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The NIO1 negative ion source: investigation and operation experience

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1) Introductory remarks on NBI (neutral beam injectors)

2) NIO1 general setup

3) NIO1 front multipole and dipole filters

4) NIO1 planned accessories (Cs evaporator, CRD)

5) New Extraction grid, accelerator disassembling and realignment

6) Experimental beam results

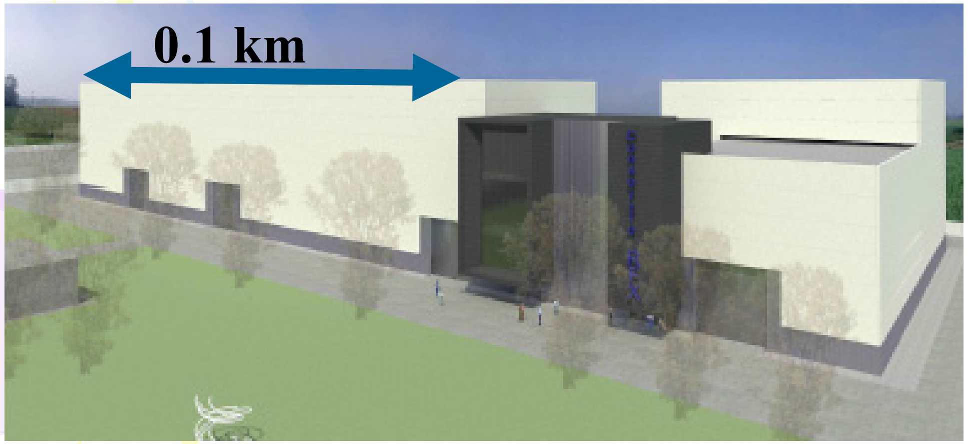
7) Conclusions.

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 negative ion sources and of the multi-beamlet optics. The NIO1 (Negative Ion Optimization 1) source is developing a systematic test programme of magnetic configurations, including permanent magnet filter up to 15 mT dipole strength, tunable current filter up to 4 mT strength (parallel or crossed to the previous), and ion deflection compensation system in the extraction gaps. Results for both crossed and parallel configuration are presented. The radiofrequency system takes full advantage of the programmable frequency amplifier capability, to start the plasma and later to optimize coupling with plasma. Operation experience with borosilicate rf window and improved power limit are reported, as well operational breakdown limit Vbr are discussed, together with improvements obtained with the installation of a cryogenic pump. The interrelation between bias voltage, bias plate current and magnetic configuration is outlined. Major diagnostic systems (including cameras and emission spectrometers) have been integrated with the acquisition system along with the data measured by several power supplies (including the high voltage supplies, the rf generator and bias supplies, the pressure measurements and the beam currents): among the several diagnostic used, the role of simple current measurement and some optical observation is noted. Beam extraction up to V_s=19 kV, bias and filter effects are discussed.

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



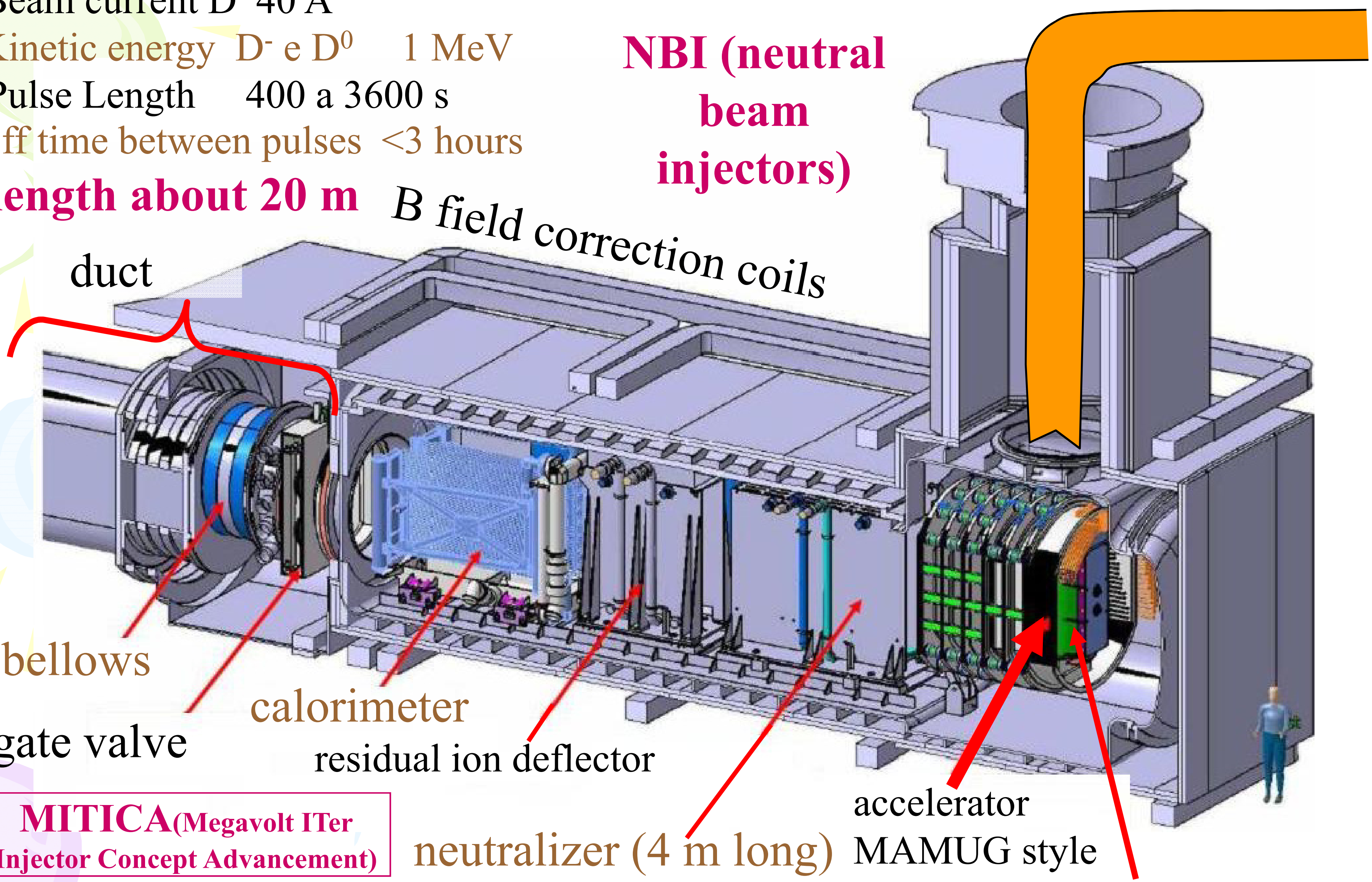
Design of building PRIMA-MITICA (from P. Sonato, RFX, 2009) and building view (from V. Toigo, 2015)

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

MITICA = 1 MV/40 A beam

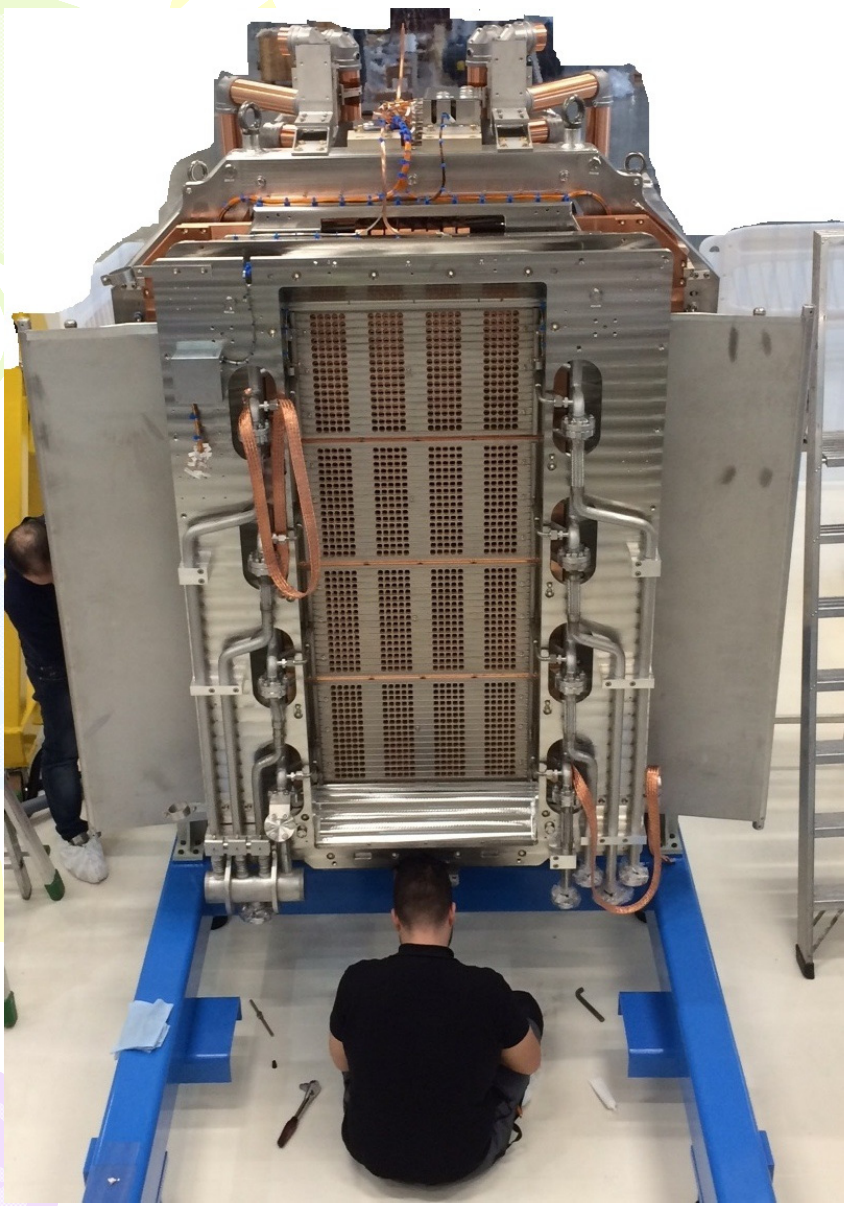
SPIDER = 100 kV/55 A system

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

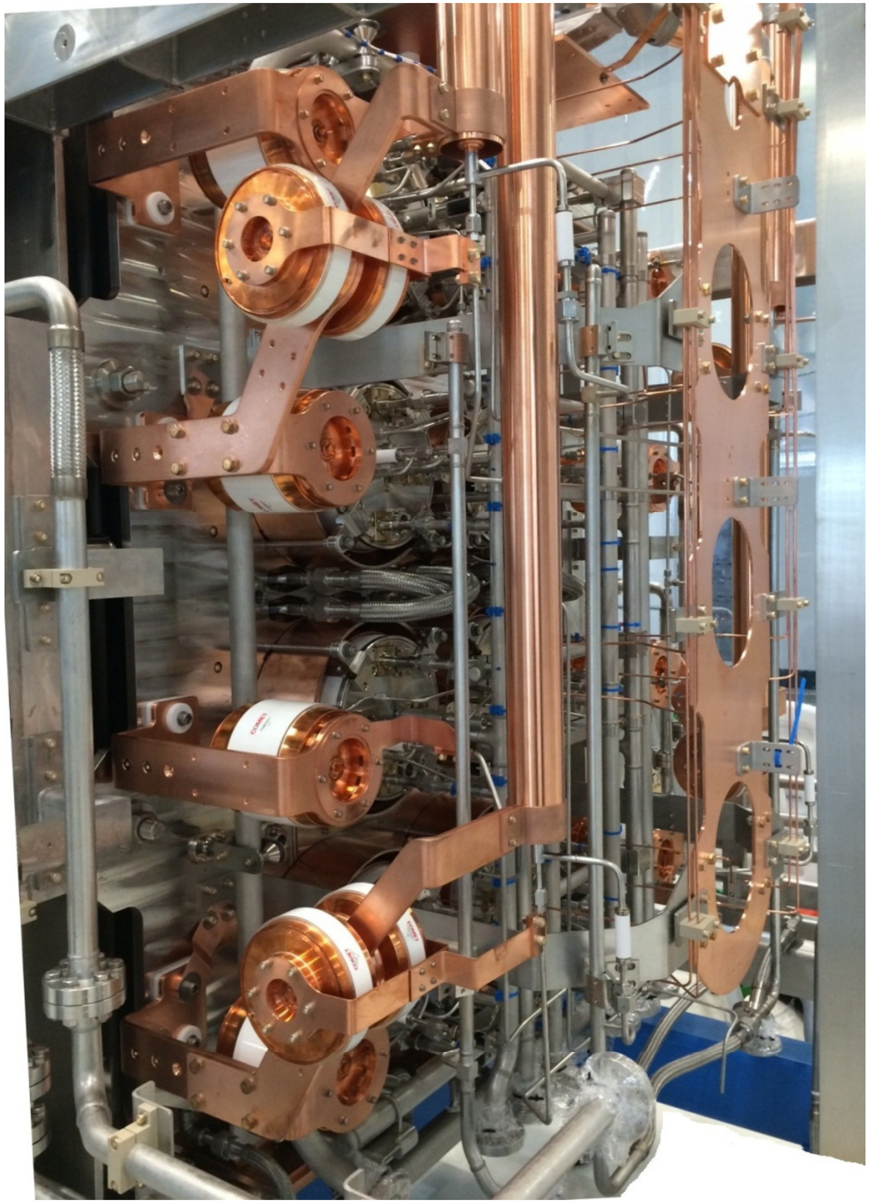


MITICA(Megavolt ITer Injector Concept Advancement)

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



Front view of SPIDER, note Grounded Grid



View of SPIDER (behind-side); note capacitor (white) and rf connection (shiny solid copper)

