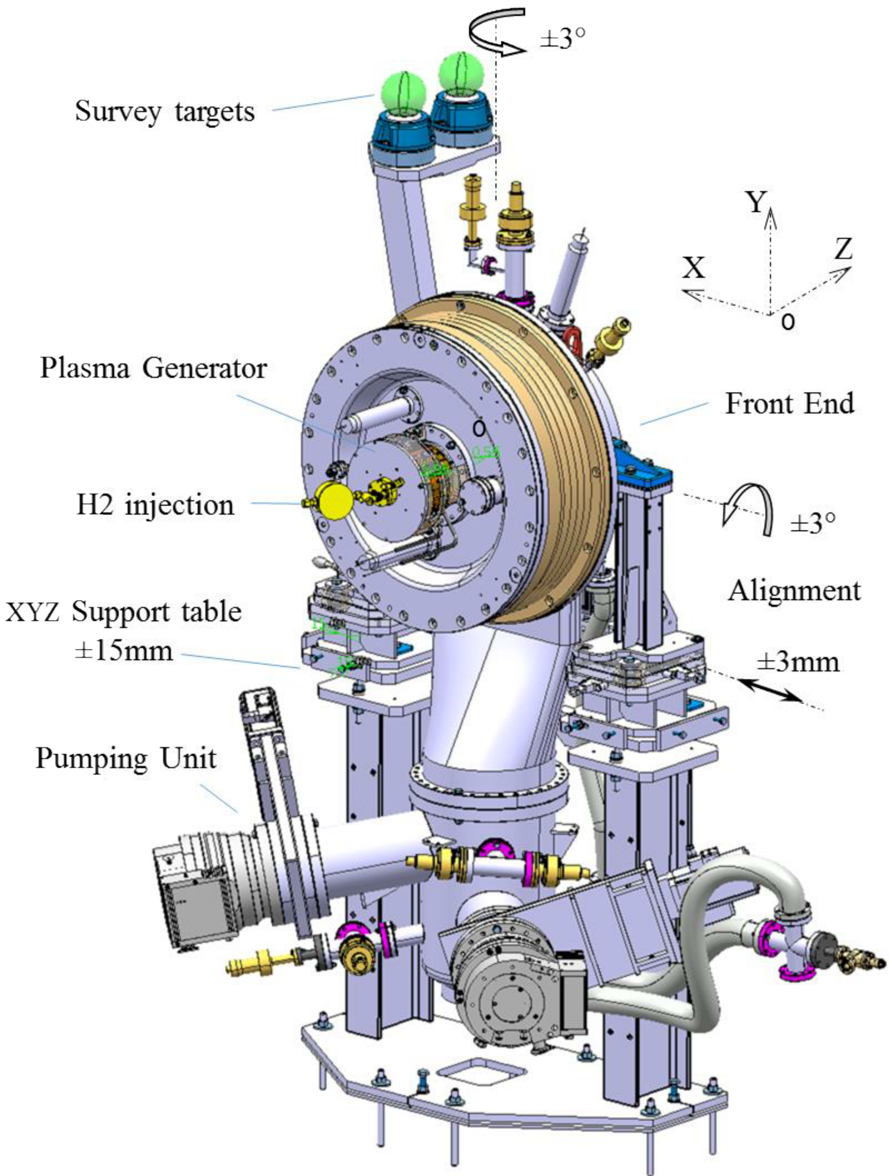
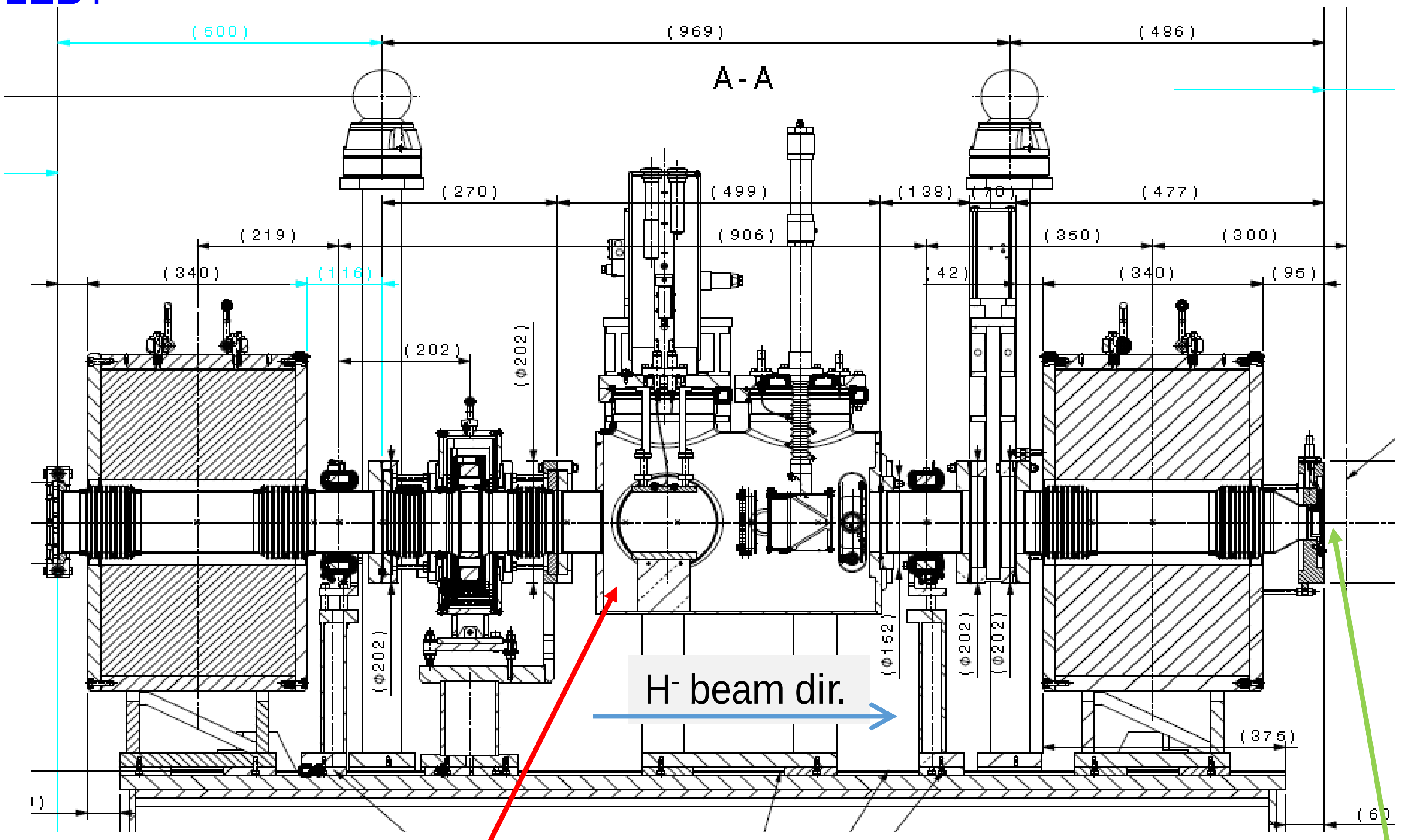
Linac4 H^- source R&D: Cusp free ICP

- Fundamental plasma studies of the ISO3 plasma confirmed by OES spectroscopy showed that a Magnetic cusp reduces the efficiency of external antenna RF-ICP plasma heating.
- An IS03 prototype was operated cusp free at Linac4; Results from a short test are presented.
- Cesiation: Linac4 ion sources are monthly loaded with typically 5 mg Cs
- The Cusp free unit was operated in a Cs-loss compensation mode, to stabilize the co-extracted electron current and improve operation's stability.
- Linac4 is foreseen to operates at 0.8 and 2 Hz repetition rates. Electro magnetic valve's injection show improved stability vs. temperature and are being calibrated.

