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PIP-II Injector Test LEBT Operation for the RFQ

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PIP-II Technical Meeting

26 July 2016

Outline

- LEBT transport scheme (reminder)
- Case studies in the LEBT
  - Profile measurements and simulations
  - Emittance measurements
- LEBT tuning for operation
  - Setup
  - RFQ transmission measurements
- Conclusion

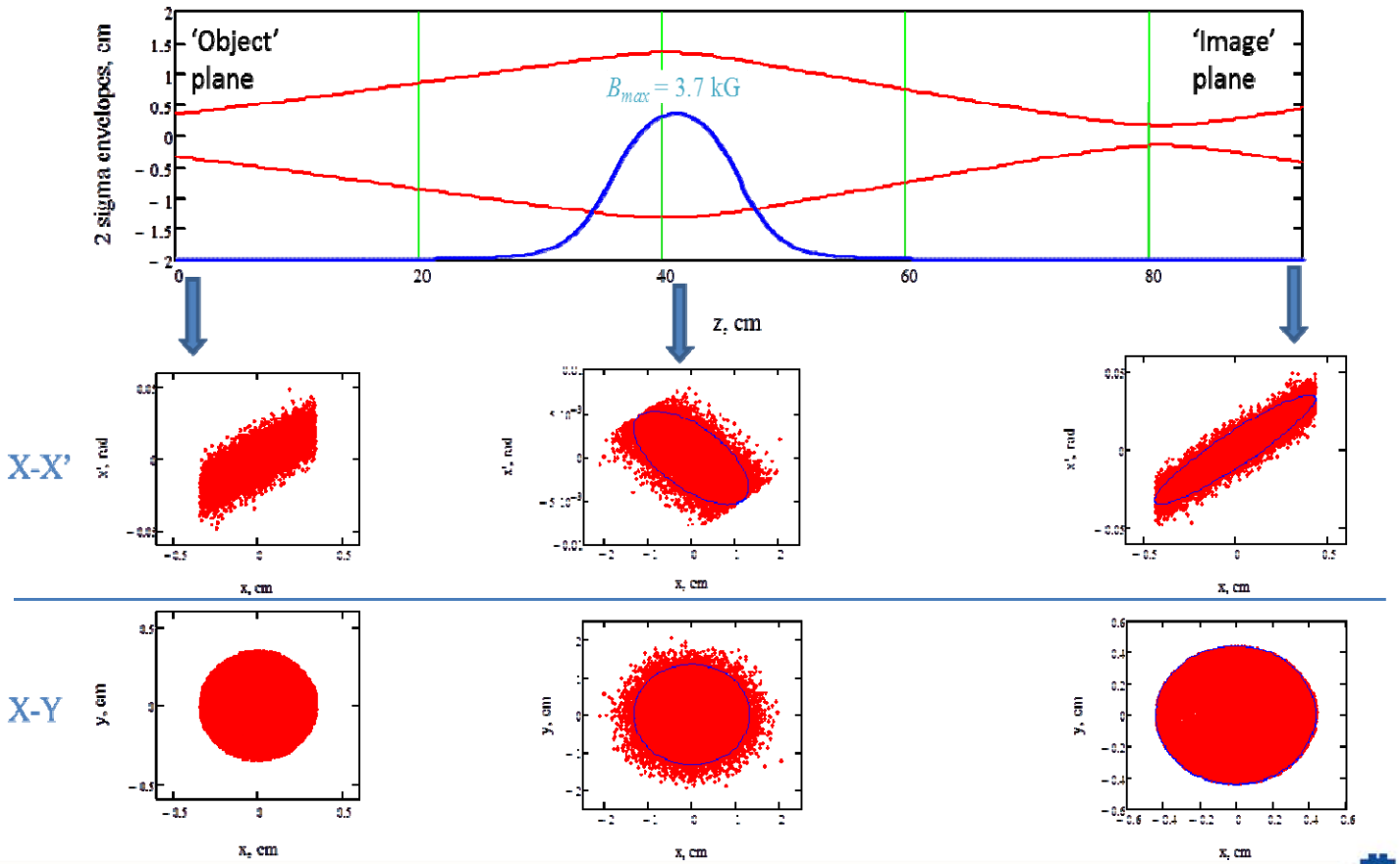
LEBT beam transport concept (reminder)

- Ion source generates a uniform spatial density distribution
  - Velocities have a Gaussian distribution
- Completely neutralized beam transport from the ion source through Solenoid #1
- At the image plane of Solenoid #1, the distribution becomes uniform again*
  - **Neutralization is interrupted here**
- Phase advance over the remaining length of the LEBT is kept low
  - Beam distribution stays close to uniform and emittance growth is *suppressed*

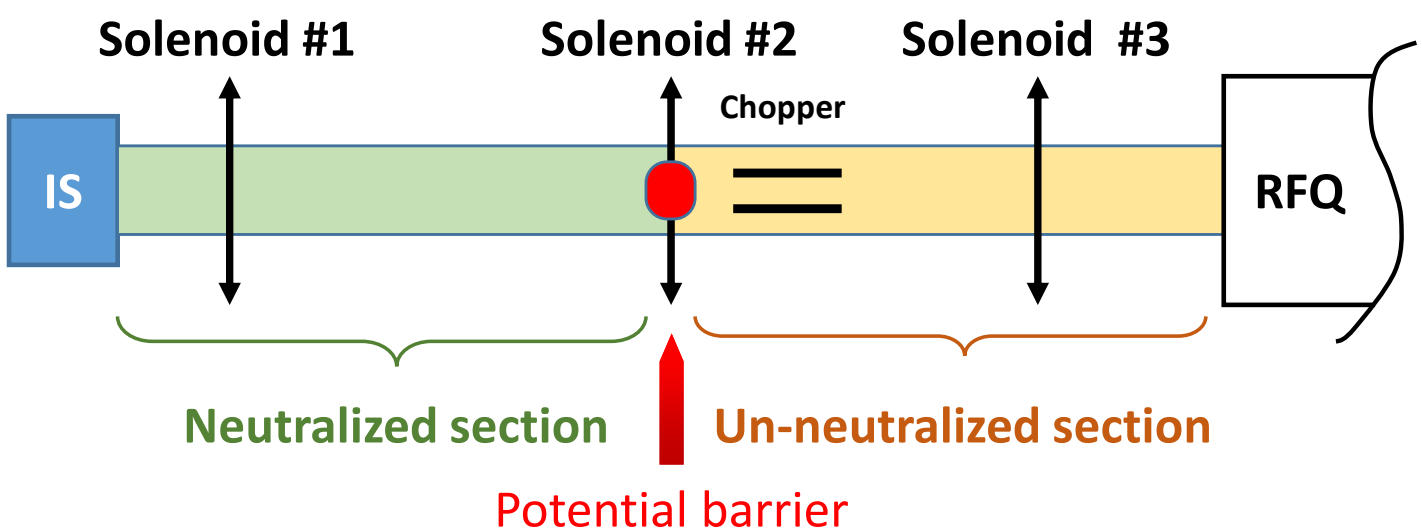
* *theoretically, at a fixed location downstream of Solenoid #1, the beam current density distribution may be uniform or Gaussian depending of the solenoid current setting i.e. phase advance*

