Source H^- du LINAC4 au CERN: Modélisation plasma et extraction

DESY vol. source electron-dump @ 45 kV

2010: We must in ll
- *Measure & calibrate*
- *Model & simulate*
- *Produce & test*

- Au CERN, le Linac4, un nouvel injecteur linéaire H^- de 160 MeV, est en cours d'installation. Le Linac4 fait partie de l'amélioration du complexe d'accélérateurs prévue pour augmenter la luminosité du grand collisionneur de hadrons (LHC); il remplace le Linac2 qui a produit durant quatre décennies des protons de 50 MeV. Le plasma d'hydrogène de la source H^- est généré dans une chambre en alumina par couplage inductif avec un solénoïde alimenté par une radiofréquence de 2 MHz. Les ion H^- sont produits par *dissociation d'une molécule excitée de dihydrogène associée à un électron de basse énergie* ainsi que par échange de charge et réémission d'une surface de molybdène recouverte de césium et soumise au flux des composants du plasma d'hydrogène.
- Les modélisations et calibrations entreprises pour décrire la formation de faisceau H^- sont en cours, elles pour finalité l'optimisation de l'injection du faisceau H^- dans l'accélérateur quadripolaire à radiofréquence opéré à 352 MHz (RFQ). Les calibrations, modèles et codes de simulations ainsi que les méthodes expérimentales de validation des modèles de simulation du couplage inductif (NINJA), de la formation (Keio-BFX et ONIX) et de l'optique de faisceau (IBSimu) sont brièvement décrites. L'amélioration de la résolution et des conditions aux limites devrait permettre, en couplant les résultats des simulations, d'obtenir une description du faisceau pouvant être directement comparée aux mesure de profil et d'emittance.

H^- ***Volume*** prod.
M. Bacal

H^- ***Cs-surface*** prod.
Y. Belchenko
G. Dimov
V. Dudnikov

Linac4 IS Collaborations	
IPP Garching	U. Fantz, S. Briefi, A. Hurlbatt, D. Wunderlich, F. Bonomo
University of Jyvaskyla	O. Tarvainen, T. Kalvas
SNS	M. Stockli, R. Welton, B. Han *et.al.*
KEIO University	A. Hatayama 畑山明聖 K. Hoshino, K. Miyamoto
LPGP Orsay	T. Minea
ISIS	D. Faircloth
BNL	J. Alessi, A. Zelenski
J-PARC	A. Hueno

Thank you ☺

CERN

J.P. Corso, J. Coupard, M. Wilhelmsson, F. Fayet, D. Steyeart, E. Chaudet, Y. Coutron, A. Dallocchio, P. Moyret, S. Mathot, Y. Body, R. Guida, P. Carriè, A. Wasem, J. Rochez, D. Aguglia, D. Nisbet, C. Machado, N. David, S. Joffe, P. Thonet, J. Hansen, N. Thaus, P. Chigggiato, A. Michet, S. Blanchard, H. Vestergard, M. Paoluzzi, M. Haase, A. Jones, A. Butterworth, A. Grudiev, R. Scrivens, M. O'Neil, P. Andersson, S. Bertolo, C. Mastrostefano, E. Mahner, J. Sanchez, I. Koszar, U. Raich, F. Roncarlo, F. Zocca, D. Gerard, A. Foreste, J. Gulley, C. Rossi, G. Bellodi, J.B. Lallement, M. Vretenar, A. Lombardi, S. Intoudi, N. Houet, B. Teissandier, C. Charvet

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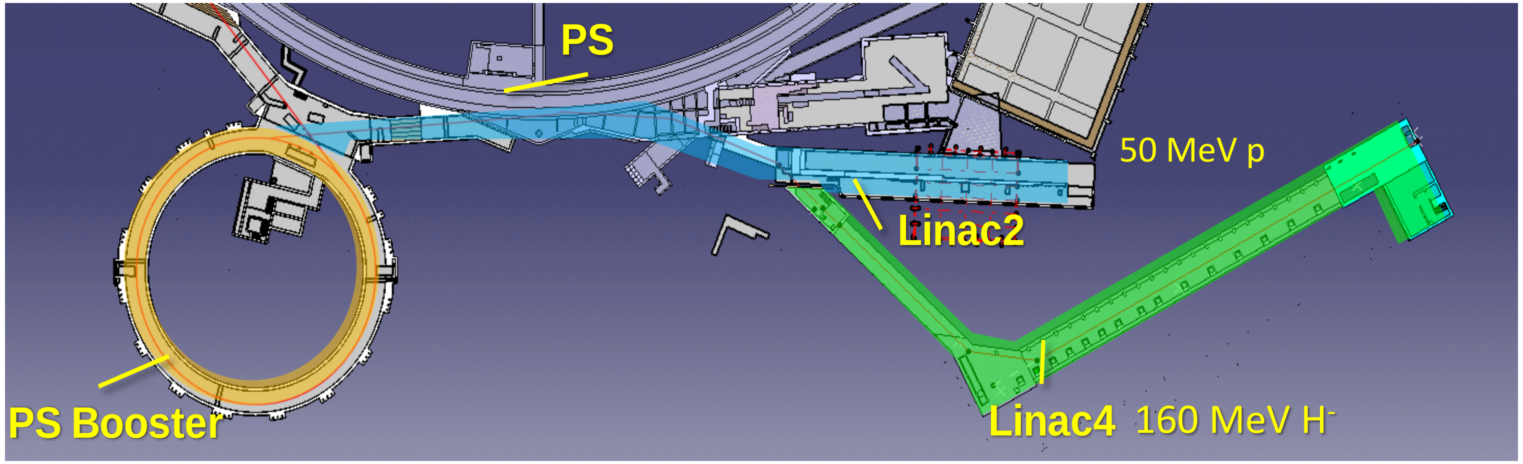
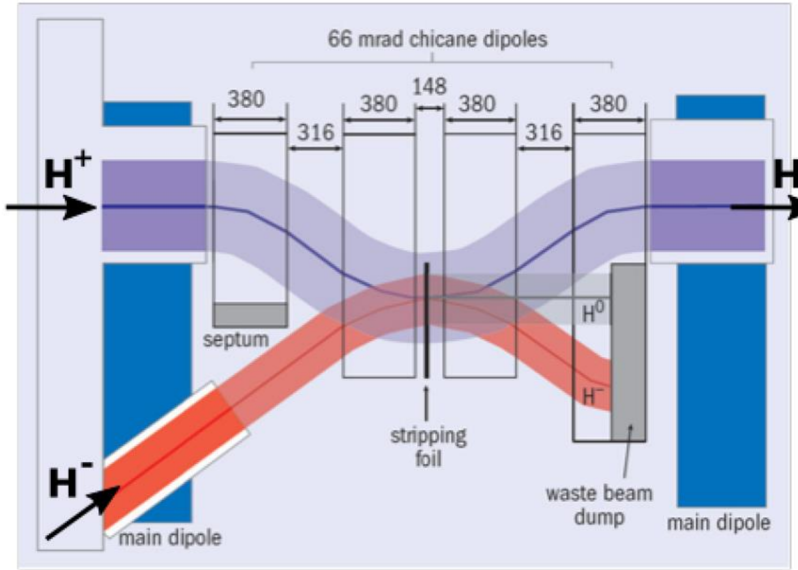
Daniel	Fink	Fell.	
Jose	Sanchez	Dipl, Tech-Fell.	
Jaime	Gil Flores	Tech-Fell.	
Stefano	Mattei	PhD.	
Daniel	Noll	Fell.	
Chiara	Pasquino	Tech-Fell.	
Cristhian	Valerio	PhD.	
Sylvia	Izquierdo	Tech-Fell.	
Mahel	Devoldere	Tech-Fell.	
Ana	Vnuchenko	Fell.	
Marco	Garlasche	Fell.	
David	Rauner	Phd.	Uni. Augsburg
Serhiy	Mochalsky	Fell.	LPGP Orsay
Taneli	Kalvas	PhD.	Jyvaskyla Univ.
Masatoshi	Ohta	太田雅俊	Keio Univ.
Masatoshi	Yasumoto	安元雅俊	
Kenjiro	Nishida	西田健治朗	
Takanori	Shibata	柴田崇統	
Takashi	Yamamoto	山本尚史	
Shu	Nishioka	PhD.	
Wakaba	Kobayashi	Dipl.	
Max	Lindquist	Dipl.	

CERN's Linac4

Upgrade of the LHC injector chain:
From: 50 MeV *p* Linac2
To: 160 MeV *H^-* Linac4

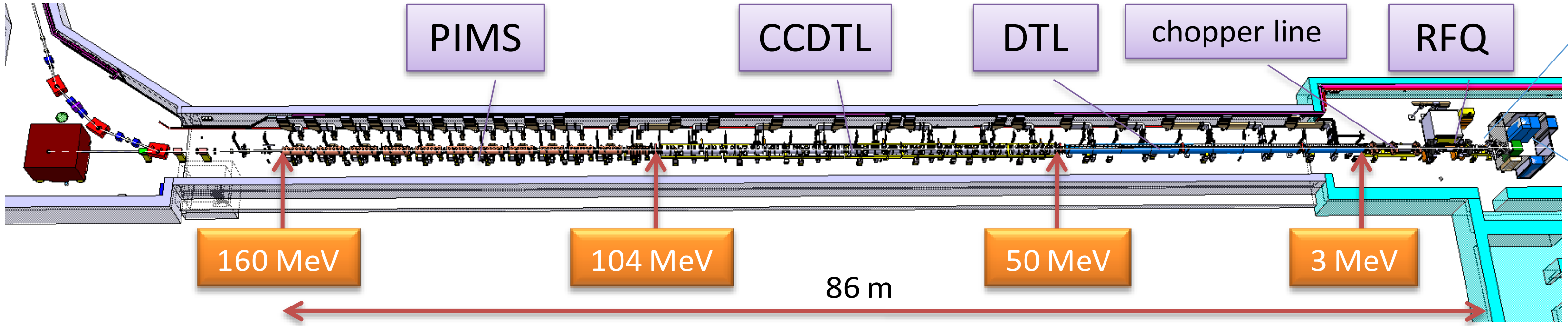


2 electrons striping *($H^- \rightarrow p$)* at injection Into the PS-Booster



2020 Connection to PSB

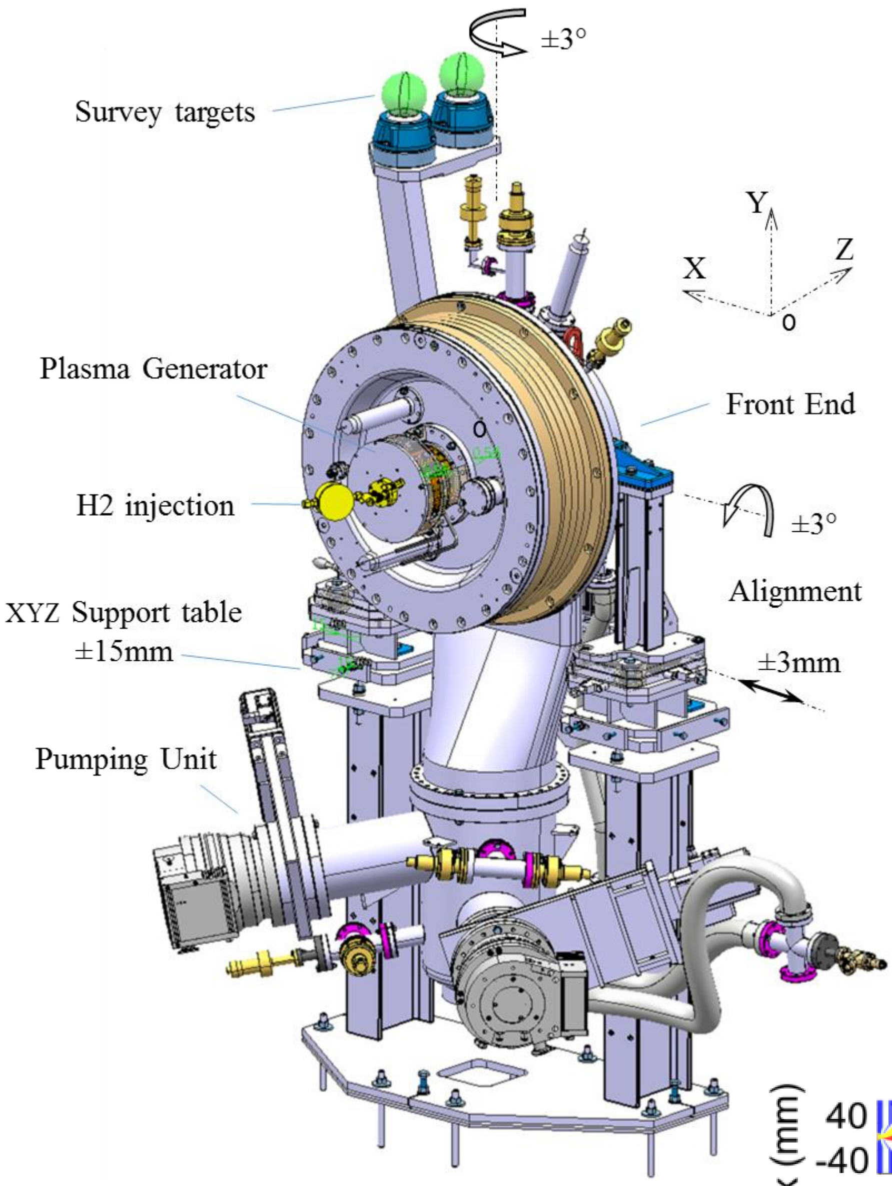
2019 : 160 MeV Reliability run

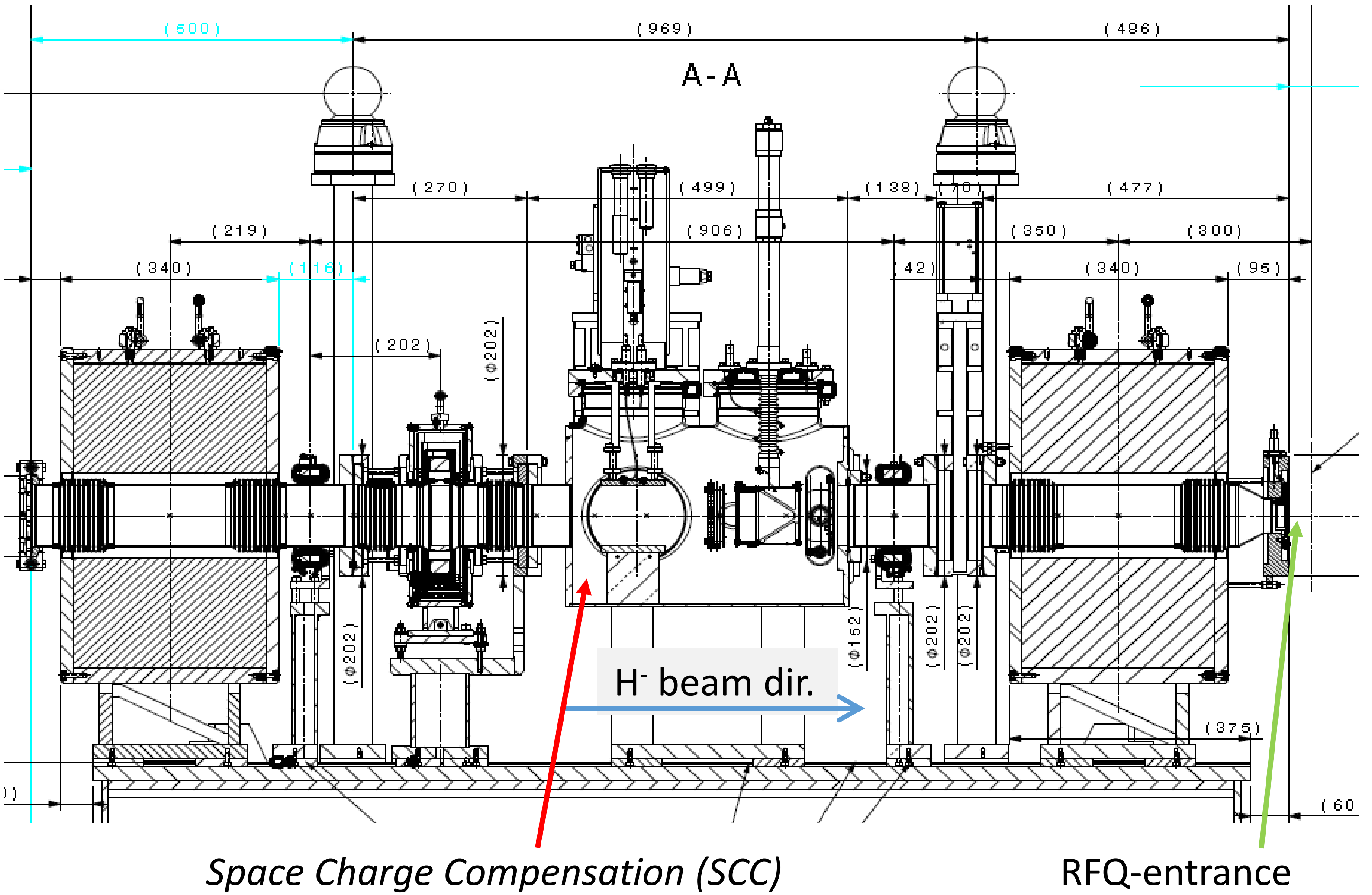


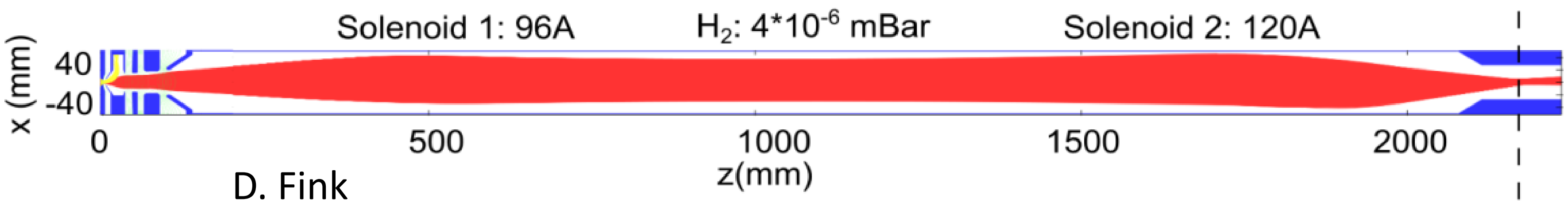
- ✓ 20 mA at the end of Linac4 to produce all 2018 CERN p-beams
- ✓ 32 mA achieved after 3MeV RFQ
- ➢ 40 mA (LS3) needed to double ISOLDE beam intensity

M. Vretenar *et.al., Progress in the Construction of Linac4 at CERN*, *LINAC12*, Tel Aviv, *LINAC14*, Geneva

Layout of the Linac4 front end and LEBT







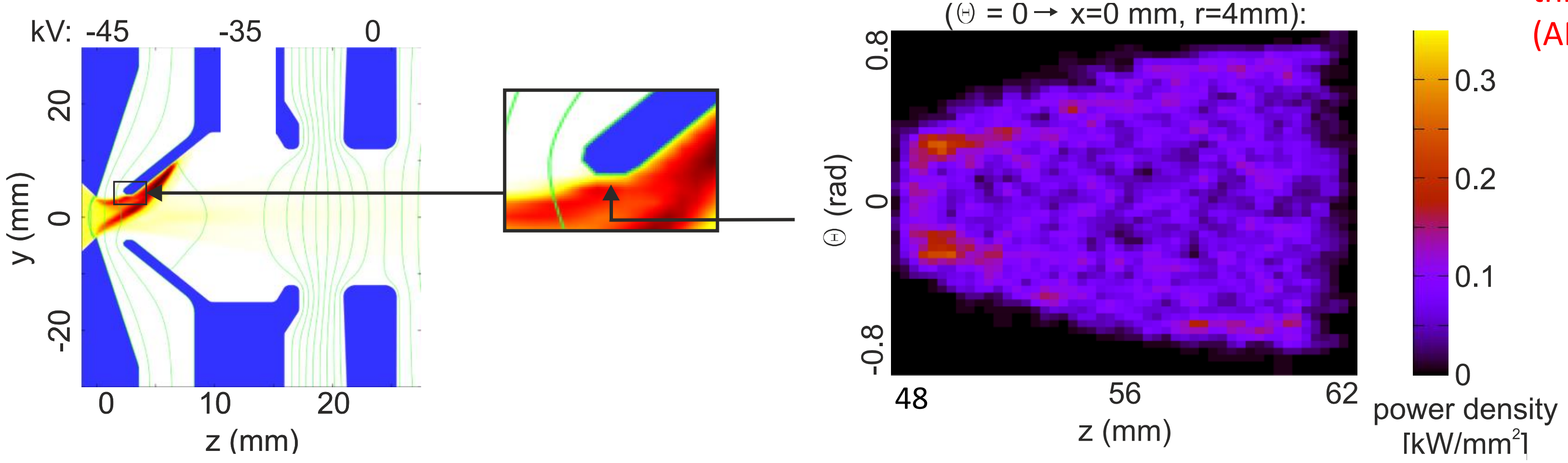
D. Fink

IS02: too high filter field — *Power Density on Titanium Puller-Dump*

✓ IBSimu Ok for engineering

I) Cesiated surface production: I(H^-): 40-50 mA, e/H^-: 4, I(e): 200 mA

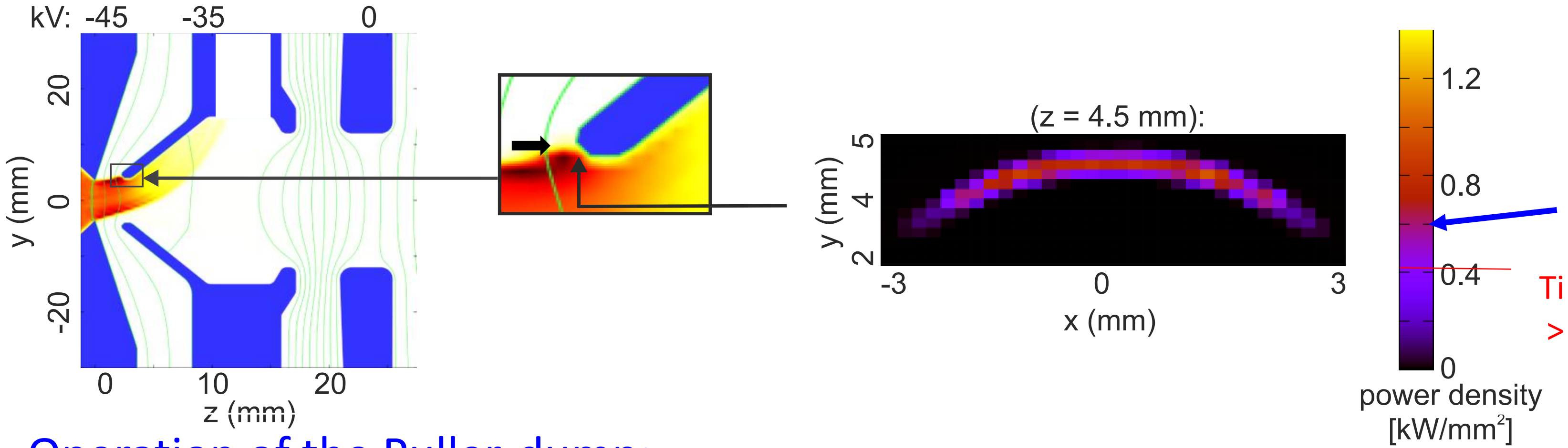
Ti-Damage threshold (ANSYS)



IBSimu inputs to the extraction optics design:

1) e-beam surf. power density
2) Secondary electron origin and yield
3) Residual gas ionization tracking

