Key parameters for the H^- velocity distribution at the plasma meniscus of a caesiated negative ion source

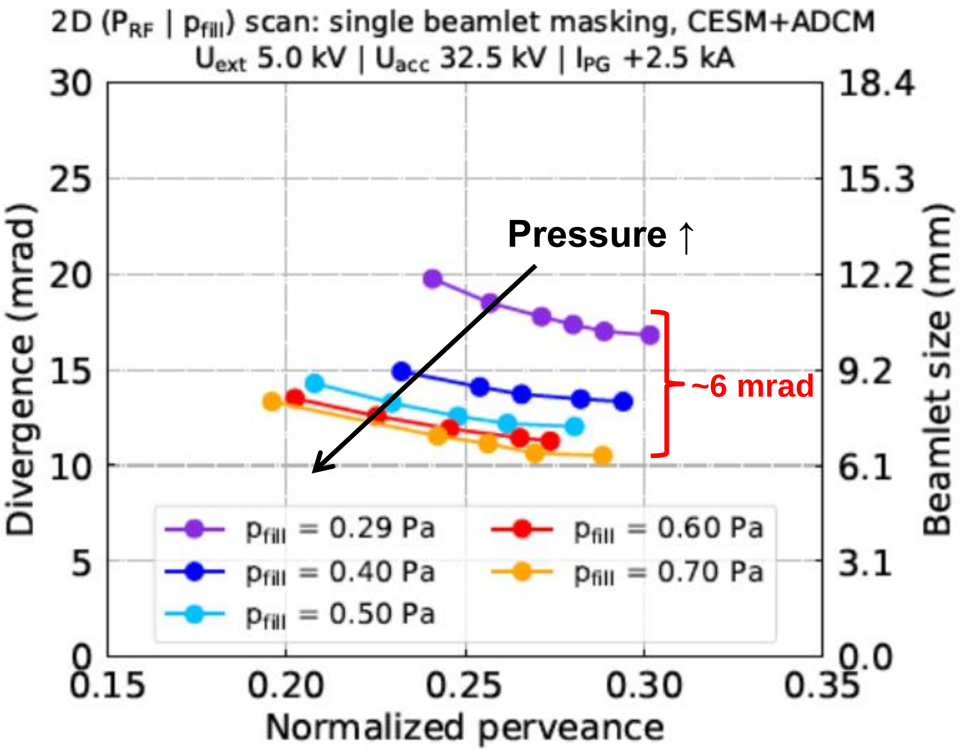
A. Pimazzoni, E. Sartori, G. Serianni and P. Veltri

8th International Symposium on Negative Ions, Beams and Sources
Padova, Italy, October 2-7, 2022

Outline

- Motivation
- ICARO: a test particle code w/ Monte Carlo collisions
  - Description and comparison with literature
  - Investigation of the pressure dependence
- Coupling of ICARO to a ray tracing code

Motivation: beamlet optics, experiments



N. Den Harder et al. 2022 J. Phys.: Conf. Ser. ***2244****, 012053*

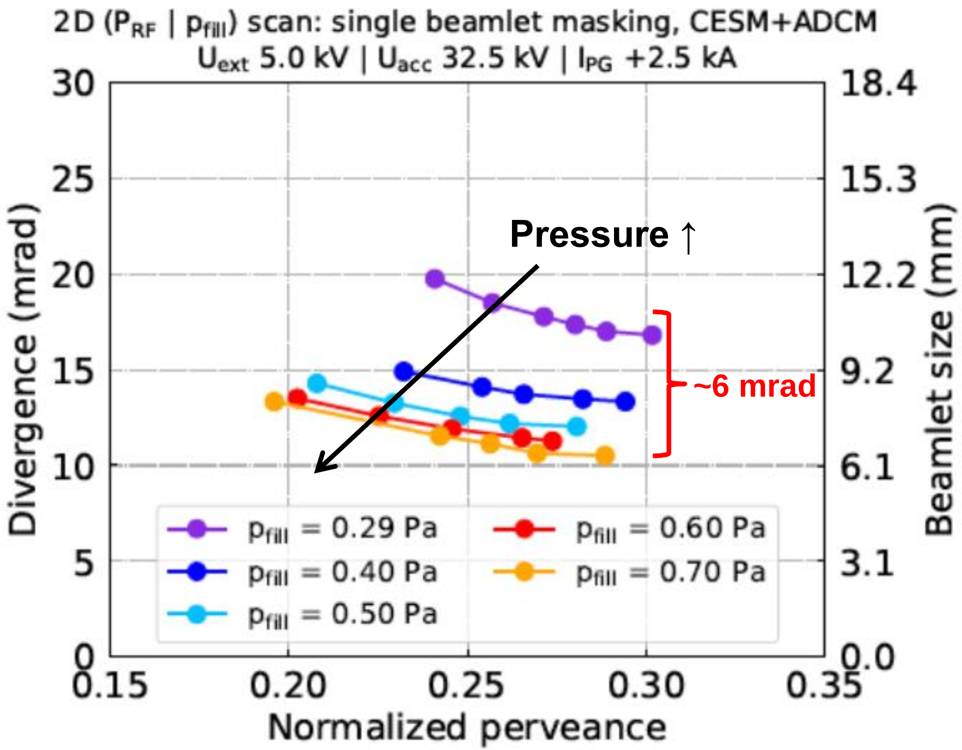
Talk by P. Veltri Mon O5

Experimental evidence

Beam divergence from RF sources under development for the ITER HNB/DNB is highly sensitive to the source filling pressure

$$Div = Div(I_{ex}/U_{ex}^{1.5}, E_{beam}, T_{H-})$$

Motivation: beamlet optics, experiments



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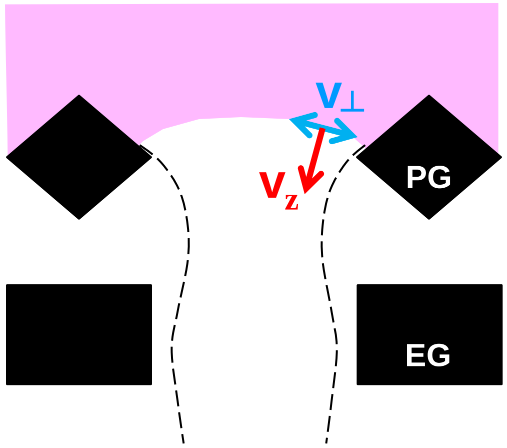

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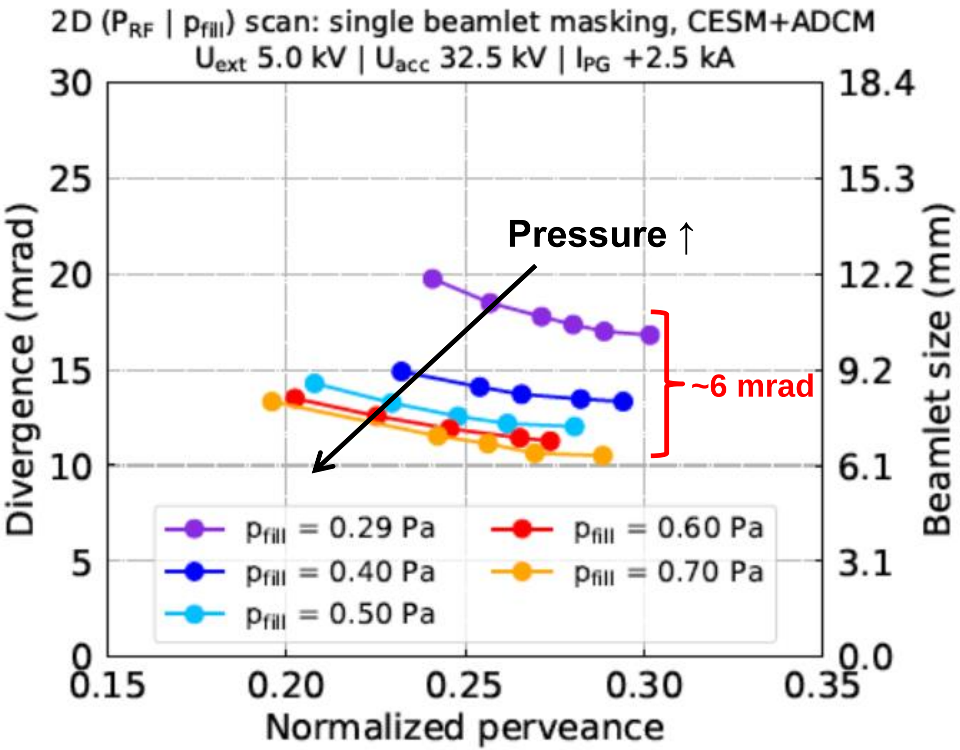

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Experimental evidence
Beam divergence from RF sources under development for the ITER HNB/DNB is highly sensitive to the source filling pressure

$$Div = Div(I_{ex}/U_{ex}^{1.5}, E_{beam}, T_{H-})$$

Hypothesis
Being perveance and beam energy the same, we can conclude that pressure affects the negative ion velocity distribution at the plasma meniscus
But how?

Outline

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  - **Description and comparison with literature**
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ICARO: Plasma domain and particle motion

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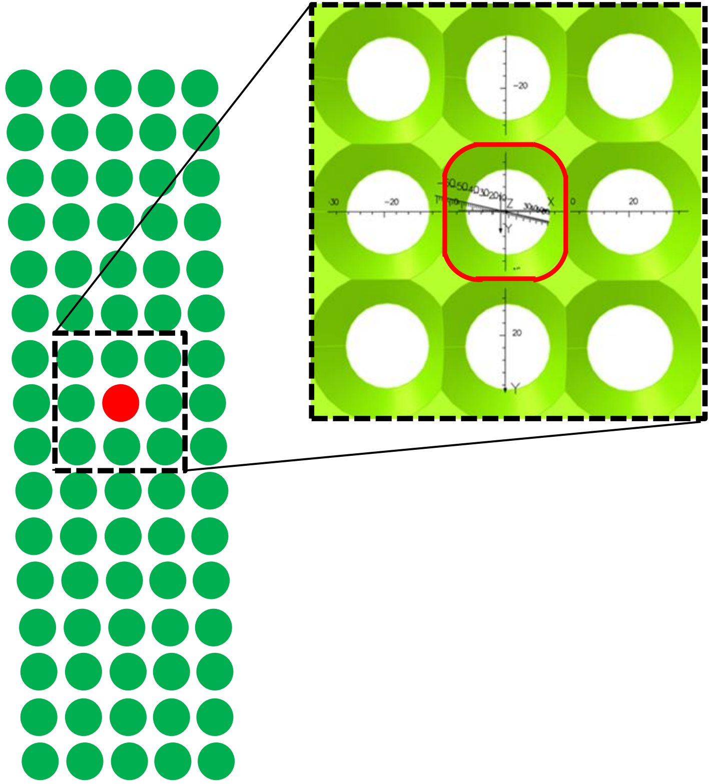
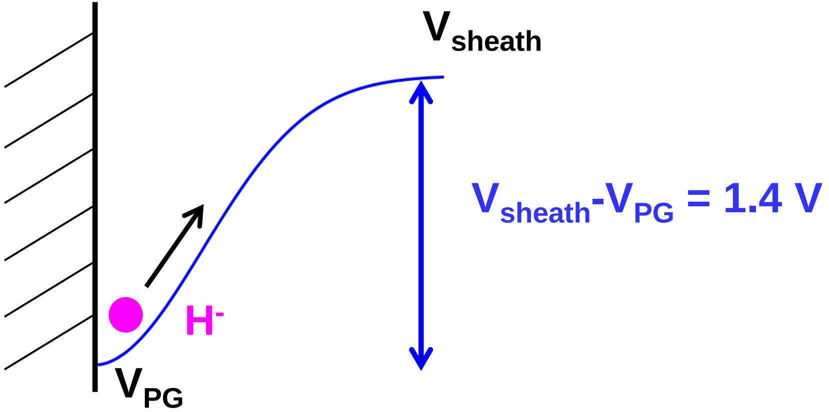


SPIDER beamlet group: 5x16 apertures

- Emission with a cosine distribution from the upstream chamfered part of the PG (only from the aperture centered in [0,0] mm)
- H^- are emitted from the PG with an initial energy that already considers the potential difference V_{sheath}-V_{PG}
  - Virtual cathode is not considered yet



