Matching measured beam dynamics with ASTRA simulations at REGAE

Ultrafast Beams and Application Workshop 2019

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Deutsches Elektronen-Synchrotron

Yerevan
July 02-05, 2019

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

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Outline

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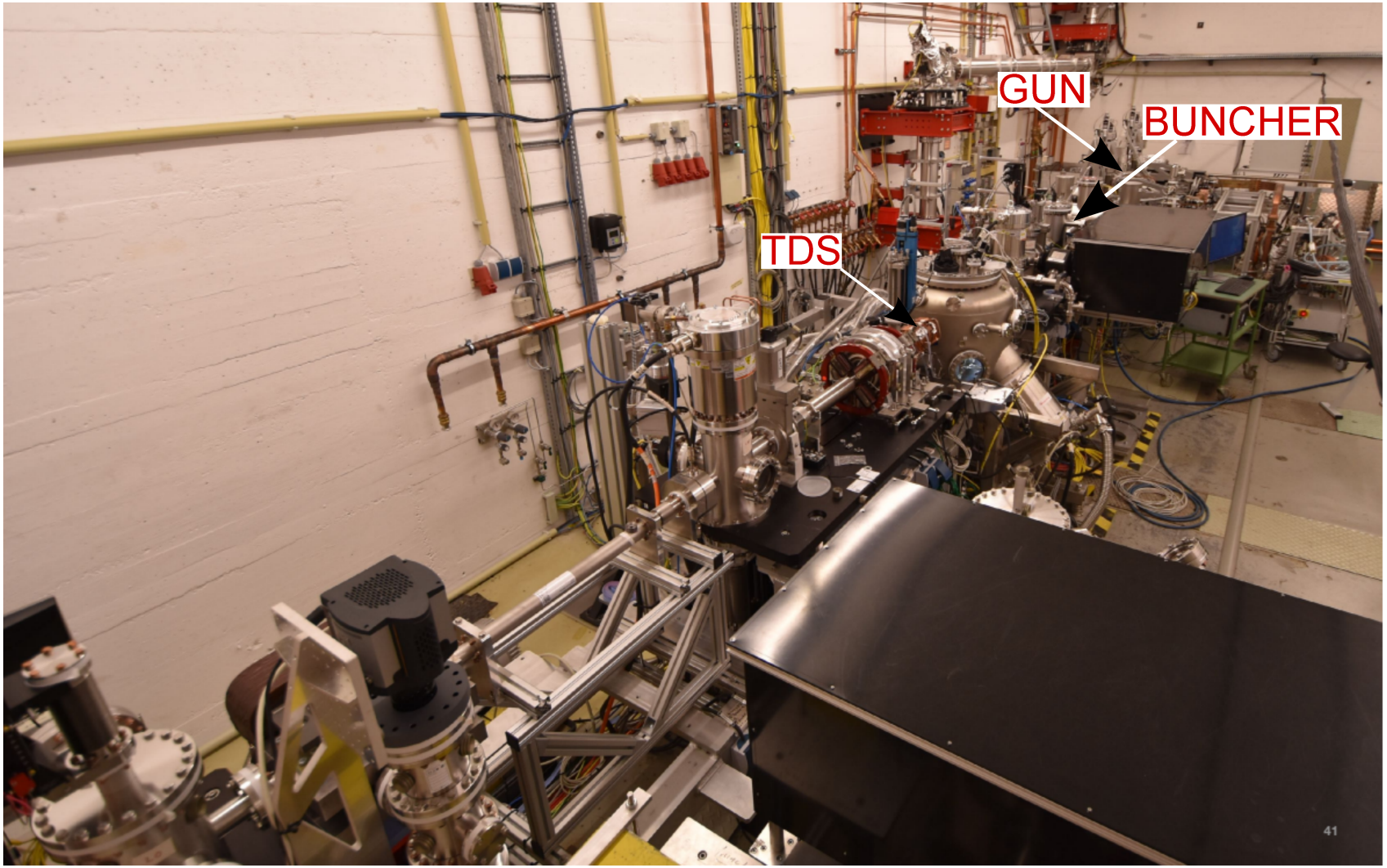
REGAE - Relativistic Electron Gun for Atomic Exploration



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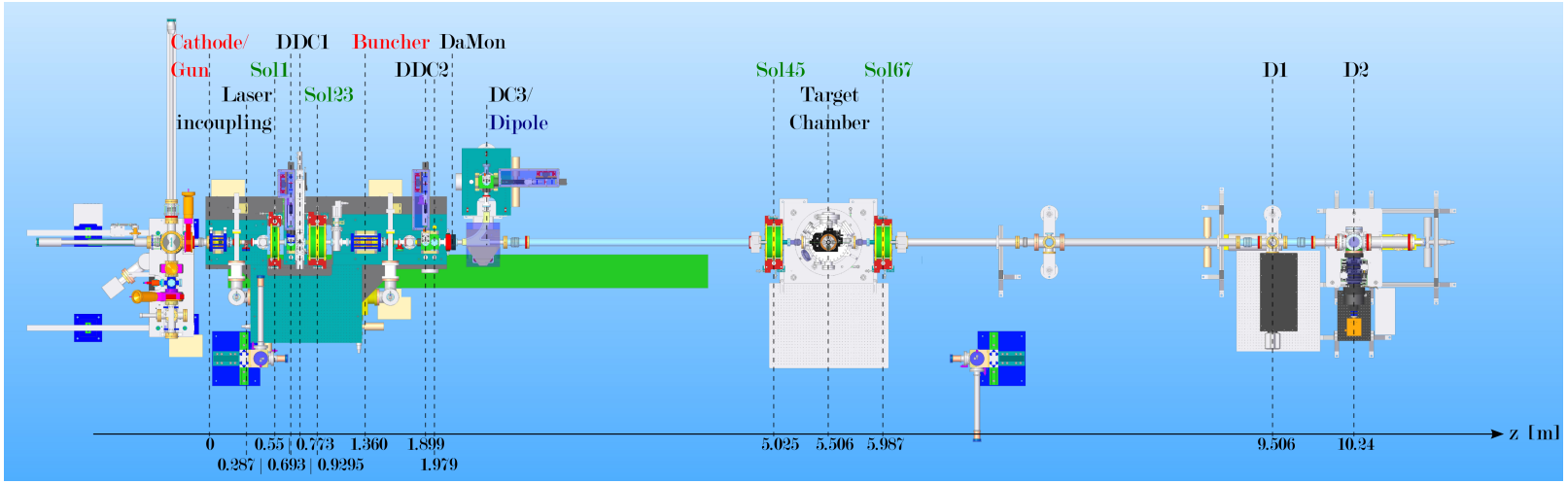

total length	$\sim 10\,\mathrm{m}$
E_{kin}	$5\,\mathrm{MeV}$
bunch length	$\sim 10\,\mathrm{fs} \;\hat{=}\; 3\,\mu\mathrm{m}$
bunch charge	$< 100\,\mathrm{fC}\ (< 0.5 \cdot 10^6\, e^-)$
trans. norm. emittance	$\sim 0.01\,\pi$ mm mrad

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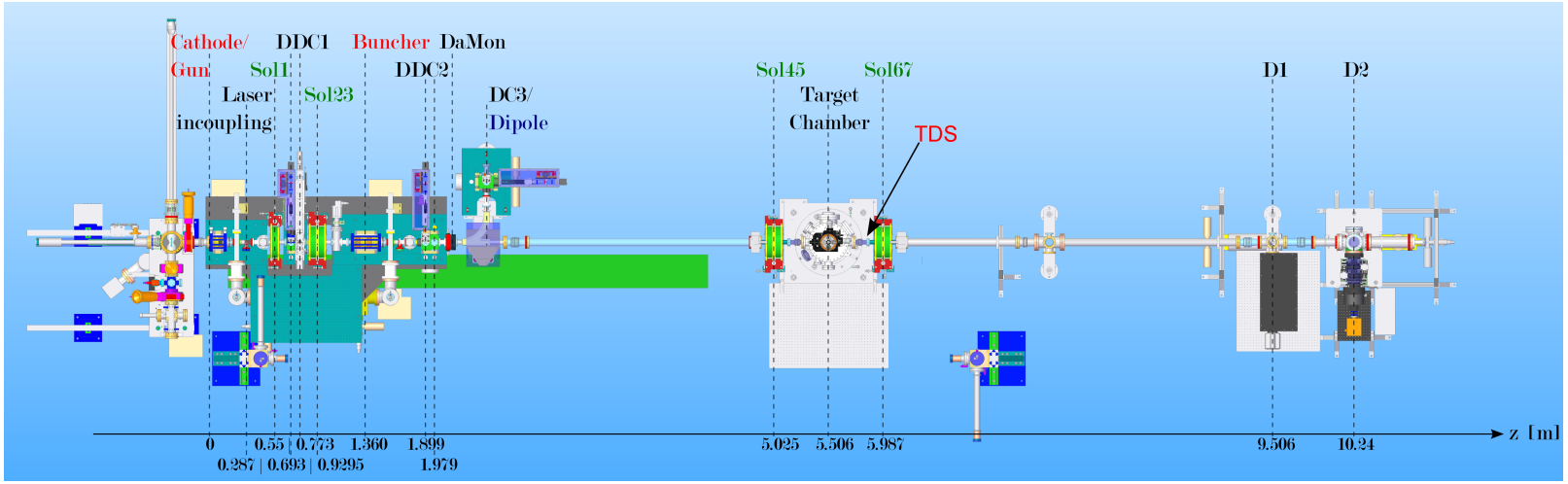

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- Ultra low charges
  - electron detection
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- Approaching fundamental limit caused by *shot noise*
  - caused by dark current (DC)

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ASTRA - A Space Charge Tracking Algorithm

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  - Apertures (collimators, incoupling mirrors)
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- ASTREG: live feeding of ASTRA

