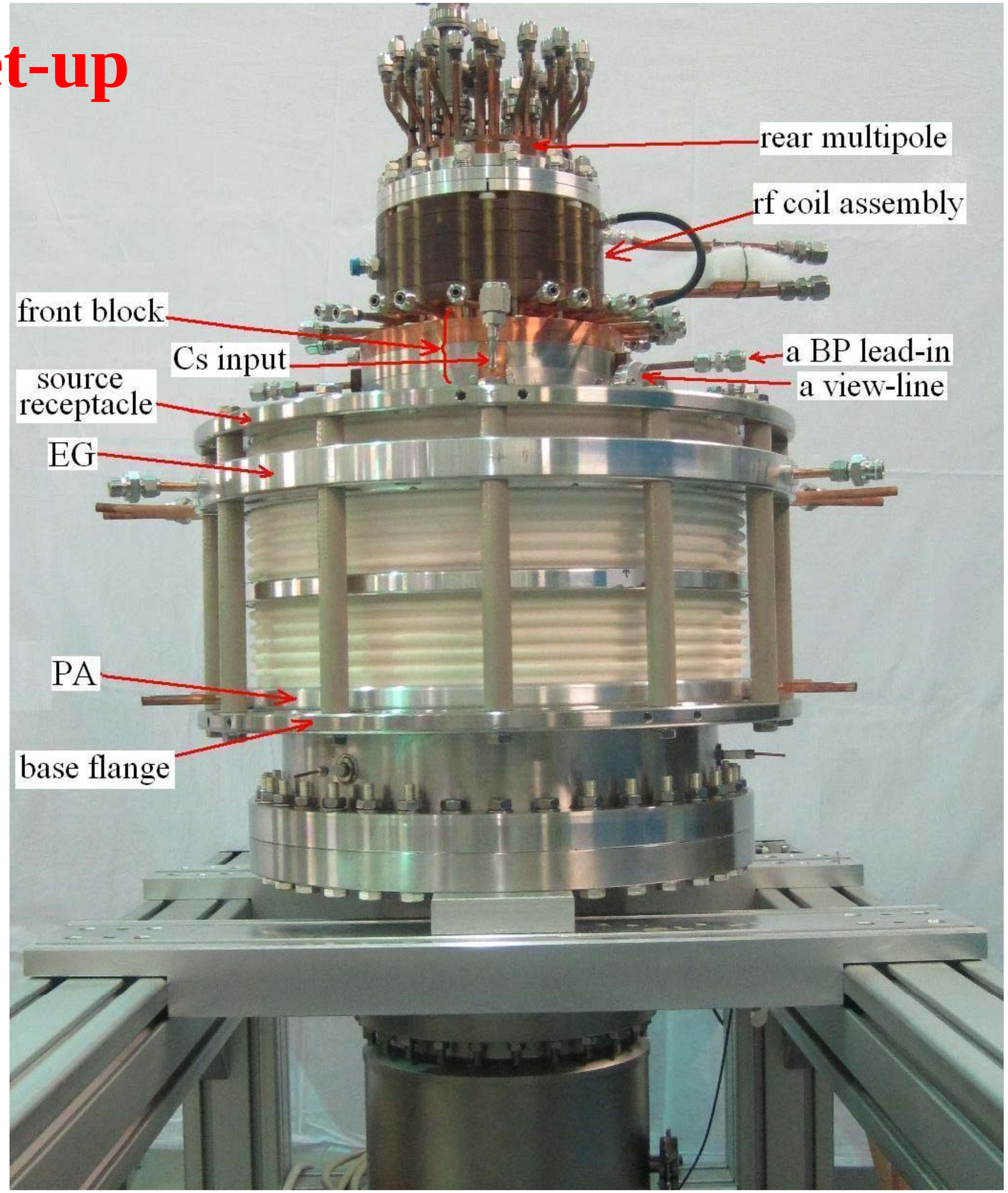
Calorimeter/beam dump (INFN) delivered to RFX in January 2014

First source operation in July 2014

Hydrogen supply line installed (2014)

New closed water cooling system installed Sept.-Nov. 2014; rf 2.5 kW generator repaired 2014. Water from technical plant enough for full power operation in April 2015

60 kV holding verified in January 2015(at source off)