ICARO: Plasma domain and particle motion

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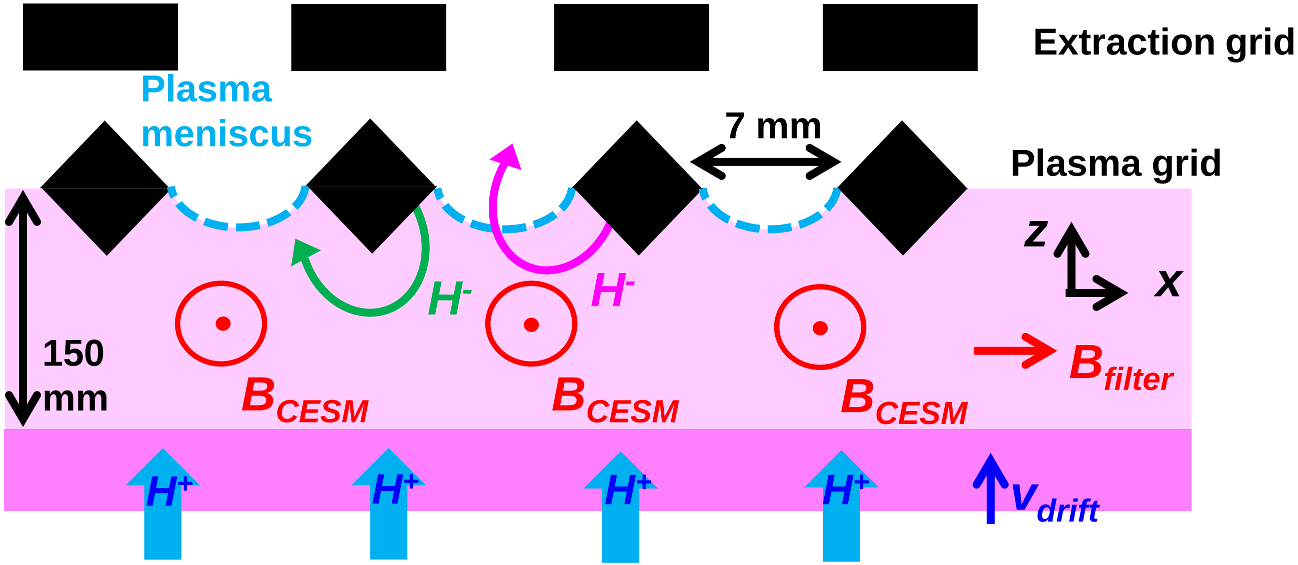
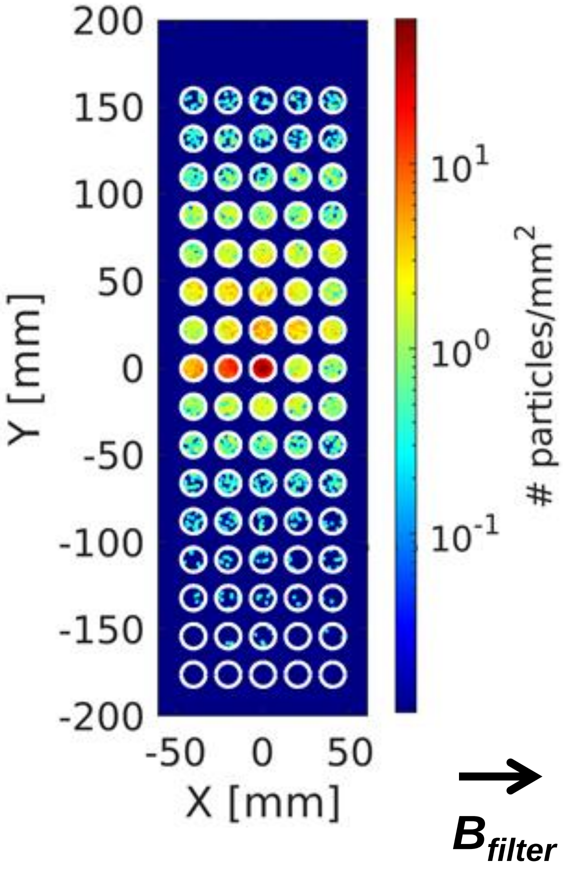
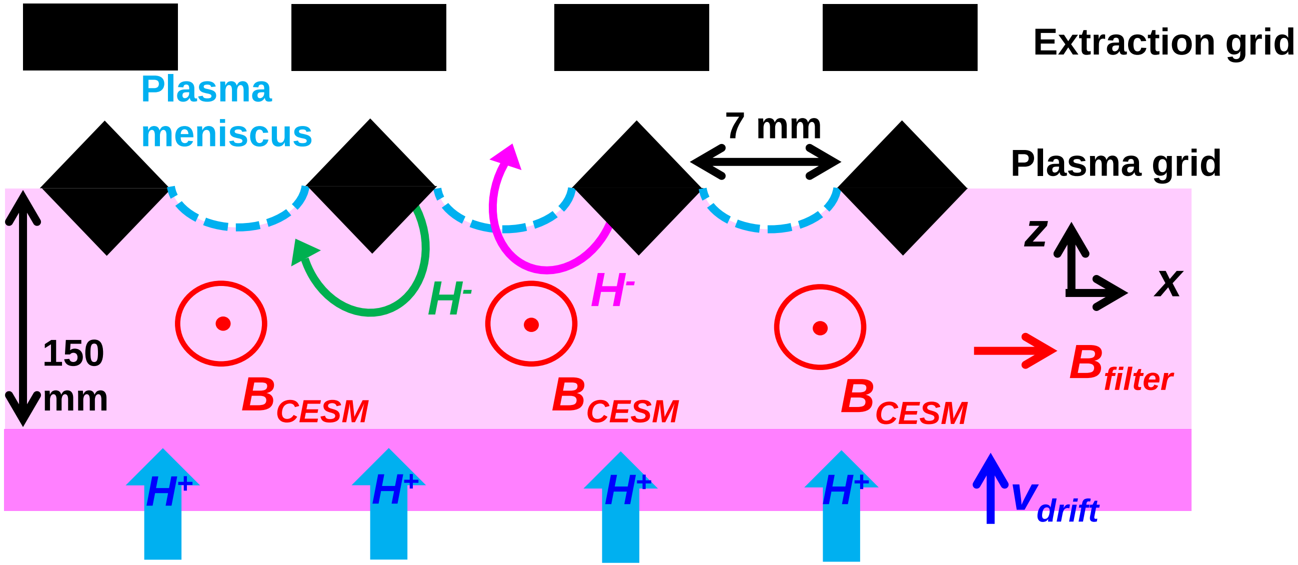
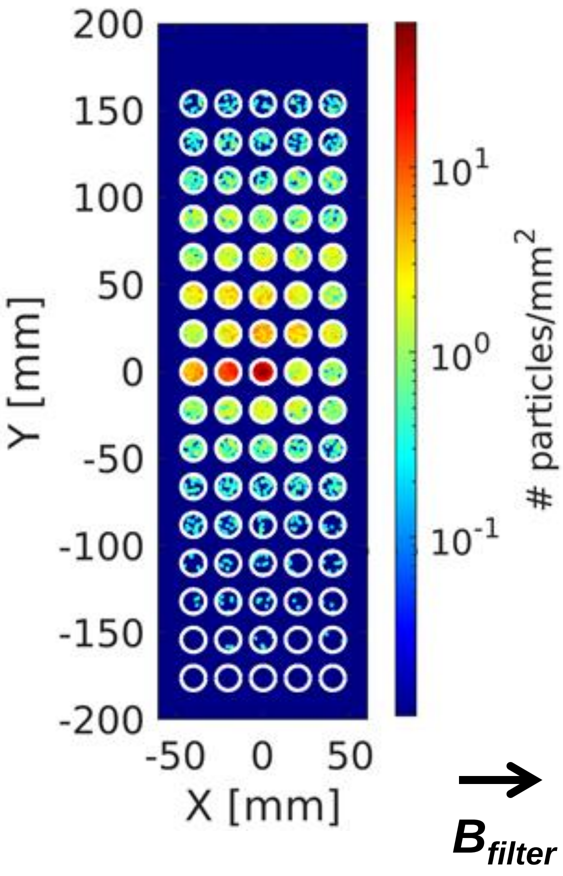




- Particles are moved in the magnetic field (CESM=magnets in the EG; Filter field $B_{filter}=B_x=2mT$)
- dt is adjusted so to keep ds=0.5 mm at each step
- The domain length is set to 150 mm

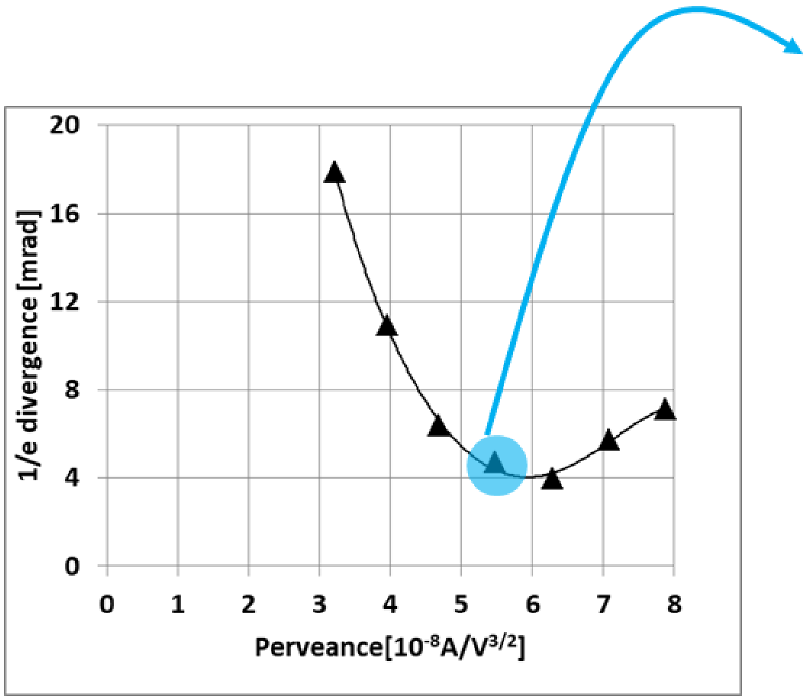
ICARO: Plasma domain and particle motion

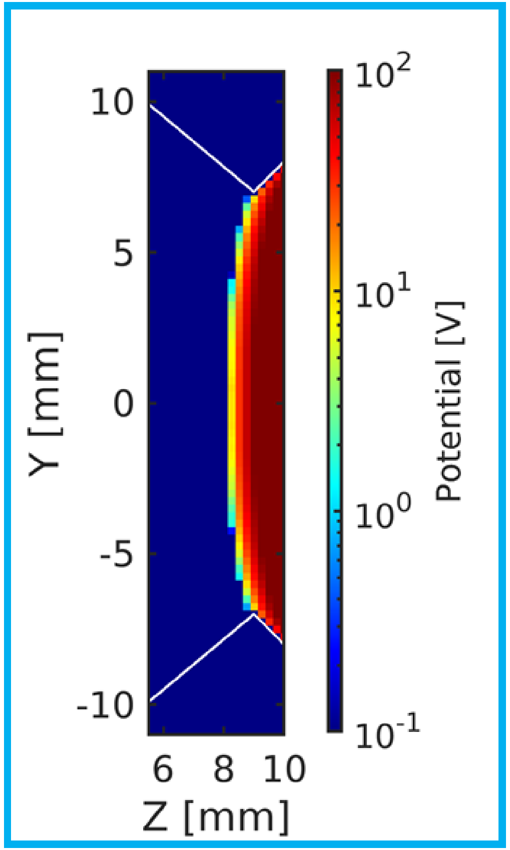




- Plasma parameters (n_{H+},n_{H-},n_e,T_e,T_{H+},v_{drift}) and gas parameters (n_{H0},n_{H2},T_{H0},T_{H2}) assumed homogeneous
- Only H^+ are considered as positive ions
- Collisions are implemented with Monte Carlo method

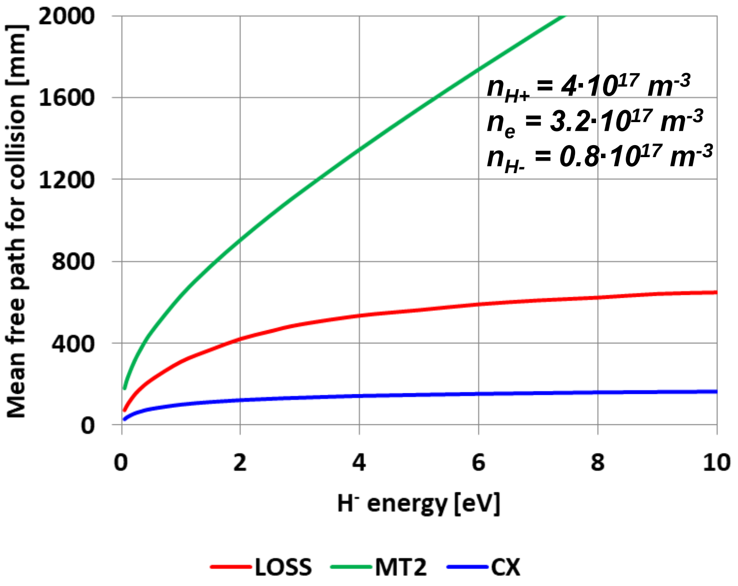
ICARO: Plasma meniscus





- The meniscus surface is loaded from OPERA3D
- **Perveance match** case (Π=5.5-6.3·10^{-8} A/V$^{3/2}$) are considered; this meniscus is very flat, so that the direct extraction is expected to be very little

