Presentation at "Workshop Transizione Energetica (INFN-E e INFN-A) 21-22th Feb '24, INFN-LNS

Neutral Beam Production for fusion reactors: some activities

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INFN sez. BA, LNL, MIB; collaboration with RFX, CNR-ISTP, Univ. Padova

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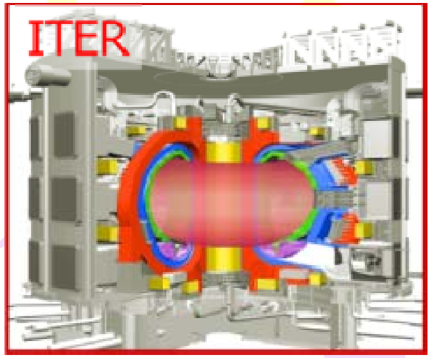
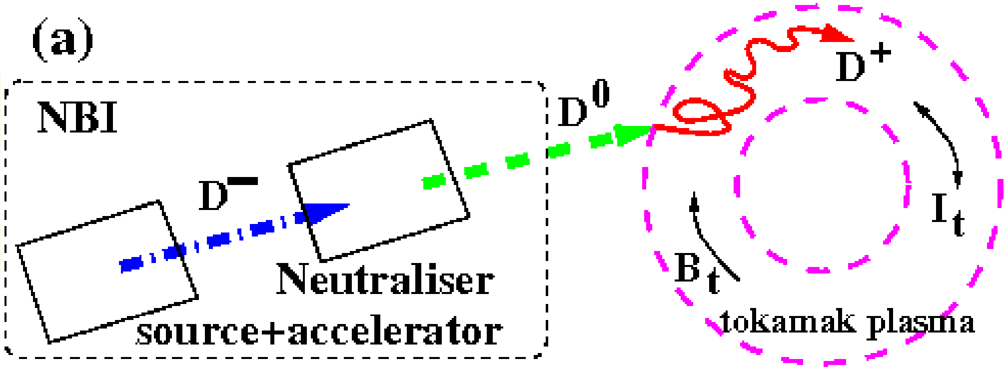
1) Introductory remarks on NBI (neutral beam injectors)

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



1-3 dpa/lifetime



Concept of NBI: D$^-$ are more easily converted to D^0 than D$^+$ would be; then D^0 ions may enter a magnetically confined plasma and are ionized to D+ which heat the plasma and drive toroidal current I_t (from Fig 1a in Cavenago, Il Nuovo Cimento 39 C (2016) 291 doi 10.1393/ncc/i2016-16291-0)

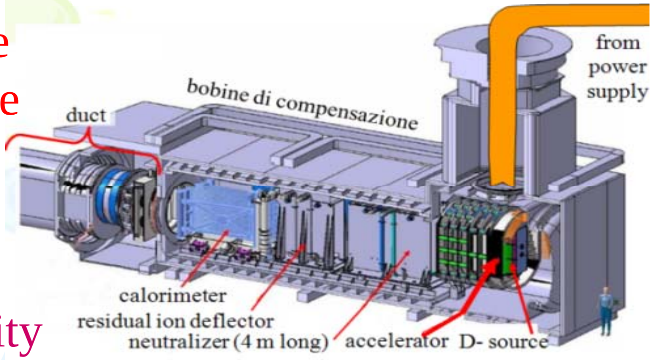
But the negative ion sources are more complicate to build and operate for the same reason: the binding energy of one e and D^0 is only 0.76 eV requesting a cold plasma. This motivates NBTF, with SPIDER and MITICA

NBTF= Neutral Beam Test Facility

MITICA = 1 MV/40 A beam

SPIDER = 100 kV/55 A system

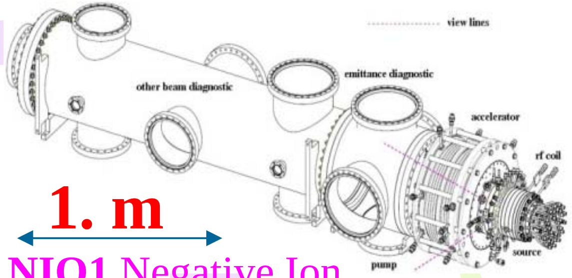
Front view of SPIDER, note Grounded Grid



MITICA

DEMO may require Cs-free operation; surely a fusion reactor requests >> 10^8 s operation . Radiofrequency (rf) ion sources were preferred by ITER to arc sources for durability.

But rf sources tend to give a lower beam quality and to be inefficient in Cs-free condition.



NIO1 Negative Ion Optimization step 1

NIO1 programme aims at investigating these physical issues in a drastically reduced scale, still preserving/including:

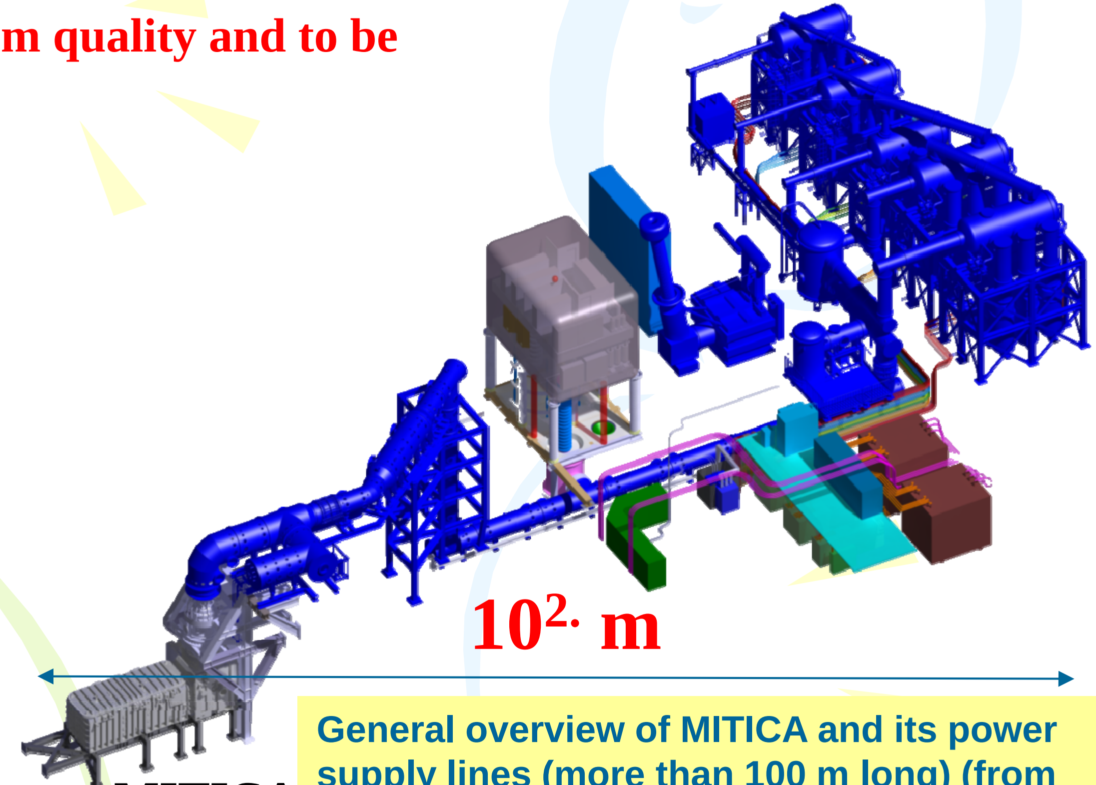
+multi beamlets (9)

+continuous operation (surface evolution)

+multipole magnets also behind RF coil [see M.C et al. Rev. Sci. Instrum. 81, 02A713 (2010) doi: 10.1063/1.3271247]

+ Cs-free operation or carefully controlled Cs coverage

+new technology tests, as necessary for addictive manufacturing, and easy access



General overview of MITICA and its power supply lines (more than 100 m long) (from G.Serianni, ICIS 2019)

Building covered surface	**7050 m^2**
Height	**26 m**

1.2) Motivation and perspectives

Accelerator development is recognized as one of the leading activity of CSN5 and INFN/A; the Neutral Beam Injectors envisioned in the fusion reactor researches (fostered by INFN-E) are accelerators, perhaps of exceptional size and complexity (many beamlets).

Fusion reactor researches are a primary goal for social application of nuclear physics. Any (even minimal) contribution to NBI reseaches should thus be welcomed and adequately supported

We emphasize physical understanding of underlying accelerator and plasma physics in particular:

+long term stability of apparatus [NIO1* has surpassed the 10^4 s continuous beam time per day, while most of installations dwells with order 10^2 s long operation (see next slide), and final aggregate goal is in the 10^8 s range]

+transport of negative particles in plasmas and uniformity of their extracted beams

+energy efficiency and recovery, high voltage holding

[*] J. Inst, 14 sept 2023, doi: 10.1088/1748-0221/18/09/C09009,

1.3) The 6/2023 state of art: beam lifetime in H$^-$/D$^-$ sources for fusion

The issue of durability is usually postponed to the actual operation of full-scale prototypes for current density ji= 30 A/m2 without cesium and 300 A/m2 with cesium. Often (to save power) the source is kept running for a period of T1 seconds, during which N beams are extracted, each lasting T2 seconds; T2 is more significant to correctly include ionic gas pumping. In a real fusion reactor we can think of using two NBI systems for each injector (so as to regenerate one while the other supplies the beam). In the case of NIO1 we have T1=T2 > 10^4 s, 9 beamlets, every day of use but j_i=27 A/m^2 without cesium and up to now, only 60 A/m^2 with cesium

NIO1, T2>10000 s CW, ji=50 A/m2, **9 beamlets** **vedi J.Inst, Barbisan et al, 2022, doi: 10.1088/1742-6596/2244/1/012052**

CRAFT, ji=140 A/m2, T2=105 s **doi:10.1088/1748-0221/18/07/C07017 :**

"The results also show that, the generation of negative ions in the first 10 seconds is much better, recycling of Cs tends to stabilize after 20 seconds of plasma discharge"

ELISE, T2=10 s for cooling problems at ji=300 A/m2, **about 600 beamlet** **doi: 10.1088/1742-6596/2244/1/012049 : in 100s pulses ij << 100 A/m2**

SPIDER, T2=30 s ji=150 A/m2, extracted 80 beamlet out of 1280 (old data),

JPARC, T2<1 ms, 25 Hz repetition, ji=200 A/m2 **doi: 10.1088/1367-2630/aaa39e : in 100s pulses ij << 100 A/m2, 1 beamlet**

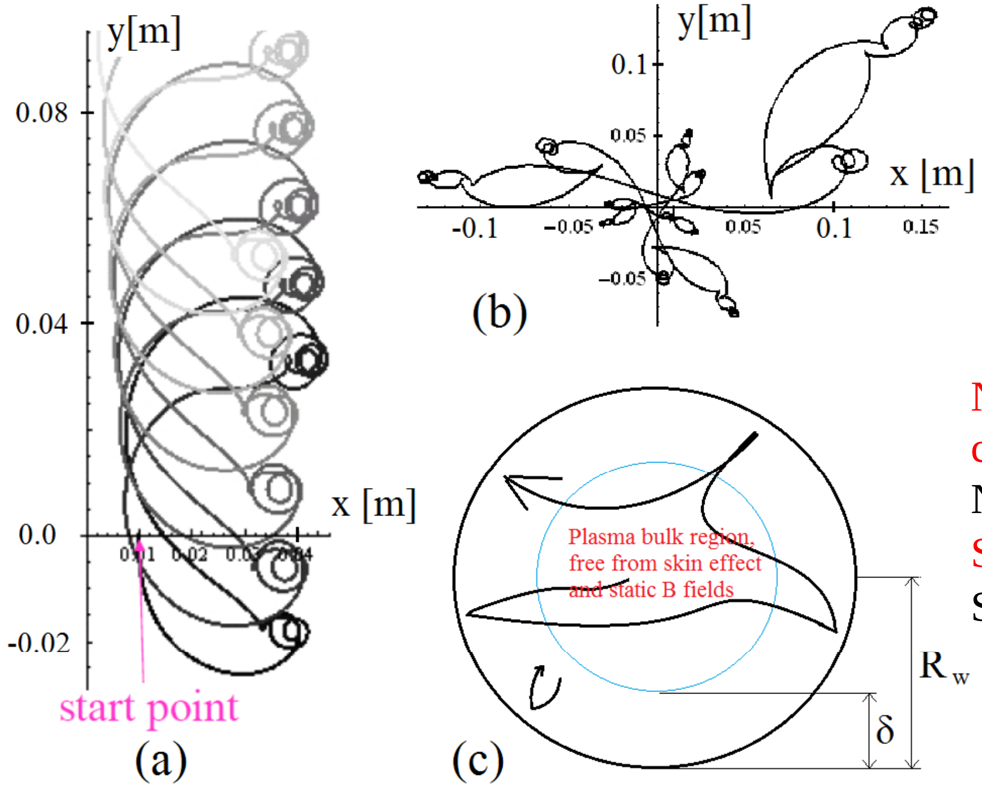
BINP, T2>5000 s, ji>200 A/m2 but Penning H- source, 1 beamlet **doi: 10.1063/1.4828373**