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 2014

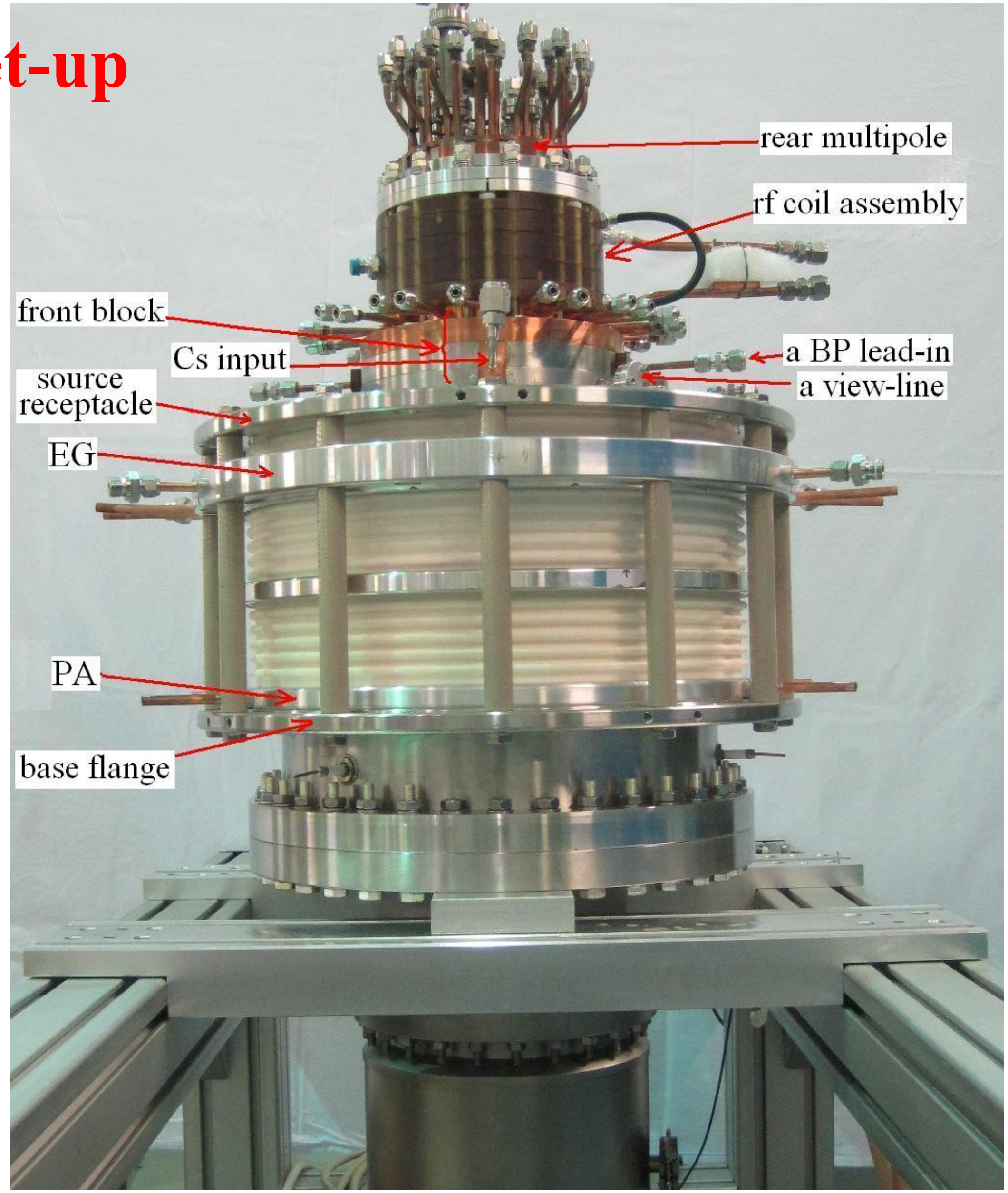
Calorimeter/beam dump delivered to RFX in January 2014

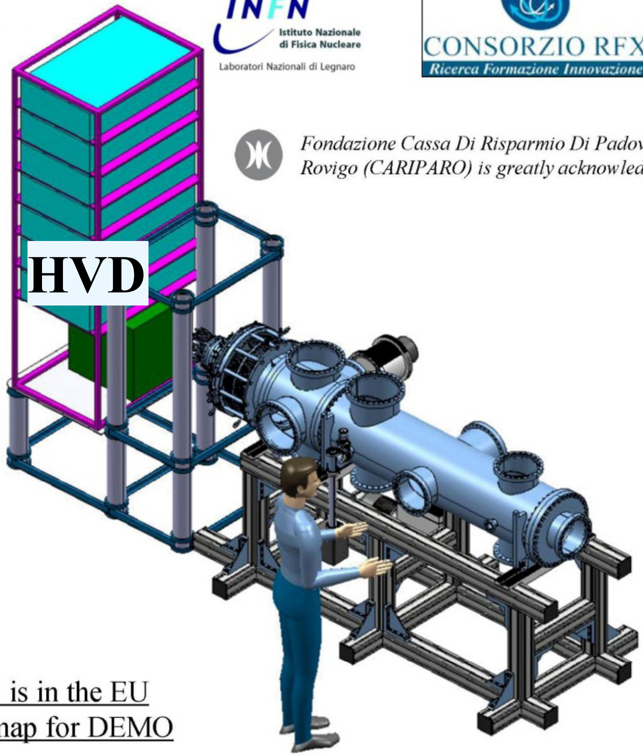
First source operation in July 2014

<u>Hydrogen supply line installed (2014)</u>

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

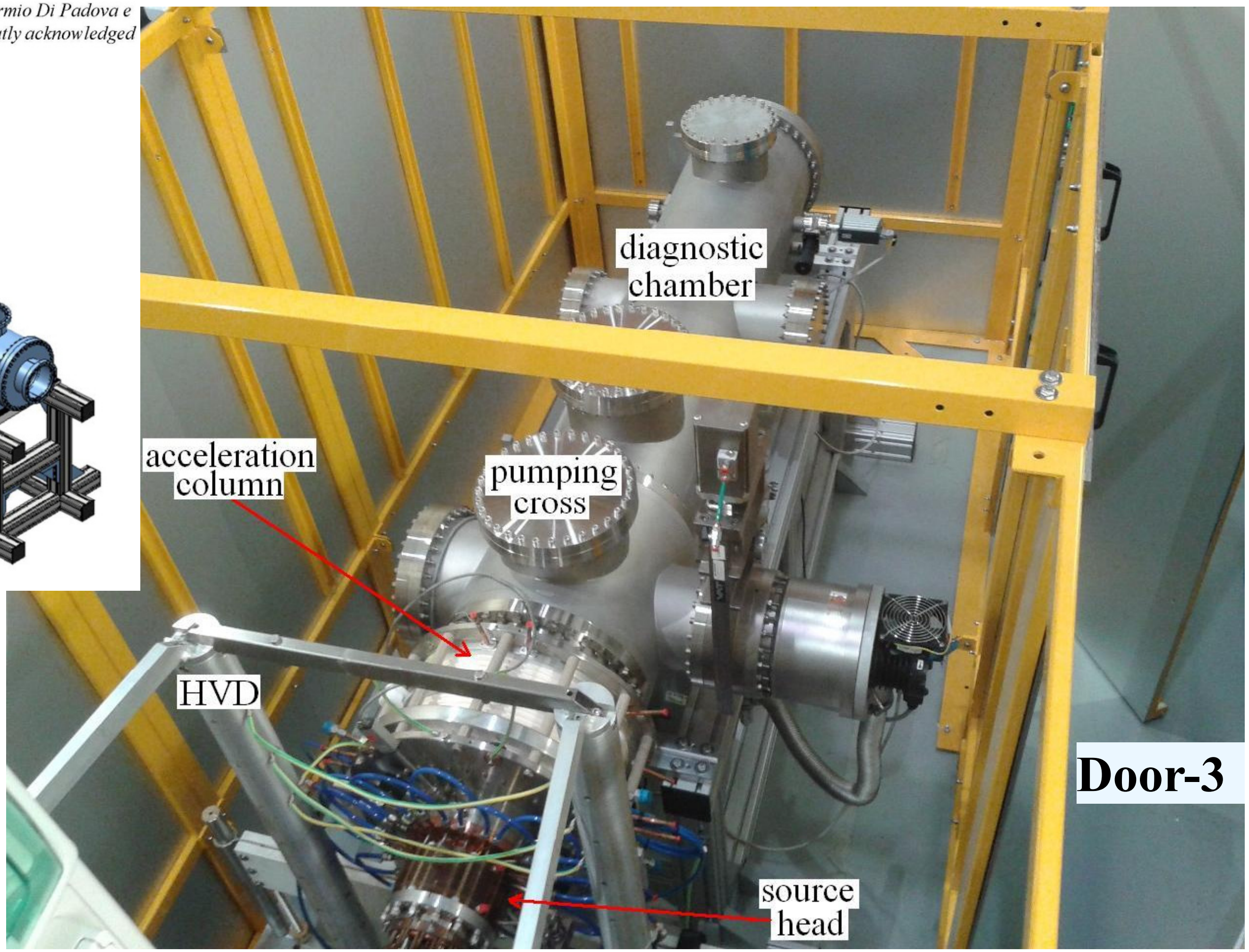
60 kV holding verified in January 2015(at source off)





Fondazione Cassa Di Risparmio Di Padova e Rovigo (CARIPARO) is greatly acknowledged

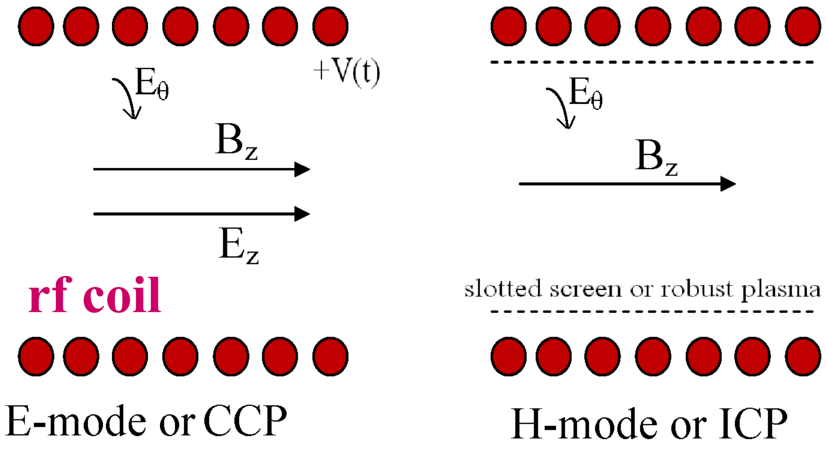
2.1) general setup and concept



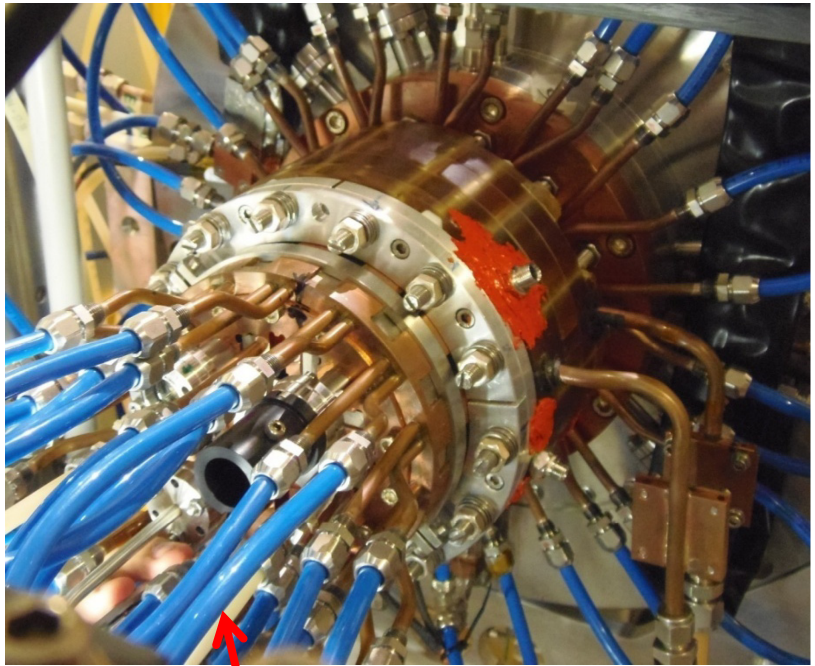
NIO1 is in the EU roadmap for DEMO

Figure: Isometric view of NIO1 and HVD (high voltage deck)

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

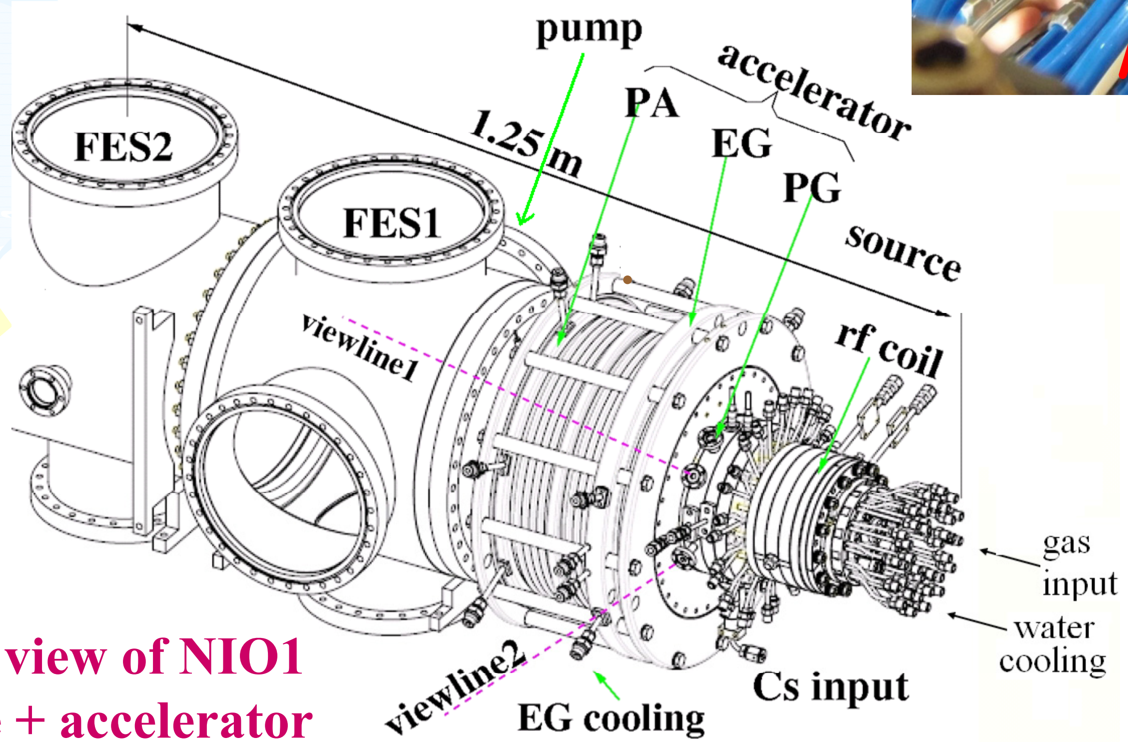


Simple explanation of coupling modes



Source head close-up view

All NIO1 parts are cooled by a closed circuits system; water (60 kg) changed each few months with high purity water from LNL purification plant



