ELBE Radiation Source, its accelerator R&D and future upgrade options

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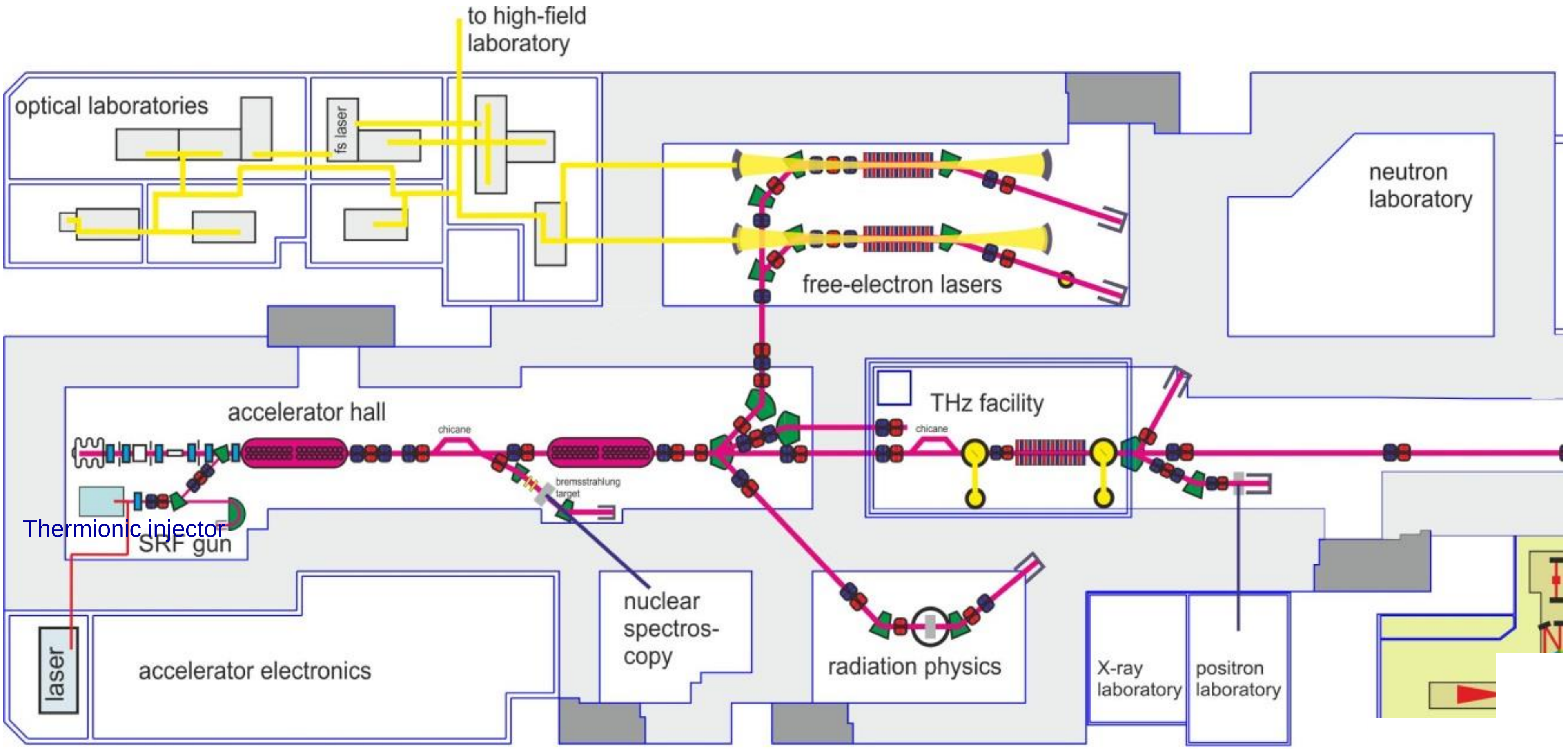
HZDR/ELBE

Outline

1. ELBE – user facility
2. SRF gun at ELBE
   (R&D transitioning to user operation)
3. JLab – HZDR bunch length measurements interferometer
   (R&D transitioning to routine machine setup)
4. Large Dynamic Range transverse beam profile measurements
   (R&D to-do)
5. Future ELBE – upgrade / new facility

ELBE :: Radiation Source

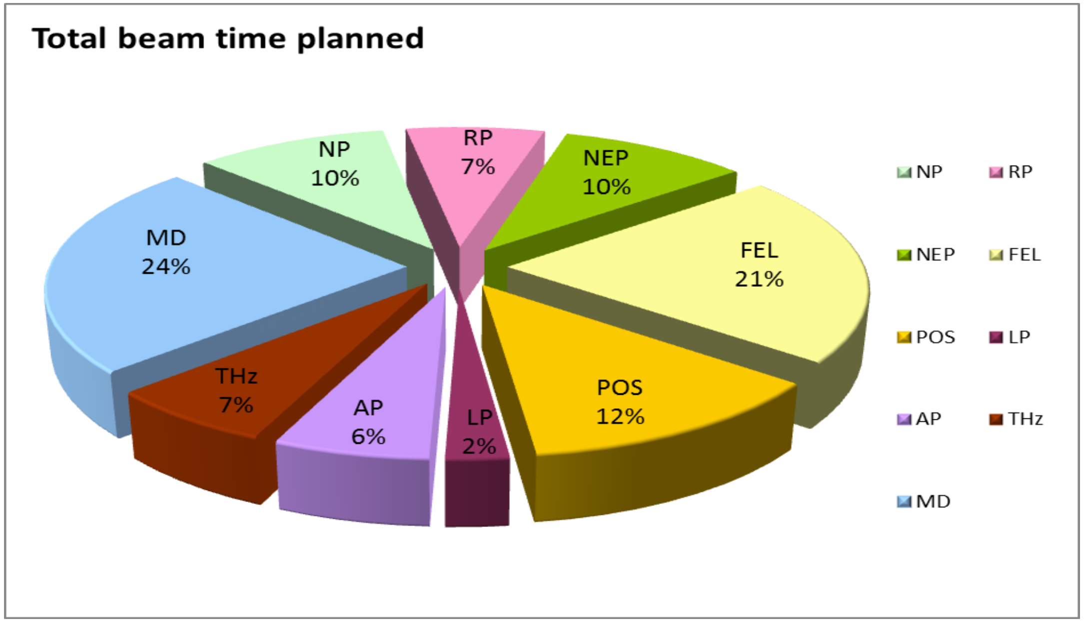


E_b = 34 MeV, f_b = 13 MHz, $<I_b>$ = 1 mA

Q_b = 77 pC (thermionic gun), Q_b = 300 pC (SRF gun at 100 kHz),

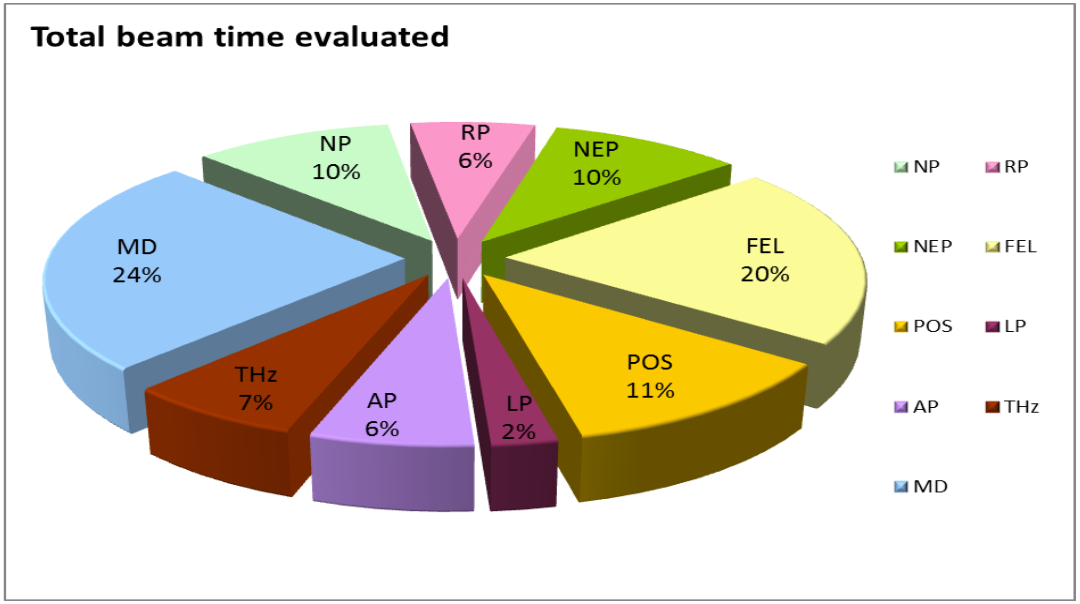
9-cell 1.3 GHz TESLA cavities

ELBE :: Users



Hours in total:

Scheduled	6348
Used	6056
Effiency	85%
External users:	71 %



Courtesy of P. Michel

ELBE :: Publications 2015 - 2016

Nuclear physics	3
FEL	8
THz	3
Detectors	2
Neutron physics	1
Positrons	5
Accelerator physics	3
Total:	25

(~173 hours of user beam time per paper)

Next:

enable multi user operation

Approach – fast kicker

13 MHz → 100 kHz

Journals:

Nucl. Instr. & Meth. A,

Phys. Stat. Sol. B,

Journ. Of IR, Millimeter and THz Waves,

APL Materials,

Phys. Rev. B/C,

Phys. Scribta,

Phys. Rev. Lett.,

Eur. Phys. Journal A,

Journ. of Instrum.,

Journal of Physics,

Journal of Electr. Materials,

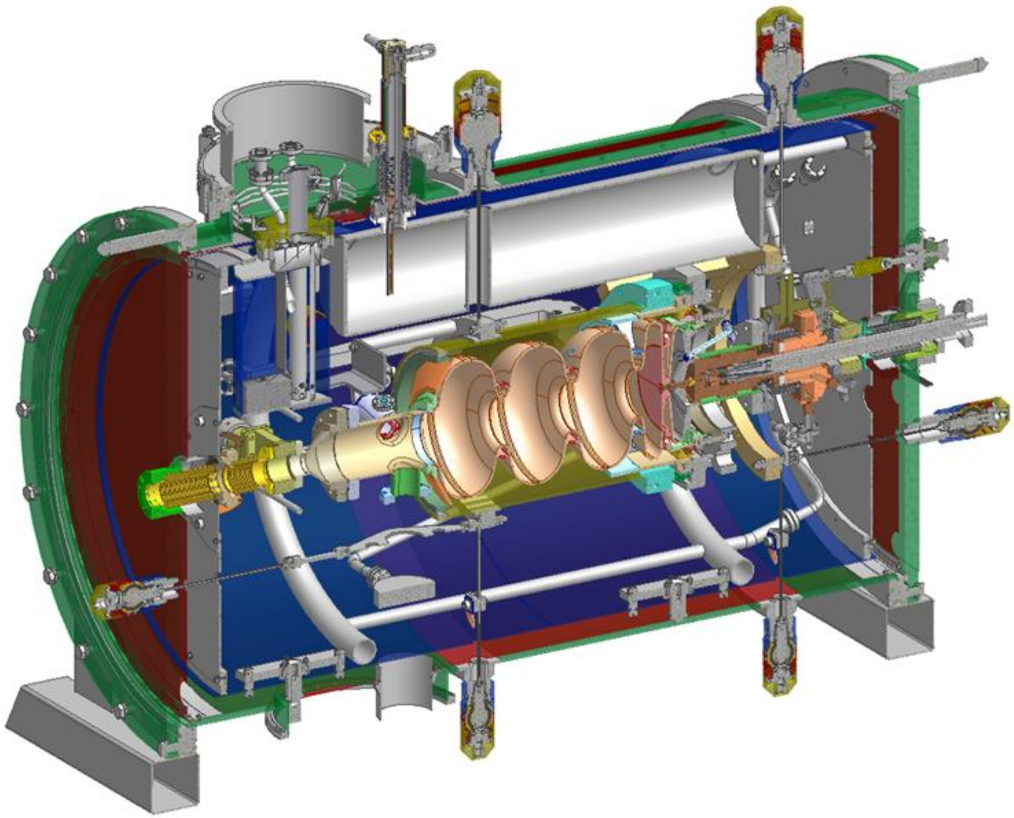
Scribt. Rep., Struct. Dyn., Appl. Phys. Lett.

Courtesy of P. Michel

ELBE :: SRF Gun

Courtesy of J. Teichert

- High bunch charge (1 nC) for THz, pulsed neutron and positron beam production
- Low emittance, medium to high charge with short pulses for THz-radiation and x-rays by Thomson scattering
- For FELs: 13 MHz, 80…120 pC

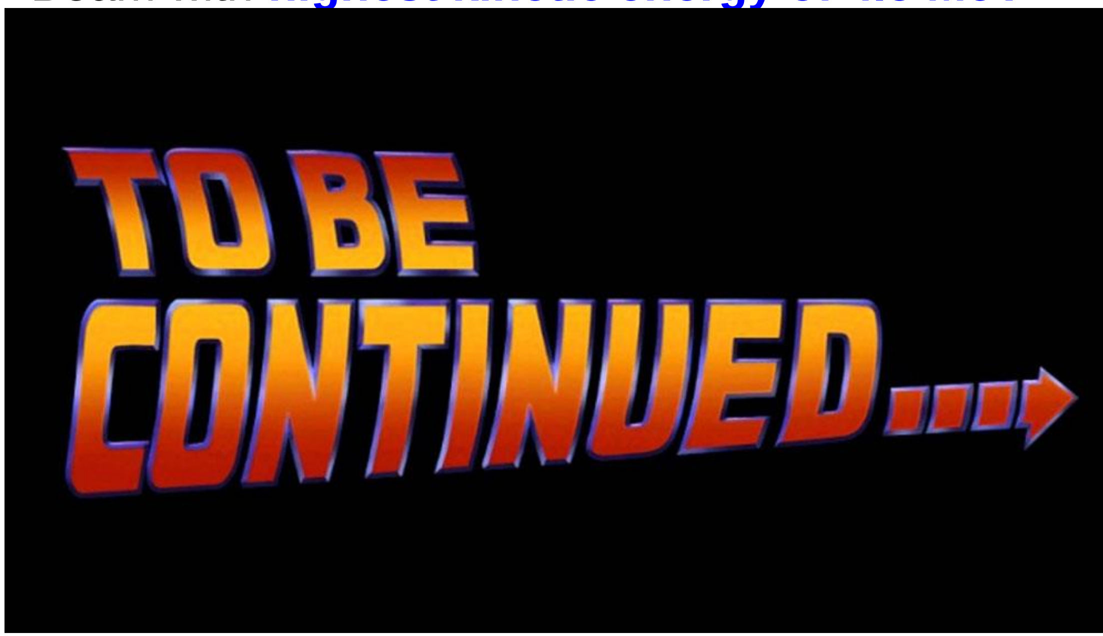


Mode	FEL	High Charge
final electron energy	≤ 9.5 MeV	
RF frequency	1.3 GHz	
operation mode	CW	
Photo cathode	Cs_2Te	
bunch charge	80 pC	1 nC
repetition rate	13 MHz	500 kHz
laser pulse (FWHM)	4 ps	15 ps
transverse rms emittance	1 mm mrad	2.5 mm mrad
average current	1 mA	0.5 mA

ELBE :: SRF Gun

Courtesy of J. Teichert

May	2014	Gun installation finished
June	2014	First beam with Cu photocathode
Aug.	2014	RF commissioning ready , 25.6 MV/m maximum peak field
Feb.	2015	Beam with **highest kinetic energy of 4.5 MeV**
Jan.	2015	
Feb.	2015	mission
Nov.	2015	
Jan.	2016	y
		measurement
March	2016	**0 pC**
June	2016	
		pC, 100 kHz
Dec.	2016	**User shifts for TELBE, 4 x 12 h, Mg cathode, 80 pC, 100 kHz**
Feb.	2017	Beam with Cs_2Te cathode, without multipacting, 200 pC,
		2 weeks lifetime only due to cathode cooling problem
March	2017	TELBE/ARD shifts, 100 pC short pulses, high THz power



Joined ELBE – JLab accelerator R&D

Bunch Length Measurements at ELBE

- Options for **ps** and **sub-ps** σ_t measurements
  - EO direct Coulomb field measurements
  - Transverse deflector (TCAV)
  - Frequency domain technique

- TCAV: no space, no €€€, no small transverse emittance, no emittance dominated beam

- Electro-Optical: setup at the end of LINAC, not easy at low beam energy (34 MeV max) and moderate charge (77 pC) not yet a routine measurements

- Martin-Puplett Interferometer (MPI) as simple and robust tool for routine, every day measurements made by any operator

- For super-radiant THz source upgrade:
  Q: could MPI measure 200 fs and below?

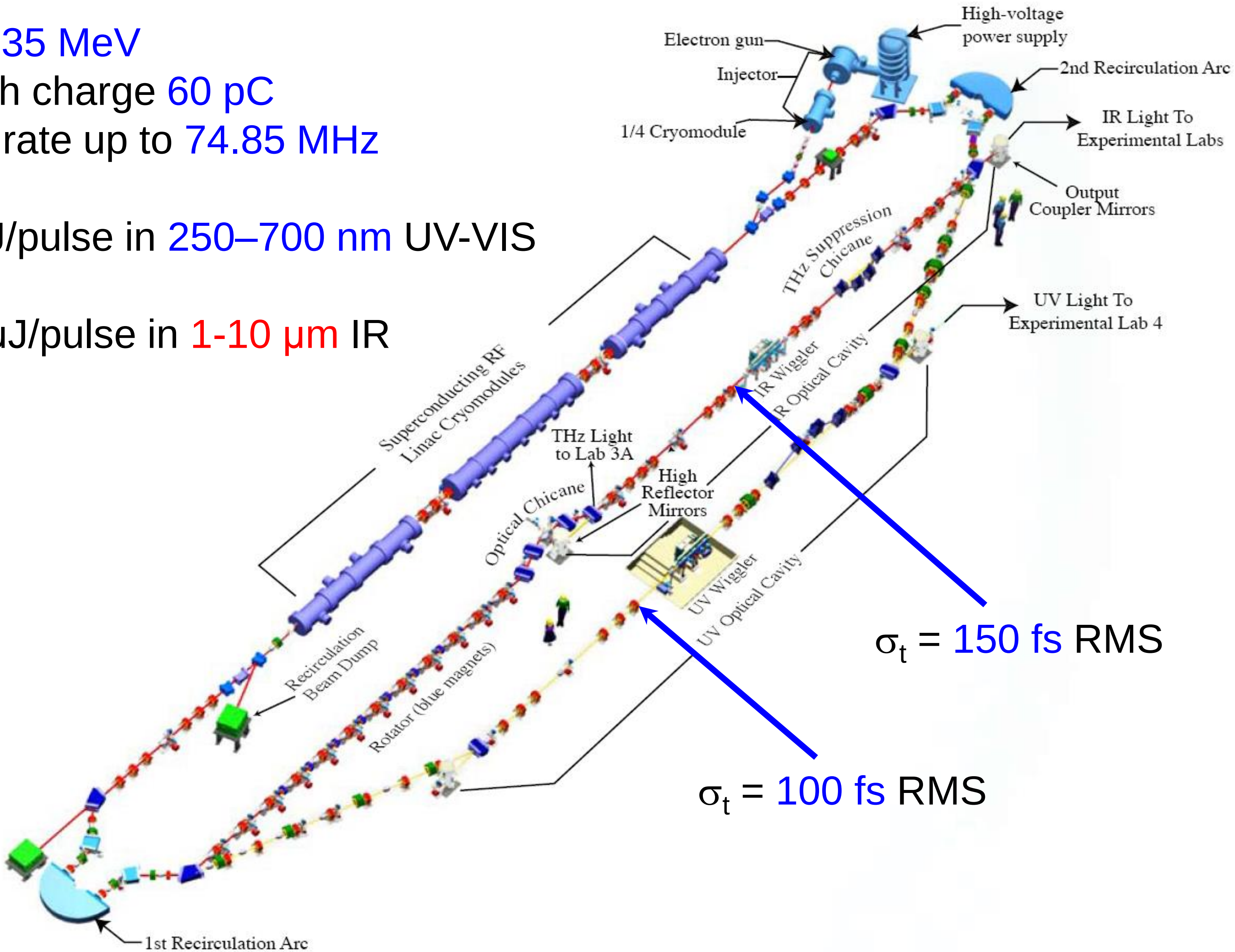
- **A:** JLab FEL measured σ_t down to ~100 fs; shows that instrument has enough bandwidth for ~ 50 fs σ_t measurements

JLab IR/UV Upgrade :: Bunch length

E = 135 MeV
Bunch charge 60 pC
Rep. rate up to 74.85 MHz

25 μJ/pulse in 250–700 nm UV-VIS

120 μJ/pulse in 1-10 μm IR

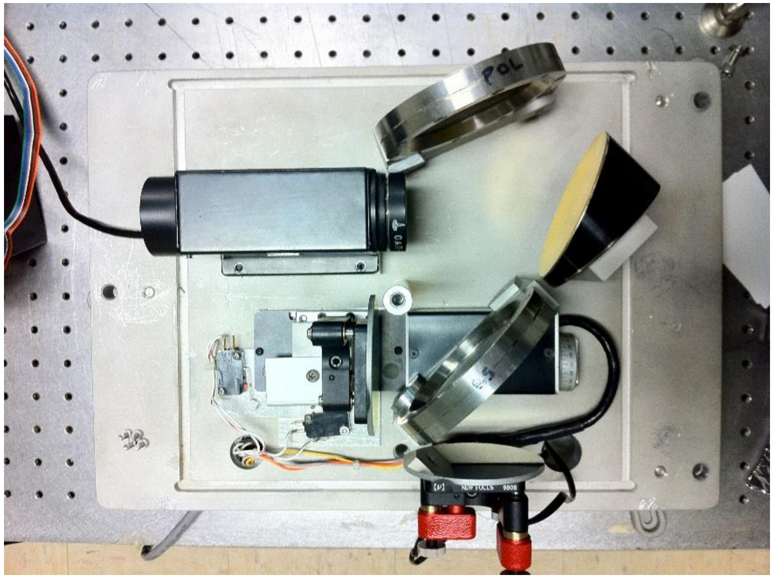


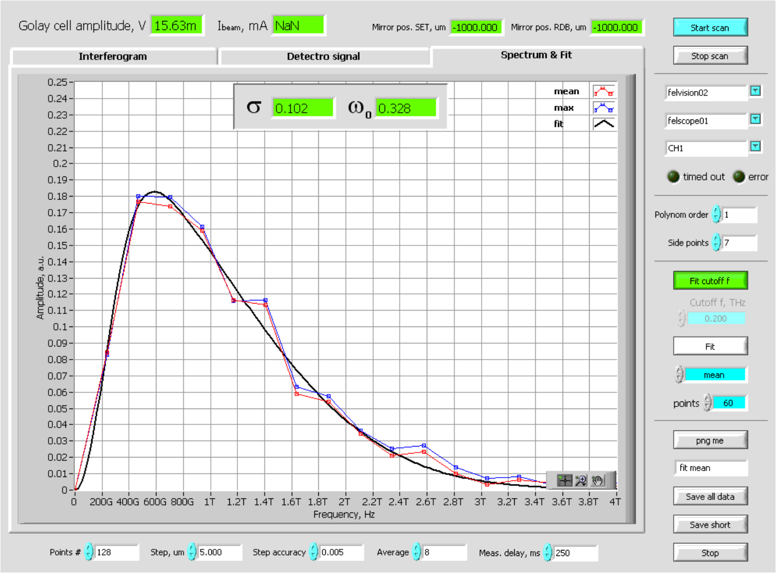
σ_t = 150 fs RMS

σ_t = 100 fs RMS

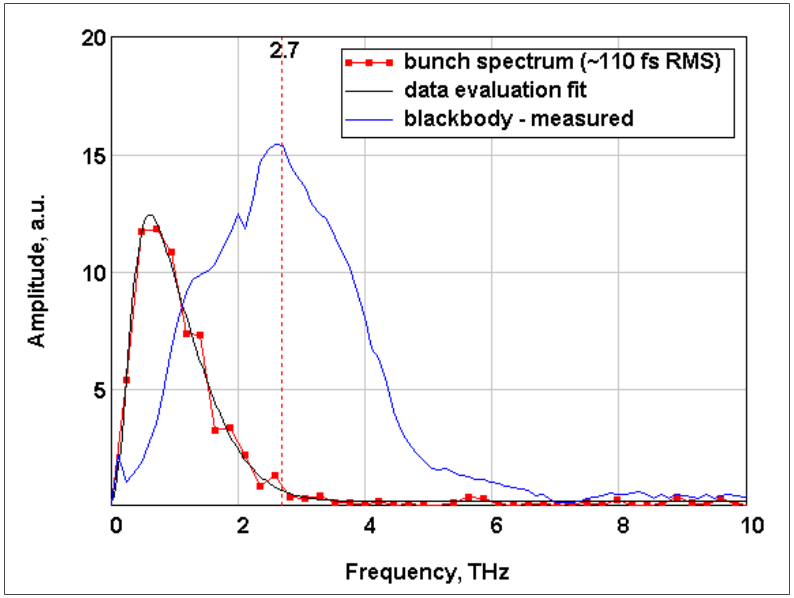
JLab FEL Interferometer

- "Simplified" interferometer with 1 detector; in air; used with TR
- Robust and simple enough for any operator – no expert needed for measurements
- σ_t = 100 fs RMS at UV FEL
- UV FEL had much more gain than 1D model predicted with σ_t=100 fs

