Oral presentation at Miniworkshop on Accelerators, Legnaro, 17/02/2015

INFN contribution to Neutral Beam Injectors at RFX and NIO1

Marco Cavenago, Laboratori Nazionali di Legnaro-**INFN**, Legnaro (PD) Italy

1) *Introduction: fusion and (high current) accelerators; overview of the neutral beam injection (NBI):*

2) *Status of NIO1 experiment*

3) *Simulations and analytical models*

4) *Perspectives*

5) *Conclusion*

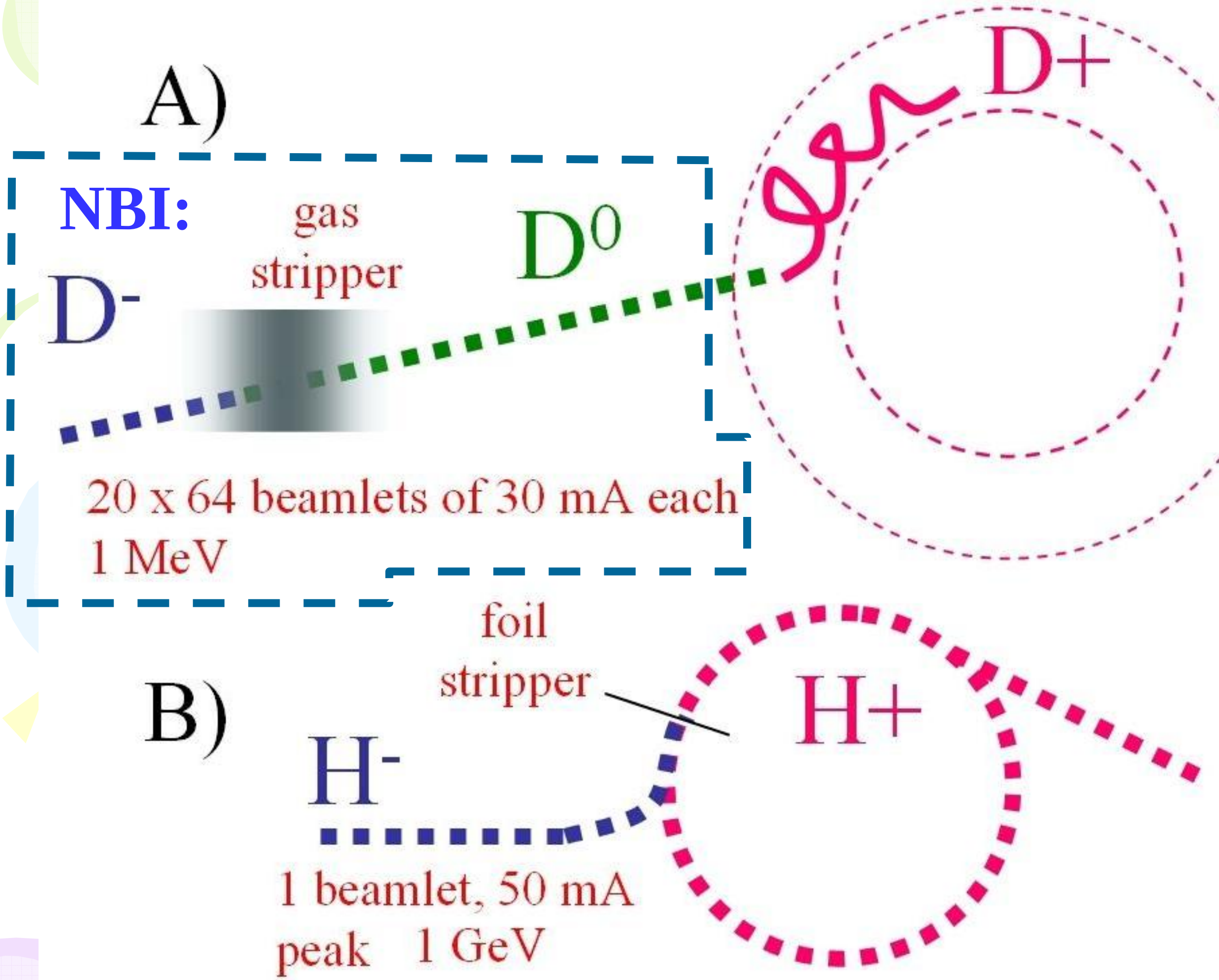
Abstract

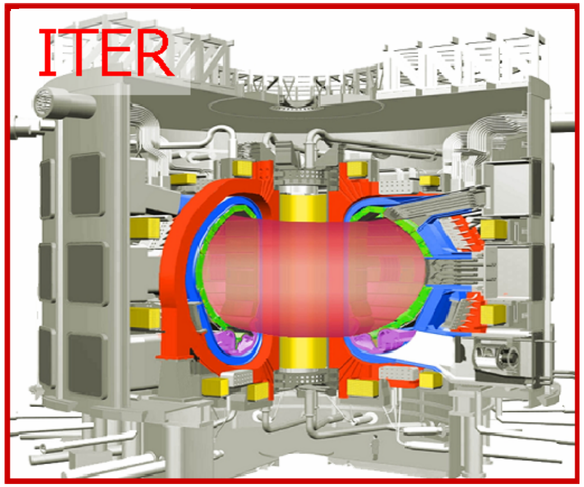
Enhancement of negative ion sources for production of very large ion beams is a very active research field nowadays, driven from demand of fusion [typical injector MITICA (Megavolt ITer Injector Concept Advancement) specification are 1 MV, 1280 beamlets, total 55 A of D- beam, converted flux 10^{20} atoms/s] and beam compression applications. Prototypes SPIDER and MITICA are under construction at Consorzio RFX.

The production of negative ion beams is in itself a task of impressive difficulty, which requests a detailed understanding of the ion source and of the beam transport, dominated by the nonlinear effects of the beam space charge. After a general overview of the accelerator system, we discuss a test source NIO1 developed in collaboration between INFN-LNL (Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Legnaro) and RFX, and its ancillary equipment developed under INFN gr5 projects Nio2beam and Beam4fusion and INFN-E. The status of NIO1 installation and first experiments is detailed.

Recent progress in modeling extraction systems (relevant both to NIO1 and MITICA) is also described.

1) Introduction: fusion and (high current) accelerators





1-3 dpa/lifetime

<=Negative ion beam and sources (NIBS) make beam storage simpler

1MV negative ion beam are easy to convert into neutrals and/or positive ions: this is used to concentrate beam power in regions with high magnetic fields: A) tokamaks; B) circular accelerators

Beam current D^- 40 A

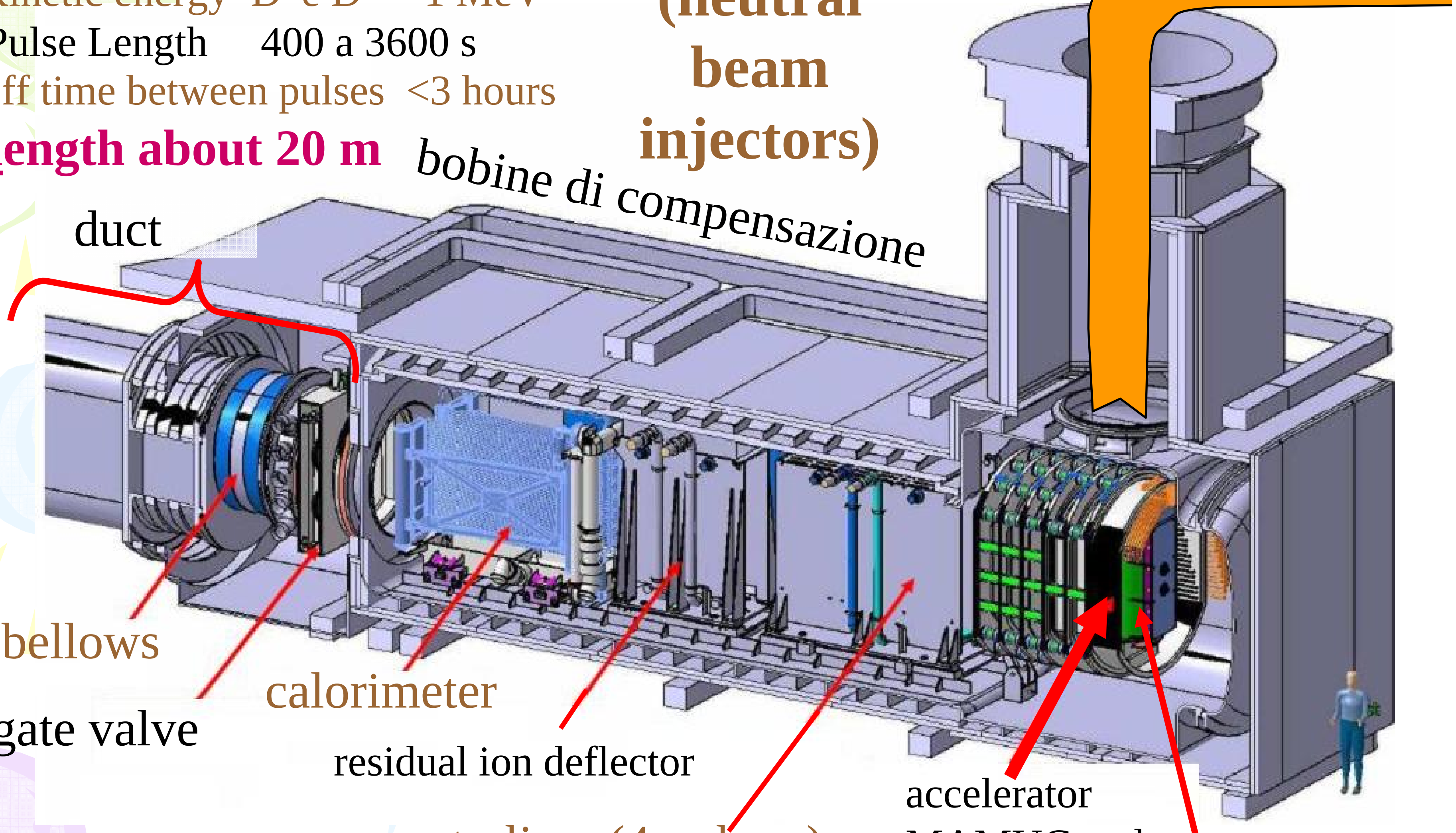
Kinetic energy D^- e D^0 1 MeV

Pulse Length 400 a 3600 s

off time between pulses <3 hours

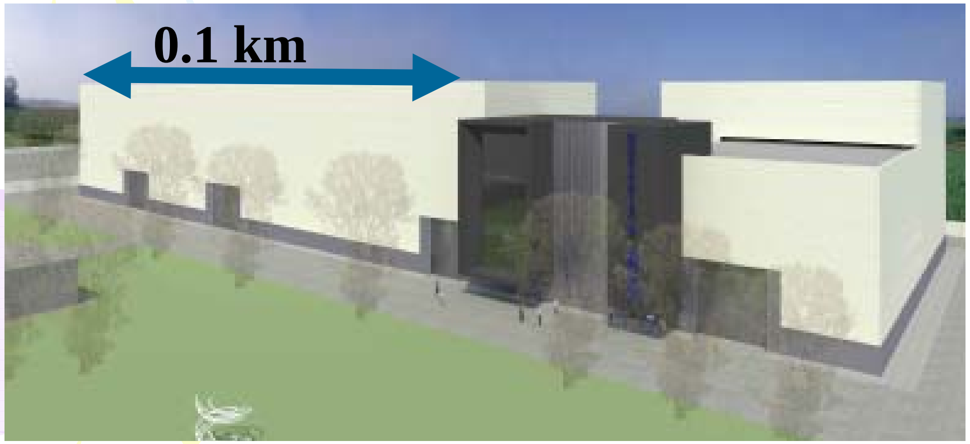
length about 20 m

NBI (neutral beam injectors)