Intermediate goal: ITER, 1280 beamlets T2=3600 s, j_i=200 A/m^{2,} (for D-, equivalent to 300 A/m^2 for H$^-$)

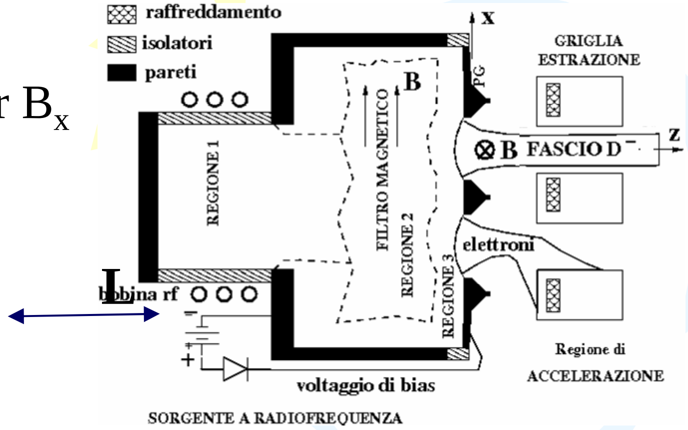
DTT (to be built) aims: T2<=100s.

1.4) physical remarks on ICP (inductively coupled plasma) sources

1) Two region of different plasma temperature and size: driver T_e, R_d, L_d and expansion region T_2, D_e, L_e, filter B_x



Electron acceleration by RF in: a) planar geometry; b) weakest cylindrical plasma; c) sketch for dense plasma and stochastic effect. See Cavenago, **J. Inst.** 2024, 10.1088/1748-0221/19/01/C01017 and references 11, **12** and 15 here within: the picture above is an update of fig.2 in ref 11 there. See also M. Cazzador, **Thesis, Univ PD** 2014



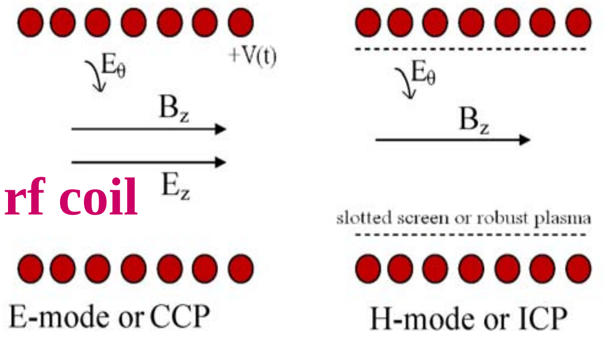
Typical rf (radiofrequency) IS scheme (similar to Batman, IPP-Garching, ..., NIO1)

NIO1 Cs-free 11 mT (discovery of O_2 conditioning and later N_2 to Xe conditioning*),

NIO1 Cs-based 3 to 8 mT (*,+)

SPIDER Cs-based with FS: data in progress

SPIDER (**) Cs-free 2 to 3 mT (then rf issues)

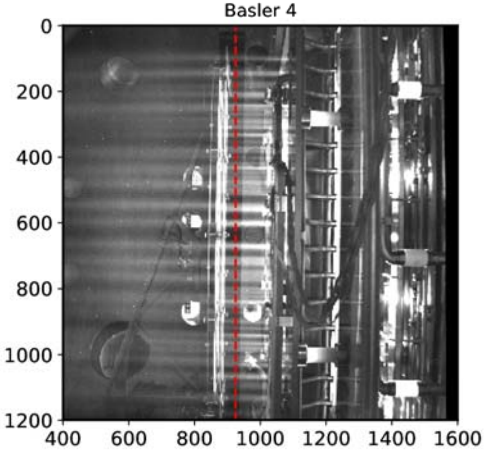


Simple explanation of coupling modes

2) Some updates of experiment progresses

SPIDER (see Serianni et al. doi: 10.1109/TPS.2022.3226239)

An example of Spider beamlets (axis in pixels)



Aims of SPIDER experimentation in 2024

SPIDER is going to restart operation soon in 2024.

Main goal of campaign is to test beam operation (extraction and acceleration) over one (almost) entire segment (a segment corresponds to 2 RF drivers, see next slide)

Other features added in the shutdown include :

+modified cesium oven nozzles,

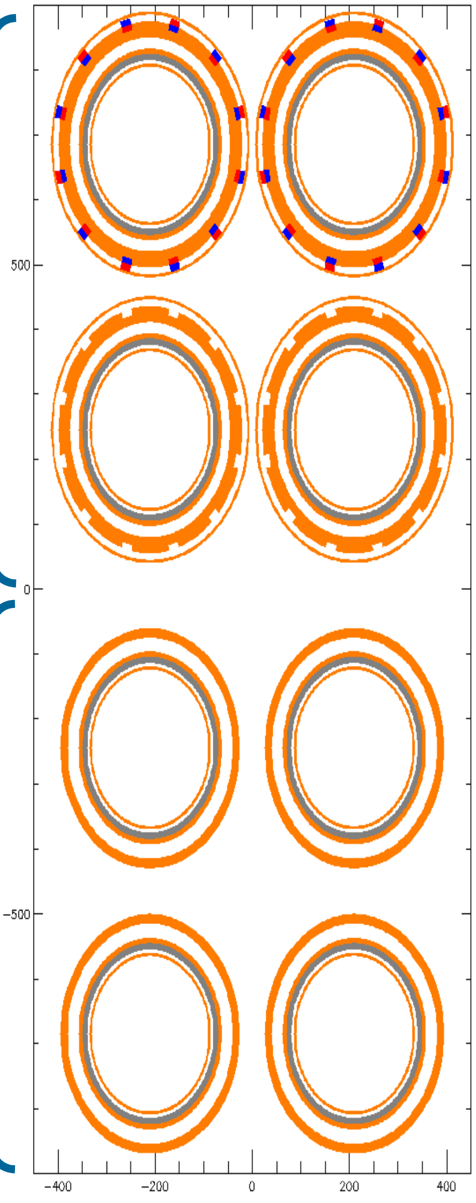
+different gas injection points,

+permanent magnets behind RF coils (as in NIO1) starting only for 2 driver coils out of 8.

View of SPIDER (behind-side); note capacitor C_{par} , C_{ser} (white) and rf connection (shiny solid copper); vessel pressure p_2

New layout of: RF drivers; plasma grid mask; open apertures (*)

new RF drivers

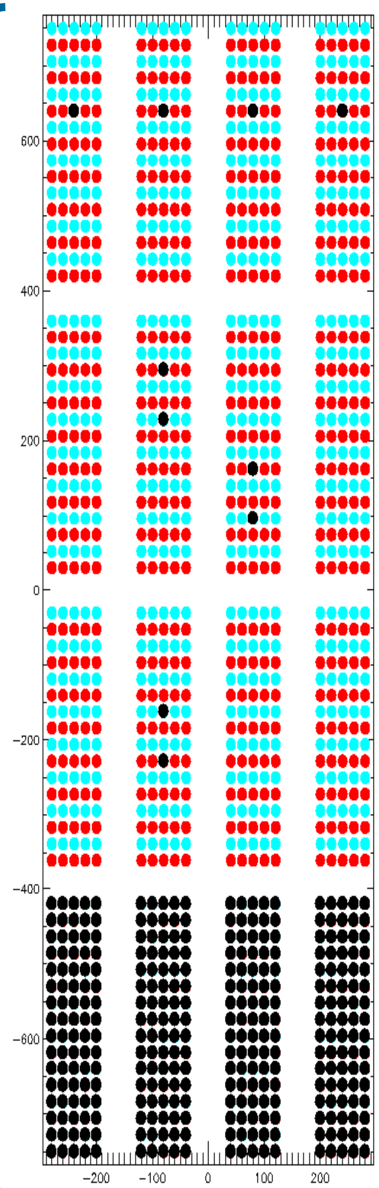


original RF drivers

(*) adapted from G Serianni (for NBTF team) *NAC09 - item #03 - Experiment plan for MINION and SPIDER*, **24/10/23**

Layout of RF drivers

Plasma grid mask (seen from beam dump)



6th aperture

Aleft: RF drivers with permanent magnets, (red+blue rectangle markers) in the upper segment only. At right: map of opened holes (black dots) distribution.

2.2) NIO1: a) summary of pending upgrades

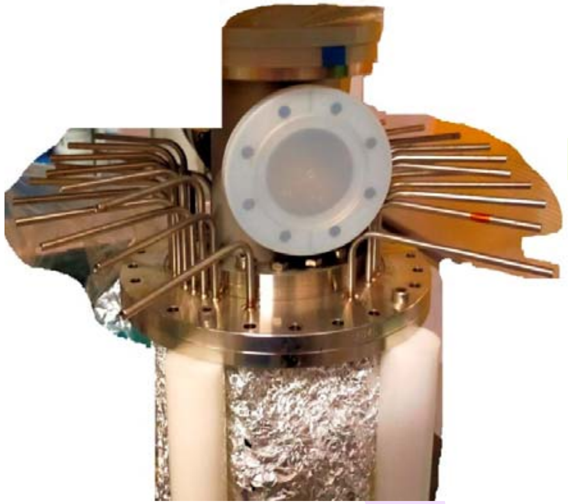
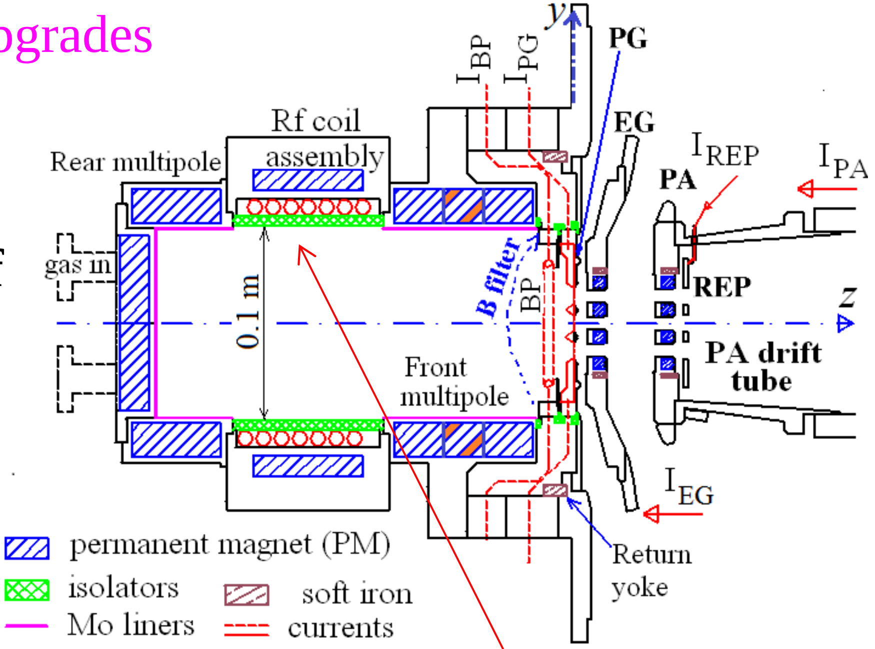
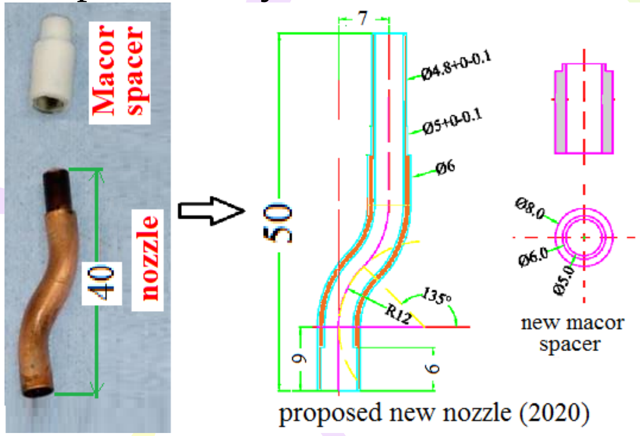