LEBT beam transport concept illustration

- PIC-like simulations through one solenoid
  - Initial distribution has a uniform current density distribution but Gaussian in the velocity space



LEBT transport scheme (reminder)

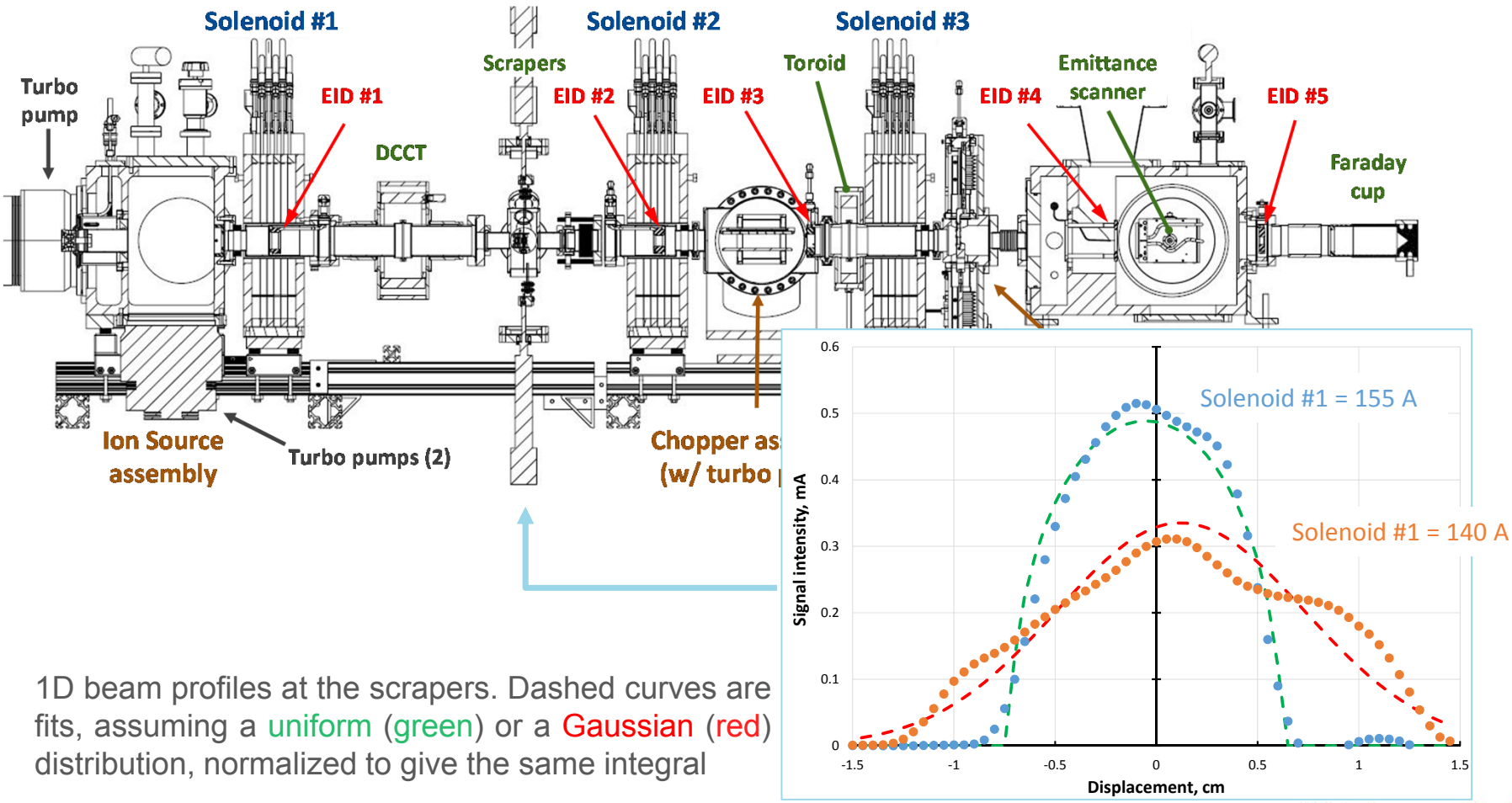


- High vacuum pressure
  - Gas load from ion source
- Neutralizing particles confined by potential barrier

- Low vacuum pressure
  - Vacuum pumping station
  - Limits rate of production of neutralizing particles
- Clearing electric field
  - Sweeps neutralizing particles out of the beam path

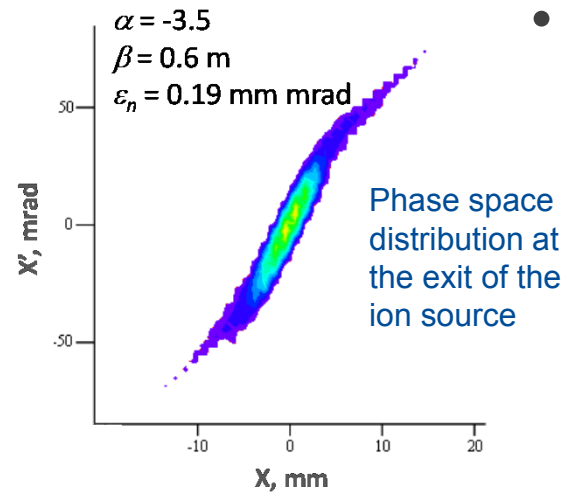
Profiles measurements

- Same ion source settings, different solenoid #1 currents
  - 5 mA (DCCT), near the end of a 1 ms pulse

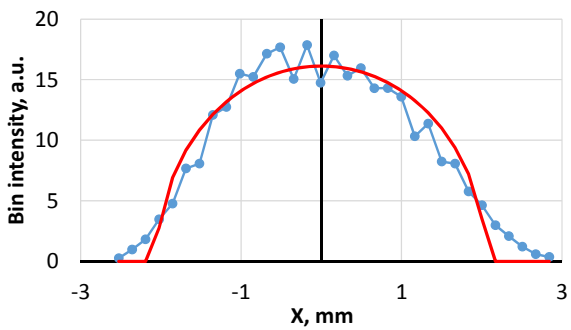


1D beam profiles at the scrapers. Dashed curves are fits, assuming a uniform (green) or a Gaussian (red) distribution, normalized to give the same integral

