

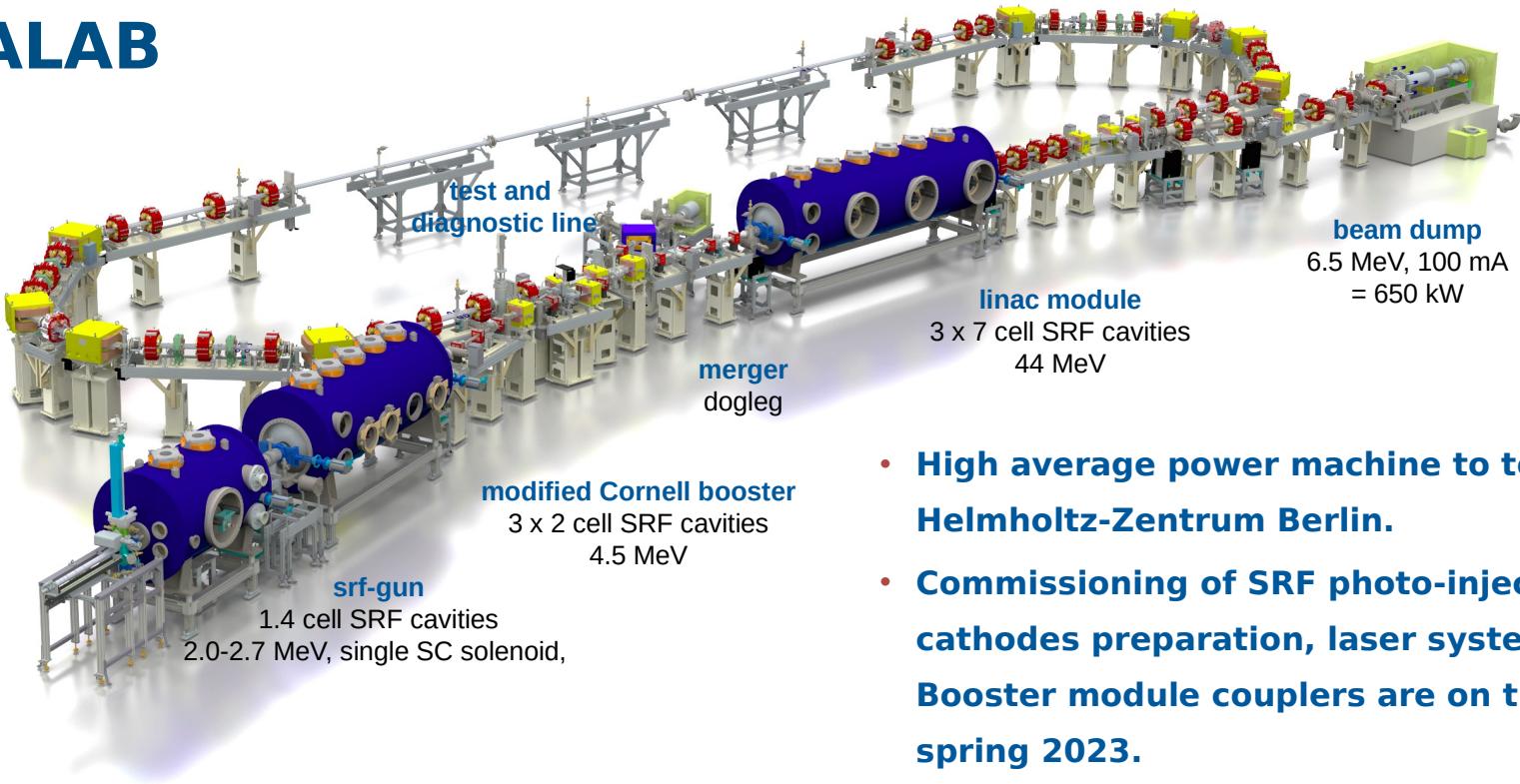


# ULTRA SHORT PULSES AND LOW JITTER FOR TIME-RESOLVED EXPERIMENTS AT SEALAB

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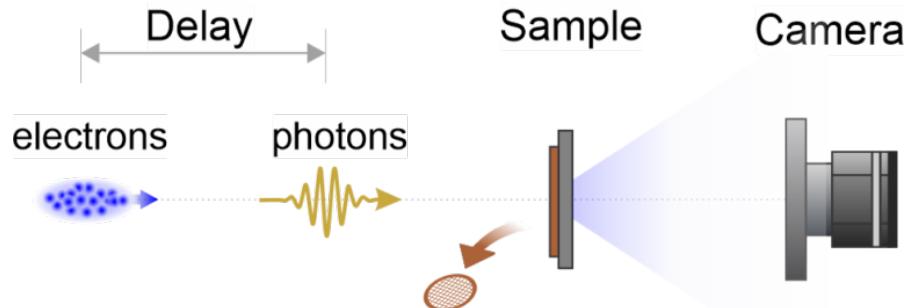
# SEALAB



- **High average power machine to test ERL technologies and applications in Helmholtz-Zentrum Berlin.**
- **Commissioning of SRF photo-injector on-going: high quantum efficiency cathodes preparation, laser system, high-power RF conditioning of SRF. Booster module couplers are on track to allow first beam from the injector spring 2023.**
- **However, main LINAC missing for now. Looking for new science cases : Ultrafast Electron Diffraction with the injector!**