Figure: (a) horizontal zy section of NIO1 source and electrode; note filter position;



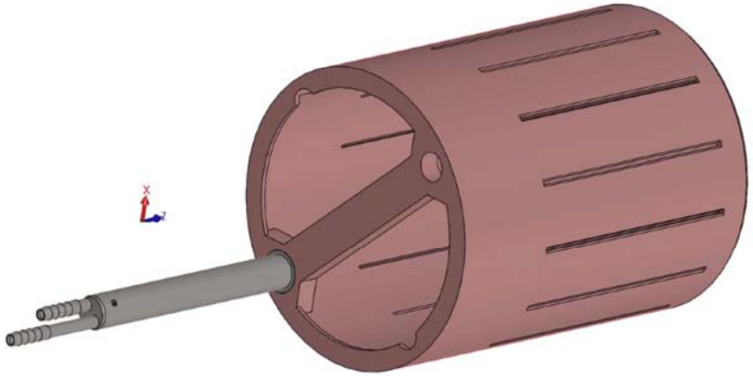
The end calorimeter for NIO1 (not yet installed). Recently a grid front electrode was built, to add energy analysis/recovery basic capability. Thermocouples already installed, IR camera and viewports procured

space available to a Faraday Shield



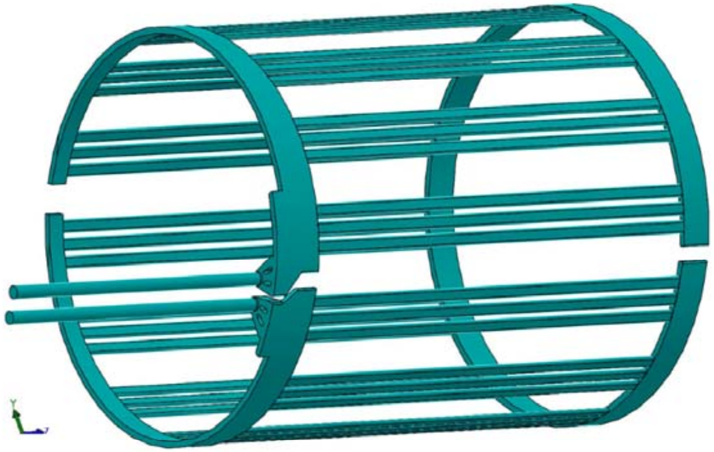
proposed new nozzle (2020)

Cesium performance of NIO1 may require: (1) the new nozzle designed in 2020, just a 10 mm longer S-bend tube!!; (2) gas conditioning (for in-vacuum in-situ final cleaning)



The Faraday Shield: Both inox and copper parts by Addictive Manufacturing, including water hose connections (under construction)

more on Faraday Shield



Water circuit, with subdivisions to fit AM

For 3D printing optimizations, 3 copies of the Faraday shields are under production.

We can thus plan to spray one of them by molybdenum (or Ta?)

These surface may join the durability of Mo liners (the present NIO1 liners, 0.5 mm thick) to the robustness and cleanliness of one piece

Full Mo shields may be considered in a ten year development

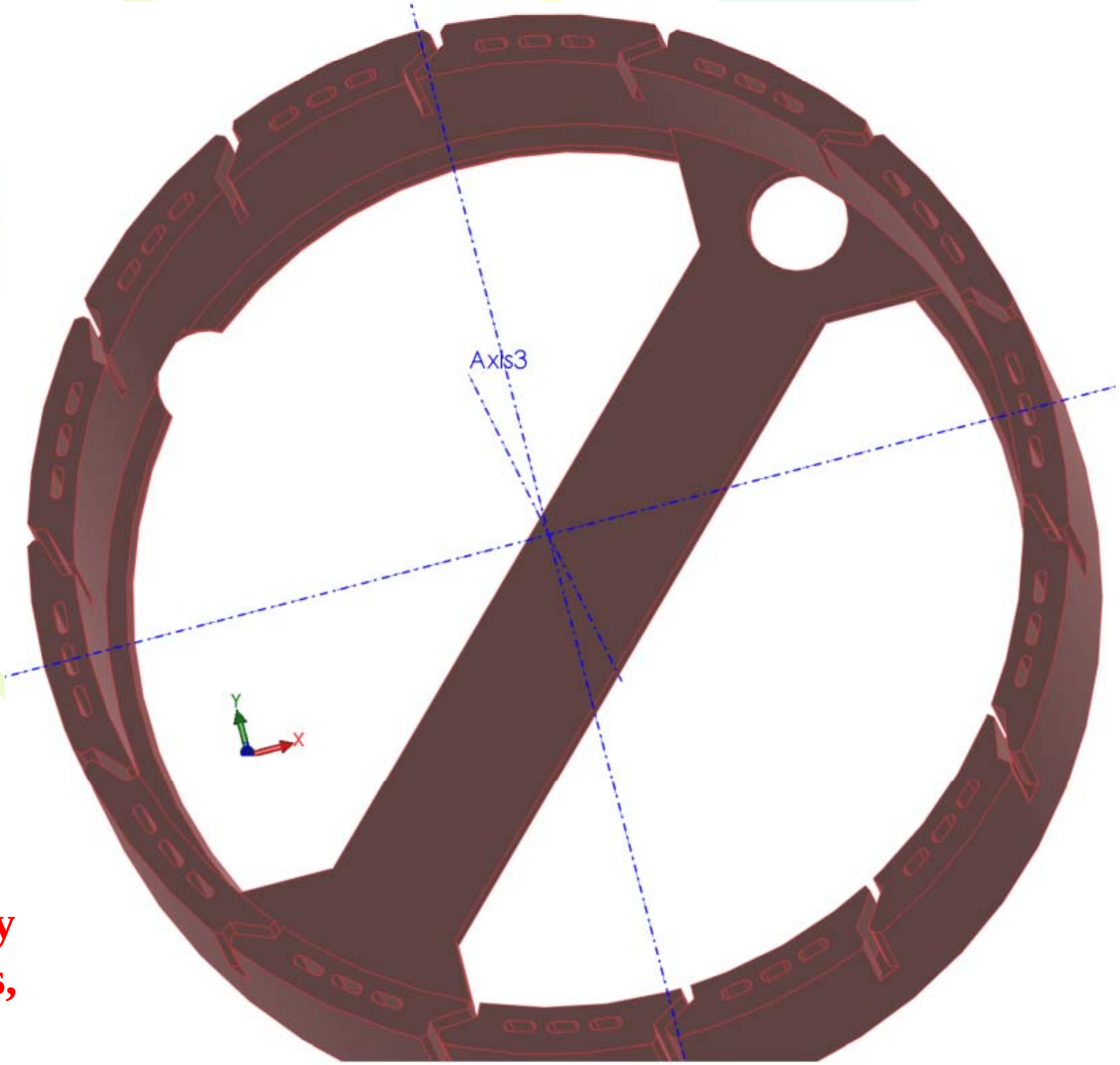
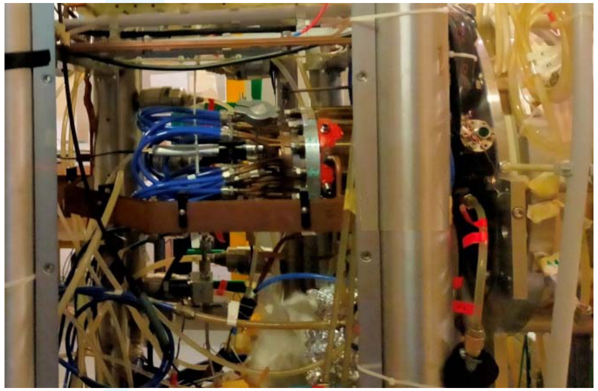


Figure: cut view of a Faraday shield (14 S-shaped cuts to be placed between multipole cups, 42 water channels)

NIO1 b): 2023 status

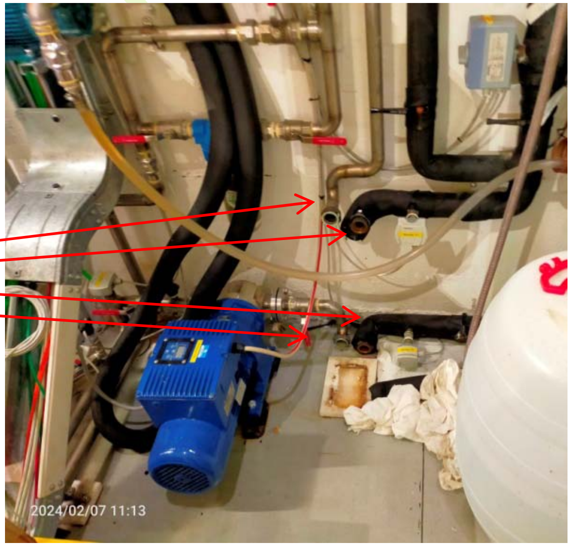
In 2023 there were difficulties (announced only at the last moment) of RFX to support NIO1 operation (which was delayed to 2024); this because new other tasks were begun (rather well financed) and manpower was in huge demand. Let us observe that: 1) the manpower saved from NIO1 is minimal, in comparison to other tasks; 2) some manpower was needed to temporarily dismount from NIO1 parts for other experiments; 3) from the point view of accelerator science and research, this stop is absolutely regrettable; 4) to restart NIO1 operation (as we hope soon) needs all of your support,. Just for your info, some recent photos are here posted

NIO1 external installation

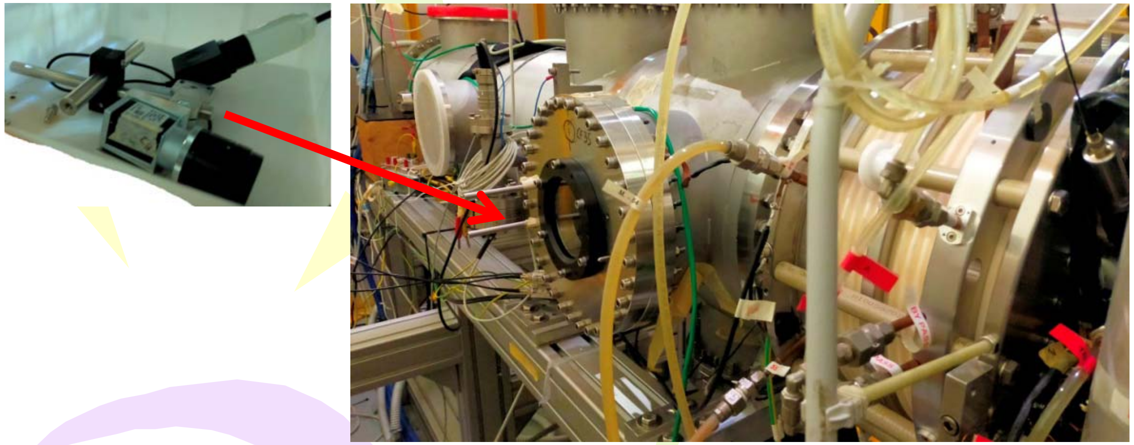


NIO1 ion source; note watercooling for continuous (CW) operation, well over the 2.5 kW installed RF

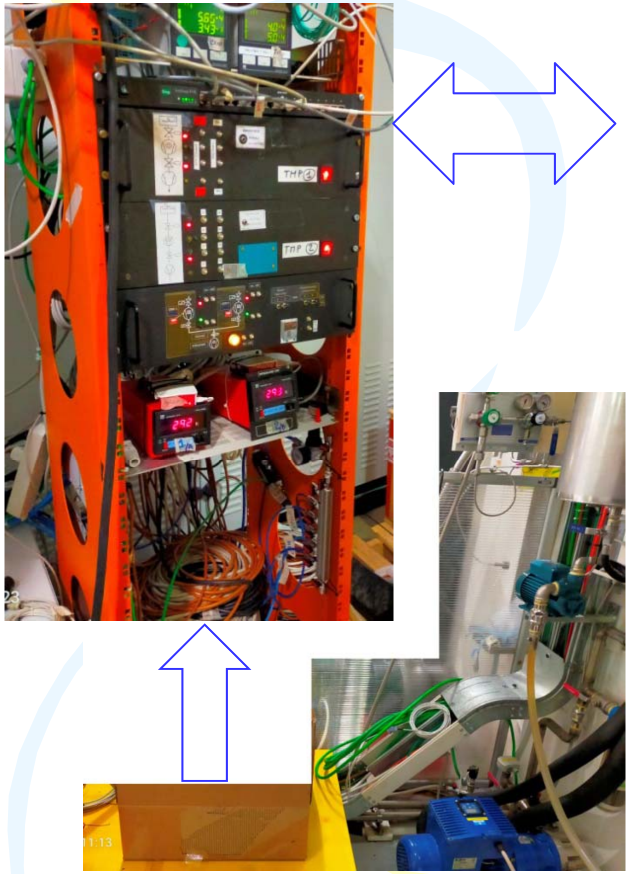
NIO water cooling detail: the heat-exchanger was temporarily removed to other experiments, see its connections opened



