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Chopping and Transport of Low-Energy Ion Beams for FRANZ

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Outline

1) Introduction: Neutron Production

2) Overview: The FRANZ Facility

3) LEBT and Chopper System
   a) E×B Chopper Concept
   b) Numerical Simulations
   c) Experimental Results

3) Conclusion

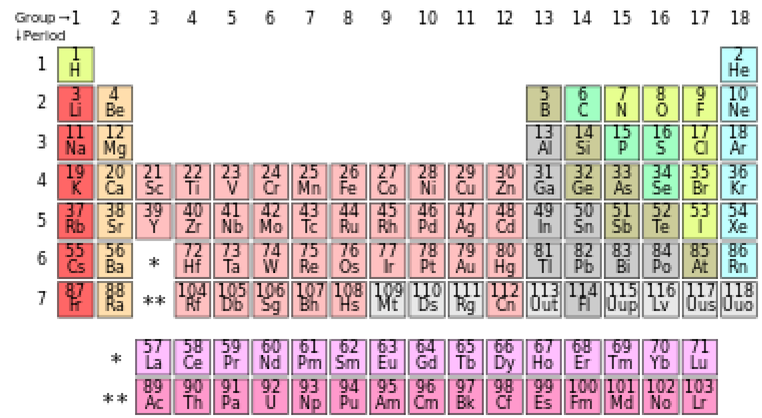
Introduction: Neutron Research

- Material Science
- Sensitivity for magnetic properties
- High penetration depth in material
- Sensitivity for different isotopes
- Sensitivity to light elements (e.g. hydrogen)
- Neutron imaging
- Test radiation durability (detectors, fusion materials)
- Cancer treatment (BNCT)
- Neutron capture process relevant for ADS, nuclear astrophysics, …

Introduction: Nuclear Astrophysics

Stellar nucleosynthesis:

- About 50% of the element abundances beyond iron are produced via the s-process.
- s-process takes place in AGB stars.
- Neutron temperature: $k_B T$ = 8 to 90 keV [Reifarth et al., 2014].
- Modelling requires neutron capture cross-sections from 1 to 400 keV.

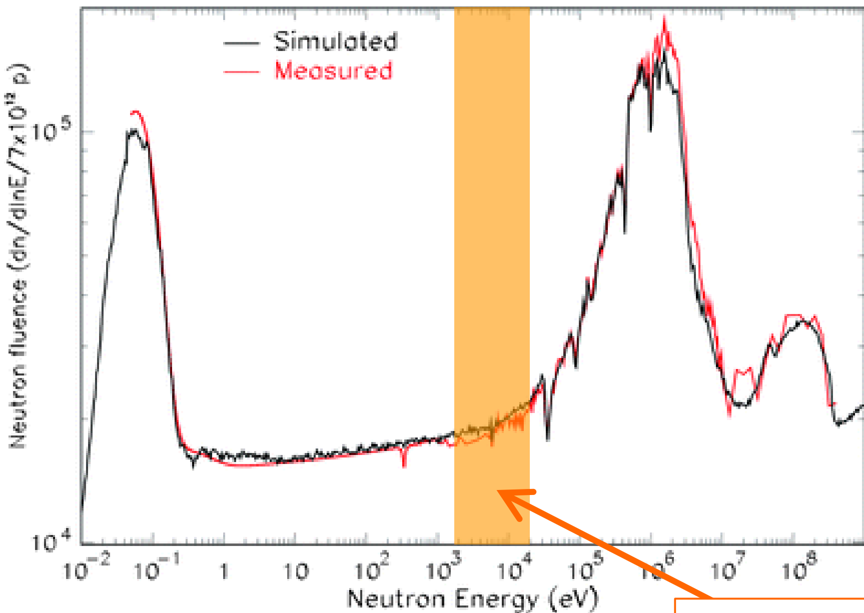


Introduction: Neutron Production Facilities

	Fission Reactors	Spallation Sources	Small-Scale Accel.-Driven Facilities
Typical production mechanism	fission of ^{235}U	high energy protons (100s MeV to GeV) on heavy metal target.	protons/deuterons (several MeV) on Li or Be target.
Costs	> 100 M€	> 1 G€	$\sim 1 \ldots 10$ M€
Neutron flux	high (average) flux $\approx 1e15 \frac{n}{s \cdot cm^2}$	High (peak) flux $= 4e16 \frac{n}{s \cdot cm^2}$ (ESS)	Moderate flux $< 1e7 \frac{n}{s \cdot cm^2}$
Time structure	challenging	CW (SINQ), short pulse (SNS), long pulse (ESS)	CW to short pulsed
Neutron energy	MeV, moderated to thermal spectrum	$W_n < W_p$ (emerging particles); $1 \ldots 10$ MeV (evaporating particles)	$1 \ldots 500$ keV
Angle distribution	isotropic	forward / isotropic	kinematic collimation

Neutron Energy Spectrum

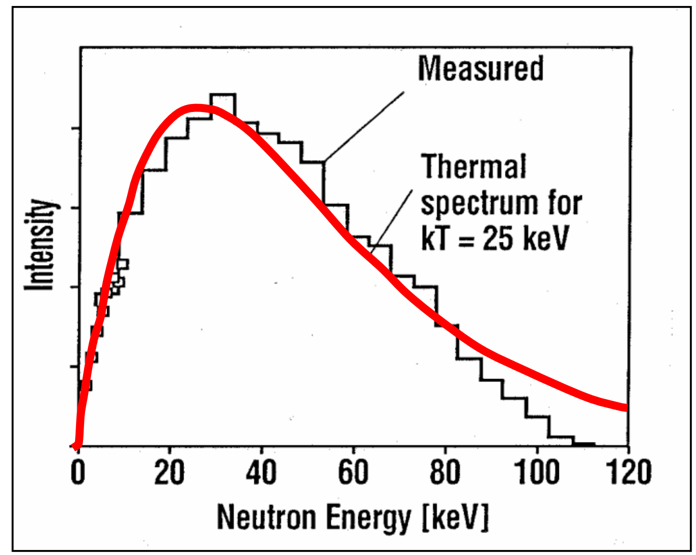
Spectrum from Spallation Source (20 GeV protons on Pb target)



n energy: 1…100 keV

Measured at n-TOF, CERN (flight path: 200m) [Colonna et al., 2010].

Spectrum from small-scale facility using the $^7\mathrm{Li(p,n)}^7\mathrm{Be}$ reaction.

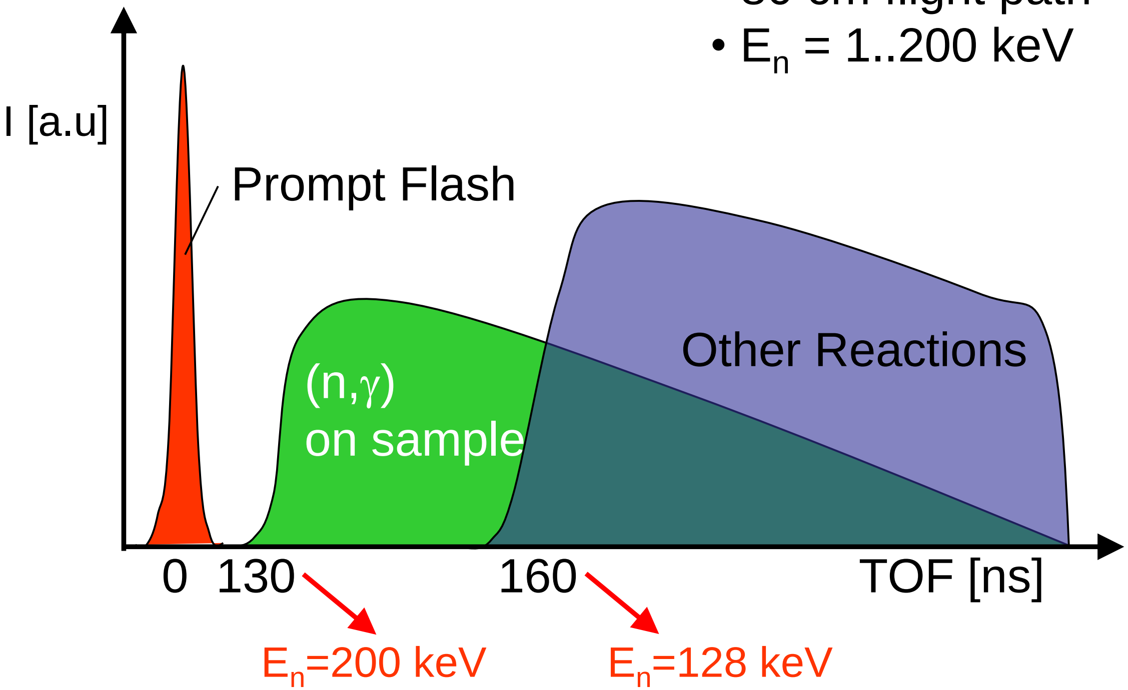


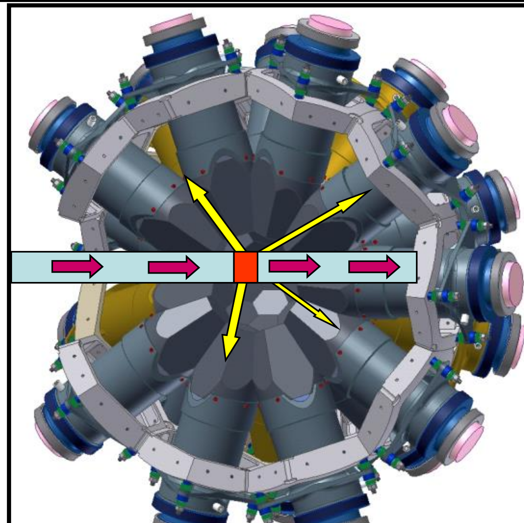
Measured at FZ Karlsruhe for a primary proton energy of 1.991 MeV (flight path: 0.8m) [Beer et al., 2001].

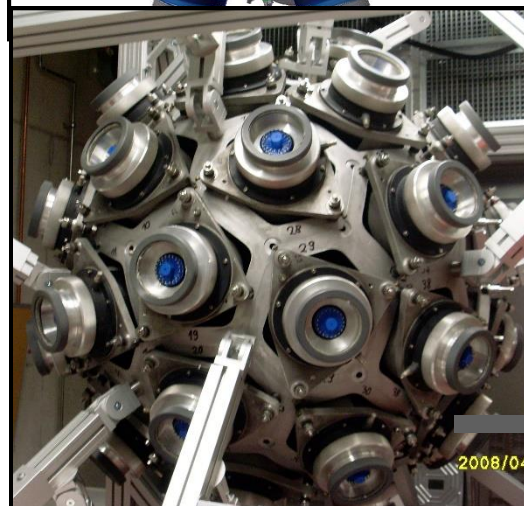
Time-of-Flight (TOF) Method

- TOF method allows to measure the neutron capture cross-sections as a function of the neutron energy.
- Pulsed primary beam and fast (<1 ns) gamma calorimeter required.
- Adequate neutron spectrum assures low background.

- 80 cm flight path
- E_n = 1..200 keV







4π BaF_2 detector at Frankfurt.

Frankfurt Neutron Source FRANZ

FRANZ is currently under construction at Frankfurt University:

- Deliver neutrons for nuclear astrophysics and material sciences
- Accelerator test bench
- Education of students in accelerator physics

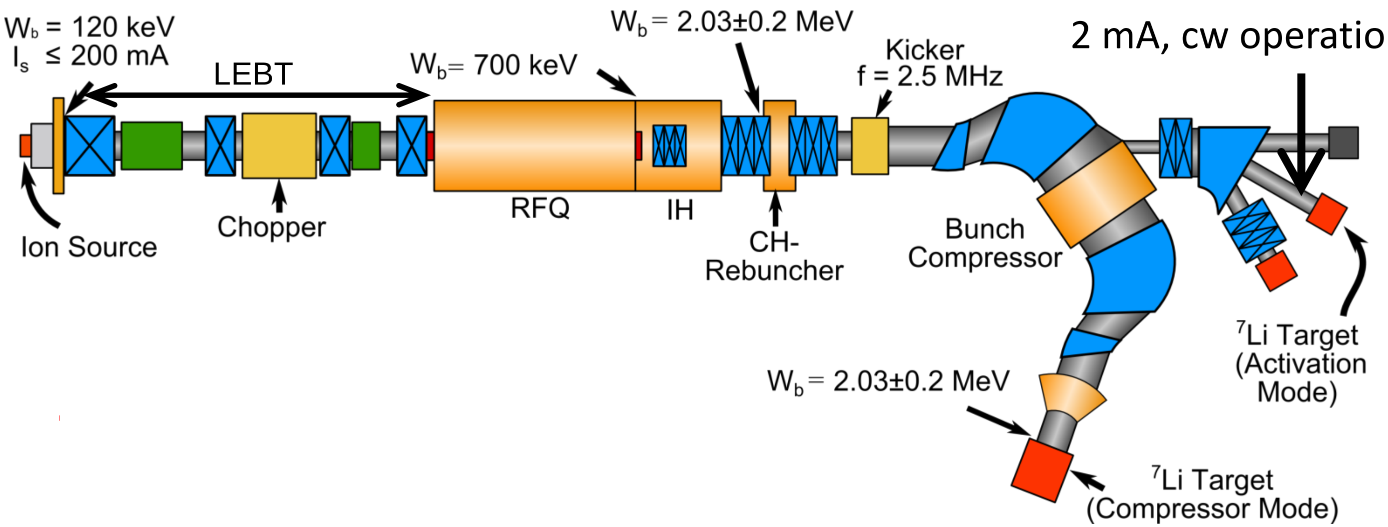
Experimental Hall, IAP

Physics Building, Goethe-Universität Frankfurt

Frankfurt Neutron Source FRANZ

Frankfurt Neutron Source FRANZ

Activation Mode:
2 mA, cw operation



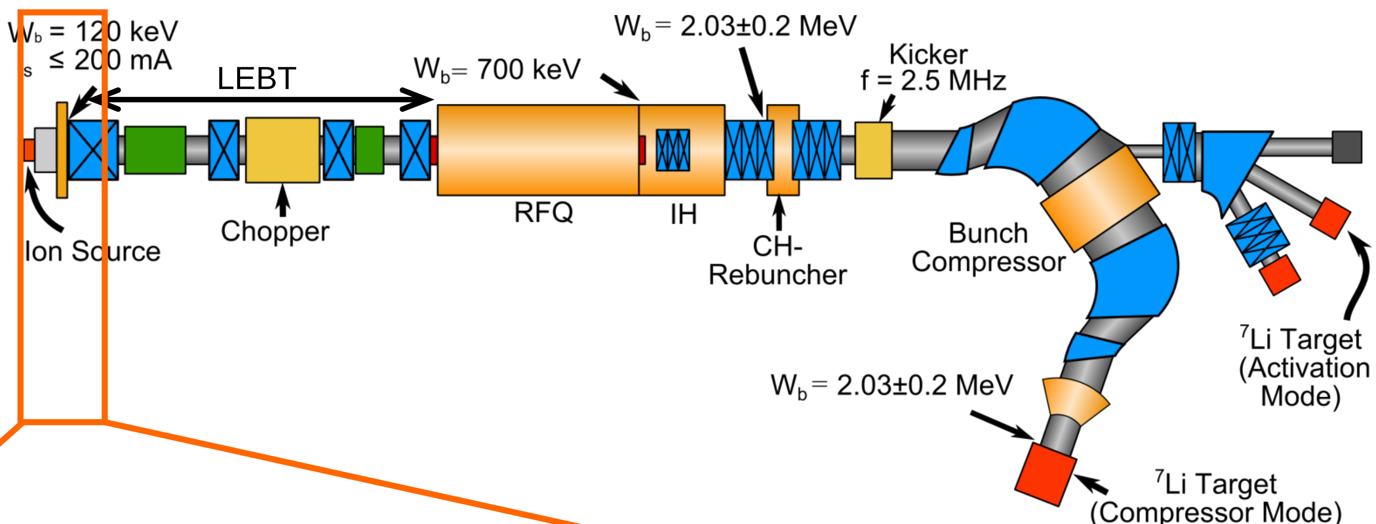
Goal in *Compressor Mode*:
- Deliver a high (peak) neutron flux,
- produced via the $^7Li(p,n)^7Be$ reaction,
- for the energy-dependent measurements of n-capture cross sections (using TOF).

⇨

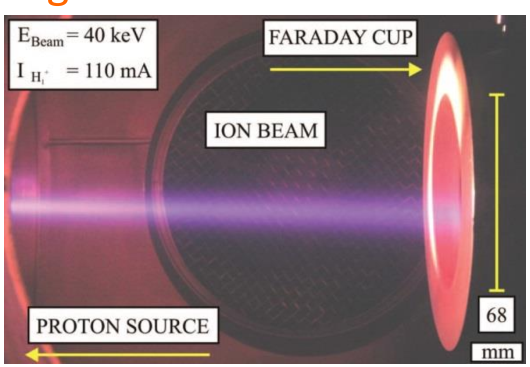
This requires a primary proton beam
- with high intensities (50-200 mA),
- at 2 MeV beam energy,
- with a challenging time structure (1 ns, 257 kHz).

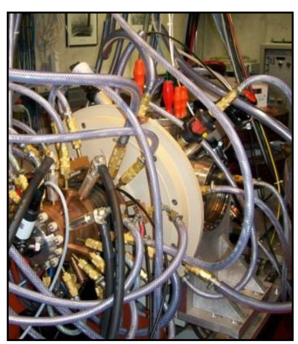
Frankfurt Neutron Source FRANZ

Frankfurt Neutron Source FRANZ



High-Current Ion Source





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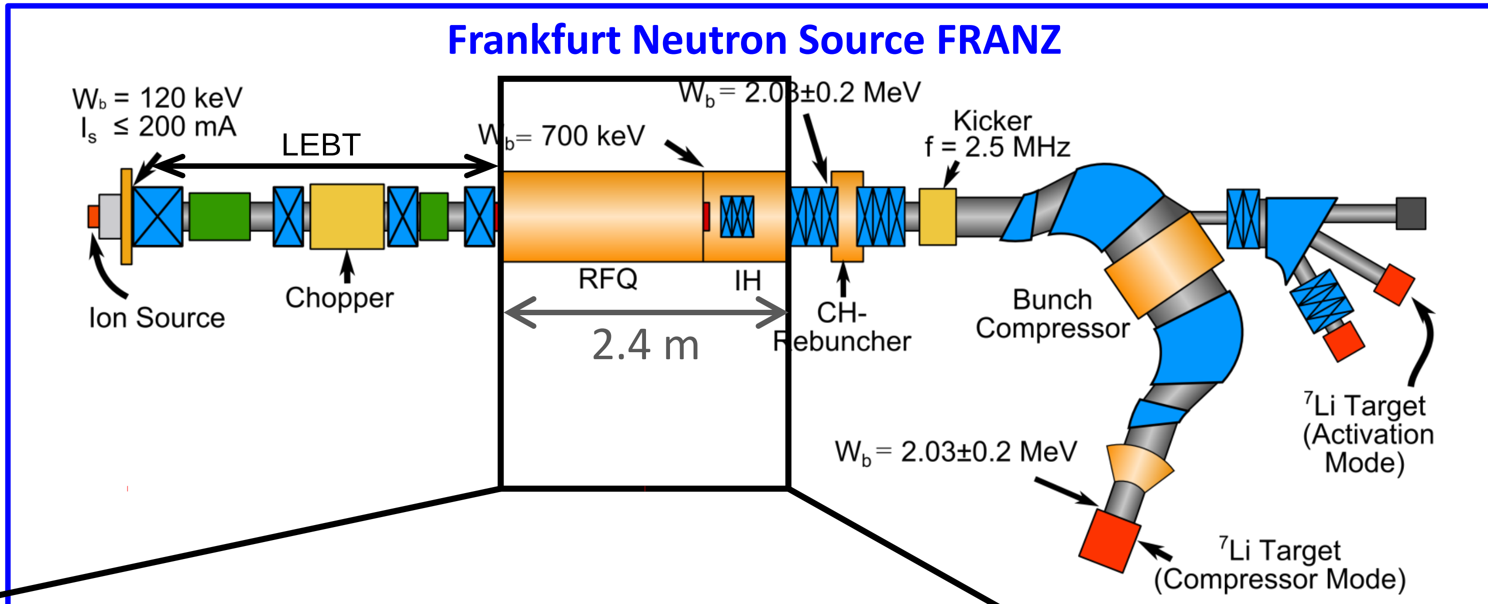
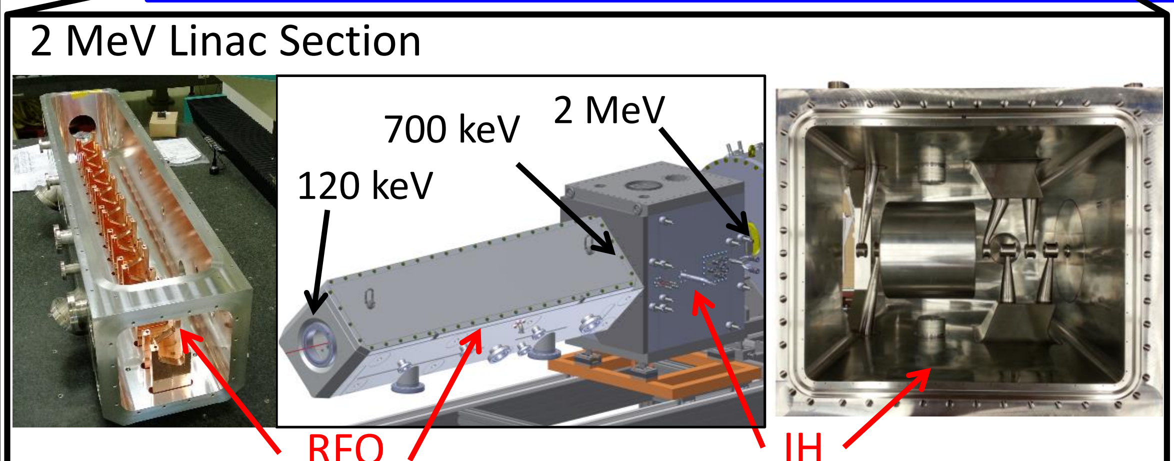
- Arc-discharge driven ion source
- Proton current: 50 mA (240 mA)
- Current density: 480 mA/cm^2
- DC operation
- Proton fraction > 90 %
- Beam energy: 120 keV
- $\varepsilon_{rms, norm}$ < 0.08 mm· mrad

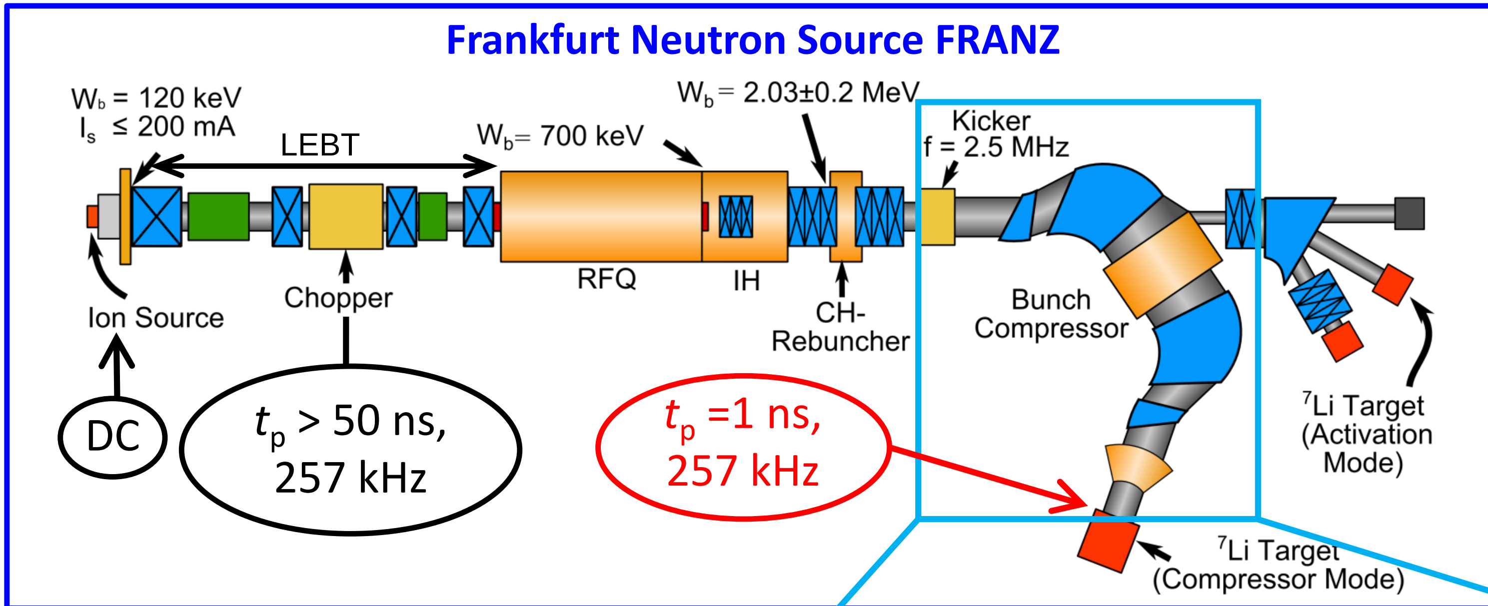
Frankfurt Neutron Source FRANZ



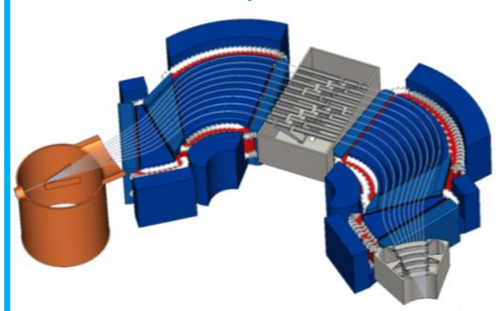


- CW operated
- f_{rf} = 175 MHz
- RFQ under construction
- IH is being copper plated
- RFQ test module tested with P_{rf} ≈ 115 kW/m