Detail view of NIO1 source + accelerator

2.2) the 2016 setup

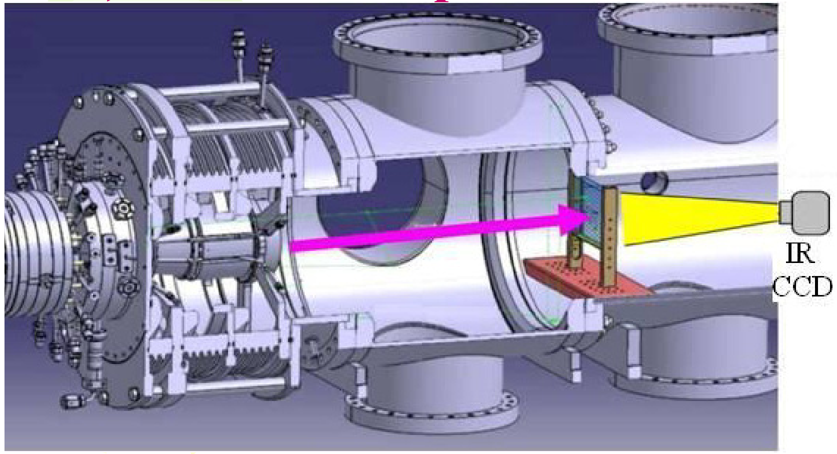
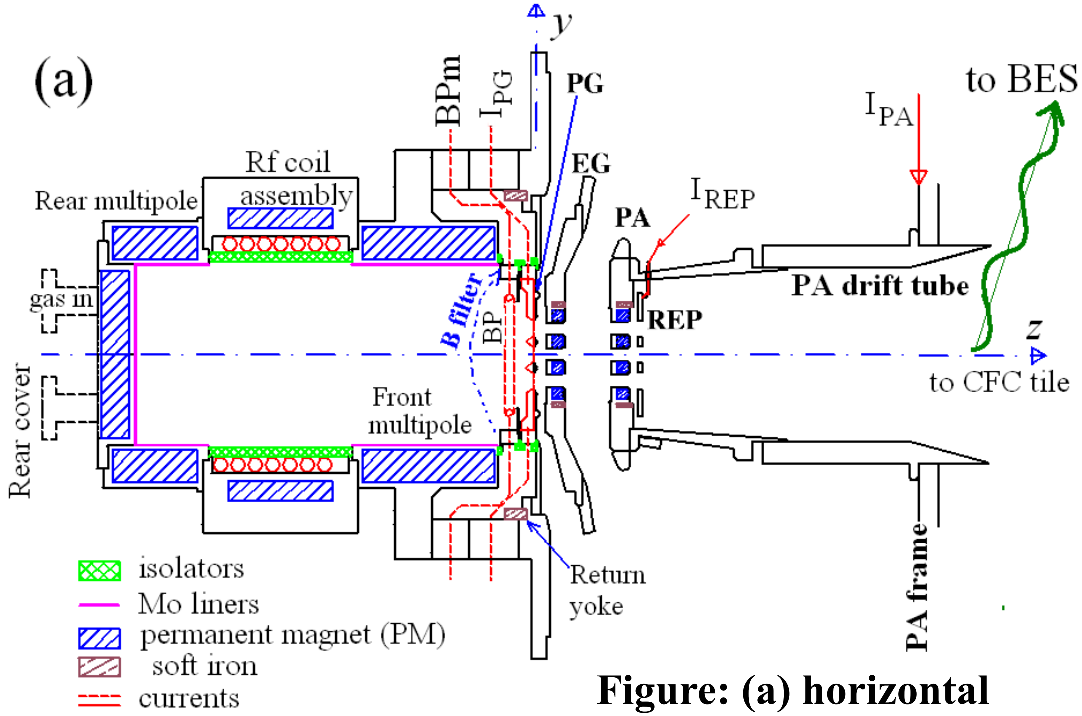


Figure: Cut view of NIO1 pumping cross, showing CFC tile



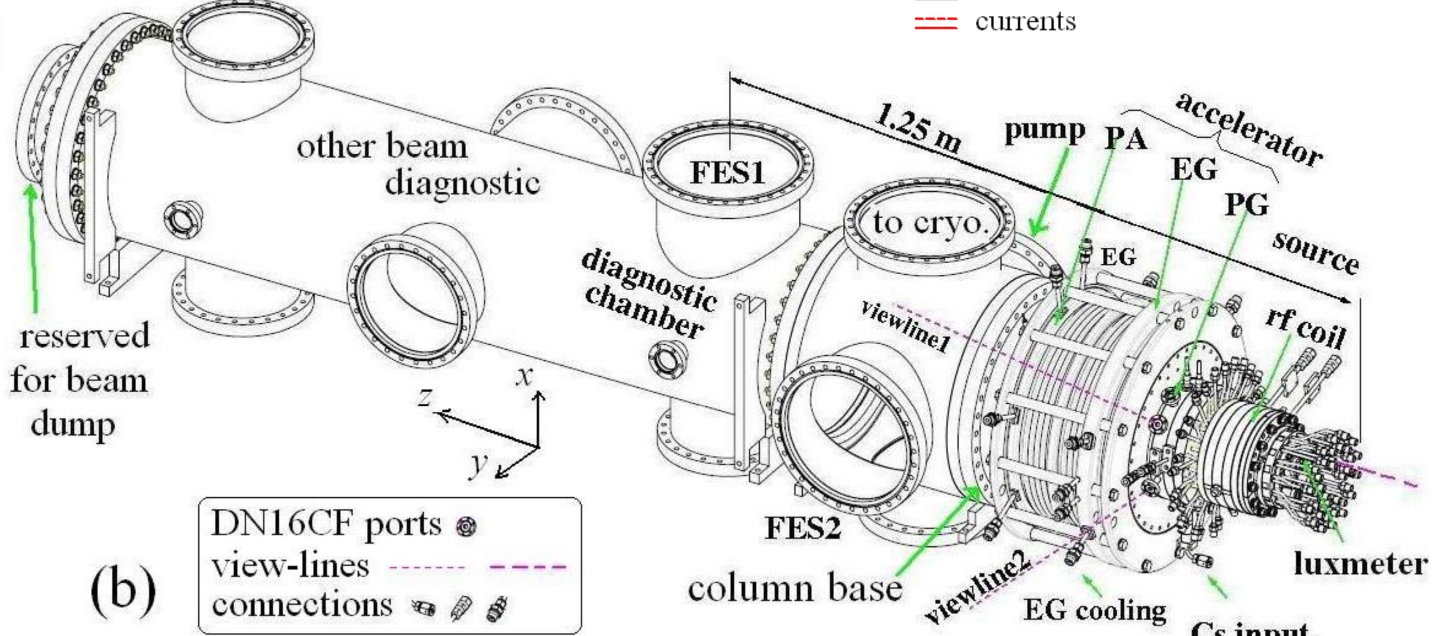


Figure: (a) horizontal zy section of NIO1 source and electrode; note filter position;
(b) isometric view of NIO1 vacuum vessel

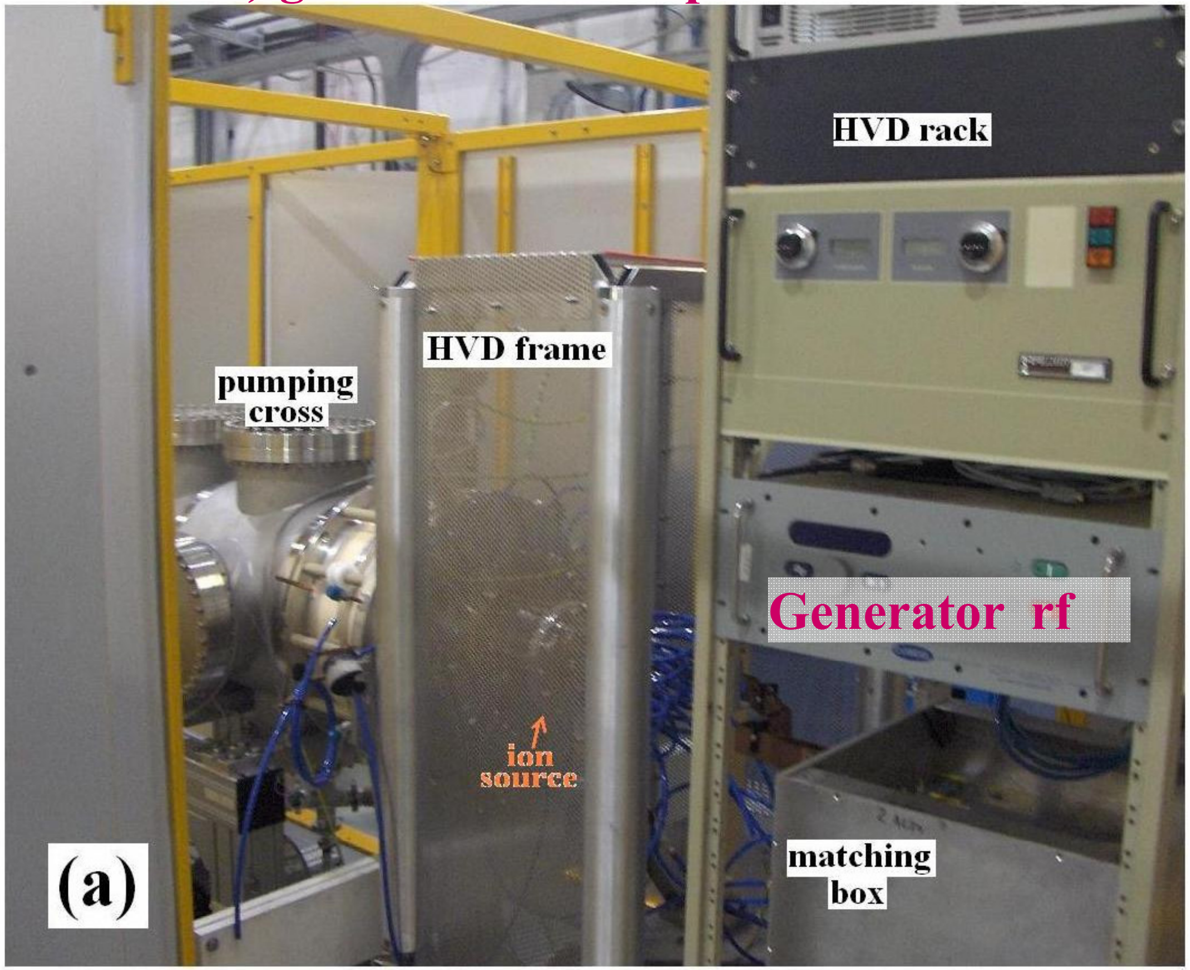
NOMINAL VALUES

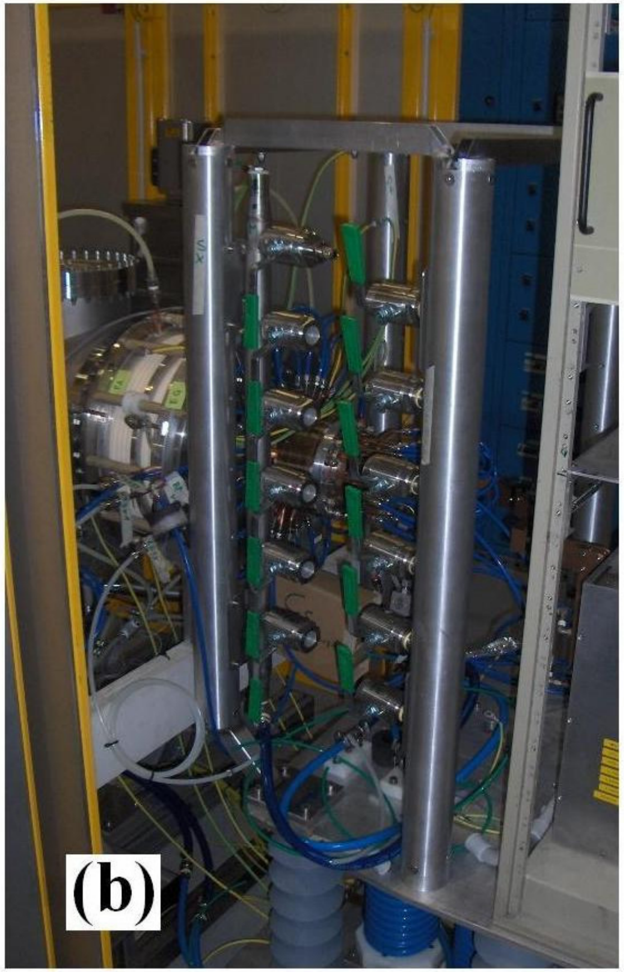
$V_s = -V_{PG} < 60$ kV

$V_e = V_{PG} - V_{EG} < 9$ kV

require better pumps: another TP is now in use

2.3) general HVD setup



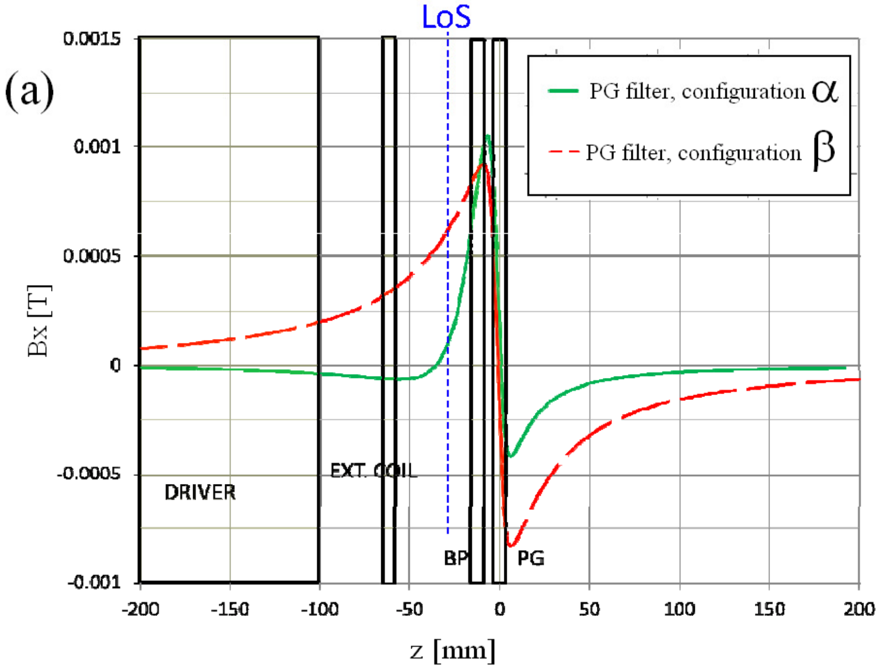


(a) NIO1 installed, with source covered by high voltage deck, rf matching box in the foreground, acceleration column, diagnostic chamber in the background. Two doors of Pb shielding were opened to make photographs

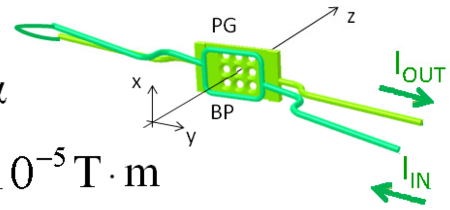
OTHER DETAILS ON INSTALLATION: M. De Muri et al., *Fus. Eng. Des.,* **96-97**, pp 249-252 (2015); M. Cavenago et al., *AIP Conf Proc* ***1655***, 040006 (2015).

