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Chopping High-Intensity Ion Beams at FRANZ

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Outline

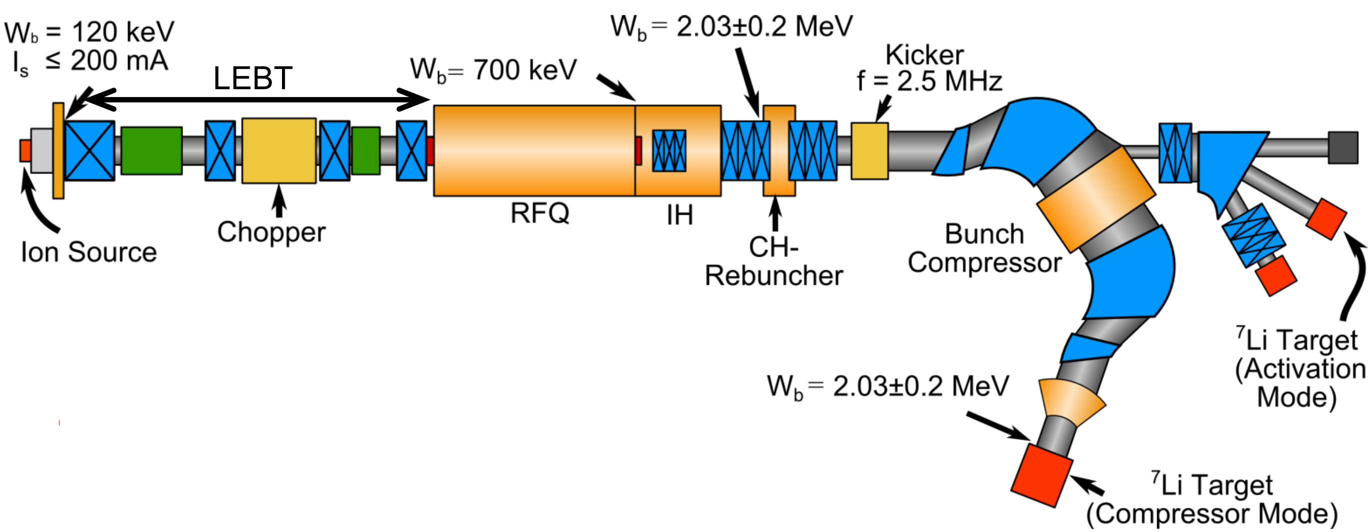
1) Introduction: The FRANZ facility

2) Chopper System
   a) E×B Chopper Concept
   b) Numerical Simulations
   c) Experimental Results

3) Conclusion

Introduction: FRANZ

Frankfurt Neutron Source FRANZ



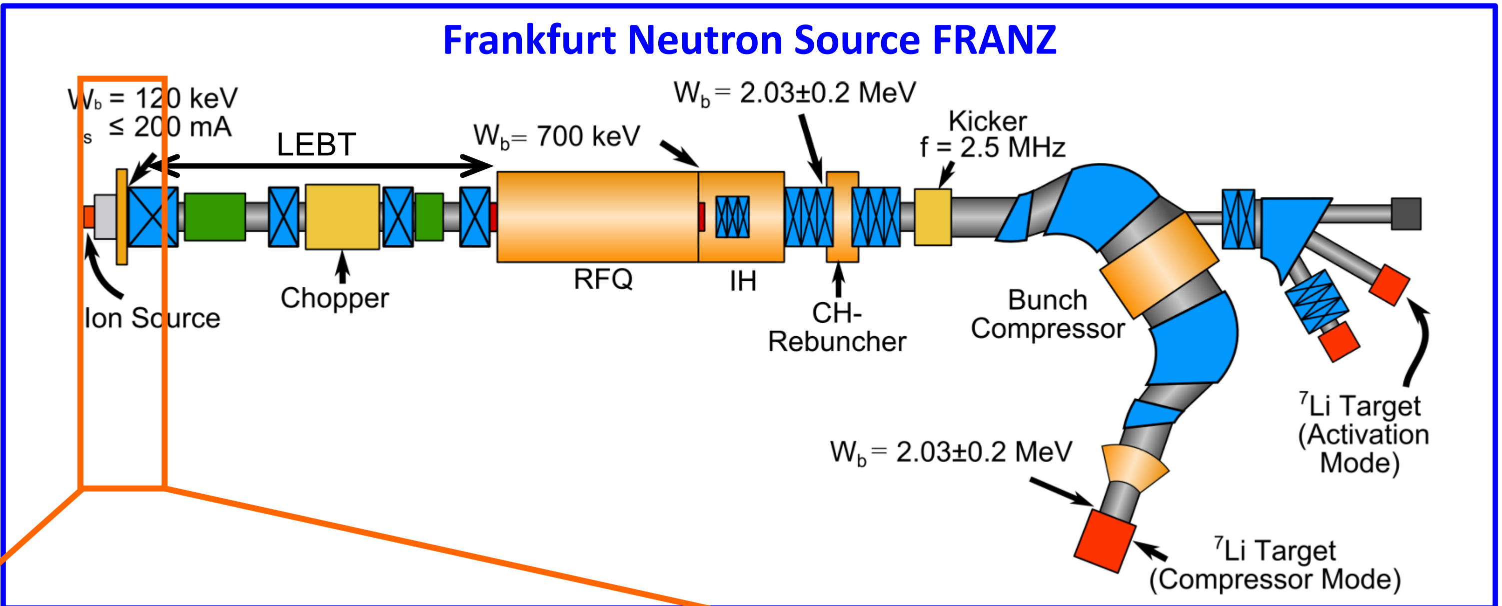
Goal (*Compressor Mode*):

- Deliver a high (peak) neutron flux,
- produced via the $^{7}Li(p,n)^{7}Be$ reaction,
- for the energy-dependent measurements of n-capture cross sections (using TOF).

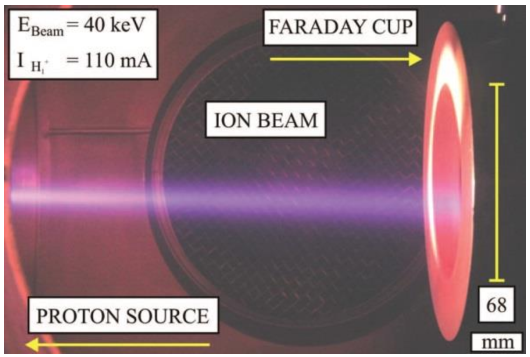
This requires a primary proton beam

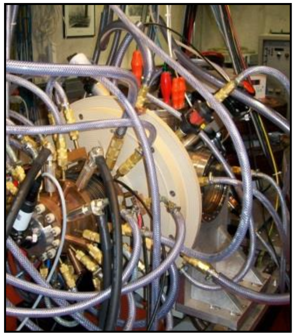
- with high intensities (50-200 mA),
- at 2 MeV beam energy,
- with a challenging time structure (1 ns, 257 kHz).

Introduction: FRANZ



High-Current Ion Source





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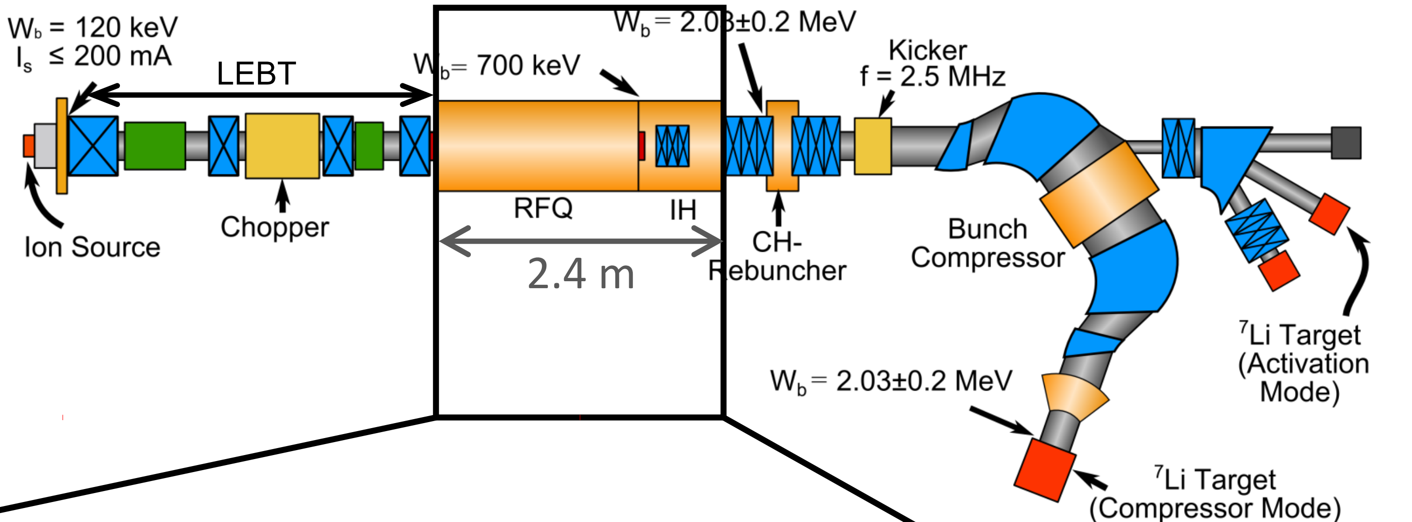
- Arc-discharge driven ion source
- Proton current: 50 mA (240 mA)
- DC operation
- Proton fraction > 90 %
- Beam energy: 120 keV
- Triode extraction system

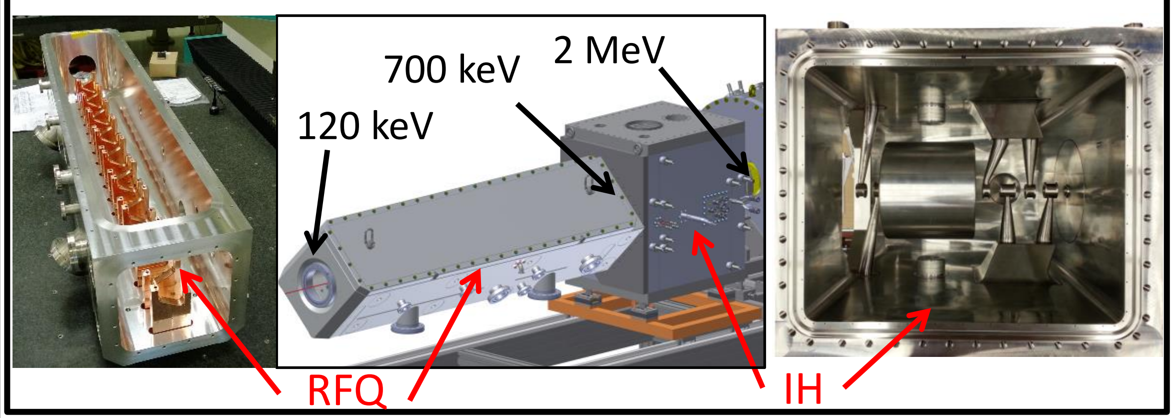
B. Klump et al., LINAC'14, MOPP063

Introduction: FRANZ

Frankfurt Neutron Source FRANZ



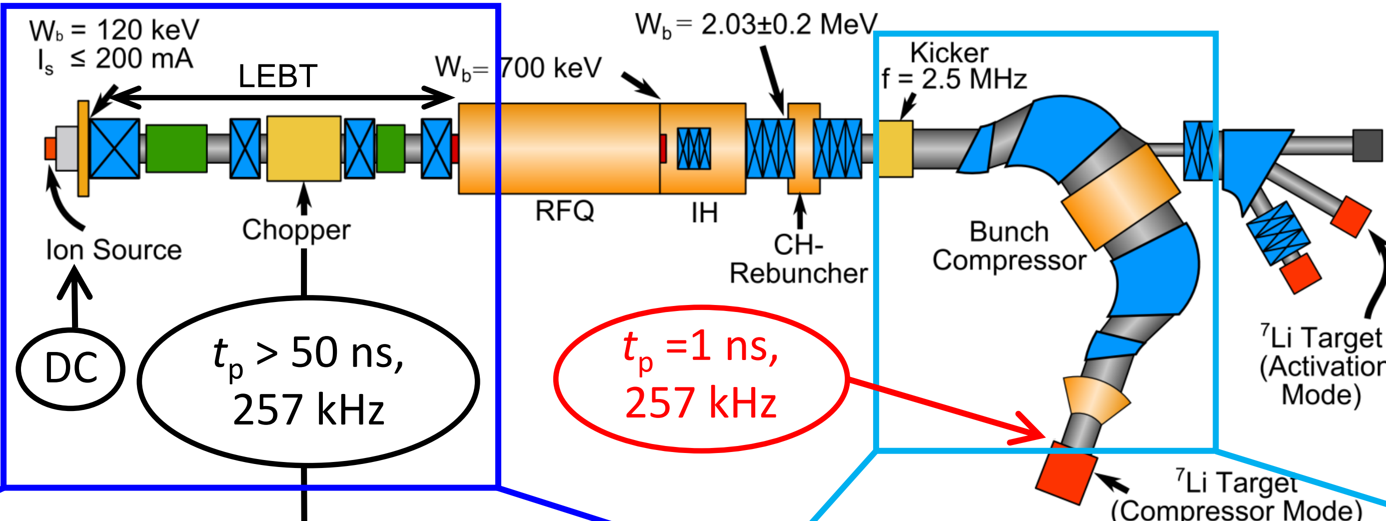
2 MeV Linac Section



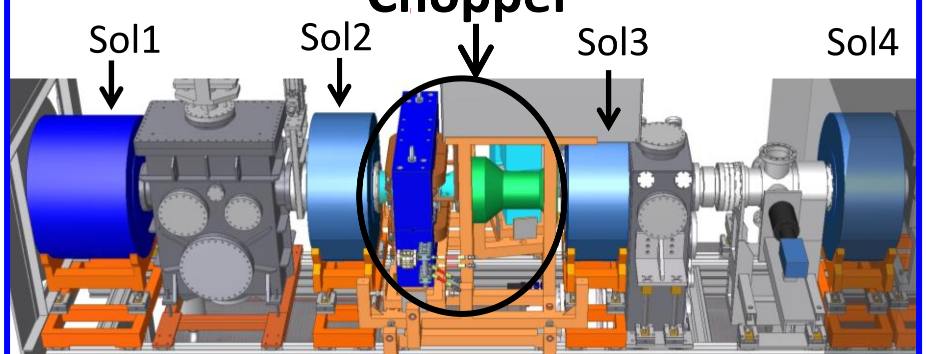
- CW operated
- f_{rf} = 175 MHz
- RFQ under construction
- IH to be copper plated
- RFQ test module tested with P_{rf} ≈ 115 kW/m

Introduction: FRANZ

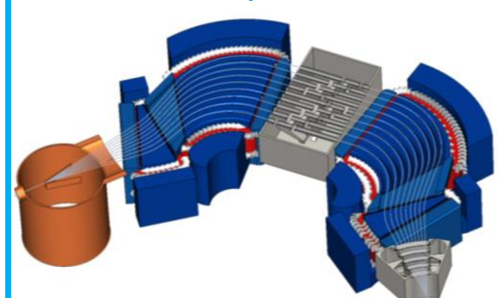
Frankfurt Neutron Source FRANZ



LEBT Section



Bunch Compressor



- Mobley Type
- Electric Kicker (f = 2.5 MHz)
- Magnetic Guiding System
- Rebuncher Cavities

L. P. Chau et al., LINAC’10, MOP100

E×B Chopper: Motivation

Requirements: Chopping a dc beam at
– *low energy* (120 keV)
– *high intensity* (50 mA)
– *high repetition* rate (257 kHz),
– *producing a short beam pulse:* 50 ns / 3.9 μs.

Electric Deflection

Disadvantages: Risk of voltage breakdowns, especially at high beam intensities and especially for high duty cycles for the electric deflection field.

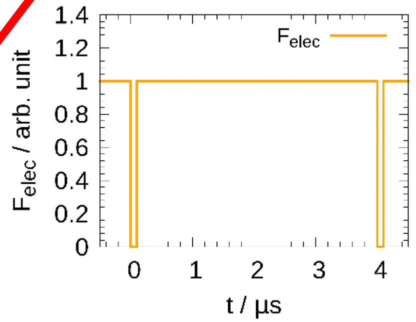
Magnetic Deflection

Disadvantages: High power consumption, especially at high repetition rates.

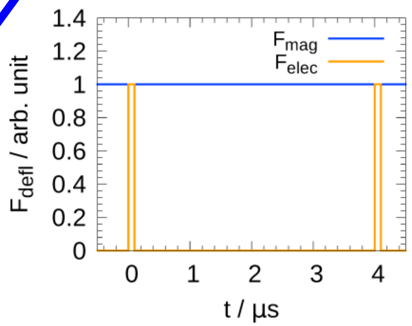
Concept

Combining pulsed electric and static magnetic deflection in an E×B (Wien-filter) field configuration.

