Relazione a workshop 'INFN-Energia e Industria verso Horizon 2020 e nuovi mercati', Genova, 16/01/14

Iniettori di fasci atomici di alta intensità per il riscaldamento di plasma per fusione - sorgenti e fasci di ioni negativi

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1) Introduction: fusion and (high current) accelerators; overview of the neutral beam injection (NBI): intense and negative ion beam and sources (NIBS)

2) Status of NIO1 construction

3) Simulations and analytical models

4) Conclusion

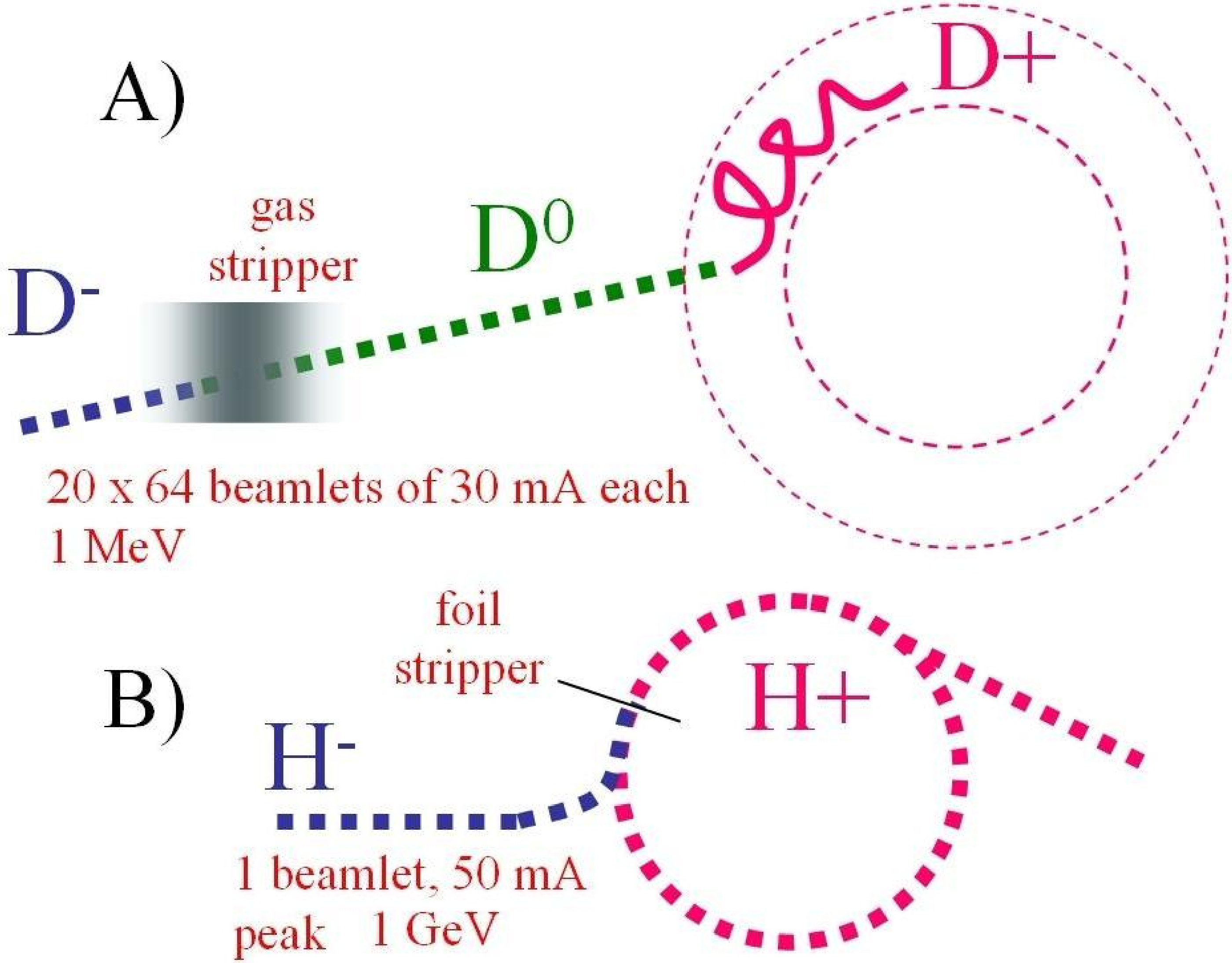
Abstract

High intensity ion beams are required to supplement other plasma heating methods in most tokamak reactors, including the ITER project, where three neutral beams (10^{20} atoms/s each, 1 MeV energy, obtained by conversion of negative ion beams of 40 A, 1 MeV) are required. Relation to projects DEMO (a tokamak reactor) and IFMIF (two 130 mA 40 MeV D+ beams) is briefly discussed.

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 is detailed.

Recent progress in modeling of a generic extraction system is also described.

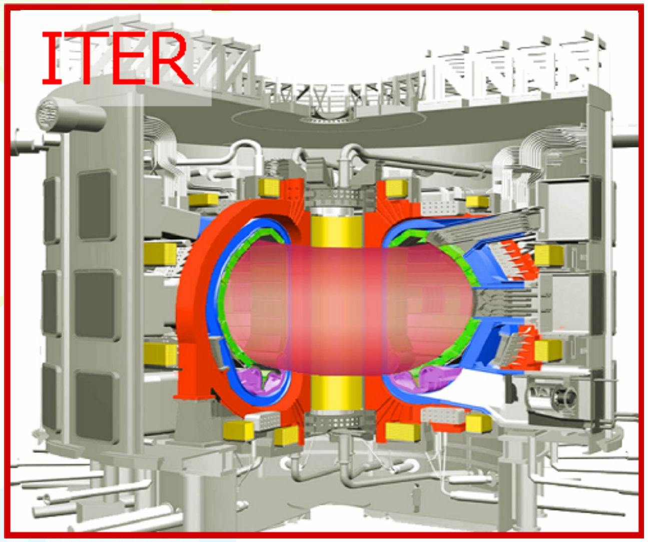
1) Introduction: fusion and (high current) accelerators



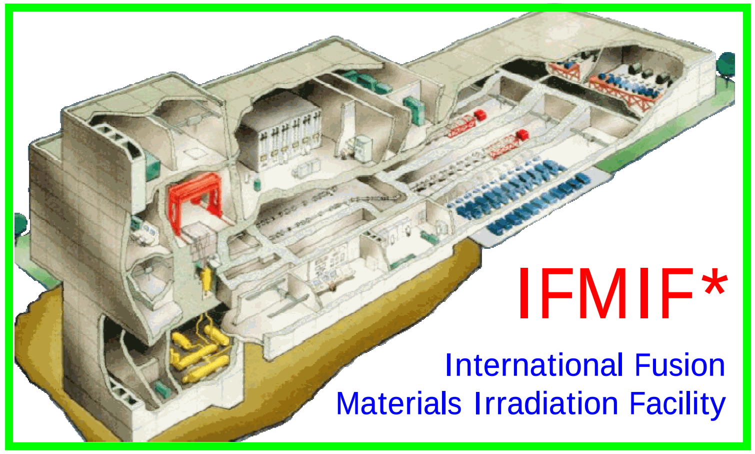
1MV negative ion beam are easy to convert into neutrals and/or positive ions: this is used to concentrate beam power in regions with high magnetic fields: A) tokamaks; B) circular accelerators

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

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

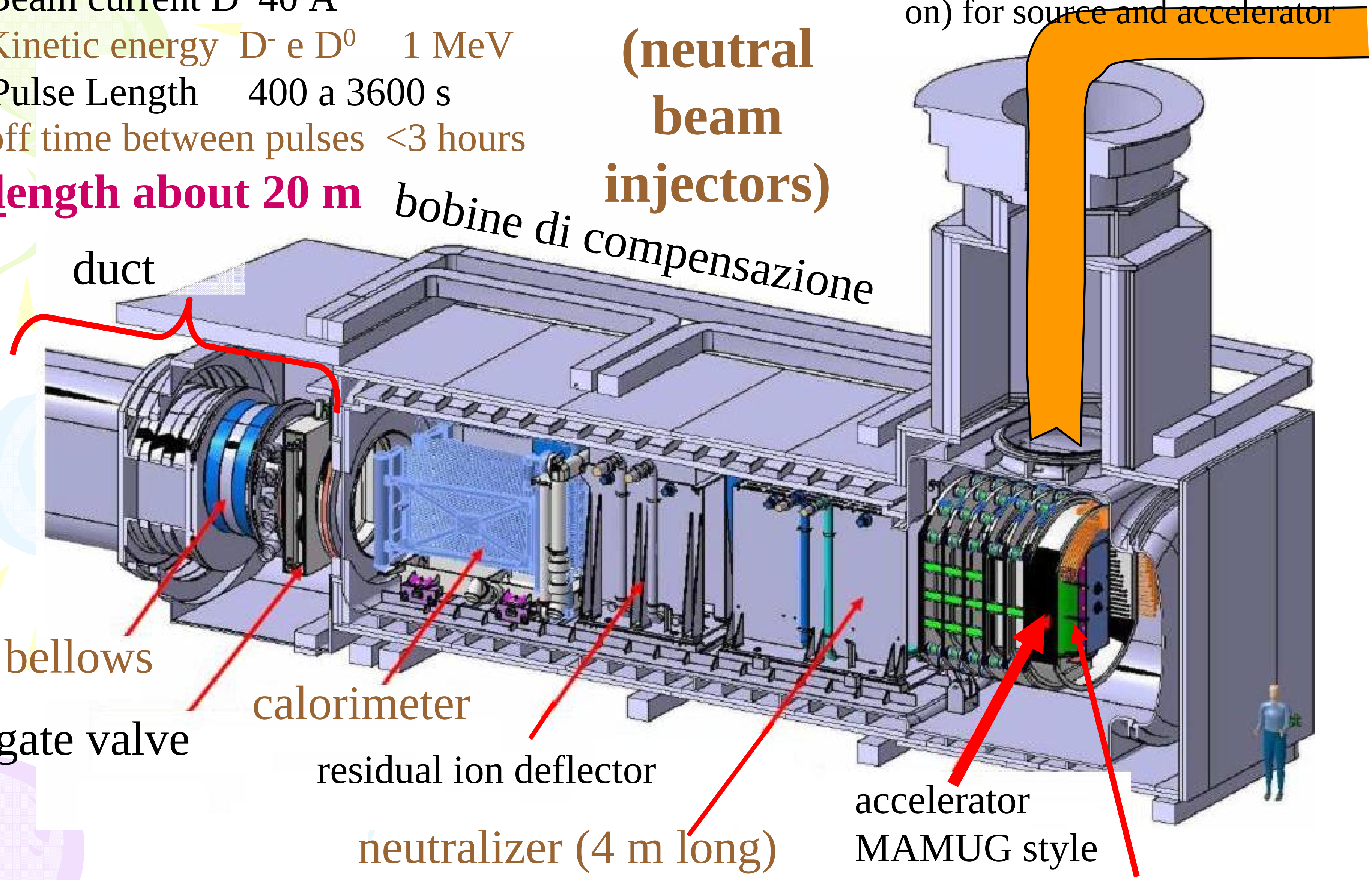
Material issues are divided into :

plasma facing power load (from α)