3) NIO1 front multipole and dipole filters

3.1) new C-conductors (July 2016) and new magnet filter (Dec. 2016)



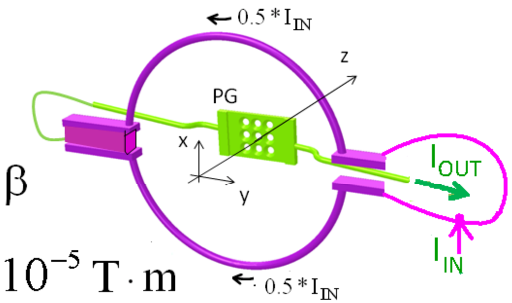
config a =



Configuration α

$$\int_{z_{driver}}^{z_{PG}} |B_x| dl = 1.98 \cdot 10^{-5}\, \mathrm{T \cdot m}$$

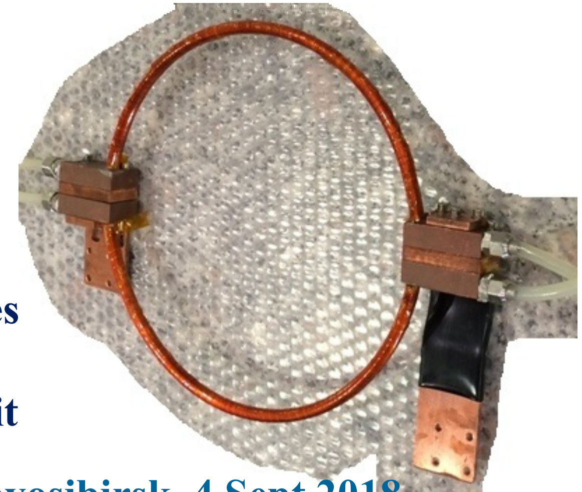
config b =



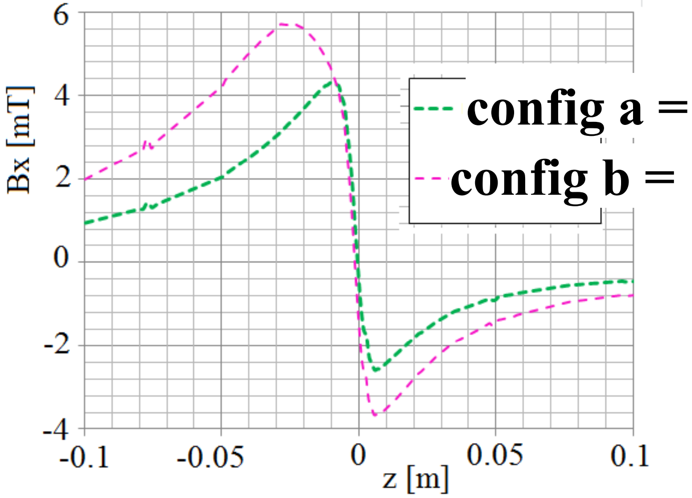
Configuration β

$$\int_{z_{driver}}^{z_{PG}} |B_x| dl = 4.07 \cdot 10^{-5}\, \mathrm{T \cdot m}$$

Figure: (a) field B_x vs z, with I_{PG}=100 A (b) old circuit; (c) circuit using C-conductors

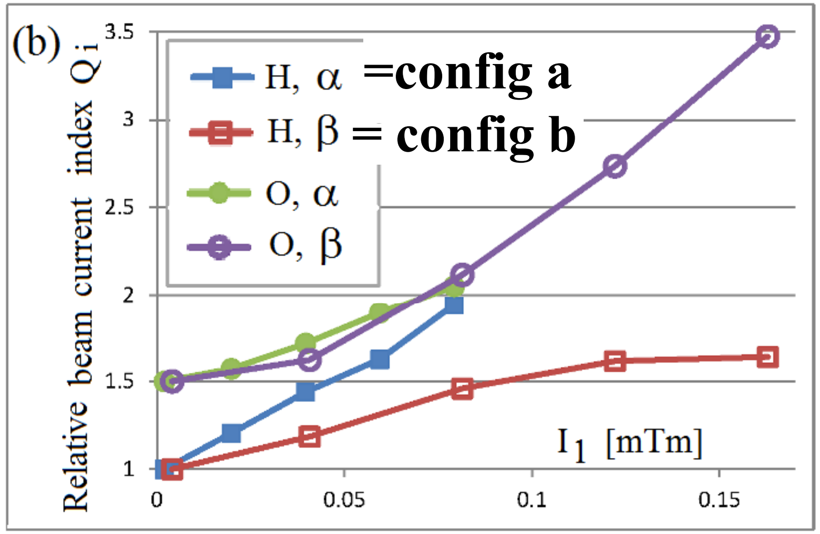


It is noted that |Ie|, the extracted electron current typically decreases when we rise the magnetic filter current (from 10 to 400 A); this is beneficial, but 400 A is kind of a technical limit. So we change circuit get more field integral, at least



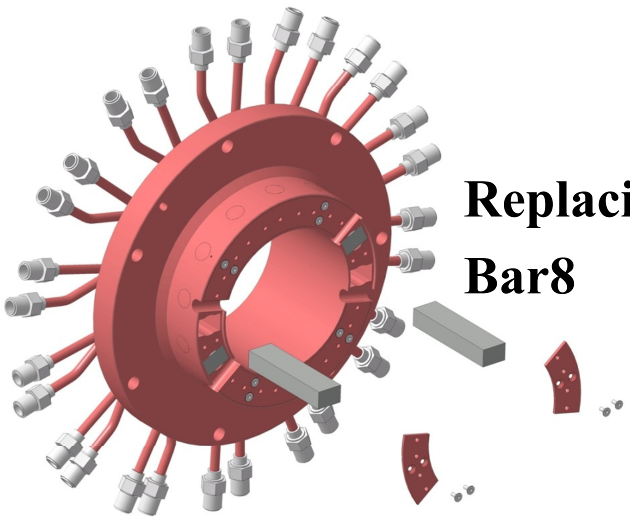
Field with IPG=400 A (maximum)

Quest for more field !

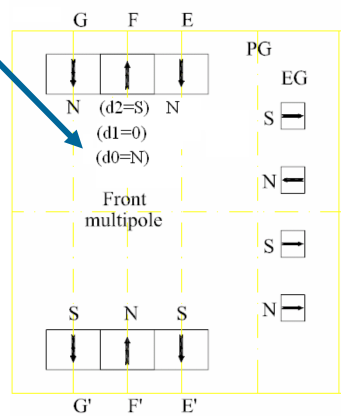


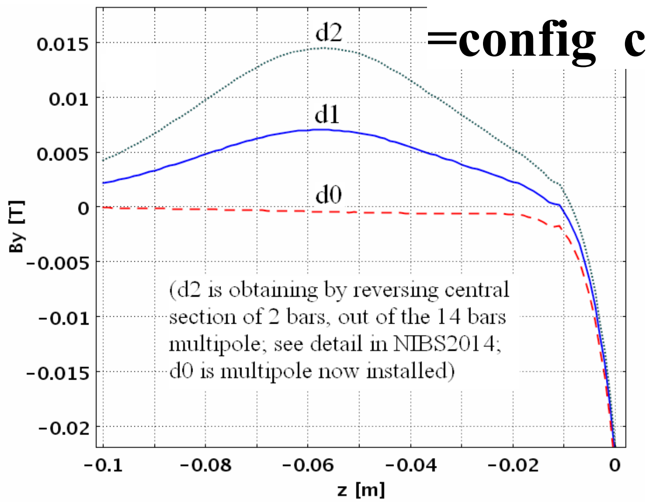
Oxygen yield vs I_1=\int B_x dz

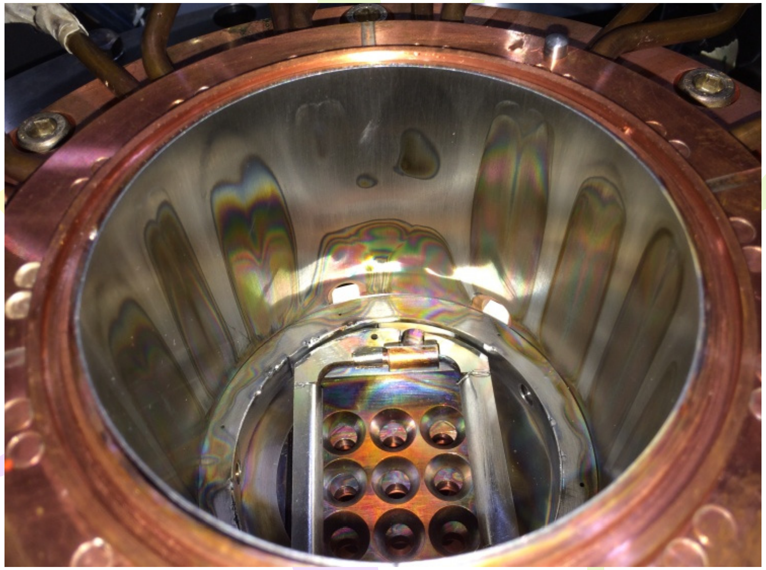
3.2) 1st solution: reversing 5% of the multipole magnet volume (d2) gives 160 G. This may mimic the effect of 1600 A effect



Replacing Bar8







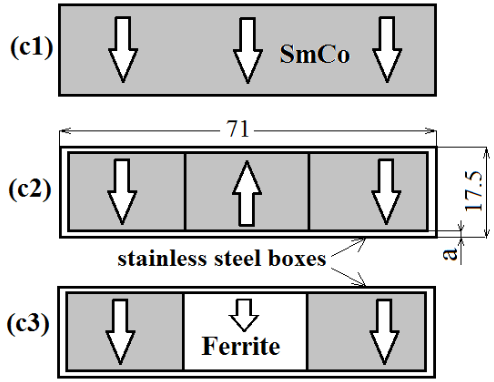
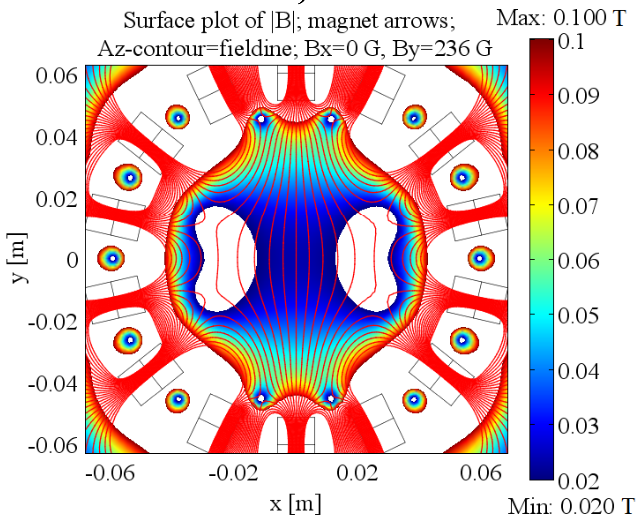
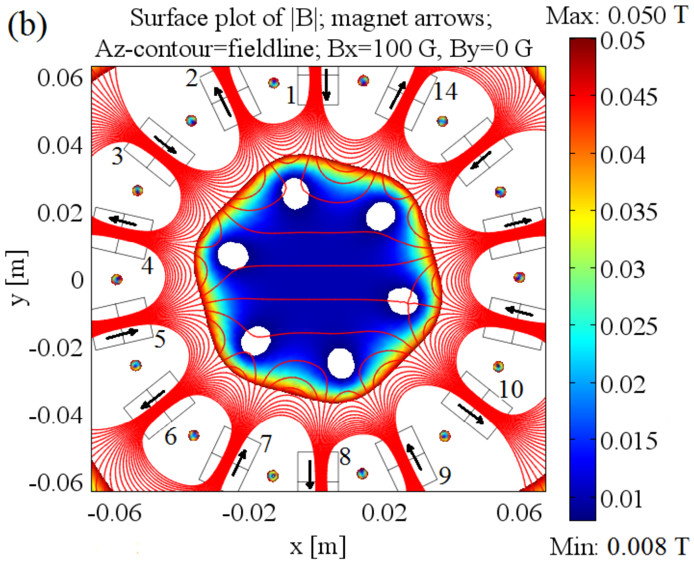


Figure: simple or simply modified multipole bars: (c1) solid block; (c2) central piece is reverse, note containing box thickness; (c3) central piece is different

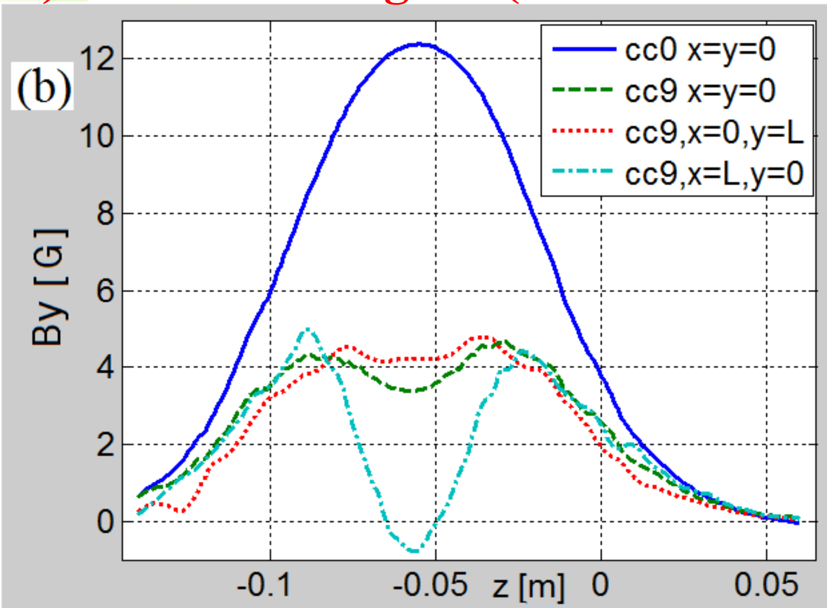
By=15 mT damage multipole confimement, now we want less