Frankfurt Neutron Source FRANZ



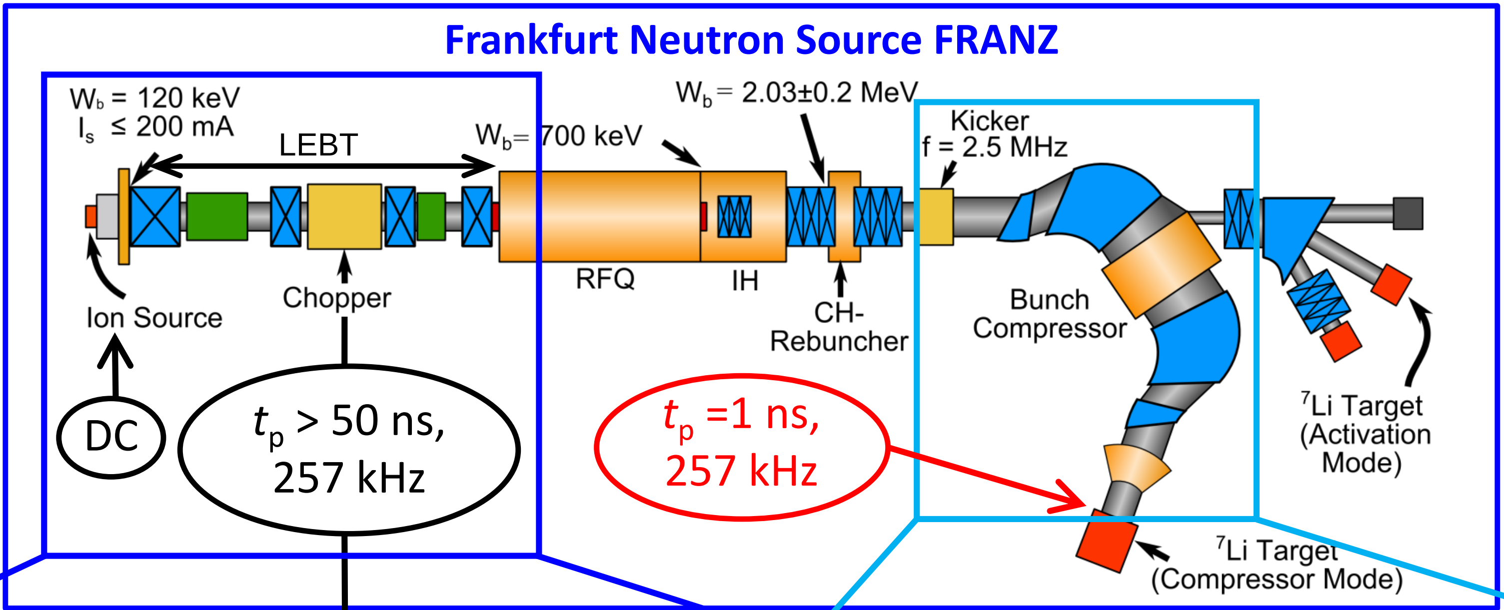
Bunch Compressor

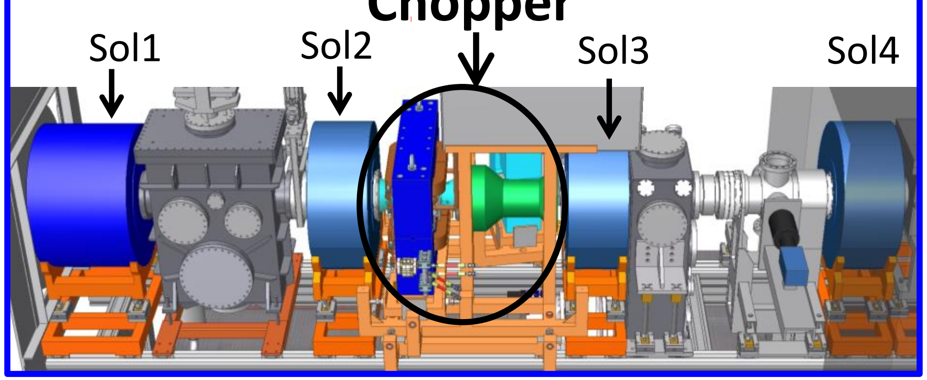


- Mobley Type
- Electric Kicker (f = 2.5 MHz)
- Magnetic Guiding System
- Rebuncher Cavities

L. P. Chau et al., LINAC'10, MOP100

Frankfurt Neutron Source FRANZ





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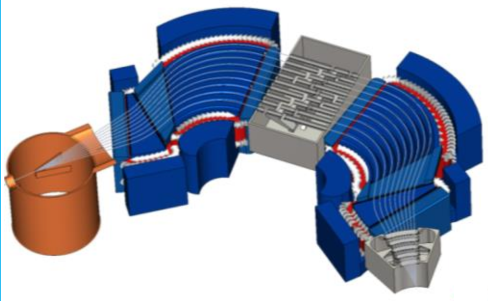

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L. P. Chau et al., LINAC’10, MOP100

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 a high duty factor of the electric deflection field.

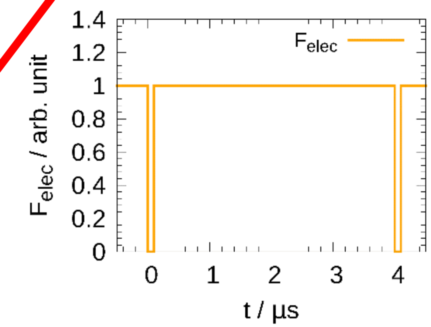
Magnetic Deflection

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

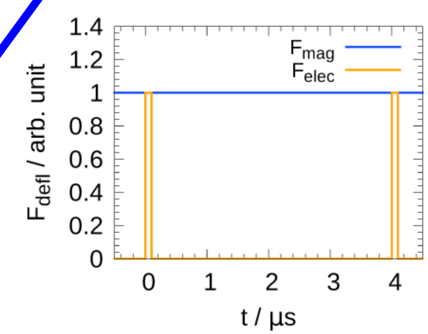
Concept

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

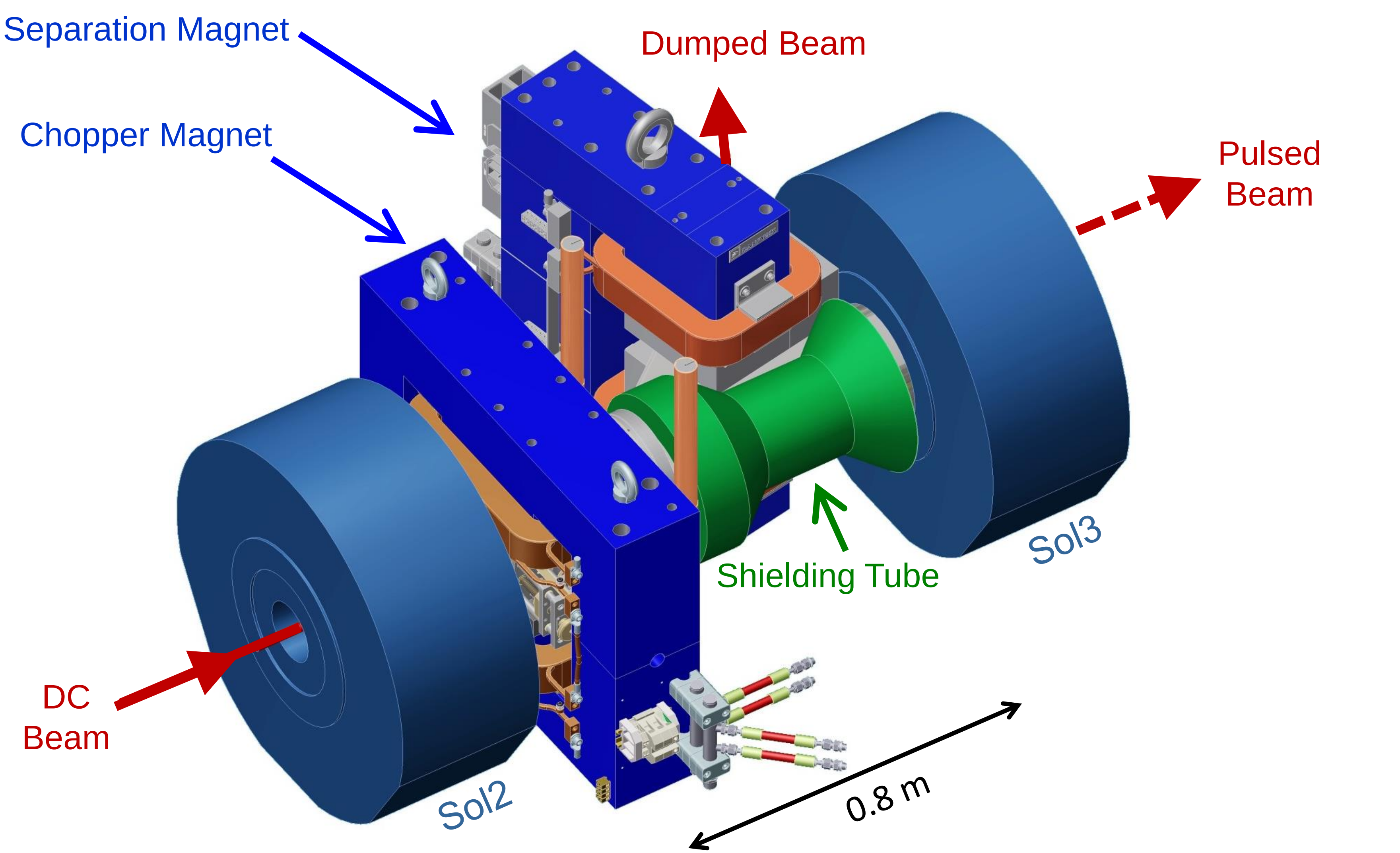
High duty cycle for electric field.



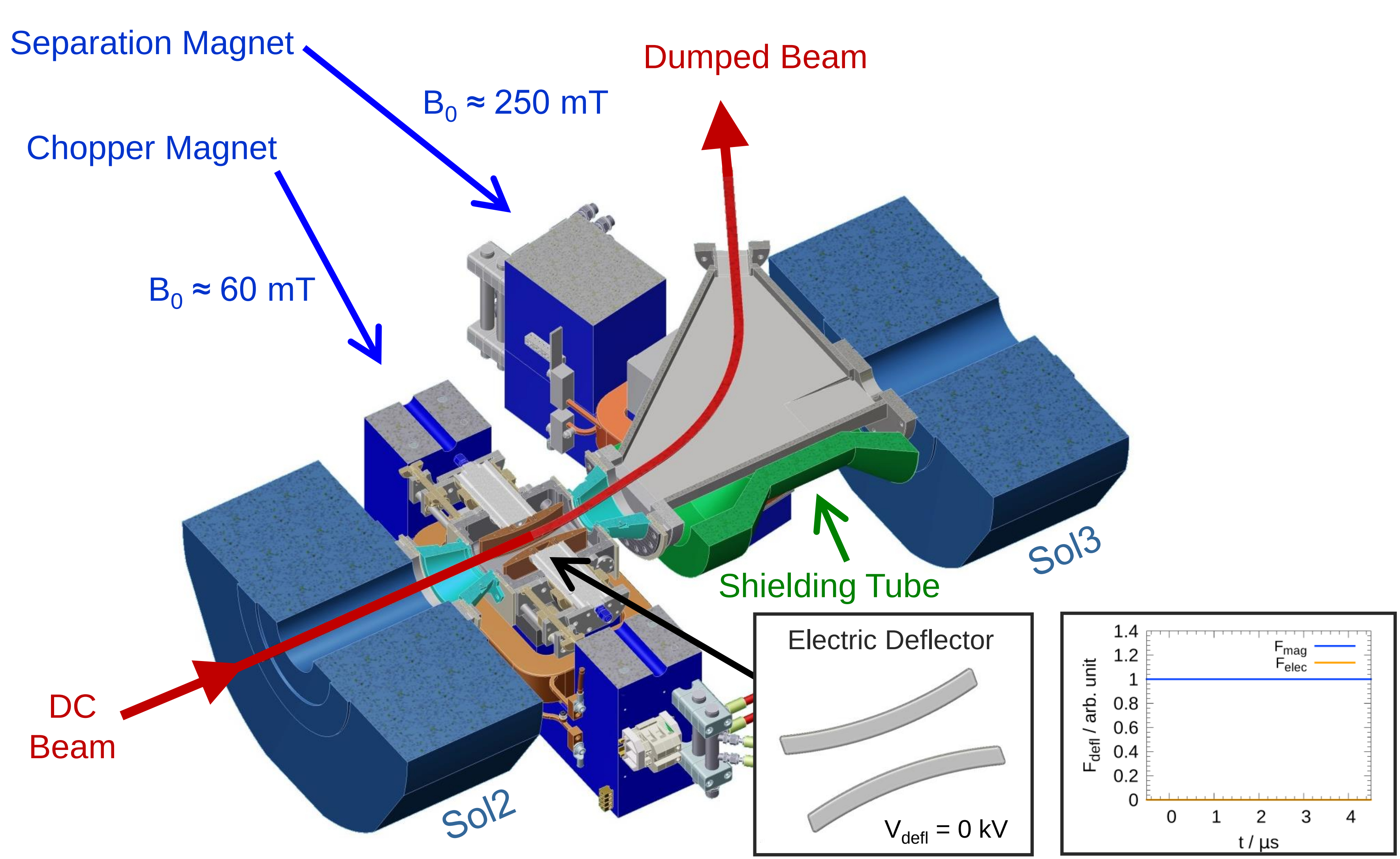
Low duty cycle for electric field.



E×B Chopper: Concept



E×B Chopper: Concept



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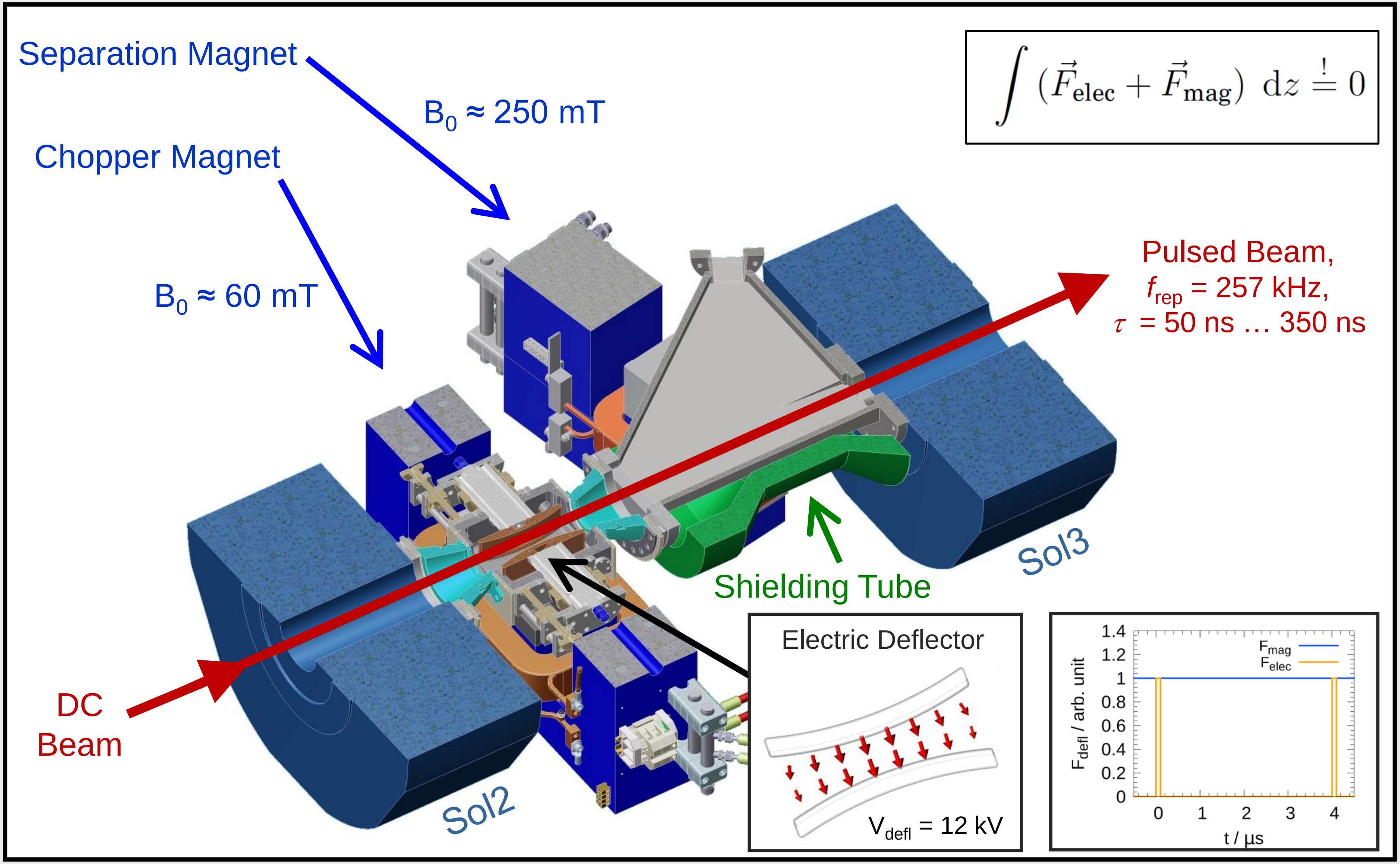
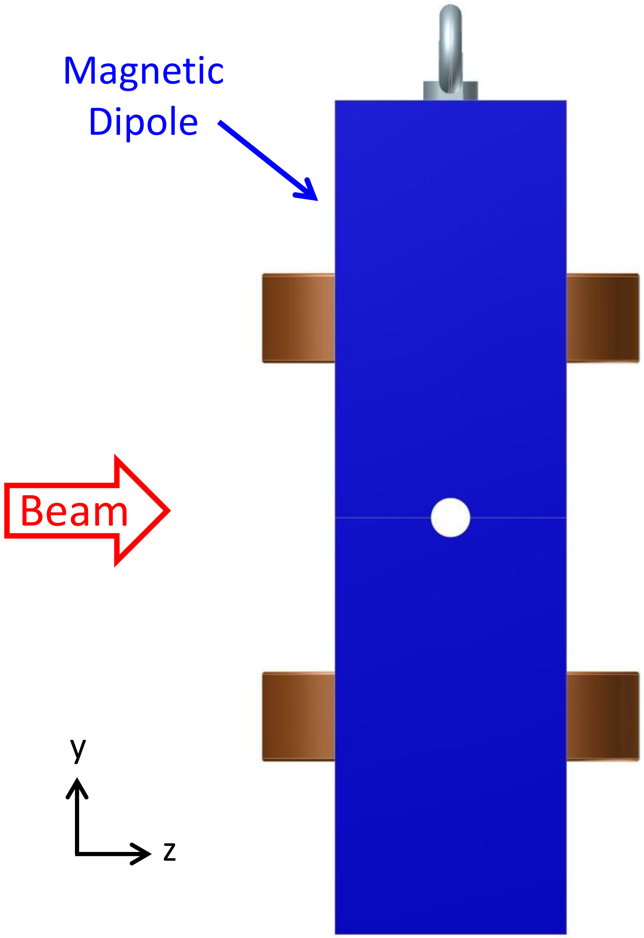
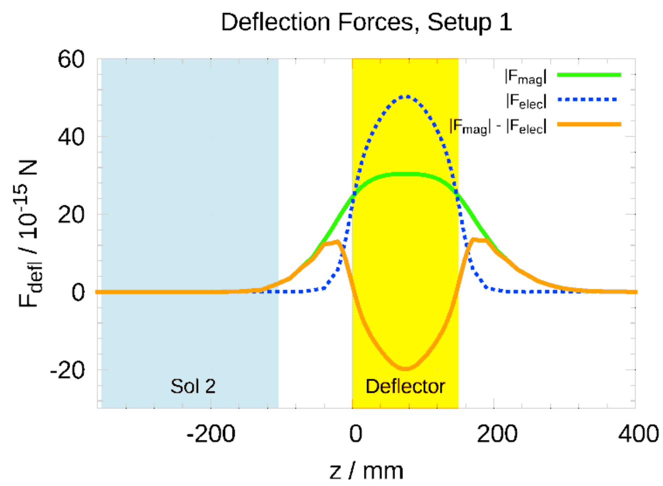
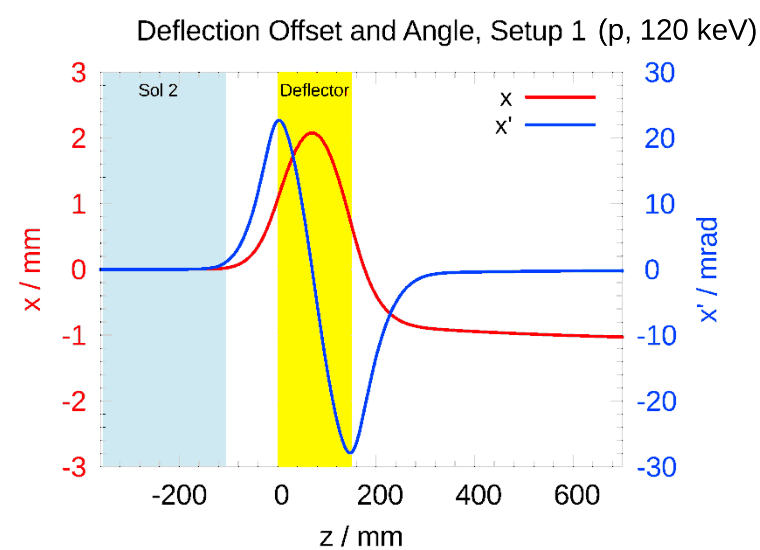


Beam Dynamics in Static E×B Fields

Longitudinal Matching of Deflection Forces







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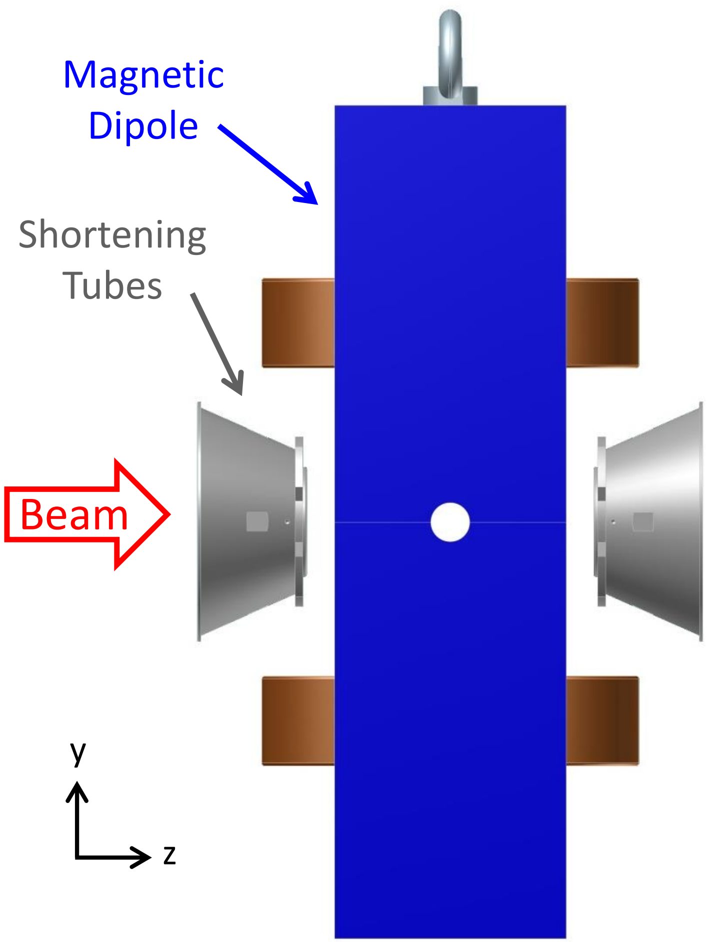

