Space-Charge Compensation in the PXIE LEBT

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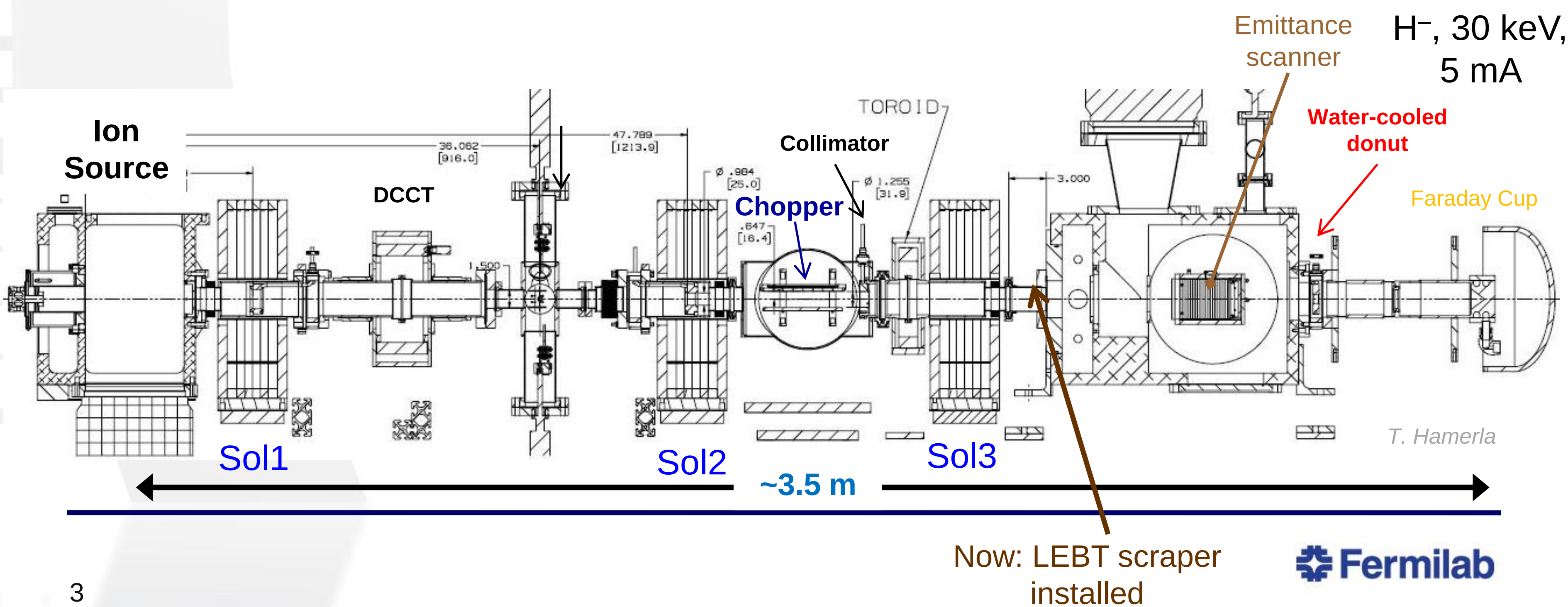
Outline

- Introduction
- Model of Space-Charge Compensation in the PXIE LEBT
  - Potential Map of the PXIE Beamline
  - Pressure Distribution and Ionization Cross Sections
  - Different Compensation Regions in the PXIE LEBT
- Measurements
  - Time behavior
  - Measuring the Ion-Clearing Current: Experimental Setup
  - Results and Comparison with Model
- Conclusion and Outlook

Introduction: PXIE LEBT

Design Goals:

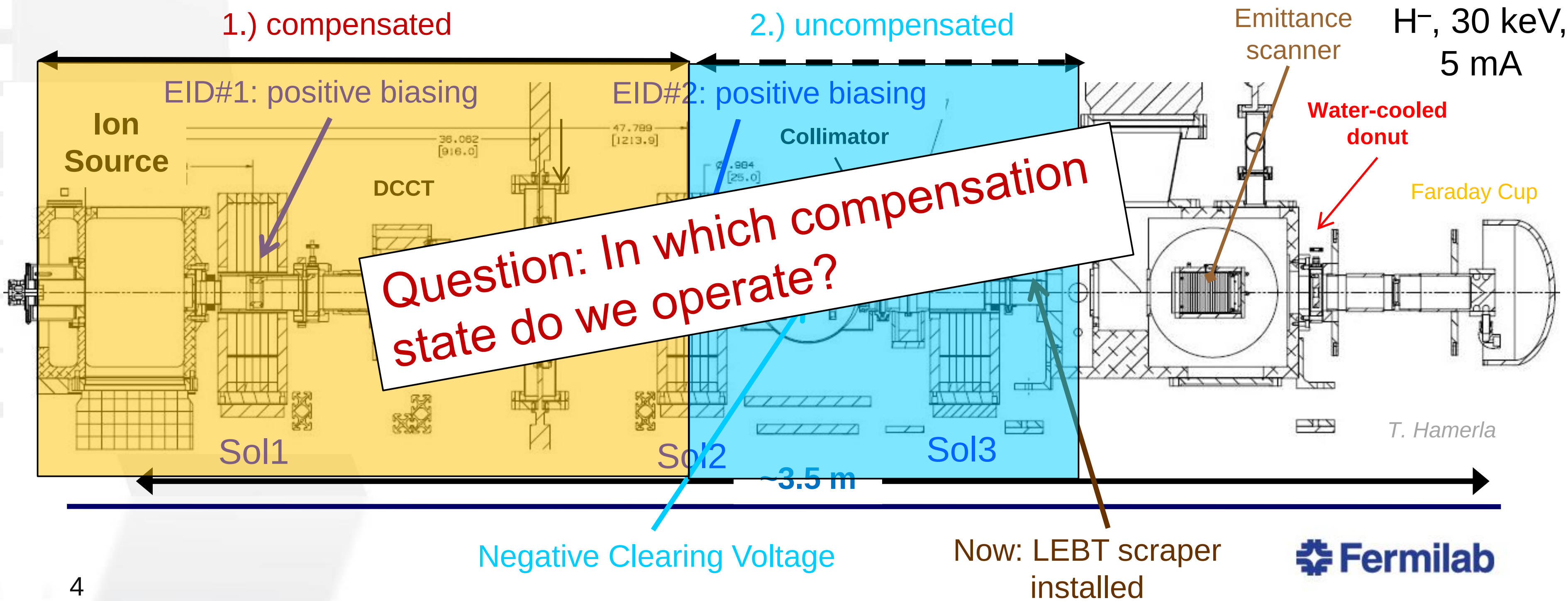
- Low gas pressure in RFQ (for high reliability)
- Chopper (to produce pulses with short duration and rise times)
- Provide beam with low emittance for RFQ injection



Introduction: PXIE LEBT

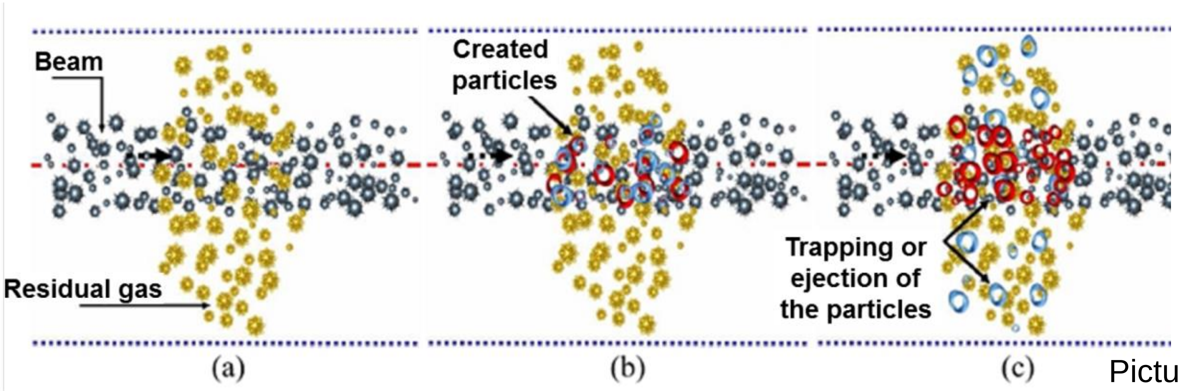
Solution:

- Two LEBT subsections: 1.) compensated, 2.) uncompensated.
- Feasibility of the concept has been demonstrated.
- ***However: To minimize emittance growth and increase reproducibility, intermediate state of compensation should be avoided.***



Model of Space-Charge Compensation

- Residual gas molecules (H_2) are ionized by beam ions (H^-) and are radially trapped in the negative beam potential.