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

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

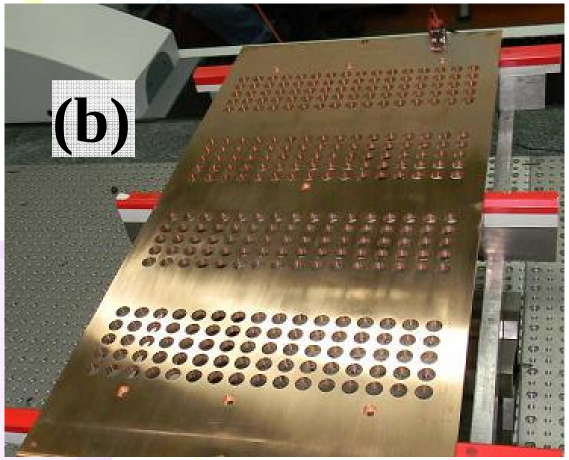


Design of buiding PRIMA-MITICA (from P. Sonato, RFX, 2009) and building view (from V. Toigo, 2015)

Covered surface	**7050 m^2**
Heigth	**26 m**

MITICA = 1 MV/40 A beam

SPIDER = 100 kV/55 A system



SPIDER PARTS (courtesy RFX) :
a) Vacuum Vessel, (ZANON, Schio);
b) beam electrode (Cecom, Guidonia);
c) beam dump and calorimeter (India domestic agency)

Mitica is a 1 MV (40 A net beam) electrostatic accelerator.

High voltage holding about 1 MV was demonstrated in smaller system (1 A beam, Naka) .

Modelling includes: cascades of particles between electrodes, probabilistic models, beam and gas effects

Anyway, vacuum voltage holding always needs dedicated experiments

800 kV High Voltage Test facility at DEI, Facolta' di Ingegneria, Univ. Padova (power supplies +/- 400 kV from INFN)

2) NIO1 and related activities

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

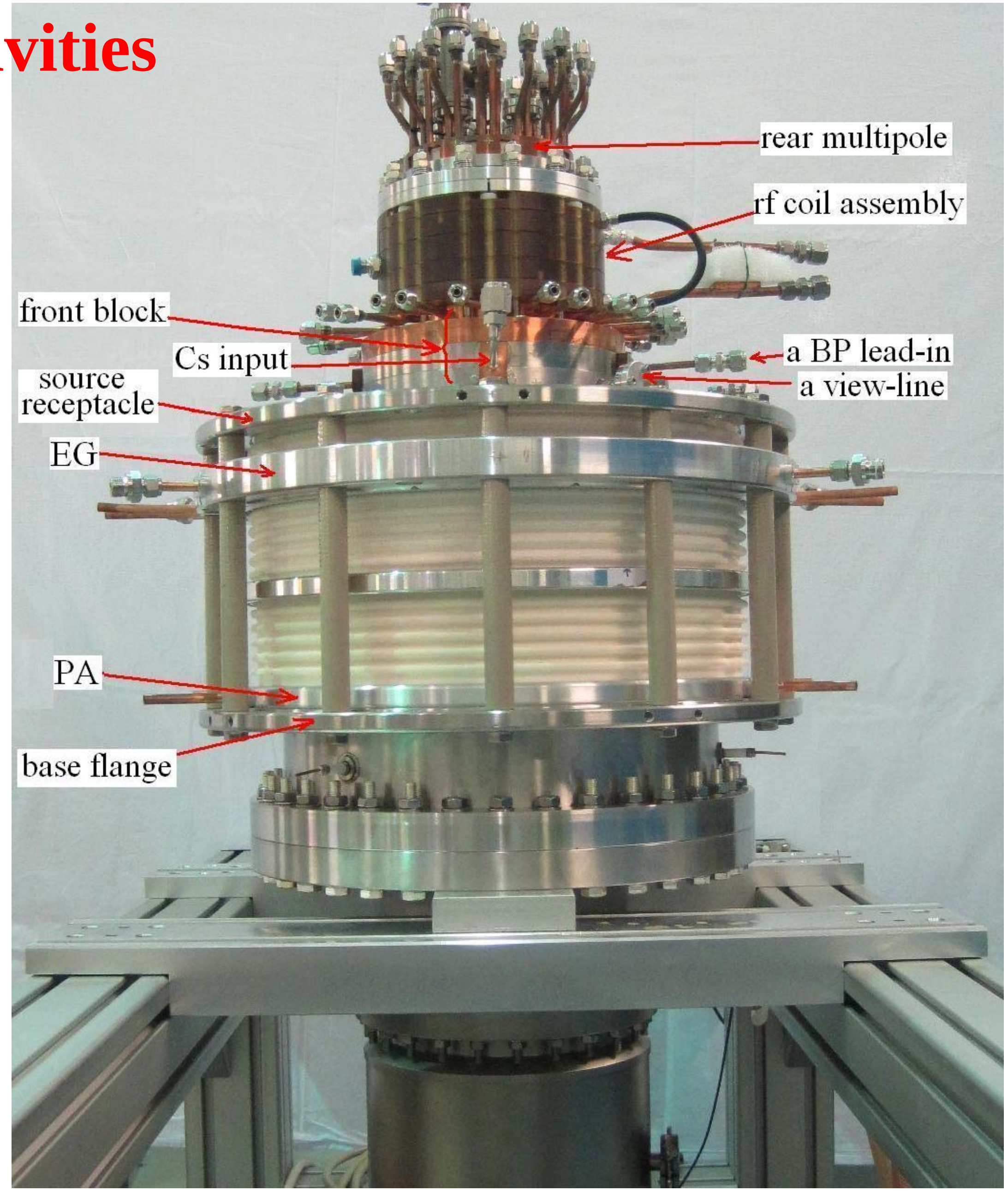
Calorimeter/beam dump (INFN) delivered to RFX in January 2014

First source operation in July 2014

Hydrogen supply installed

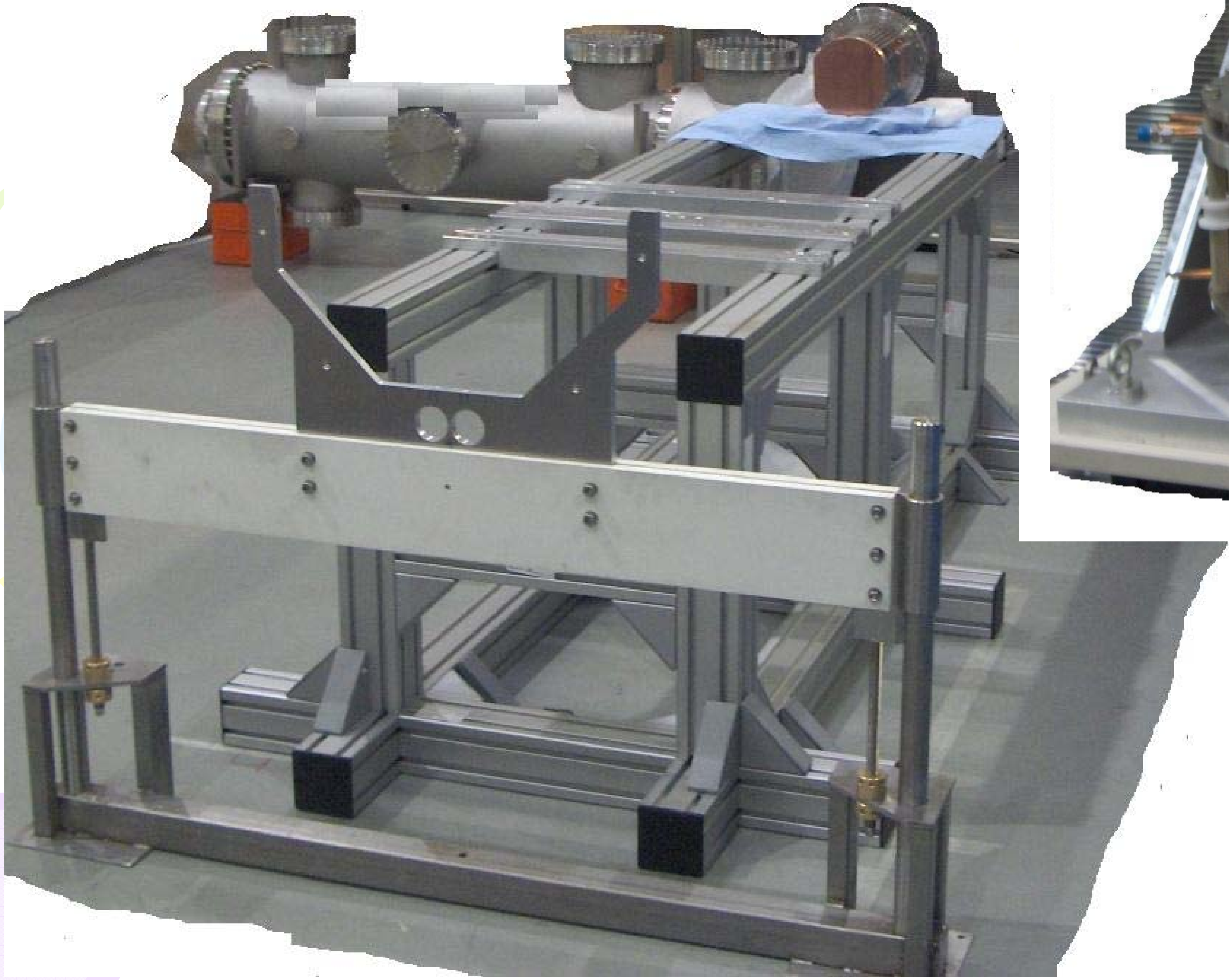
New closed water cooling system installed Sept.-Nov. 2014. Water from technical plant not yet enough for full power operation