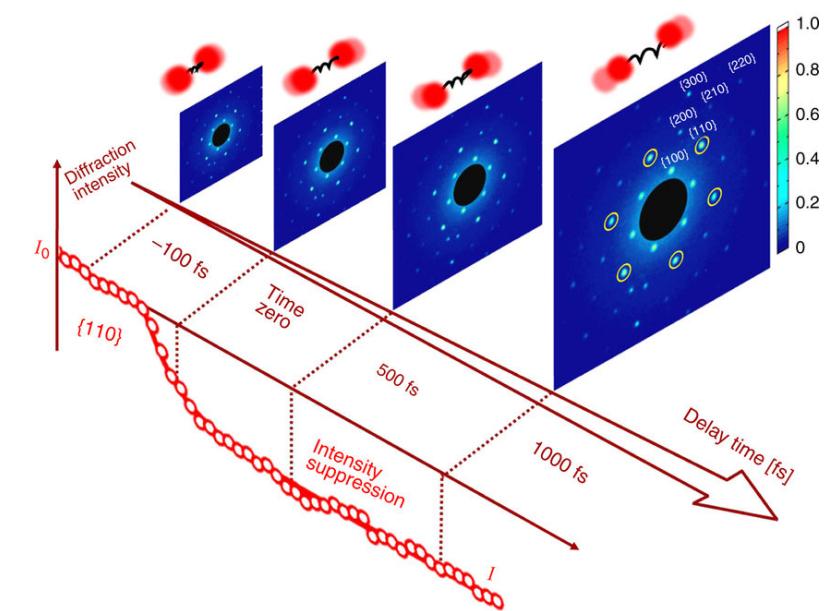
VISIT THIS AFTERNOON !!

# ULTRAFAST ELECTRON DIFFRACTION



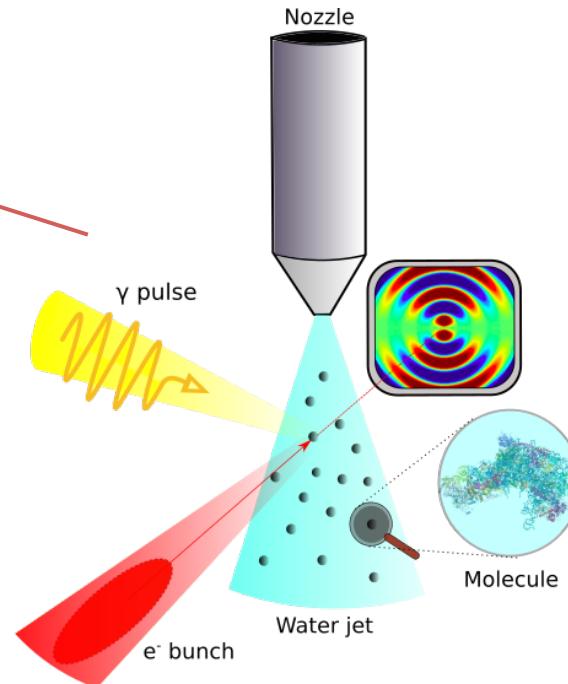
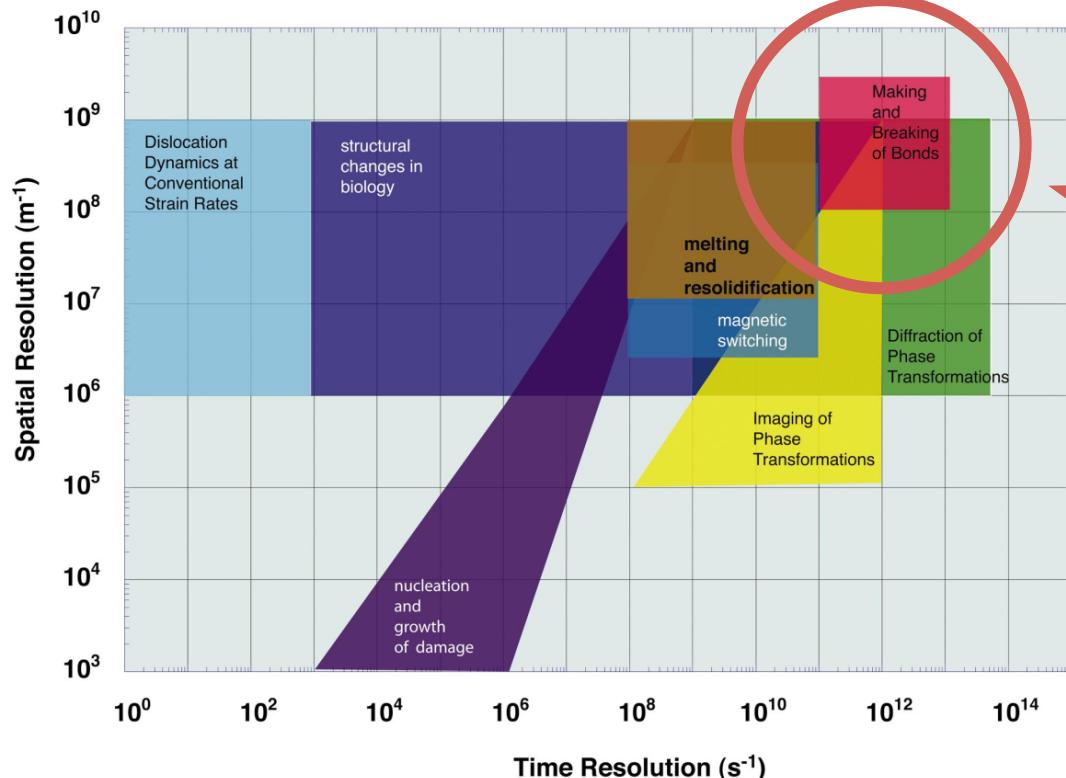
## Step by step description of the UED pump-probe process:

- A photon pulse excites the target.
- After some time delay, an electron bunch scatters in the same target.
- The diffraction pattern of the scattered electrons is recorded.
- The process is repeated for a different time delay.
- **Goal:** To obtain a “video” of the photo-induced structural dynamics.