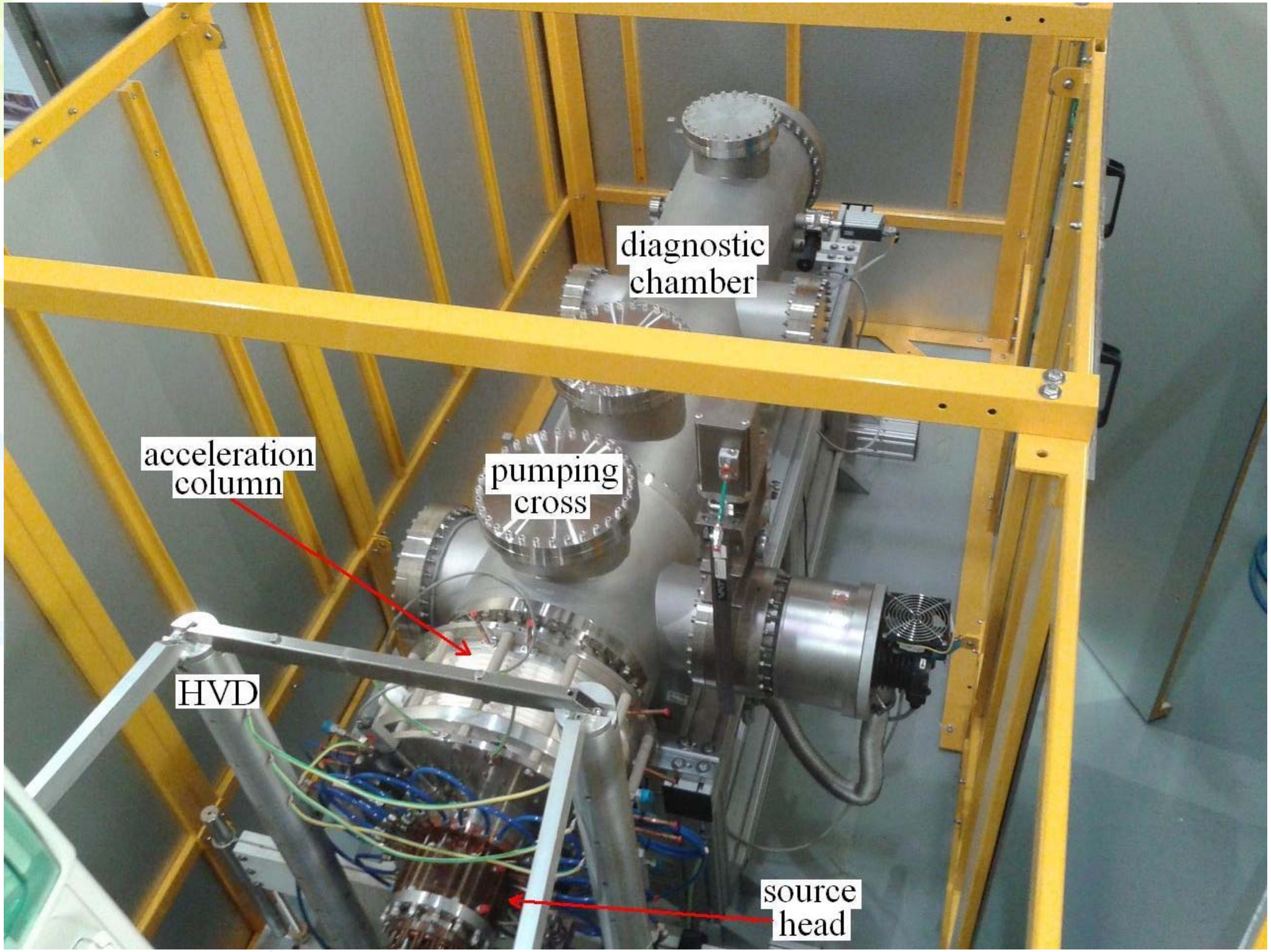
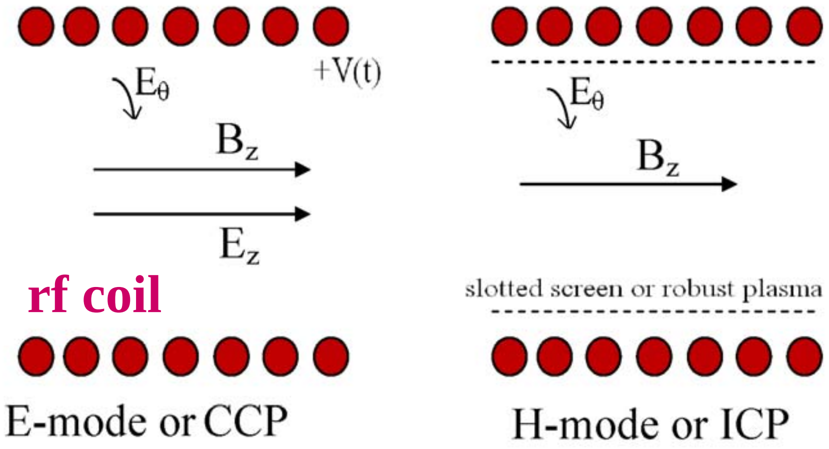
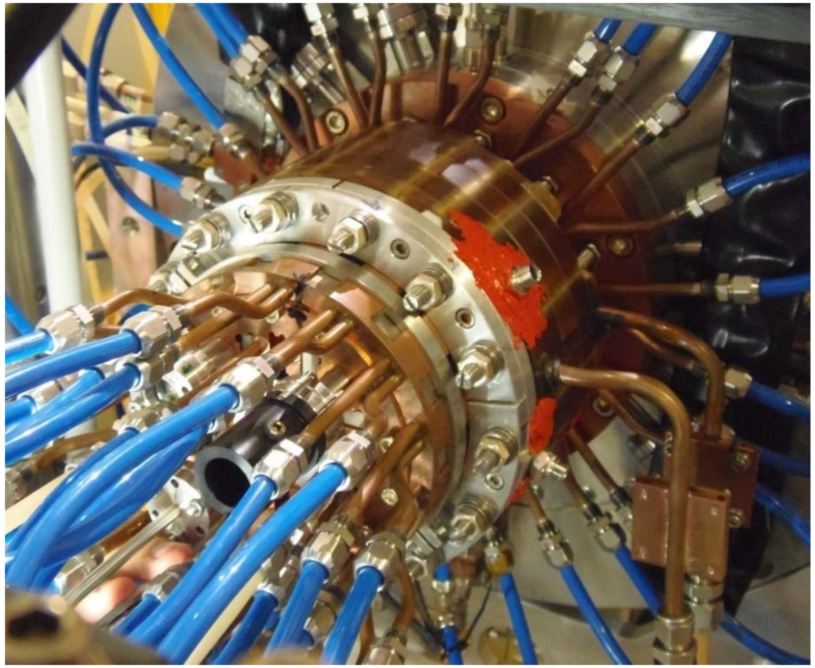


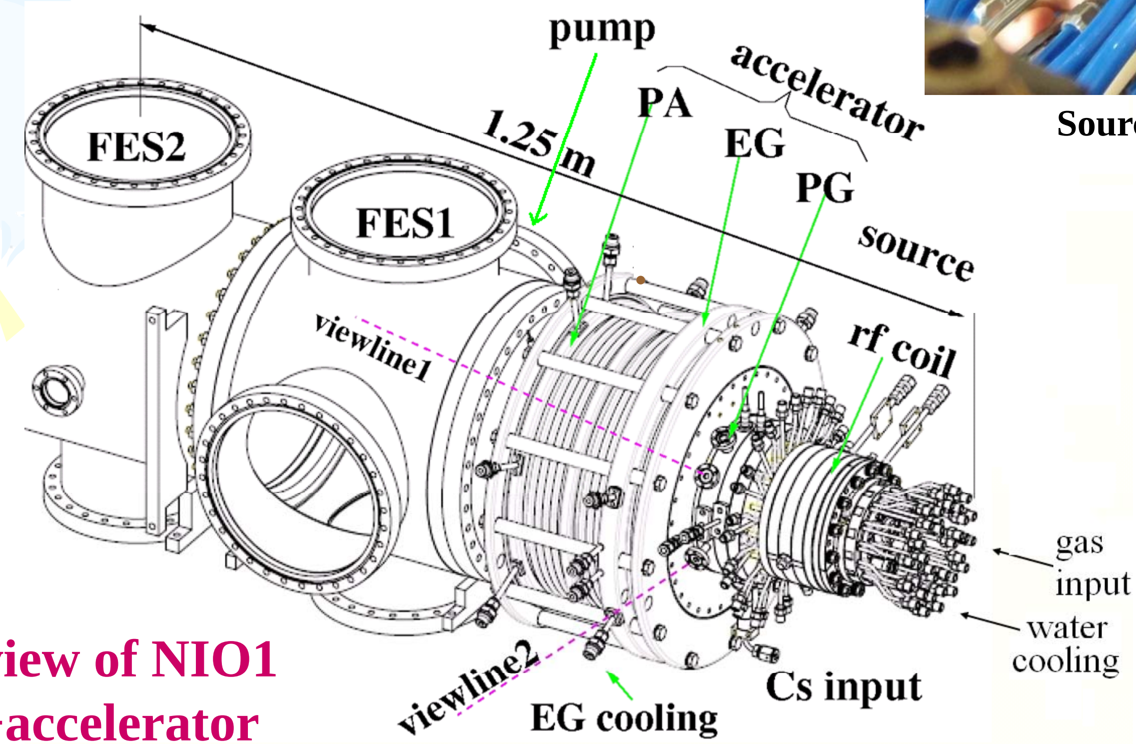
Figure 1 Overview of NIO1 source, acceleration column and diagnostic chamber (as labelled); HVD cover removed to make source head visible.



