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Caesium balance of the ISIS H^- Penning ion source in long pulse operation

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Co-authors: Dan Faircloth, Scott Lawrie

Outline

1 ISIS H^- Penning ion source

2 Motivation for long pulses

3 Caesium balance model

4 Results and conclusions

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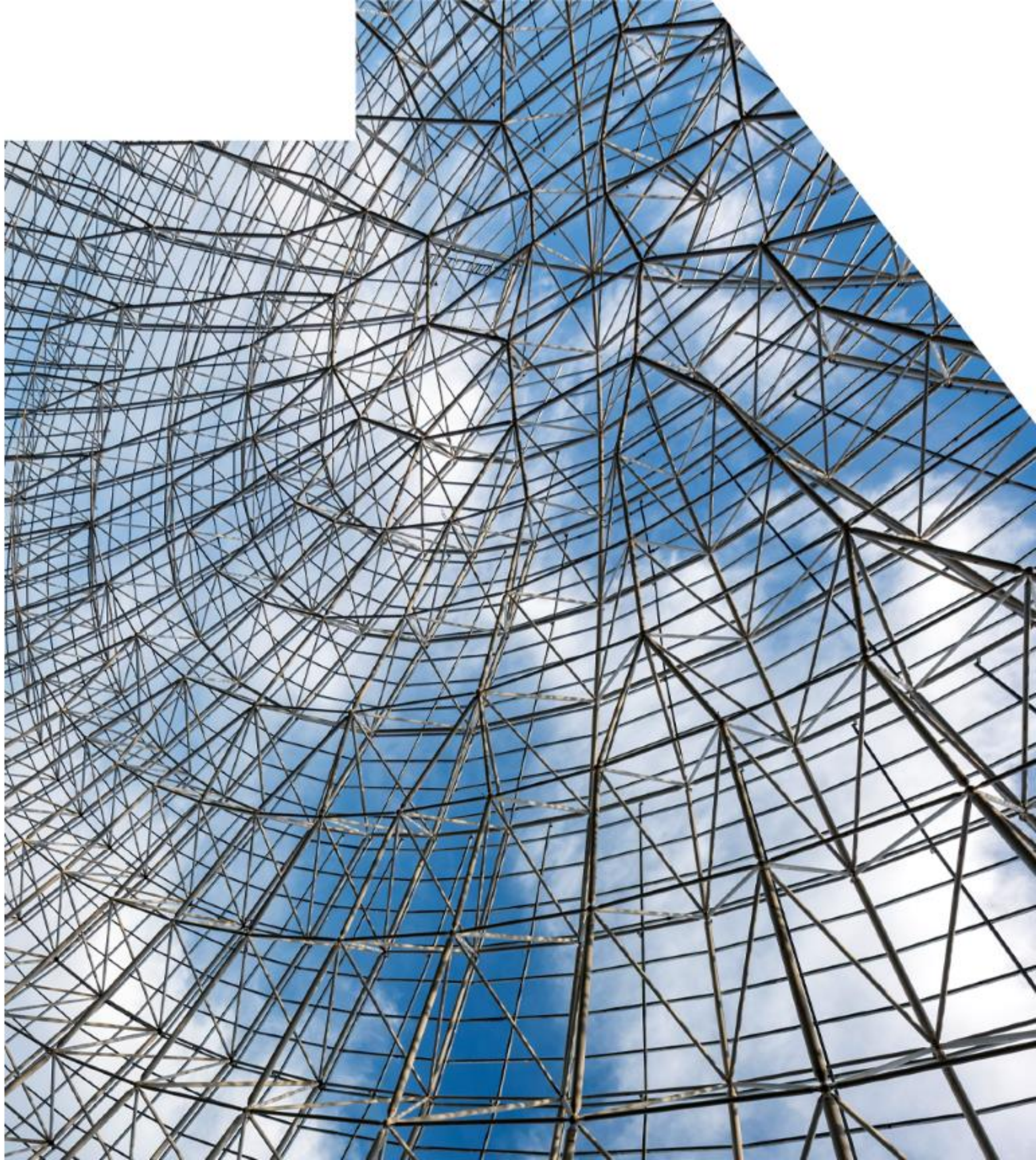
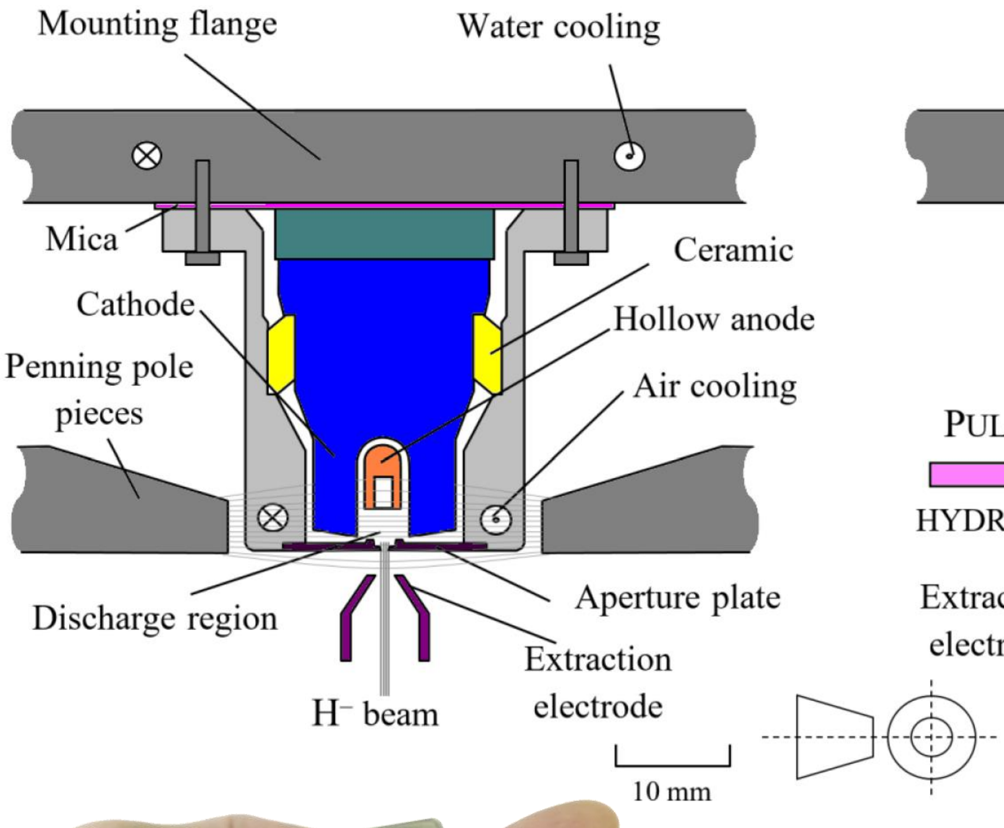
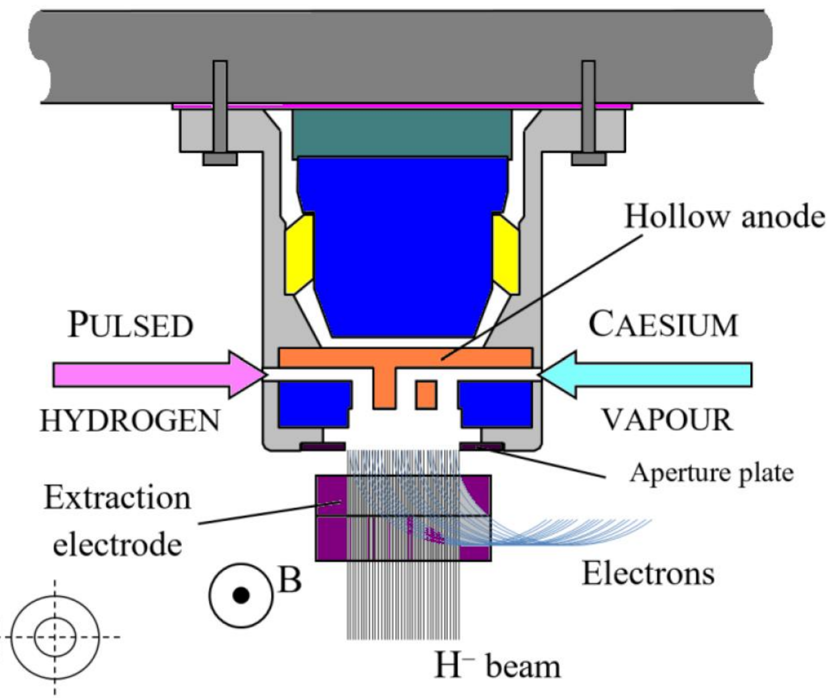
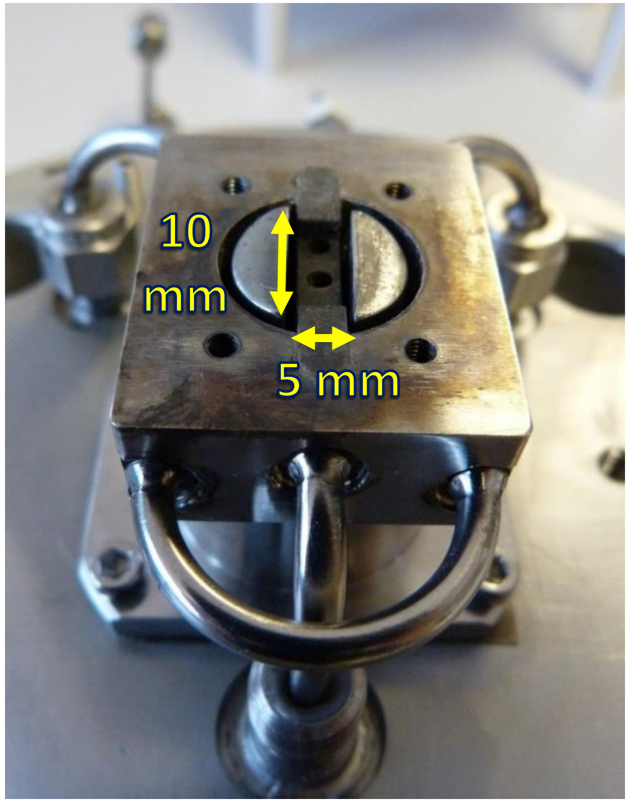