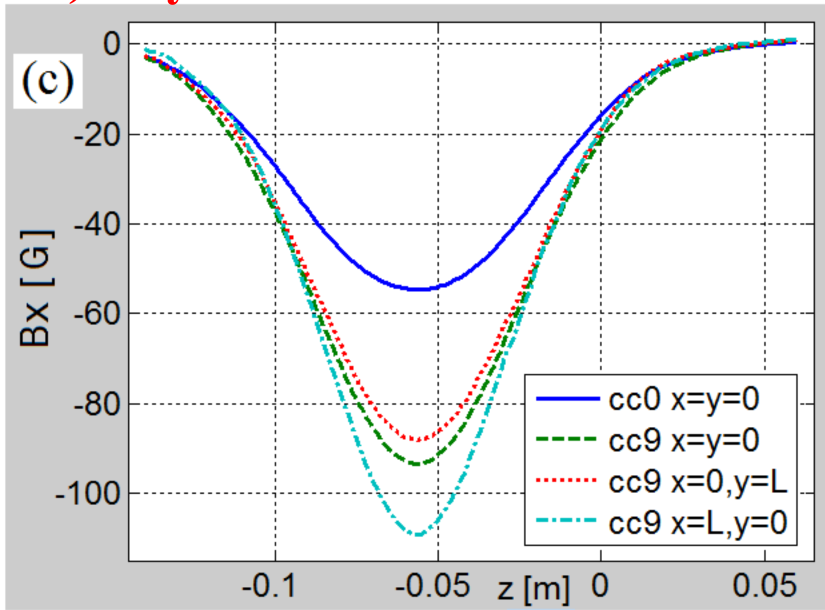




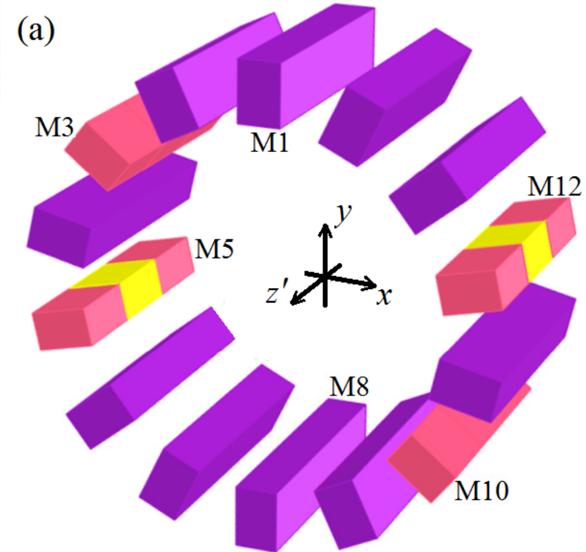
2D concept of isobars for config c style anc config f style (Cavenago, Baltador, Veltri, ICIS2017, in press); white island are confinement leak. Note regular hexagon in config'f' concept.Confirming 3D simulations mostly completed to appear soon (Baltador et al)

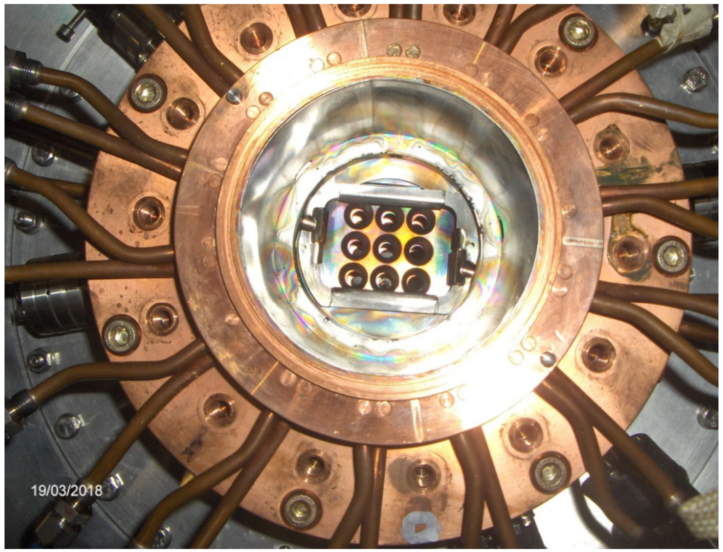
3.3) towards config ‘f’ (or cc17 =cc9-cc17): By=0 Bx= 5 mT





Field for cc0=extra effect; cc9 preliminary study of config ‘f’





. cc9 = preliminary study of config ‘f’

4) NIO1 planned accessories (Cs evaporator, CRD)

Figure: NIO1 cesium oven, partially dismounted, and removed from its test stand, where it is covered by a thermal insulation

Toven = 430 K

Tflange = 280 K

T gate and pipe = 470 K

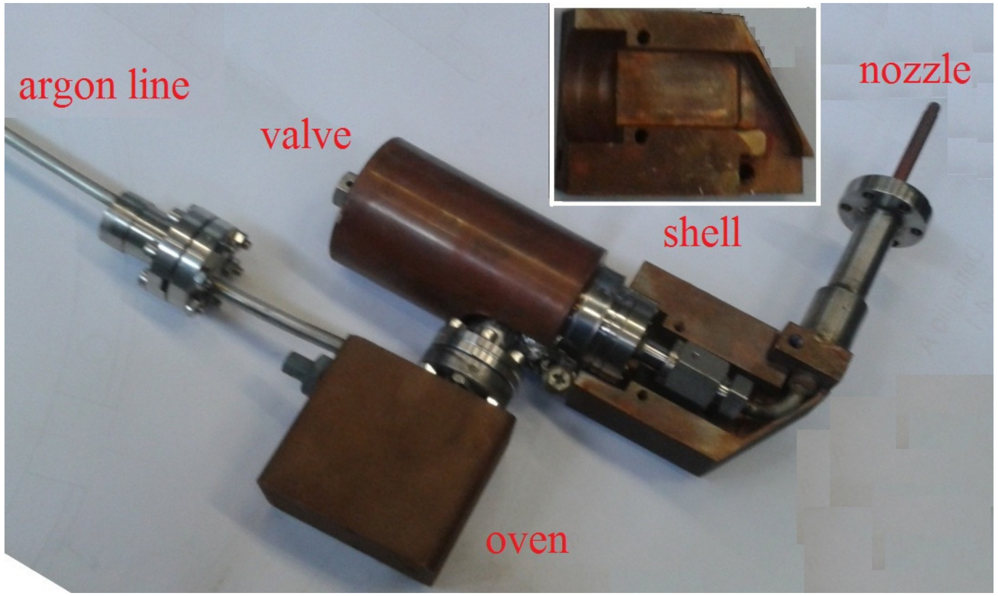
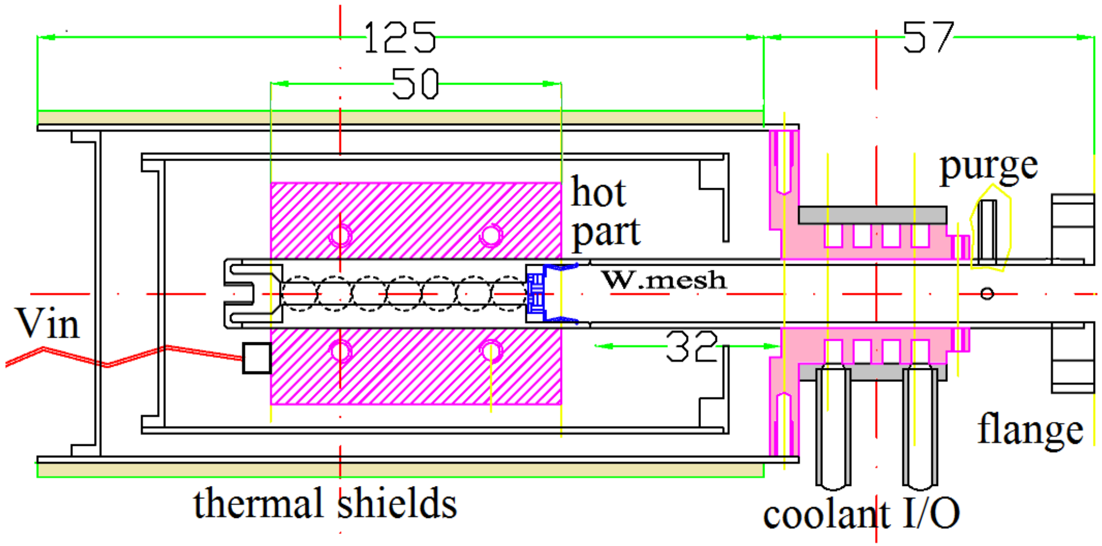


Figure: design of the second Cs evaporator for NIO1, using solid pellets

Toven = 1000 K

Tflange = 400 K



4.3) The flange for CRD installation in NIO1, integrating shutter and micrometric mirror movements; built July 2018; under installation

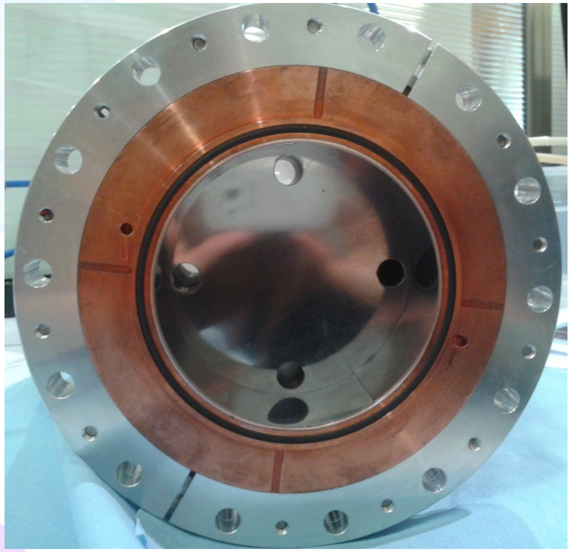


Figure below : Front multipole walls covered by Mo liners; during this maintenance also mounting studs were improved

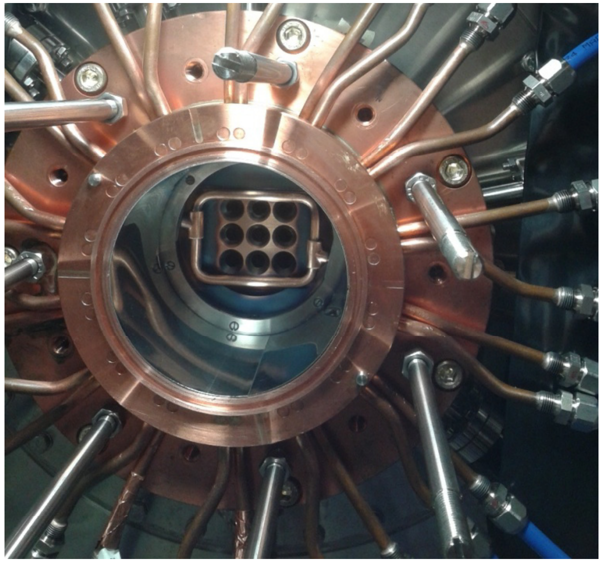
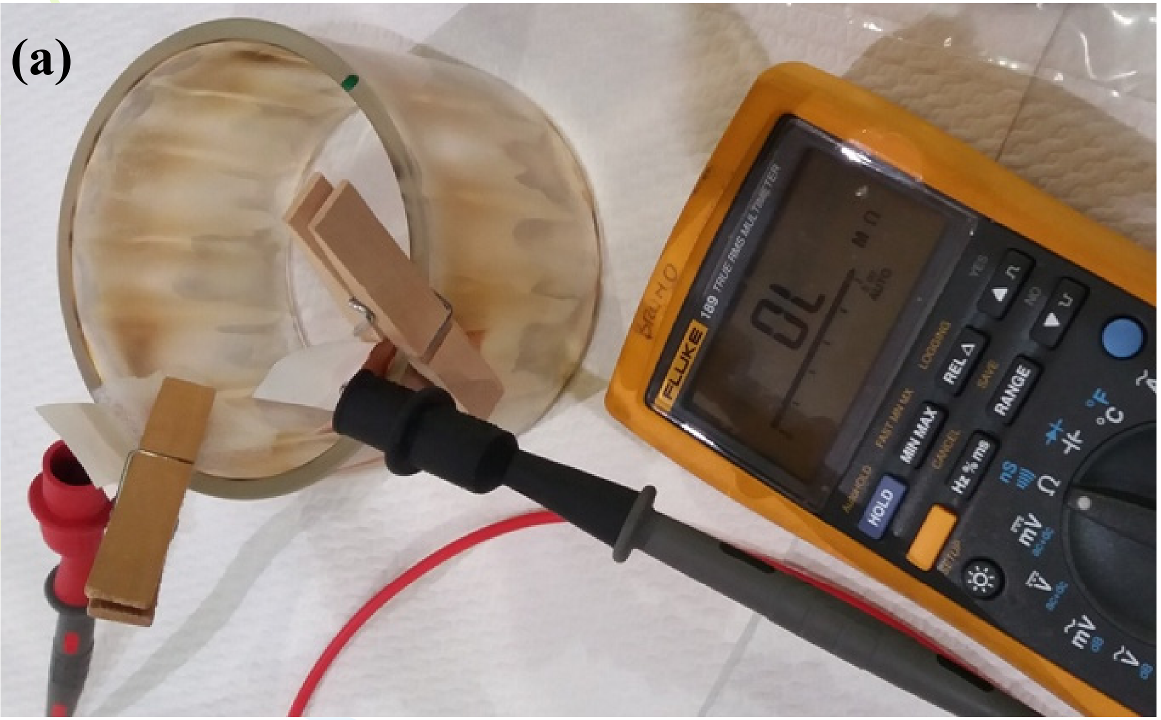


Figure above: Rear cover and multipole covered by Mo liners; note a liner also protects O-ring