Profiles – Measurements vs. Simulations



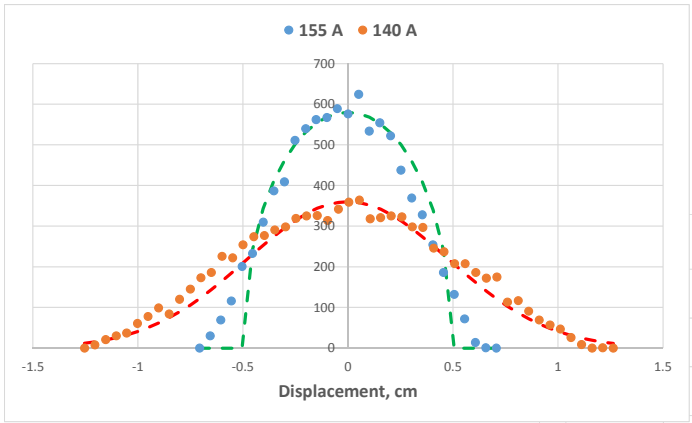
Backpropagation



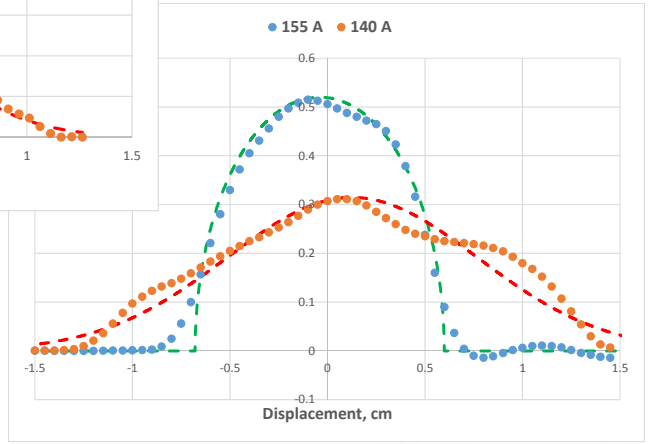
Comparison of a 1D current density distribution from a *back propagated* phase portrait (blue circles) and a uniform distribution fit (red)

- Simulations initialized with measured Twiss parameters at the exit of the ion source
  - Distribution of particles is *ideal* (Uniform density and Gaussian in velocity space)

Simulations



Measurements

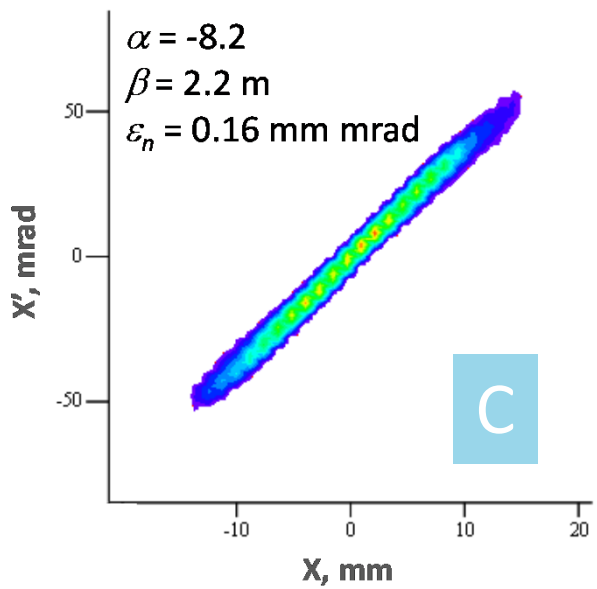


Note: Binning interval (horizontal axis) is the same for simulations and measurements

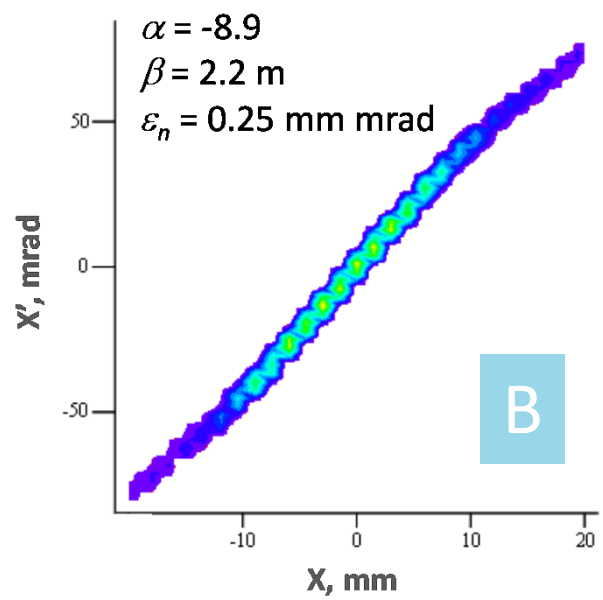
Phase space measurements

- Phase space distributions for 2 different focusing solutions but the same ion source tune

	Sol. #1 [A]	Sol. #2 [A]	Sol. #3 [A]	ε_n (rms) [μm]	α	β [m]
B	154	187	223.5	0.25	-8.9	2.2
C	143	158	240	0.16	-8.2	2.2