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

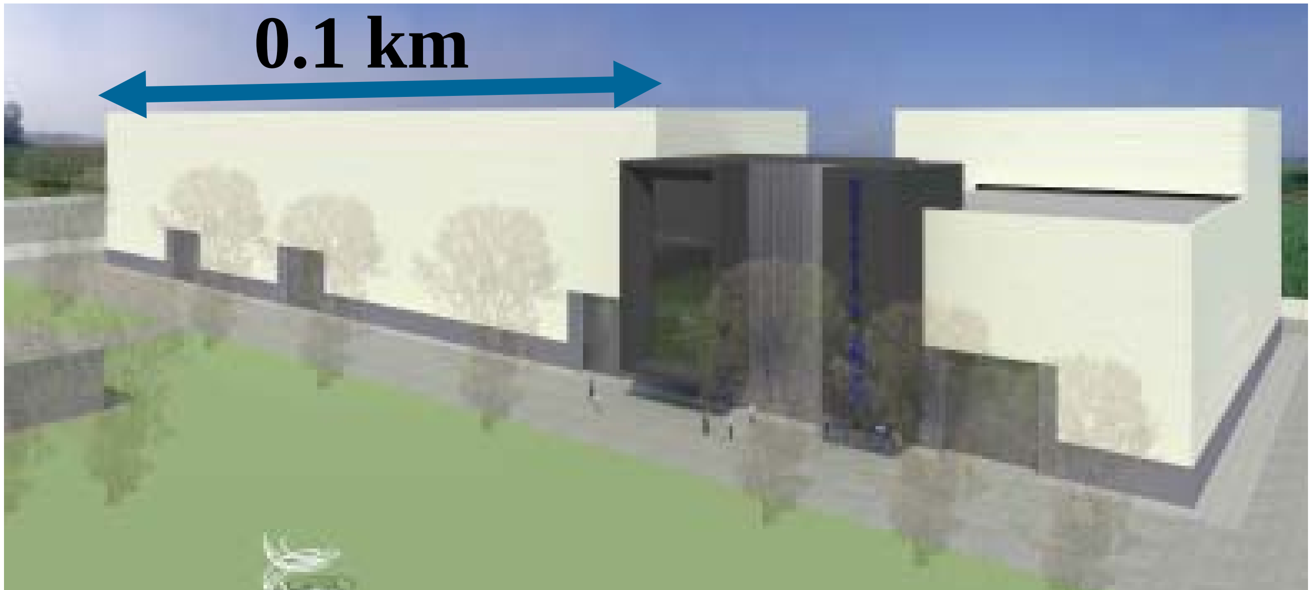
Beam current D^- 40 A
Kinetic energy D^- e D^0 1 MeV
Pulse Length 400 a 3600 s
off time between pulses <3 hours
length about 20 m

NBI (neutral beam injectors)



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)

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

MITICA = 1 MV/40 A beam

SPIDER = 100 kV/55 A system

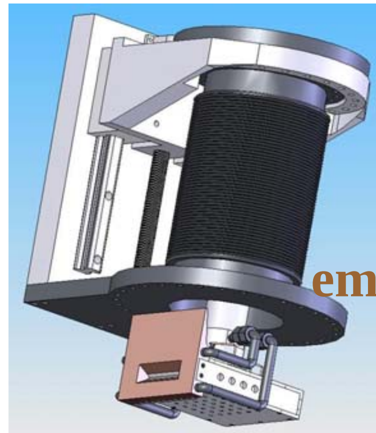
2) INFN contributions to NBI and NIBS development

NIBS =negative ion beam and source

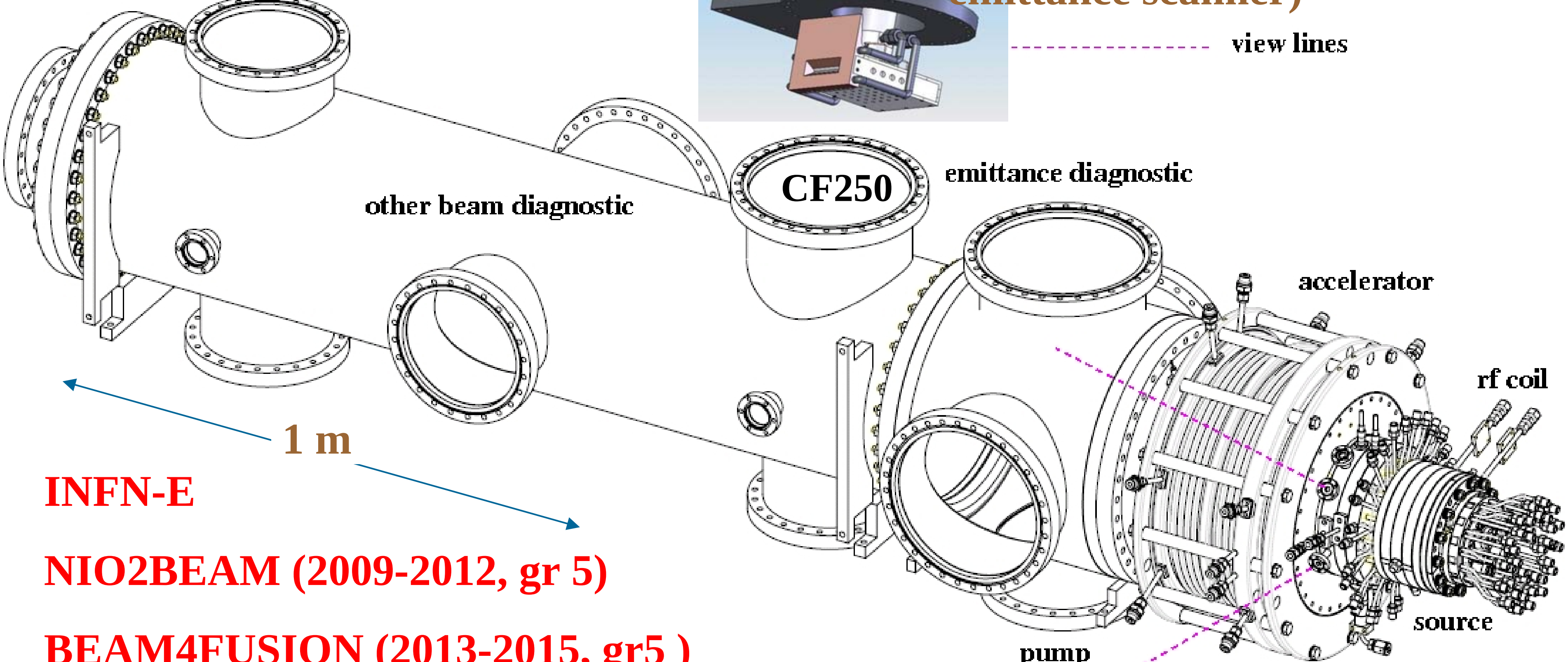
2.1) NIO1 + theory + beam detectors (here discussed)

2.2) neutron diagnostic

2.3) HV handling



FES (fast emittance scanner)



INFN-E

NIO2BEAM (2009-2012, gr 5)

BEAM4FUSION (2013-2015, gr5)

A versatile test ion source (NIO1, 130 mA, 60 kV, 9 beamlets) is under construction, together with a beam emittance meter for simulation validation (INFN+RFX)