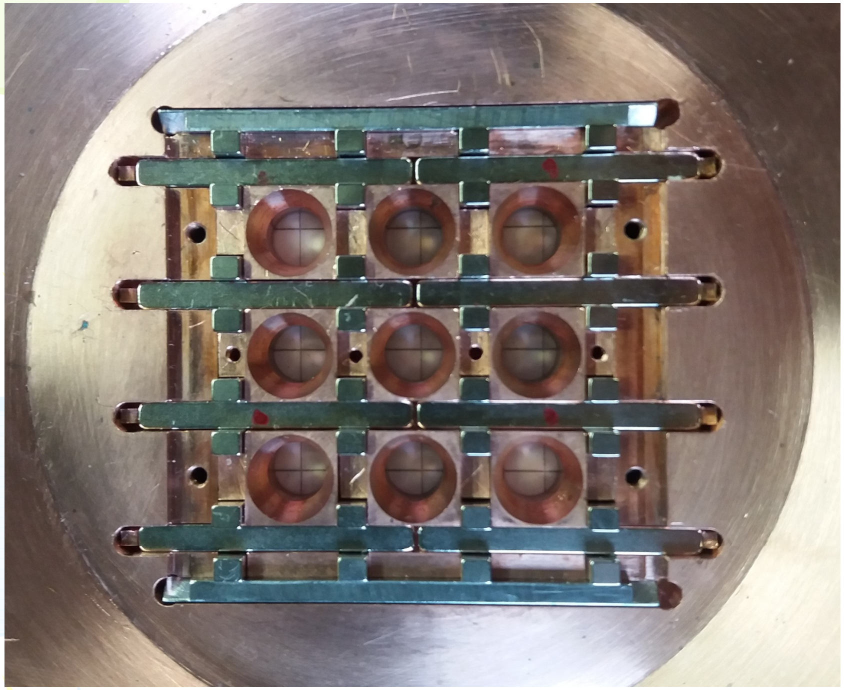
(a) With liners (and correct use of conical washers): now open circuit and 1.8 kW reached with borosilicate glass (aka Pyrex)

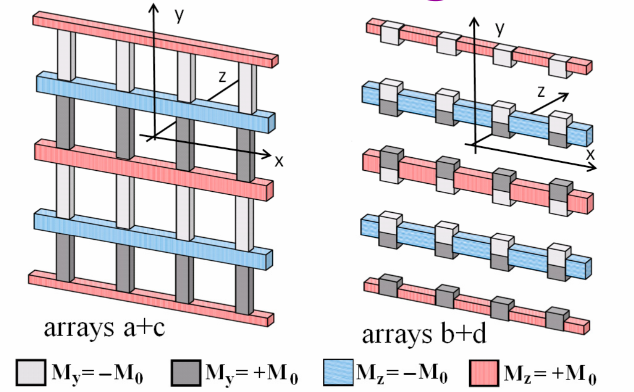
(b) Without liners: R about 150 Ohm, Al2O3 break at 1.7 kW



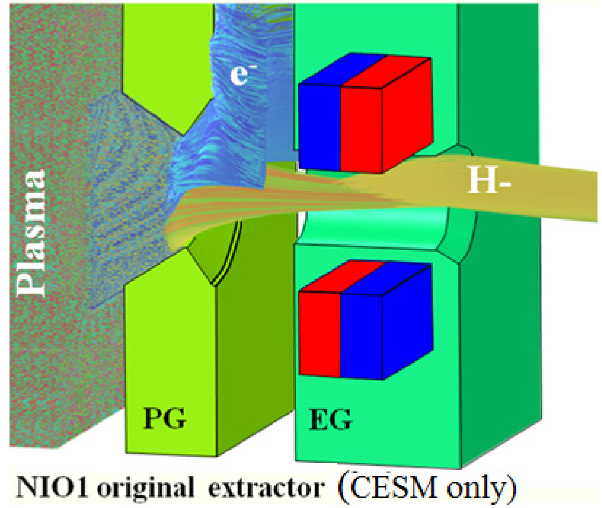
(b) OLD STATUS OF source walls and rf window: After operation at rf power 1.7 kW, a vacuum loss appeared (probably for elastic bolts unbalanced loosening, possible with vibration; finer mechanical adjustments are in progress). The opening of the source makes some observation possible: some wall deposit 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

5) New Extraction grid, *accelerator and realignment*





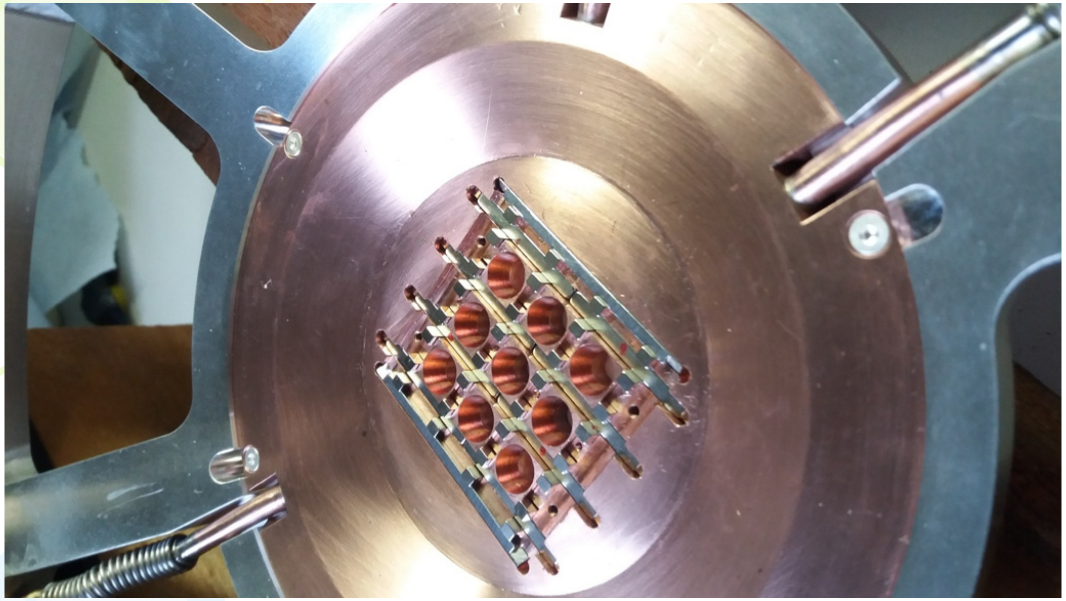
The CESM (red and blue magnets)
The ADCM concept (gray magnets) and some variants



The new extraction grid can hold either standard CESM configuration or CESM+ADCM configuration (Chitarin et al RSI 2013), with many variants (Cavenago and Veltri, PSST 2014)

Upper and lower bar in iron, to reduce end effects

Some comparison of the old extraction grid of NIO1 (known to tolerably deflect the ion beam from 3D simulation) and the new EG grid, using many more magnets



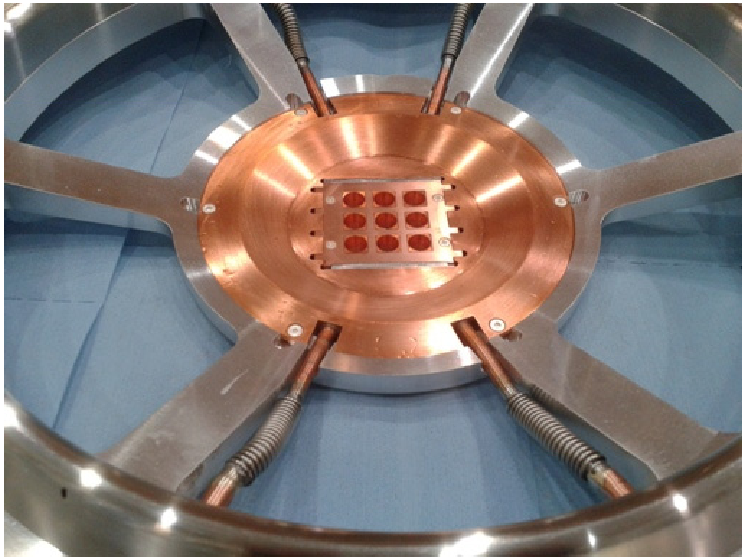


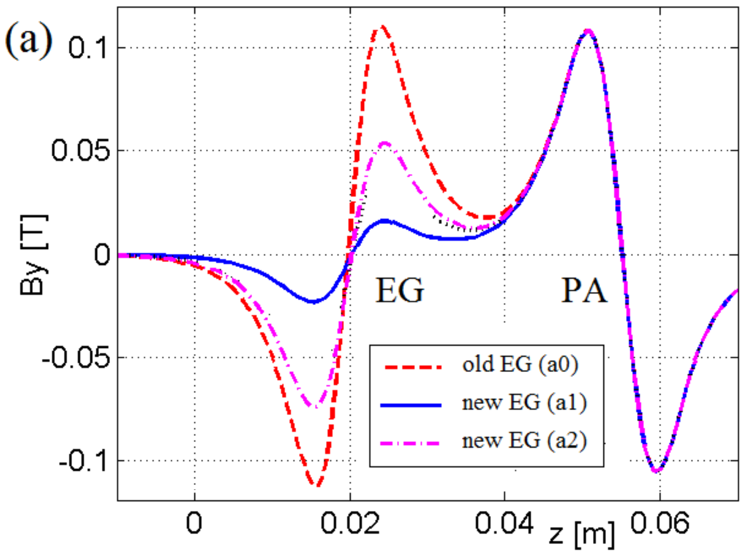
Figure: The new EG (see C Baltador et al. NIBS2016, Veltri et al. NIBS014, Cavenago et al. PSST 2014)

B_y for several setup

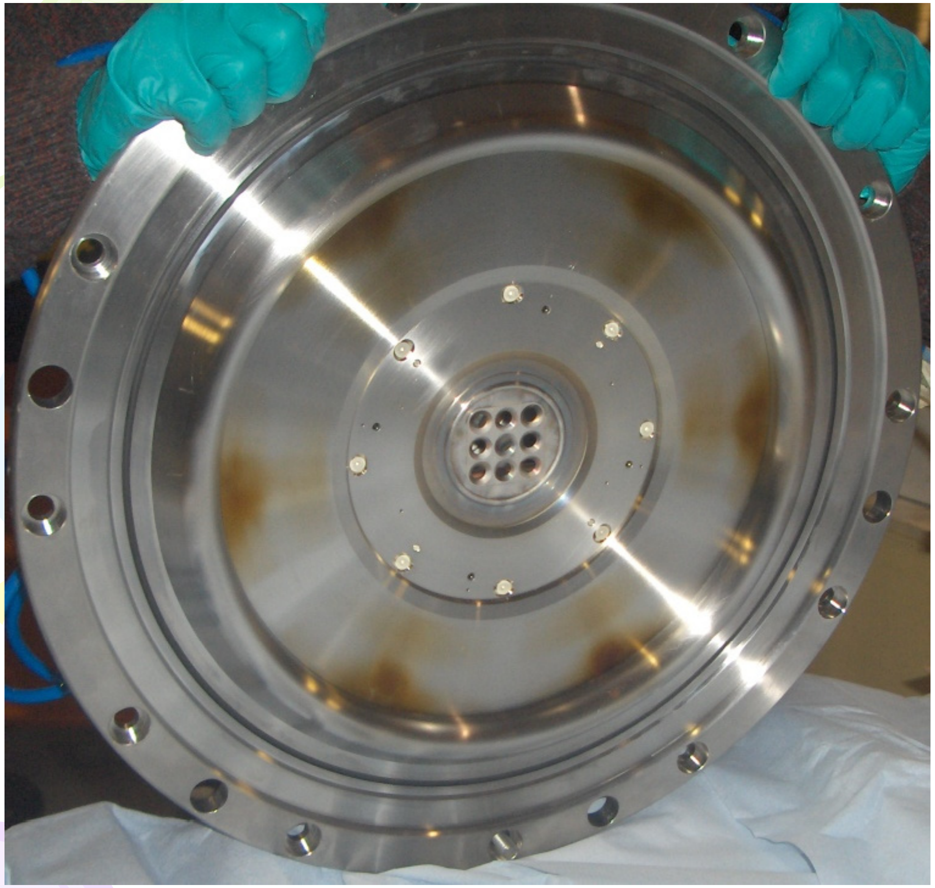
(CESM only) : Config a, b, c -> blue curve a0

(with Weak ACDM): Config d, e -> red curve a1

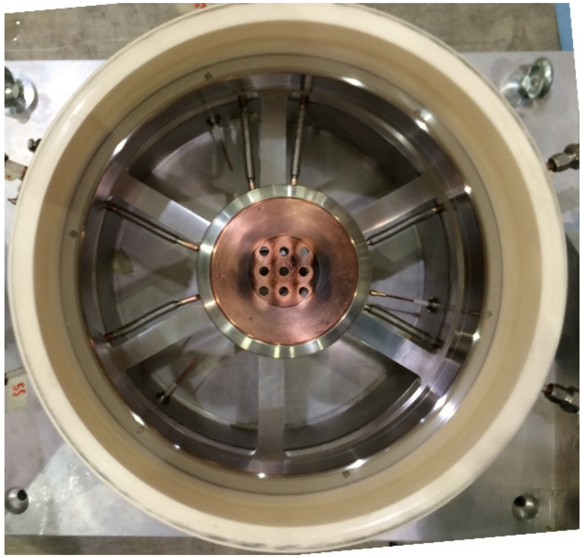
(with Stronger ACDM): Config f ->violet curve a2



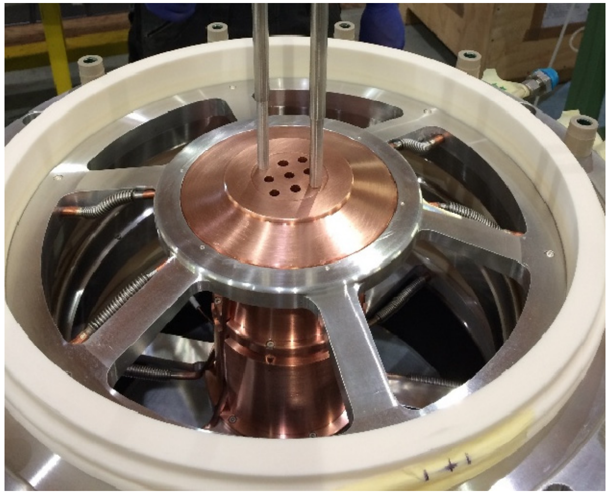
5.2) Realignment, verification of beam sputtering



The PG flange with 6 sputter marks



May 2017 disassembly config ‘c’ = the old EG: note burns with a zigzag patterns



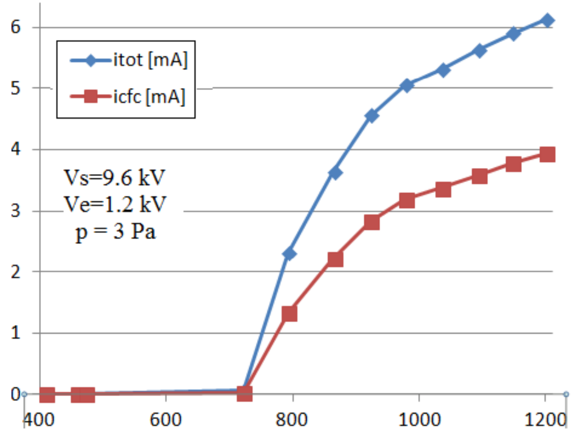
The new EG being aligned for tests; note also the accelerator column and PEEK bars