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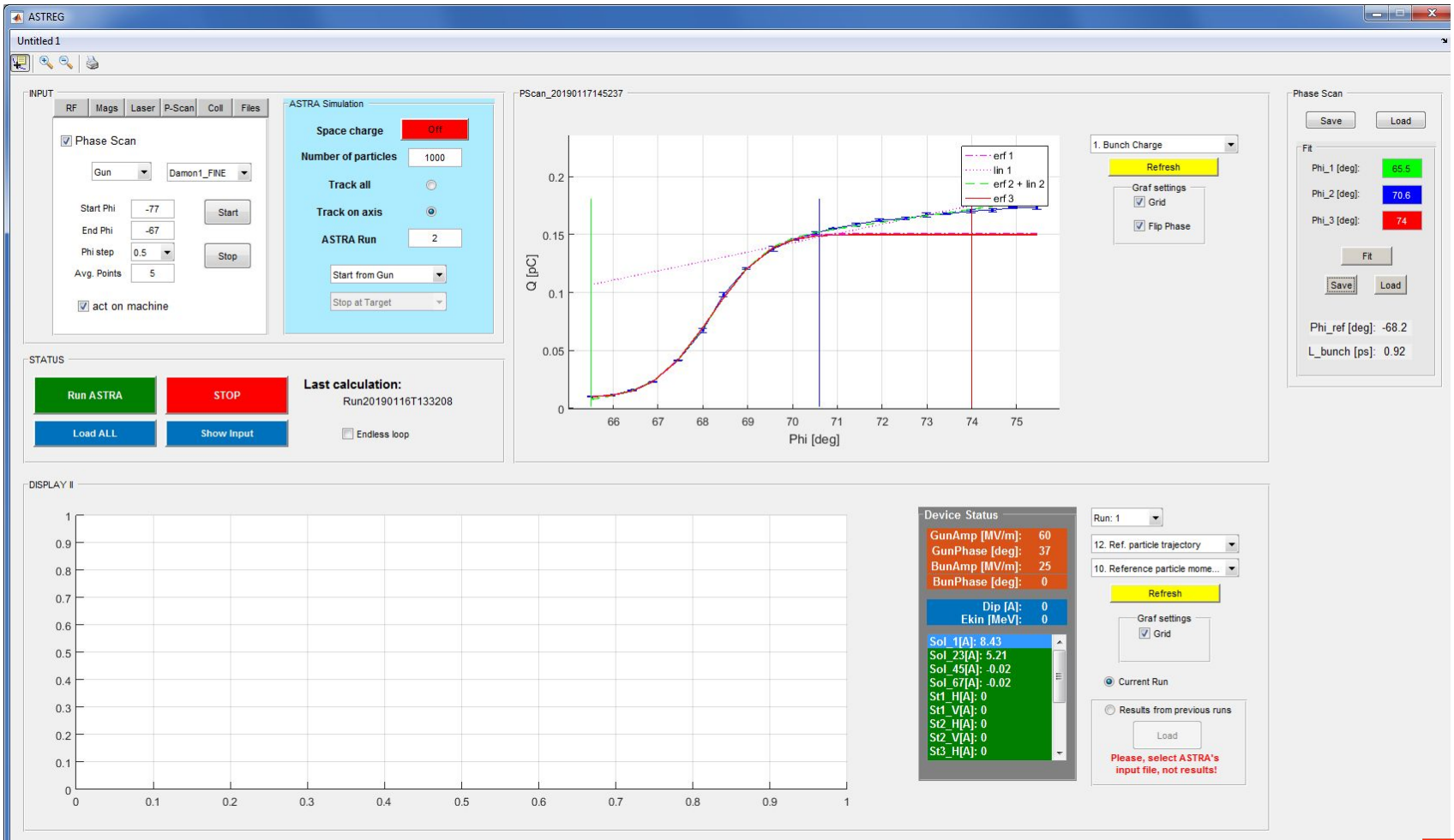
- beam based machine alignment (magnets, collimators, cavities)
- beam based RF gradient and phase calibration (GunAmp/Phase, Buncher...)
- verify magnet field of magnets regarding simulated field maps
- profound knowledge of your initial cathode laser parameters

ASTREG - Online beam dynamics tool

- under development!
- partially operable: phase scan, matching RF parameters,...



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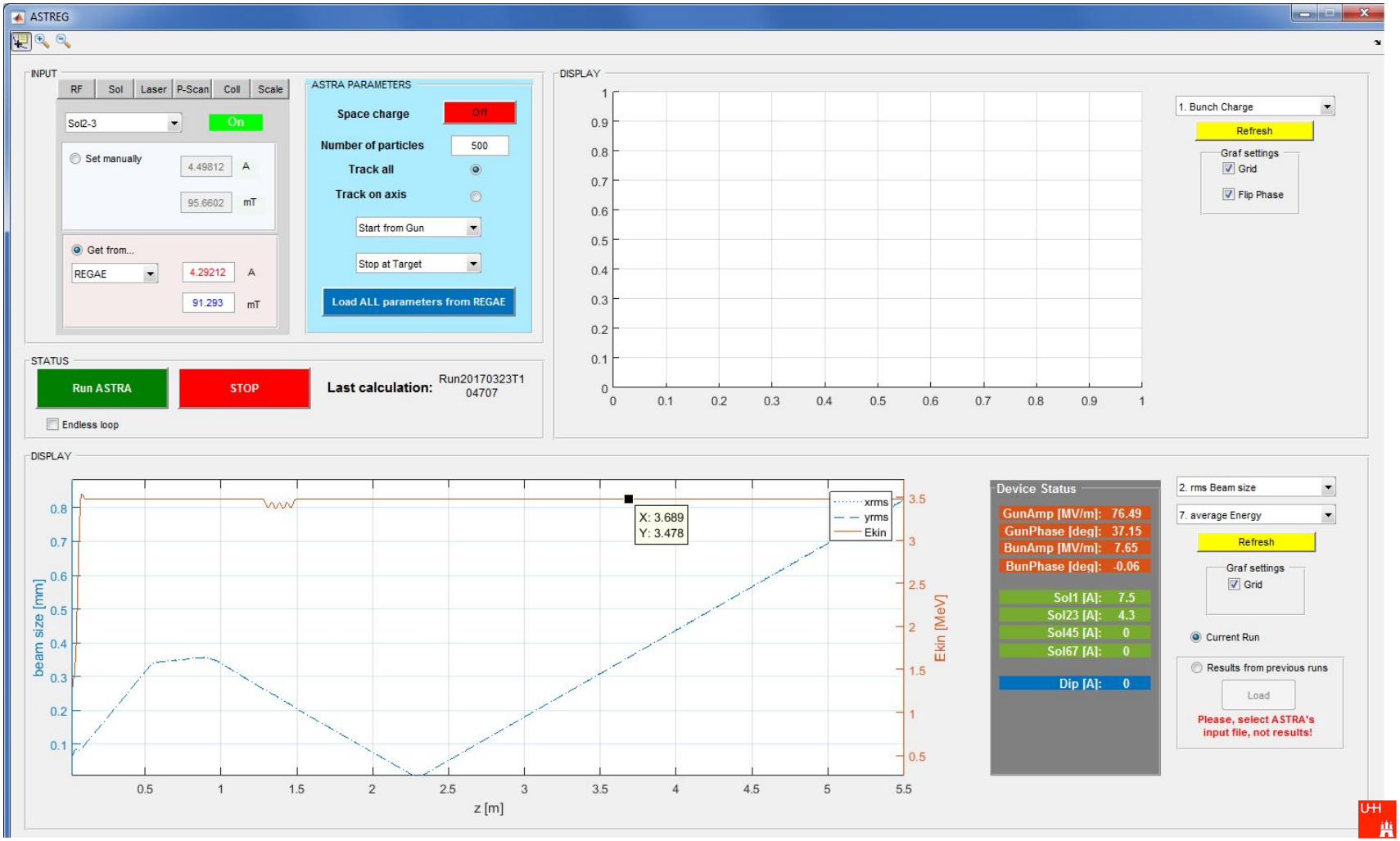

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Phase Advance Scan

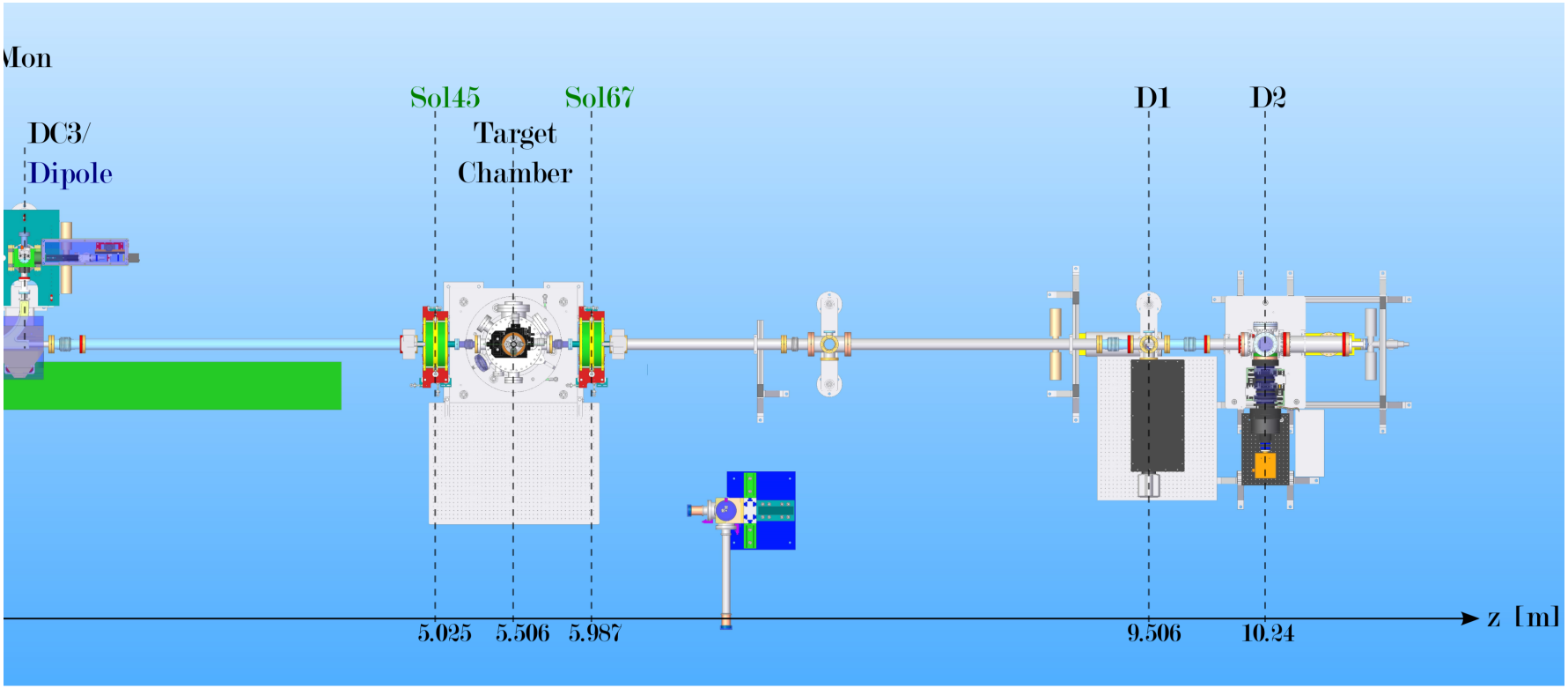
> *Linear least-square fit* to determine beam parameters