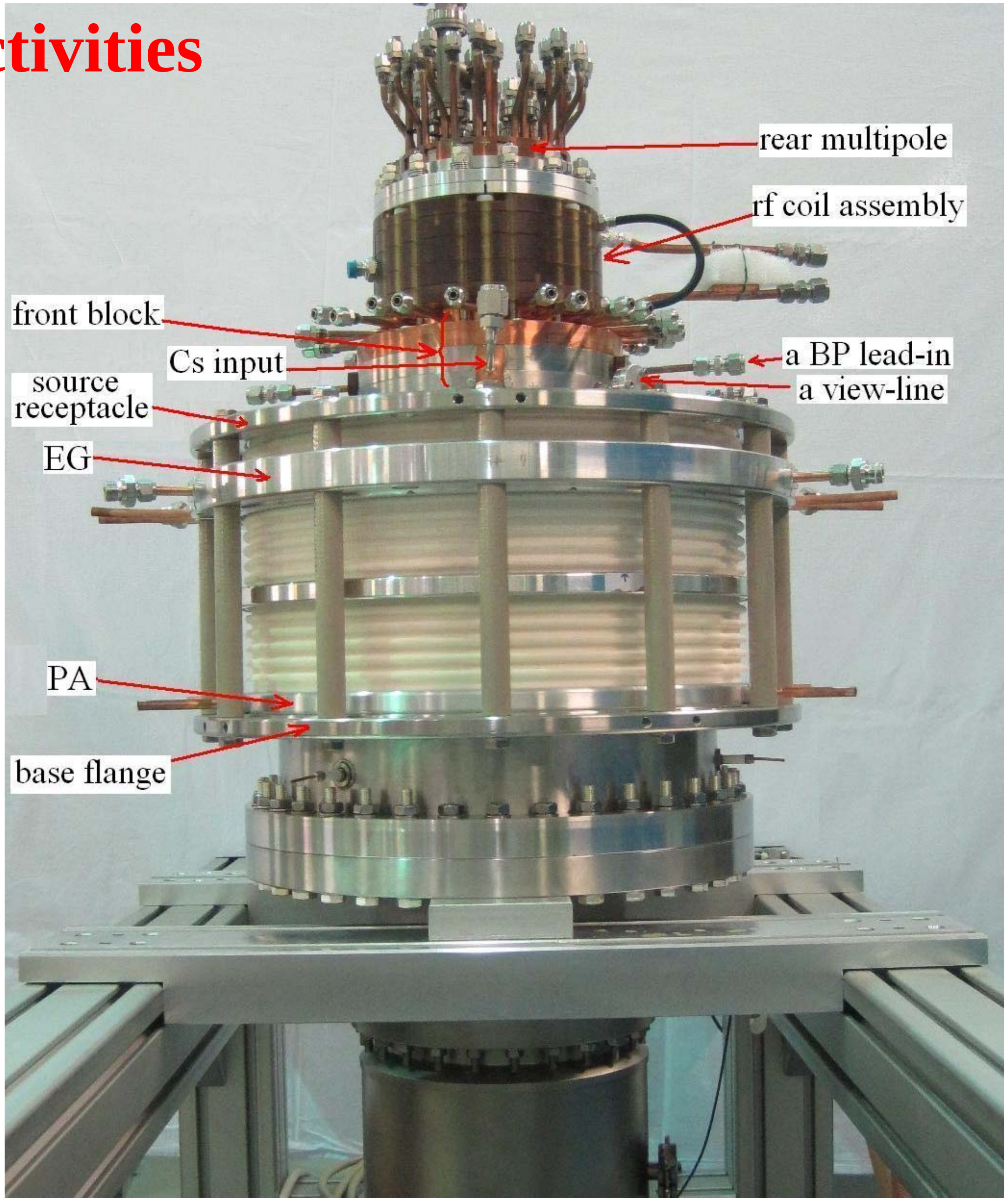
2.1) NIO1 and related activities

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 ('culla') completed in December 2013. Alignment in progress

Calorimeter/beam dump delivered to RFX in January 2014; under tests

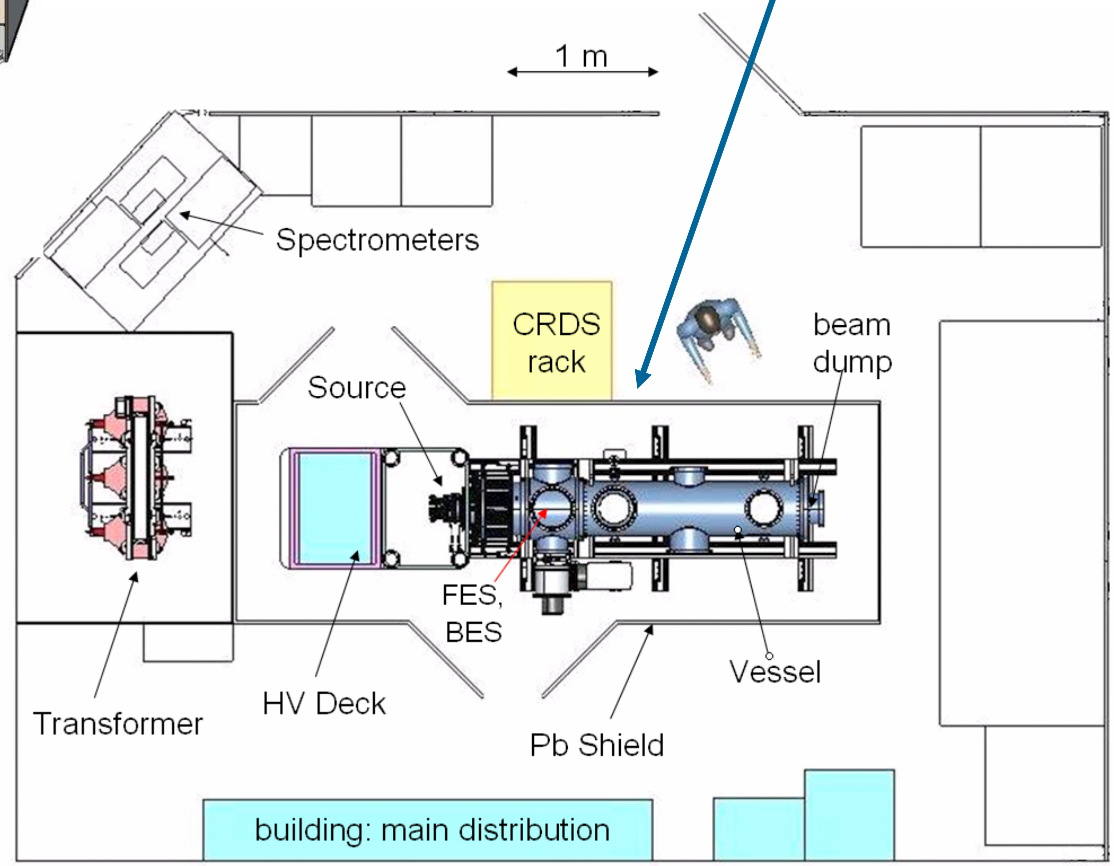


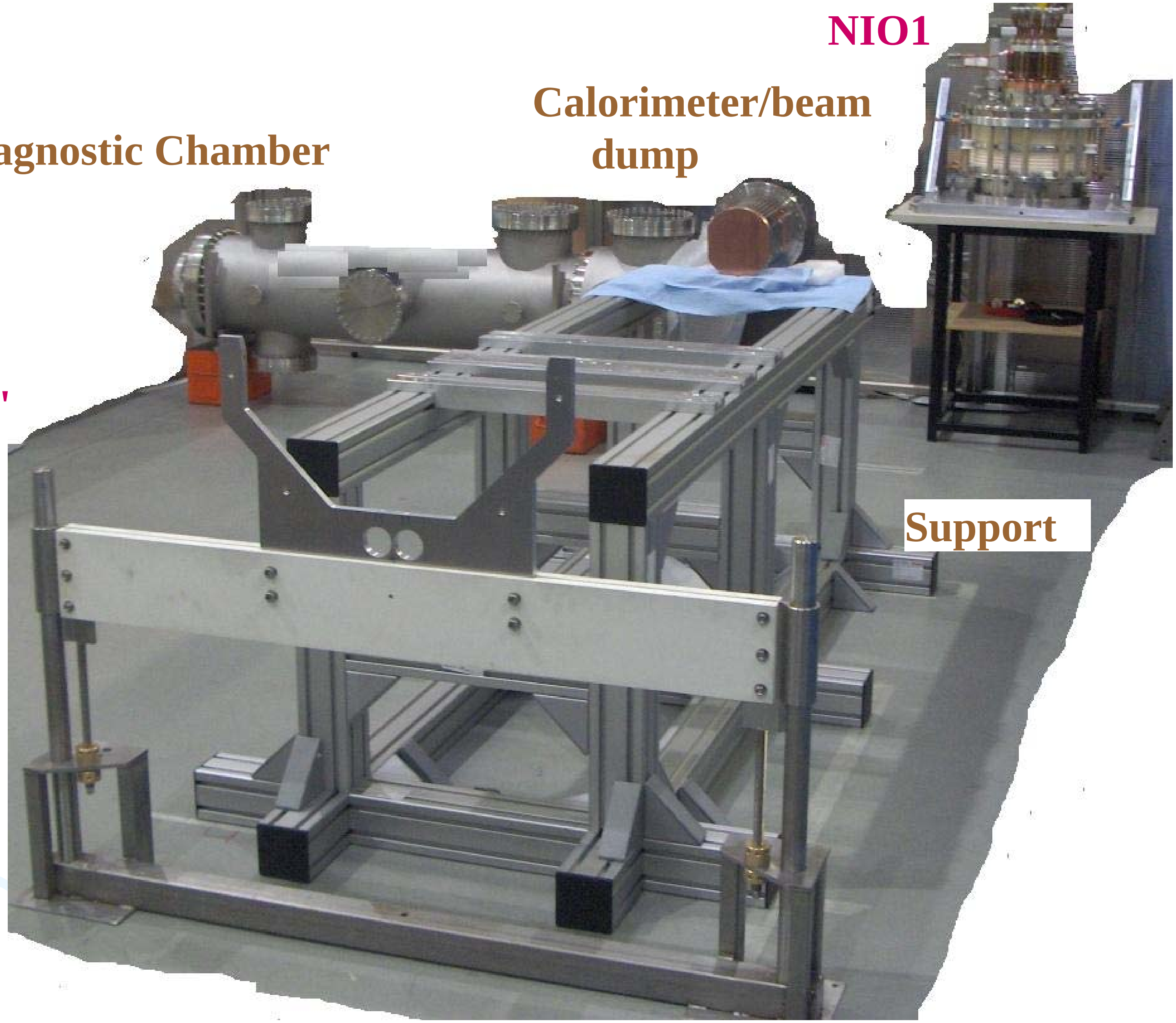
deck box

The source is cantilevered on the accelerating column: alignment techniques are being carefully optimized.