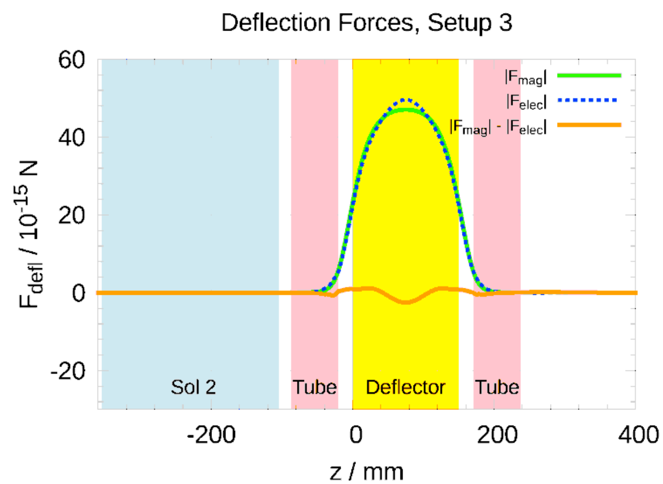

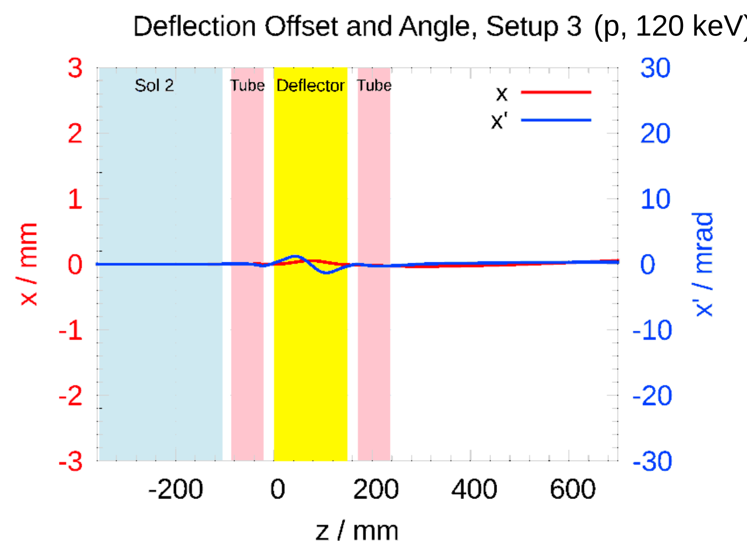

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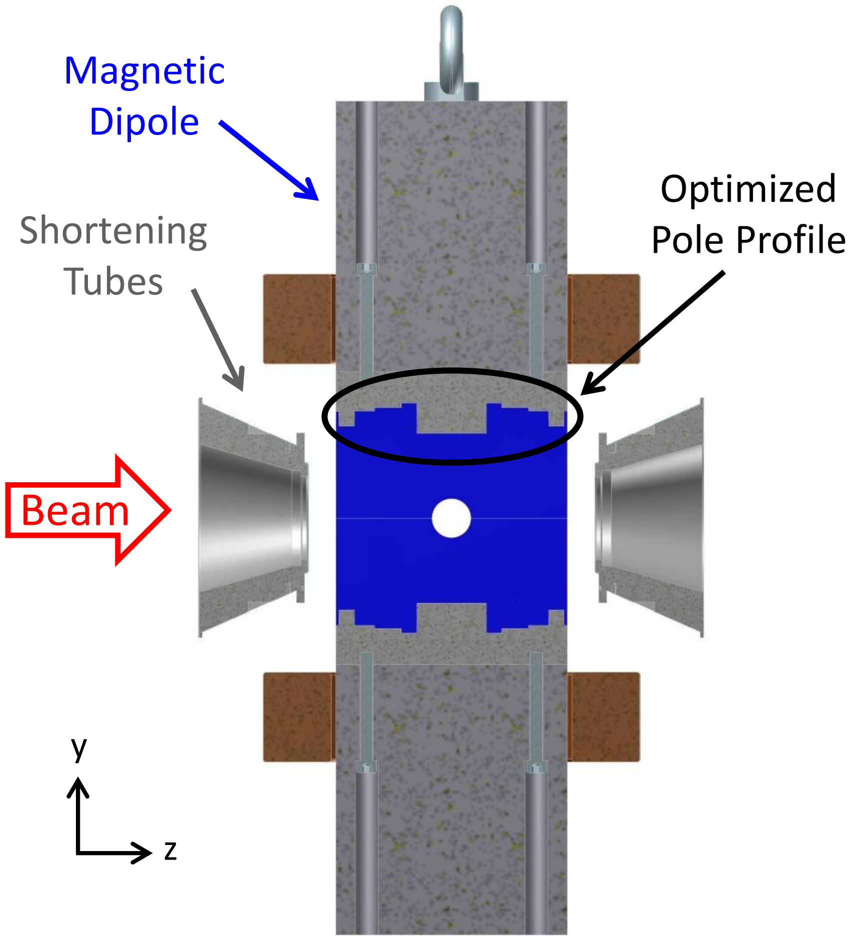
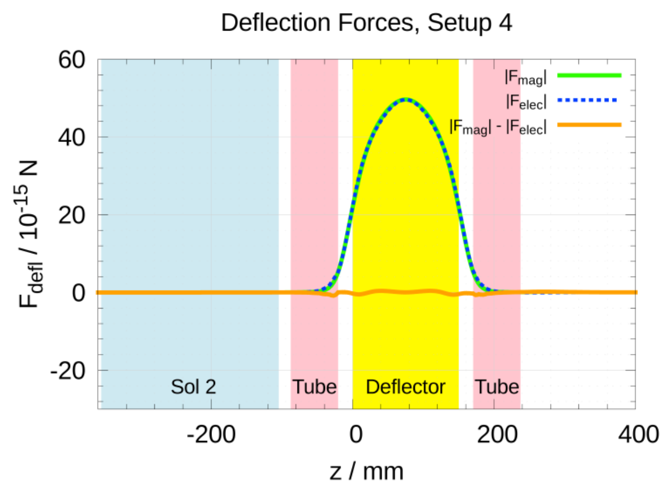
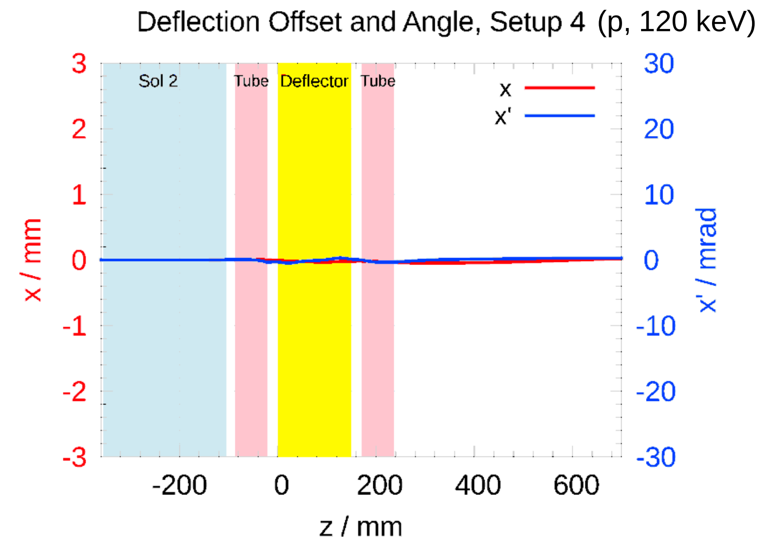
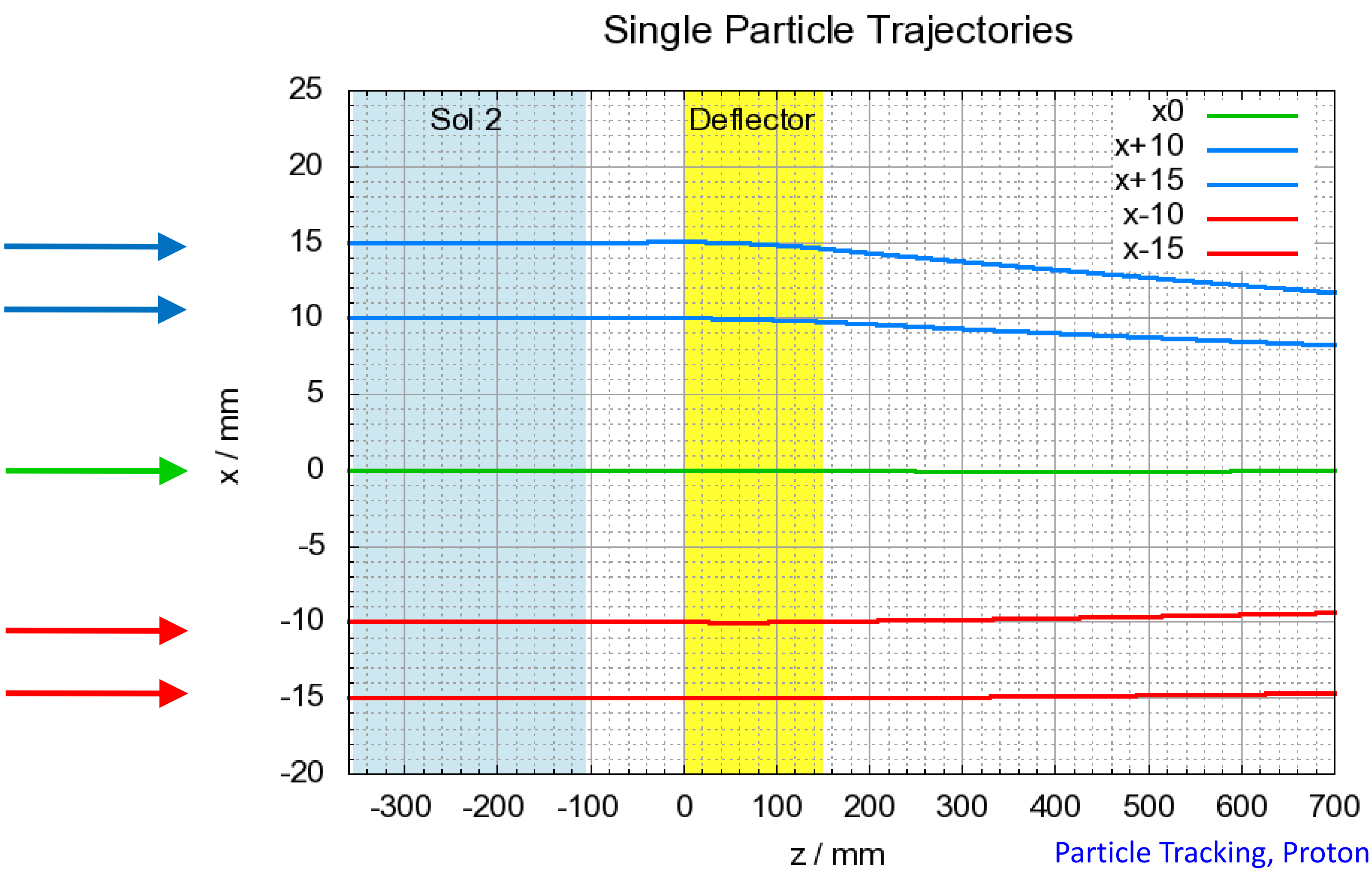






Beam Dynamics in Static E×B Fields

Transverse Matching of Deflection Forces

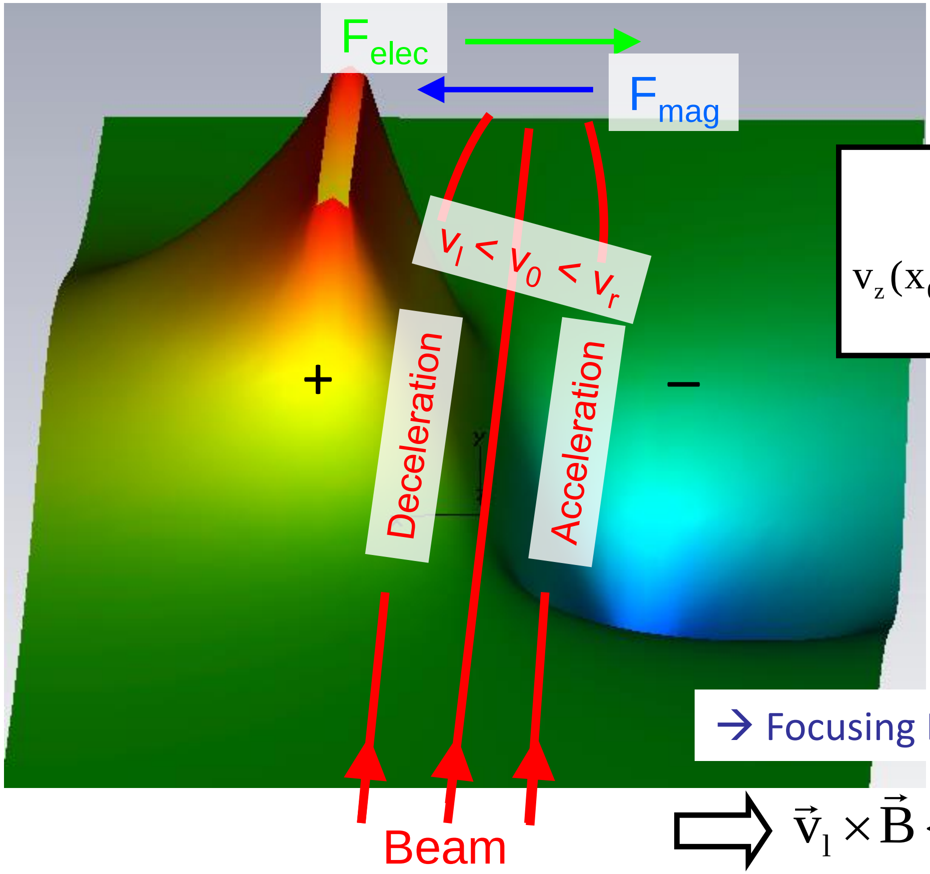


Particle Tracking, Protons, 120 keV.

Beam Dynamics in Static E×B Fields

Effect 1: Wien-Focusing Effect.

$$\int q \cdot (\vec{E} + \vec{v}_\mathrm{p} \times \vec{B})\ \mathrm{d}z \overset{!}{=} 0$$



Velocity Change:

$$v_z(x_0) = \sqrt{\frac{2e(U_b + E_x x_0)}{m_p}}$$

→ Focusing Effect in *x* direction.

$$\Rightarrow \vec{v}_l \times \vec{B} < \vec{v}_0 \times \vec{B} < \vec{v}_r \times \vec{B}$$

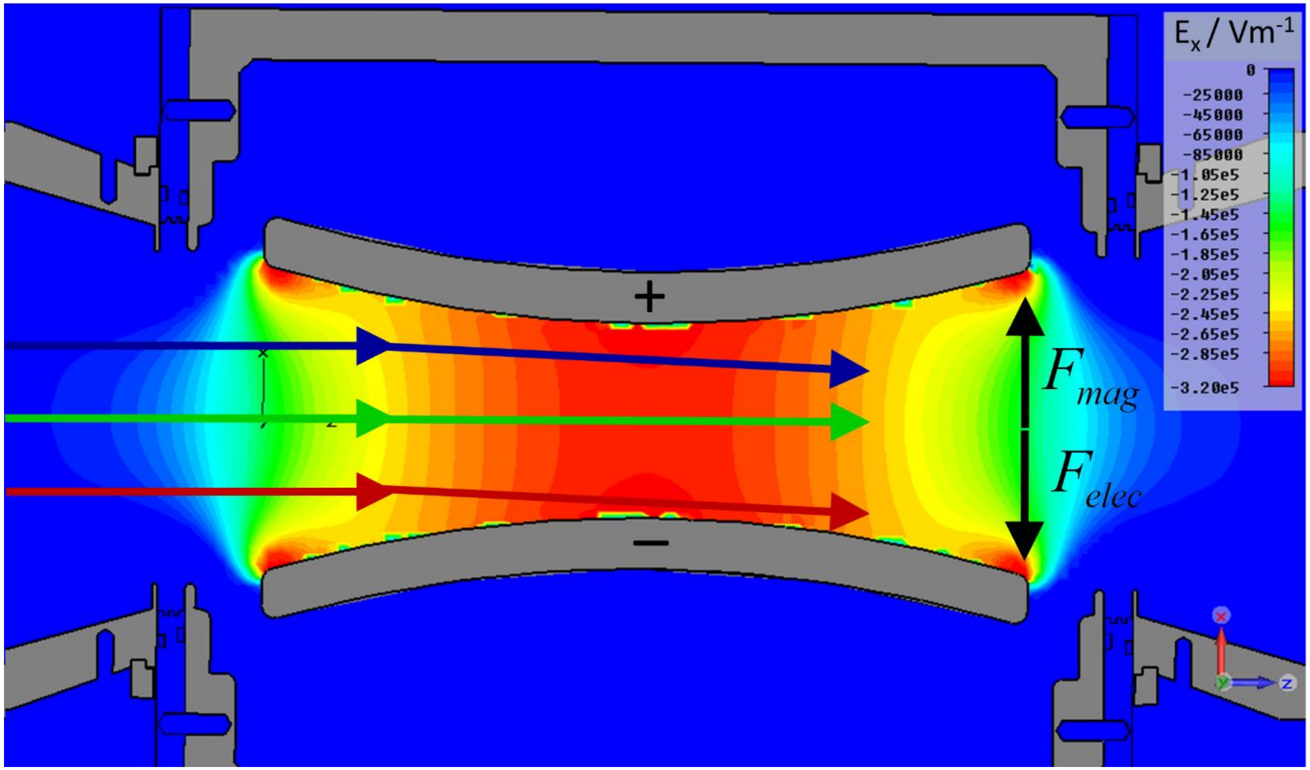
Beam Dynamics in Static E×B Fields

Effect 2: Given inhomogeneous field distribution.

$$\int F_{elec}\, dz\,|_{x=0mm} = \int F_{mag}\, dz\,|_{x=0mm}$$

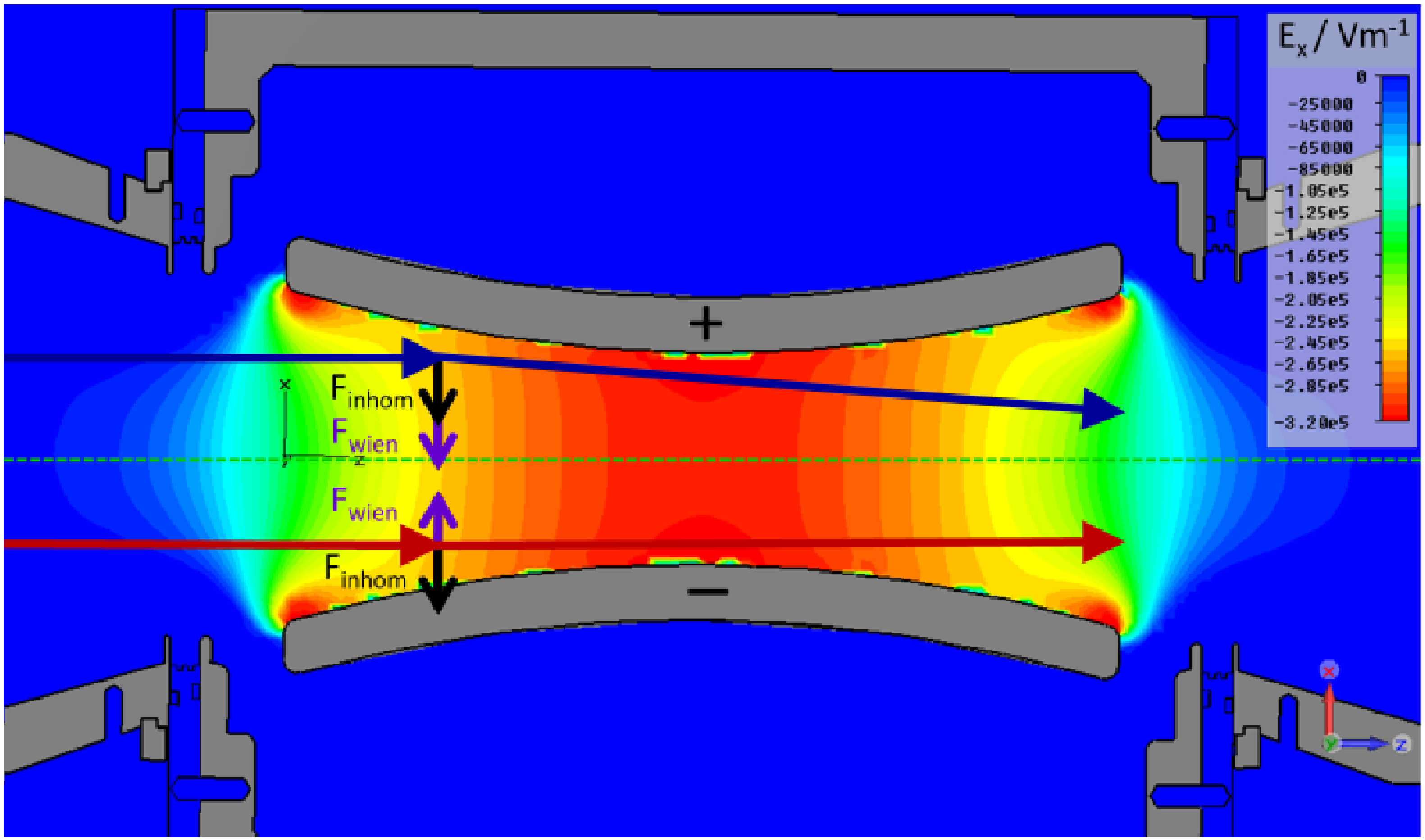
$$\int F_{mag}\, dz\,|_{x=\pm 15mm} < \int F_{mag}\, dz\,|_{x=0mm}$$

$$\int F_{elec}\, dz\,|_{x=\pm 15mm} > \int F_{elec}\, dz\,|_{x=0mm}$$

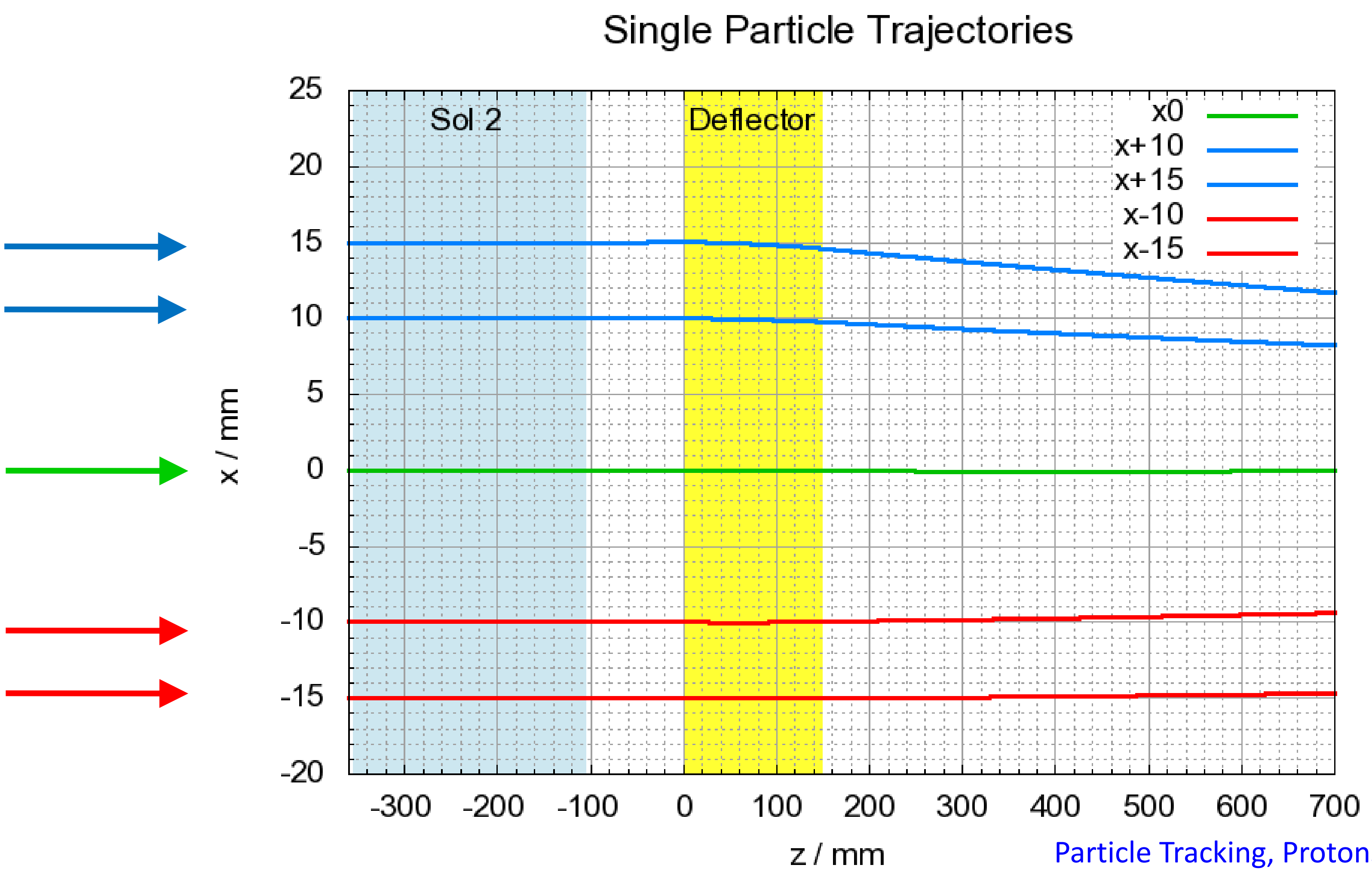


Beam Dynamics in Static E×B Fields

Superposition of both effects.