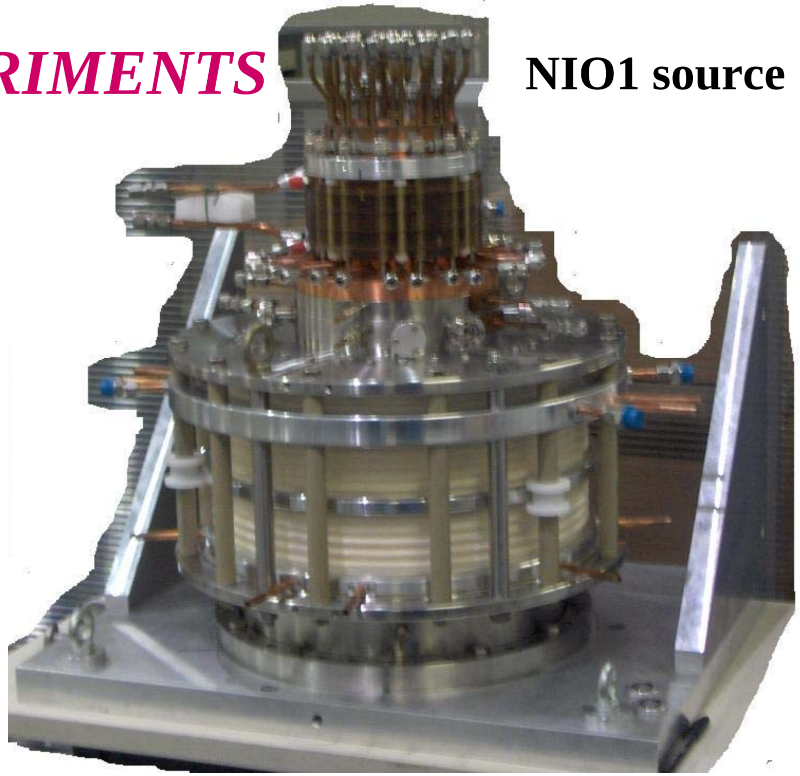
60 kV holding verified in January 2015(at source off)