M.-F. Lin et al., Nat. Commun. 8, 1745 (2017).

# ULTRAFAST ELECTRON DIFFRACTION – GOAL?



**Needed for molecular UED:**

- Spatial resolution  $> 10^8 \text{ m}^{-1}$ .
- $\epsilon_{n,\perp} \sim 10\text{nm} - \text{rad}$
- Time resolution  $> 10^{13} \text{ s}^{-1}$ .  
$$\sqrt{\sigma_t^2 + \sigma_{ToF}^2} \leq 100\text{fs}$$
- Bunch charges in the fC range.
- High repetition rate, MHz range.

Hence, we need an accelerator with:

- MeV energy (reduces space-charge forces, compression)
- nm-rad emittances
- Bunch length smaller than 100fs
- Better ToF stability than 100fs



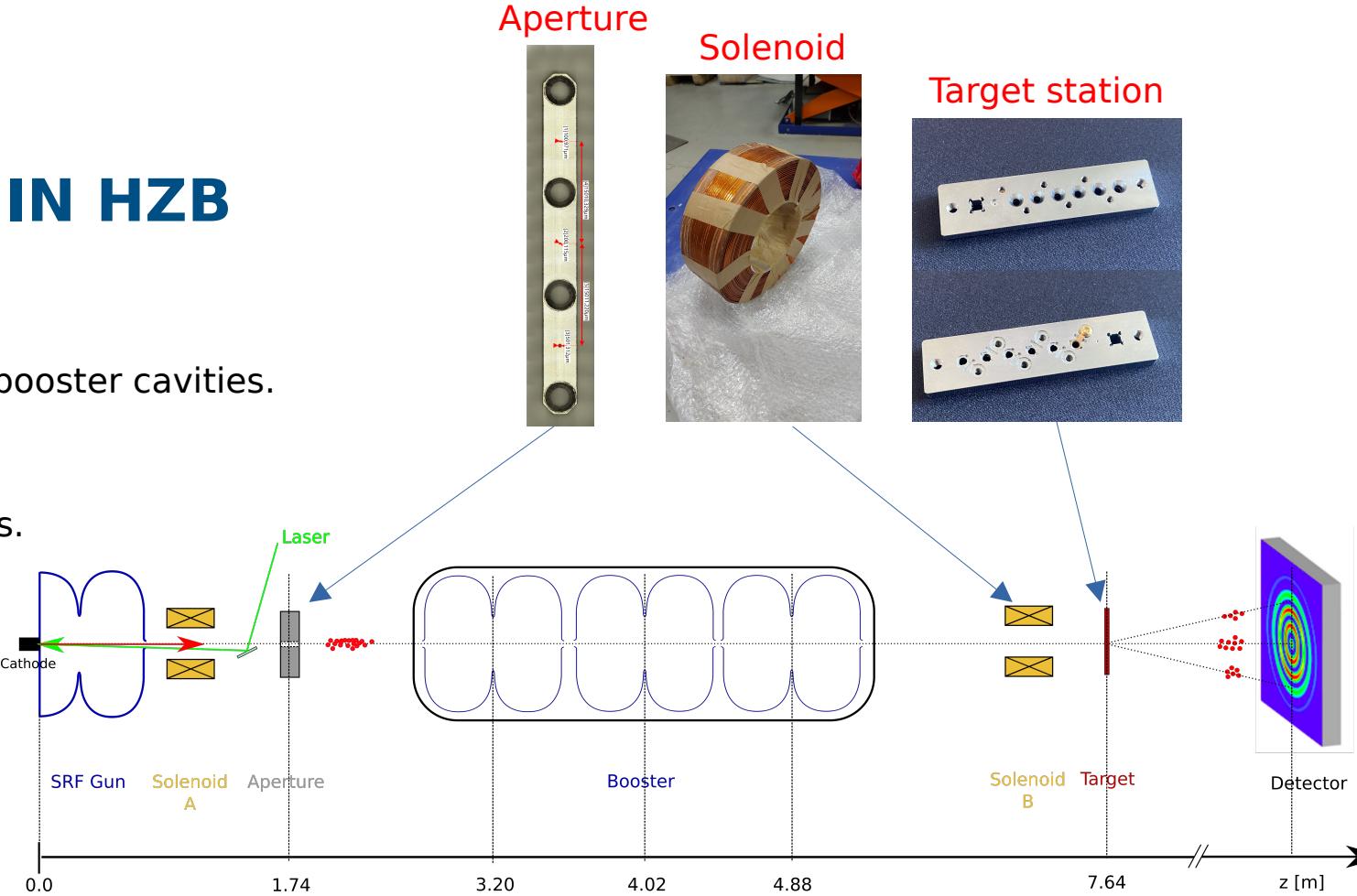
# THE SRF PHOTONINJECTOR IN HZB

## The beamline:

- Superconducting L-band electron gun and 3 booster cavities.
- MHz repetition rate (initially, GHz later).
- 515nm drive laser. Minimum pulse length 1ps.
- Trans. norm. emittances mm-mrad range.
- Energy between 1MeV and 3.5MeV.
- Bunch charge pC to nC range.