Picture from N. Chauvin (2014).

- Space-Charge Compensation build-up time is given by:

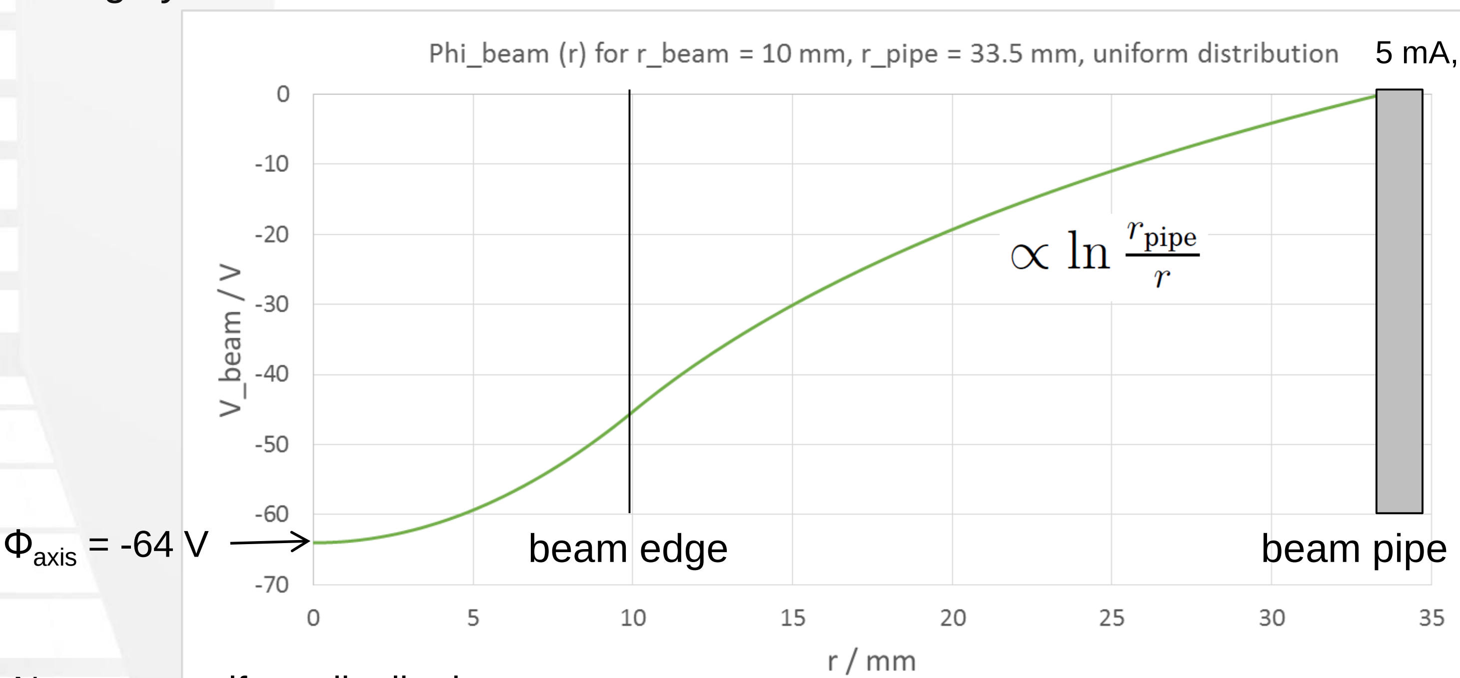
$$\tau_{\text{comp}} = \frac{1}{n_{\text{gas}}\sigma_{\text{i}} v_{\text{p}}}$$

M. Reiser (2008)

Radial Beam Potential Distribution

Round beam, uniform charge distribution, inside an infinitely long cylindrical tube.

$$\Phi_b(r) = \frac{I_b}{4\pi\epsilon_0 \cdot v_p}\left(1 + 2\ln\left(\frac{r_{pipe}}{r_b}\right) - \frac{r^2}{r_b^2}\right)$$



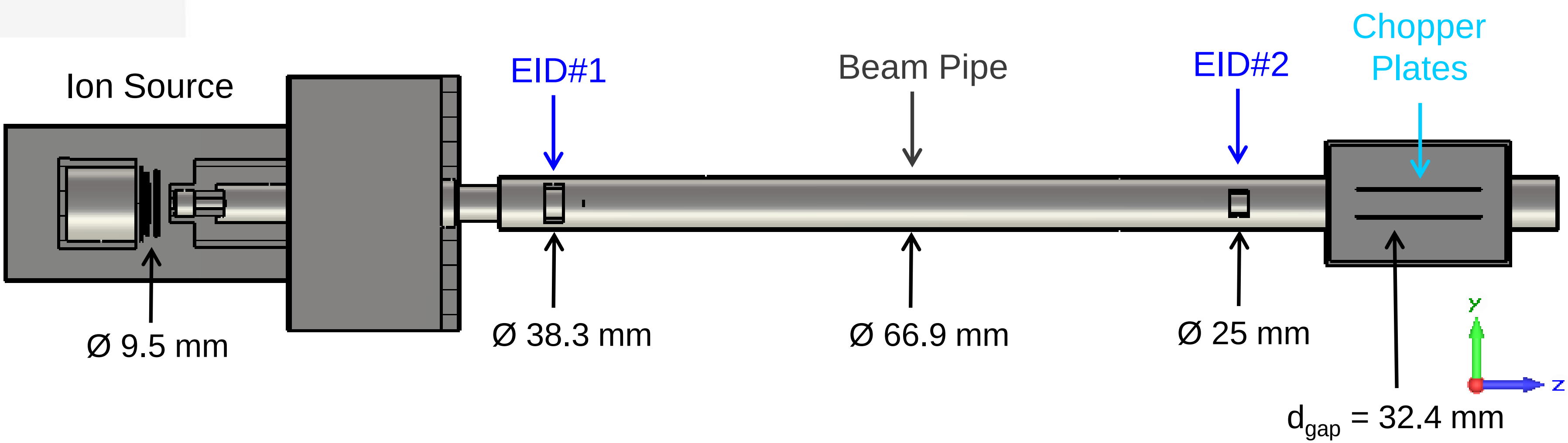
For $T_{ion} \approx 1$ eV
→ $\eta_{scc} \approx 98\%$
(considering only radial losses)

Note: non-uniform distributions can produce higher potential.

→ Low level of radial losses expected.

Estimation of longitudinal loss channels

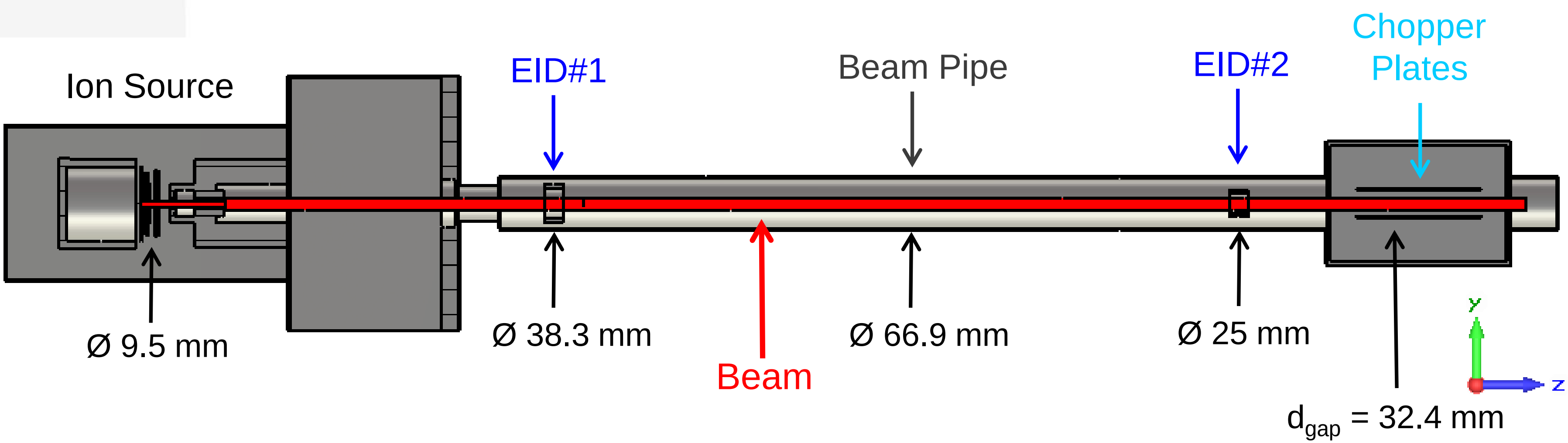
Simple model of PXIE LEBT, including external voltages…



Note: MEBT scraper not included.