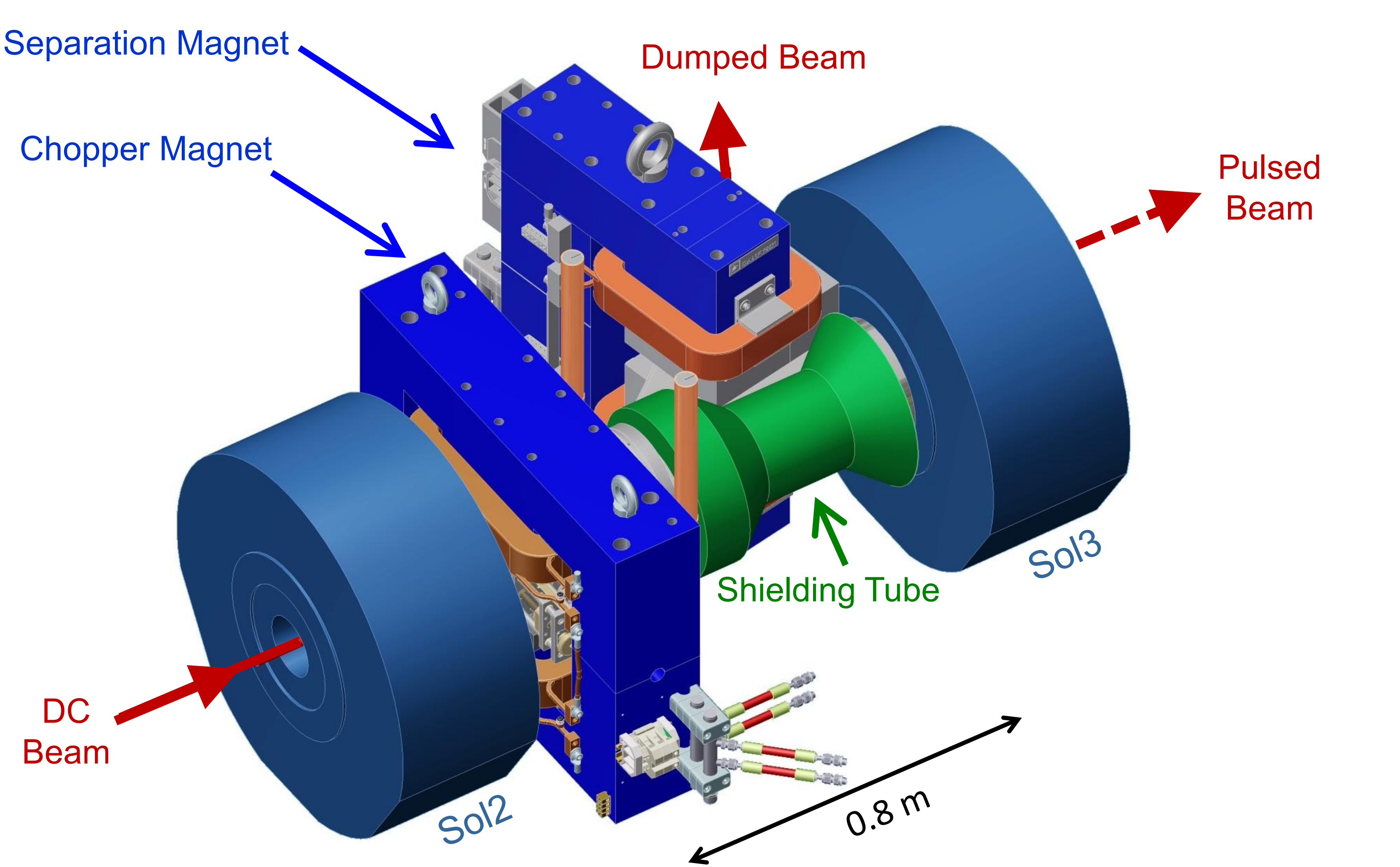
High duty cycle for electric field.



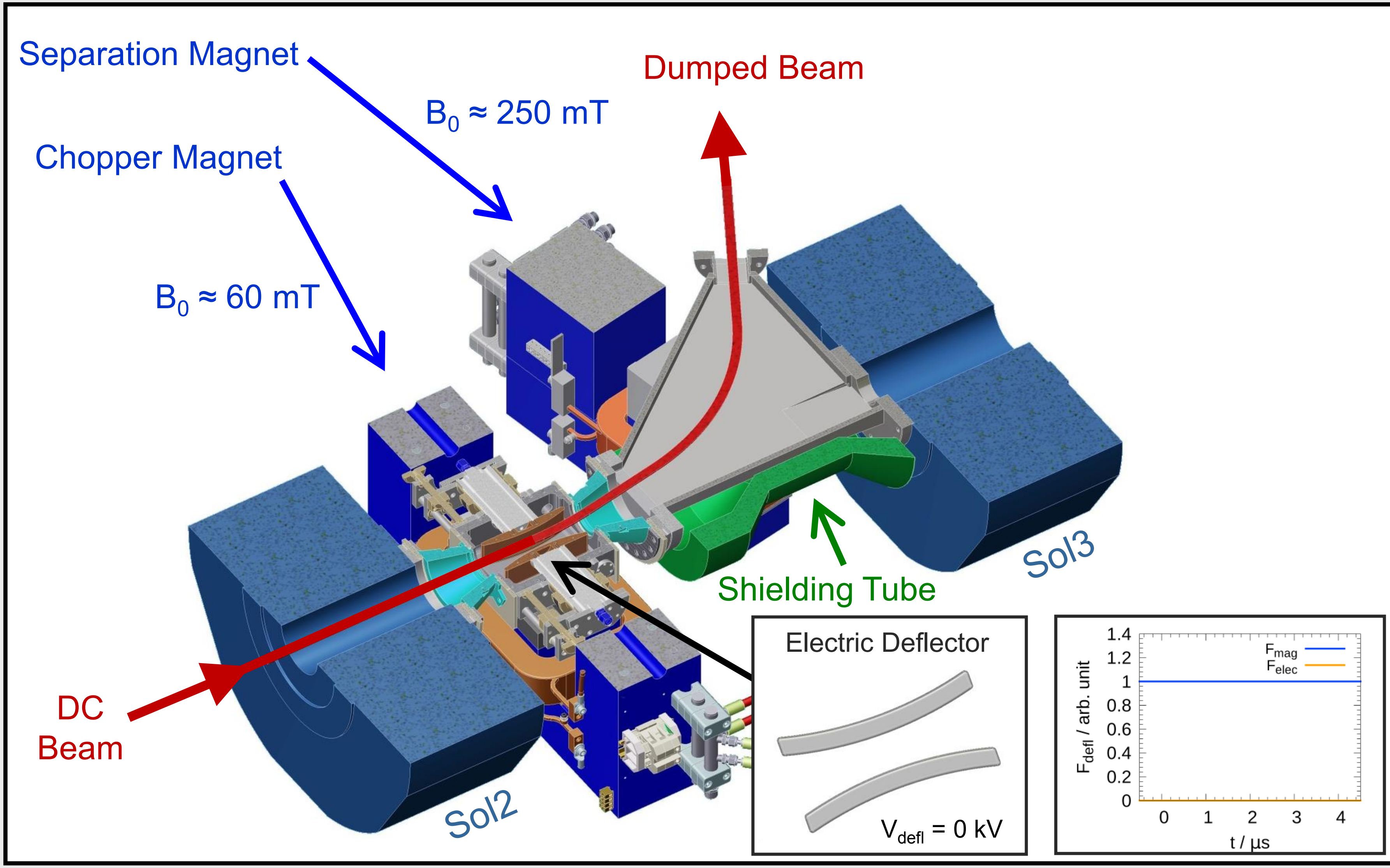
Low duty cycle for electric field.



E×B Chopper: Concept

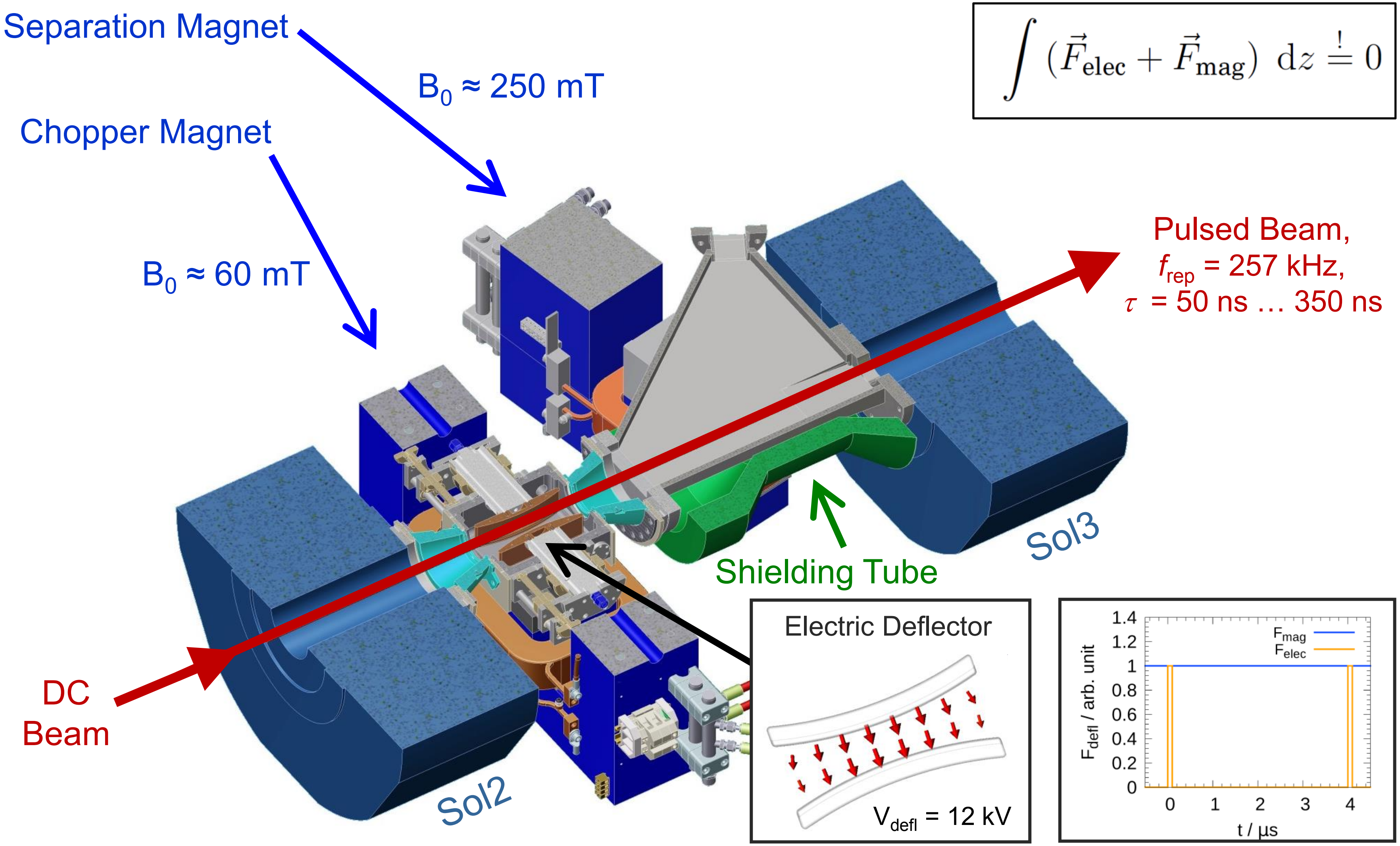


E×B Chopper: Concept



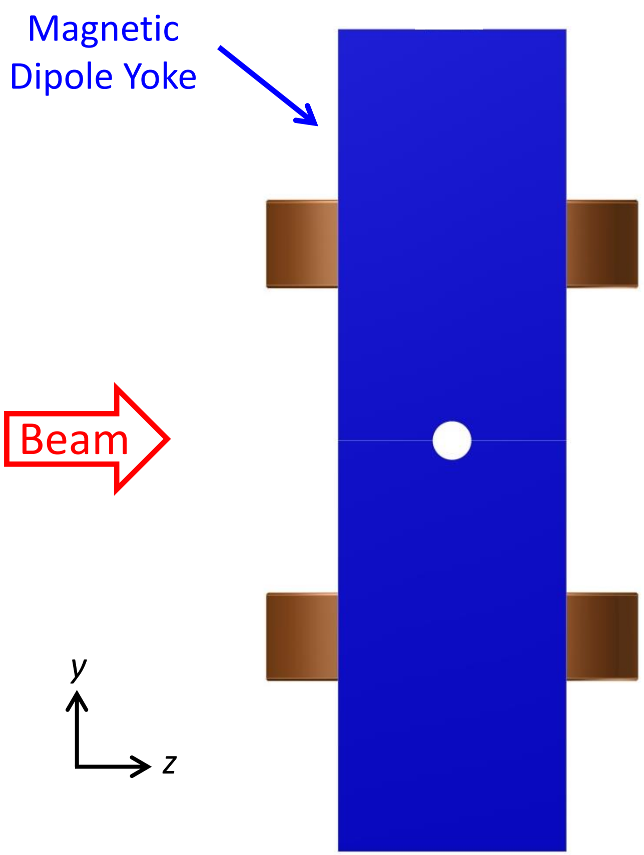
E×B Chopper: Concept

$$\int \left(\vec{F}_{\rm elec} + \vec{F}_{\rm mag}\right)\, {\rm d}z \overset{!}{=} 0$$



Beam Dynamics in Static E×B Fields

Longitudinal Matching of Deflection Forces



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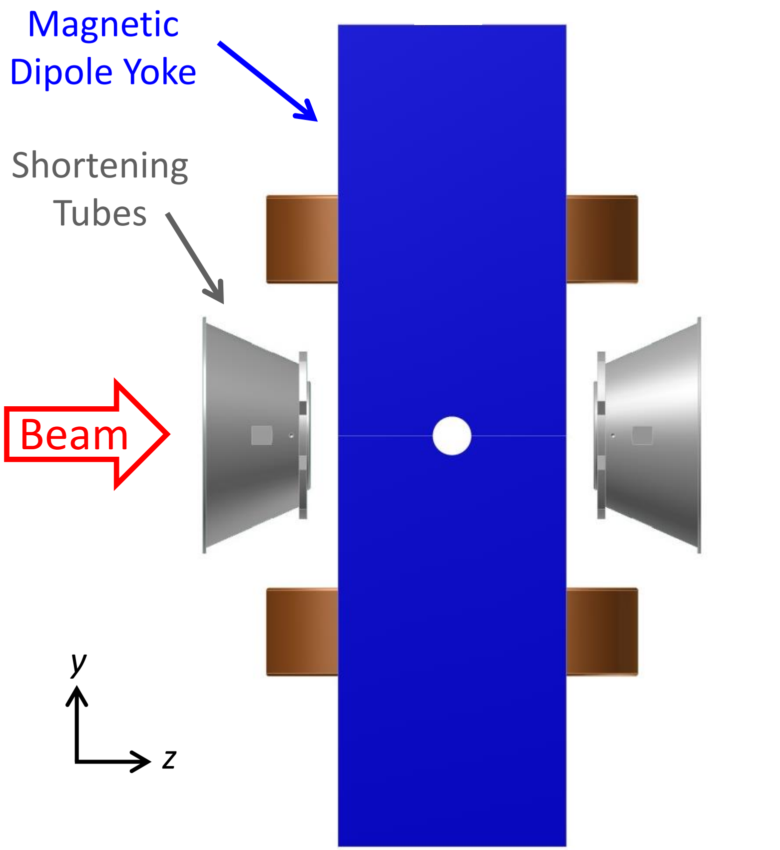

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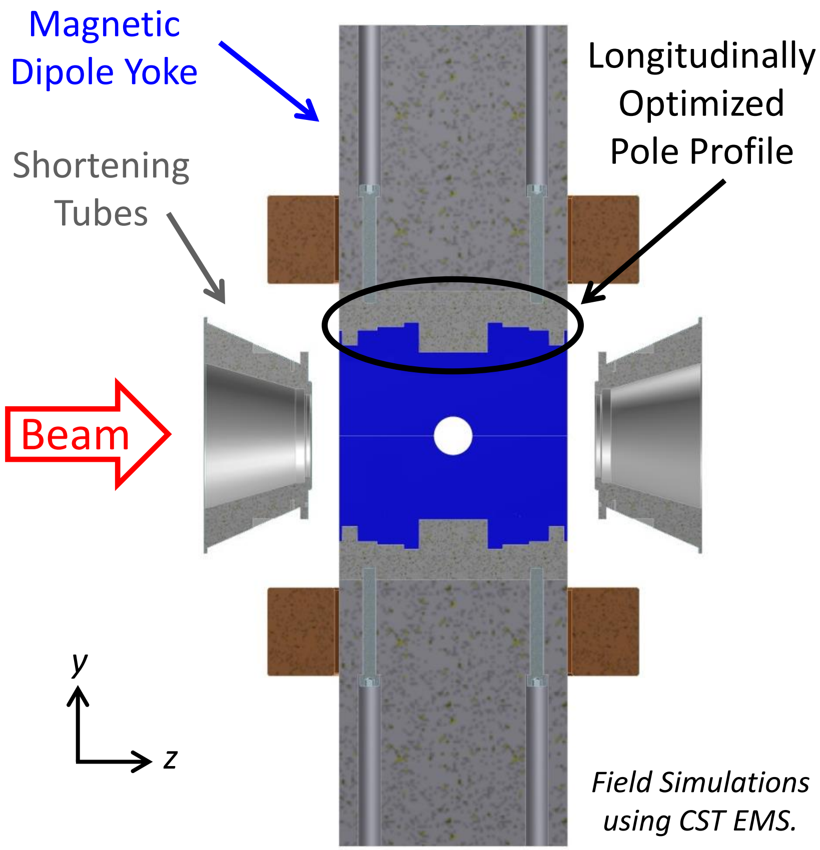
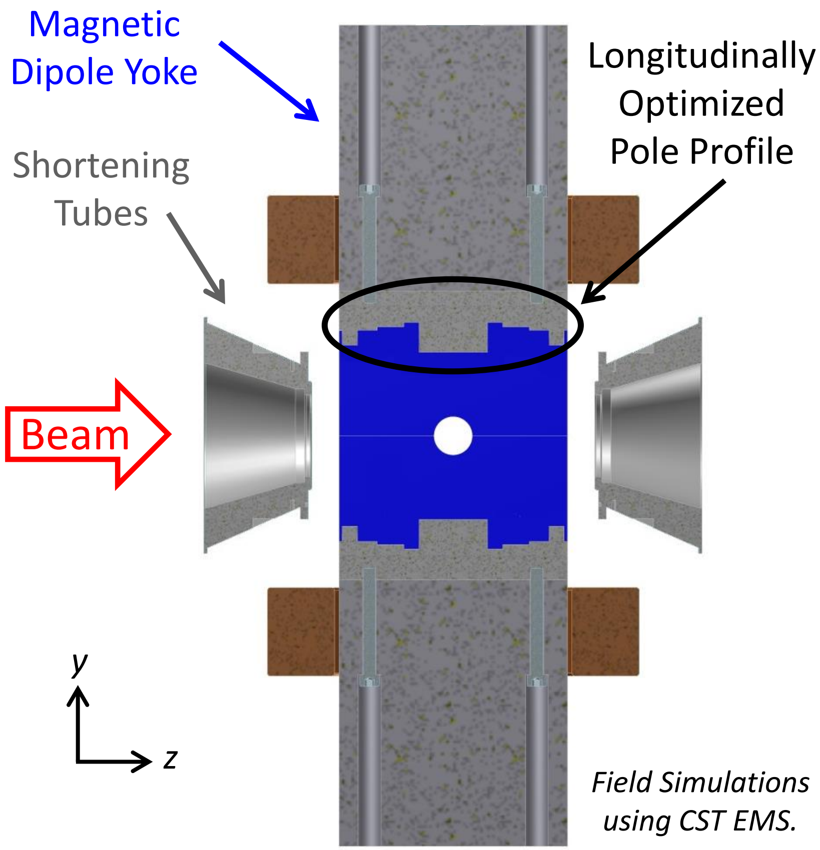