ISIS H^- Penning ion source

ISIS surface plasma Penning ion source

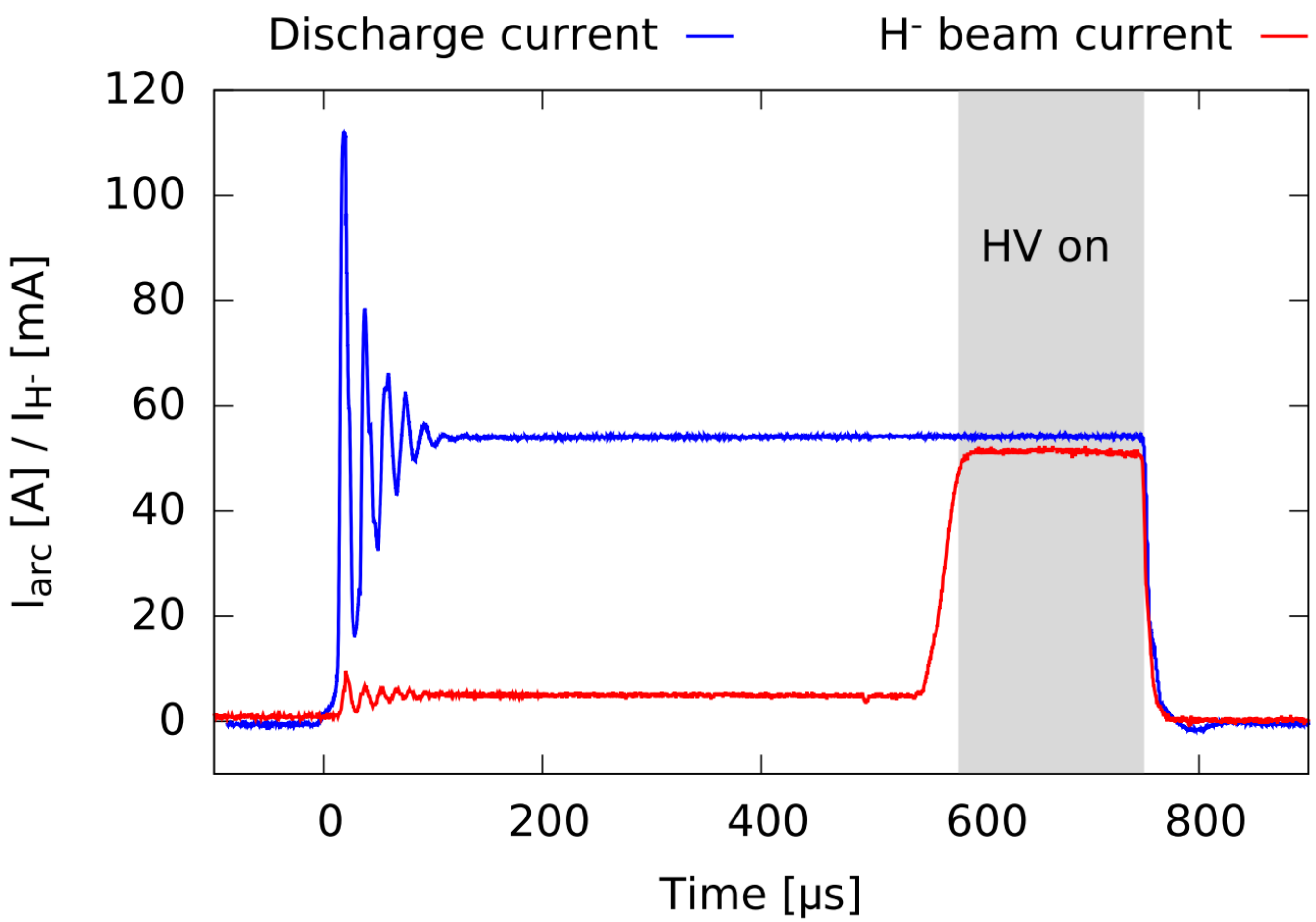






ISIS surface plasma Penning ion source

55 mA of H^- current with a 1.5 % duty factor at 50 Hz (300 μs pulses)



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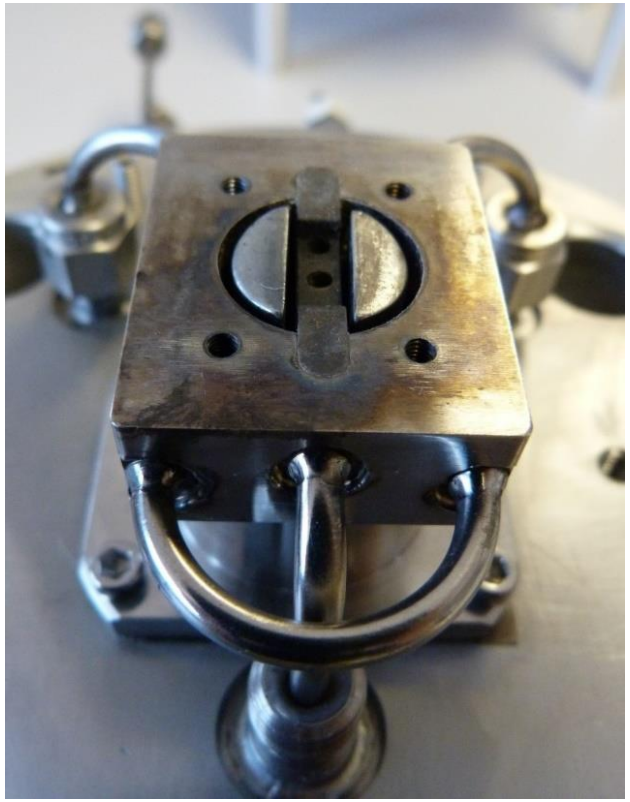
ISIS surface plasma Penning ion source



The discharge is sustained by electron emission from the cathodes and ionisation of Cs and H_2 by the "primary electrons".

H^- ions are surface produced on the cathode, accelerated by the cathode sheath, and then undergo resonant charge exchange with neutral H atoms.

$$H^-_{fast} + H(1s)_{slow} \rightarrow H(1s)_{fast} + H^-_{slow}$$

The slow H^- ions are then extracted through a slit. The extracted H^- current depends on the surface production yield.

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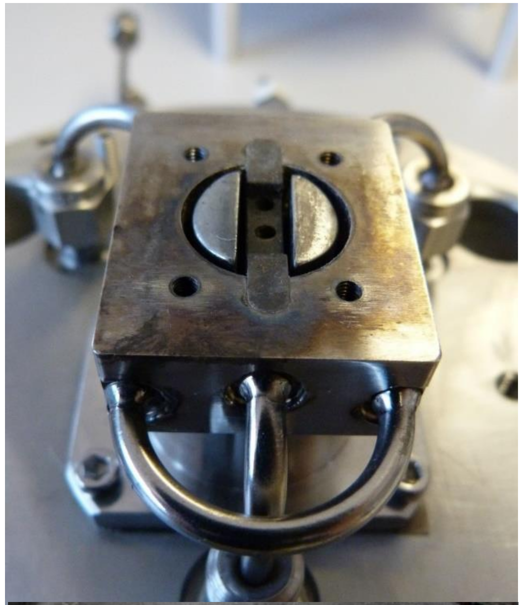
PHYSICAL REVIEW A VOLUME 41, NUMBER 9 1 MAY 1990

Charge transfer and electron detachment for collisions of H^- and D^- with H

M. A. Huels, R. L. Champion, L. D. Doverspike, and Yicheng Wang
Department of Physics, College of William and Mary, Williamsburg, Virginia 23185
(Received 17 November 1989)

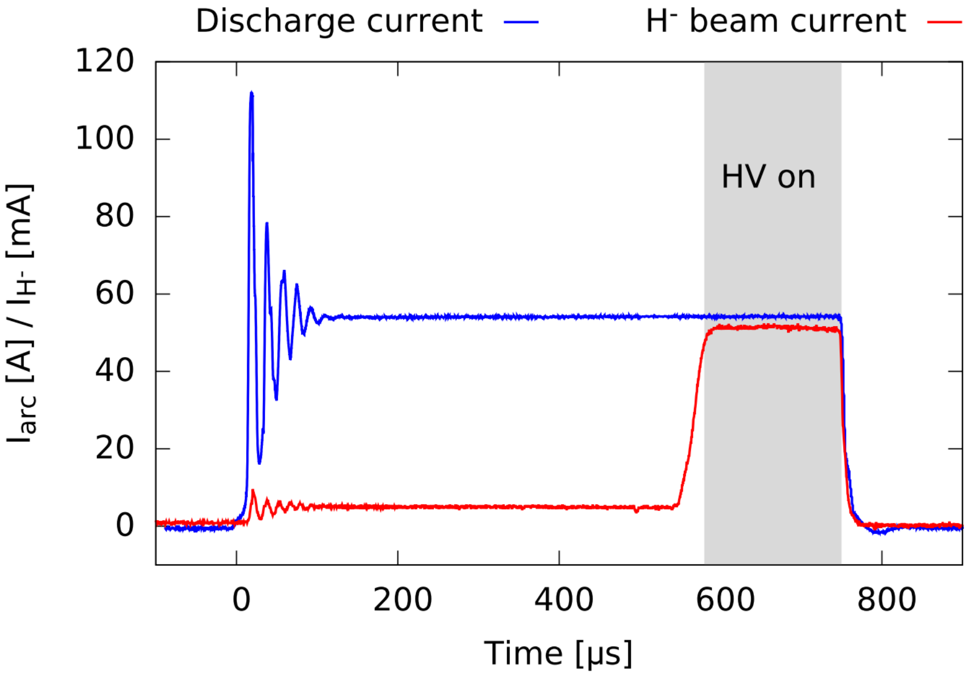
ISIS surface plasma Penning ion source



The discharge power of 2 – 4 kW (pulsed) is distributed across the 2 x 49 mm^2 surface area

Hot surfaces and significant temperature fluctuation and erosion of the cathode surface

Yet the conditions for producing the H$^-$ beam are constant through the (up to) 1 ms discharge pulse



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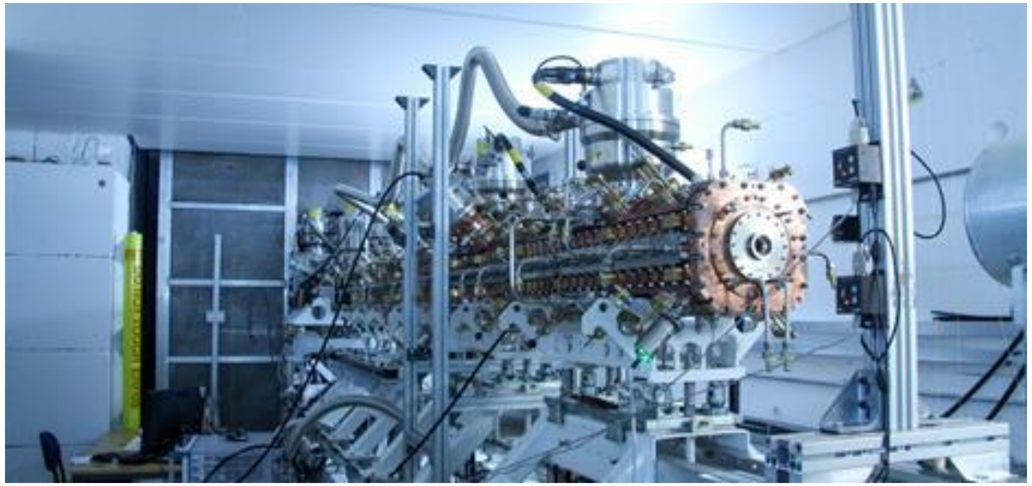
Motivation for developing the Cs balance model for long pulse operation