NIO1: parts of the HV deck



NIO1: beamline view looking from the source (in the inset the CCD camera previously used for beam observation)

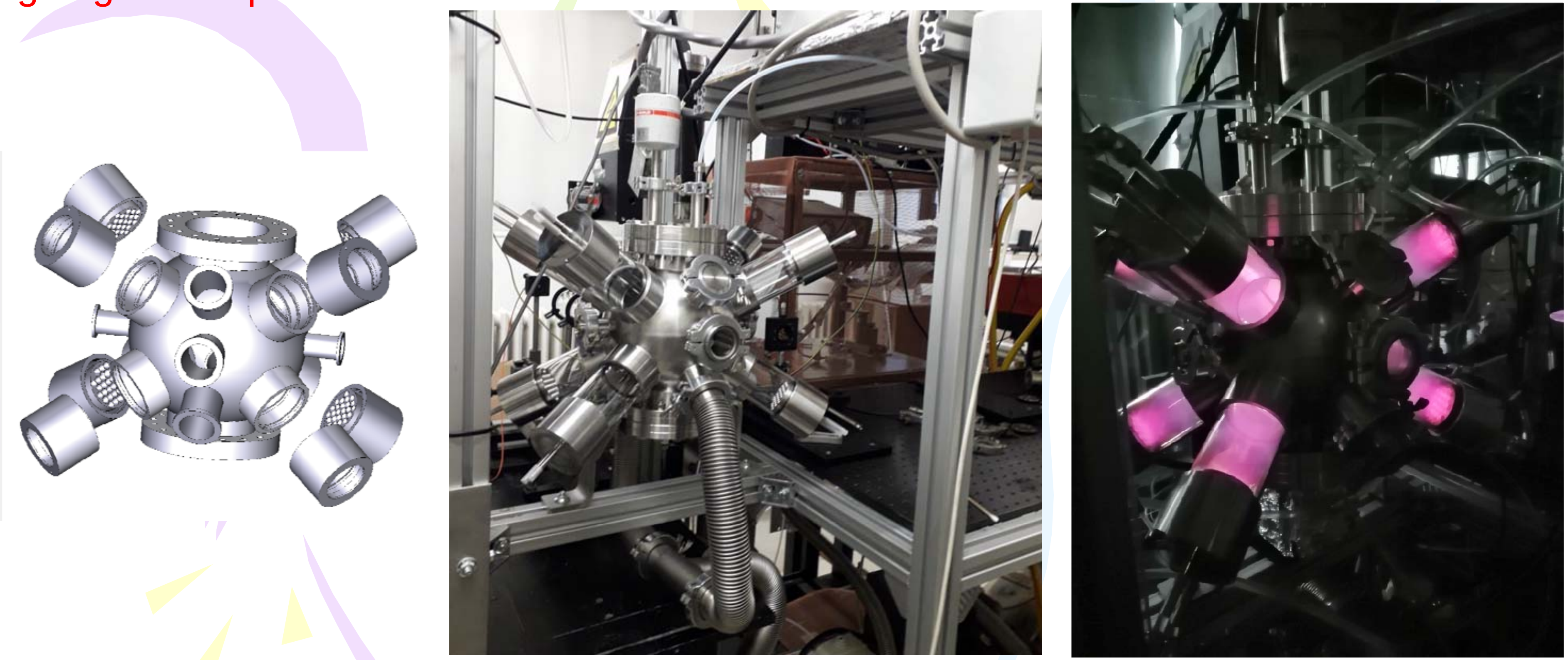


NIO1: the pump rack, now taken temporarily away

NIO1: a beamline view (with the source in the background); note open flanges, from which pumps were removed (we may worry for cesium oven oxidation; we will probably learn something)

2.3) IBC (inverse brush cathode) installation at BA

The reflex configuration of the IBC ion source aims to improve separation of hot electrons (for H2 excitation) and cold electrons, for production of H-: this request two driving cathode, one opposite to the other. In BA installation (Dilecce, Variale, et al.), we have four driver couples (total= 8 cathodes), whose main insulator gap length is going to be optimized in 2024.



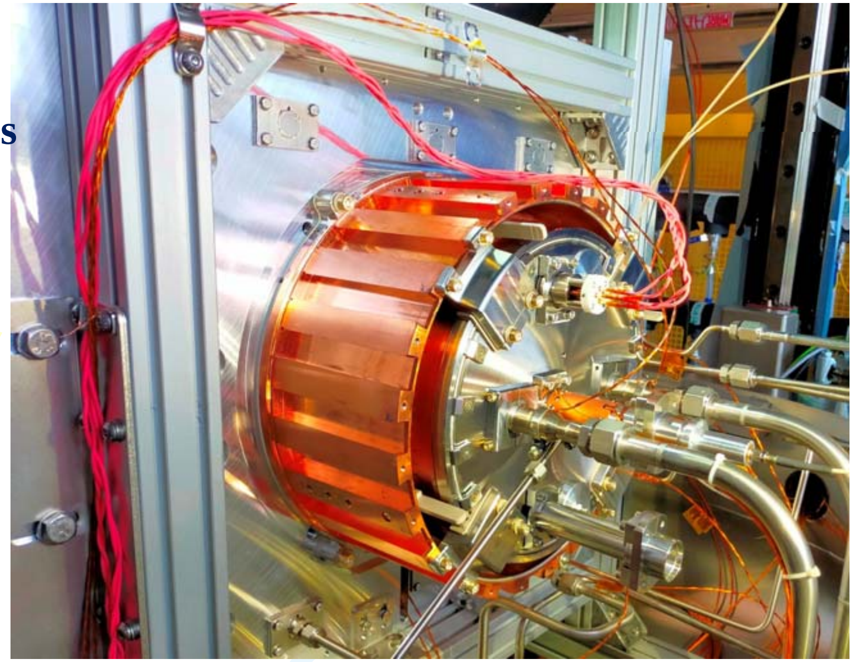
a) isometric view, note grids inside; b) photo; c) photo in H_2 operation

2.4) The MINION experiment at RFX

It consists of 0.2 m long, 0.3 m diameter cylindrical plasma chamber; no extraction holes for beams

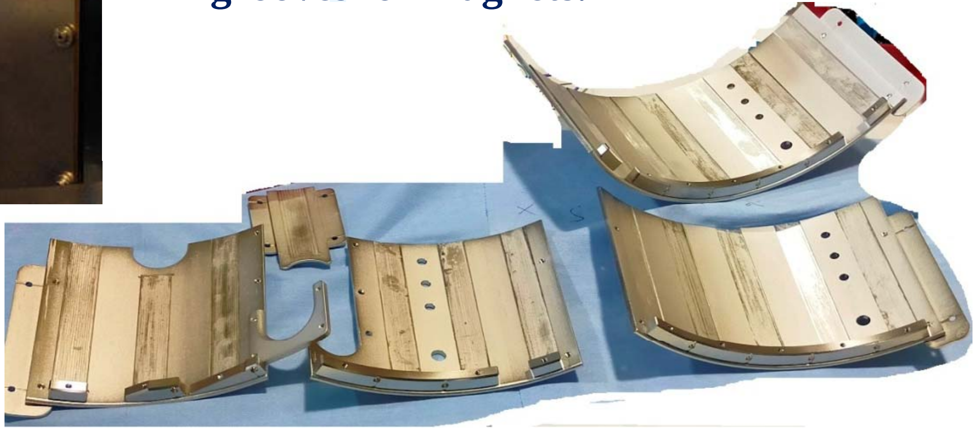
Installed RF power 40 kW to 100 kW, pulse duration of the order of 12 seconds, of which 4 s at stable frequency

Main purpose was to verify that plasma can turn on even when multipoles are placed on the coil : confirmed (apparently some people had reserves about this result, by the way proved in NIO1 2016 doi: 10.1063/1.4932616 even with only 1.5 kW RF)



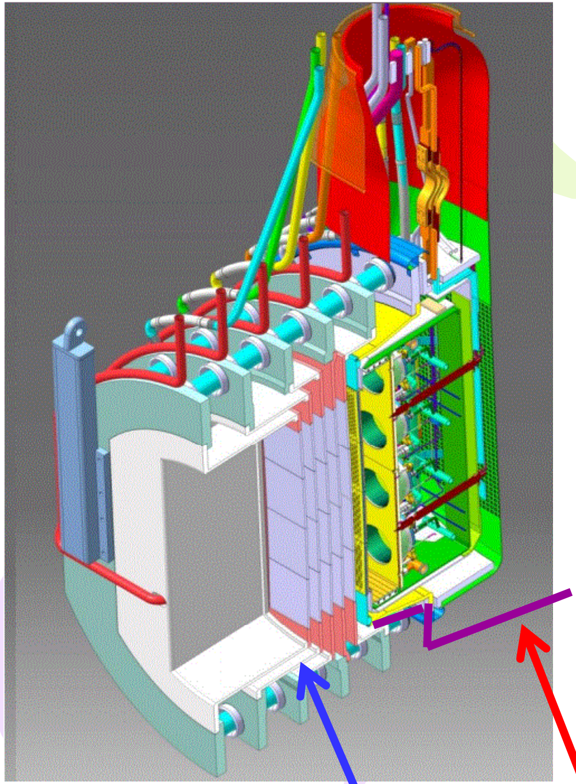
MINION: front plate: note the red wires for the filament and the copper shield (at some distance over the RF coil) with grooves for magnets.

MINION: front plate: note the central PEEK hole for Langmuir probe insertion and the cooling tube (only for short pulse operation)



Ferromagnetic shields: since SPIDER will have two multipole systems nearby , they are decoupled by ferromagnetic shield, see parts with groove for magnets

2.5) Towards MITICA



Mitica: **Beam source BS** (letf) and opened vessel (on the right)

For a generic beam source, we also investigate: intermediate electrode and extra pumping hole (see arrows and following slides)

Initial references for further readings:

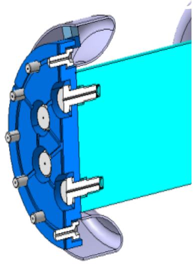
D Marcuzzi e al doi 10.1016/j.fusengdes.2023.113590

G Serianni e al doi 10.1109/TPS.2022.3226239

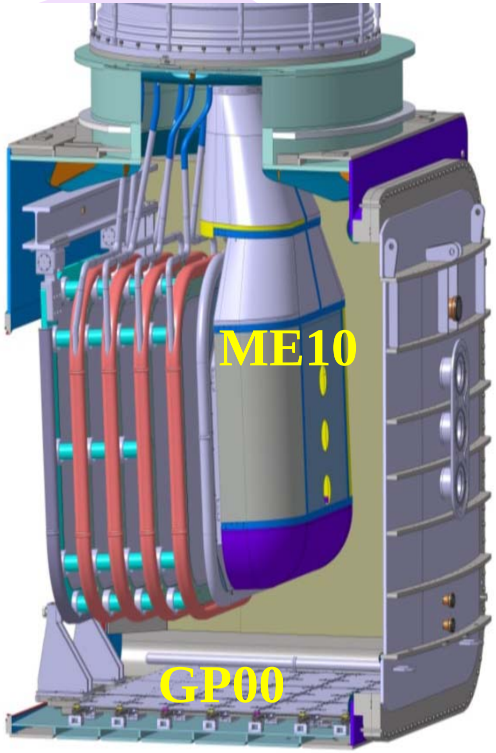
https://www.igi.cnr.it/ricerca/negative-ion-neutral-beam-injection/mitica/come-fatta-mitica/

