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

$E_b = 34\text{ MeV}, \quad f_b = 13\text{ MHz}, \quad <I_b> = 1\text{ mA}$

$Q_b = 77\text{ pC}$ (thermionic gun), $Q_b = 300\text{ pC}$ (SRF gun at 100 kHz),

9-cell 1.3 GHz TESLA cavities
ELBE :: Users

Total beam time planned

- MD: 24%
- THz: 7%
- AP: 6%
- LP: 2%
- POS: 12%
- NEP: 10%
- RP: 7%
- FEL: 21%

Total beam time evaluated

- MD: 24%
- THz: 7%
- AP: 6%
- LP: 2%
- POS: 11%
- NEP: 10%
- RP: 6%
- FEL: 20%

Hours in total:

- Scheduled: 6348
- Used: 6056
- Efficiency: 85%

External users: 71%
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,
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,

Courtesy of P. Michel
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

<table>
<thead>
<tr>
<th>Mode</th>
<th>FEL</th>
<th>High Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>final electron energy</td>
<td>≤ 9.5 MeV</td>
<td></td>
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<tr>
<td>RF frequency</td>
<td>1.3 GHz</td>
<td></td>
</tr>
<tr>
<td>operation mode</td>
<td>CW</td>
<td></td>
</tr>
<tr>
<td>Photo cathode</td>
<td>Cs₂Te</td>
<td></td>
</tr>
<tr>
<td>bunch charge</td>
<td>80 pC</td>
<td>1 nC</td>
</tr>
<tr>
<td>repetition rate</td>
<td>13 MHz</td>
<td>500 kHz</td>
</tr>
<tr>
<td>laser pulse (FWHM)</td>
<td>4 ps</td>
<td>15 ps</td>
</tr>
<tr>
<td>transverse rms emittance</td>
<td>1 mm mrad</td>
<td>2.5 mm mrad</td>
</tr>
<tr>
<td>average current</td>
<td>1 mA</td>
<td>0.5 mA</td>
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<tr>
<td>Month</td>
<td>Year</td>
<td>Event</td>
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<tr>
<td>-------</td>
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<td>-------</td>
</tr>
<tr>
<td>May</td>
<td>2014</td>
<td>Gun installation finished</td>
</tr>
<tr>
<td>June</td>
<td>2014</td>
<td>First beam with Cu photocathode</td>
</tr>
<tr>
<td>Aug.</td>
<td>2014</td>
<td>RF commissioning ready, 25.6 MV/m maximum peak field</td>
</tr>
<tr>
<td>Feb.</td>
<td>2015</td>
<td>Beam with highest kinetic energy of 4.5 MeV</td>
</tr>
<tr>
<td>Jan.</td>
<td>2015</td>
<td>Photocathode transfer system installed</td>
</tr>
<tr>
<td>Feb.</td>
<td>2015</td>
<td>First test with Cs₂Te—strong multipacting &amp; field emission</td>
</tr>
<tr>
<td>Nov.</td>
<td>2015</td>
<td>Mg photocathodes, laser cleaning</td>
</tr>
<tr>
<td>Jan.</td>
<td>2016</td>
<td>Upgrade of Cs₂Te photo cathode preparation ready, QE measurement</td>
</tr>
<tr>
<td>March</td>
<td>2016</td>
<td>First beam with Mg photocathode</td>
</tr>
<tr>
<td>June</td>
<td>2016</td>
<td>ELBE/ARD shifts beam with 200 pC in ELBE</td>
</tr>
<tr>
<td>Dec.</td>
<td>2016</td>
<td>User shifts for TELBE, 4 x 12 h, Mg cathode, 80 pC, 100 kHz</td>
</tr>
<tr>
<td>Feb.</td>
<td>2017</td>
<td>Beam with Cs₂Te cathode, without multipacting, 200 pC, 2 weeks lifetime only due to cathode cooling problem</td>
</tr>
<tr>
<td>March</td>
<td>2017</td>
<td>TELBE/ARD shifts, 100 pC short pulses, high THz power</td>
</tr>
</tbody>
</table>

Courtesy of J. Teichert
Joined ELBE – JLab accelerator R&D
Bunch Length Measurements at ELBE

- Options for ps and sub-ps $\sigma_t$ 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 $\sigma_t$ down to ~100 fs; shows that instrument has enough bandwidth for ~ 50 fs $\sigma_t$ measurements
JLab IR/UV Upgrade :: Bunch length

\[ E = 135 \text{ MeV} \]
Bunch charge 60 pC
Rep. rate up to 74.85 MHz

25 \( \mu \text{J/pulse} \) in 250–700 nm UV-VIS

120 \( \mu \text{J/pulse} \) in 1-10 \( \mu \text{m} \) IR

\[ \sigma_t = 150 \text{ fs RMS} \]
\[ \sigma_t = 100 \text{ fs RMS} \]
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
- $\sigma_t = 100$ fs RMS at UV FEL
- UV FEL had much more gain than 1D model predicted with $\sigma_t=100$ 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

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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 – enable measurements with CW beam
MPI @U37 :: data evaluation

- At IR/UV Upgrade interferometer data evaluation – bunch length extraction was made in frequency domain, NLSF + Gaussian beam estimation.

- 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

24.07

- 3.2°

- 29.8°

27.07

- 1.9°

- 27.3°
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 $<I_b>$ 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

- 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
\( \sigma = 12 \text{ mm} \)

Gaussian halftone dot apodizer
\( \sigma = 6 \text{ mm} \)

The same data in Log scale
Central line of pinhole images

- Measurements with dynamic range of $\sim 10^6$
- 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
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
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
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 $\rightarrow$ radiation properties) to translate radiation source requirements to electron beam requirement

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 $\sigma_{x,\text{ini}}$ and initial energy spread $\sigma_{E,\text{ini}}$ accelerated on $\cos(\omega_0 t + \phi_{\text{RF}})$ RF waveform from $E_{\text{ini}}$ to $E_{\text{fin}}$.