Layout of the Linac4 front end and LEBT





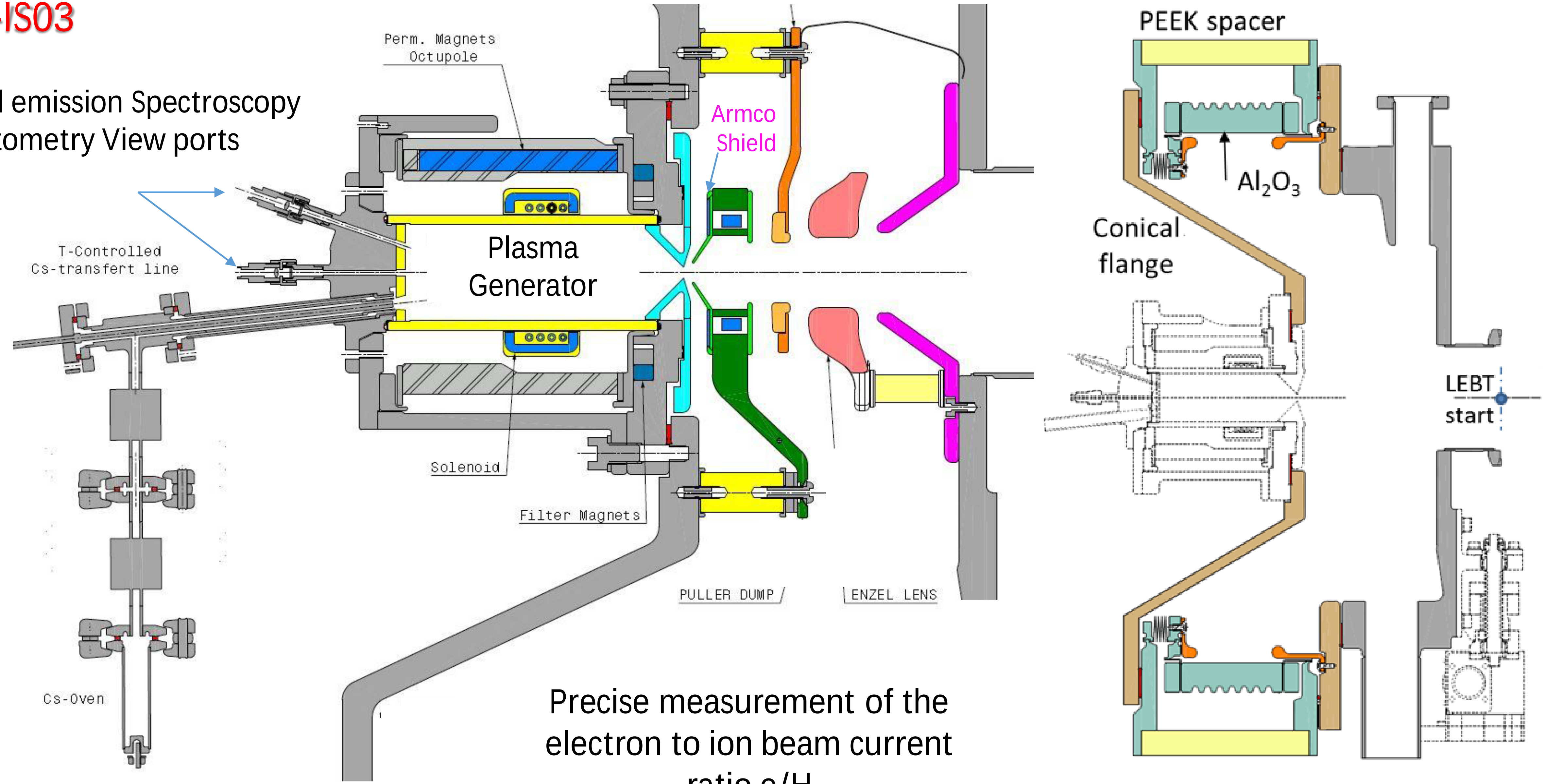
RFQ-entrance

H_2-regulation for Space Charge Compensation (SCC)
Setting 6.4 ~4-6 10^{-6} mbar

RF-ICP driven, Cs-surface H- source of Linac4

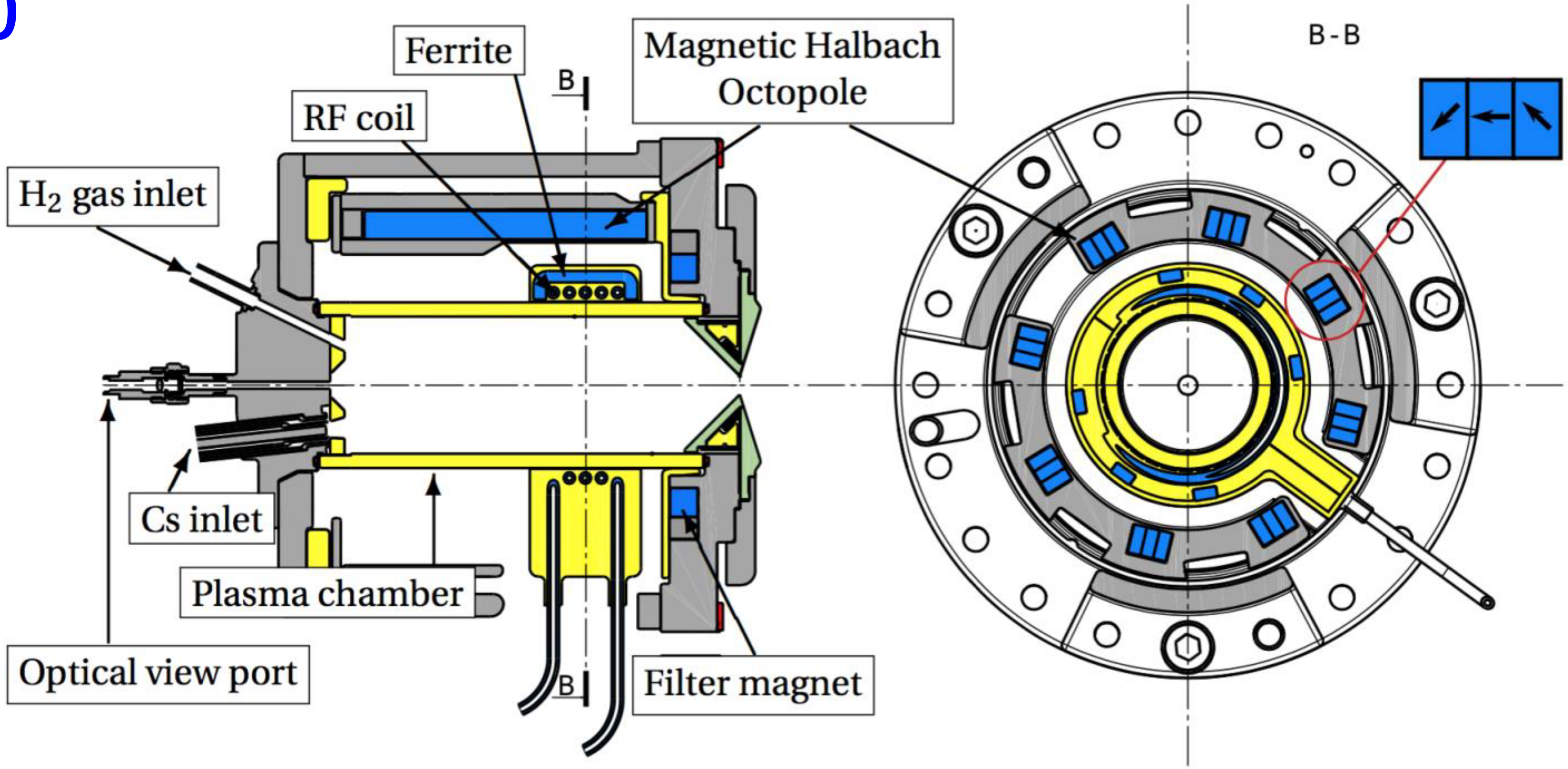
L4-IS03

Optical emission Spectroscopy & photometry View ports



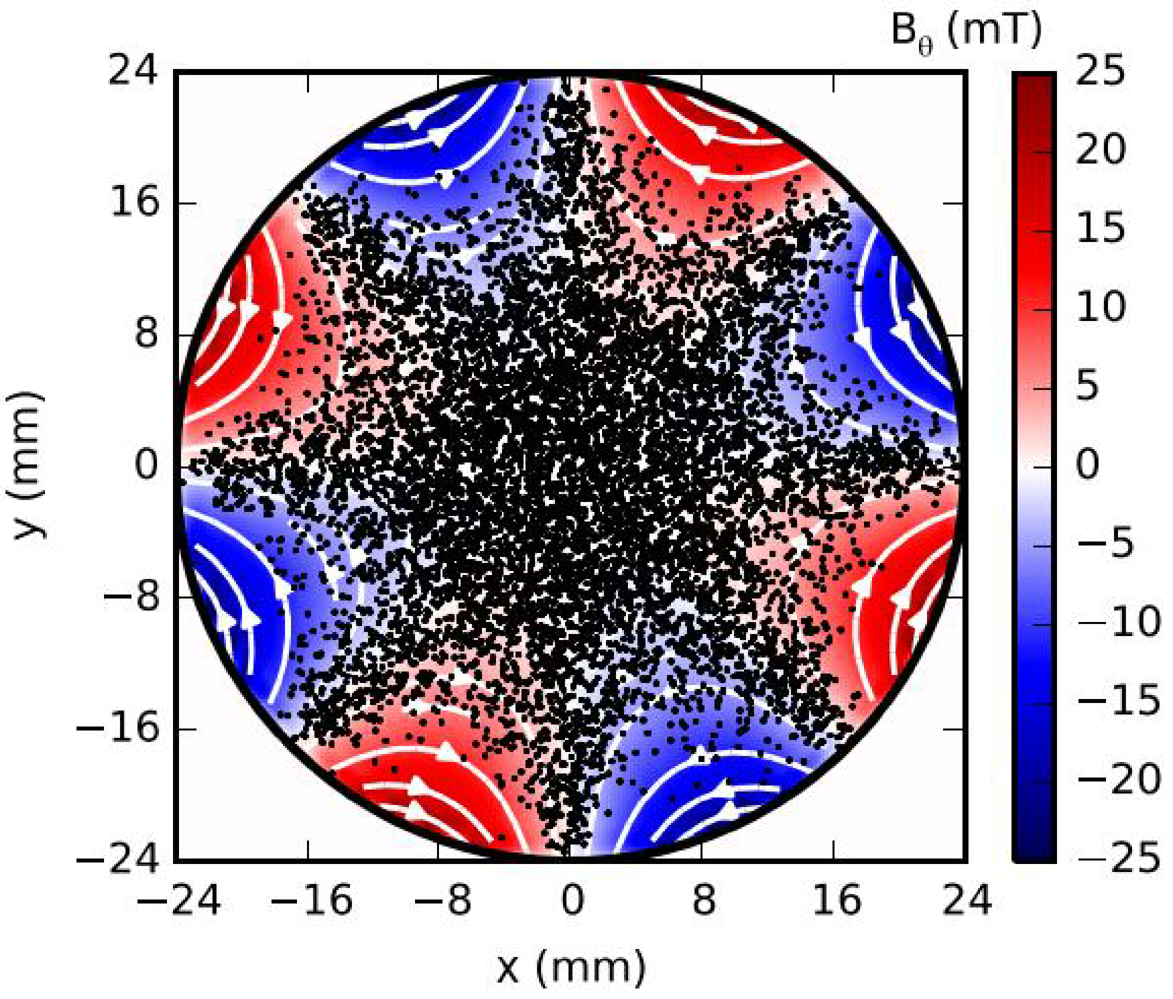
Precise measurement of the electron to ion beam current ratio e/H

IS03 magnetic Cusp

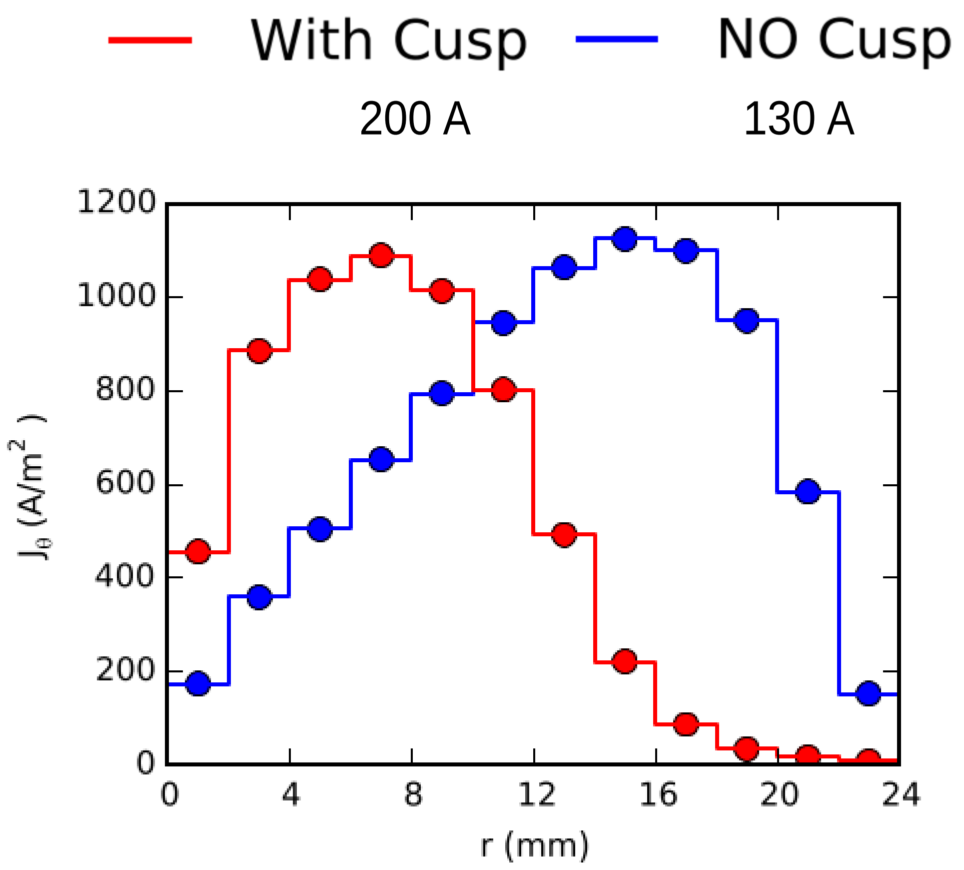


- The Cusp of IS03 is a set of 24 permanent magnets configured in Halbach offset octupole
- In filament sources cusps reduce electron-loss on the walls of the plasma chamber.
- For external antenna RF-Inductive Coupled Plasma the cusp affects acceleration of electrons in the periphery of the plasma chamber.

Simulation (S. Mattei's PhD thesis)



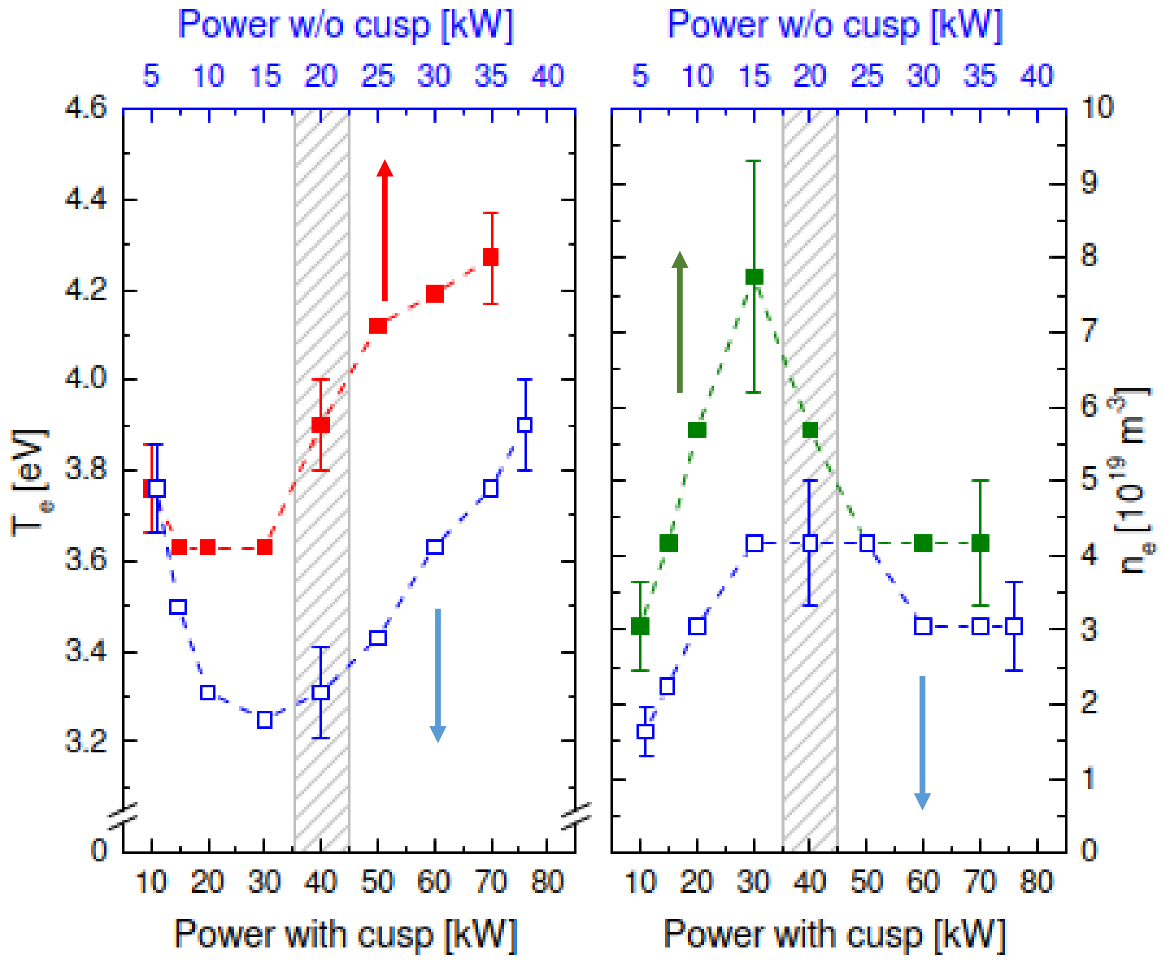
Cusp B-field and Electron density



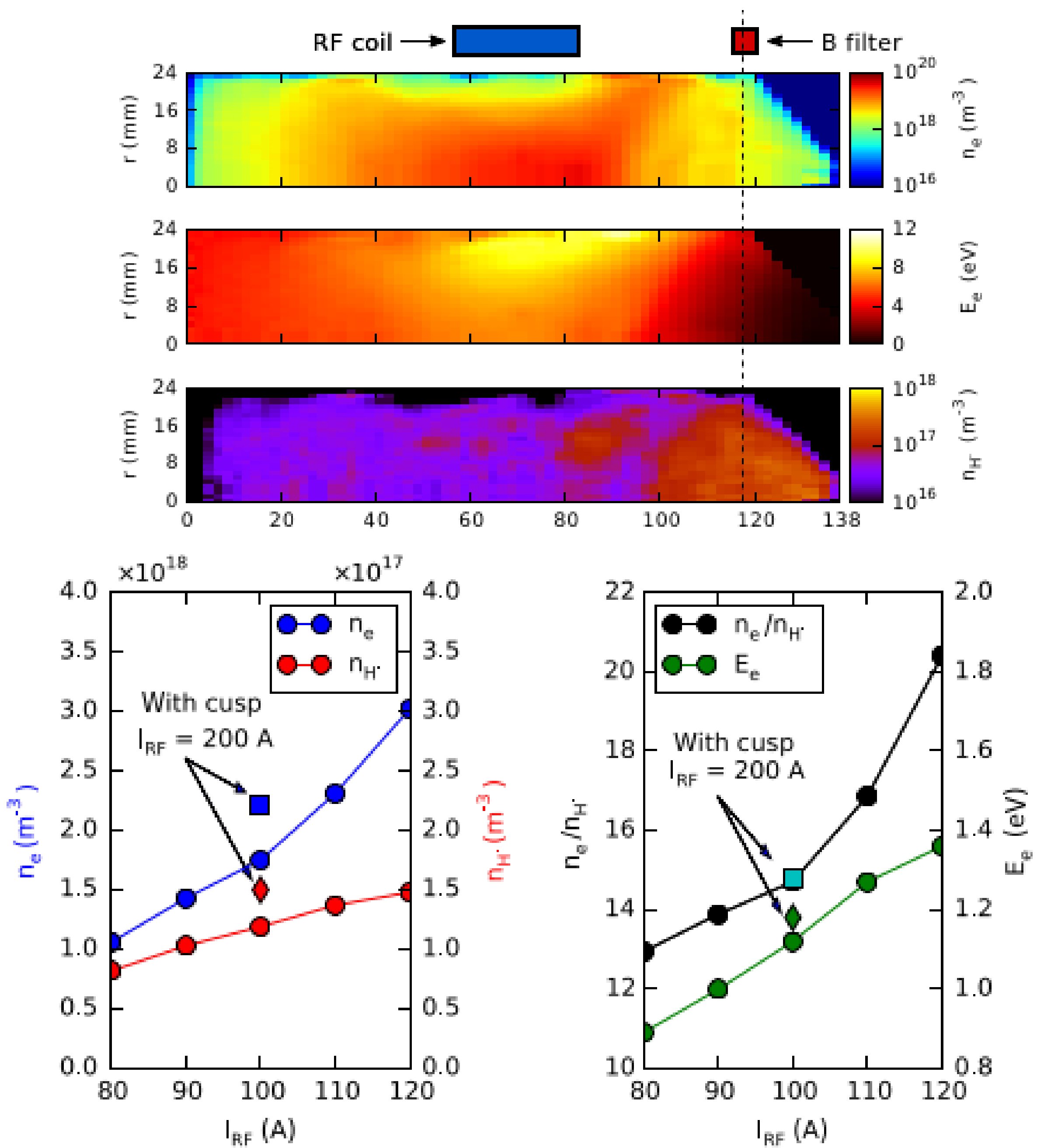
J_θ is the ICP induced plasma current averaged during the first RF half cycle