$$\mathbf{X} = \mathbf{M} \cdot \mathbf{X_0}$$

$$x_{\mathrm{RMS}}{}^2(z) = \begin{pmatrix} M_{11}{}^2 & 2\,M_{11}\,M_{12} & M_{12}{}^2 \end{pmatrix}^\top \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}$$

$$a_1 = x_{0,\mathrm{RMS}}{}^2, \quad a_2 = x_{0,\mathrm{RMS}}(x_{0,\mathrm{RMS}})', \quad a_3 = \frac{\epsilon_x{}^2}{x_{0,\mathrm{RMS}}{}^2} + (x_{0,\mathrm{RMS}})'^2$$

Emittance measurement: Setup



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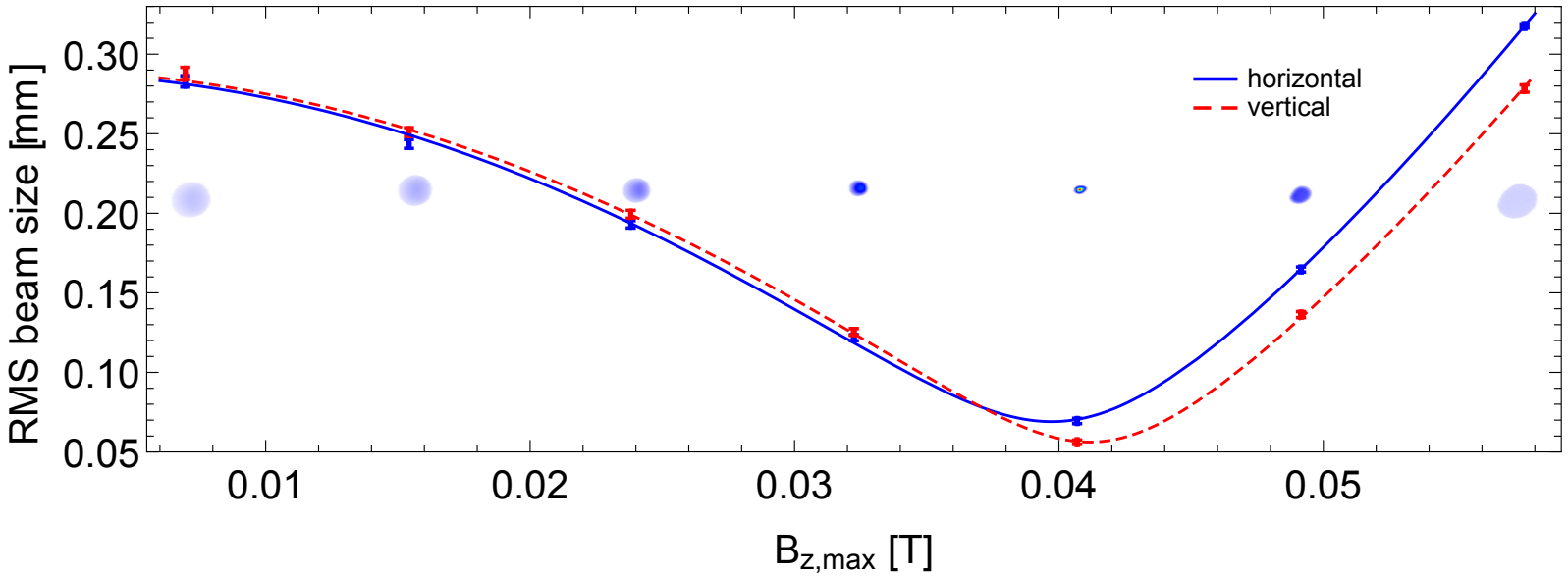
Emittance measurement

> $Q = 37.6(6)\,\mathrm{fC}$

> $E_{\mathrm{kin}} = 2.45\,\mathrm{MeV}$



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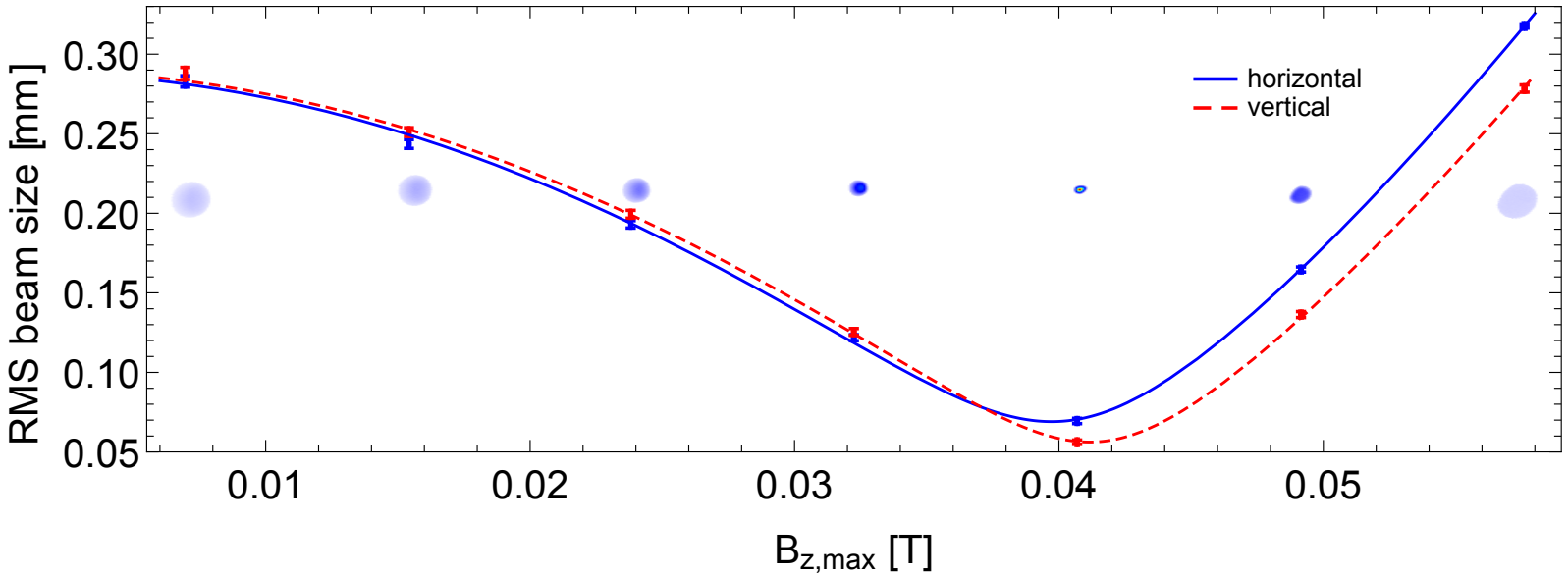

fit parameters	horizontal	vertical
$\epsilon_{\mathbf{n}}$ [π mm mrad]	0.0271(7)	0.0209(8)
ini. beam size [µm]	244(1)	231(1)
ini. envelope slope [µrad]	12.8(3)	17.7(3)
$\tilde{\chi}^2$	2.7	1.2

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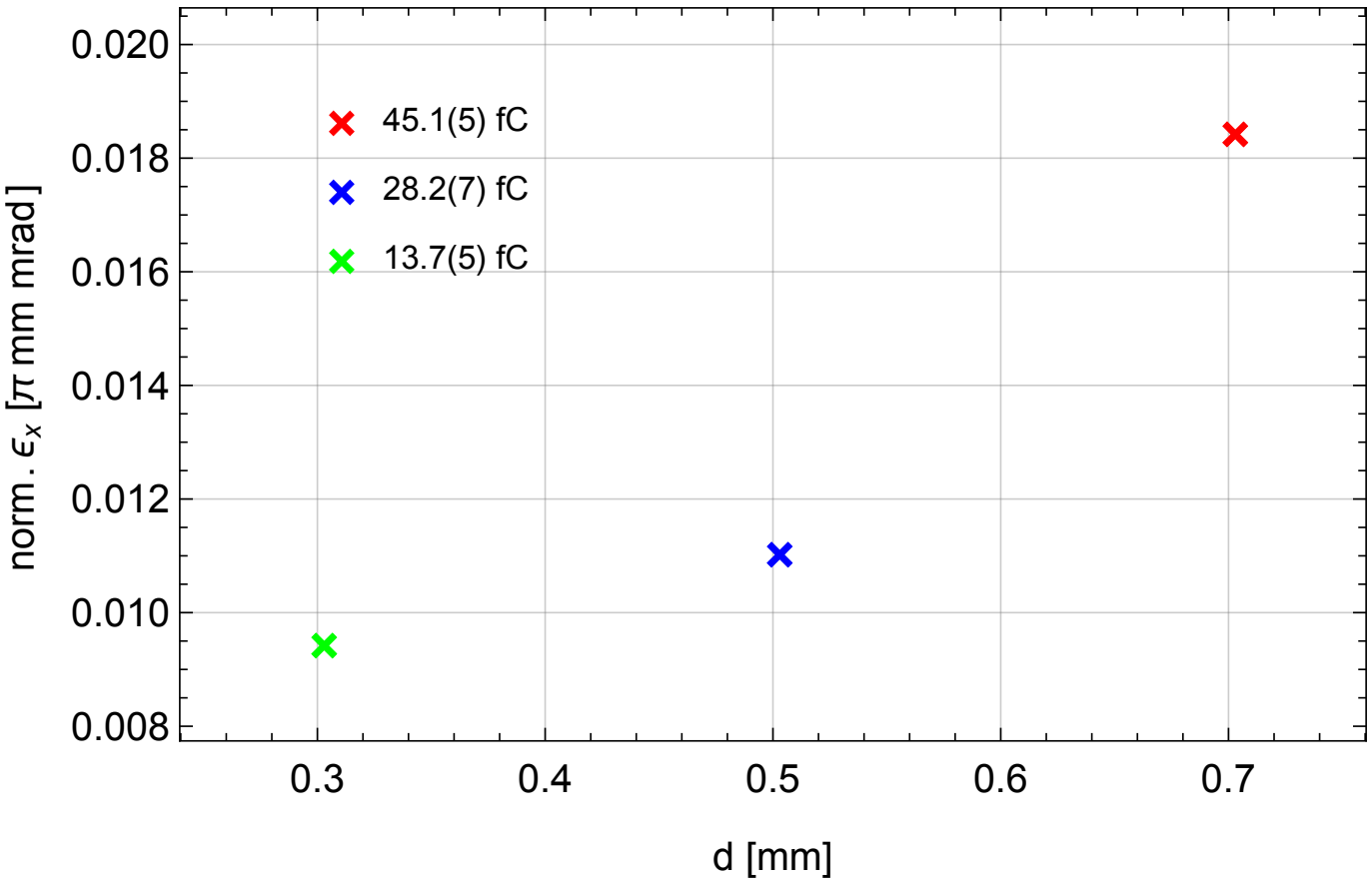
Lowest measured emittance