- SPD ($X_f = M_{\text{compr}} \cdot M_{\text{linac}} \cdot X_0$) is applied to collective of particles; bunch length (second order momentum) is calculated from resulting distributions.

- This approach gives analytical formulas for bunch length

\[
\sigma_{z,\text{fin}} = \sqrt{(1 + h \cdot R_{56})^2 \sigma_{z,\text{ini}}^2 + \left(\frac{E_{\text{ini}}}{E_{\text{fin}}}\right)^2 R_{56}^2 \sigma_{\delta,\text{ini}}^2}
\]

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

\[
\sigma_{z,\text{fin.min}}(\phi_{\text{RF}}) = \left(\frac{E_{\text{ini}}}{E_{\text{fin}}}\right) \left( -\frac{1}{h(\phi_{\text{RF}})} \right) \sigma_{\delta,\text{ini}} \]

min possible bunch length (when all correlations removed).

To remove linear correlation optimal $R_{56}$

\[
R_{56,\text{opt}} = -\frac{1}{h}
\]

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

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

with second order chirp

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

P. Emma, Section 4.5 “Bunch compression” in “Handbook of Accelerator Physics and Engineering ” p. 334-337
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 $R_{56}$
Implications for beam-to-RF stability

at optimal compression

\[ \sigma_{z, \text{fin.min}}(\varphi_{RF}) = \left( \frac{E_{\text{ini}}}{E_{\text{fin}}} \right) \left( \frac{1}{h(\varphi_{RF})} \right) \sigma_{\delta, \text{ini}} \]

- Top-right picture assumes optimally adjusted \( R_{56} \) and \( T_{566} \) for each \( \varphi_{RF} \)
- 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 \( \Delta \leftarrow \Delta \varphi = 0.035 \) deg beam-to-LINAC

1 % bunch length \( \Delta \leftarrow \Delta \varphi = 0.016 \) 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
  – $\sigma_{\text{t.min}} \sim 150$ fs (IR-FEL), $\sim 100$ fs (UV-FEL)

* Measurements and modeling: $\varepsilon_z$ injector $= 25$ keV-ps

* Measurements: $\varepsilon_z$ full compression $= 75$-$80$ keV-ps

* The increase of $\varepsilon_z$ 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?
LONGITUDINAL SPACE CHARGE EFFECTS IN THE JLAB IR FEL SRF LINAC


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.
Questions:

- What is $\sigma_{t \text{ comp}} = \sigma_{t \text{ comp}}(Q, b)$ to be expected realistically?
- What is the contribution of the longitudinal space charge (LSC) effect in LINAC to possible $\sigma_{t \text{ comp}}$?
- What are requirements on injector output beam for optimal compression / $\varepsilon_z$ preservation? ($\sigma_{t \text{ inj}}, \delta E_{\text{ inj}}, <E>_\text{ inj}, \alpha_{x(y) \text{ inj}}, \beta_{x(y) \text{ inj}}$)
- How LINAC configuration will affect $\varepsilon_z$ preservation?
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) vs 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 (?) vs 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

100 pC, 3 ps, 1 keV, -6 deg

3 ps

43 fs
Long. phase space linearization 1 nC

- Automate
- Scan parameter space
- Main parameters:
  - $Q_b$
  - initial $\sigma_E$
  - $\phi$ 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 :: $\sigma_{t0} = 3$ ps, 10 MV/m :: lessons

* Shows the difference when accelerating on two different sides of RF crest
* Initial $\sigma_E$ makes difference for 100 pC – 200 pC
* For $Q_b > 200$ pC, essentially no difference from initial $\sigma_E$
* $\sigma_{t\text{compressed}} (1\text{nC}) \sim \times 10 \sigma_{t\text{compressed}} (100\text{pC})$ … 😞
* Interpretation: $\sigma_{E\text{slice}}$ due to space charge for $Q_b > 200$ pC is $>> \sigma_{E0}$
* Note: collective effects in compressor will make it even worse
* Next: try to increase $\sigma_{t0}$ to reduce peak current and space charge
* Run 2 $\sigma_{t0}=4.5$ps, Run 3 $\sigma_{t0}=6.0$ps – show improvements for 200 – 300 pC, but virtually no difference for high charge
* To use $\sigma_{t0}$ as a knob to improve at 1 nC would require $\sigma_{t0} = 30$ps (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 :: $\sigma_{t0} = 6 \text{ ps, 20 MV/m}$

※ 20 MV/m much better than 10 MV/m

※ Initial $\sigma_E$ 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 $\sigma_{E\text{ slice}}$ – i.e. bunch compressibility?
Backup Slides
ELBE – Radiation Source (all)
Sensitivity (left plot) $\sim 0.14$ fs/mV

Variation measured with sample rate of 5 Hz and bunch frequency of 585 kHz $\sim 50$ mV

The measurements is the observation of detector signal amplitude without any adjustment in accelerator

The variation is $\sim 7$ fs (peak-to-peak), i.e. $\sim 5\%$
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
Typically **average** PMT current must be \( \leq 100 \, \mu A \) (photo cathode live time)

With low duty cycle beam (100 \( \mu s \) @ 60 Hz) PMT current within the 100 \( \mu s \) 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 \( \mu A \) 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 \( \mu V \) noise for 10 V signals), \( 10^4 \) is realistic
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