II) Volume production: I(H^-): 40-50 mA, e/H^-: 40, I(e): 1600 mA



H^-: 30 mA, e/H^-: 20,

H^-: 15 mA, e/H^-: 40, I(e): 600 mA

Ti Damage > 500 mA

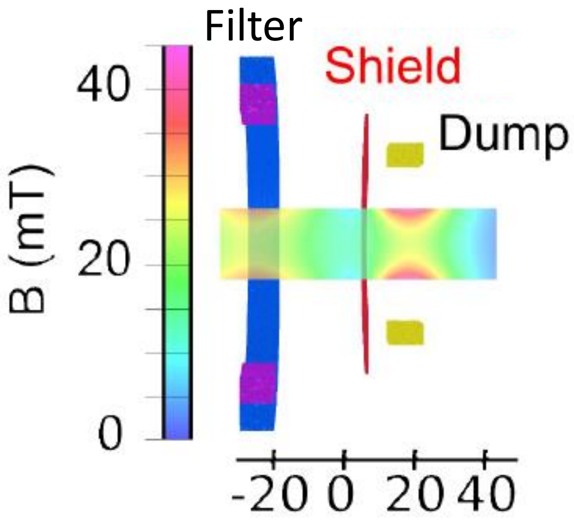
- IS02b operated in volume mode with excess electron current
- W-puller dump instead of Ti

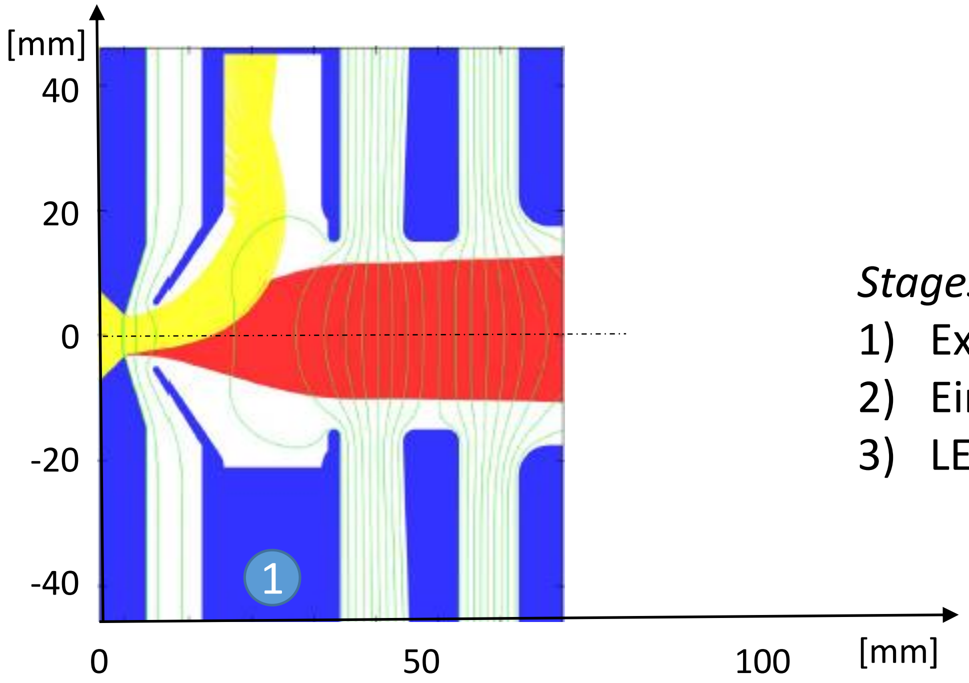
Operation of the Puller-dump:

- Withstands power density in Cs-surface nominal operation.
- Limited to a 500 mA electron current

Courtesy of D. Fink

IS03 IBSimu H^- beam and electron-dump Simulation



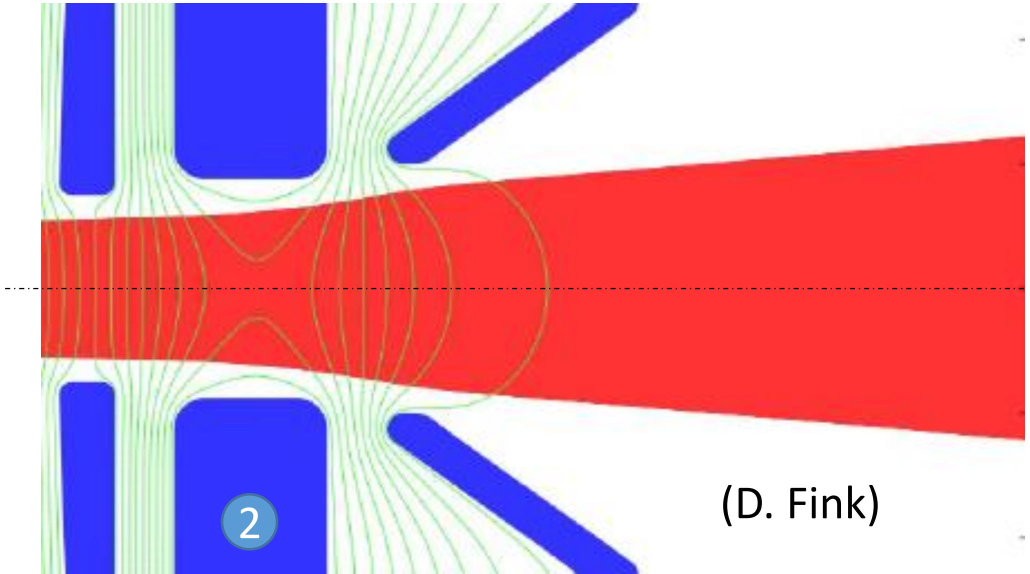


Stages:

1) Extraction and e-dump
2) Einzel lens
3) LEBT (not shown)

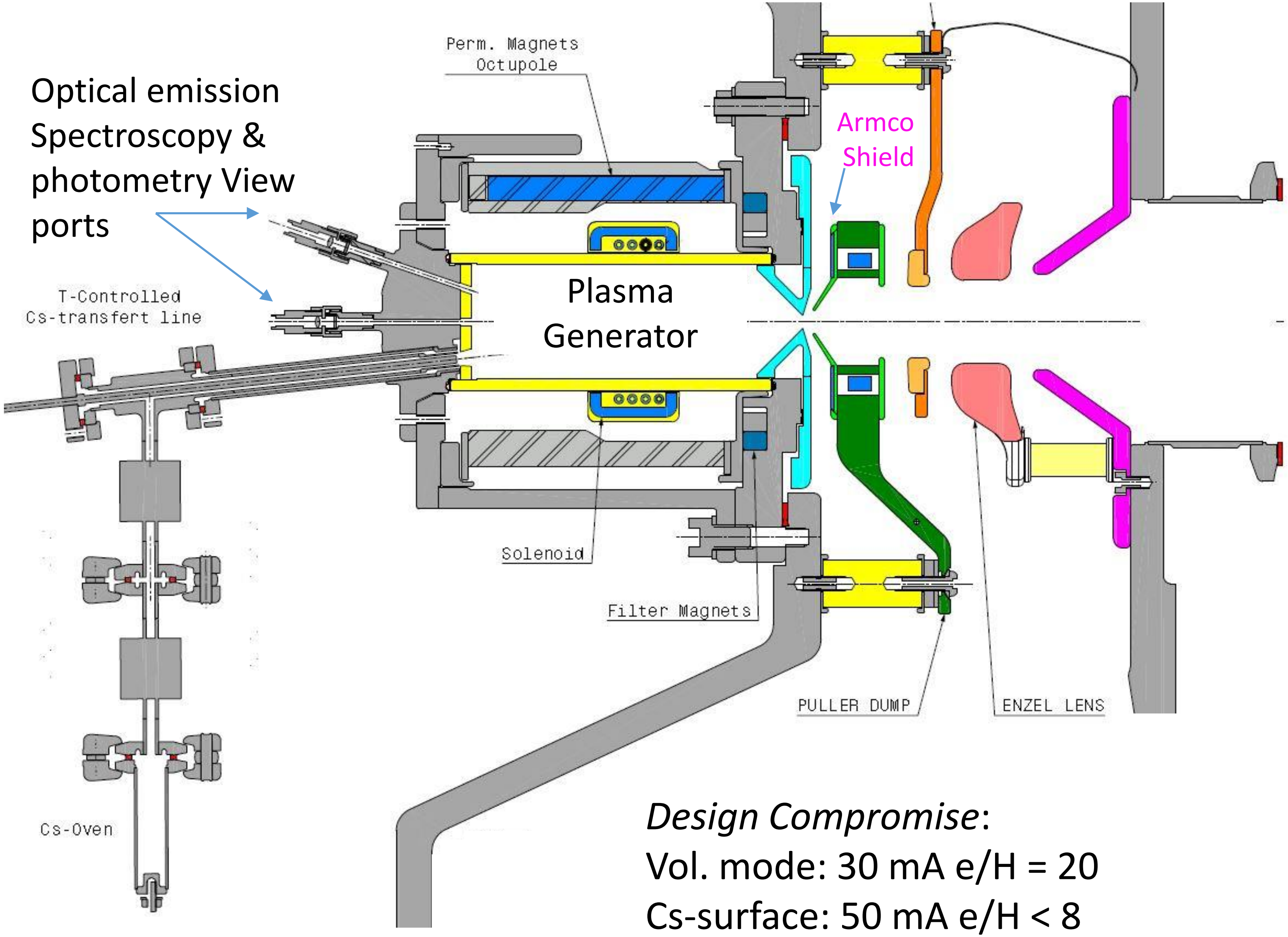
Settings:
40 mA H^- e/H = 3
U (Source, puller, Einzel)
= -45, -35.5, 35 kV
Sol_1,2 = 97, 100 A
LEBT SCC 4E-6 mbar

$\mathcal{E}_{norm, RMS}$ = 0.34 π·mm·mrad
At RFQ entrance (2.23 m)

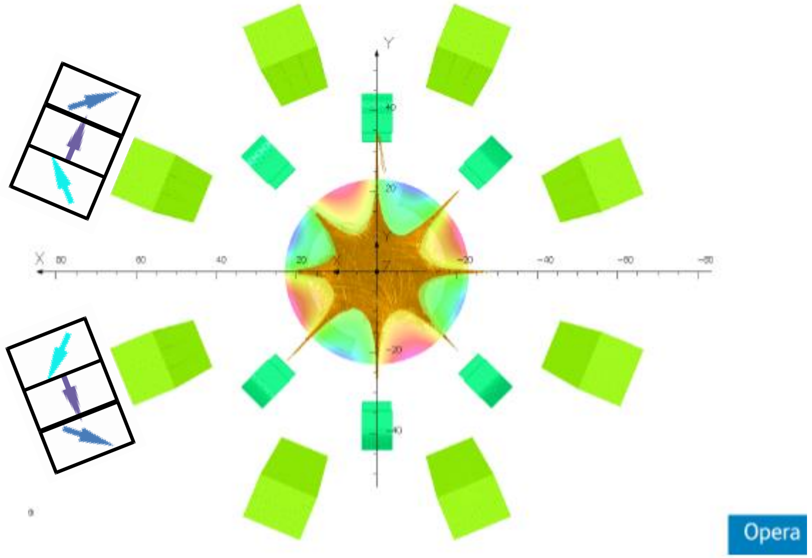


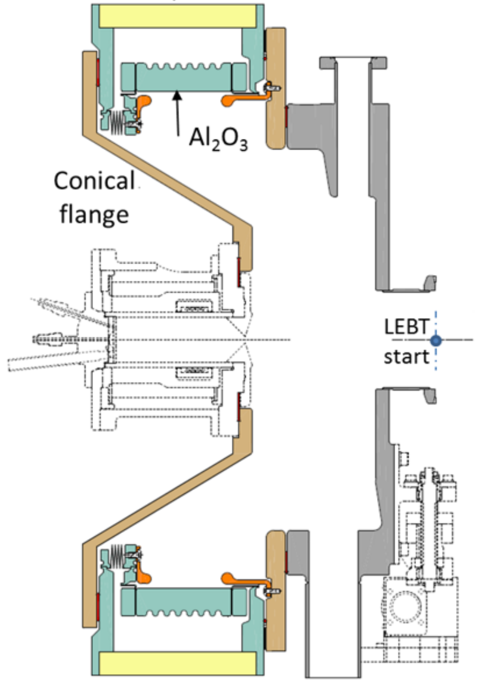
(D. Fink)

L4-IS03 RF-ICP driven H^- source IS03



Offset Halbach 8-pole cusp field





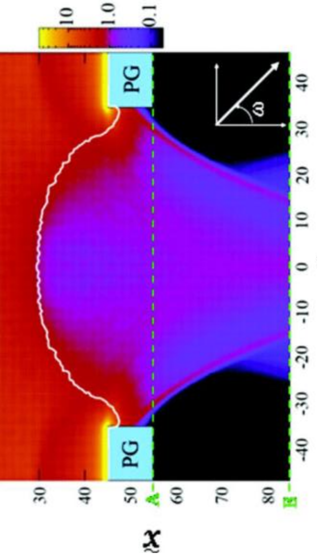
Design Compromise:
Vol. mode: 30 mA e/H = 20
Cs-surface: 50 mA e/H < 8

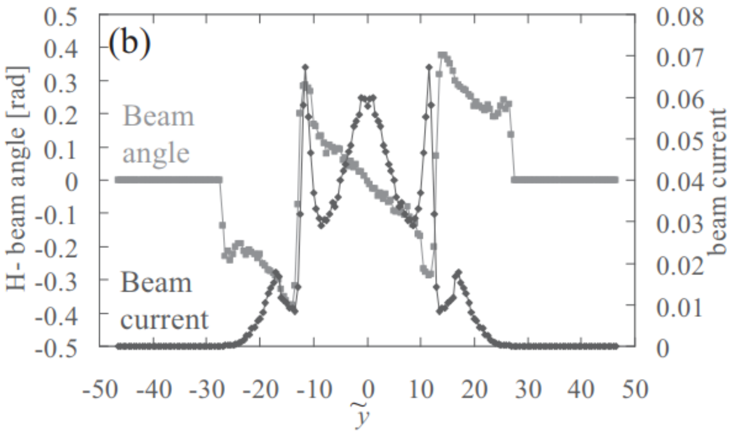
H^- beam Halo in cesiated surface ion source

Illustration of the impact of direct extraction from a cesiated surface located in the vicinity of the meniscus surface with magnetic field.

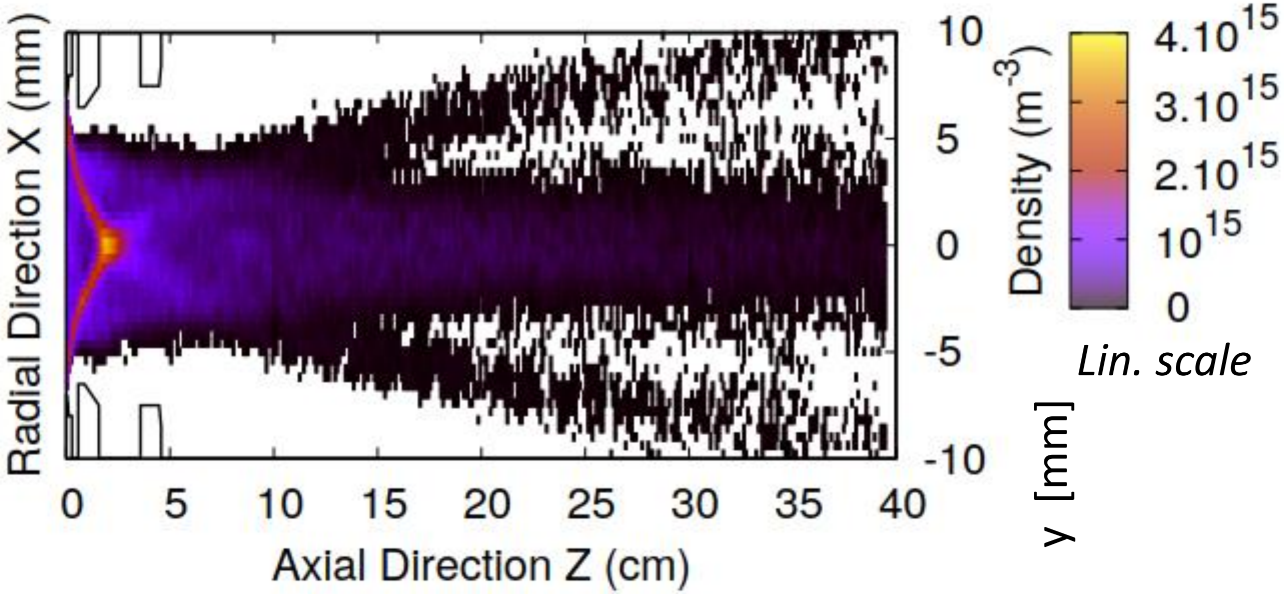
Thesis A.Revel
August 2015, LPGP p.43, fig. 2.10

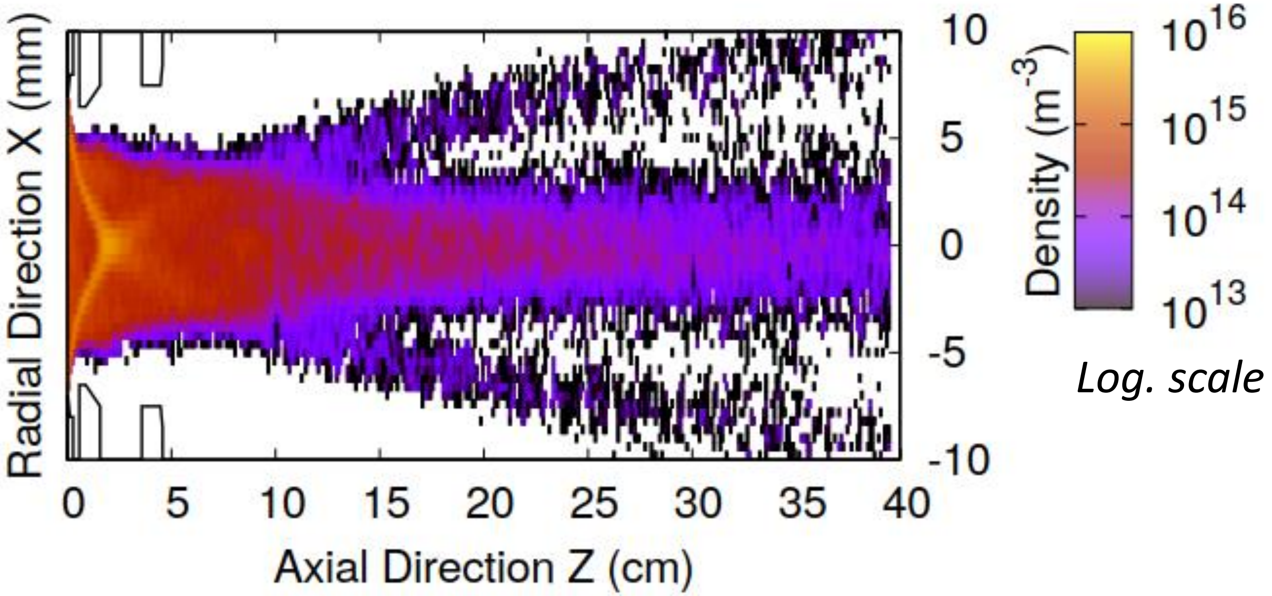
Myamoto et. al. 2012-17



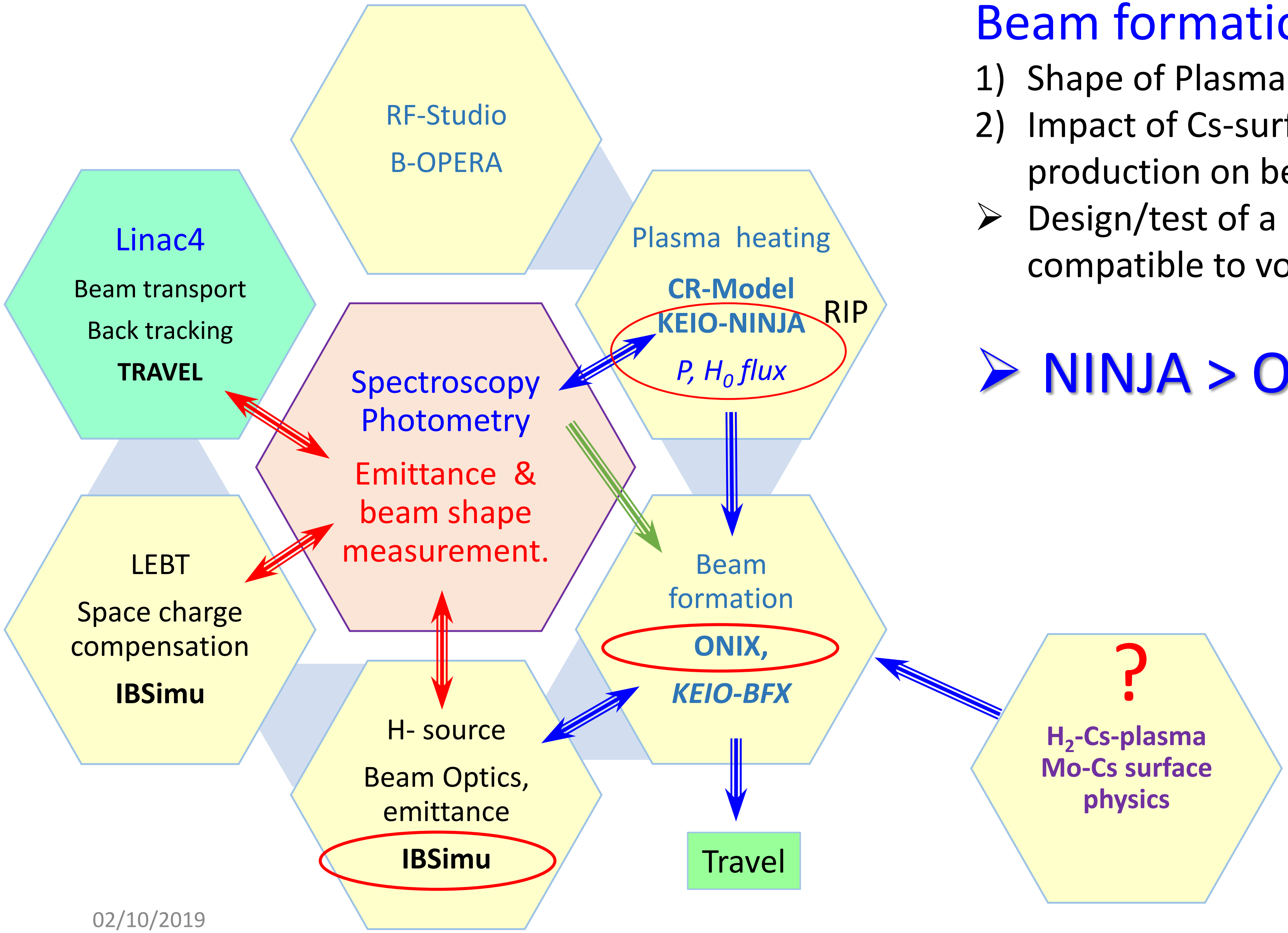


Beam profile and angular distribution





H^- ions Beam formation: Next step



Beam formation questions:

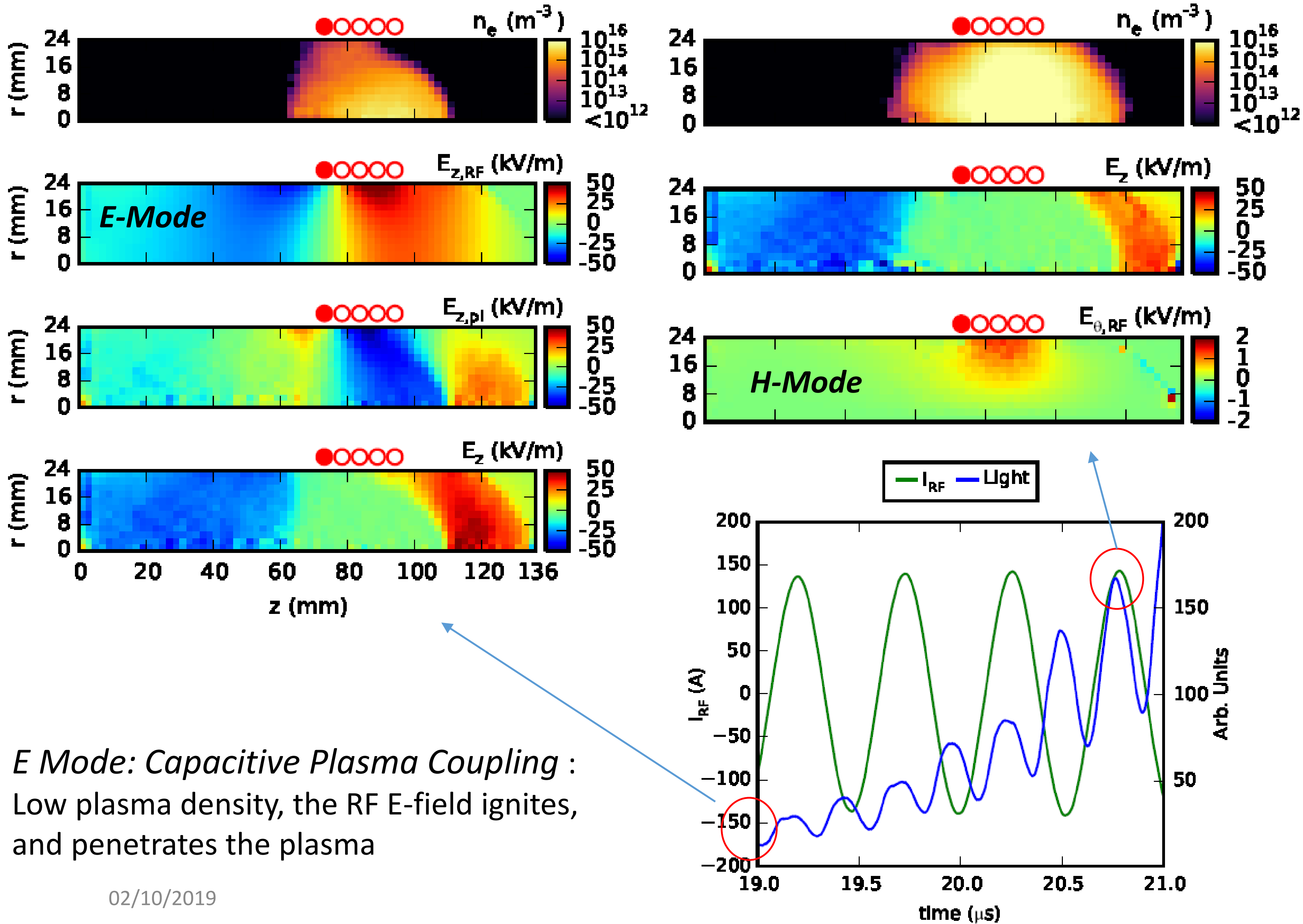
1) Shape of Plasma Meniscus ?
2) Impact of Cs-surface geometry and H^- Surface production on beam emittance / halo ?