Front End Test Stand (FETS) at RAL

The Front End Test Stand (FETS) goal is 60 mA / 2 ms H^- beam pulses at 50 Hz



https://www.ppd.stfc.ac.uk/Pages/FETS.aspx

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62 mA at 50 Hz, 1 ms pulses

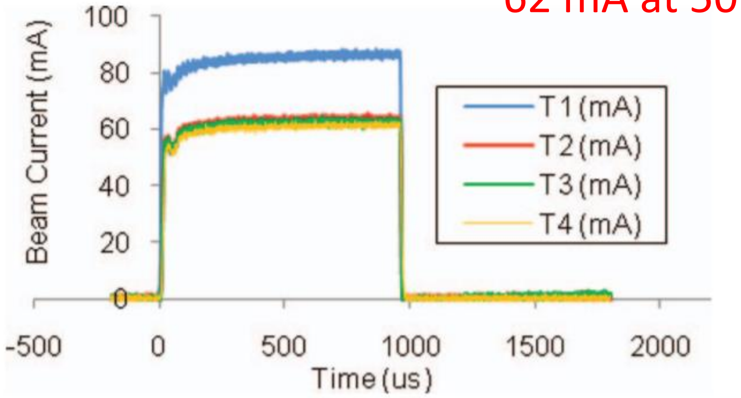

FIG. 8. (Color online) Beam current profiles of 62 mA at 50 Hz 1 ms. (1.2 ms, 60 A discharge, 19.6 kV extraction voltage, 65 keV beam, 180 °C caesium oven, 16 $mLmin^{-1}$ H_2.)

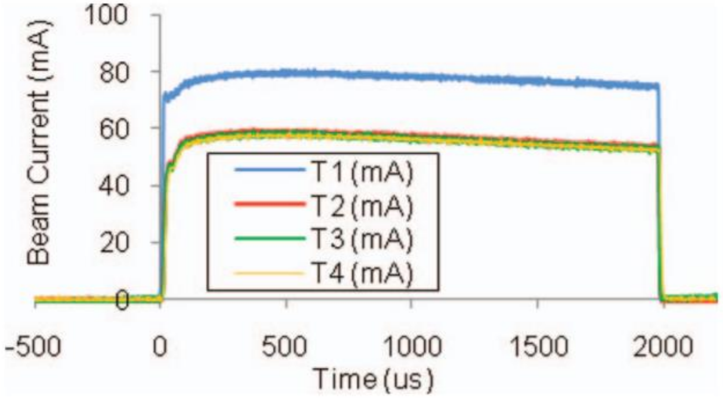

FIG. 9. (Color online) Beam current profiles of 60 mA at 25 Hz. (2.2 ms, 64 A discharge, 19.6 kV extraction voltage, 65 keV beam, 190 °C caesium oven, 16 $mLmin^{-1}$ H_2.)

60 mA at 25 Hz, 2 ms pulses

Neutrino super beam upgrade of the ESS facility

The European Spallation Source neutrino Super Beam Conceptual Design Report

A. Alekou[f,r], E. Baussan[o,**], A.K. Bhattacharyya[j], N. Blaskovic Kraljevic[j], M. Blennow[p,q], M. Bogomilov[n],
B. Bolling[j], E. Bouquerel[o], O. Buchan[j], A. Burgman[h,**], C.J. Carlile[r], J. Cederkall[h], P. Christiansen[h], M. Collins[i,j],
E. Cristaldo Morales[l], P. Cupiał[a], L. D'Alessi[o], H. Danared[j], D. Dancila[r], J. P. A. M. de André[o], J.P. Delahaye[f],
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E. Fernandez-Martinez[k,**], B. Folsom[j,**], T. Fukuda[w], N. Gazis[j,**], B. Gålnander[j], Th. Geralis[d], M. Ghosh[t,u,**],
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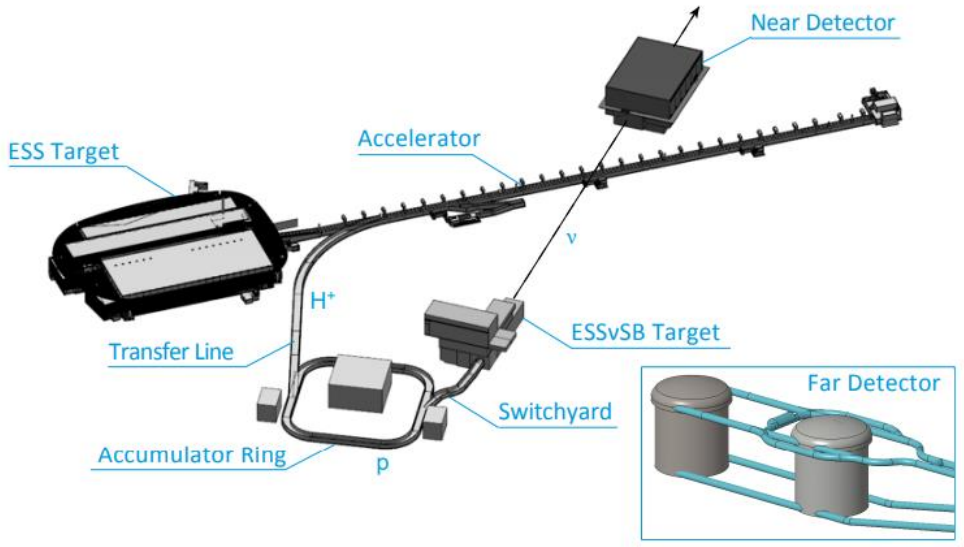
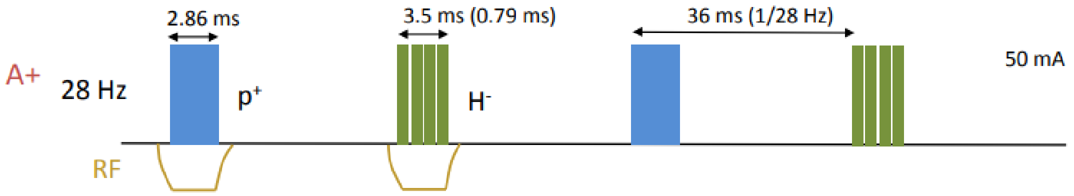
Ł. Łacny[a], M. Lindroos[j], C. Maiano[j], C. Marrelli[j], C. Martins[j], M. Mezzetto[m], N. Milas[j], M. Oglakci[b], T. Ohlsson[p,q],
M. Olvegård[r,**], T. Ota[k], J. Park[h,1], D. Patrzalek[j], G. Petkov[n], P. Poussot[o], R. Johansson[j], S. Rosauro-Alcaraz[v],
D. Saiang[c], B. Szybiński[a], J. Snamina[a], G. Stavropoulos[d], M. Stipčević[t], R. Tarkeshian[j], F. Terranova[l], J. Thomas[o],
T. Tolba[g,**], E. Trachanas[j], R. Tsenov[n], G. Vankova-Kirilova[n], N. Vassilopoulos[e], E. Wildner[f], J. Wurtz[o],
O. Zormpa[d], Y. Zou[r]



https://arxiv.org/pdf/2206.01208.pdf

Baseline design: 70 mA, 3 ms H^- pulses at 14 Hz repetition rate

The ISIS Penning SPS is a contender



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Can the ISIS Penning source make 70 mA, 3 ms H^- pulses at 14 Hz?

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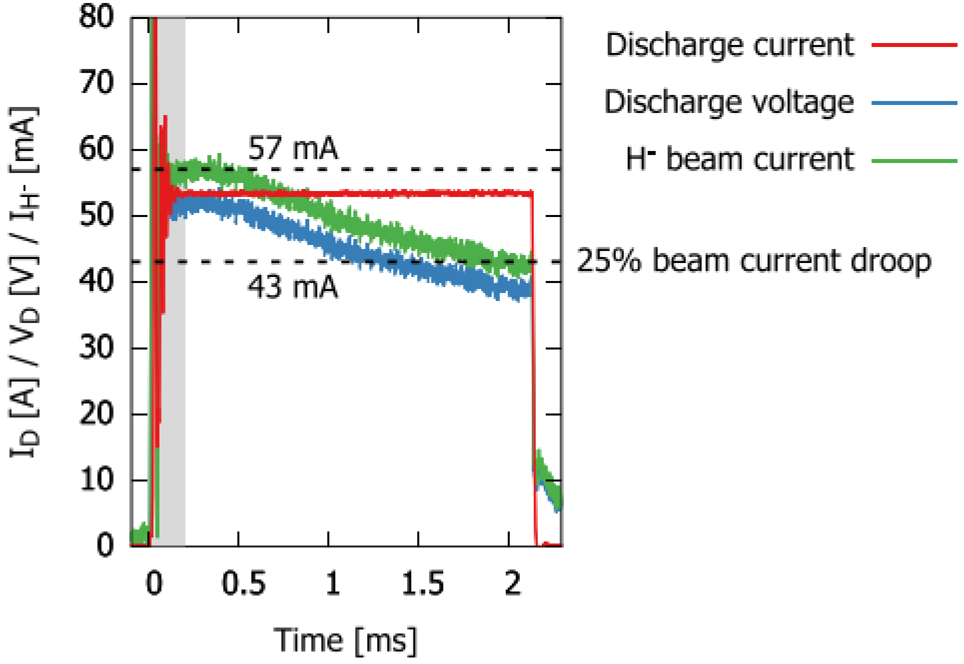
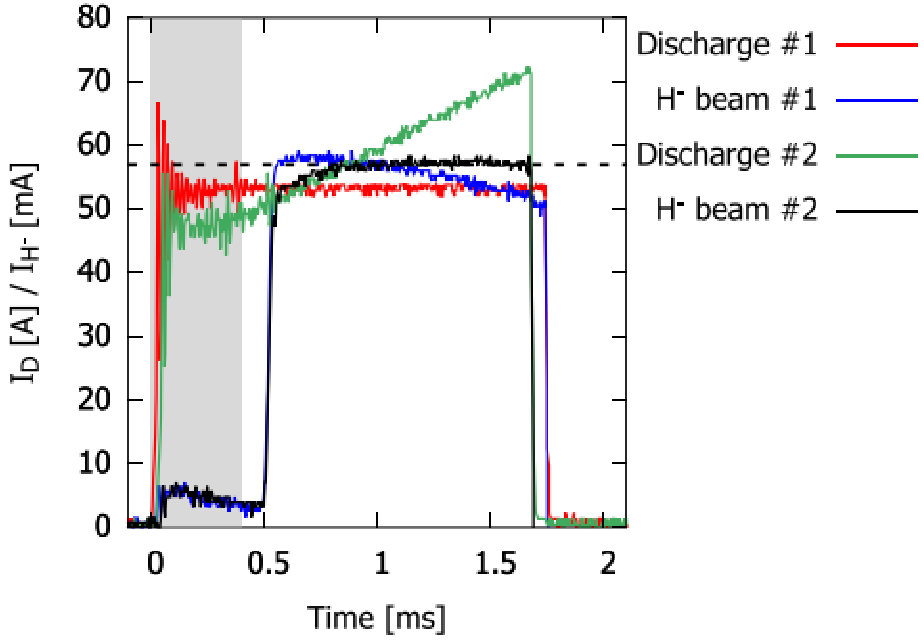
Extending the pulse length of the ISIS Penning source