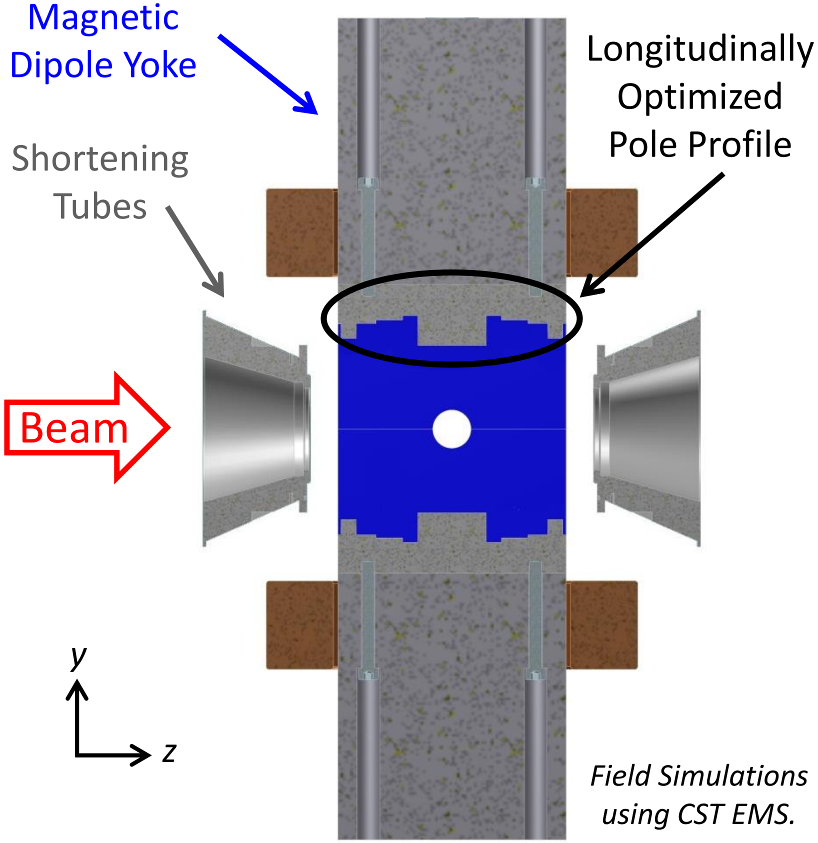
Beam Dynamics in Static E×B Fields



Particle Tracking, Protons, 120 keV.

Beam Dynamics in Static E×B Fields

Longitudinal Matching of Deflection Forces



Field Simulations using CST EMS.

- Minimizing horizontal beam movement
- Minimizing position offset

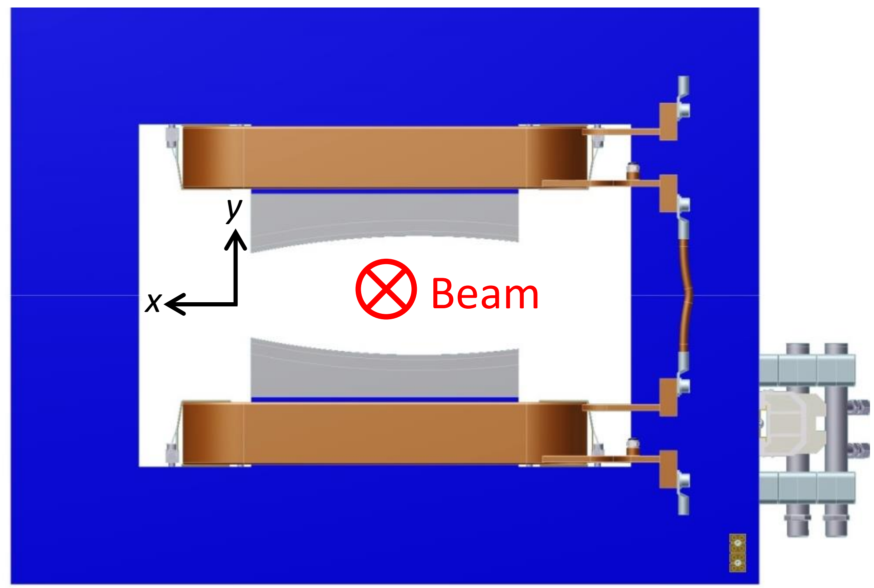
Transverse Matching of Deflection Forces

Optimized Pole Profile:

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

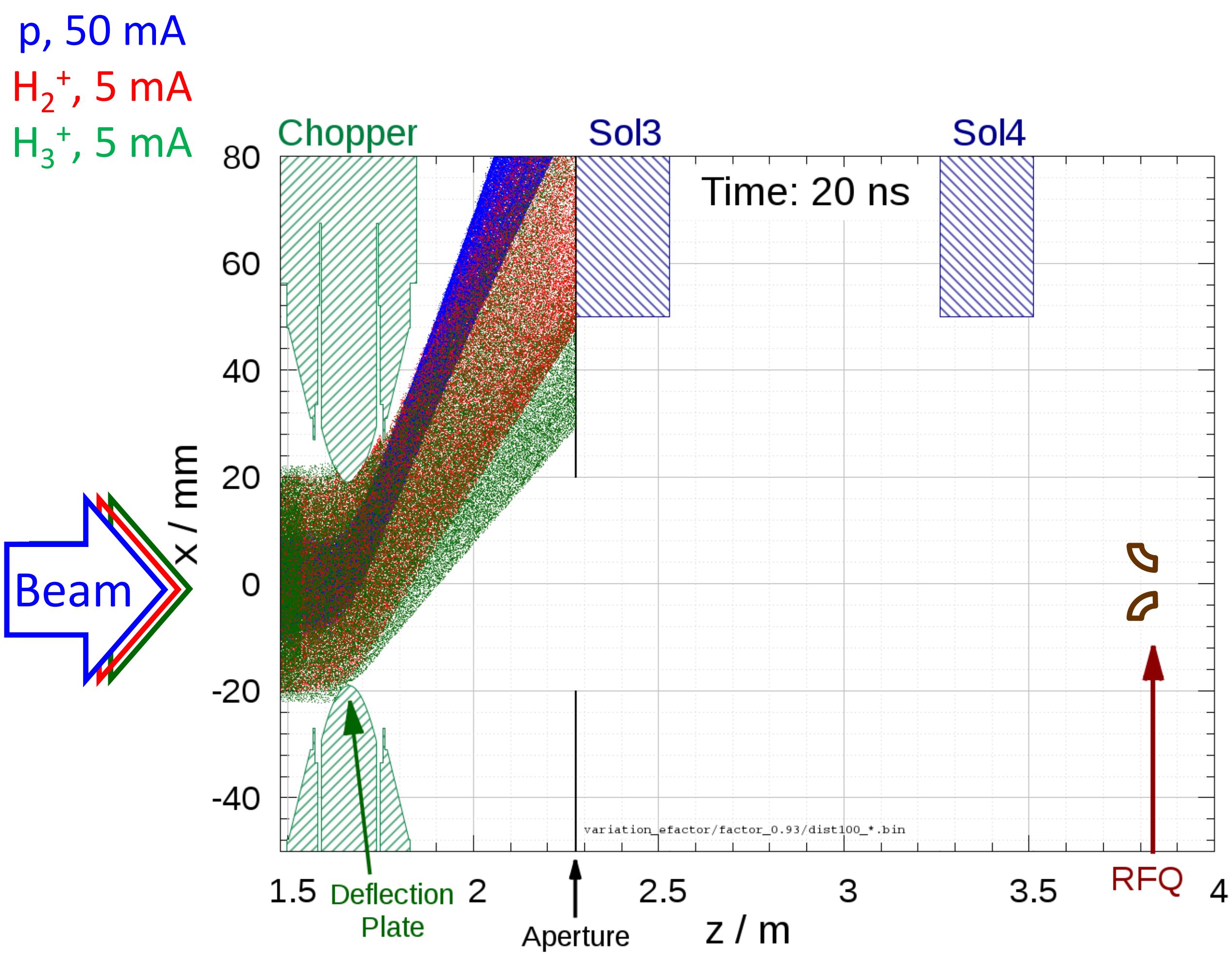
Compensation of Velocity Change

Field Homogenization



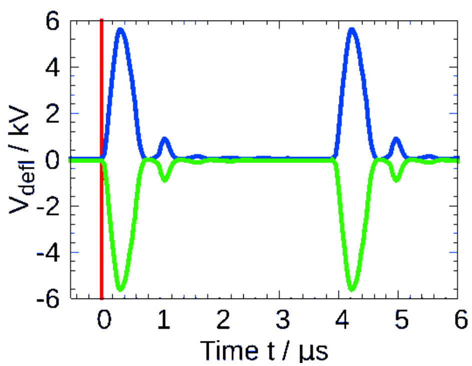
- Focusing in both transverse planes
- Preserving cylindrical symmetry

Beam Shaping Simulation



Input Data

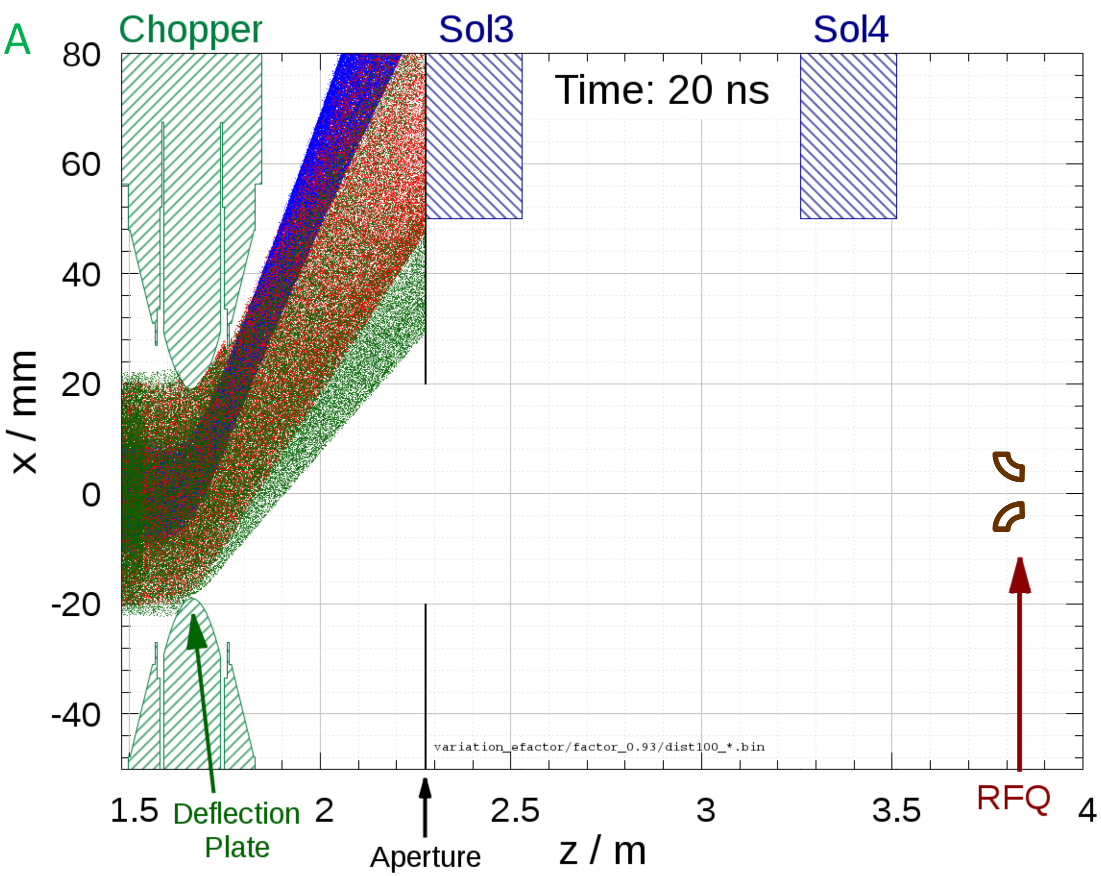
- W_b = 120 keV
- I_{proton} = 50 mA
- Matched Input Distribution
- 3d *E*-field of deflect. plates
- 3d *B*-field of chopper magnet
- 3d *B*-field of solenoids
- Measured HV Pulse



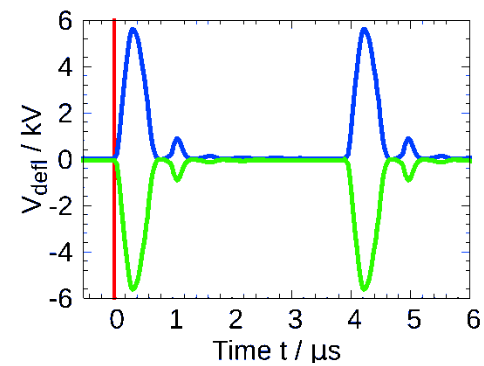
Beam dynamics calculations using PIC-Code Bender. → By Daniel Noll.

Beam Shaping Simulation

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



Voltage Pulse



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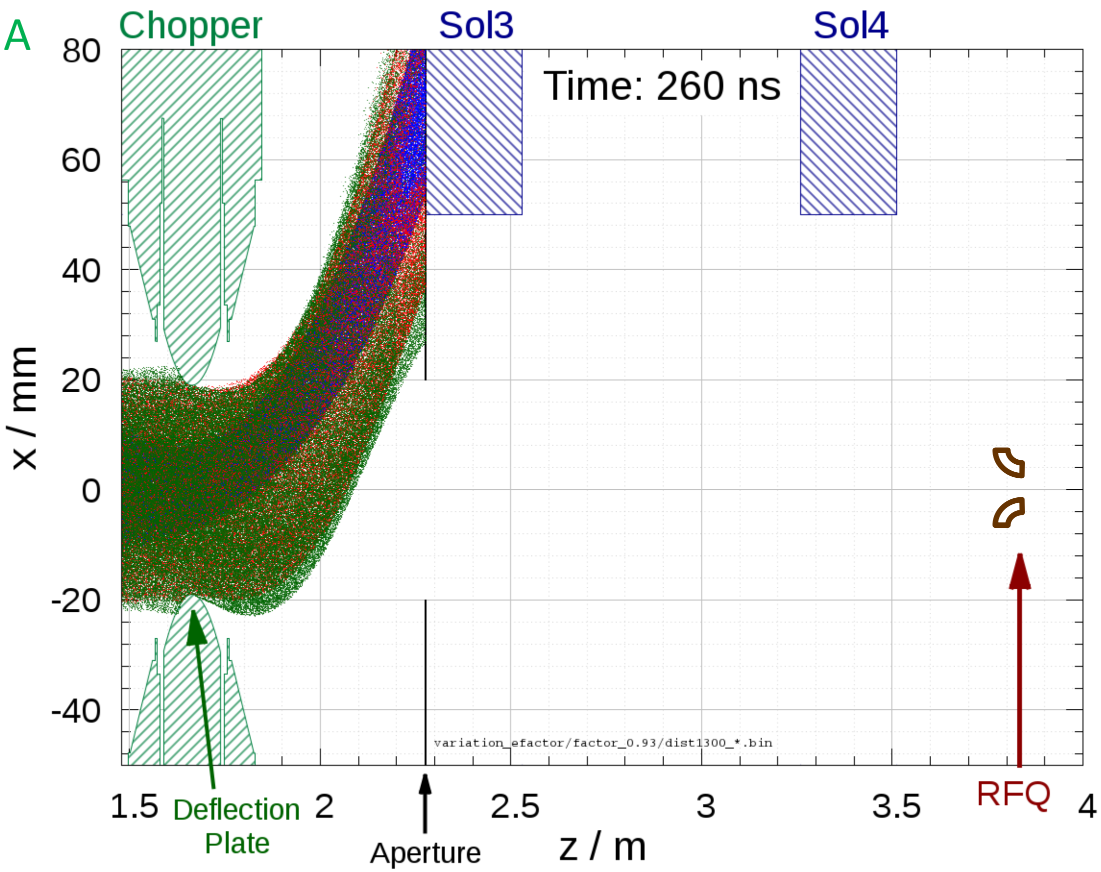

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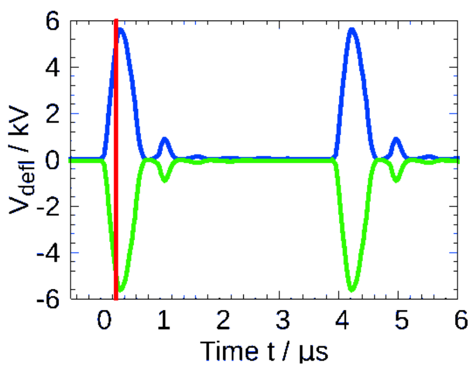

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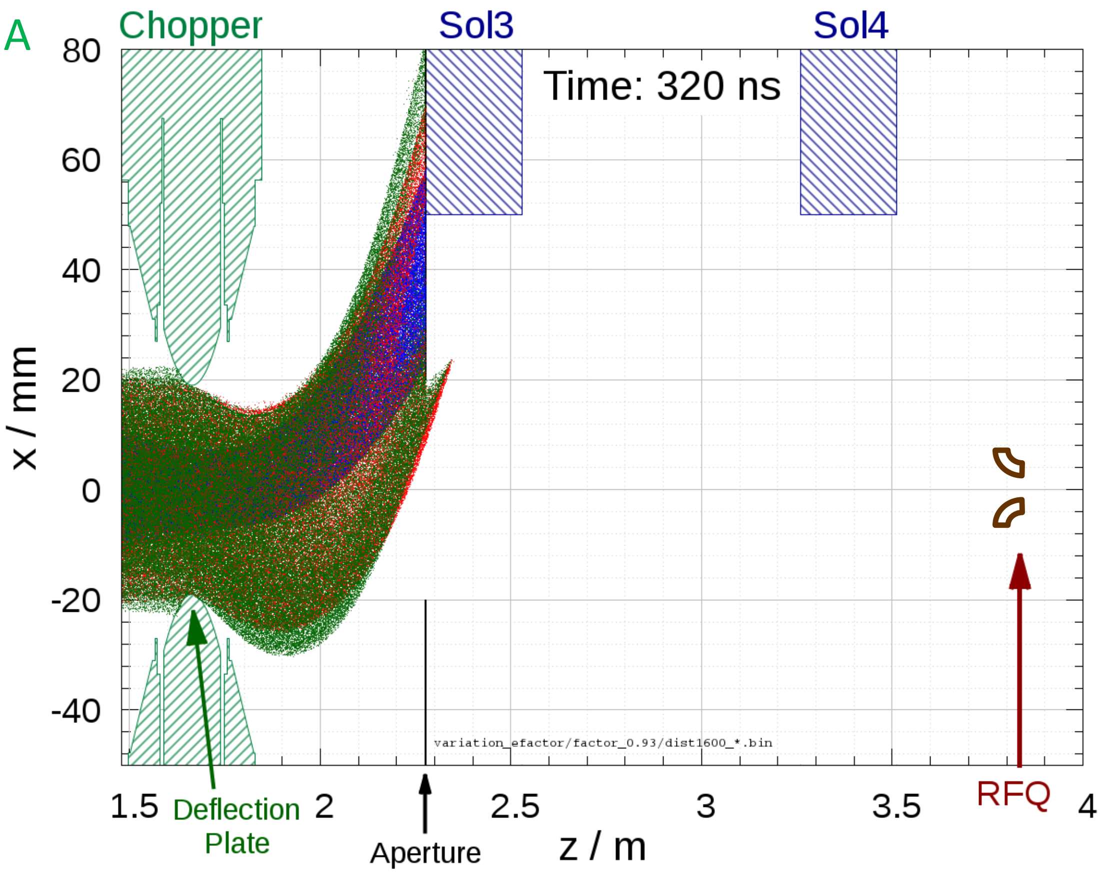

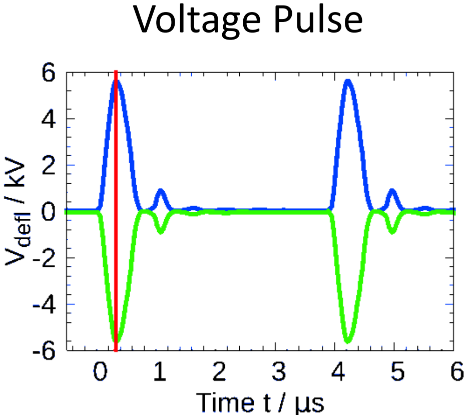

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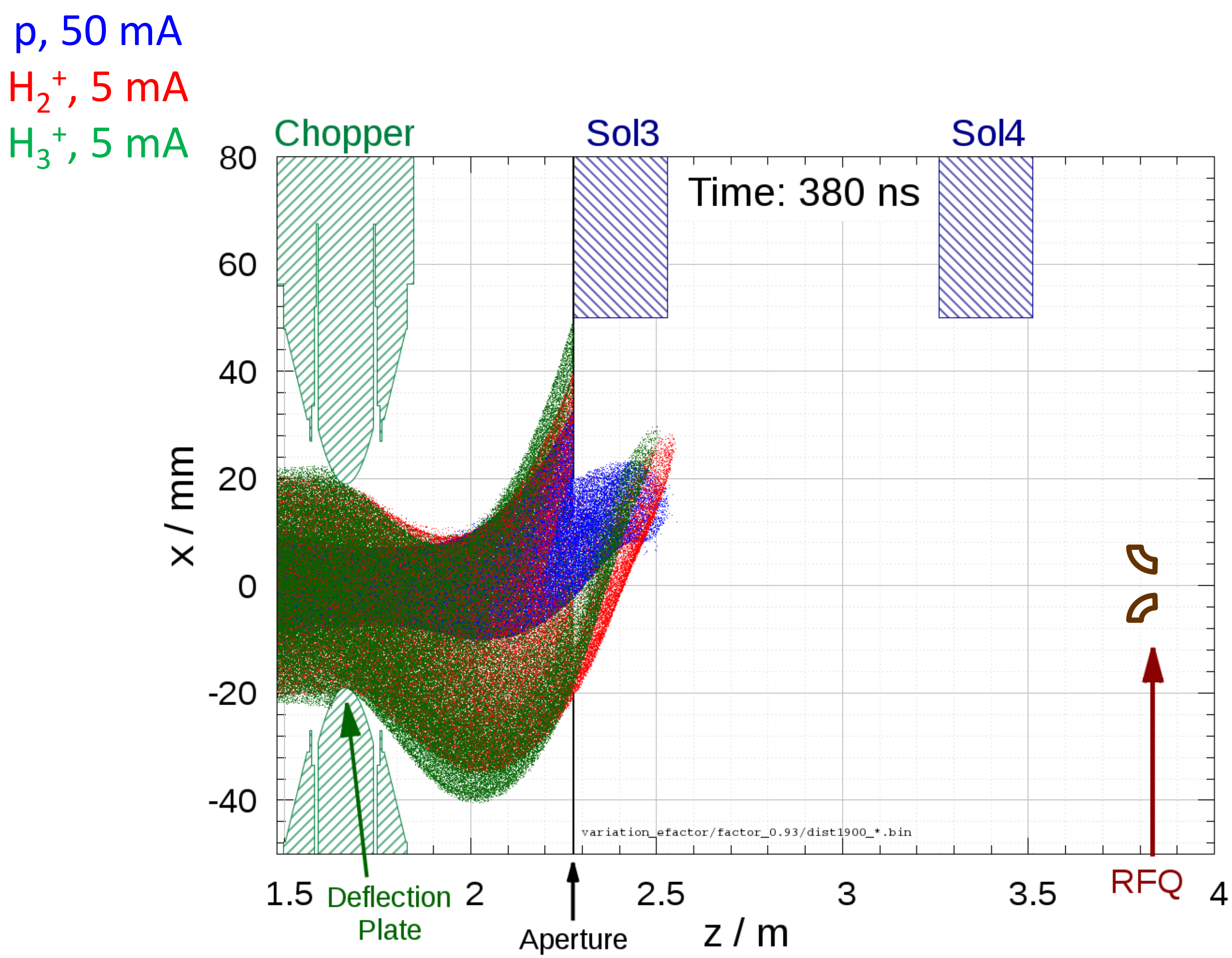