➢ Design/test of a low e/H extraction (not compatible to vol. operation)

➢ NINJA > ONIX / BFX <> IBSimu

Collaborations:
NINJA & BFX: KEIO-university
ONIX: LPGP Orasy, IPP-Garching

NINJA : Plasma Heating simulation :E/H transition

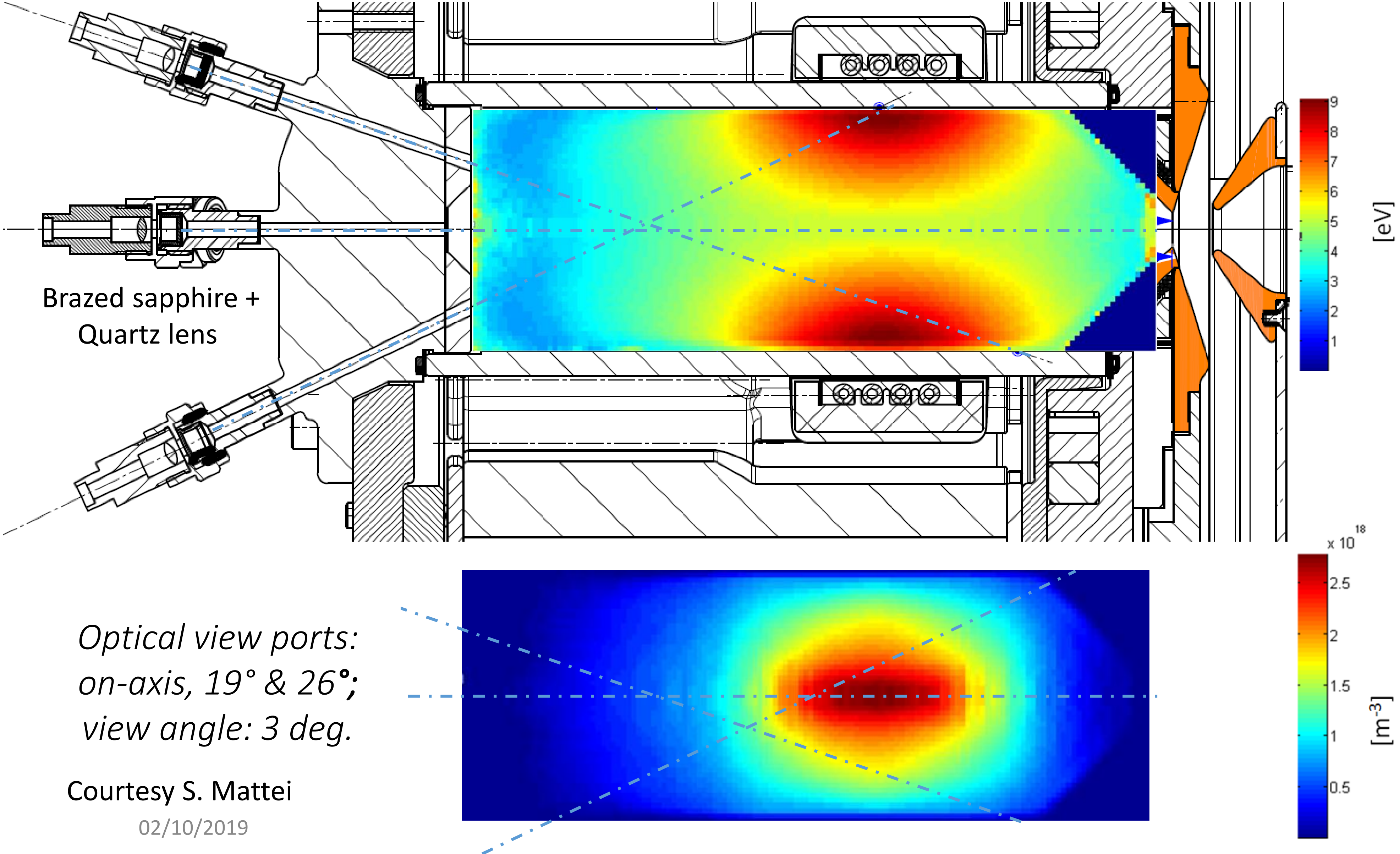


H Mode: Inductive Plasma Coupling :
At elevated plasma density, the RF E-field cannot penetrate the plasma

E Mode: Capacitive Plasma Coupling :
Low plasma density, the RF E-field ignites, and penetrates the plasma

Simulation of Plasma density and electron-energy:

1 RF-cycle average: KEIO RF-code simulation → NINJA

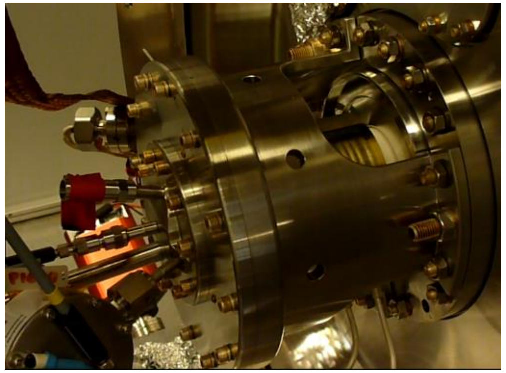


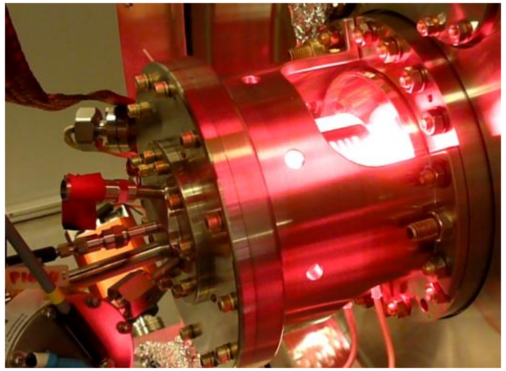
Optical view ports: on-axis, 19° & 26°; view angle: 3 deg.

Courtesy S. Mattei

Determination of discharge parameters via OES at the Linac4 H^- ion source

S. Briefi, D. Fink, S. Mattei, J. Lettry, and U. Fantz





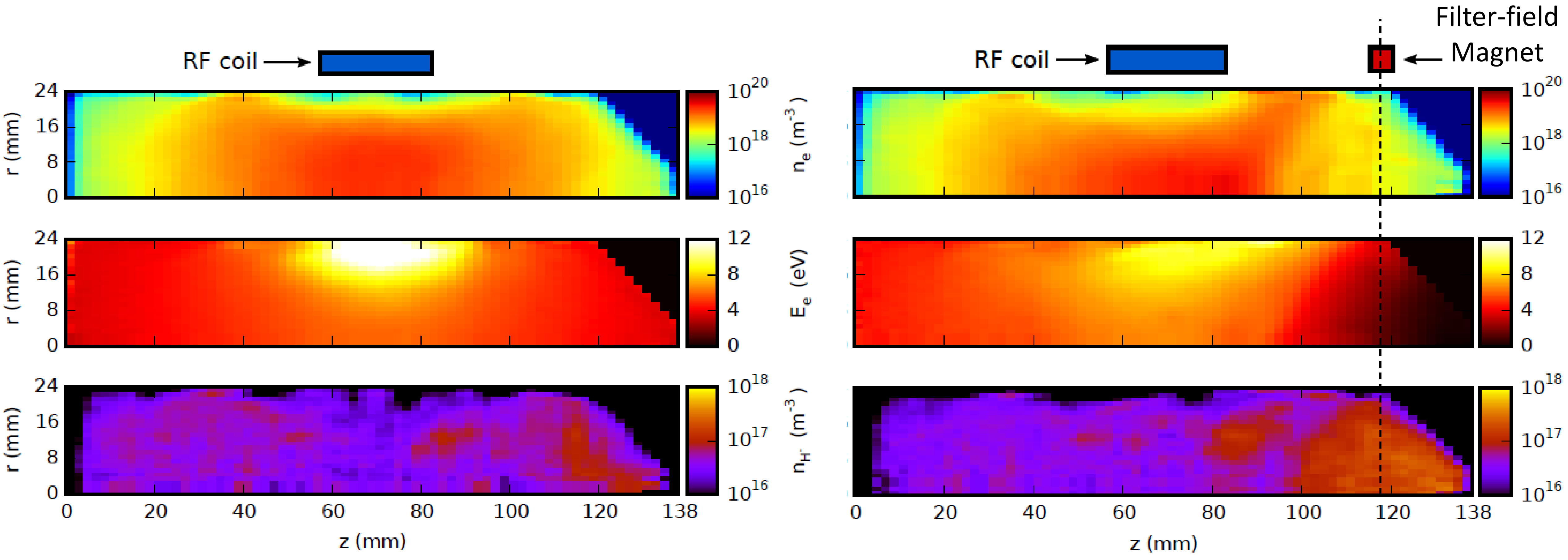
Atomic: Balmer Photometry (Plasma ignition) & Spectro.
Molecular: Fulcher band Spectroscopy

IS02-cusp free 20/4/2015

IS03 Filter field by NINJA

Simulation results, by inserting a dipole filter field:

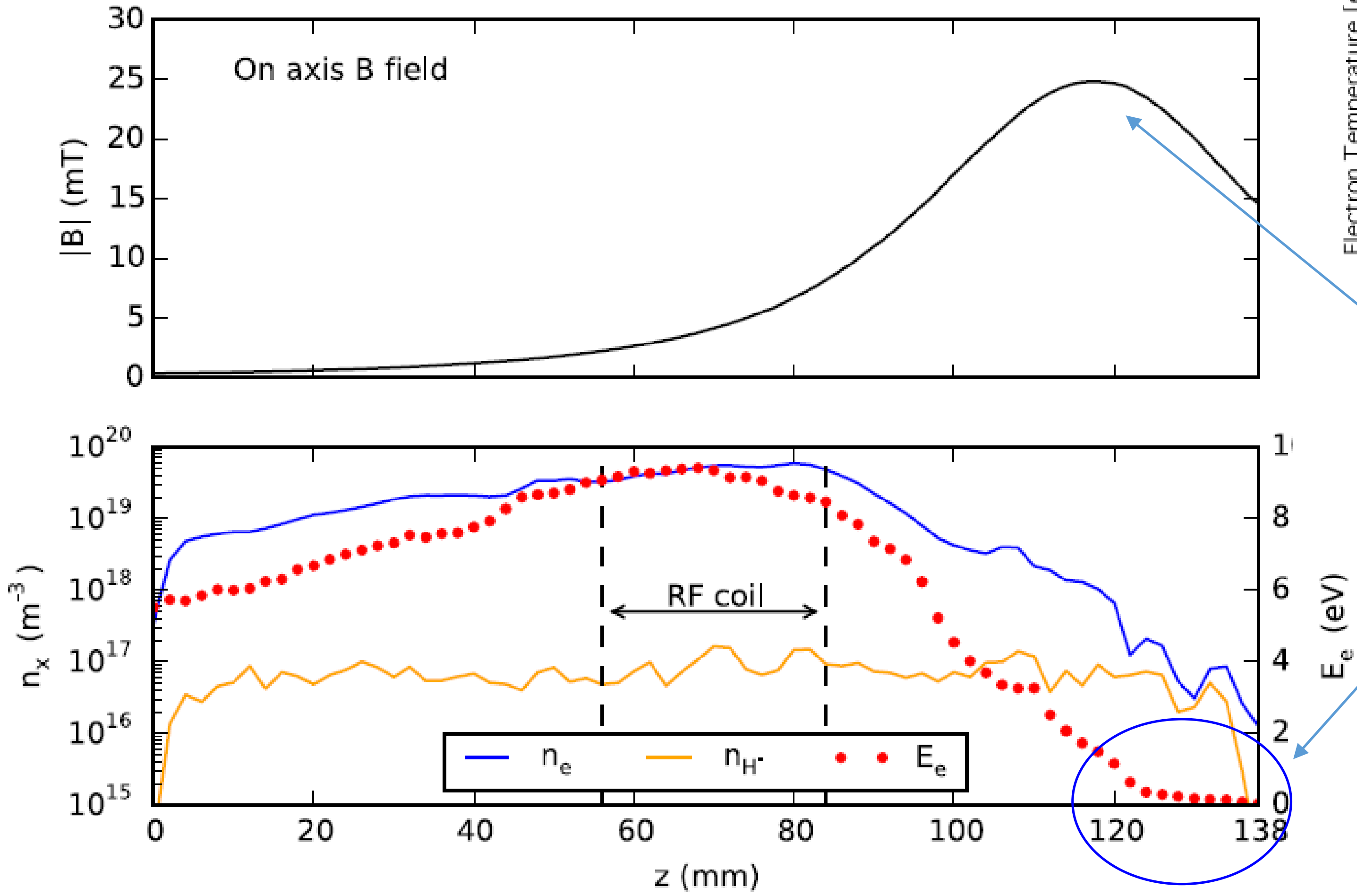
1) *Reduced electron density* n_e
2) *Reduced electron energy* E_e
3) *Enhanced* H^- *density in the beam formation region* n_{H^-}



No filter field

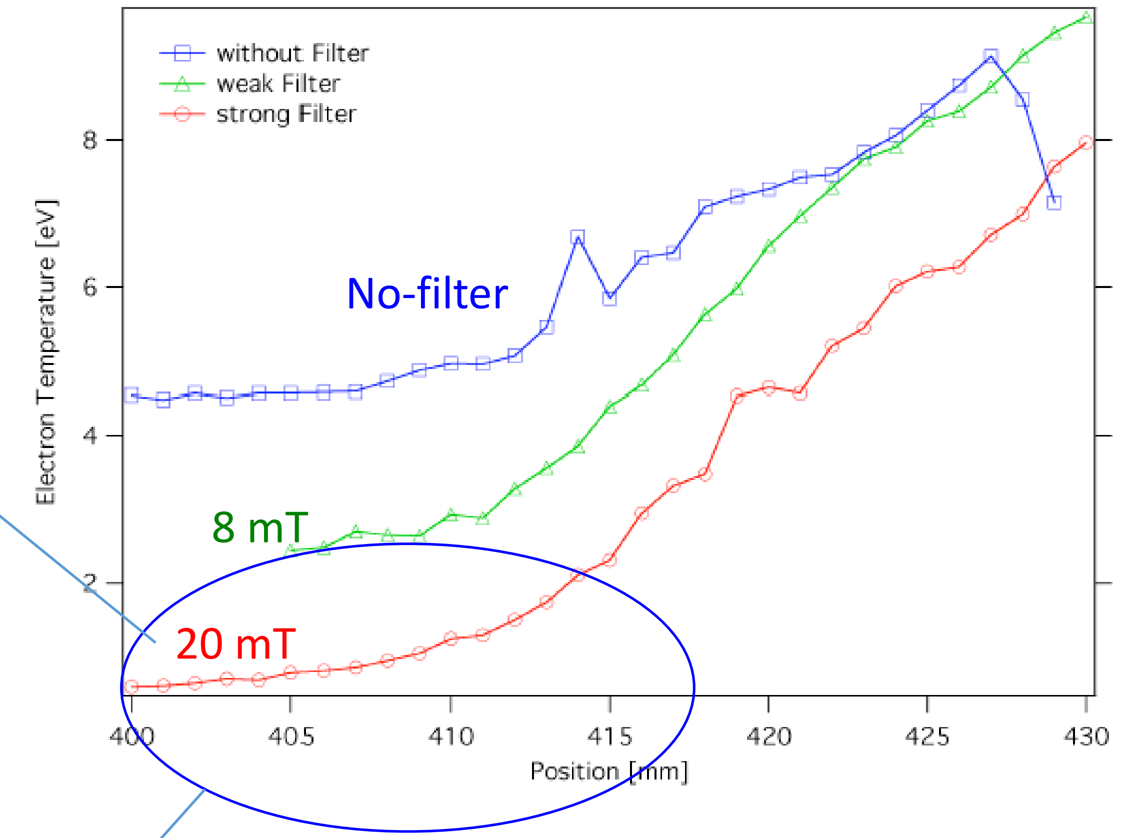
With filter field

NINJA (L4IS) vs. Laugmuir gauge meas. (SPL Plasma generator)



e/H = 100

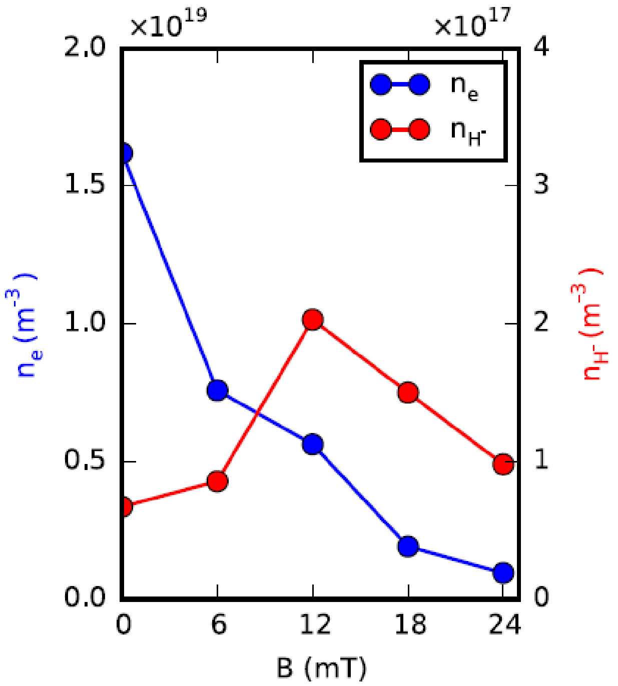
e/H = ~1



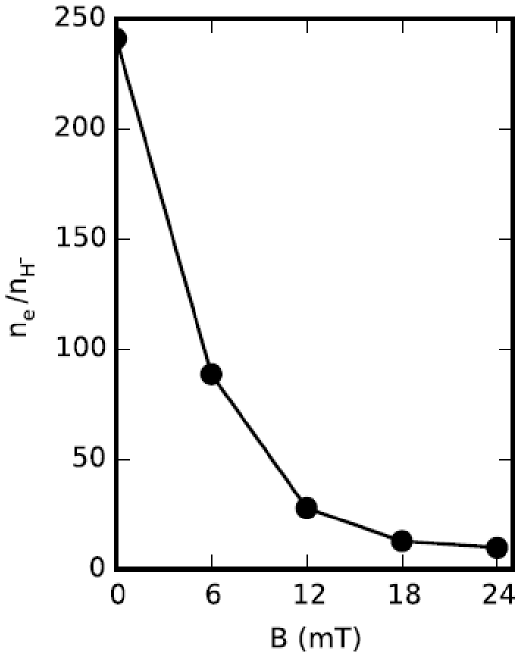
SPL (cooled) plasma generator
C. Schmitzer

NINJA Filter field and H2 pressure: *Beam formation region (z > 118 mm).*

Filter field (mT)

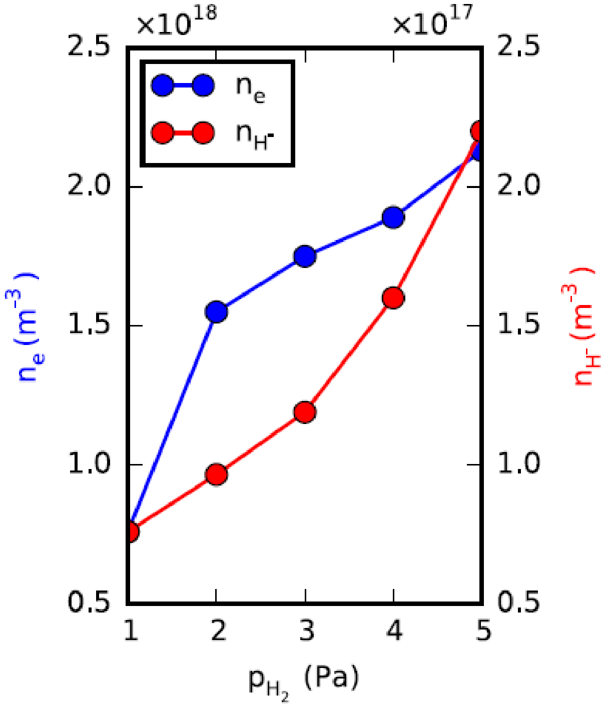


Electron density ***ne***
H^- density ***nH°***

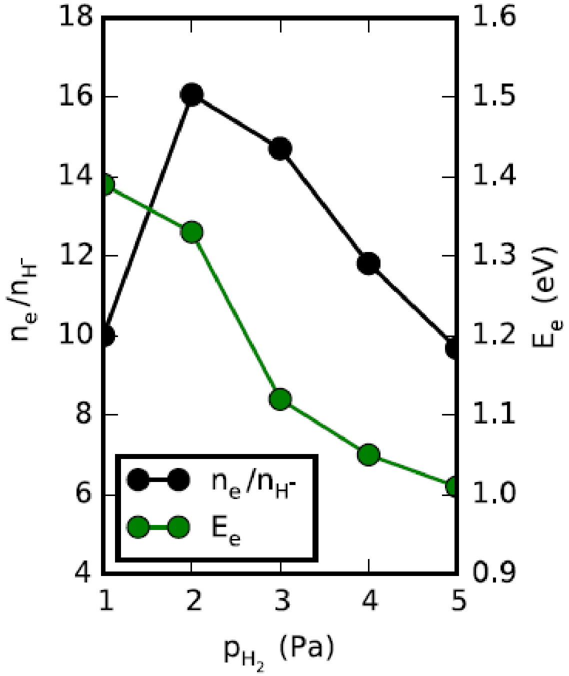


Electron to H^- density ratio (*ne/nH^-*) ≠ e/H.