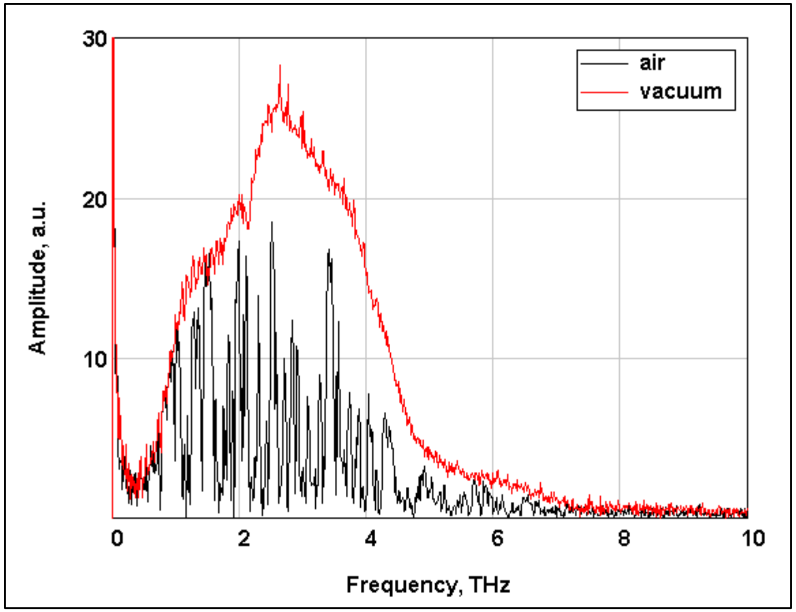


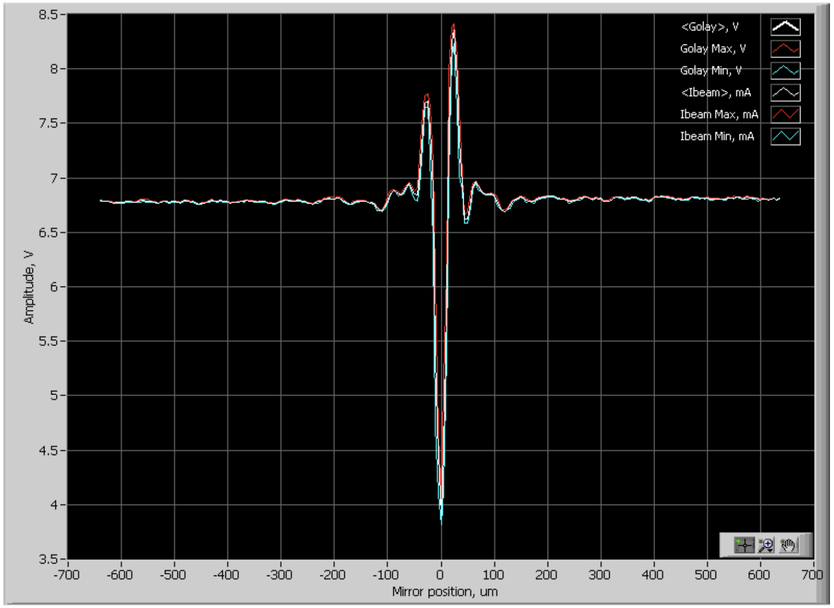


JLab FEL bunch length

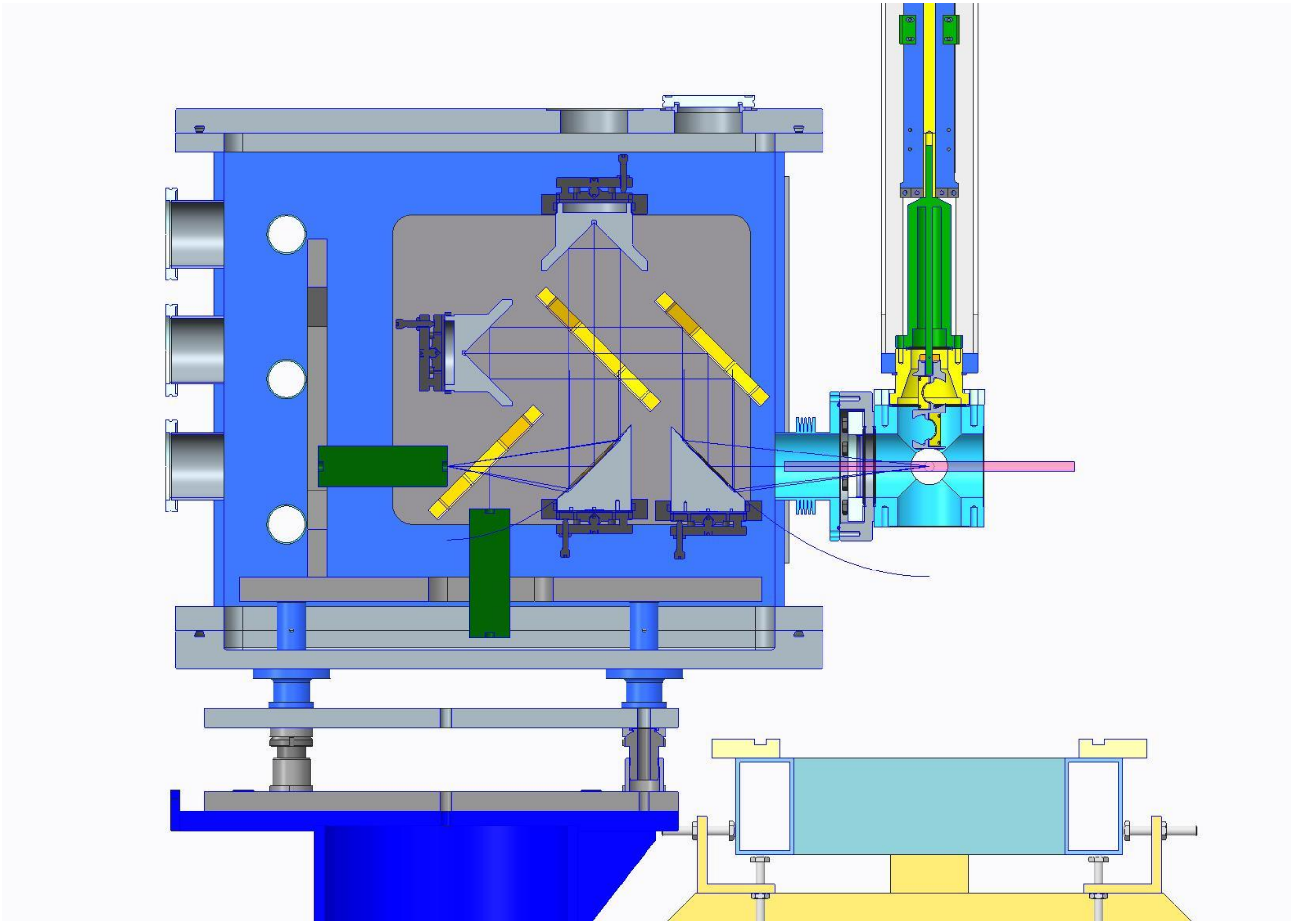


- Measurements of black body spectrum shows bandwidth of the system
- JLab instrument is good for ~ 50 fs
- Measurements in air vs. in vacuum show absorption effects (~ 1 m)



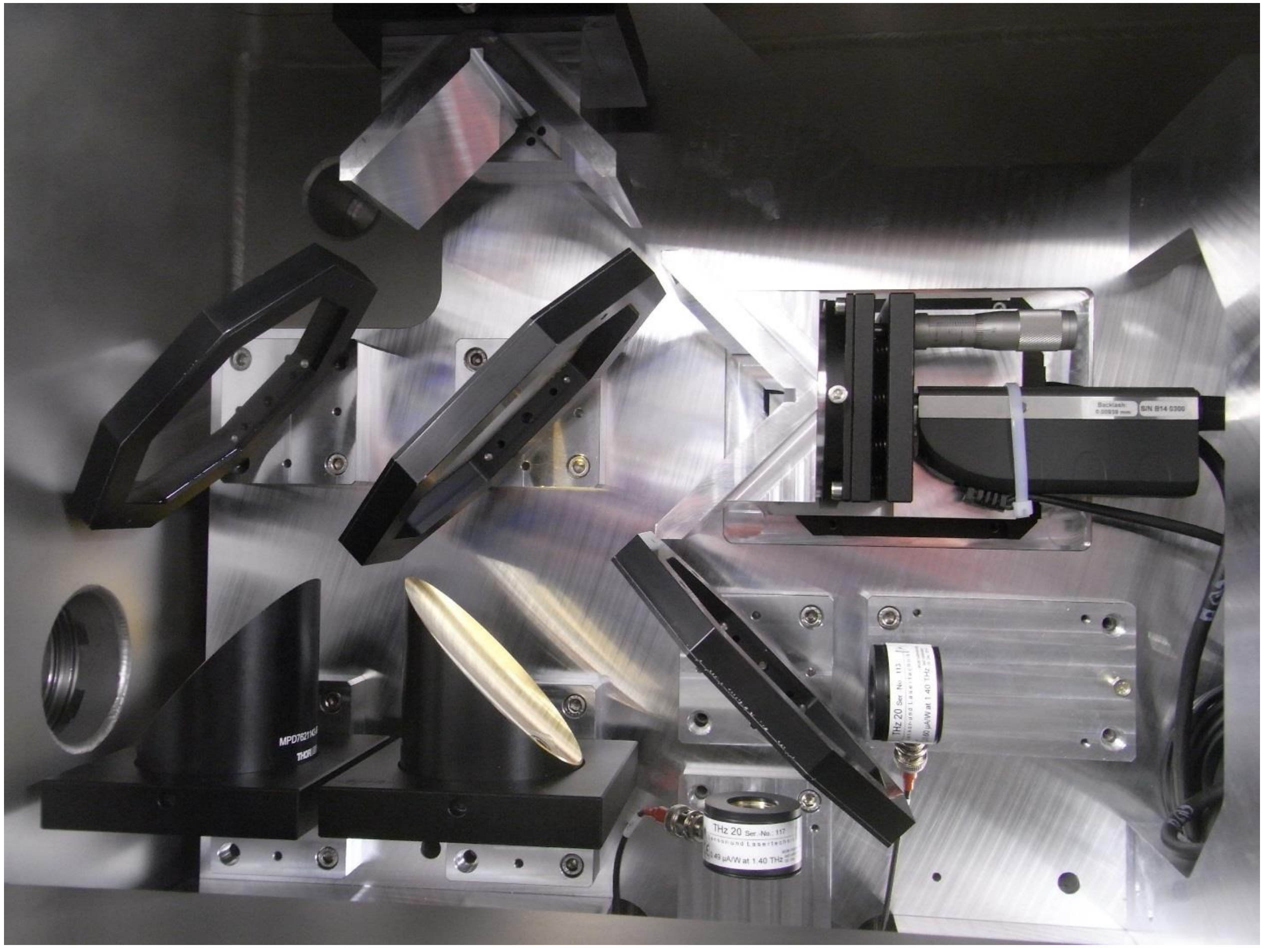


ELBE :: Martin-Puplett Interferometer



- Interferometer for ELBE – proper Martin-Puplett interferometer
- Wire-grid polarizers scaled down by factor 2 to allow shorter than 50 fs measurements
- Built with vacuum chamber to reduce air absorption

ELBE :: Martin-Puplett Interferometer



- Interferometer for ELBE – proper Martin-Puplett interferometer
- Wire-grid polarizers scaled down by factor 2 to allow shorter than 50 fs measurements
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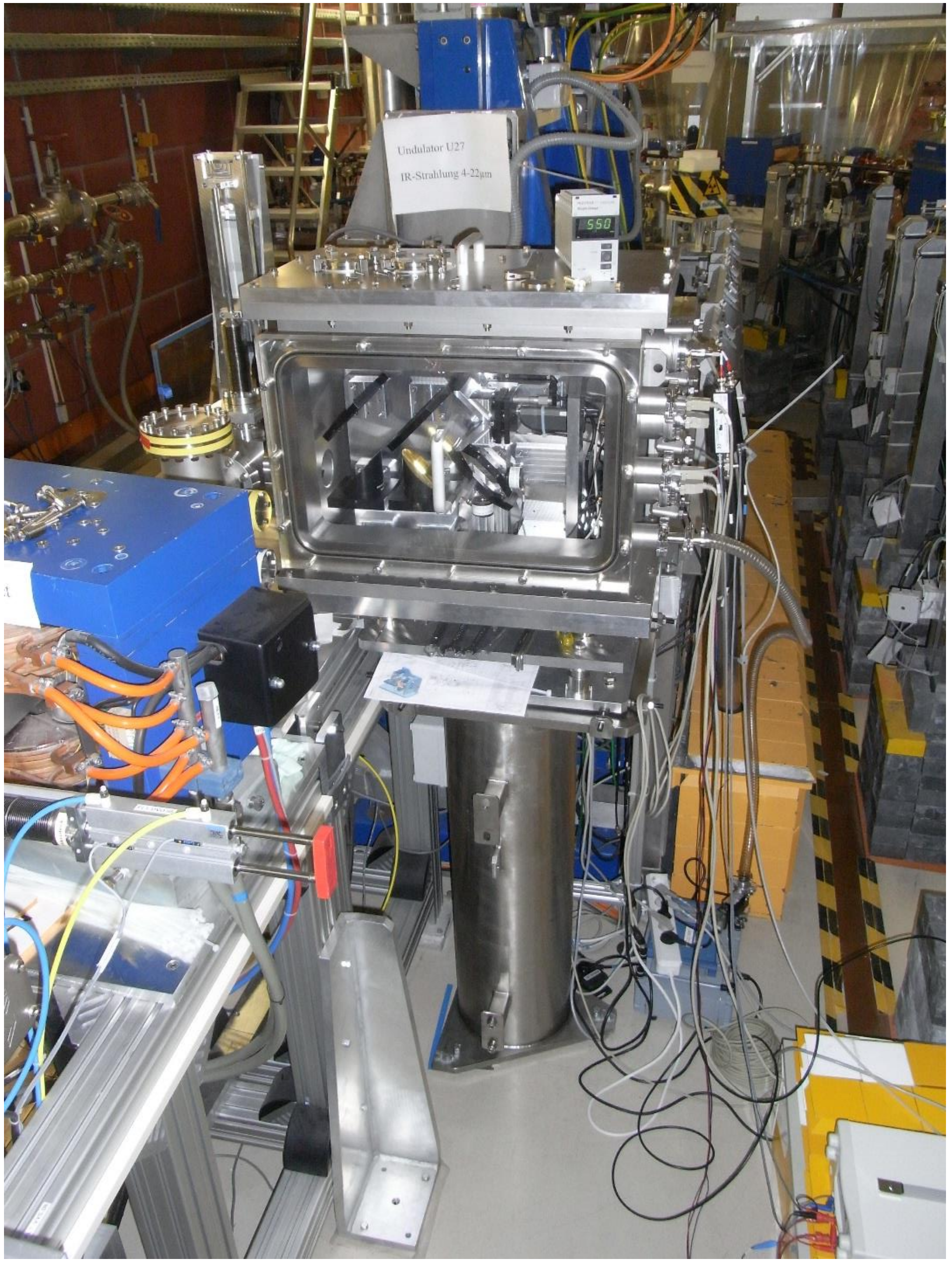
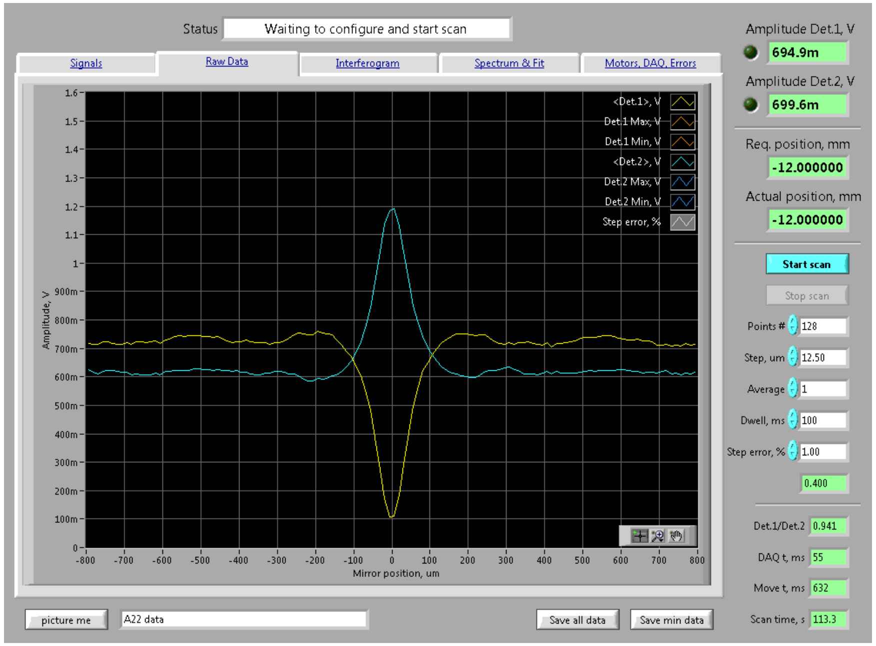
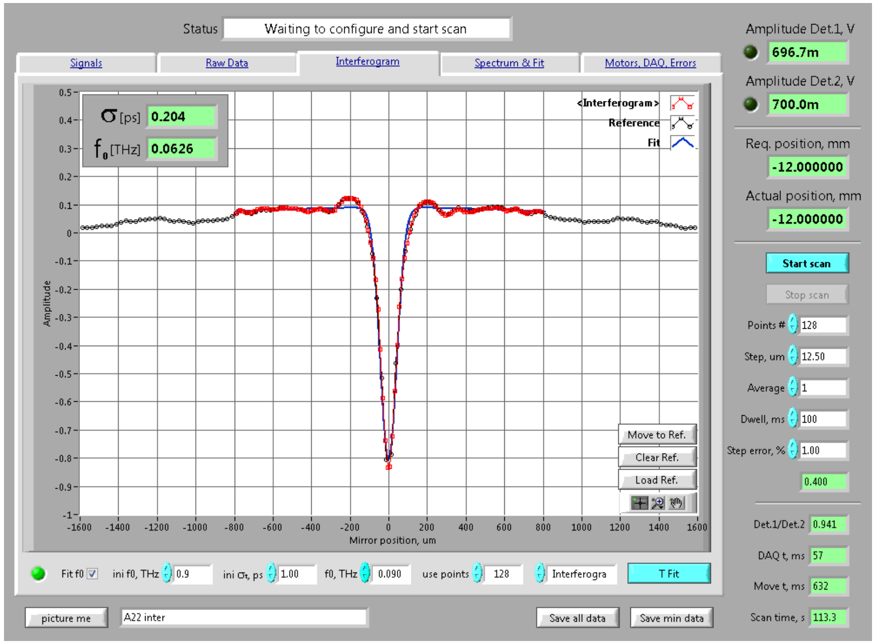
ELBE :: Martin-Puplett Interferometer

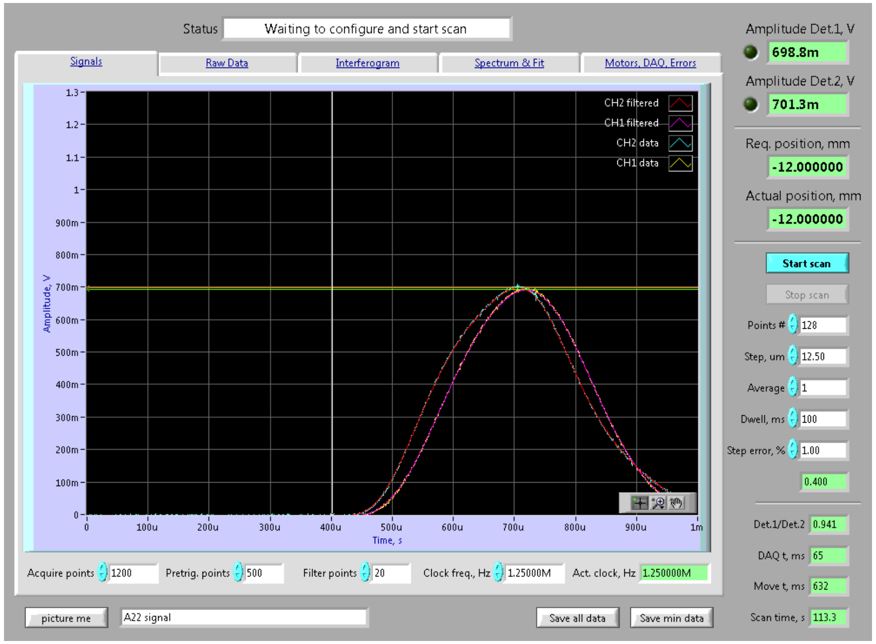
- MPI installed at FEL beam line downstream of undulator
- Used with CTR – diagnostic beam mode only (for now)
- One measurement takes ~ 1 min (128 point)
- OTR viewer at the same location for transverse beam profile measurements
- Next #1: shorten measurements time to 5 sec. – diagnostic beam at 25 Hz + continues motion of scanning mirror + gap less DAQ.
- Next #2: fast detectors to see each bunch at 13 MHz – towards digital beam based feedback
- Next #3: move to CSR/CER port at last dipole before the undulator – anable measurements with CW beam