- ➢ Heating curent strongly enhanced in the periphery of the plasma chamber

Plasma parameters OES measurement & simulation



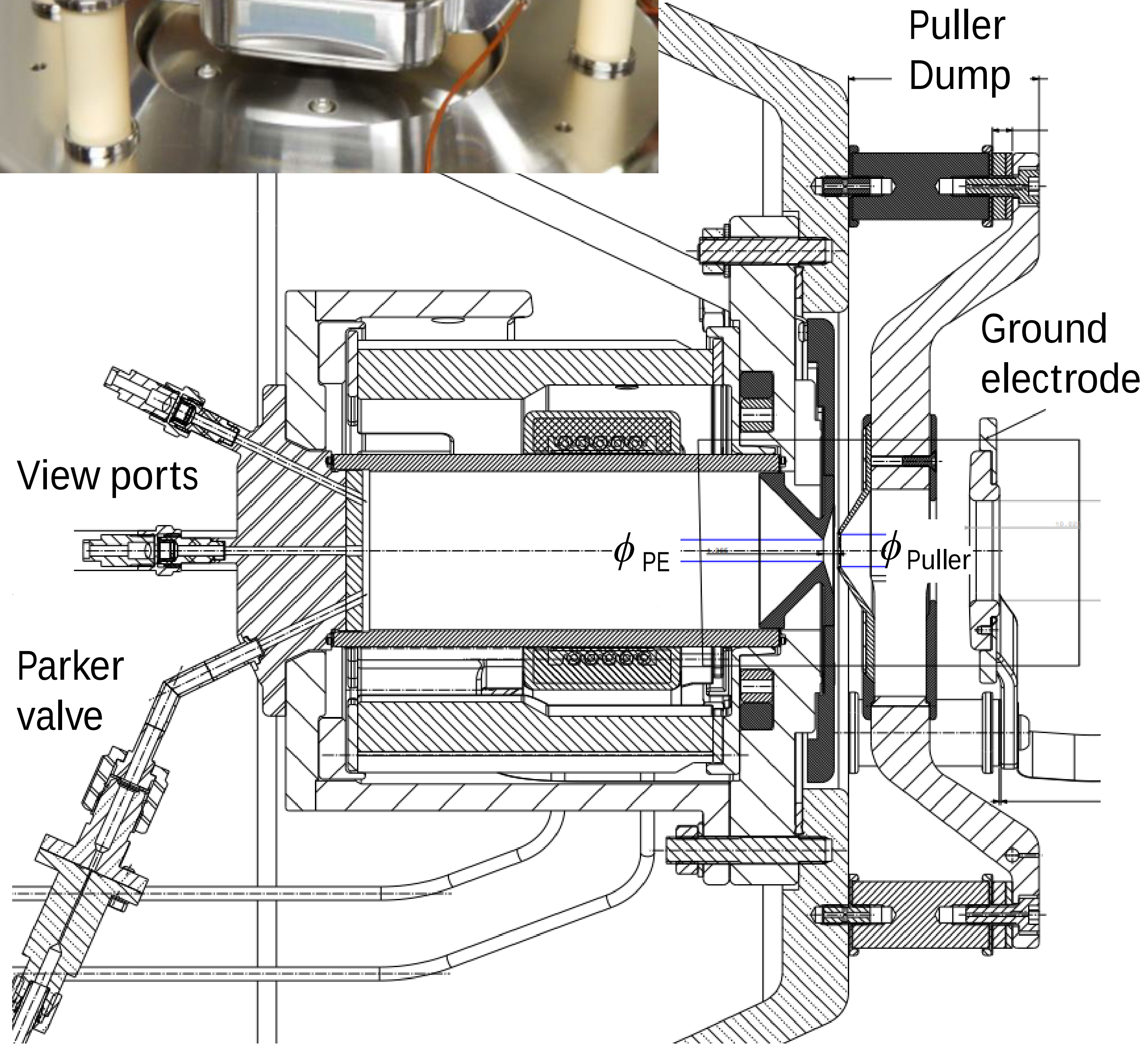
Electron temperature and electron density

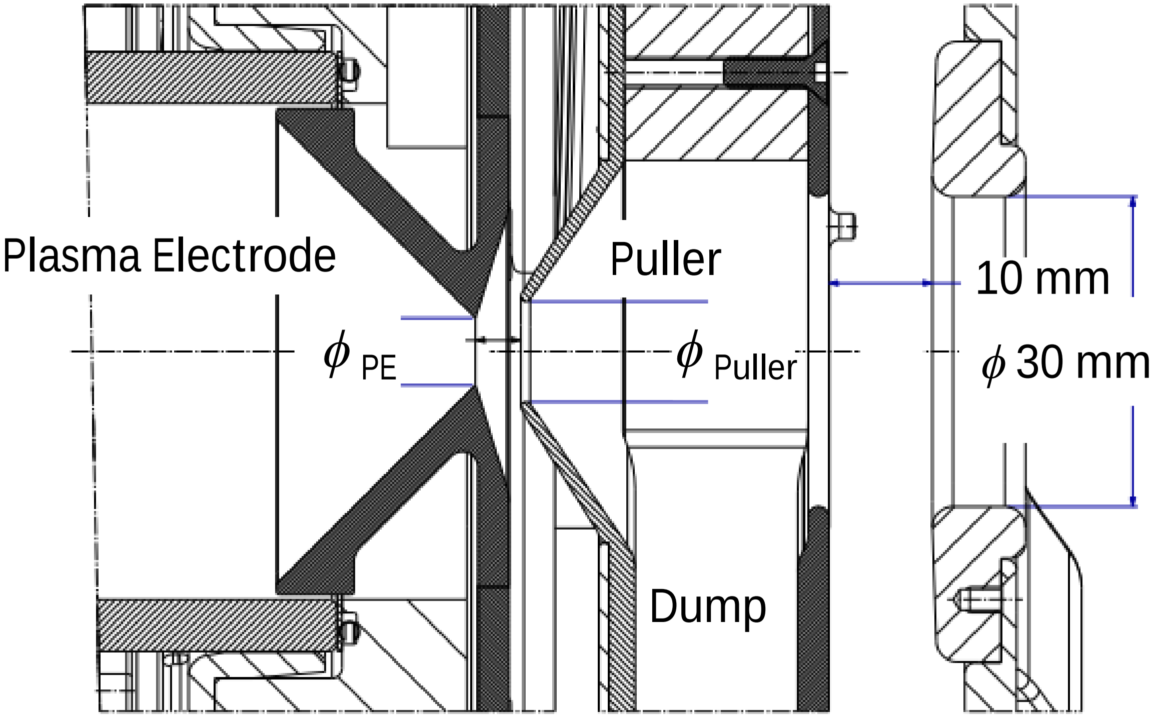


Electron and H^- density in the beam formation region

S. Mattei PIC MC NINJA, S. Briefi OES, Modelling and analysis

Linac4 IS03 Cusp free

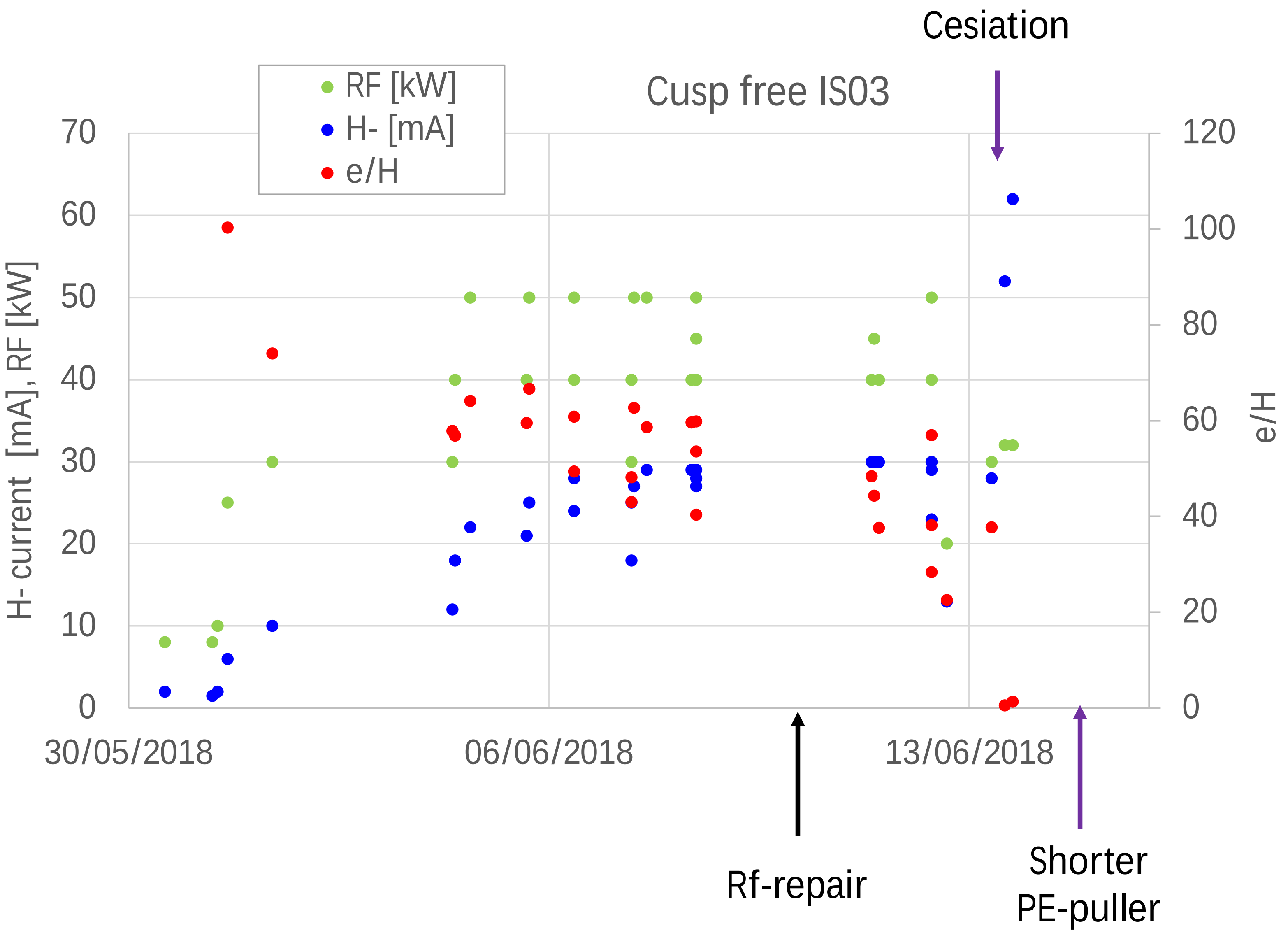




Extraction gap: 3.4 mm (nom. 4.4 mm)
ϕ plasma electrode aperture: 7mm
ϕ Puller electrode aperture: 9.7mm

Cusp housing replaced by an Al. spacer to ensure proper location of the Filter magnet

Volume mode operation



Polished and baked-out PE
aperture ϕ 7 mm

Startup: 10 days

- ✓ H^- beam : 29 ±1 mA
- ✓ e/H : 41 ±3
- ✓ RF : 37 ±7 kW
- ✓ Volume : 0.8 mA/kW

- ✓ Cs-Surf. : 2 mA/kW
- ✓ 62 mA, e/H : 1

IS03 Cusp | Cusp-free Vol. | Cusp-free Cs-surf

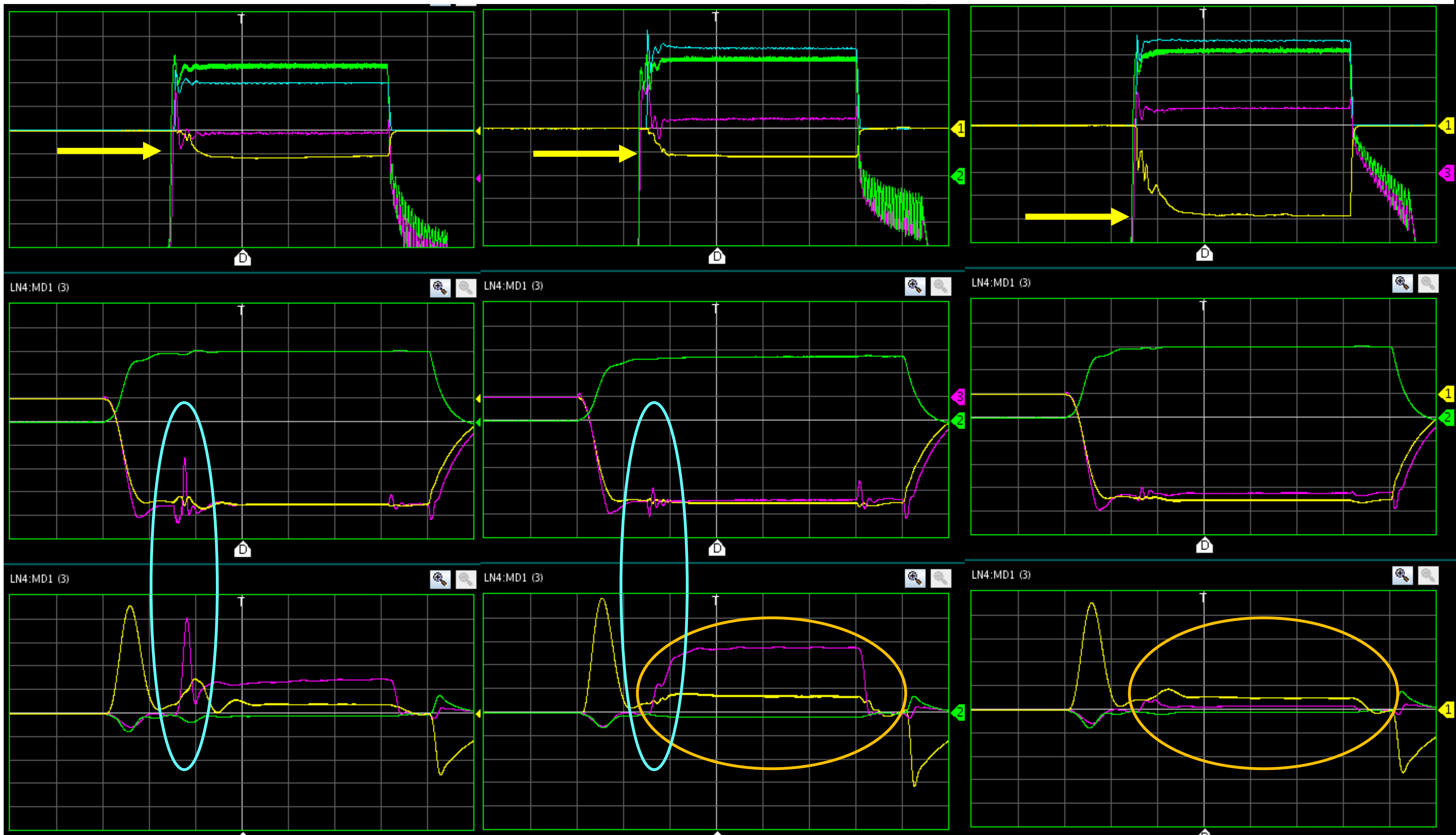
ϕ 6.5 mm,
30 mA, e/H ~20 (vol.)
60 mA, e/H = 1 (Cs-surf)

Puller : 11.4 kV & d=3.5 mm

30 mA,
(ϕ 7.0 mm e/H ~40)

62 mA
(ϕ 7.0 mm, e/H ~1)

- ✓ Cusp free plasma ignition takes place at reduced RF-power and reduces the electron burst observed during capacitive plasma ignition.
- ✓ Cesiation induces surface production of H^- ions in the vicinity of the plasma electrode aperture, the resulting negative potential supresses co-extracted electrons to a large fraction.