Hydrogen pressure *pH2*



Electron density ***ne*** and volume produced H^- density ***nH^-***.

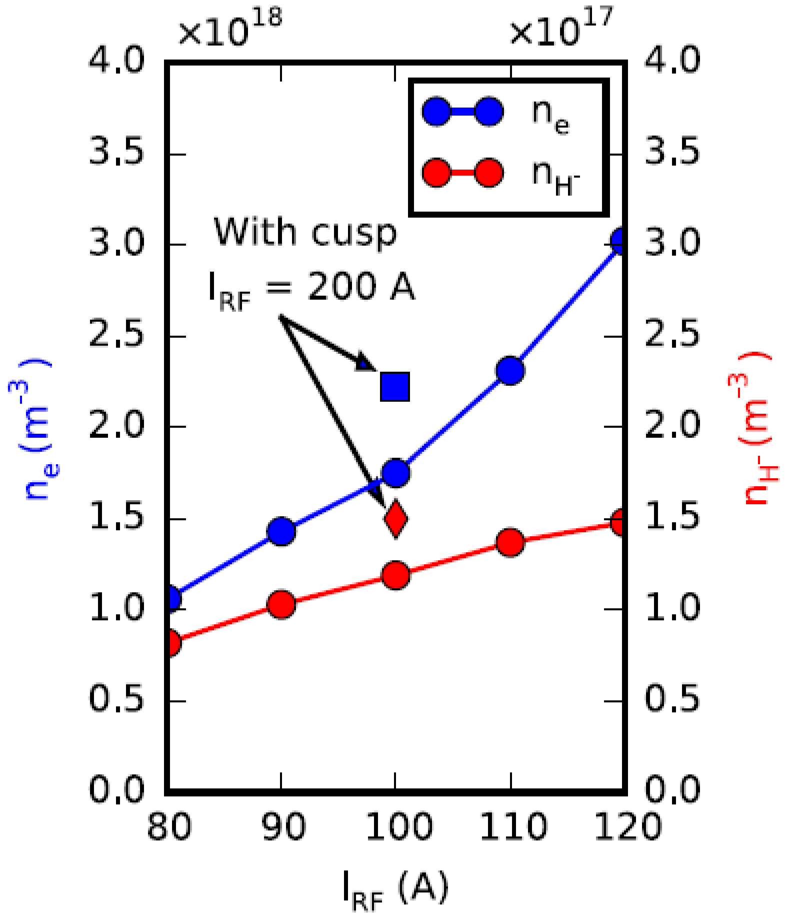


Electron to H° density ratio *ne/nH^-* and electron energy *Ee*

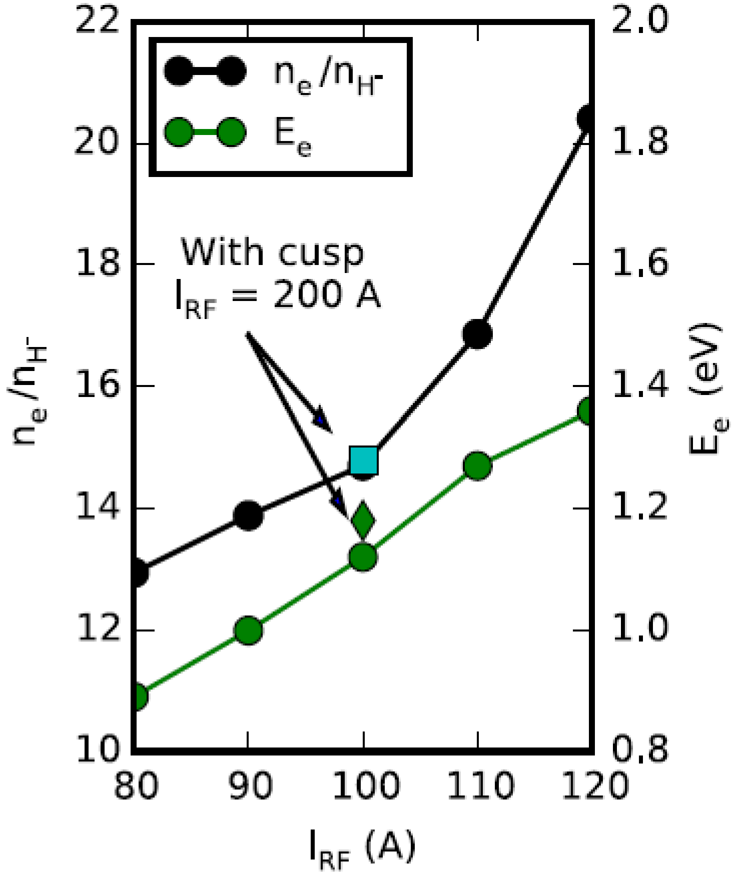
To make it clear: we measure e/H the ratio of extracted electron to H^- beam currents (not densities)

In vol. mode e/H = ~10-30

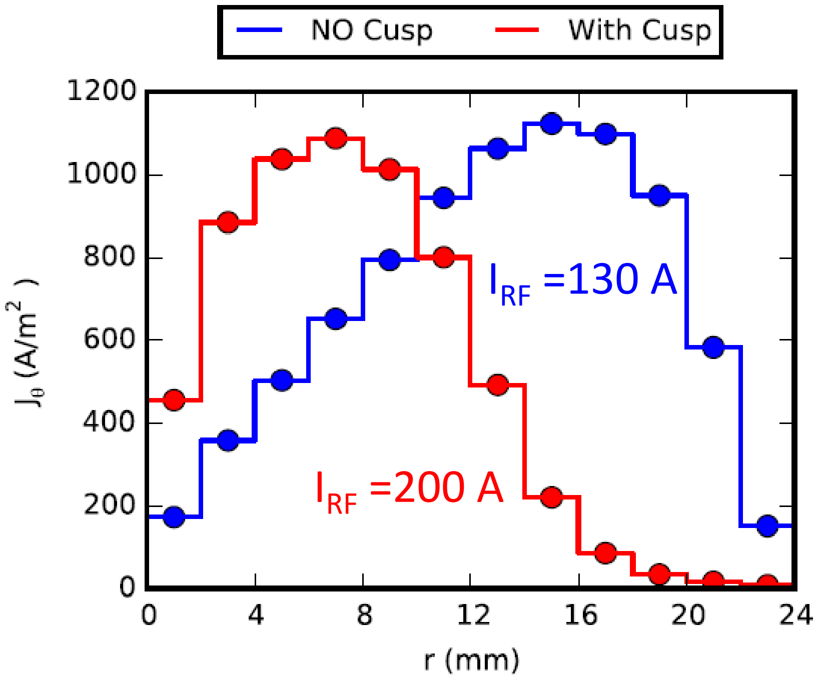
Beam formation region :
Effect of the ICP coil current I_{RF} and cusp field



Electron density n_e
volume produced H^- density n_{H^-}



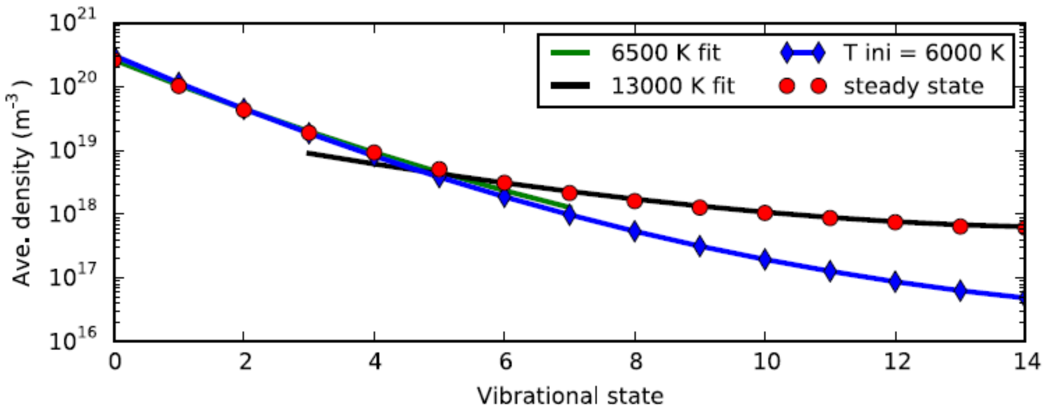
Electron to H^- density ratio n_e/n_{H^-}
and electron energy E_e



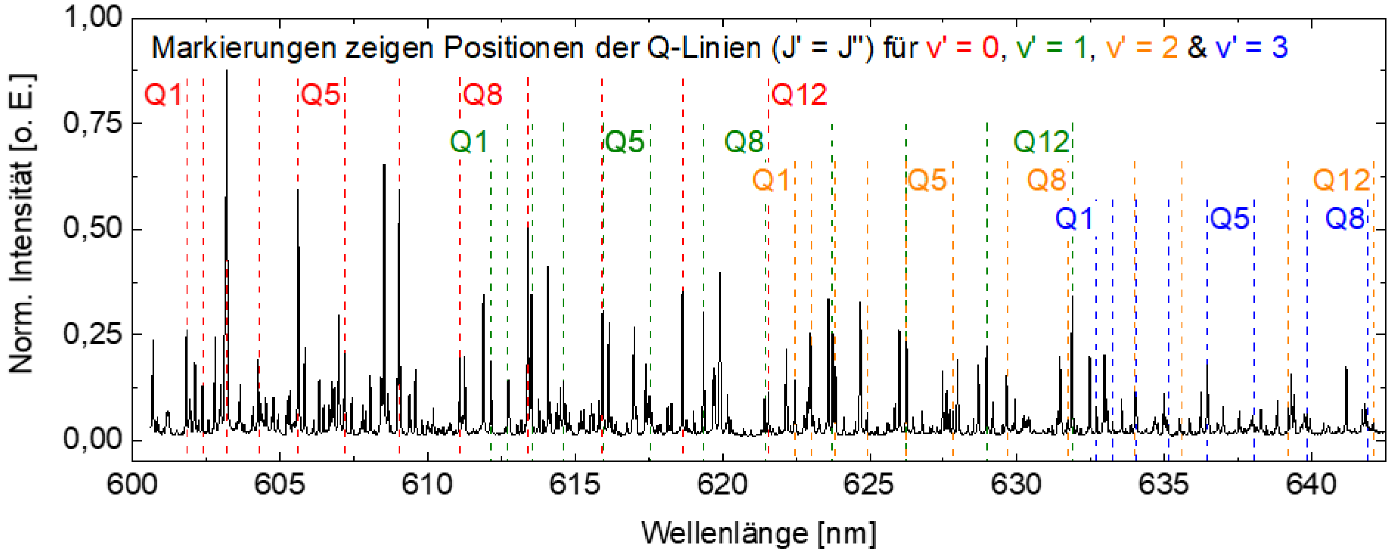
We observe a cusp induced reduction of the plasma heating efficiency but also of the expected electron and H^- ion density

NINJA vs. OES:

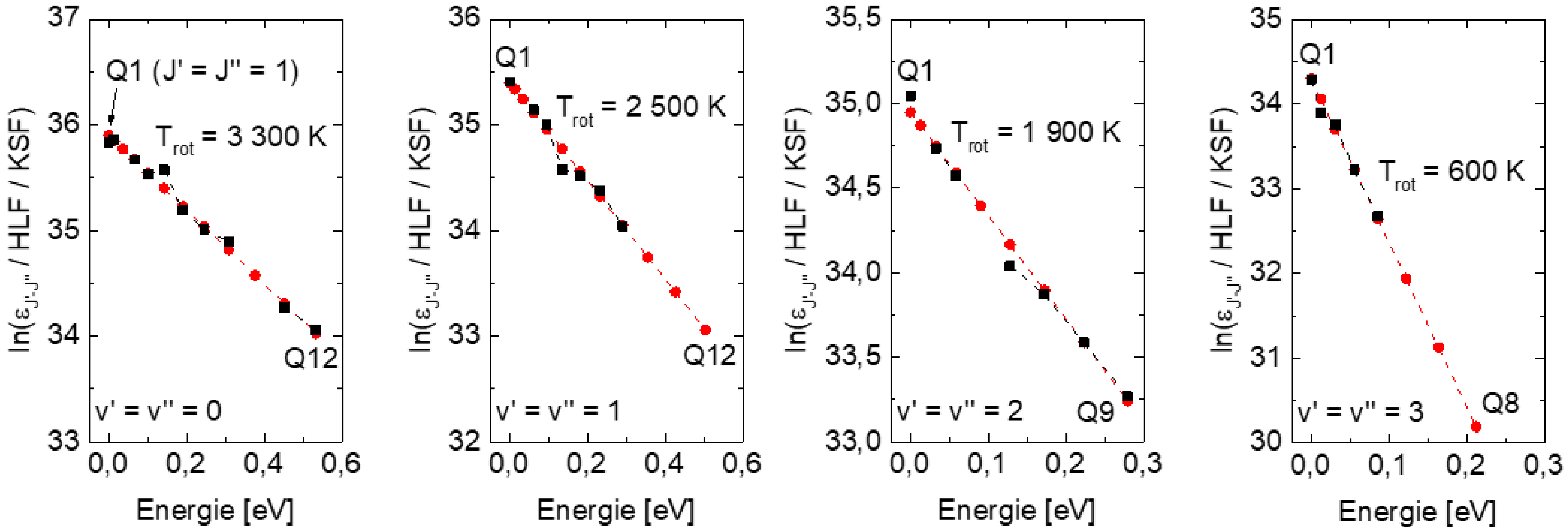
Distribution of excited molecular states



Simulated molecular excited states and Optical emission spectroscopy of the Fulcher Band

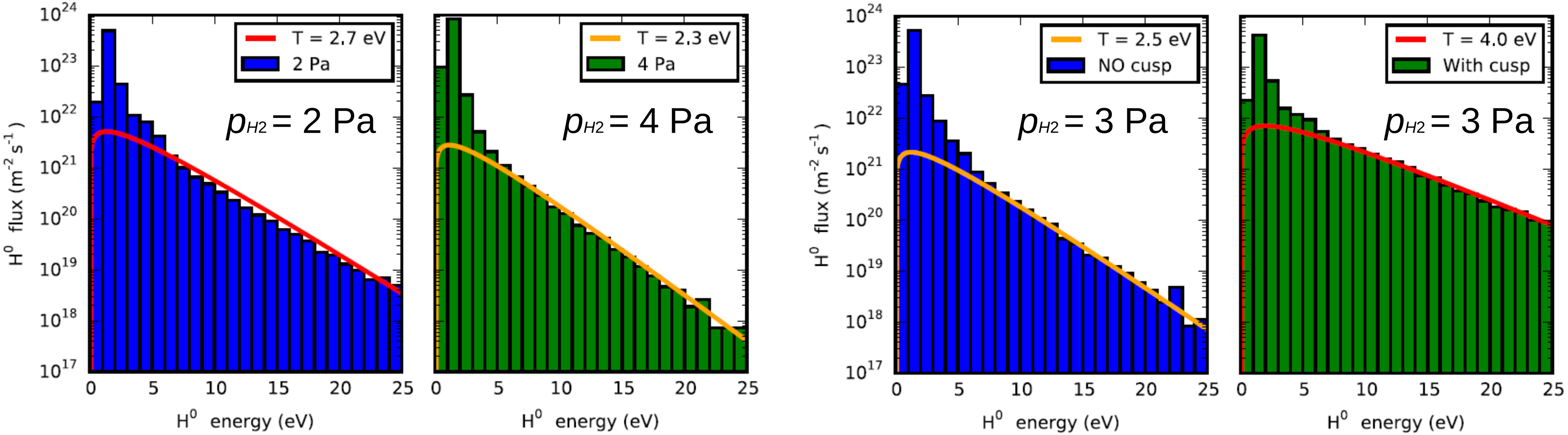


S. Briefi, Uni. Augsburg, 2015:
Analysis of the Fulcher band spectra and modelling



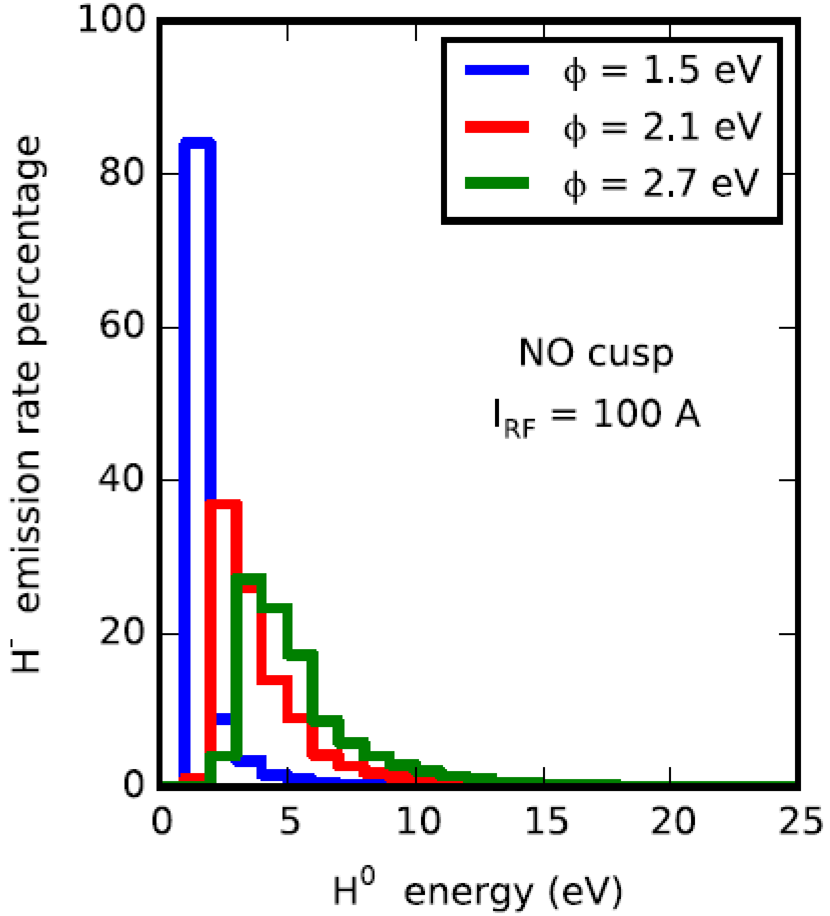
H_0 *flux simulation:*
Energy distribution of the H_0 flux impinging onto the plasma electrode

No cusp, coil current I_{RF} = 100 A — With cusp, I_{RF} = 200 A.

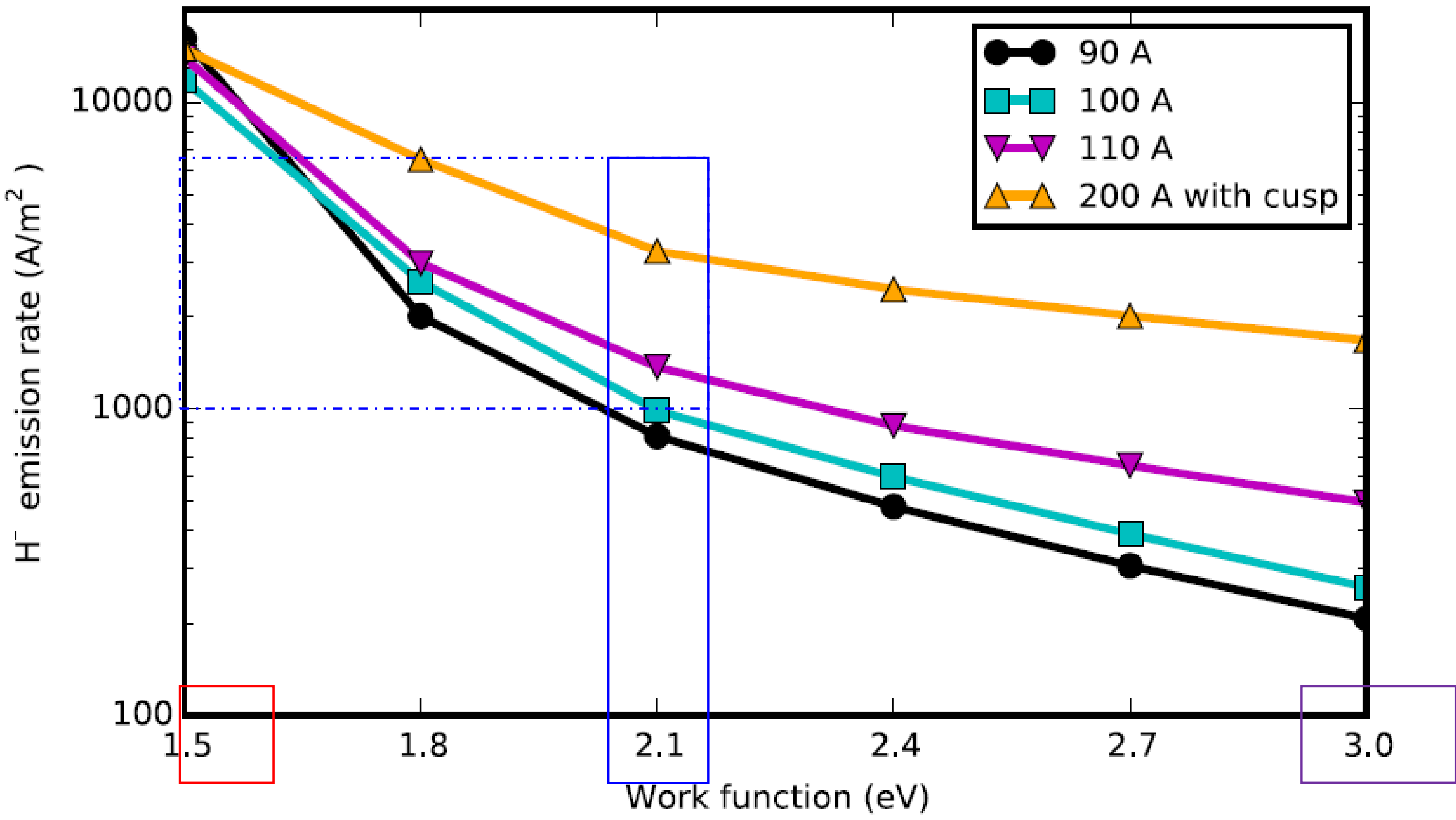


The energy distributions are characterized by a low-energy (< 5 eV) non-thermal component and a high-energy thermal component corresponding to the temperature of the positive ions

Plasma electrode H⁻ emission rate (work function, EEDF)