- pC charge at cathode (Cs_2Te)
- strongly collimated beam



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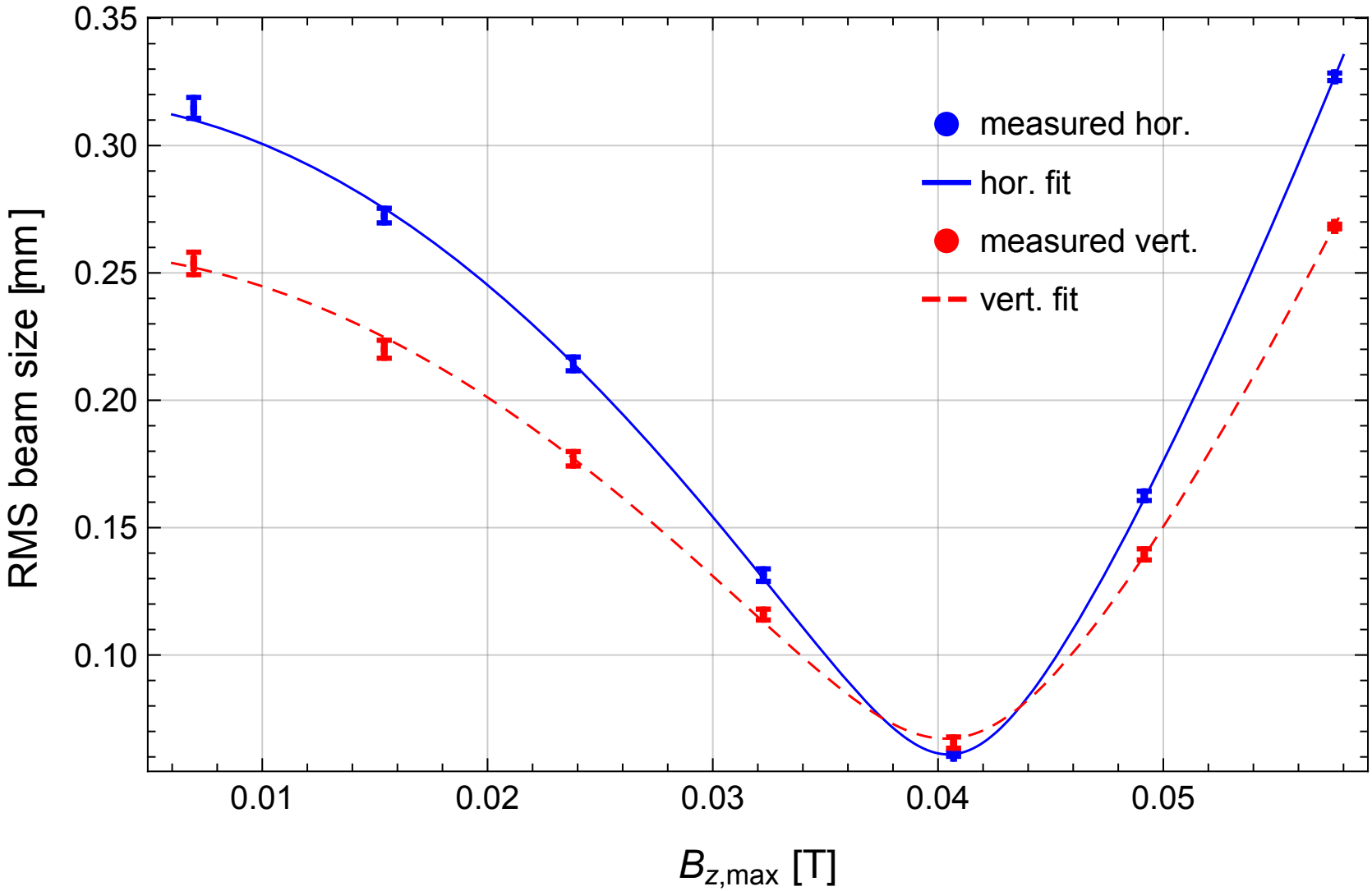
Compare measurement with simulation



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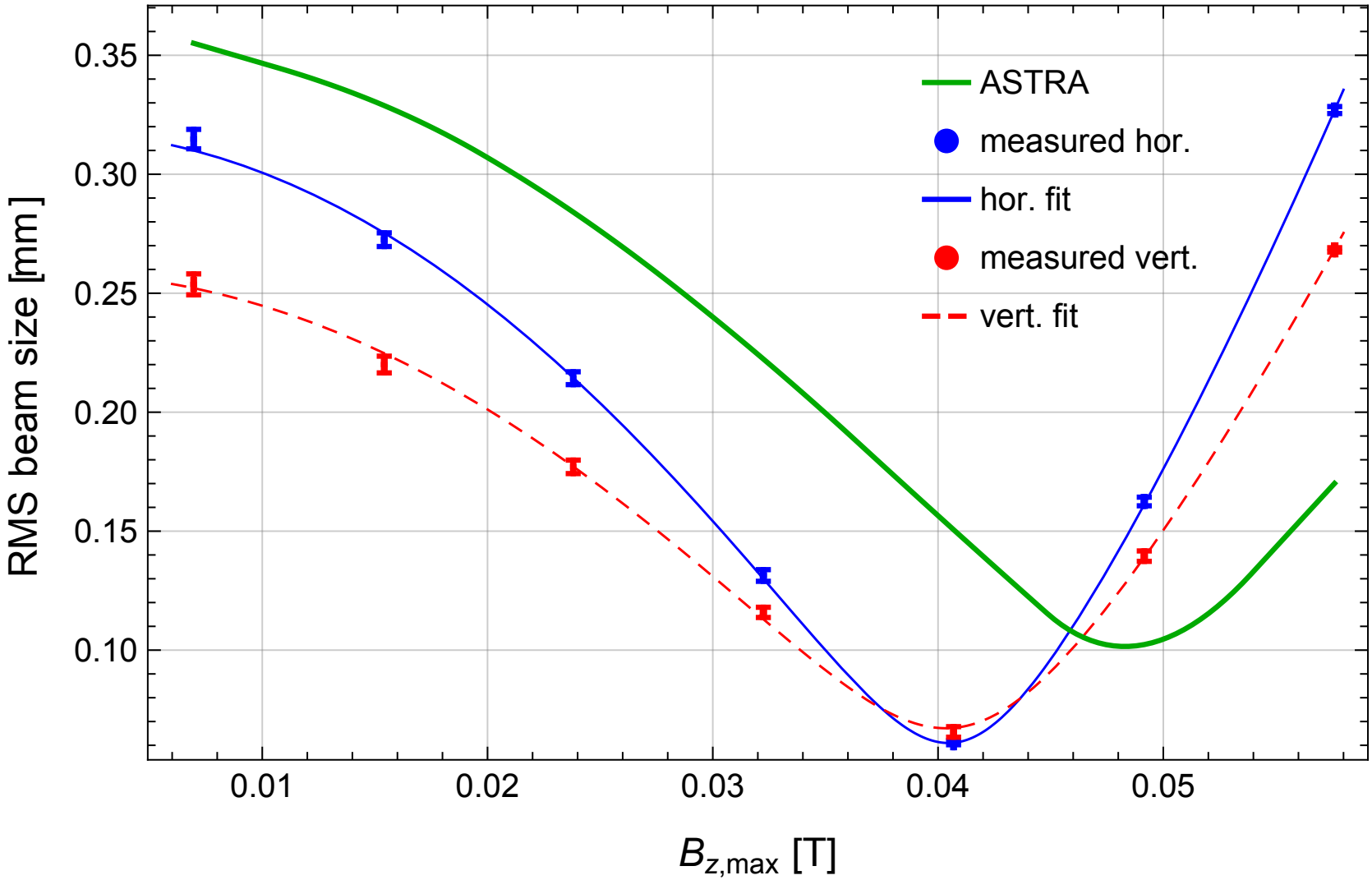
ASTRA simulations

> Comparison between measurement and ASTRA simulation

Device	**Set value machine**	**Set value ASTRA**
Sol1	1.00 A	21.7 mT
Sol23	4.19 A	88.9 mT
Sol45	off	0.0 mT
Sol67	0.3 A to 2.7 A	6.8 mT to 57.4 mT
Coll1 [mm]	1.1	1.1
$x_{\mathrm{RMS,l}}$ [mm]	0.314	0.314
$y_{\mathrm{RMS,l}}$ [mm]	0.255	0.255
$t_{\mathrm{RMS,l}}$ [ps]	0.5	0.5
Gun Ampl [MV/m]	60.30(3)	60.30
Bun Ampl [MV/m]	11.60(1)	11.60
DaMon [pC]	0.0376(6)	0.0376
E_{kin} [MeV]	2.45	2.45