**Not every parameter is ideal for UED!!**

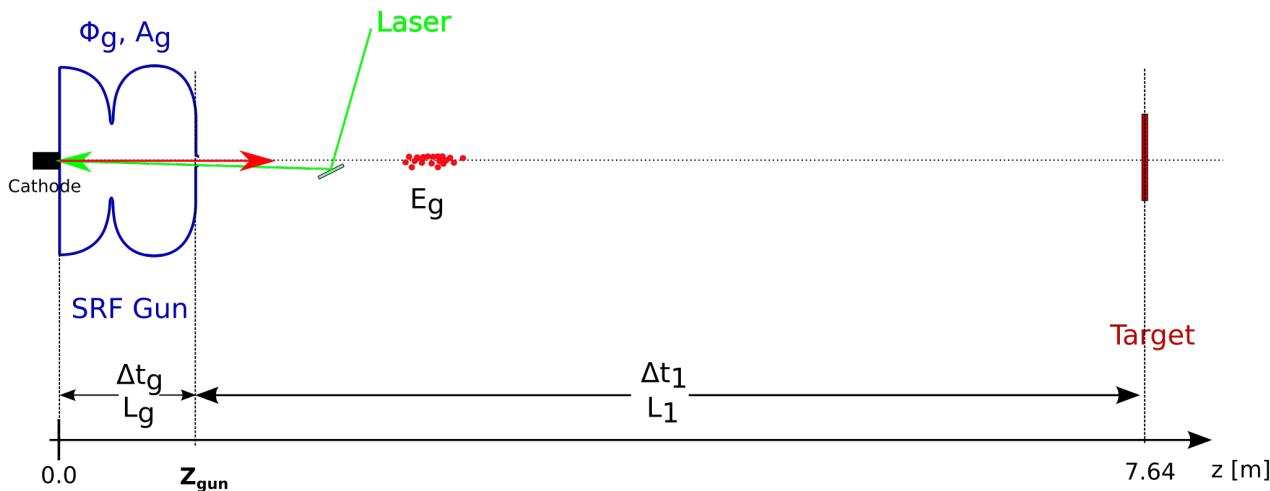
- Emittance too large → Aperture
- Laser pulse too long
- Fluctuations in cavities



First constraint: Extract more charge  
than needed close and collimate!

| Injector mode             | UED mode |
|---------------------------|----------|
| Energy                    | ~ 6 MeV  |
| $Q_{\text{bunch}}$        | 77 pC    |
| $\Delta t_{\text{bunch}}$ | ps       |
| $\epsilon_{\perp,n}$      | μm rad   |
| Repetition rate           | 1 MHz    |
|                           | ~ 3 MeV  |
|                           | 50 fC    |
|                           | fs       |
|                           | nm rad   |
|                           | 1 MHz    |

# TIME OF FLIGHT JITTER



We develop an analytical model of the time of flight jitter:

- Astra simulations are used to calculate beam energy and time to exit the gun as a function of gun amplitude and phase

$$\sigma_{ToF}^2 = \left( \frac{\partial t_g}{\partial A_g} - \frac{L_1}{m_0 c^3 (\gamma_g^2 - 1)^{3/2}} \left( \frac{\partial E_g}{\partial A_g} \right) \right)^2 \sigma_{A_g}^2 + \left( \frac{\partial t_g}{\partial \phi_g} - \frac{L_1}{m_0 c^3 (\gamma_g^2 - 1)^{3/2}} \left( \frac{\partial E_g}{\partial \phi_g} \right) \right)^2 (\omega \sigma_{RL})^2$$