- Minimizing horizontal beam movement
- Minimizing position offset

Transverse Matching of Deflection Forces

Beam Dynamics in Static E×B Fields

Longitudinal Matching of Deflection Forces



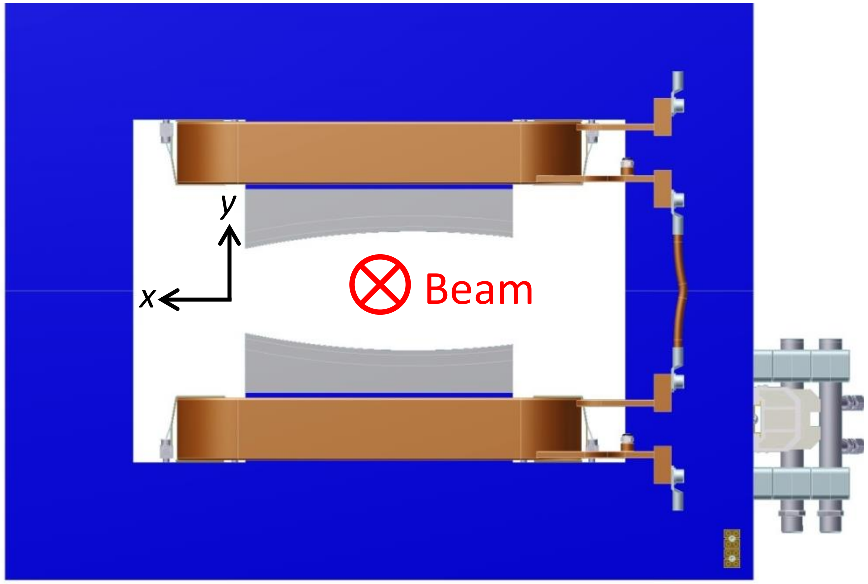
- Minimizing horizontal beam movement
- Minimizing position offset

Transverse Matching of Deflection Forces

Optimized Pole Profile:

$$y(x) = \frac{1}{2} h_{gap} \cdot \frac{1}{\sqrt{1 - b \cdot \frac{E_x}{V_{acc}} \cdot x}} - c \cdot x^2$$

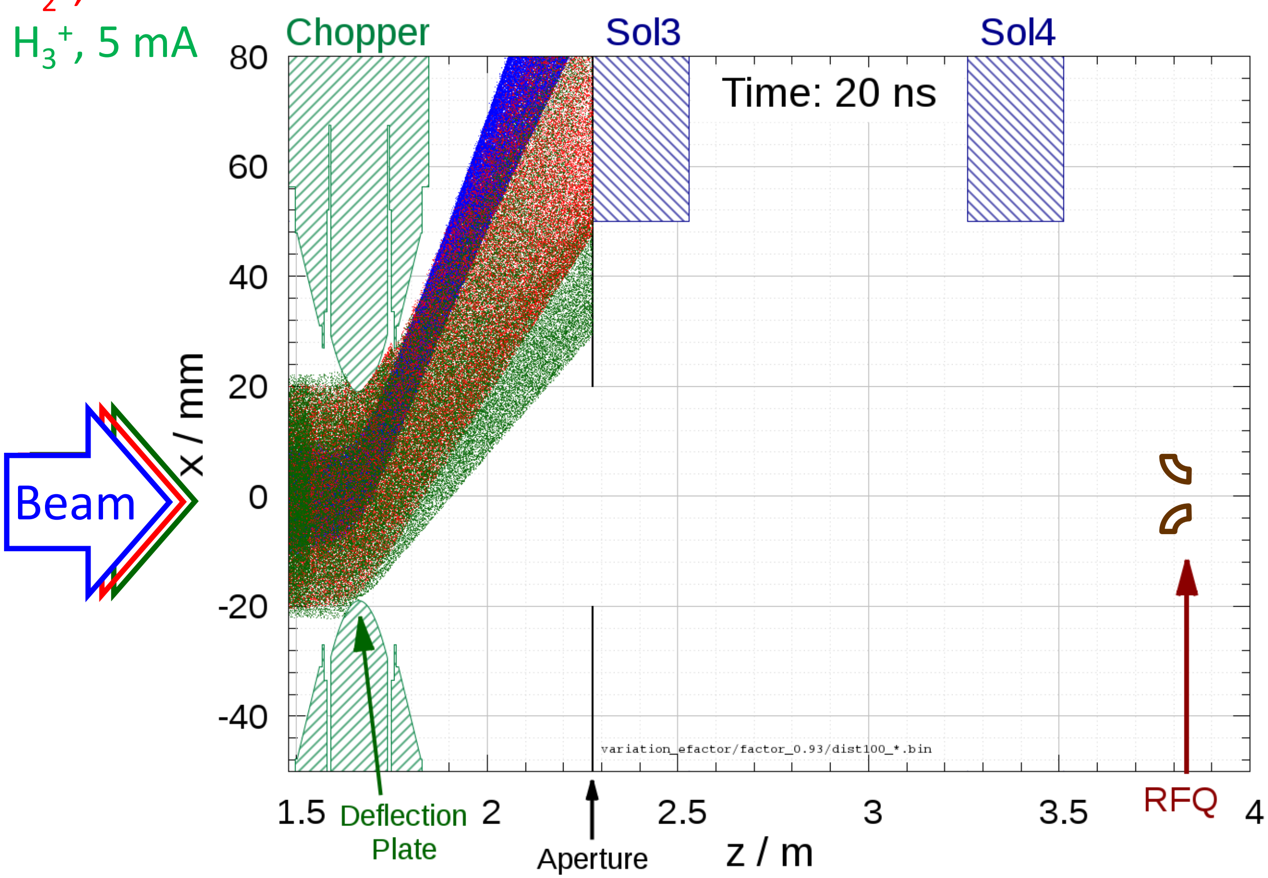
Compensation of Velocity Change; Field Homogenization



- Focusing in both transverse planes
- Preserving cylindrical symmetry

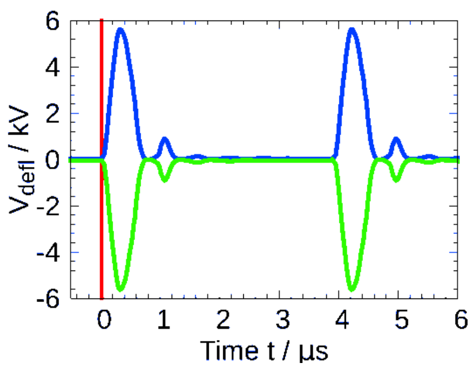
Beam Shaping Simulation

p, 50 mA
H_2^+, 5 mA
H_3^+, 5 mA



Input Data

- W_b = 120 keV
- I_{proton} = 50 mA
- Matched Input Distribution
- 3d *E*-field of deflect. plates
- 3d *B*-field of chopper magnet
- 3d *B*-field of solenoids
- Measured HV Pulse



Beam dynamics calculations using PIC-Code Bender. → D. Noll, LINAC'14, MOPP065.

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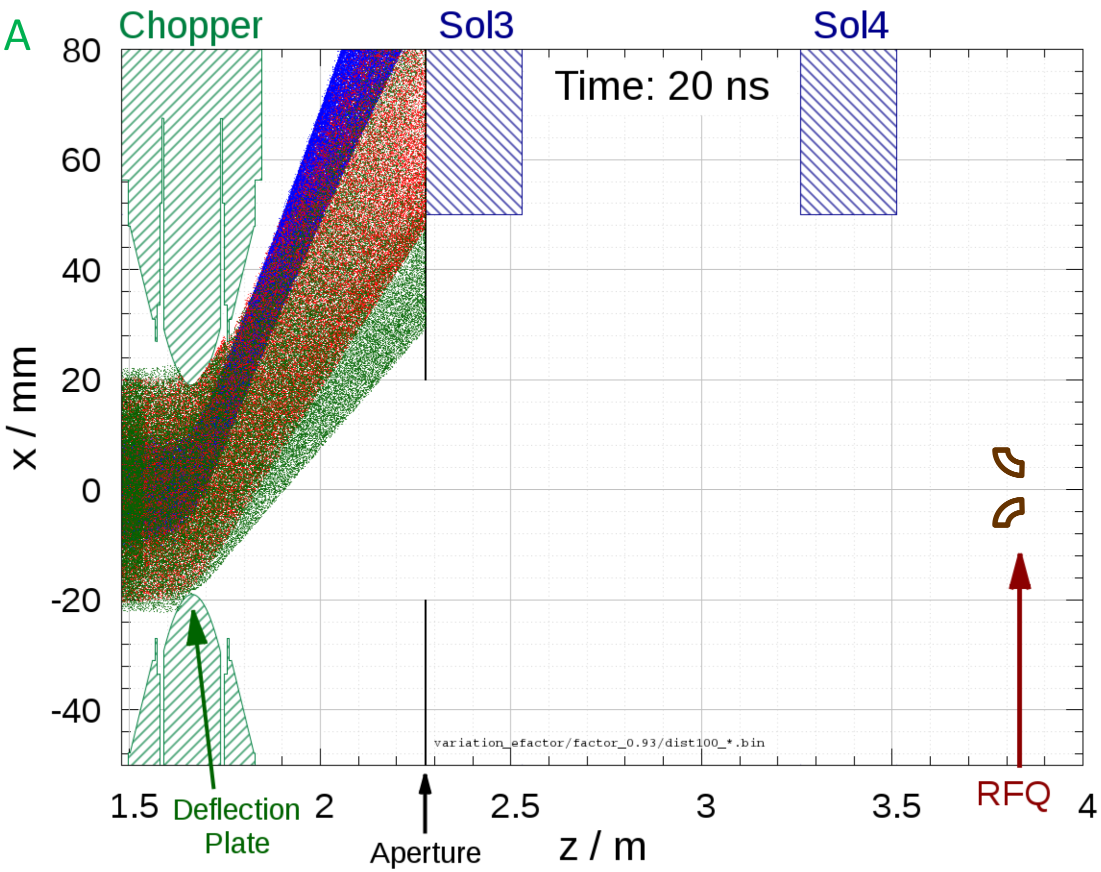
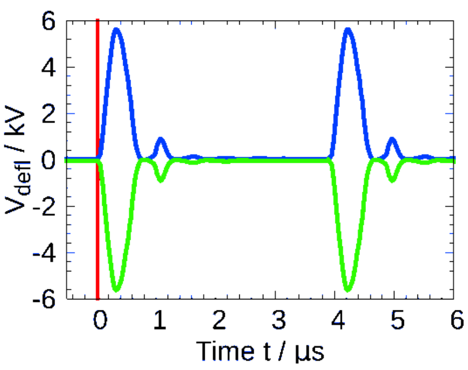


Voltage Pulse



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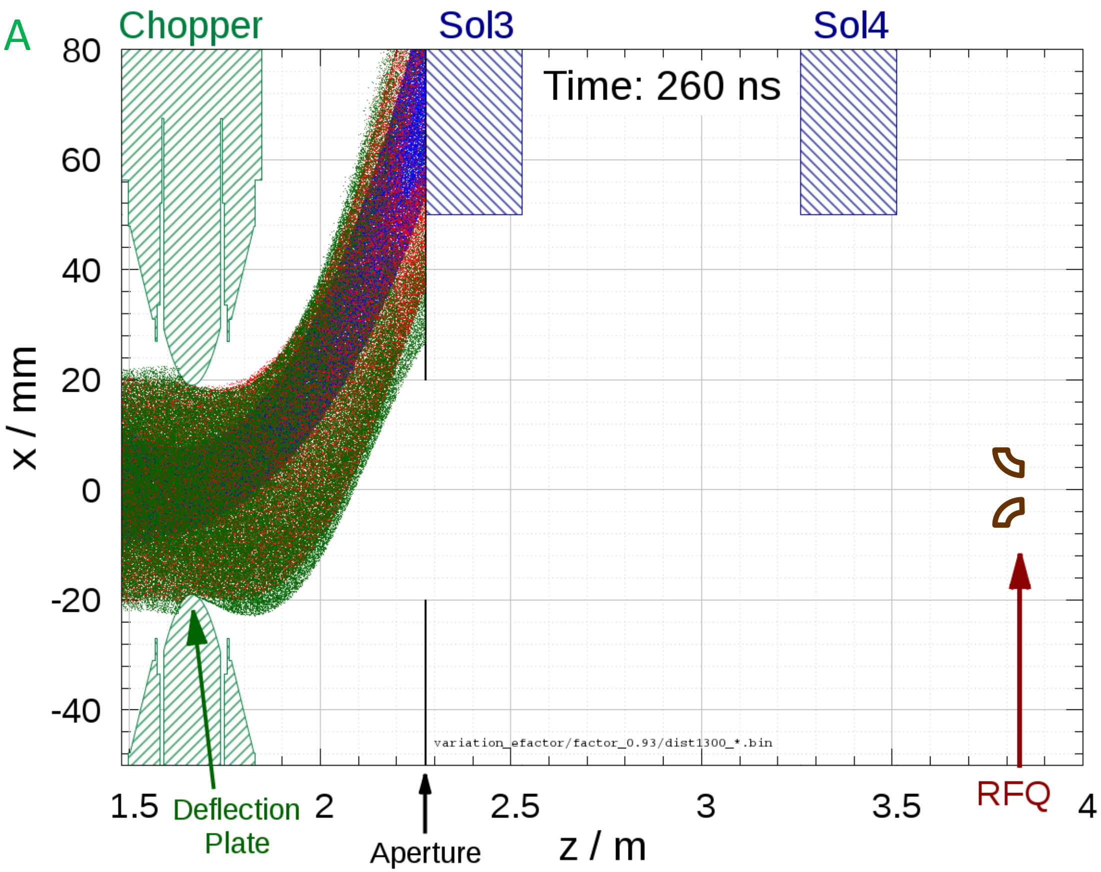

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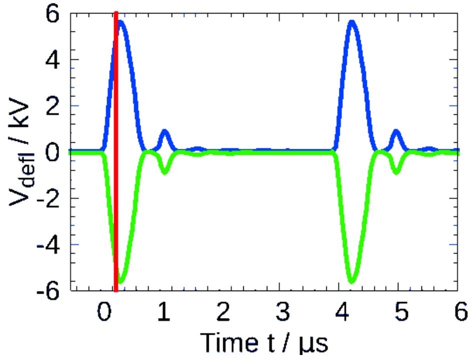

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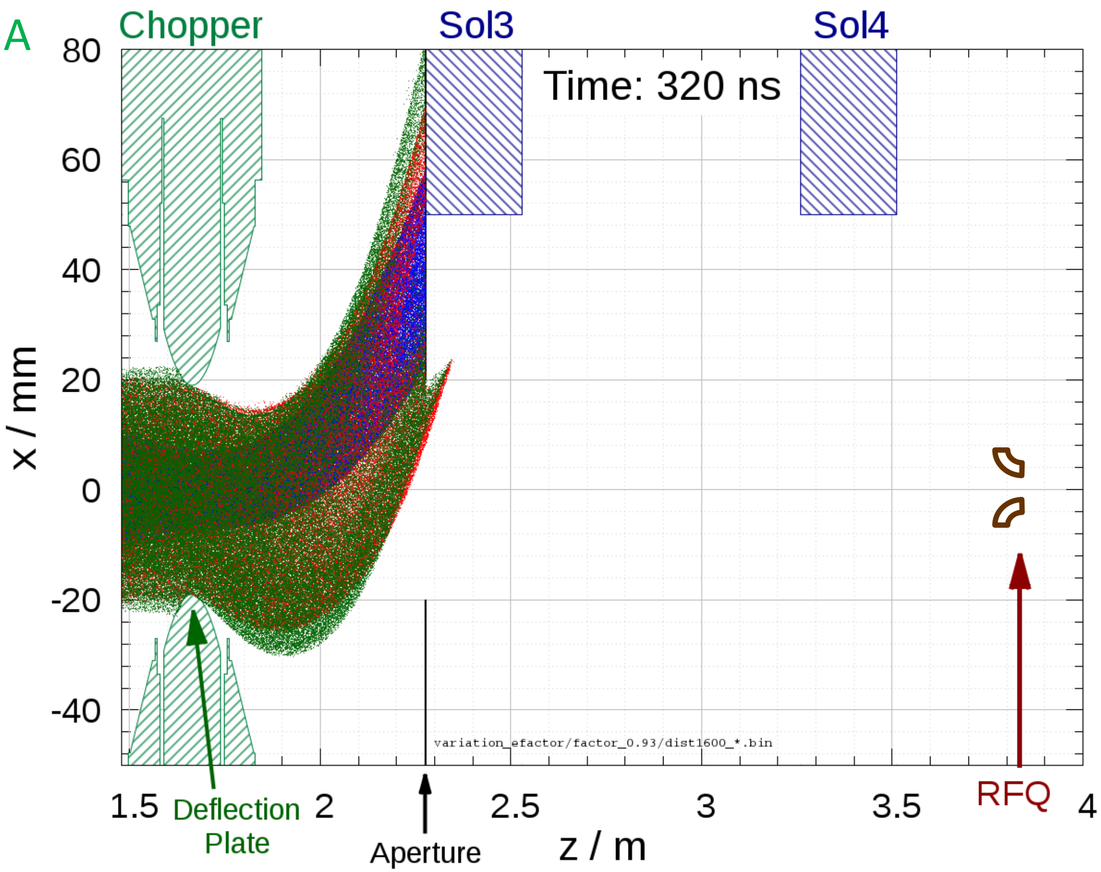

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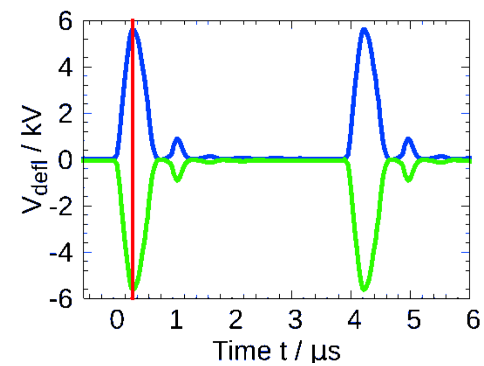