H⁻ emission rate as a function of the impinging H_0 energy

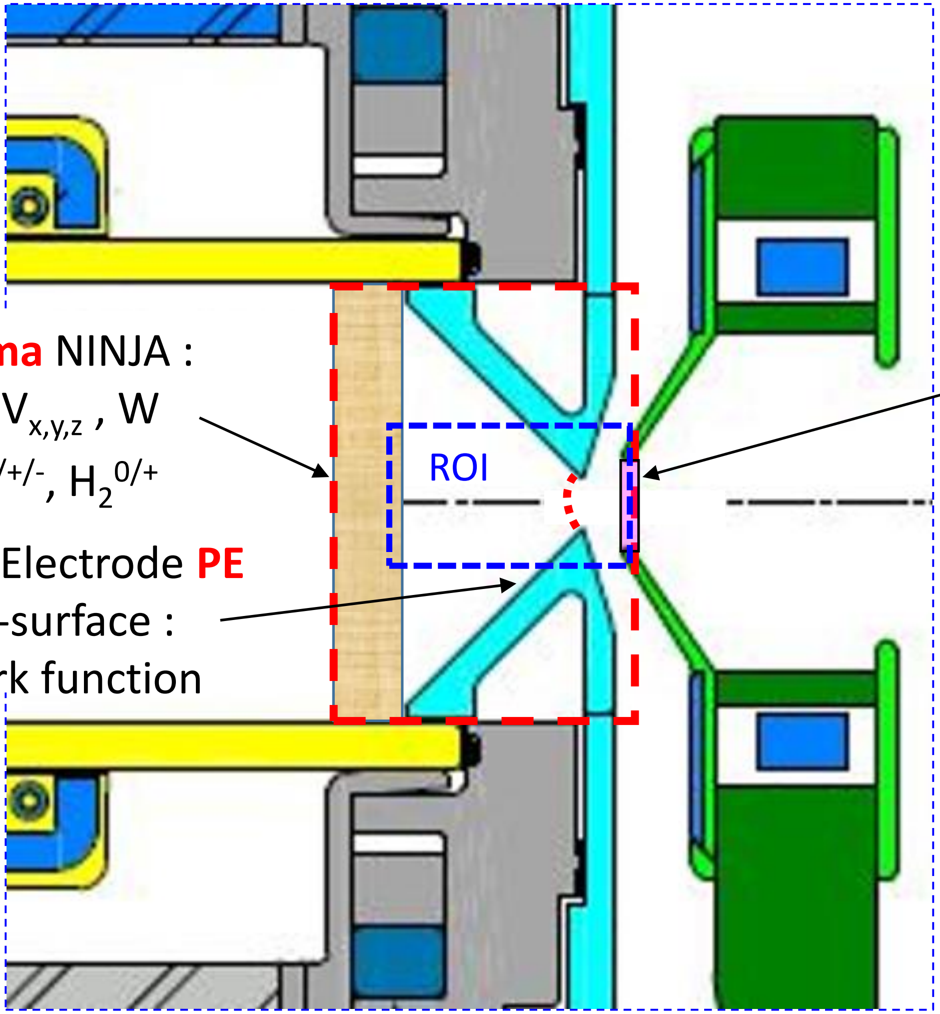


H⁻ emission rate from the plasma electrode due to backscattering of impinging H_0.
Work function: 1.5-1.6 eV partially coated cesiated molybdenum, 2.1 eV bulk caesium and 4.3-4.9 eV uncoated molybdenum

Beam formation region: PIC Initial and Boundary conditions

NINJA & IBSimu → BFX/ONIX → IBSimu & Path

Mag. Filter $\mathbf{B_F}$ e-dump $\mathbf{U}_{Puller}$, $\mathbf{B}_{ed}$



1) **Plasma** NINJA :
x,y,z, $V_{x,y,z}$, W
e, $H^{0/+/-}$, $H_2^{0/+}$

2) Plasma Electrode **PE**
Mo-Cs-surface :
eff. Work function

3) **Puller** E-field from
IBSimu iterations if needed:
I_o (e), I_o (H^-),
I(t,e), I (t,H^-),
U (PE, Puller)

Initial conditions:

Upstream form Meniscus
- Derived from Smoothed NINJA plasma populations

Down stream form Meniscus
- Derived from Smoothed e & H^- IBSimu beams

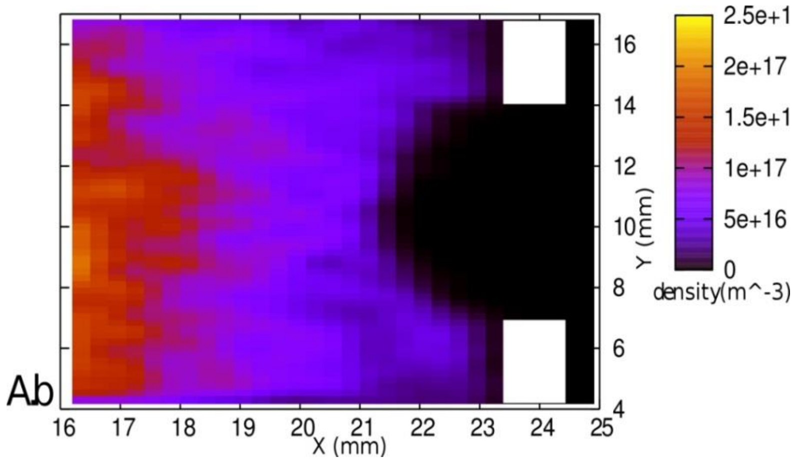
Output of IS03 BFX/ONIX

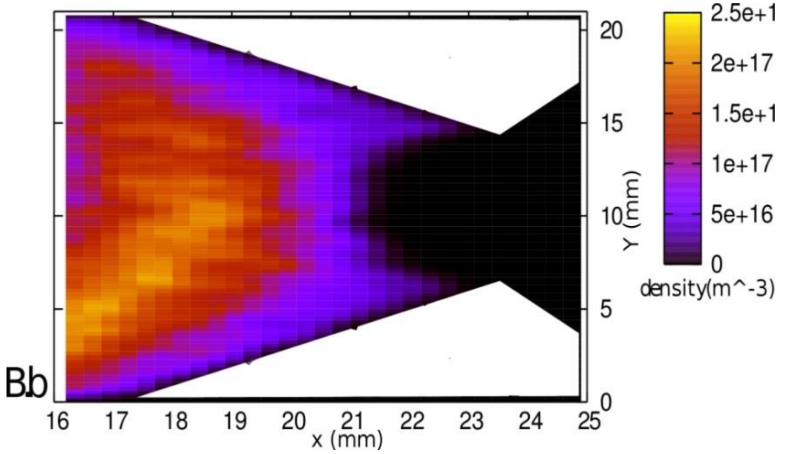
x,y,z, $V_{x,y,z}$, W (e, H^-) (p, H_2^+)
x_o,y_o,z_o, (vol, PE-surf, initial)

Equilibrium is driven by the properties of the Boundaries :
Tracking convergence via of av. populations / tot. energy
- Particle source (plasma and Plasma Electrode)
- Particle sink (all boundaries)
- Plasma sheath, plasma potential
- Most initial particle lost

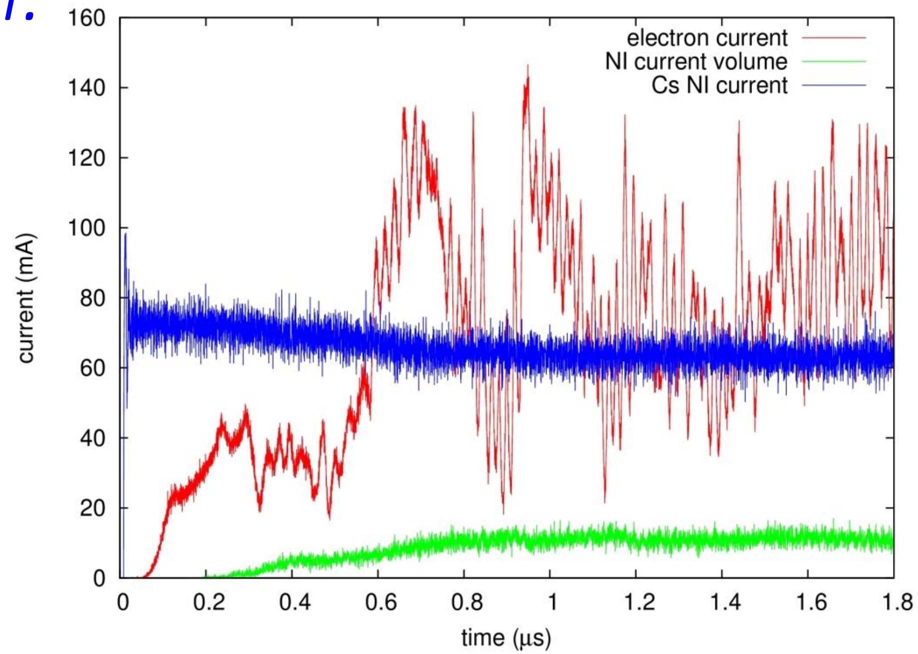
ONIX simulation plasma-beam formation:

IS01 & IS02 steady state H^+ density



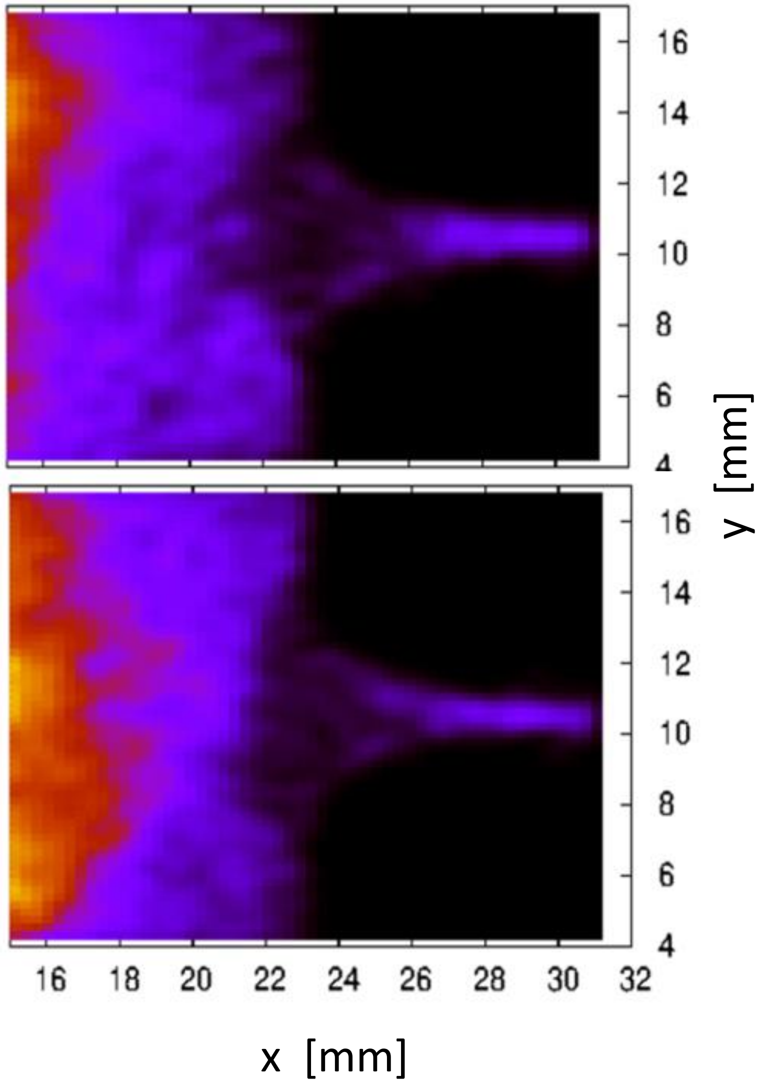


Collaboration with
LPGP Orsay France



13 runs @ 2weeks & 20 cpus:

IS-01, (volume production)
IS-02, Vol. & Surface H^-
Surf. prod. Rate (1-7 kA/m^2)
filter field strength
positive and negative ion extraction
Super particles density
plasma density *(5×10^{17}-2×10^{18} m^{-3})*
electron to ion ratio (5:5-1:10)



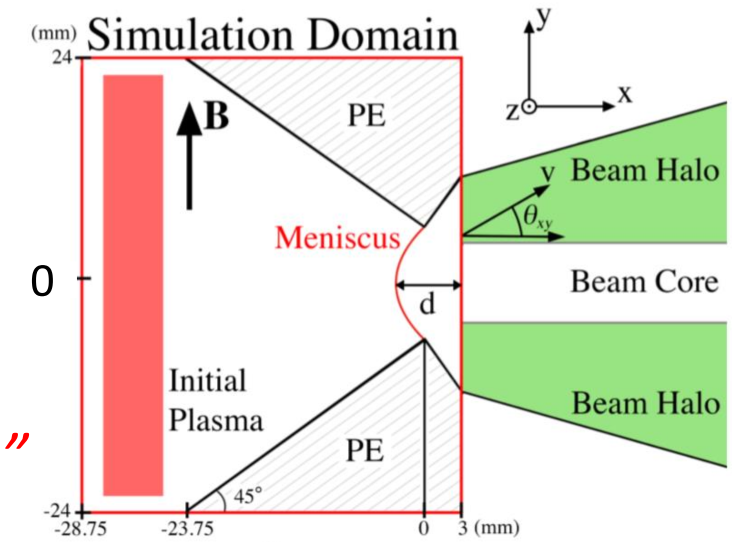
Serhiy Mochalskyy 2012

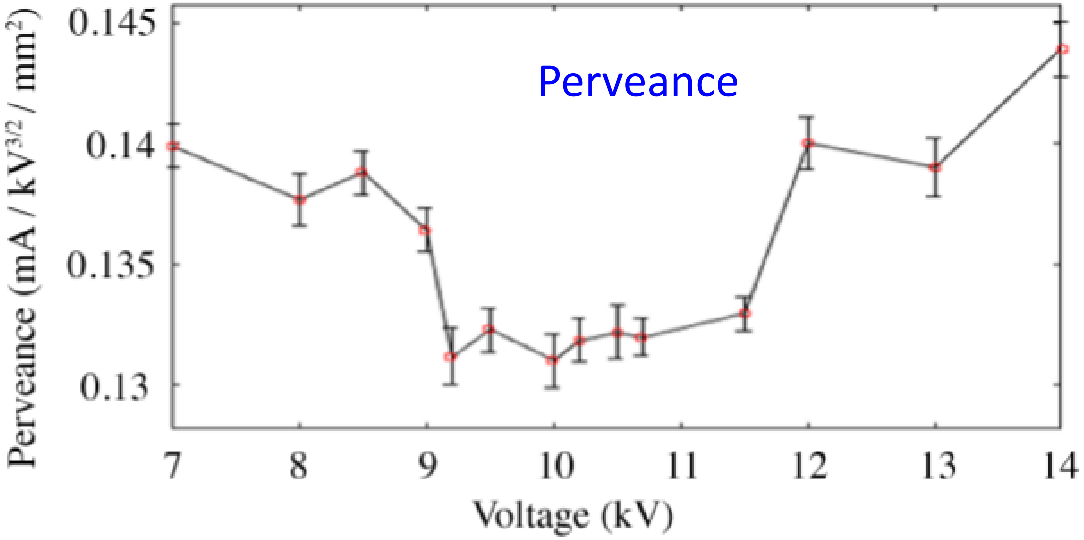
Beam formation simulation - a short summary

- Specialists
  - Serhiy Mochalskyy LPGP, CERN
    - Author of first version single hole periodic boundary conditions ONIX_V0_p, Thesis
    - Simulation of CERN's IS01 and IS02 sources PE ϕ 6.5 mm, with non-periodic boundary conditions ONIX_V1_np_64 (64 neighbouring points), (4 month) parameter sensitivity study.
  - Adrien Revel LPGP, IPP
    - Simulation of one aperture BATMAN and ELISE at IPP, ONIX_V2_p_64 (8 month) parametric geometry.
  - Mauricio Montellano IPP :
    - Detail simulation of ITER NBI relevant source 30'000 cpu days/ 2.5 μs real time
    - H^- induced potential well (1.4 eV, 0.2 mm)
  - Niek den Harder : coupling ONIX to IBSimu achieved
  - Max Lindqvist KEIO University
    - CERN IS03 beam formation, KEIO-BFX : 3D PIC with scaling (3.5×10^{-2})
- Outlook
  - Thesis at IPP (tbc.)
  - Fellowship at CERN (1/10/2019) in collaboration with IPP and LPGP
    - Goal developing ONIX_V2_np_64, improve boundary conditions (no scaling low plasma density)
    - Pushing experimental setup on Cs-layer, emittance, profile and angular distributions (scan plasma density)
    - Compare ONIX, BFX & measurements (using IBSimu or ONAX)

Effects of the extraction voltage on the beam divergence for a H^- ion source

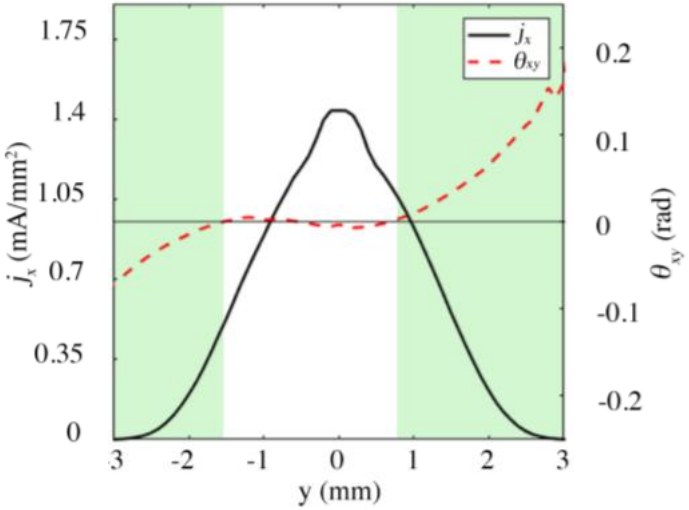
Keio-BFX "observables"



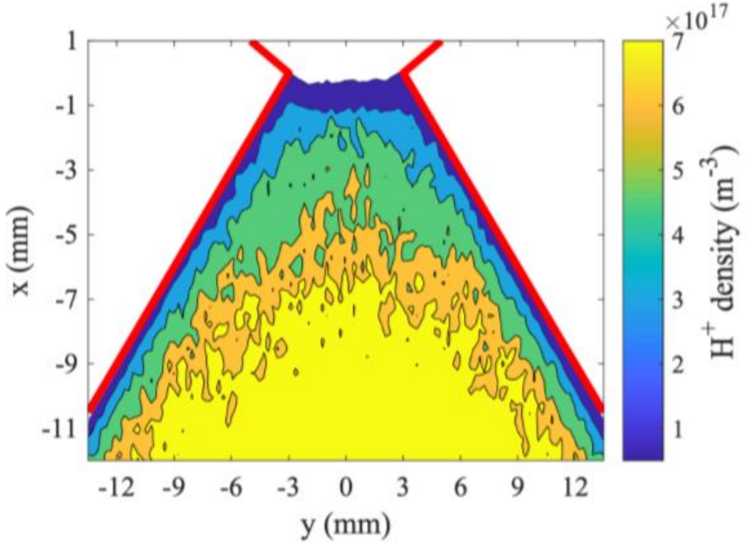


e^- density	10^{18} m^{-3}
e^- temperature	3.6 eV
H^- and H^+ temperature	1.6 eV
$e^-:H^+:H_2^+:H_3^+$	60 : 45 : 4.5 : 10.5
e^- Debye length (λ_{De})	1.41×10^{-5} m
e^- thermal velocity	7.96×10^5 m/s
e^- plasma frequency (ω_p)	5.64×10^{10} rad/s
Extraction voltage	$7 - 14$ kV
Real size	$31.75 \times 48 \times 48$ mm
Scaling factor	3.5×10^{-2}
Number of superparticles	2,500,000
Mesh	$128 \times 193 \times 193$
Mesh size	$0.625\ \lambda_{De}$
Time step	$0.4/\omega_p = 7.09 \times 10^{-12}$ s
Simulation time	$50,000$ time steps $= 0.35\ \mu$s
Magnetic field strength	$10 - 18$ mT

Divergence



Meniscus



*M. Lindqvist, S. Nishioka, K. Miyamoto, K. Hoshino, J. Lettry, and A. Hatayama, Journal of Applied Physics **126**, 123303 (2019)*

H^- sources' Perveance

- C. D. Child, *Discharge from hot CaO*, Phys. Rev. 32, 492–511, 1911.
- I. Langmuir, *The effect of space charge and residual gases on thermionic currents in high vacuum*, Phys. Rev. 2, 450–486, 1913.

Comparing H^-/D^- sources types *combined beam of electrons and H^- (D^-) ions*:

Setup	*Exp. data*		*two beams*
U, d, S	*I_{H-}, e/H,*	→	$\Pi_{nH-} + \Pi_{ne}$

Perveance: $\Pi = J_{ex}/U_{ex}^{3/2}$

federica.bonomo@ipp.mpg.de

At saturation: Π_{CL} *(m, d)* $= J_{CL}/V_a^{3/2}$

Norm Prev. $\Pi_n = \Pi / \Pi_{CL}$

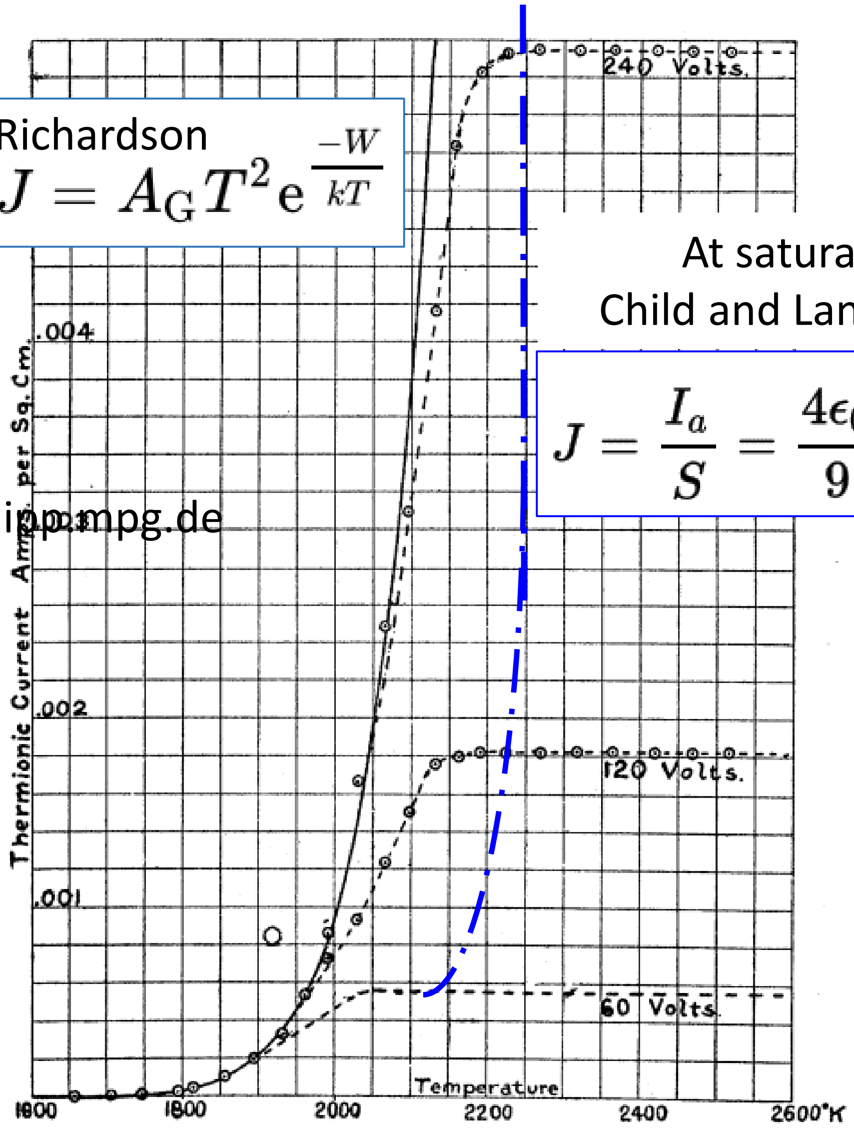
- R. Uhlemann and G. Wang, *Modified perveance law for neutral-beam ion sources*, 2879 Rev. Sci. instrum, 60, 1989.