Simple explanation of coupling modes

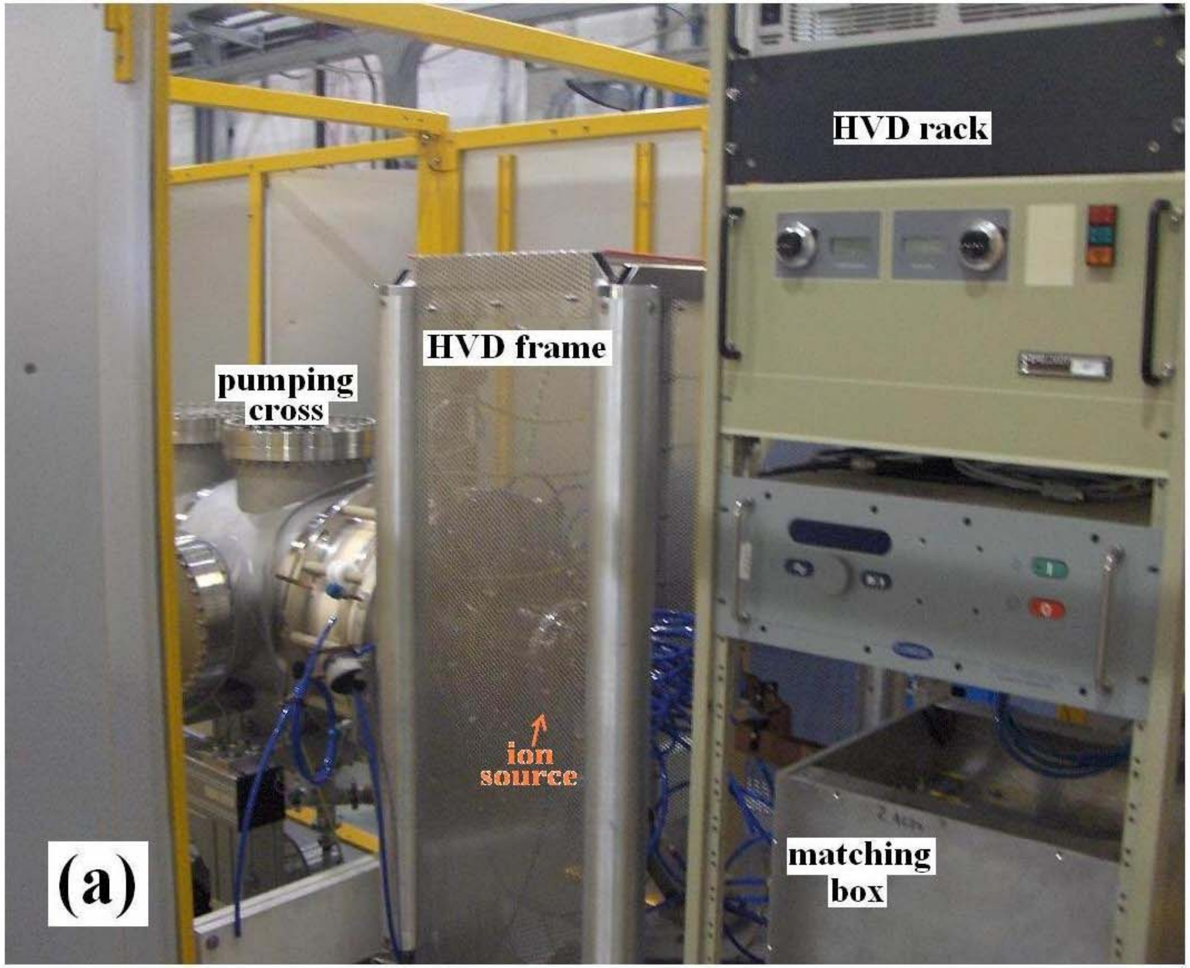


Source head close-up view



Detail view of NIO1 source+accelerator

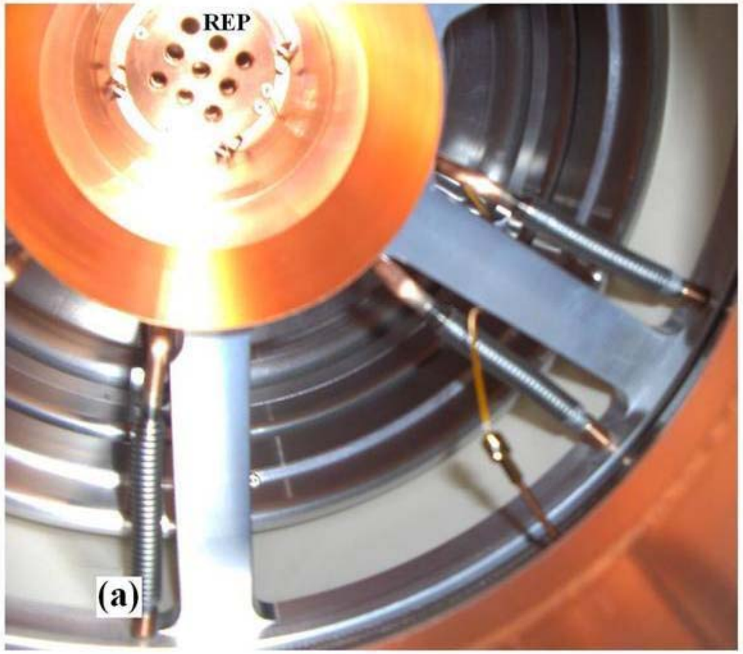
Some water cooling loops for extraction grid EG

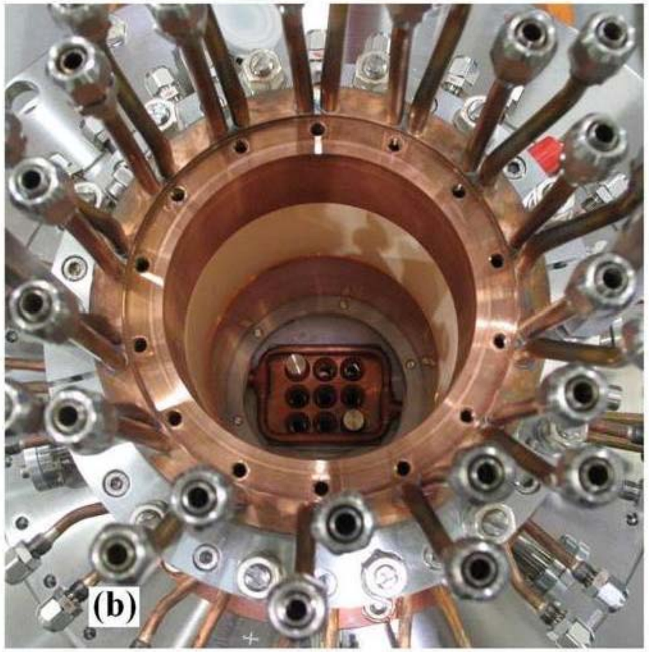


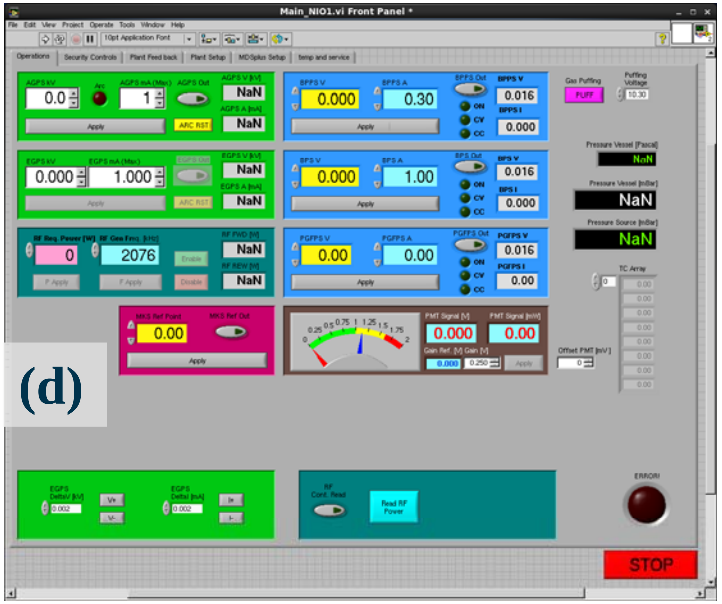
(a) NIO1 installed, with source covered by high voltage deck, rf matching box in first sight, acceleration column, diagnostic chamber in the background. Two doors of Pb shielding were opened to make photographs