2.1) NIO1 INSTALLATION AND 1st EXPERIMENTS

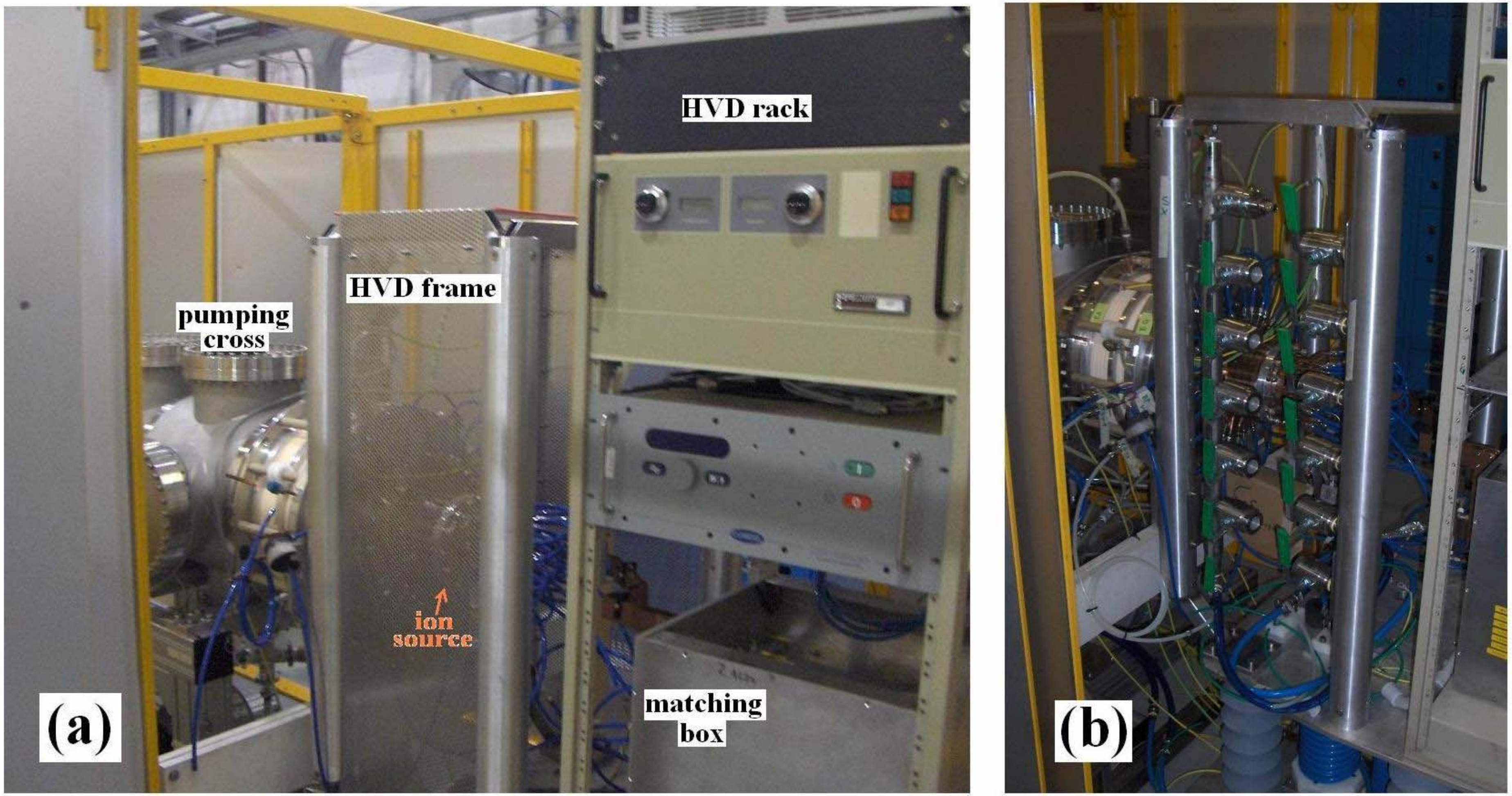
NIO1: Assemblies, support, alignments





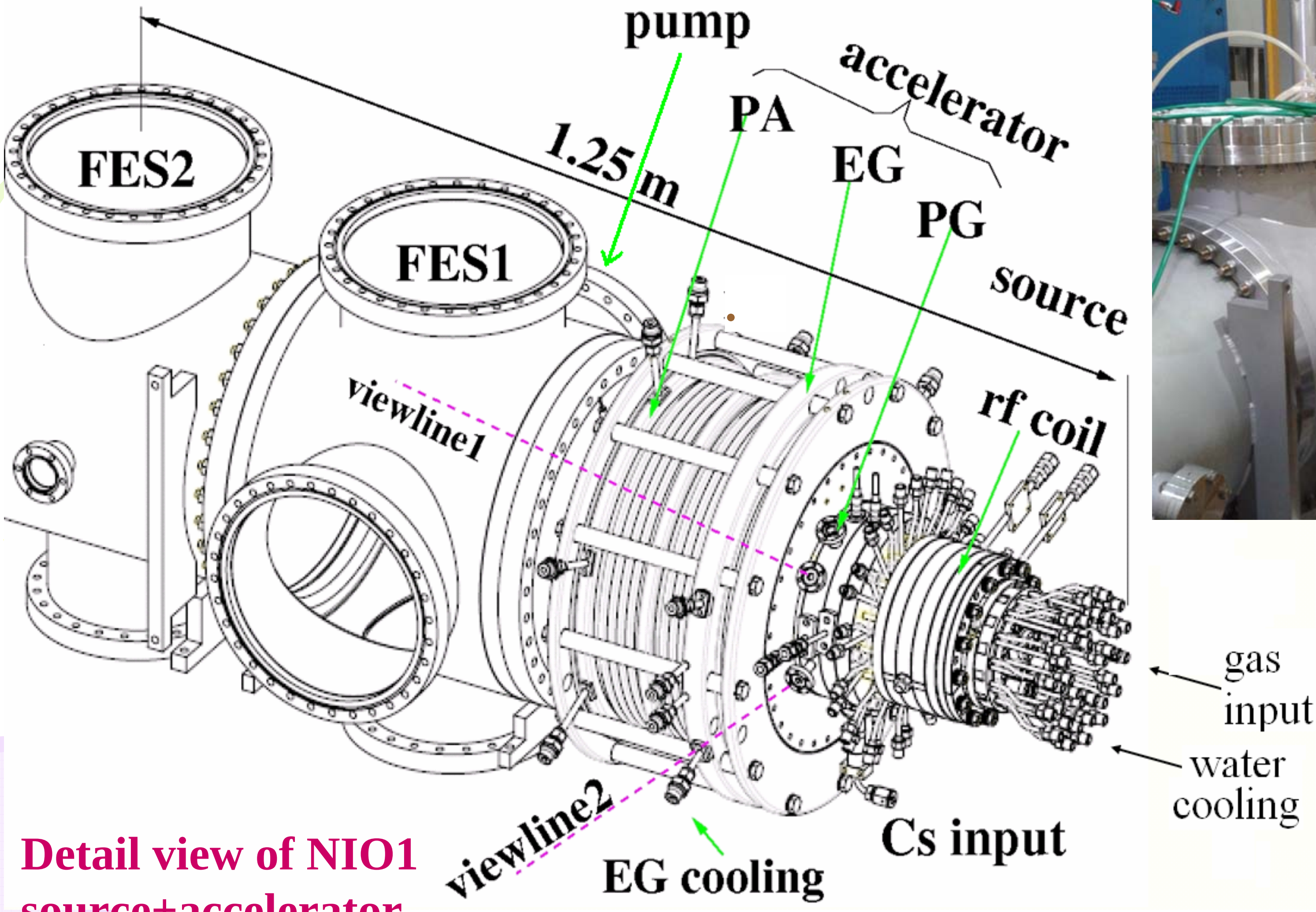
NIO1 source

static calorimeter



(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

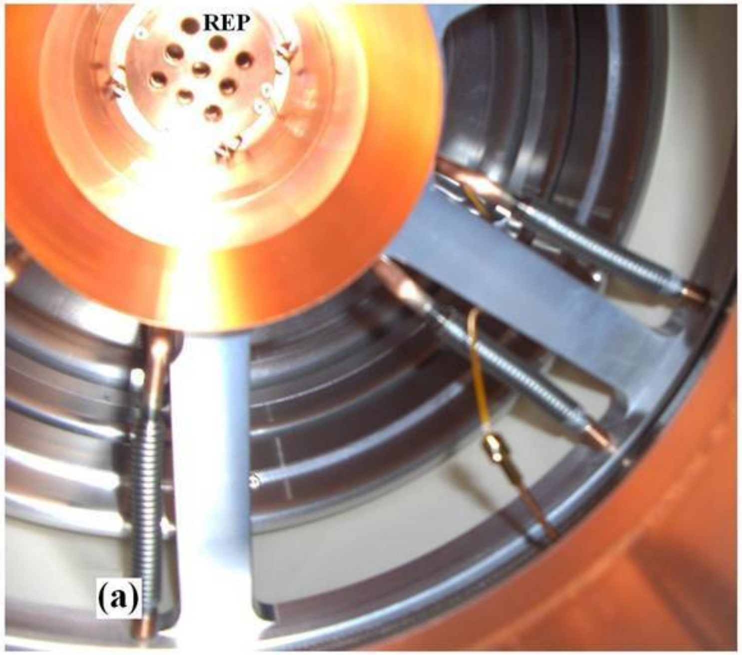
MORE DETAILS ON INSTALLATION M. De Muri et al., SOFT2014.

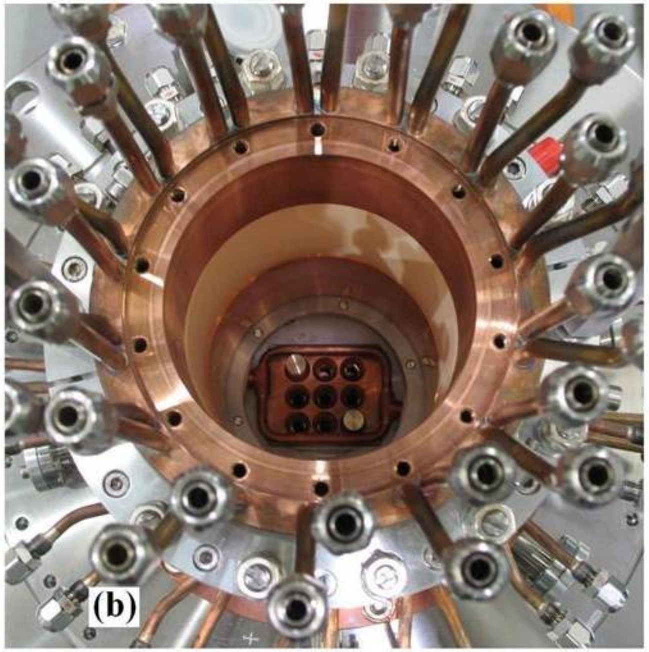


Some water cooling loops for extraction grid EG

Detail view of NIO1 source+accelerator

(a) view of PA ; (b) source opened for alignment; (c) water to HVD; (d) lead shield

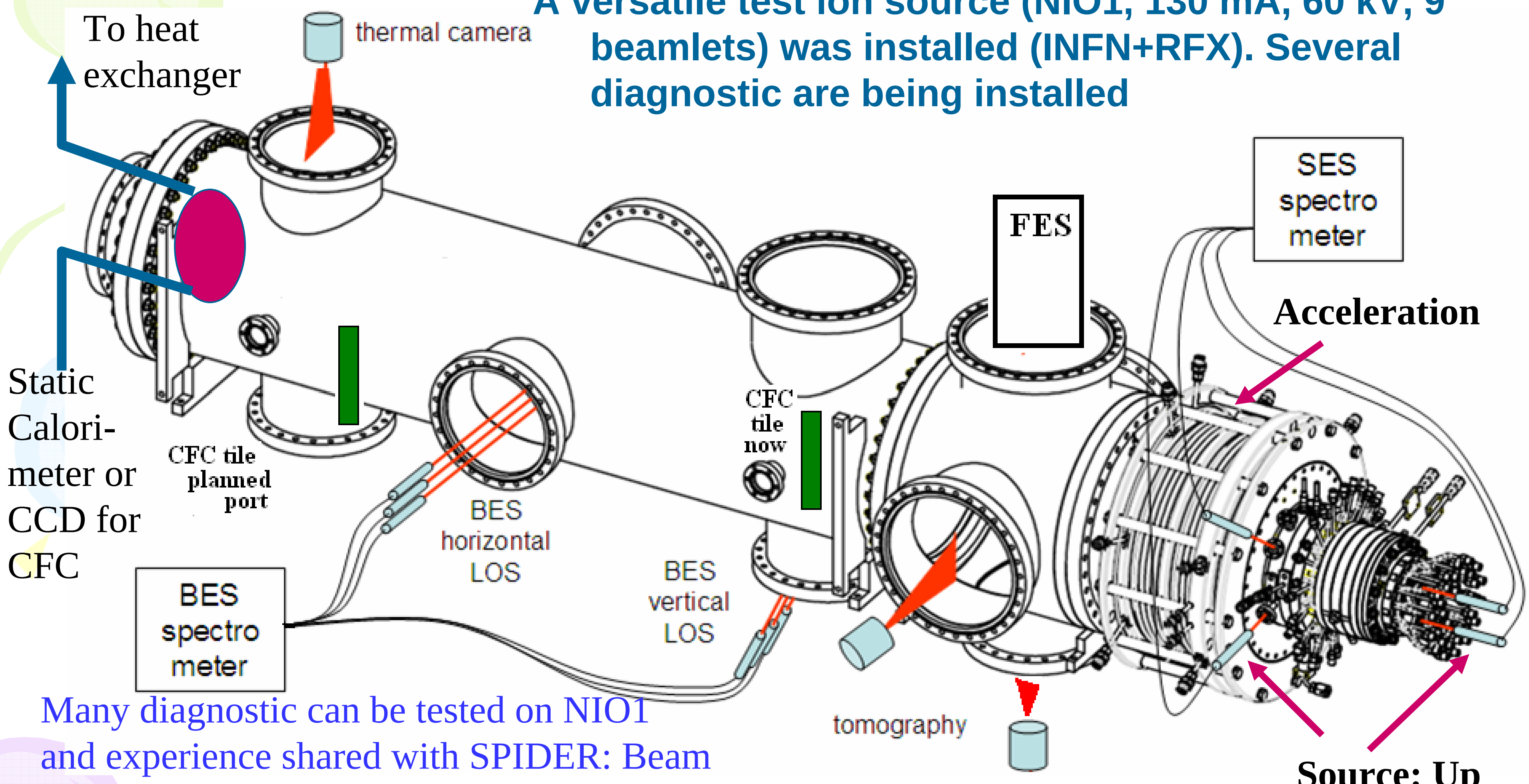




Pb box main doors

2.2) Plan of optical diagnostic and calorimetry scheme

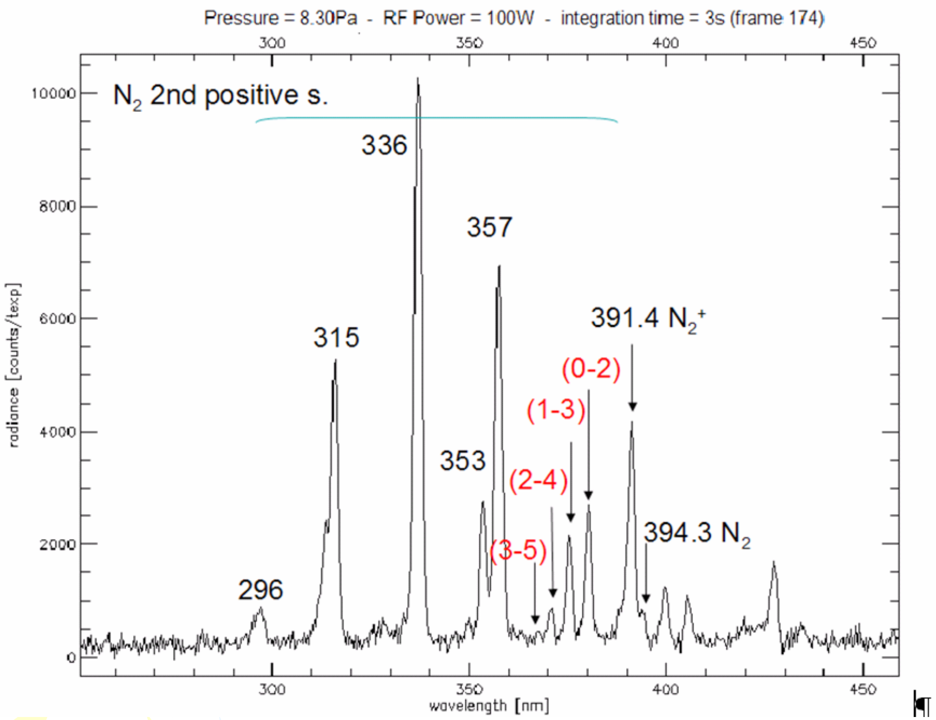
A versatile test ion source (NIO1, 130 mA, 60 kV, 9 beamlets) was installed (INFN+RFX). Several diagnostic are being installed