ICARO: Collisions



Cross-sections
- C.F. Barnett, *Atomic Data for Fusion*, Volume 1, (ORNL-6086),1990.
- T. Tabata et al., *Atomic Data and Nuclear Data Tables* **76,** 1–25 (2000)

Gas parameters
- *U. Fantz at al., Front. Phys. 9:709651 (2021)*

CC are treated as in *T. Takizuka, H. Abe J. Comput. Phys.,* ***25*** *(1977)*

Momentum transfer w/ plasma

CC: $H^- + H^+ \rightarrow H^- + H^+$

Momentum transfer w/ gas

CX: $H^- + H_0 \rightarrow H_0 + H^-$

MT2: $H^- + H_2 \rightarrow H^- + H_2$

Neutralization by the plasma

DE: $H^- + e^- \rightarrow H + 2e^-$

MN: $H^- + H^+ \rightarrow H_0 + H_0$

AD_+: $H^- + H^+ \rightarrow H_2$

Neutralization by the gas

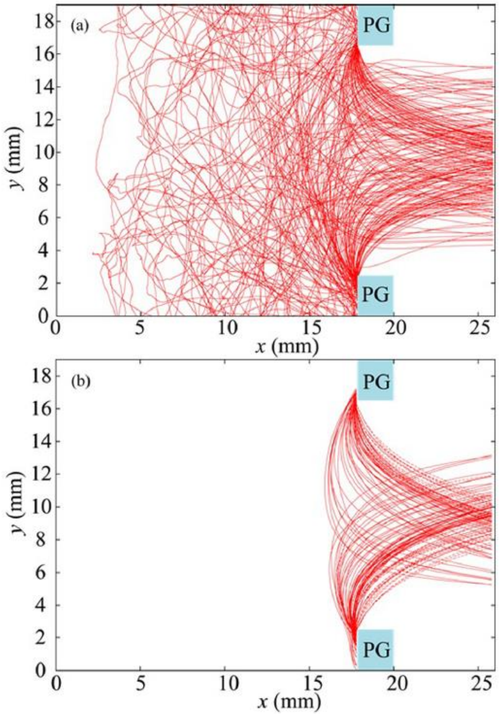
AD_0: $H^- + H_0 \rightarrow H_2 + e^-$

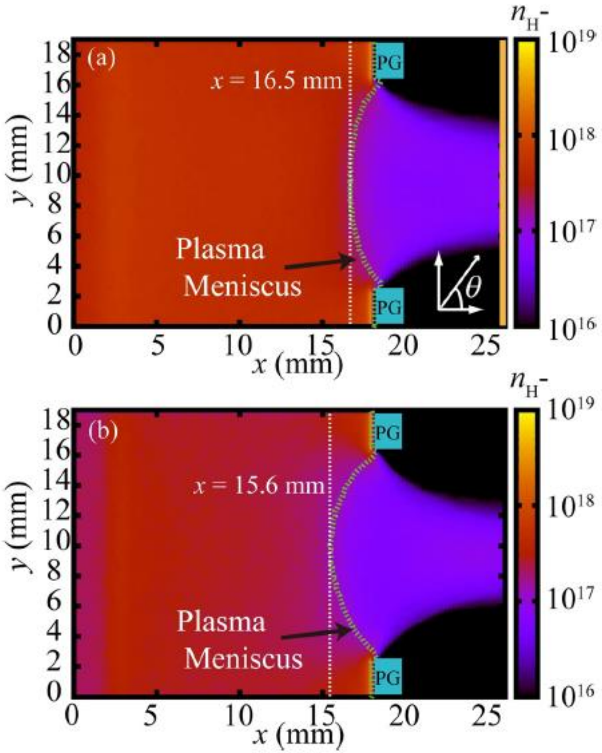
D_2: $H^- + H_2 \rightarrow H_0 + H_2 + e^-$

The role of Coulomb collisions (CC)

w/ CC
(H^+ - H^-)

w/o CC





Coulomb collisions strongly affects the extraction probability and the meniscus.

W/o CC, particles are extracted only through direct extraction ➔ Poor optics

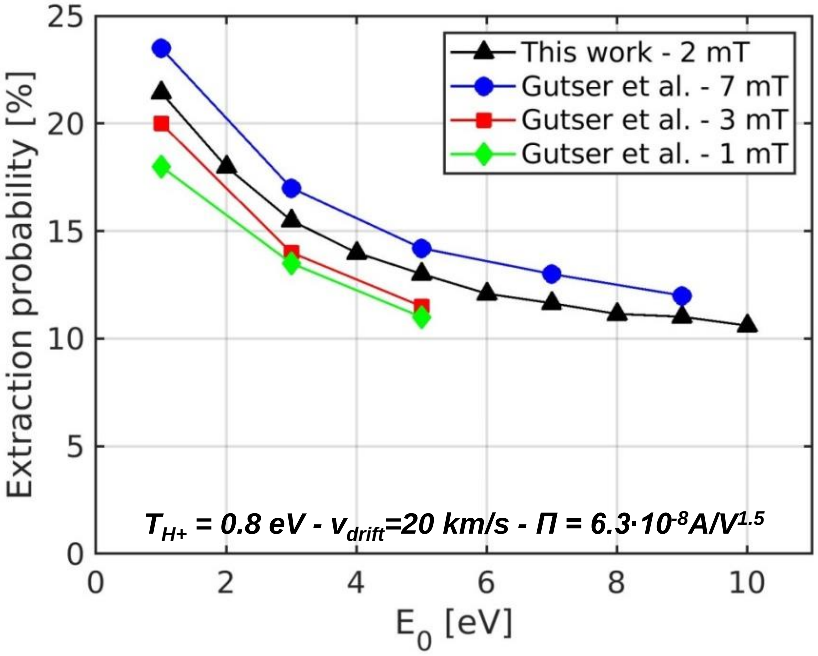
$\nu_{CC} \sim |\mathbf{v}_{H+} - \mathbf{v}_{H-}|^{-3}$

S. Nishioka et al. J Appl. Phys. ***123****, 063302 (2018)*

ICARO: comparison with TP in literature (TrajAn*)

	R. Gutser et al. *	This work
$T_{H2,1}$ [K]	1200	630 **
$T_{H2,2}$ [K]		4600 **
$T_{H0,1}$ [eV]	0.8	0.19 **
$T_{H0,2}$ [eV]		2.5 **
$n_{H2,1}$ [m^{-3}]	$4.0 \cdot 10^{19}$	$1.0 \cdot 10^{19}$
$n_{H2,1}$ [m^{-3}]		$0.5 \cdot 10^{19}$
$n_{H0,1}$ [m^{-3}]	$10 \cdot 10^{18}$	$2.2 \cdot 10^{18}$
$n_{H0,2}$ [m^{-3}]		$2.2 \cdot 10^{18}$
T_{H+} [eV]	0.8	[0.4,1.6]
v_{drift} [km/s]	0	[10,20]
T_e [eV]	2.0	2.0
n_e [m^{-3}]	$5.0 \cdot 10^{17}$	$3.2 \cdot 10^{17}$
n_{H+} [m^{-3}]	$5.5 \cdot 10^{17}$	$4.0 \cdot 10^{17}$
n_{H-} [m^{-3}]	$0.5 \cdot 10^{17}$	$0.8 \cdot 10^{17}$

Extraction probability $p_{extr} = \frac{N_{extr}}{N_{tracked}}$



* R. Gutser et al. PPCF **52** (2010) 045017

** U. Fantz at al., Front. Phys. 9:709651 (2021)

Energy distribution of positive ions

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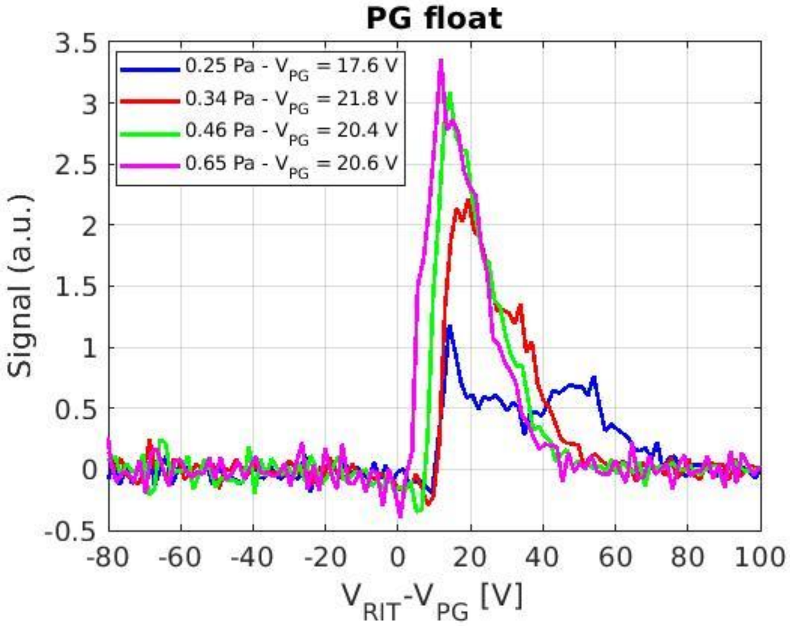
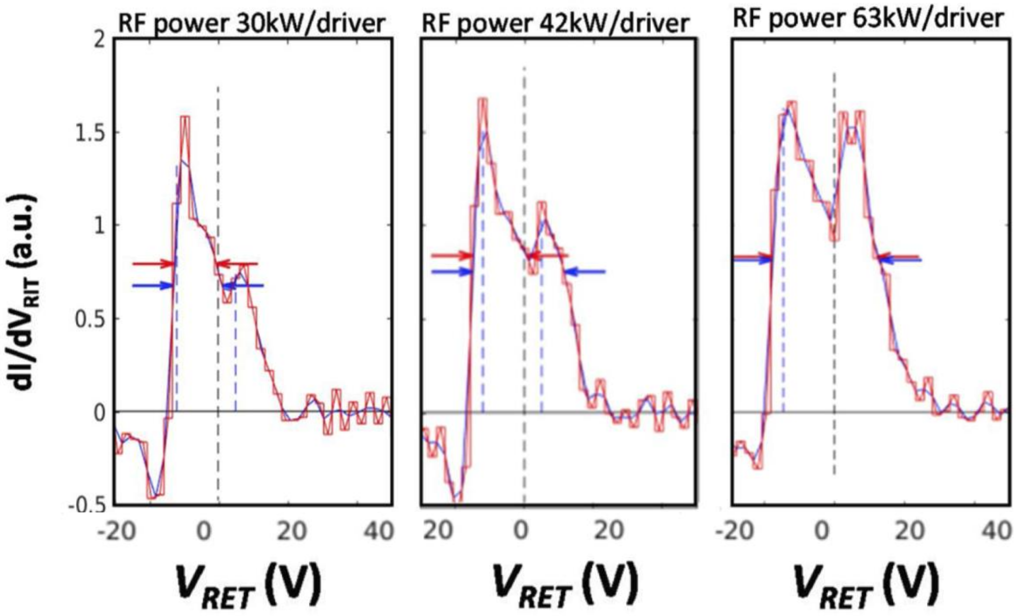
The dependence of the positive ion energy distribution on the source parameters was investigated in SPIDER with a retarding field energy analyzer (RFEA)

Pressure dependence

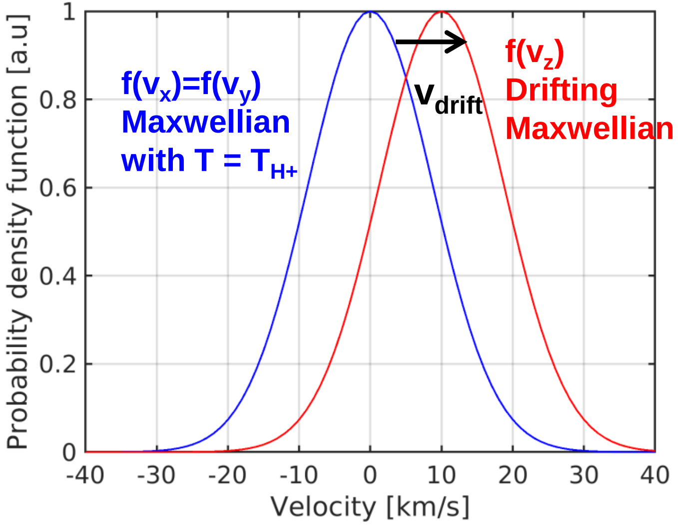


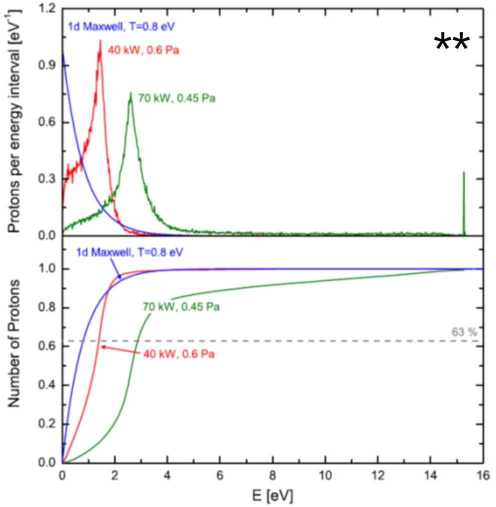
RF power dependence



E. Sartori et al. Fus. Eng. Des. 169 (2021) 112424

ICARO: Positive ion velocity distribution





*@ **BATMAN (IPP, Garching)***

Mach probe:

*v_{drift}~10 km/s for p_{fill} = 0.7 Pa**

Probes+ MC models:

T_{H+}~0.8 eV @ PG for

*P_{RF}= 40 kW/dr - p_{fill} = 0.6 Pa***

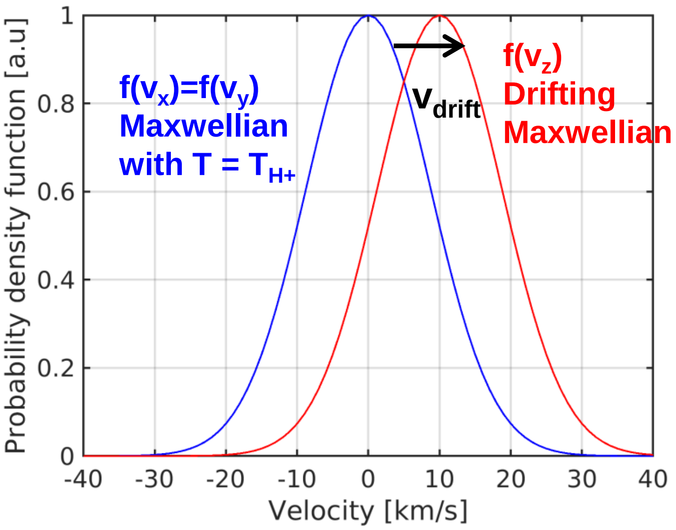
The efficacy of CC depends on:

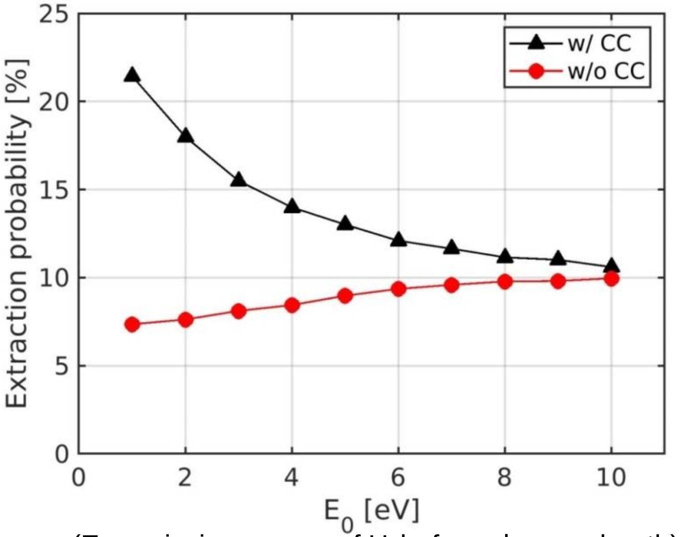
- E_{H-}
- n_{H+}
- $f(E_{H+})$ ➔ T_{H+}, v_{drift}

** M. Bandyopadhyay et al. A.J. Appl. Phys. **96**, 4107 (2004)*

*** D. Wuenderlich et al., PPCF**54** (2012) 125002*

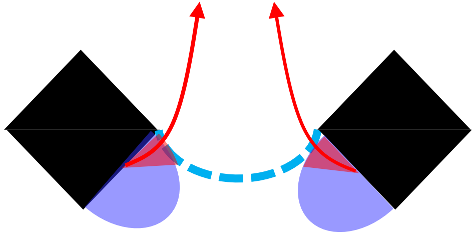
ICARO: Efficacy of Coulomb Collisions





(E_0: emission energy of H^- before plasma sheath)

$$p_{extr} = \frac{N_{extr}}{N_{tracked}}$$



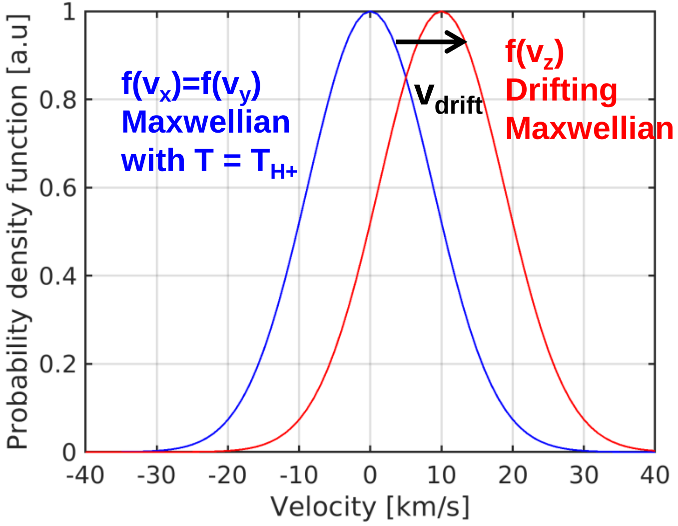
The efficacy of CC depends on:

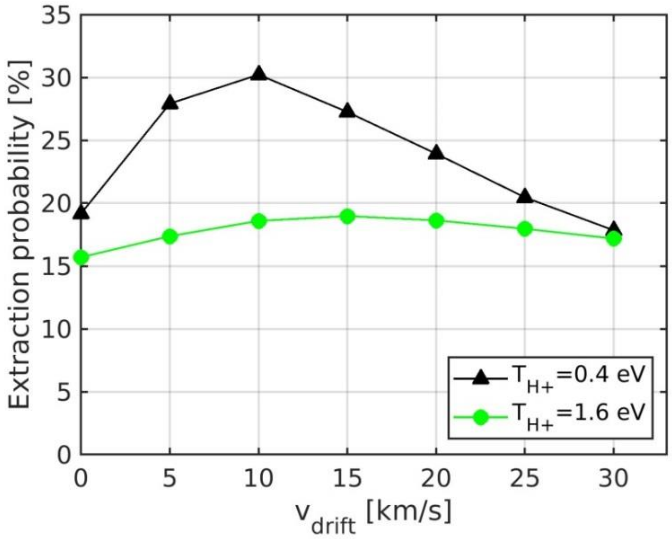
- E_{H-}
- n_{H+}
- $f(E_{H+})$ ➔ T_{H+}, v_{drift}

Since $v_{CC} \sim |\mathbf{v}_{H+} - \mathbf{v}_{H-}|^{-3}$ CC are more effective for low energy H^-

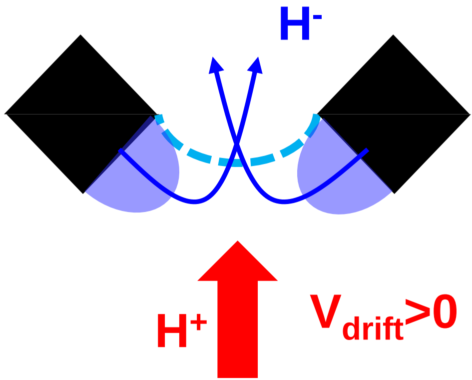
Favourable emission angle

ICARO: Efficacy of Coulomb Collisions





$$p_{extr} = \frac{N_{extr}}{N_{tracked}}$$

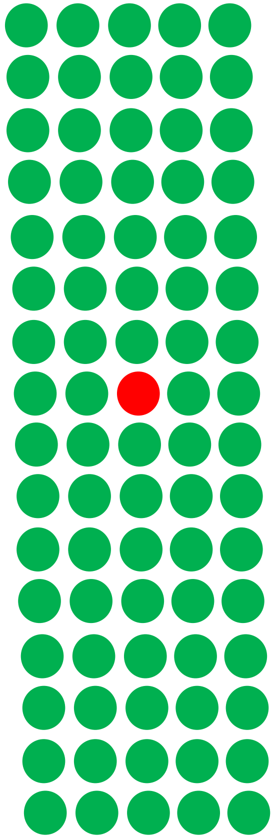


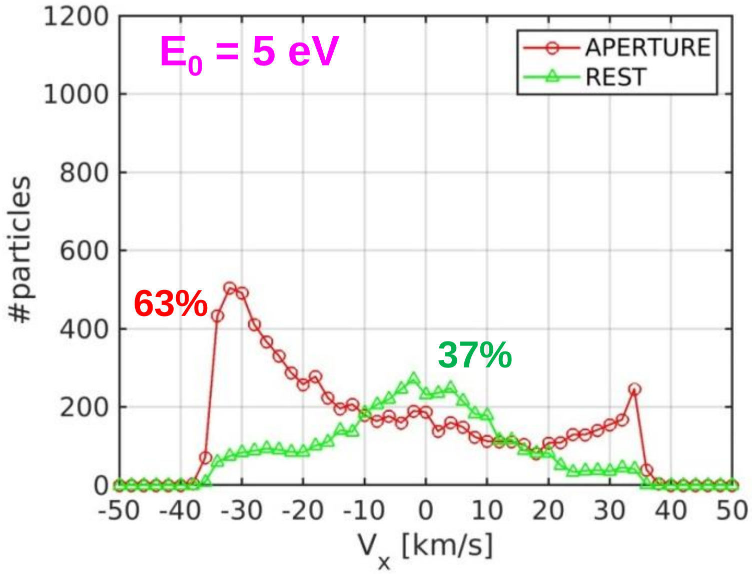
The efficacy of CC depends on:

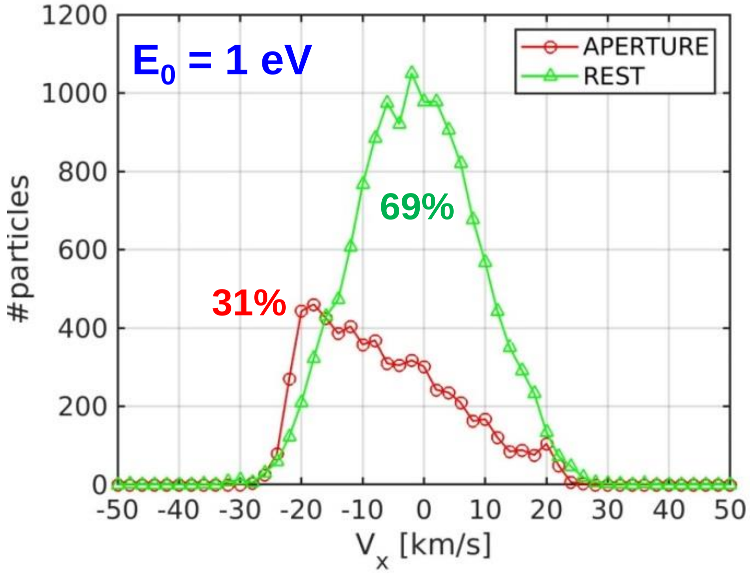
- E_{H-}
- n_{H+}
- $f(E_{H+})$ ➔ T_{H+}, v_{drift}

Since $v_{CC} \sim |\mathbf{v}_{H+} - \mathbf{v}_{H-}|^{-3}$ there is an optimum drift velocity for H^+ ions. Beyond this velocity, CC lose efficacy

Results: velocity distribution at meniscus







- H^- emitted with large energies are unlikely to be brought back to the apertures by collisions and magnetic fields.
- For H^- emitted with low energy, CC are effective in reversing the H^- velocity

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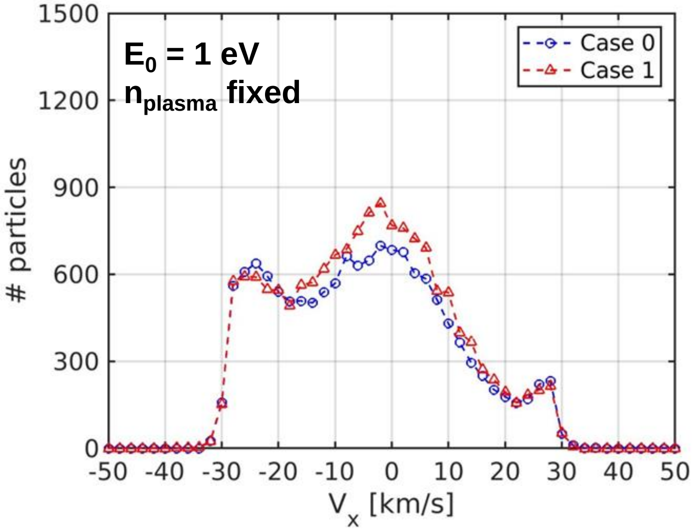
  - **Investigation of the pressure dependence**