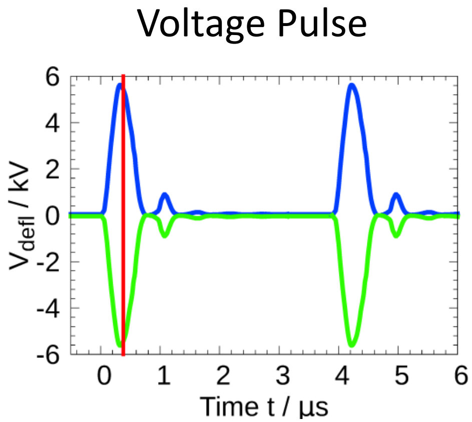

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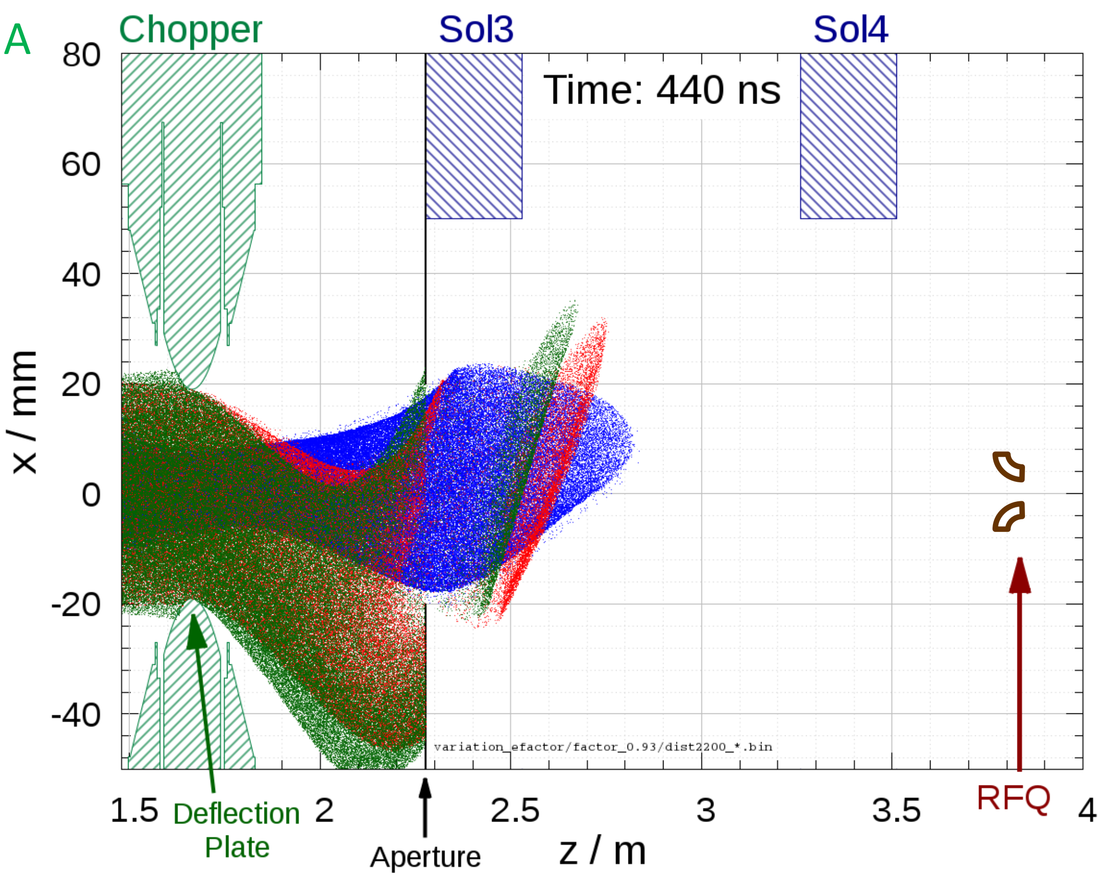

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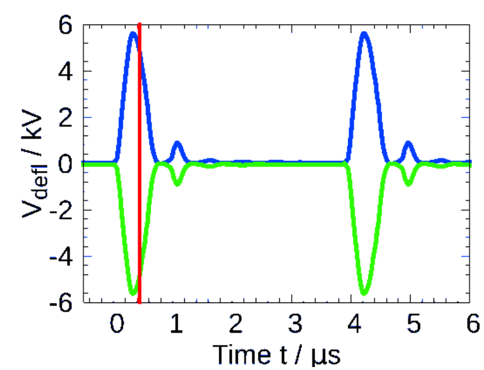

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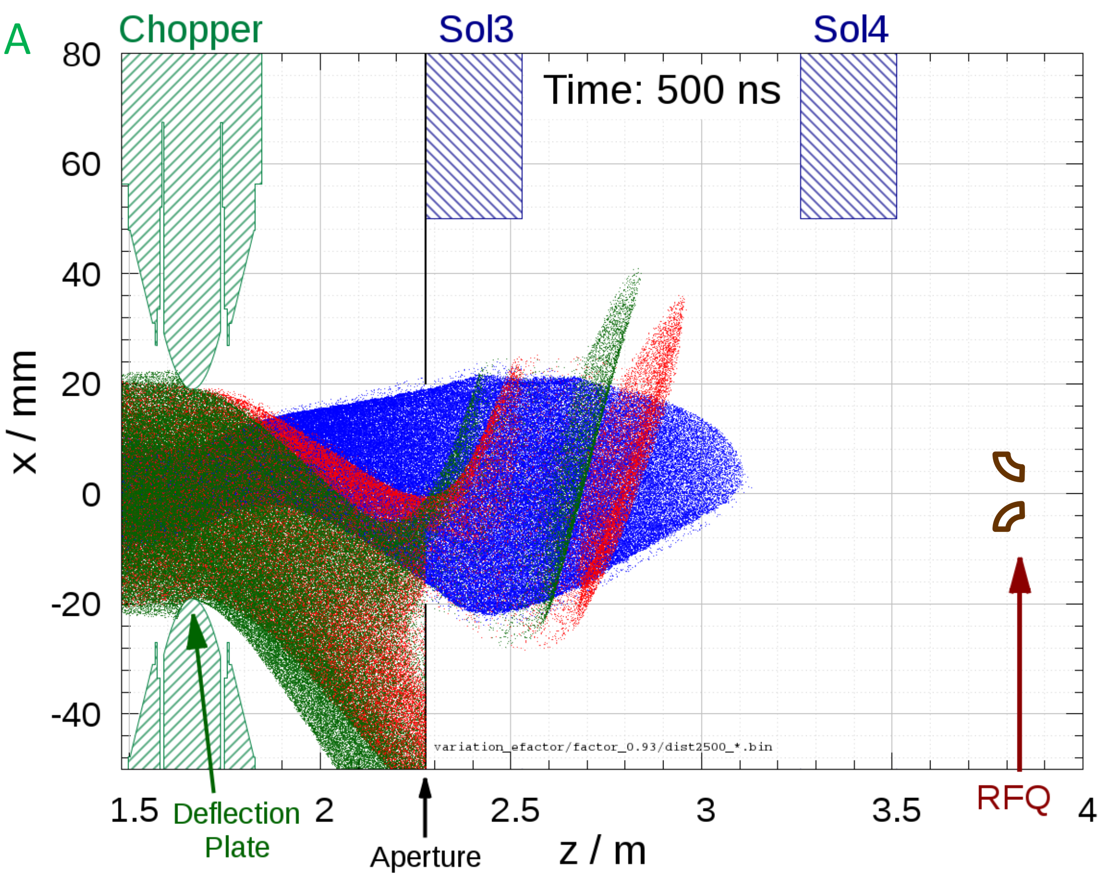

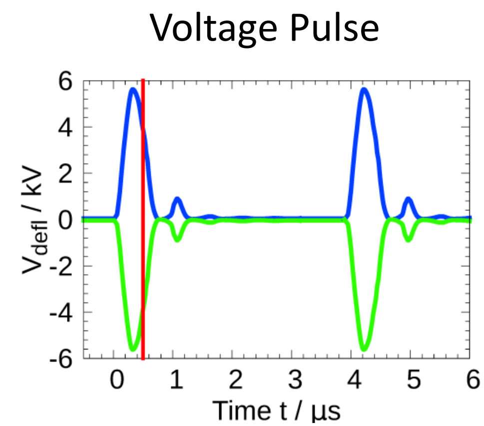

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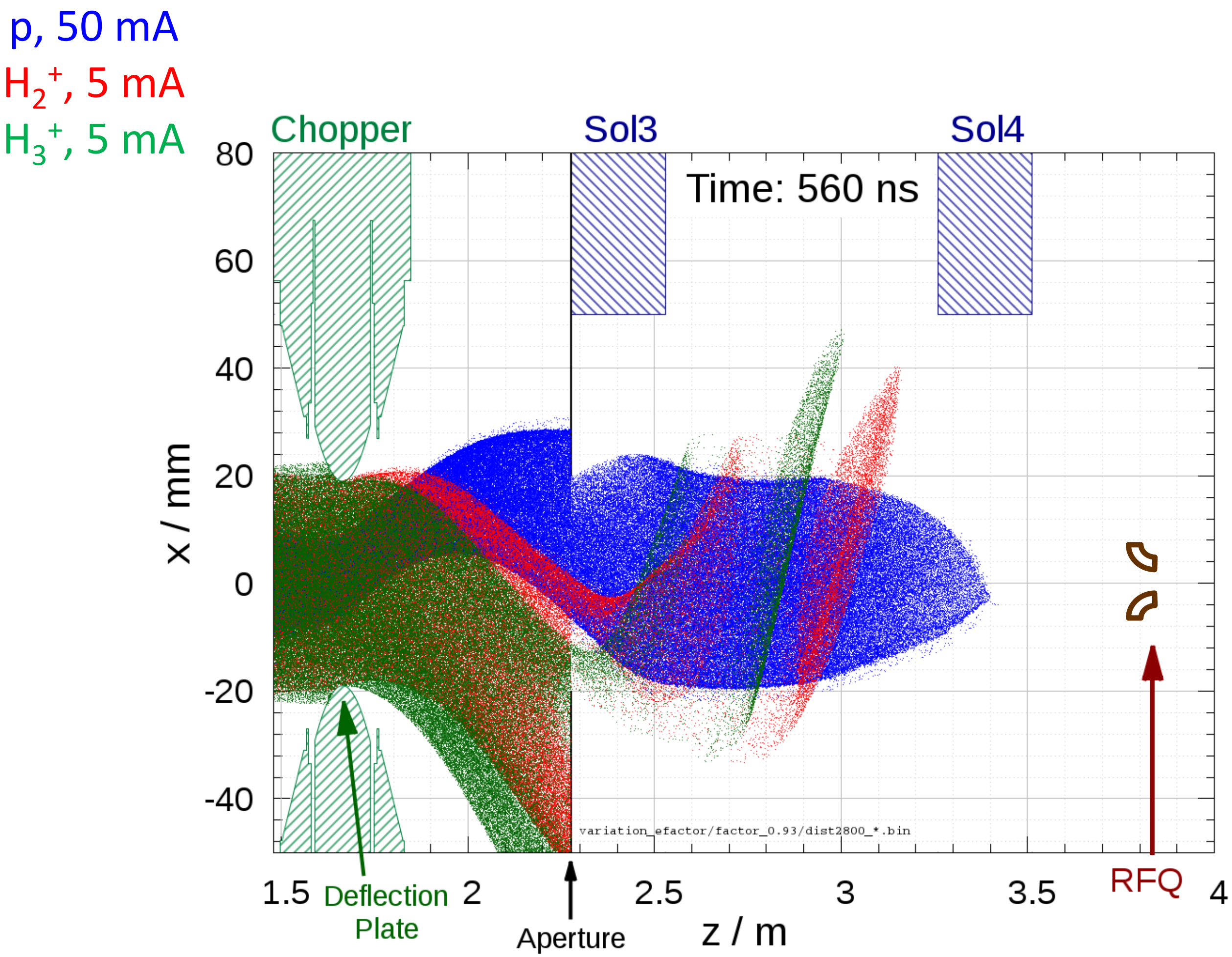

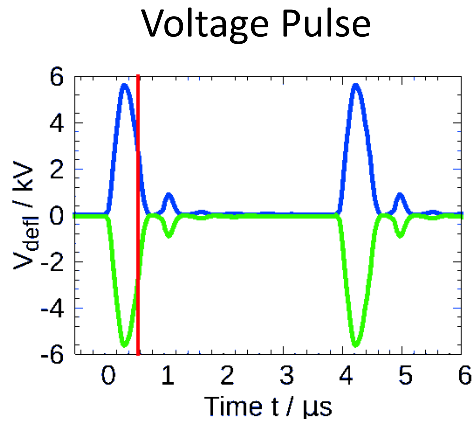

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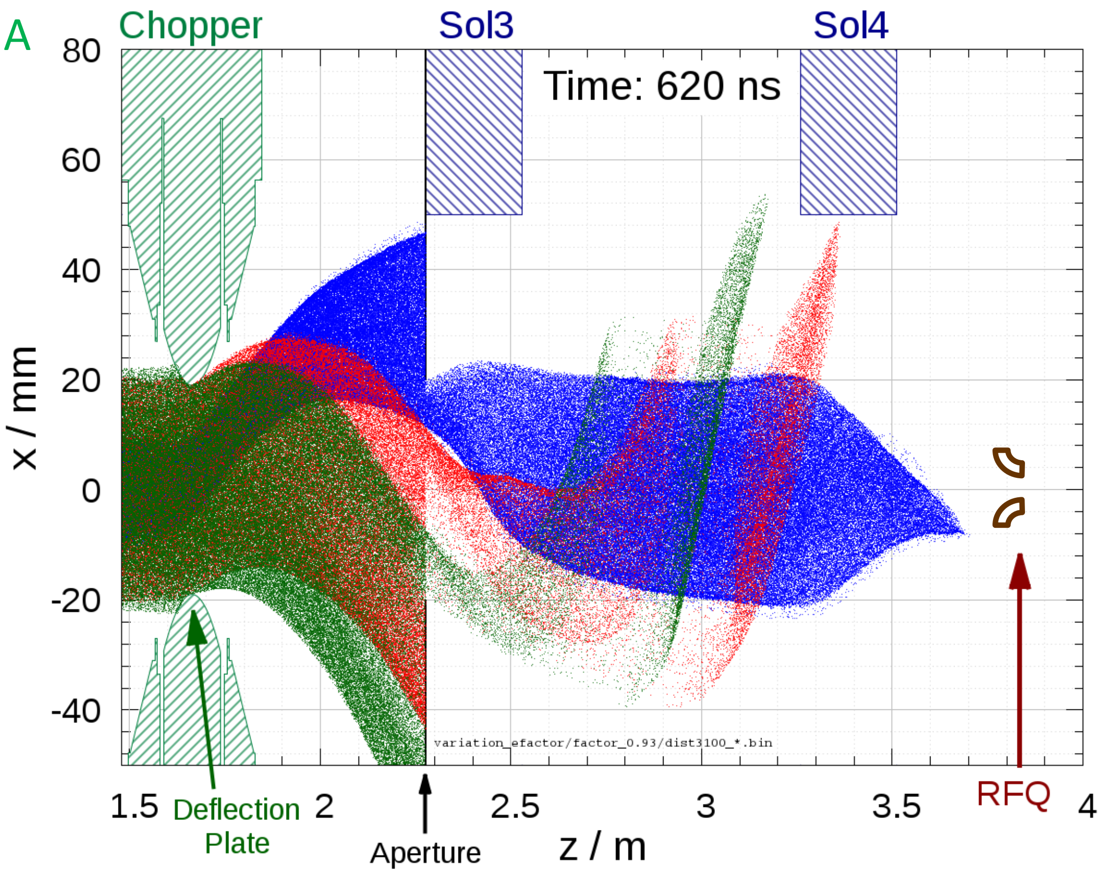
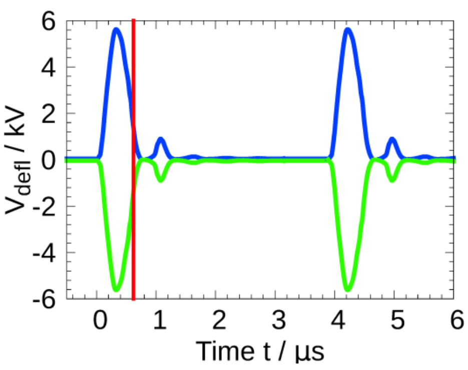
Beam Shaping Simulation

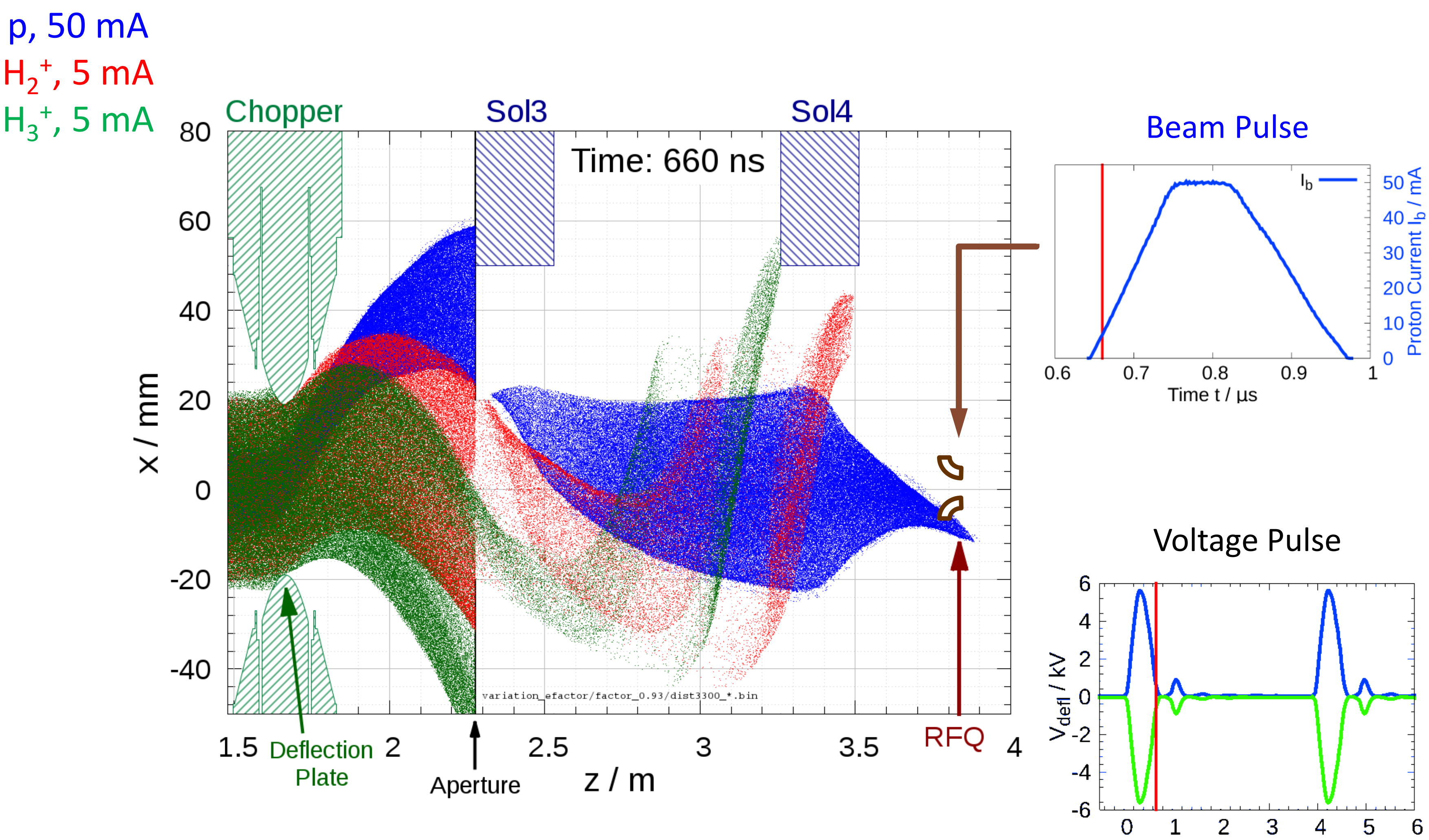
p, 50 mA
H_2^+, 5 mA
H_3^+, 5 mA





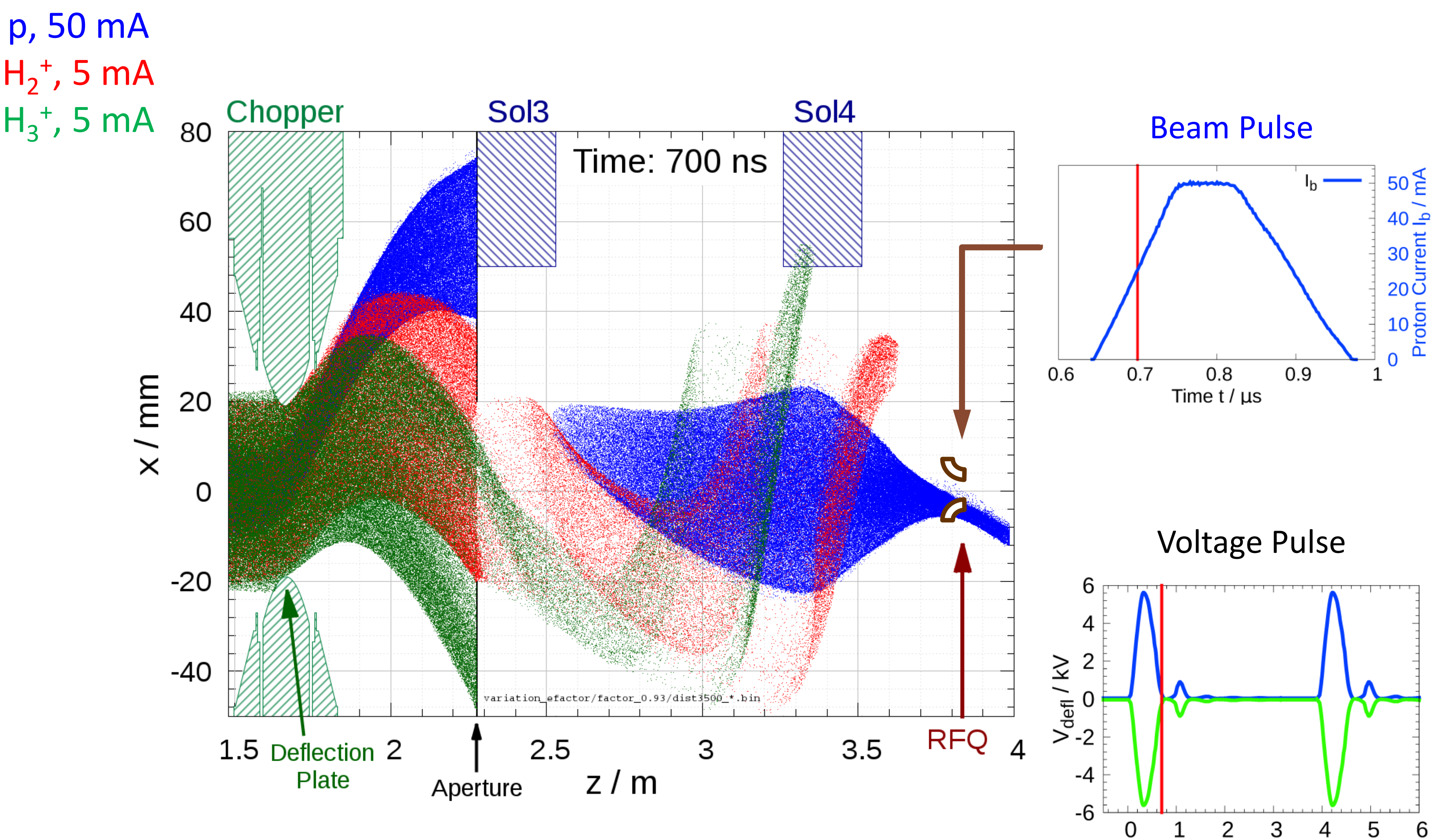
Beam dynamics calculations using PIC-Code Bender.

Beam Shaping Simulation



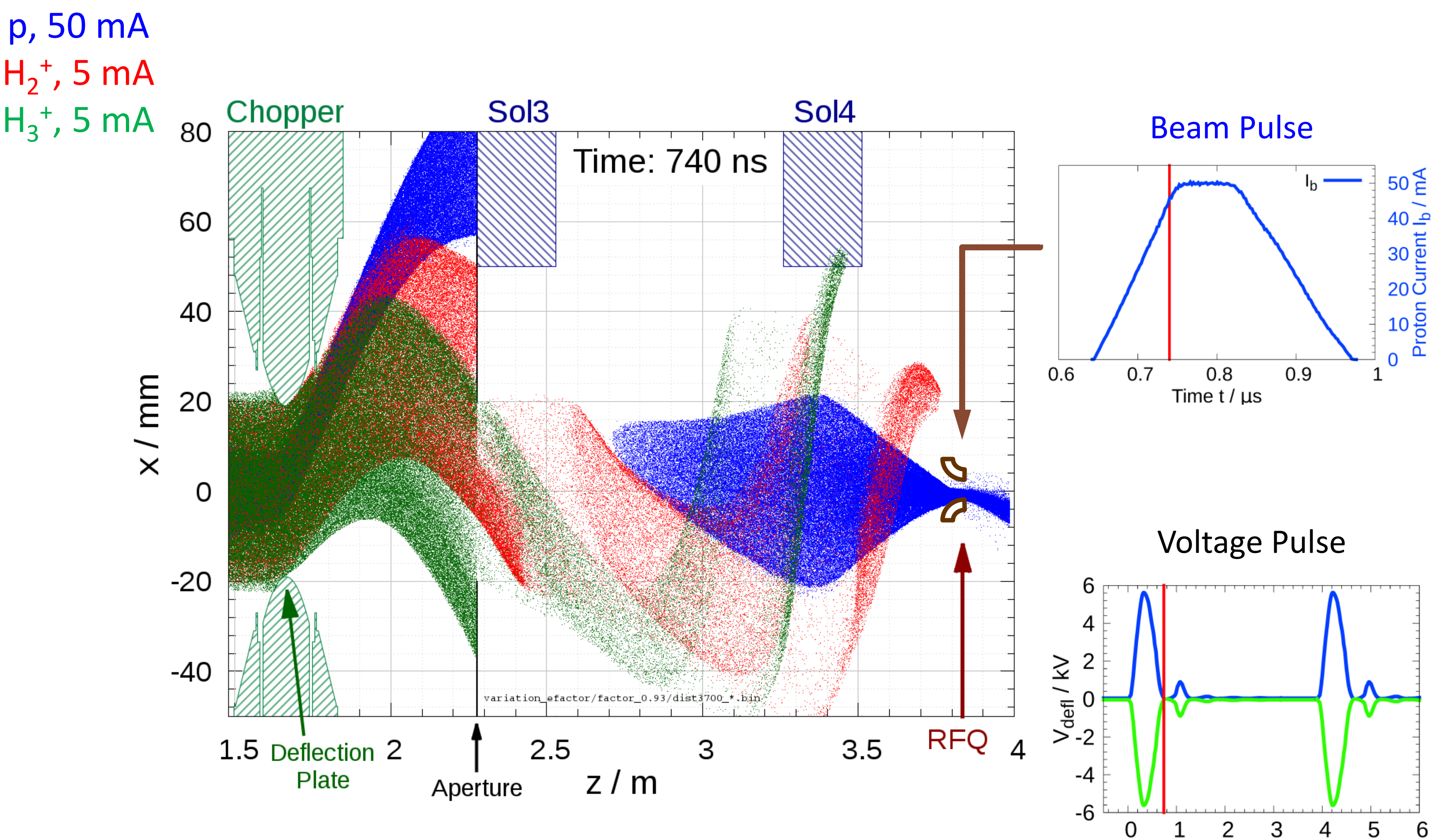
Beam dynamics calculations using PIC-Code Bender.