Studies on a critical gap: -1MV, 1m, in vacuum

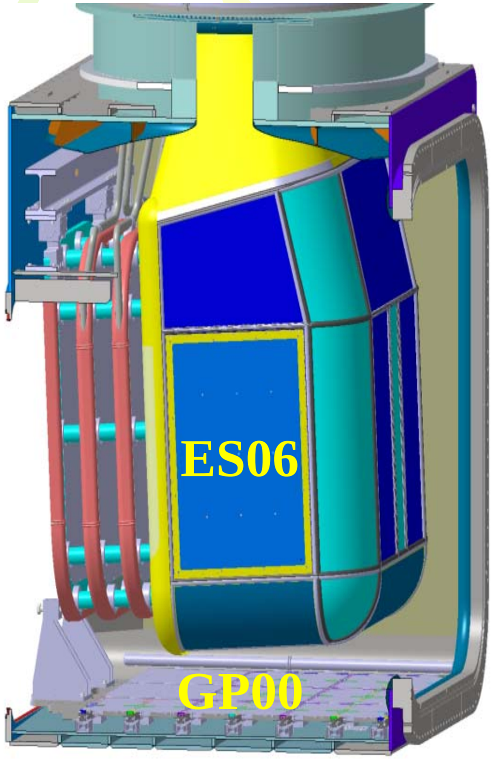
+mockup to test voltage holding of MITICA beam source
+test an intermediate electrostatic shield
Electrodes:
ME10: mockup of plasma source + extraction grid
MExx: mockup of accelerator grid
GP00: ground plate   ES06: -600kV electrostatic shield



new PEEK post–insulators



Mockup similar to planned MITICA setup



Mockup as before plus an electrostatic shield

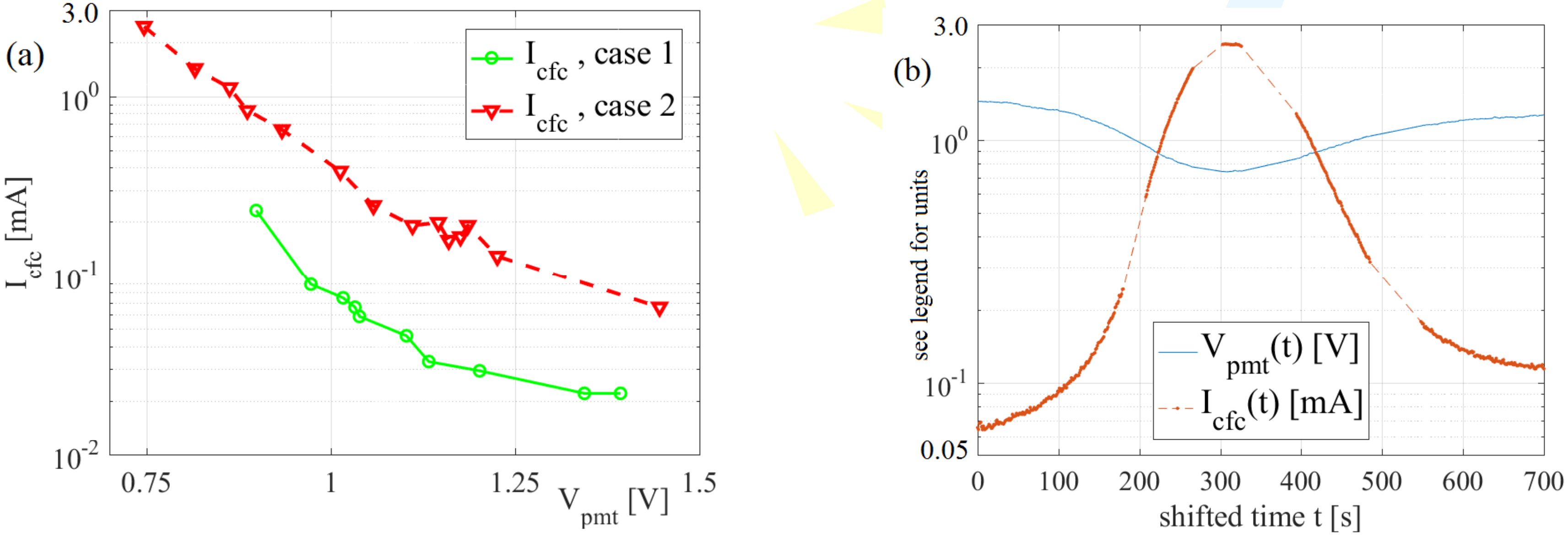
Figures above: photo of some mockup electrode sub-assemblies. Figures left: rendering of setup without and with shield to be tested

This slide condensed from slides D Aprile, G. Berton, S. Denizeau, T. Patton, N. Pilan, M. Tollin, M. Valente and G. Chitarin Design of electrodes for High Voltage Tests in MITICA 05/02/2024, IE group meeting

3) New results, and a summary of researches

3.1) a result: 2023 analysis of 2018 NIO1 transients

Def: A transient is a change of extracted current I_{cfc} or I_a at fixed control parameter

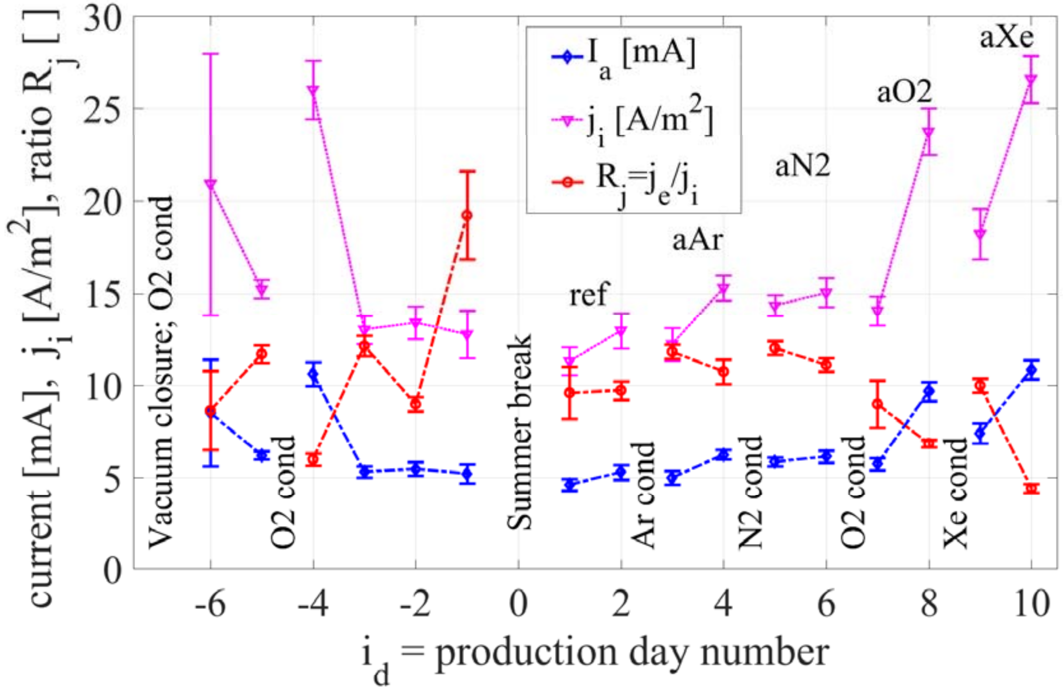


see Figure 2, MC et al, J. Inst, 2023. (a) Anti-correlation of I_{cfc} and V_{pmt} during transients, for the following two cases of fixed control parameters: 1) RF power P_k = 1.2 kW, filter current I_{pg} 0 A, pressure ps = 0:75 Pa, beam voltage Vs = 4 kV, and extraction voltage Ve = 0:5 kV, compare with Ref. [M. Cavenago et al. 2018]; 2) with P_k = 1:3 kW, ps = 0:9 Pa, Ipg = 400 A, Vs = 4 kV and Ve = 0:45 kV, compare with Ref. [F. Taccogna et al. 2021]; typical error 5 %; (b) discovery of anticorrelation of time variation of beam current indicator I_{cfc}(t) or I_a and plasma luminosity signal V_{pmt} (t), during a transient, at the fixed conditions of case 2.

Another example of transients is weather (ruled by nonlinear equations as plasmas are)

Gas mixing: simultaneous feeding of two gases to ion source. Used in ECRIS to boost high charge state of an heavy gas.

3.2) Our gas conditioning definition: after one day of NIO1 operation with a heavy gas (with extraction on), in the following 2 to 6 day operation with H_2 gas the H- production improved, even if heavy gas was pumped away, as verified by spectrography. Gas conditioning was discovered with O2 as a method to stabilize transient in the good state (high current, low light) . Similar to ' Crop rotation' in agriculture. Experiments require an uncesiated (as NIO1<2020) or a fully cleaned source (water rinsing)



2019 gas conditioning of several gases in NIO1 (J Inst 2023, fig 7: Summary of typical daily results for I_a, j_i and R_j vs day index i_d, which enumerates the H^- production days, eg. set 'ref' is i_d= 1,2, set after argon 'aAr' is [3,4], set 'aXe' is i_d= 9,10; days i_d<0 refer to previous oxygen conditionings; other line breaks are conditioning days (as labeled by 'cond'); typical std is 5 %, as better shown by error bars, except just after the vacuum closure.

3.3): activity summary on theory and simulations ***(some of them presented at NIBS2022 and/or published)***

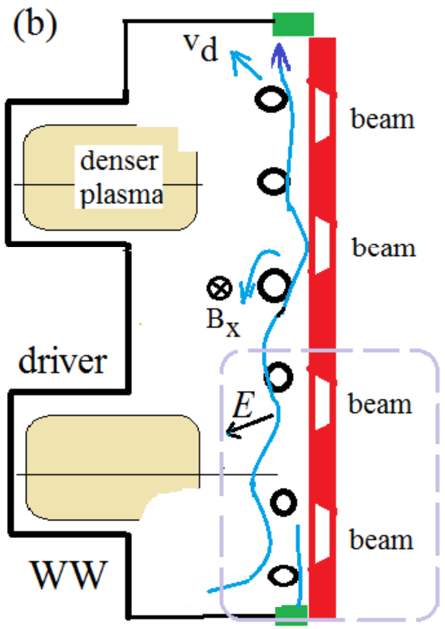
Drift velocity v_d in plasmas and disuniformity

The magnetic filter necessary in negative ion source and the electric presheath necessary for beam extraction provoke a transverse plasma drift, called E x B drift, , whose effect on plasma disuniformity must be minimized. This drift is controlled (and sometimes enhanced) by the polarization of the bias plate, which can a simple plate or set of more electordes as a Plasma Ion Funnel, immersed into the plasma. We model the plasma shieded E field with an effective space charge density $n_1(u)$

$$-\lambda_D^2 \,\triangle\, u = n_+ - n_- \equiv n_1 \quad , \quad u = \frac{e\phi}{T_e} \qquad \lambda_D = (\epsilon_0 T_e/e^2 N_{e0})^{1/2}$$

where $n_1(u)$ is extrapolated from plasma sheath theory. Then drift velocity is

$$\hat{\mathbf{v}}_d = -\mu_e \frac{\hat{\mathbf{G}} - \mu_e \hat{\mathbf{G}} \times \mathbf{B}}{1+(\mu_e B)^2} \quad , \quad \hat{\mathbf{G}} = \mathbf{E} + \frac{1}{n_e}\mathrm{grad}(n_e T_e/e)$$



Drift v_d in ion sources, rectangle is simulation domain, circles are bias electrodes

High voltage breakdown theory (see elsewhere)

High voltage holding also depend on long gap effects, as for example studied at LNL for electrostatic ion spectrometer, and now in collaboration with RFX

Plasma RF coupling and effective filter action (see elsewhere)

Radiofrequency (RF) coupling efficiency and plasma stability are strongly related. We discuss simple modeling possibly including the gas conditioning effect discovered in NIO1

Energy recovery (see next slides)

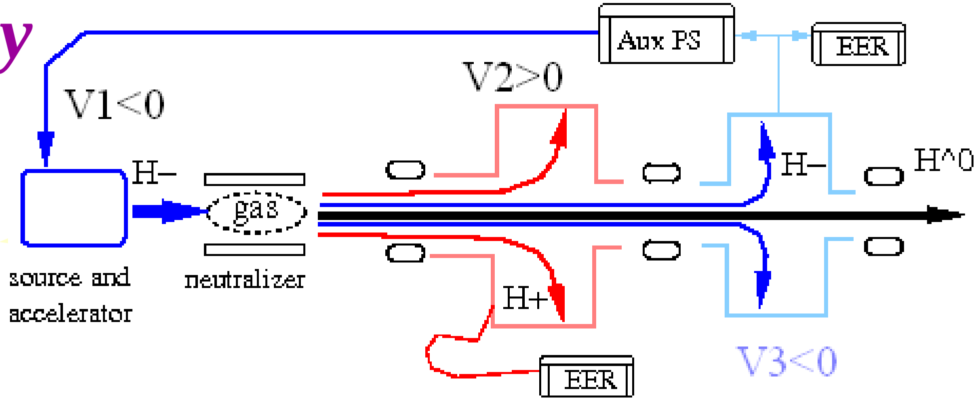
Neutral beam conversion has a limited efficiency (<55%, say 0.4 in real devices) so that reactor energy balance request recovery of the energy of the residual beams