$\Pi_{opt} = 0.6\ \Pi_{CL}$

Richardson
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

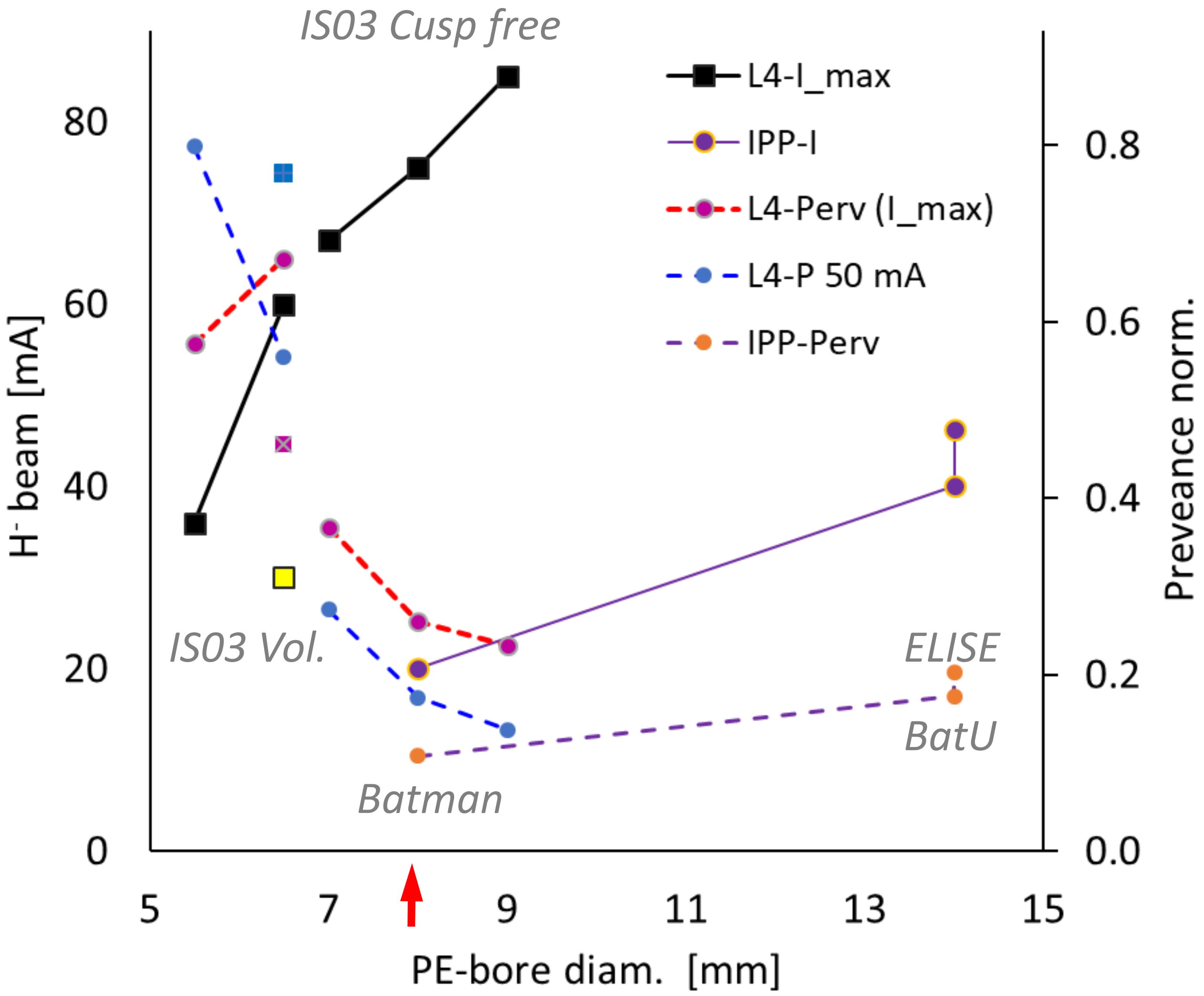
At saturation: J_{CL}
Child and Langmuir's law:

$$J = \frac{I_a}{S} = \frac{4\epsilon_0}{9}\sqrt{2e/m_e}\frac{V_a^{3/2}}{d^2}$$



Thermionic electron current density form a hot cathode

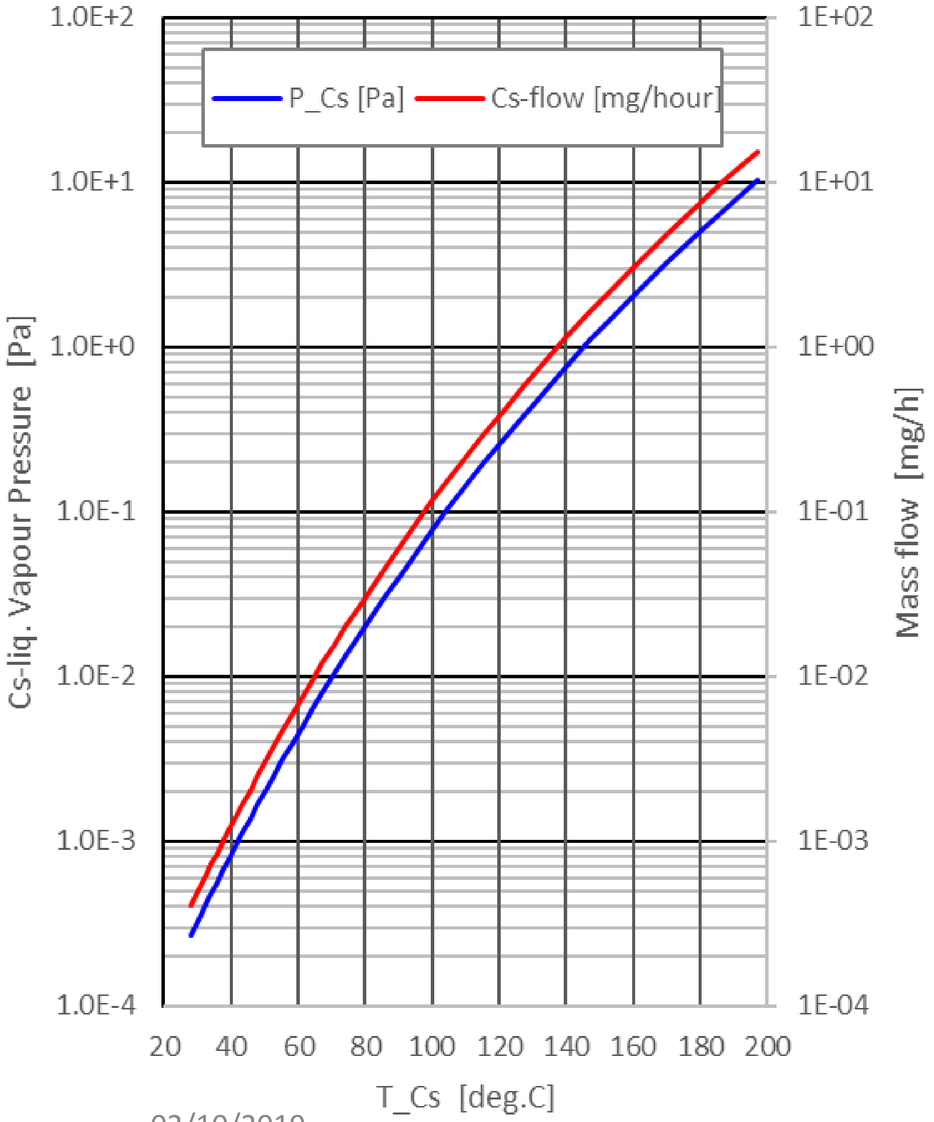
Comparing H^- sources via Normalized Perveance



		PE_diam [mm]	e/H	I_exp	N_Perv (I_exp)	N_Perv (50mA)
Linac4	Vol.	6.5	20	30	0.46	0.77
	Cusp OH	5.5	4	36	0.58	0.80
	8-pole	6.5	3	60	0.67	0.56
	Cusp Free	7	1	67	0.37	0.27
		8	1	75	0.26	0.17
		9	1	85	0.23	0.14
NBI-IPP	Batman	8	1	20	0.11	
	BatU	14	1	40	0.18	
	Elise	14	1	46	0.20	

Goal : Operation of the L4 single hole H^- source at perveances corresponding to nominal current of IPP test sources

Cs-mass flow control & measurements



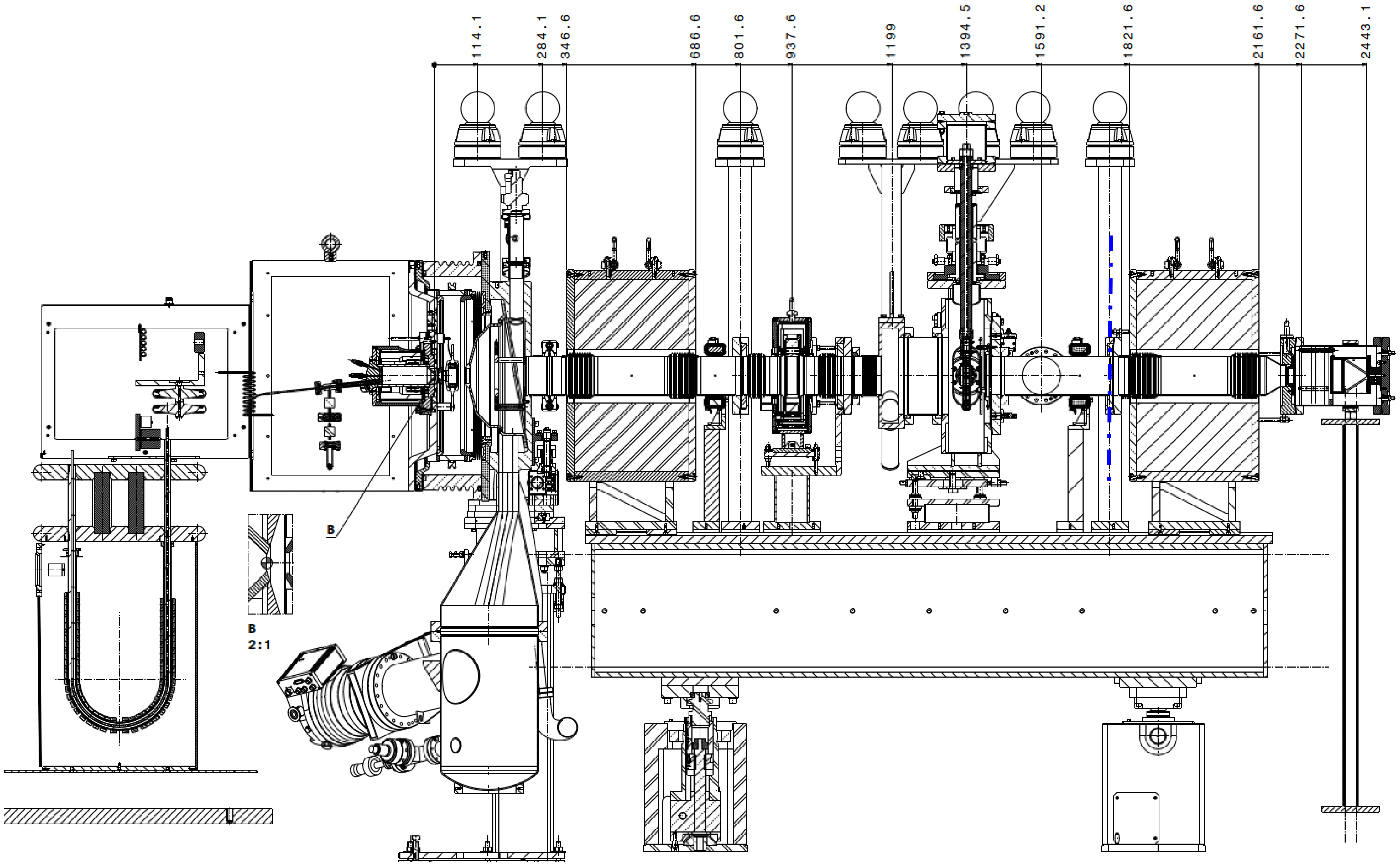
Measurement Options:

1) Hydrogen and Deuterium
2) Protons + H^{2+} + H^{3+},electrons, D^- and H^-
3) Volume mode and Cs-surface mode:
4) PE-geometries and Puller fields
5) Spectroscopy
6) Cs-thickness on PE

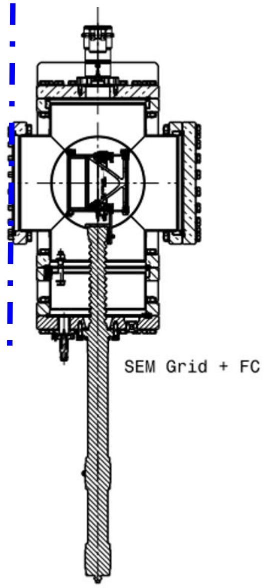
- ➢ Beam Emittance
- ➢ Beam Profile
- ➢ Beam divergence BES

- Tune op. parameter to chosen Perveance
- Cs-flow control allows keeping e/H < 1
- Beam intensity set via autopilot

1) ISTS : 2 sol. with E-meter and RFQ box or SEM grid



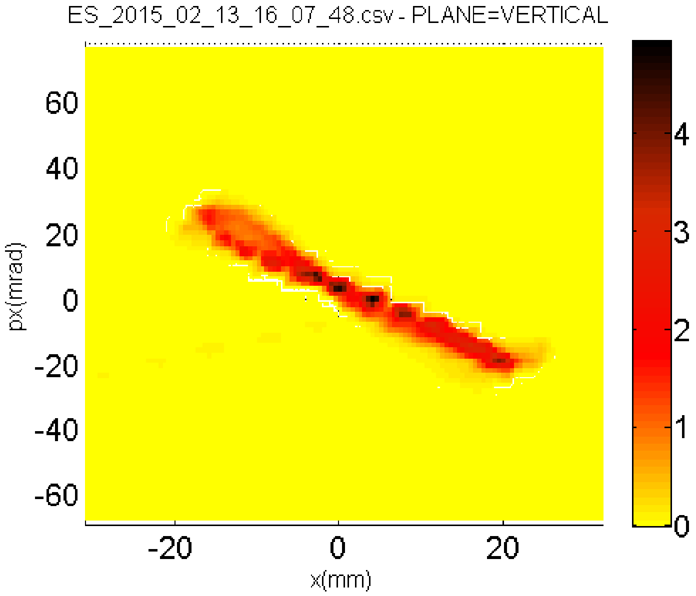
Cross equipped with SEM grids and BES telescope or Faraday cup



Emittance & Back Tracking

IS02$_b$ emittance meas.:

- ✓ H^- intensity [0-380 μs] 45 mA
- ✓ Electron to ion ratio: 1.3
- ➢ 90% within 0.3 π·mm·mrad $_{RMS}$
- ➢ Expected RFQ-transmission 83%
- ➢ Max seen after RFQ 30 mA

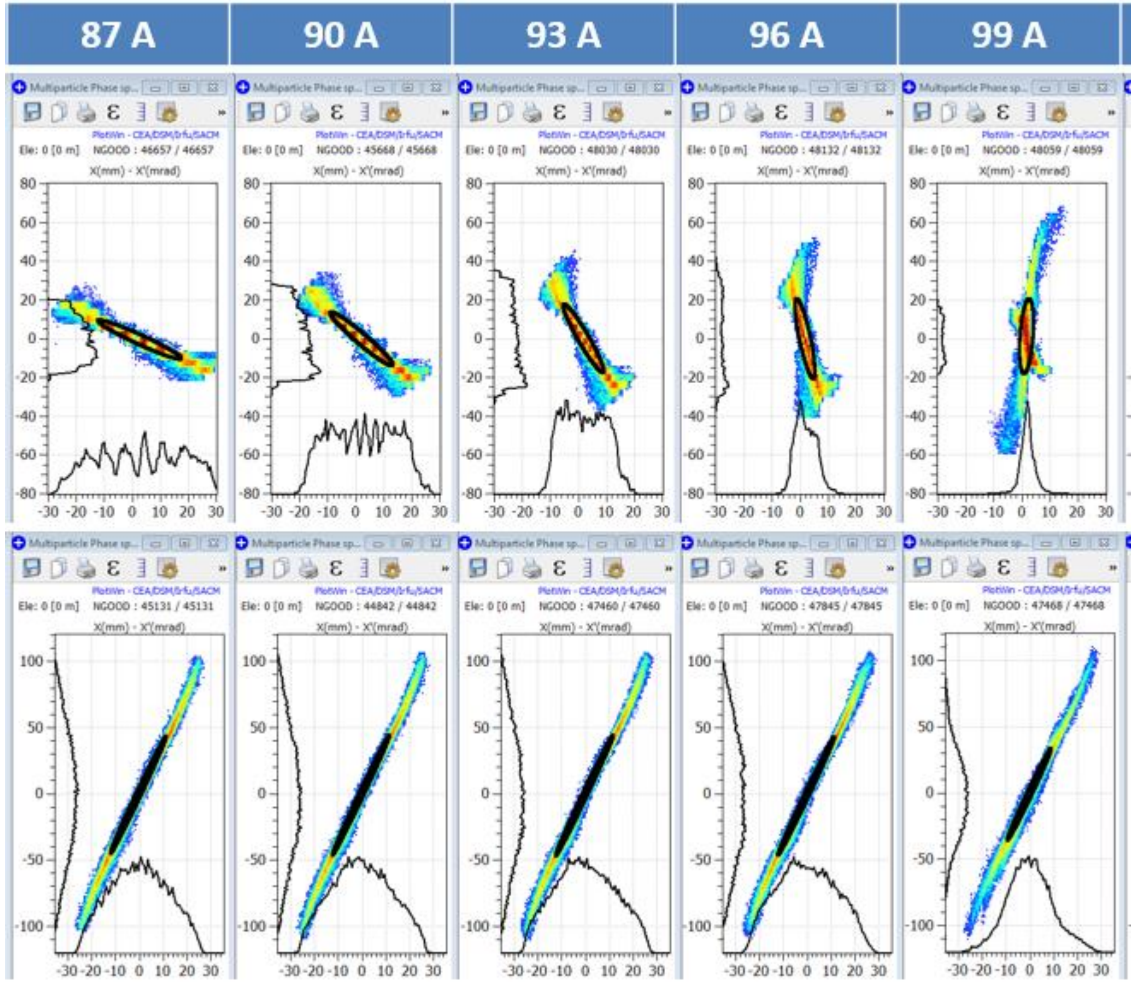


2015-01-10

Courtesy: R. Scrivens, D. Fink & J.B. Lallement

Back Tracking:

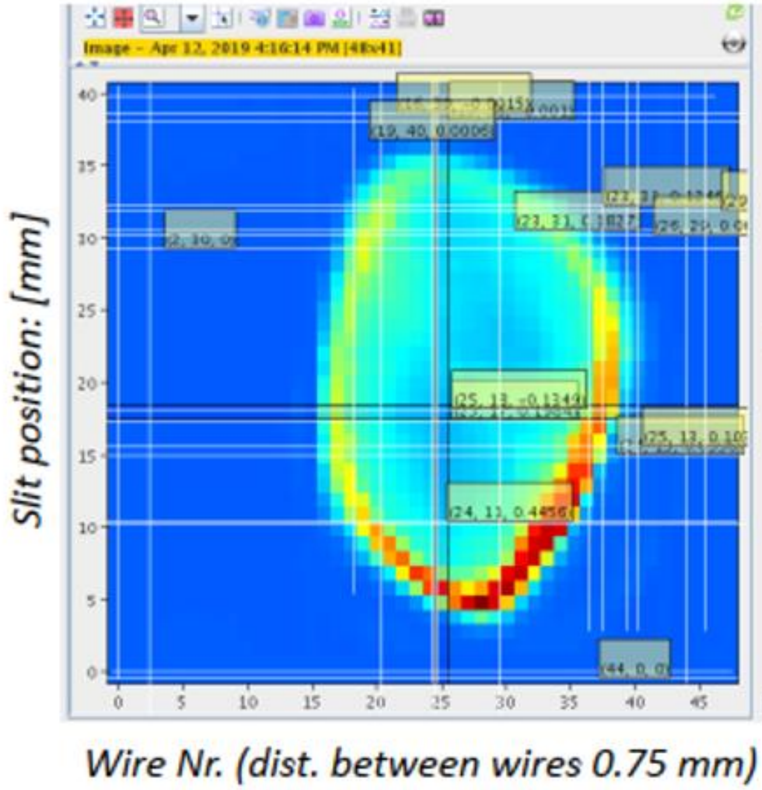
- ✓ Sampling from ε-meas. distributions.
- ✓ Back tracking to an arbitrary beam origin.
- ✓ Validate back tracking stability vs. optics setting
- ➢ Transport from this origin through the Linac4

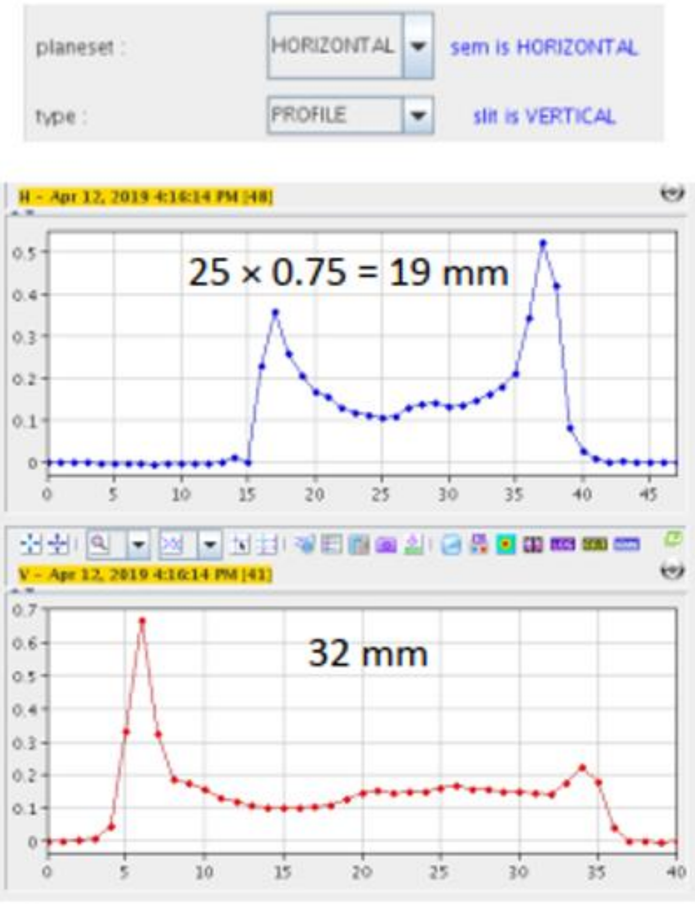


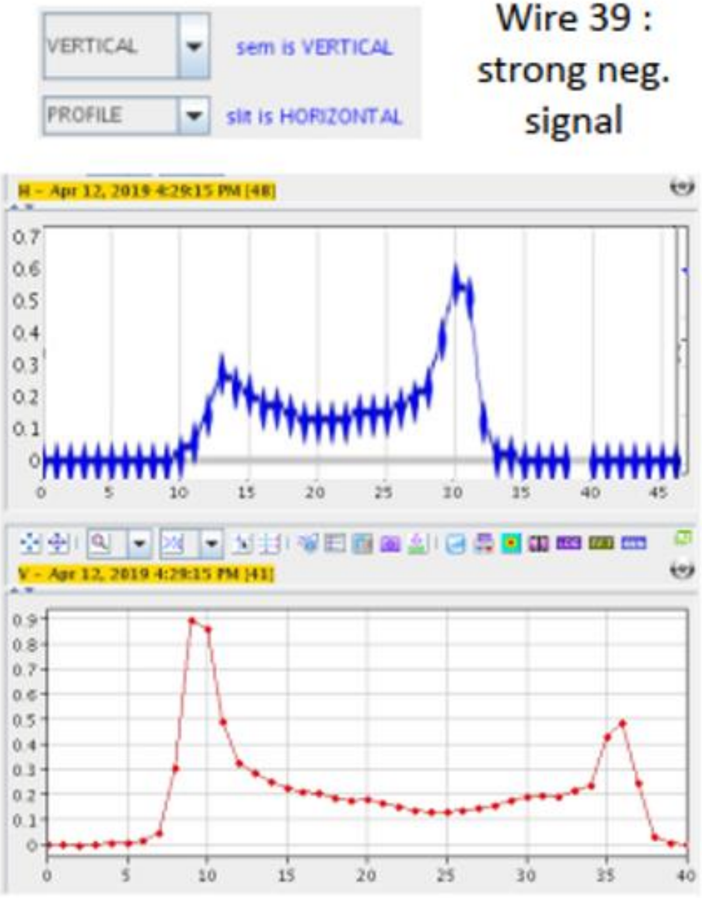
Beam profile: To improve particle extraction form emittance