**The electron bunches sample different fields than the nominal in the gun. The reasons are:**

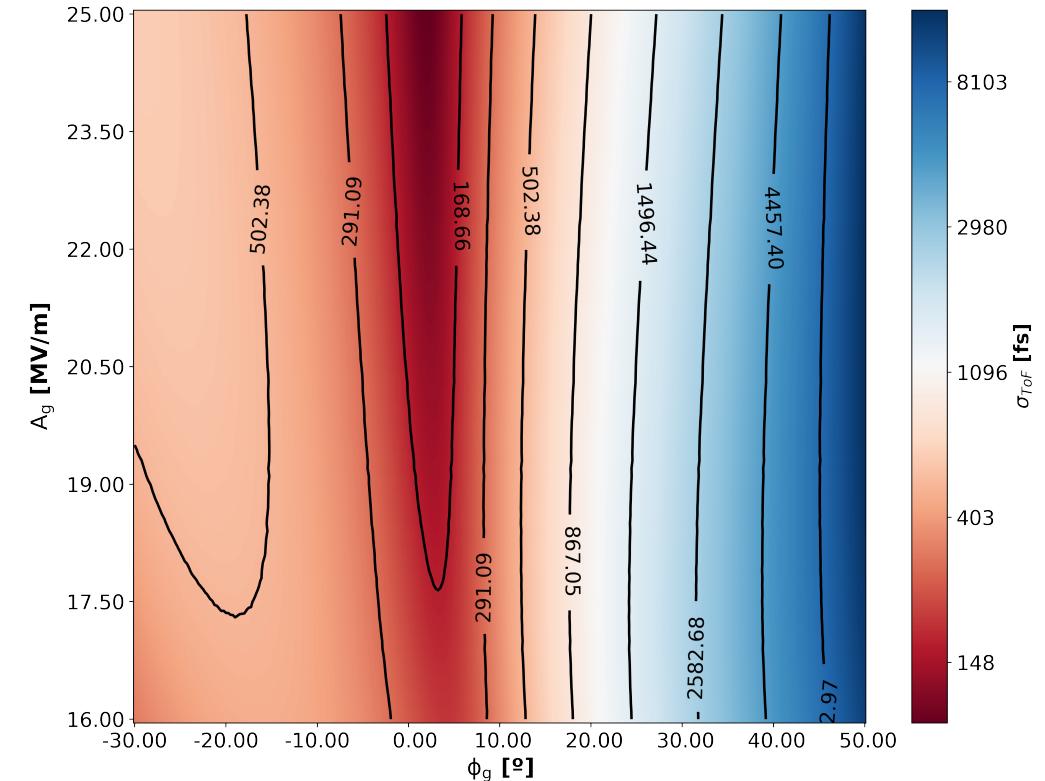
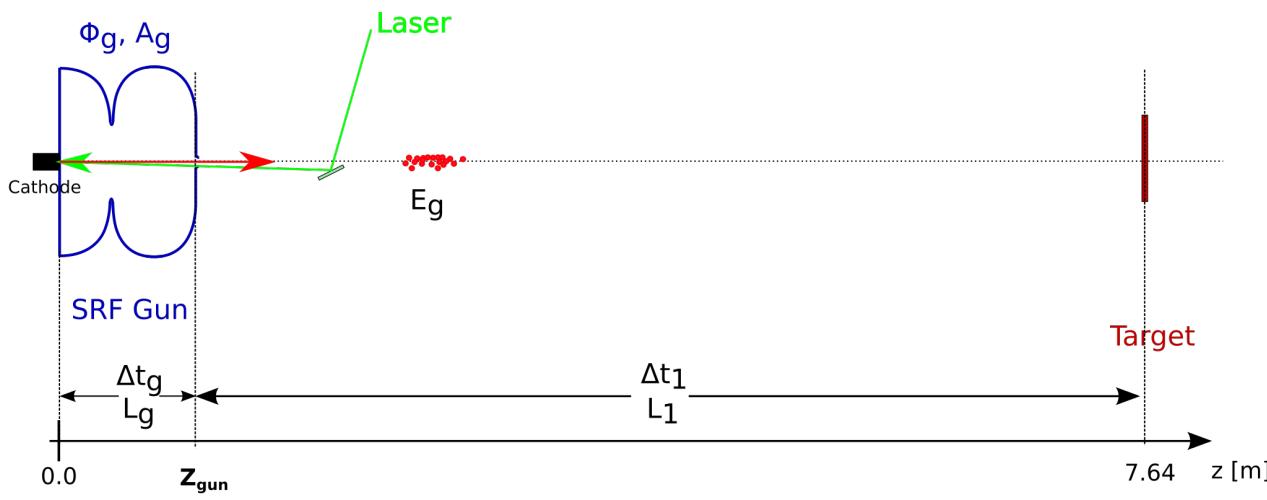
- The laser pulse arrival jitter at the cathode
- The phase jitter in the gun
- The amplitude jitter in the gun.

| Parameter          | Fluctuation                |               |
|--------------------|----------------------------|---------------|
| Laser arrival [fs] | 300                        | $\sigma_L$    |
| RF Phase [°]       | 0.05                       | $\sigma_\phi$ |
| RF Amplitude       | $1 \times 10^{-4} \cdot V$ | $\sigma_A$    |

Timing jitters in the gun can be combined:

$$\sigma_{RL} = \sqrt{(\sigma_\phi/w)^2 + \sigma_L^2} \sim 320 \text{ fs}$$

# TIME OF FLIGHT JITTER

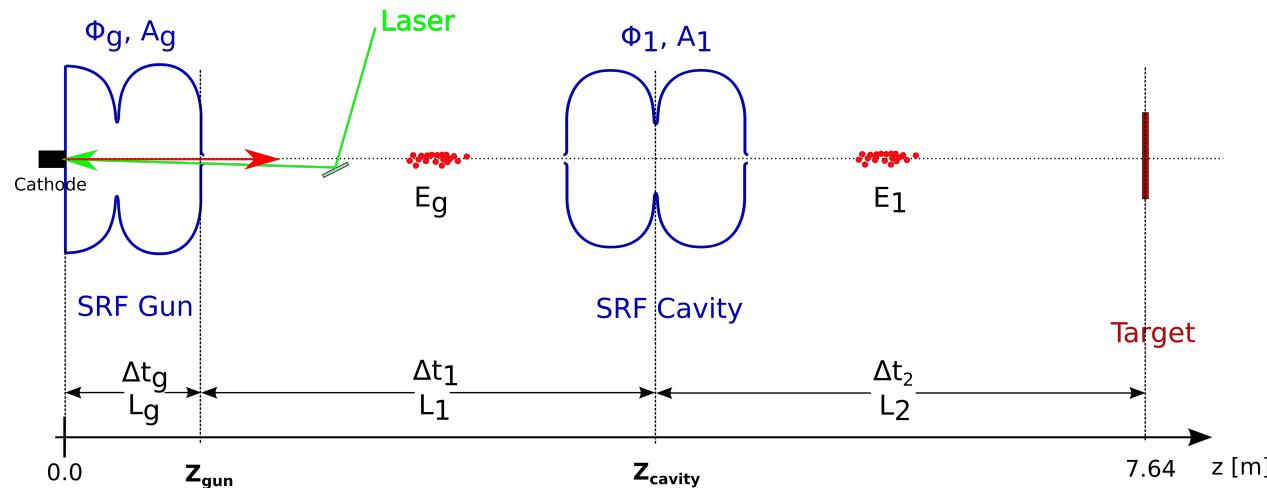


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# TIME OF FLIGHT JITTER - FURTHER CAVITIES