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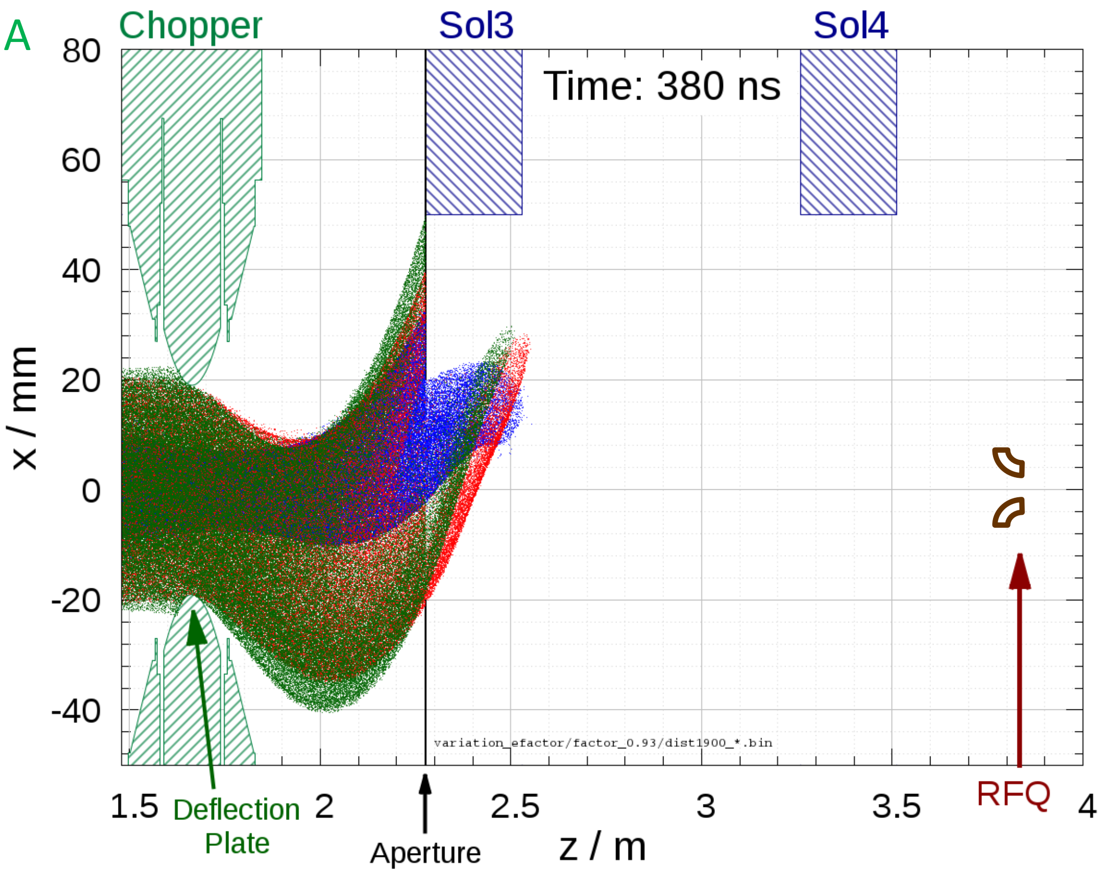

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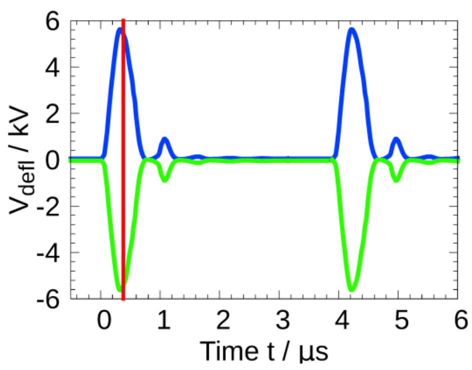

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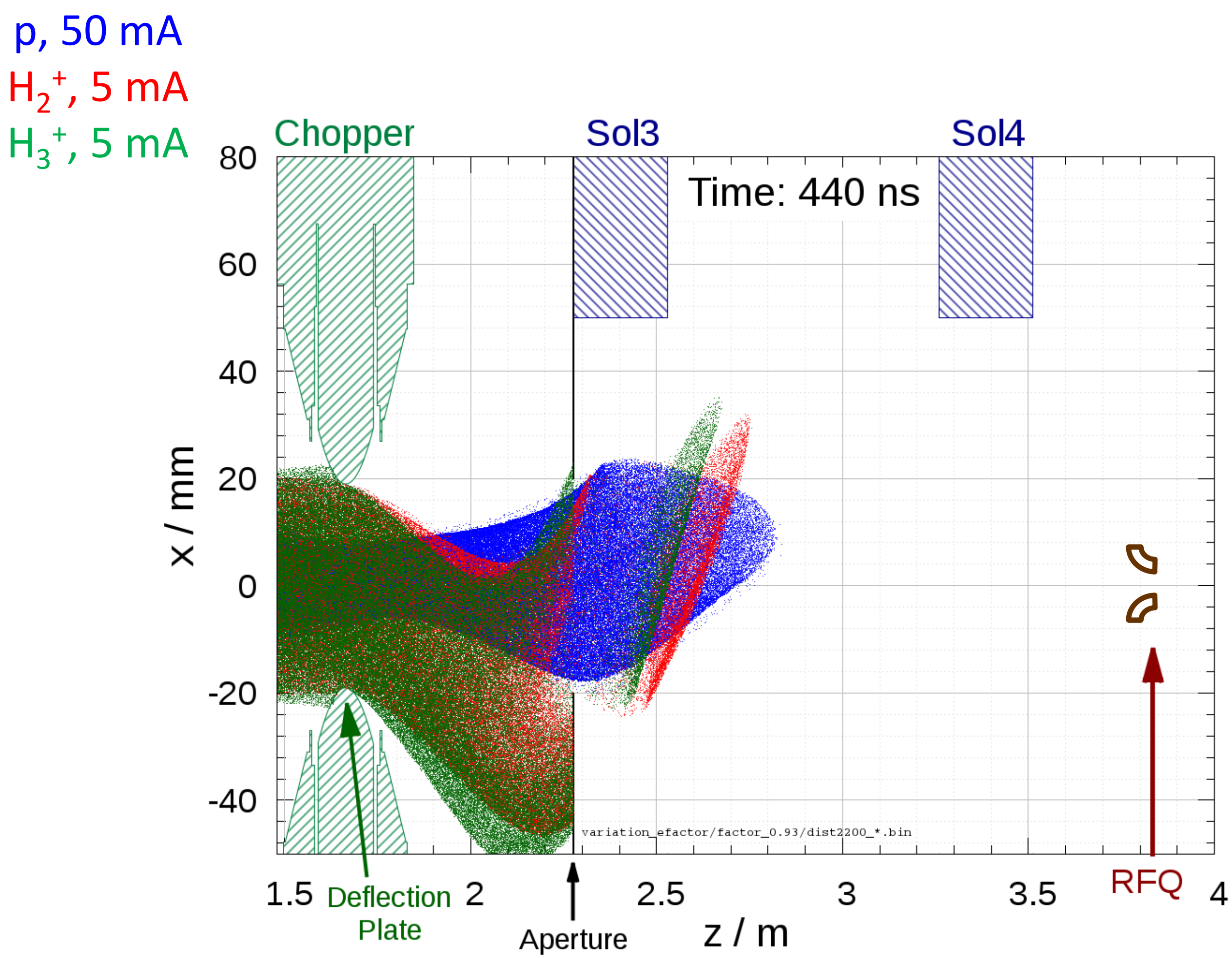

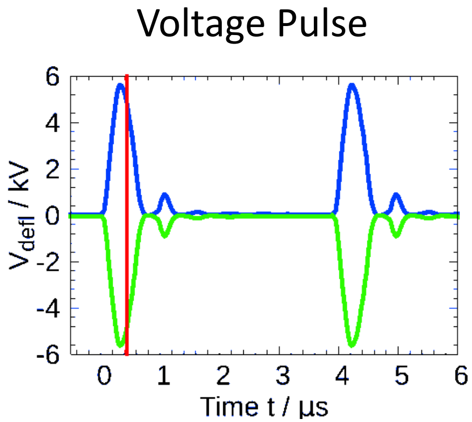

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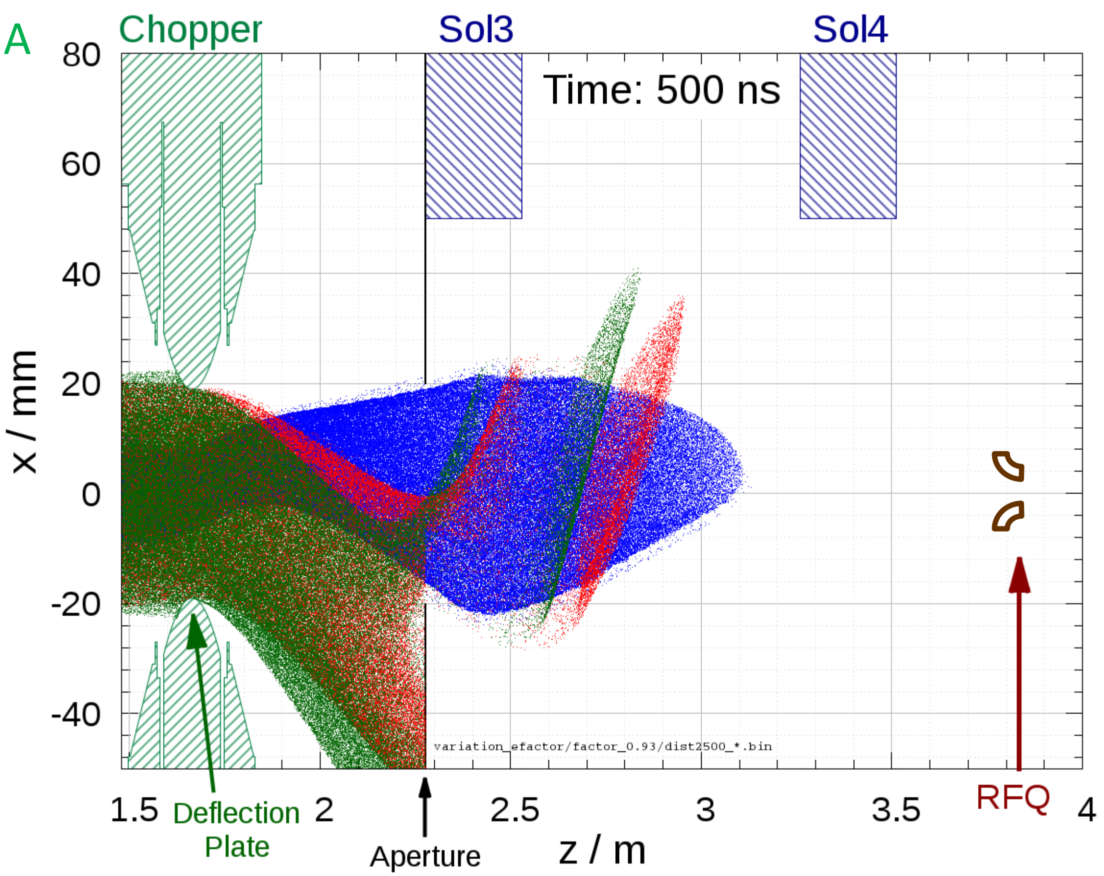

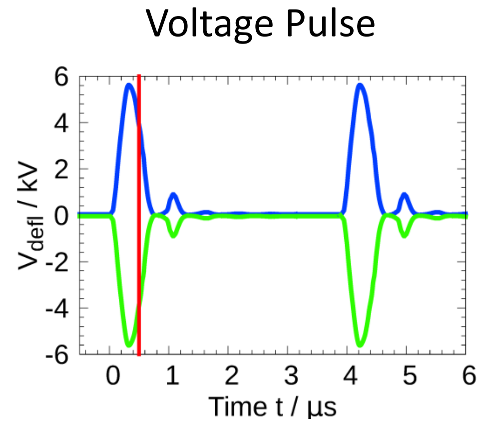

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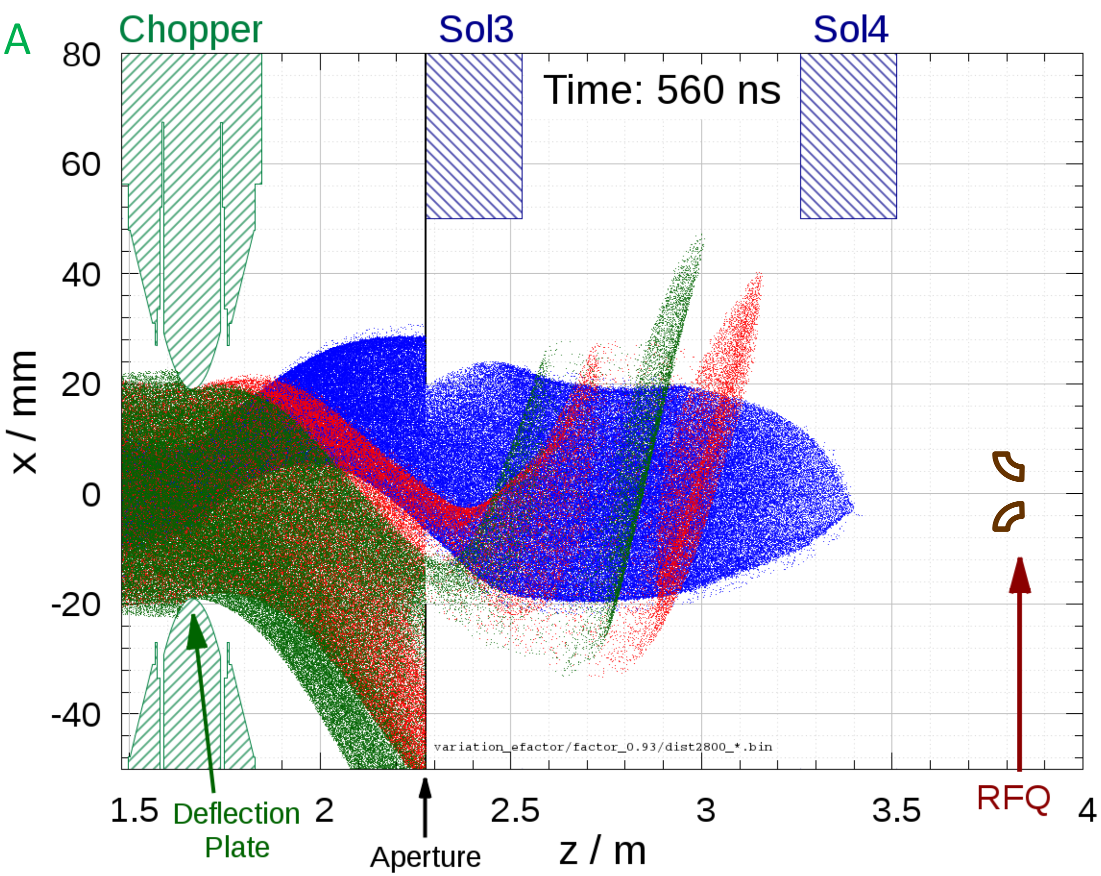

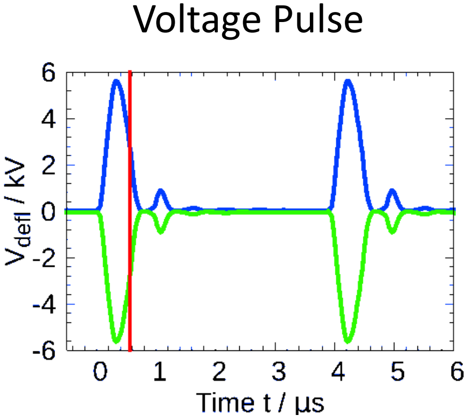

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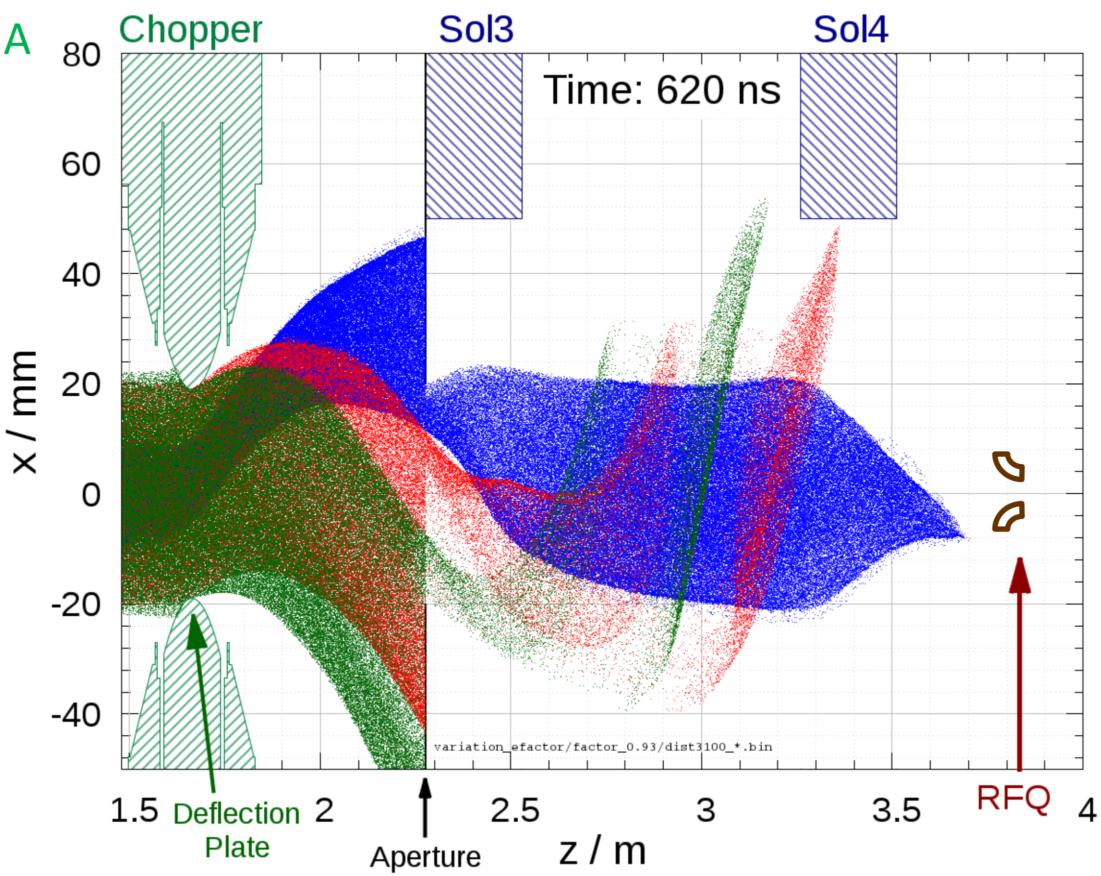
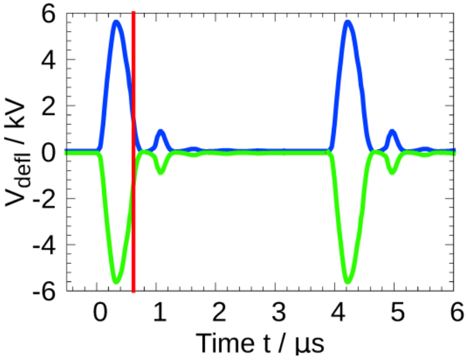