Shielding box

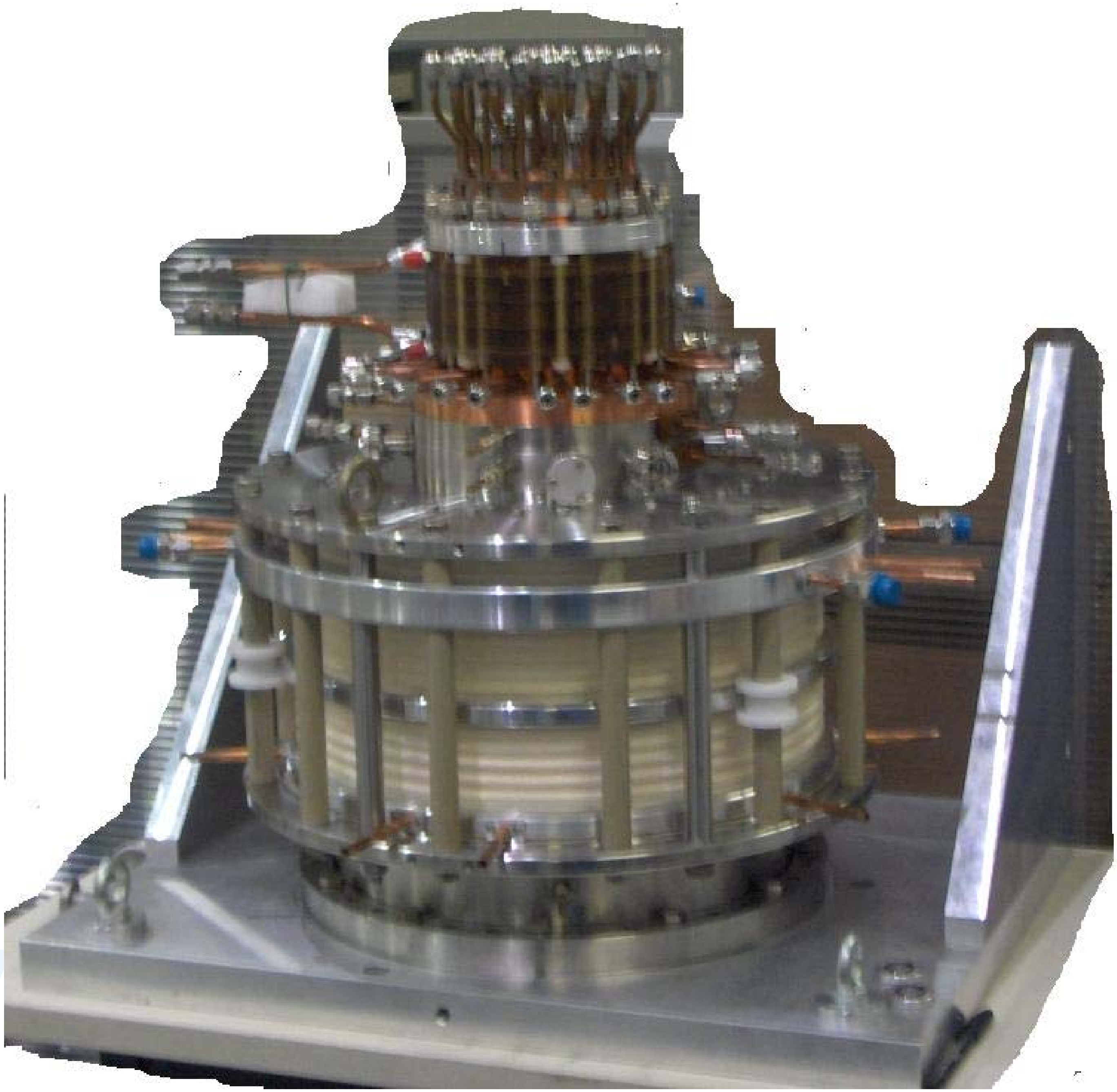
The -60 kV source terminal support mainly the rf machting box, the cable connection to the source and part of the optical lines; other larger HV equipments stay in the HV desk box

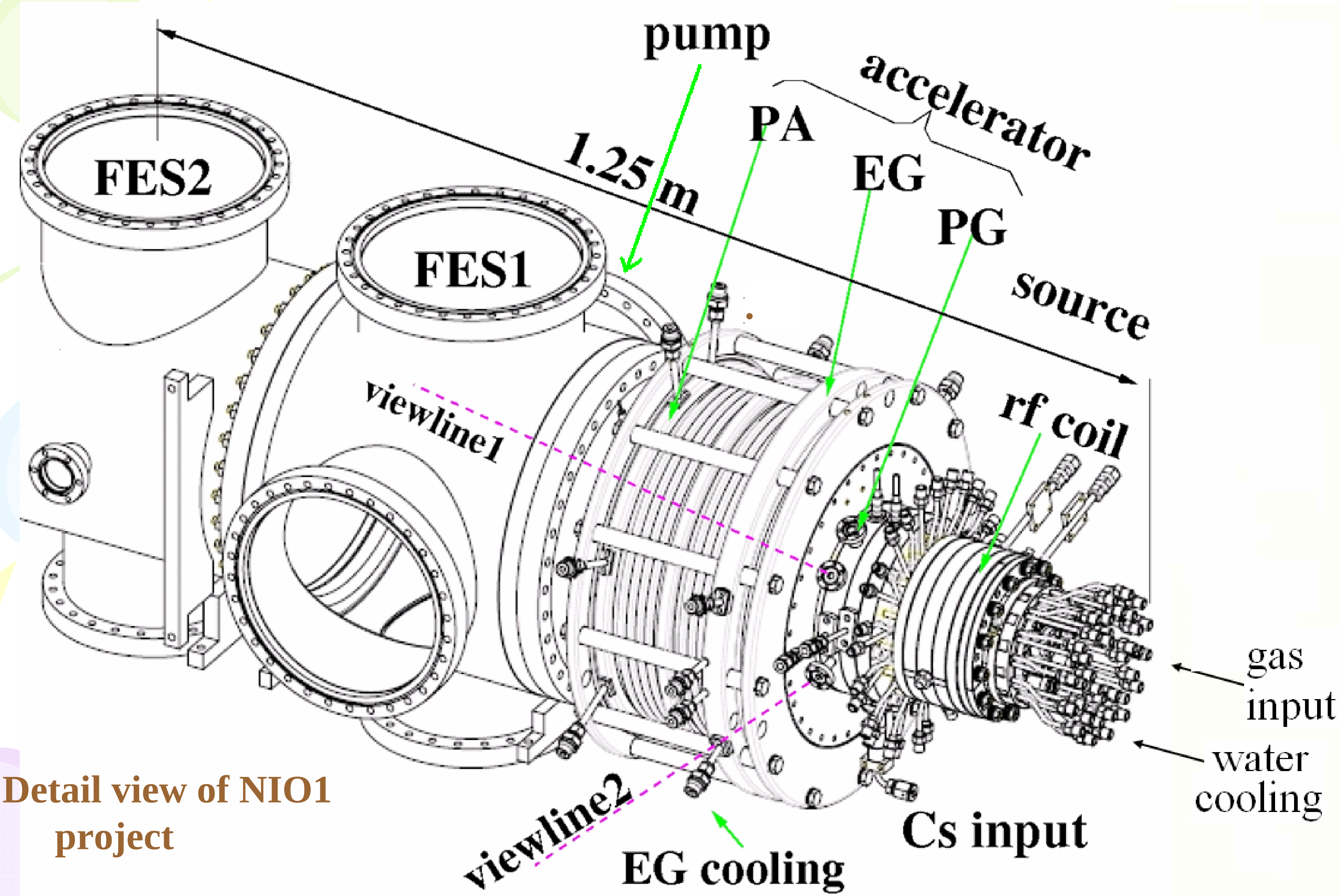




View of the NIO1 assembly area: note supports and beam dump are placed near their final position, while NIO1 and its diagnostic chamber are visible in the background

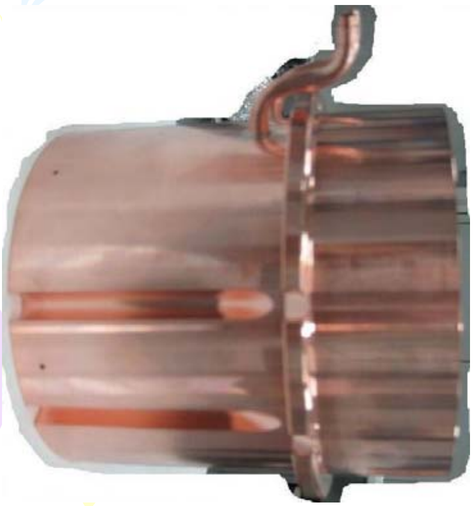
NIO1 after ceramic cleaning and realignment, as mounted on the assembly tool