OTHER DETAILS ON INSTALLATION M. De Muri et al., Fus Eng Des; M. Cavenago et al., AIP Conf Proc 1612

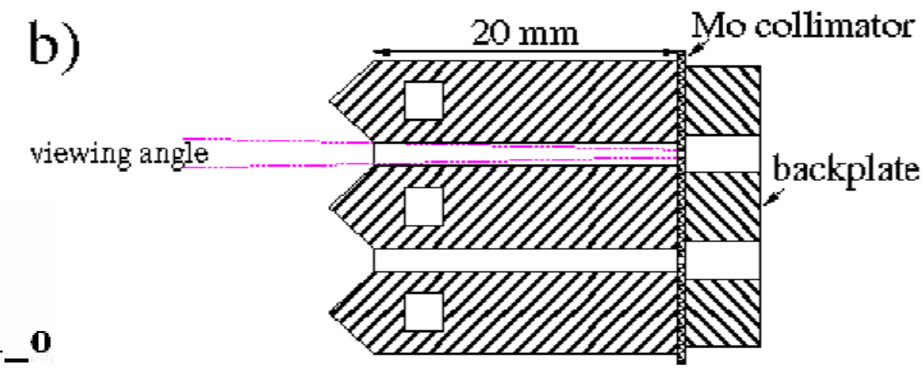
(a) view of PA ; (b) source rear opened for alignment; (c) water to HVD; (d) main control screen