Voltage Pulse



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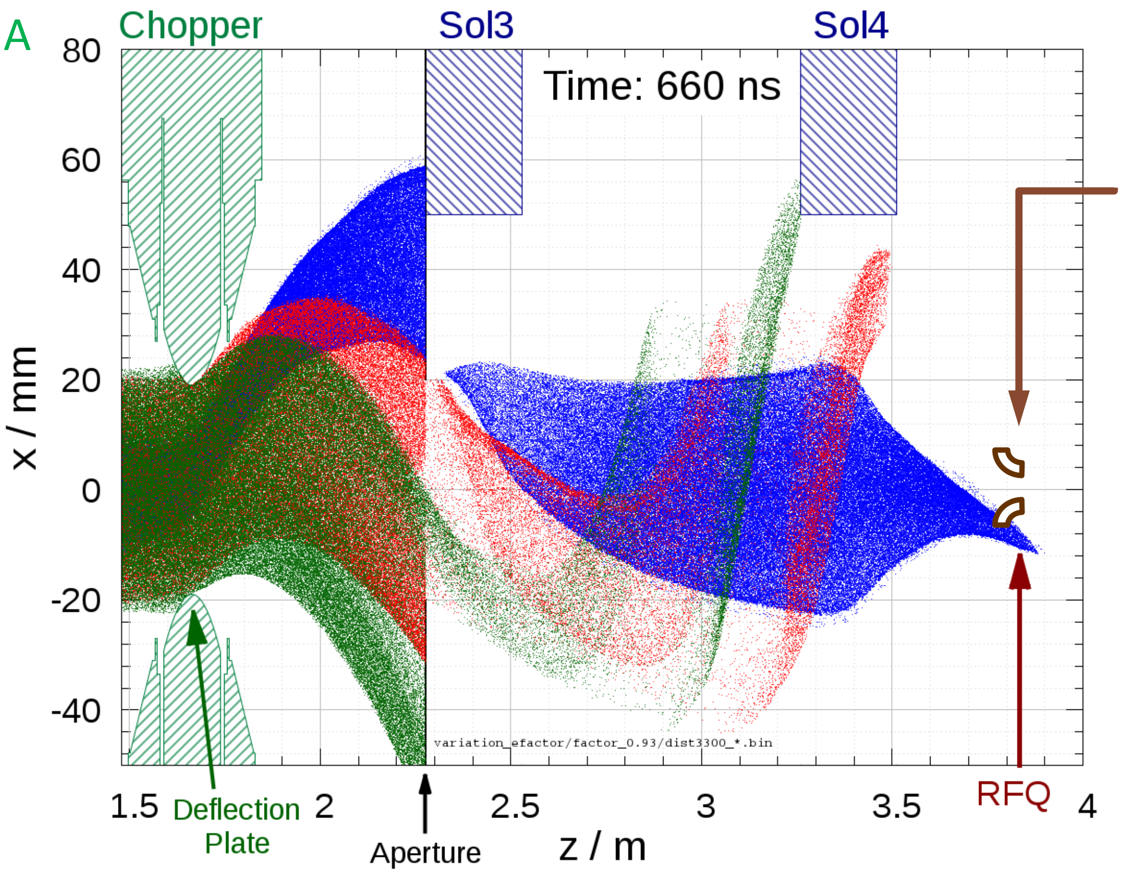

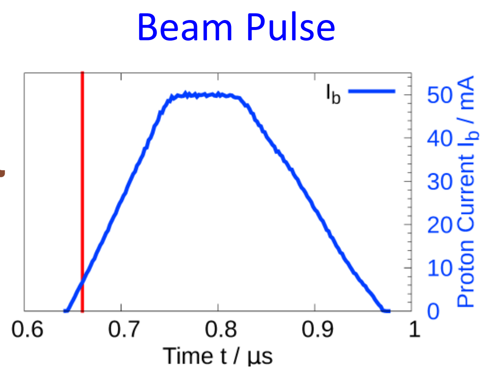

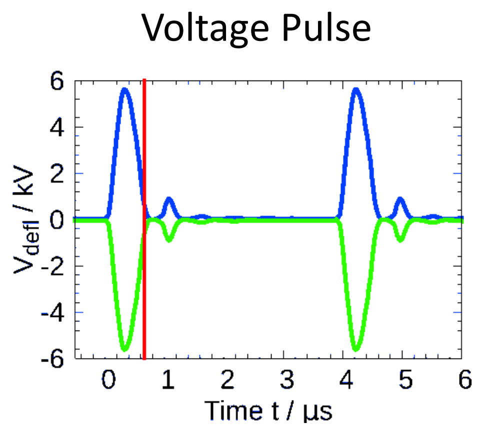

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Beam Shaping Simulation

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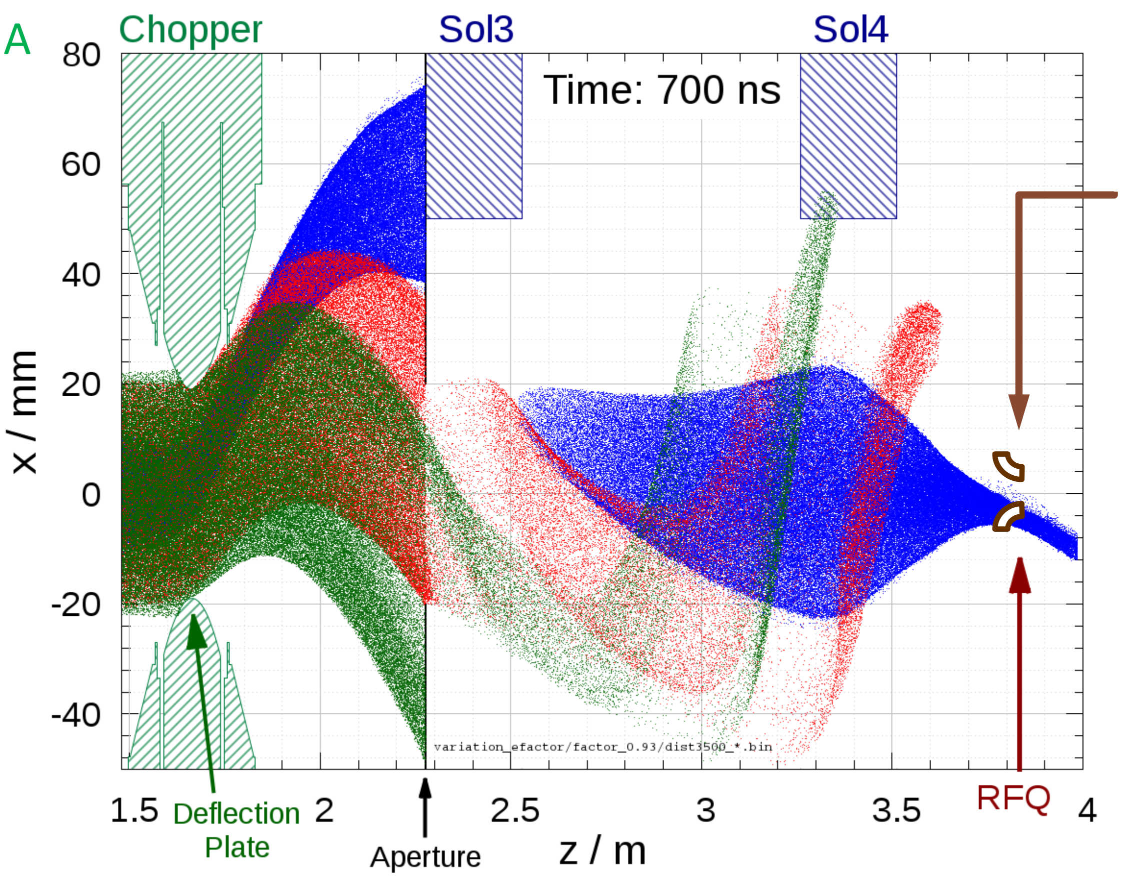

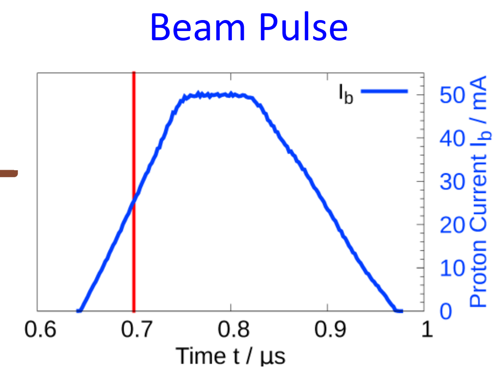

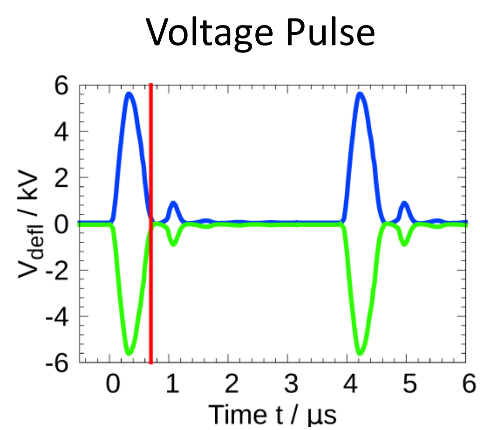

Beam dynamics calculations using PIC-Code Bender.

Beam Shaping Simulation

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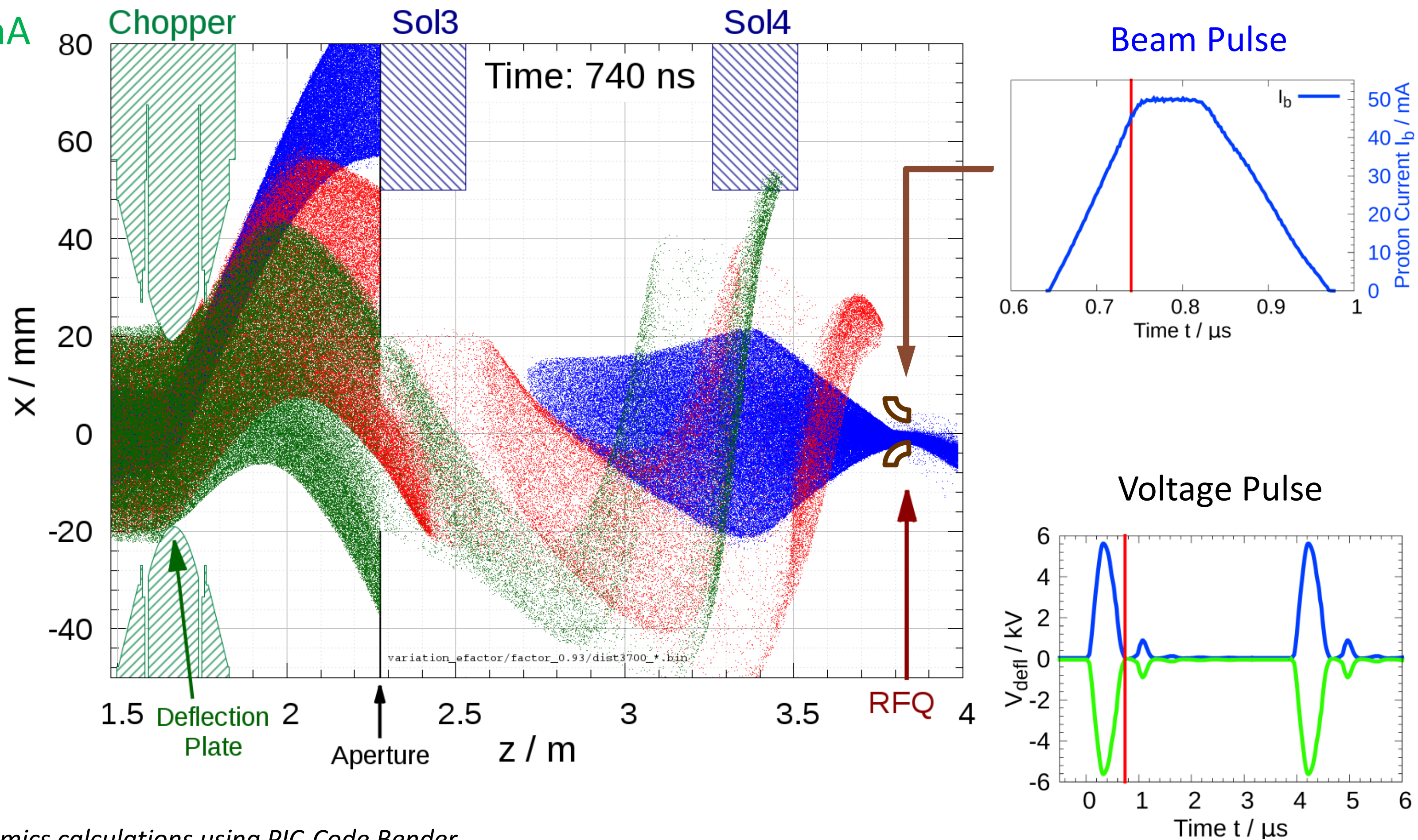

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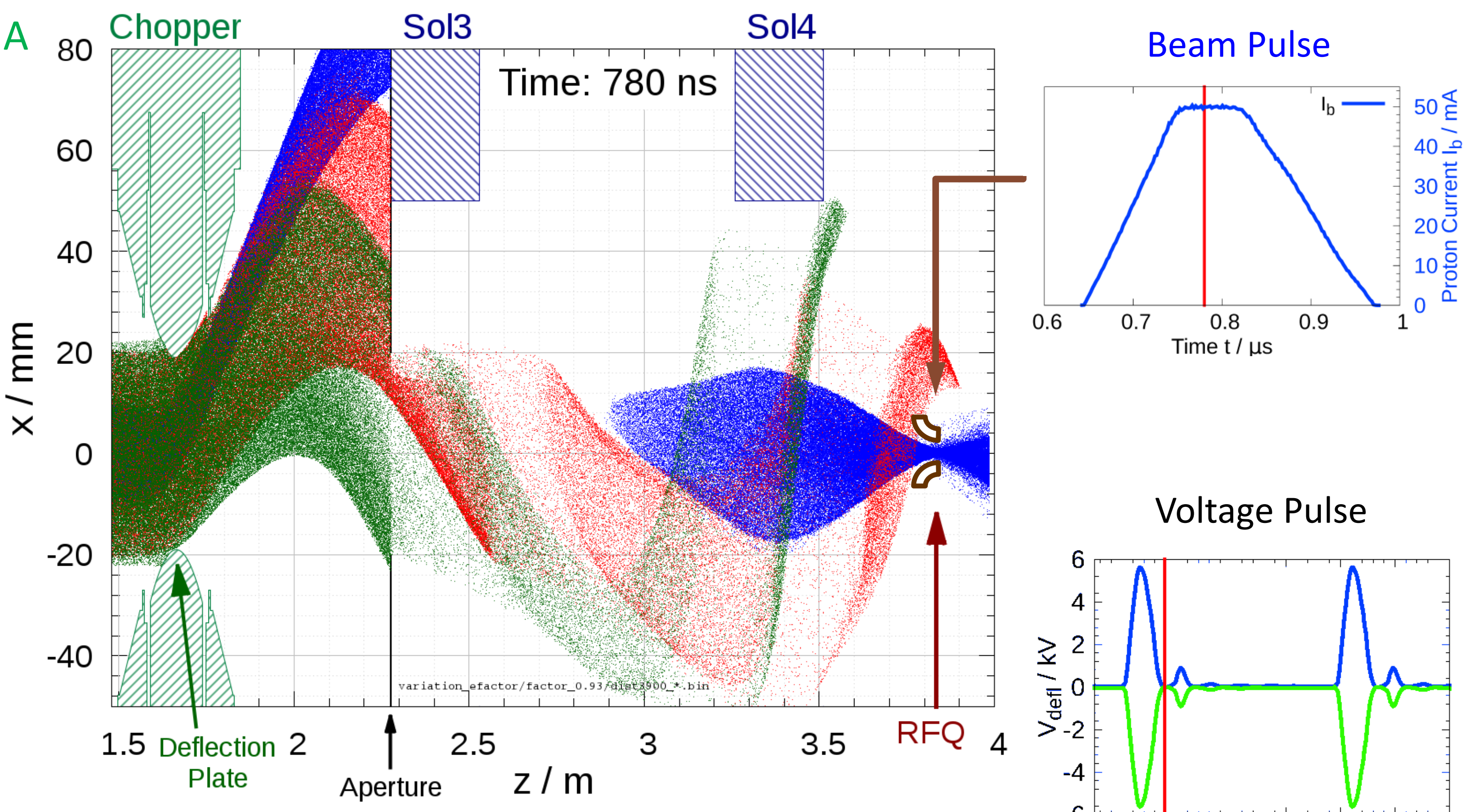
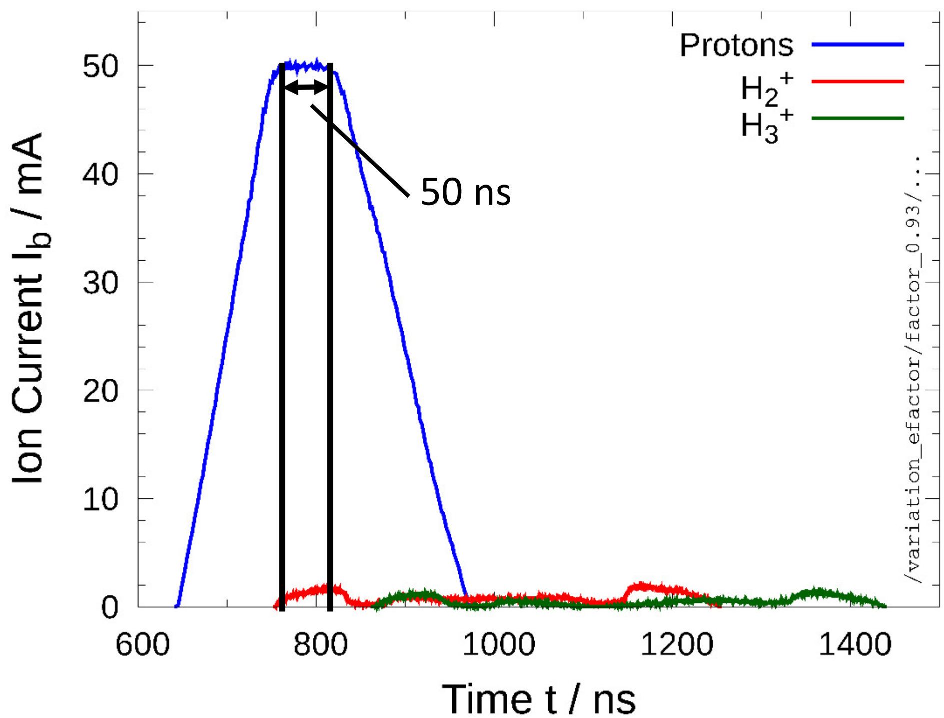


Beam dynamics calculations using PIC-Code Bender.