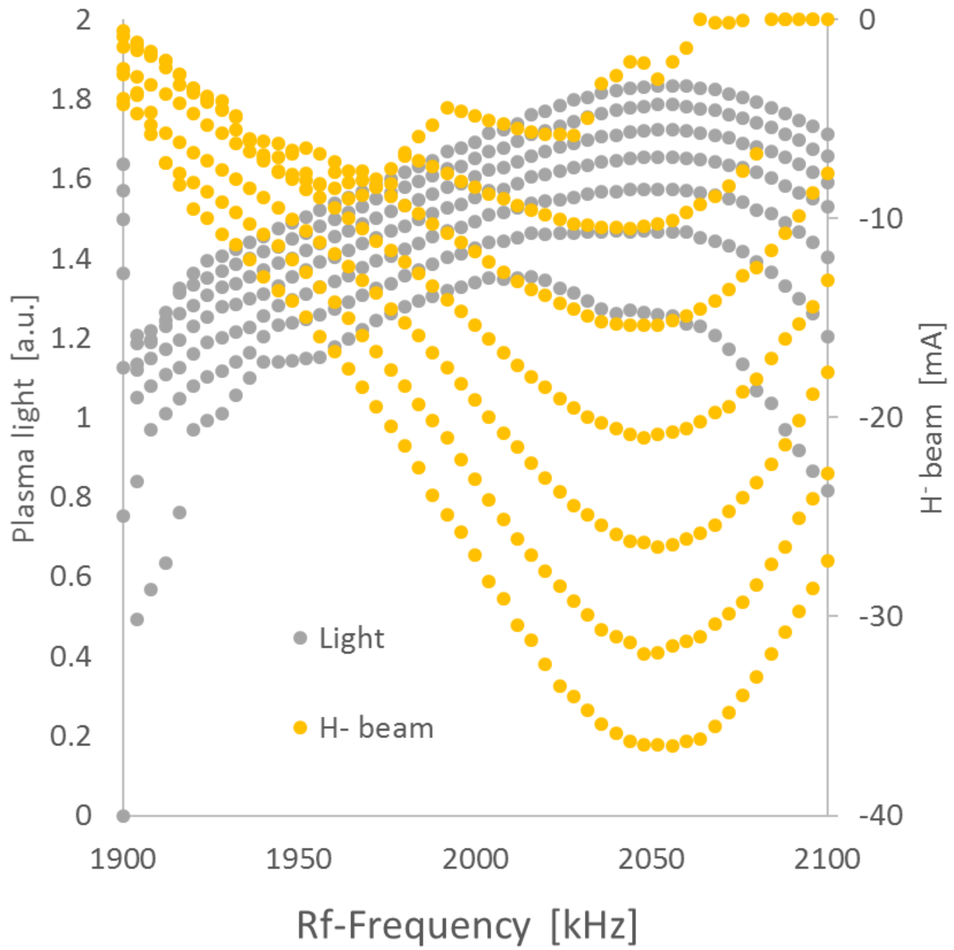


Cs-surface systematics, June 14,20

- 7 h + 9 h measurement provided ~ 1800 sets of cesiated surface data at e/H from 3.5 to 4.5
- Source parameters settings :
  - H_2 pulse width, 180-190 µs in steps of 2.5 µs
  - RF-freq. 1.9 to 2.1 MHz in steps of 4 kHz,
  - RF-power 15-45 kW in steps of 5 kW
- Systematic measurement to improve control's algorithm

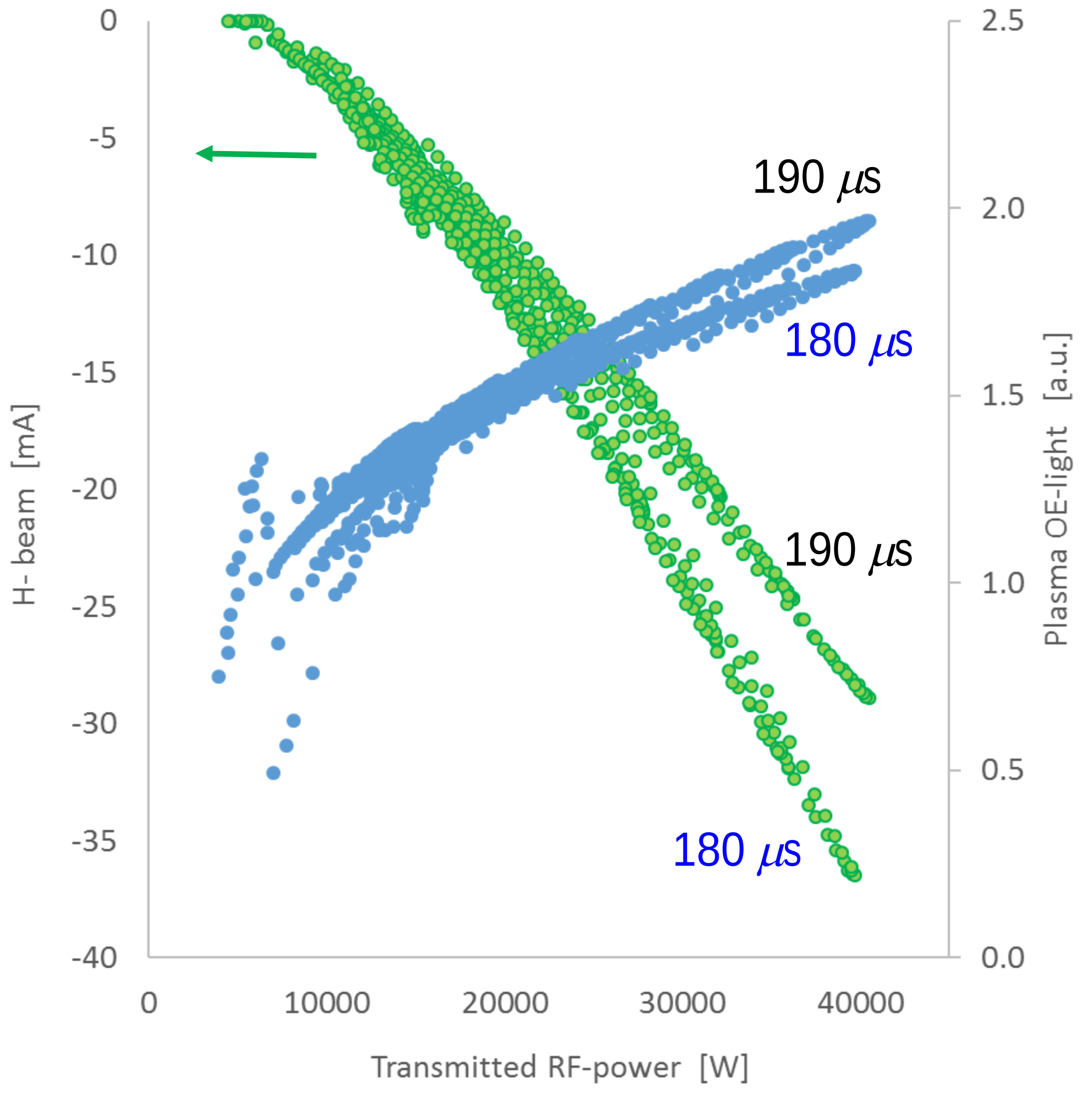
Measured :
1) RF-Fwd power
2) RF-Refl power,
3) RF-Phase,
4) H^- current BCT,
5) OE Plasma light intensity

Input to Kobayashi-san RF-coupling analysis

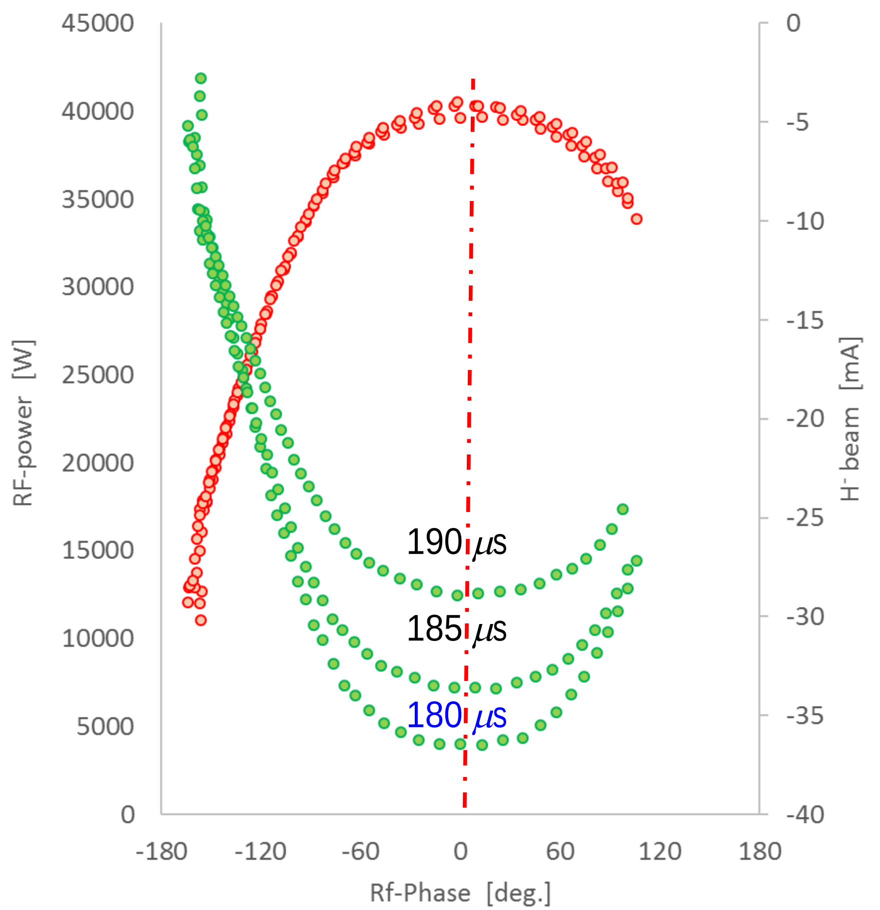


Courtesy of D. Noll

H^- beam vs. RF-power & phase



EM-valve opening duration:

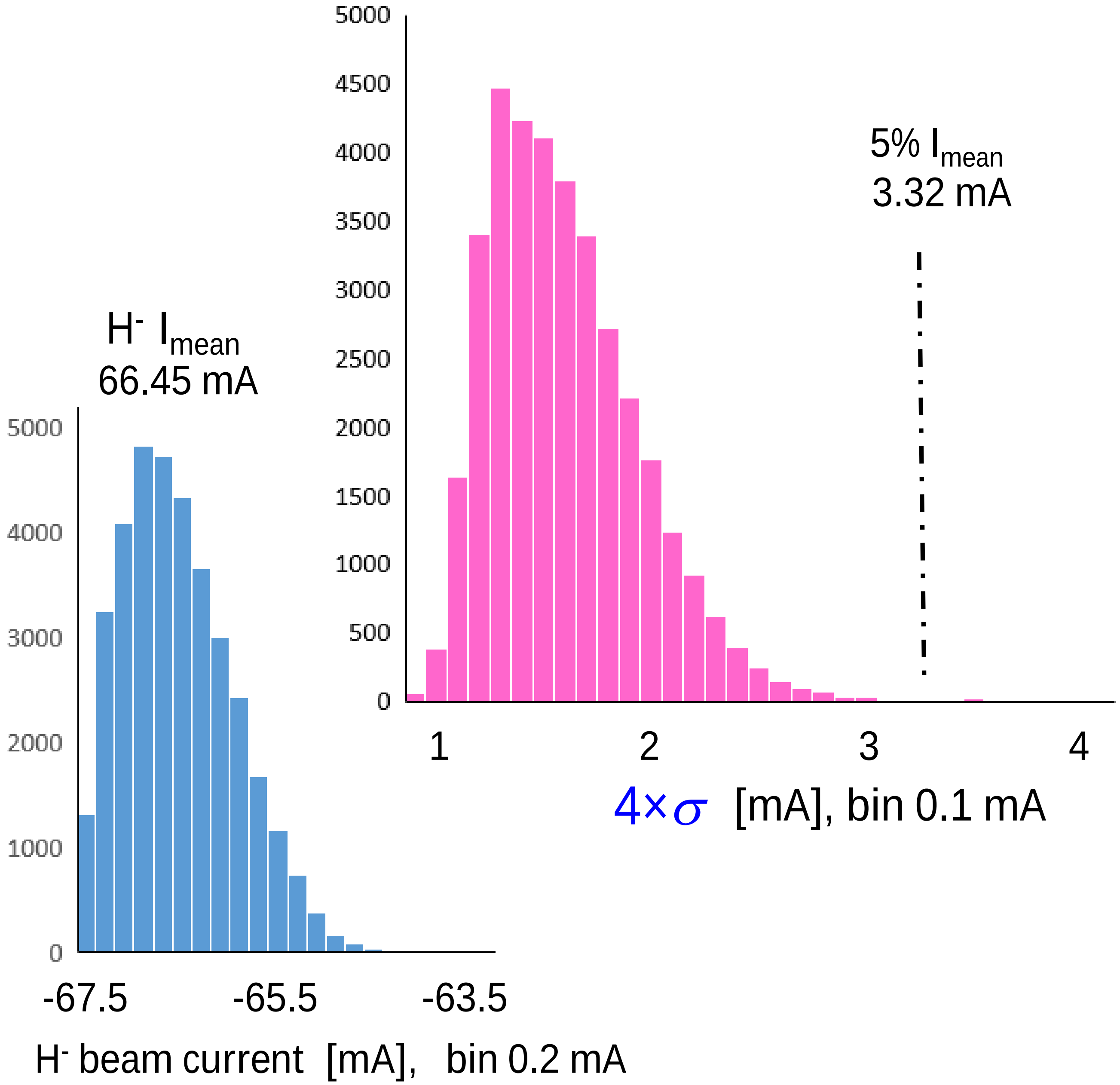


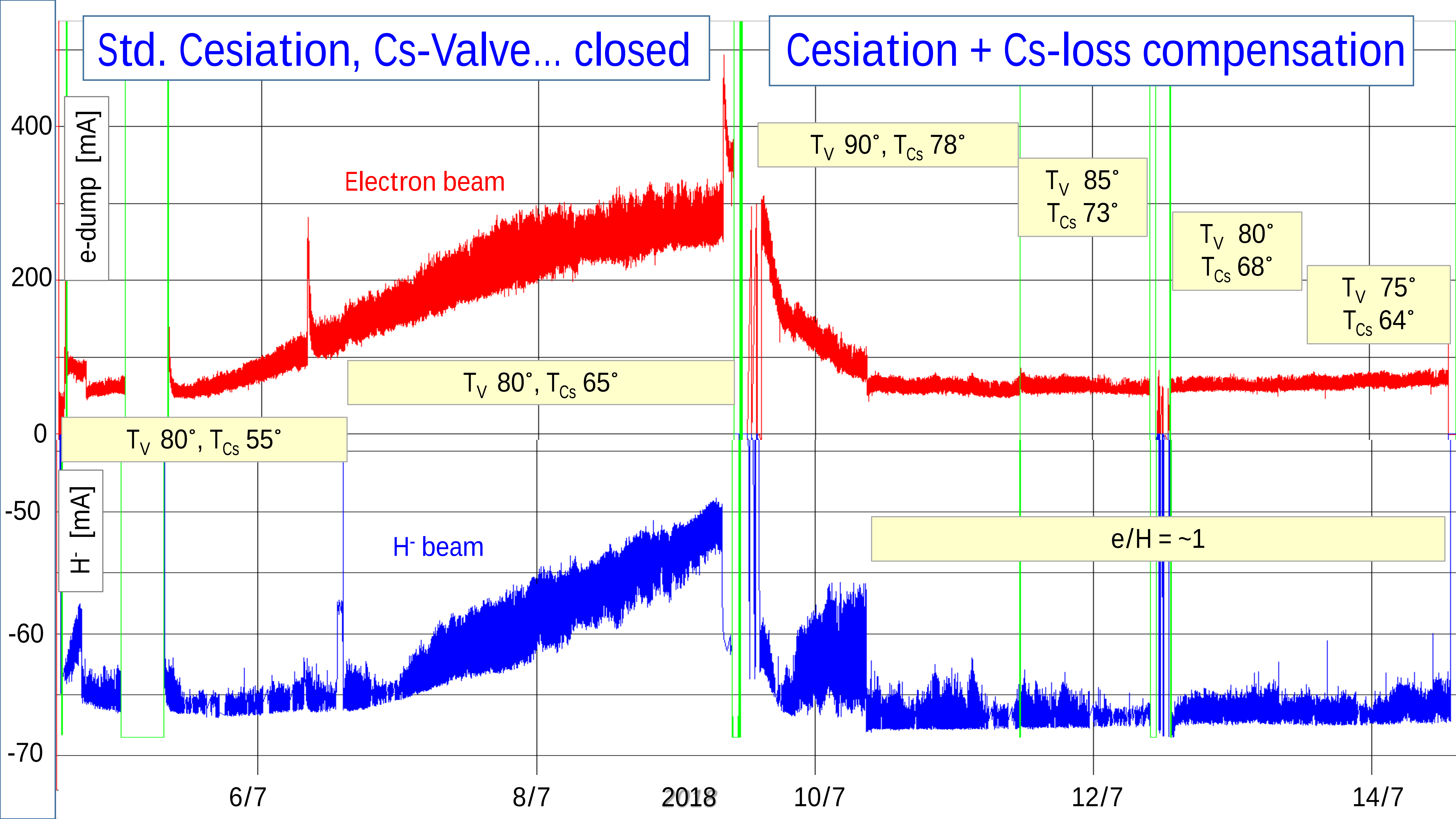
1) More Hydrogen improves RF coupling and plasma density but reduces beam intensity
2) RF-frequency scan: RF-phase = 0 correspond to highest H^- yield
3) The H^- yield is extremely sensitive to the H_2 injection, much less to the RF- phase.

Beam flatness ...

Illustration: flat beam in the LEBT upstream the RFQ

- For 0.6 ms H^- pulse duration, the flatness specification is below 5% (of the beam current). After the RFQ
- For short pulse duration 2%
- The flatness is defined as a multiple (4×) of the standard deviation σ.
- Flat beam:= $4\times\sigma < n\%\ I_{MEBT}\ (H^-)$

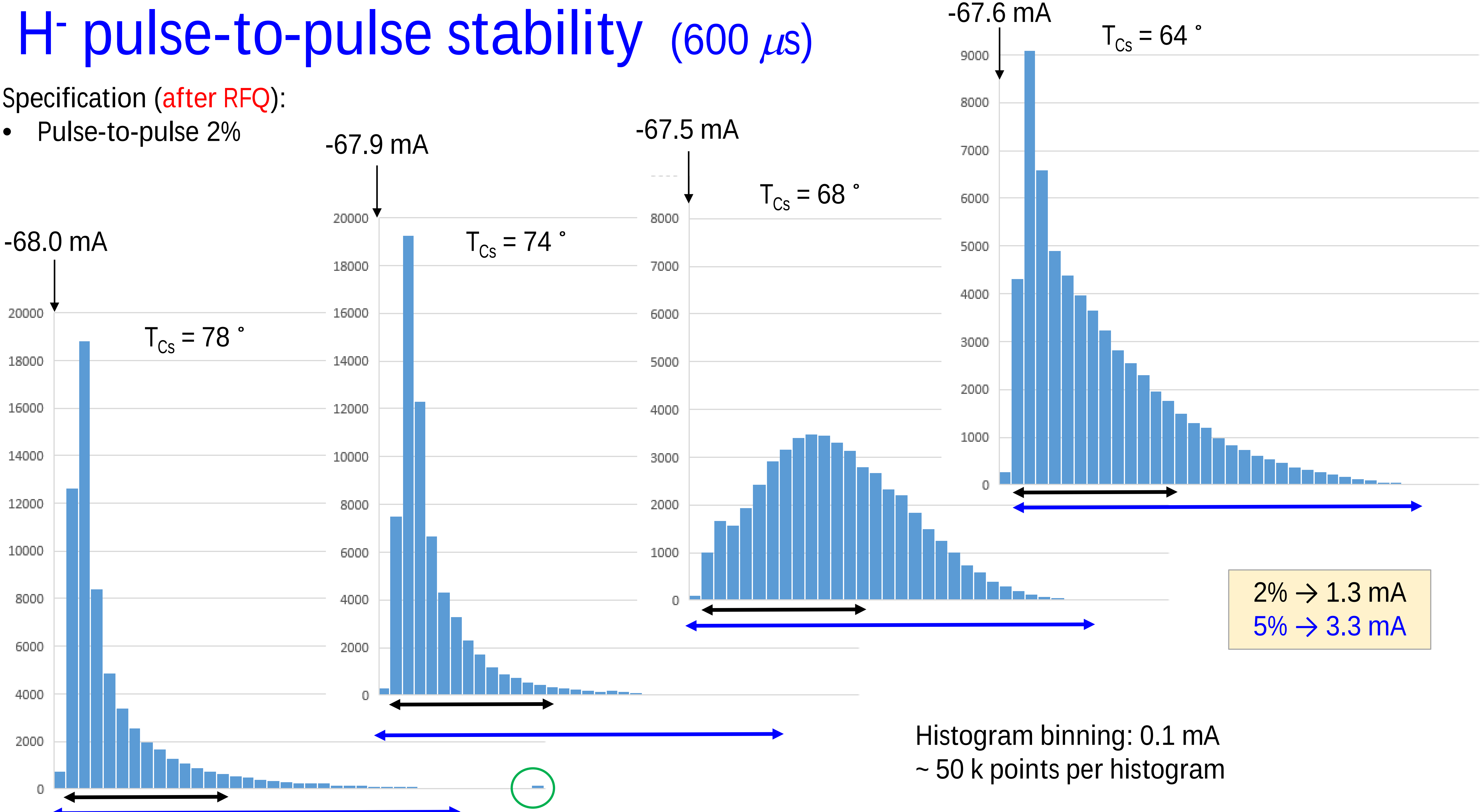



Std. Cesiation, Cs-Valve… closed
Cesiation + Cs-loss compensation
e-dump [mA]
400
200
0
Electron beam
T_V 90°, T_Cs 78°
T_V 85°
T_Cs 73°
T_V 80°
T_Cs 68°
T_V 75°
T_Cs 64°
T_V 80°, T_Cs 65°
T_V 80°, T_Cs 55°
H- [mA]
-50
-60
-70
H- beam
e/H = ~1
6/7
8/7
2018
10/7
12/7
14/7

H^- pulse-to-pulse stability (600 μs)

Specification (after RFQ):

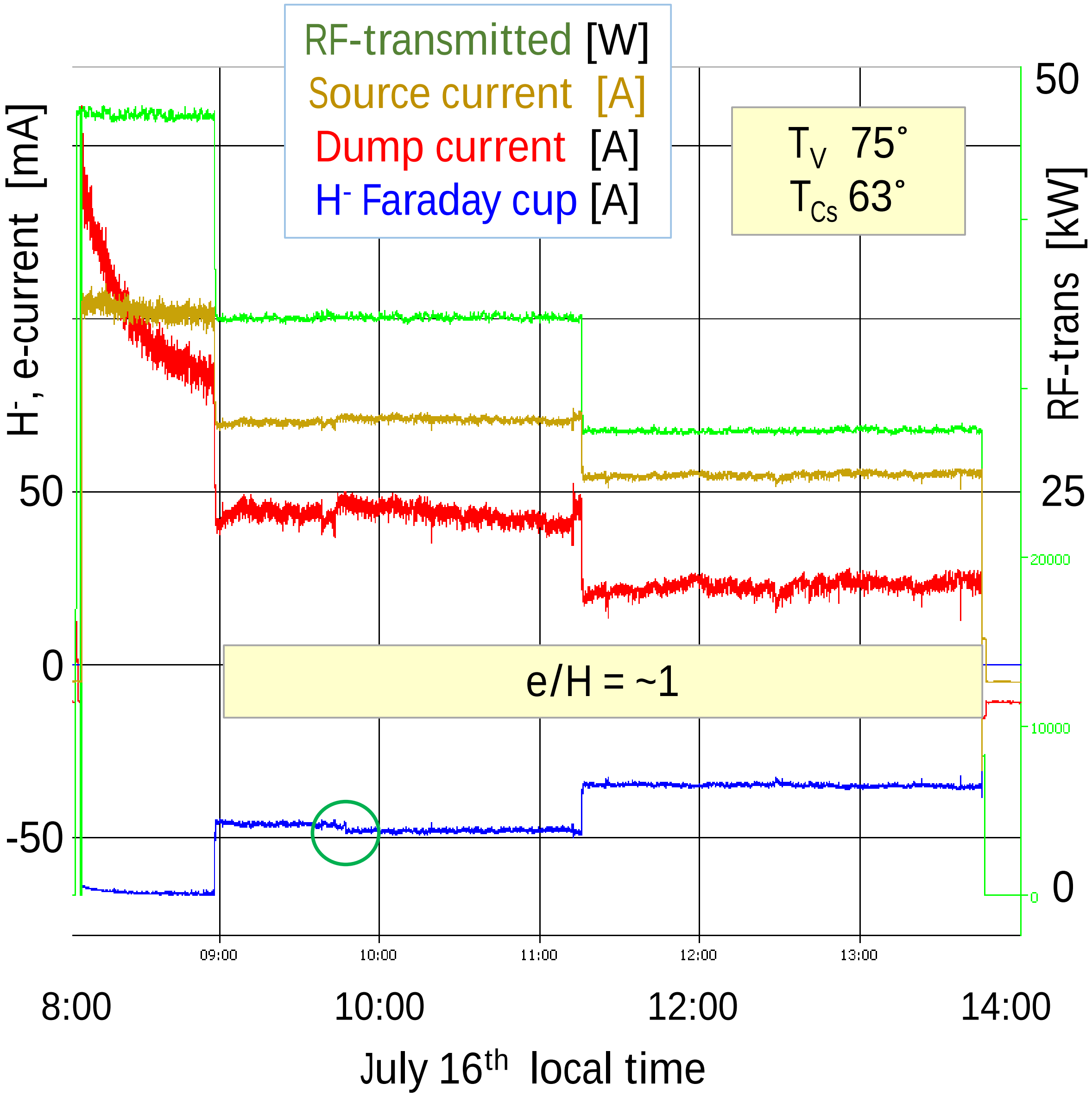
- Pulse-to-pulse 2%

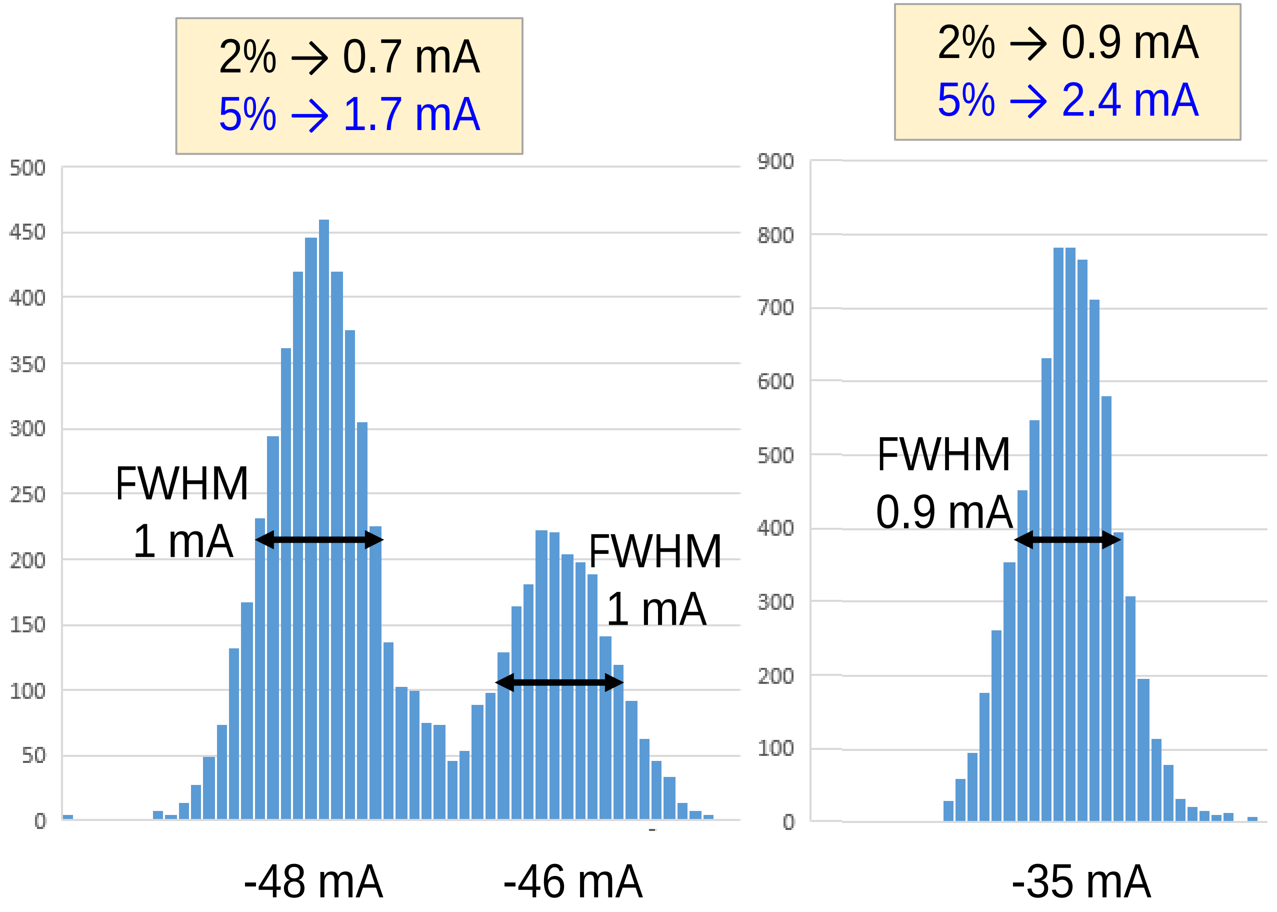


2% → 1.3 mA
5% → 3.3 mA

Histogram binning: 0.1 mA
~ 50 k points per histogram

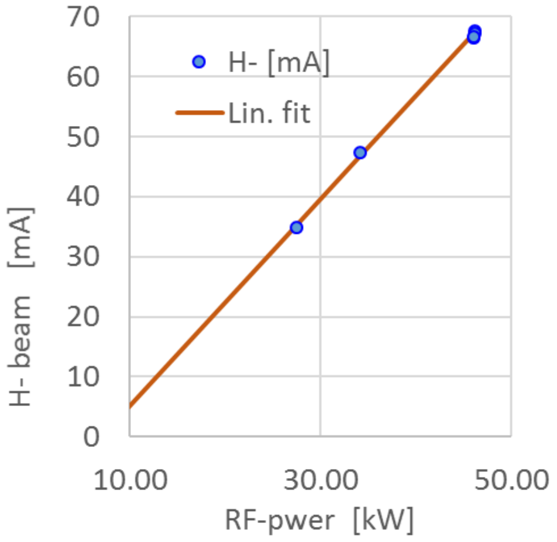
Tests at low RF-power + Cs-loss compensation; Preparation of 25 and 45 mA H^- beams