MPI @U37 :: data set

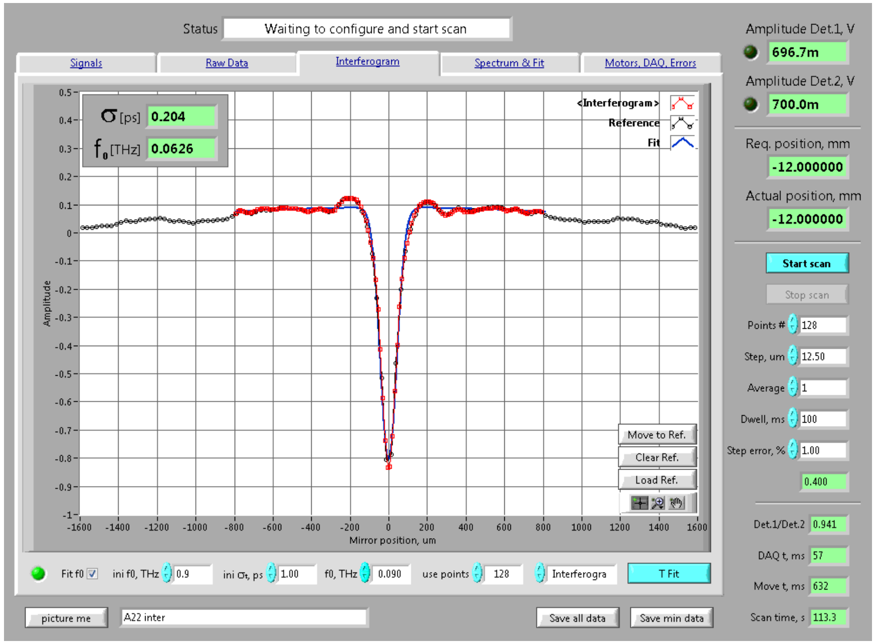




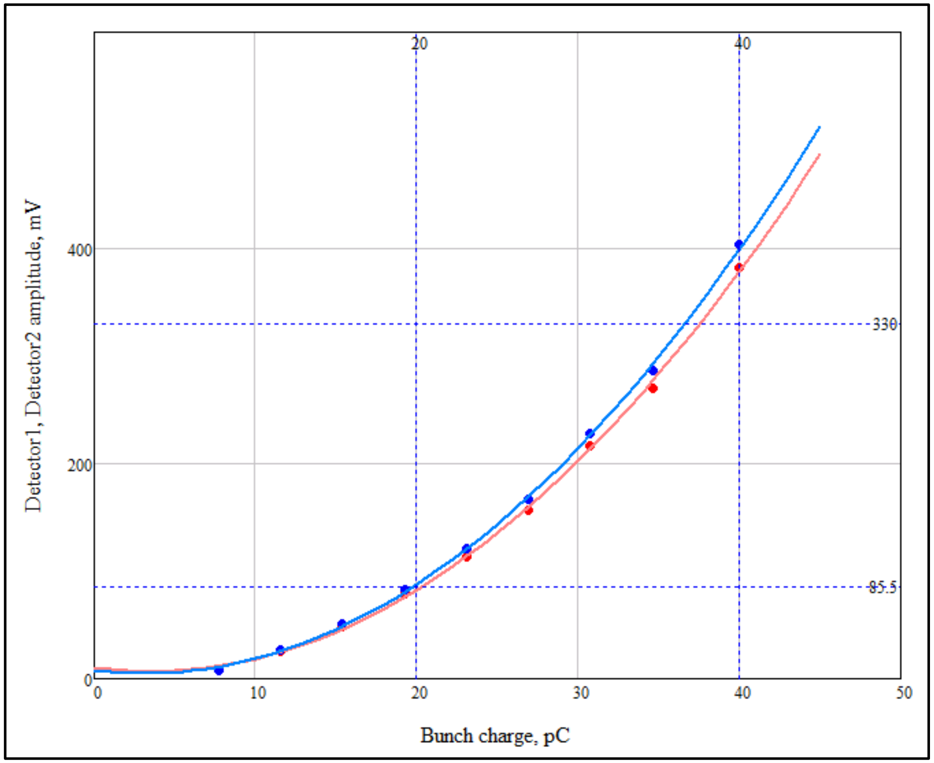


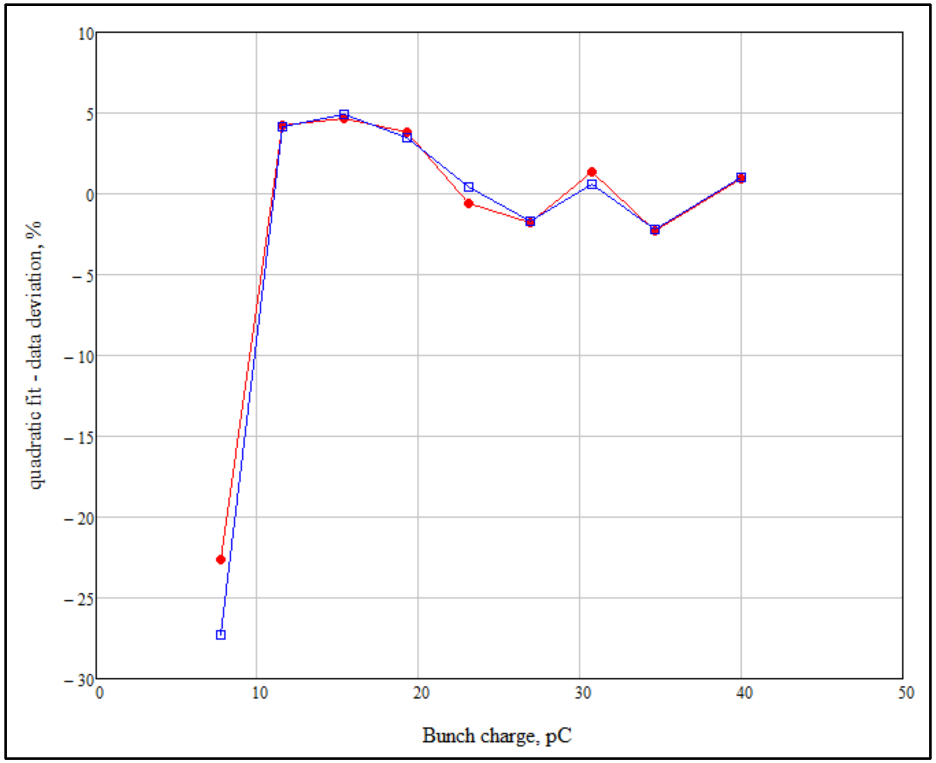
MPI @U37 :: data evaluation

- At IR/UV Upgrade interferometer data evaluation – bunch length extraction was made in frequency domain, NLSF + Gaussian beam essamtion
- Works OK, need to pay attention to the fit quality; cannot expect every user to do this right
- Disadvantage – fit uses only fraction of data points
- With ELBE MPI data frequency domain fit is often difficult
- Changed to data evaluation with time domain NLSF
- Always used all data points for fit
- Much more robust

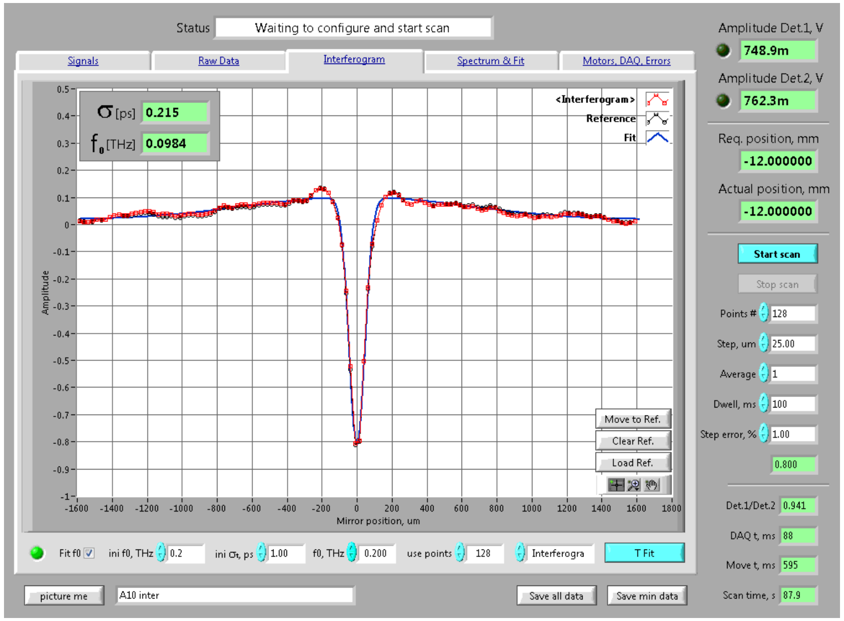


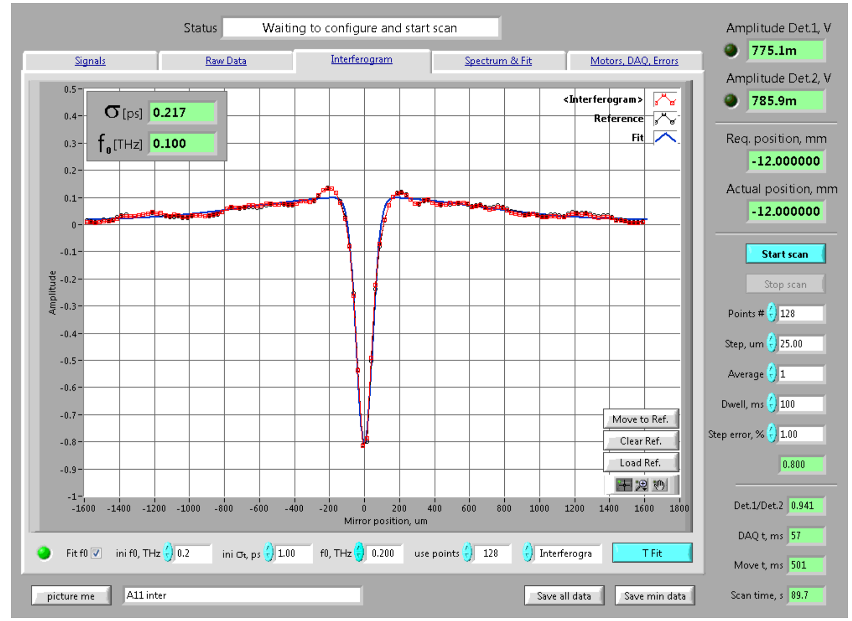
Detectors signal amplitude vs. bunch charge

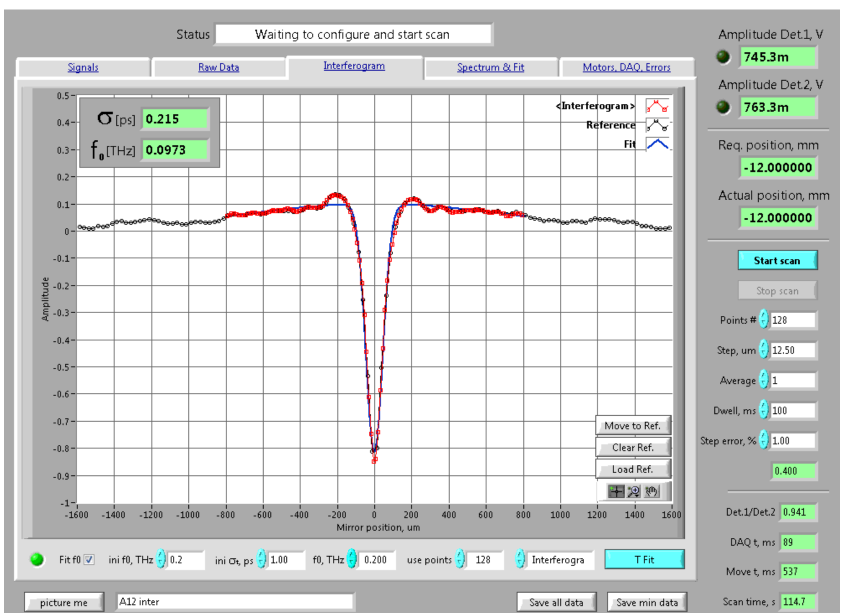


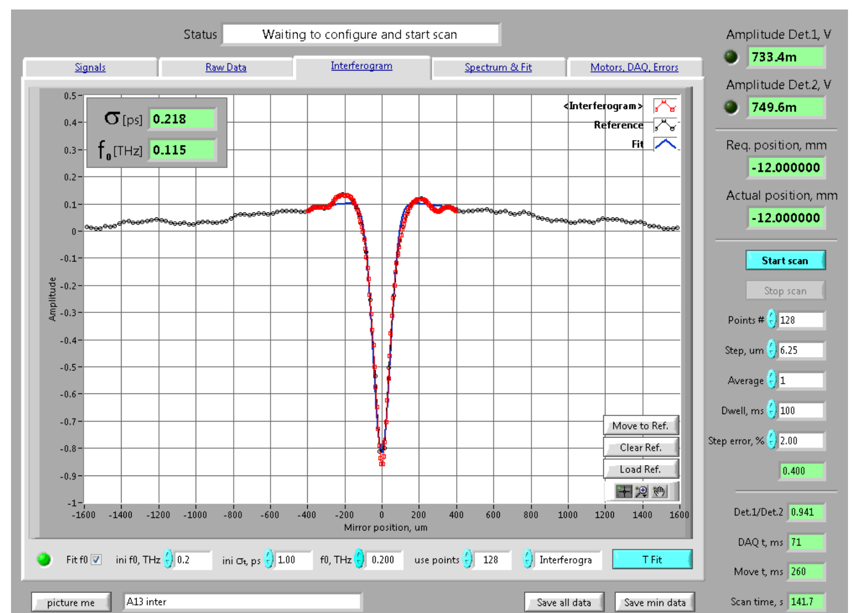


34 MeV :: 215 fs bunch length :: reproducibility

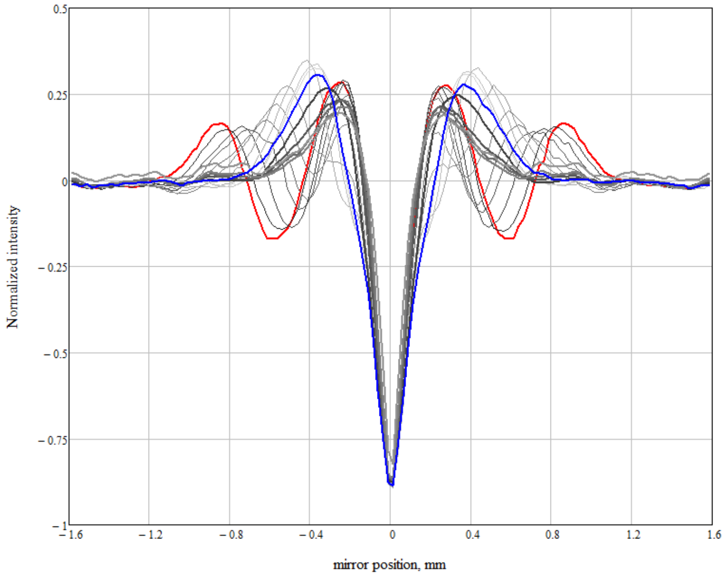


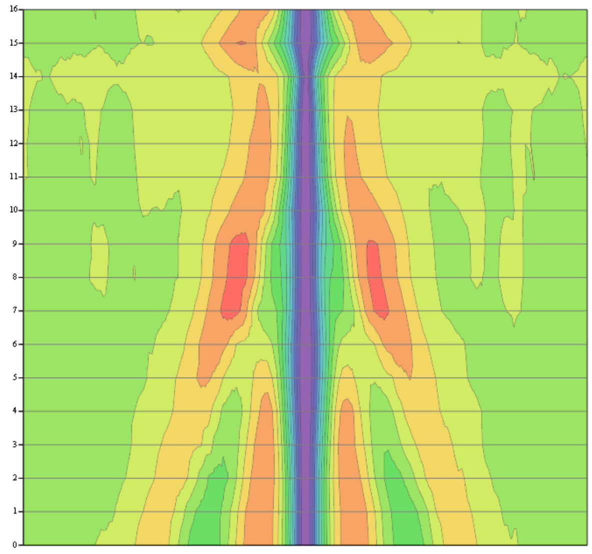


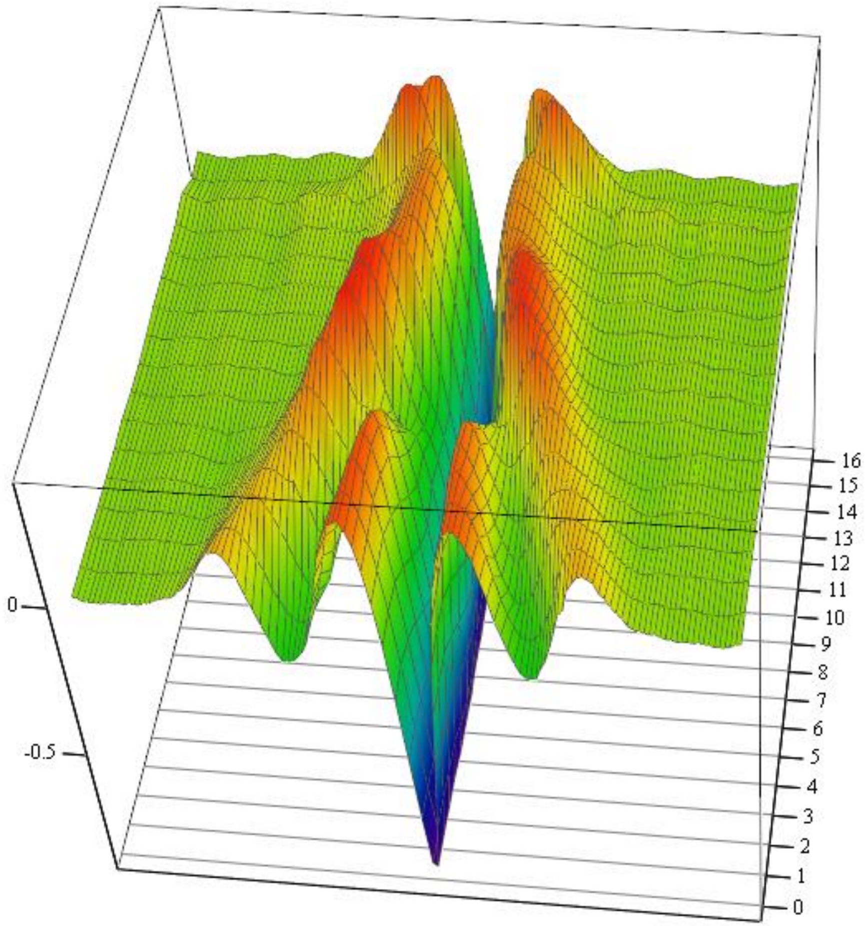




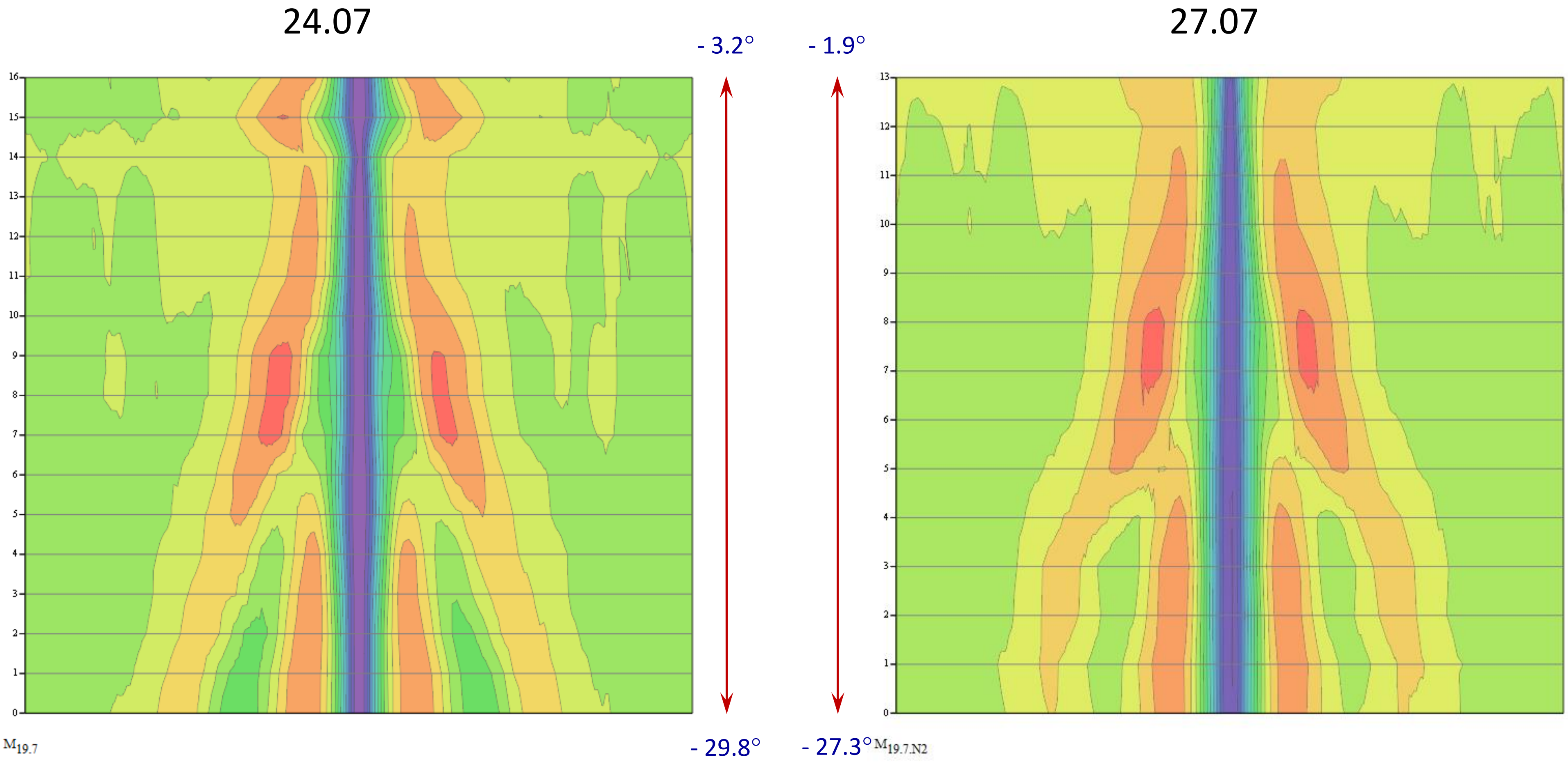
U37 :: MPI2 :: 19.7 MeV vs. LA2 phase





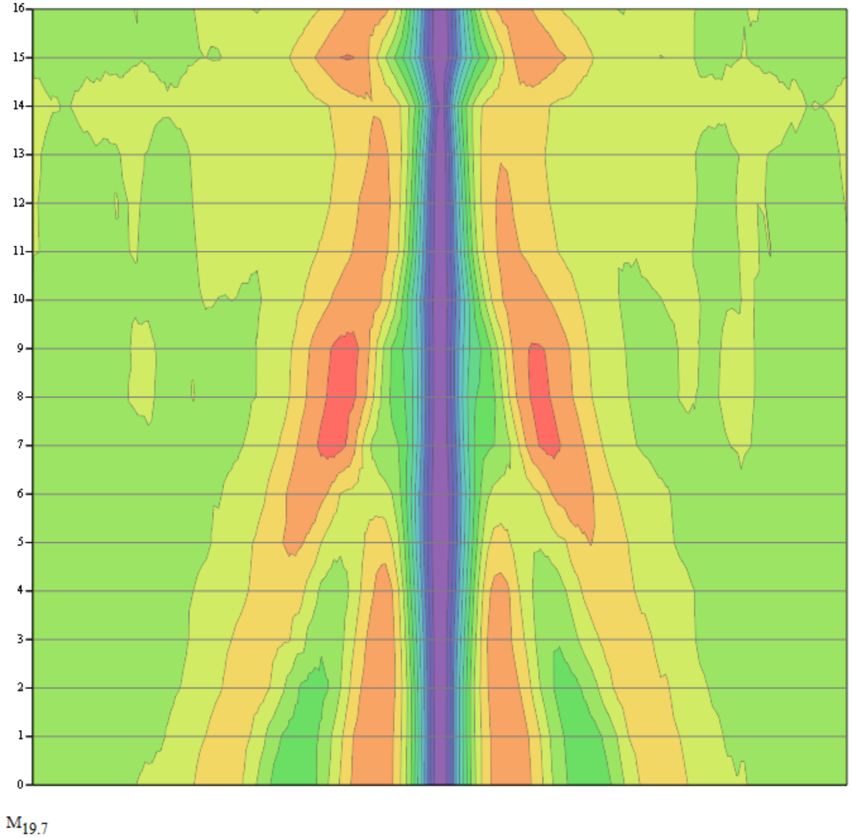


19.7 MeV vs. LA2 phase / 24.07 vs. 27.07



19.7 MeV vs. 30 MeV vs. LA2 phase

19.7 MeV



30 MeV

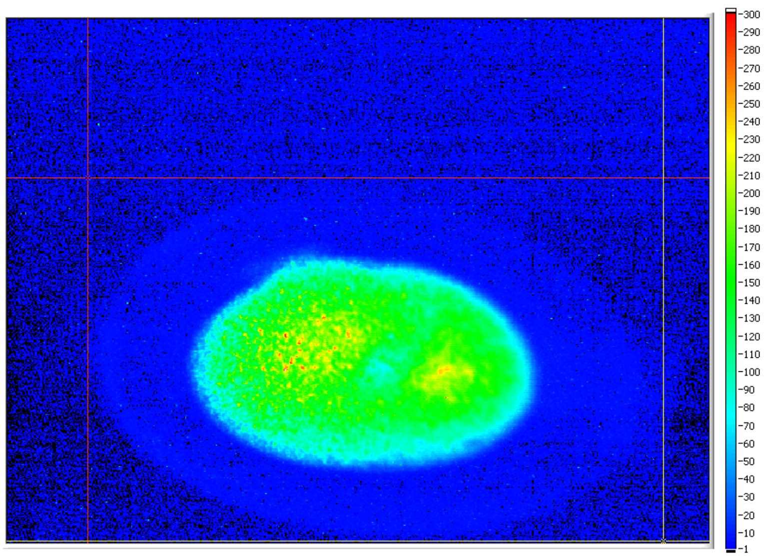
Beam Halo :: brief recap

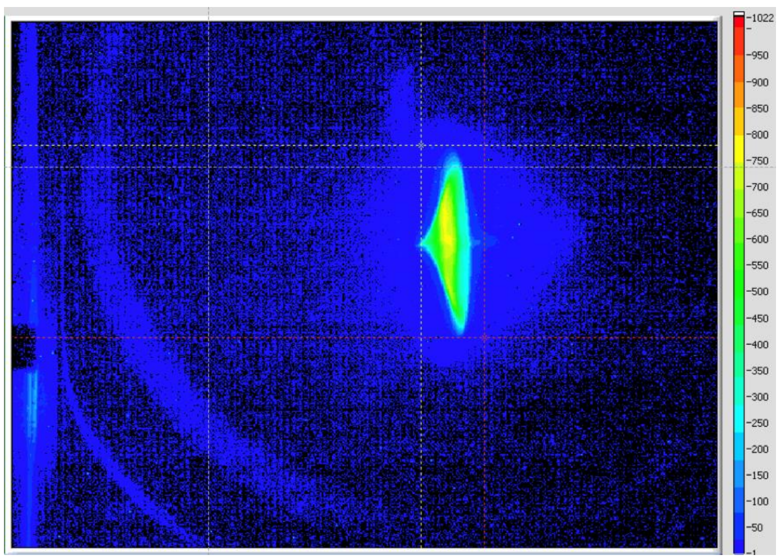
- JLab's IR/UV Upgrade FEL with 10 mA average current has shown that beam halo is a serious operational issue for such class of machines