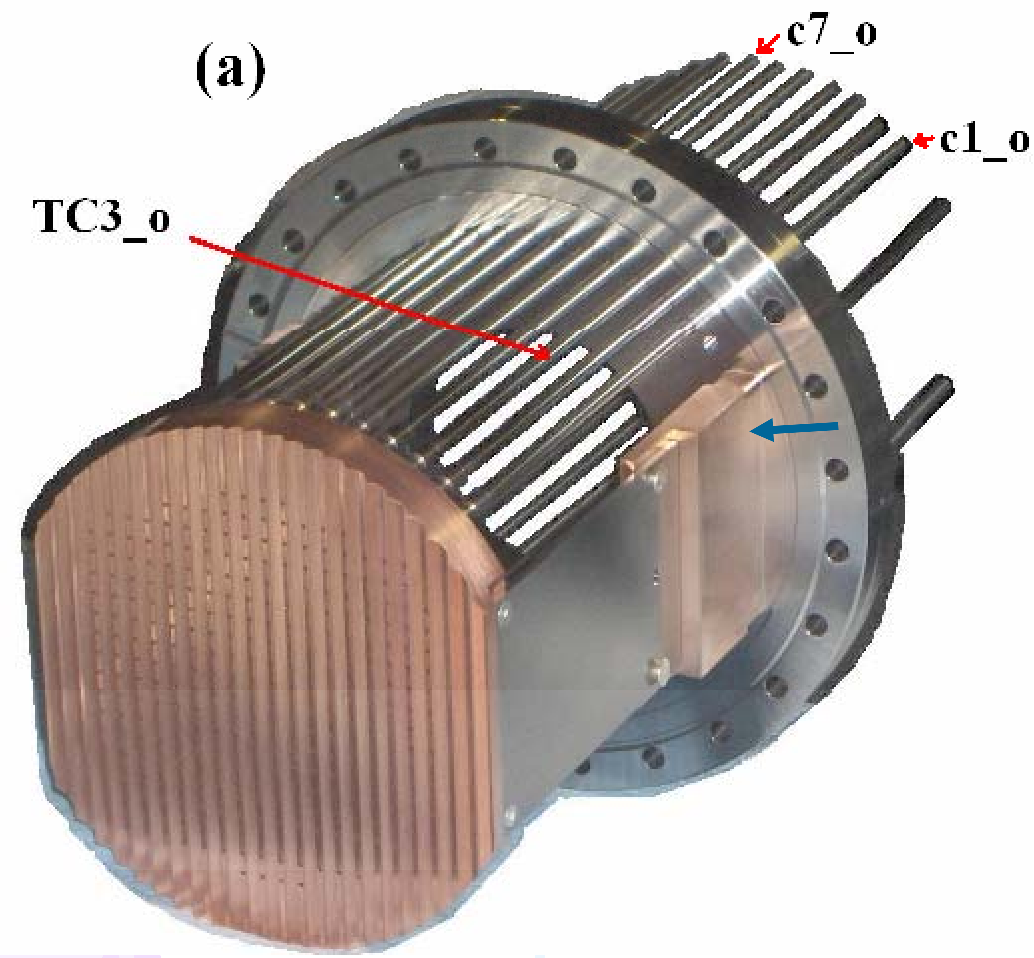


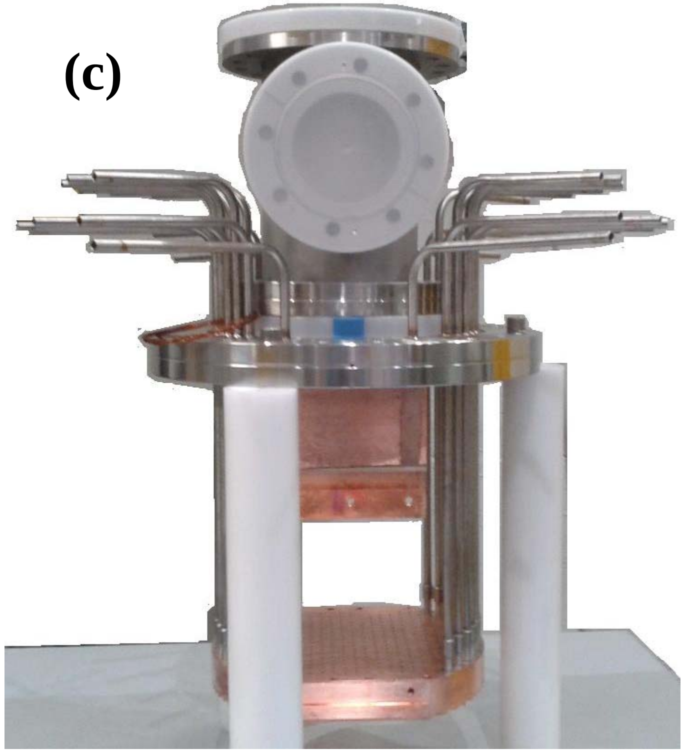


The static beam dump/calorimeter



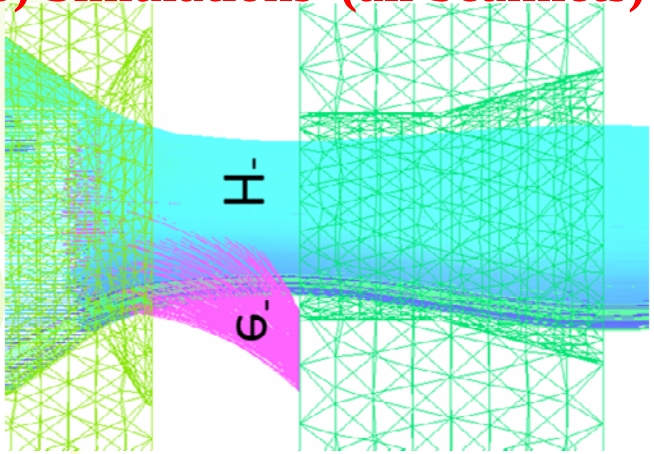
(b) Beam dump: scheme of pepper pot extension [see Cavenago et al, Rev Sci Instrum, online 18 Oct 2013, on paper vol. 85, 02A704 (2014)]

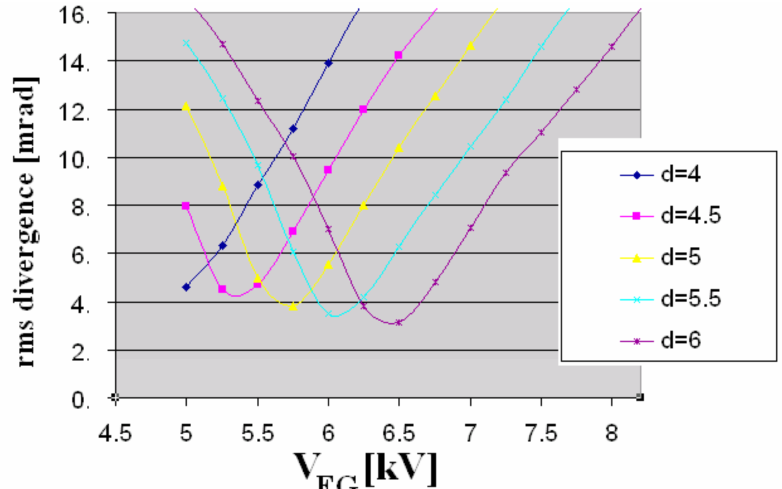




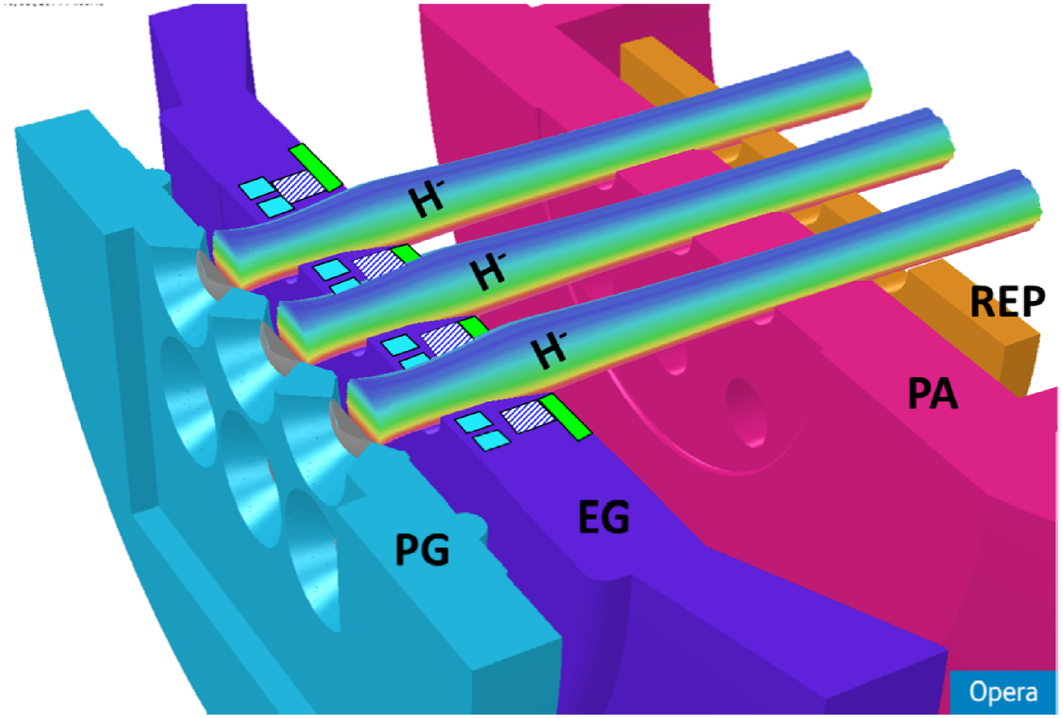
(a): Beam dump/calorimeter, with marks at some channels and thermocouple (TC) reserved positions; (c) with a cross for viewport and multipin feedthroughs assembly

3) Simulations (all beamlets)





Rms divergence of NIO1 output beam vs Extraction Grid Voltage VEG for several distance d of EG e PG electrodes (SLACCAD simulations, NIBS'2014, Garching, October 2014)



Simulation of the whole NIO1 extraction with OPERA/SCALA (TM) (see Veltri et al, NIBS'2014)

NIO1 compact size help simulations. At ICIS2015 conference (New York City, 23-28 th August 2015):

1) Fonnesu et al. , poster .TuePS33 (EAMCC for 9 beamlets)

2) Sartori et al., poster, MonPE25, gas flow in all NIO1 (air or H2)

3) Sartori et al., poster , MonPE26, space charge compensation

4) Taccogna et al, poster , TuePE30, extraction from 1 to 10000 eV

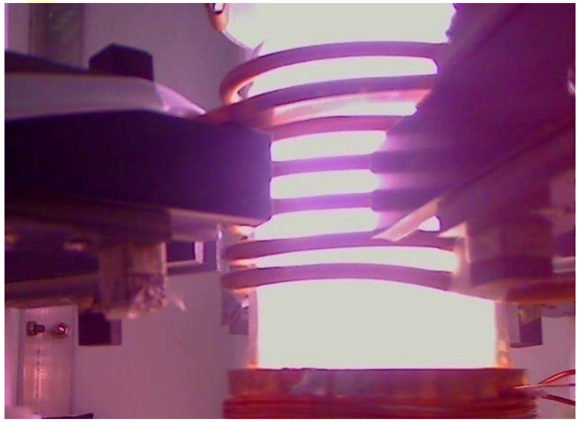
5) Variale et al, poster, ThuPe19, concepts for energy recover