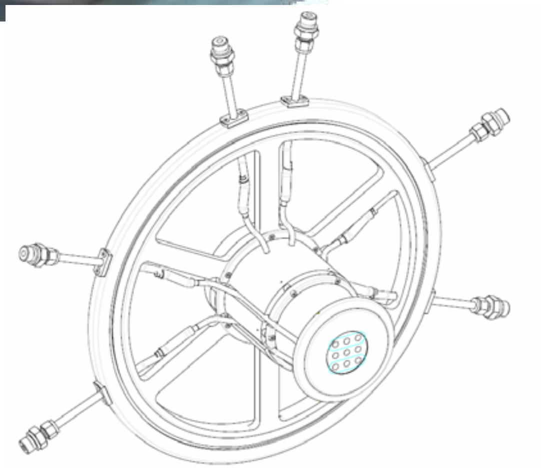




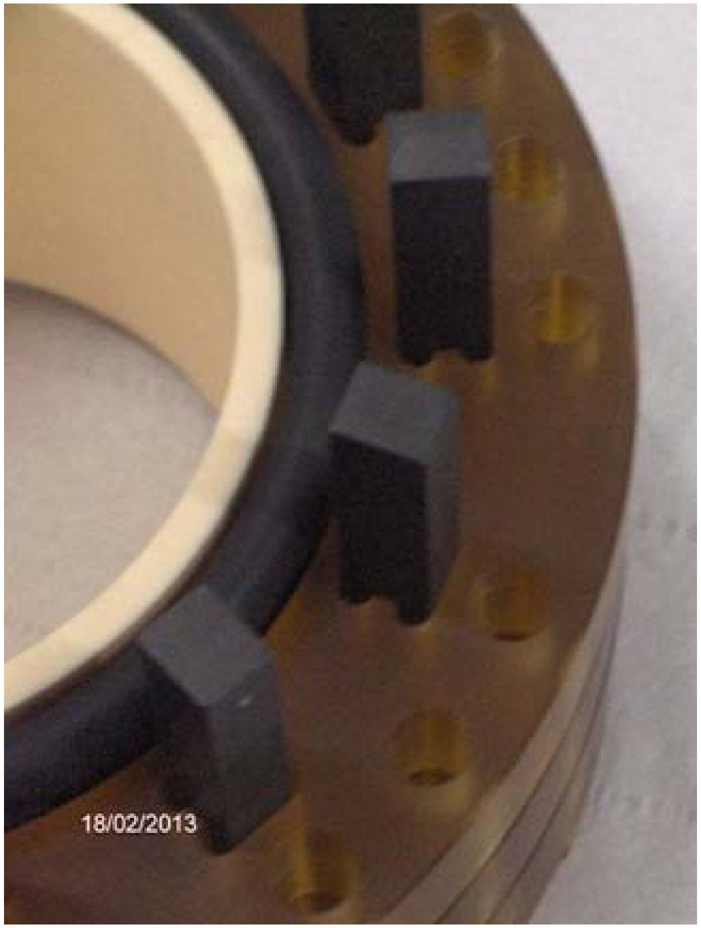
Detail view of NIO1
project

Inside NIO1: mastering the electrodeposition cooling channel construction



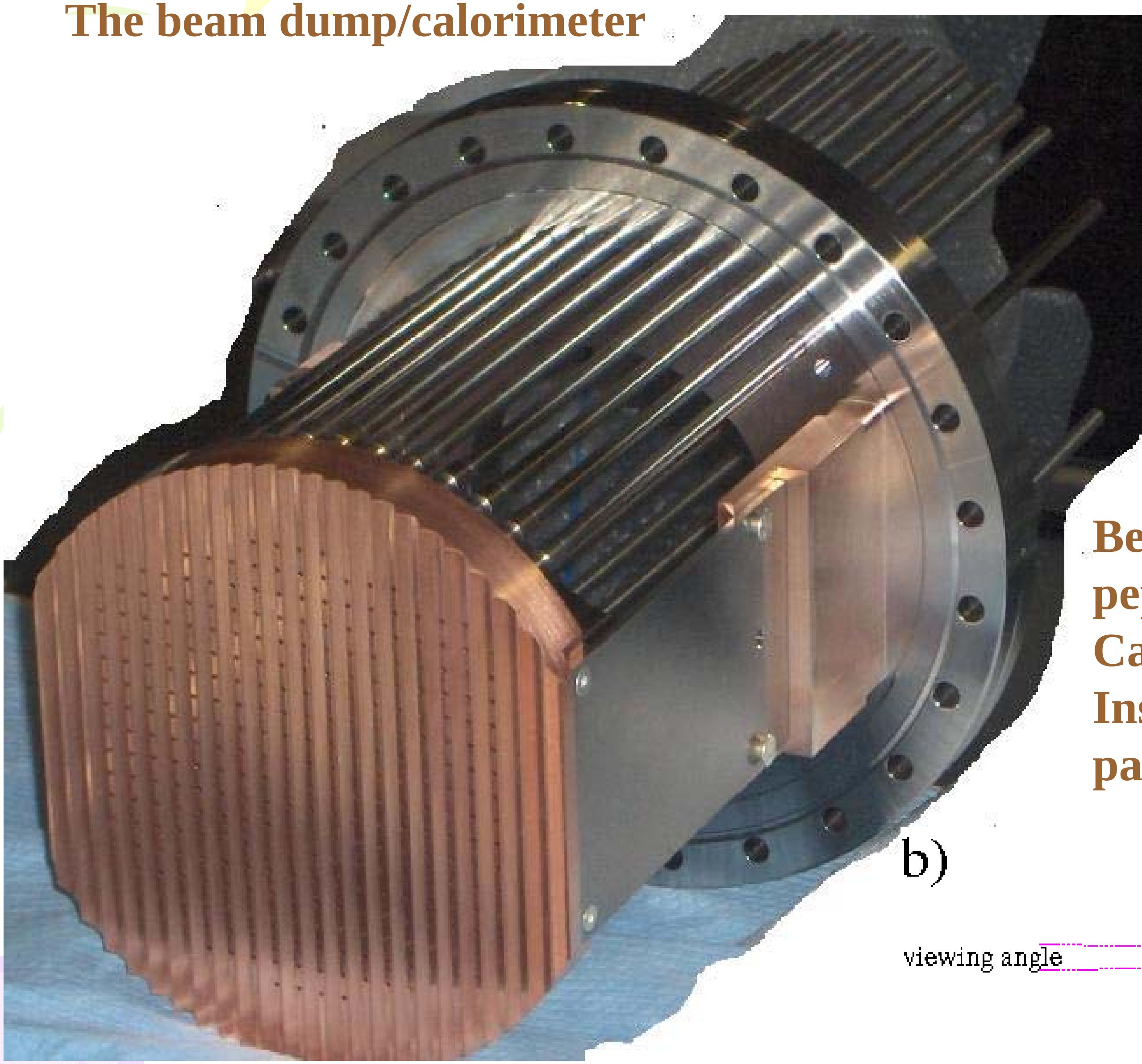


The post acceleration grid

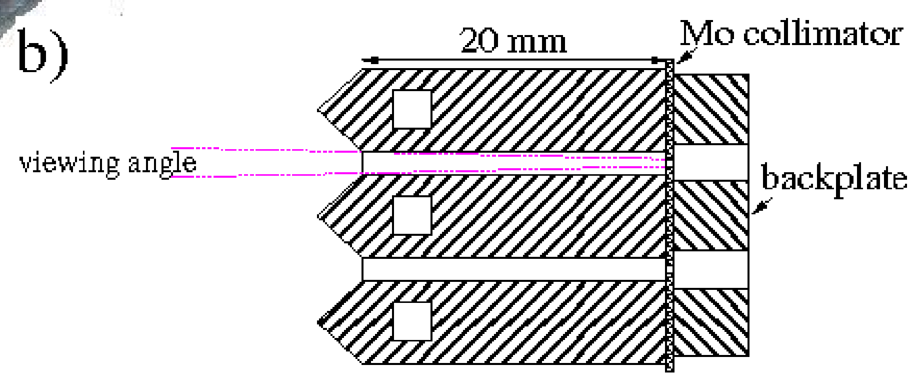


The rf coil assembly, featuring the ferrite confinement magnet

The beam dump/calorimeter

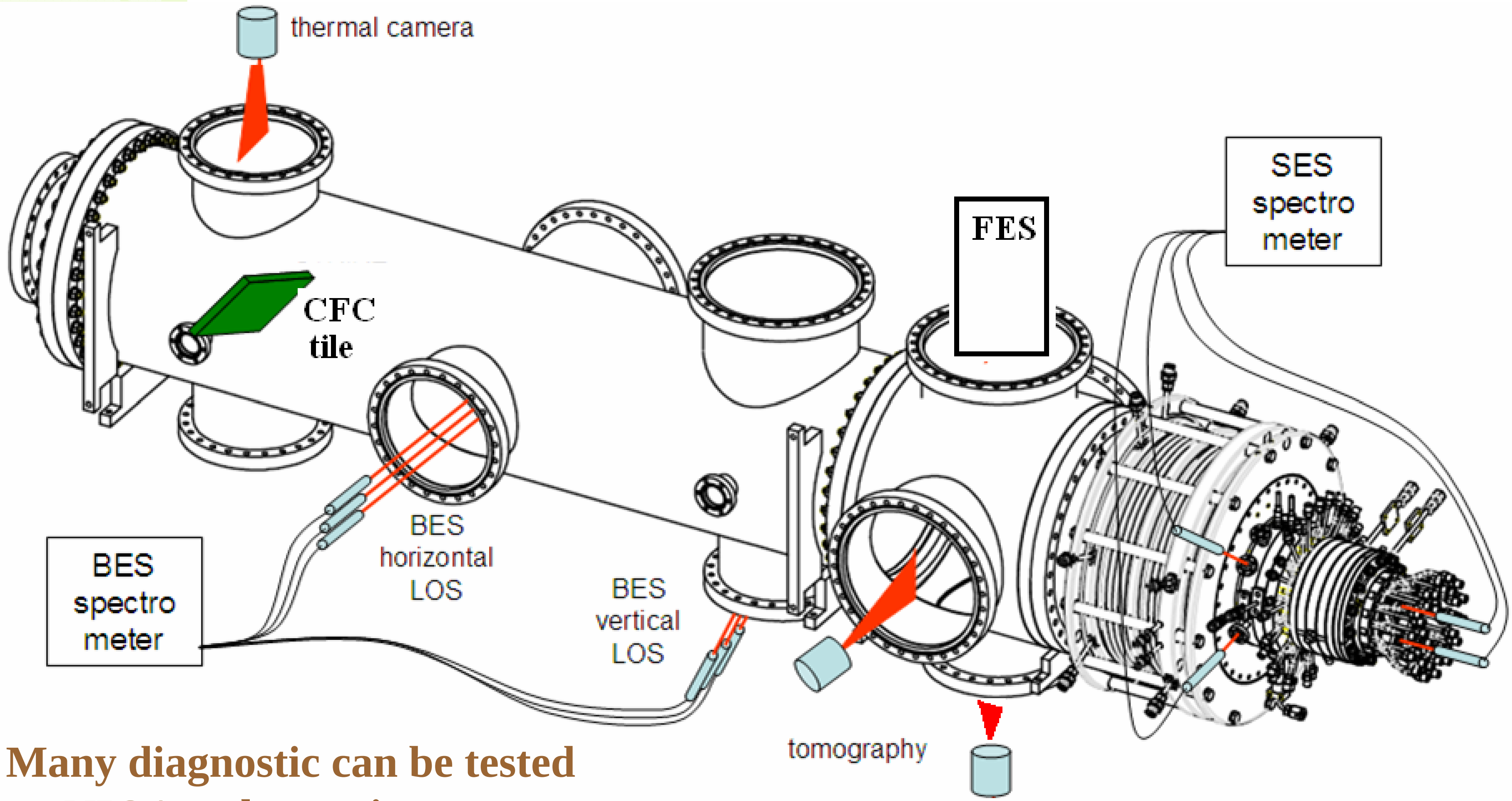


Beam dump: scheme of pepper pot extension (see Cavenago et al, Rev Sci Instrum, online 18 Oct 2013, paper vol 85, 02A704 (2014))