- We suggested that Large Dynamic Range (LDR) transverse beam profile measurements is one of necessary steps in solving beam halo problem

- At ELBE with 1 mA $\langle I_b \rangle$ beam losses and beam halo are less critical than at IR/UV Upgrade, but still is a limiting factor, which is difficult and time consuming to deal with

- Better halo measurements and understanding is important for ELBE

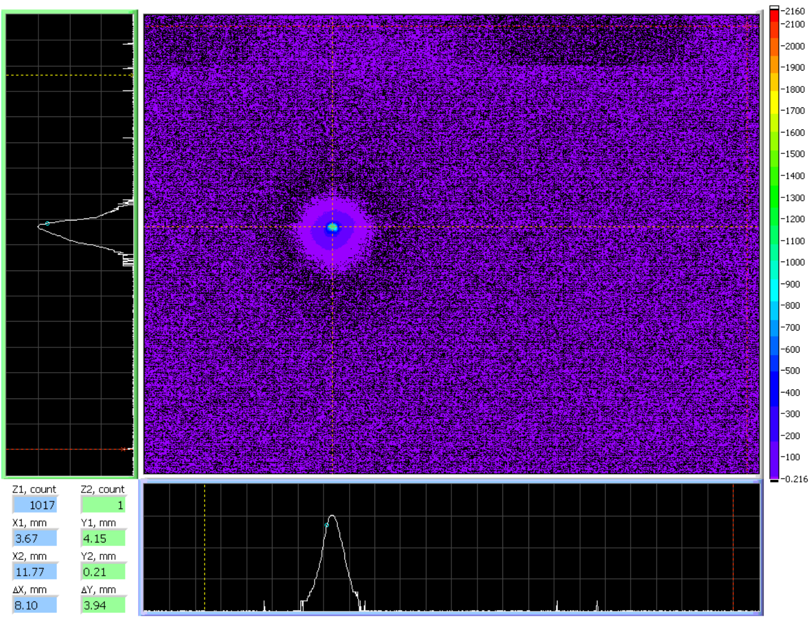


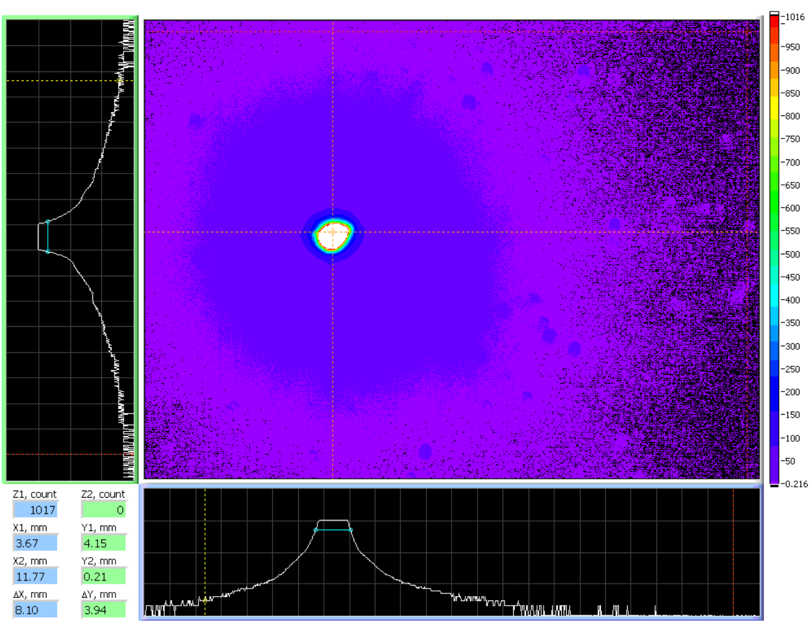


Beam Halo :: brief recap cont.

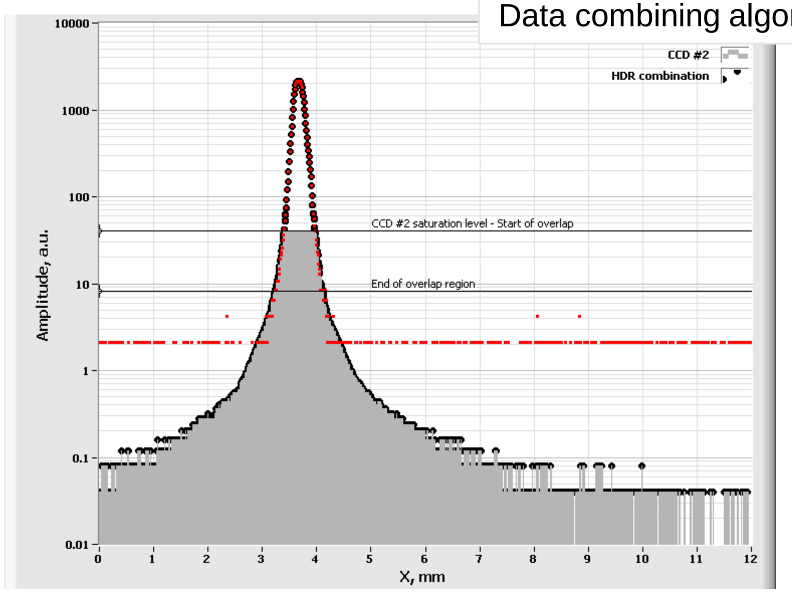
- Two techniques developed at JLab FEL for LDR transverse beam profile measurements: LDR imaging, LDR wire-scanner
- A lot of design and construction of diagnostic hardware – never demonstrated before at accelerators
- First prototypes were used for first Dark Light beam test
- By the time design and implementation was done – JLab FEL program (beam operation) has ended (end of ONR funding)
- ELBE was only accessible and operational CW facility with beam allowing to continue LDR test and development
- Part of JLab’s LDR measurements hardware was moved to ELBE (within existing CRADA)

Sensors :: 2-CCD cameras





Data combining algorithm

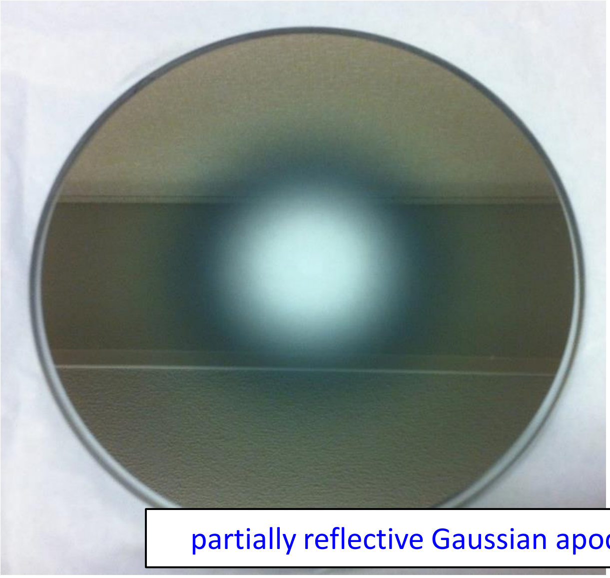


- ❖ Two images (on the left) measured simultaneously with integration times 20 us and 400 us
- ❖ Background measurements and subtraction is crucial! Made separately for two sensors and subtracted on-line.
- ❖ Combining algorithm is efficient enough to provide 5 Hz repetition rate for 1024x768 images
- ❖ Demonstrated dynamic range of ~ 5E+4 (factor of 100 increase)
- ❖ Integration time is used for normalization and overlap
- ❖ Averaging also improves SNR and therefore DR (but requires beam stability)

Amplitude apodizers

- Apodizers manufactured using half-tone-dot process
- Average optical density (OD) adjusted via the average dot density
- It is a 2D binary array of 10 µm pixels with transmission of either 0 or 100 %
- “error diffusion” algorithm used to translate required OD to dot density
- Power spectrum (spatial frequencies) of a pixelated apodizer is different from an ideal continuously variable one
- The claim of the “error diffusion” algorithm is that it adds to an ideal power spectrum only at high spatial frequencies – one of the first things to be tested on a bench
- If pixels are small enough, the high spatial frequency “noise” does not affect image
- Alternative technique – partially reflective coatings (difficult to program profile)

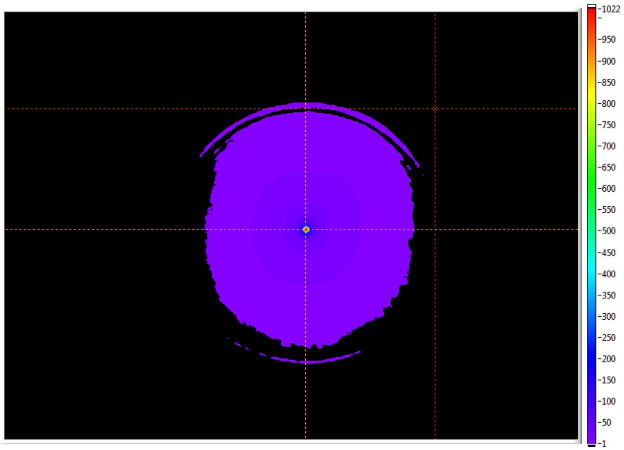
halftone dot Gaussian apodizer



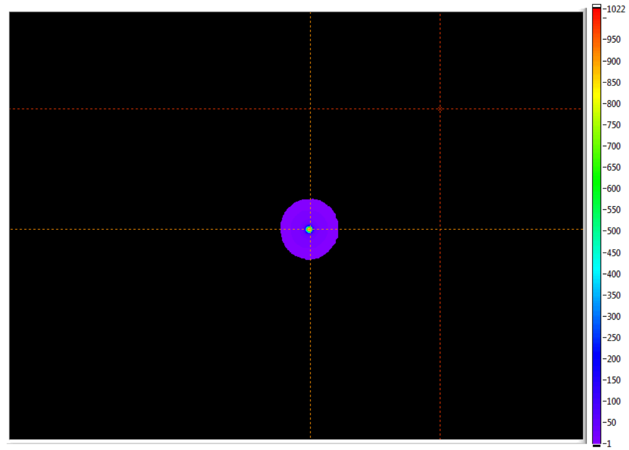
partially reflective Gaussian apodizer

Images of pinhole

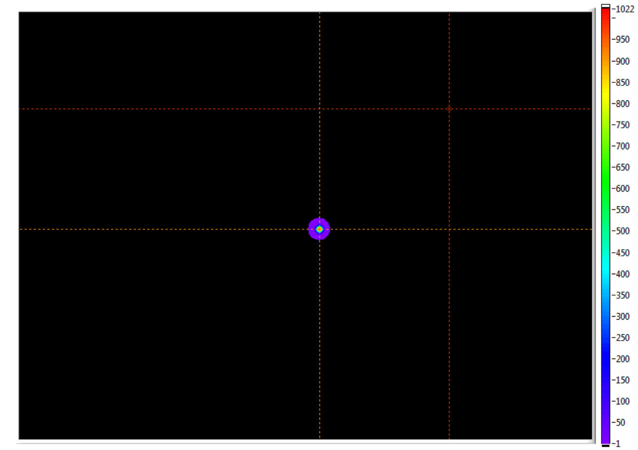
Regular optical system -
no apodizer



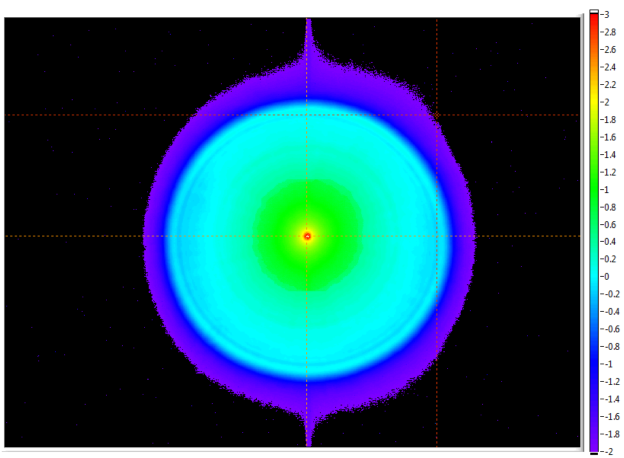
Gaussian halftone dot apodizer
σ=12 mm

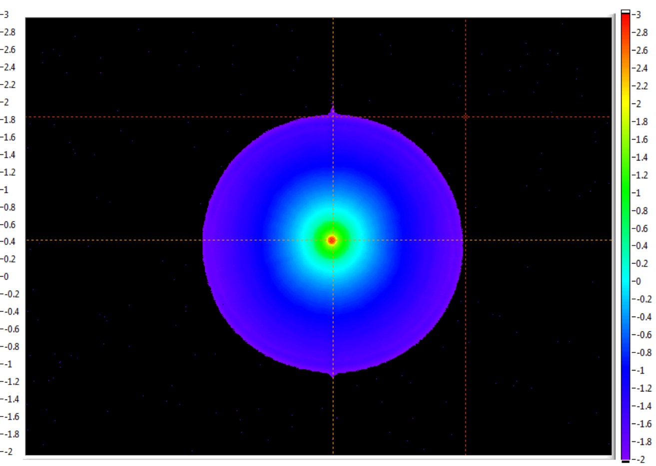


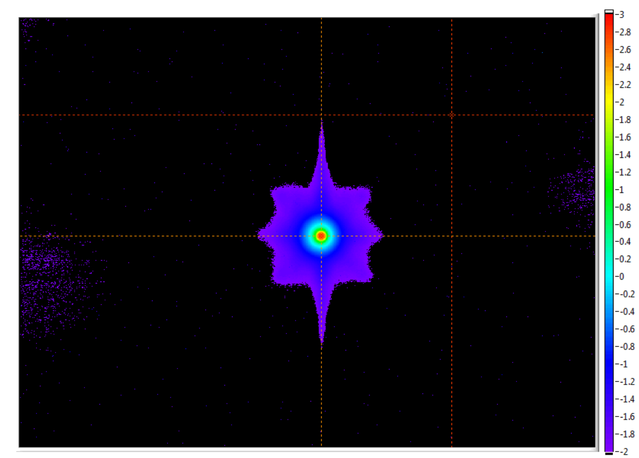
Gaussian halftone dot apodizer
σ=6 mm



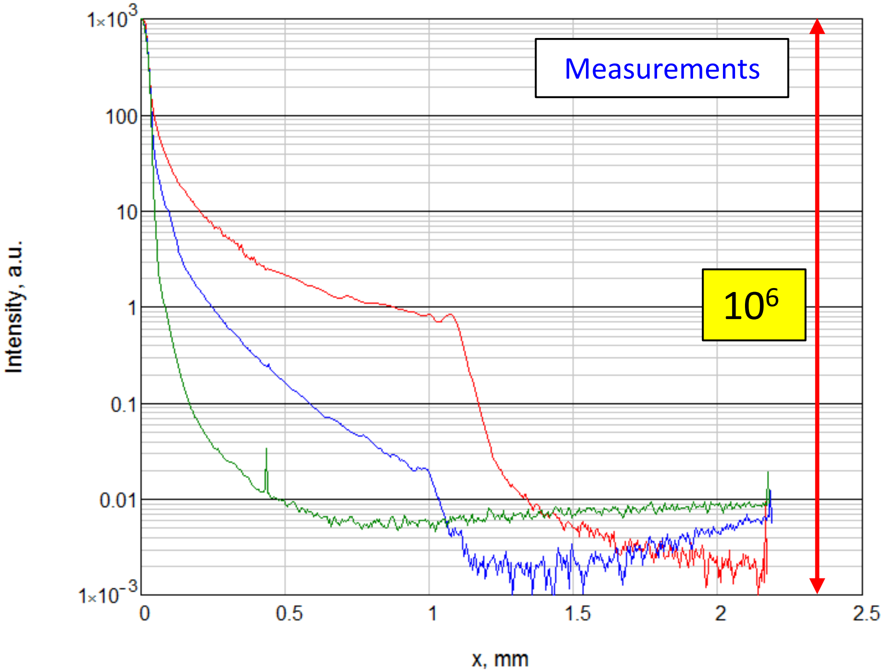
The same data in Log scale

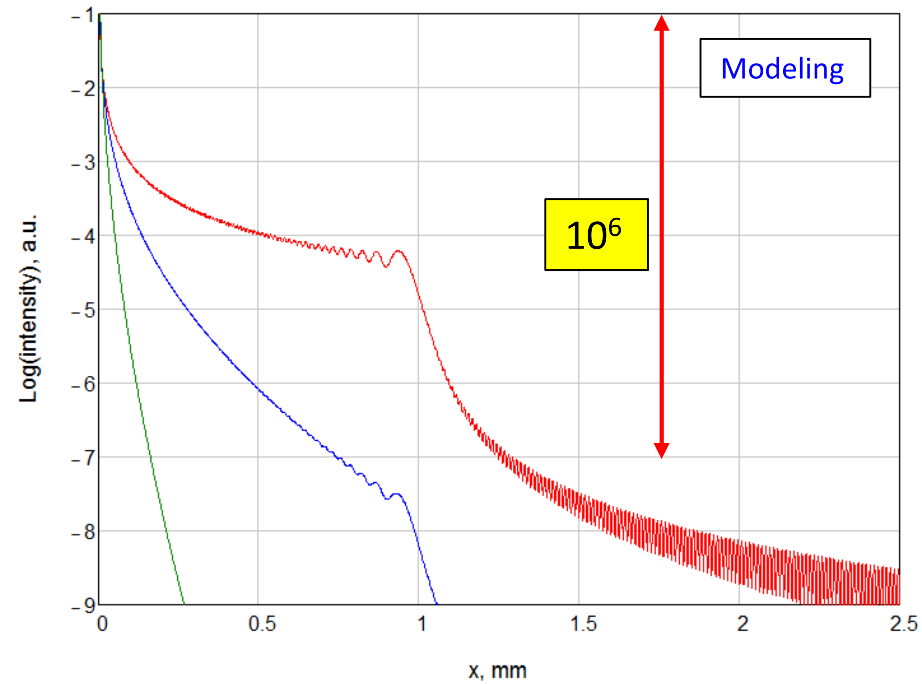






Central line of pinhole images

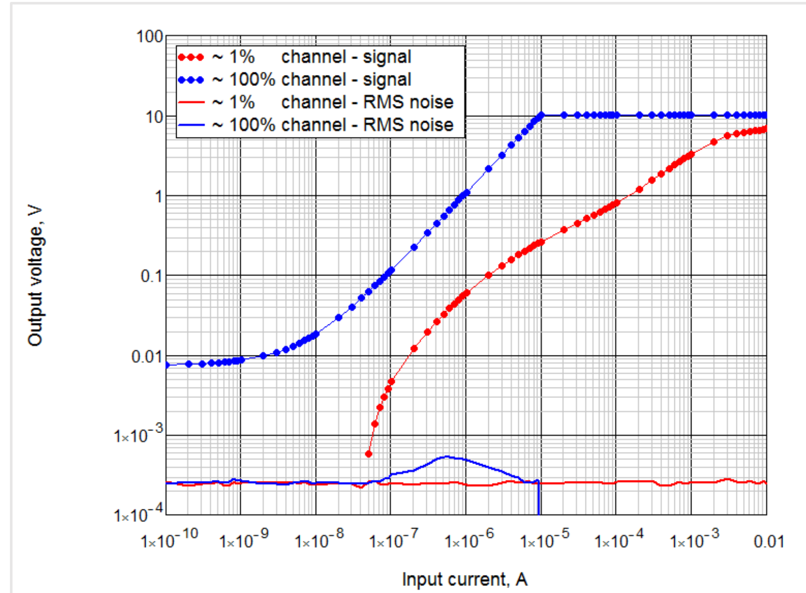




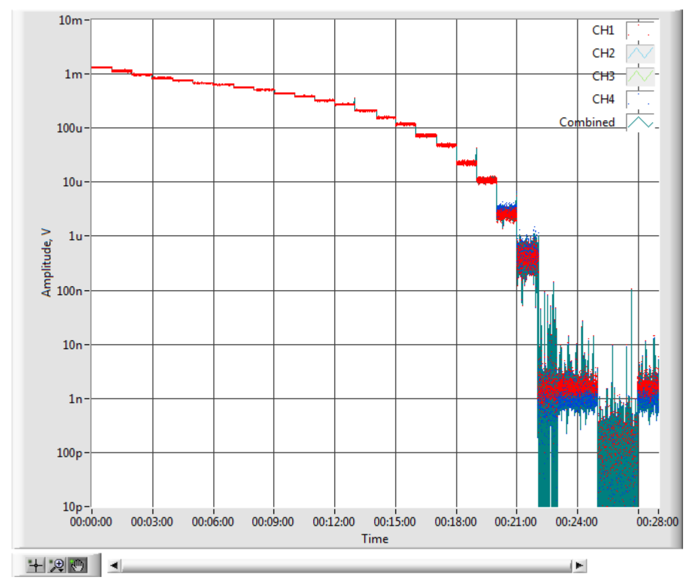
- Measurements with dynamic range of ~ 10^6
- Measured large reduction of the PSF “diffraction tails” intensity
- Calculations predicting even larger effect
- More measurements required to understand the measurements vs. modeling discrepancy
- Possible reasons for discrepancy: optics aberrations, scattering (at the bottom of the measurements range), need to cross-check exact apodization functions

LDR wire-scanner :: Dual Gated Integrator

- Output of each GI is digitized with 16-bit ADC at 4 MS/s
- Output of a GI is available for digitalization during charge integration – better than the gate width time resolution
- Results of GI calibration with a precision current source in the range from 100 pA through 10 mA are shown
- Signal level up to 10 V; noise level (RMS) ~ 250 µV
- Non linearity of the "1 % channel" (red) is due to nonlinear operation of the current mirror, too little current for bipolar transistors – next iteration to use FET current mirror



- GI-x2 measurements of a pulsed PMT signal
- Upper limit of 2 mA is due to HV divider (not the GI-x2)
- Low end 2 nA PMT dark current level; specification - (3 nA typical 20 nA max)
- Measurements with two gates allows to dynamically measure and subtract the dark current.
- Then limiting factor is the GI-x2 intrinsic noise level – equivalent to ~ 100 pA
- 60 points per sec. ➟ 5 sec. beam profile measurements



ELBE :: Upgrade / New facility

- Call from HZDR director to consider and suggest a new CW SRF facility (evolution of ELBE)

- One suggestion under consideration is to significantly extend THz source capability (new THz source):
  - pulse energy **100 μJ – 1 mJ**
  - from ~ 1 THz up to 10 - 20 THz
  - 100 kHz – 1 MHz repetition rate
  - provide quasi-single-cycle pulse capability (broadband source)
  - 10 user beam lines
  - Motivation not so much in THz, but **high field physics**

- Working title DALI (Dresden Advanced Light Infrastructure)

- Zero order guess (without detailed calculation)
  – **1 nC** x **1 MHz** (1 mA) → split 10 x 100 kHz
  – 100 MeV (?)
  – 10 super radiant undulator sources – relatively narrow band source
  – CDR / CER for quasi-single-cycle sources

Upgrade / New facility :: path forward

- The source is on Helmholtz society road map for large facilities. But …

- It must be shown that science case for such THz facility is indeed strong enough for a new facility construction

- Make case for accelerator and source (sources) side of the facility
  - is it possible (1 mJ pulse energy from supper-radiant) ?
  - what are limitations and risks?
  - what are most optimal architecture for accelerator-source?

- Work on science case and source design in parallel

- By the end of 2018 have some form of conceptual design (status) report;
  - to be used for next iteration of the road map discussion

DALI :: beam physics :: critical issues

1. Injector (E_b<10 MeV) design / optimization for smallest longitudinal emittance (small uncorrelated energy spread)

2. Bunch Compression including collective effects: CSR, space charge, microbunching instability, wakes (up to 1 nC)

3. "Advanced" concepts (a trick) for coherence enhancement;
   emittance exchange, modulated Drive Laser + modulation compression

4. From beam to radiation: SR, Edge Radiation, Wiggler, Undulator, FEL (6D phase space → radiation properties)
   to translate radiation source requirements to <u>electron beam requirement</u>

5. Stability analysis: sensitivities to deviations from working point

6. Critical beam diagnostics: feasibility of setting up the machine per designed beam dynamics

Work in progress ...