ASTRA: Emittance measurement



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Compare measurement and ASTRA simulation

Parameter	ASTRA simulation	REGAE measurement
Charge [fC]	37.1	37.6(6)
E_{kin} [MeV]	2.45	2.45
ini. beam size [µm]	209	262.0(5)/212.0(7)
ini. envelope slope [µrad]	22.6	17.4(1)/12.7(1)
norm. emittance [π mm mrad]	0.0252(3)	0.0248(3)/0.0235(3)
$\widetilde{\chi}^2$	-	1/1.5

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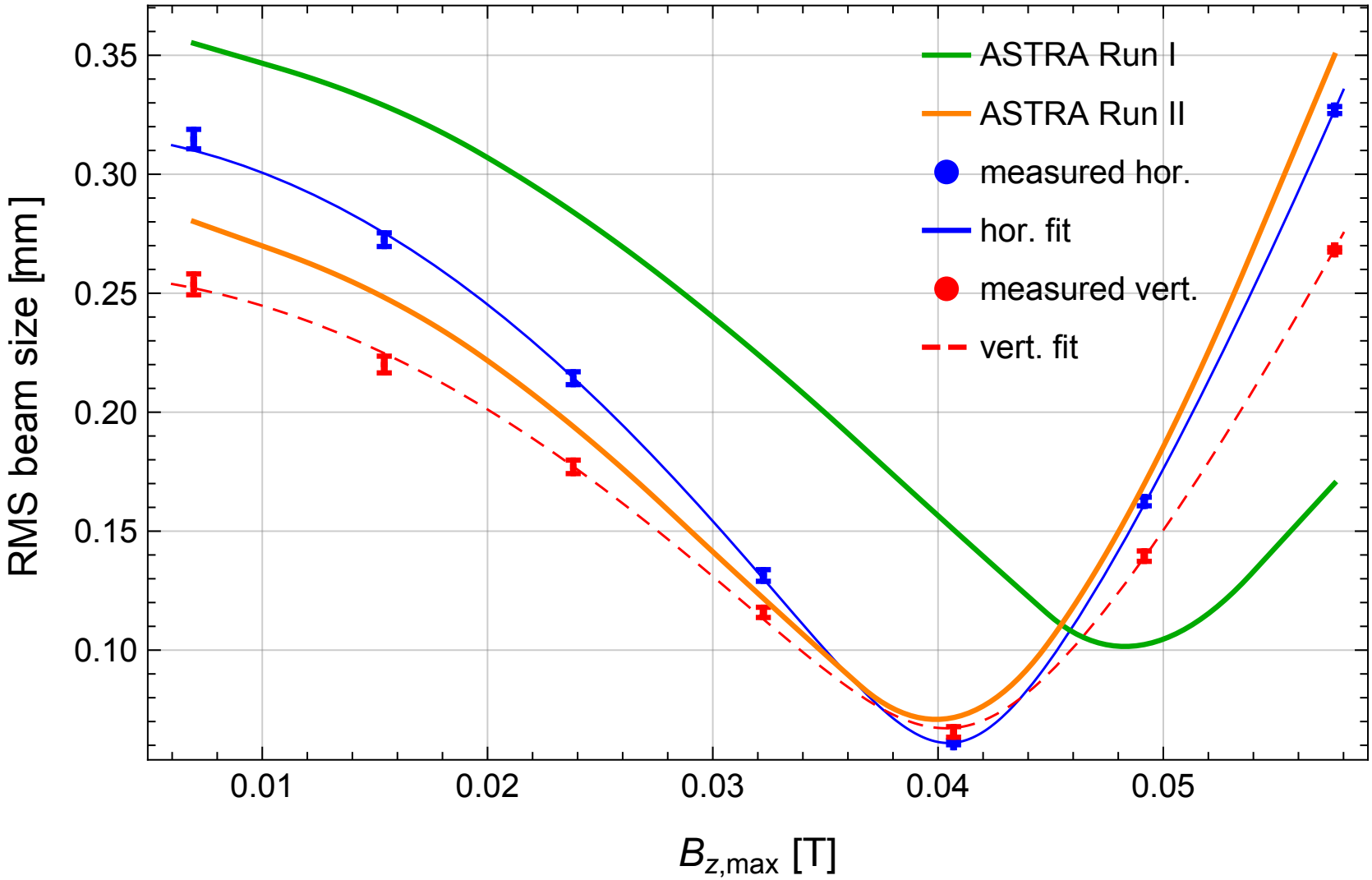

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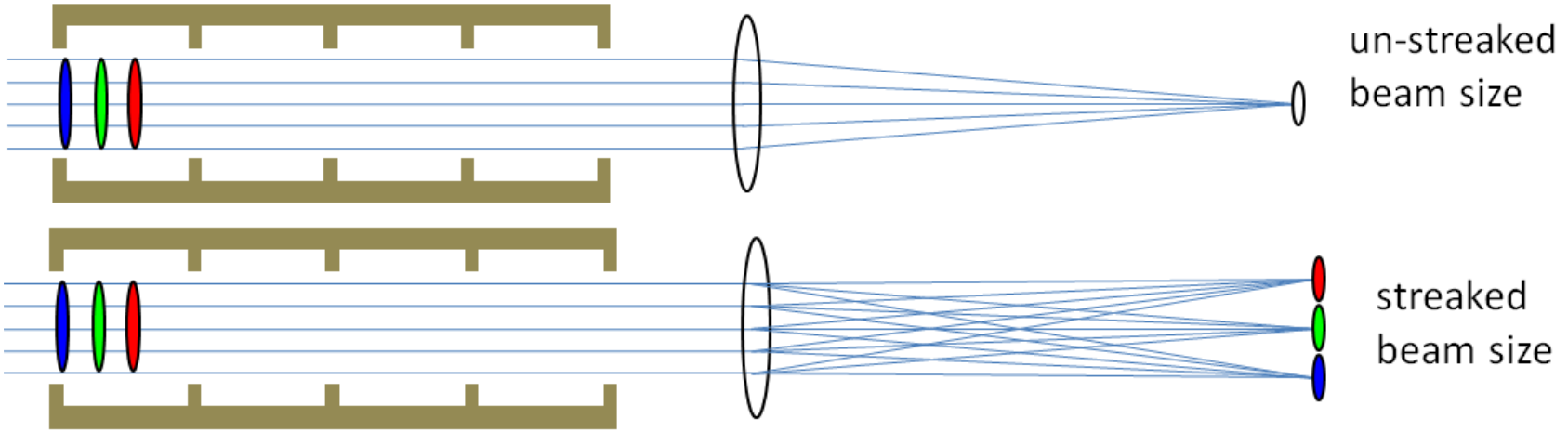
Compare measurement and ASTRA simulation

Parameter	ASTRA Run I	ASTRA Run II	REGAE
Charge [fC]	37.1	37.1	37.6(6)
E_{kin} [MeV]	2.45	2.45	2.45
$x_{0,\mathrm{RMS}}$ [µm]	209	262.6	262.0(5)/212.0(7)
$(x_{0,\mathrm{RMS}})'$ [µrad]	22.6	-10.0	17.4(1)/12.7(1)
$\epsilon_{n,\mathrm{RMS}}$ [π mm mrad]	0.0252(3)	0.0255(7)	0.0248(3)/0.0235(3)
$\widetilde{\chi}^2$	-	-	1/1.5

Outline

TDS - Transverse Deflecting Structure



$$R = \frac{\sigma_{\mathrm{sc,un-streaked}}}{\sigma_{\mathrm{sc,streaked}}} = \frac{\sigma'_{\mathrm{TDS,uncor.}}}{\sigma'_{\mathrm{TDS,introduced}}} = \frac{\epsilon}{\sigma_y}\frac{c\,p_z}{e\,k\,V} = \frac{\epsilon_n\,m_0\,c}{\sigma_y\,e\,k\,V}$$

A high resolution power 1/R requires: large int. voltage V, short wavelength (large k) , small emittance ϵ_n and large beam size in TDS σ_y.

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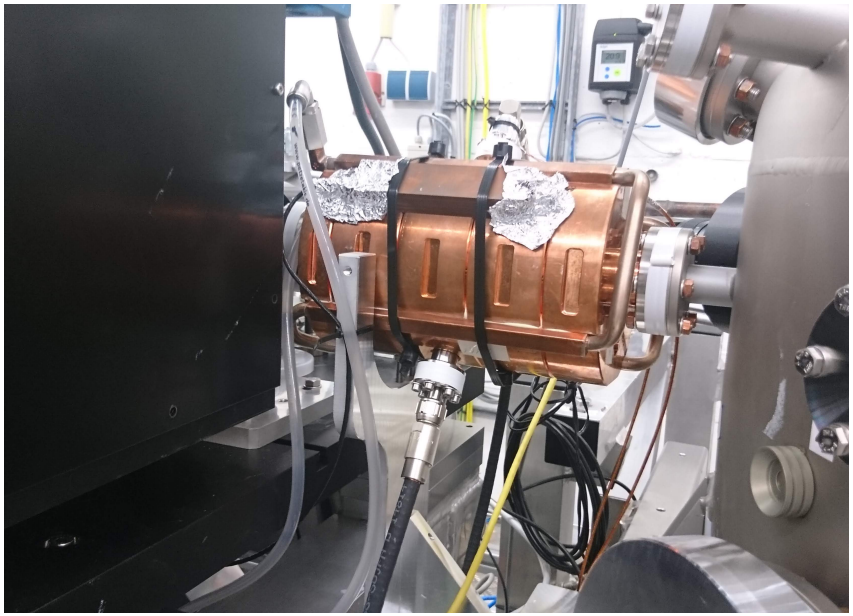
TDS - Transverse Deflecting Structure

- 3 GHz S-band cavity; manufactured in Armenia
- 4 fs resolution; strongly depending on setup:
  - adjusted 90°-phase advance
  - ini. beam size -> non-linearities
  - beam emittance -> resolution on screen