Extending the pulse length of the ISIS H^- Penning ion source

Cite as: Rev. Sci. Instrum. 90, 103311 (2019); doi: 10.1063/1.5126729
Submitted: 4 September 2019 • Accepted: 8 October 2019 •
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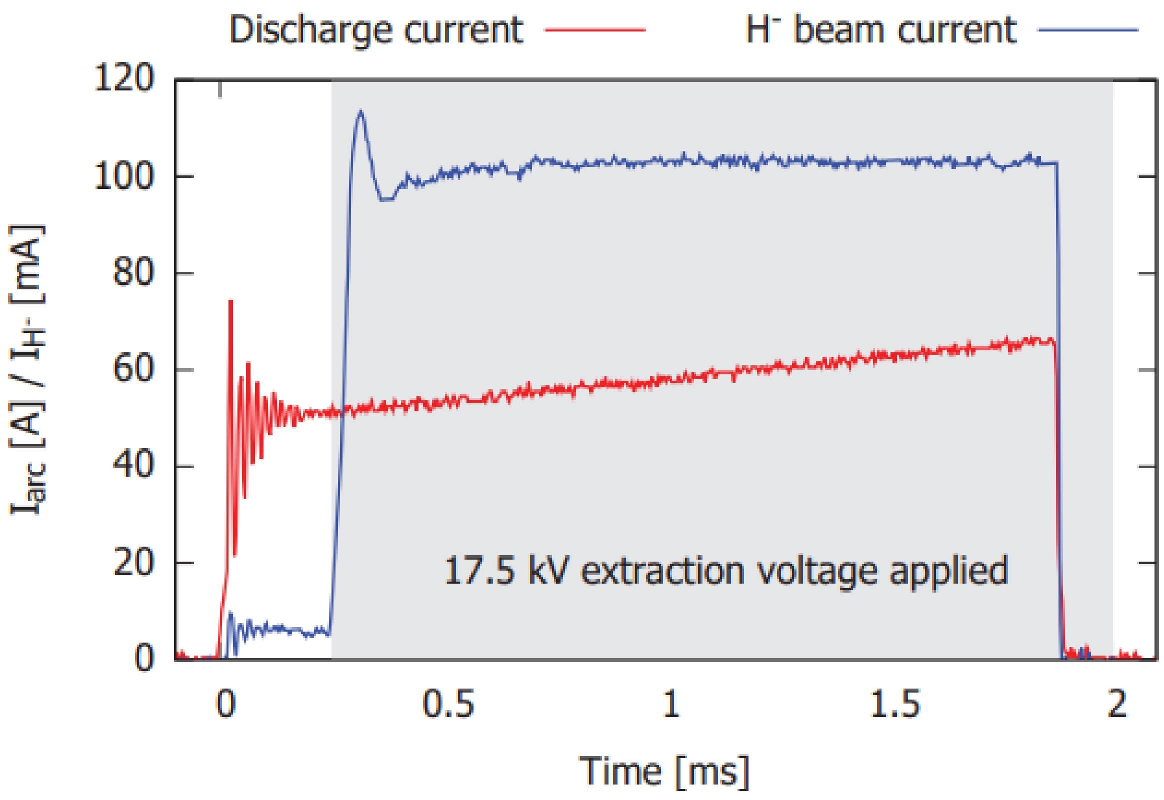
Extending the pulse length of the ISIS Penning source



1.65 ms, 100 mA H^- beam pulse at 25 Hz with 1.2 mm x 10 mm extraction slit

The pulse length is limited by the 110 mC charge capacity of the discharge power supply

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Controlling the shape of the ISIS H^- penning ion source beam pulse

Cite as: AIP Conference Proceedings **2373**, 050001 (2021); https://doi.org/10.1063/5.0057735
Published Online: 30 July 2021

T. Sarmento, O. Tarvainen, R. Abel, et al.

Extending the pulse length of the ISIS Penning source

A feasible "brute force" method to reach 3 ms pulses would be to upgrade the discharge power supply to 300 mC by doubling the number of insulated-gate bipolar transistors (IGBTs) from 6 to 12 and converting the power supply cooling from forced air to water.

Alternatively we could seek to understand the root cause of the beam current droop and somehow compensate for it…

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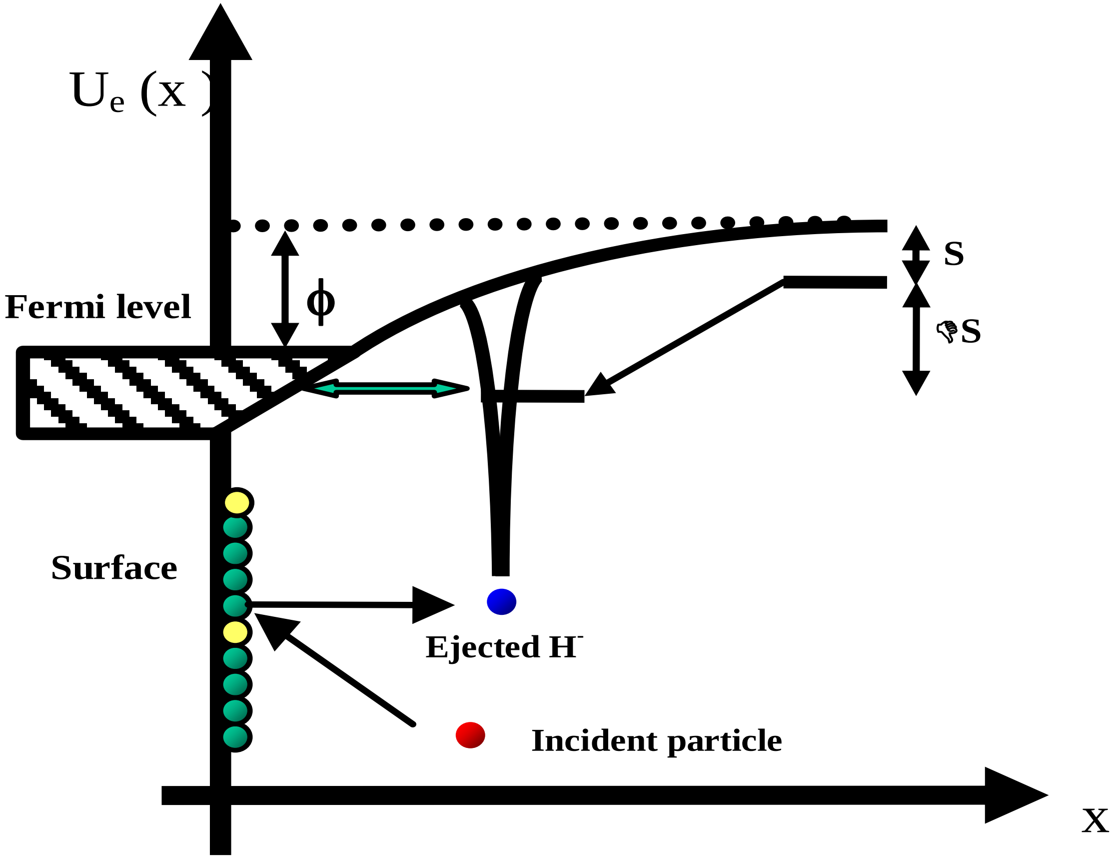
The caesium balance model – from short to long pulses

Surface ionization yield



Original figure by R.F. Welton, ICIS'07 tutorial

The resonant surface ionisation yield Y

$$Y \simeq \frac{2}{\pi} \exp\left(-\frac{\pi(\phi(\theta) - S)}{2av_{||}}\right)$$

where

S is the electron affinity of hydrogen (0.754 eV)

a is semi-empirical constant (2-5 x 10^{-5} eVs/m)

$v_{||}$ is the negative ion escape velocity

AND $\phi(\theta)$ is the surface work function

ELSEVIER

Surface Science

Volume 118, Issue 3, 2 June 1982, Pages 697-710

Theoretical models of the negative ionization of hydrogen on clean tungsten, cesiated tungsten and cesium surfaces at low energies

B. Rasser *, J.N.M. Van Wunnik, J. Los

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Caesiated surface work function

ELSEVIER
Surface Science
Volume 175, Issue 1, 1 September 1986, Pages 226-240

Semi-empimcal mathematical relationships for electropositive adsorbate induced work function changes ☆

G.D. Alton [a]

$$\phi(\theta) = \phi_0 + \frac{6\Delta\phi_m}{(3-\theta_m)\theta_m}\theta - \frac{3\Delta\phi_m(\theta_m+1)}{(3-\theta_m)\theta_m^2}\theta^2 + \frac{2\Delta\phi_m}{(3-\theta_m)\theta_m^2}\theta^3$$

θ_m is the fractional monolayer Cs coverage corresponding to minimum work function (0.5-0-7)

$\Delta\phi_m \cong -1.24[\phi_0-0.5(I_A+E_A)]$ is the maximum change of the work function from clean metal.