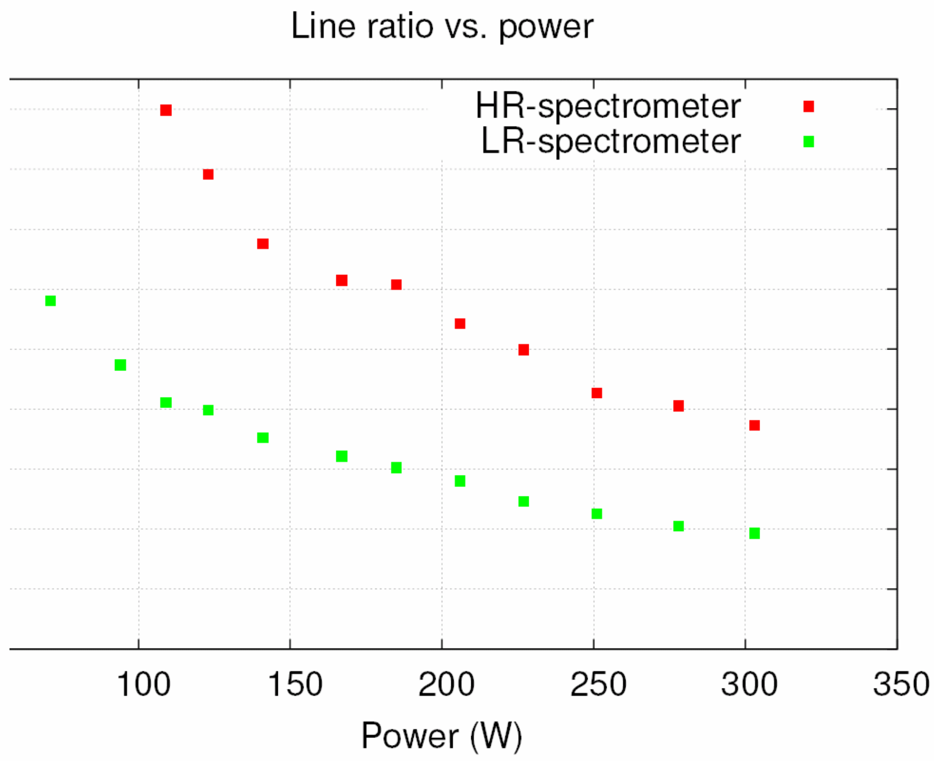


Many diagnostic can be tested on NIO1 and experience shared with SPIDER: Beam Emission Spectroscopy BES, CFC tile (10 s maximum insertion time at rated power), Fast Emittance Scanner FES (3 s), static calorimeter (>10000 s)

Fiber optic diagnostic is simpler to install

2.3) First Nio1 Experiments results

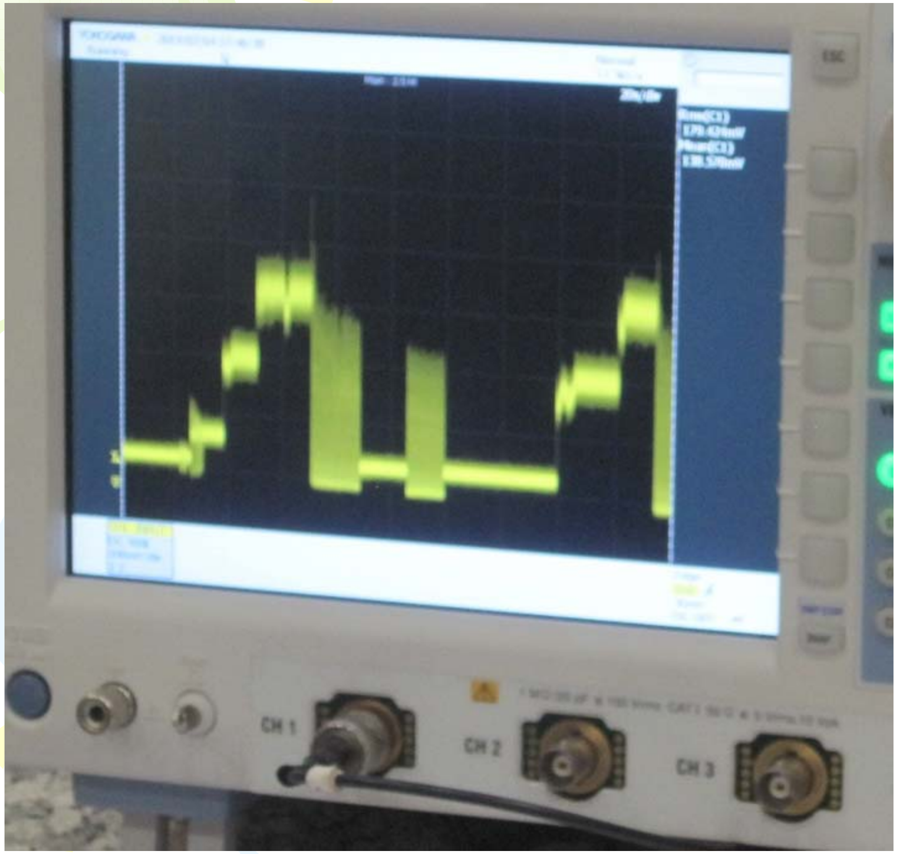




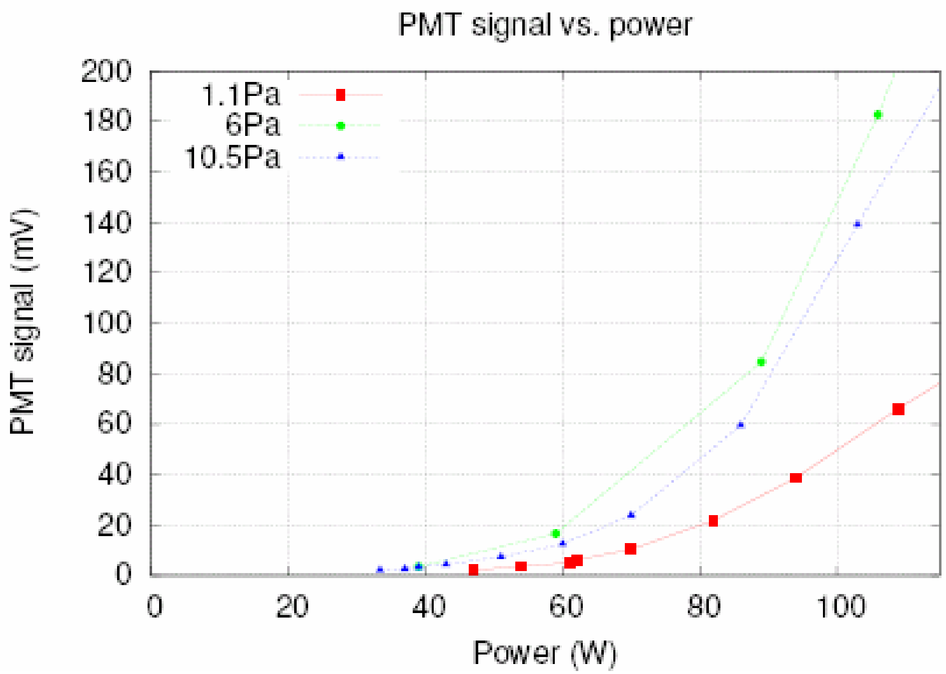
Part of spectra, with nitrogen lines (A. Mimo, thesis, Padua 2014; see Zaniol et al., NIBS2014). Source parameter filling pressure 8.3 Pa, Prf= 100 W, spectrometer integration time 3s)

Ratio of internsity nitrogen lines 391/394 (A. Mimo, thesis, Padua 2014; see poster Zaniol et al., NIBS2014). Background from air (oxygen, argon, etc) and possbly strongly non Maxwellian EEDF.

1st RESULTS WITH NIO1; support gas =air



Source luminosity (a.u.) as measured by a photomultiplier at rf power level Prf= 50, 80 and 100 W, with the stabilized rf generator, as limited by avalaible cooling at that moment available.



Plasma light signal vs rf power, low power region (A. Mimo, thesis, Padua 2014; see poster Zaniol et al., P2-07), for several source parameter filling pressures. For larger rf powers, growth becomes about linear

2.4) Work to do (next) on NIO1

1) To complete the cooling water infrastructure for NIO1 (unfortunately there was an hidden shortage of room cooling water) . A CFC calorimeter (not water cooled) and an air cooled rf generator was installed on NIO1 as a temporary back-up.

2) Beam extraction with O plasma at lower voltage and power, for preliminary test with the CFC calorimeter.

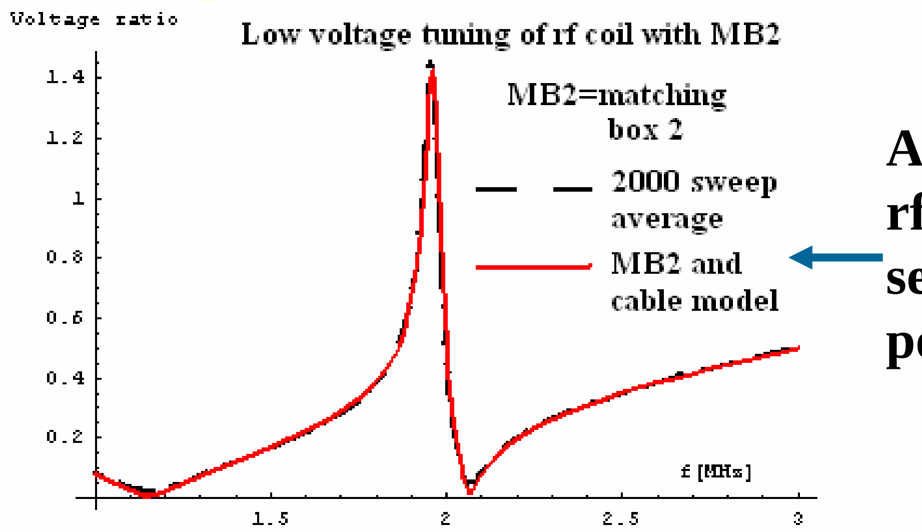
3) Validation of RFX interlocks for operation; control system; PLC system

4) To complete rf matching in NIO1 system, according to experience at LNL MetAlice test-stand (transition from E to H coupling and low pressure operation routinely achieved)

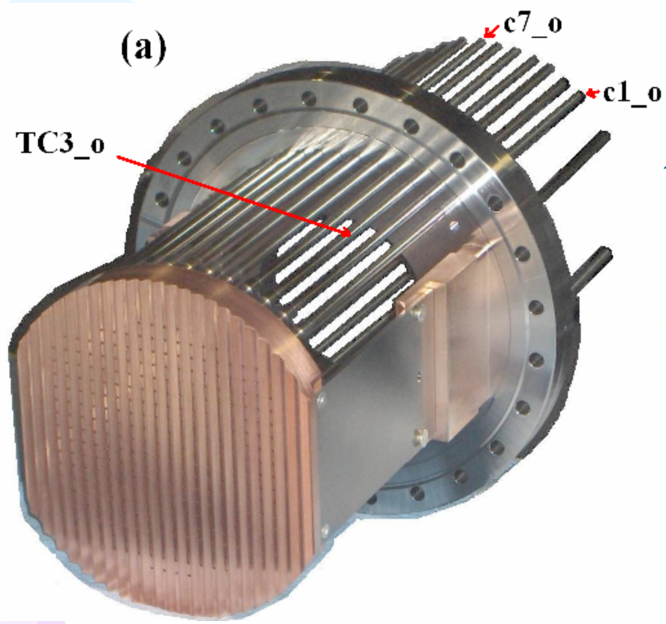
5) Install the static calorimeter with electronics, calibration of its thermocouples, development of pepper pot Mo mask.