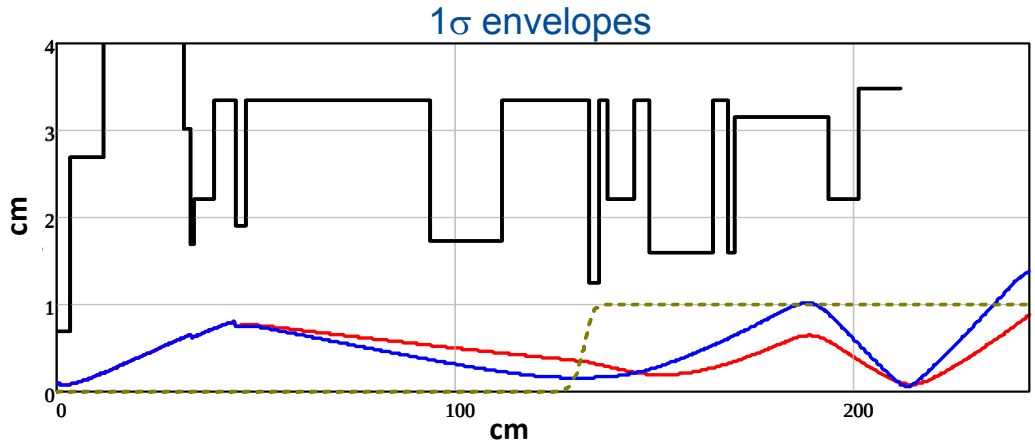


5 mA, 50 μs chopped pulse near the end of a 1.5 ms IS pulse



Phase space measurements vs. simulations

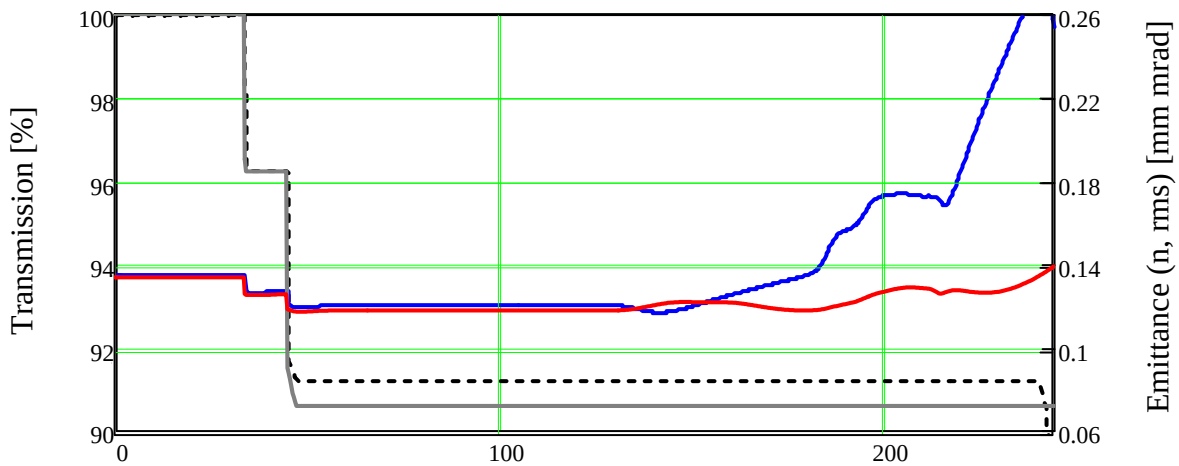
- Measurements
  - α_{Blue} = -8.9 ; β_{Blue} = 2.2 m
  - α_{Red} = -8.2 ; β_{Red} = 2.2 m
- Simulations
  - α_{Blue} = -21.3 ; β_{Blue} = 6.1 m
  - α_{Red} = -16.7 ; β_{Red} = 4.4 m



Blue ≡ Case B

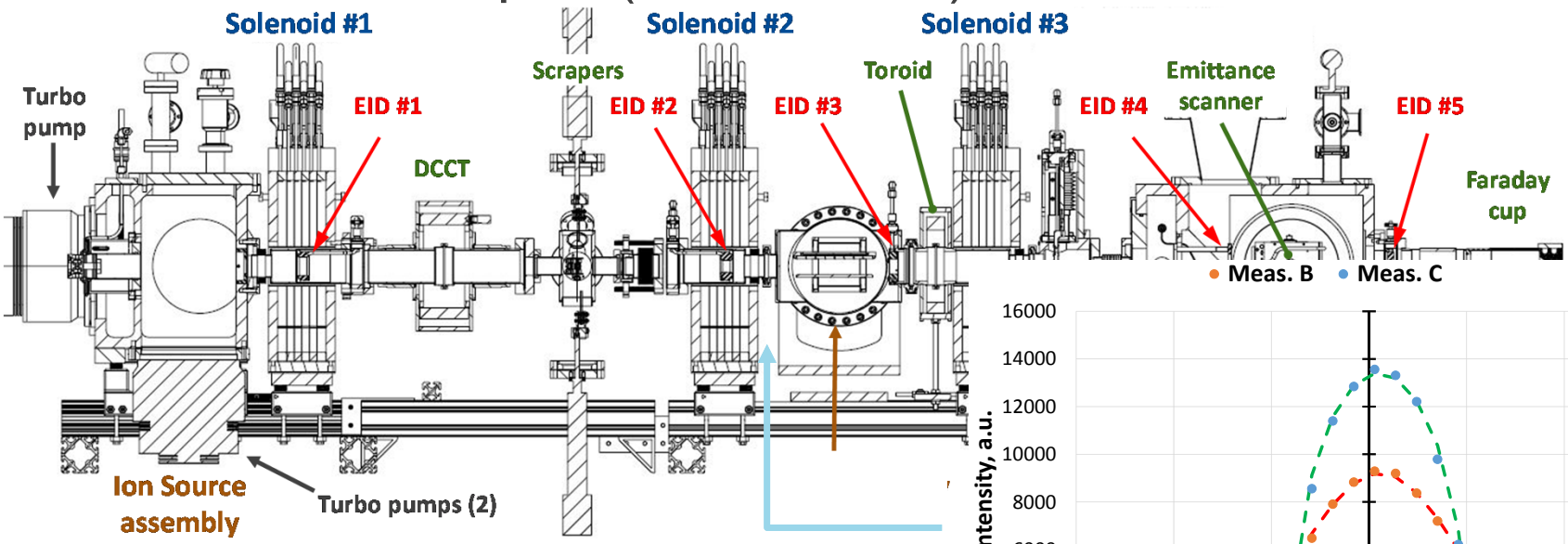
Red ≡ Case C

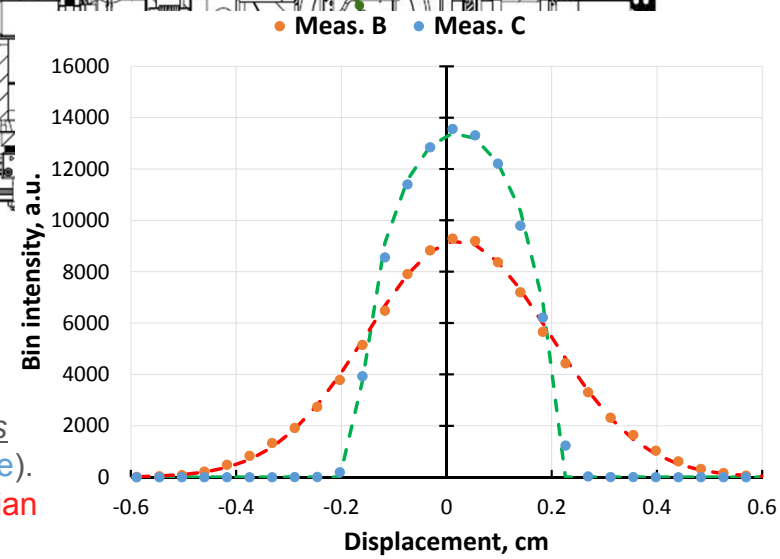
- Measurements
  - ε_{Blue} = 0.25 mm mrad
  - ε_{Red} = 0.16 mm mrad
- Simulations
  - ε_{Blue} = 0.26 mm mrad
  - ε_{Red} = 0.14 mm mrad



Corresponding profiles simulations near EID #2

- As expected from the model, the *simulated* profile for the case that leads to the smaller *measured* emittance is uniform near the *theoretical* transition from neutralized to un-neutralized transport (i.e. ~EID #2)