Beam Shaping Simulation



Beam dynamics calculations using PIC-Code Bender.

Beam Shaping Simulation



Beam dynamics calculations using PIC-Code Bender.

Beam Shaping Simulation

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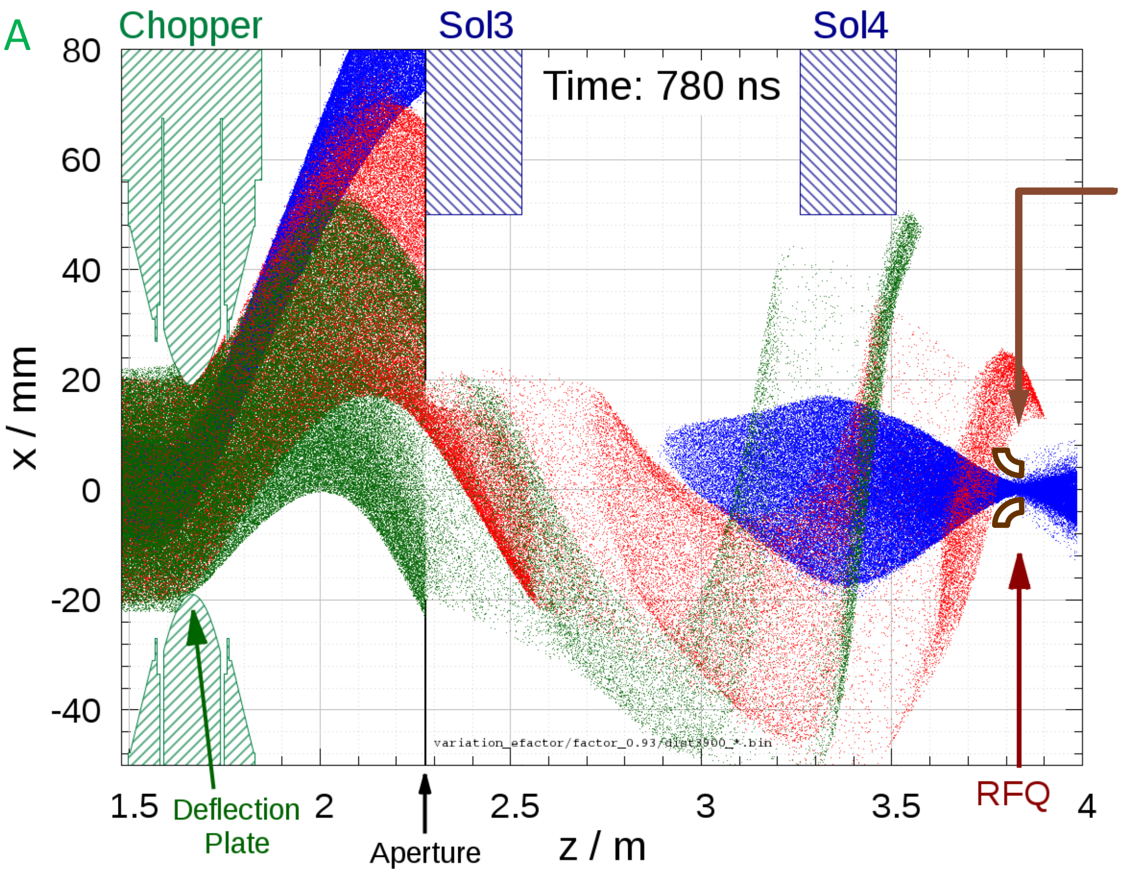
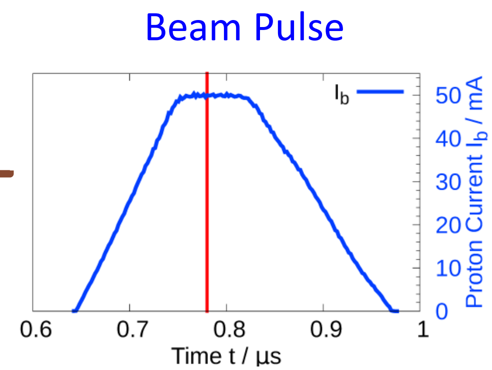
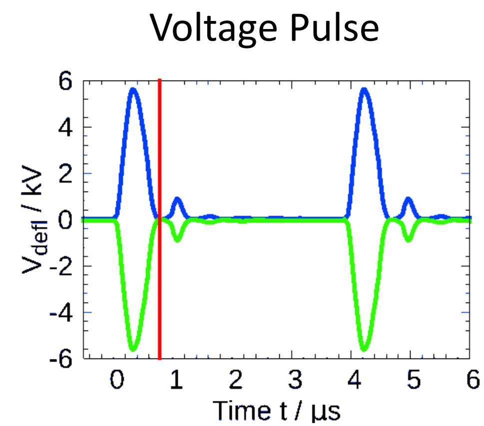


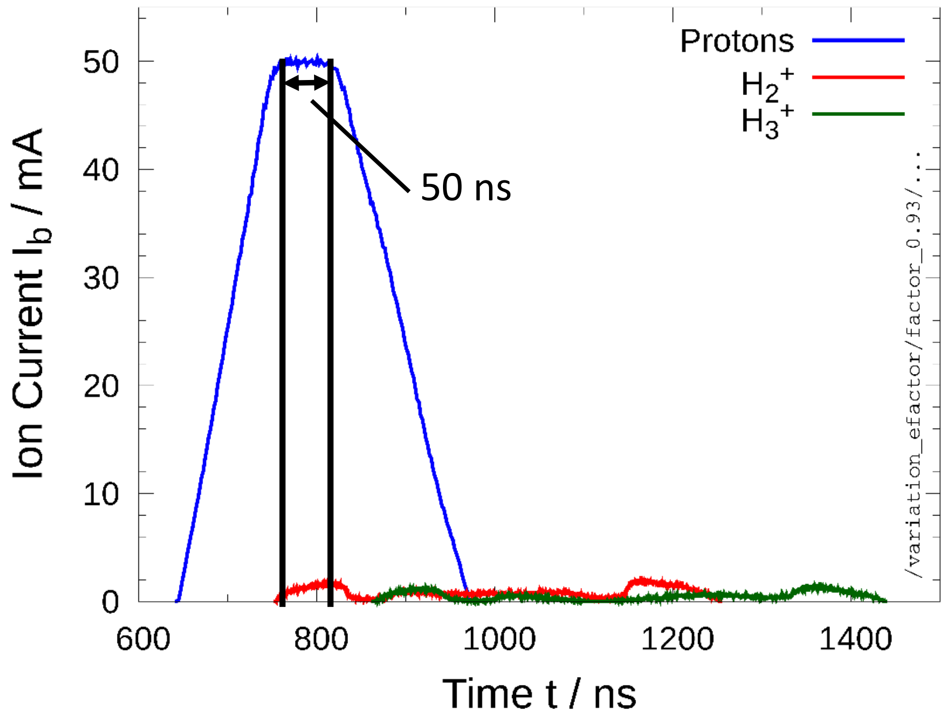




Beam dynamics calculations using PIC-Code Bender.

Beam Shaping Simulation

Simulated Pulse Shape at the RFQ Entrance



Results of Numerical Simulations:

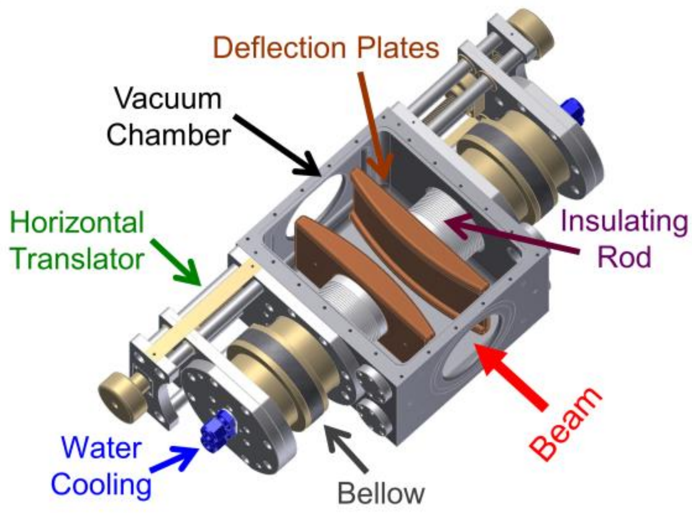
- Time requirements fulfilled.
- 50 ns flat top:
  - Position offset below ±0.3 mm (necessary condition: *longitudinal* matching of deflection forces).
  - Low emittance.
  - Cylindrical symmetry preserved (necessary condition: *transverse* matching of deflection forces).
- Low transmission for H_2^+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

Simulated without collimator system in front of the RFQ.

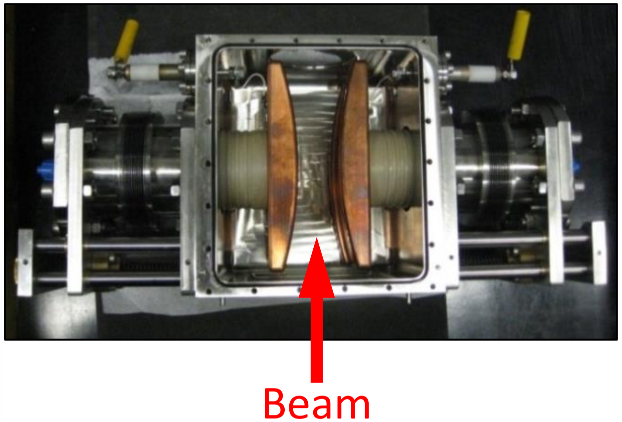
Chopper Hardware Design

Electric Deflector

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

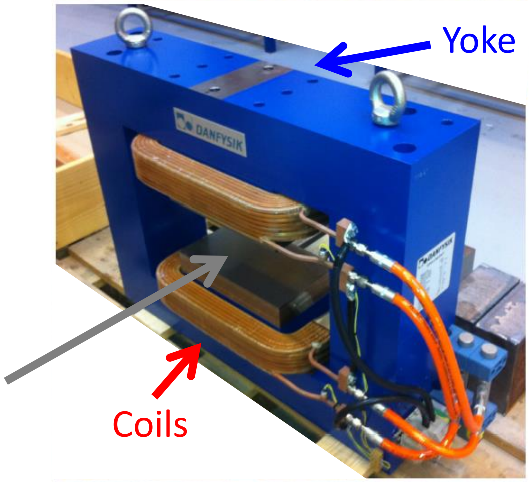


Deflection Chamber

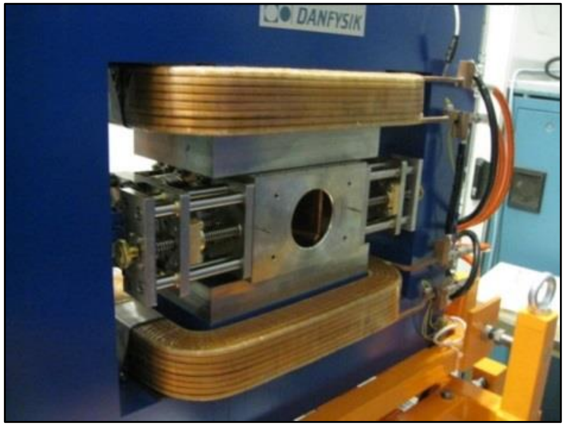


Magnetic Dipole

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



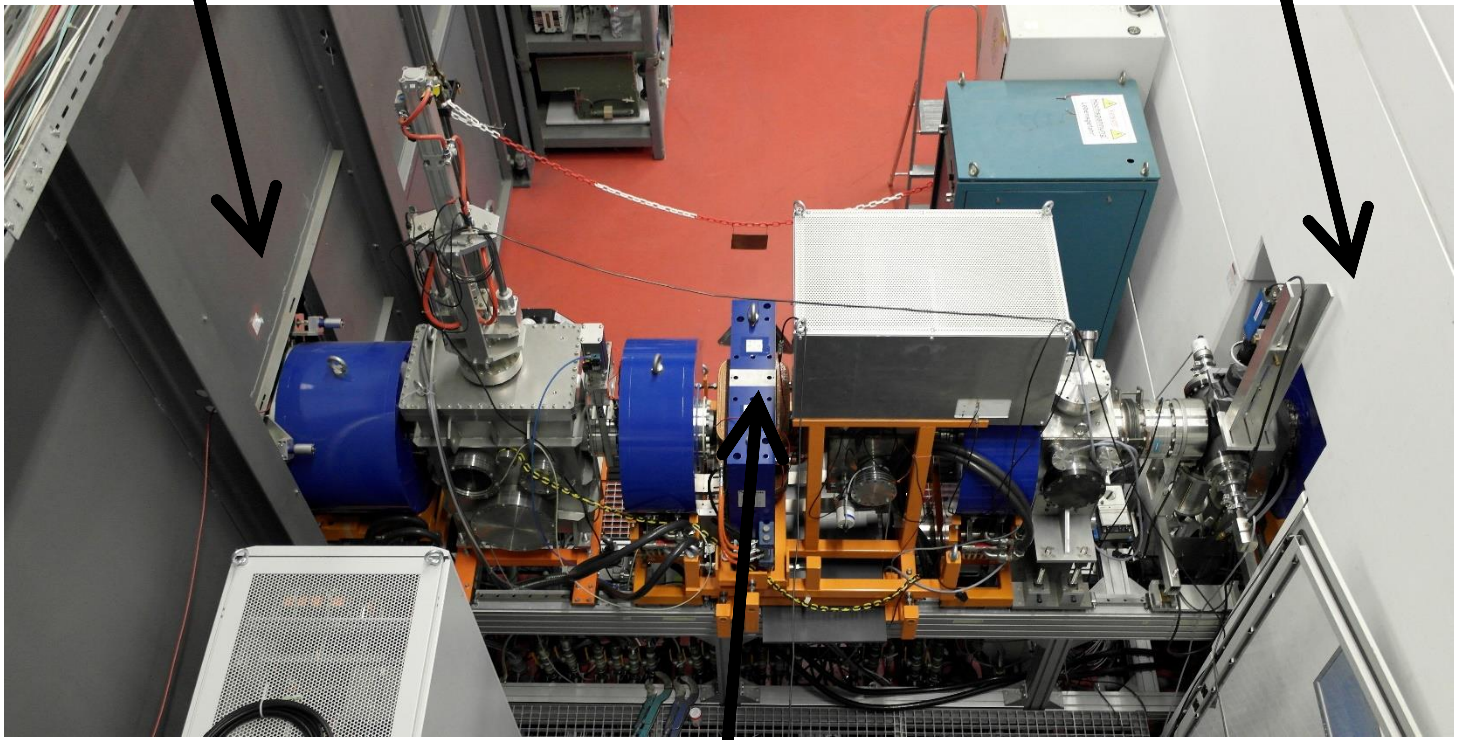
Deflection Chamber in Dipole



Commissioning

HV Terminal: 150 kV

Concrete Shielding
for linac and neutron target

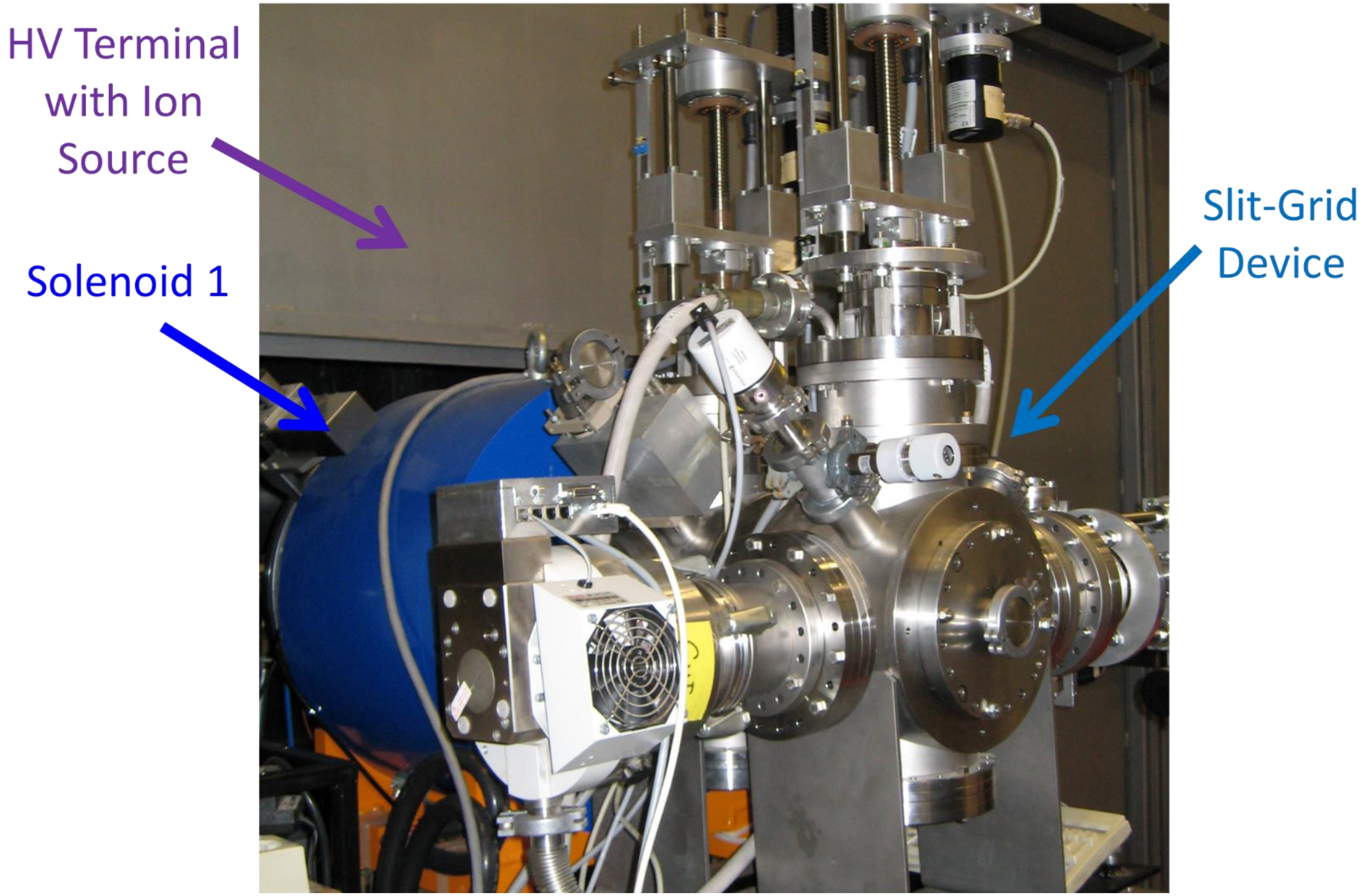


LEBT Section and E×B chopper

Measurements: DC Beam

Emittance measurement behind Solenoid 1

He^+,
10 keV,
0.9 mA

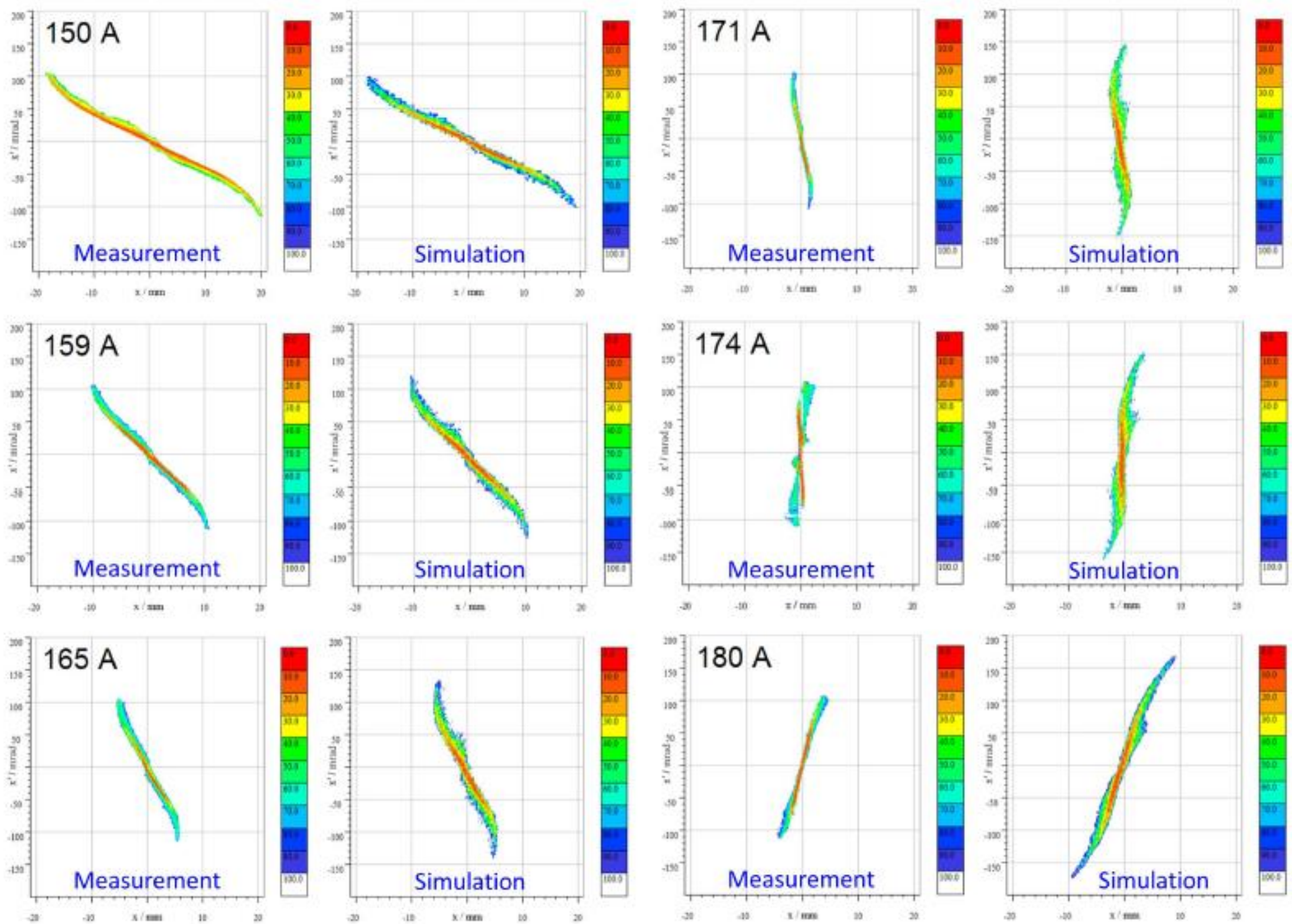


Measurements: DC Beam

He^+,
10 keV,
0.9 mA

Measured using slit-grid device, installed behind Sol1.

Simulated using Lintra code, assuming 85% space charge compensation.