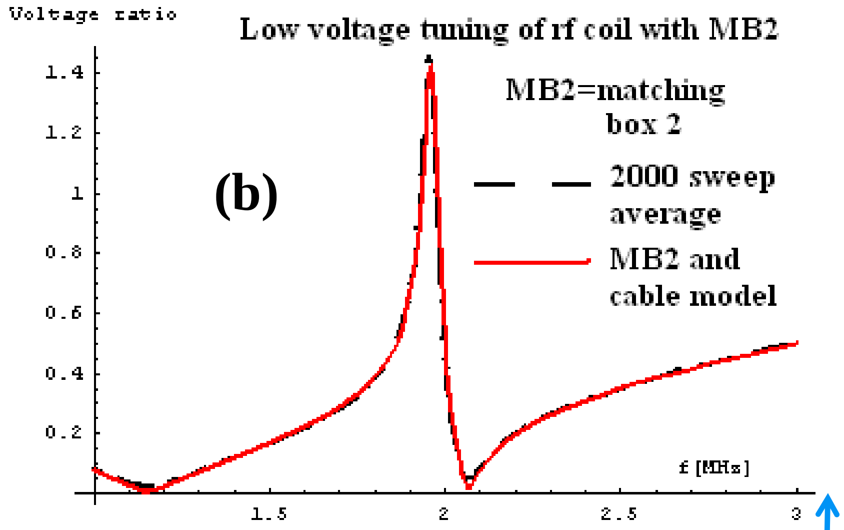
and

6) Barbisan et al. , poster ThuPE01 , H_2 experiments

4) Results: 4.1 rf matching

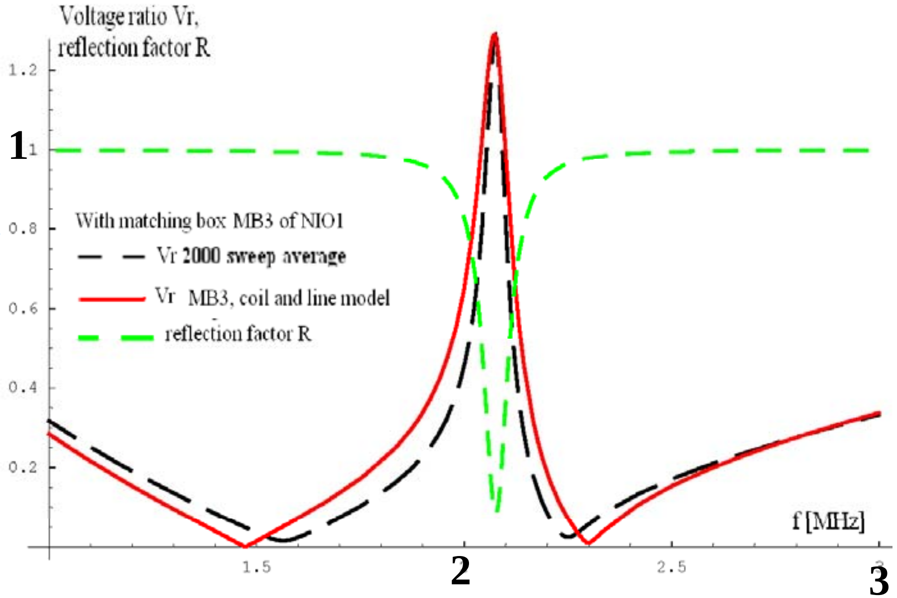
(a) Plasma of O/N at 2 Pa, rf forward about 200 W, B_z about 10 G





Experience at LNL MetAlice test-stand (a) transition from E to H coupling and low pressure operation routinely achieved; (b)Very accurate rf model seems possible.

Low voltage (no plasma) matching of NIO1 (note here some differences between model and measurement)



4) Results: 4.2: clear transition with rf power for air

Increasing rf power, a typical jump in luminosity is observed for air on 3 different diagnostics:

Luximeter

Fiber+PMT

Spectrometer (low res 1nm)