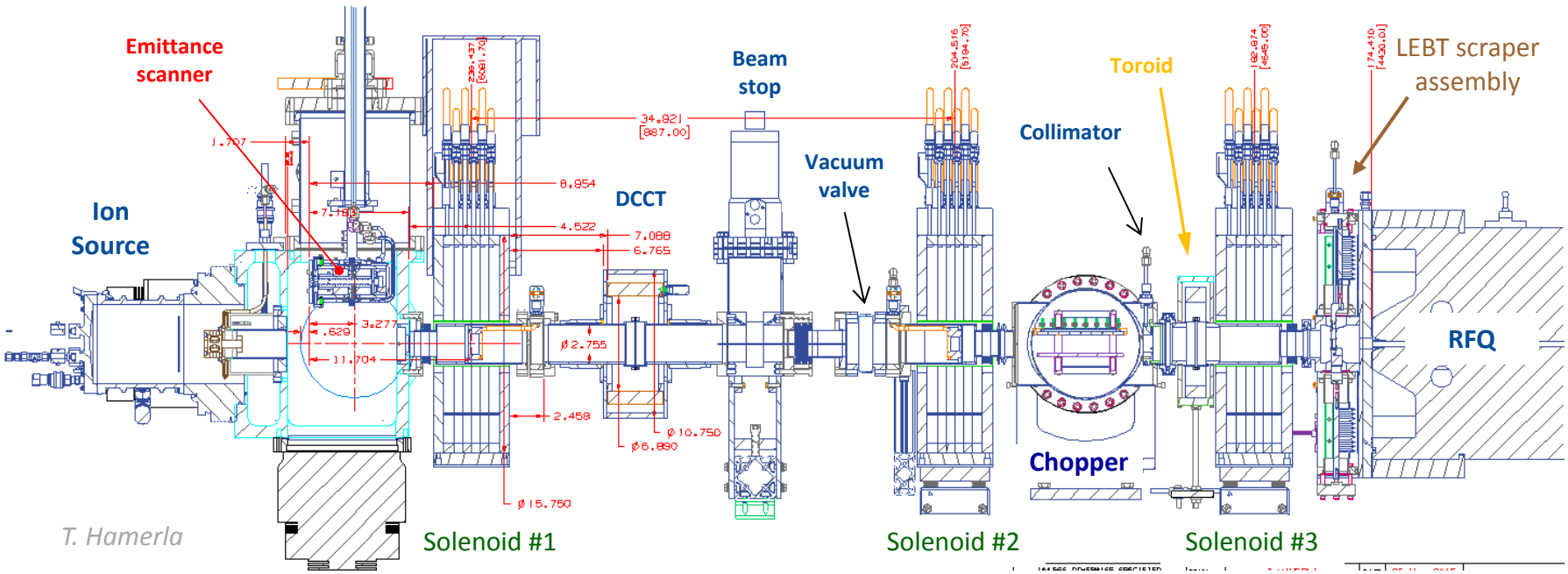
1D beam profiles 20 cm downstream of EID #2 *from simulations* corresponding to measurements settings B (orange) and C (blue). Dashed curves are fits, assuming a uniform (green) or a Gaussian (red) distribution.

LEBT transport scheme - Conclusion

- Convincing **evidence** that the transport scheme with an **un-neutralized section** was realized:
  - Ion source current density distribution sufficiently close to uniform (with help of scraping upstream of 1st solenoid)
  - Appropriate tuning of the phase advance through the 1st solenoid such that the beam current density distribution is again uniform at the transition to the un-neutralized section
  - Limited neutralization downstream of the kicker (good vacuum)
  - Low emittance at the end of the beam line
- Concurrently, *improper tuning* of the beam line leads to:
  - *Unsatisfactory* current density *profile*
  - *Large emittance* at the end of the beam line *even with some scraping* upstream

Current LEBT configuration with RFQ

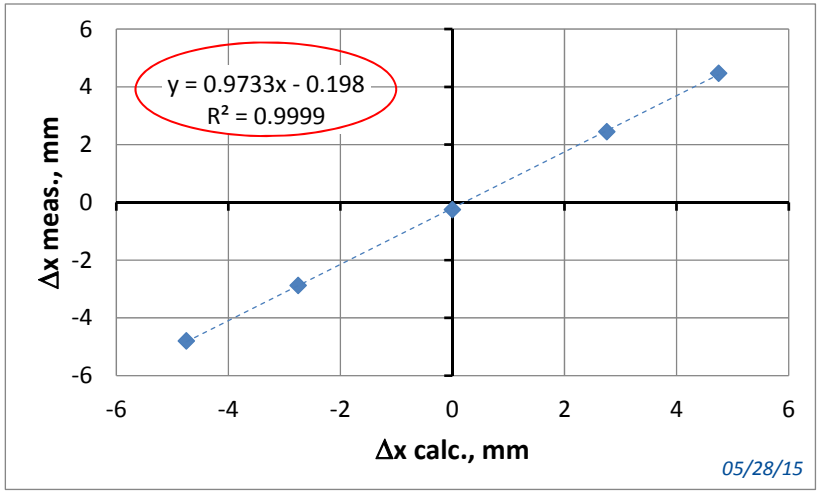
- Beam stop for personnel protection
  - Will be removed when bending dipole magnet is installed



LEBT basic tuning

- Two components
  - Twiss functions (→ IS settings, Solenoid currents)
  - Alignment (→ Position and angle of the beam at the entrance of the RFQ)
- Use tools and knowledge from commissioning activities
  - Preferred optics solution including IS settings
  - Position & angle 'bumps' at the entrance of the RFQ
- Maximize transmission through the RFQ
  - Not good enough for fine tuning → Need to evaluate emittances