Beam Shaping Simulation

Simulated Pulse Shape at the RFQ Entrance



Simulated without collimator system in front of the RFQ.

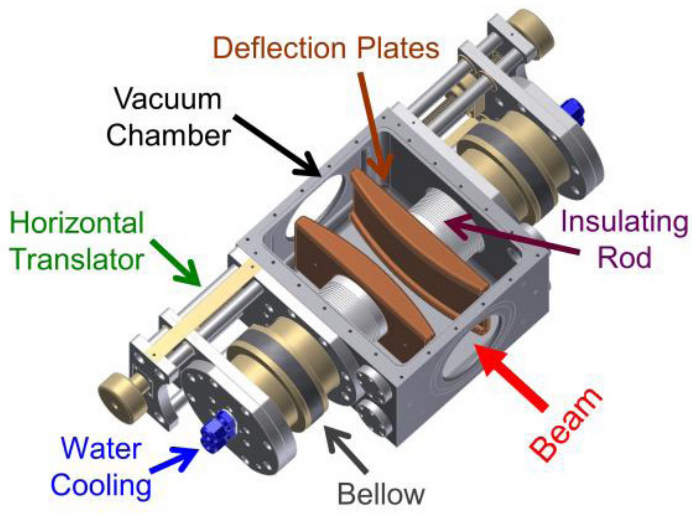
Results of Numerical Simulations:

- Time requirements fulfilled.
- 50 ns flat top:
  - Position offset below ±0.3 mm (necessary condition: *longitudinal* matching of deflection forces).
  - Low emittance.
  - Cylindrical symmetry preserved (necessary condition: *transverse* matching of deflection forces).
- Low transmission for H_2^+ and H_3^+ ions (pulsed velocity filter).

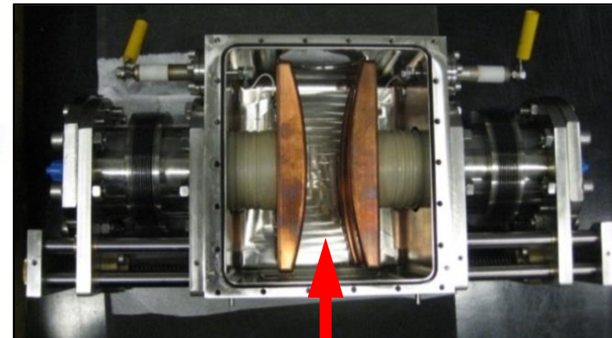
Chopper Hardware Design

Electric Deflector

$$V_0 = \pm 6 \text{ kV}$$
$$f_{rep} = 257 \text{ kHz}$$
$$l_{plate} = 15 \text{ cm}$$
$$h_{plate} = 8 \text{ cm}$$



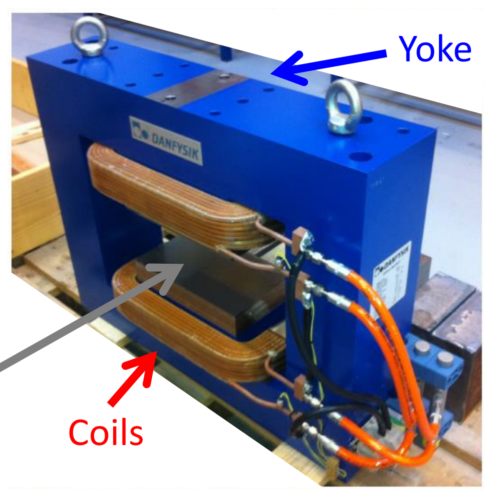
Deflection Chamber



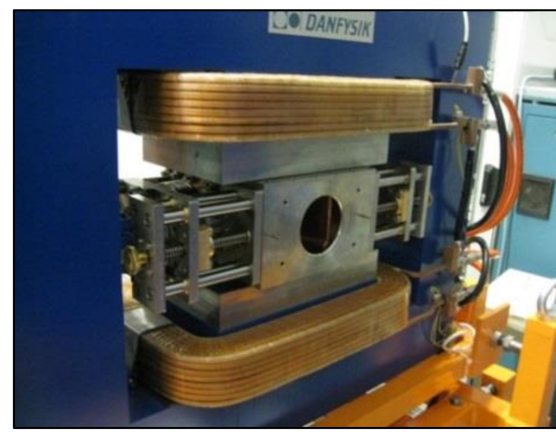
Magnetic Dipole

$$B_0 = 130 \text{ mT}$$
$$I_{coil} = 130 \text{ A}$$
$$l_{dipole} = 15 \text{ cm}$$
$$h_{gap} = 11 \text{ cm}$$

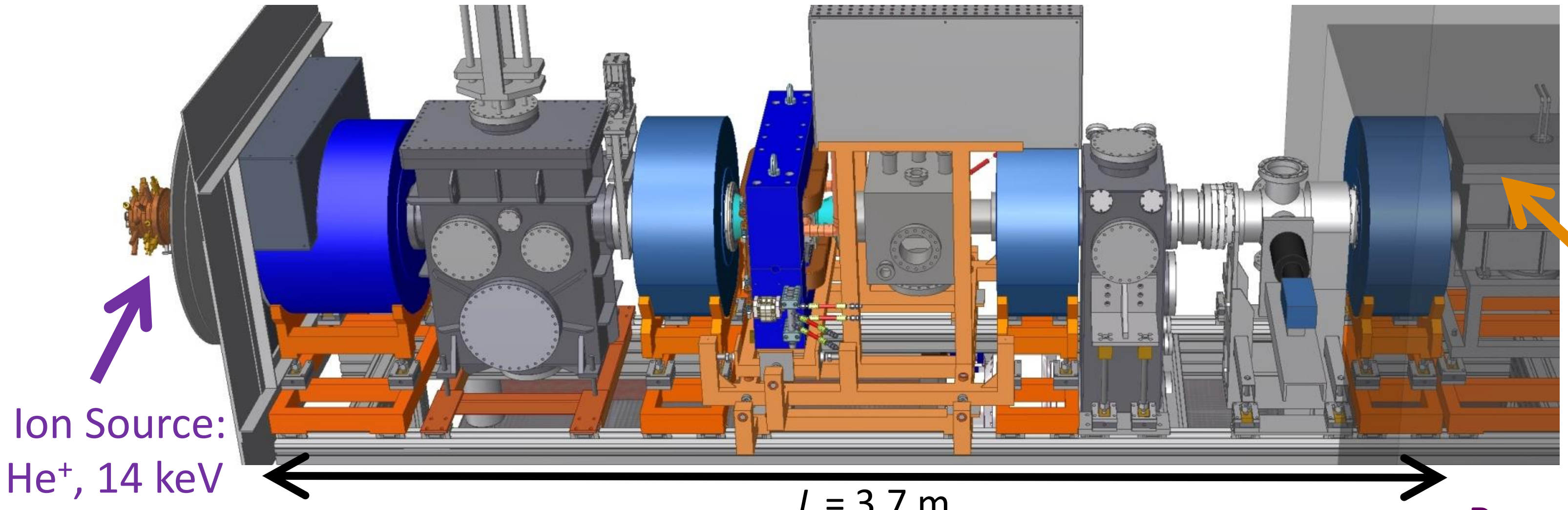
Exchangeable Pole Plates

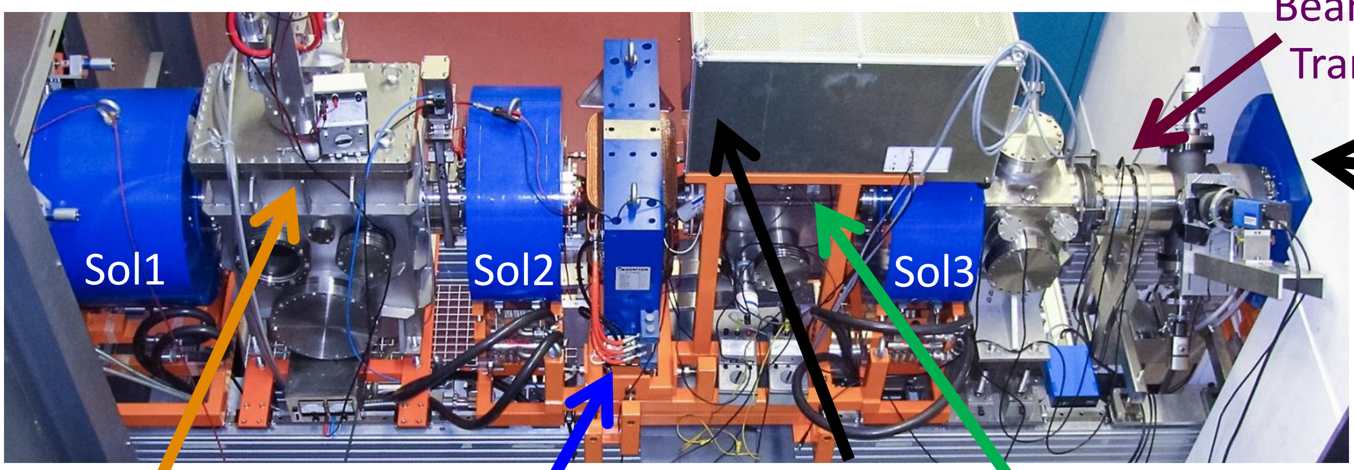


Deflection Chamber in Dipole



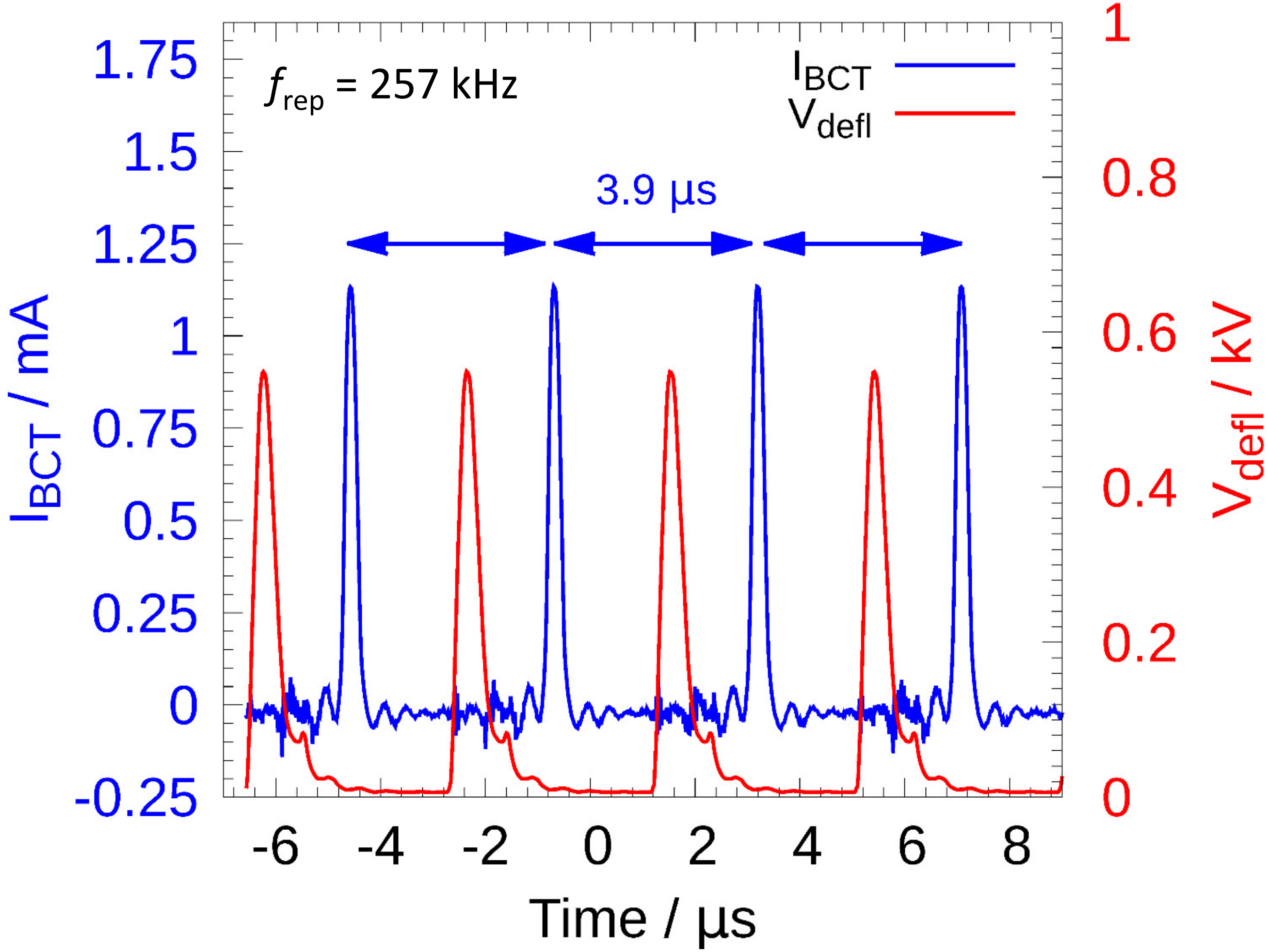
Experimental Setup: FRANZ LEBT





Measurements: Repetition Rate

- Beam chopping at 257 kHz experimentally achieved.
- Ratio of Pulsed to DC Beam Current of 95.2% ± 1.6% achieved.



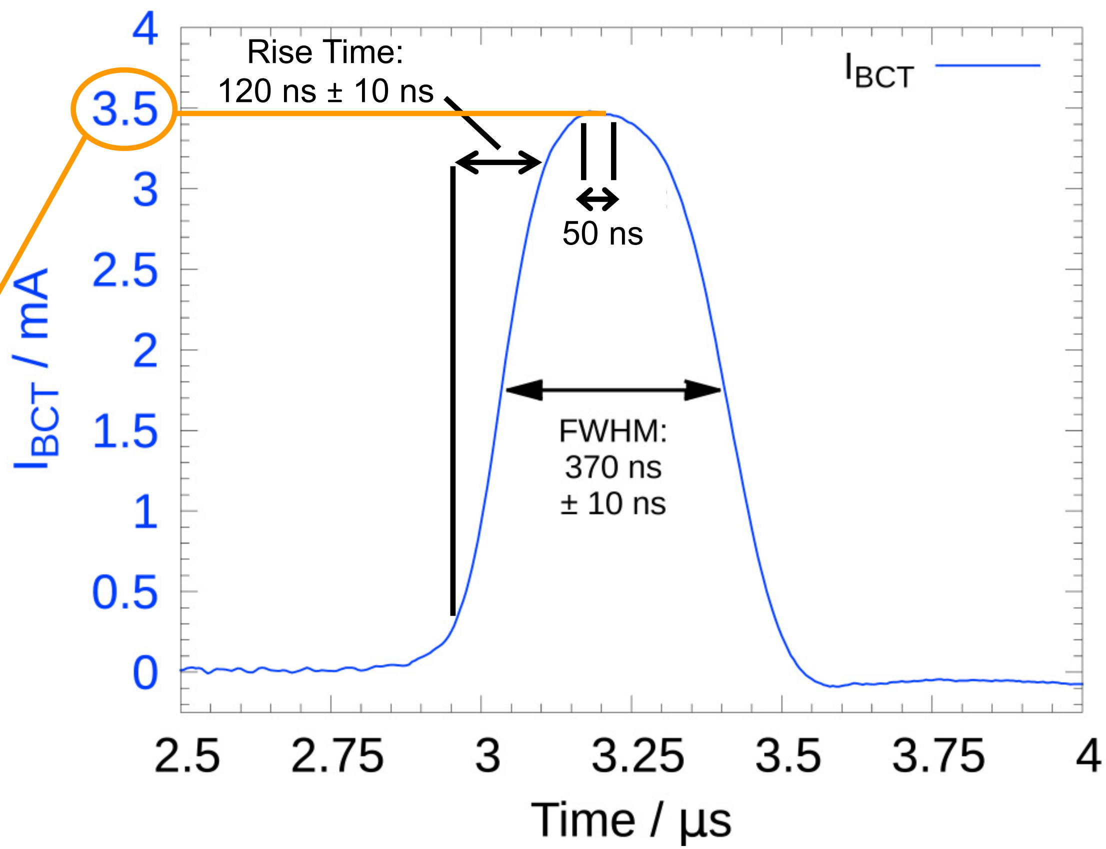
He^+, 14 keV
$r_{aperture}$ = 50 mm
I_{dipole} = 40.0 A

Measurements: Pulse Shape

- Reliable chopping and transport was achieved even for high-perveance beams.