Estimation of longitudinal loss channels

Simple model of PXIE LEBT, including external voltages…



…and approximating H^- beam as cylinder with constant radius and constant charge density.

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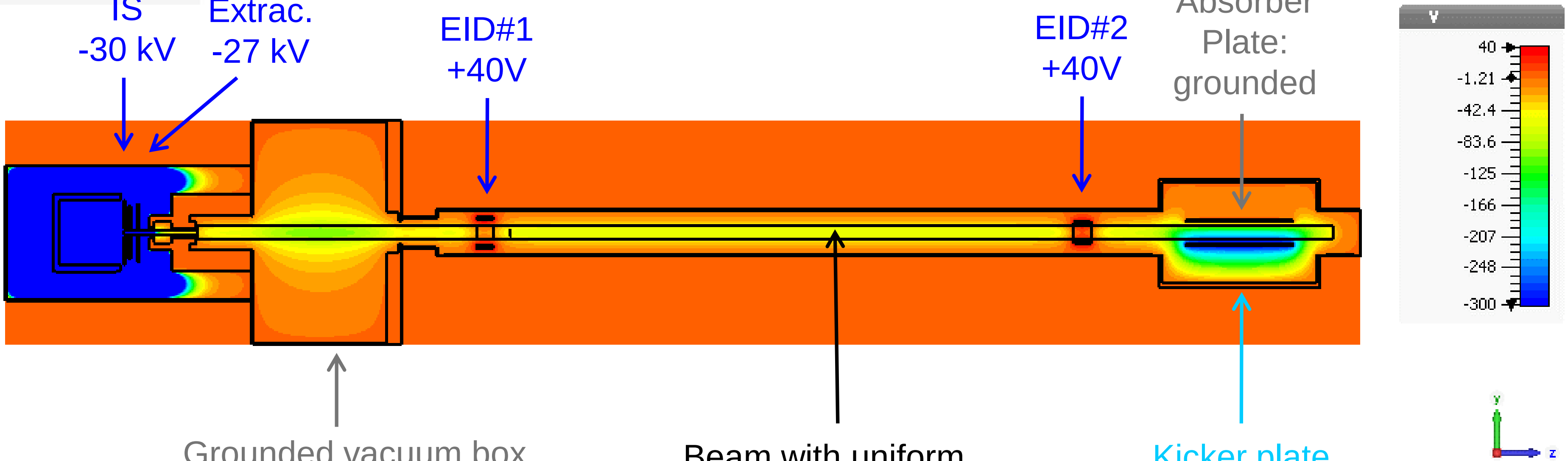
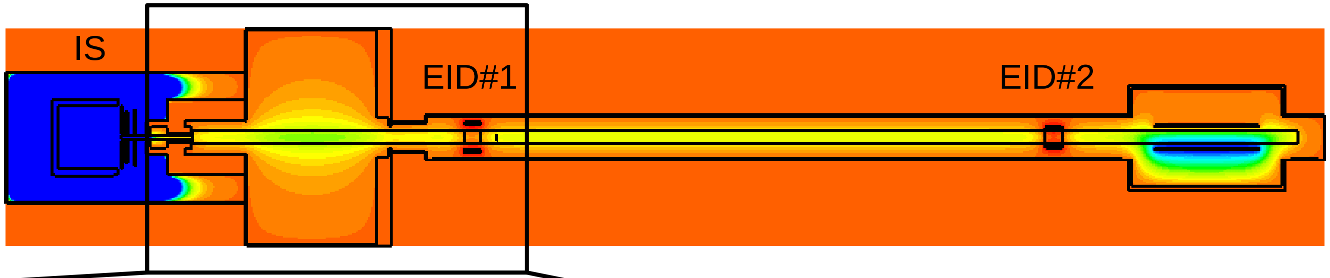
Potential Map of PXIE LEBT

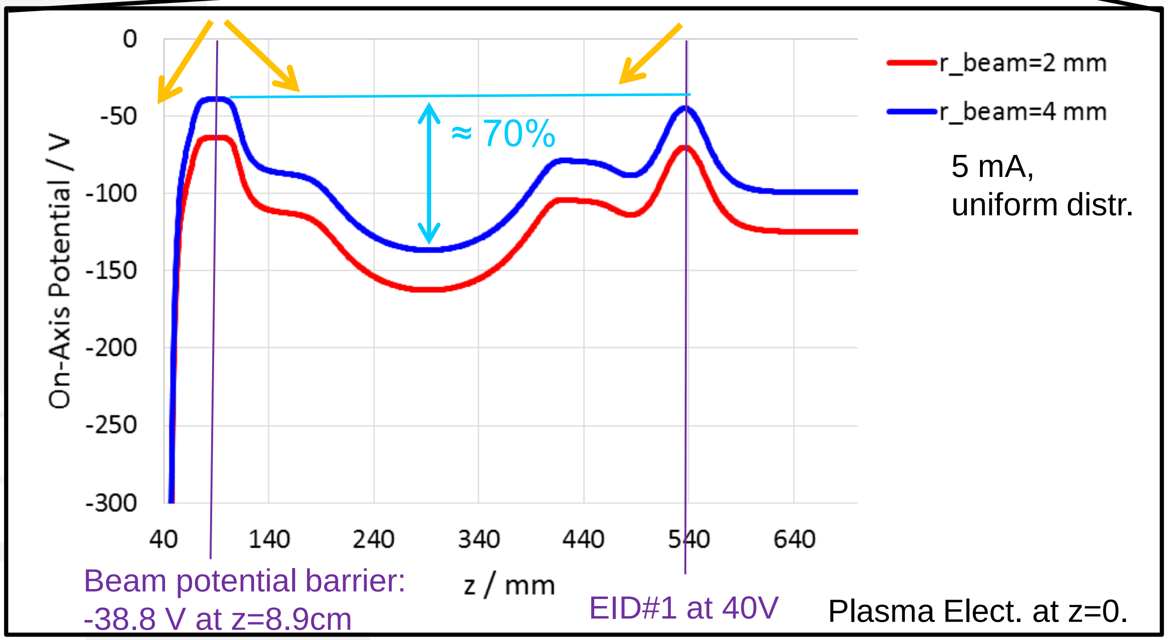


Simulations with CST EMS.

Potential Map of PXIE LEBT I

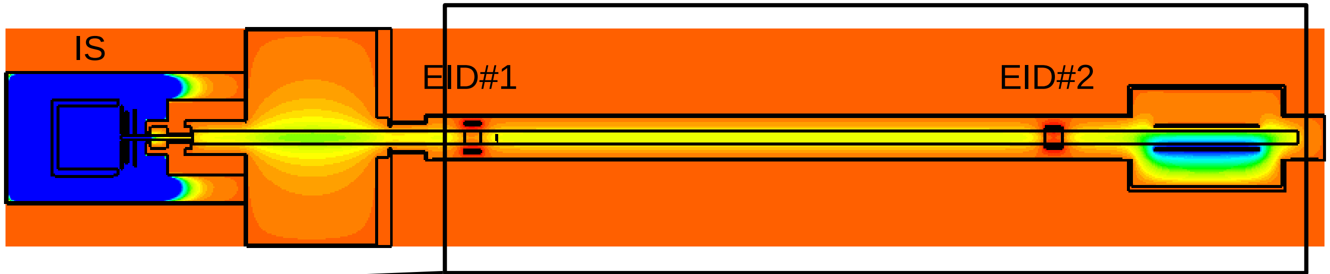
Note: no suppression electrode used for IS.