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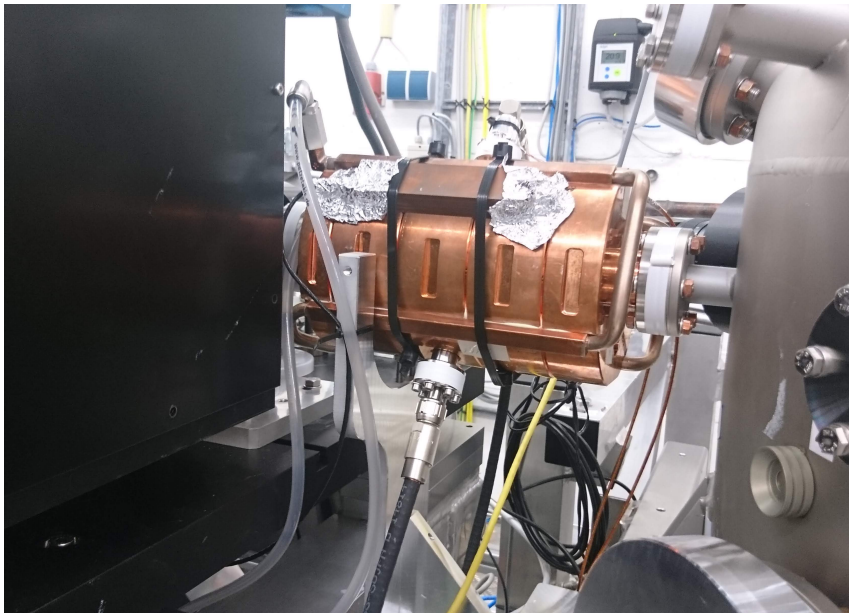
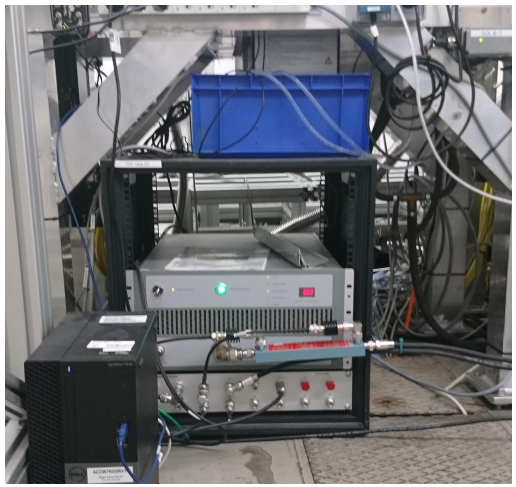
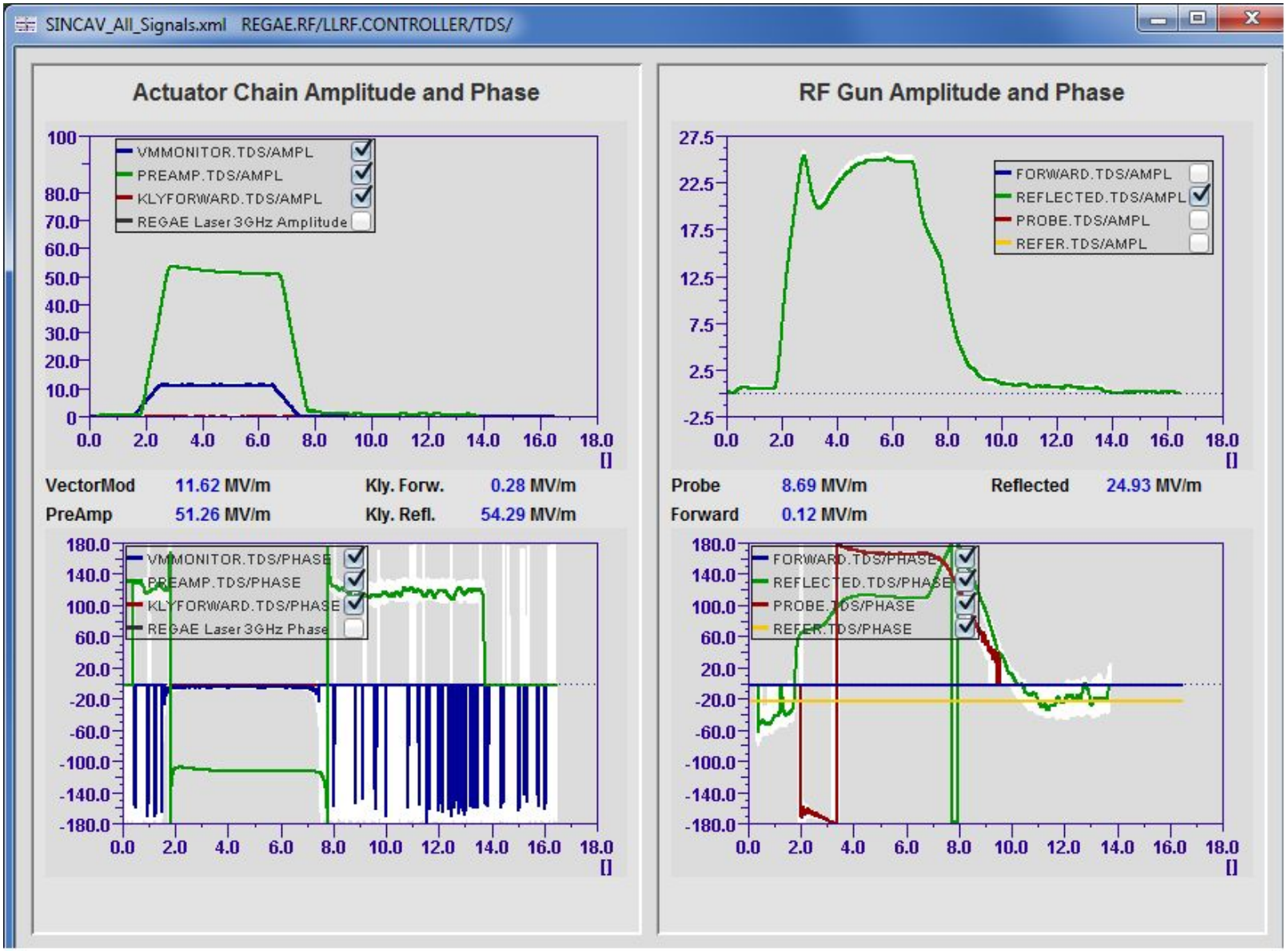




- 3GHz 5kW High Power Amplifier from Microwave Amps Ltd
- small 210 W ThermoTek T255p water chiller

TDS: temperature tuning



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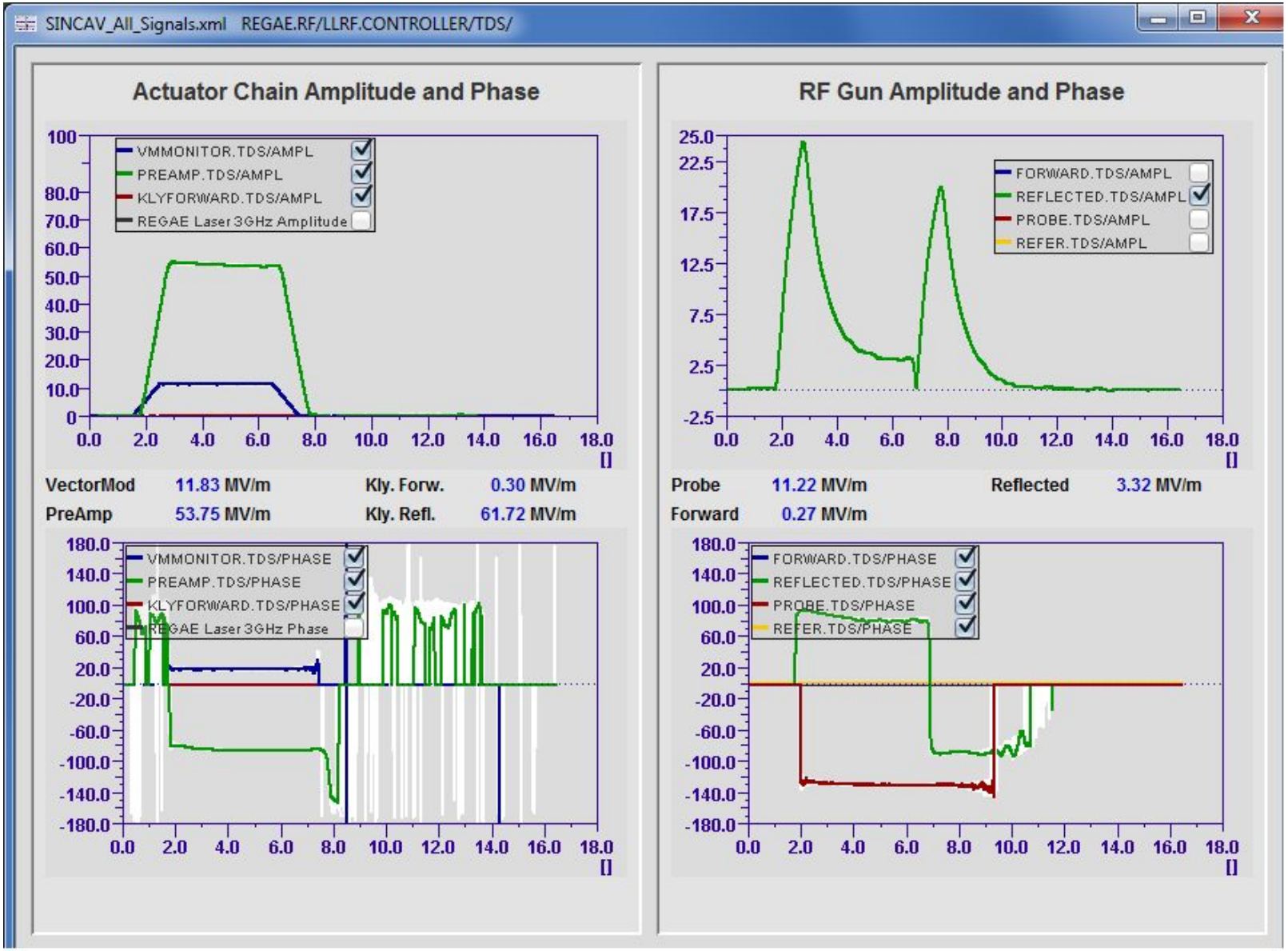