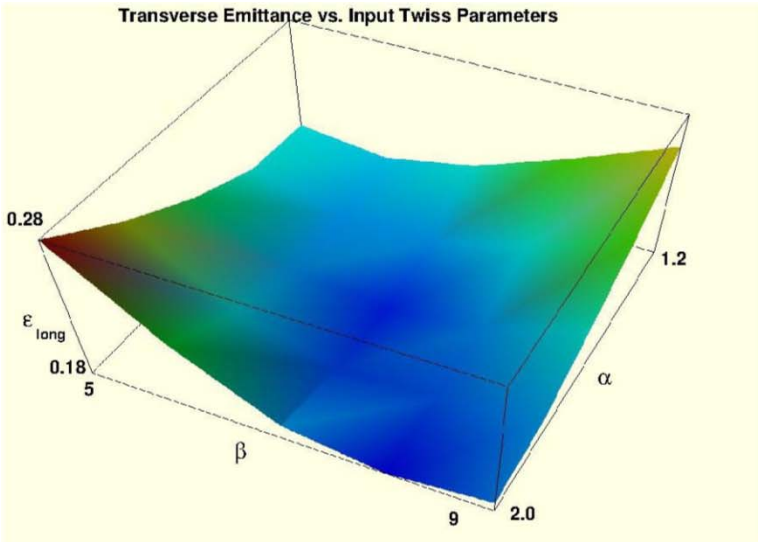
Data from phase space measurements

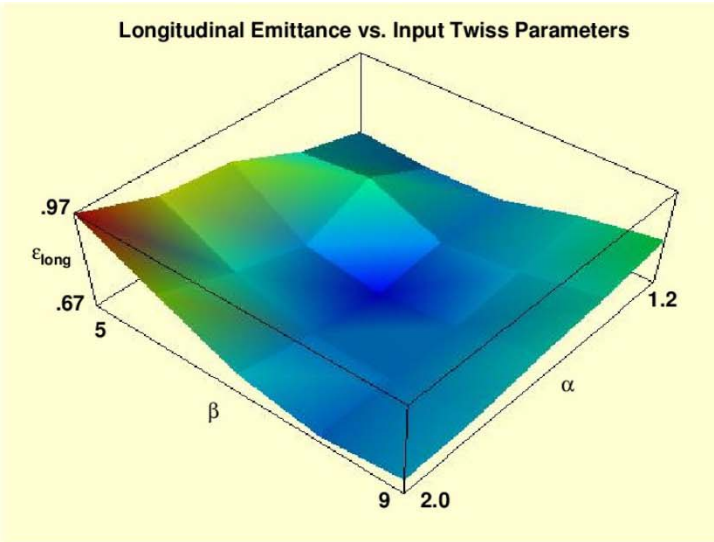


E.g.: Horizontal MULT

Transmission alone is not the best criterion to assess performance

- According to simulations, the RFQ transmission for a properly matched beam should be 99.8%
  - Relatively little dependence on Twiss functions



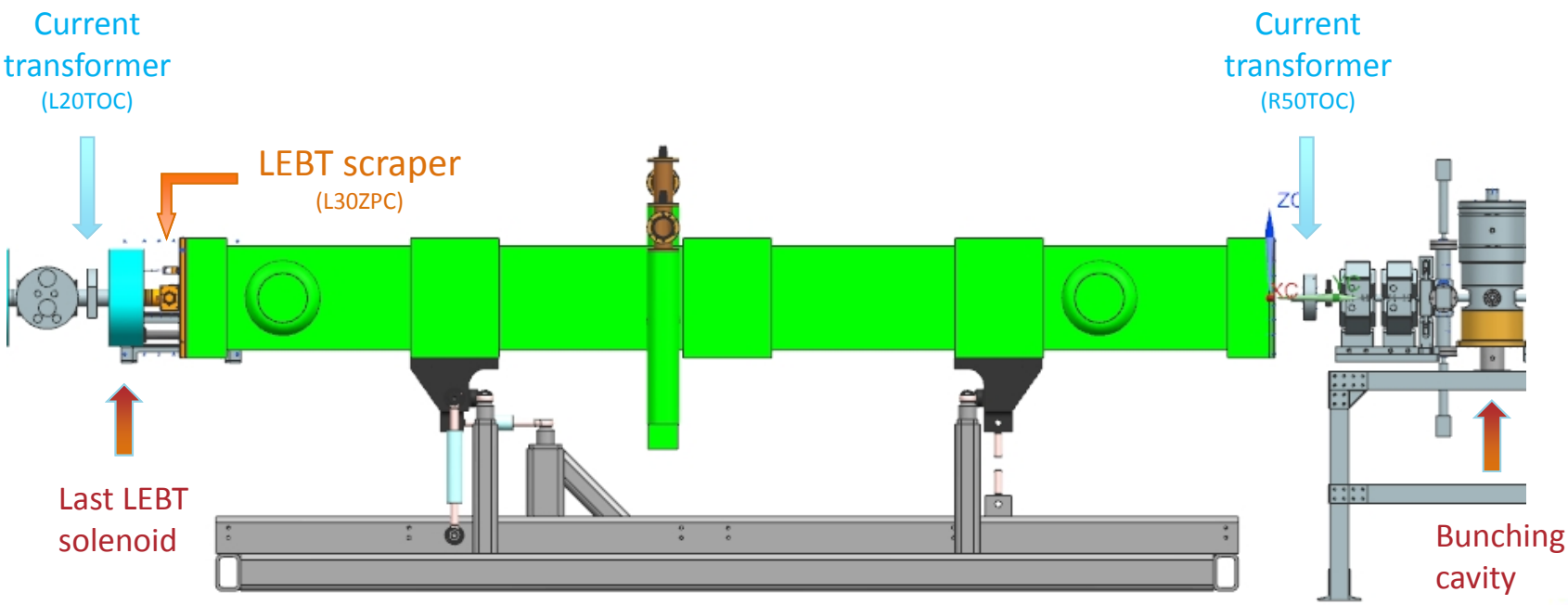


Simulations from J. Staples (2012 Project X collaboration meeting). Transmission >99% for all data points.

  - Unfortunately, I am unaware of similar simulations for the effect of the input emittance on transmission

Transmission measurements setup

- Identical, cross-calibrated current transformers before and after the RFQ
  - Transmission efficiency: R50TOC/(L20TOC-L30ZPC)
    - For averaged values “C” → “A”
  - *Caveat*: absolute values not very accurate due to background subtraction difficulties and other ‘noise’ (e.g.: RF pulse)



Transmission for operation (*based on 6/27/16 data*)

- Best settings (IS on "*high side*") 138.2/158/238.3 A for Solenoids #1, 2 and 3 respectively
  - 86% → 88-89% steering
  - 86% through 9-mm hole with LEBT scraper <0.2 mA

Probably ~100% in reality

- Nominal settings before RFQ installation (7/6/15; IS on "*high side*") 138.2/158/244.8 A for Solenoids #1, 2 and 3 respectively
  - 86%
  - 86% through 9-mm hole with LEBT scraper ~0.3 mA (min. achievable)

≡ Difference may be easily explained with 'known' IS drift

Measurements for case studies B & C

- IS and LEBT settings same as Cases B & C measurements on earlier slides
  - Except for steering
  - Measured Twiss parameters before RFQ installation are not "matched" to the RFQ's
- "Low emittance" beam (Case C) transmission is ~5% *higher* than the "High emittance" beam (Case B)
  - Data from 6/10/16
  - Mismatch is supposed to be the same
  - Best 'operational' settings were 15-20% higher !!
    - Not optimal steering for either case ?
- Quad scans in MEBT (7/18/16 & 7/19/16) do not indicate that the emittance out of the RFQ is different between cases B and C

Conclusions

- Nominal settings obtained from LEBT commissioning are virtually the same as the settings that presently give best transmission through the RFQ
  - Measurements (beam size, emittance) taken before the RFQ installation indicate that the transport scheme with un-neutralized section is realized
    - At least qualitatively (i.e. trends), there is good agreement between simulations and measurements

- Transmission measurements of the case studies do not contradict conclusions from LEBT commissioning
  - Present quality/stability of the measurements (e.g.: toroids) does not allow to be more quantitative

References

- "Low Emittance Growth in a LEBT with Un-neutralized Section", IPAC 2016 paper (http://accelconf.web.cern.ch/AccelConf/ipac2016/papers/tupmr033.pdf) and poster presentation
- "Scheme for Low Energy Beam Transport with a non-neutralized section", arXiv:1504.06302 (https://arxiv.org/abs/1504.06302)
- PIP-II Technical Meeting, "LEBT Commissioning Update", March 24, 2015