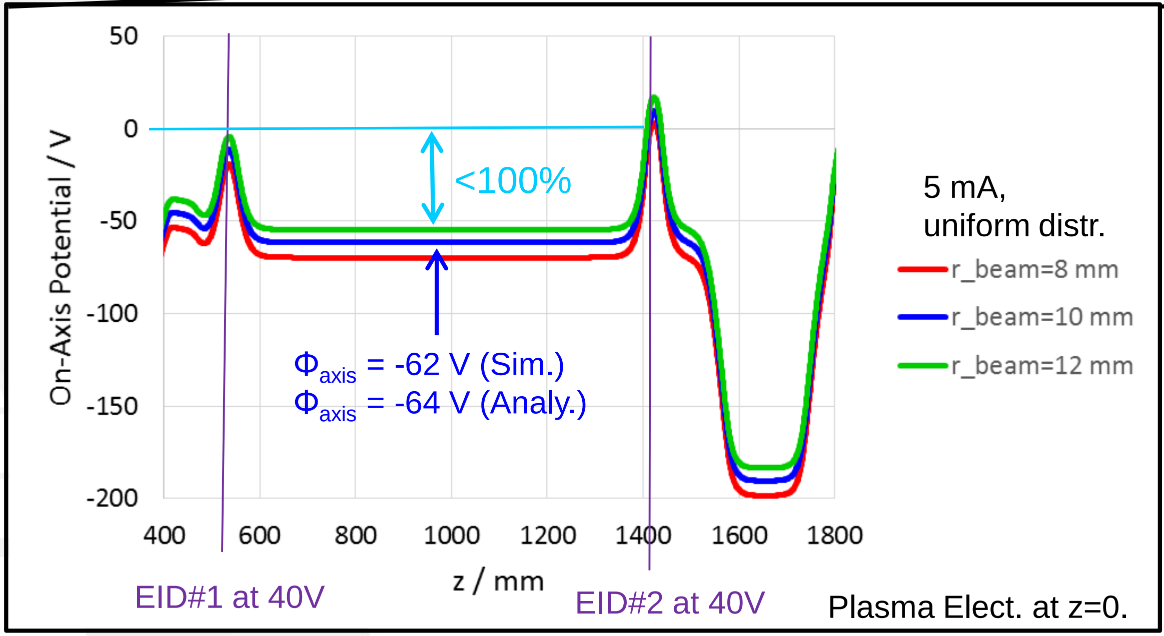




- Longitudinal variation of on-axis potential creates potential wells.
- Potential barrier of ≈ –40V inside ground electrode.
- Exact position and height depends on beam current, envelope and distribution (for given geometry).
- Loss channel of positive ions to IS.
- Simple model indicates compensation degree below 70% in this region.

Potential Map of PXIE LEBT II

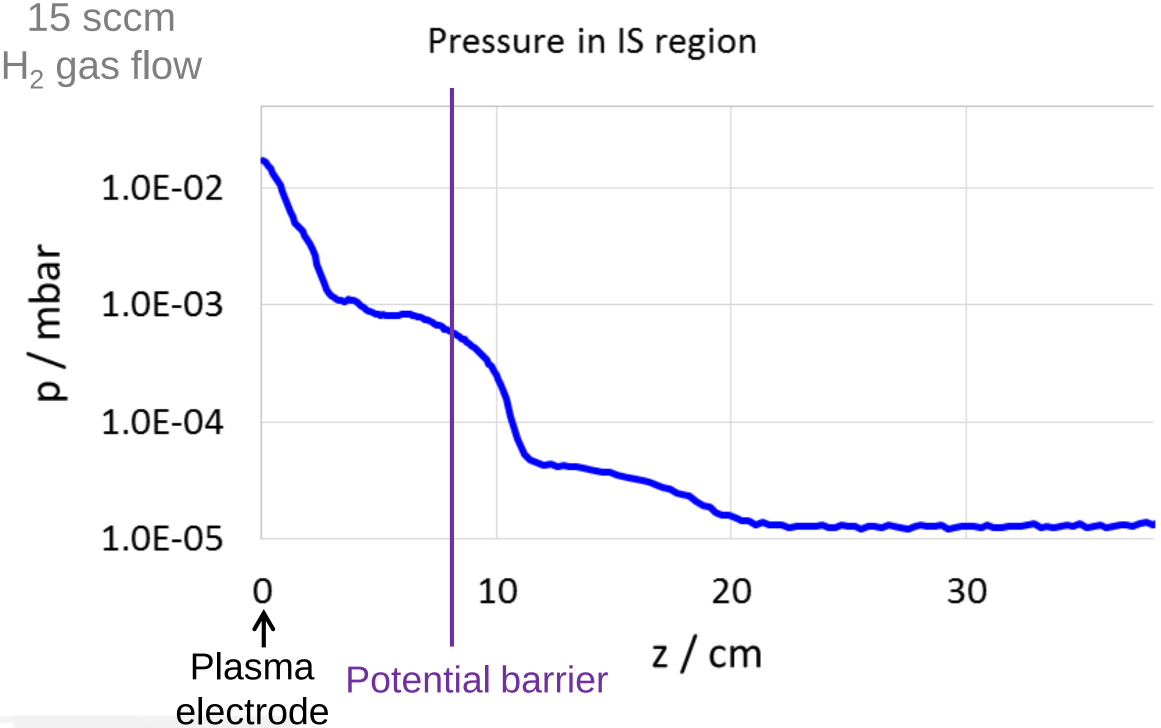




- For uniform beam with large radius: EID potential high enough to trap positive ions.
- For non-uniform beam (or r_{beam} smaller than 6 mm) EID potential of +40V is too low to reach full compensation.
- This can reduce the compensation degree between EID#1 and EID#2.

Pressure Distribution in PXIE LEBT

15 sccm
H_2 gas flow



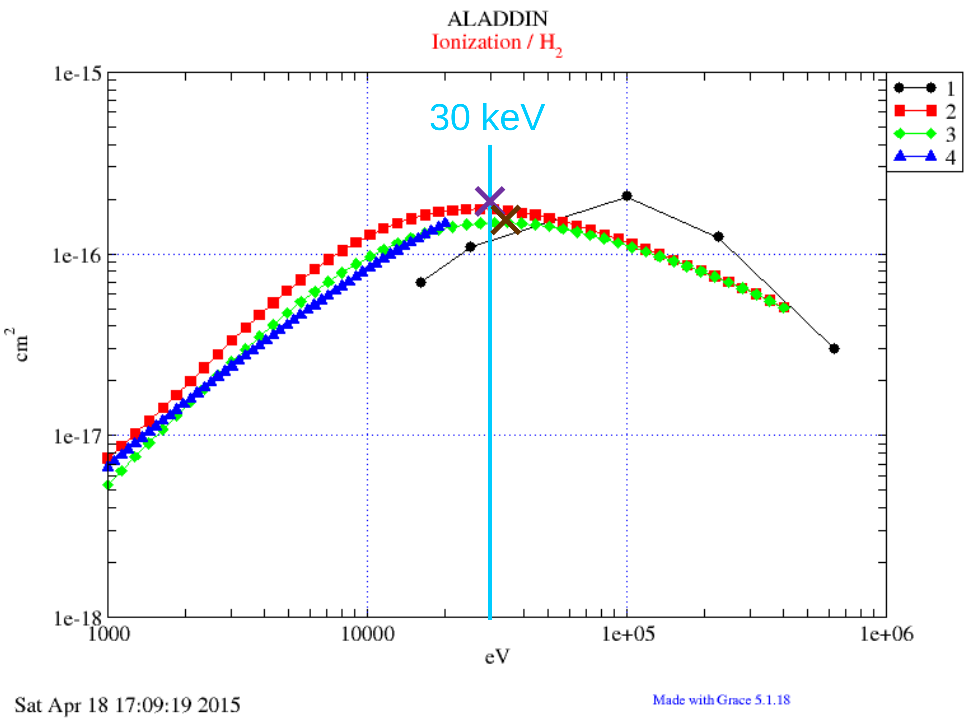
Simulation with MOLFLOW by A. Chen.

- Simulated pressure distribution gives high gradient in IS.
- Total pressure drop consistent with analytical model (developed based on molecular flow through serial and parallel circuits of pipes and apertures).

Constant pressure assumed in LEBT downstream of IS vacuum box.

Ionization Cross Sections

Deviations of ≈ ±30% in literature. (Nearly) all cross sections measured for protons.