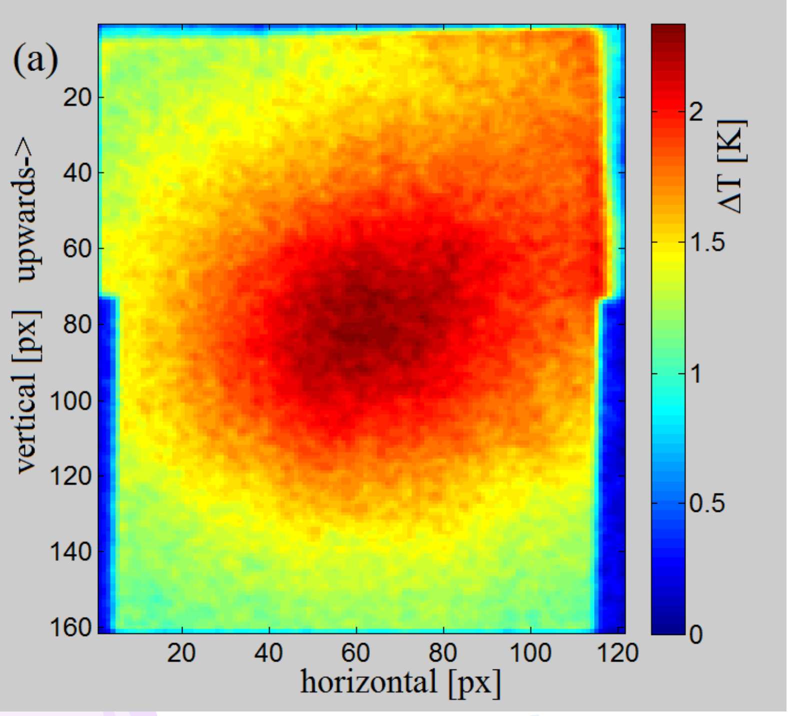
6) Experimental beam results

1) H-mode transition very simple to obtain after Liners

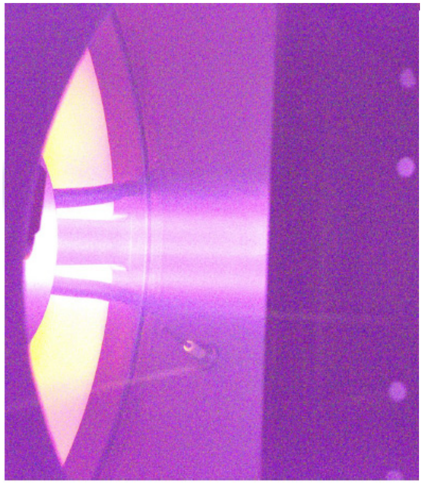
2)Beamlet balancing is very difficult to achieve; with consequences on beam optic

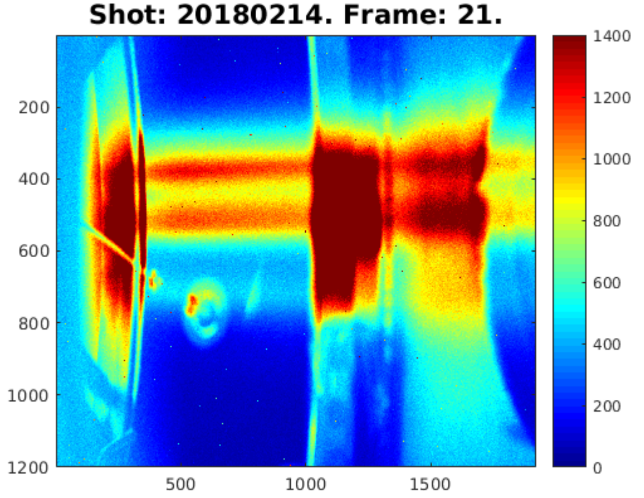
(b): H- current (ICFC,Itot) vs microwave power Pn; applied voltage held conservatively 9.6 kV. Note H mode (Pn>0.8 kW) is needed to make beam



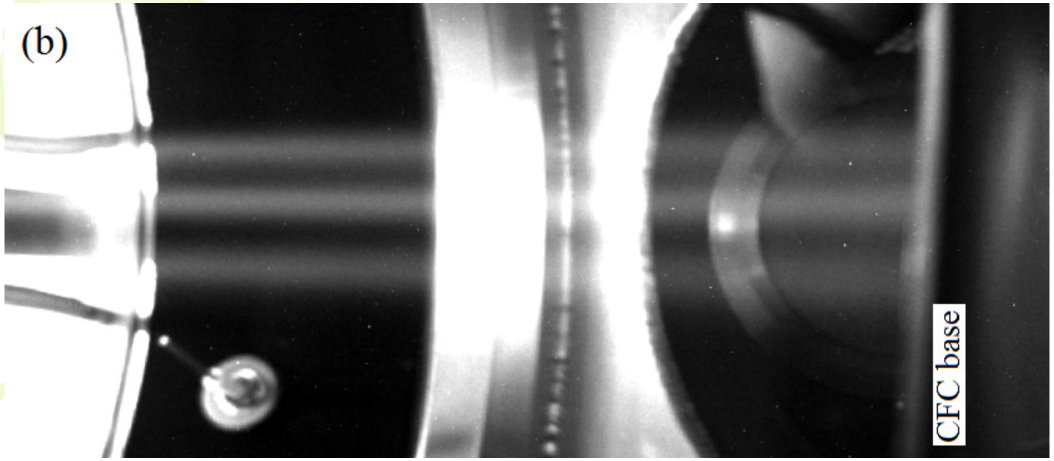


(a) Temperature rise ΔT on the CFC tile in 150 s, 1 px = 0.75 mm;

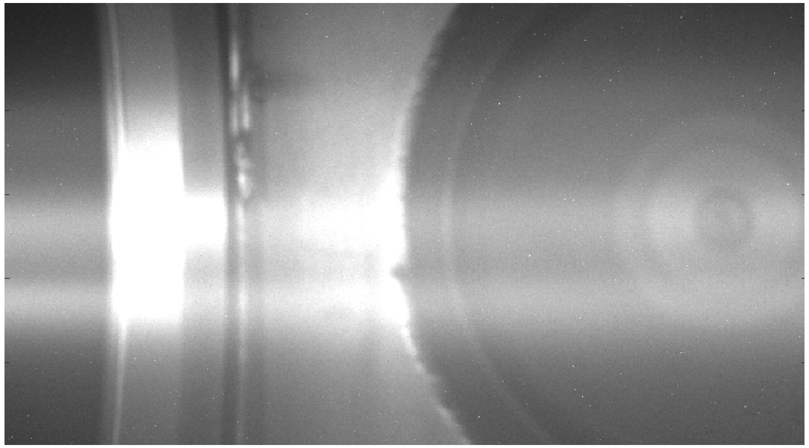




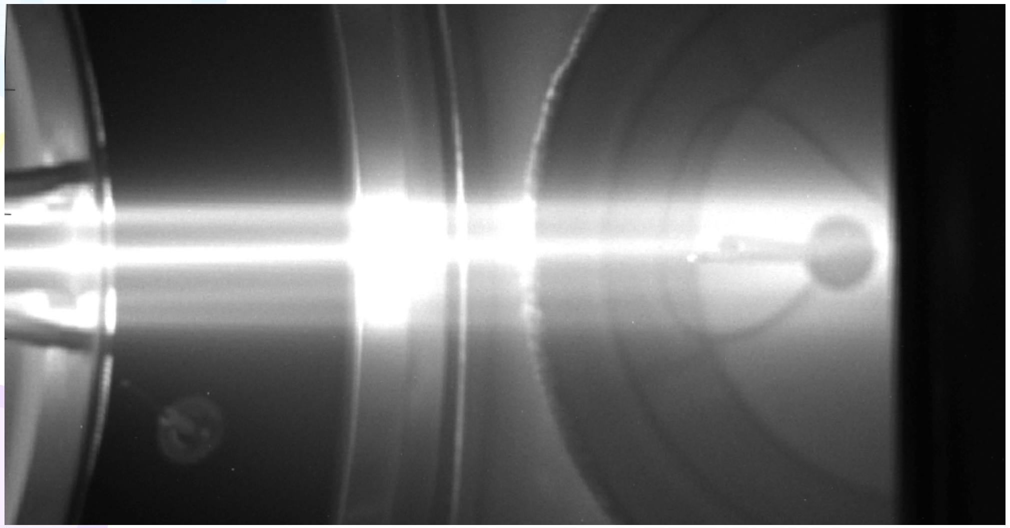
NIO1 Beams, up to 4 mA (April 2017), view from down; note 3 rows of beamlet, with spacing difference possibly due to old EG magnets.



New EG, config ‘d’ beam bottom view, note CFC tile was moved forward (to appear in AIP-CP)



From December 2017 lateral views are also recorded, but fainter



New EG, config ‘d’ beam bottom view, with third beamlet split

6.2) The breakdown voltage improvements for H2 (no problems for O2 up to the25 kV installed limit)

a) Original NIO1 magnet

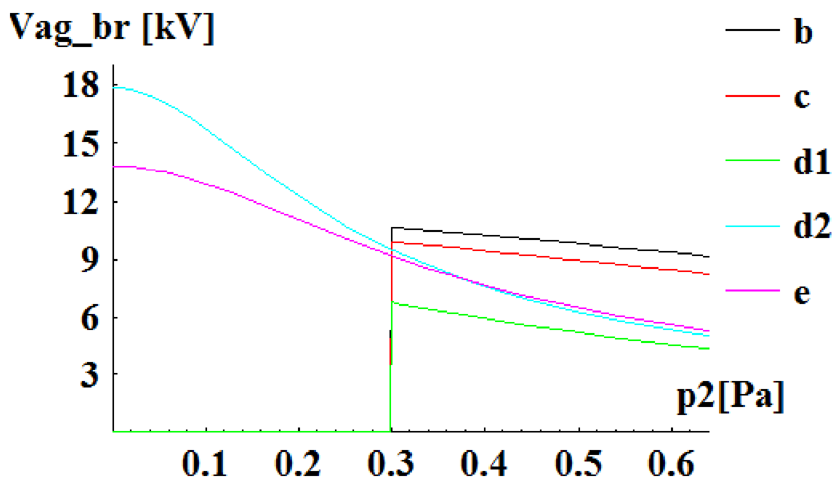
b) C-conductors

c) Filter By=15 mT

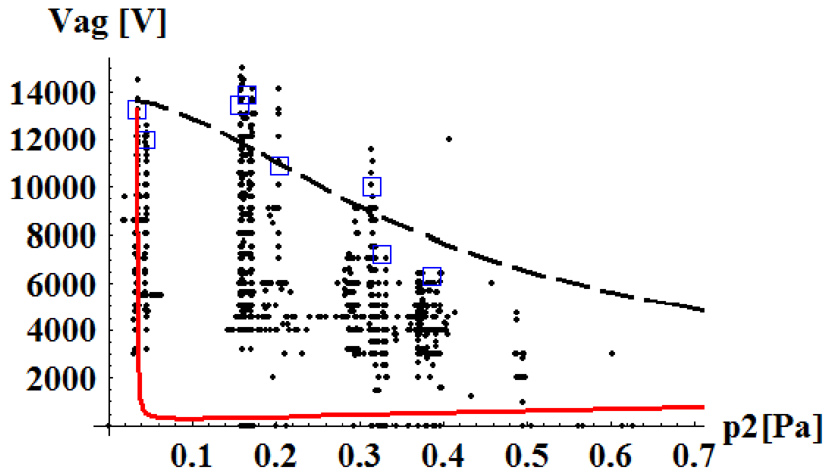
d) New EG with ADCM; d2) one cryopump added

e) Stronger ADCM

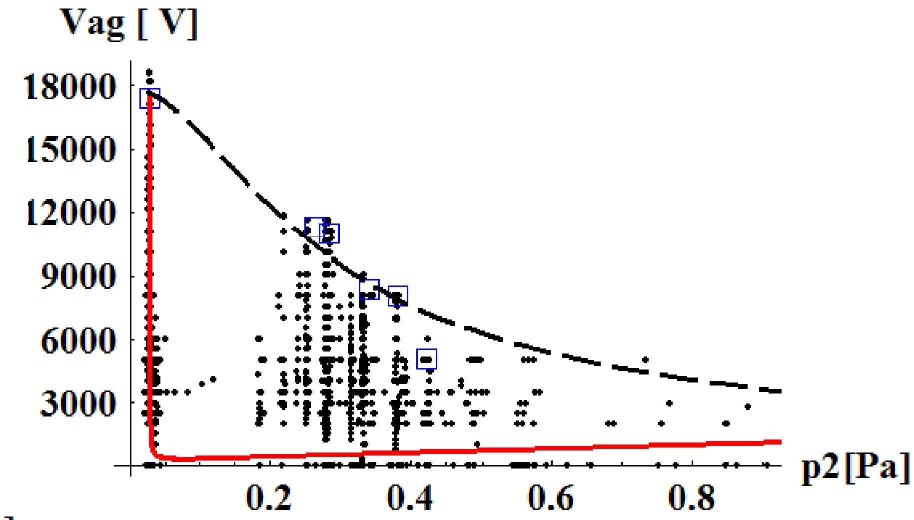
f) Filter Bx=5 mT, By=0 (in progress, from end July 2018)



Trends of Breakdown voltage vs vessel pressure for H2 for config b-e

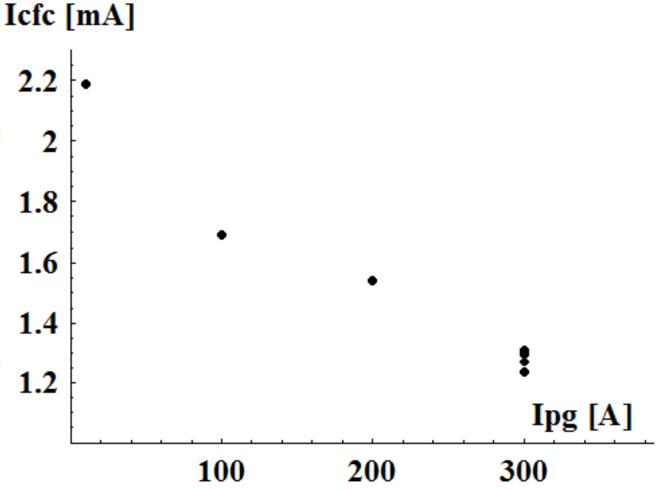


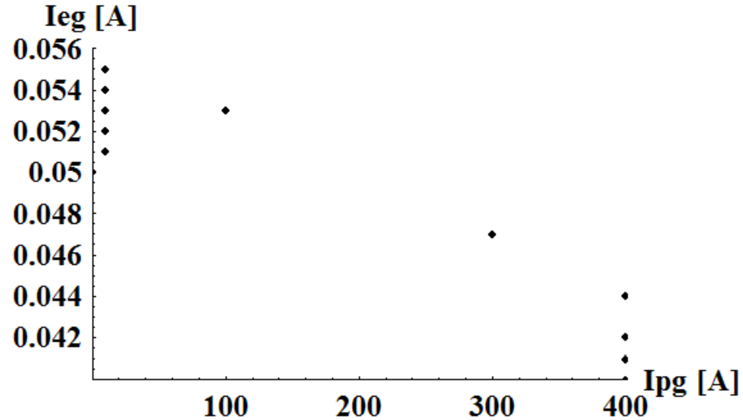
Accumlated data for config ‘e’