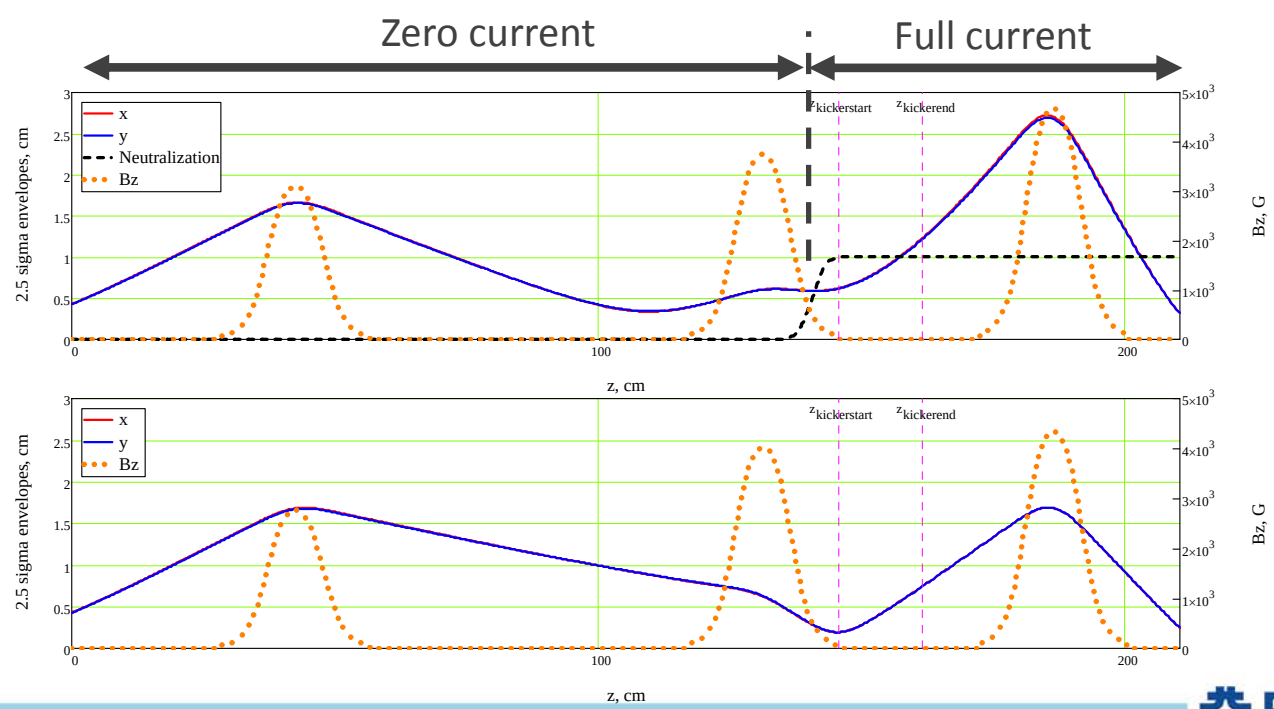
Additional slides

Maximum vs. partial neutralization transport schemes

- Beam potential profile along the beam line tailored by means of biasing electrodes (located in solenoids #1 and #2, a.k.a. EID #1 & #2), the kicker plate and/or an additional electrode downstream (EID #3 or LEBT scraper)
  - Maximum neutralization: EID #1 @ +50V, EID #2 and kicker plate grounded, EID #3 or LEBT scraper @ +50V
  - Partial neutralization: EID #1 & #2 @ +50 V, kicker plate at -300 V, EID #3 or LEBT scraper positively biased or grounded

Partial neutralization scheme

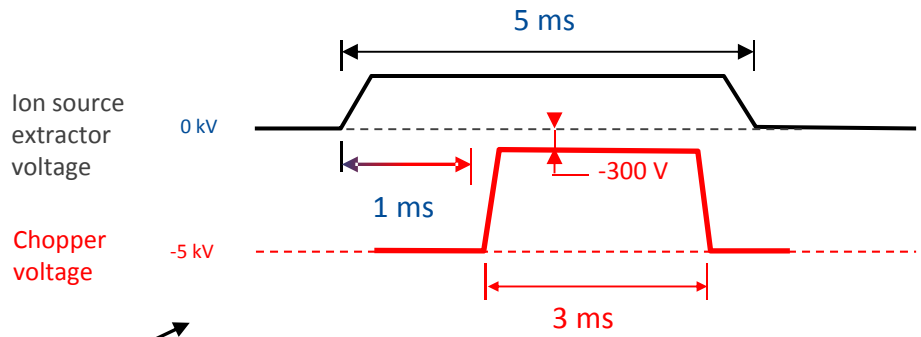
Complete neutralization transport

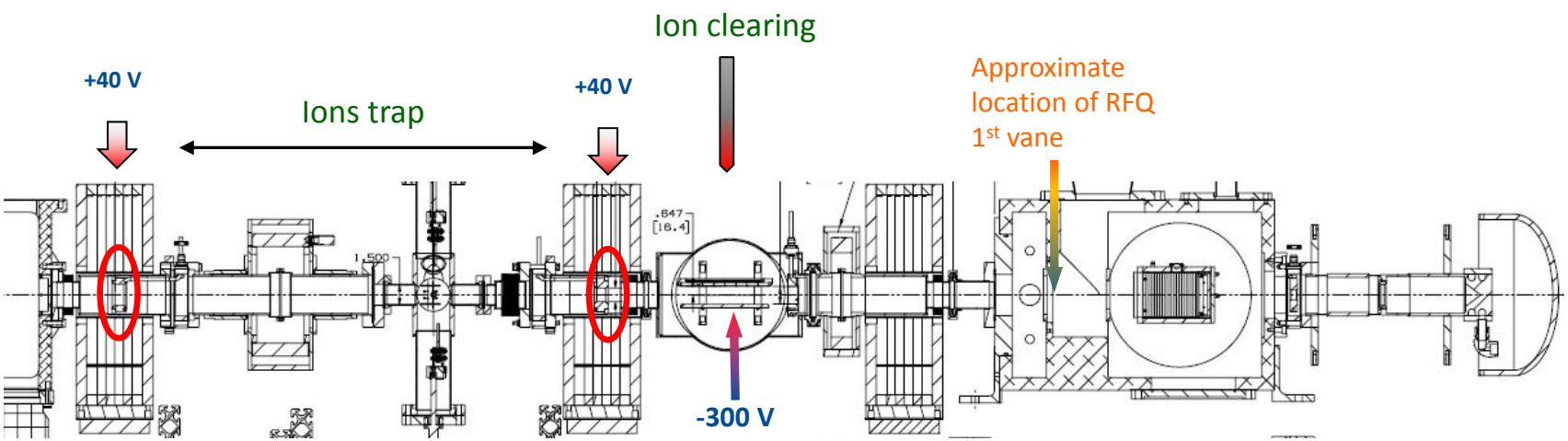


For illustration only

Space-charge 'enhanced' configuration (i.e. partial neutralization scheme)