Improved pumping (see next slides)

Operation to 500 kV and beyond request a goof pumping of gas in the accelerator; additional holes with improved design in the electrode supports are here proposed

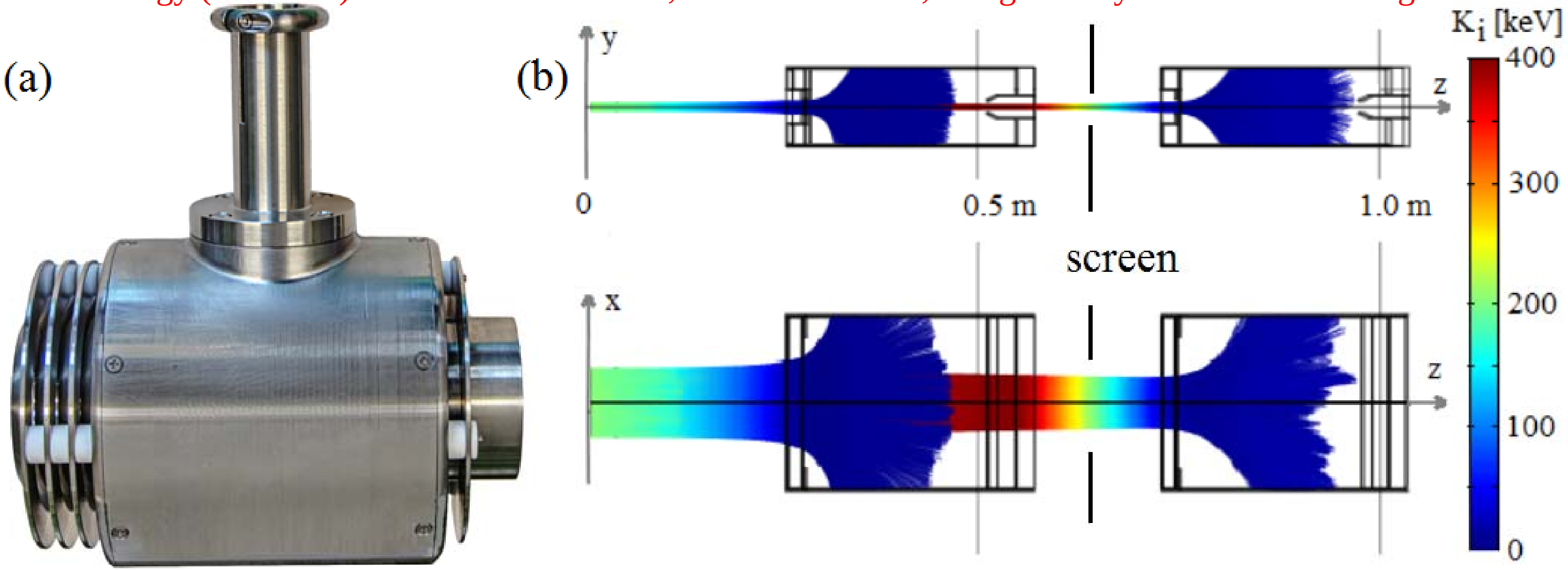
4) The beam energy recovery

In a gas neutralizer, the H^- converted to H^0 fraction is 55% at maximum; residual beams include the further ionized particles H^+ and the uncoverted H^- fractions. These beams must be intercepted before damaging tokamak walls and their energy recovery (ER) may be necessary in real power plants. Design using magnetic or electric field to deflect them on two collectors was sometimes considered.



energy recovery improved conceptual design

We proposed ER systems where deflection is produced by beam space charge itself, as controlled by suitably designed collector. Novelty of this proposal deserved a reduced voltage test, for example 20 keV ion with round collectors, for NIO1 or TRIPS (LNL) installation . Two collector model were built, and power supplies were purchased (or under procurement). Simulated H- energy (and sizes) were increased to 100, 200 and 500 keV, and geometry extended to rectangular.

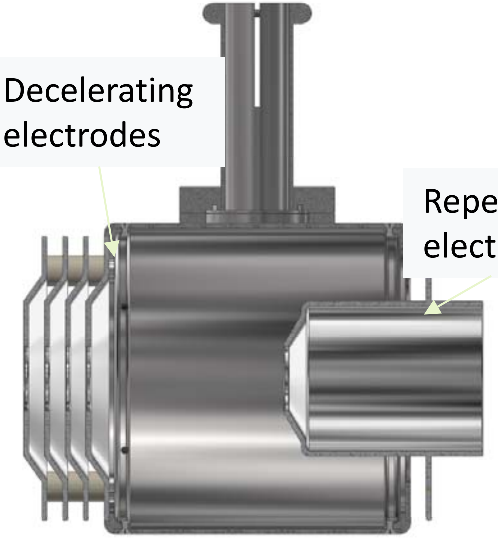


(a) round ER collector (photo photo credits: A. Lorenzi, Servizio Documentazione LNL); (b) simulation for rectangular input residual beams of 200 keV D+/- . Note that D- are stopped in the negatively biased first collector, where D+ reach 400 keV

The collectors for beam recovery tests on TRIPS (or NIO1)

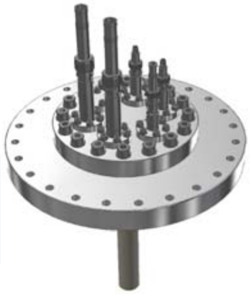
The first produced collector:

(see V. Variale et al, RSI, 2020, doi: 10.1063/1.5128668)



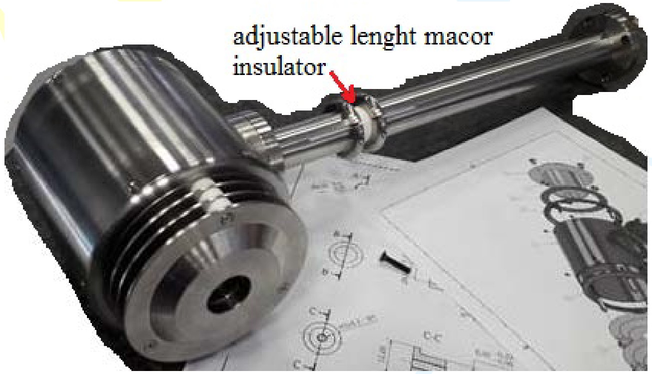
Decelerating electrodes

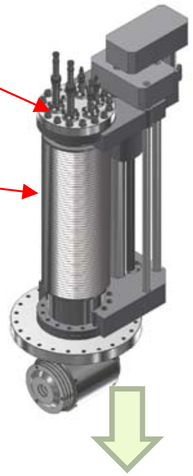
Repel electrode

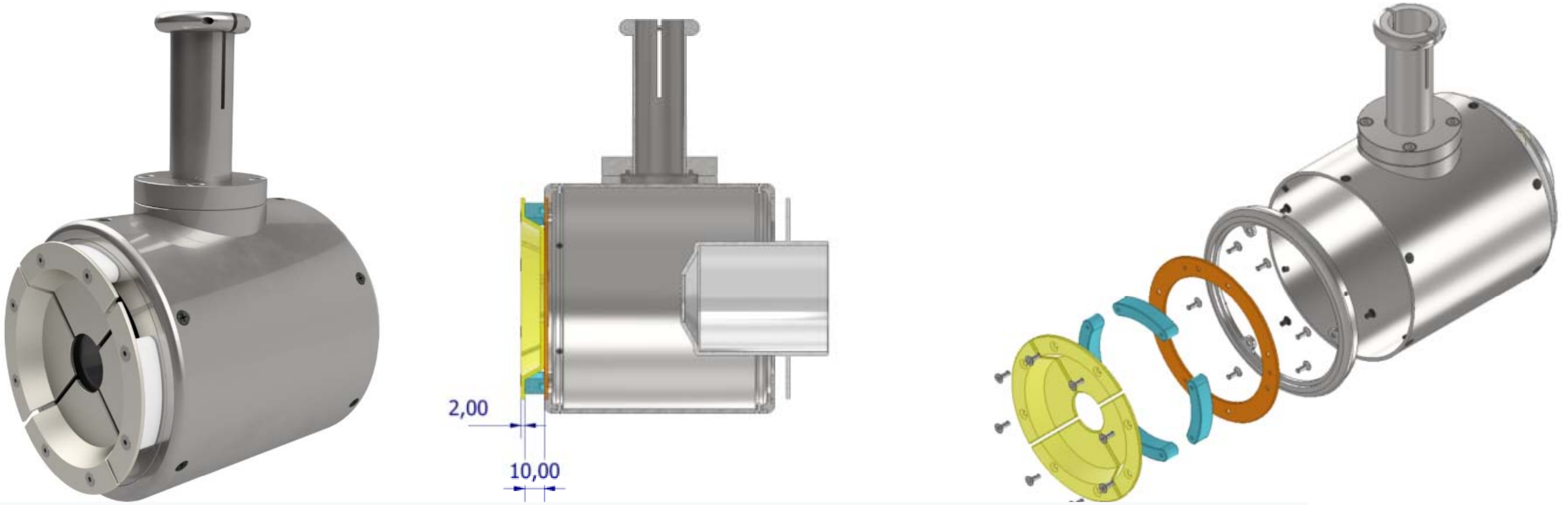


CF flange with feedthroughs

A mechanical Linear shift with stepping motor could be also used



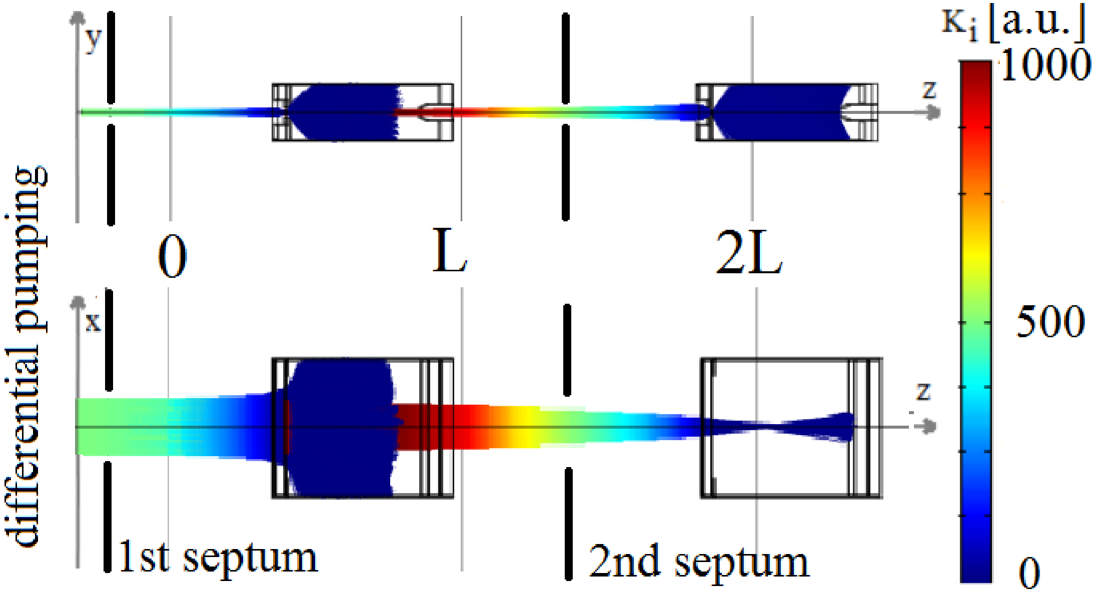




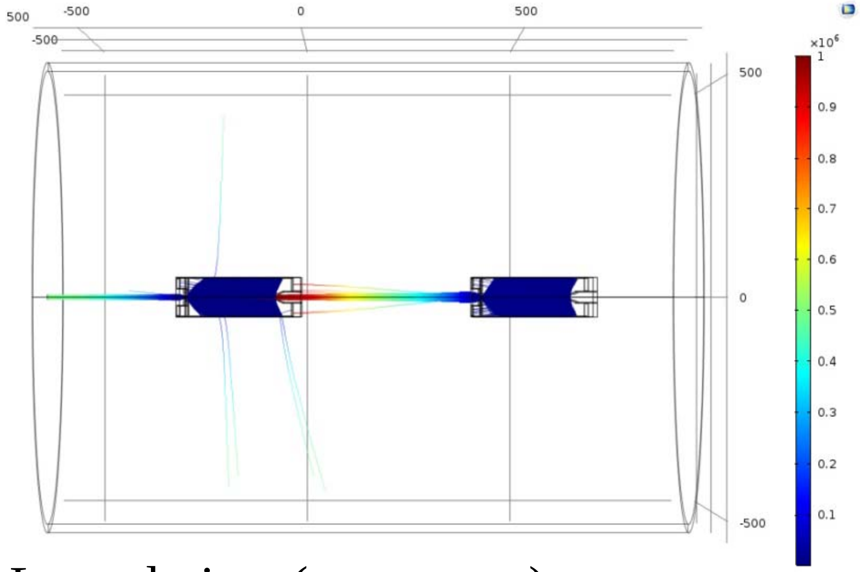
Second produced collector has four sector on the fronts to sense beam misalignments