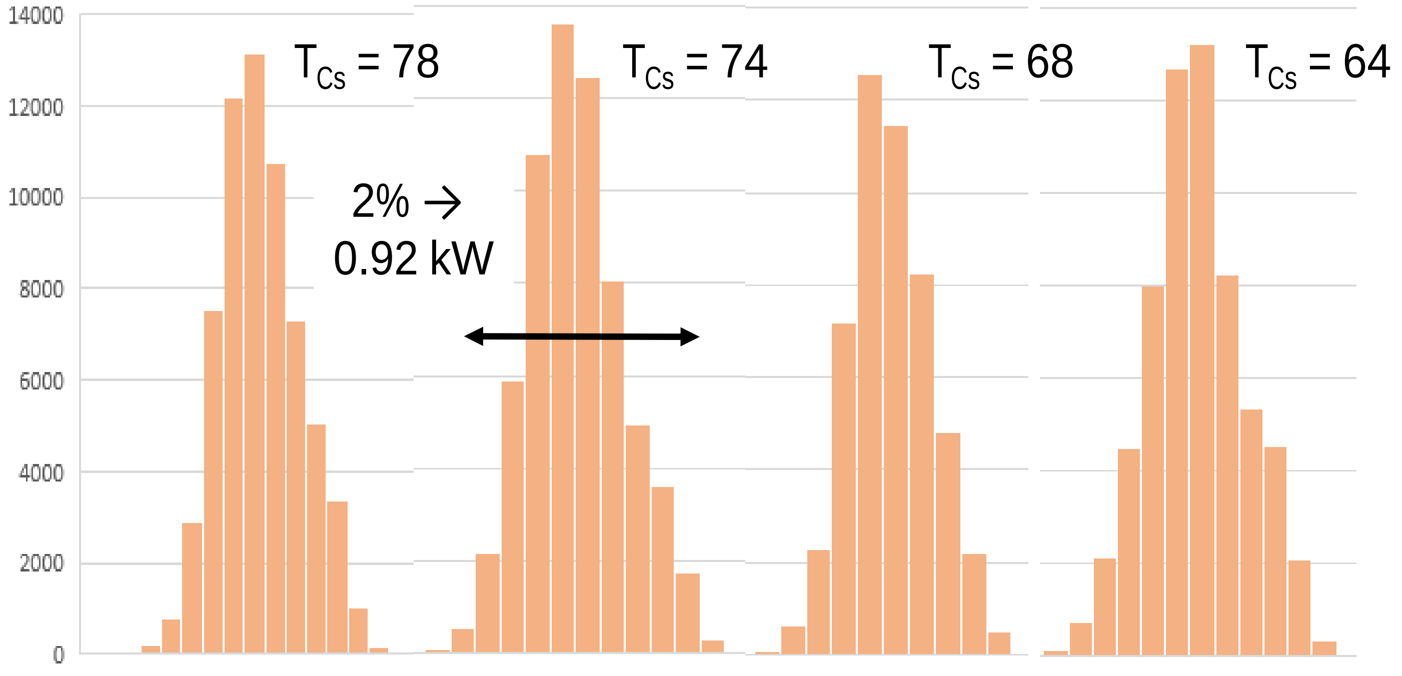


- H^- beam stability close to 5% but only in absence of source parameters tuning
- 2% pulse to pulse is not achieved. Hypothesis fluctuation of the H_2 feed

RF- stability
&
RF-H$^-$ correlation

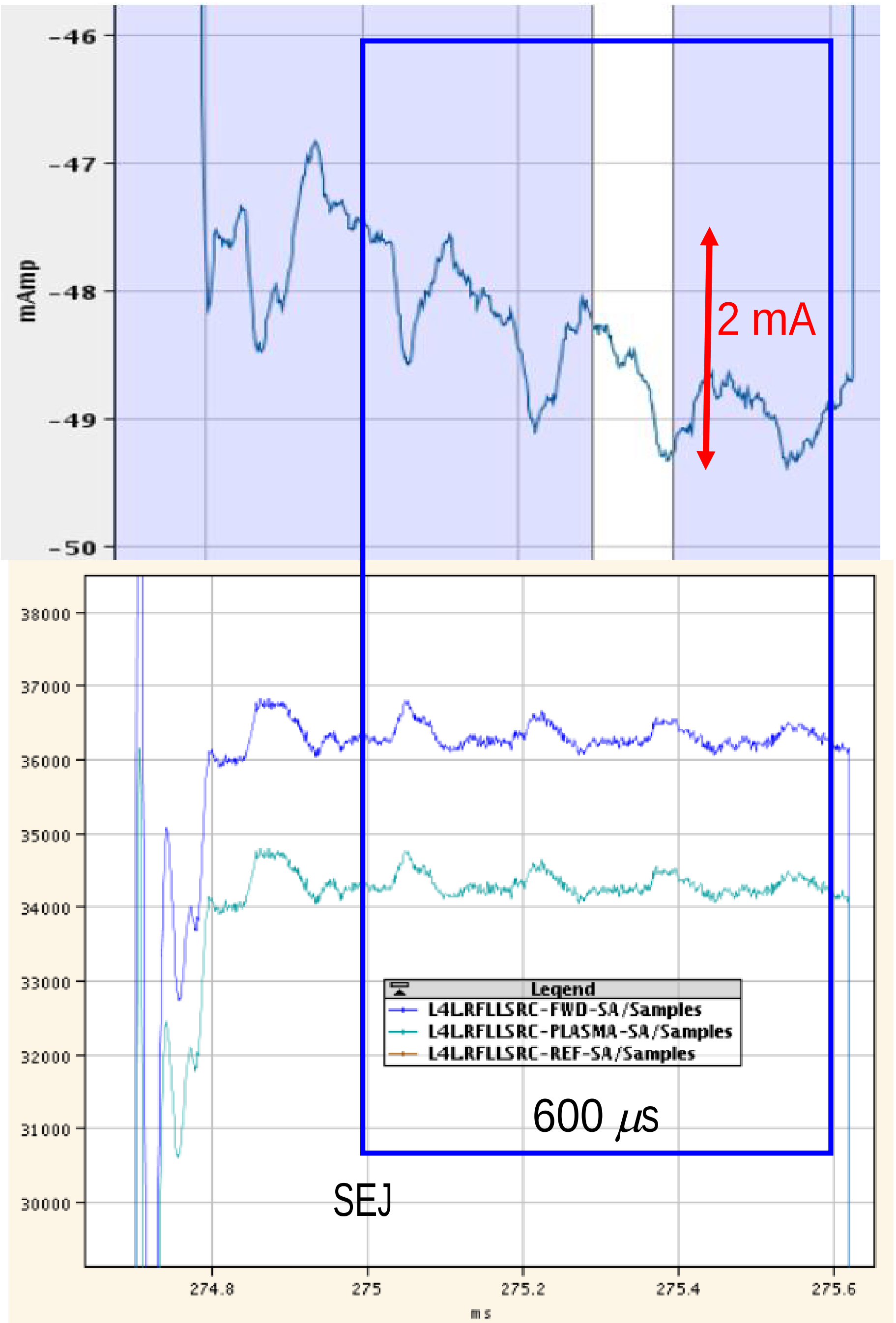


Rf-power averaged over 600 μs, Bin: 0.1 kW
RF-power mean value 46.2 kW

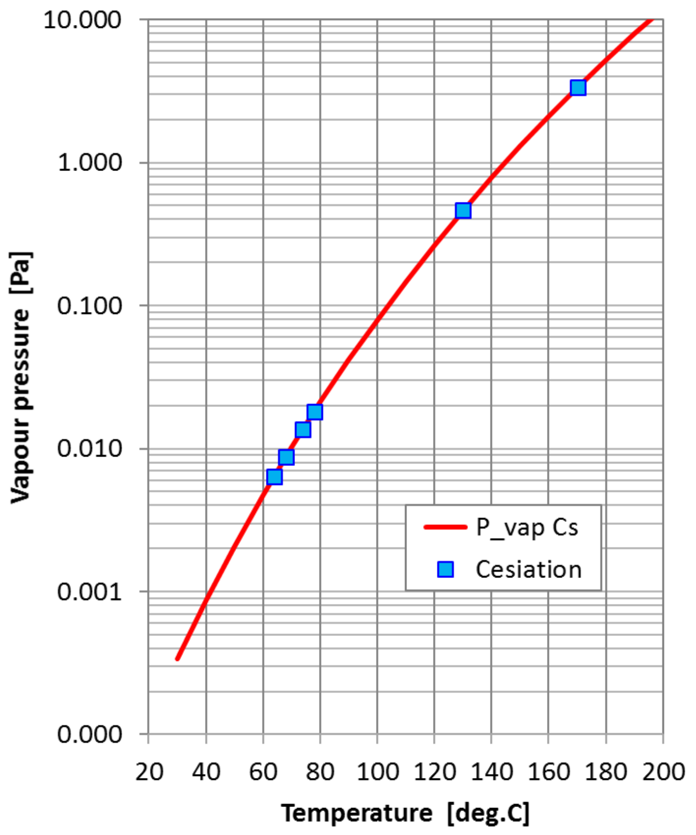


A fluctuation of RF power of 2% induces 2% current fluctuation
Slope during the tests 1.7 mA/kW

Single pulse at 34 kW RF-power



Monthly vs. dc cesiation



- During the pulse most of the Cs in the plasma is ionized and cannot escape the plasma chamber, after plasma extinction, the high vapour pressure of Cs induces its migration into the front end and LEBT through the plasma electrode aperture.
- The SNS H^- source's plasma is always on at low power; its operation is very stable during ~5 weeks, (no sign of beam degradation)
- We can compensate the losses after an initial cesiation

				Cs consumption	
Cesiation mode	Temp [deg.C] Valve,	Oven CCV,	AQN	[mg/ month]	[mg/ year]
Monthly	220	170		5.0	60.0
	200	130		2.1	25.0
Cs-loss comp.	90	75	78	19.5	234.1
	85	70	74	14.6	175.2
	80	65	68	9.3	112.0
	75	60	64	6.9	82.4

Cs-consumption		g/year
SNS	RF	0.36
J-PARC	LaB6	5.40
BNL	magnetron	4.38
HERA	magnetron	1.10
ISIS	Penning	43.80

Long-duration test mandatory to find the lowest Cs-flux needed towards 1 year of operation

- It looks like the total amount of Cs is not prohibitive if operated around 70 deg.C
- Preliminary calibration with Inficon quartz balance on gold substrate neglects re-emission of Cs-atoms, more reliable calibration via IPP/Augsburg method wishful.

Conclusion 1

- Cusp-free IS03 shows strong operational advantages in Cs-Mo surface production mode few sparks within a week. Regretfully its emittance not yet measured at the test stand.
- Under standard “monthly” cesiation, the peak performance of IS03 sources (i.e. max. current) cannot be maintained; the degradation of cesiated surface properties induces an increase of co-extracted electrons and reduction of the H^- yield.
- A cesiation followed by compensation of the Cs-losses demonstrated high stability during 4 days at maximum H^- yield (67 mA) and 6 h at nominal currents (47, 35 mA).
- Meeting stability and flatness criteria in the LEBT require improvements of the sub systems, a smoothing (to be demonstrated) is expected after the RFQ.
- The electron to ion ratio was stable during the test (e/H ~1), this is deemed optimum for this type of source.
- The Cs consumption of the compensation mode is estimated to 200 mg/year; After 4 years operation at the test stand under similar duty factor (Magnetron tests consumption: 600 mg + tests of all units), vacuum flanges located at positions relevant for the RFQ showed Cs surface densities below 0.01 $\mu g/cm^2$.
- This new operation requires multi month testing, Once validated, it may ease operation. During the test we only performed a daily check (Autopilot is still orphan)
- This mode is in the spirit of the risk analysis (min. Cs), however, the Cs-procedure and a new Temp. based interlock are required.

The contributions of Sebastien, Christian, Nicolas, Francesco, Didier and Mike was essential and is hereby acknowledged.