Compression :: single particle dynamics

- Considered a beam with initial RMS bunch length $\sigma_{x.ini}$ and initial energy spread $\sigma_{E.ini}$ accelerated on $\cos(\omega_0 t+\phi_{RF})$ RF waveform from E_{ini} to E_{fin}
- SPD ($X_f = M_{compr} \cdot M_{linac} \cdot X_0$) is applied to collective of particles; bunch length (second order momentum) is calculated from resulting distributions
- This approach gives analytical formulas for bunch length

$$\boxed{\sigma_{z.fin} = \sqrt{(1 + h \cdot R_{56})^2 \sigma_{z.ini}^2 + \left(\frac{E_{ini}}{E_{fin}}\right)^2 R_{56}^2 \sigma_{\delta.ini}^2}}$$

where $h = -\frac{2\pi}{\lambda}\left[1 - \frac{E_{ini}}{E_{fin}}\right] tan(\varphi_{RF})$ is chirp

$$\boxed{\sigma_{z.fin.min}(\varphi_{RF}) = \left(\frac{E_{ini}}{E_{fin}}\right)\left(-\frac{1}{h(\varphi_{RF})}\right)\sigma_{\delta.ini}}$$

min possible bunch length (when all correlations removed)
To remove linear correlation optimal R_{56}

$$R_{56.opt} = -\frac{1}{h}$$

Taking second order correlation (from RF curvature) in to account:

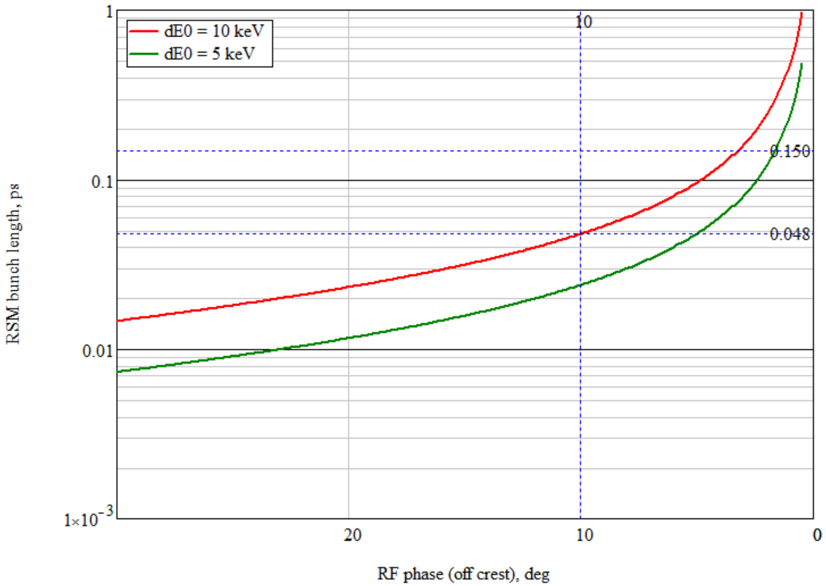
$$\boxed{\sigma_{z.fin.2} = \sqrt{(1 + h \cdot R_{56})^2 \sigma_{z.ini}^2 + \left(\frac{E_{ini}}{E_{fin}}\right)^2 R_{56}^2 \sigma_{\delta.ini}^2 + R_{56}^2 \left(h_2 + \frac{T_{566}}{R_{56}} h^2\right)^2 (2 \cdot \sigma_{z.ini}^4)}}$$

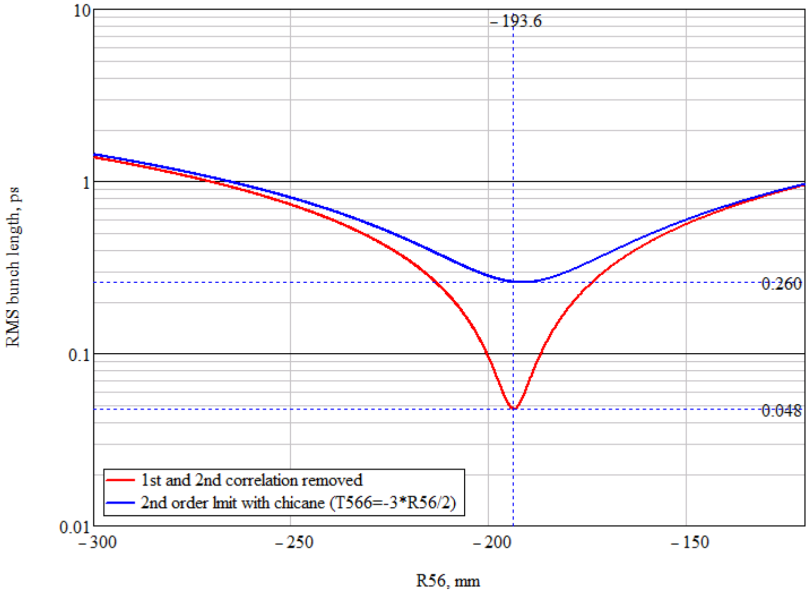
with second order chirp

$$h_2 = -\frac{2\pi^2}{\lambda^2}\left[1 - \frac{E_{ini}}{E_{fin}}\right]$$

P. Emma, Section 4.5 “Bunch compression” in “Handbook of Accelerator Physics and Engineering ” p. 334-337

JLab IR-Upgrade check

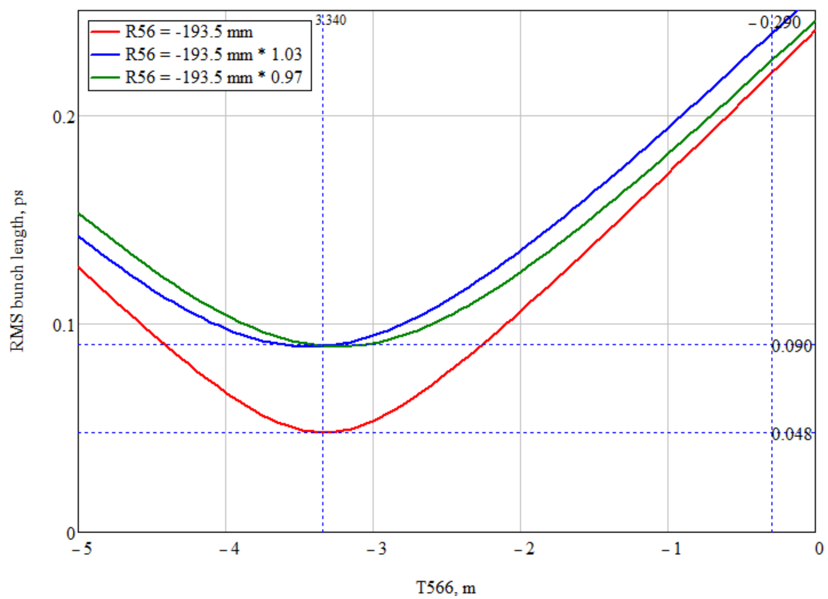




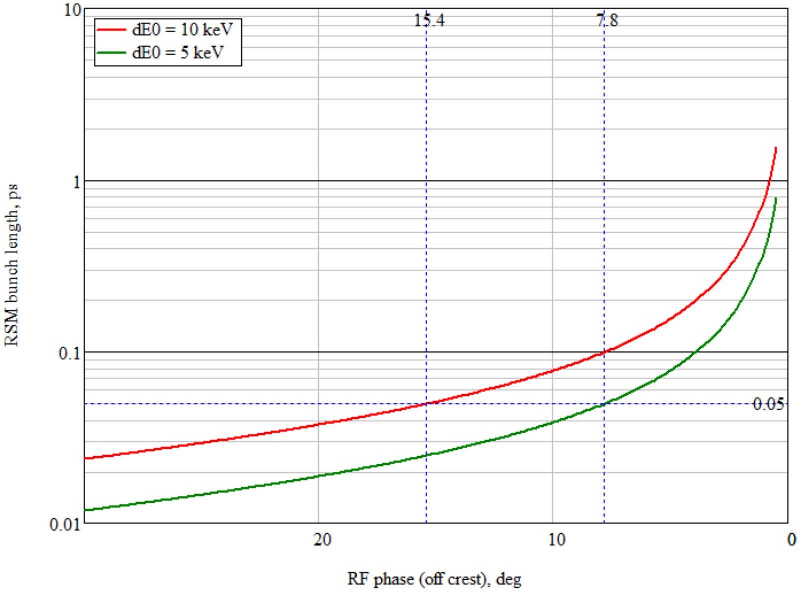
IR-Upgrade (JLab's 10 kW FEL) LINAC:

– accelerated beam from 9 MeV to 135 MeV
– accelerated -10 deg off-crest; 1497 MHz cavities
– at injection: 2.5 ps, 10 keV
– using second order magnetic compressor
  routinely operated with ~ 150 fs bunch length

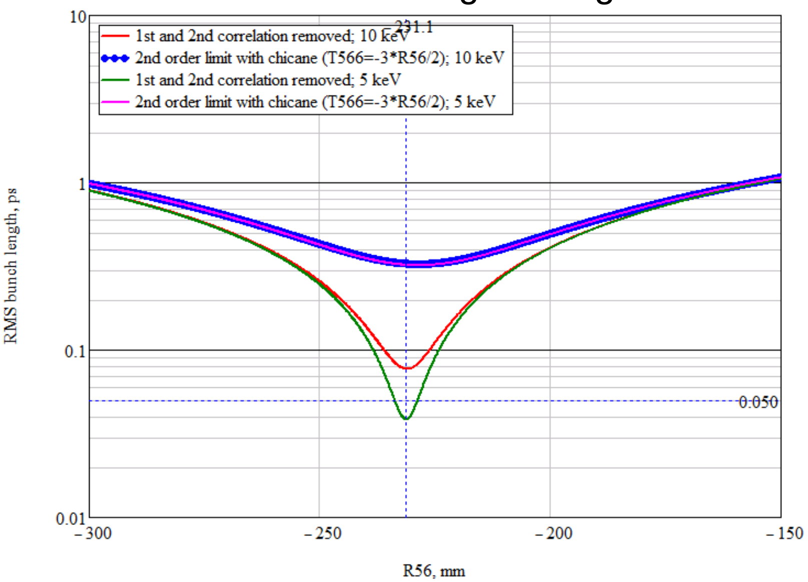
– R_{56} and T_{566} predicted by this SPD consideration are in agreement with values used at the machine
– difference between predicted bunch length of 48 fs and demonstrated 150 fs is due to collective effects in the LINAC



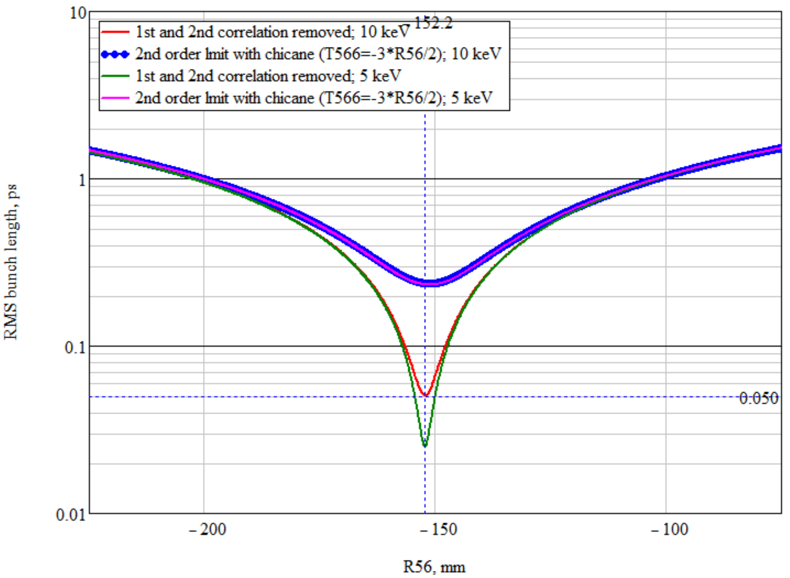
1.3 GHz 100 MeV LINAC :: Compressor's R_{56}



accelerating -10 deg off-crest



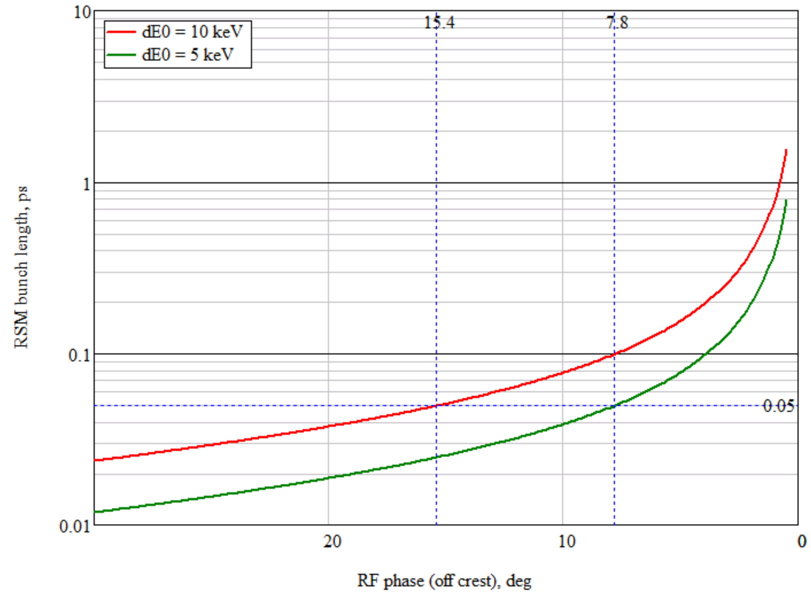
accelerating -15 deg off-crest



Implications for beam-to-RF stability

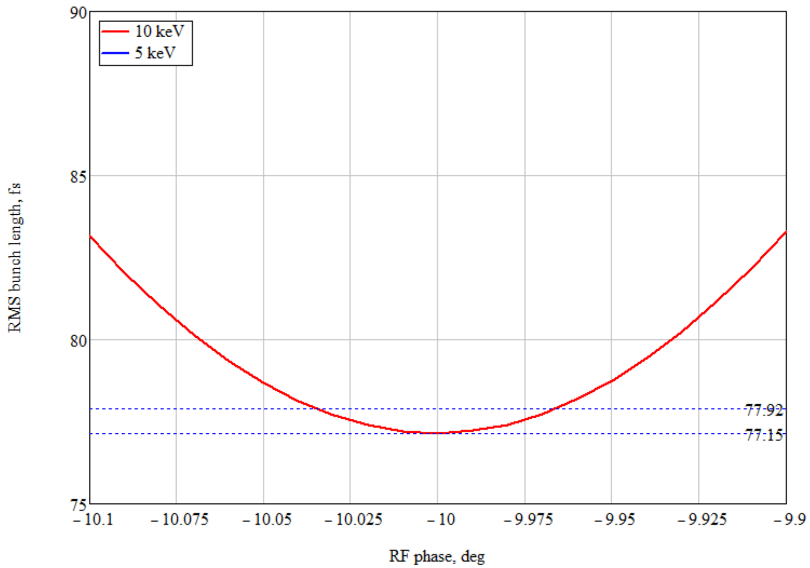
at optimal compression

$$\sigma_{z.fin.min}(\varphi_{RF}) = \left(\frac{E_{ini}}{E_{fin}}\right)\left(-\frac{1}{h(\varphi_{RF})}\right)\sigma_{\delta.ini}$$

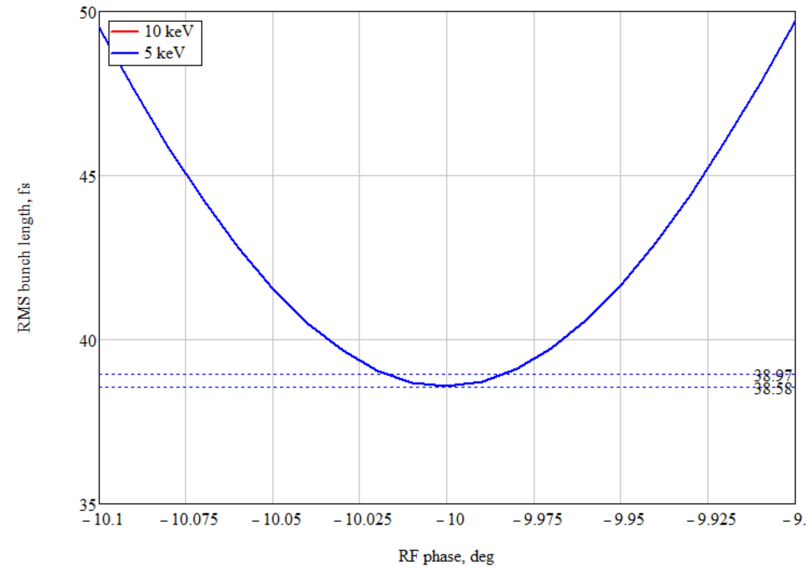


- Top-right picture assumes optimally adjusted R_{56} and T_{566} for each ϕ_{RF}
- In reality R_{56} and T_{566} are fixed
- consider - 10 deg off-crest acceleration and 3 ps initial RMS bunch length

1 % bunch length Δ ← Δϕ = 0.035 deg beam-to-LINAC



1 % bunch length Δ ← Δϕ = 0.016 deg beam-to-LINAC



Compression :: space charge

- Practical experience: JLab's FEL (IR-Upgrade)
  – CW SRF LINAC, 130 MeV, 10 mA, 135 pC
  – non-linear (second order) magnetic compressor
  – $\sigma_{t.min}$ ~ 150 fs (IR-FEL), ~ 100 fs (UV-FEL)
- Measurements and modeling: $\varepsilon_{z\ \mathrm{injector}}$= 25 keV-ps
- Measurements: $\varepsilon_{z\ \mathrm{full\ compression}}$= 75-80 keV-ps
- The increase of ε_z was attributed to space charge (longitudinal) in the LINAC – PARMELA model

  ----
- **Q:** how this effect will affect bunch compression for DALI ?
- **Q:** is it real, i.e., can we reproduce this ?

IR-Upgrade experience

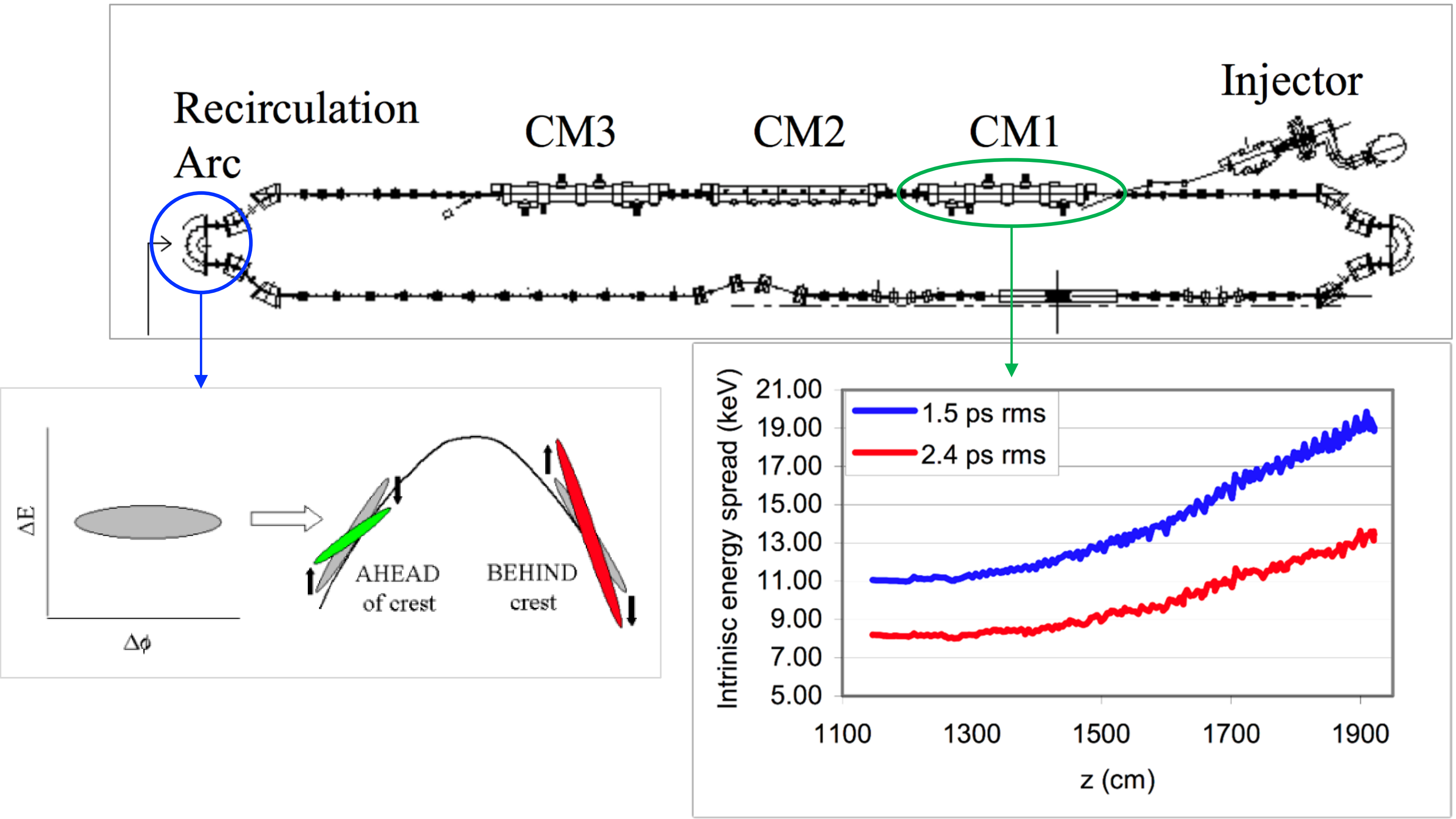
C.H.G. Hernandez-Garcia et al. / Proceedings of the 2004 FEL Conference, 363-366 363

LONGITUDINAL SPACE CHARGE EFFECTS IN THE JLAB IR FEL SRF LINAC

C. Hernandez-Garcia*, K. Beard, C. Behre, S. Benson, G. Biallas, J. Boyce, D. Douglas, H. F. Dylla, R. Evans, A. Grippo, J. Gubeli, D. Hardy, K. Jordan, L. Merminga, G. Neil, J. Preble, M. Shinn, T. Siggins, R. Walker, G. P. Williams, B. Yunn, S. Zhang, TJNAF, Newport News, VA 23606, USA

Abstract

Observations of energy spread asymmetry when operating the Linac on either side of crest and longitudinal emittance growth have been confirmed by extending PARMELA simulations from the injector to the end of the first SRF Linac module. The asymmetry can be explained by the interaction of the accelerating electric field with that from longitudinal space charge effects within the electron bunch. This can be a major limitation to performance in FEL accelerators.



DALI :: Bunch length

Questions:

- What is $\sigma_{t\ comp} = \sigma_{t\ comp}(Q_{b})$ to be expected realistically?
- What is the contribution of the longitudinal space charge (LSC) effect in LINAC to possible $\sigma_{t\ comp}$?
- What are requirements on injector output beam for optimal compression / ε_z preservation ? ($\sigma_{t\ inj}$, δE_{inj}, $\langle E \rangle_{inj}$, $\alpha_{x(y)\ inj}$, $\beta_{x(y)\ inj}$)
- How LINAC configuration will affect ε_z preservation ?