Accumlated data for config ‘d2’, binning point (square), fit (lines)

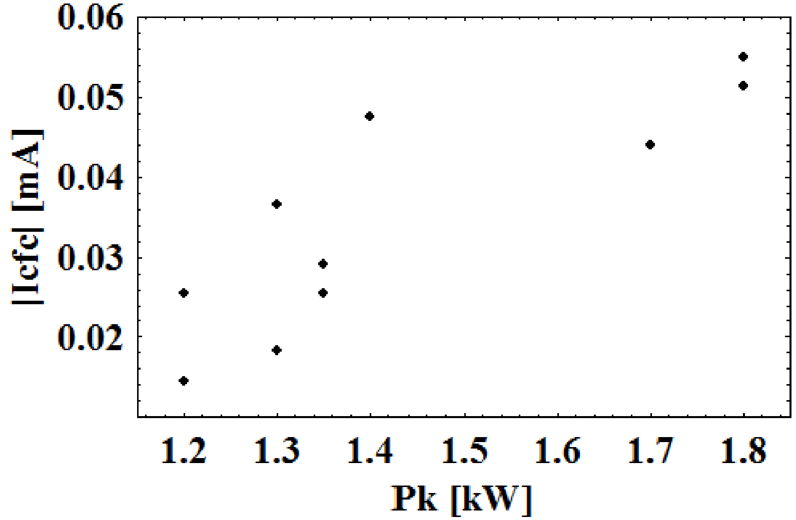
Beam current issues





Beam current with p1=0.4 Pa for config 'e' and Pk=1.2 kW similarly decreases with Ipg,

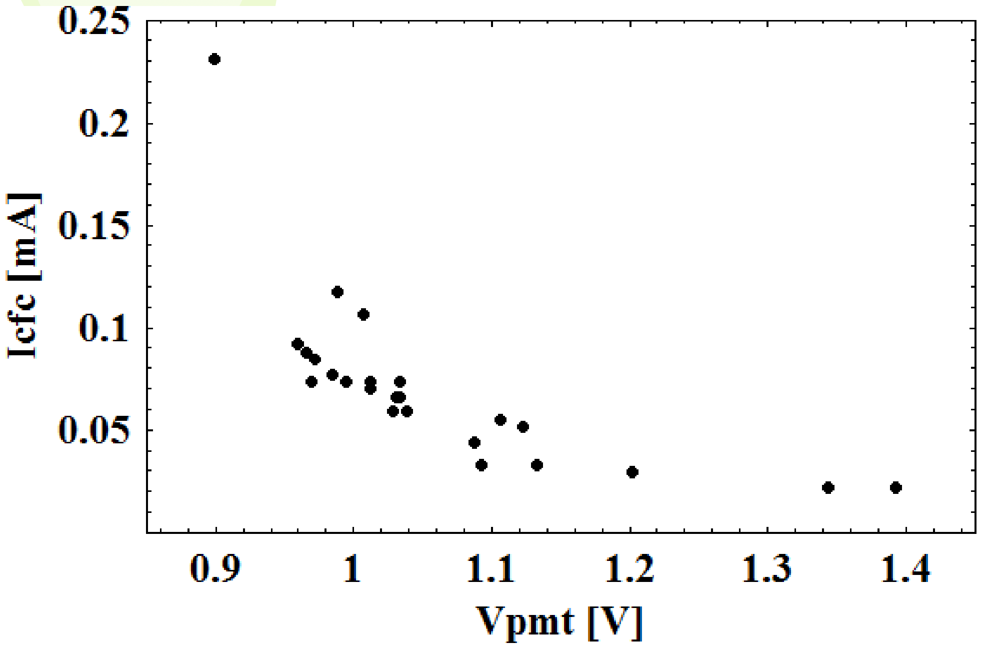
Beam current with p1 = 0.75 Pa for conf 'd2' decreses with filter Ipg



In general well collimated beam current has decreased going form config b (best to now) to e; reason is still being investigated (cleaner walls and electrodes? Dirtier walls and electrodes? Unbalanced magnetic field? Accidental?), while breakdown shows some improvements)

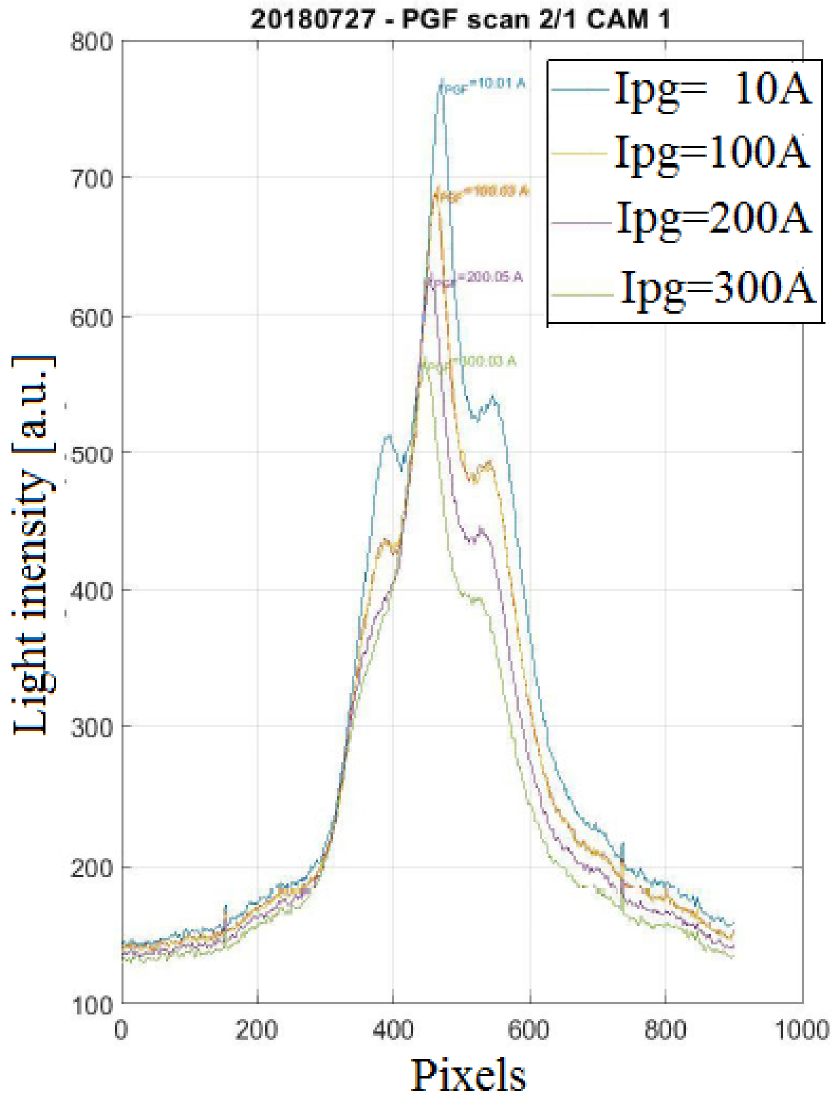
Beam current with p1=0.4 Pa for config 'e' increase with Pk, at least up to 1.5 kW,

Other result for comfig 'e'

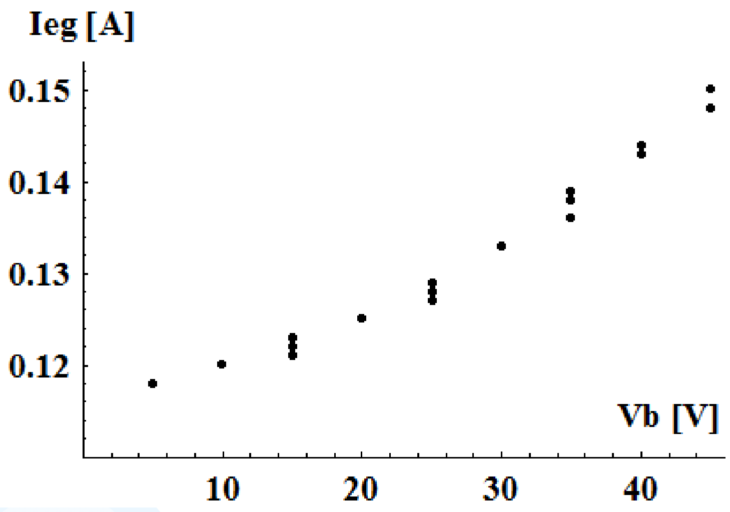


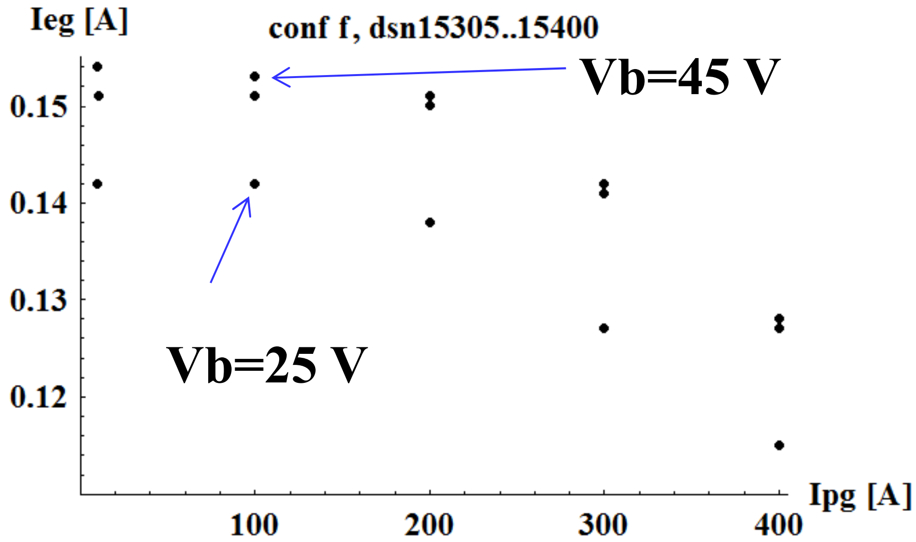
The puzzle of config 'e' : beam current increase with low luminosity (Vmpt) at alll control fixed, mainly Pk=1.2kW, Ipg=10 A, p1=0.75 Pa; the spontaneous or transient effect

Preliminary result for config 'f'

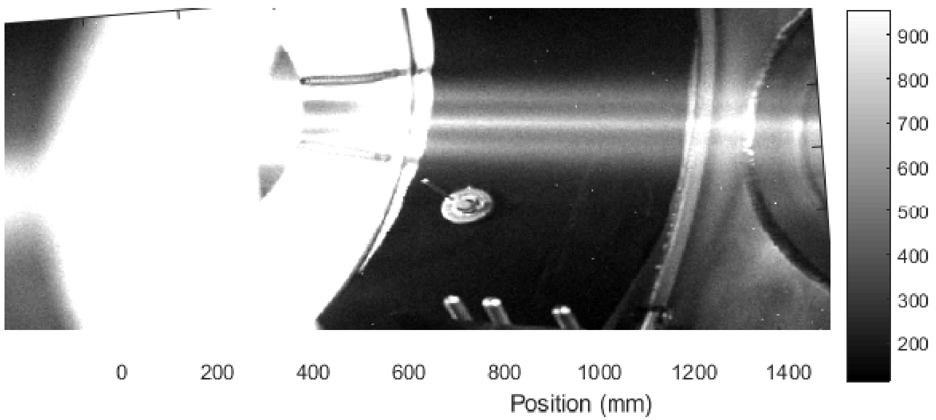


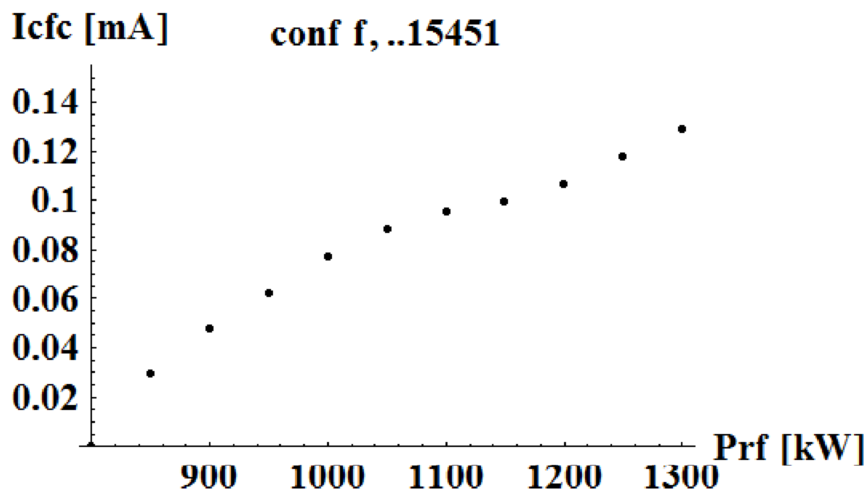
Some beam image and inferred profiles for several filter current





The coextracted electron current for Vb (bias voltage) and filter current for config 'f'; preliminary results seems more regular than for previous configurations





Beam current vs rf power for config 'f'

7) 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.

After confirming the distinction between E and H modes, improving the experimental procedure for hydrogen, the beam extraction was investigated at moderate acceleration power and rf current. Wall liner were very effective for allowing larger rf power use. Due to limited source size (3 x 3 beamlets), beamlet uniformity is an issue.

Several bias and magnetic configurations were tested; important upgrades and investigations implemented are new EG installation and new filter permanent magnets, and cryogenic pumps.

A large database of beam current dependence is being accumulated for several magnetic configuration, up to now with some difficulty in reproducing best performances

Thank you for attention

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