H^- beam 42 mA

H/V: 1.65 -2.2 A







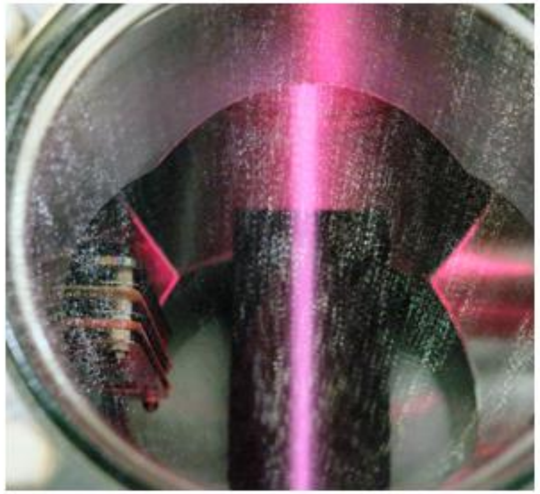
Wire 39 : strong neg. signal

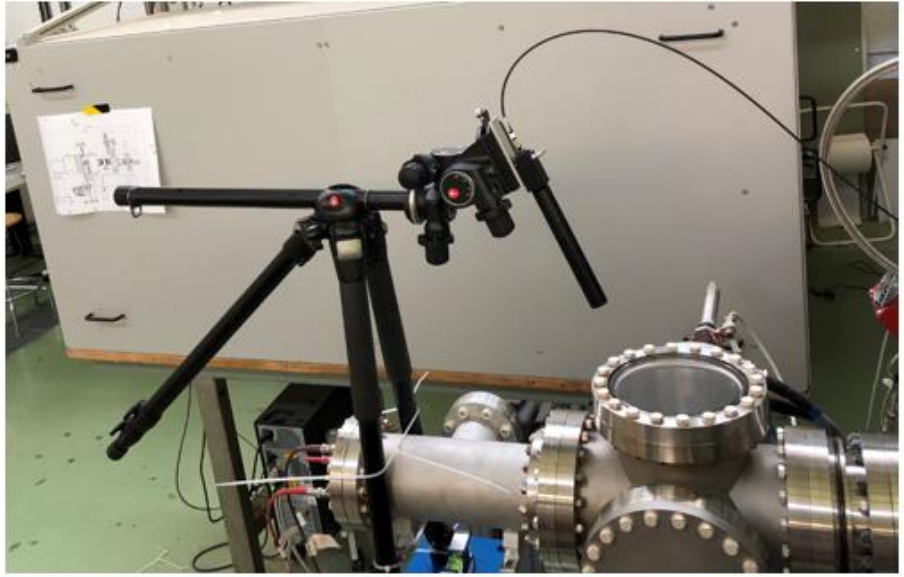
- Beam asymmetry: 19 × 32 mm, due to beam convergence.
- Asymmetric Bird's nest shape
- Naming refers to the E-measurement

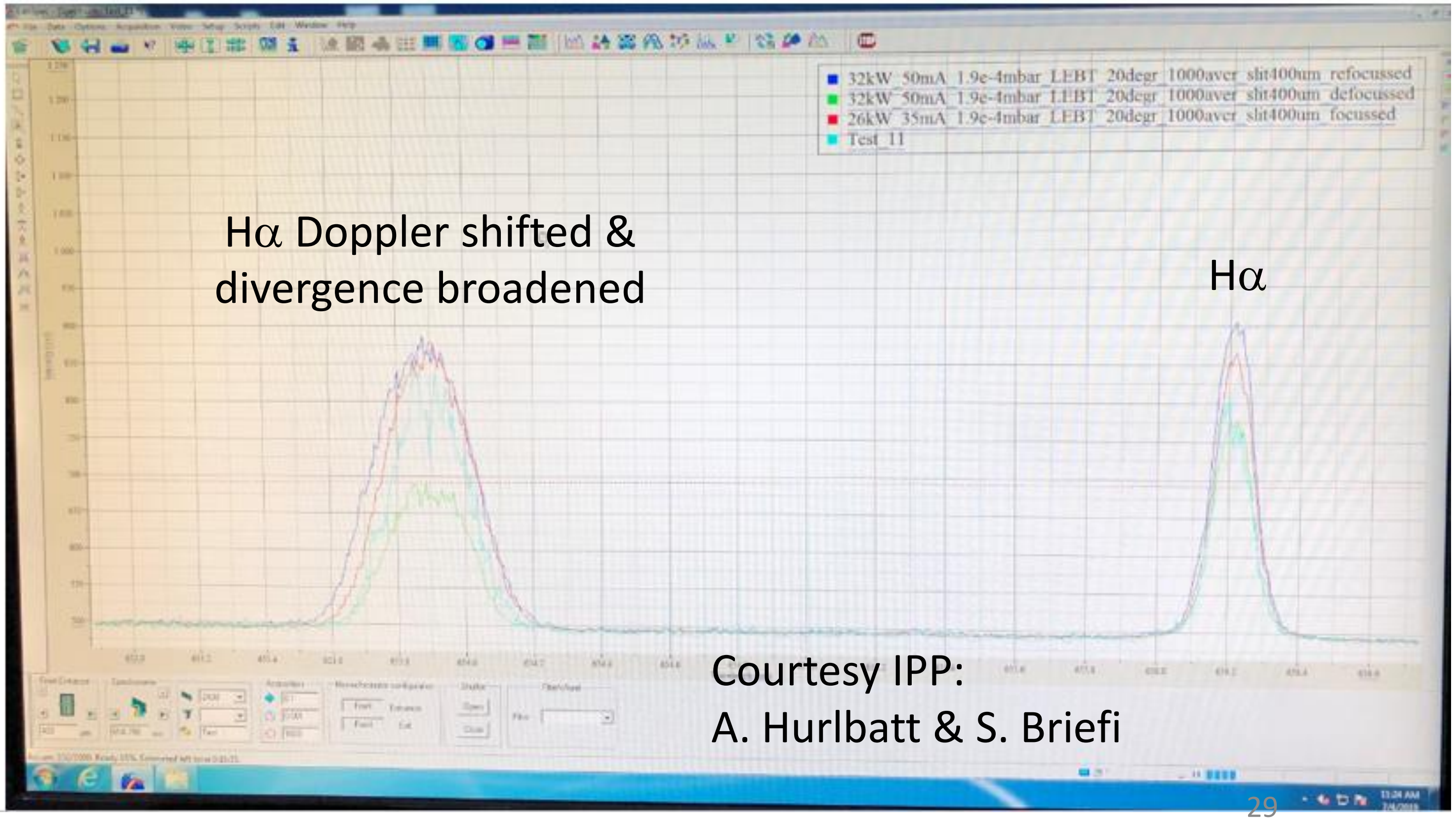
12,24/04/2019

Great support form Stephane Bart Pedersen Federico and BI-team

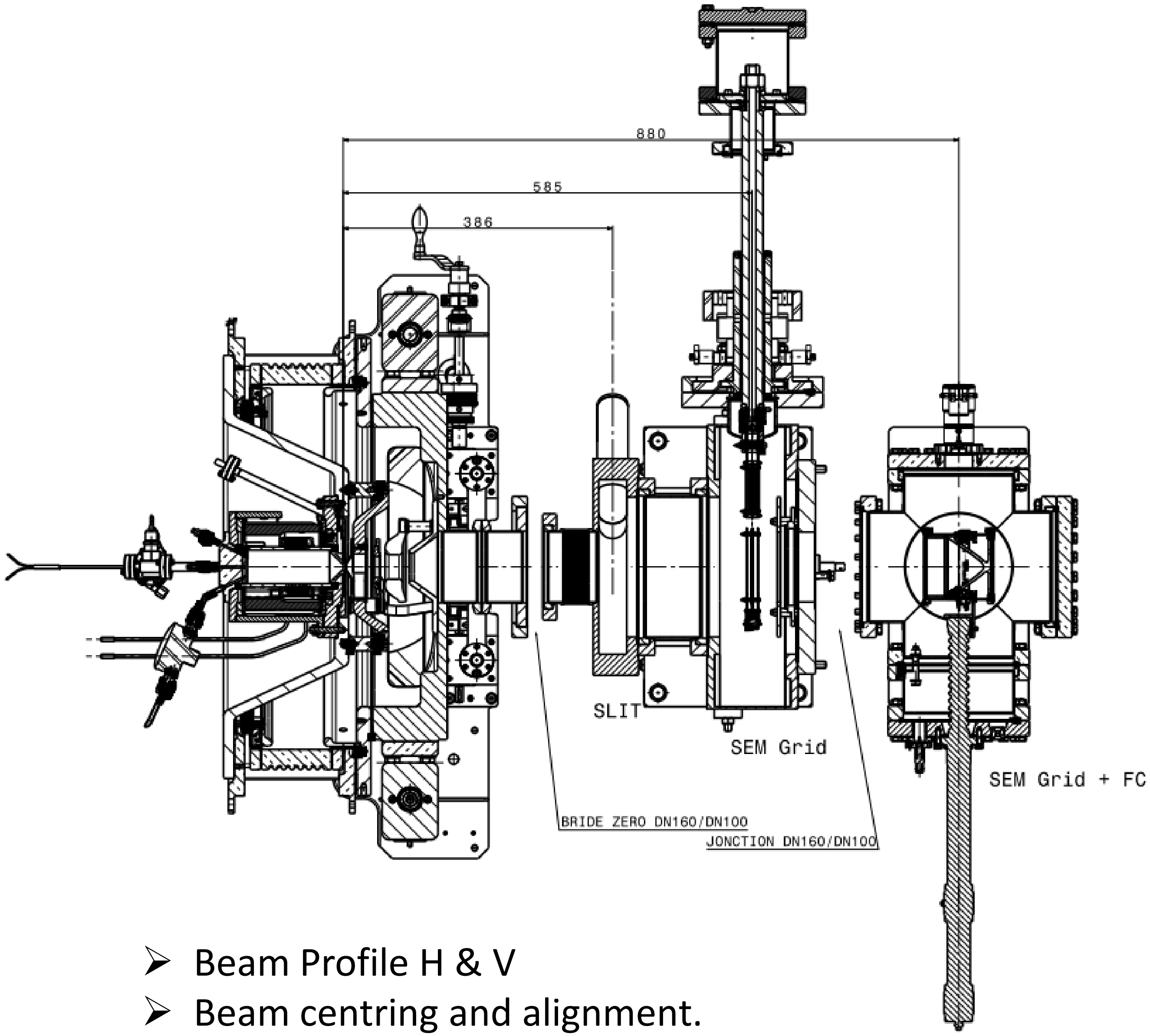
Stefan & Andrew, 2019/07/02-04
first BES @ CERN's IS03

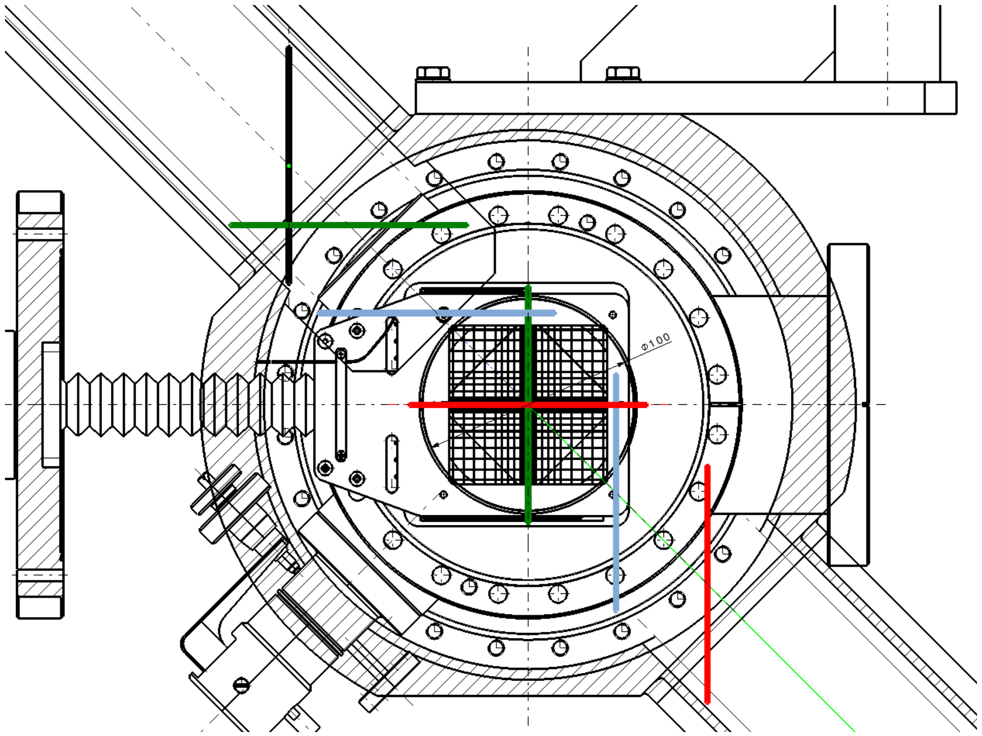






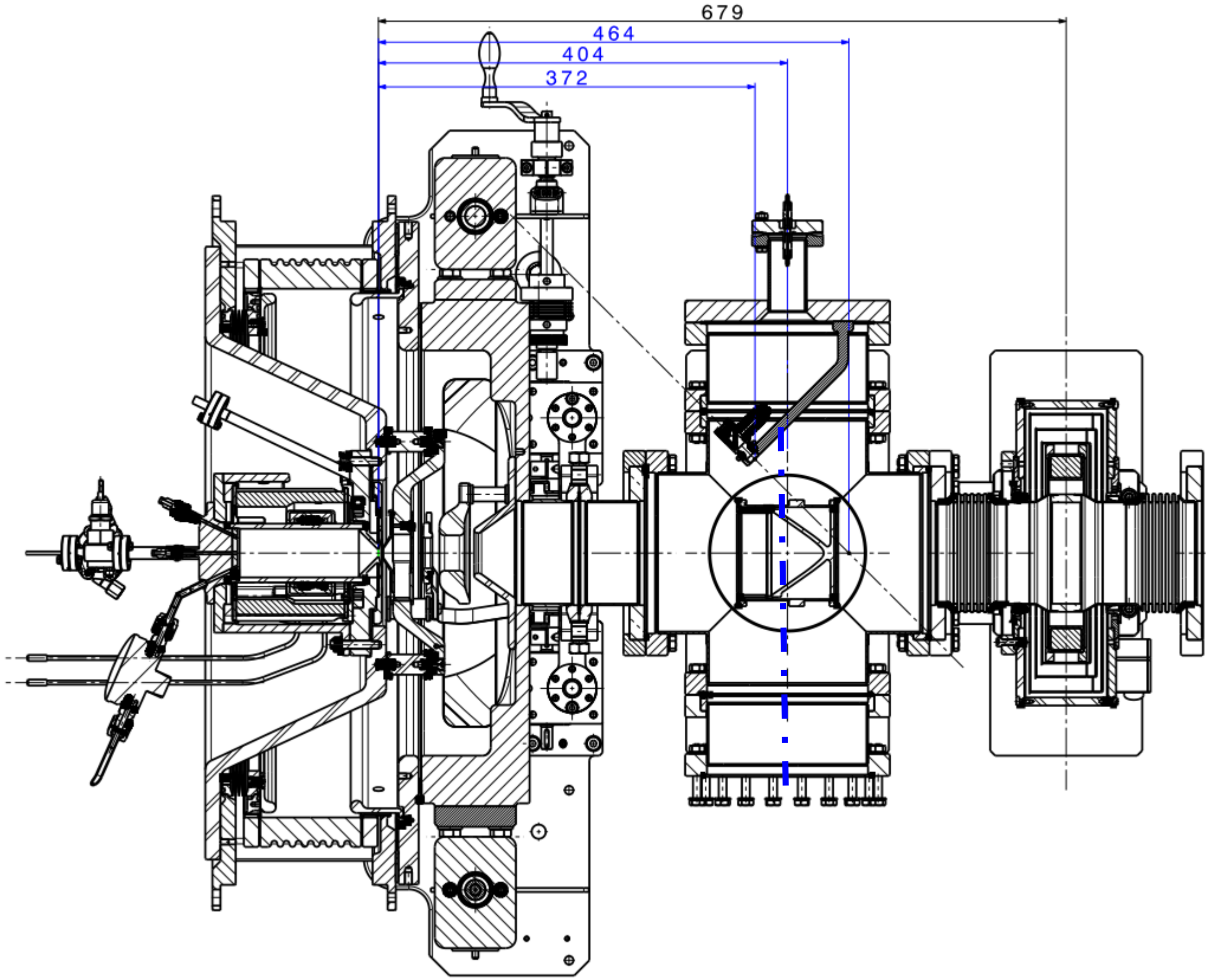
2) E-meter + x-y beam profile (2D) and BES



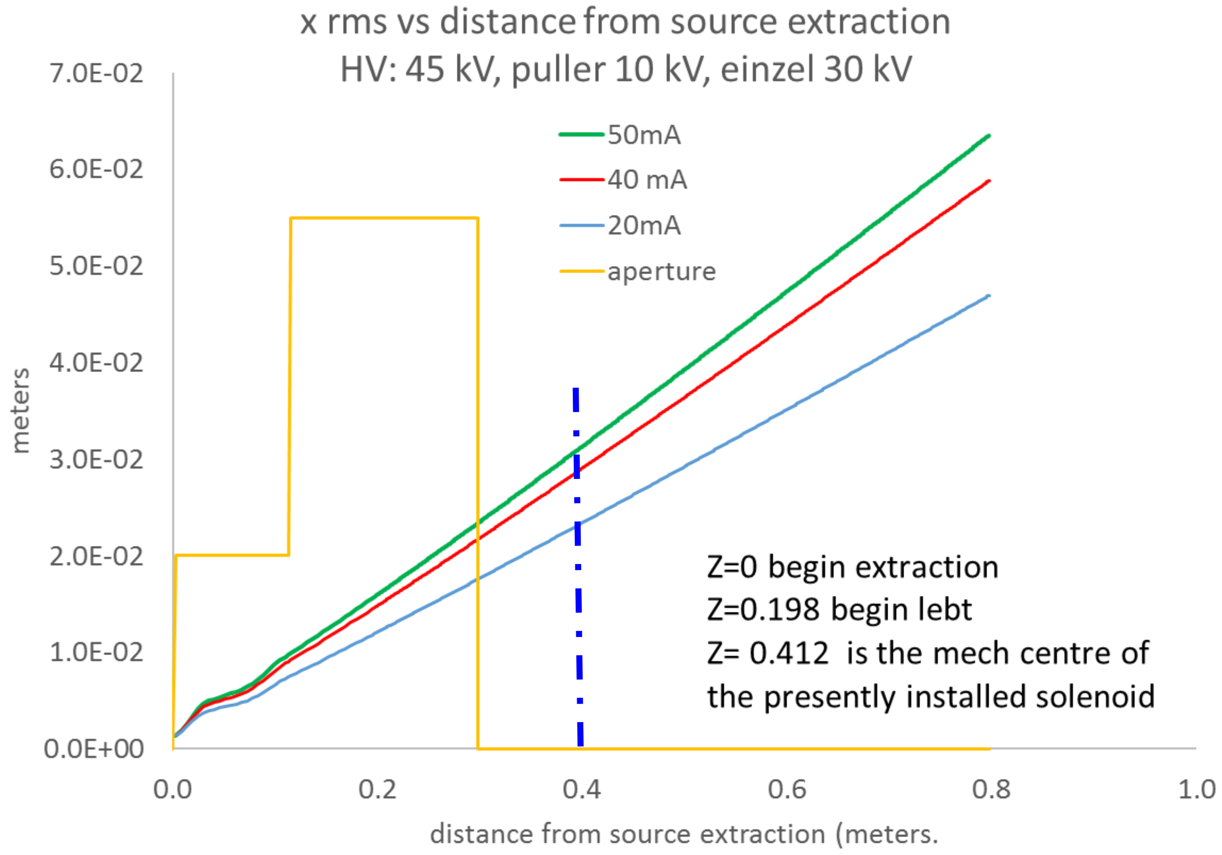


- Beam Profile H & V
- Beam centring and alignment.

1) BES detection and SEM grids + BCT



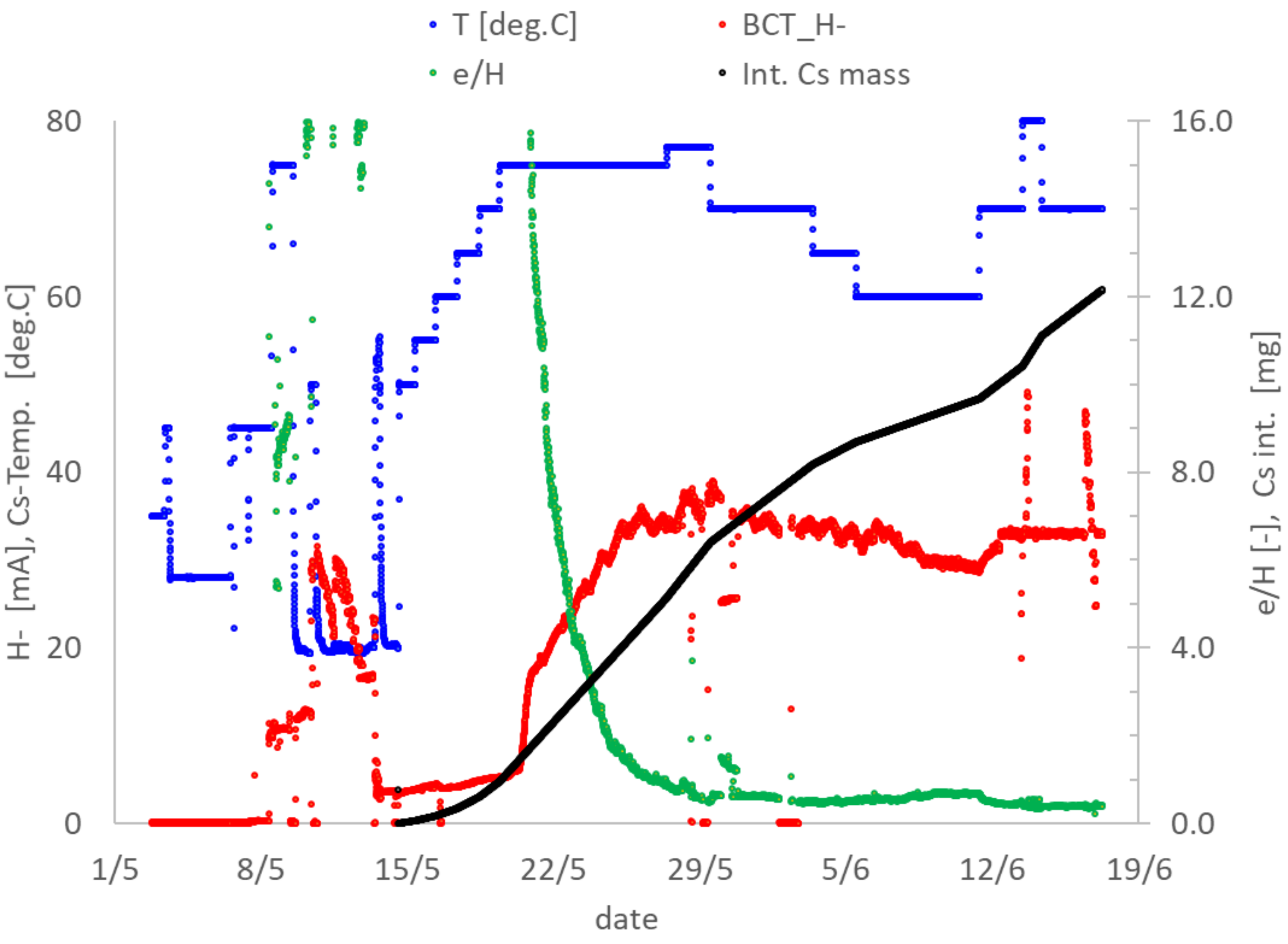
400 mm from the source is the limit for BES meas. without Solenoid, further downstream, a large fraction of the beam will be intercepted by the pipe.