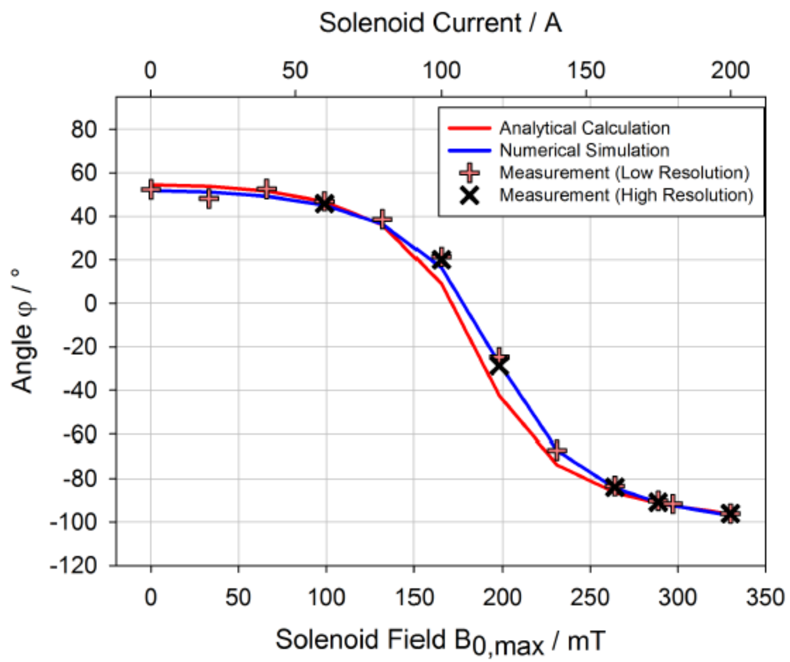


Measurements: DC Beam

He^+,
10 keV,
0.9 mA

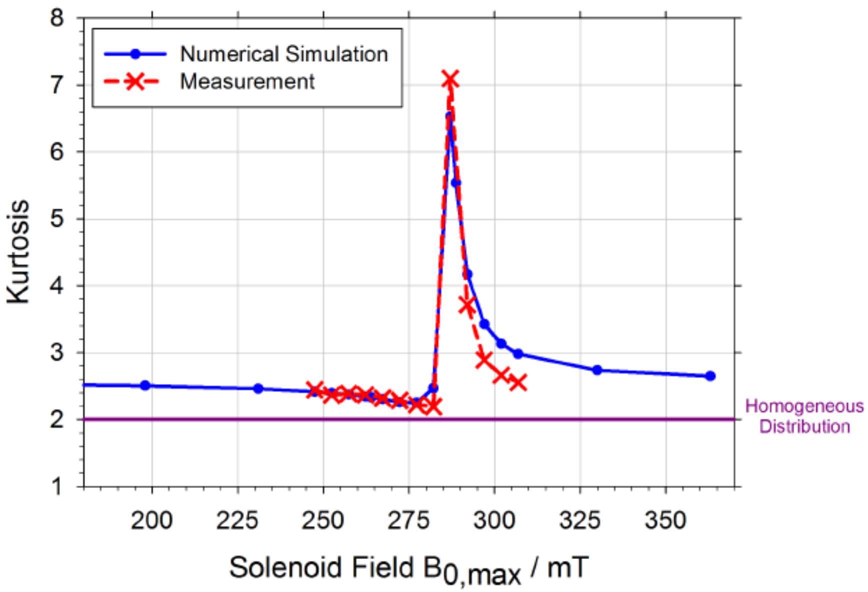
Phase-space angle

$$\tan 2\varphi = \frac{2\alpha}{\gamma - \beta}$$

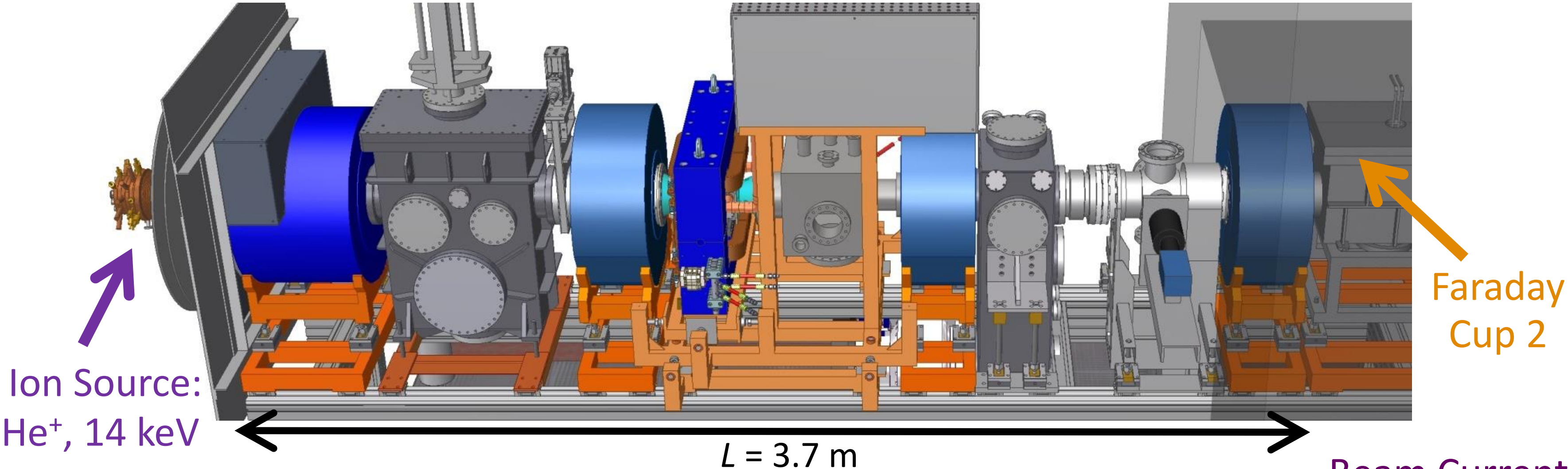


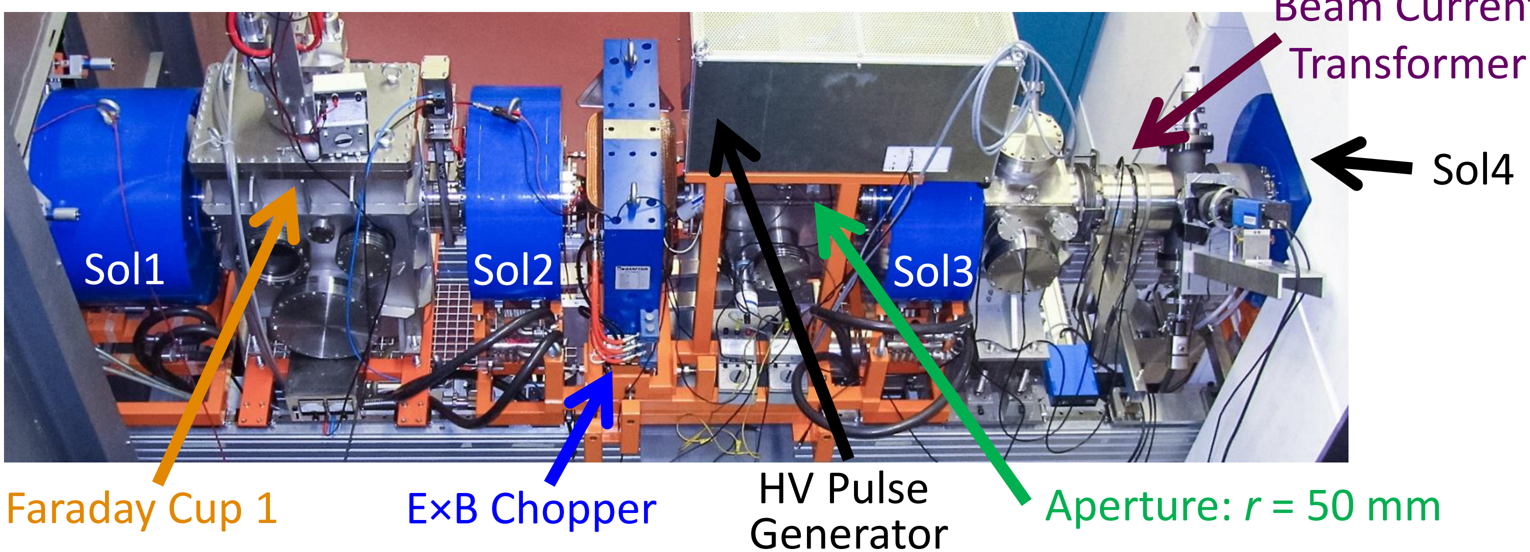
Kurtosis

$$\kappa = \frac{\overline{x^4}}{\overline{x^2}^2}$$



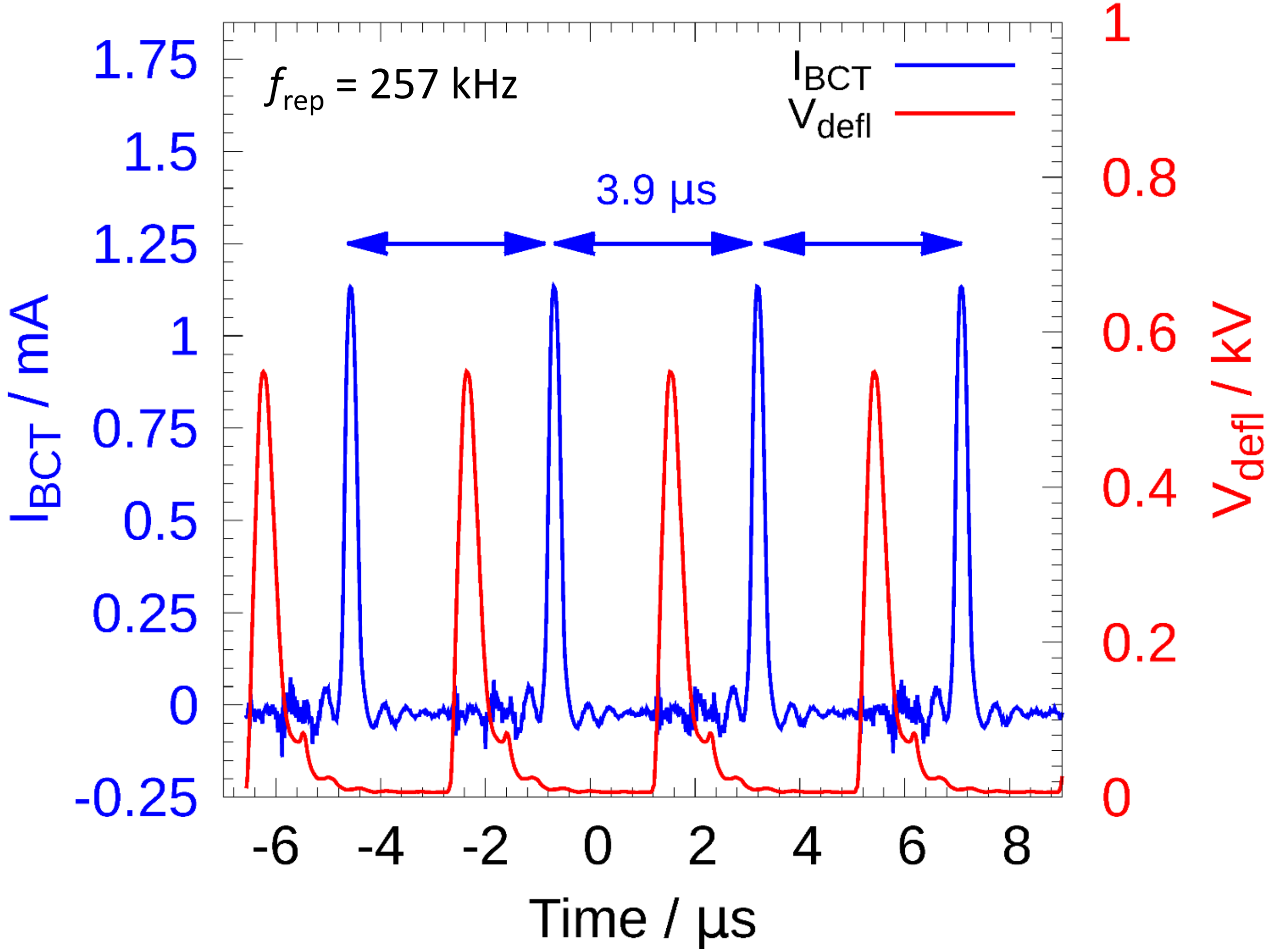
FRANZ LEBT: Overview





Measurements: Repetition Rate

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



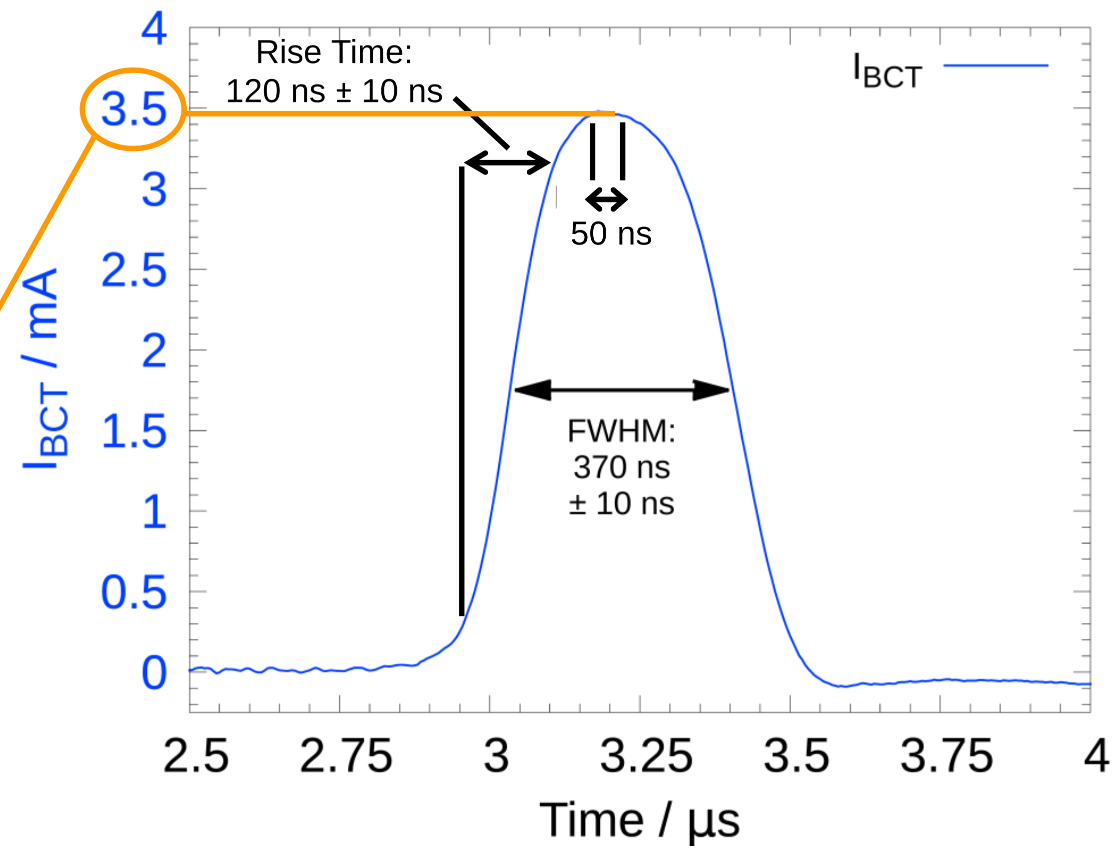
He^+, 14 keV
$r_{aperture}$ = 50 mm
I_{dipole} = 40.0 A

Measurements: Pulse Shape

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

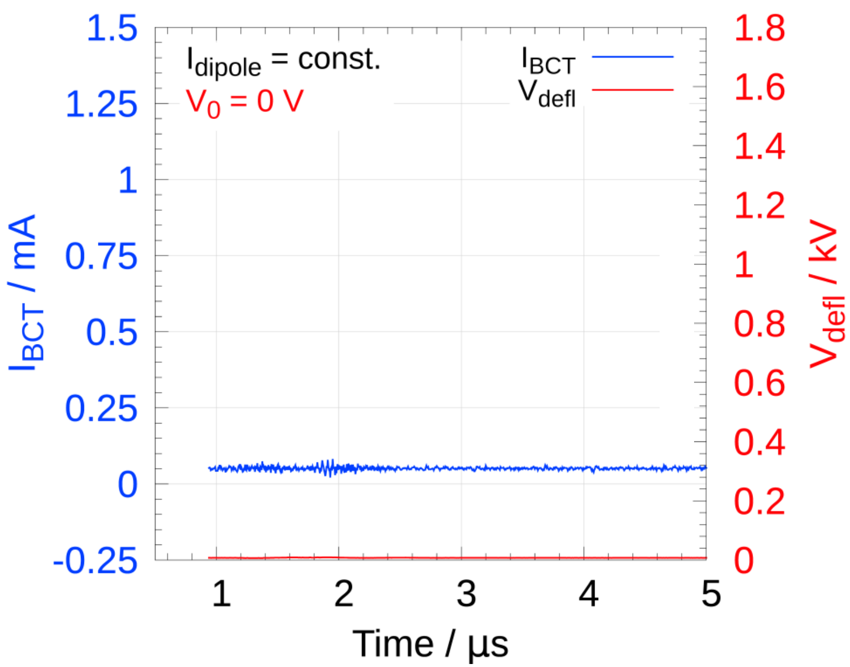
Gen. perveance K = 2.73e-3
(equivalent to 175 mA, p, 120 keV).

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



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

Measurements: Variation of Wien Ratio

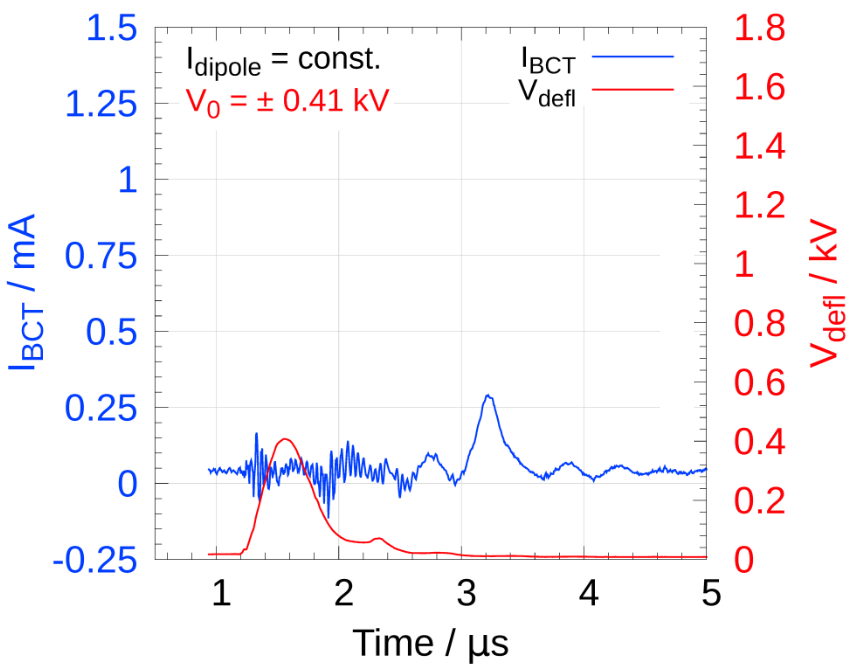


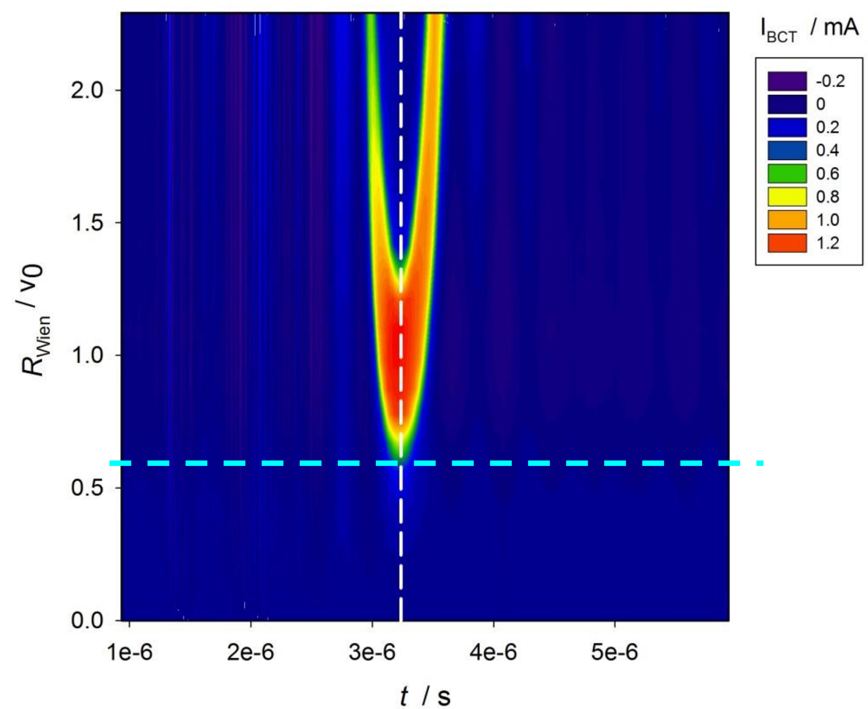
He^+, 14 keV
$r_{aperture}$ = 50 mm
I_{dipole} = 40.0 A

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

E_x → sweep
B_y → const.

Measurements: Variation of Wien Ratio





He⁺, 14 keV

$r_{aperture}$ = 50 mm

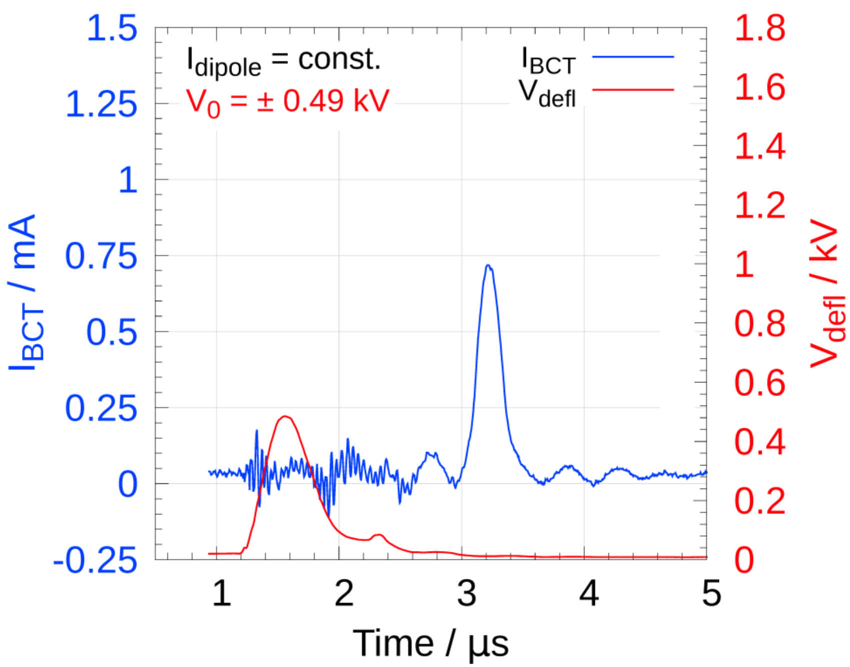
I_{dipole} = 40.0 A

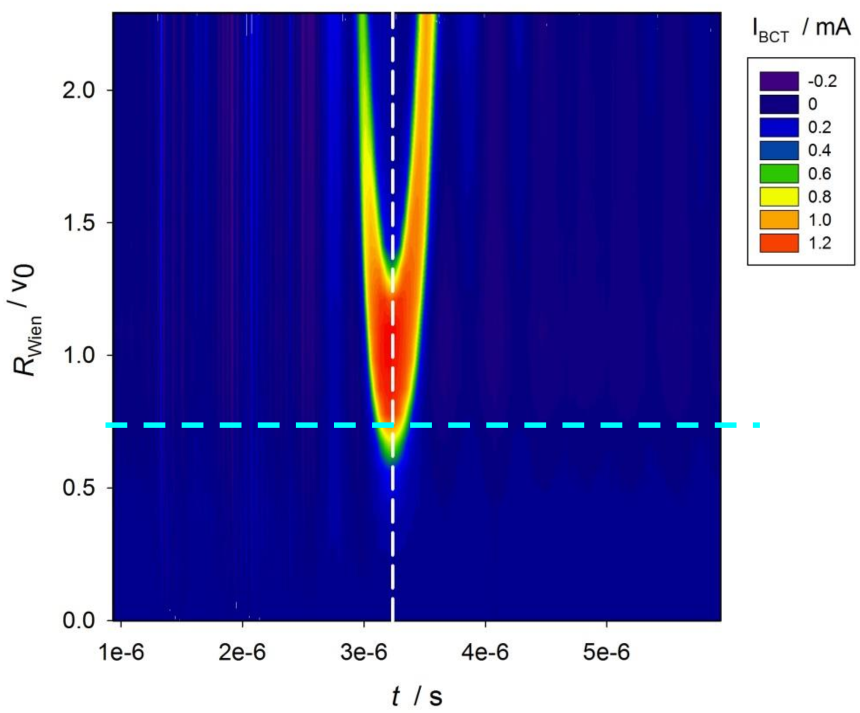
$$R_{\mathrm{Wien}} = \frac{\int E_x \,\mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \,\mathrm{d}z}$$

E_x → sweep

B_y → const.