In simulations for 500 keV ions, the charge collection efficiency η is practically 1 and the energy recovery efficiency ε remains a little bit lower : ε =98% than the SIMION simulations (>99%). Intermediate septum may be useful to control gas flow and focus

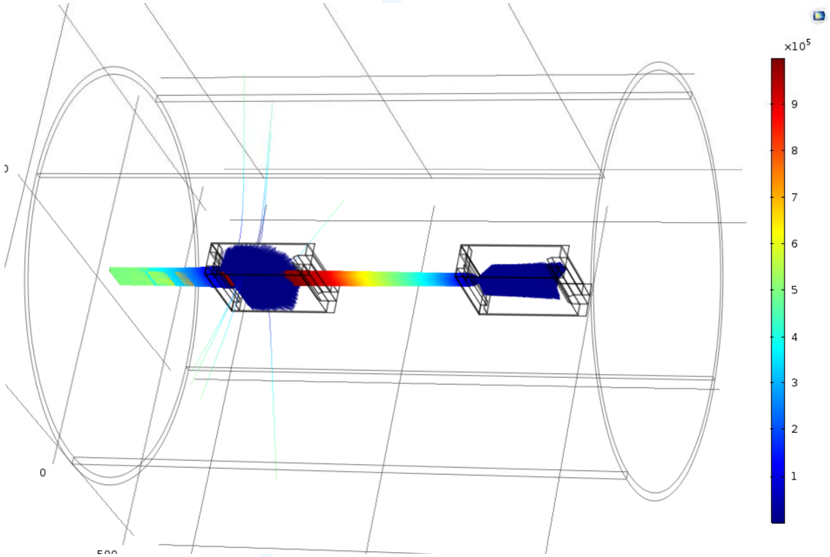
Case with Vc1=497 kV; Vr1=508 kV; Vc2= 490 kV; Vr2= 509 kV



In case of 500 keV D^- , we need L >1 m, which need lots of RAM storage and CPU time for solution

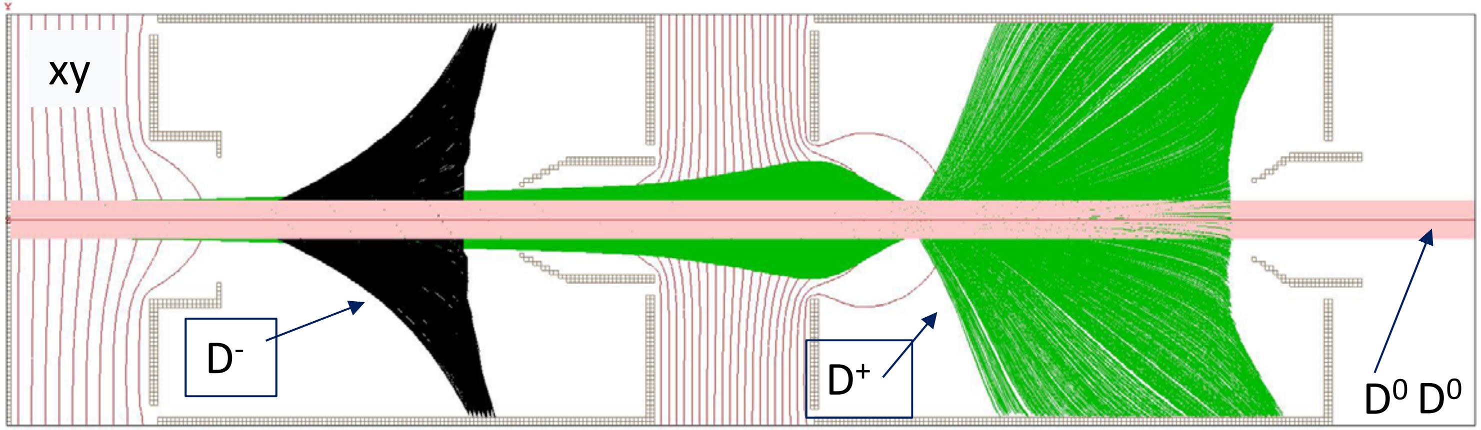


Lateral view (no septum)

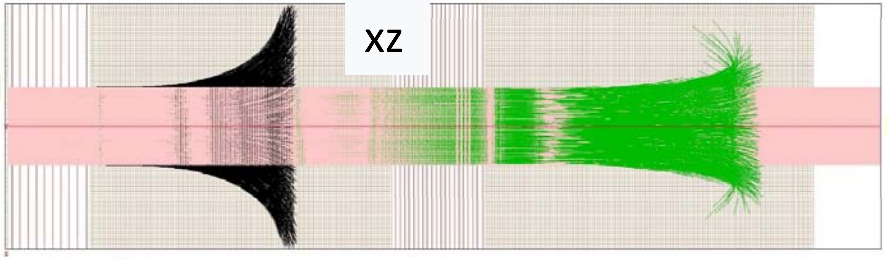


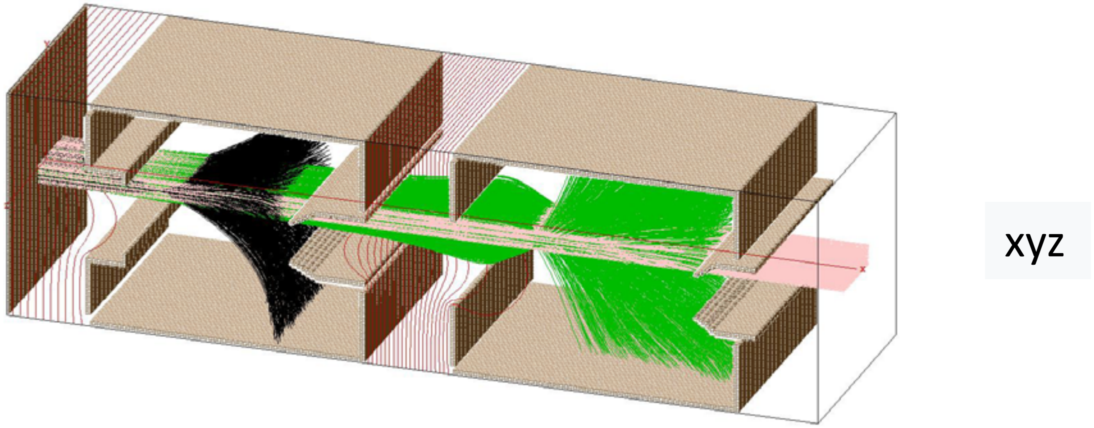
3D view: same parameters

Beam recovery simulations with a double stage collector 100 keV ions



Simion: For Eki=100 keV with Vg1=-99350 V; Vc1=-99400 V; Vr1=-100800 V; Vg2= 99200 V; Vc2= 99250; Vr2= 100800 V





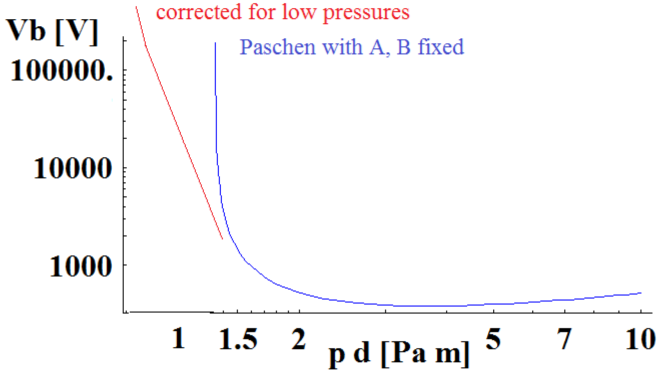
Note: Both the D^- and D^+ ions are recovered with a collection efficiency of 100% . However the ions D^+ are recovered, in average, with a higher residual energies. In the figures it is shown also the neutral beam (D^0).

5) HV control: pumping through electrodes, for sources after SPIDER (eg DTT, ..)

The holding of DC high voltage in vacuum gaps is a complicate subject of physics, since many physical phenomena have the chance and time to evolve into a break-down and then a spark

The simpler description (valid for low voltages and reasonable pressures p, say > 0.5 Pa to have an idea) is the Paschen law: the breakdown voltage is:

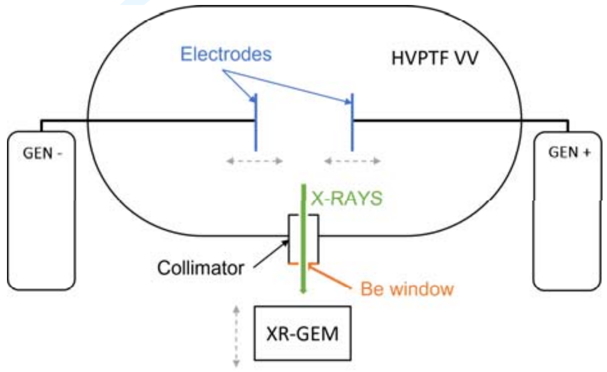
$$V_b = \frac{B\,p\,d}{\ln[A\,p\,d/\ln(1+\gamma_s^{-1})]} > 0$$



Paschen laws (log-log-plot)

with d the gap and A, B, γ_s respectively are the saturation coefficient, the 2nd ionization constant and the secondary emission multiplication factor [17]. They slowly depend on E/p , where E=Vb/d is the electric field

For longer gaps and High Vacuum, the breakdown voltage scales as $d^{0.5}$ (longer gap effect); moreover the larger the facing electrode surfaces S, the larger the probability (Pilan, De Lorenzi, ...) that some point fluctuation will trigger an overall discharge. This empirical accounted saying V_b proportional to $S^{-0.1.}$ In some geometry, effect of regenerative cascades of particle is important and (with lengthy calculations) it may predict the discharge point (many works, from Cavenago et al 2008, to N. Pilan et al. 2023)