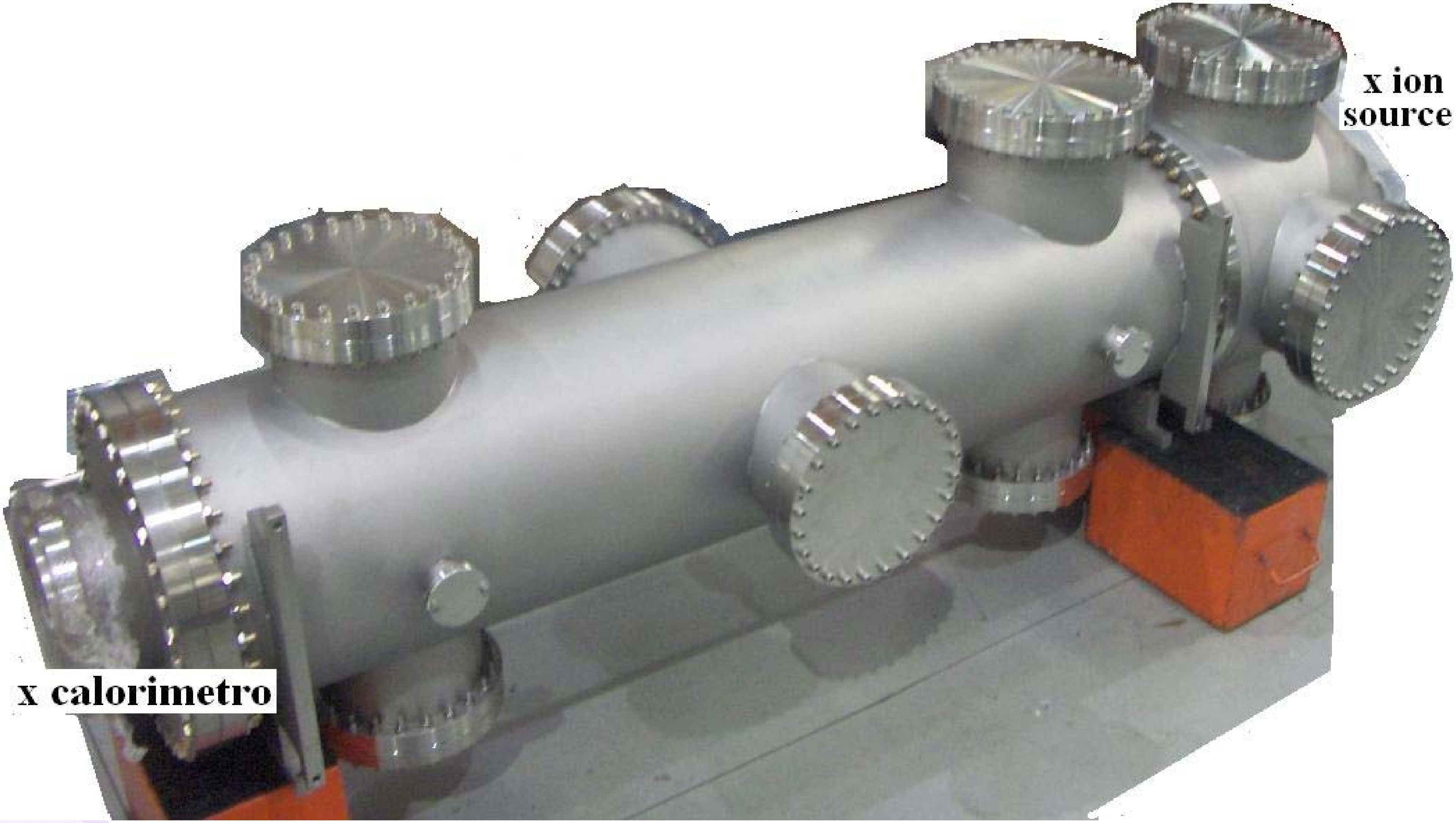
Beam dump/calarimeter

The NIO1 optical diagnostic and calorimetry scheme

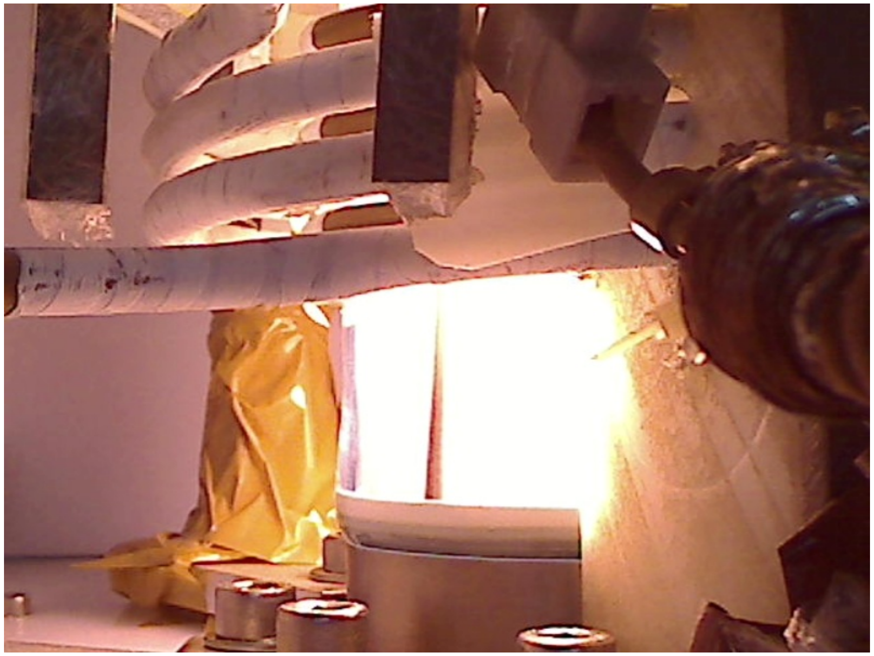


Many diagnostic can be tested on NIO1 and experience shared with SPIDER: BES, CFC tile, etc

Fiber optic diagnostic is simpler to install



The beam diagnostic chamber



Examples of radiofrequency plasma (gas: air) for tests of amplifier and matching box: **Transition between plasma regimes finally happens (p order of 5 Pa, power from 200 to 350 W) . A true-2-Megapixel webcam was used; autofocus still on. Next step is comparison without Faraday cage. Transition seems related to an impedance jump**

3)Recent theoretical studies

Motivation: megawatt beam need precise* aiming

3.1) Optimization of Extraction Grid deflecting magnetic fields (completed July 2013, mostly to be published)

3.2) Pic code for NIO1 accelerator geometry (reported 2013 ICIS)

3.3) Laminar and Vlasov studies of realistic ion extractors (that is, with anode lens effect treated in non-linear and selfconsistent way); reported ICIS (Tokyo, September 2013), SIF (Trieste, September 2013) and Vlasovia (Nancy, November 2013); partly published

3.4) Space charge compensation

3.5) Multi-grid optics (that is. SPIDER, MITICA, NIO1)

Some detail of item 3.3 only follows:

3.3) Beyond 'the moderately converging ion flow'.

A standard design of ion (and electron Pierce 1954) source extractor envisions a conically converging ion flow; convergence is stopped by the anode lens effect: th design assumes that space is exactly balanced by electrode shaping

A new model (Cavenago, Rev. Sci. Instrum, 83, 113301, 2012) was proposed which allows some tapering of beam, due to space charge effect even before anode, where the usual anode lens effect is added. Predictions for perveance/beam divergence were fully worked out (with help of symbolic computation)

113301-2 M. Cavenago Rev. Sci. Instrum. **83**, 113301 (2012)

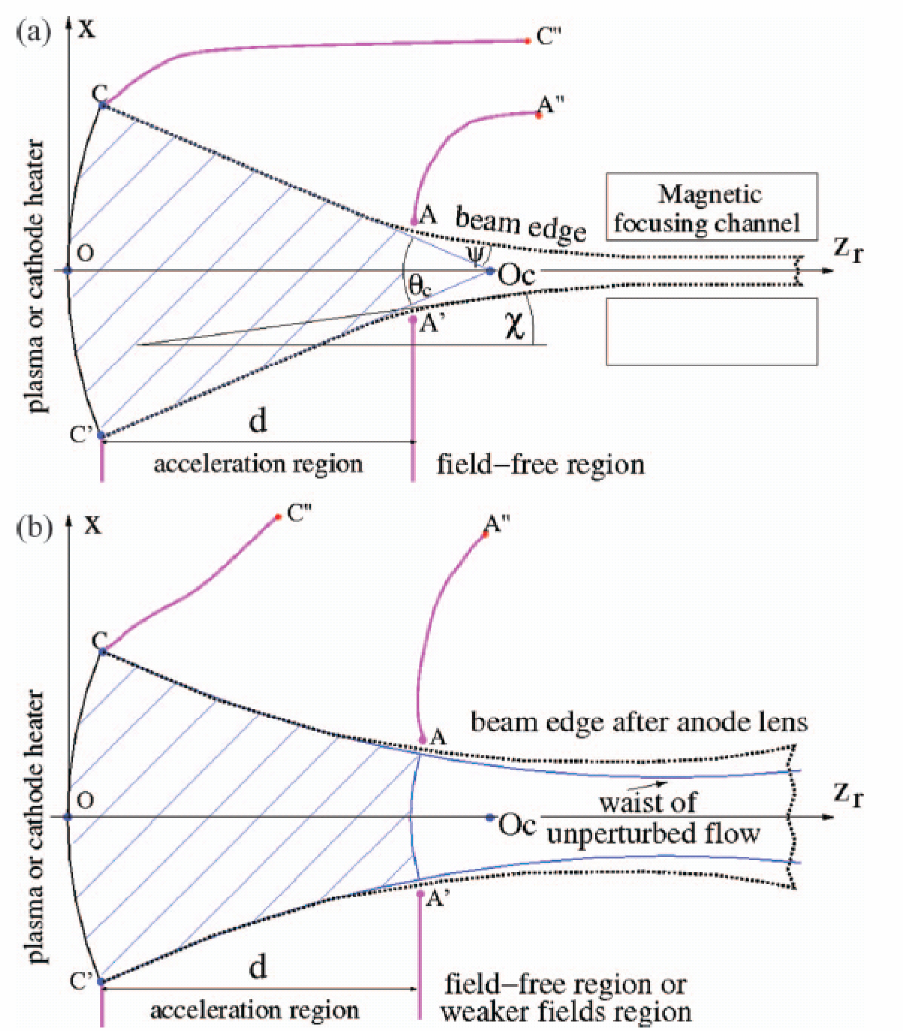


FIG. 1. (a) Scheme of strongly convergent flow (solid line); flow perturbed by anode lens effect also shown (dotted line) and (b) scheme of a moderately convergent flow.