At this jump, air show descreasing Te, as expected for E-H transition

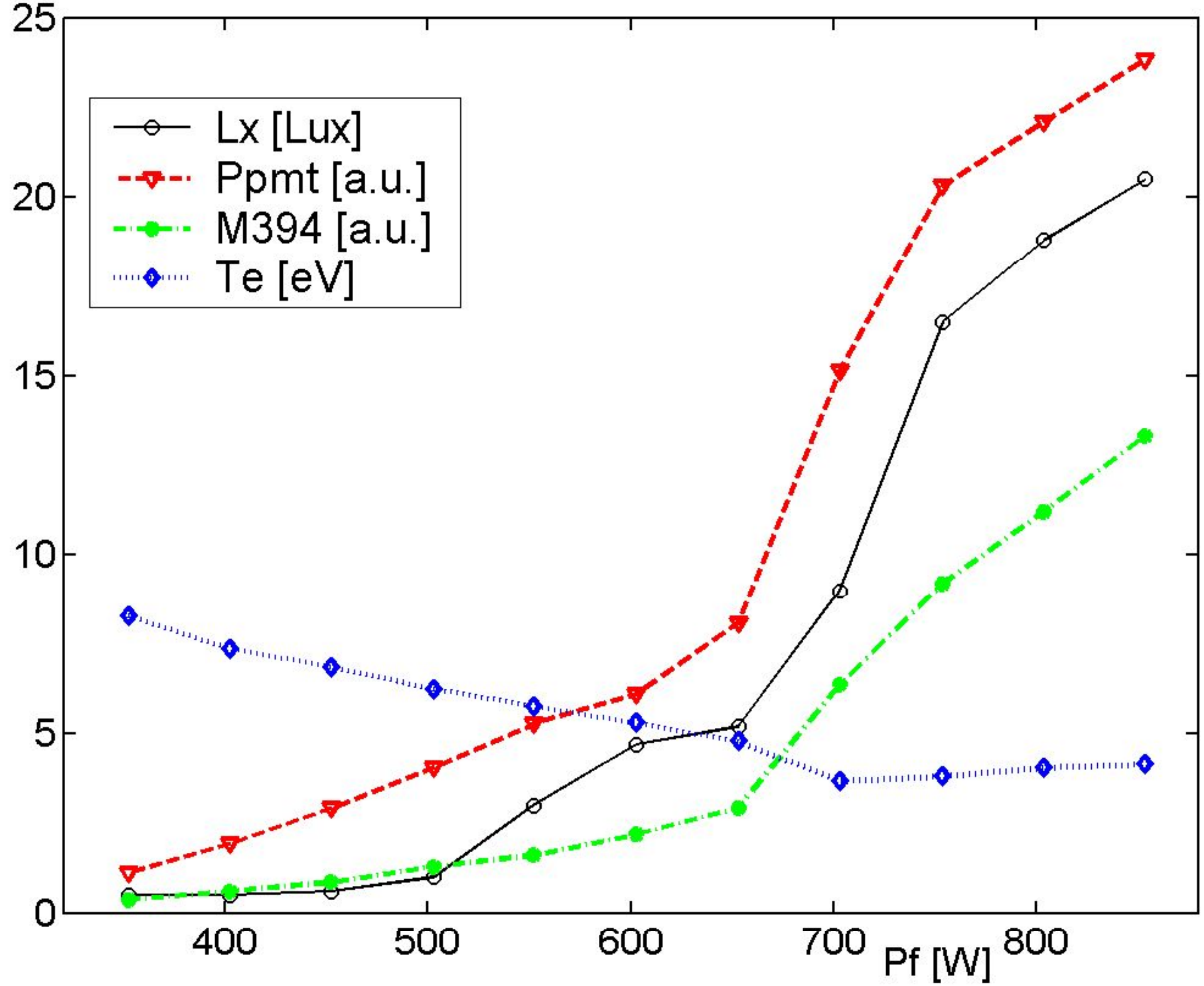
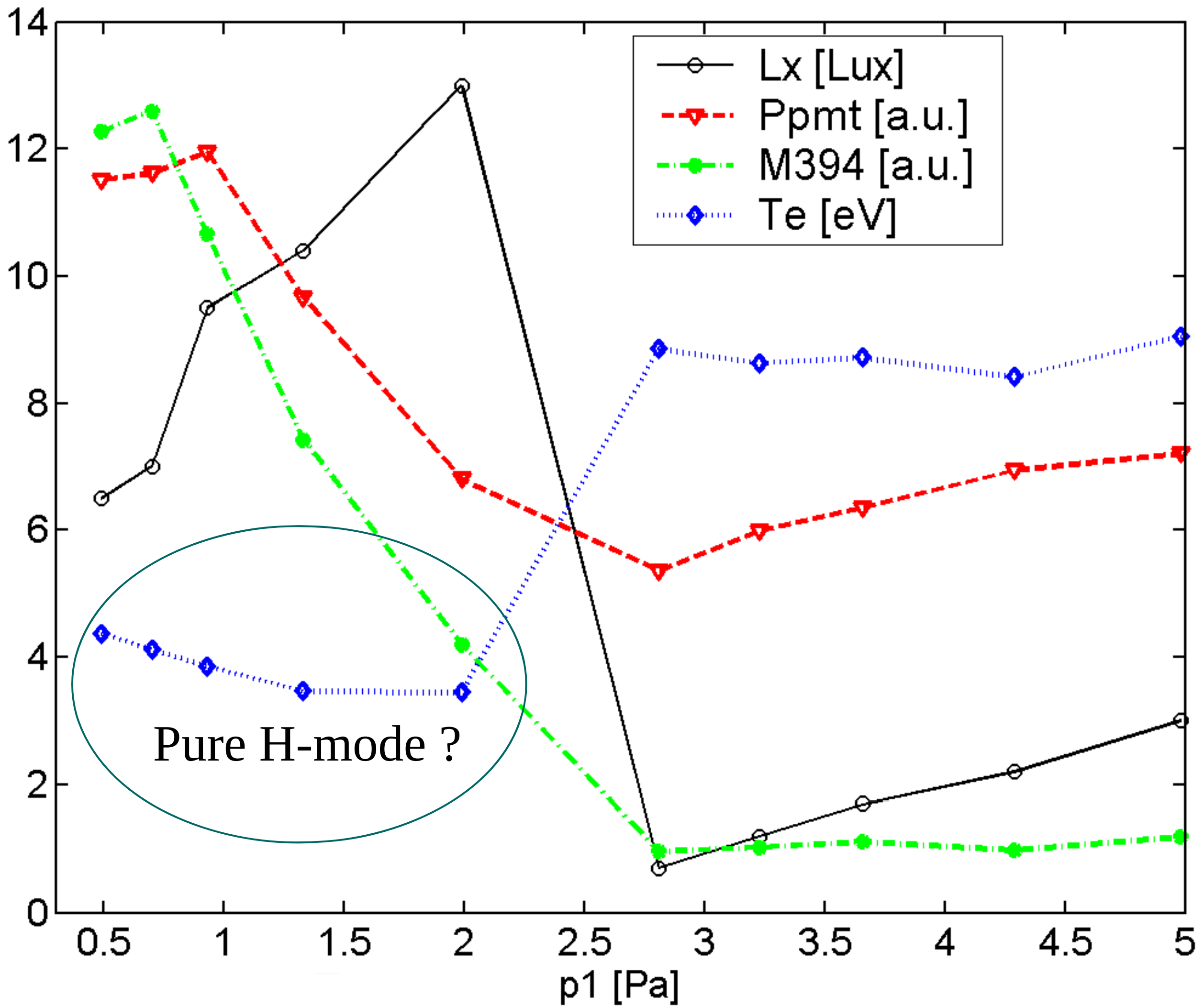


Figure : Plasma luminosity L_x vs forward rf power P_f at p_1=0.9 Pa; also shown P_{pmt} (1 a.u. = 10 mW) and M_{394} (1 a.u. = 10^{17} ph/s/m^2) and apparent electon temperature T_e; typical error +/- 10 %



(*) For each pressure, Pf was decreased, to get E-mode, and then rised until net power P reached set level

Figure : Plasma luminosity L_x vs source pressure p1 (air) at constant net(*) rf power $P=P_f - P_r=0.47$kW ; also shown P_{pmt} (1 a.u. = 10 mW) and M_{394} (1 a.u. = 10^{17} ph/s/m^2) and T_e; typical error +/- 10 %

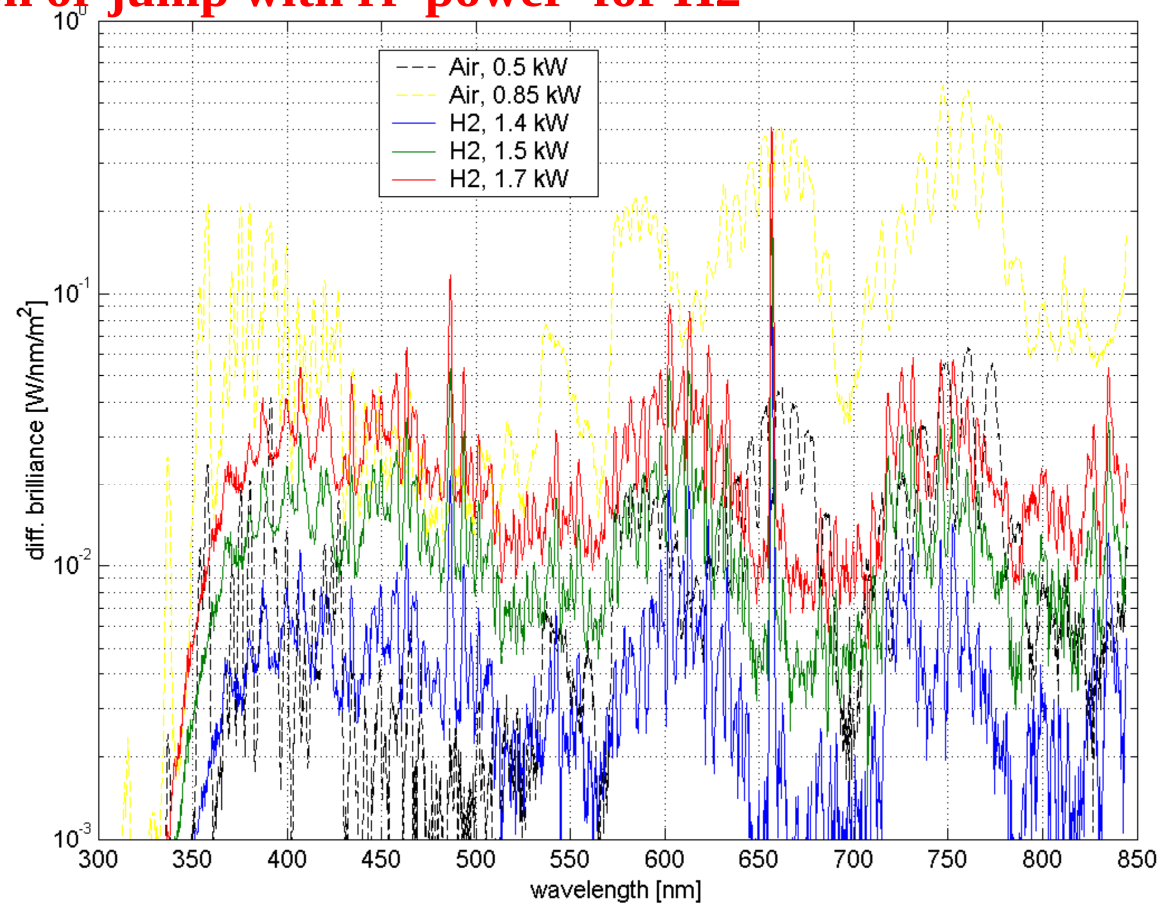
4) Results: 4.3: transition or jump with rf power for H2