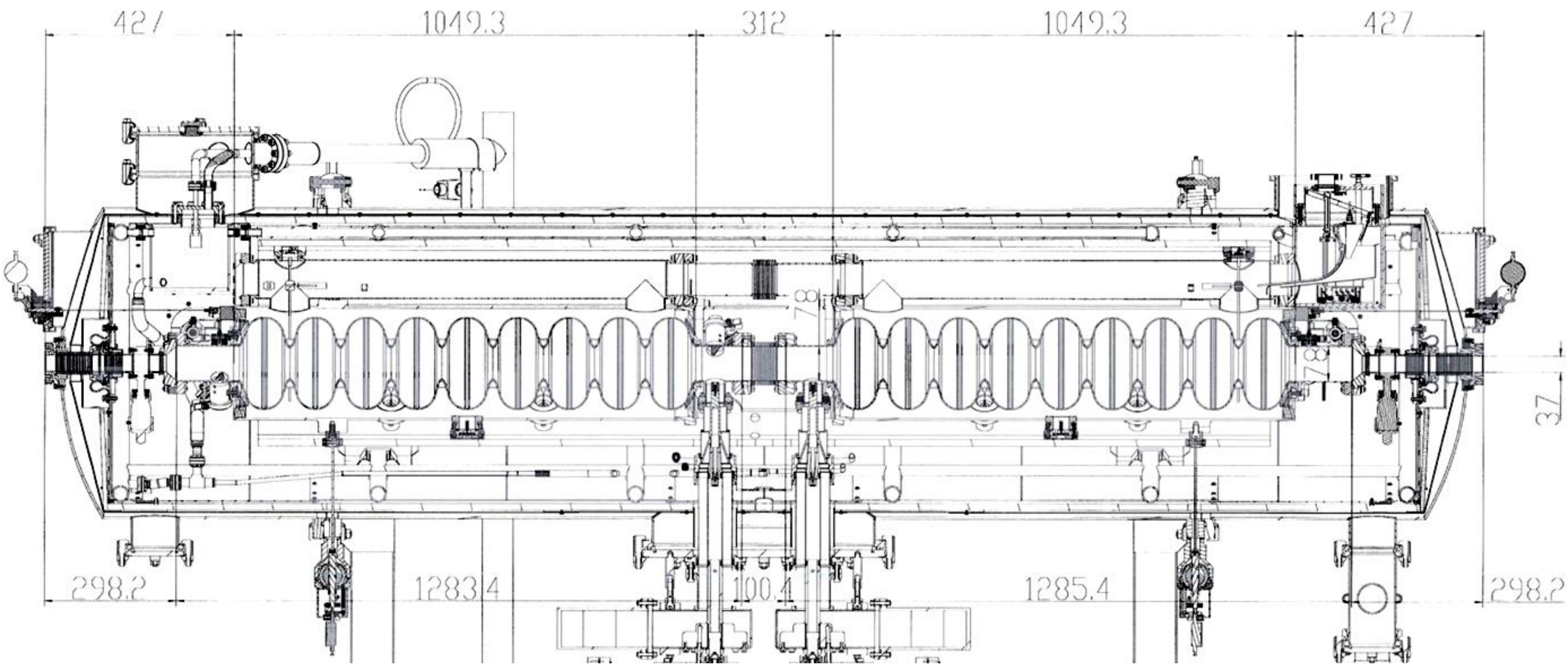
DALI :: LINAC

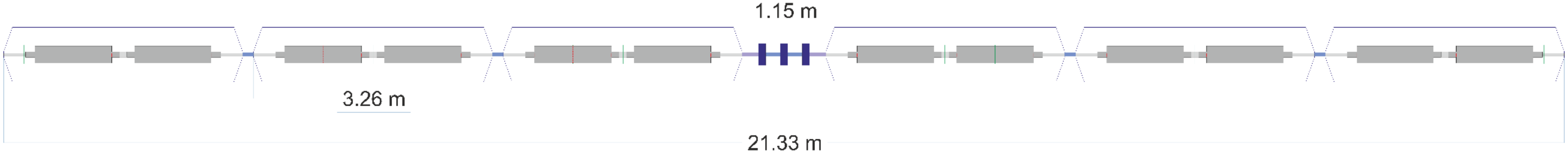
- To model LSC in LINAC need to imagine what the LINAC could look like.
- Q: What are options ?

1. more ELBE modules (x2 9-cell 1.3 GHz TESLA cavities)
2. other 1.3 GHz CW modules : XFEL (not CW) v LCLS-II
3. all new low frequency few 100 MHz SRF spoke cavities – would allow much longer bunch length in injector and LINAC to reduce the LSC effect, could operate at 4 K (?) v 2 K

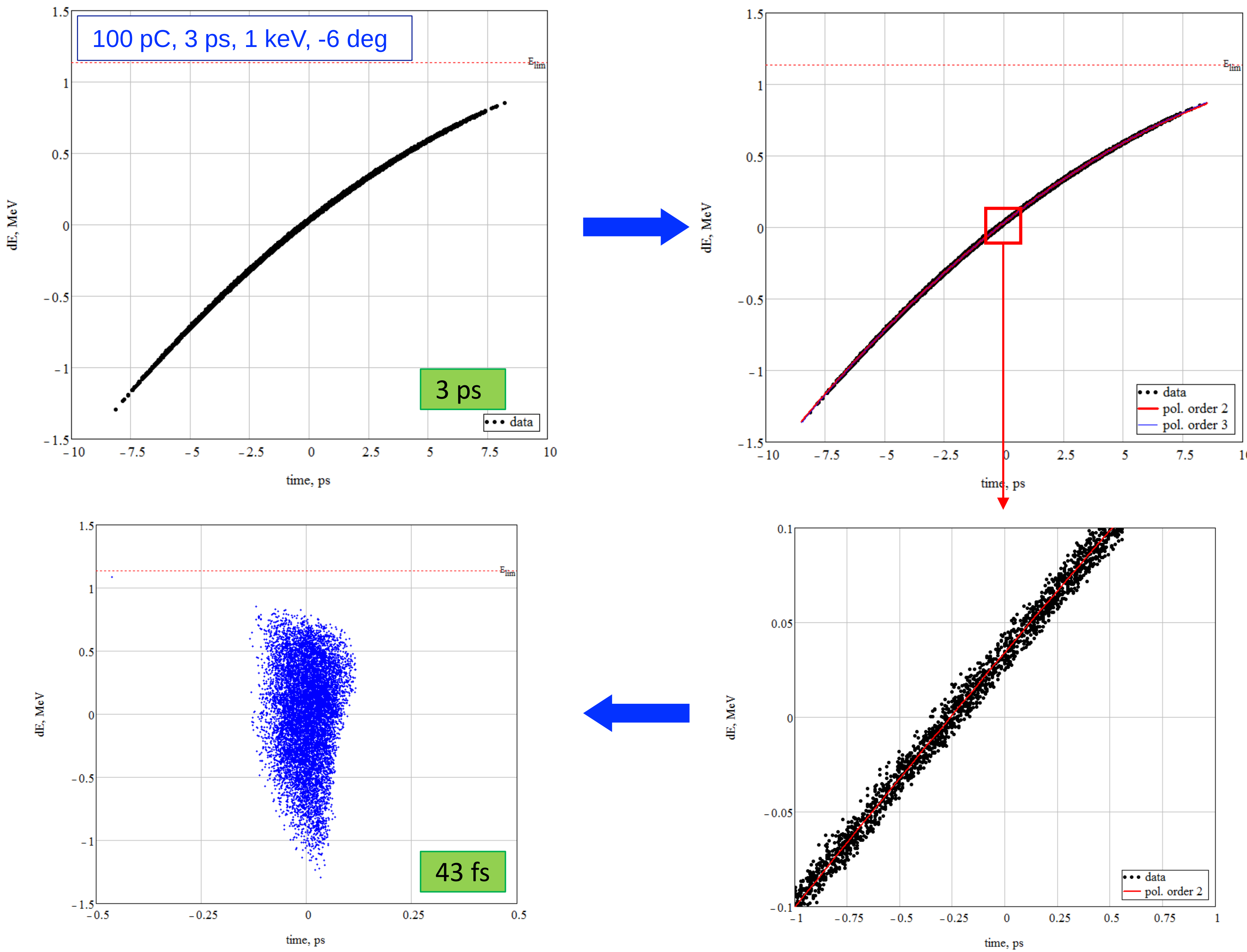
- Start with conservative option: ELBE modules with gradient on the order of magnitude as used now: 10 MV/m;
  assume need some redundancy: 1-2 cavities more

ELBE :: LINAC module

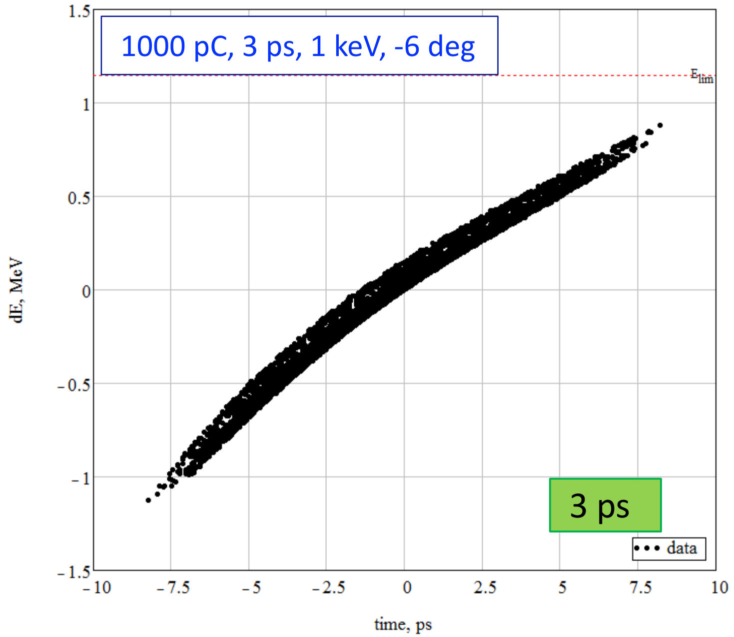


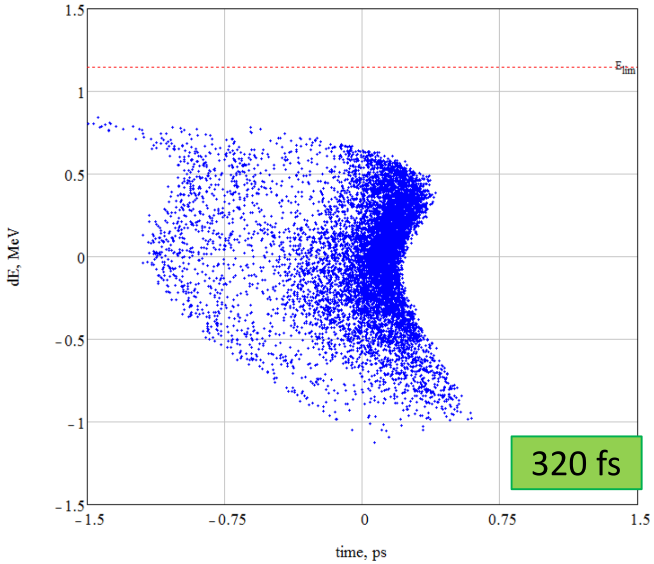


Long. phase space linearization 100pC



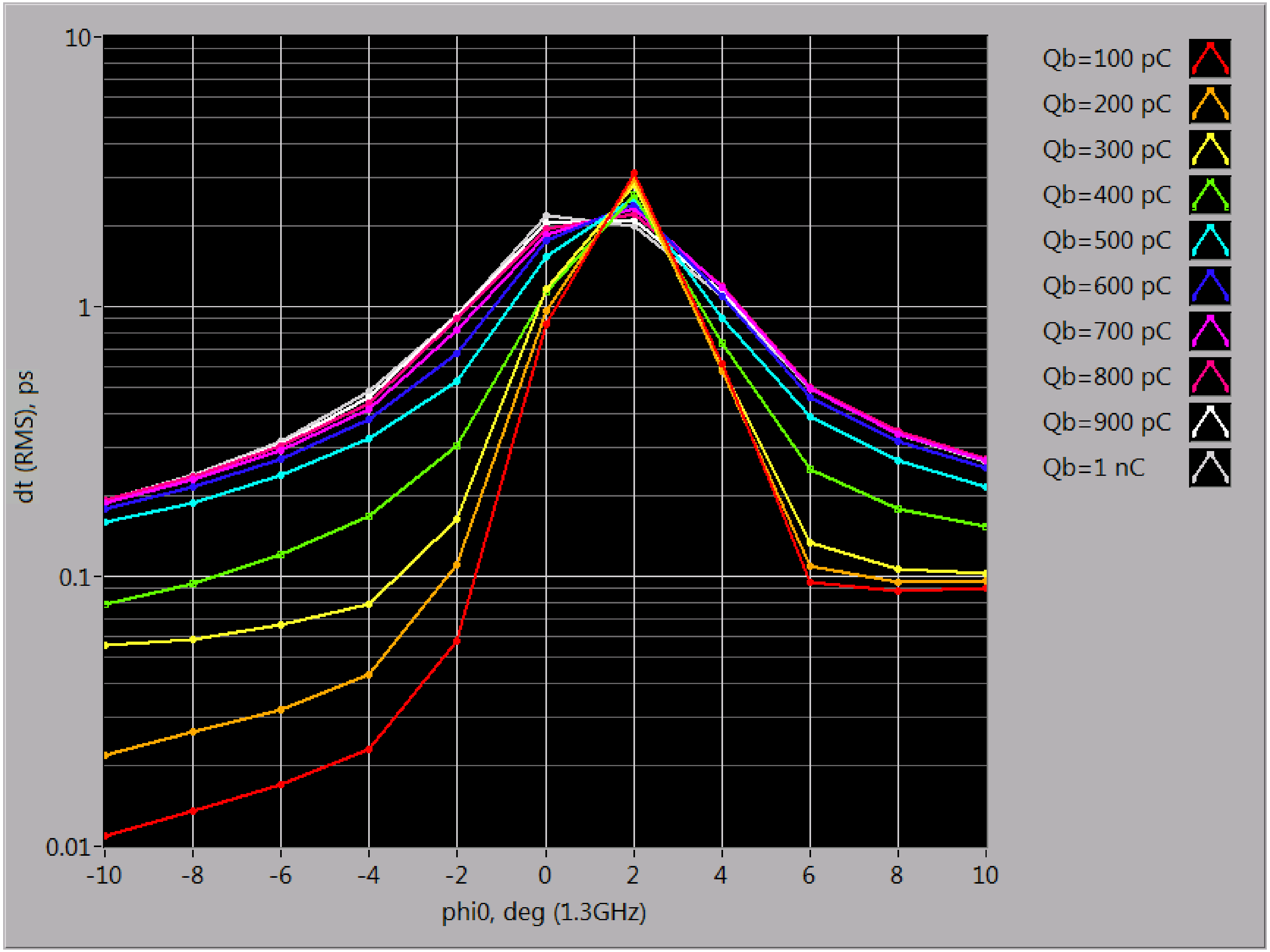
Long. phase space linearization 1 nC



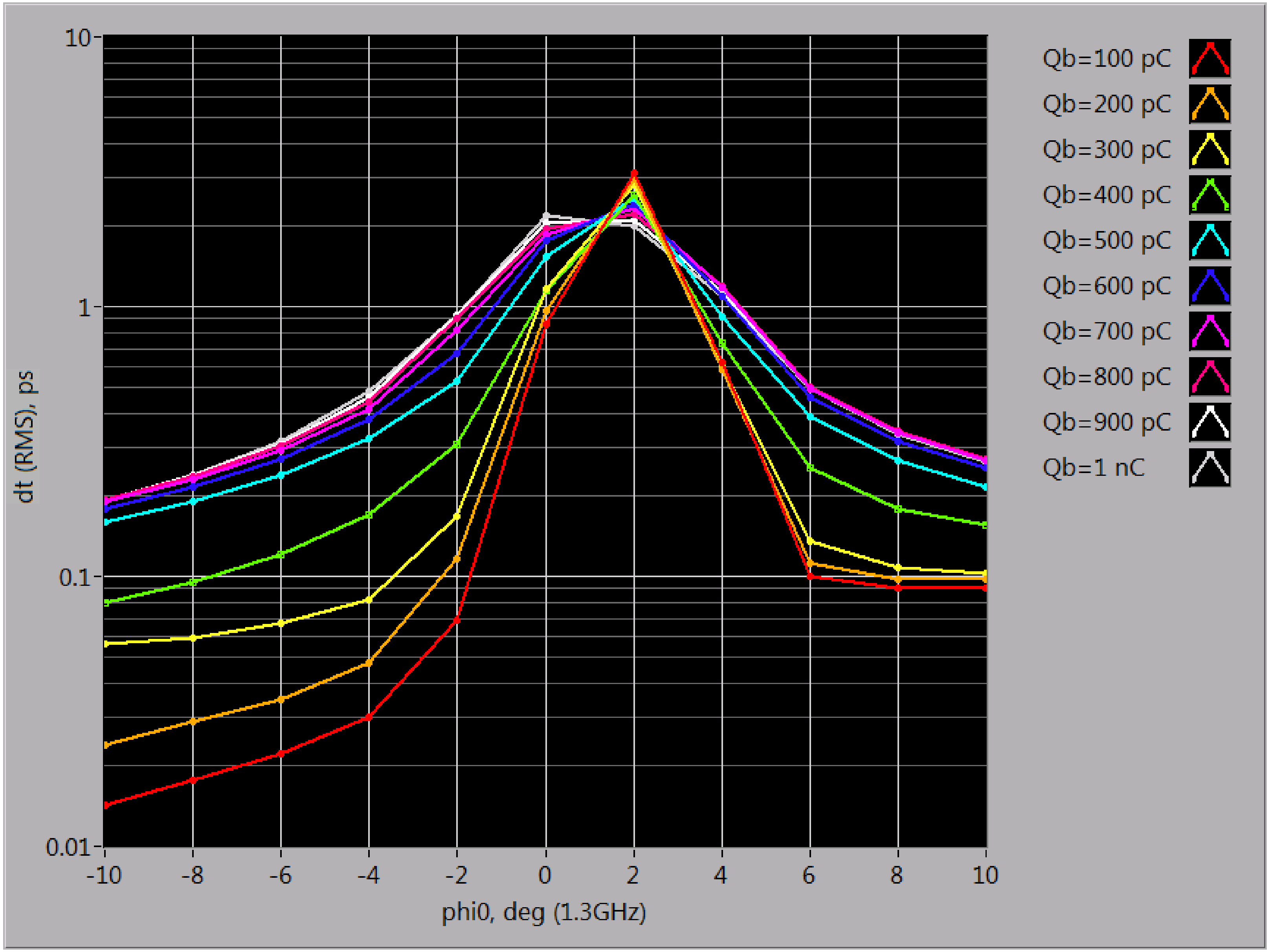


- Automate
- Scan parameter space
- Main parameters:
  - Q_b
  - initial σ_E
  - ϕ LINAC (injection)