**Energy gain after a booster cavity:**

$$\Delta E \approx A \cos(\phi) = A \cos(\phi_0 + w\Delta t)$$

Where:  $\Delta t = t_g + t_1$

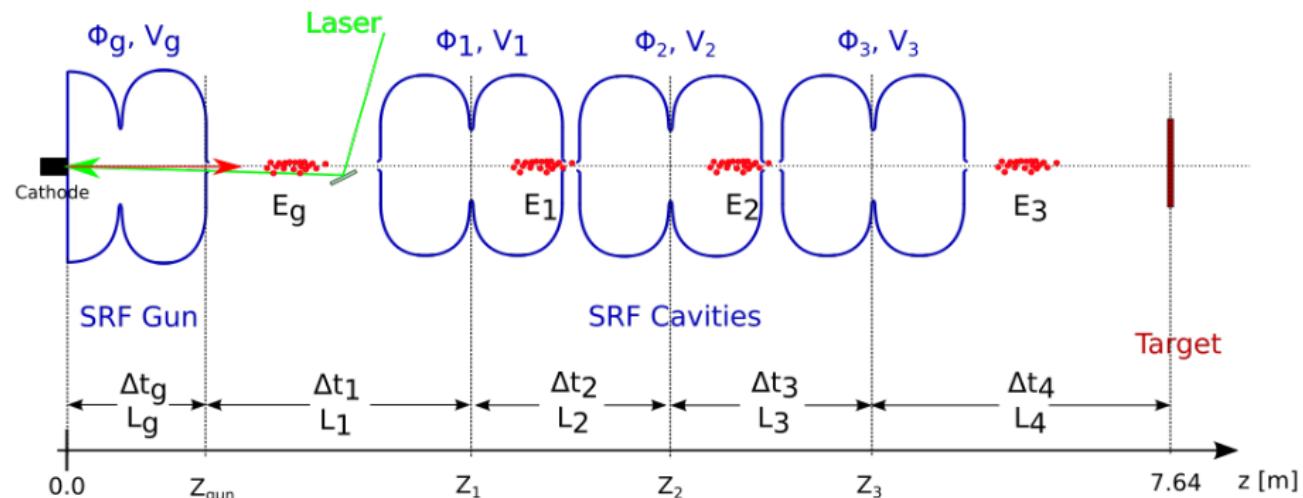
Which depend on the energy at/after the gun.

- One can then calculate  $E_1$ ,  $t_2$  and express the  $ToF = t_g + t_1 + t_2$  as a function of all cavity parameters in the beamline and the previously simulated derivatives of the gun flight time and energy. Then:

$$\sigma_{ToF}^2 = \left( \frac{\partial ToF}{\partial A_g} \right)^2 \sigma_{A_g}^2 + \left( \frac{\partial ToF}{\partial \phi_g} \right)^2 (\omega \sigma_{RL})^2 + \left( \frac{\partial ToF}{\partial \phi_1} \right)^2 \sigma_{\phi_1}^2 + \left( \frac{\partial ToF}{\partial A_1} \right)^2 \sigma_{A_1}^2$$

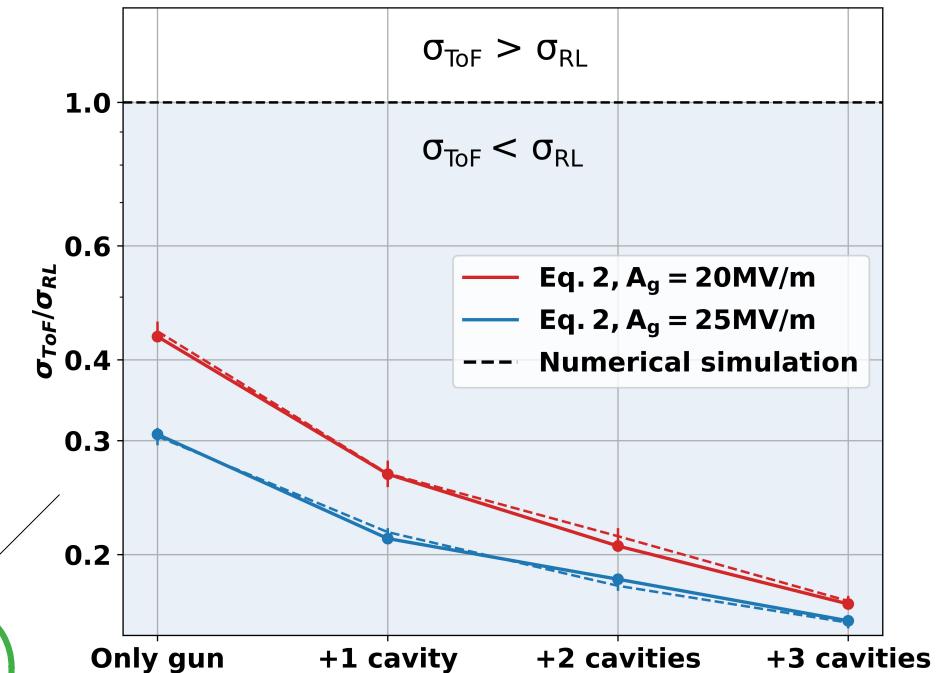
**This can be extended to an arbitrary number of cavities**

# TIME OF FLIGHT JITTER - SRF PHOTONINJECTOR



The minimums are achieved at working points with nearly on-crest gun emission, this suppresses the effect of laser to RF mismatch in the ToF jitter.

Second constraint: Emission close to on-crest!