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

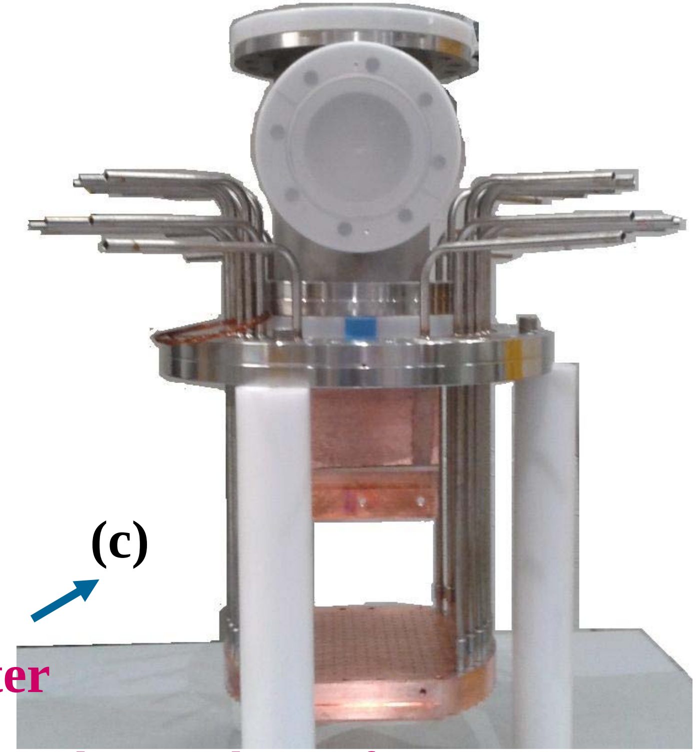
6) Move the LNL Cs oven to RFX



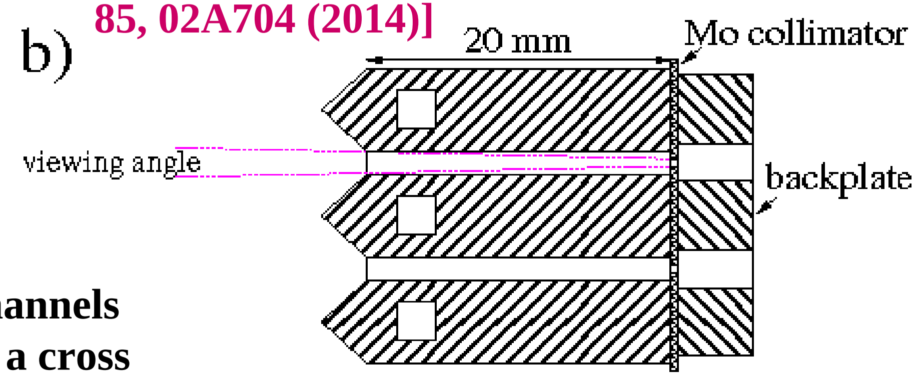
Accurate rf model seems possible



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)]

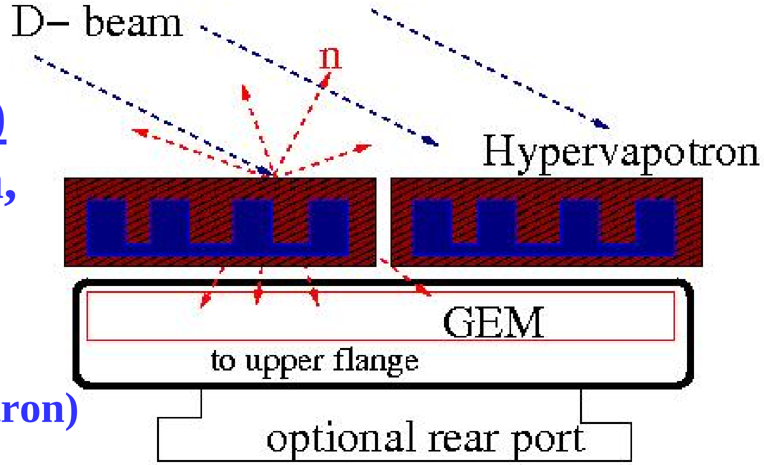


(a): Beam dump/calorimeter, with marks at some channels and thermocouple (TC) reserved positions; (c) with a cross for viewport and multipin feedthroughs assembly

2.5) Other INFN contributions to NBI and fusion

A) Beam4fusion group 5 experiment (BA, LNF, LNL, MI, MIB) includes:

1) design of NIO1 and collaboration to its installation ;



2) construction of GEM (gas electron multiplier) detectors and integrated electronics for neutron, for monitoring:

SPIDER/MITICA (2.45 MeV neutrons from D implanted in calorimeters, also known as Hypervapotron)

tokamak (2.45 MeV vs 14 MeV neutrons discrimination);

3) in progress: studies of beam space charge compensation, and new concepts for NBI for Demo (D^+/D^-/electron beam merging, energy recovery and plasma neutralizers).

B) Additional support was provided by INFN-E [for present application of GEMs to tokamak KSTAR see F. Murtas slides in recent 11/02/15 meeting on INFN-E].

3)Recent theoretical studies

Motivation: megawatt beam need *precise* aiming

3.1) Optimization of Extraction Grid deflecting magnetic fields [M. Cavenago and P. Veltri, *Plasma Sources Sci. Technol.*, 2014]

3.2) Pic code for NIO1 accelerator geometry [P. Veltri and M. Cavenago, RSI, 2014]

3.3) Laminar and Vlasov studies of realistic ion extractors; reported at ICIS (Tokyo, September 2013), SIF (Trieste, September 2013) and Vlasovia (Nancy, November 2013) and published [M. Cavenago, RSI, 2014, M. Cavenago, EPJ-D, 2014]

3.4) Multi-grid optics, that is. SPIDER, MITICA, NIO1; partly published [P. Veltri, M. Cavenago and C. Baltador, AIP-CP in press, 2015]

3.5) Collisional effects in magnetic filter and in beam extraction (several works in progress); physics of complex plasmas.

Some detail of item 3.1 only follows:

3.1) THEORETICAL AND NUMERICAL STUDIES FOR MITICA E NIO1

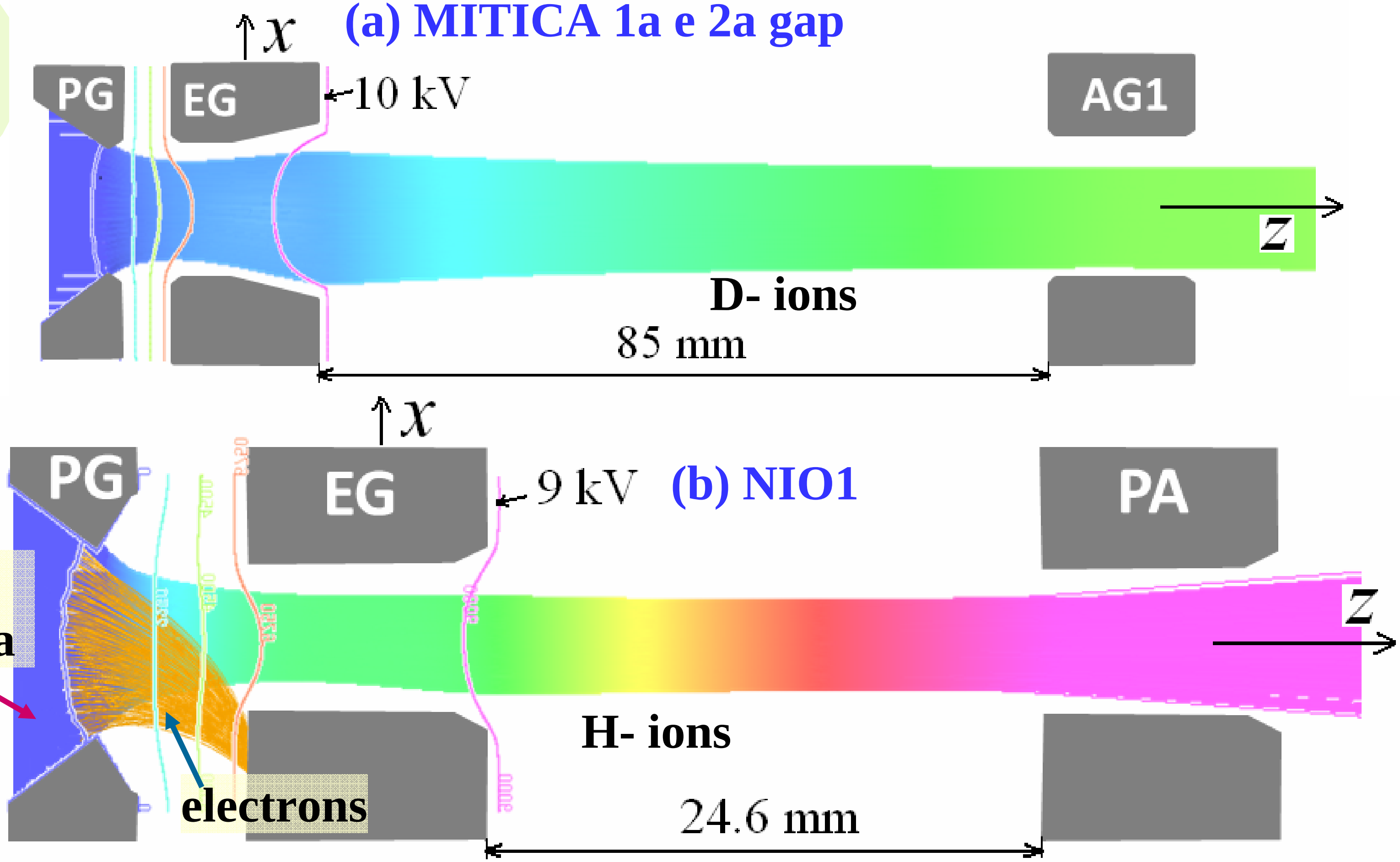
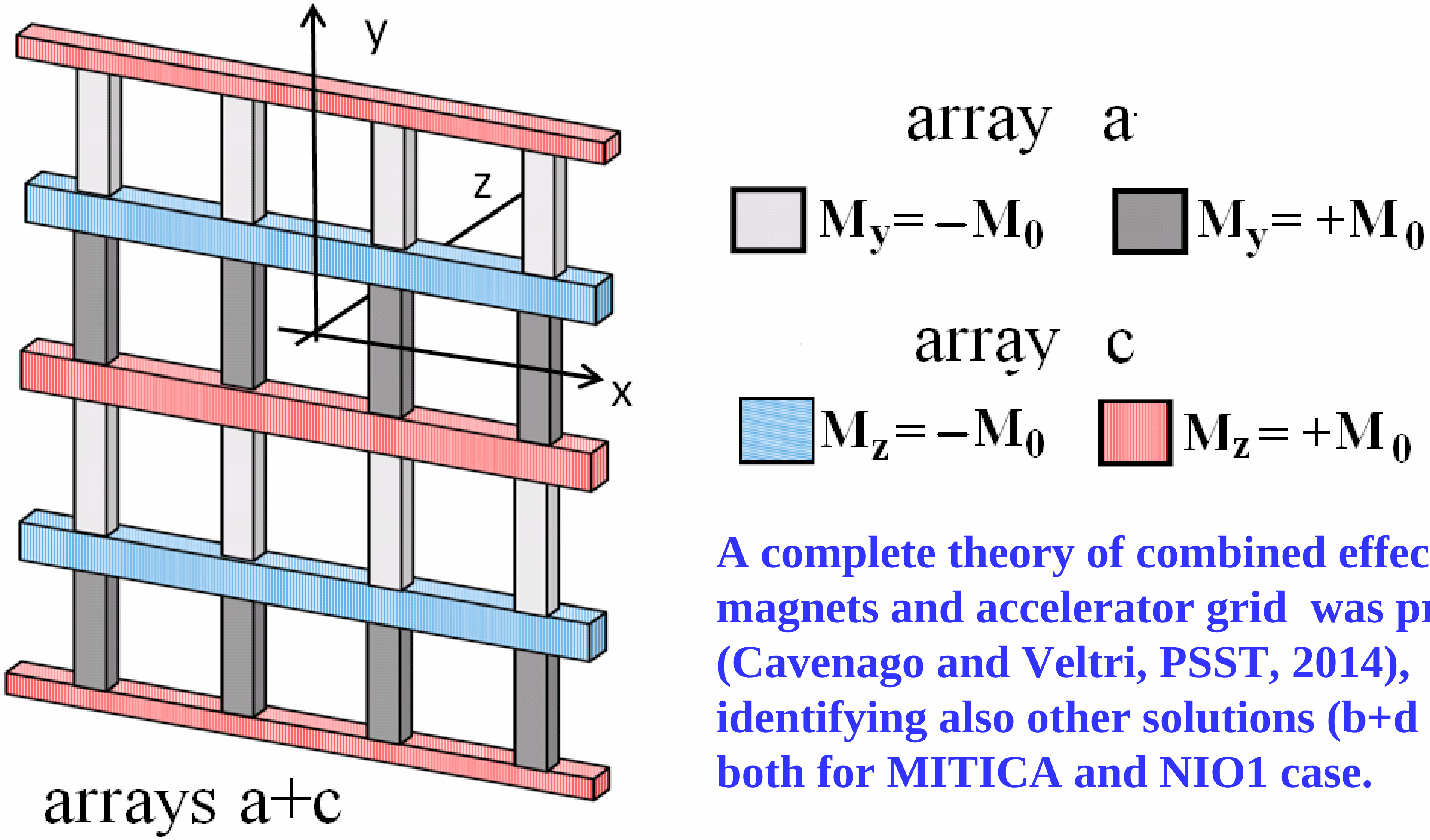