- Coupling of ICARO to a ray tracing code

Pressure dependence

	p_{fill} [Pa]	Density of gas species	T_e [eV]	T_{H+} [eV]	v_{drift} [km/s]
Case 0	0.3	$n_{standard}$	2	0.8	20
Case 1	0.6	$2n_{standard}$	1	0.8	20



The **optics dependence on pressure**:

- **Cannot be explained** by the increased gas density in the extraction region (Case 0 vs Case 1)

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Case 0	0.3	$n_{standard}$	2	0.8	20
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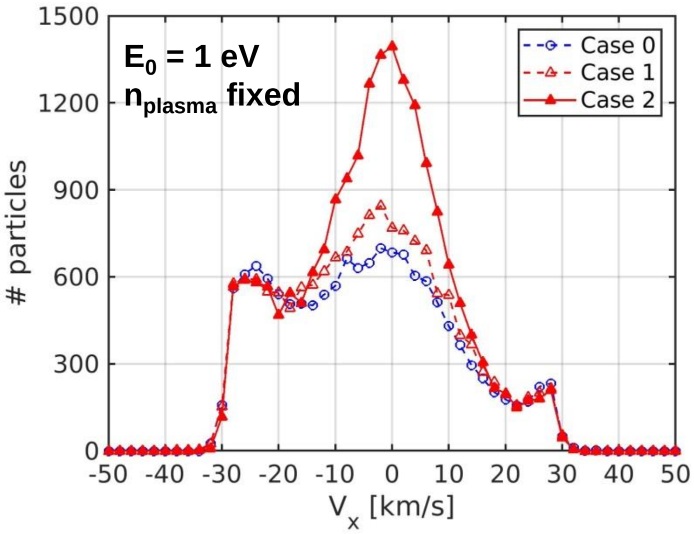
Case 2	0.6	$2n_{standard}$	1	0.4	10 *



The **optics dependence on pressure**:

- **Cannot be explained** by the increased gas density in the extraction region (Case 0 vs Case 1)
- **Can be explained** by reduced energy of the positive ions (Case 0 vs Case 2)

* M. Bandyopadhyay et al. *A.J. Appl. Phys.* **96**, 4107 (2004)

Pressure dependence

	p_{fill} [Pa]	Density of gas species	T_e [eV]	T_{H+} [eV]	v_{drift} [km/s]
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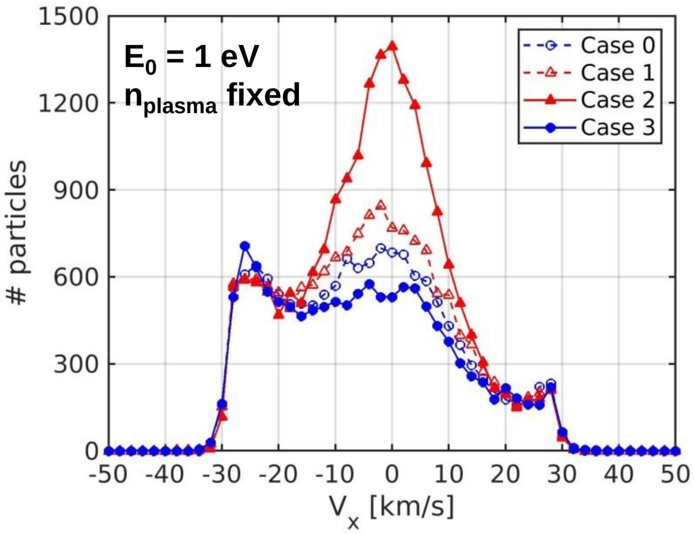
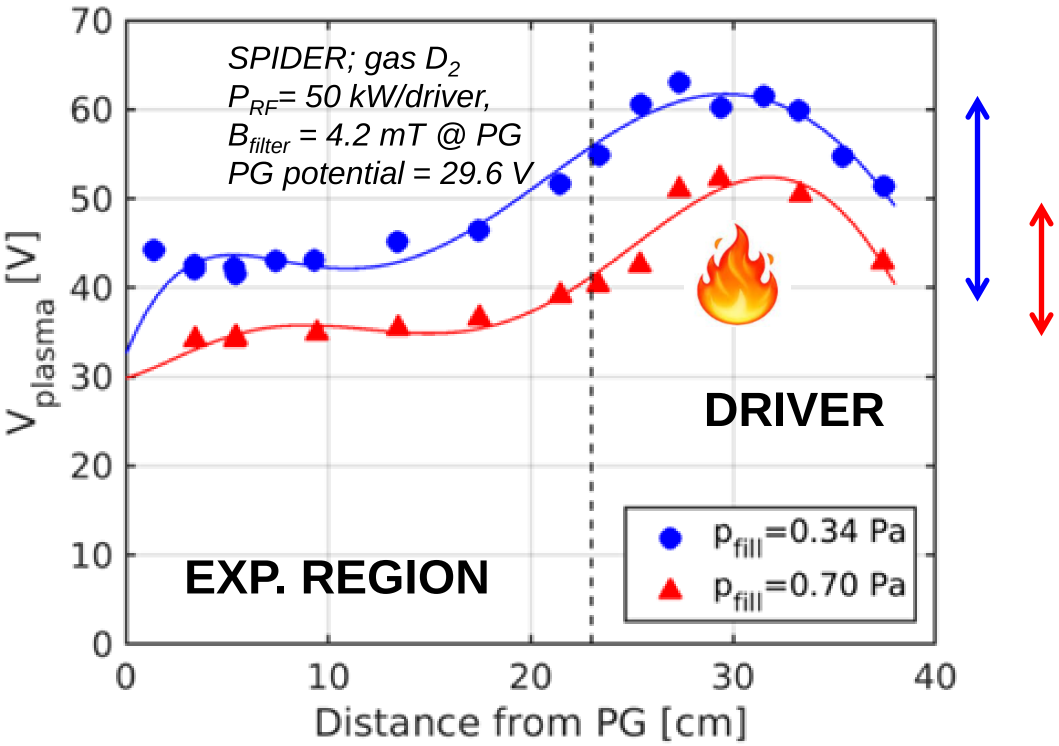
Case 3	0.3	$n_{standard}$	2	1.6	20



The effect of pressure is not local, due to MT with neutrals, but global, as pressure affects the whole discharge

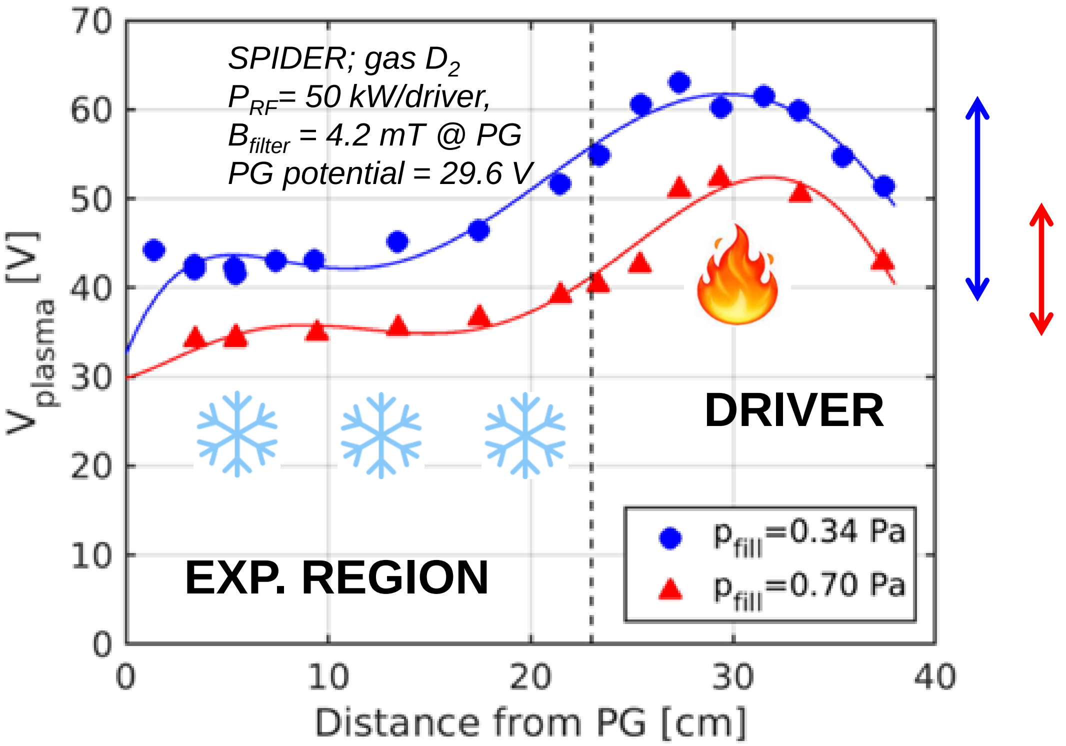
Pressure influences the H^- extraction via the positive ion energy distribution (which controls CC efficacy)

Energy balance for positive ions



Energy source term: potential slide between RF drivers and plasma grid

Energy balance for positive ions

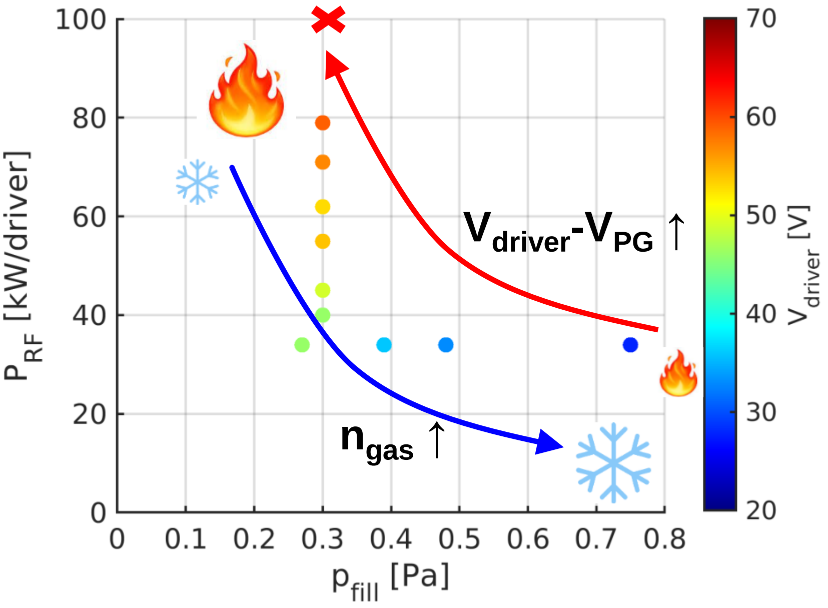


Energy source term:
potential slide between RF drivers and plasma grid

Energy loss term:
Collisions with neutrals (H^0,H_2) in the expansion region

Plasma potential in RF sources

Expected working point (100 kW/dr – 0.3 Pa)



Data are from:
P. McNeely et al., J Appl. Phys. ***18*** *(2009) 014011*

$p_{fill} \leq 0.3$ Pa is needed to limit stripping losses

We cannot increase the energy loss term for positive ions

P_{RF} ~ 100 kW/driver is needed to assure the target current density (330-355 A/m^2) with p_{fill} = 0.3 Pa. By increasing P_{RF}:

The energy source term for positive ions would increase

The energy loss term would decrease (neutral depletion)

T_{H+} and v_{drift} are expected to increase

Plasma potential in RF sources

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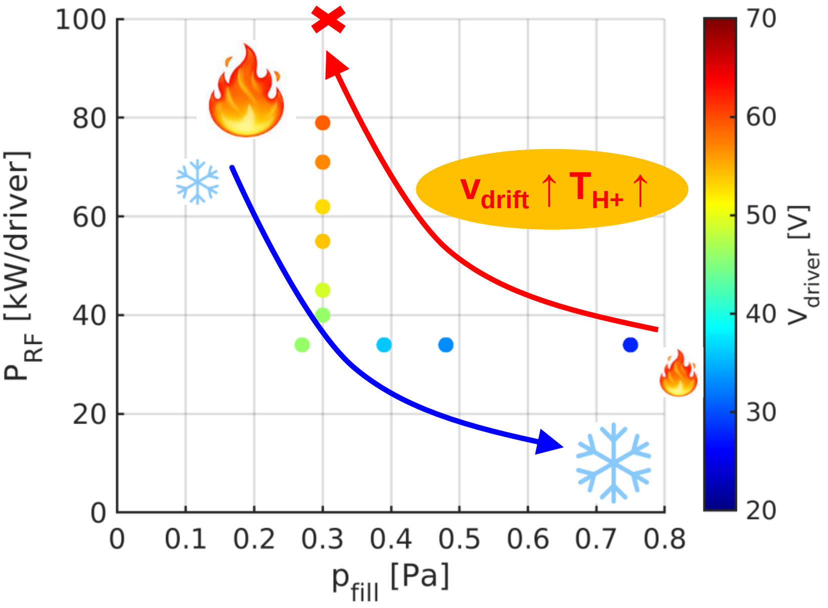

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The energy loss term would decrease (neutral depletion)