With Cs I_A of 3.89 eV and E_A of 0.47 eV we obtain $\Delta\phi_m$ = -2.59 eV for Molybdenum

Caesium adsorption and desorption fluxes

The caesium adsorption flux from kinetic gas theory

$$\Gamma_a = \frac{1}{4} n_{\mathrm{Cs}} v = \frac{p_{\mathrm{Cs}}}{\sqrt{2\pi k T_{eq} m_{\mathrm{Cs}}}}$$

Semi-empirical expression for the caesium desorption flux from refractory metals

$$\Gamma_d = \Gamma_{d,0} \exp\left(\frac{-e(3.37 - 2.78\theta)}{kT_s}\right)$$

AIP | Journal of Applied Physics

A model for the stationary cesium coverage on a converter surface in a cesium seeded hydrogen discharge

P. W. van Amersfoort, Ying Chun Tong, and E. H. A. Granneman

Citation: Journal of Applied Physics **58**, 2317 (1985); doi: 10.1063/1.335953

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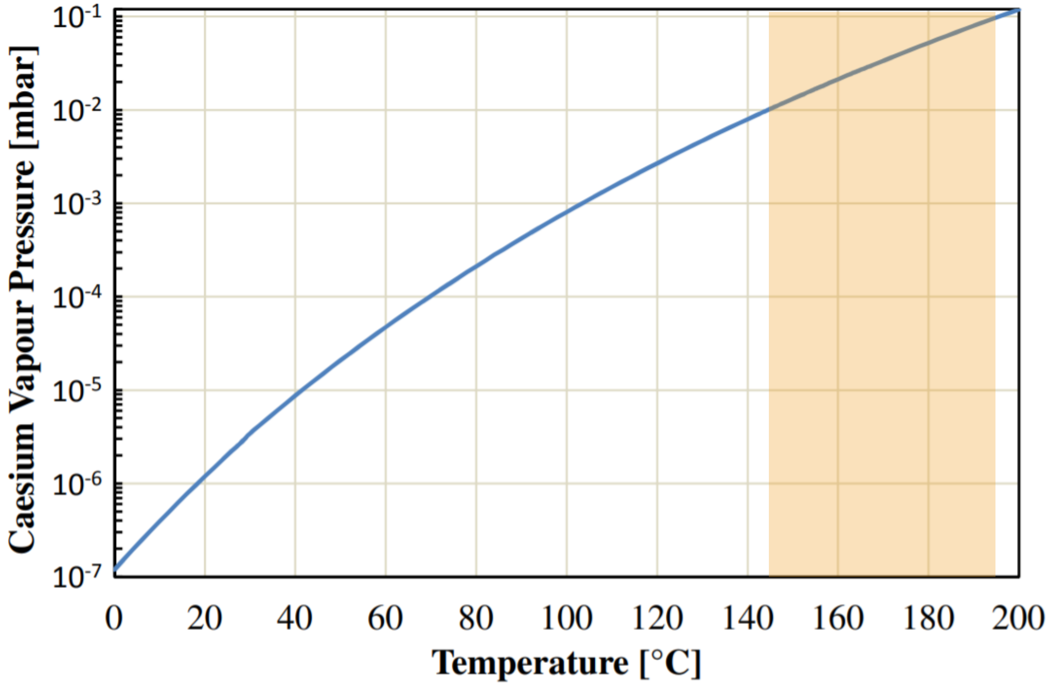
Caesium pressure of the ISIS ion source?



145 – 195 °C oven temperature implies
1-10 Pa caesium pressure

5 g caesium ampoule is consumed in approx. 50 days, which equates to 1.2 µg/s escaping through the 0.6 mm x 10 mm extraction slit.

Using $$\Gamma_a = \frac{1}{4} n_{\mathrm{Cs}} v = \frac{p_{\mathrm{Cs}}}{\sqrt{2\pi k T_{eq} m_{\mathrm{Cs}}}}$$

results in 0.115 Pa caesium pressure, which is supported by quartz microbalance measurements suggesting 0.1 – 1 Pa.

0.1 – 10 Pa used for the model

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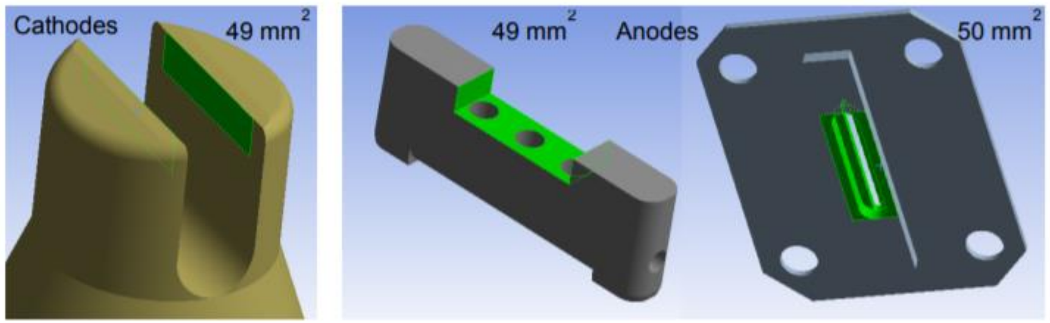
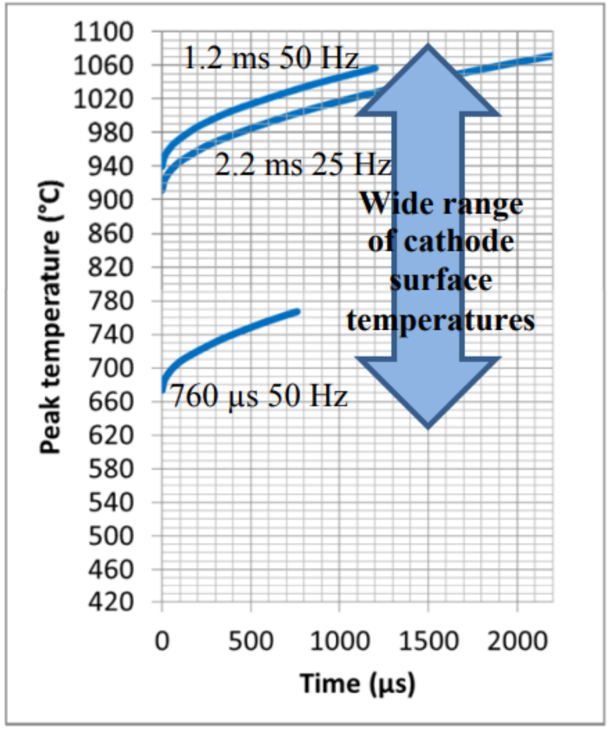
Cathode temperature of the ISIS ion source?

Operational and theoretical temperature considerations in a Penning surface plasma source

Cite as: AIP Conference Proceedings **1655**, 030013 (2015); https://doi.org/10.1063/1.4916440
Published Online: 14 April 2015

D. C. Faircloth, S. R. Lawrie, H. Pereira Da Costa, and V. Dudnikov





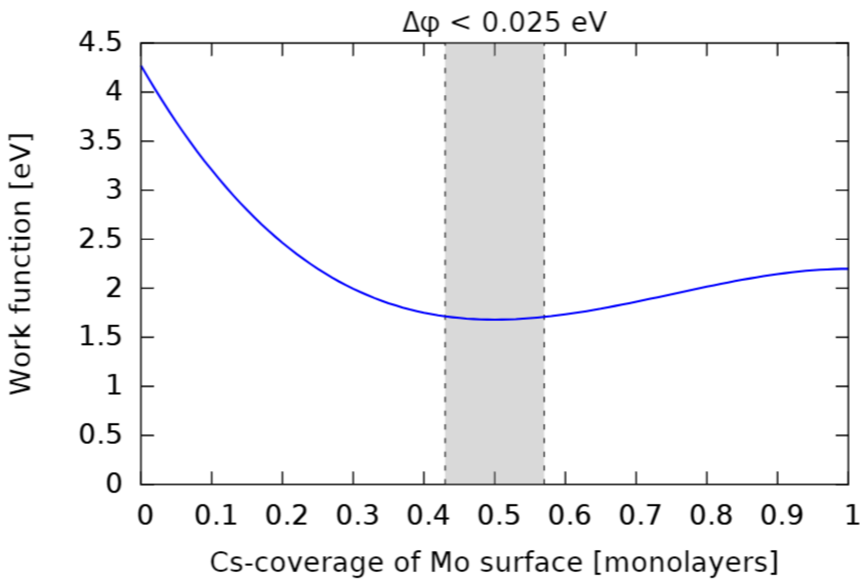
Conclusions:

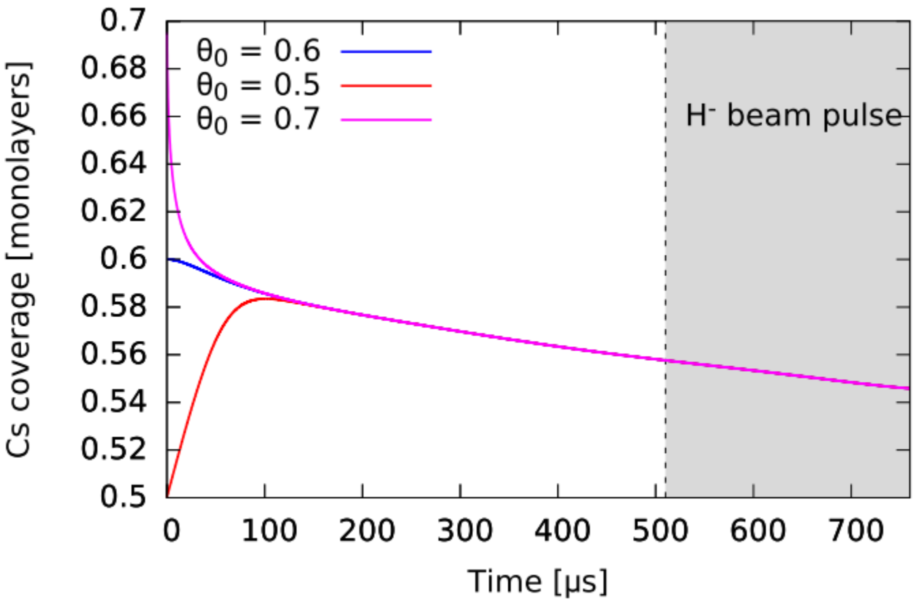
- The bulk temperature depends on the average power
- The transient temperature depends on the instantaneous power
- Allows extrapolating to "arbitrary" pulse lengths and duty factors

Caesium balance of the cathode surface

We can model the cathode surface caesium balance by calculating the change of the caesium coverage in time step dt using the dynamic cathode surface temperature together with desorption and adsorption fluxes at certain caesium pressure. The free parameter is the caesium coverage in the beginning of the discharge pulse.