From IAEA Data Base: https://www-amdis.iaea.org/ALADDIN/collision.html

1: D. Elizaga, L.F. Errea, J.D. Gorfinkiel, C. Illescas, A. Macias, L. Mendez, I. Rabadan, A. Riera, A. Rojas, P. Sanz, IAEA-APID-10 (2002) p:71

2: C.F. Barnett, ORNL-6086 (1990) p:D-2

3: C.F. Barnett, ORNL-6086 (1990) p:D-4

4: R.K. Janev, W.D. Langer, K. Evans Jr., D.E. Post Jr., H-HE-PLASMA (1987)

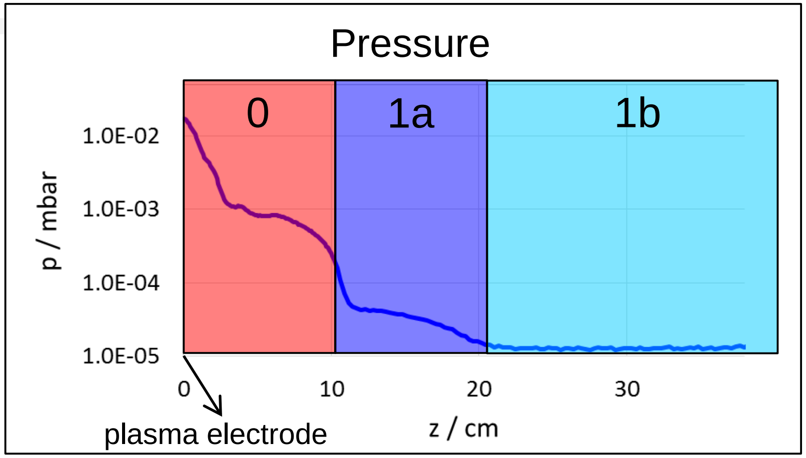
σ_i = 1.93e-16 cm^2
(p, 30 keV)
Rudd et al., *Cross sections for ionizaton of gases by 5—4000-keV protons and for electron capture by 5—150-keV protons*, Phys. Rev. A, Vol. 28, Num. 6 (1983)

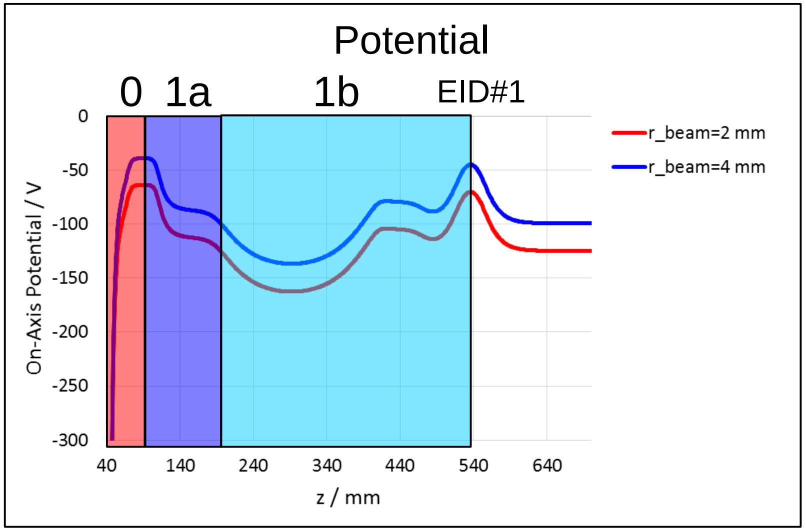
σ_i = 1.5e-16 cm^2
(H^-, 35 keV) → used for calculations.
Y. Fogel et al., J. Explt. Theoret. Physics (USSR), 38, 1053 (1960). Quoted in: Sherman et al., *H− beam neutralization measurements in a solenoidal beam transport system*, AIP Conference Proceedings 287, 686 (1992)

Different Regions for SCC

- Region 0: from plasma electrode to potential barrier (Δz ≈ 10 cm)
  - High pressure, but positive ions lost to IS (production rate significantly lower than loss rate). No compensation is expected.
- Region 1a: potential barrier to end of upstream IS vacuum box (Δz ≈ 10 cm)
  - High pressure (t_{comp} ≈ μs), but ions accel. downstream (Region 1b).
- Region 1b: end of US IS vacuum box to EID#1 (Δz ≈ 30cm)
  - Lower pressure, compensation increases until potential well is filled (≈ 70%)

Region 1: t_{comp} ≈ 60 μs (analytical)





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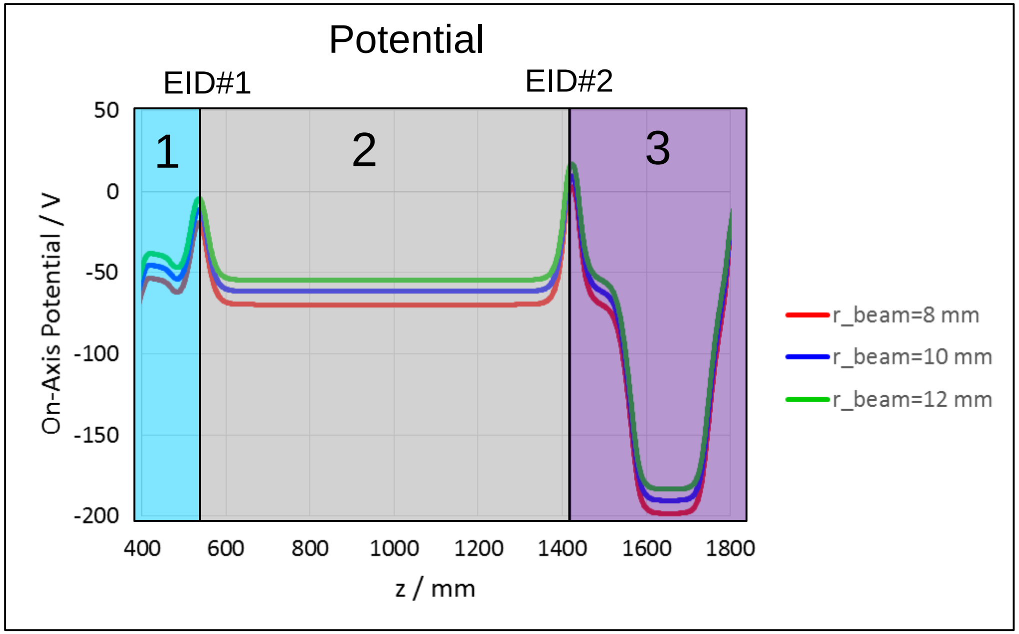
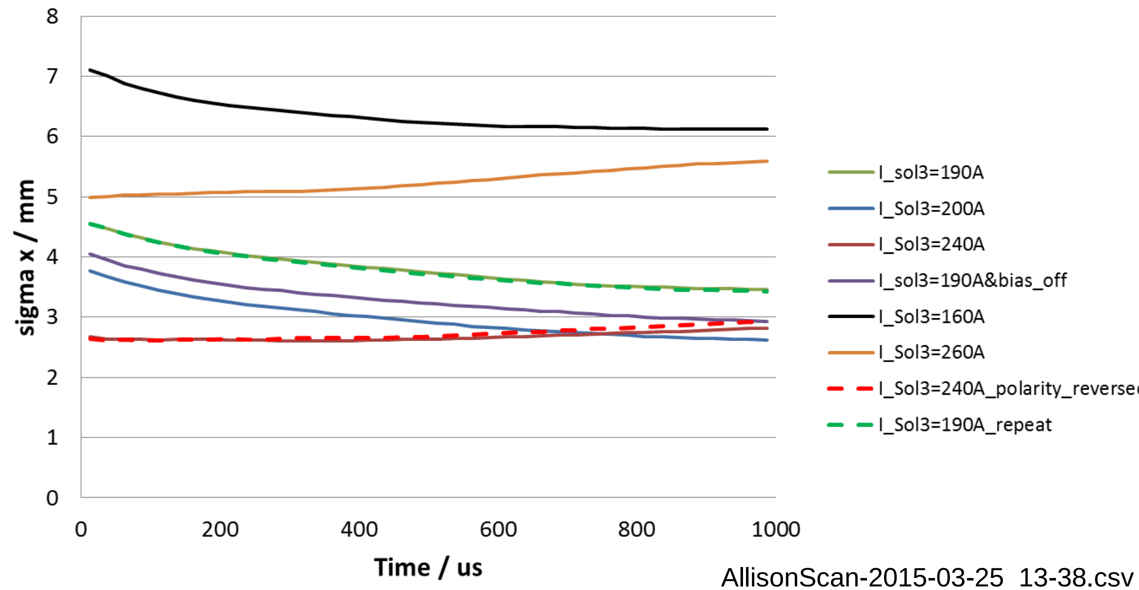
Different Regions for SCC

- Region 2: EID#1 to EID#2 ($\Delta z \approx$ 90cm)
  - Low pressure → $t_{comp} \approx$ 200 µs
    (for Region 1 & 2 combined: $t_{comp} \approx$ 100 µs)
- Region 3: Chopper (EID#2 to LEBT scraper)
  - Ions cleared to kicker plate.
  - Without clearing voltage:
    $t_{comp} \approx$ 2 ms