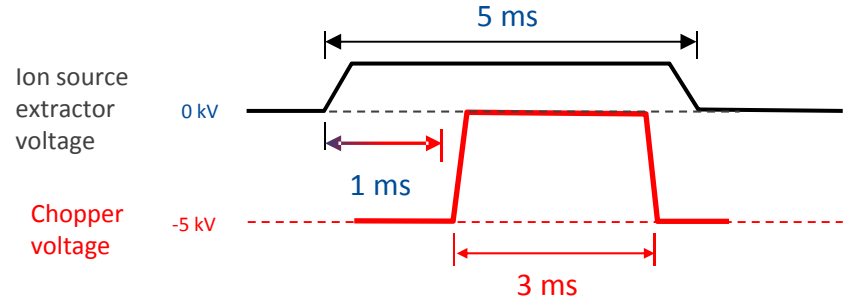
- Positive biasing of electrically isolated diaphragms to contain ions
- Clearing field at the chopper
- Vacuum downstream of solenoid #2: low 10^{-7} torr
- Chopped beam

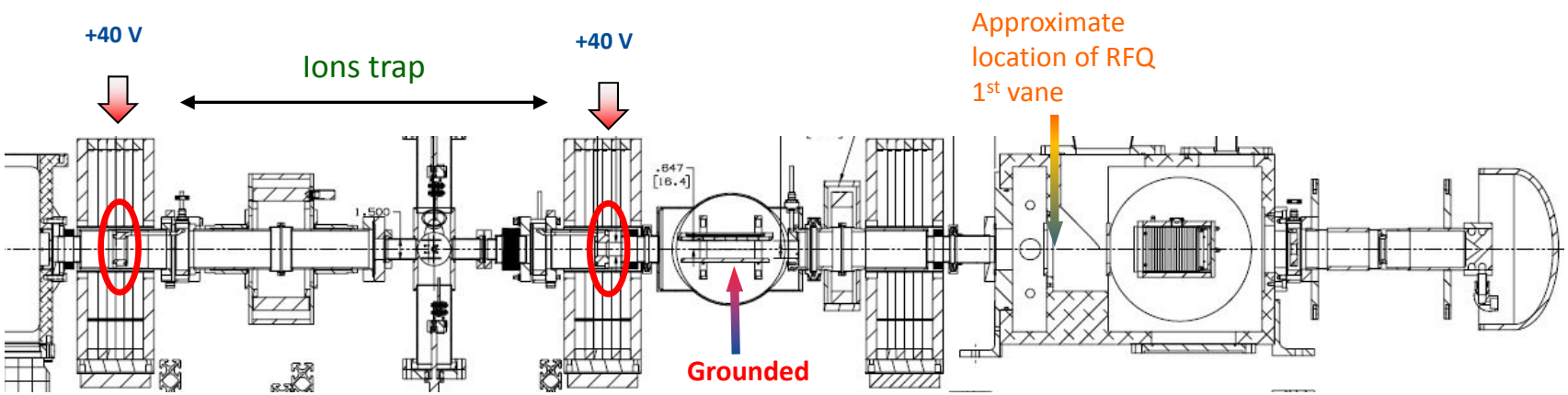


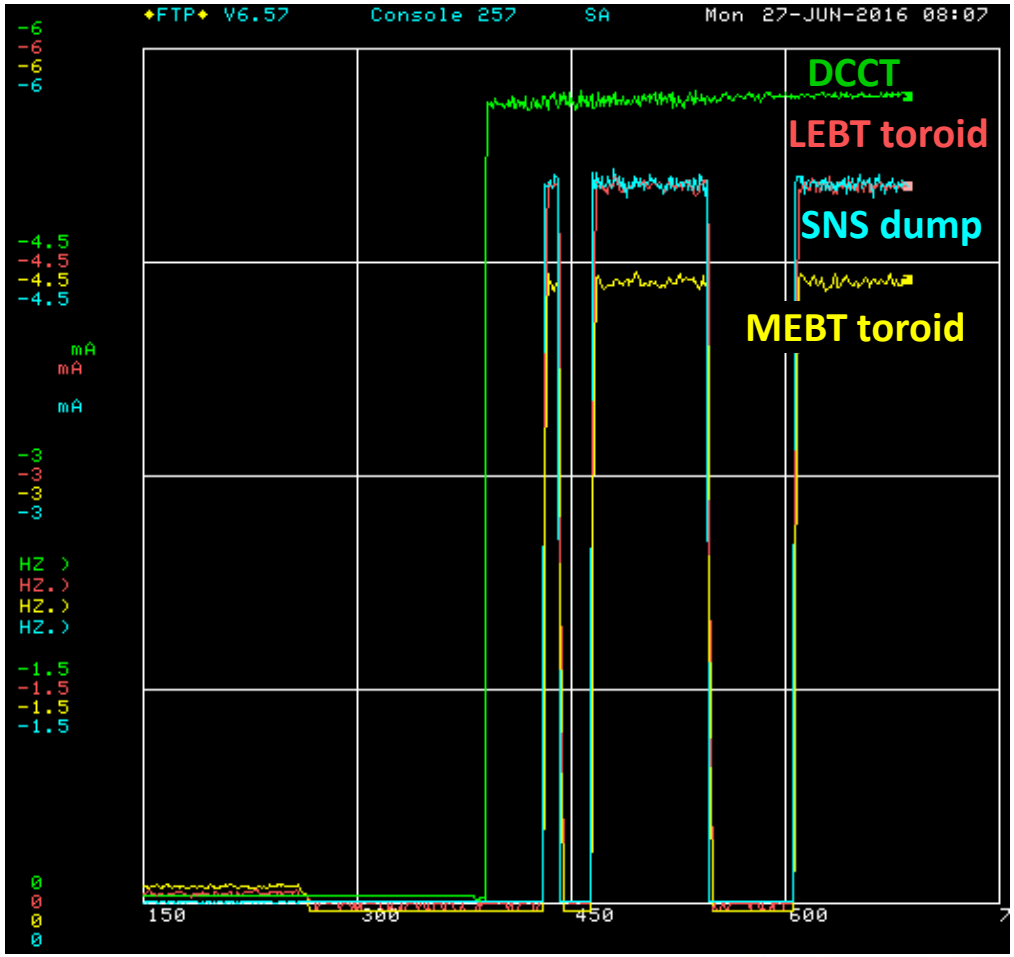


Configuration without ion clearing (i.e. maximum neutralization scheme

- Positive biasing of electrically isolated diaphragms
- No DC offset at the kicker plate
- Chopped beam





Relative transmission measurements

- Various issues with instrumentation *currently* prevent absolute measurements to better than 10-20%
  - $I_{SNS\ dump} > I_{MEBT\ toroid}$!!
  - Relative measurements are sufficient for optimization of the optics and trajectories