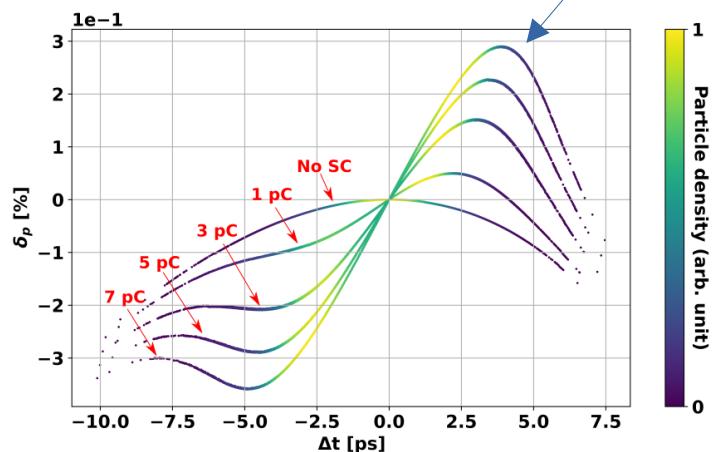
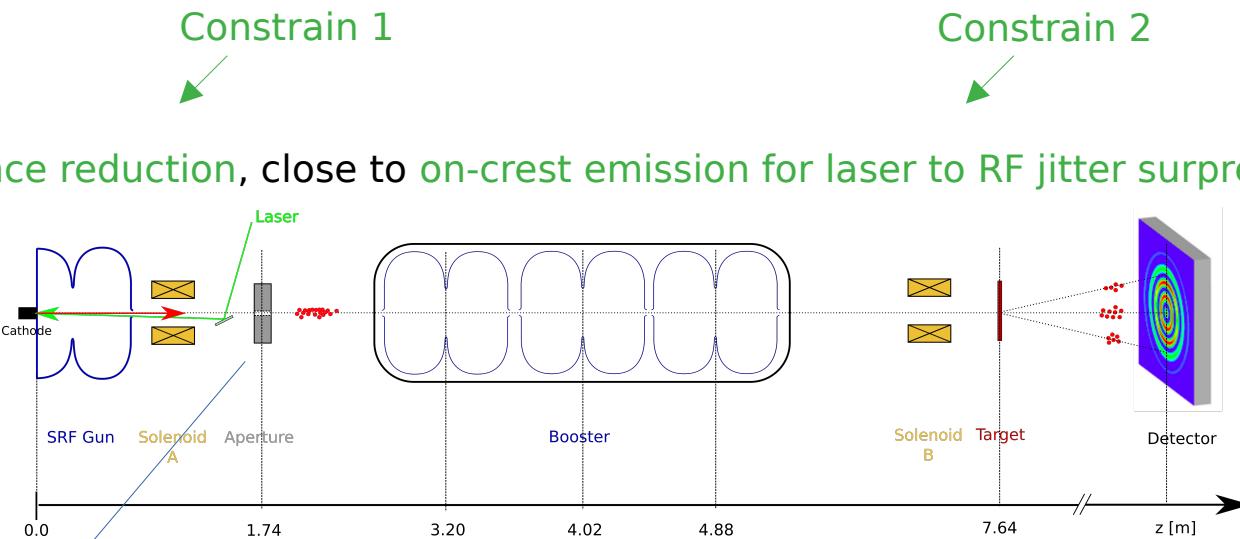


B. Alberdi et al., Sci. Rep. 12, 13365 (2022).

# BUNCH COMPRESSION - SPACE CHARGE

- Space charge plays a big role.
- We want: **Collimation for emittance reduction, close to on-crest emission for laser to RF jitter suppression and compression at the same time!**

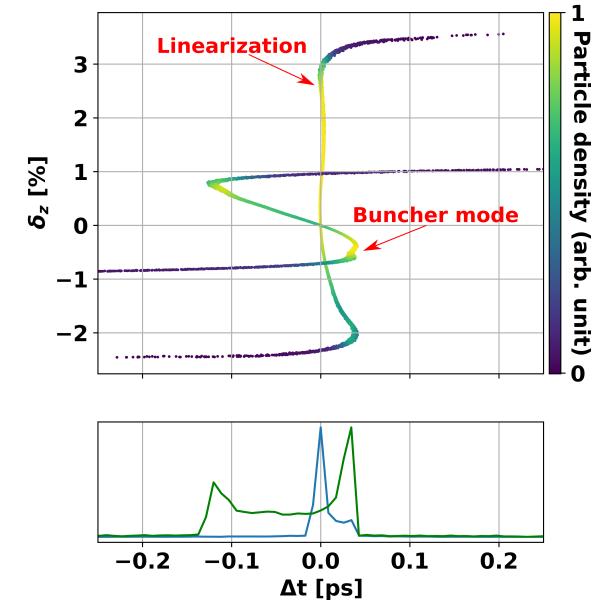
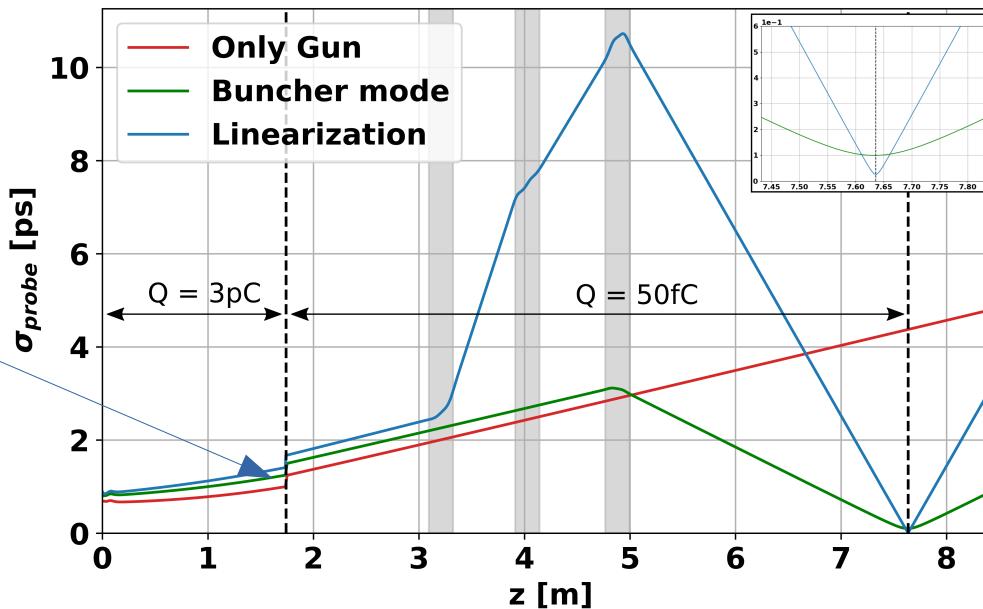
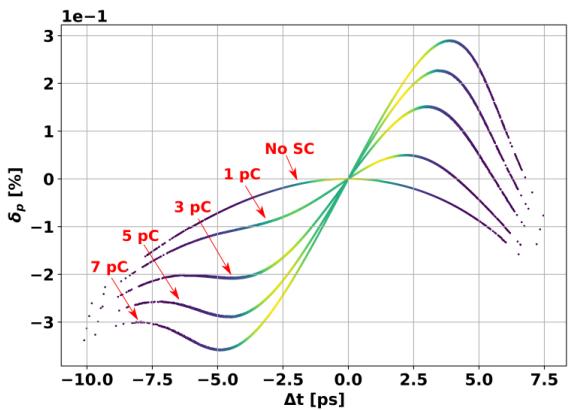
Constrain 3