Measurements: Time behavior

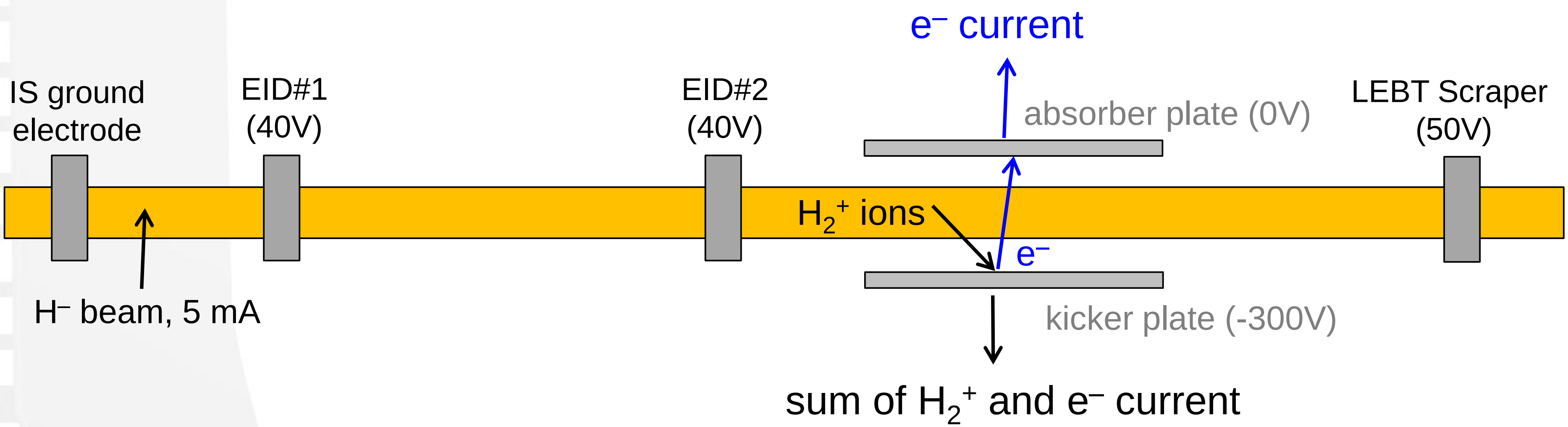
- No dedicated device to measure space-charge compensation (beam potential) available.
- As presented in former meetings, measured time behavior of beam properties in agreement with calculated compensation time within order of magnitude. But ambiguities remained regarding compensation state.



AllisonScan-2015-03-25_13-38.csv

2 ms pulse from IS, 1 ms pulse from chopper. EID1 and EID2 biased at 40V. Clearing voltage at -300V. FC donut biased at 50 V. 25 μs bins for AS.

Measurements: Experimental Setup



→ Approach: measure directly the positive ion current using the chopper setup.

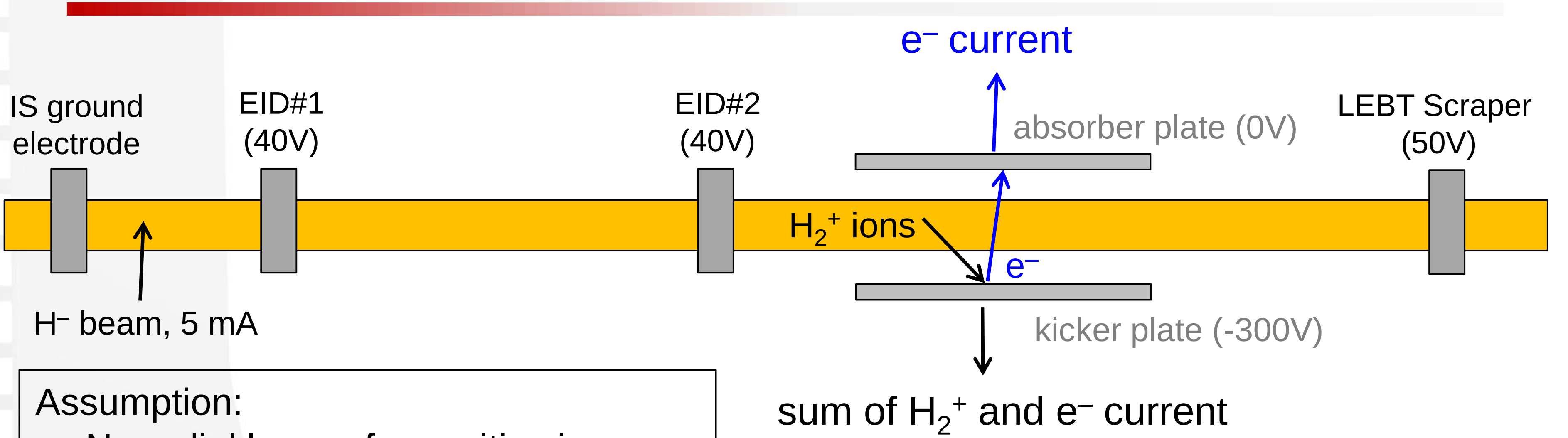
Measurement

Positive-ion current on kicker plate:

$$I_{H_2^+} = I_{kicker} - |I_{absorber}|$$

Beam losses inside chopper have to be minimized.

Ion-Clearing Model



Assumption:

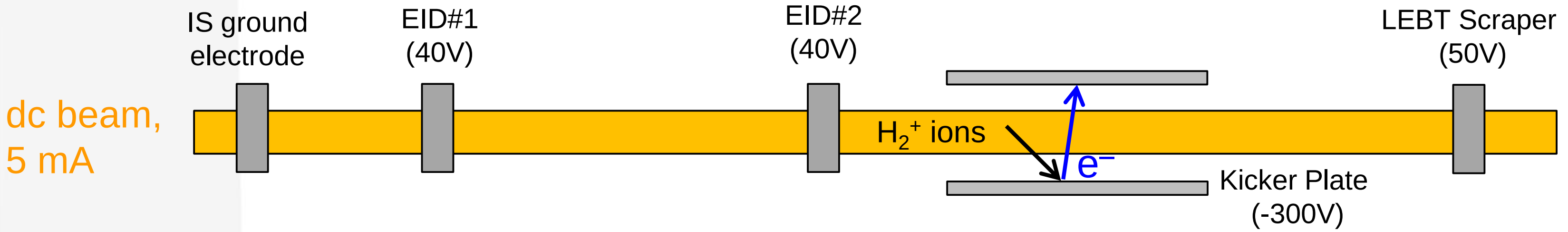
- No radial losses for positive ions.
- Ionization electrons are removed radially from beam and do not contribute to ionization.
- Completely impermeable barriers if EIDs and LEBT scraper are biased.
- Completely permeable barriers if not biased.

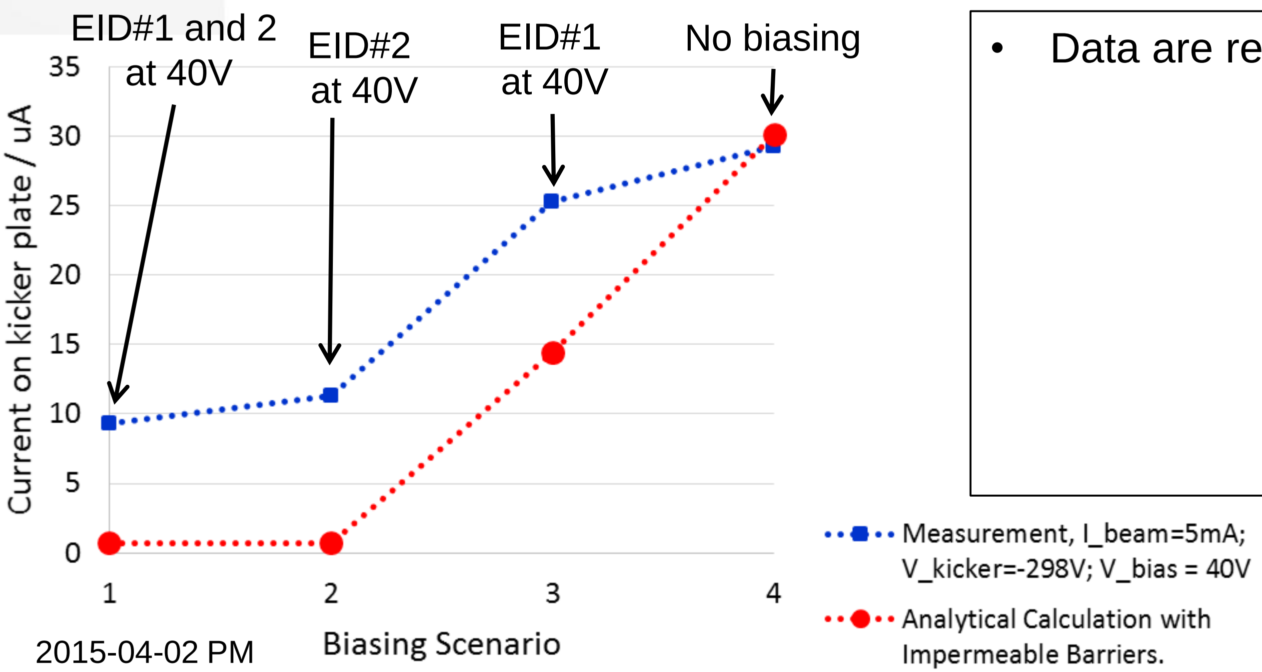
Analytical Calculation

Positive-ion current (from length Δz):

$$I_{H_2^+} = I_{\text{beam}} \cdot \Delta z \cdot n_{\text{gas}} \cdot \sigma_i$$