Hydrogen vs air

For both gases, plasma emission jumps at some power

H2 requires more rf power and gives less light

Spectra analysis of air is simply (here) based on nitrogen; H2 analysis seems more difficult



gas	f	Prf [W]	Rrefl [W]	p2 [Pa]	p1 [Pa]	luxim [Lux]	Pppmt [mW]	Brilliance [W/m^2]
Air	2016	503	3	0.042	0.95	1	40.453	5.5887
Air	2010	804	12	0.041	0.93	18.8	192.848	56.4729
Air	2010	854	20	0.041	0.93	20.5	220.999	59.4309
H2	2011	1407	14	1.100	2	0.5	25.090	2.0981
H2	2011	1608	33	1.100	2	1	49.635	6.4696
H2	2011	1709	32	1.100	2	4.5	64.881	12.2457

After operation at rf power 1.7 kW, a vacuum loss appeared (probably for elastic bolts unbalanced loosening, possible with vibration; finer mechanical adjustments are in progress). The opening of the source makes some observation possible: some wall deposit is apparent ; two conductive rings appears at rf window ceramics ends. This suggests periodical inspection of source (opening rear cover) and use of Mo liners

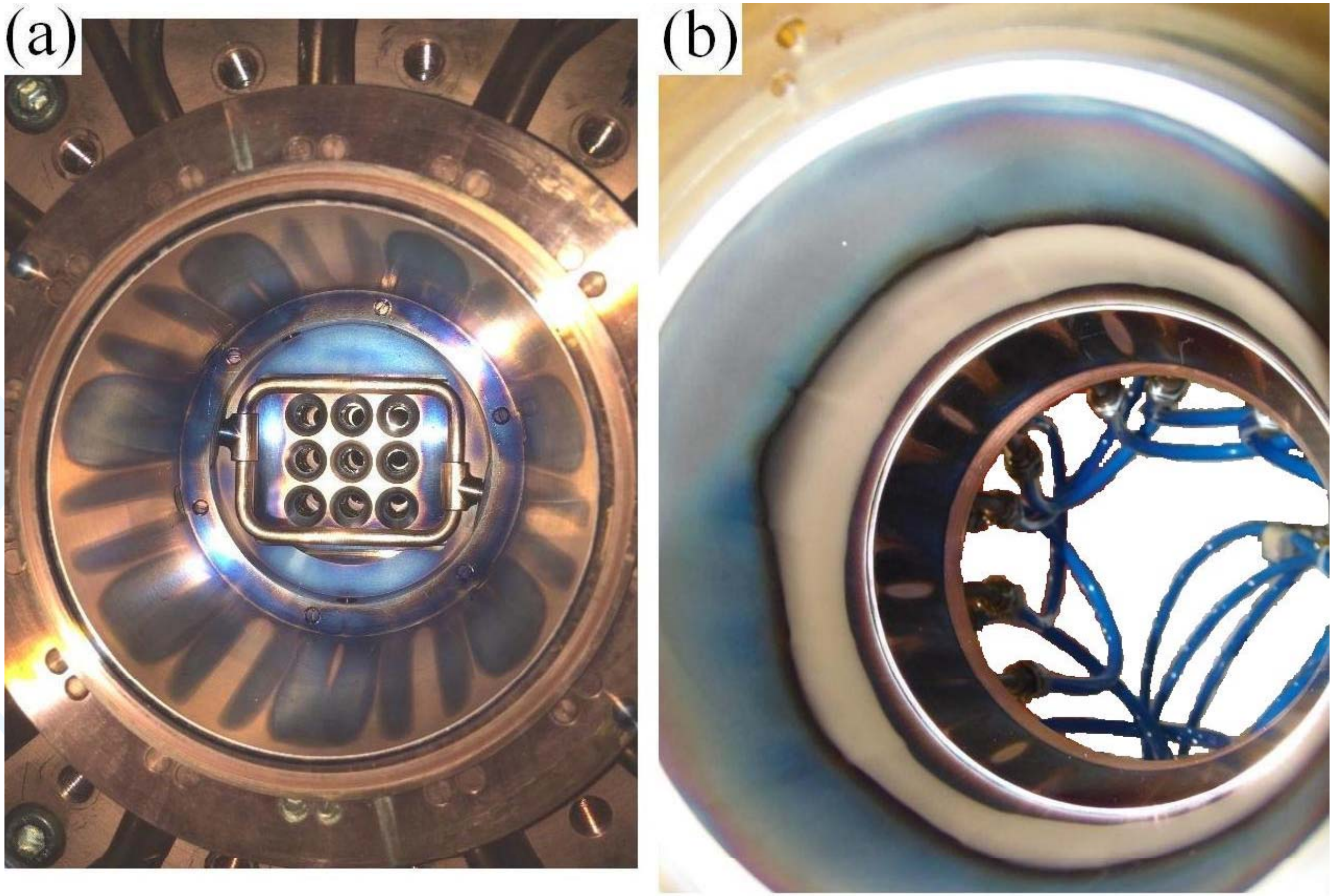


Figure 4 (a) the front multipole with bias plate and PG beam extraction holes; (b) the rf coil module with the rear multipole attached. Since NIO1 has a closed B-mod magnet configuration (as an ECRIS) the pattern of deposit is hardly surprising, but is of course worth of investigation too.

4) Conclusions

Versatile ion sources (kW beams) like NIO1 are necessary for detailed physical understanding of negative ion sources (MW beams), even if some optimization depends on source scale.

Theoretical understanding is steadly progressing, and even whole NIO1 simulations (9 beamlets) are possible for a variety of codes

NIO1 was operated both with air and with hydrogen as a filling gas; in the case of air, plasma was maintained (perhaps even ehnanced by a sharp H-mode transiton) at a low gas pressure (0.3 or 0.5 Pa) at a moderate power 0.5 kW. Scan of hydrogen pressure are less complete, but scan of rf pwer show similar transitions increasing rf power.

Thank you for attention

Acknowledgments: Work set up in collaboration and financial support of INFN group 5 (Technological Researches), INFN-E (Energy Researches), F4E (Fusion for Energy) and EUROFusion.