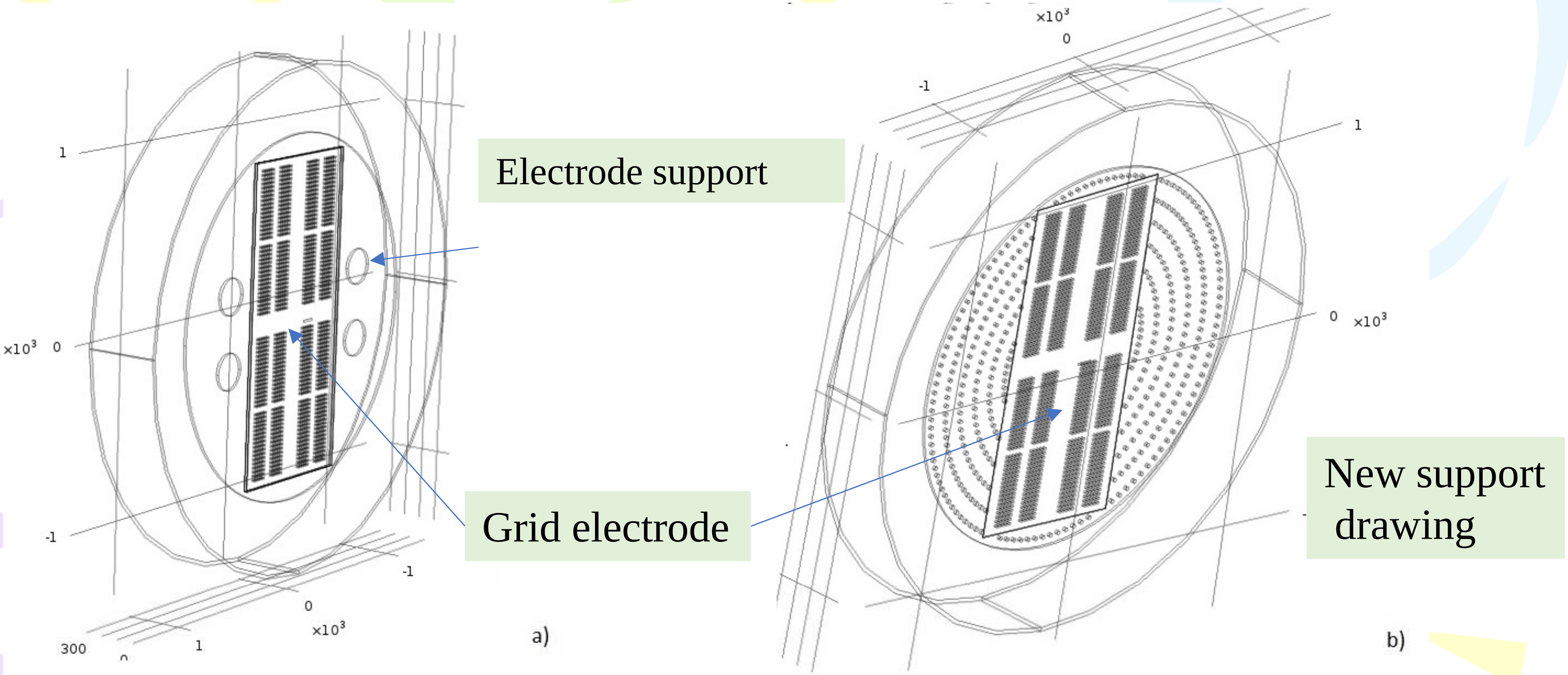
Since discharge have precursors (pre-breakdown), a part of Plasma4beam2 is devoted to observation techniques, in collaboration LNL, RFX, Univ. PD and **Milano Bicocca**

Scheme of the HVPTF facility: tests include several electrode shapes and distances; GEN +/- rated 400 kV
For view of X-ray GEM detector, see G. Croci et.al or A. Muraro or N.Pilan recent publications.

This may be also helpful to understand MITICA mock-up results

Another reason to reduce pressure in NBI accelerator is the reduction of beam stripping losses: this is rather well understood (Fubiani, 2008, EAMCC code)

To minimize the Breakdown risk, we need: 1) keep a high vacuum level in the NBI high voltage region, with additional holes in electrode supports; (2) but the electrostatic potential distortion must be avoided The new grid electrode support proposed here could improve the solution of these two problems

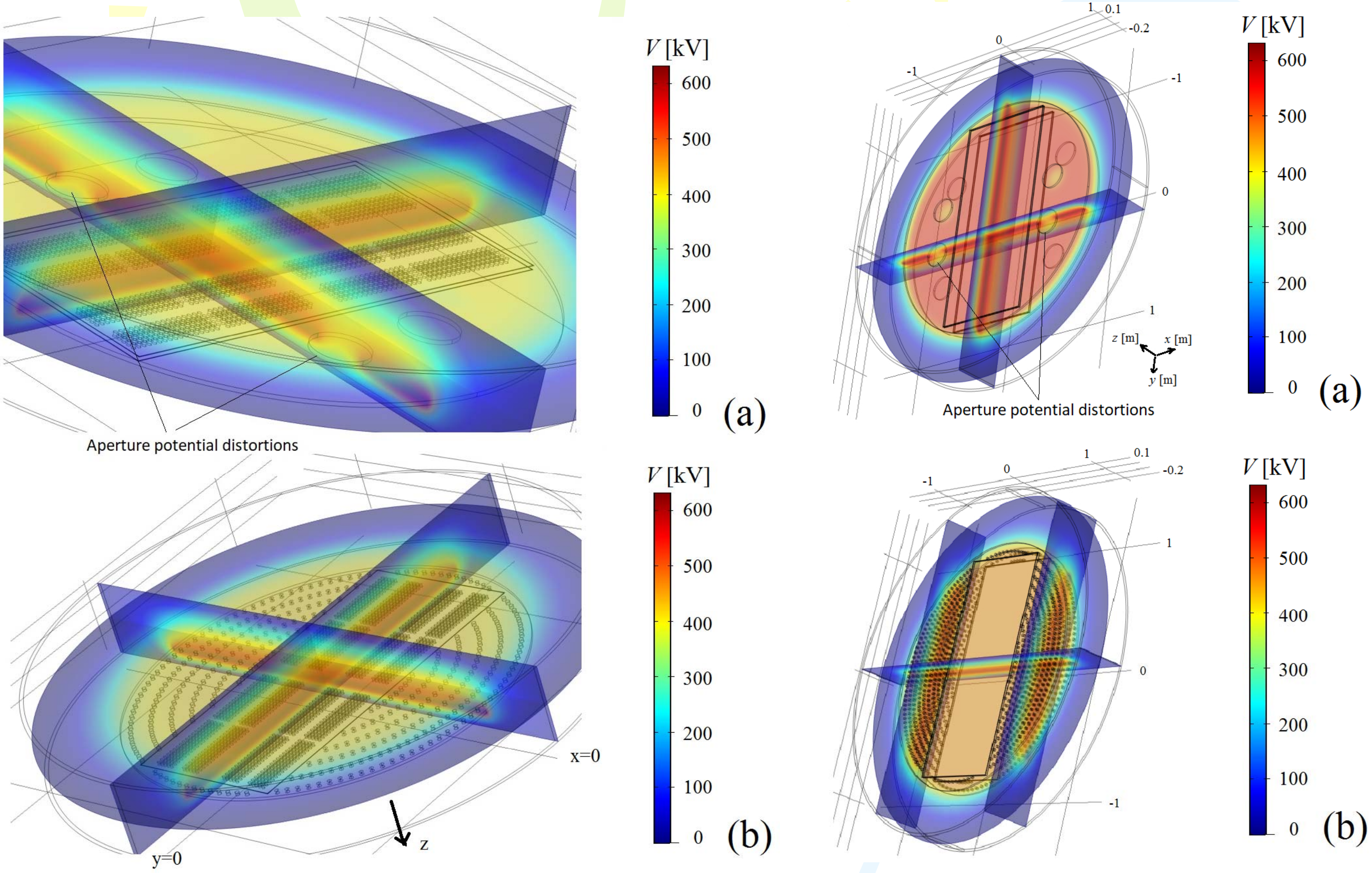


Electrode support

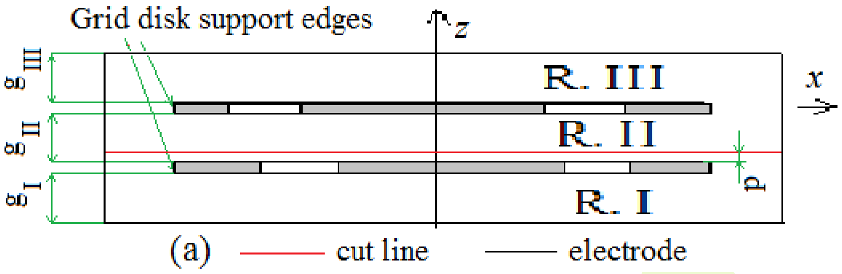
Grid electrode

New support drawing

(i) A cylindrical volume with grounded walls is considered for FME type electrostatic potential calculation (COMSOL code). the Models does not include the support connection to insulating tube, since it should be the same for the two type of support. **(ii)** The Small aperture (ai) on the new support are in parallel then the pumping speed will be proportional to the sum of the all apertures



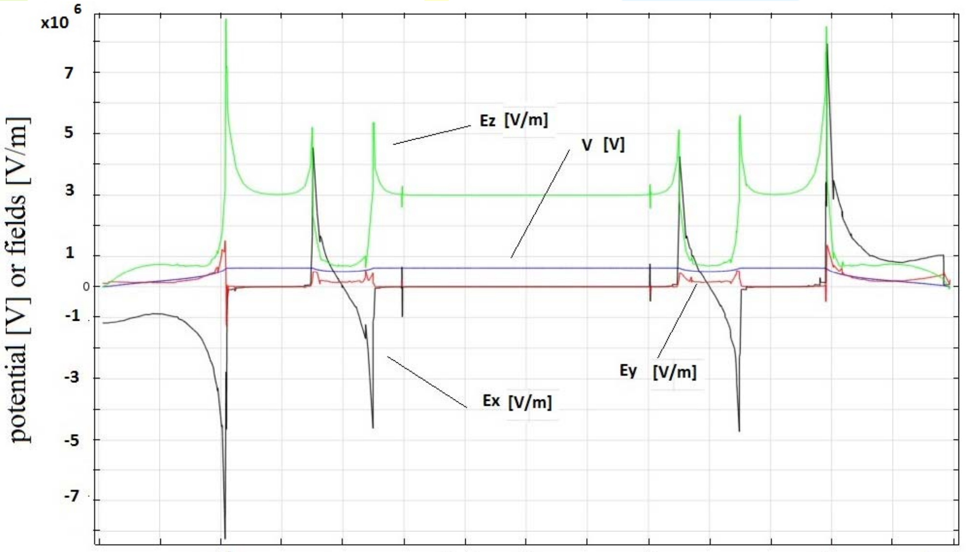
Double grid electrode supports and potential V distribution : a) large pumping apertures; b) small apertures (V. Variale et al, subm. Fus. Eng Des.)



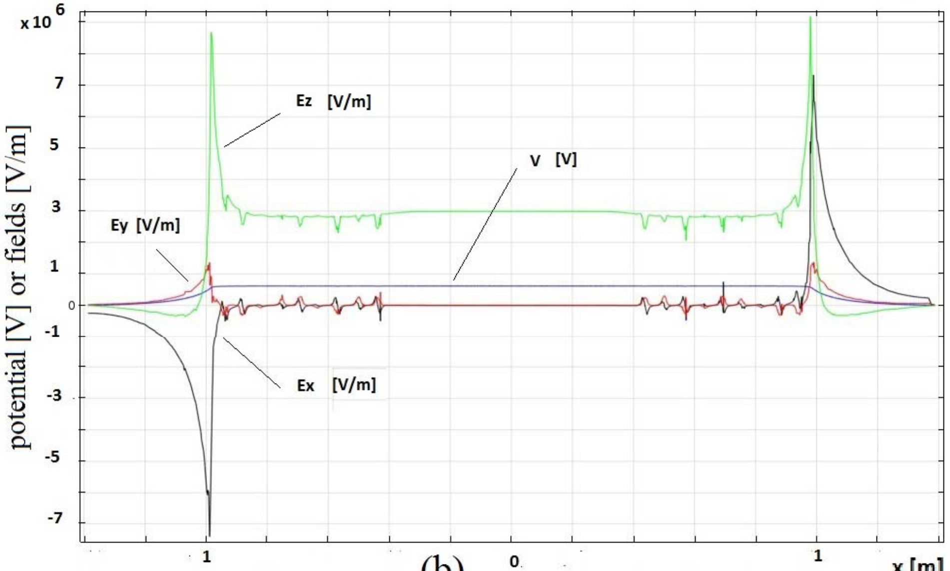
Simplified electrode geometry used in simulation before. (b) potential distortion with large aperture (c) smaller aperture.

Simulation with 5 disk electrodes (as in MITICA) and dielectric walls (as in DTT) are in progress: note that considering 1500 holes per disk, we need to include $10^{4.}$ features in simulations: it may take some work

The small aperture design also allows to tune acceleration voltages for beam focusing



(c)



(b)

6) CONCLUSIONS AND PERSPECTIVES

The innovative attitude of the INFN accelerator personnel towards neutral beam research is an important and perishable asset that should not be wasted !!

Ion source producing H^-,D^- are a good example of complex system, for which it is important to evolve design from simple experience up to modeling.

The optimization of negative ion sources (NIS) requires a flexibile dedicated test stand for accelerator studies (as NIO1 wishes to implement) in support of giant ion sources and accelerator (SPIDER, MITICA, DTT)

The use of NIS and neutral beam injectors in energy power plant (DEMO and beyond) may require residual beam energy recovery. Also progresses in HV holding is important (electrodes, pumping, diagnostic).

Coordination of these resources is challenging. Support was and is fundamental

Thank you for your attention

Acknowledgments: Work set up in collaboration and financial support of INFN-E (Energy Researches), INFN group 5 (Technological Researches, experiments PLASMA4BEAM, ION2NEUTRAL, PLASMA4BEAM2).