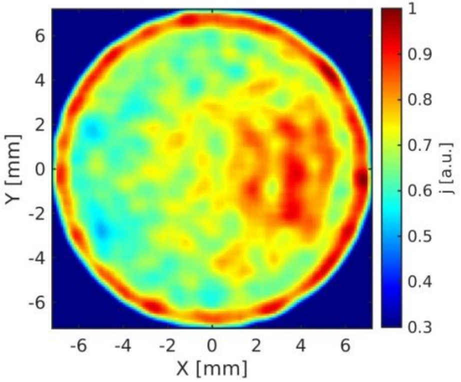
T_{H+} and v_{drift} are expected to increase

ICARO: emittance at the meniscus

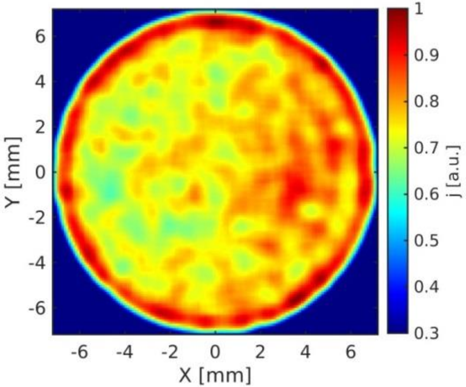
ICARO simulating H^- emission from PG with
$T_{H-} \sim R_E T_{H0} = 1.75$ eV
$T_{H0} = 2.5$ eV*
$R_E = 0.7$ **
Only H^- generation from atoms

Current density at meniscus (normalized)

0.3 Pa - $T_e = 2$ eV
$T_{H+} = 1.6$ eV
$v_{drift} = 20$ km/s



0.6 Pa - $T_e = 1$ eV
$T_{H+} = 0.4$ eV
$v_{drift} = 10$ km/s



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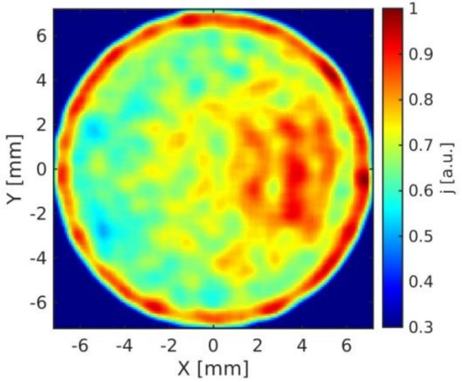
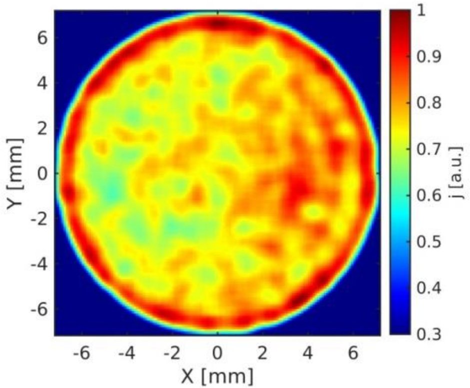
$T_{H-} \sim R_E T_{H0}$= 1.75 eV
T_{H0} = 2.5 eV*
R_E=0.7 **
Only H^- generation from atoms

0.3 Pa - T_e= 2 eV
T_{H+} = 1.6 eV
v_{drift}= 20 km/s

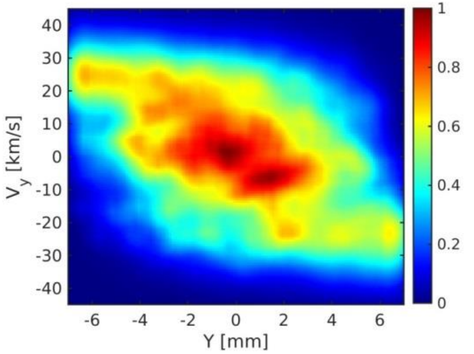
0.6 Pa - T_e= 1 eV
T_{H+} = 0.4 eV
v_{drift}= 10 km/s

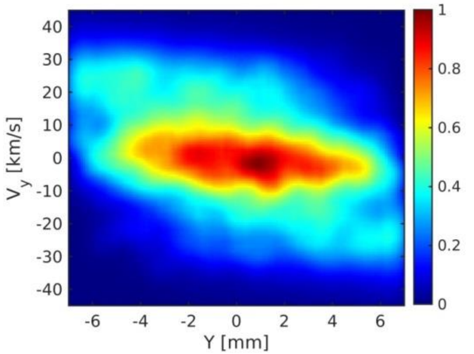
Current density at meniscus (normalized)





Emittance at meniscus (normalized) *





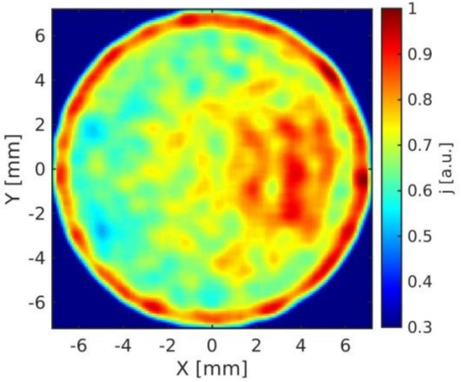
* A. Pimazzoni et al., submitted to Nucl. Fusion

ICARO: emittance at the meniscus

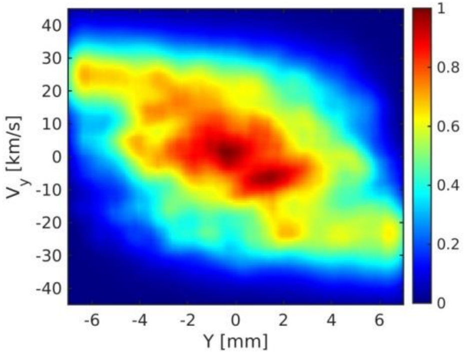
ICARO simulating H^- emission from PG with
$T_{H-} \sim R_E T_{H0} = 1.75$ eV
$T_{H0} = 2.5$ eV*
$R_E = 0.7$ **
Only H^- generation from atoms

0.3 Pa - T_e= 2 eV
T_{H+} = 1.6 eV
v_{drift}= 20 km/s

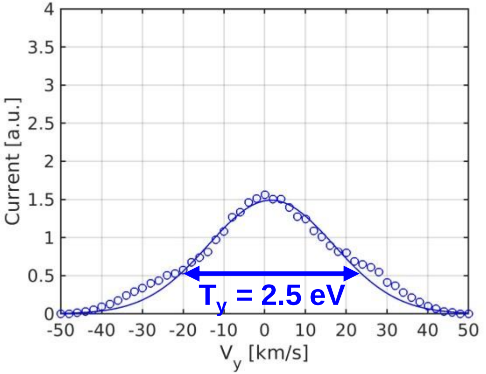
Current density at meniscus (normalized)



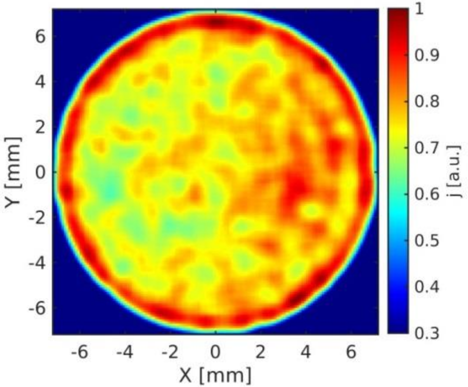
Emittance at meniscus (normalized) *

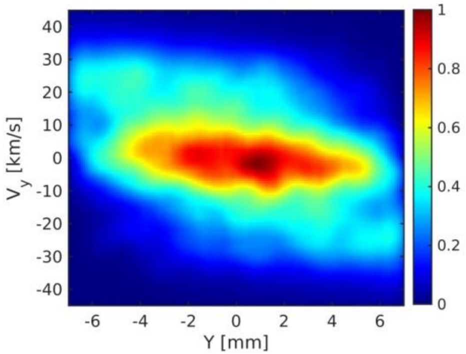


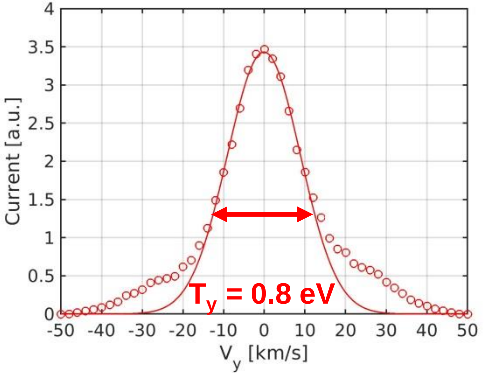
Velocity distribution at meniscus



0.6 Pa - T_e= 1 eV
T_{H+} = 0.4 eV
v_{drift}= 10 km/s







* A. Pimazzoni et al., submitted to Nucl. Fusion

Outline

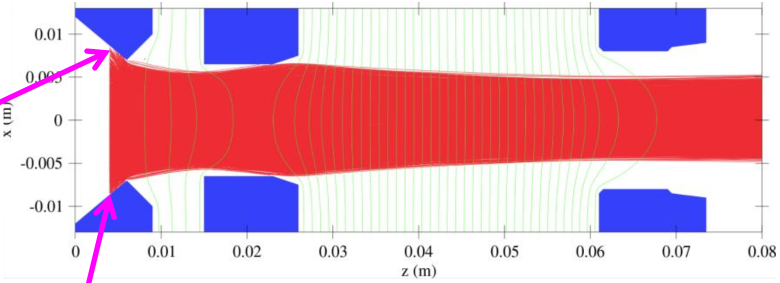
CONSORZIO RFX
Ricerca Formazione Innovazione

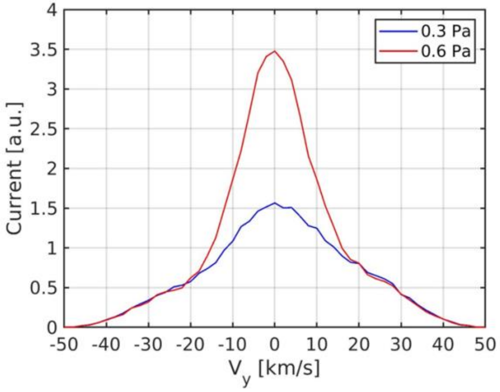
- Motivation
- ICARO: a test particle code w/ Monte Carlo collisions
  - Description and comparison with literature
  - Investigation of the pressure dependence
- **Coupling of ICARO to a ray tracing code**

Coupling with IBsimu*

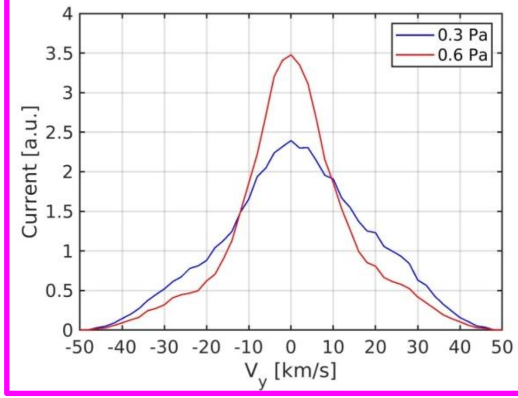
- Current is scaled so to have the same perveance and thus the same meniscus shape
- We set same I_{ex}, U_{ex} and U_{acc} to assess only the role of the emittance at the meniscus
- Settings: $j_{ext,avg}$ = 126 A/m^2
  U_{ex}=5 kV – U_{acc}= 47.5kV

*T. Kalvas et al., *Rev. Sci. Instrum.* **81**, *02B703 (2010)*





At meniscus



At meniscus (normalized)