Measurements: Variation of Wien Ratio





He⁺, 14 keV
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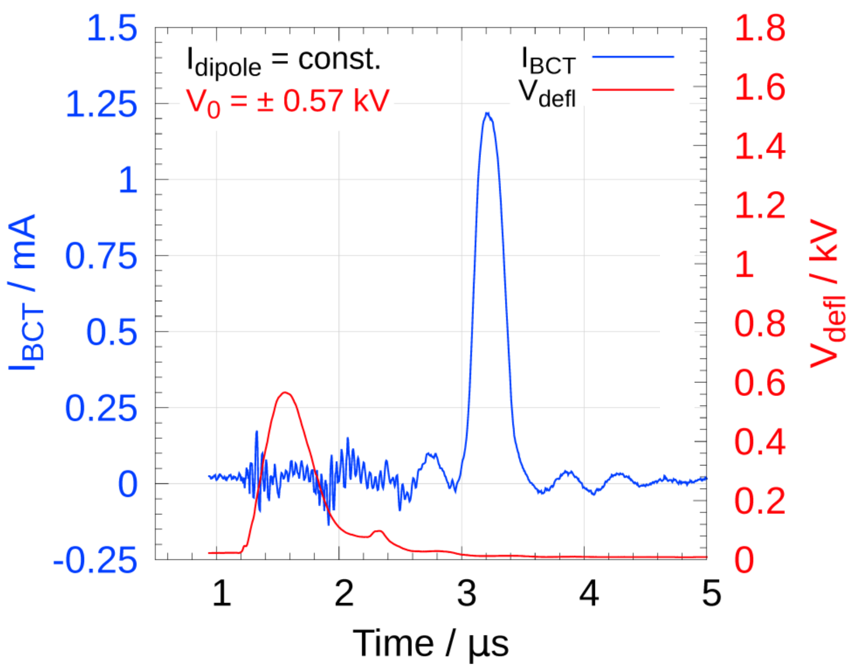

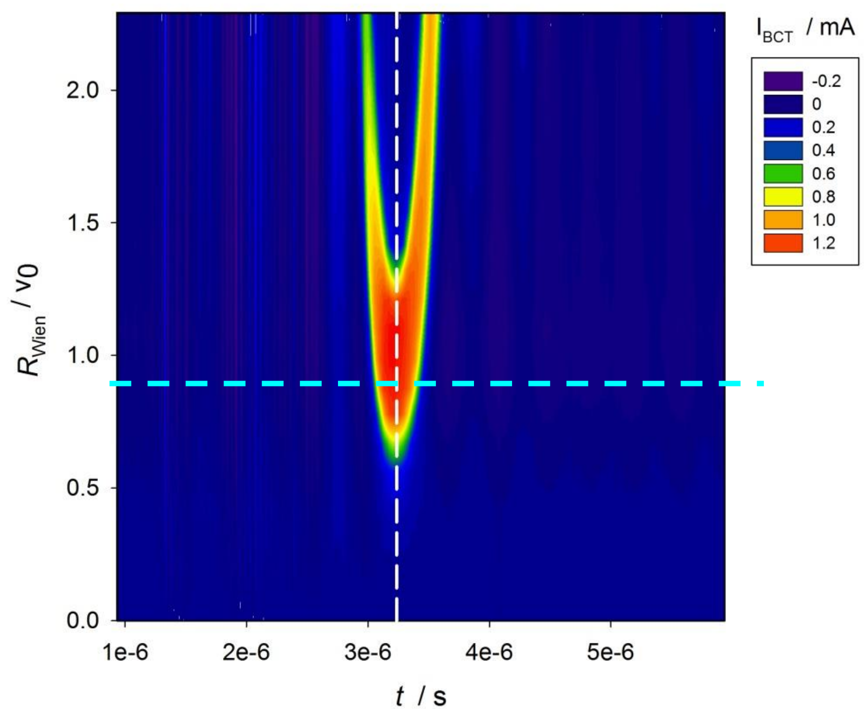

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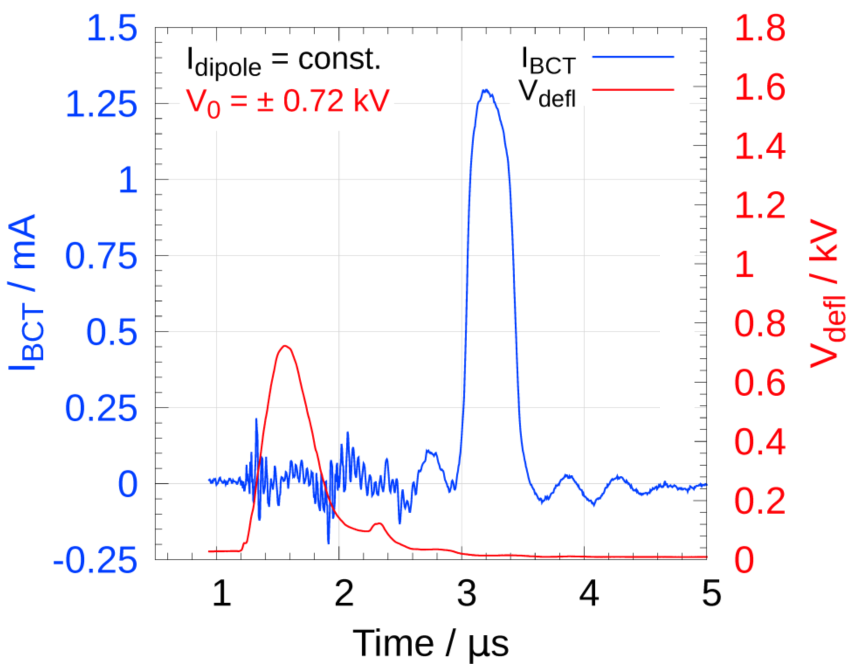
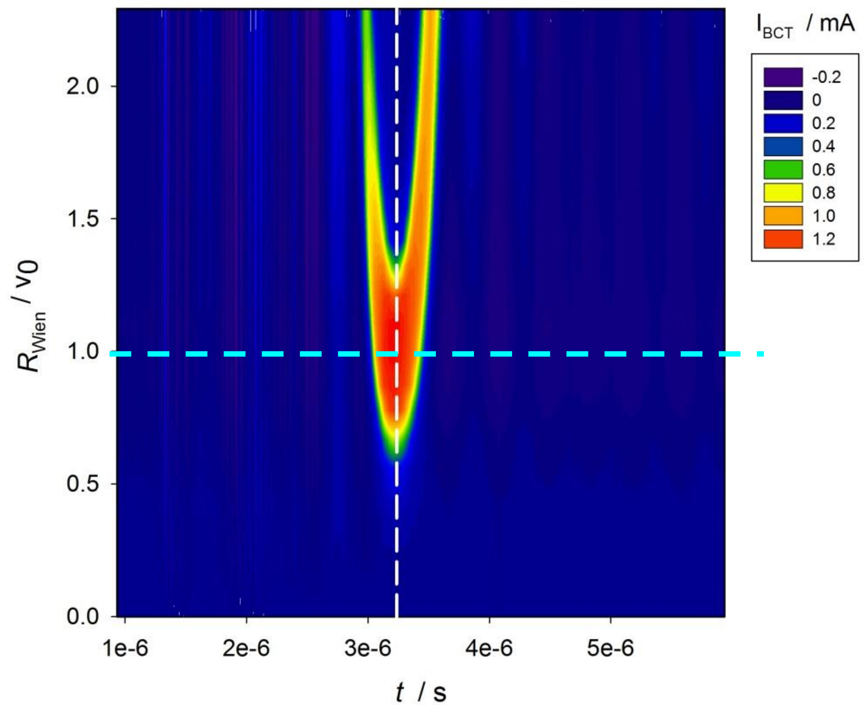
Measurements: Variation of Wien Ratio





He⁺, 14 keV

$r_{aperture}$ = 50 mm

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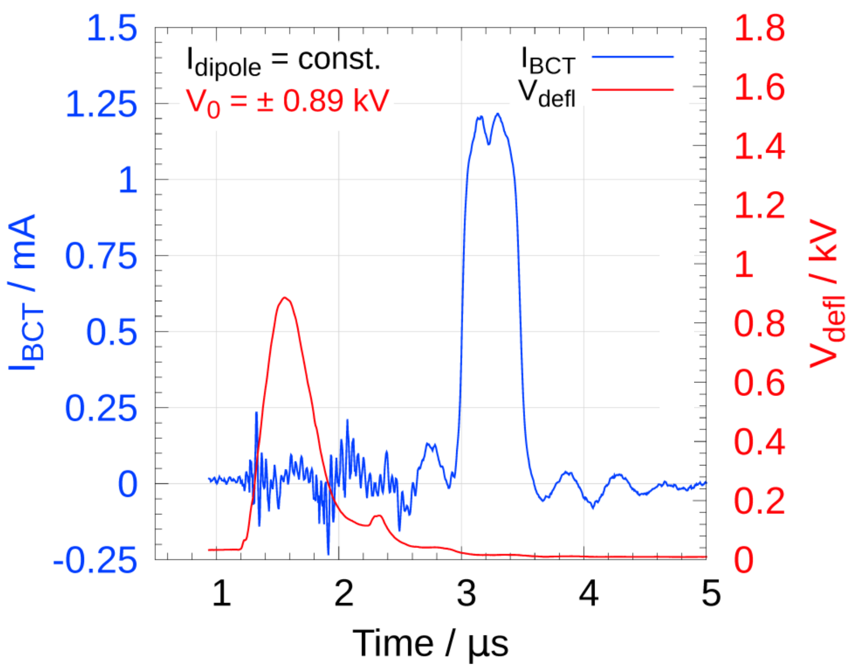
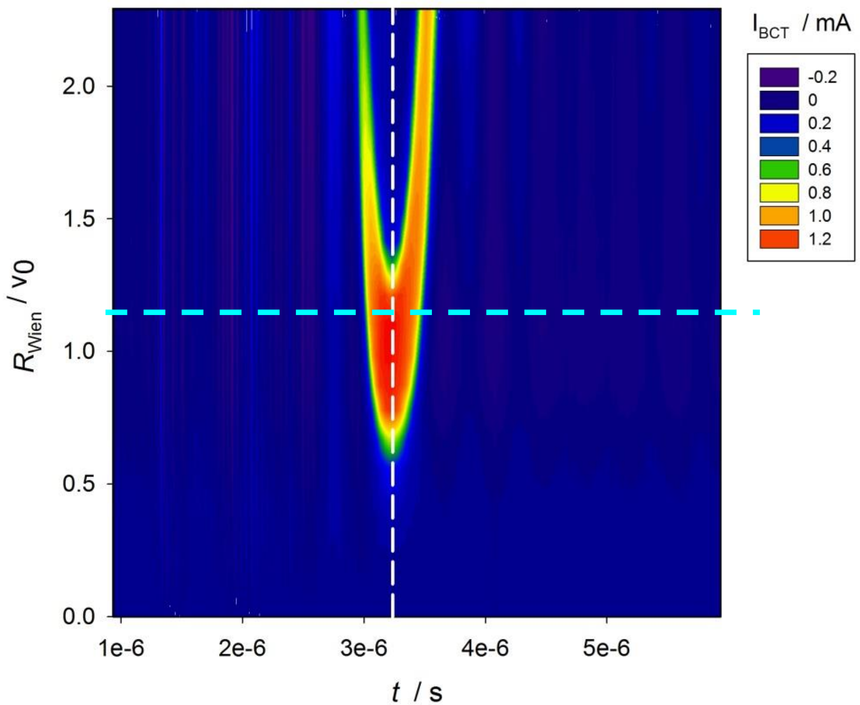
$$R_{\mathrm{Wien}} = \frac{\int E_x \,\mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \,\mathrm{d}z}$$

E_x → sweep

B_y → const.

Measurements: Variation of Wien Ratio





He⁺, 14 keV

$r_{aperture}$ = 50 mm

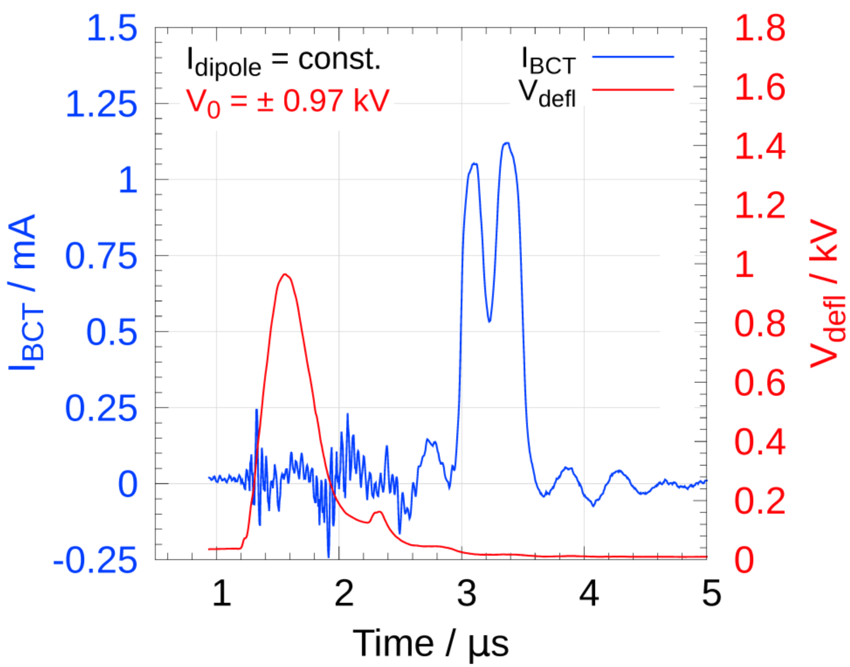
I_{dipole} = 40.0 A

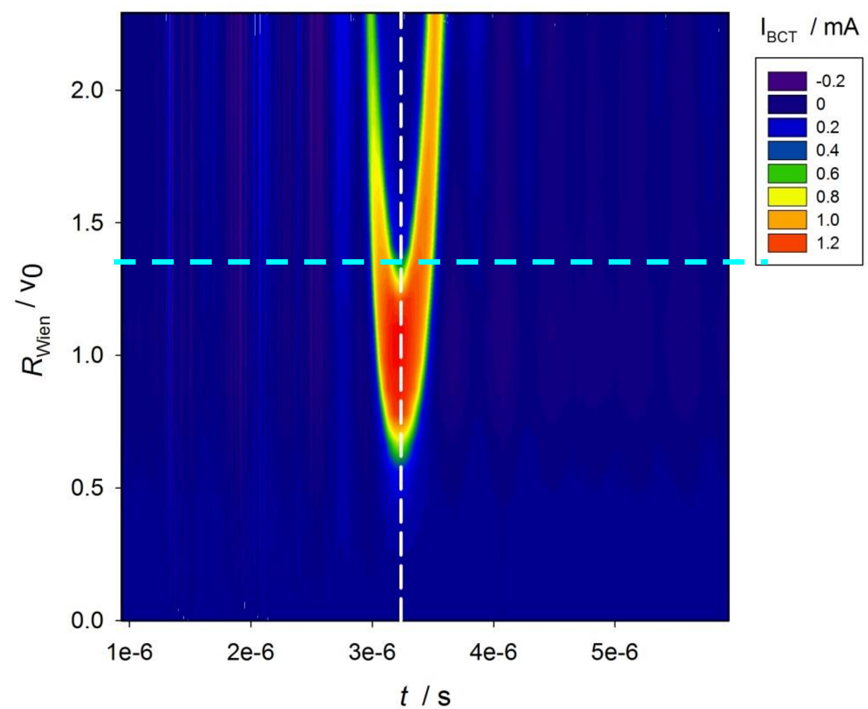
$$R_{\mathrm{Wien}} = \frac{\int E_x \, \mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \, \mathrm{d}z}$$

E_x → sweep

B_y → const.

Measurements: Variation of Wien Ratio





He$^+$, 14 keV
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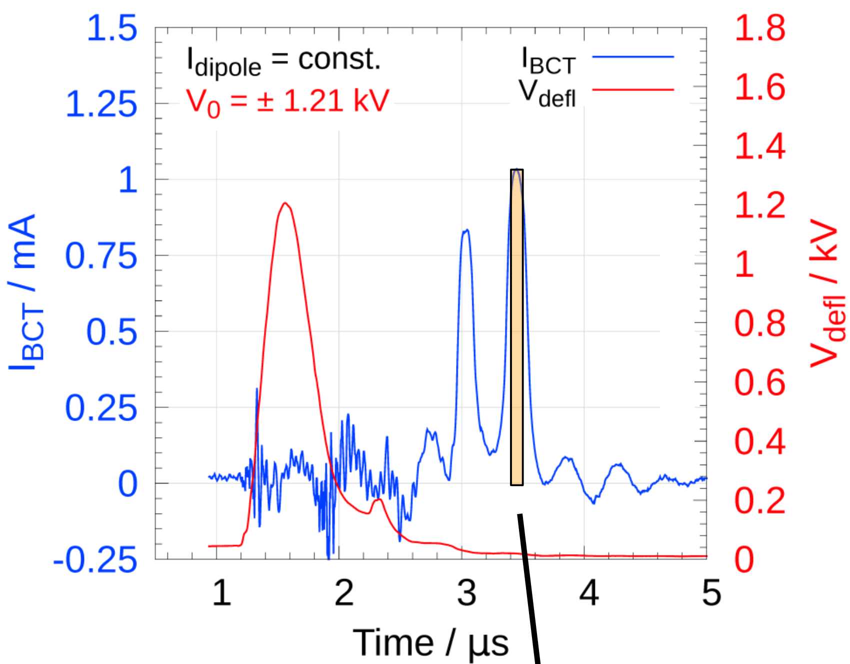
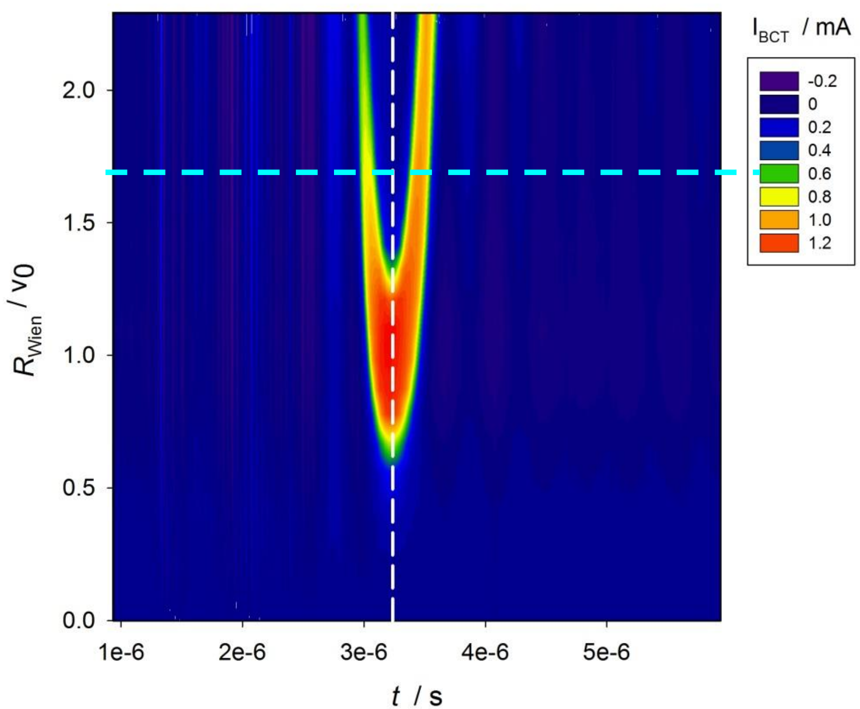
I_{dipole} = 40.0 A

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

E_x → sweep
B_y → const.

Measurements: Variation of Wien Ratio





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

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

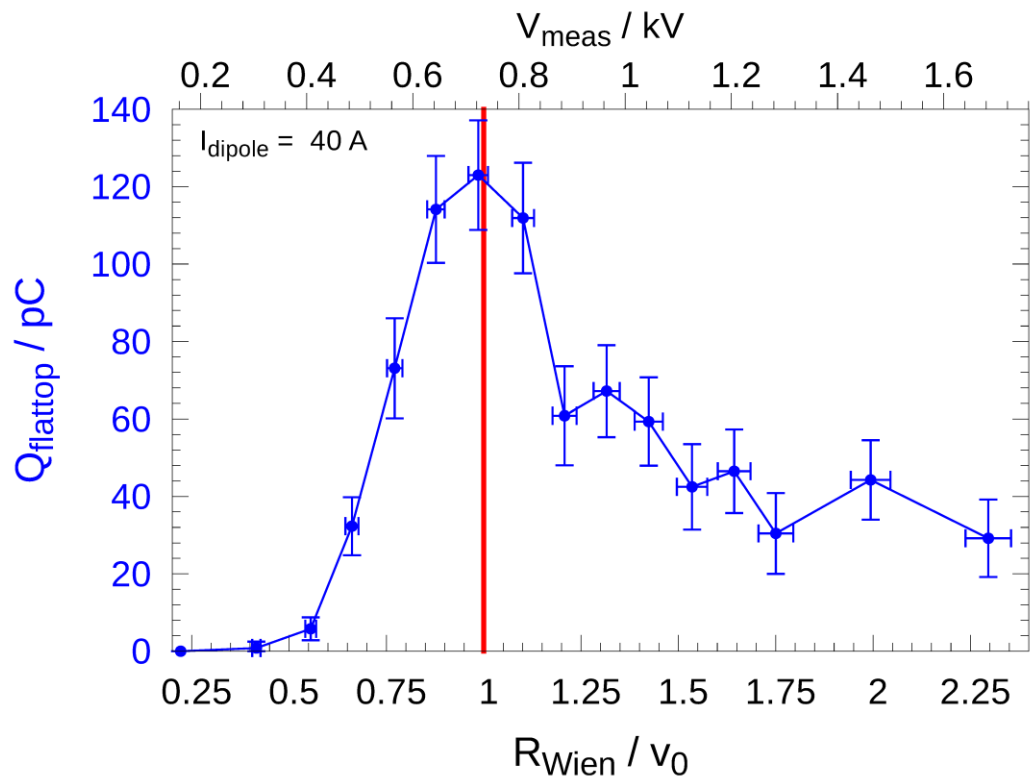
$$R_{\text{Wien}} = \frac{\int E_x \, dz \cdot f_{\text{tof}}}{\int B_y \, dz}$$

E_x → sweep

B_y → const.

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

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

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

sweep

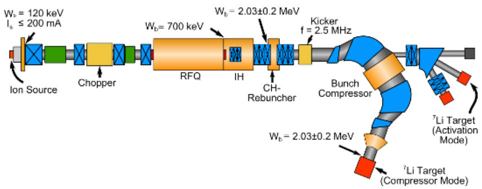
const.

LEBT: PXIE and FRANZ

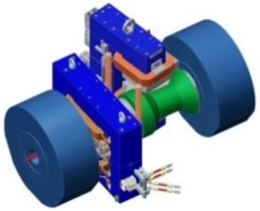
	PXIE	FRANZ – Commissioning	FRANZ - II
	H^-	He^+	p
Beam Energy	30 keV	14 keV	120 keV
Beam Current	5 (10) mA	< 3.5 mA	50 (200) mA
Beta	0.8%	0.27%	1.6%
Gen. Perveance	6.25E-04	2.74E-03	7.81E-04
Chopping in (center of) LEBT	yes	yes	yes
Pulse Length	> μs	100 ns to μs	100 ns to μs
Rep. Rate	1 to 60 Hz	103 to 257 kHz	103 to 257 kHz
Numbers of Solenoids	3	4	4

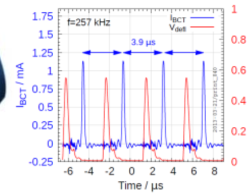
Conclusion

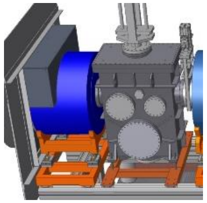
- Accelerator-driven neutron source FRANZ currently under construction.



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

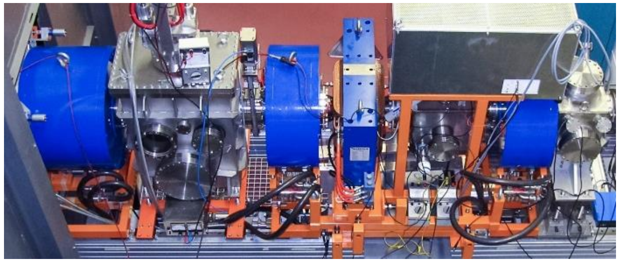


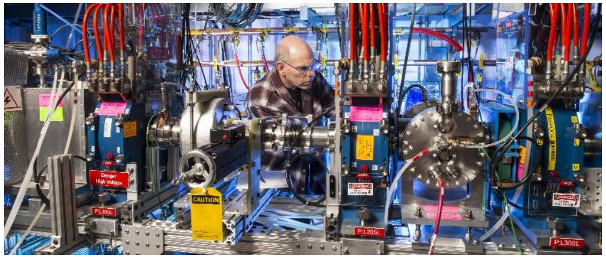




- *The LEBTs for FRANZ and PXIE allow…*
  - investigation of high-perveance beams…
  - …with positive (FRANZ) and negative (PXIE) ions…
  - …in dc or in pulsed mode…
  - …using different neutralization schemes,…

  which is a promising basis for further cooperation.





Thanks to…

- FRANZ team: M. Heilmann, B. Klump, O. Meusel, H. Podlech, U. Ratzinger, A. Schempp, P. Schneider, M. Schwarz, W. Schweizer, K. Volk.

- NNP group: A. Ates, M. Droba, S. Klaproth, O. Meusel, D. Noll, O. Payir, P. Schneider, H. Niebuhr, B. Scheible, K. Schulte, J. Wagner, K. Zerbe.

Blue skies,…
…green rivers…

…and fascinating science.
Thank you for your attention!