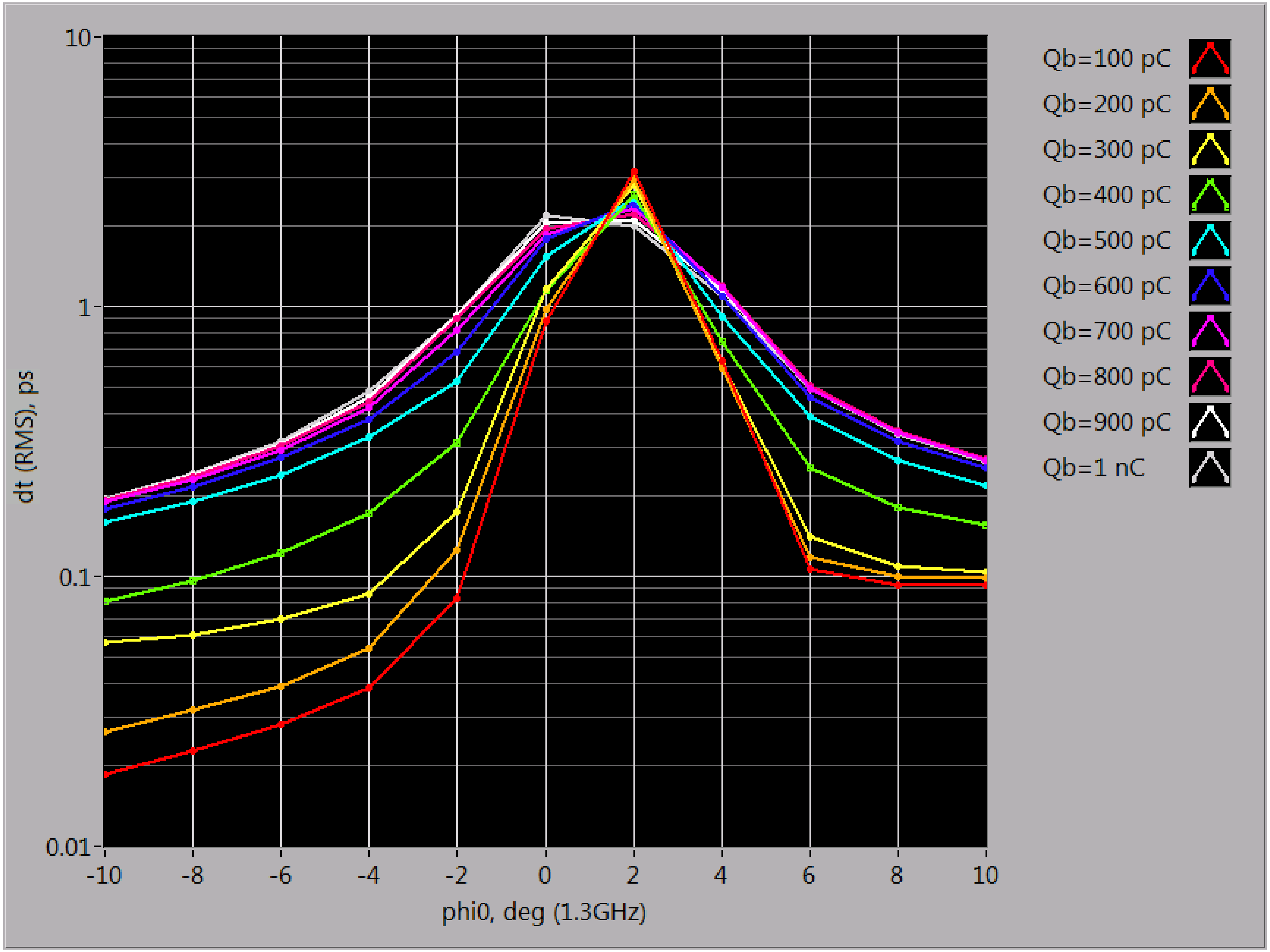
Run 1 :: 3 ps – 1 keV



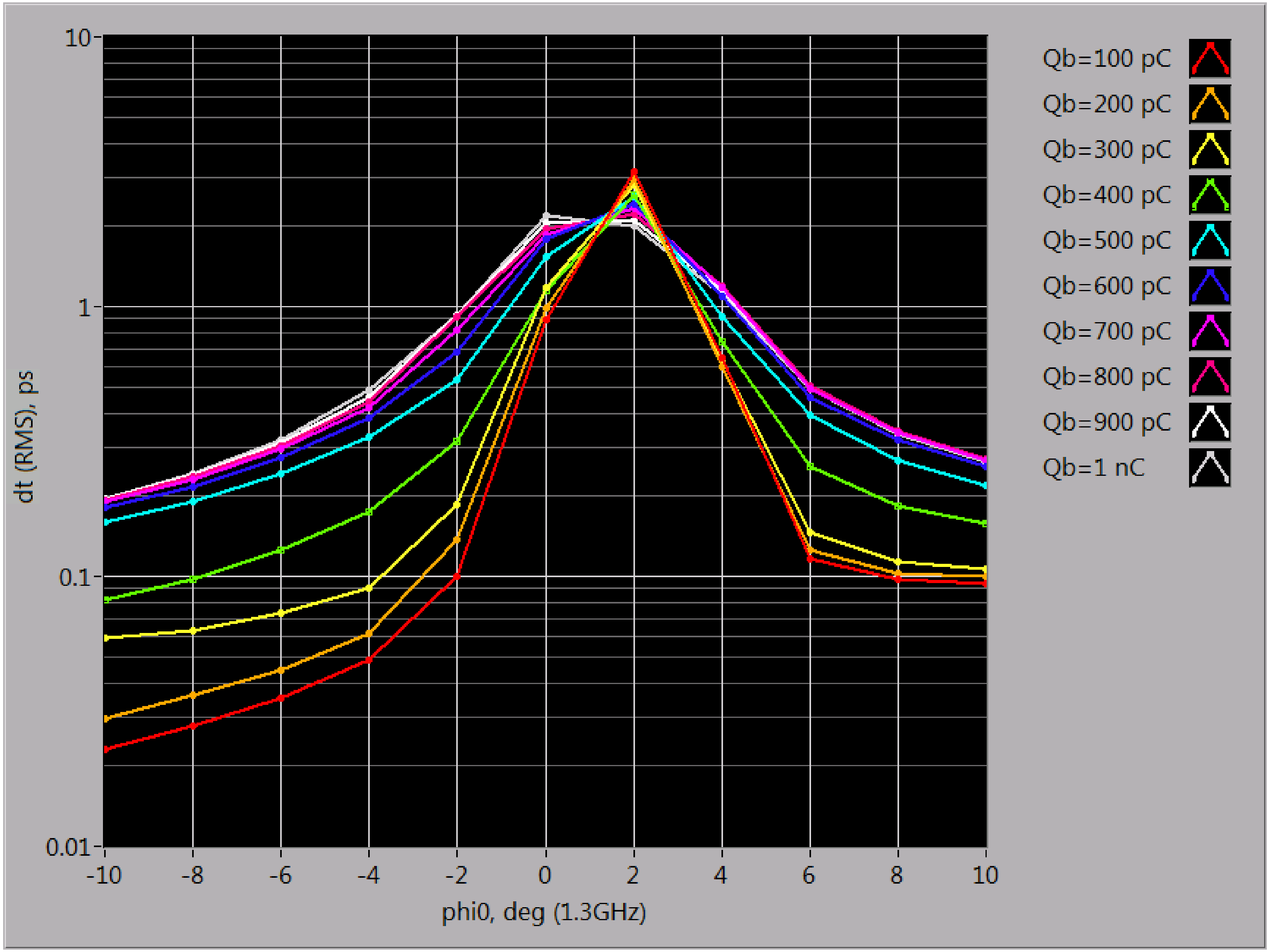
Run 1 :: 3 ps – 2 keV



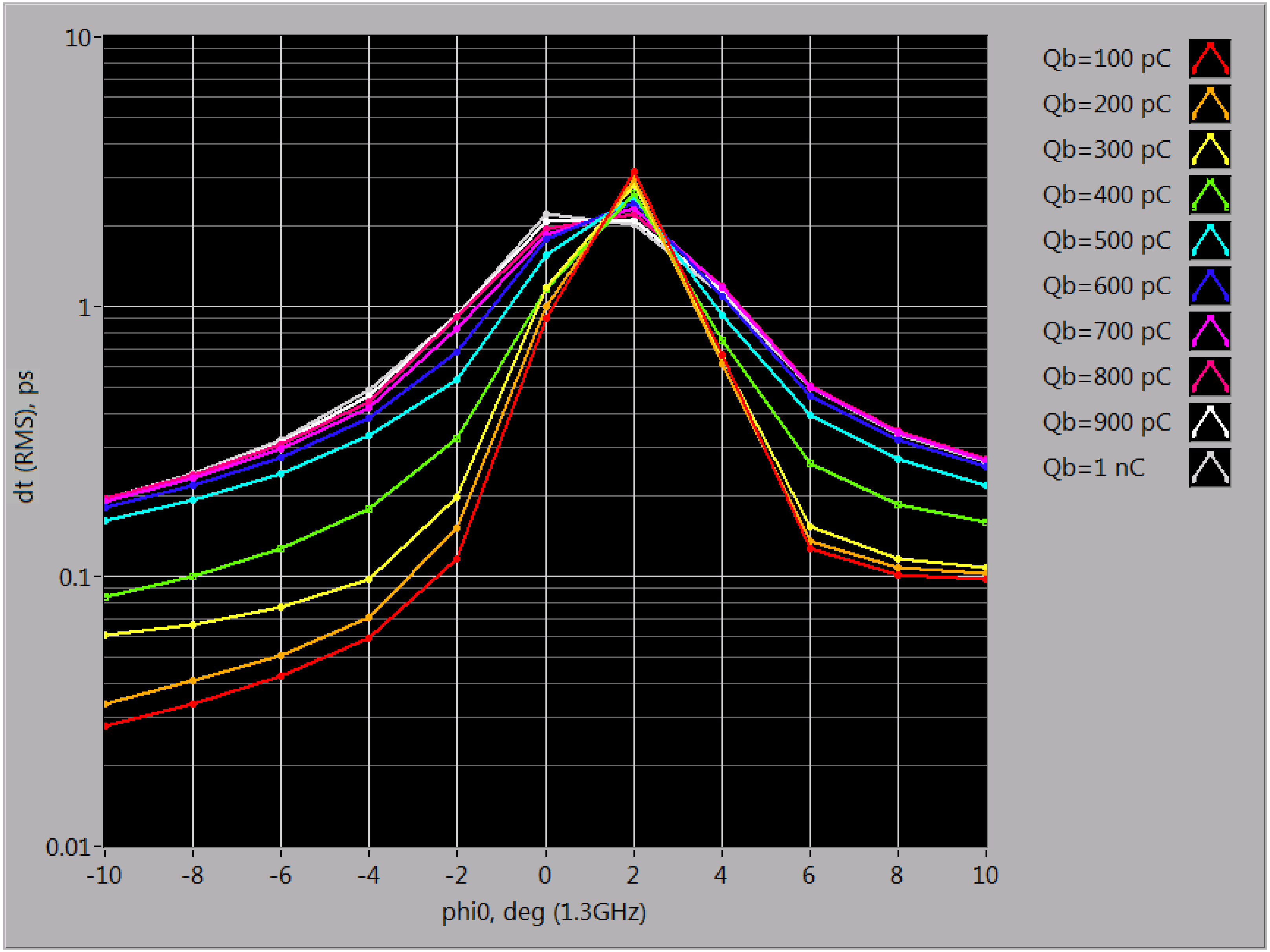
Run 1 :: 3 ps – 3 keV



Run 1 :: 3 ps – 4 keV



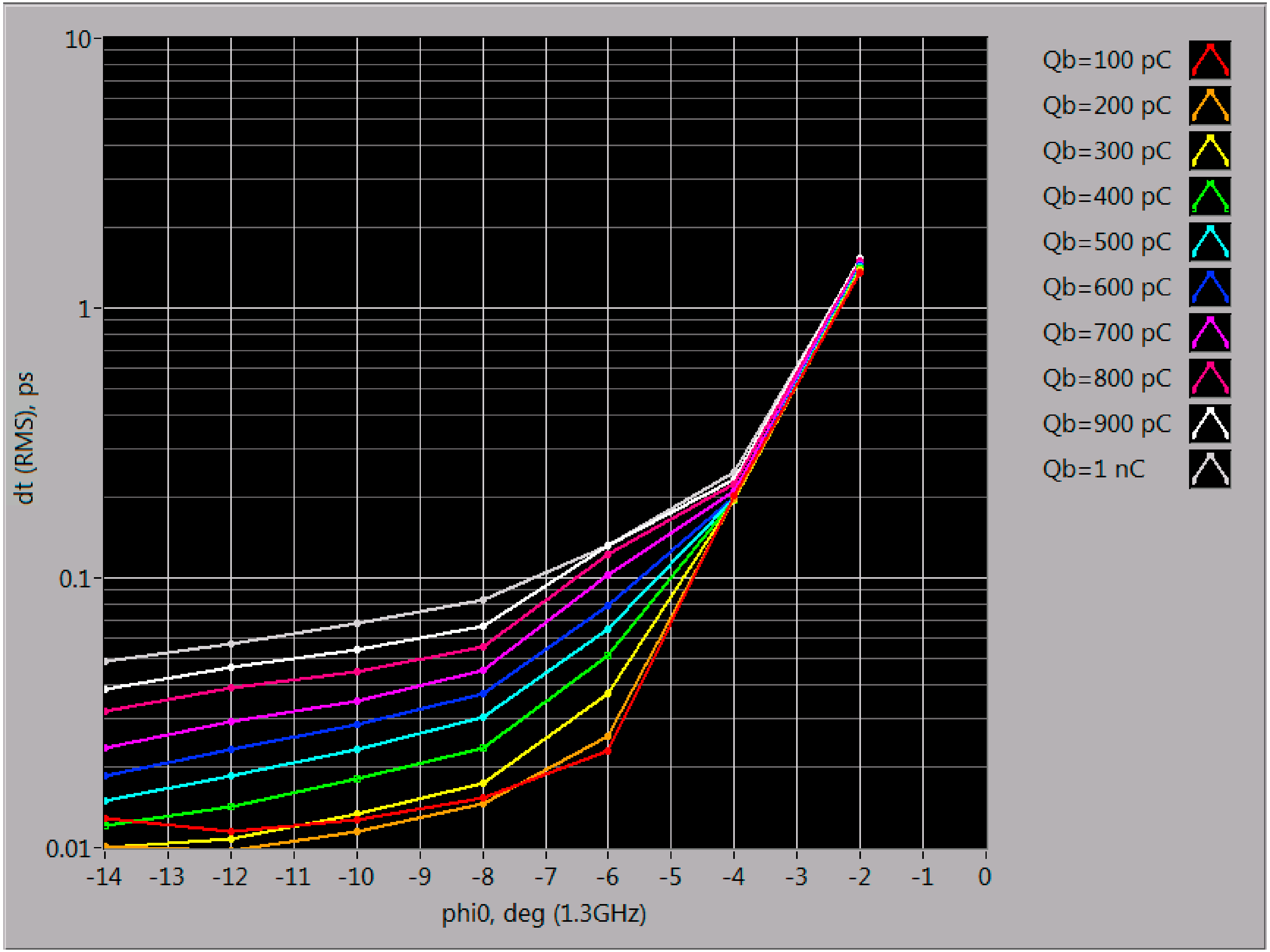
Run 1 :: 3 ps – 5 keV



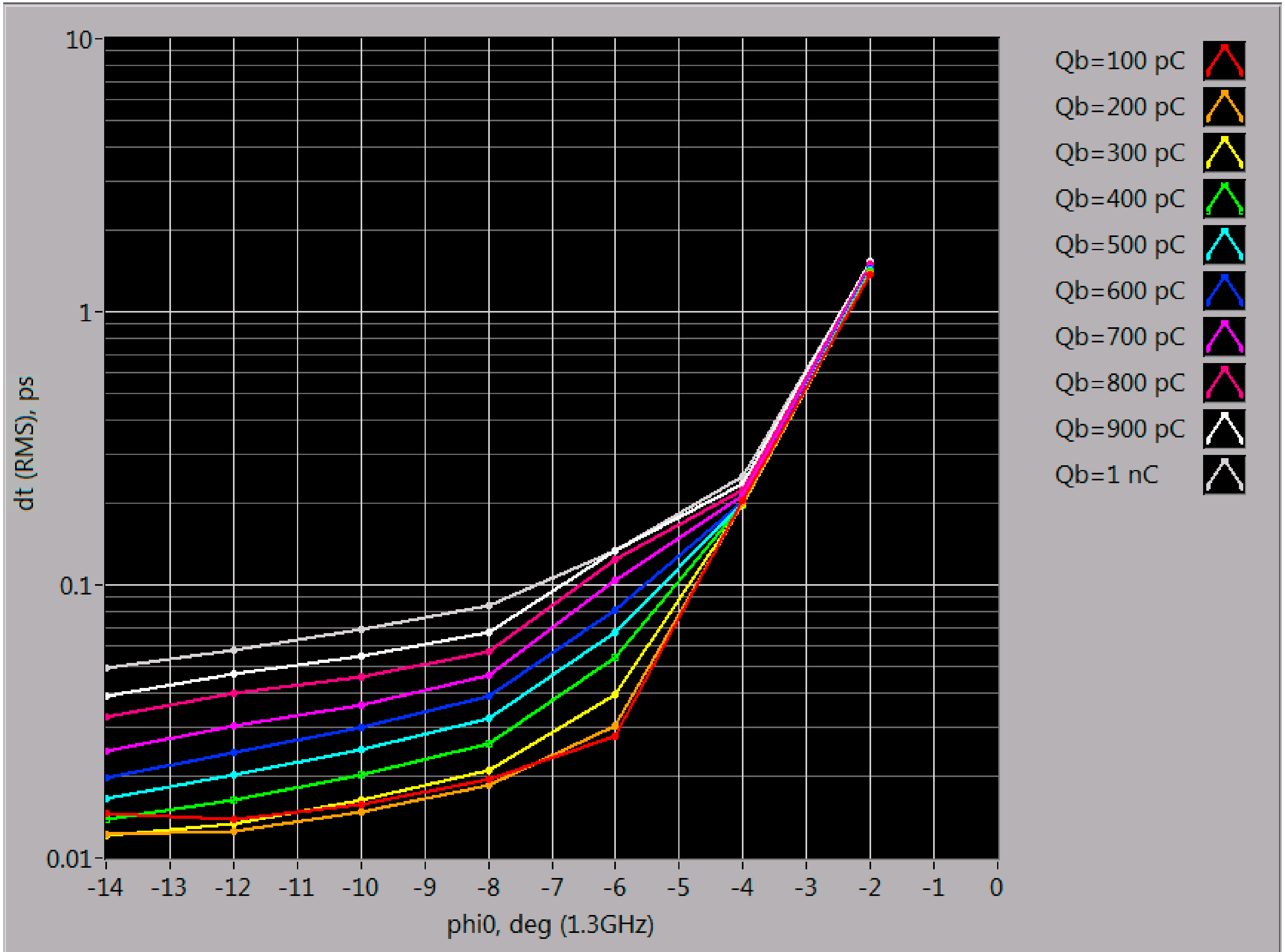
Run 1 :: σ_{t0} = 3 ps, 10 MV/m :: lessons

- Shows the difference when accelerating on two different sides of RF crest
- Initial σ_E makes difference for 100 pC – 200 pC
- For Q_b>200 pC, essentially no difference from initial σ_E
- $\sigma_{t\ compressed}$ (1nC) ~ x10 $\sigma_{t\ compressed}$ (100pC) … 😳
- Interpretation: $\sigma_{E\ slice}$ due to space charge for Q_b > 200 pC is >> σ_{E0}
- Note: collective effects in compressor will make it even worse
- Next: try to increase σ_{t0} to reduce peak current and space charge
- Run 2 σ_{t0}=4.5ps, Run 3 σ_{t0}=6.0ps – show improvements for 200 – 300 pC, but virtually no difference for high charge
- To use σ_{t0} as a knob to improve at 1 nC would require σ_{t0} = 30ps (RMS) (not feasible with 1.3 GHz LINAC)
- Next #2: try shorter LINAC with higher gradients (20 MV/m) – uses only half of the LINAC length (6 TESLA cavities) 10 MeV injection as before