Figure: (a) cancellation of the ion magnetic deflection, for MTICA with V(EG)-V(PG)=9 kV and ion current density j=340 A/m² (b): same for NIO1 with with V(EG)-V(PG)=8 kV; here the coextracted e⁻ are also shown, and stopped on the EG grid (Cavenago and Veltri, PSST, 2014).

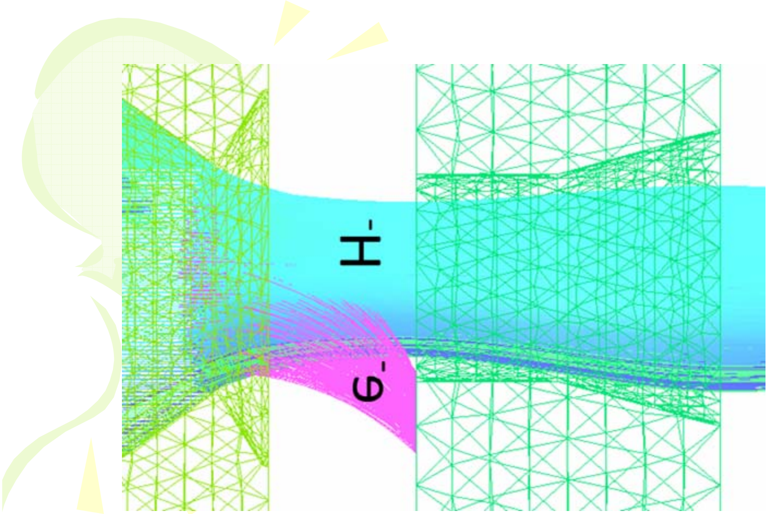
Figura: compensazione della deflessione magnetica degli ioni, caso MTICA (a) con V(EG)-V(PG)=9 kV e j=340 A/m^2 e NIO1 (b) Si noti che gli elettroni coestratti sono fermati sulla griglia EG (Cavenago and Veltri, PSST, 2014).

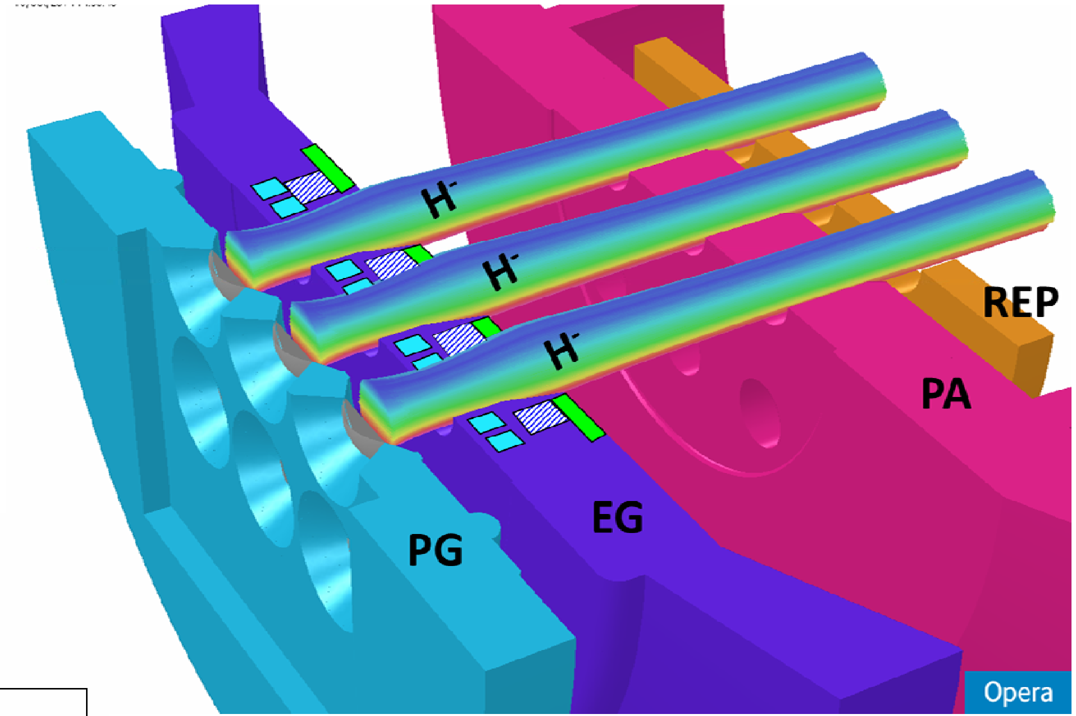
TWO MAGNET ARRAYS INSIDE THE Electrostatic Grid EG

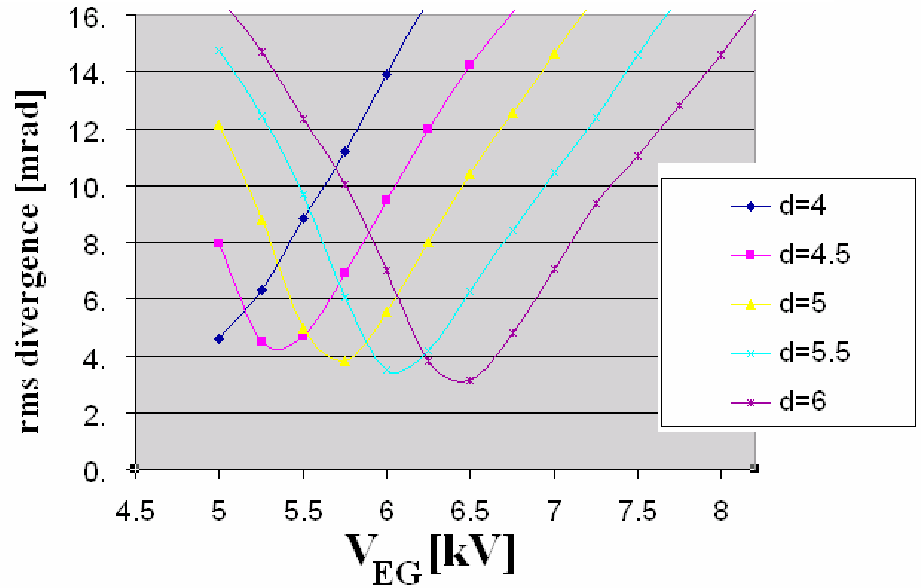
Array c leaves a residual deflection on ion beam, but dump electron beam out. It was recently observed [Chitarin et al (2013, RSI 2014), Antoni et al (RSI, 2014) , Cavenago and Veltri (PSST, 2014)] that another array like 'a' may cancel ion deflection at MITICA at 1MV.



A complete theory of combined effects of magnets and accelerator grid was proposed (Cavenago and Veltri, PSST, 2014), identifying also other solutions (b+d arrays), both for MITICA and NIO1 case.