reprinted from shown Ref., c. AIP

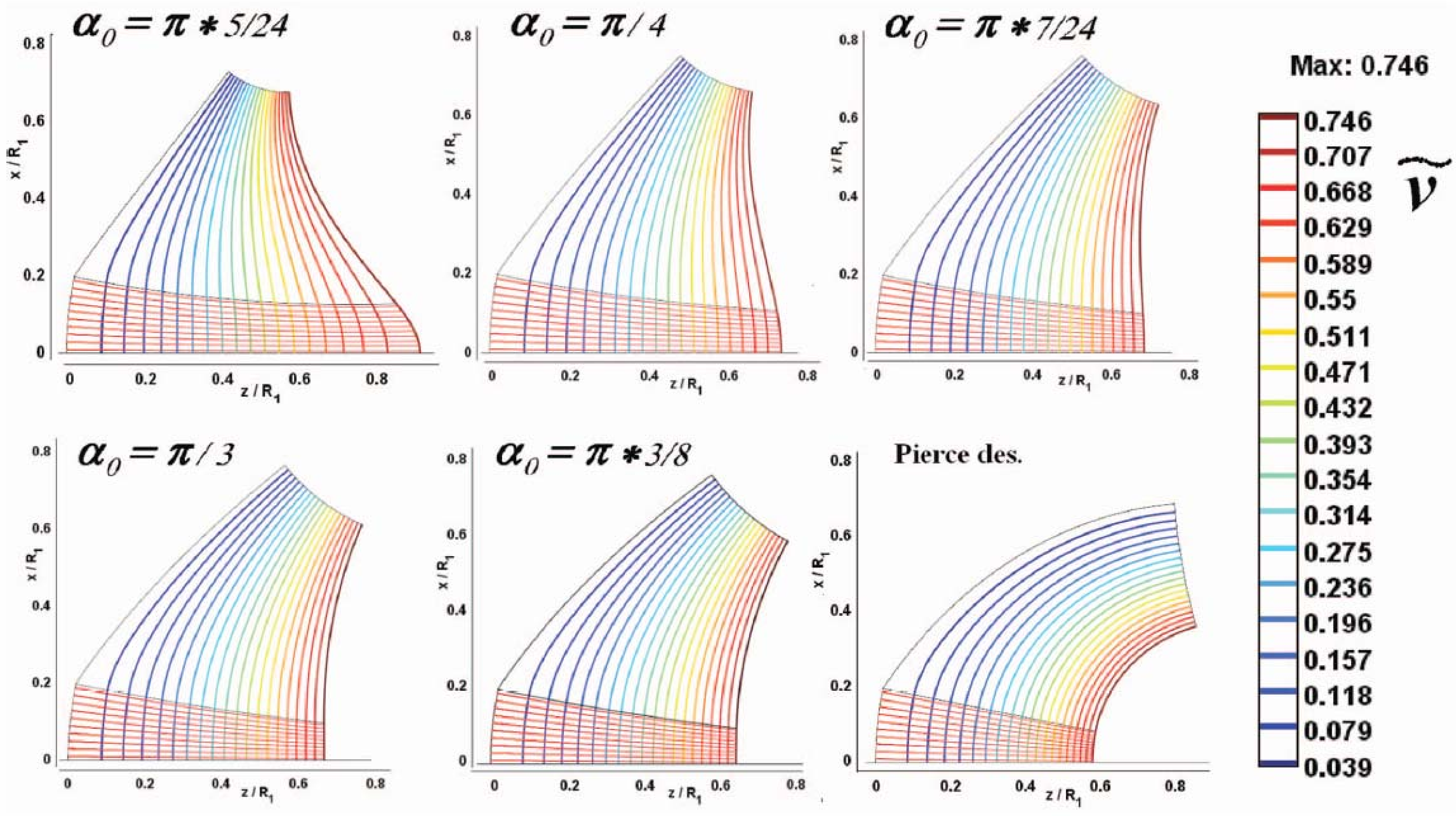


FIG. 18. Simulation results for $\tilde{v}$ equipotentials and test particle trajectories, while α_0 is increased in steps of $\pi/24$, as labelled. Fixed parameters: Cathode half span $\theta_c = 0.2$ rad and anode rescaled voltage $\tilde{v}_a = 0.7465$. Pierce design is also shown.

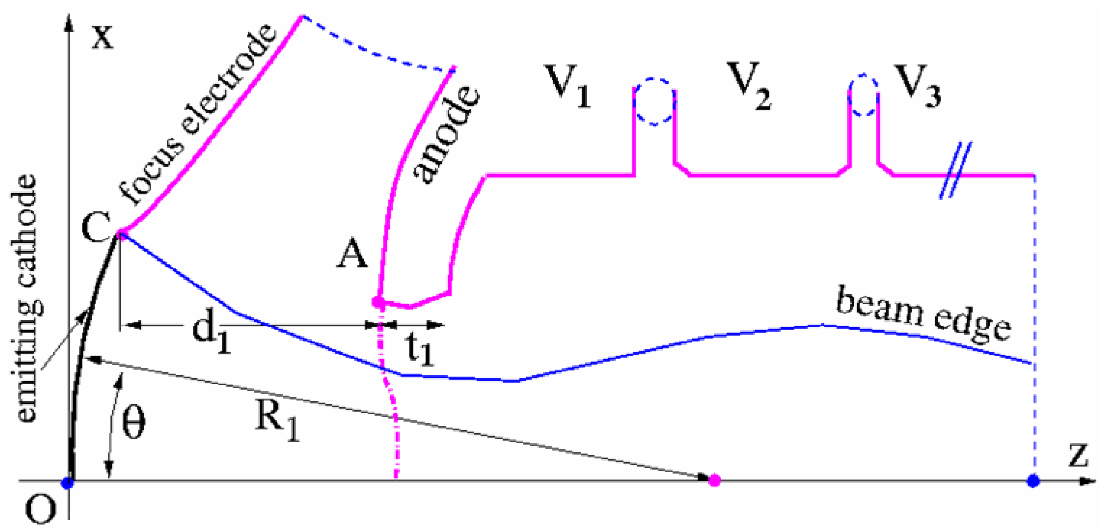
Rev. Sci. Instrum. **83**, 113301 (2012)

Electrode shape is now adjustable by so called compression parameter α_0, and is here compared to fixed Pierce design

3.3.2) Real extraction systems:

The previous theoretical models solve singularity at cathode ($\tilde{v} = 0$) and predict anode (2nd electrode) shape.

But in real extraction system we find more than two electrodes; moreover beam is perturbed when passing through the anode aperture [Davisson, 1931; Birdsall, 1957]



Laminar coupled flow equation can be still efficiently solved with moving mesh method

Mesh deforms to follow beam

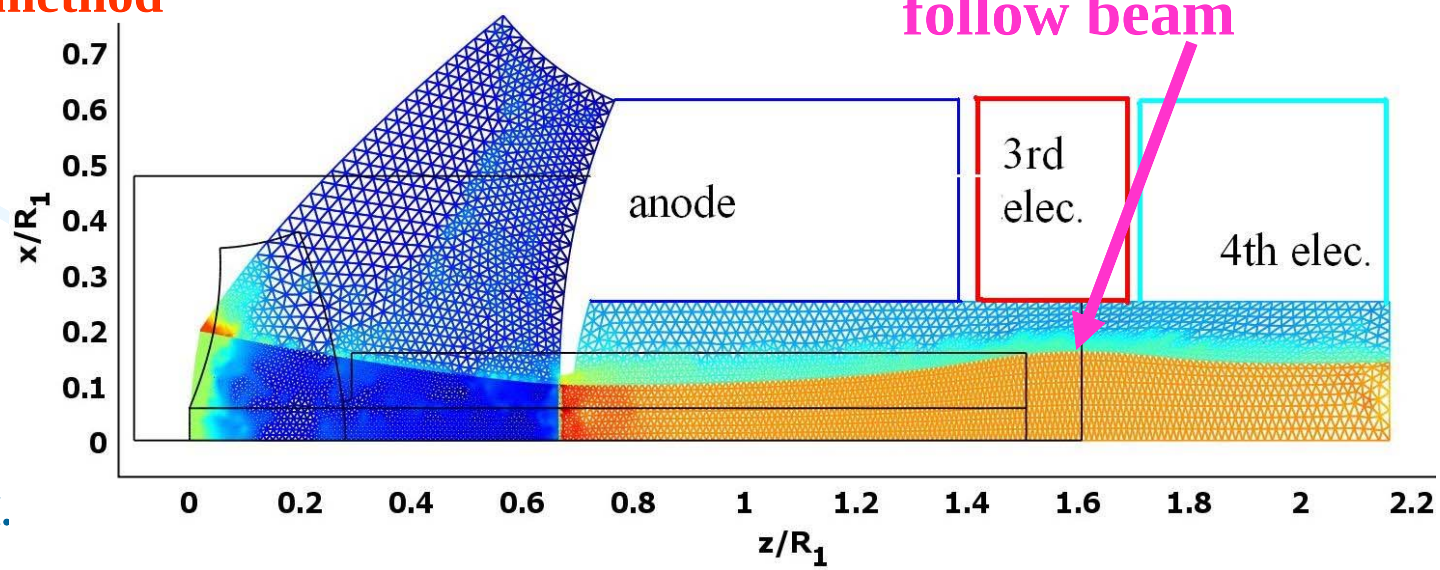


Figure: Mesh wireframe rendering; beam edge and other borders are evident from color change

M.