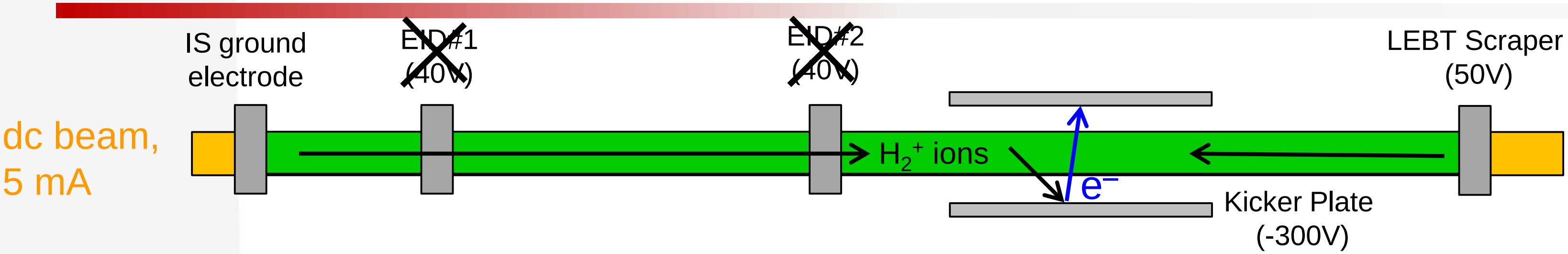
Measurements: Ion-Clearing Current

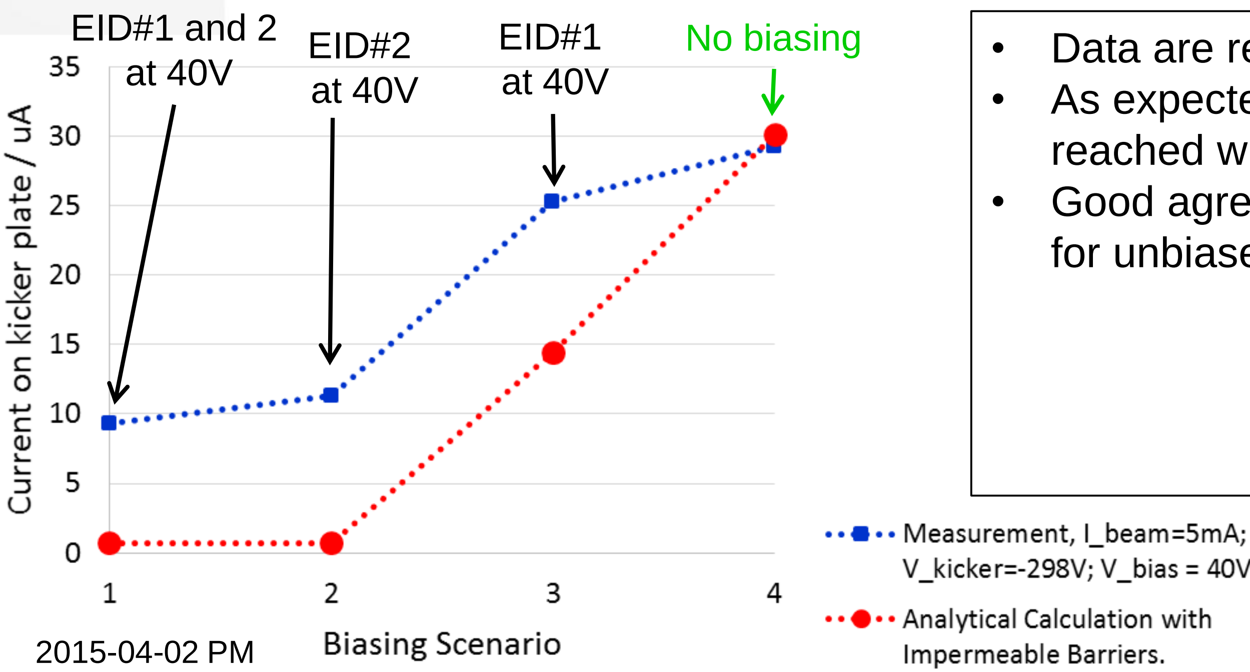




- Data are reproducible.

Measurements: Ion-Clearing Current





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- As expected, highest current is reached without biasing.
- Good agreement with analytical model for unbiased case (30 μA/ 29 μA).

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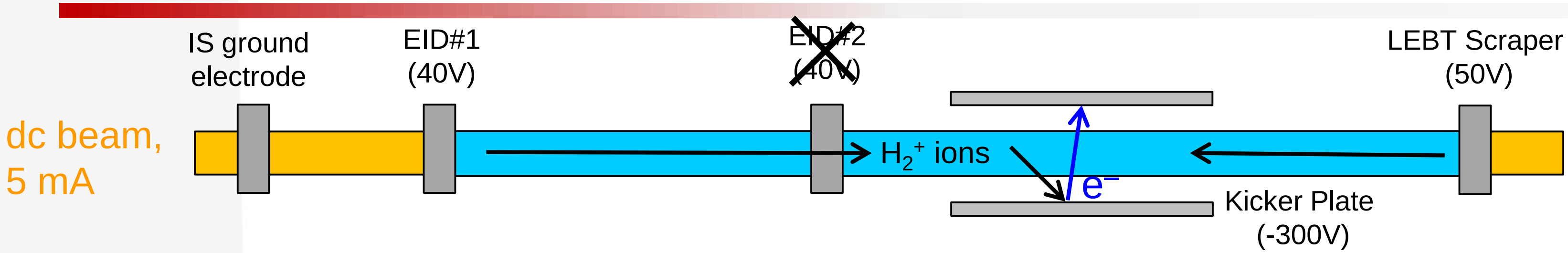