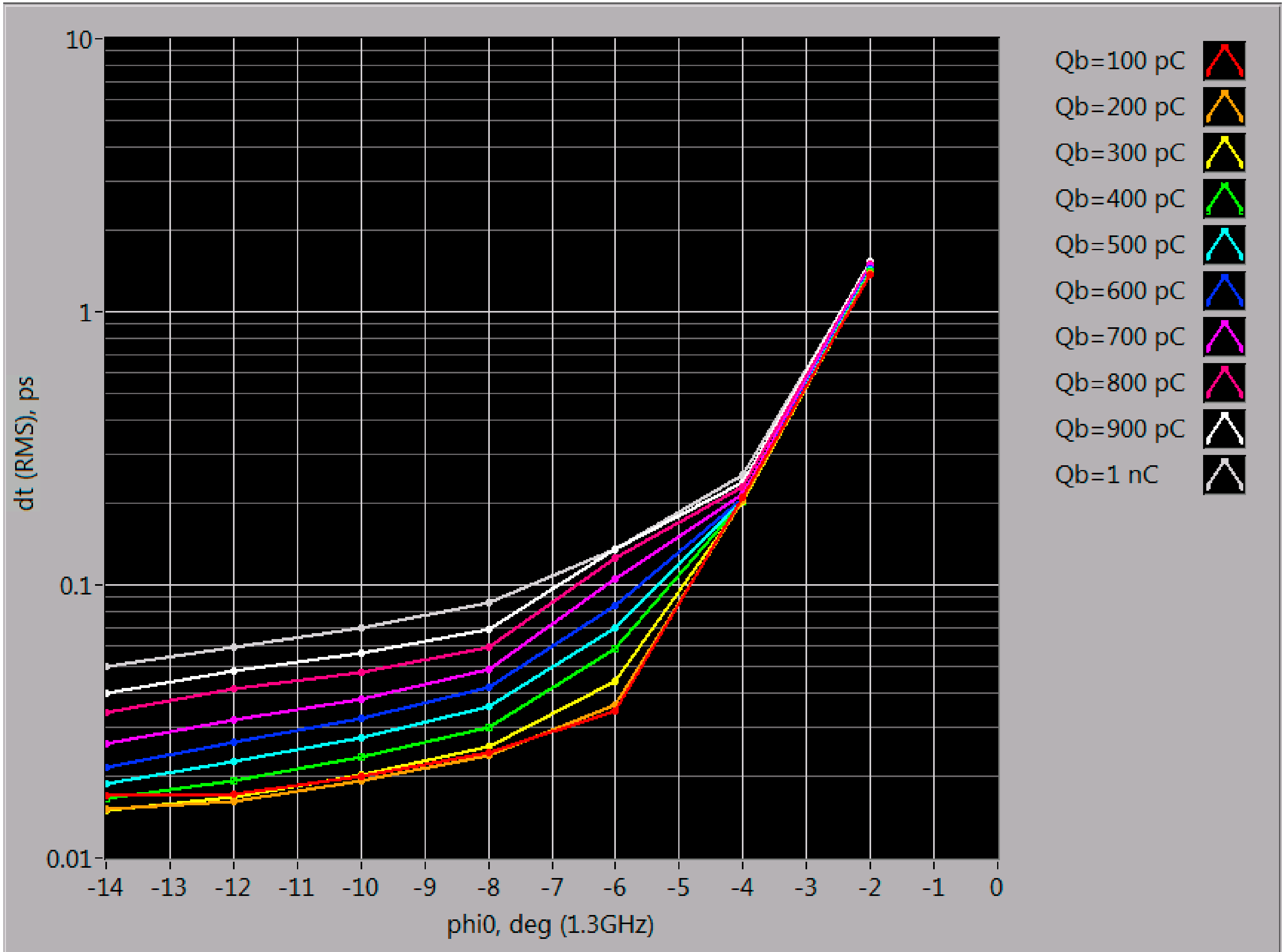
Run 4 :: 6 ps – 1 keV



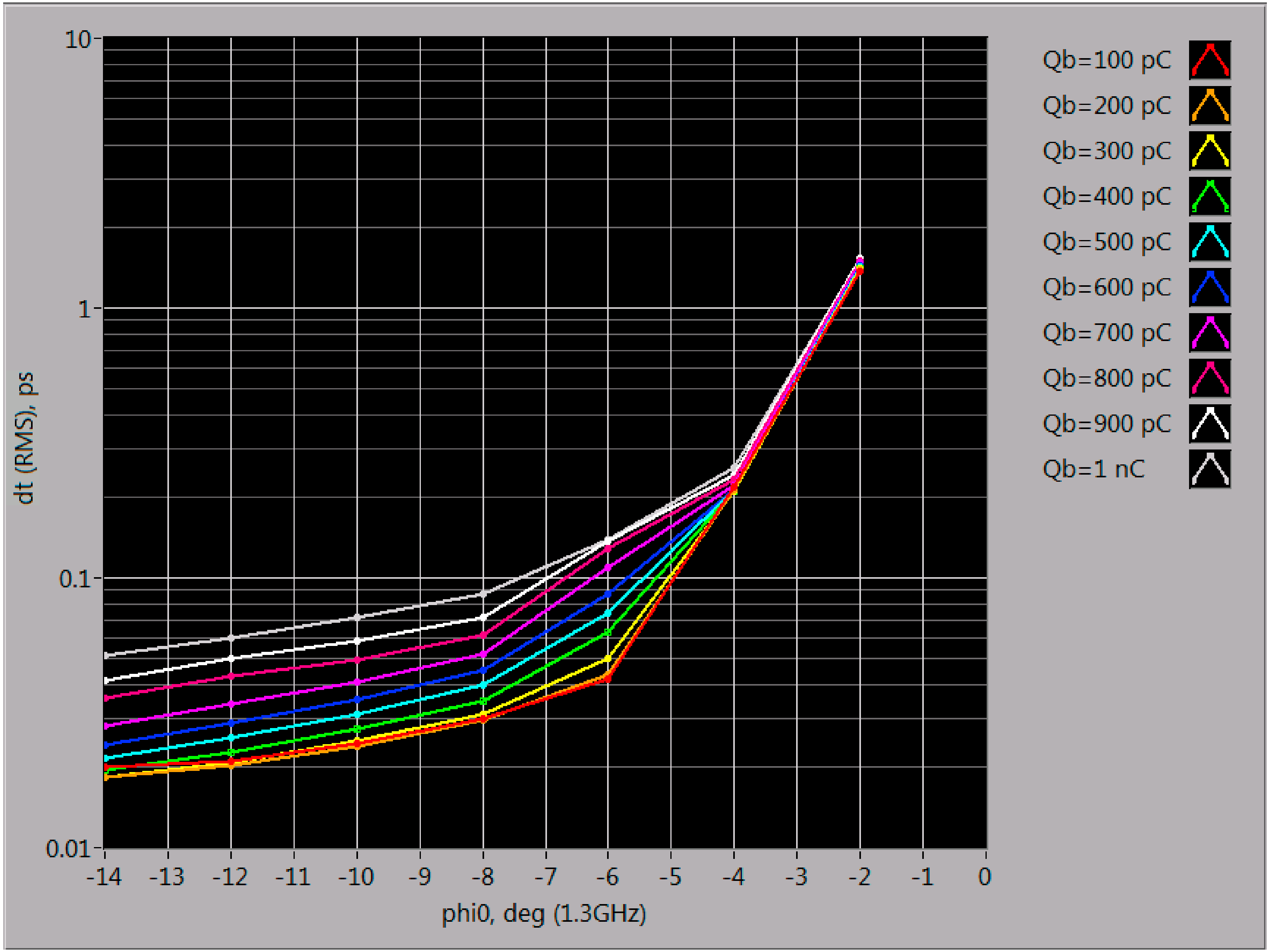
Run 4 :: 6 ps – 2 keV



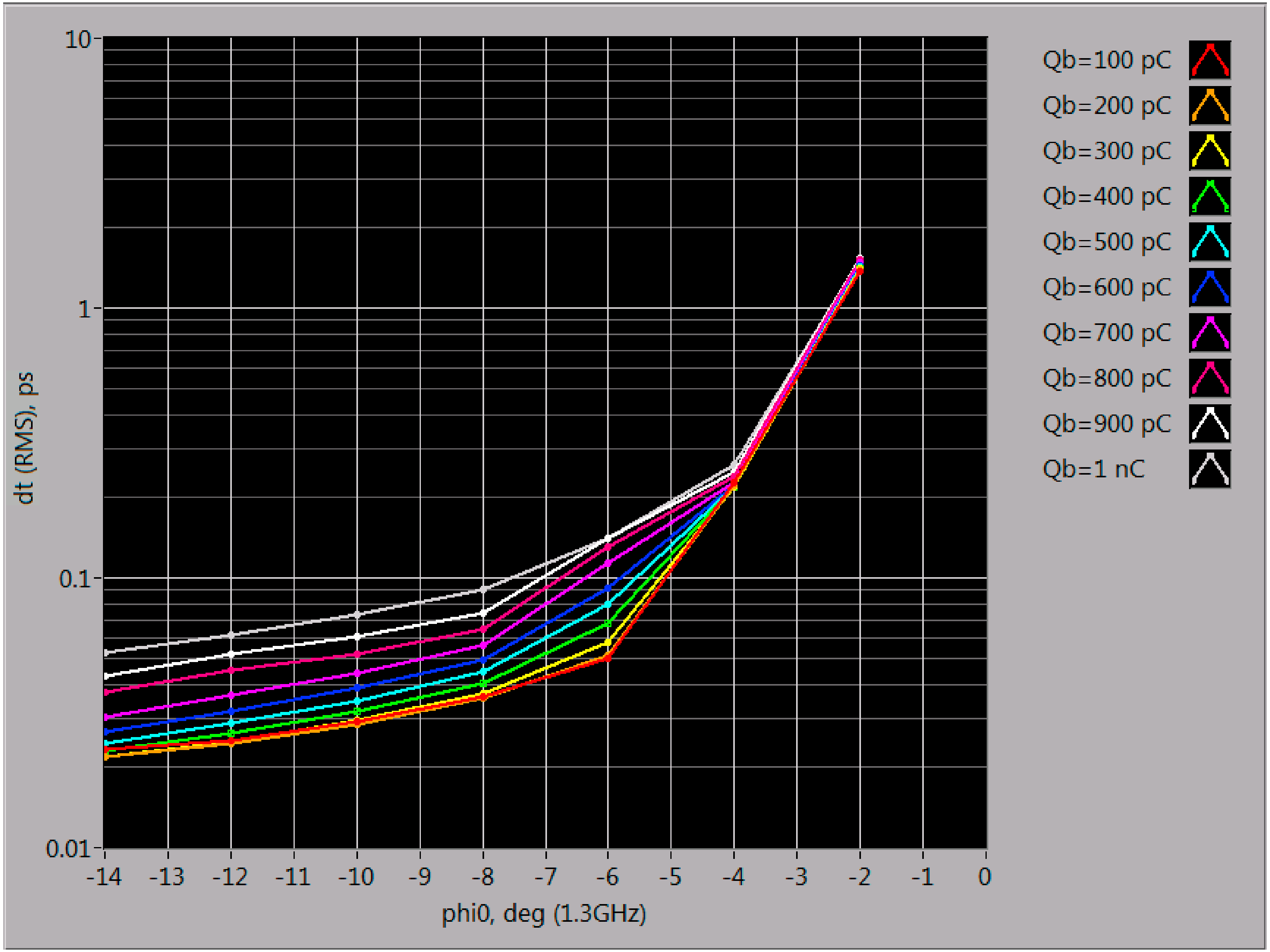
Run 4 :: 6 ps – 3 keV



Run 4 :: 6 ps – 4 keV

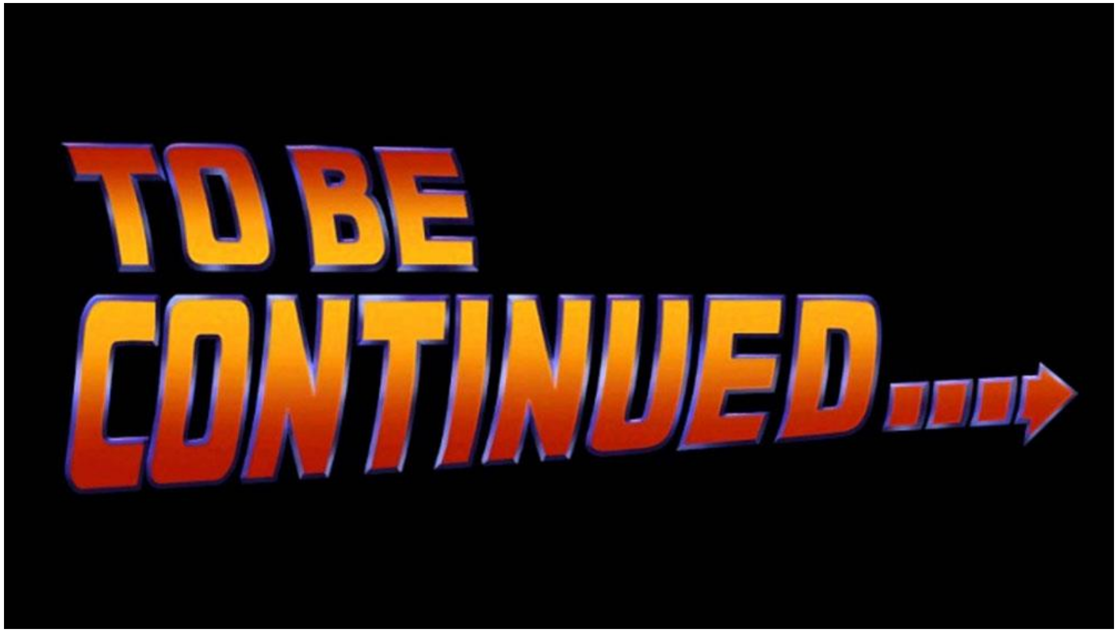


Run 4 :: 6 ps – 5 keV



Run 4 :: σ_{t0} = 6 ps, 20 MV/m

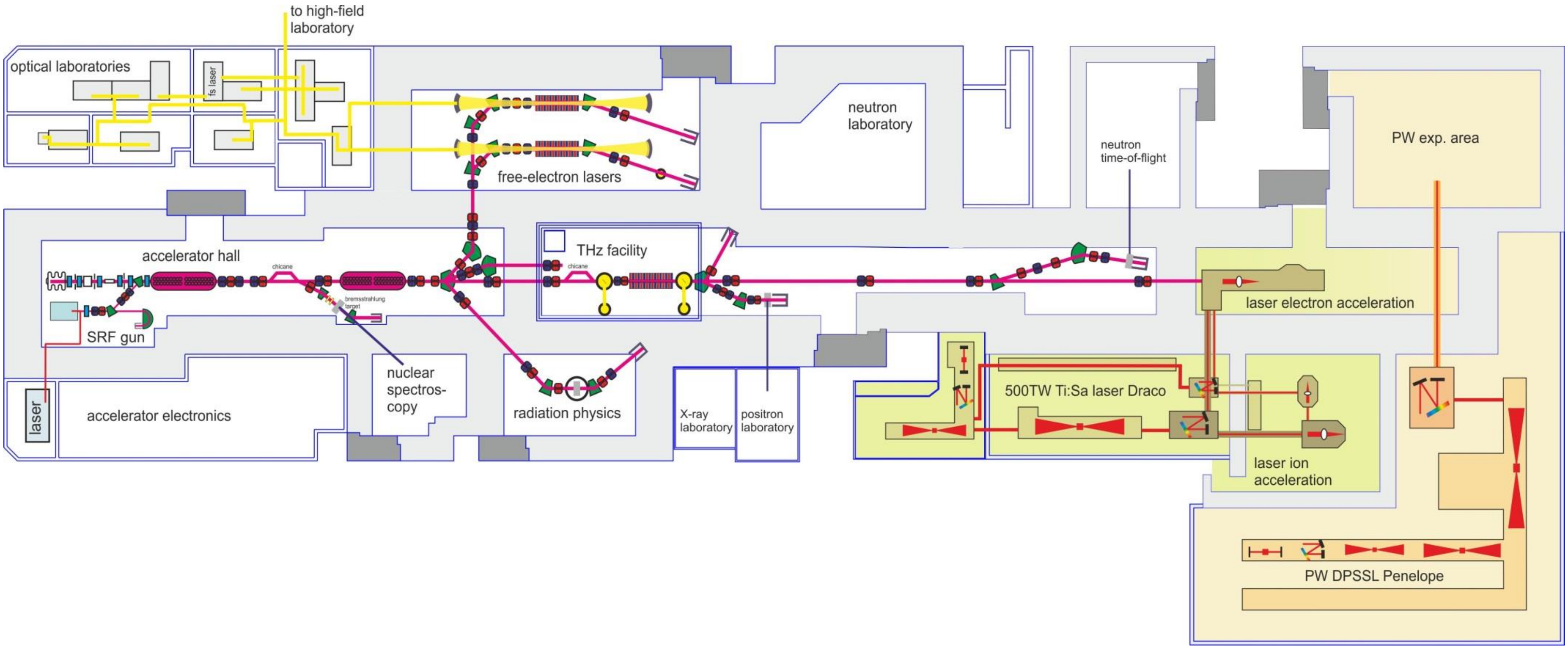
- 20 MV/m much better than 10 MV/m
- Initial σ_E makes difference for all Q_b, but a lot for 100 pC a little for 1 nC
- Interpretation: high LINAC gradient seems to be the way to go
- Next: space charge couples transverse and longitudinal dynamics
  Q: how large is this effect in this LINAC model ?
  Q: how initial Twiss parameters affect $\sigma_{E\ slice}$ – i.e. bunch compressibility ?




Fin

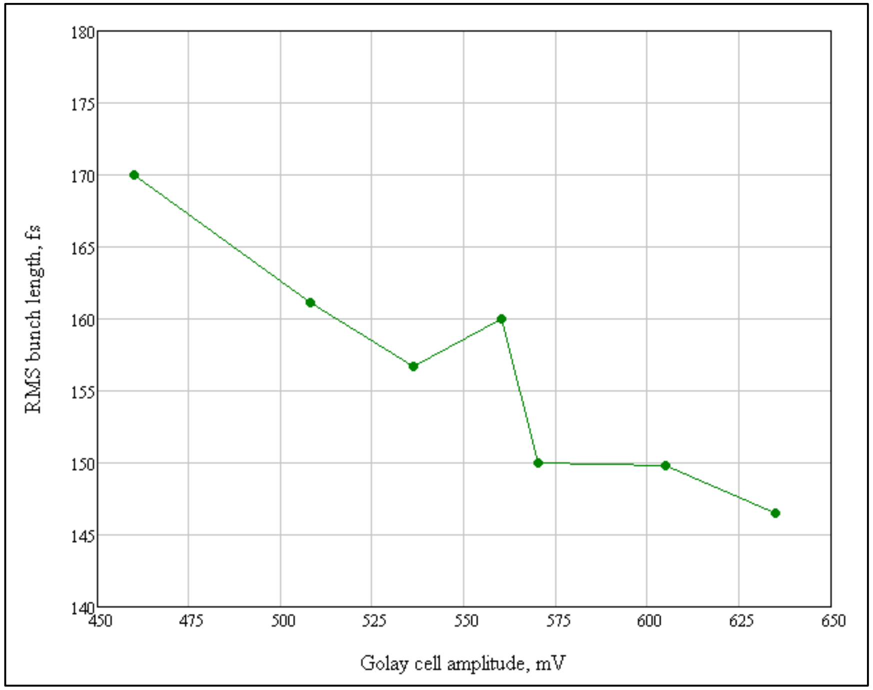
Backup Slides

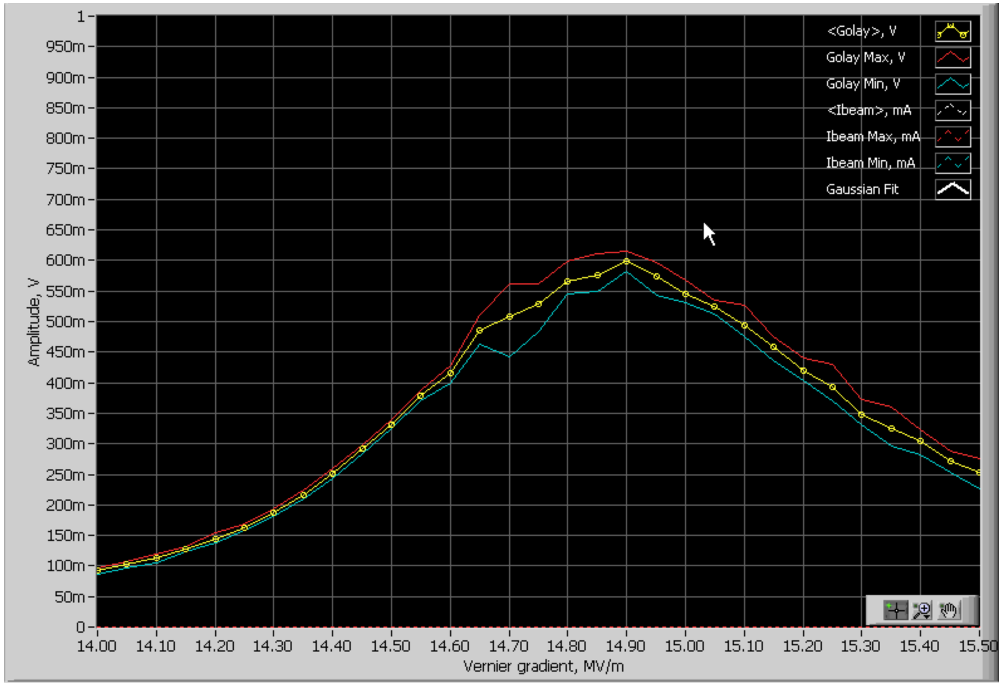
ELBE – Radiation Source (all)



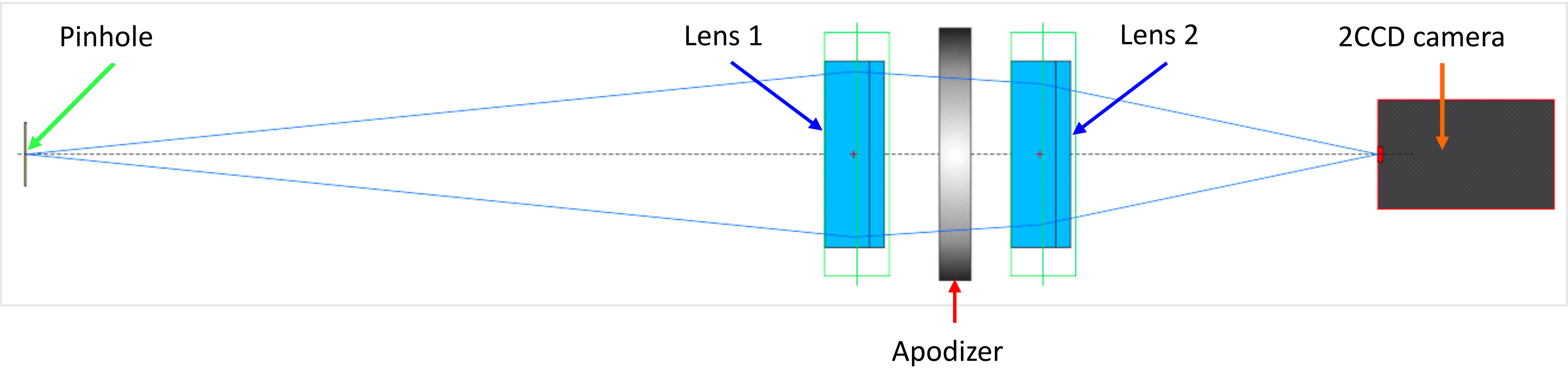
JLab FEL "BLM"

- Sensitivity (left plot) ~ 0.14 fs/mV
- Variation measured with sample rate of 5 Hz and bunch frequency of 585 kHz ~ 50 mV
- The measurements is the observation of detector signal amplitude without any adjustment in accelerator
- The variation is ~ 7 fs (peak-to-peak), i.e. ~ 5 %

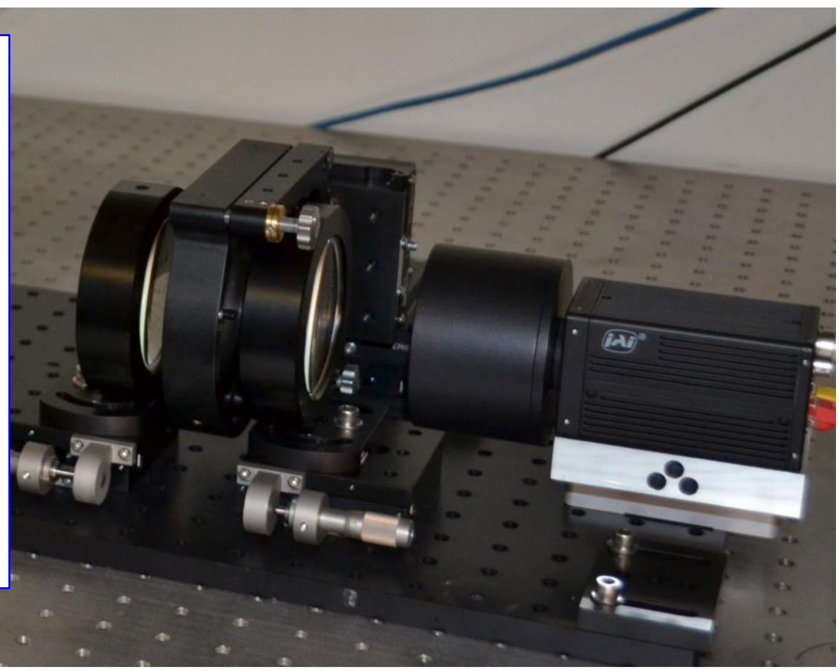




Apodizer bench test

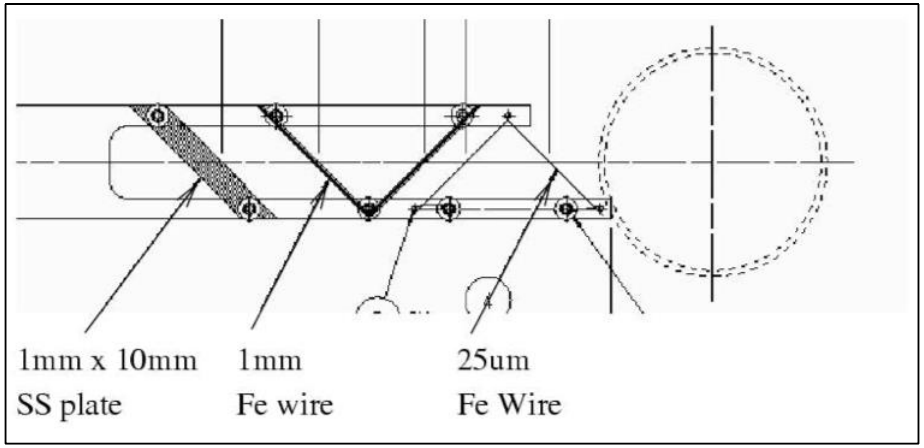


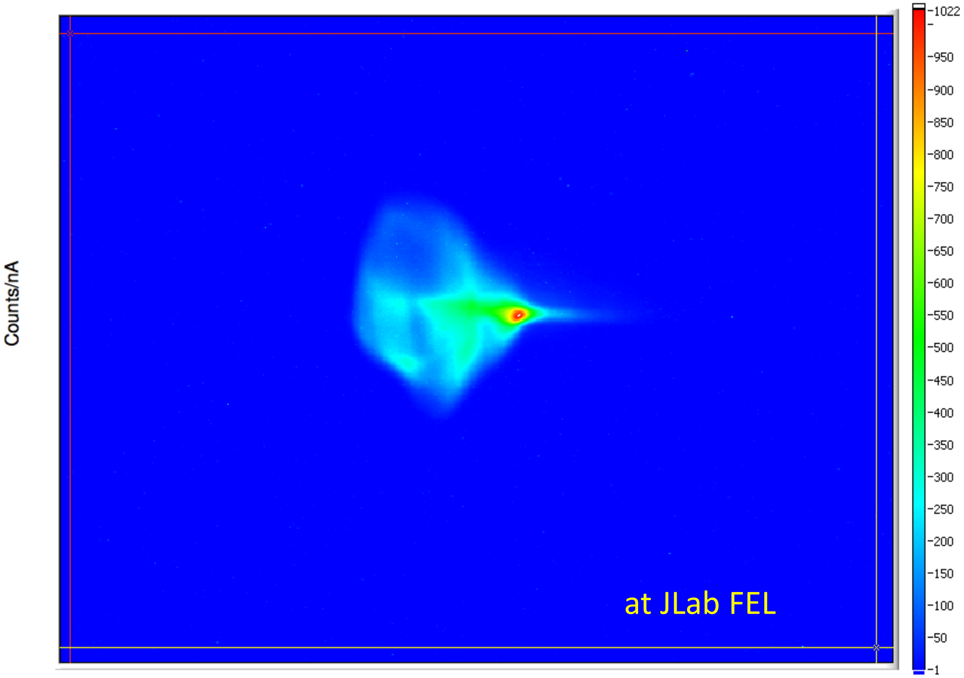
- First test and characterization of the apodizer effect
- Imaging with two achromatic doublets; can be thought off as one effective lens (Fourier plane)
- Apodizer is located in the Fourier plane
- Source: a pinhole with sharp edges (different from Gaussian source)
- For the sharp edges it is more difficult to achieve LDR, on the other hand much easier to see the effect of apodizer



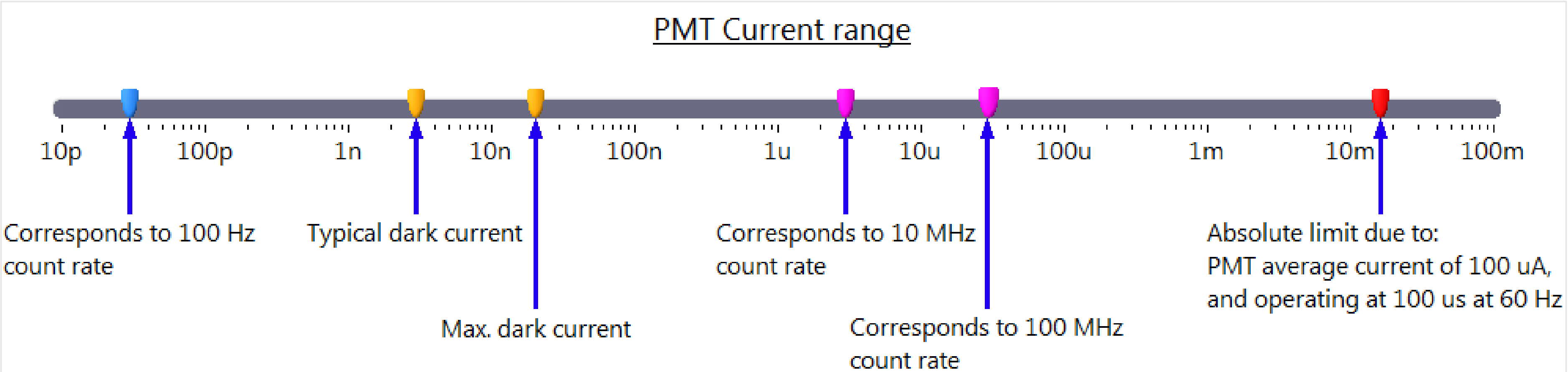
Wire-scanner with PMT and counting

- Wire-scanner measurements - very important alternative & complimentary technique to beam imaging
- CEBAF special wire-scanner is one good example of LDR measurement
- 499 MHz bunch frequency good fit for single photon counting with PMT
- Up to 100 MHz counting frequency can be used, BUT only for very low bunch charge, CW beam – long measurements times (15 min)
- For FELs and ERLs bunch frequencies of 100 kHz – 1 MHz are much more relevant (not a good fit for counting)
- Alternative to PMT pulse counting is the analog mode – measurements of current through the PMT
- Need LDR (10^6 or higher) and fast current measurements



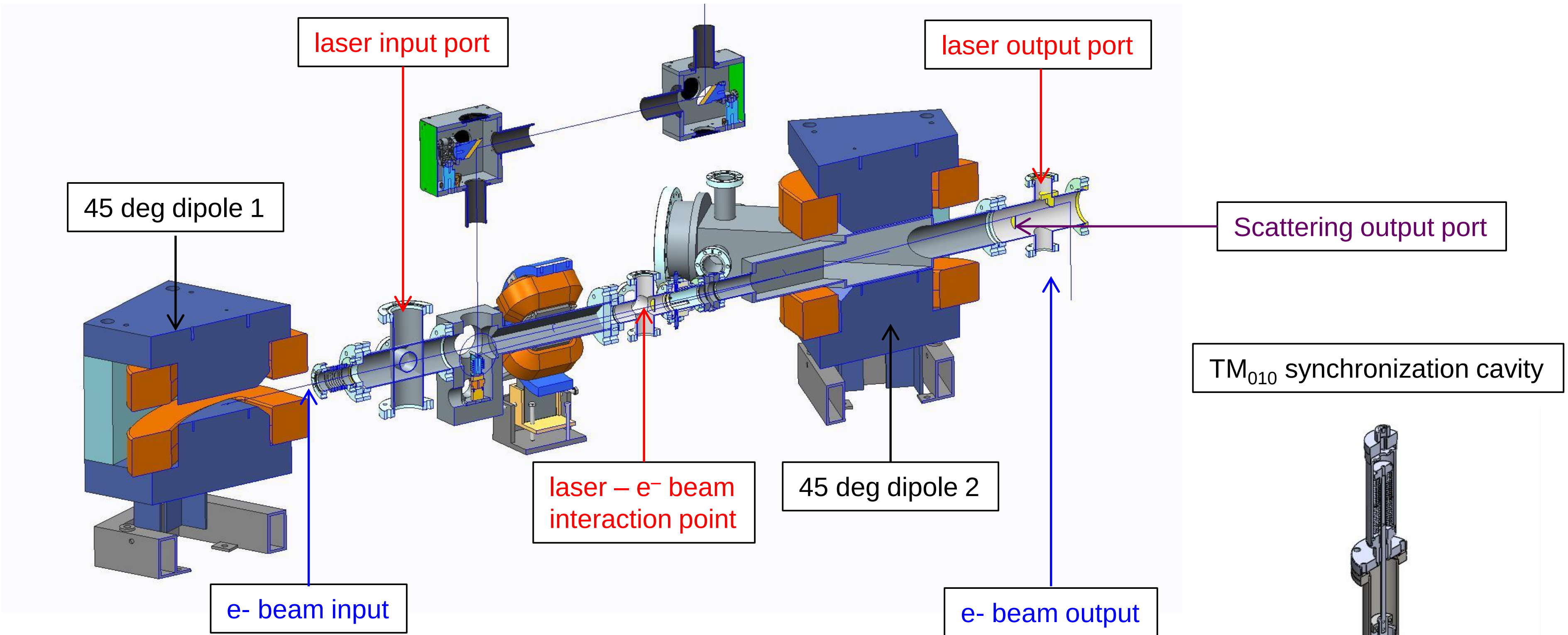


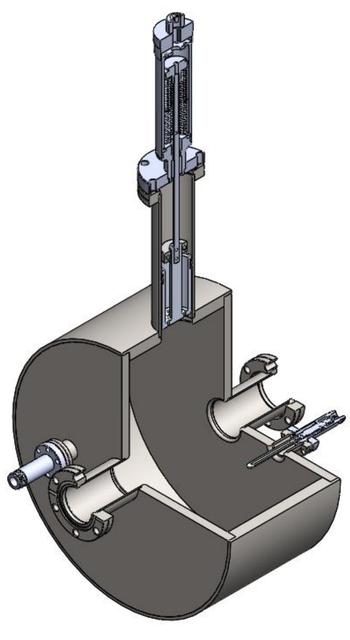
PMT current range



- Typically <u>average</u> PMT current must be ≤ 100 µA (photo cathode live time)
- With low duty cycle beam (100 µs @ 60 Hz) PMT current within the 100 µs can be much higher – few mA
- PMTs with dark current of a few nA are available (low Q.E. cathode at long wavelength)
- When counting is used, 100 MHz and 100 Hz are practical limits; correspond to 30 µA and 30 pA
- Both counting and analog mode can have 10^6 range, but analog mode accesses signals 10^3 higher and therefore is correspondently faster and/or have has better signal to noise ratio
- For low duty cycle systems, as diagnostic mode beam, gated integrator (GI) is the optimal small signal recovery technique
- For a single GI dynamic range of 10^7 is impossible (sub µV noise for 10 V signals), 10^4 is realistic

CW laser-wire setup





- Laser system is installed and commissioned: 1032 nm, **25 W**, **15-20 μJ**, 0.8-1.6 MHz, 300 fs
- Accurate beam trajectory in the dipole fringe field were required (done)
- Temporal jitter of the e⁻ beam was measured. Can be as high as ps - too large for sub-ps resolution.
- Due to the large temporal e⁻ beam jitter, synchronization of the laser via precise reference would not be sufficient
- Concept (and detailed designs) for direct laser to e⁻ beam synchronization is developed