Gen. perveance K equivalent to 175 mA, p, 120 keV.

$$K = \frac{1}{4\pi\epsilon_0}\sqrt{\frac{m_\mathrm{p}}{2q}}\frac{I_\mathrm{b}}{V_\mathrm{acc}^{3/2}}$$



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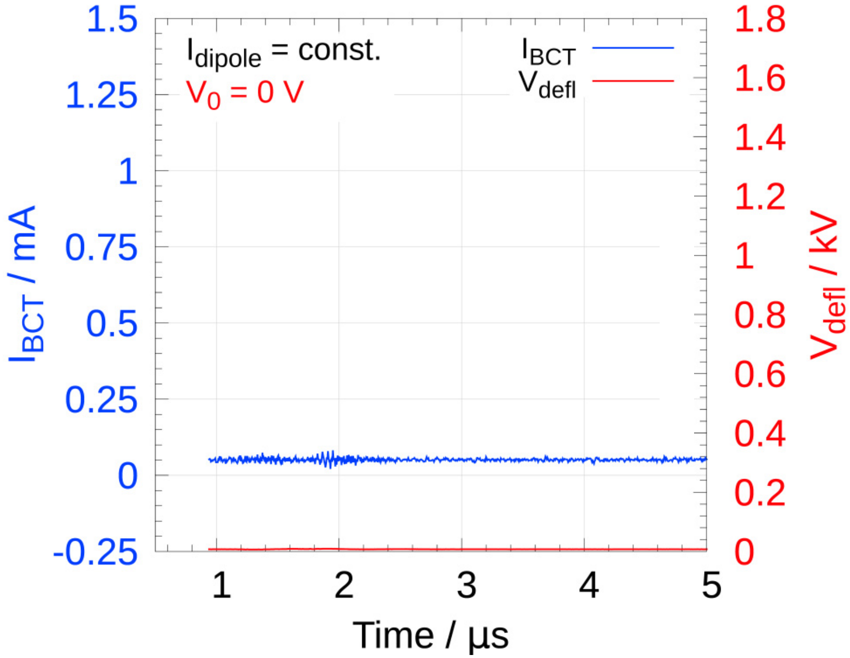
Measurements: Variation of Wien Ratio

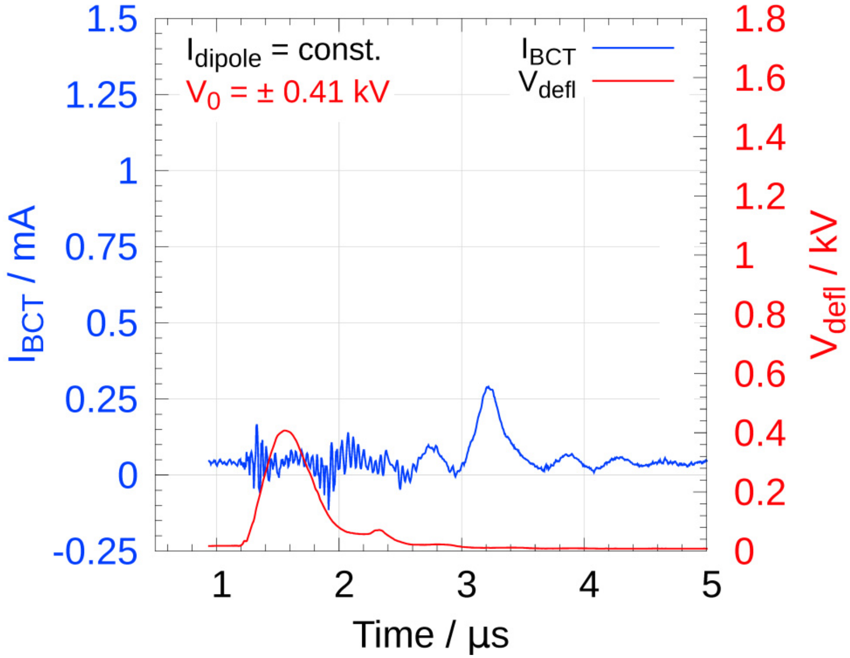


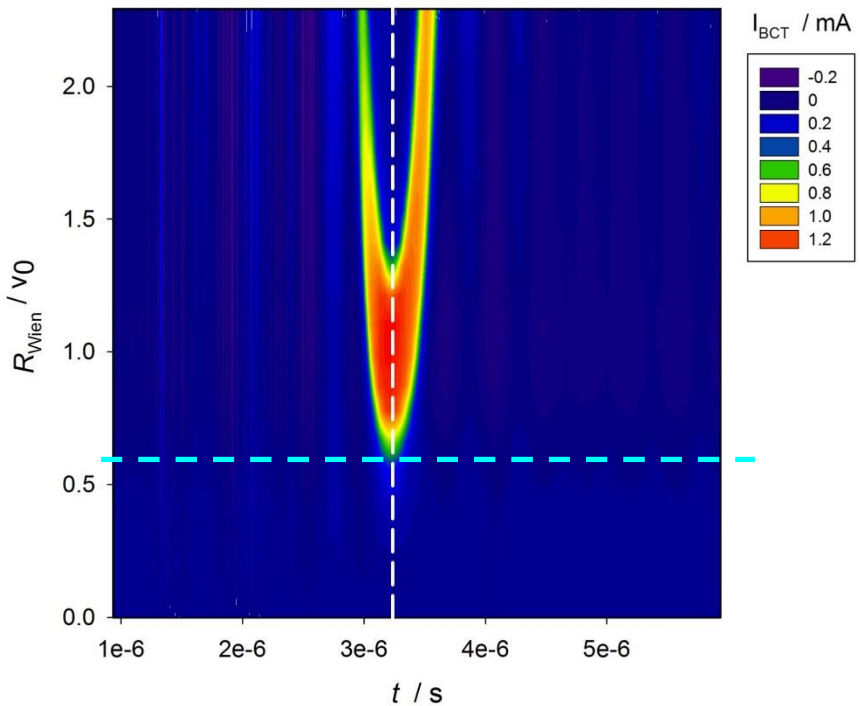
He^+, 14 keV
$r_{aperture}$ = 50 mm
I_{dipole} = 40.0 A

$$R_{Wien} = \frac{\int E_x \, dz \cdot f_{tof}}{\int B_y \, dz}$$

E_x → sweep
B_y → const.

Measurements: Variation of Wien Ratio





He^{+}, 14 keV

$r_{aperture}$ = 50 mm

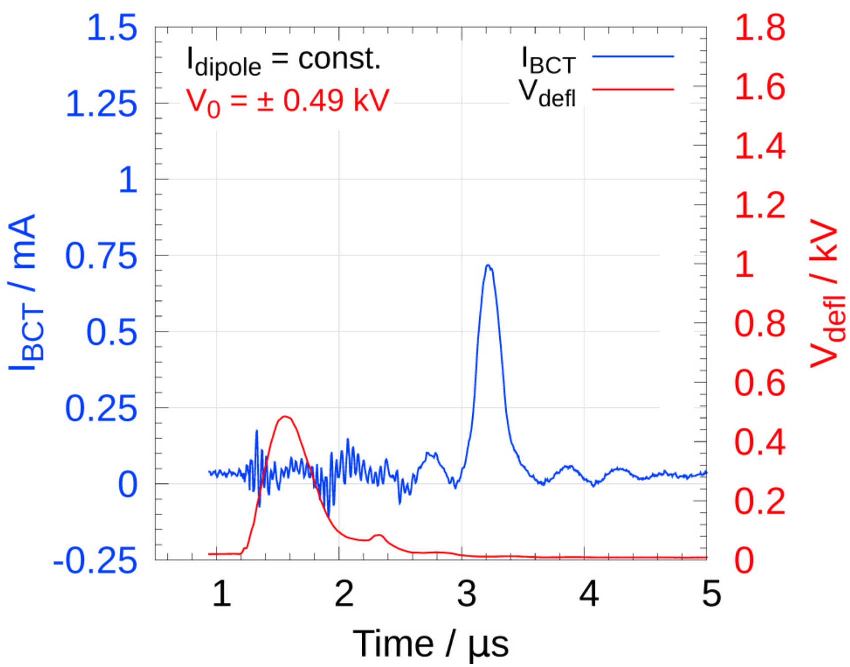
I_{dipole} = 40.0 A

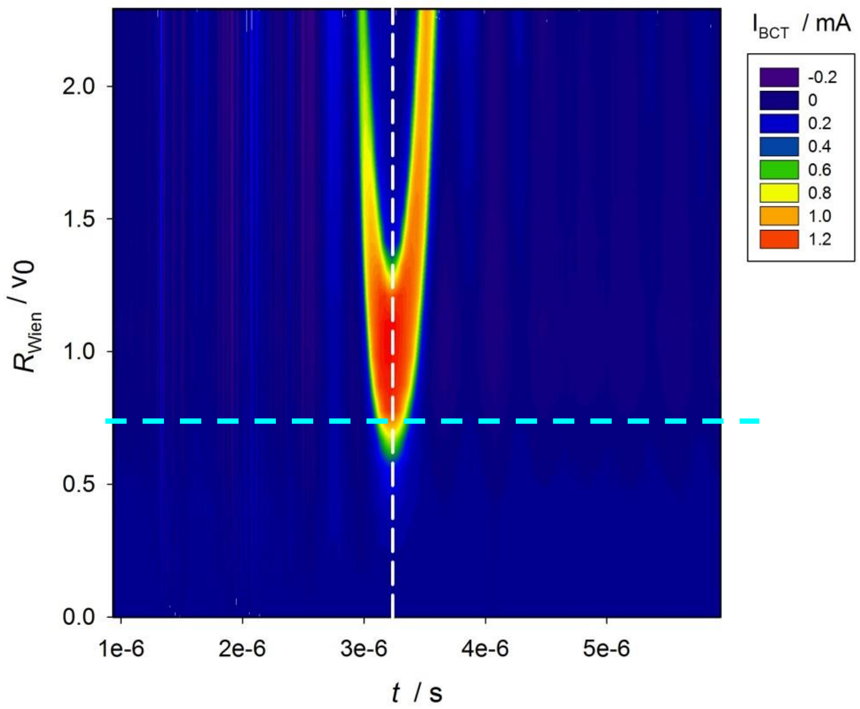
$$R_{\mathrm{Wien}} = \frac{\int E_x \,\mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \,\mathrm{d}z}$$

E_x → sweep

B_y → const.

Measurements: Variation of Wien Ratio





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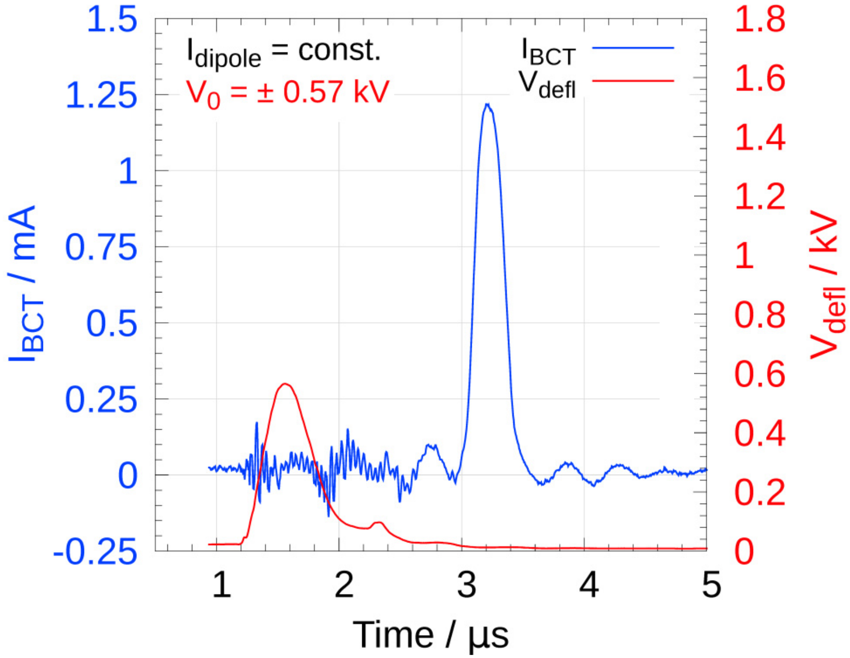
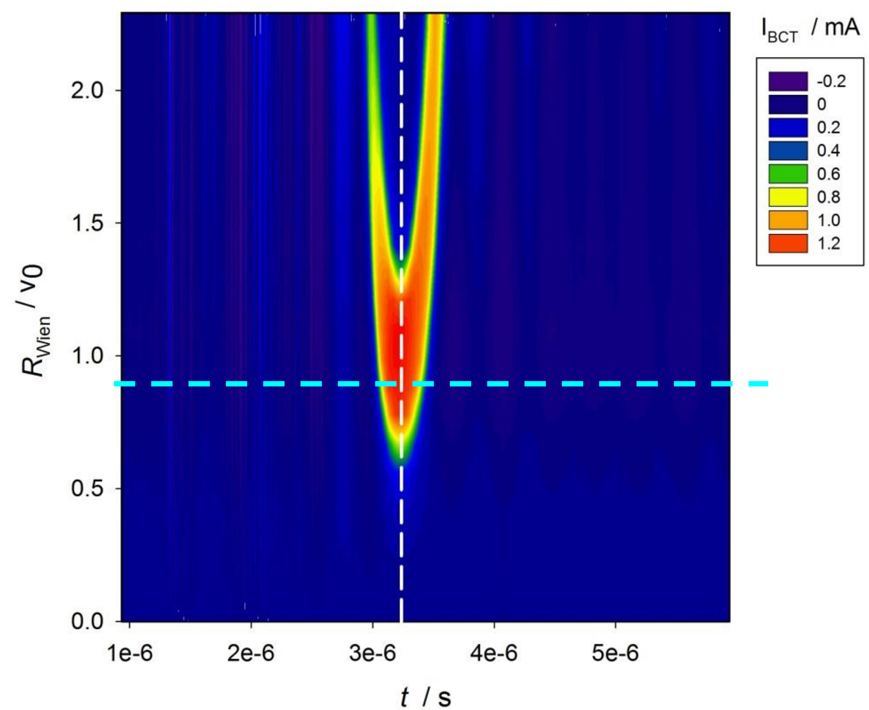
Measurements: Variation of Wien Ratio





He$^+$, 14 keV

$r_{aperture}$ = 50 mm

I_{dipole} = 40.0 A

$$R_{\mathrm{Wien}} = \frac{\int E_x \, \mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \, \mathrm{d}z}$$

E_x → sweep

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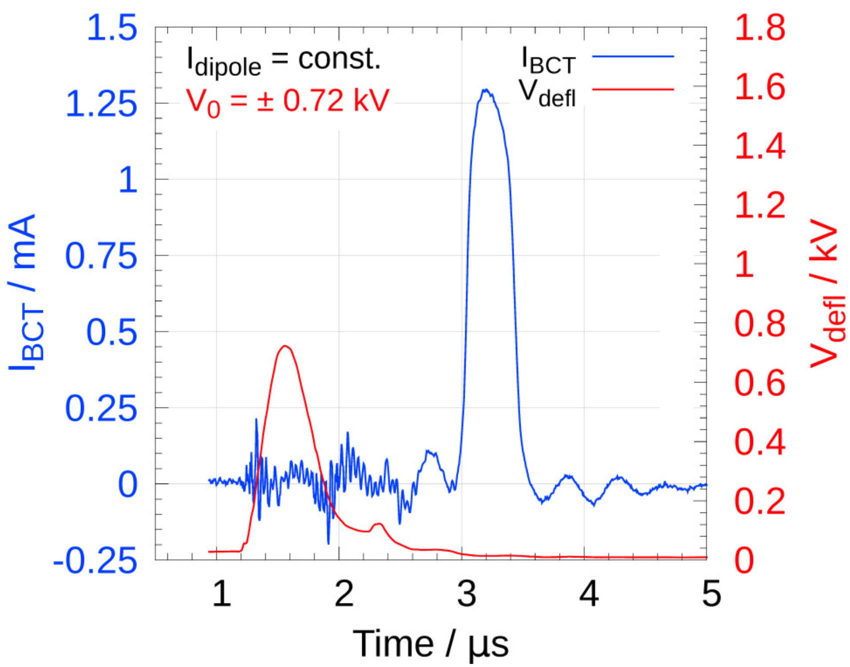
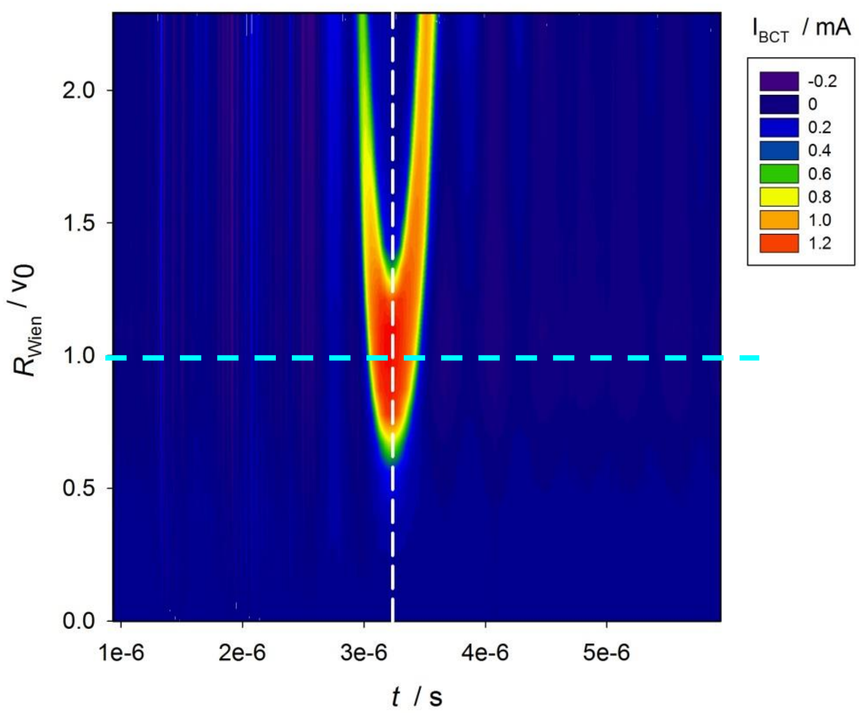
Measurements: Variation of Wien Ratio