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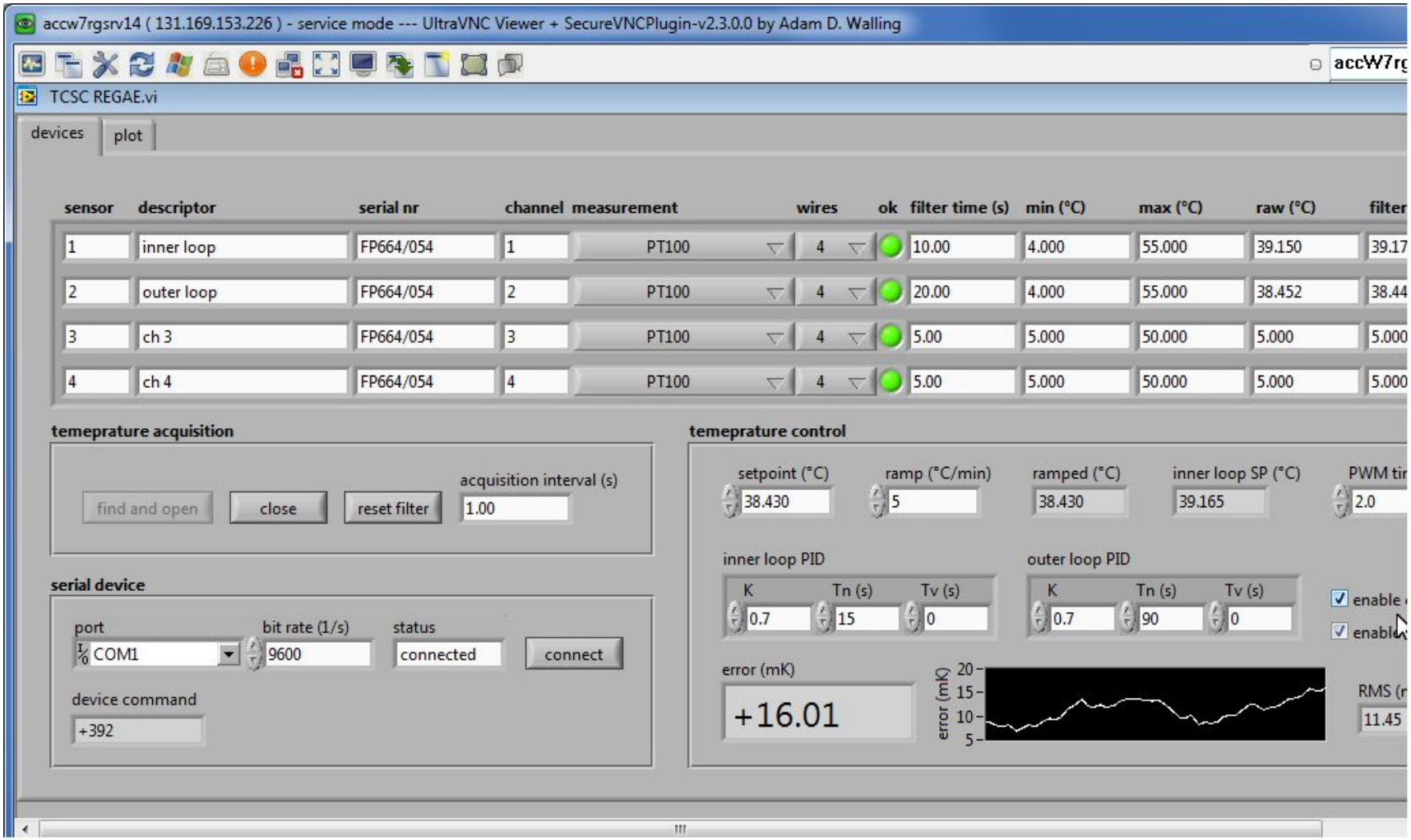

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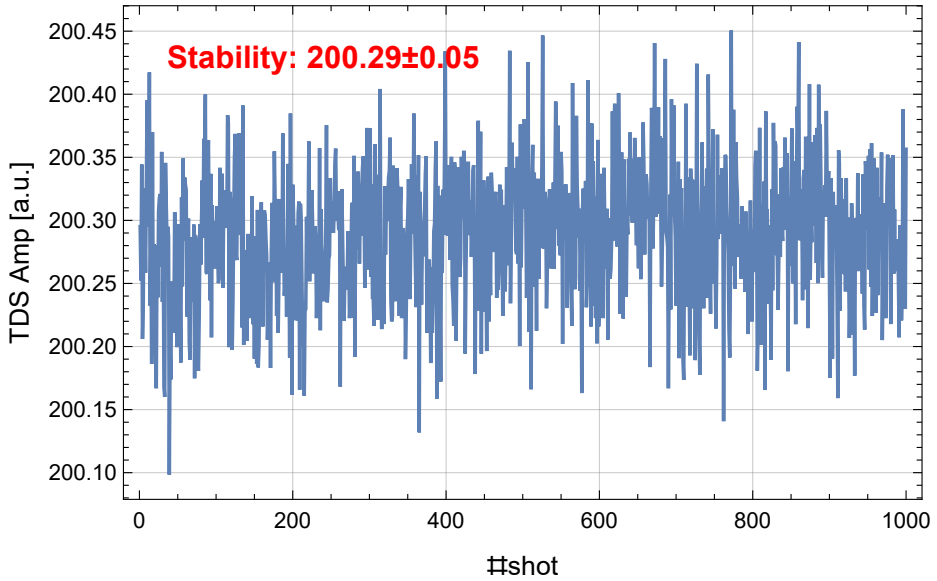
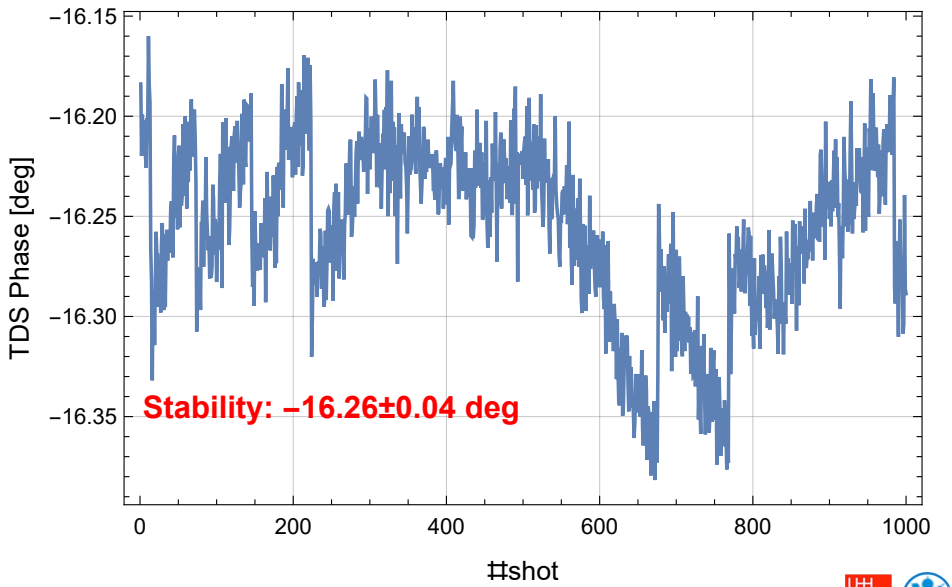
TDS: RF stability

- rel. amp stability: 0.00025



- phase stability:
  0.04°->37.0 fs



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TDS: streaking

- GunAmp: 80 MV/m -> 3.6 MeV
- bunch charge: $\sim$ 100 fC
- unbunched beam length: $\sim$ 500 fs

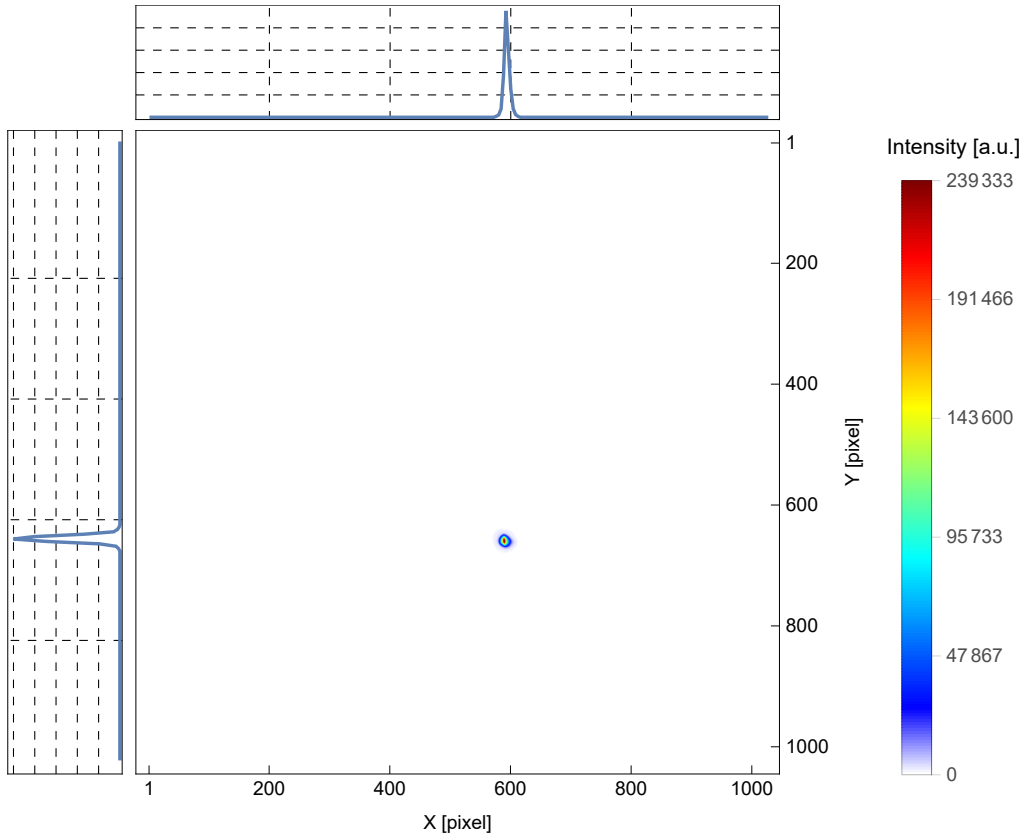

Figure: Full image of unstreaked beam @D2.