Daniel’s systematic

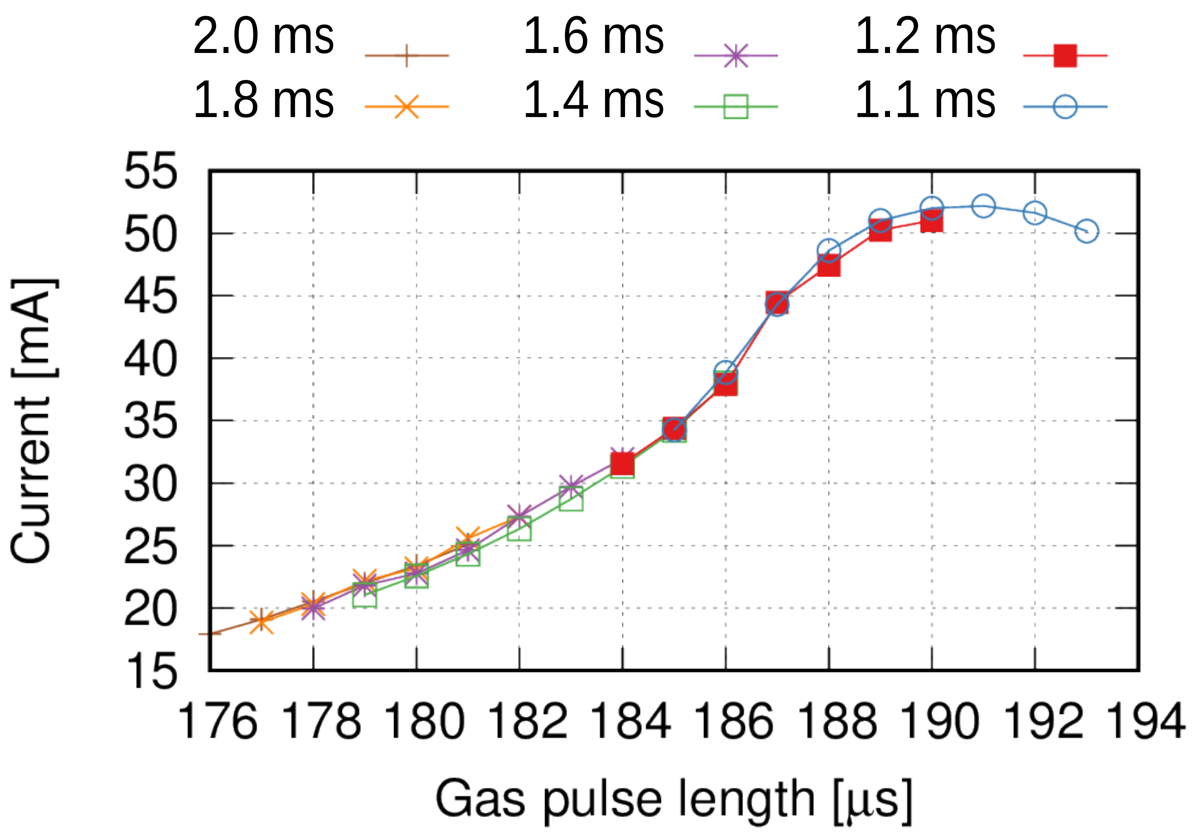
IS03 ICP Cesiated surface

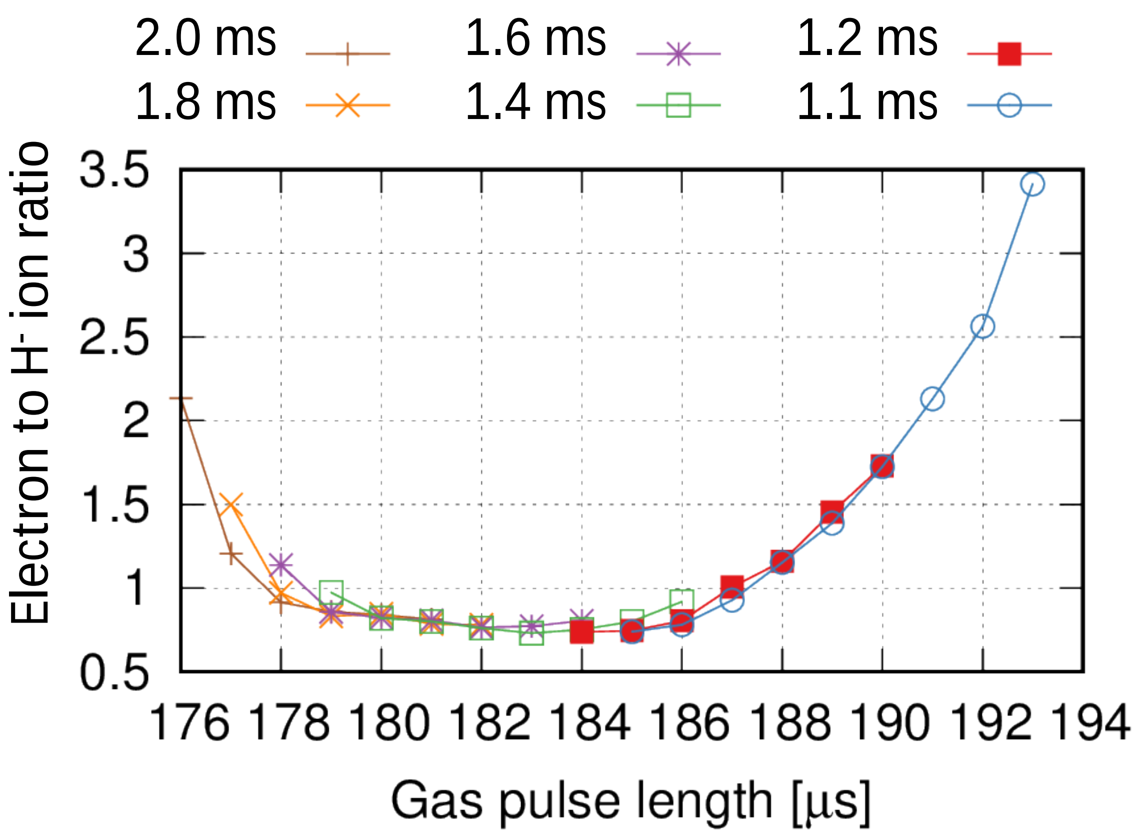
Scan of EM-H2 injection valve parameters

Courtesy of D. Noll

Timing of Gas pulse start and duration

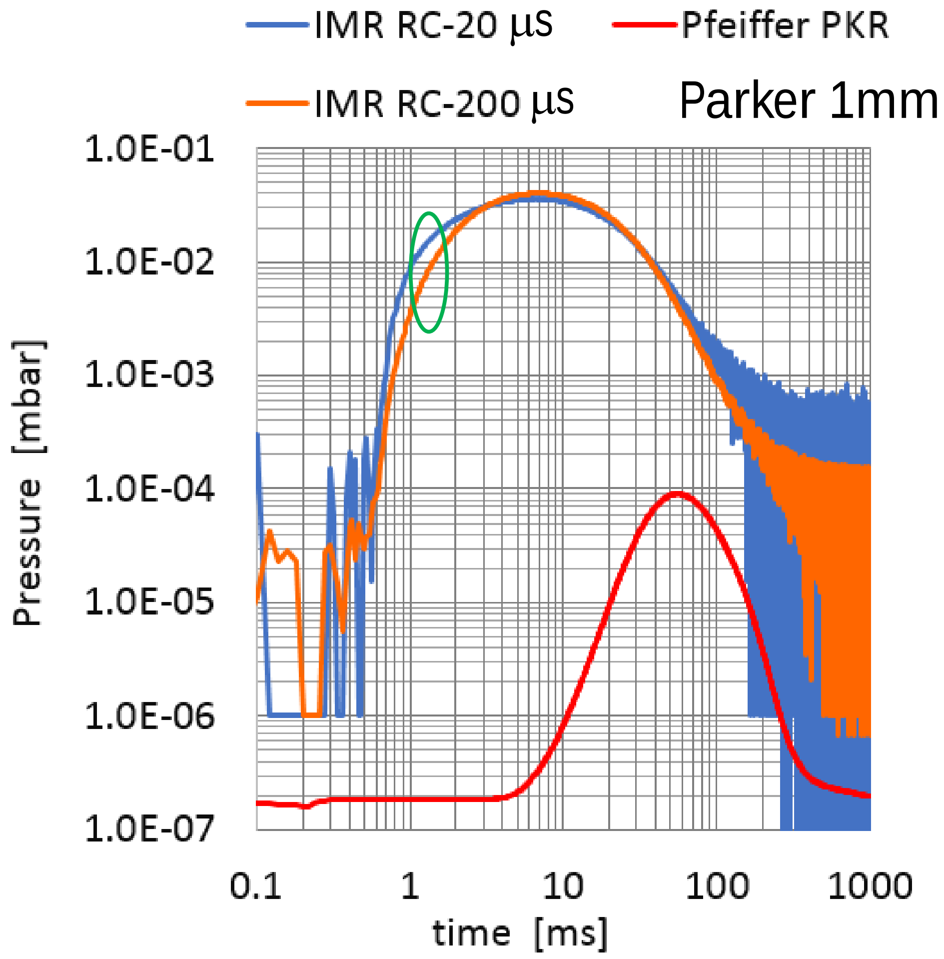
The plasma is ignited 0.2 ms before H^- beam ejection.





Pulsed H_2 injection

Parker Pulse valves Serie 9		
009-1421-900	ϕ 0.508	mm
009-1643-900	ϕ 0.9906	mm

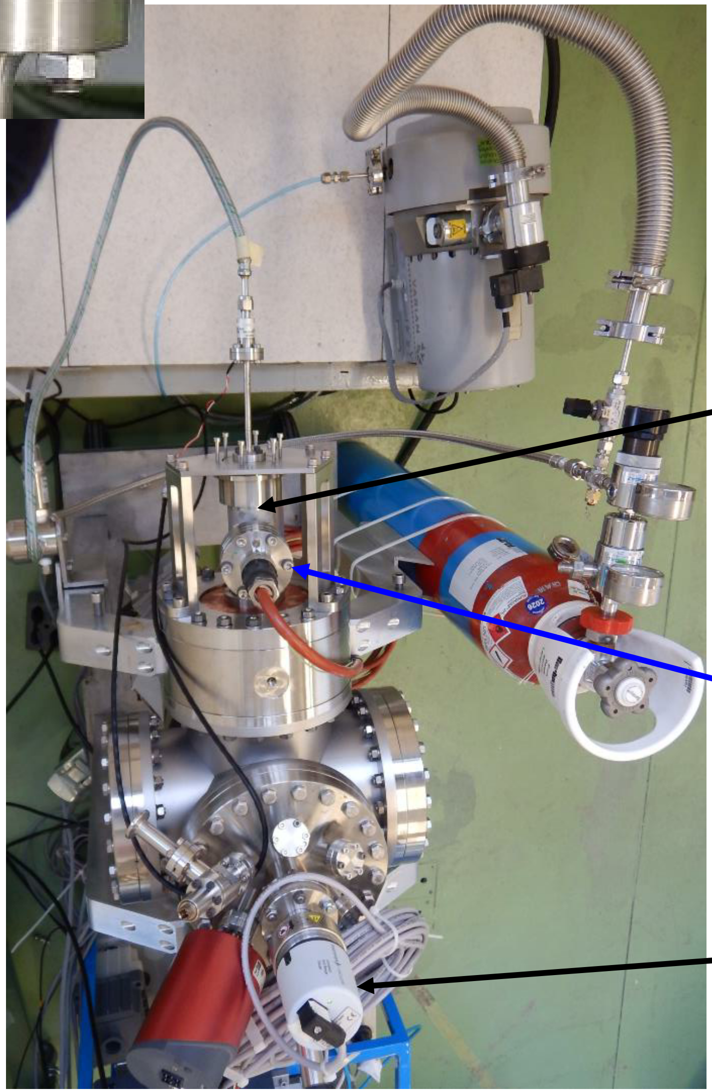


Conductance Plasma electrode hole:

PE aperture ϕ = 6.5 mm

$C_{H2} = 9.3\, d^2 \times (M_{N2}/m_{H2})^{1/2} = 14.7$ [l/s]

Pfeiffer THM 521 DN160		
gas		l/s
Nitrogen	N2	510
Helium	He	520
Hydrogen	H2	450
Argon	Ar	500



IS03 Plasma Chamber mock-up

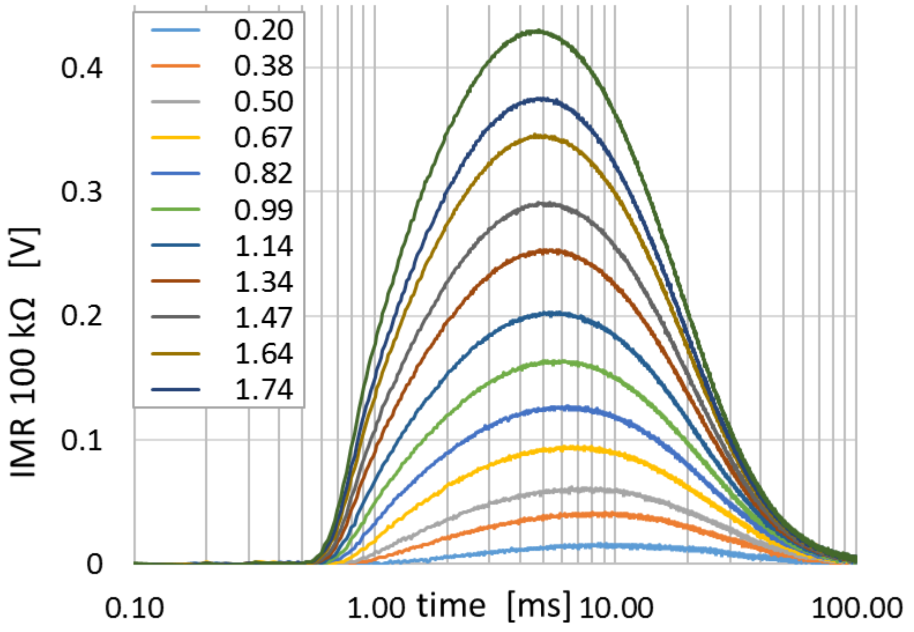
PE-hole diam.: 6.5 mm

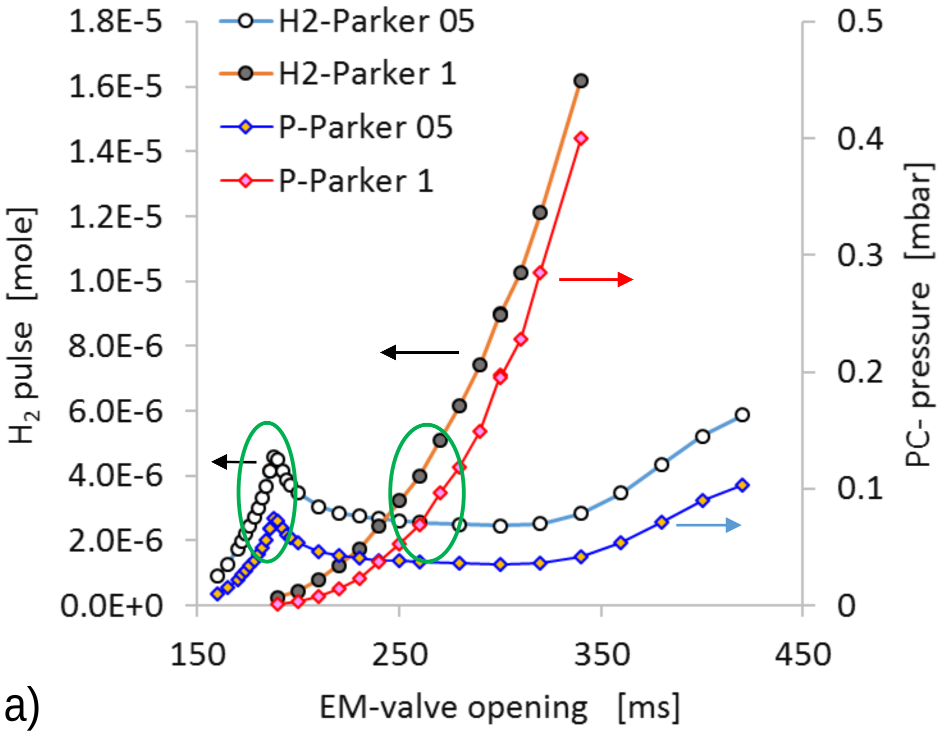
Fast gauge IMR-312 readout 100 kOhm	
N2	P = 0.123*(U^0.9984)
H2	P = 2.2*0.123*(U^0.9984)

Pfeiffer PKR	
N2[mbar]	P = 10^(1.667*U-11.33)
H2[mbar]	P = 2.4*10^(1.667*U-11.33)