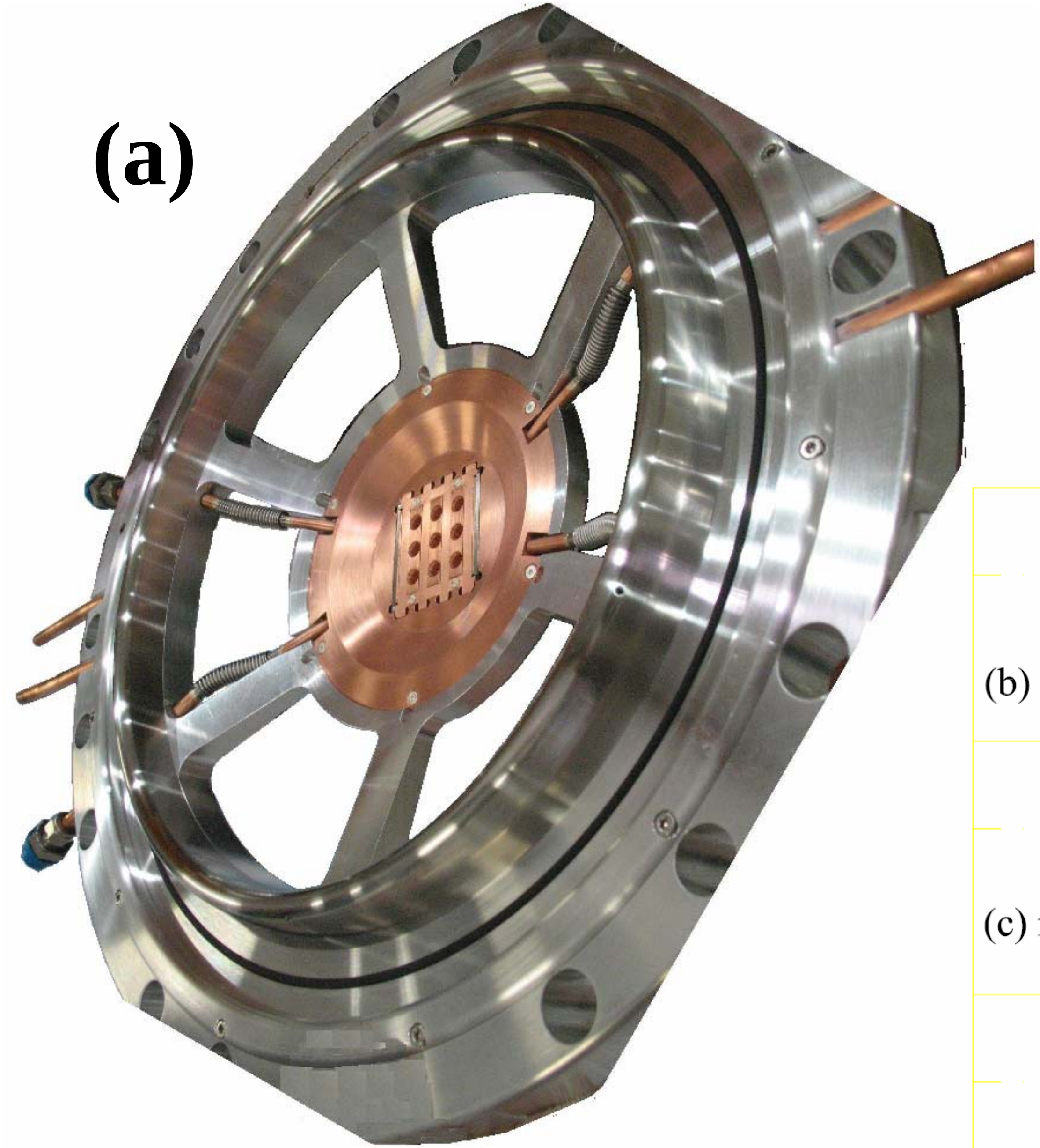


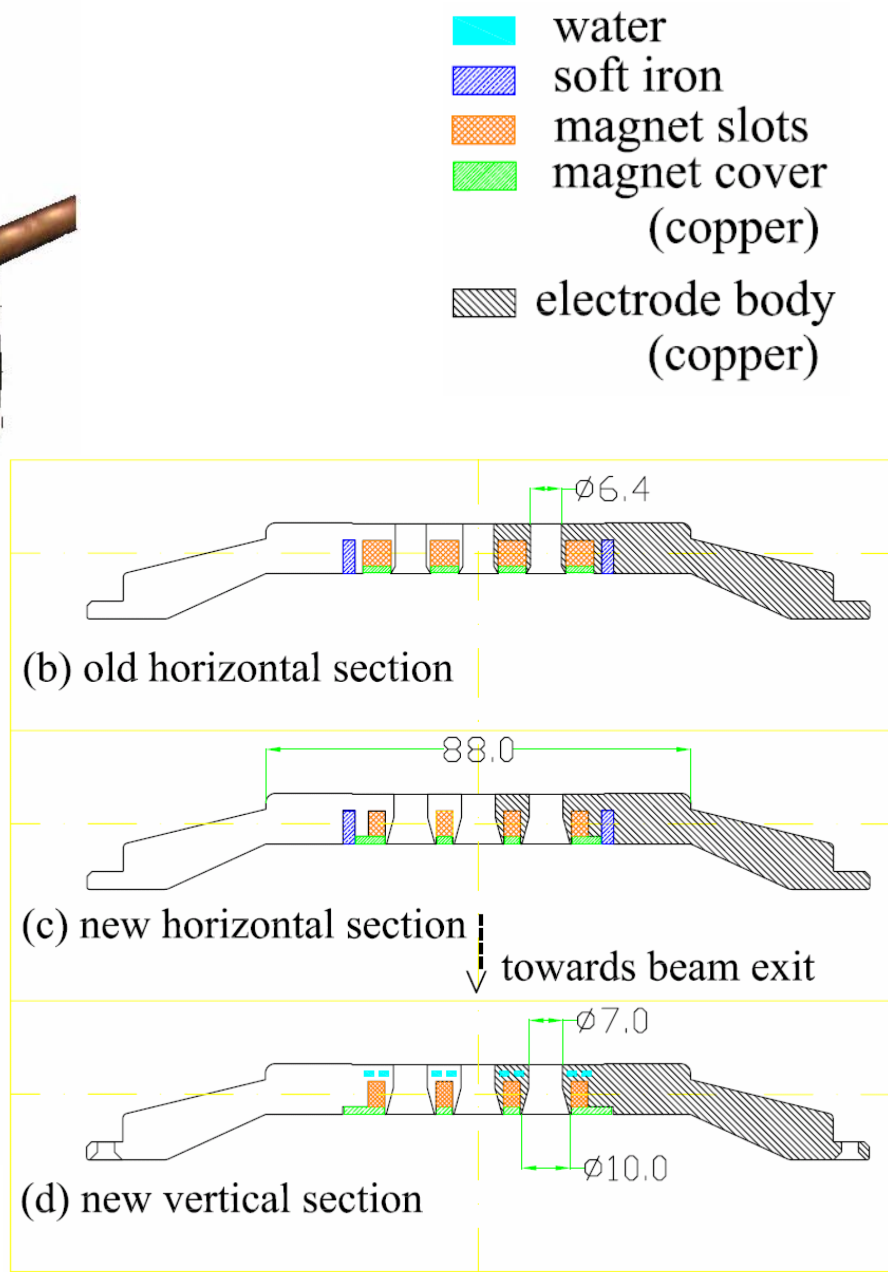




Simulation of the whole NIO1 extraction with OPERA/SCALA (TM) (see Veltri et al, 2015)

Rms divergence of NIO1 output beam vs Extraction Grid Voltage VEG for several distance d of EG e PG electrodes (SLACCAD simulations, see Veltri et al, 2015). Our code ACCPIC.v7c make these trends more precise, also with temperature effects.





Extraction grid, built (a) and (b) and new with 8 magnets slots (c) and (d)

Perspectives

1) the installation of giant NBI systems at RFX is steadly progressing; some theoretical work (and simulations also) at RFX and LNL proved to directly relevant to physics of these accelerators

2) test source NIO1 has reached its first important milestones, and is progressively recognized as important part of RFX activities

3) the collaboration with ITEP (FAI-like) was very helpful, especially for miniature RF source, and needs to be continued

4) multiphysics simulations and experiments on high voltage systems may help MITICA operations

5) multibeamlet ion sources promote advances of beam manipulation techniques, like beam merging (H+/H- and or e), beam space charge compensation and plasma based neutralizers

5) 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

NIO1 is now partly operational, some RFX technological plants are being upgraded (hopefully in this February 2015).

Diagnostic for NIO1 is developed in synergy with other source diagnostic

Rf matching box, Cs oven and rf coupling were validated on separated test stand with O/N plasmas and partly reproduced in NIO1

Thank you for attention

Acknowledgments: Financial support from INFN group 5 (Technological Researches), INFN-E (Energy Researches) and from Fondazione Cassa di Risparmio di Padova e Rovigo is gratefully acknowledged.

Tesi magistrali (Master thesis) on NIO1, year 2014, Padua University:
M. Cazzador, Analytical and numerical models and first operations on the negative ion source NIO1
A. Mimo, Diagnostics for negative ion source NIO1

Some of the most recent publications

M. Cavenago and P. Veltri, "Deflection compensation for multiaperture negative ion beam extraction: analytical and numerical investigations", ***Plasma Sources Sci. Technol.*****, vol. 23, (2014) 065024 (14pp)**

V. Antoni, P. Agostinetti, D. Aprile, M. Cavenago, G. Chitarin, N. Fonnesu, N. Marconato, N. Pilan, E. Sartori, G. Serianni and P. Veltri, "Physics design of the injector source for ITER neutral beam injector (invited)", ***Rev. Sci. Instrum*****. , vol. 85, 02B128 (5pp) (2014)**

G. Croci, G.Claps, M.Cavenago, M.DallaPalma, G.Grosso, F.Murtas, R.Pasqualotto, E. PerelliCippo, A.Pietropaolo, M.Rebai, M.Tardocchi, M.Tollin, G.Gorini, nGEM fast neutron detectors for beam diagnostics, ***Nuclear Instruments and Methods in Physics Research*** **A 720 (2013) 144–148**

M. Cavenago, "Low temperature high current ion beams and laminar flows", ***Eur. Phys. J. D*****, vol. 68, 198 (12pp) (2014)**

M. Cavenago, G. Serianni, V. Antoni et al., Development of Versatile Multiaperture Negative Ion Sources, (to appear in NIBS2014 proceedings, ***AIP Conf. Proc.*****, (2015) accepted 26 Nov. 2014)**

P. Veltri, M. Cavenago and C. Baltador, Design of the new extraction grid for the NIO1 negative ion source (to appear in NIBS2014 proceedings, AIP Conf. Proc. (2015), accepted 22 Dec. 2014)