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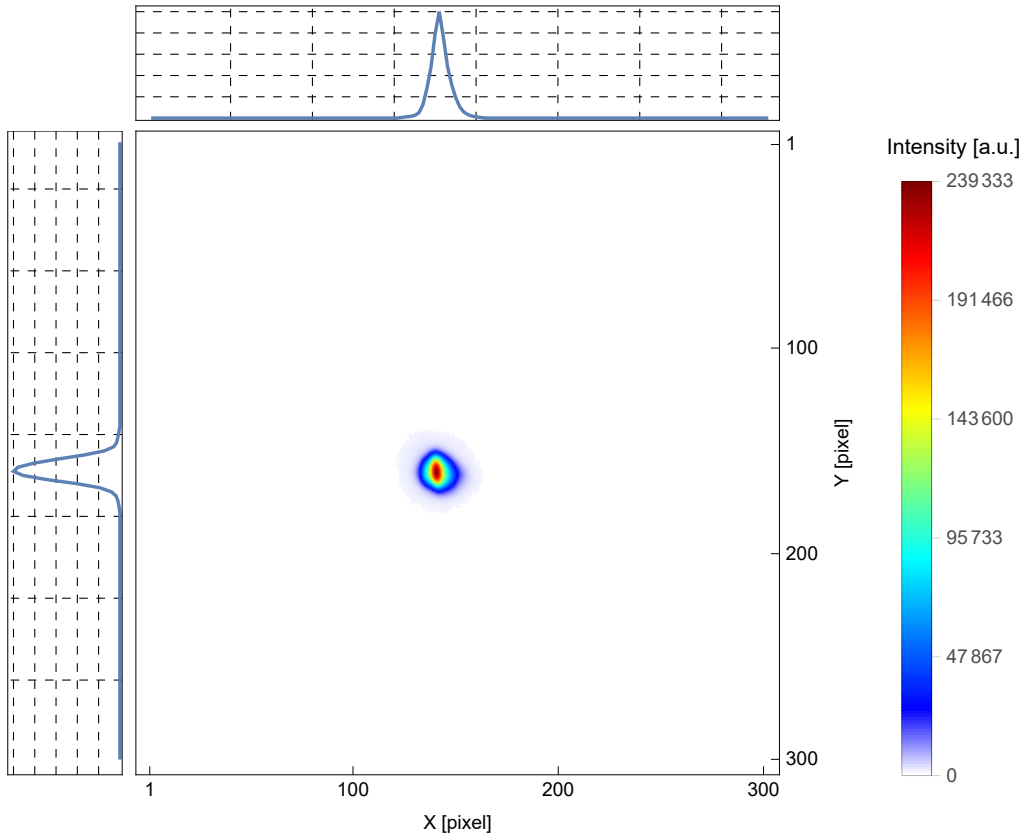

Figure: Zoomed in image of unstreaked beam @D2.

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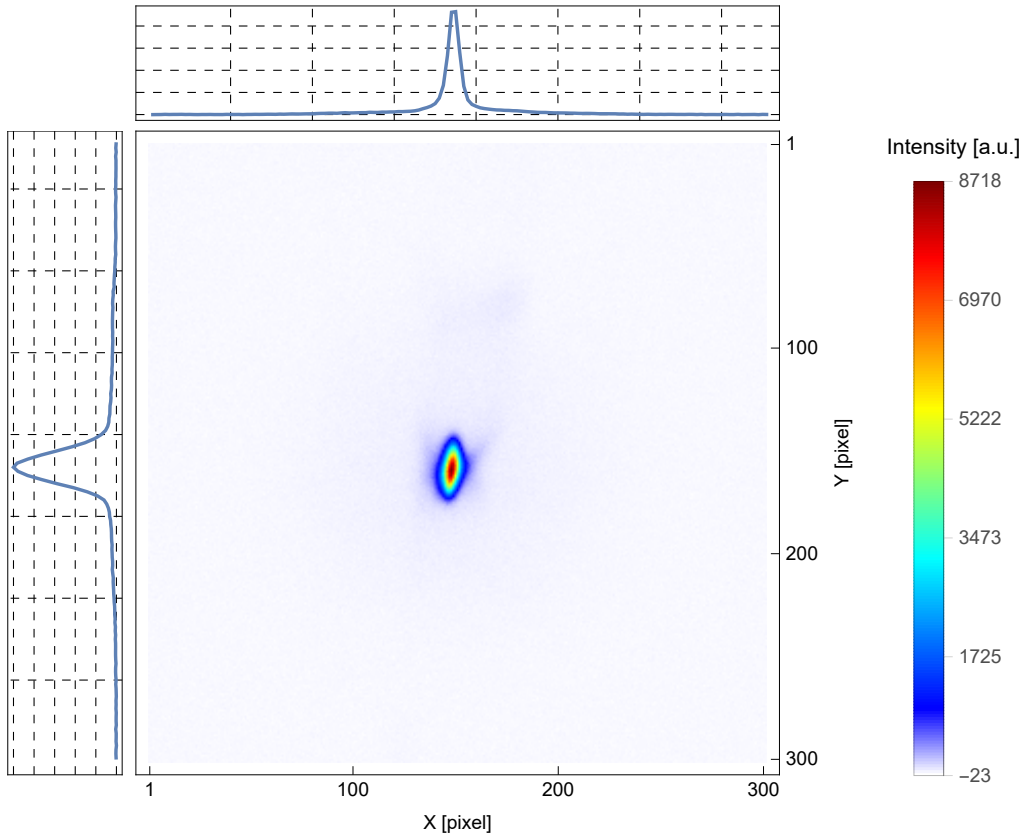

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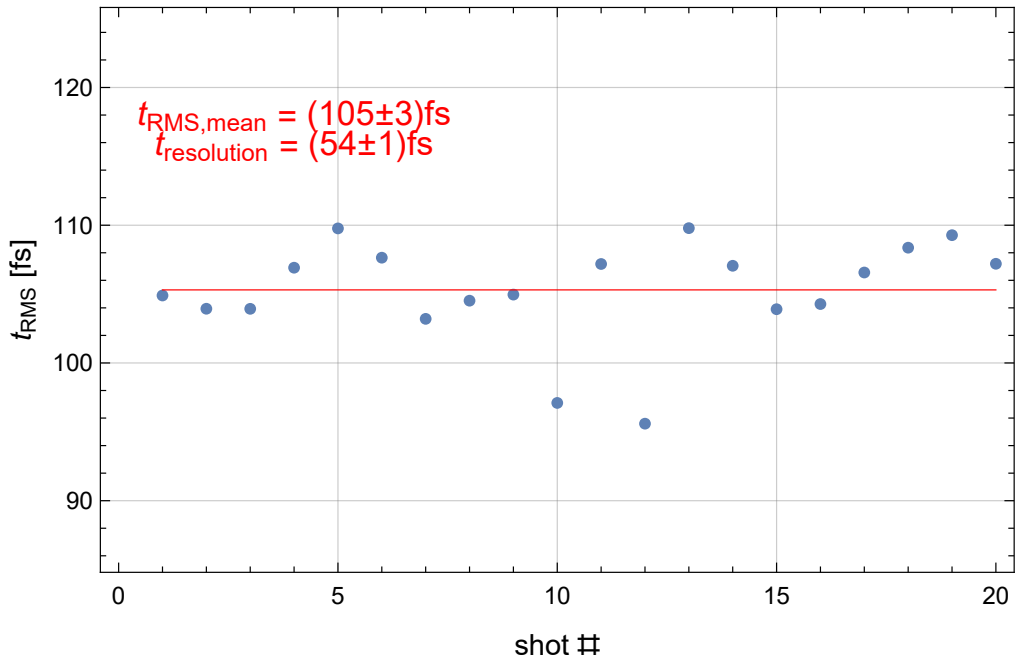

Figure: Bunch length of 20 streaked shots.

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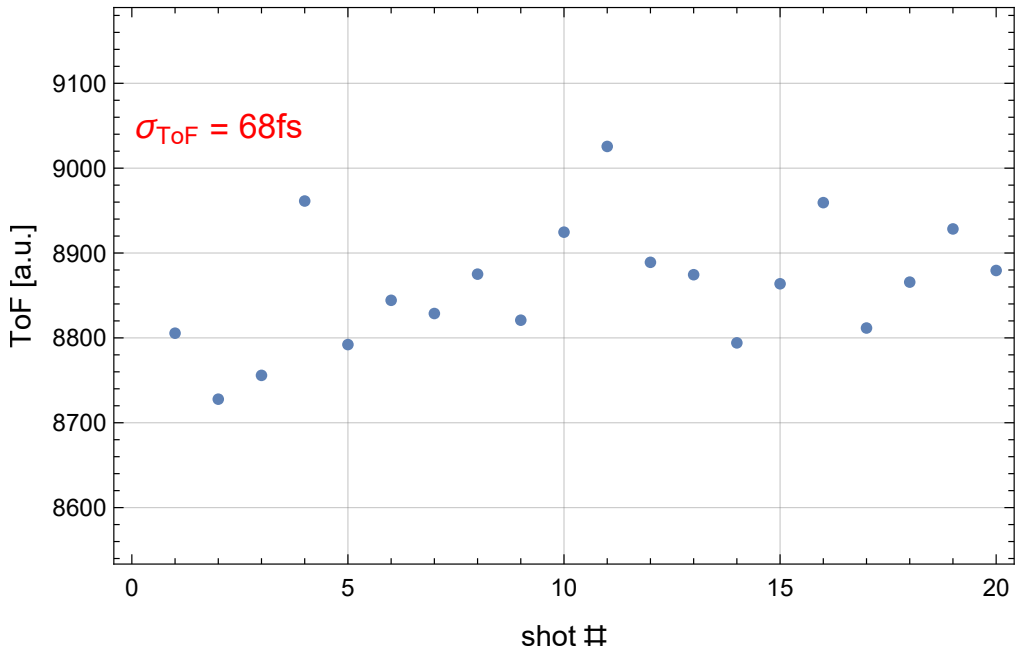

Figure: Time of flight determied from vert. jitter @D2.

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