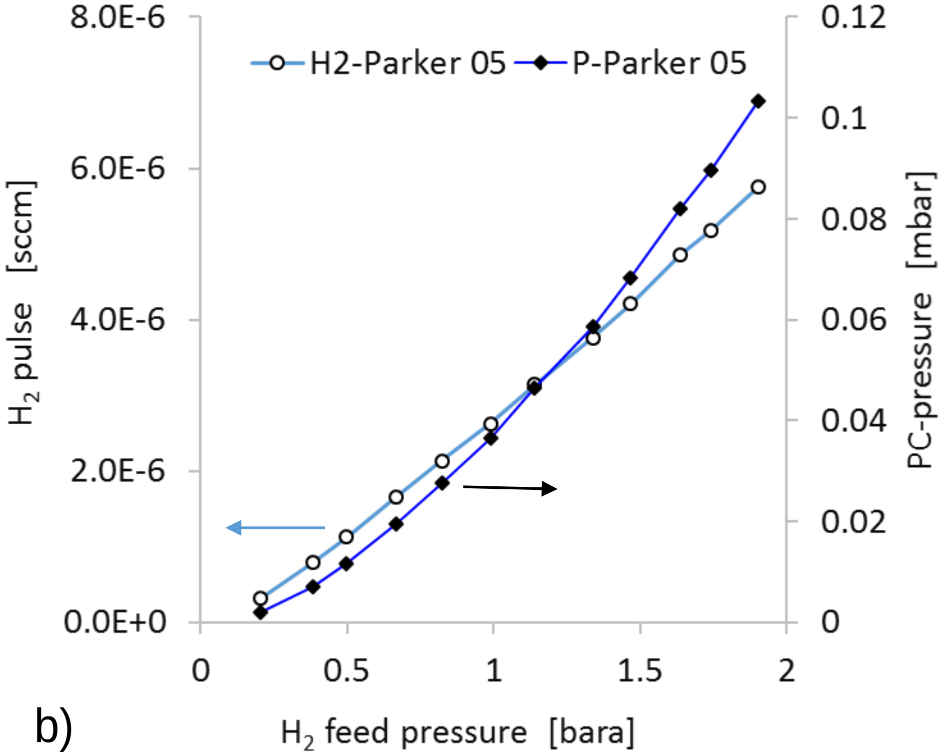
EM-Valve H_2 injection

a) Diameter of the EM-valve 0.5 and 1 mm
b) Effect of the H2 feed pressure on mass flow and pressure (0.5 mm only)
c) Pressure in the IS03 plasma Chamber (PC) ([2:3] ms average (representative of the typical operation region]





a)

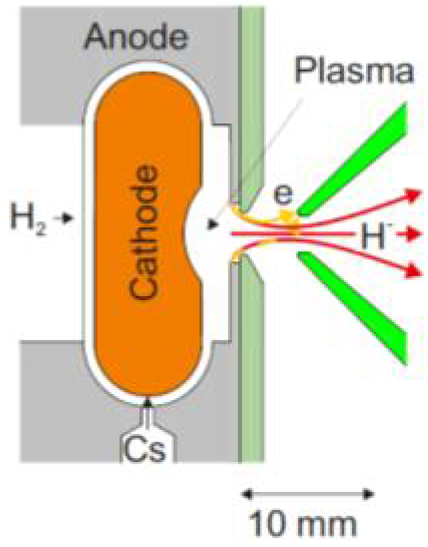


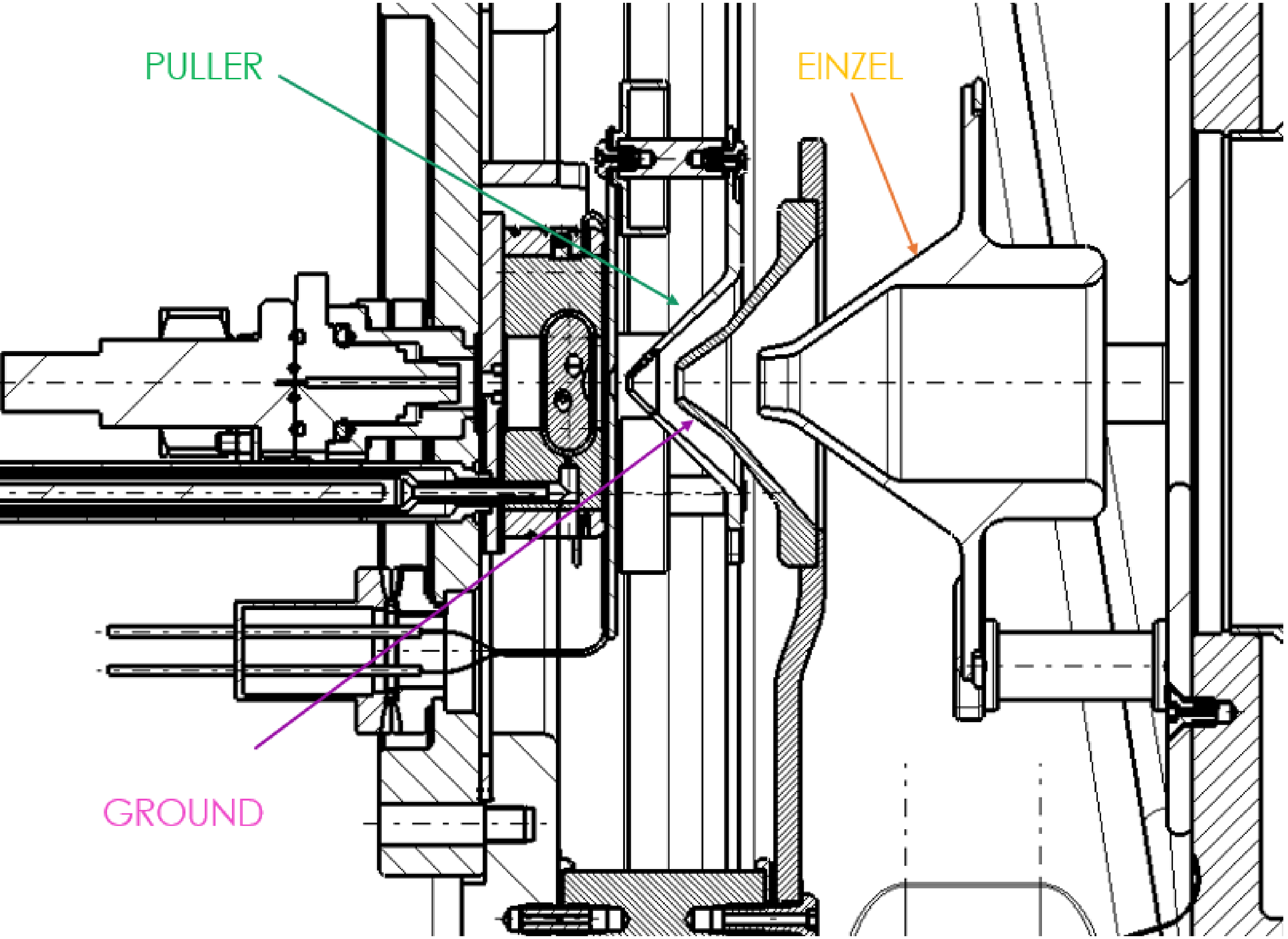
b)

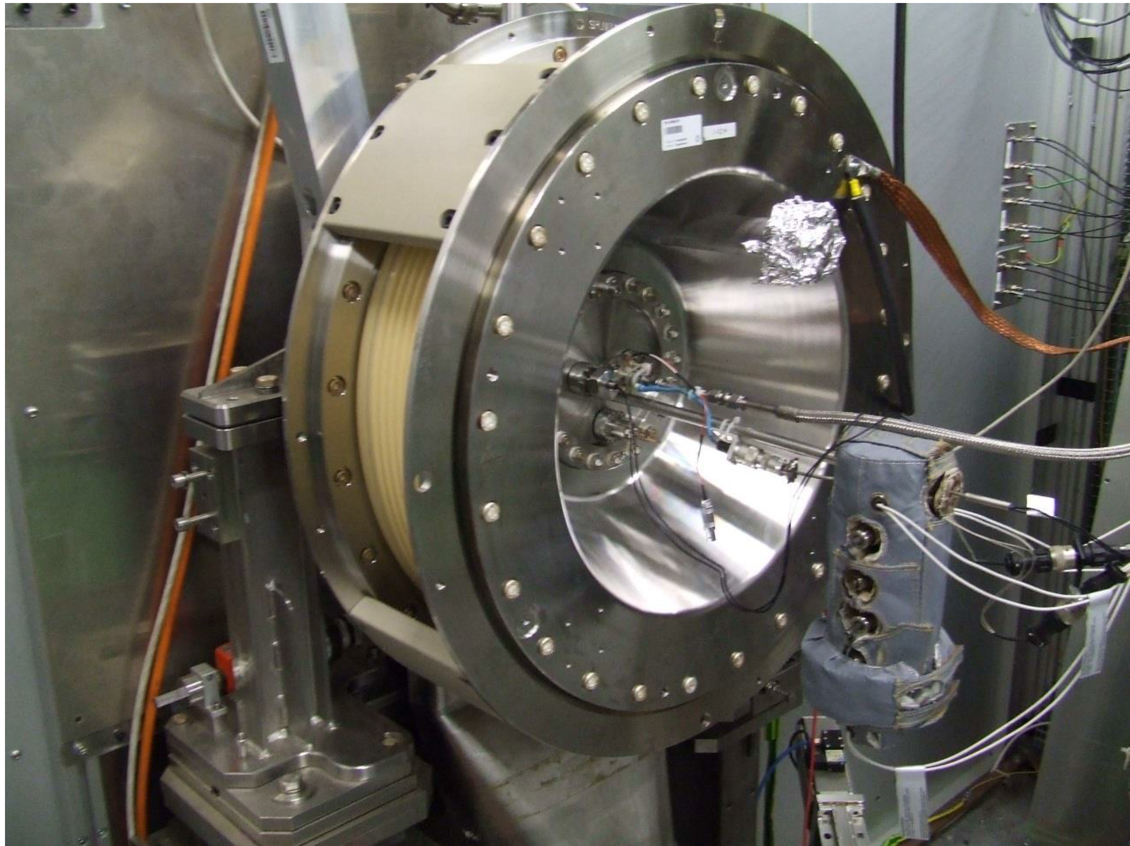
Linac4 H^- source R&D: Magnetron Discharge

- BNL's Magnetron achieved H^- beam above 100 mA and is therefore seen as a suitable candidate to provide Linac4's peak current of 80 mA.
- Engineering the adaptation of BNL's unit to Linac4 would ideally require:
  - PIC MC simulation of the Cs-H-e discharge plasma
  - PIC_MC analysis of the beam formation
  - Beam transport studies: e-dumping and minimimal emittance growth.
- Experiments on this very small unit is challenging;
  - Calibration of the dc-Cs-flow
  - Calibration of the pulsed hydrogen flow
  - Discharge impedance (straight forward)
  - OES analysis of the extraction region (viewport on beam axis to measure but really challenging interpretation)

Magnetron : BNL-Temp.-controlled

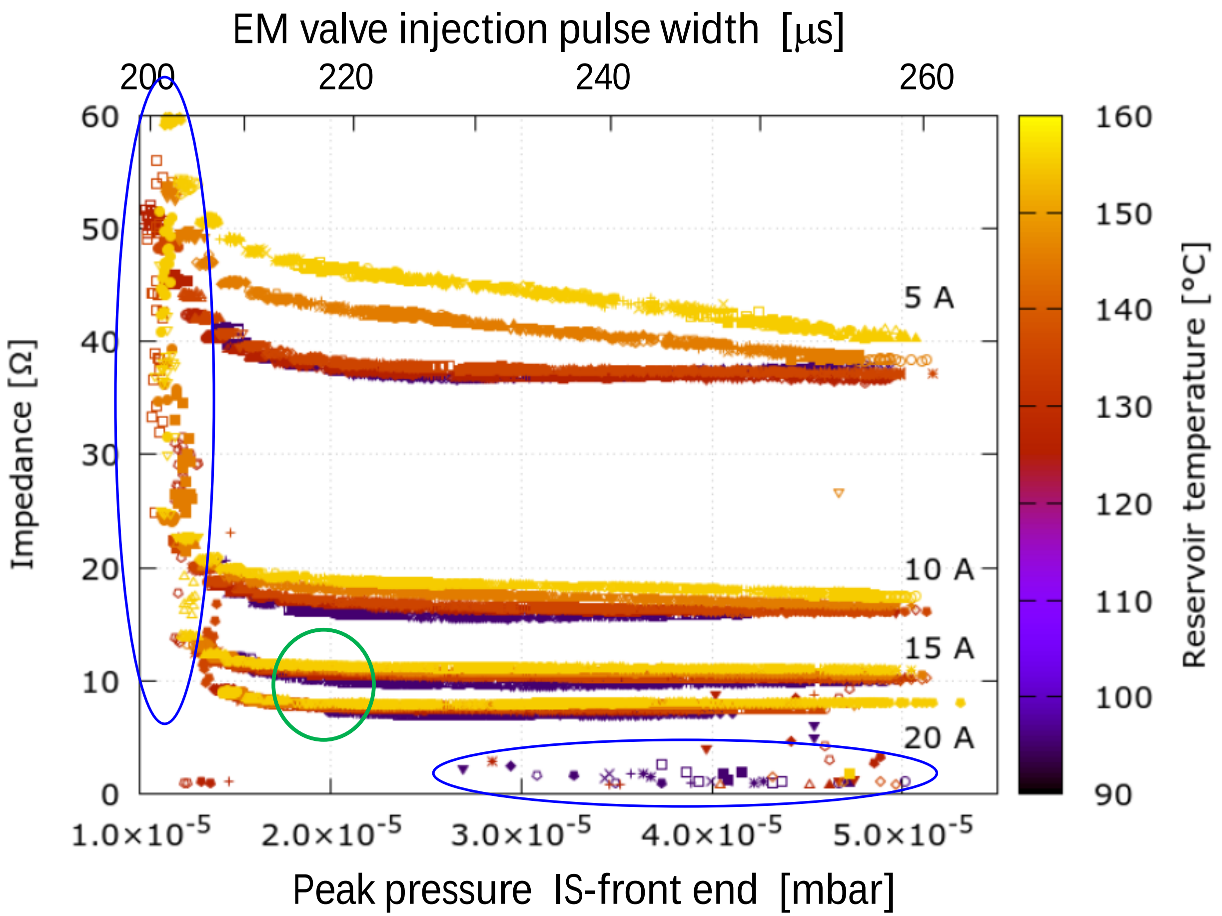






Magnetron discharge

Impedance of the discharge through the Caesium-Hydrogen plasma of BNL's magnetron



- Temperature higher than usual at BNL (100 deg.C) and would lead to high Cs consumption.
- Calibration + Modeling
  - Current surface density
  - Plasma e-density
  - H_2 flow rate
  - Cs-flow rate

Cs-Oven Temp: 155, 145, 135, 125°C
Temperature stabilization : 1h
25 values taken for each point

Courtesy of D. Noll and M. O'Neil