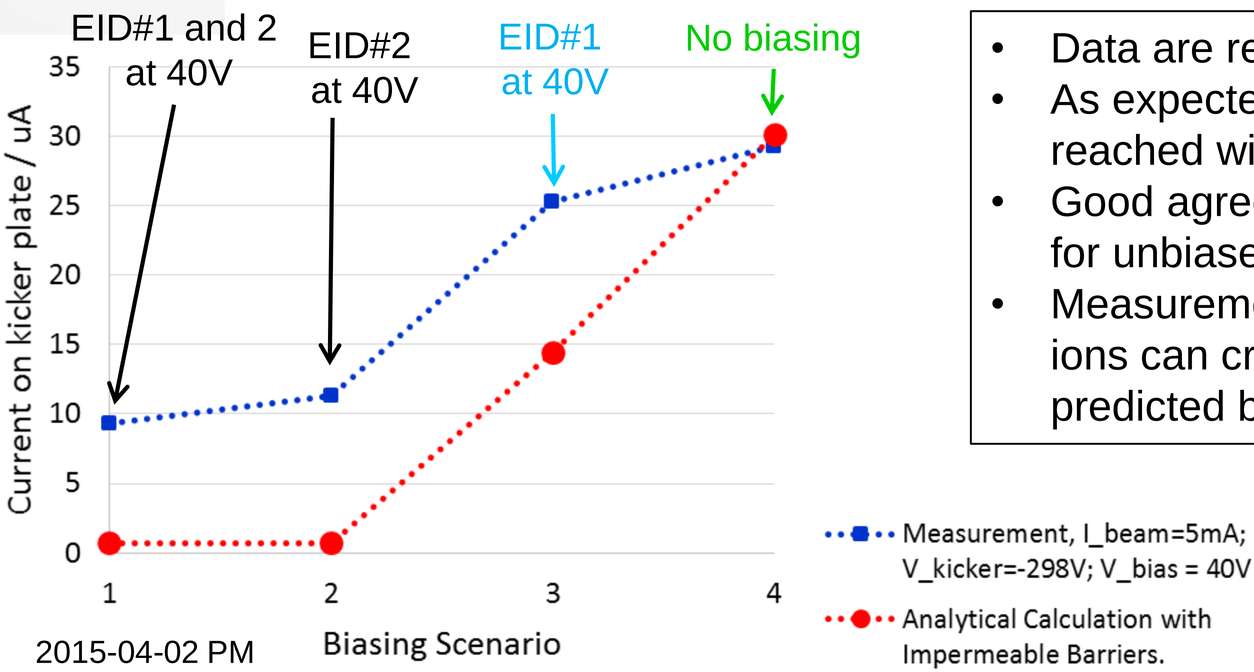

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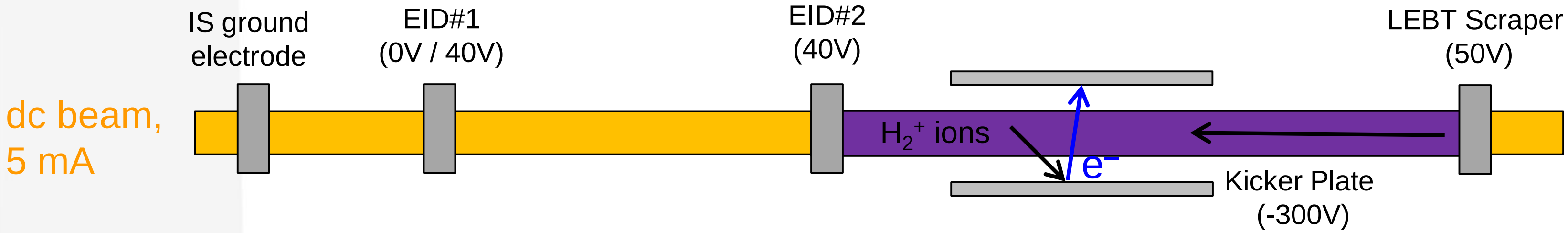

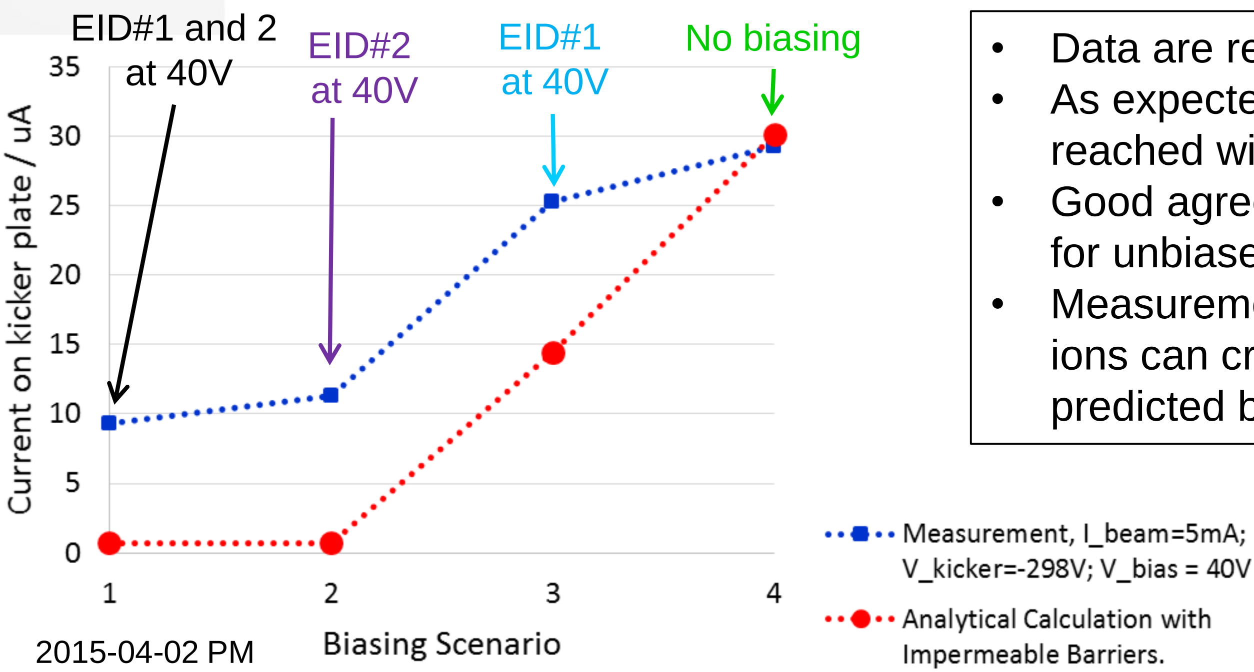

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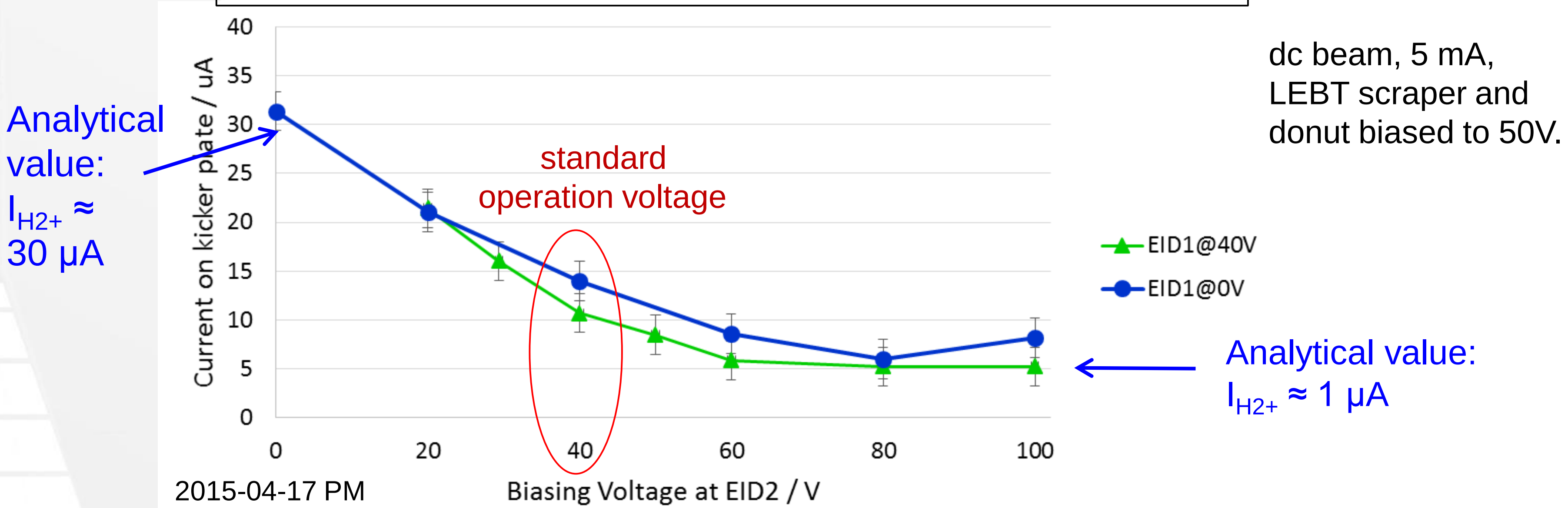
Measurements: Ion-Clearing Current

- Measurement with varying voltage on EID#2.
- Current of positive ions saturates for V_{EID2} > 80V.
- Qualitative behavior of positive ions can be predicted.
- Quantitative agreement good for unbiased case.



→ To avoid intermediate state of space-charge compensation, biasing voltage should be increased from 40V to 100V.

Conclusions

- Simple model for compensation in PXIE LEBT is based on
  - potential map (showing on-axis potential between -50 V and -150 V),
  - estimations of pressure distribution (between 1e-2 mbar and 1e-5 in IS),
  - ionization cross section of σ_i = 1.5e-16 cm^2 (variation of ±30% in literature exists).
- Model indicates
  - potential barrier of ≈ –40 V (depending on beam current, envelope and distribution) in the IS,
  - so that positive ions created upstream will be lost to IS (zero compensation),
  - while upstream of EID#1 the compensation degree can reach up to 70%.
  - Downstream of EID#2 full compensation can only be reached if the biasing voltage is high enough.

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Conclusions

- Measurements:
  - Qualitative behavior of ion-clearing current can be predicted based on the simple compensation model.
  - Good quantitative agreement for unbiased case (deviation <6%).
  - Standard biasing of 40 V is not high enough to block longitudinal movement of positive ions.
  - Intermediate compensation state in LEBT is likely.
- Current PXIE compensation scheme already allows matching of low-emittance beam into the RFQ.
- Increase biasing voltage of EID#1 and EID#2 to 100V should increase control of compensation state and support reproducibility.

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Thank you!

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