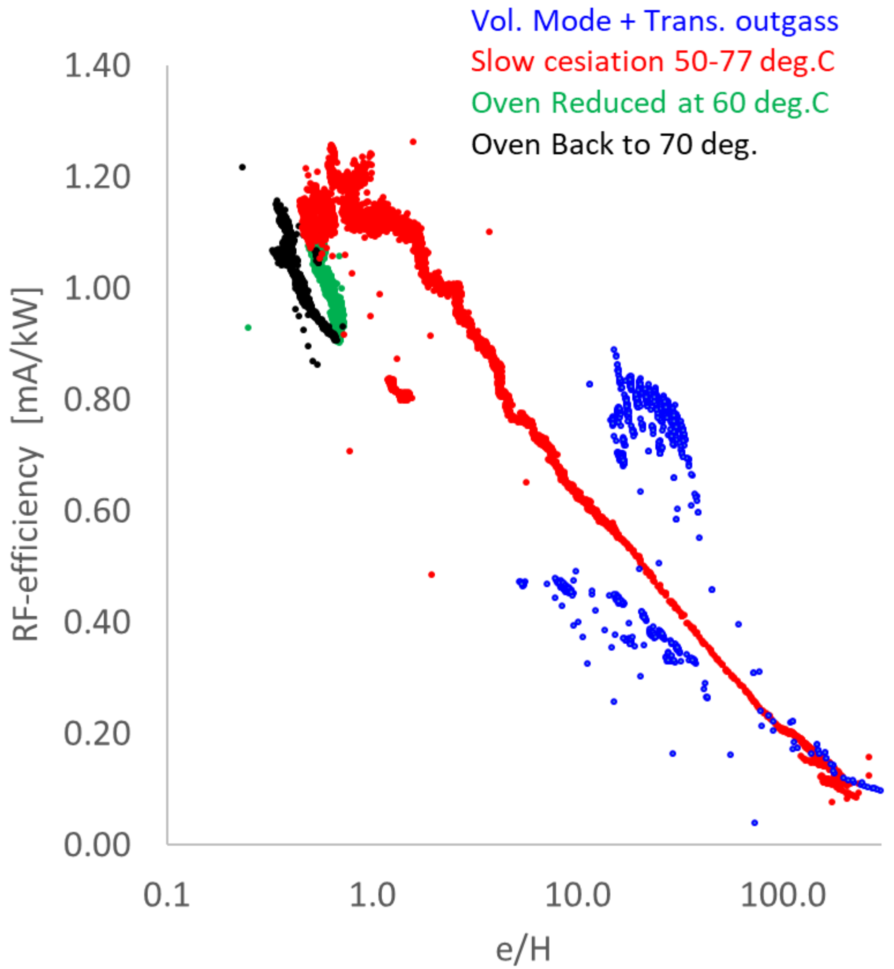
Courtesy: A. Lombardi

Cs-loss compensation tests may-June 2019

PE-ϕ : 7.5 mm

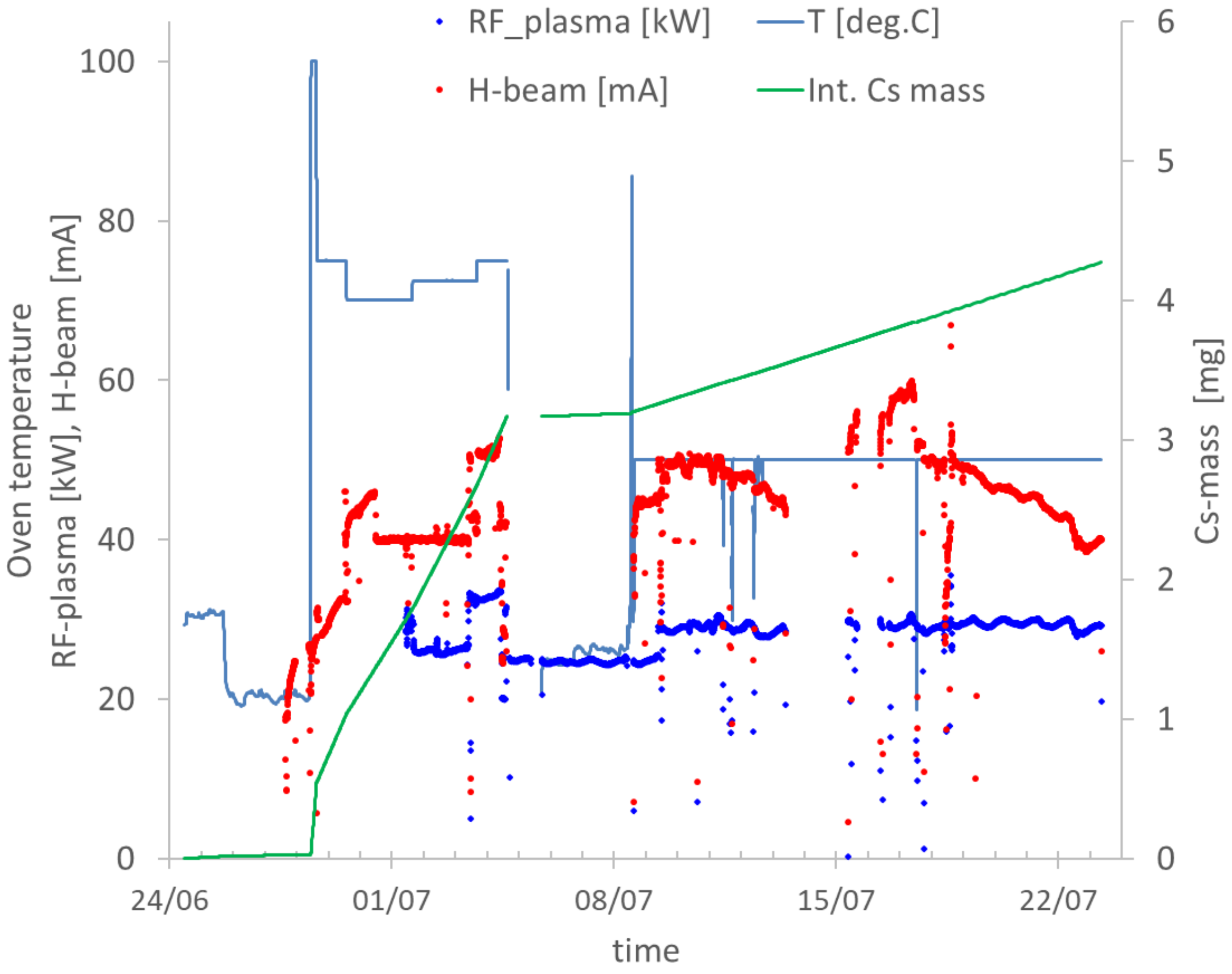


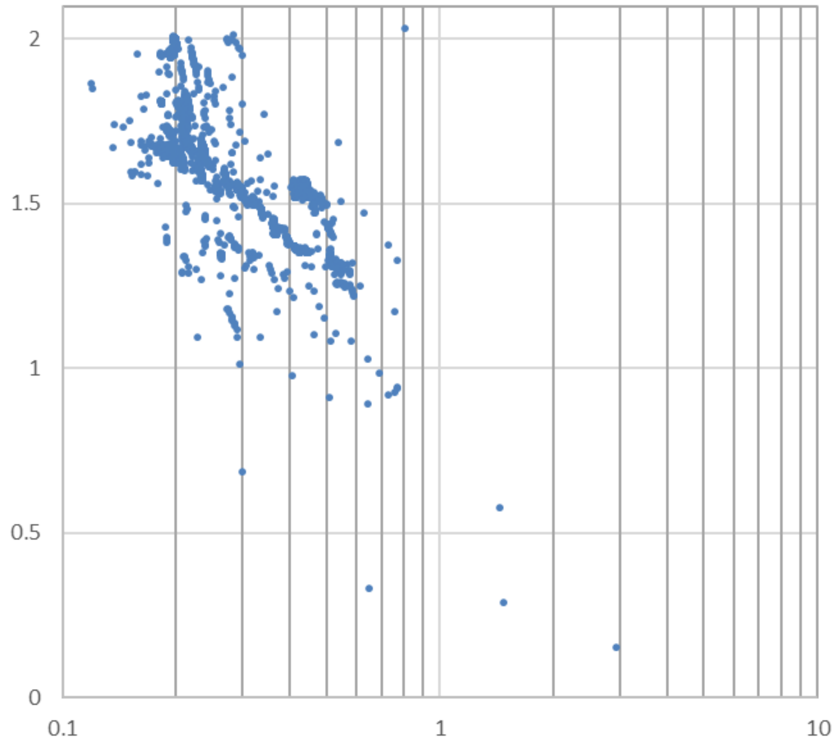
Cs-loss compensation tests e/H <1
Suspicion of pollution (initial e/H ~150)
82.64 mono-layer of Cs



BES tests June-July 2019

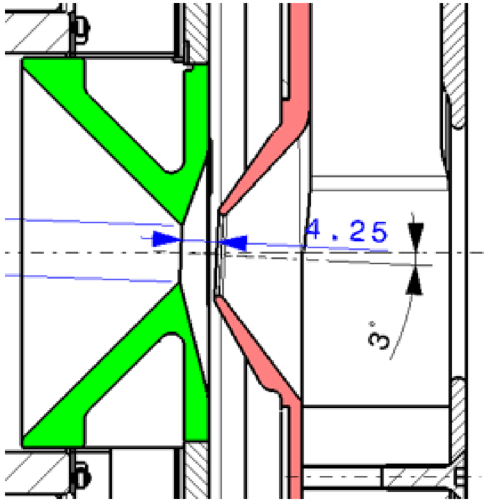
Clean PE-ϕ : 9 mm



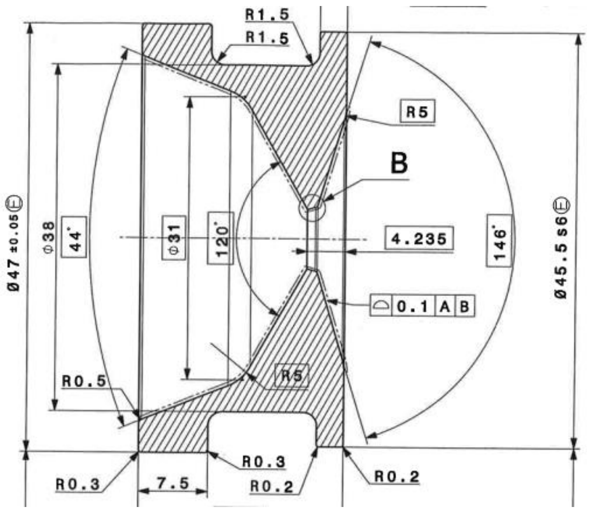


PE-Puller-dump electrodes geometry options

a) IS03, b) tilted IS03 f PE-aperture 8mm

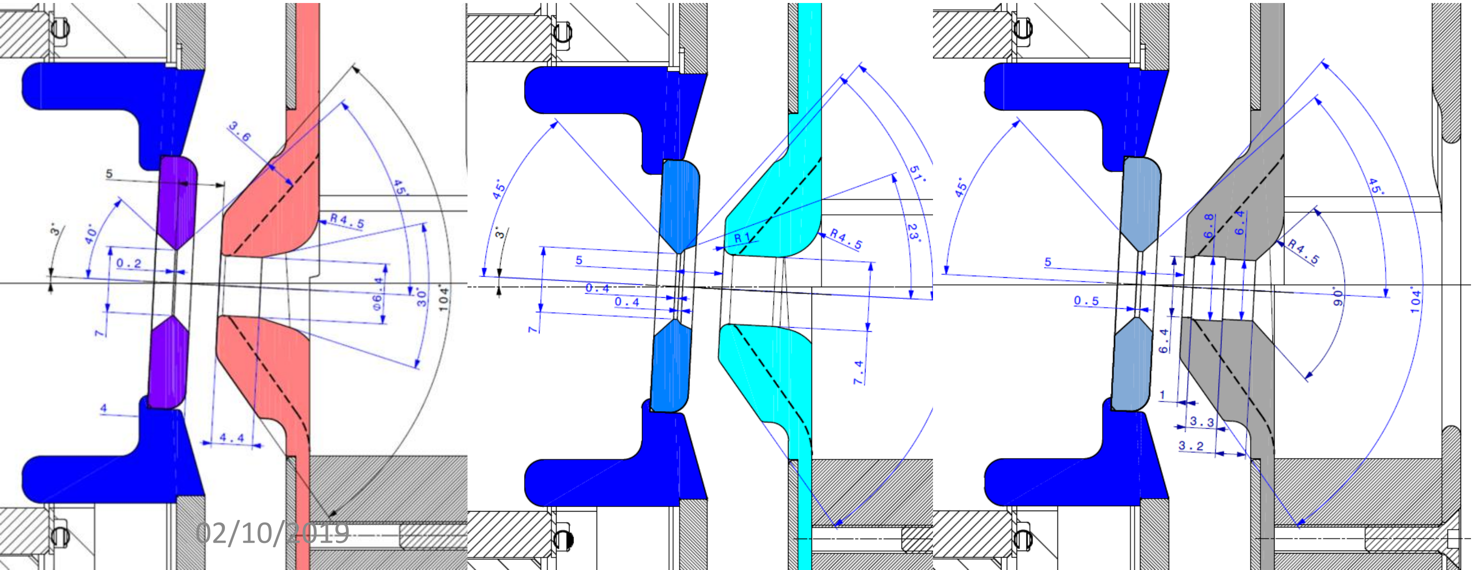


f) Variation of chamfer and inner angle of PE



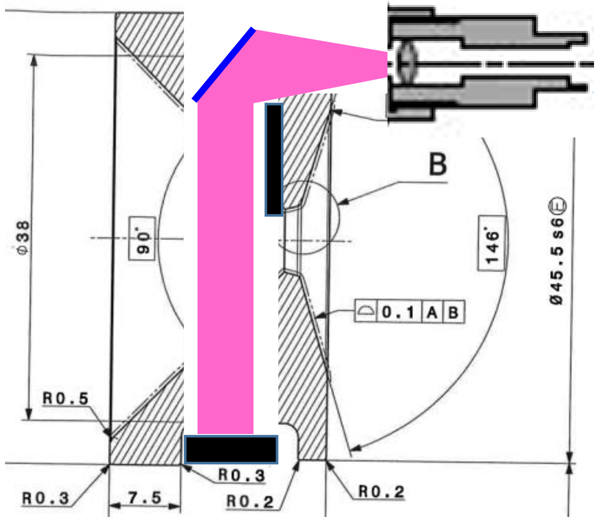
We can produce a PE with chosen plasma boundary condition (i.e. all metal)

c) ELISE, d) ITER, e) Batman, scaled down



g) Beam formation region: plasma studies configuration (no beam extracted)

Mirror *Light fiber collector*



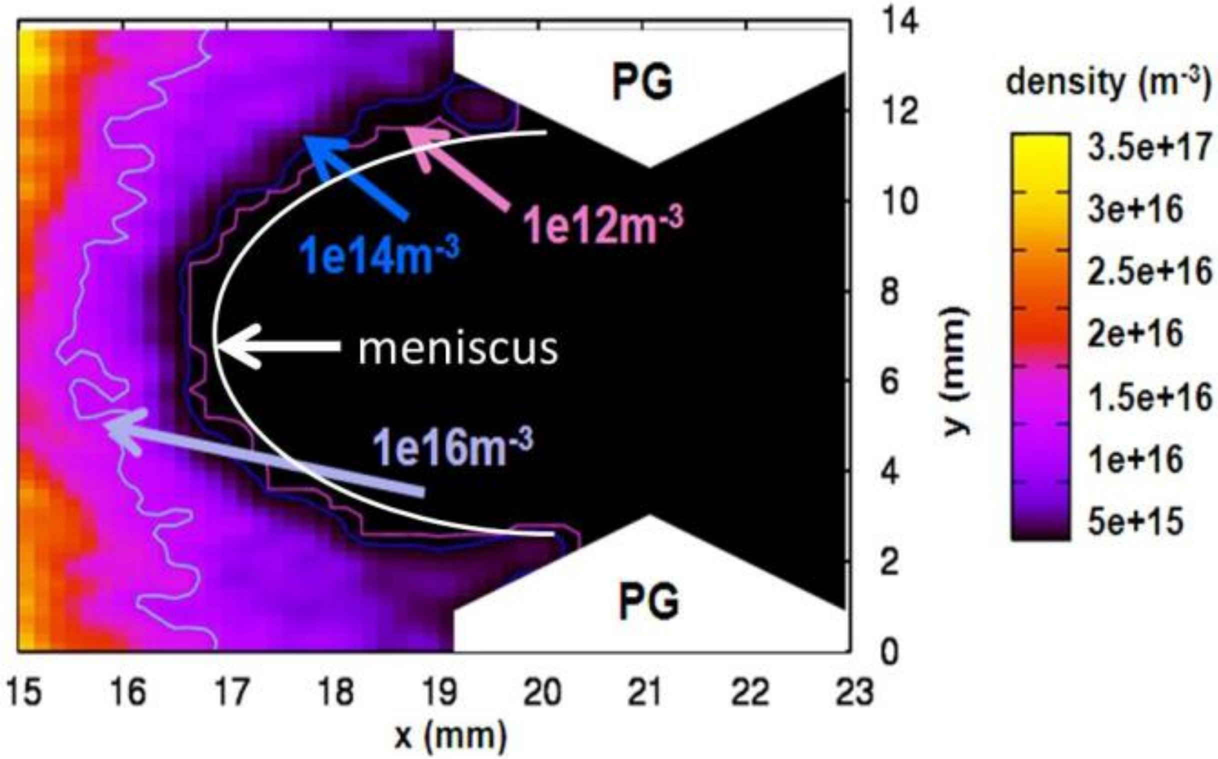
Black eloxed absorbers

Resumé et perspectives

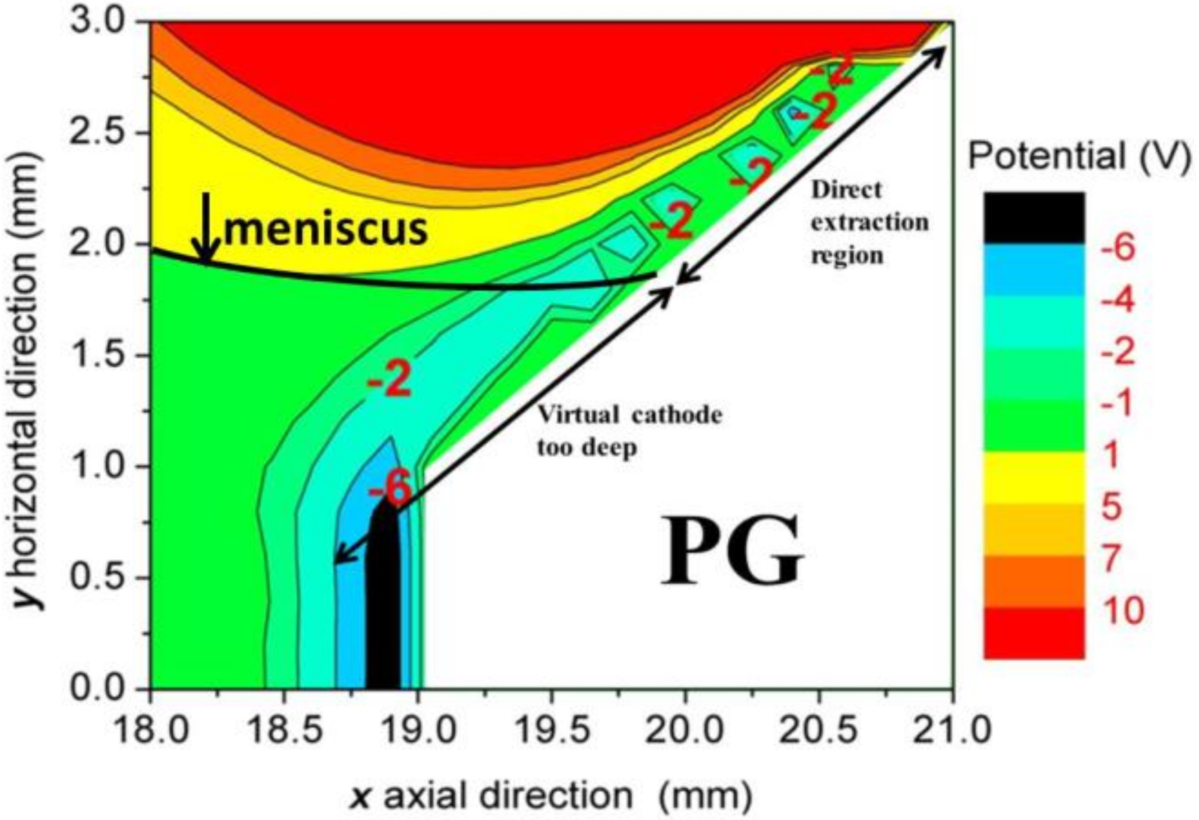
- High resolution ONIX work on Linac4 H^- source is just starting
- In collaboration with IPP and LPGP:
  - Improvement of ONIX non-periodic conditions
  - Implement flux on Cs-surface, validate down stream boundary condition (effect of beam space charge)
  - Gain knowledge on Cs-surface pot. well and plasma potential
- Experimental validation goals:
  - Validation of Emittance and profile measurement
  - Analysis of BES data closest to ion source
  - Variation of experimental setup and parameters to cover MINJA BFX and ONIX domains
  - Variation of PE and puller Geometry to minimize emittance and halo
  - Challenging OES meas. of plasma parameters in the beam formation region
  - Cs-flux requirement for Hydrogen and Deuterium

- Results expected in … 1-2 years

ONIX simulation of Fusion's tokamak Neutral Beam Injector Test bench BATMAN IPP Garching



H⁺ density distribution close to the PG
ONIX simulation of BATMAN IPP Garching



Potential distribution close to the PG

On the meniscus formation and the negative hydrogen ion extraction from ITER NBI relevant ion source
S. Mochalskyy, D. Wünderlich, B. Ruf, U. Fantz, P. Franzen and T. Minea

Tentative ongoing to add Cs, Cs^+ in the plasma
- ➢ Challenging time scale × 11.5 ($133^{½}$)

References on simulation

- S. Mochalskyy, J. Lettry, T. Minea, A. F. Lifschitz, C. Schmitzer, O. Midttun, D. Steyaert, *Numerical modeling of the Linac4 negative ion source extraction region by 3D PIC-MCC code ONIX*, *AIP Conf. Proc.* 1515 (2013) pp.31-40.
- S. Mochalskyy, J. Lettry and T. Minea, *Beam formation in CERNs cesiated surfaces and volume H^- ion sources,* New J. Phys. 18 (2016) 085011.
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- S Mattei, K Nishida, S Mochizuki, A Grudiev, J Lettry, M Q Tran, A Hatayama, *Kinetic simulations and photometry measurements of the E-H transition in inductively coupled plasmas,* Plasma Sources Sci. Technol. 25 065001(2016).
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