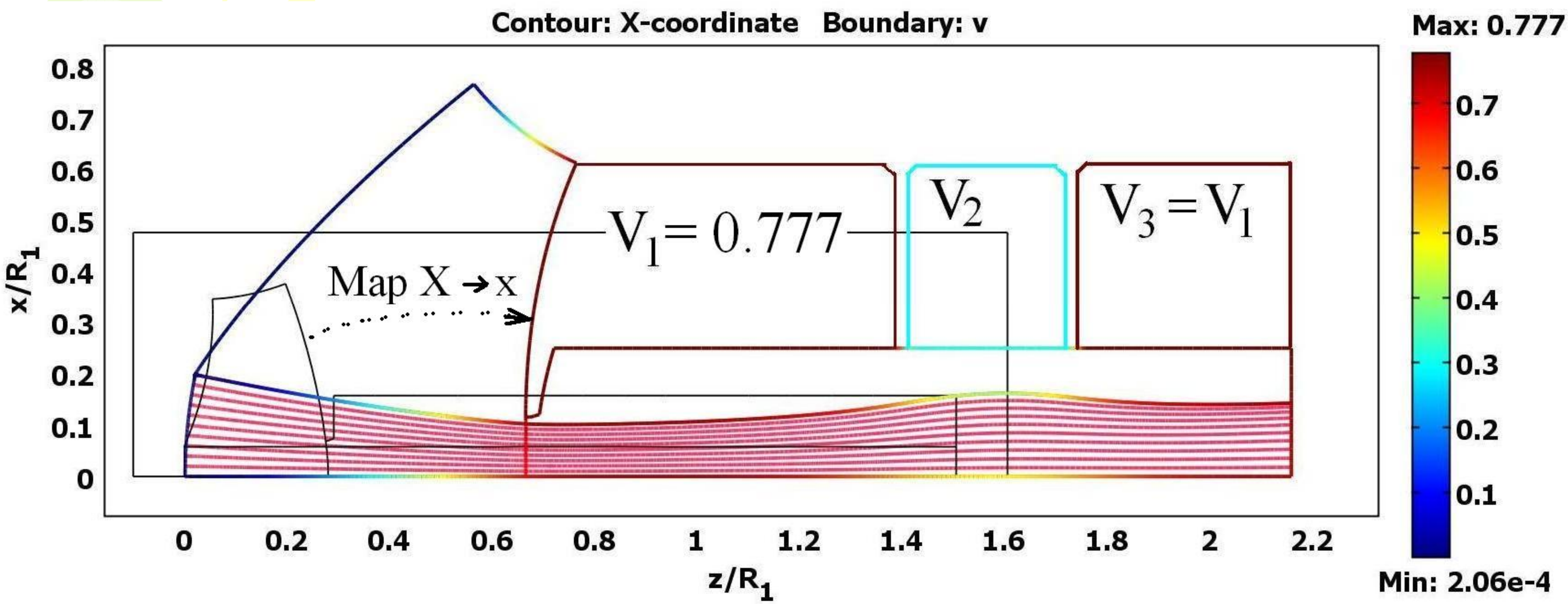


Figure: Tracing of flow lines, which coincide with coordinate X contour lines. Potential at boundary also shown; in this tetrode $V_2 = 0.4 * V_1$

2.5.2) Plasma-beam interface can be also taken into account, as discussed elsewhere [Taccogna, 2013; Benilov, 2009; Forrester, 2000; Lieberman, 1994]; corrections to ion energy are typically in the T_e+T_i order (few eV)

3.3.3) Ion temperature effects (<u>in the infinite number of rays limits</u>):

T_i is ratio between ion temperature T and extraction energy Ke; for example:

Ke=20 keV

T ranges from

T=0.1 eV

T_i= 5e-6

to

T= 0.5 eV

T_i= 2.5e-5

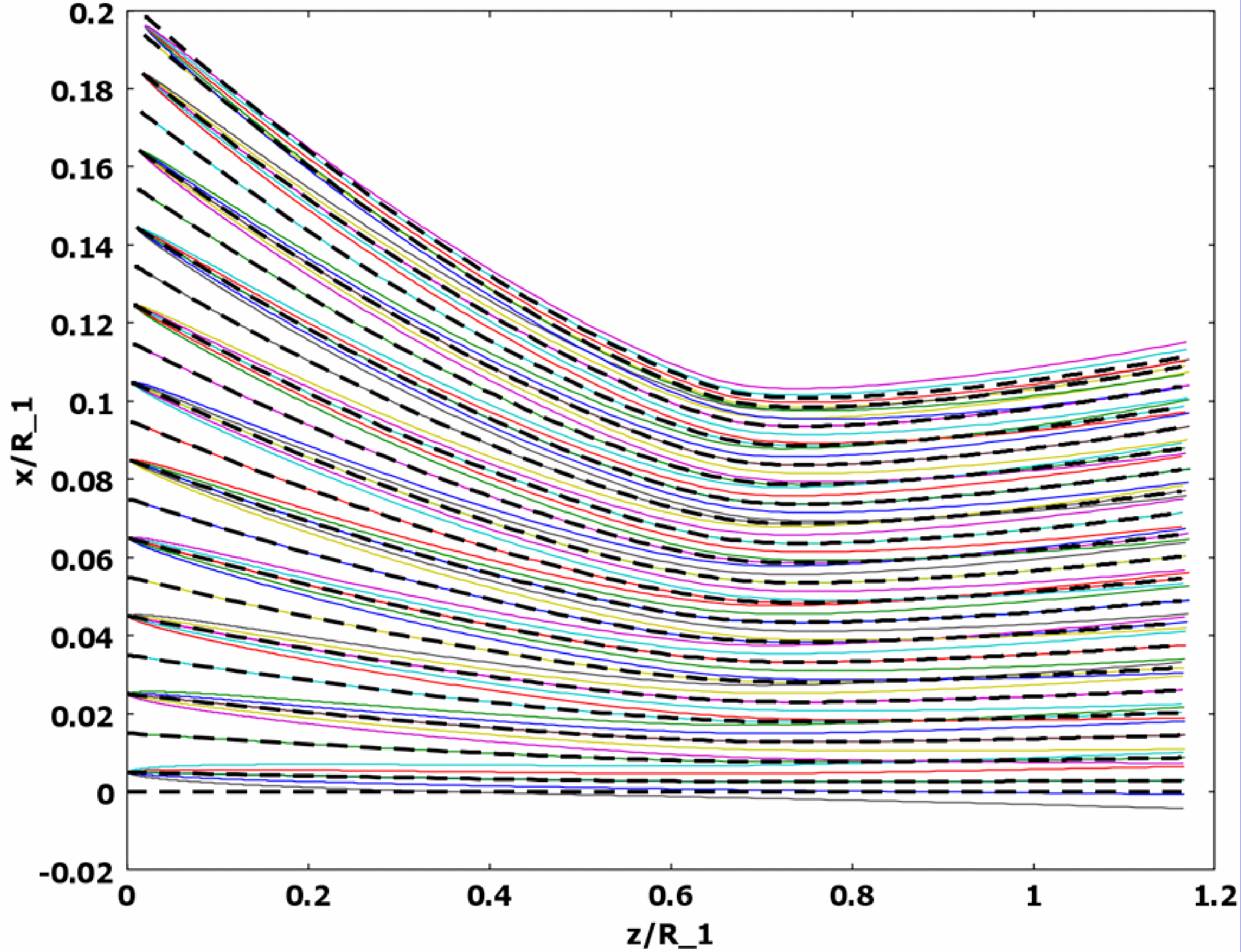


Fig 5 in z,x plane: thick dashed lines: laminar flow pattern (determining Z,X); thin solid lines, trajectories for Ti =5*10^{-6}

Ion temperature effects (follow):

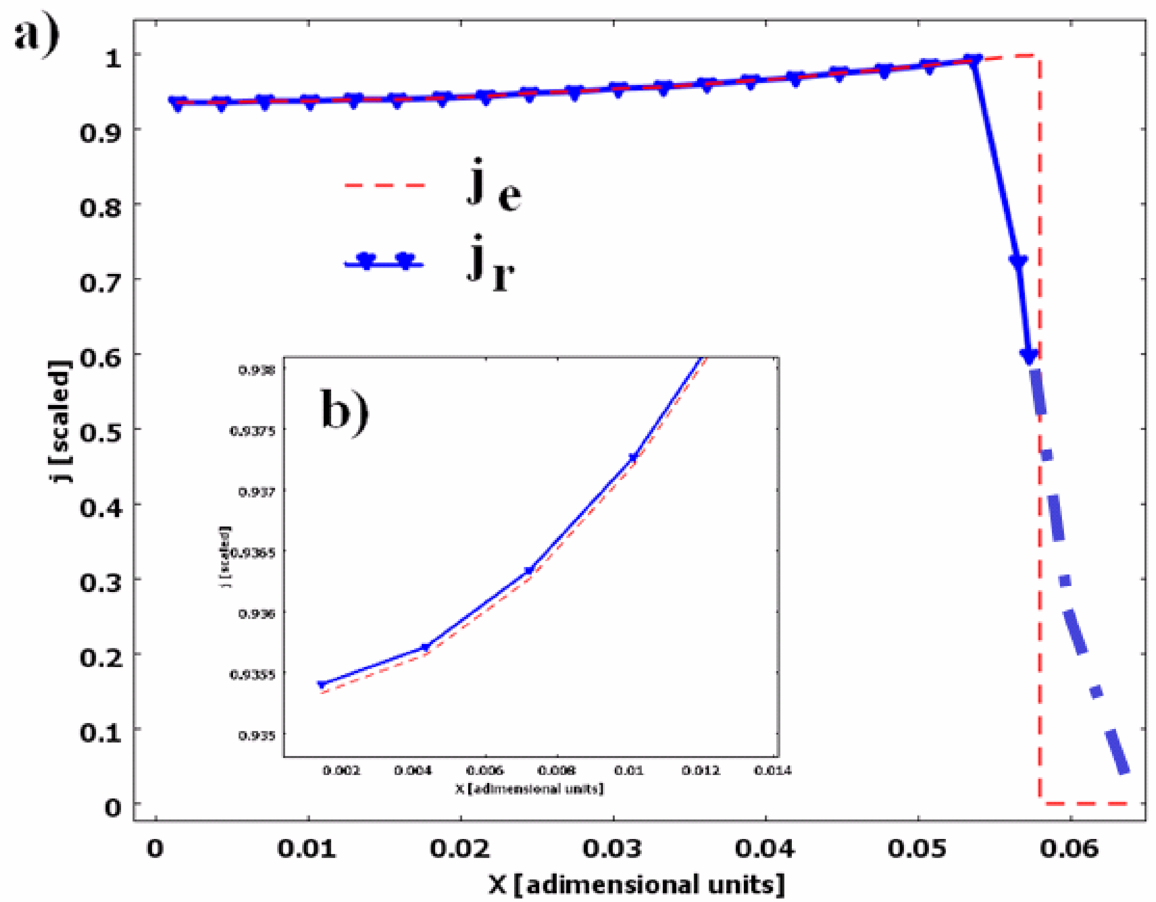


Fig 7 a) Preliminary calculation of diffused profile j_r with Z near simulation end, about 2.5 that is z=1.11 R_1, and T_i =5*10^{-6} (solid line with markers; halo guess dot-dashed) and comparison with emitted profile j_e (dashed line); they practically differ only at border. Inset b) Zoom shows the small effect of T_i on beam center

4) Conclusions

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

A survey of NIO1 design, of related code development and of experimental R&D was given.

Start of NIO1 mounting and commissioning; vacuum problem solved

Diagnostic for NIO1 is developed in synergy with other source diagnostic

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

Thank you for attention

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