But it does not matter…





Caesium balance of the cathode surface

What does matter though…

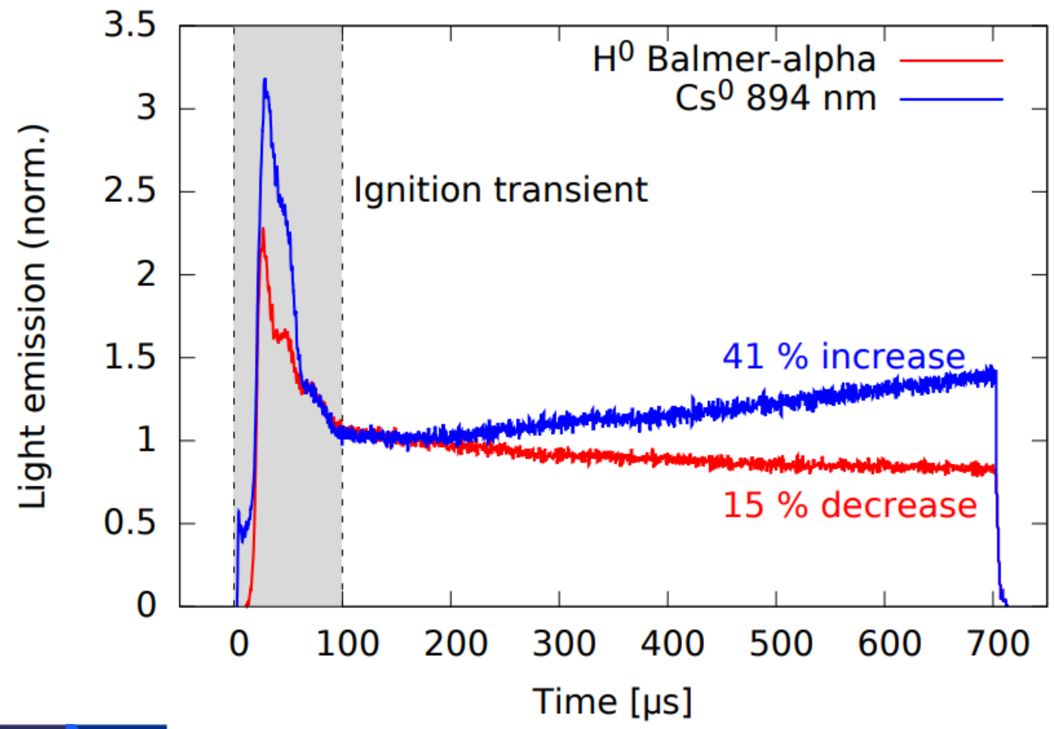
Table 1. The change of Cs coverage on the Penning ion source electrode surfaces and density in the discharge volume during the 760 μs discharge pulses at 50 Hz.

Electrode	Area [mm^2]	Surface temperature [°C]	Cs coverage [atoms]	Cs released [atoms]
Cathode	2×49	670–770	$3.17–2.91 \cdot 10^{14}$	$0.26 \cdot 10^{14}$
Anode	49	460–480	$1.87–1.84 \cdot 10^{14}$	$0.03 \cdot 10^{14}$
Aperture plate	44	480–505	$1.65–1.62 \cdot 10^{14}$	$0.03 \cdot 10^{14}$
Discharge	Volume [mm^3]	Cs pressure [Pa]	Cs density [atoms/mm^3]	Cs atom number
ISIS Penning	105	1-10	$0.83\text{-}8.3 \cdot 10^{11}$	$0.09\text{-}0.87 \cdot 10^{14}$

Most of the caesium is on the surfaces and a significant amount of it is released during the discharge pulse, especially in the beginning. At 10 Pa initial pressure in short pulse (760 μs) the effect is estimated 40% i.e. the true minimum Cs pressure is 4 Pa.

Caesium balance of the cathode surface

Most of the caesium is on the surfaces and a significant amount of it is released during the discharge pulse, especially in the beginning. At 10 Pa initial pressure in short pulse (760 μs) the effect is estimated 40% i.e. the true minimum Cs pressure is 4 Pa.



The implication is that modelling long pulses requires amending the short pulse model so that

$$p_{Cs}=p_{Cs}(t) \text{ and } \Gamma_a = \Gamma_a(t)$$

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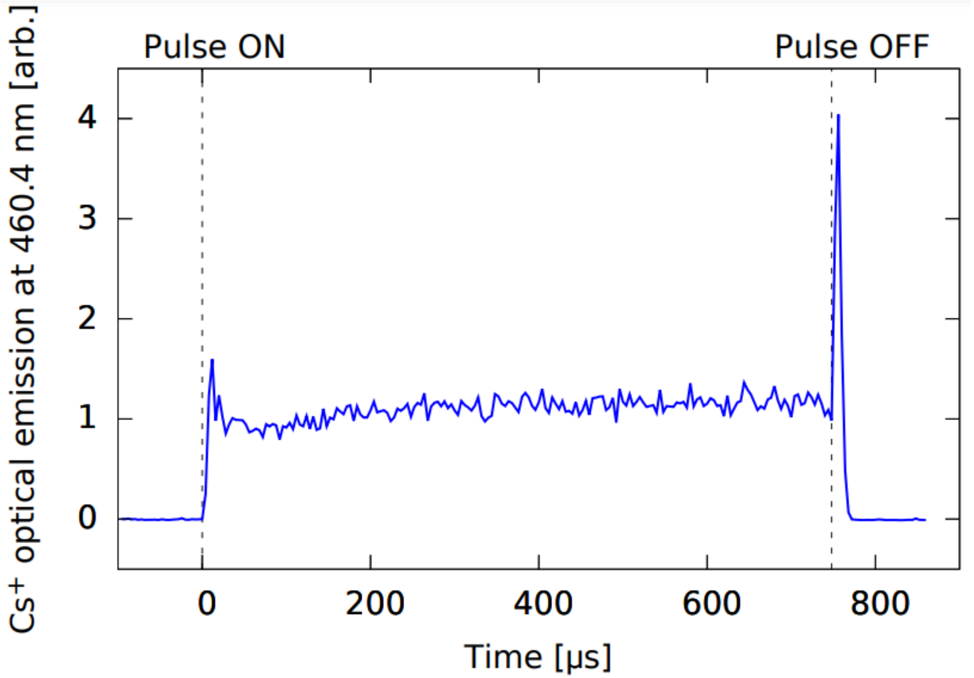
Model limitations

The thermal simulations assume a constant discharge power and heat load during the plasma pulse. This is not the case as evidenced by breakdown oscillations and discharge voltage droop.

The model does not account for the cathode erosion by Cs^+ bombardment.

Surface ionisation of Cs at temperatures approaching 1000 °C, could affect the Cs balance of the cathode.



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Long pulse results

FETS: Model predictions

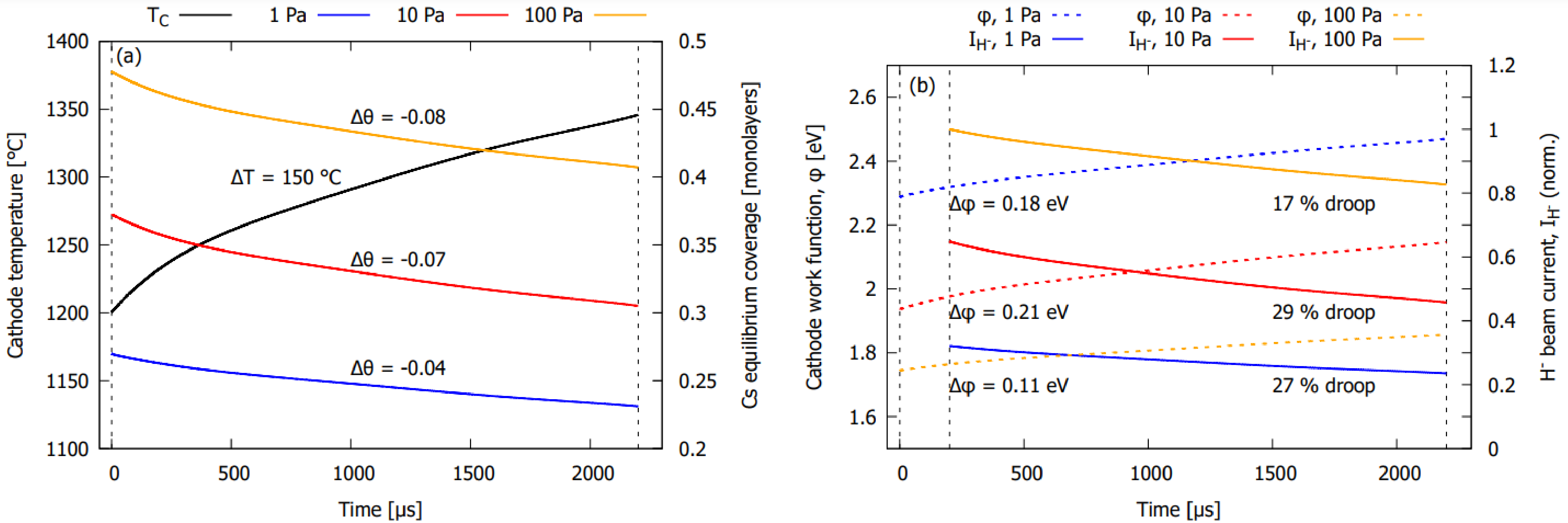

Figure 3. (a) The cathode surface temperature and equilibrium Cs coverage, and (b) the predicted variation of the cathode work function and H^- beam current for 2.2 ms discharge / 2 ms extraction pulses at 50 Hz with 1–100 Pa initial Cs pressure. The predicted beam currents are normalized to the maximum beam current achieved with 100 Pa Cs pressure.

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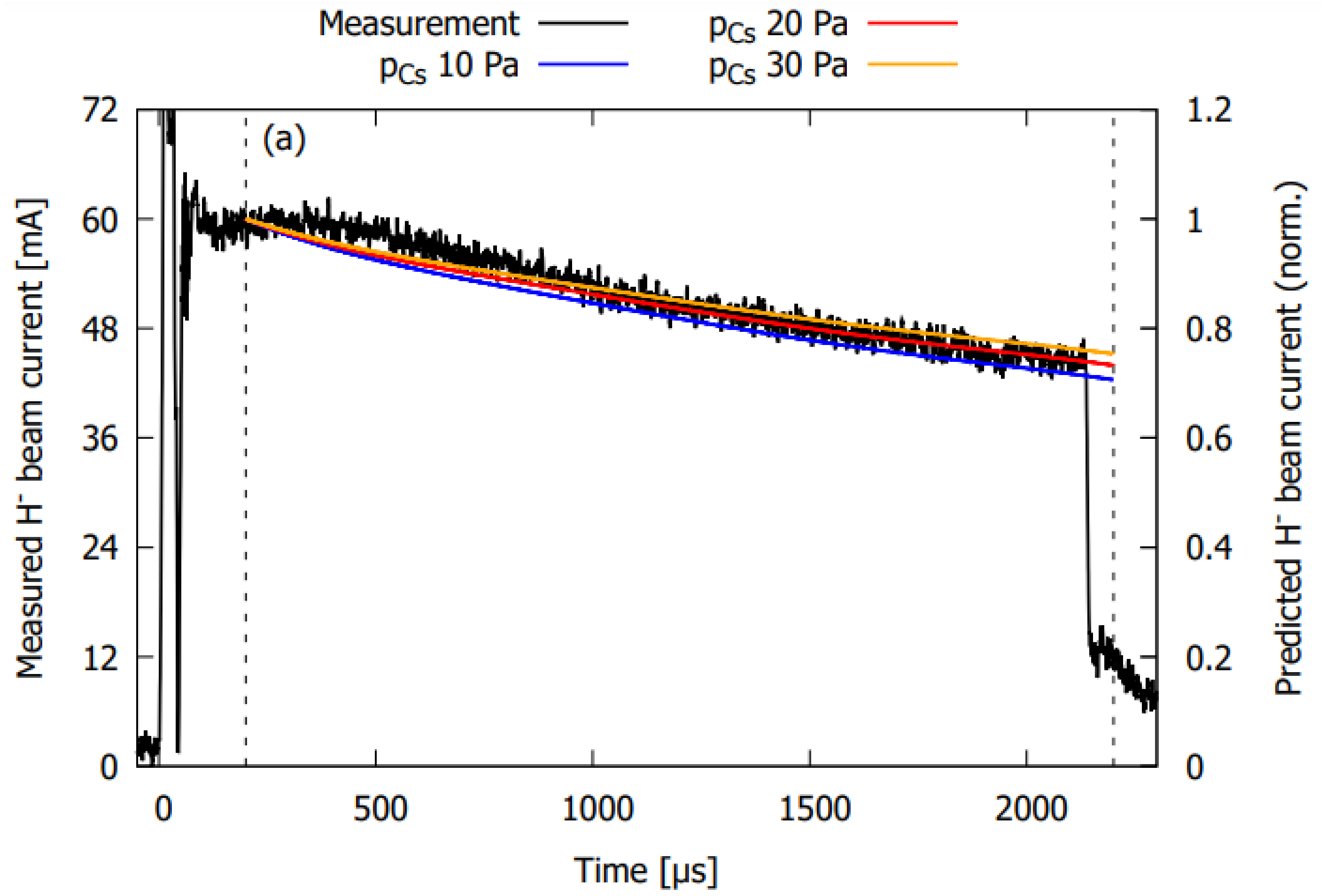
FETS: Comparison to experiment



20-30% beam current droop in a wide range of (initial) Cs pressures.