Coupling with IBsimu*

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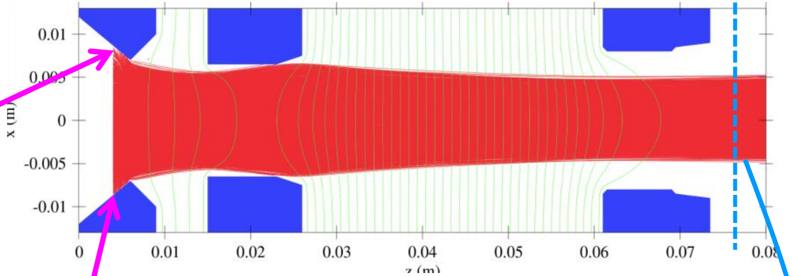
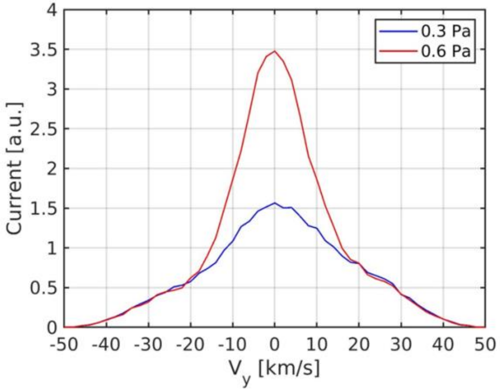
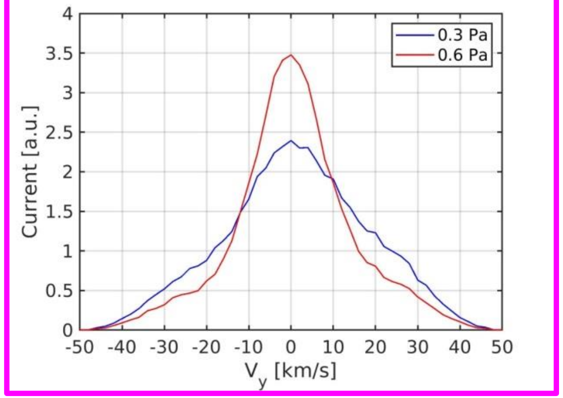
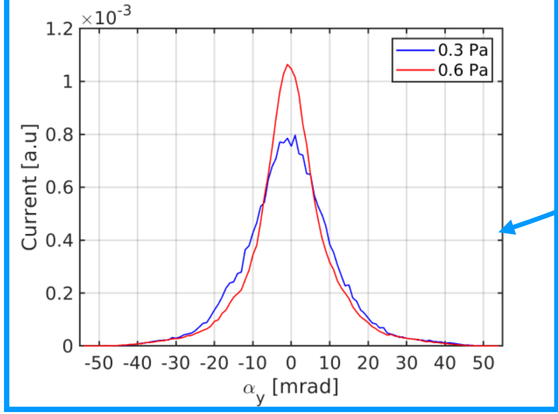




At meniscus



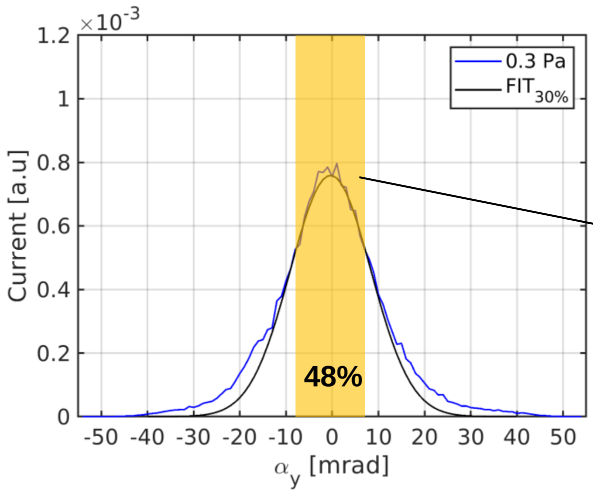
At meniscus (normalized)



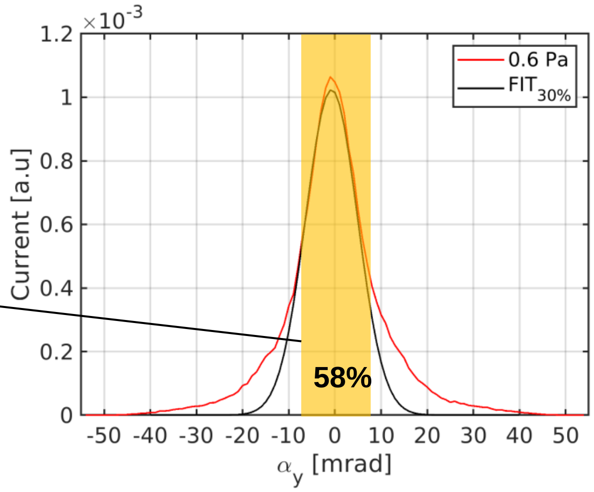
After GG

Coupling with IBsimu

P_{fill} [Pa]	$n_{H0,1}$ [$10^{18}m^{-3}$]	$n_{H0,2}$ [$10^{18}m^{-3}$]	$n_{H2,1}$ [$10^{18}m^{-3}$]	$n_{H2,2}$ [$10^{18}m^{-3}$]	T_e [eV]	T_{H+} [eV]	V_{drift} [km/s]	$div_{30\%}$ [mrad]	Fraction in ITER angular acceptance (-7,7) mrad [%]
0.3	2.2	2.2	10.0	5.0	2	1.6	20	12.3	48
0.6	4.5	4.5	19.9	9.9	1	0.4	10	8.0	58



ITER HNB «transmission window»

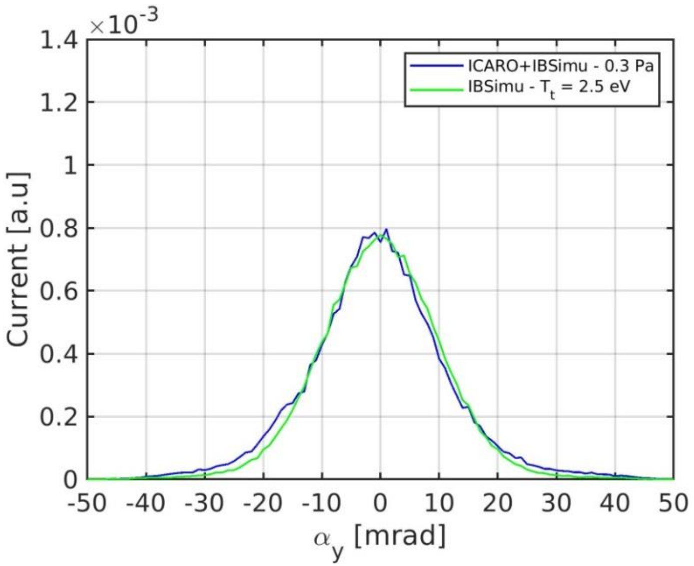


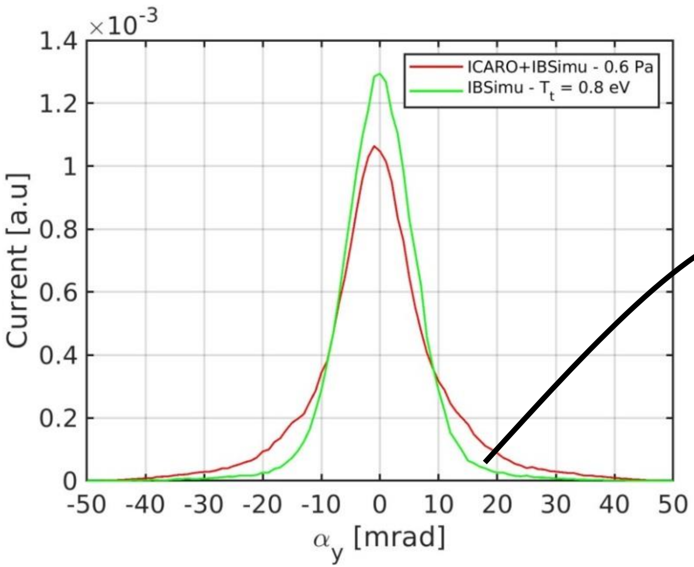
0.3 Pa - T_e= 2 eV – T_{H+} = 1.6 eV – v_{drift}= 20 km/s

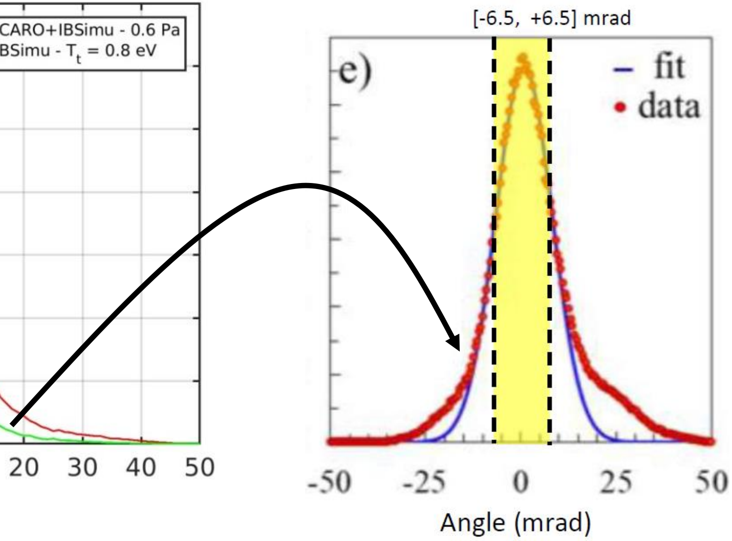
0.6 Pa - T_e= 1 eV – T_{H+} = 0.4 eV – v_{drift}= 10 km/s

Comparison with IBsimu

We compare the results by ICARO+IBSimu with the ones of a standard IBSimu run. In the IBsimu standard simulation, we set T_t equal to the estimate by ICARO







0.3 Pa - T_e= 2 eV – T_{H+} = 1.6 eV – v_{drift}= 20 km/s

0.6 Pa - T_e= 1 eV – T_{H+} = 0.4 eV – v_{drift}= 10 km/s

Talk by P. Veltri Mon O5

Using ICARO the tails seen by the beam diagnostics are reproduced

Conclusions

- A particle tracing code with Monte-Carlo collisions, named ICARO, was developed; similar to the code TrajAn by Gutser et al.
  - Trends of previous literature reproduced
  - Highlighted the effect of Coulomb collisions on the H^- velocity distribution

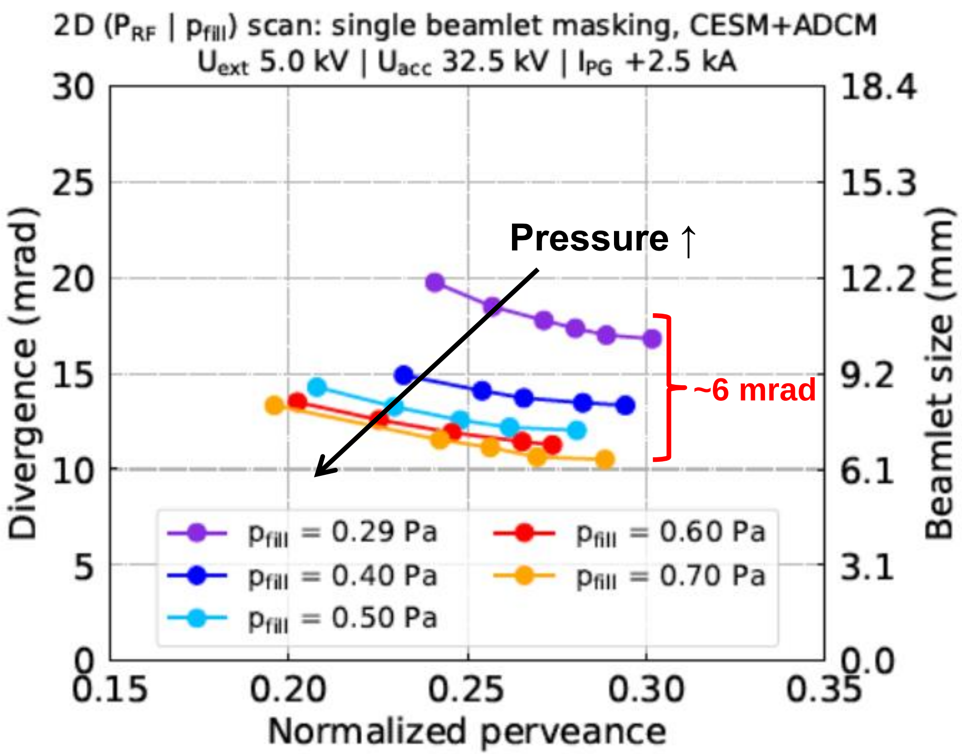
- Starting from recent measurements of the gas parameters, the code:
  - Provides a possible explanation for the optics dependence on pressure, but only postulating non-local effects (v_{drift}, T_{H+} from RF drivers)
  - Justifies the existence of a broad component (halo) for the beamlet
  - Simulated velocity distribution at GG exit seems more similar to experiments than those from standard beam acceleration models (e.g. IBsimu T_t)

Any input to experiments?