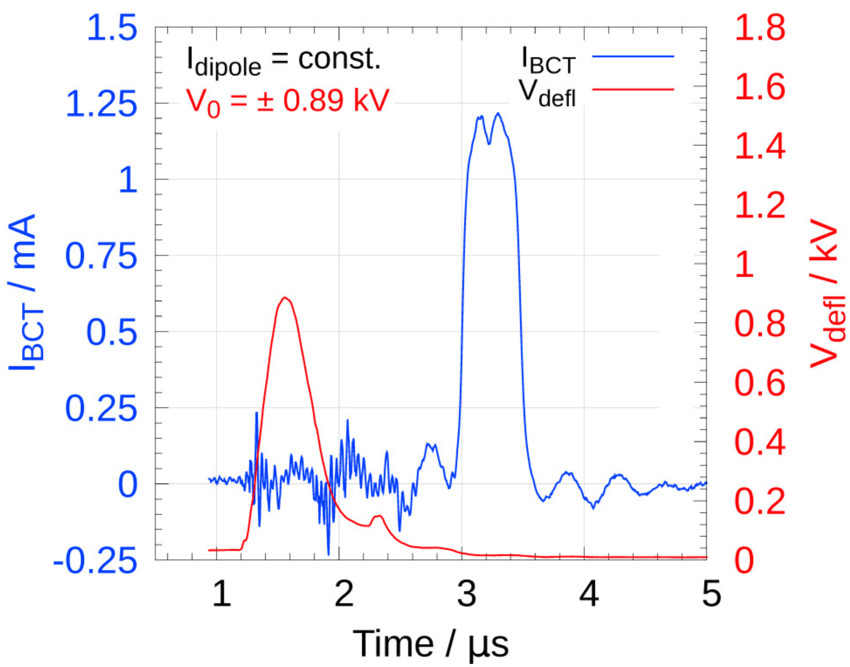


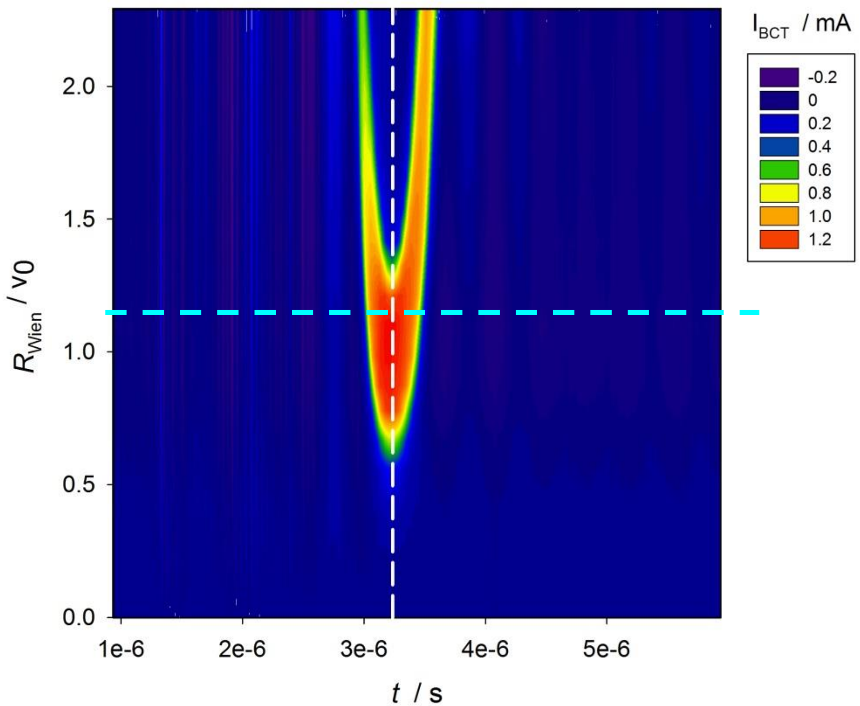
He^+, 14 keV
$r_{aperture}$ = 50 mm
I_{dipole} = 40.0 A

$$R_{Wien} = \frac{\int E_x \, dz \cdot f_{tof}}{\int B_y \, dz}$$

E_x → sweep
B_y → const.

Measurements: Variation of Wien Ratio





He$^+$, 14 keV

$r_{aperture}$ = 50 mm

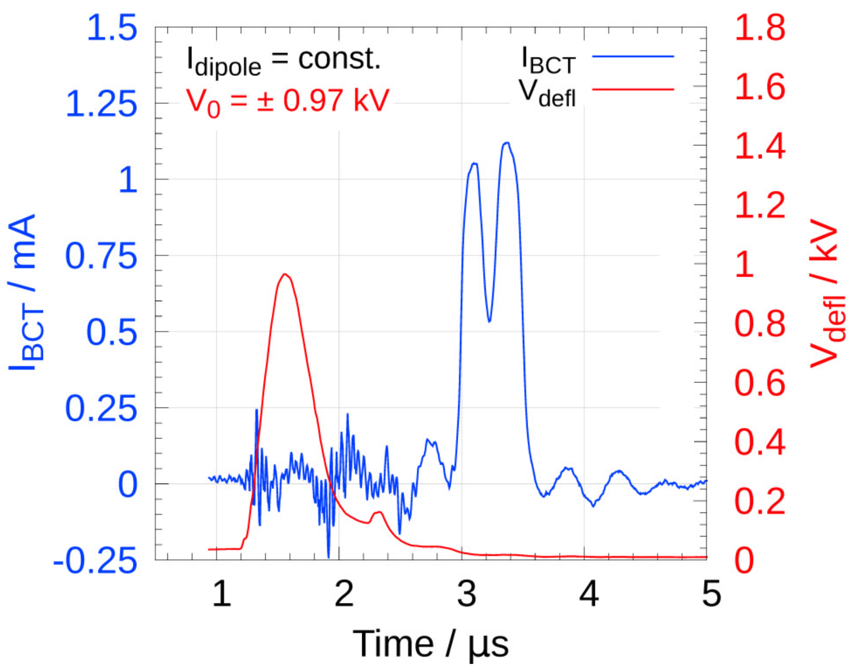
I_{dipole} = 40.0 A

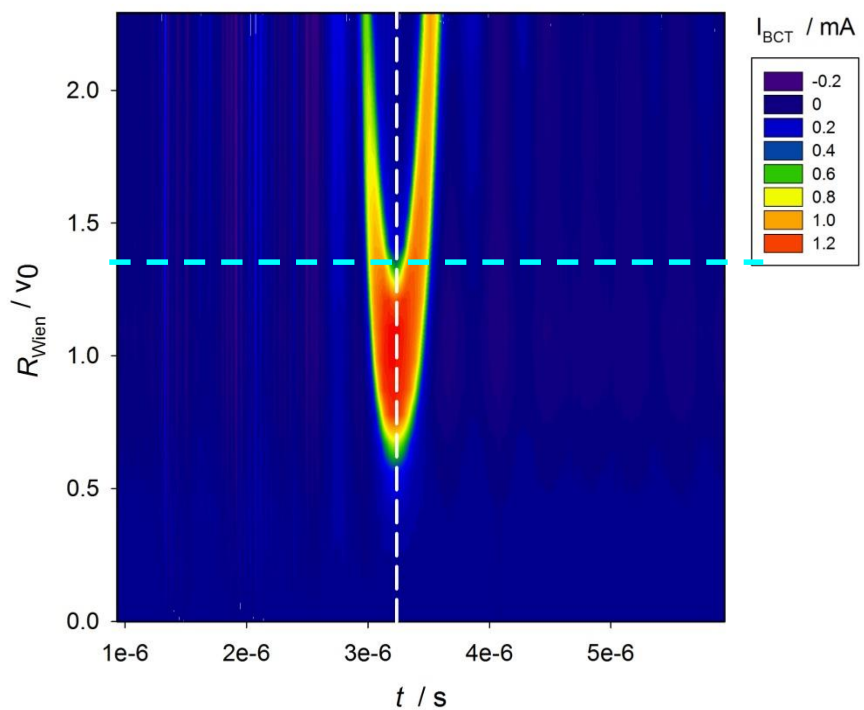
$$R_{\mathrm{Wien}} = \frac{\int E_x \, \mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \, \mathrm{d}z}$$

E_x → sweep

B_y → const.

Measurements: Variation of Wien Ratio





He⁺, 14 keV

$r_{aperture}$ = 50 mm

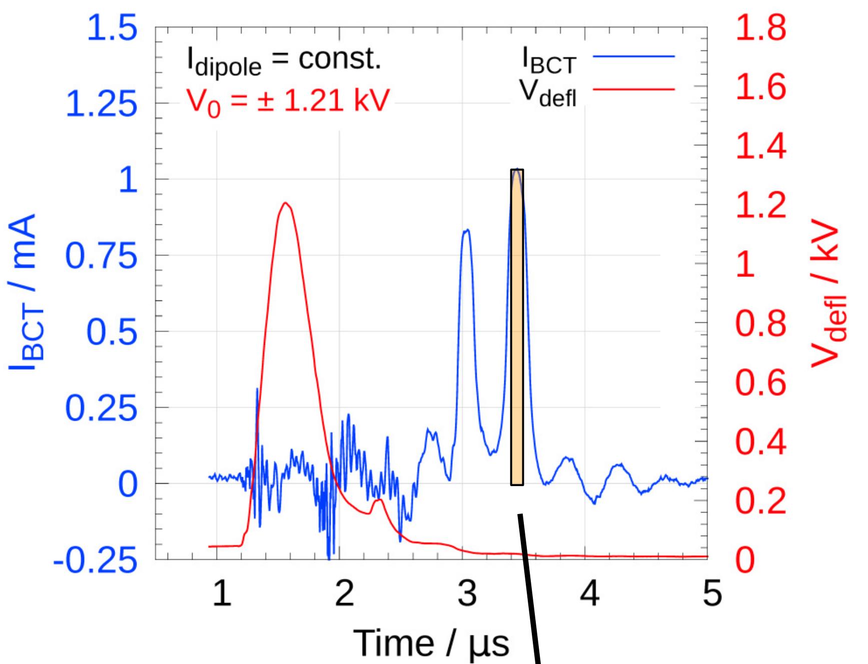
I_{dipole} = 40.0 A

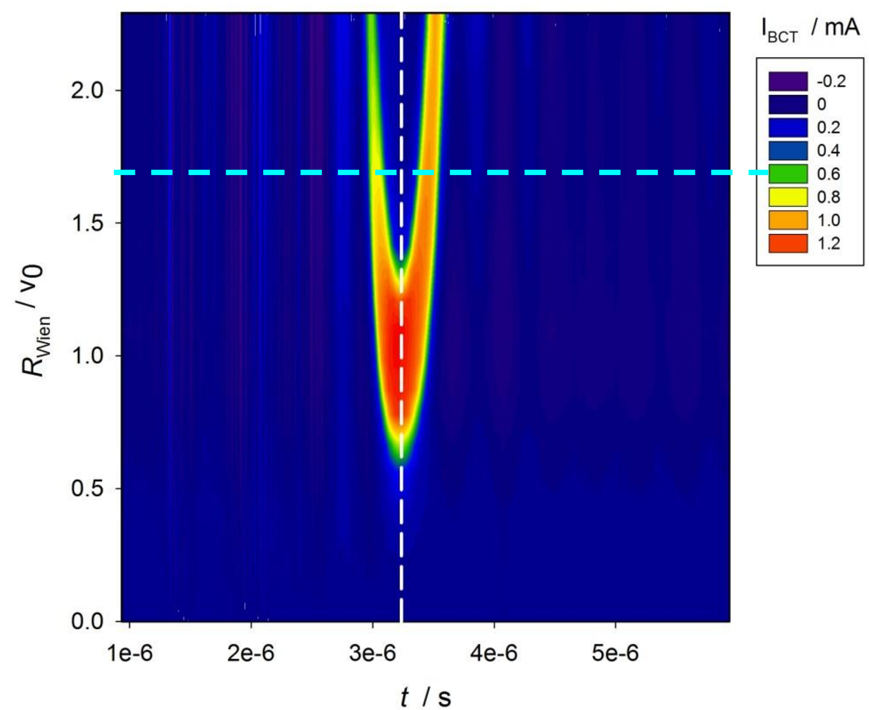
$$R_{\mathrm{Wien}} = \frac{\int E_x \, \mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \, \mathrm{d}z}$$

E_x → sweep

B_y → const.

Measurements: Variation of Wien Ratio





He⁺, 14 keV

$r_{aperture}$ = 50 mm

I_{dipole} = 40.0 A

$$Q_{\mathrm{flattop}} = I_{\mathrm{BCT}}^{\mathrm{max}} \cdot t_{\mathrm{flattop}}$$

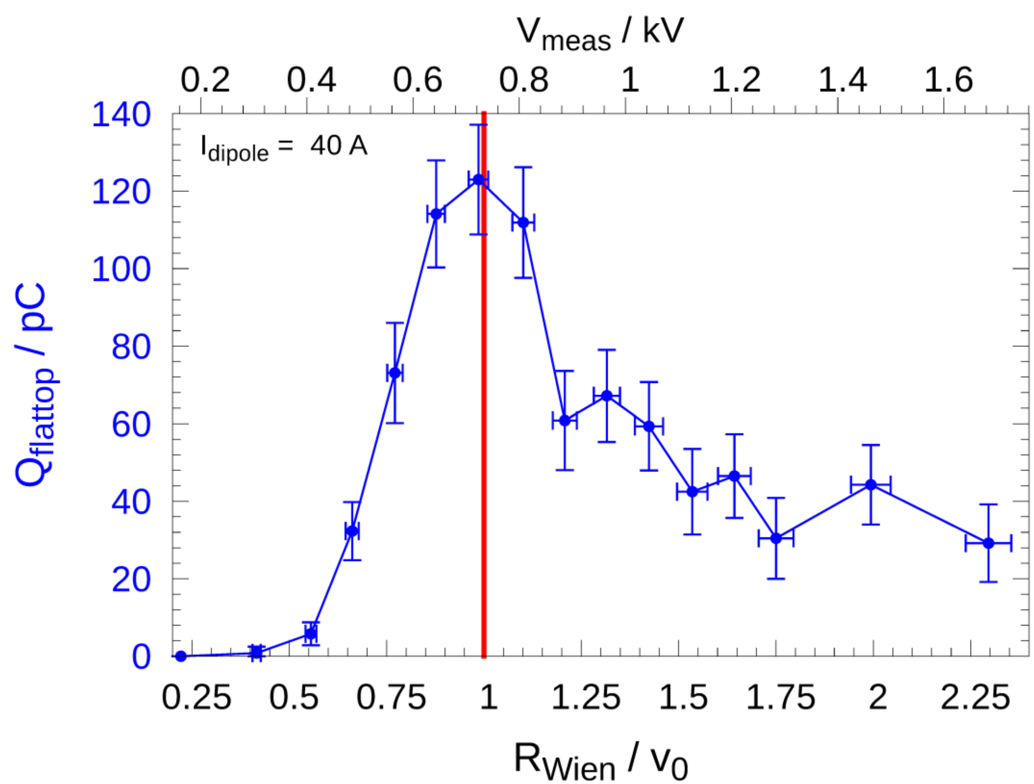
$$R_{\mathrm{Wien}} = \frac{\int E_x \,\mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \,\mathrm{d}z}$$

E_x → sweep

B_y → const.

Measurements: Variation of Wien Ratio

- Highest flat-top charge achieved for the theoretically derived Wien condition.
- Adequate matching of electric and magnetic deflection forces.



He^{+}, 14 keV

$r_{aperture}$ = 50 mm

I_{dipole} = 40.0 A

$$Q_{\text{flattop}} = I_{\text{BCT}}^{\text{max}} \cdot t_{\text{flattop}}$$

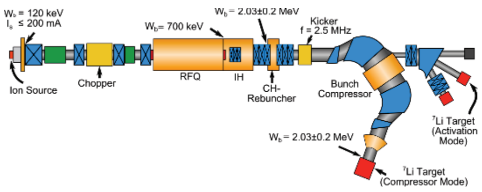
$$R_{\text{Wien}} = \frac{\int E_x \, dz \cdot f_{\text{tof}}}{\int B_y \, dz}$$

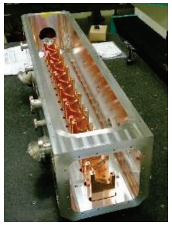
E_x → sweep

B_y → const.

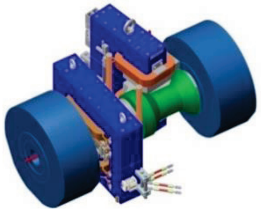
Conclusion

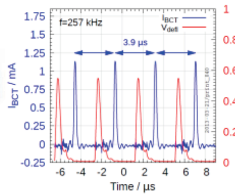
- Accelerator-driven neutron source FRANZ currently under construction.

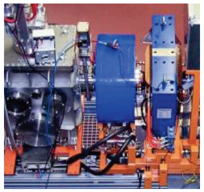




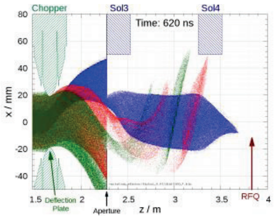
- E×B chopper and LEBT section have been commissioned with beam: ready for pulsed & dc operation.

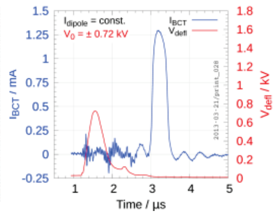


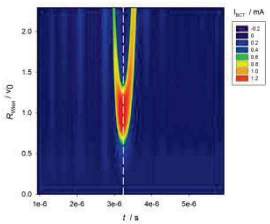


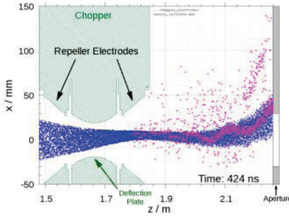


- *E×B chopper + LEBT = low-energy test stand*:
  - Transport of high-perveance beams…
  - …in dc or in pulsed mode…
  - …using different beam fractions…
  - …with or without space-charge compensation…
  - …including electron-ion interaction.









Thank you for your attention!