Good match with the experiment.

Conclusion: increasing the Cs oven temperature is not an effective measure to combat the droop.

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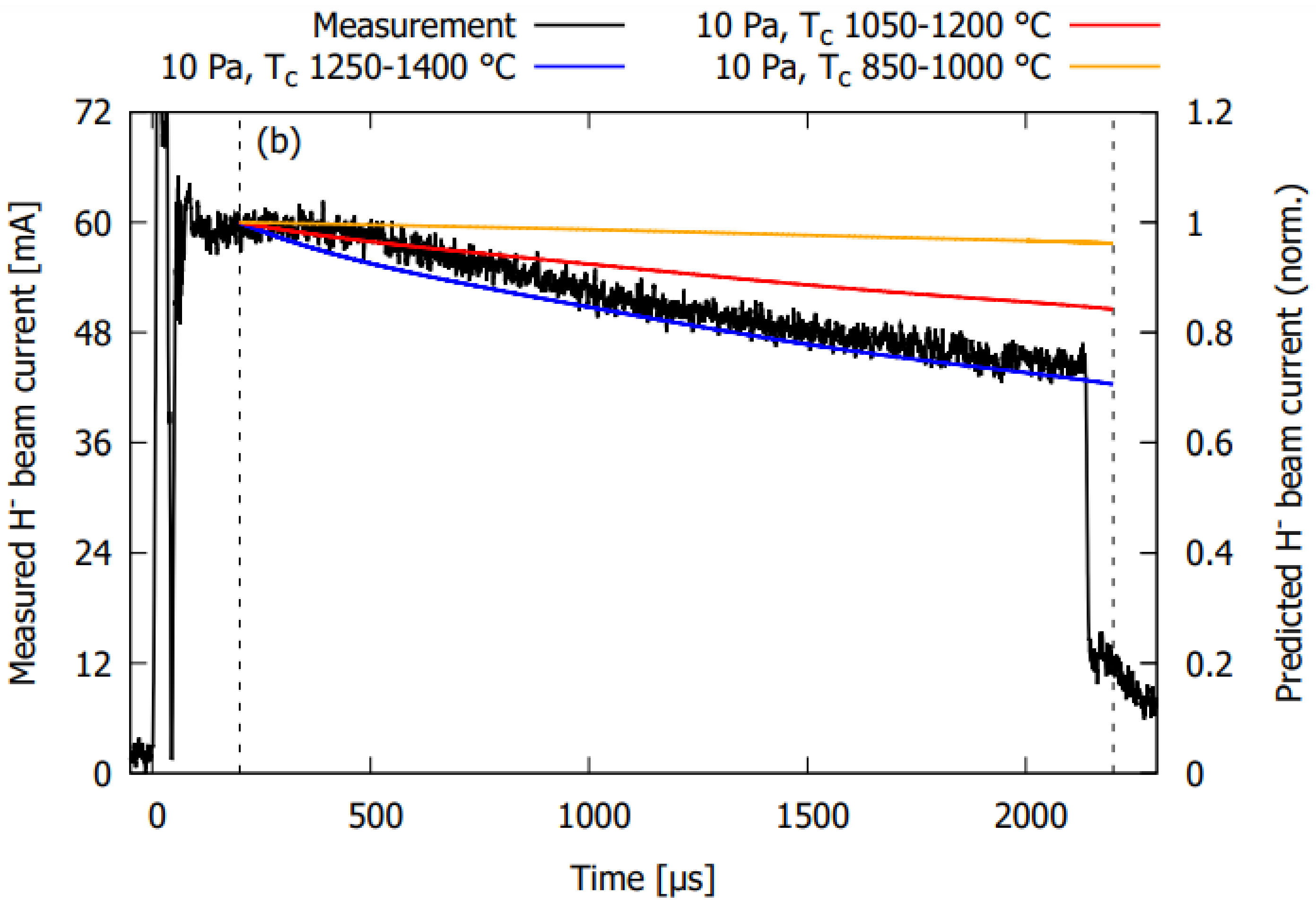
FETS: Improved cathode cooling - prediction



400 °C decrease of the cathode average temperature is predicted to eliminate the beam current droop

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ESSνSB: Model predictions

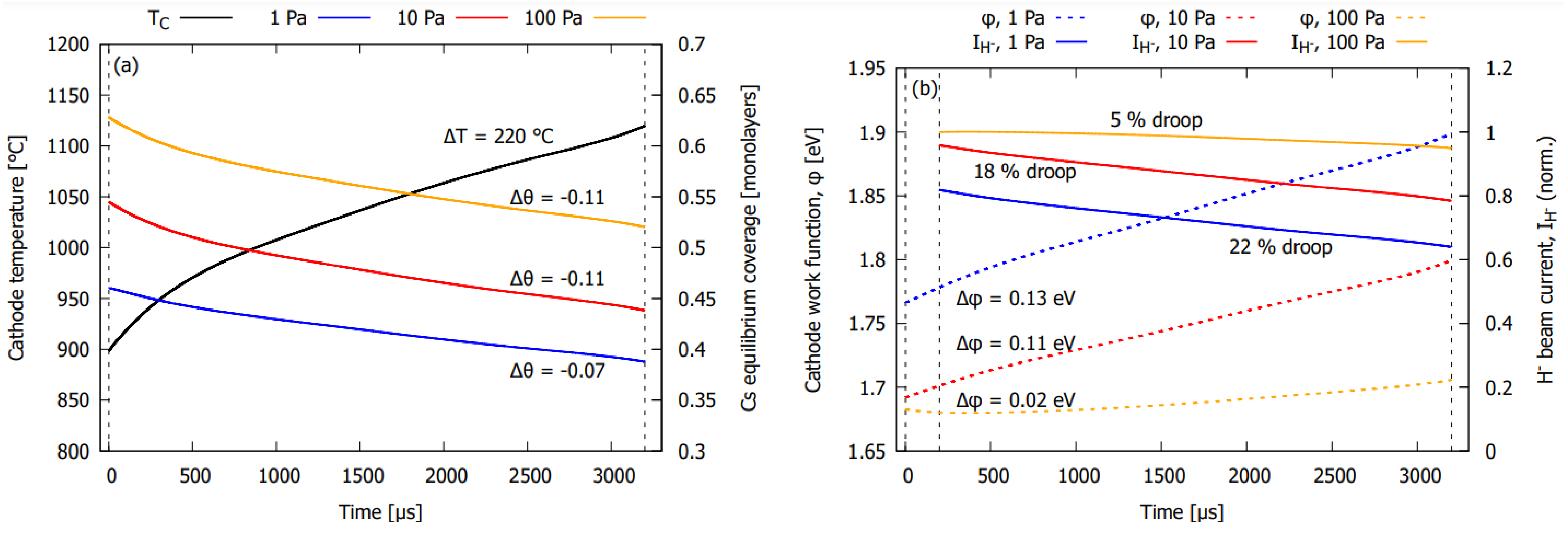
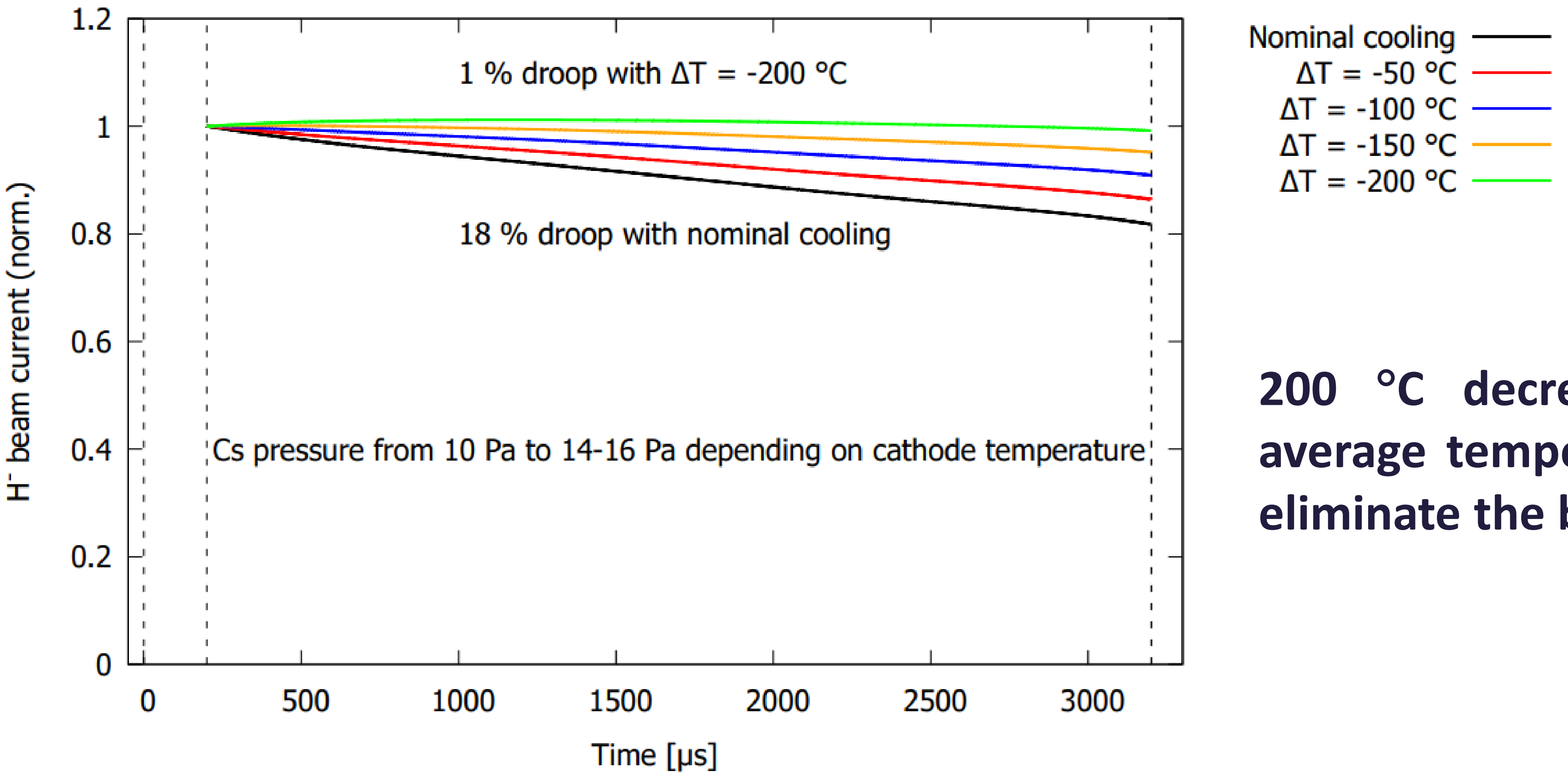