Yes: Reduce energy source term for positive ions

SPARE SLIDES

Motivation: beamlet optics, experiments



N. Den Harder et al. 2022 J. Phys.: Conf. Ser. ***2244****, 012053*

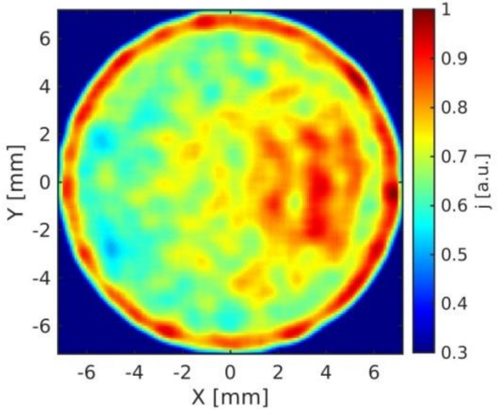
Talk by P. Veltri
Mon O5

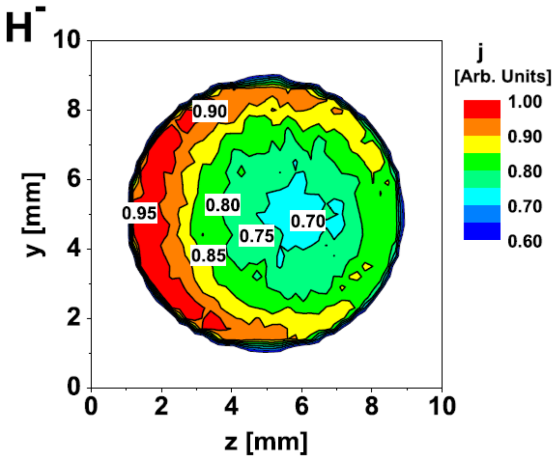
Experimental evidence

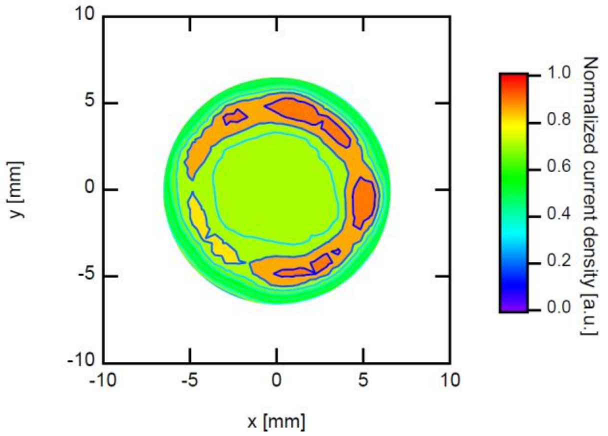
Beam divergence from RF sources under development for the ITER HNB/DNB is highly sensitive to the source filling pressure

$$Div = Div(I_{ex}/U_{ex}^{1.5}, E_{beam}, T_{H-})$$

ICARO: simulating a Maxwellian distribution







ICARO simulating H^- emission from PG with $T_{H-} \sim R_E T_{H0}$= 1.75 eV

T_{H0} = 2.5 eV*
R_E=0.7 **
Only H^- generation from atoms

* U. Fantz at al., *Front. Phys.* **9**:709651 (2021)

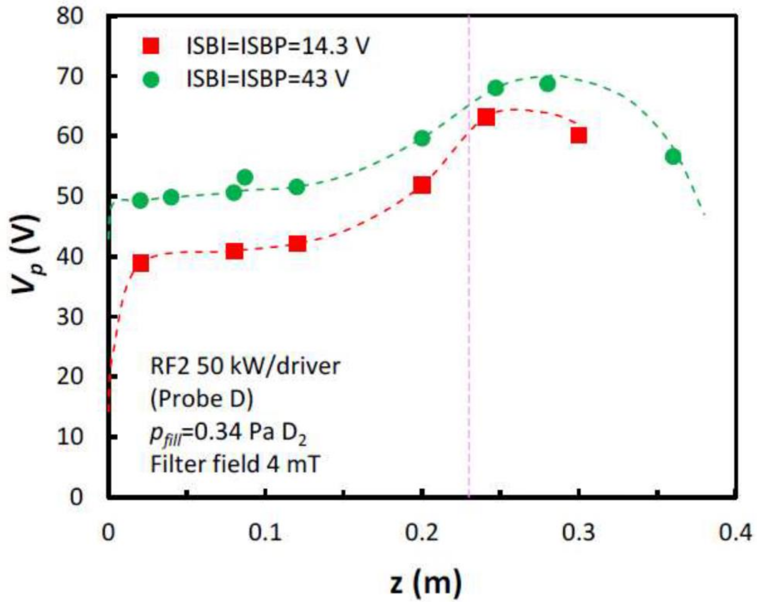
** W. Eckstein and J. P. Biersack, *Appl. Phys*. A **38**, 123 (1985)

R. Gutser et al. *PPCF* ***52*** *(2010) 045017*

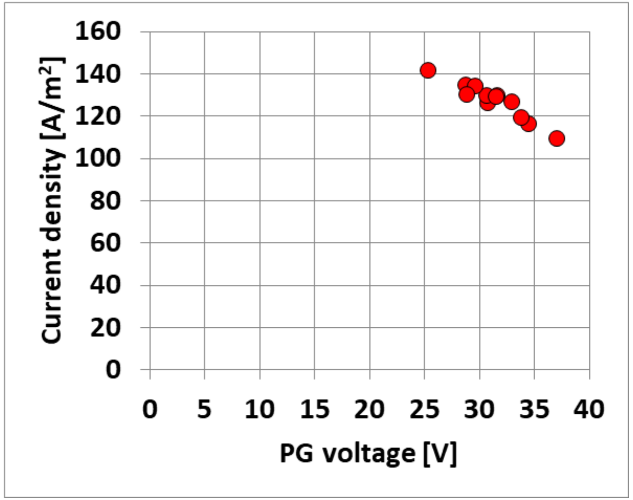
Similar code applied to the case of BATMAN (IPP, Garching)

M. Kisaki et al., *Phys.: Conf. Ser.* **2244** 012061 (2022);

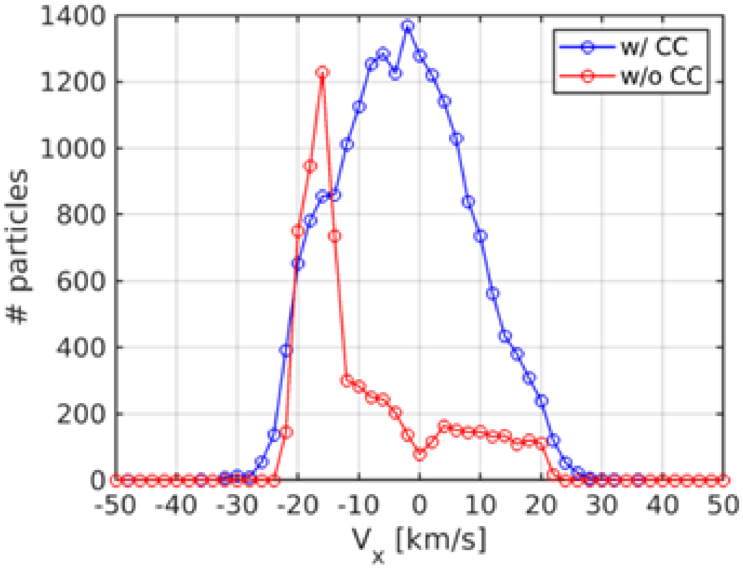
From backward tracing of particles starting from emittance measurements at the Megavolt Test Facility (QST, Japan)



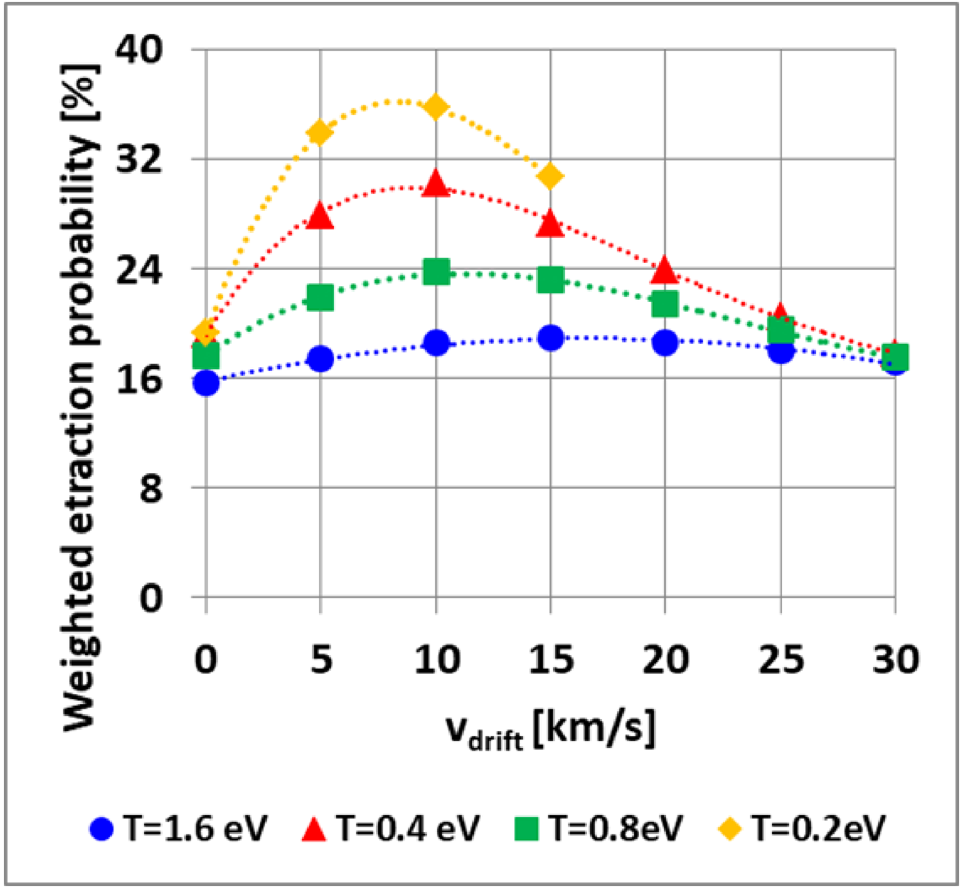
E. Sartori et al., Fusion Engineering and Design Volume 169, 2021)

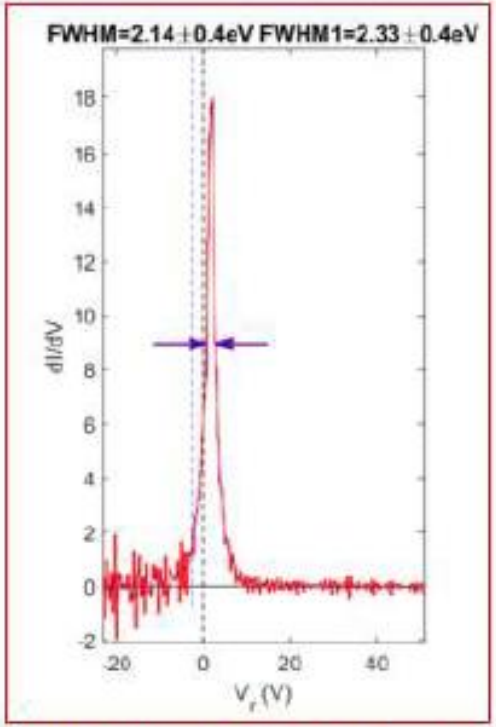


Hydrogen operation
P_{RF}= 23 kW/driver
p_{fill} = 0.36 Pa
B_{filter} = 1.7 mT



w/ CC
w/o CC
particles
V$_x$ [km/s]
1400
1200
1000
800
600
400
200
0
-50 -40 -30 -20 -10 0 10 20 30 40 50



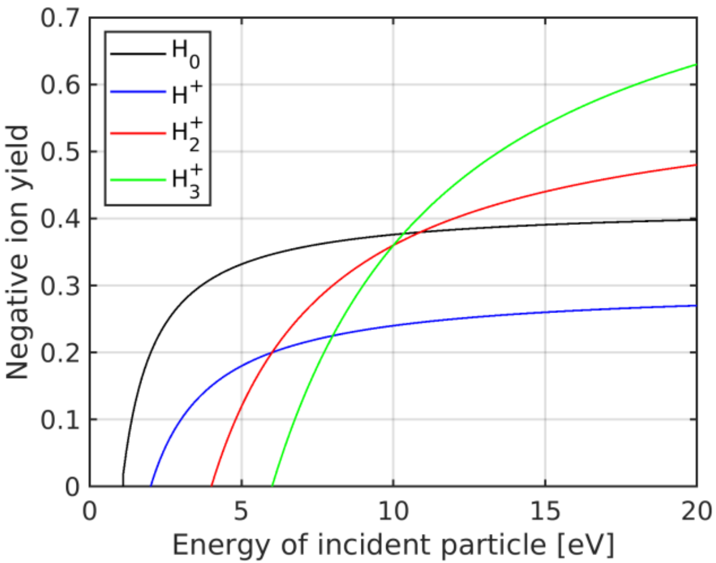


Width of Distribution

1-2 eV

Arc Source (R-NITS, @NIFS)

RFEA in arc source



$$Y(E_{in}) = R_N \eta_0 \left(1 - \frac{E_{th}/R_E}{E_{in}}\right)$$

Parameters from:
M. Seidl et al. *Journal of Applied Physics* **79**, 2896 (1996)

By scaling probe measurements at SPIDER towards 70 kW/0.3 Pa:
Typical positive ion flux onto the PG: $3\text{-}4 \cdot 10^{21} m^{-3}$.
Maxwellian flux of H^0: $0.25 n_{H0,1} (8kT_{H0}/3.14 m_H)^{0.5} = 1.4 \cdot 10^{22} m^{-3}$
The majority of the H^- is obtained from H^0.