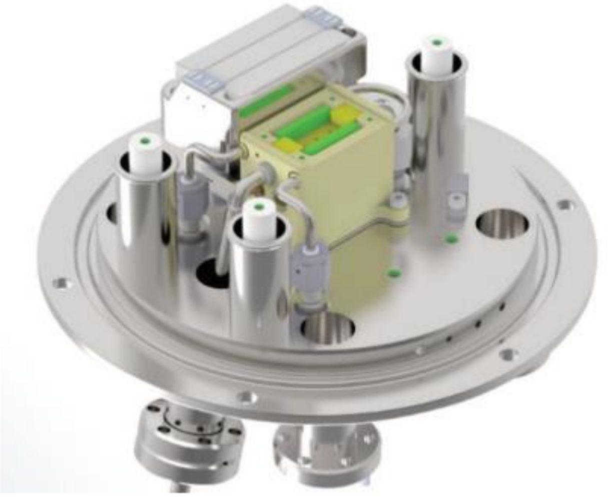
Figure 5. (a) The cathode surface temperature and equilibrium Cs coverage, and (b) the predicted variation of the cathode work function and H^- beam current for 3.2 ms discharge / 3 ms extraction pulses at 14 Hz with 1–100 Pa initial Cs pressure. The predicted beam currents are normalized to the maximum beam current achieved with 100 Pa Cs pressure.

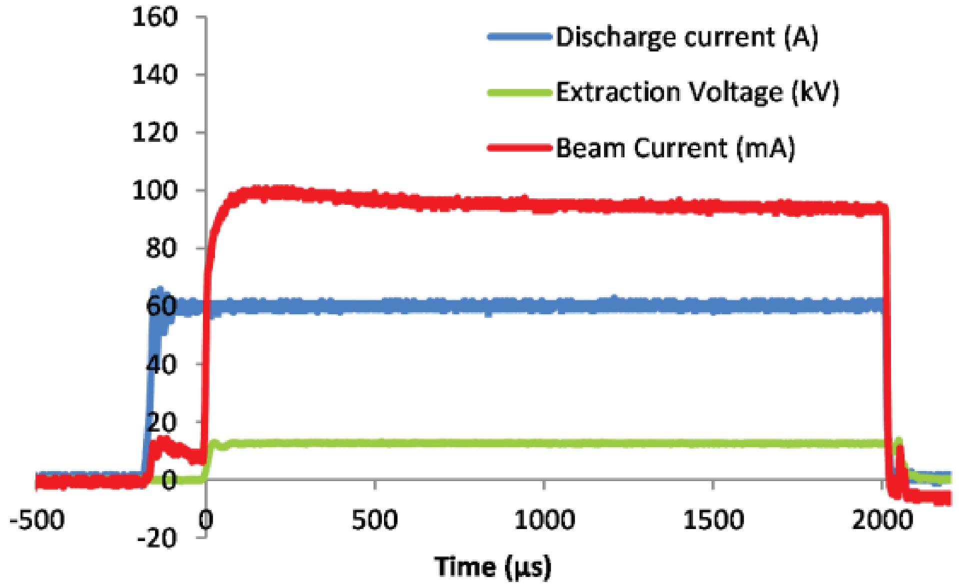
ESSνSB: Improved cathode cooling - prediction



200 °C decrease of the cathode average temperature is predicted to eliminate the beam current droop

Reduced cathode temperature – 2X source





High current results from the 2X scaled Penning source

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Published Online: 28 December 2018

D. C. Faircloth, S. R. Lawrie, O. Tarvainen, et al.

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100 mA beam, 2 ms pulses at 50 Hz

Beam transport unknown, emittance could be acceptable for the ESSνSB

3 ms pulses???

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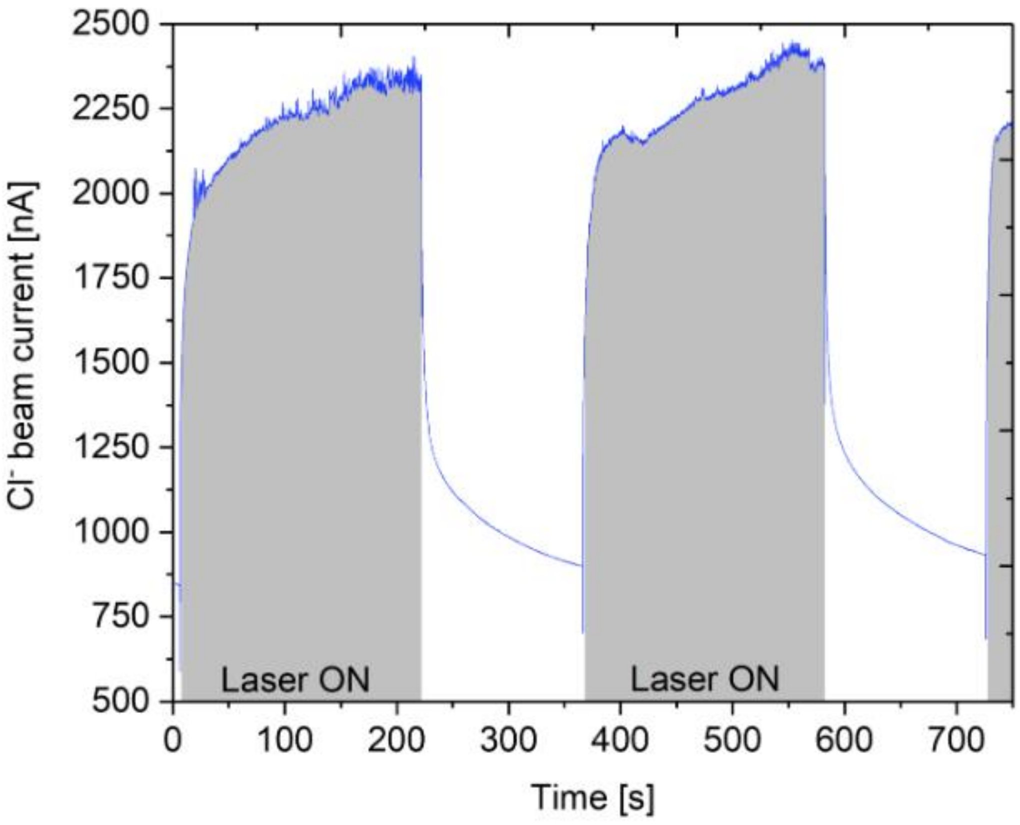
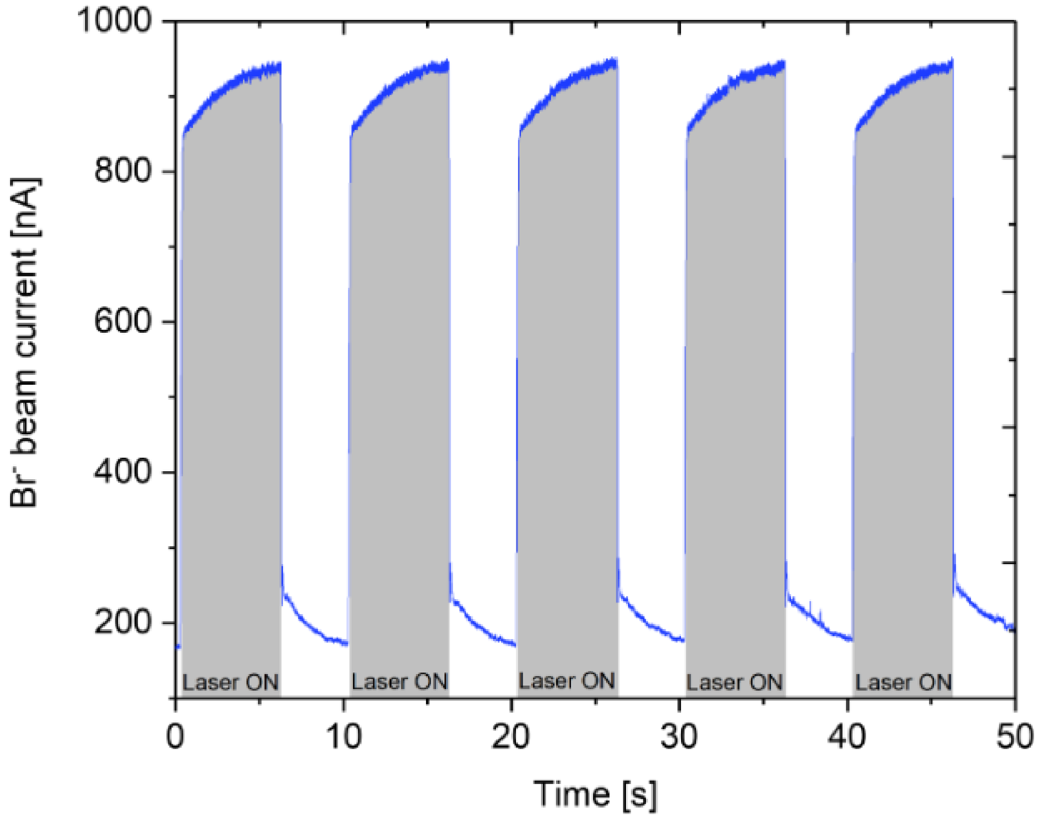
Conclusions

The Penning ion source Cs balance model, first developed for short pulse operation, can reproduce long pulse results when Cs recirculation is taken into account.

Improved thermal management of the ion source is favoured over increasing the Cs pressure as it is more effective in combating beam current droop, and prevents excessive leakage of Cs into the extraction.

Caesium balance is important for other ion sources as well, for example heavy ion SNICS





Presentation by Akbar Hossain on Friday