- The requirement of extracting more charge than necessary leaves its signature in form of longitudinal phase-space curvature.
- We will use the three booster cavities to **correct the longitudinal phase space curvature by linearizing it using the stretcher mode [1]**.

[1] B. Zeitler et al., Phys. Rev. ST Accel. Beams 18, 120102 (2015)

# BUNCH COMPRESSION - LINEARIZATION



B. Alberdi et al., Sci. Rep. 12, 13365 (2022).

The use of the three cavities allows us to emit on-crest and still linearize the bunch at the target, from 1ps → 21fs.

The buncher mode, on the other hand, is limited to 96fs bunch length.

# MOGA OPTIMIZATION OF TIME RESOLUTION

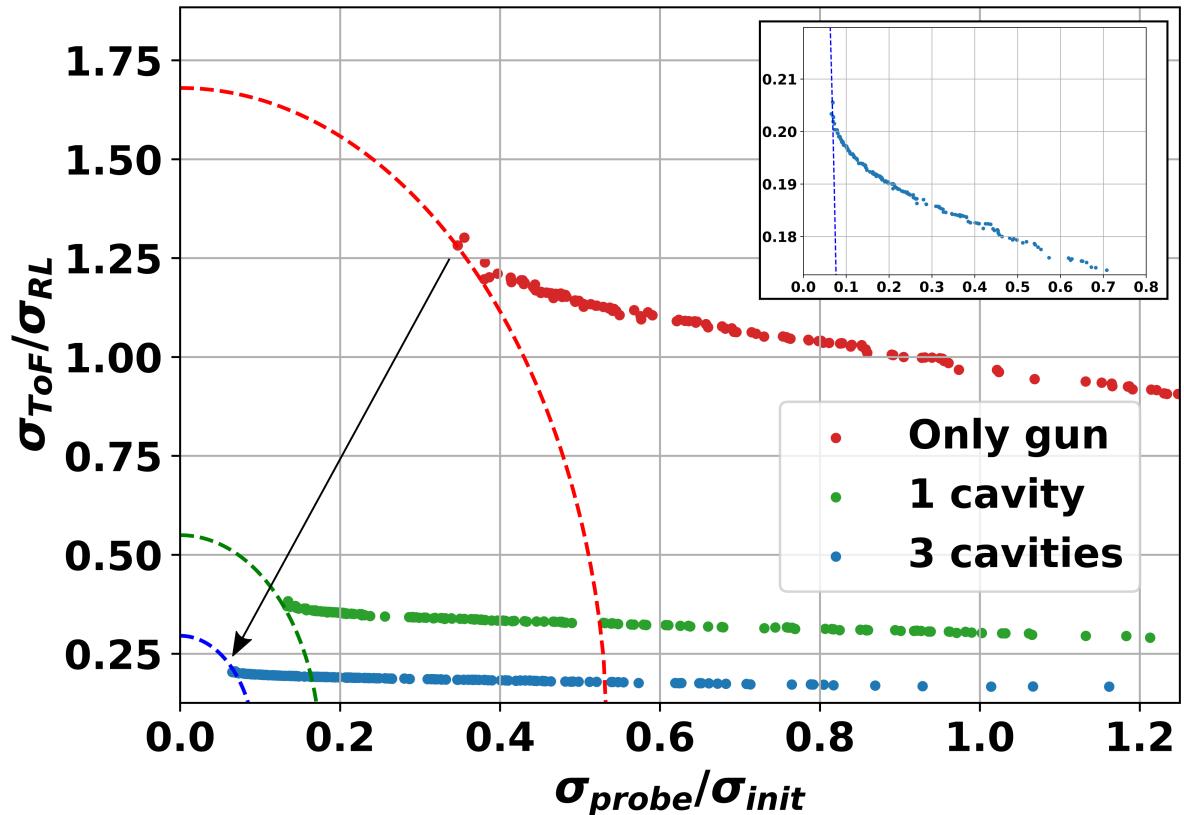
So we have achieved:

- **Emittance reduction**
- **Bunch compression**
- **Laser to RF jitter effect minimization**

However... the linearization requires to use certain working point of the additional cavities which are not beneficial for the ToF jitter. Hence:

- Find trade off: compression  $\leftrightarrow$  ToF jitter
- Find the compromise that reduces the overall time resolution (minimize both together).

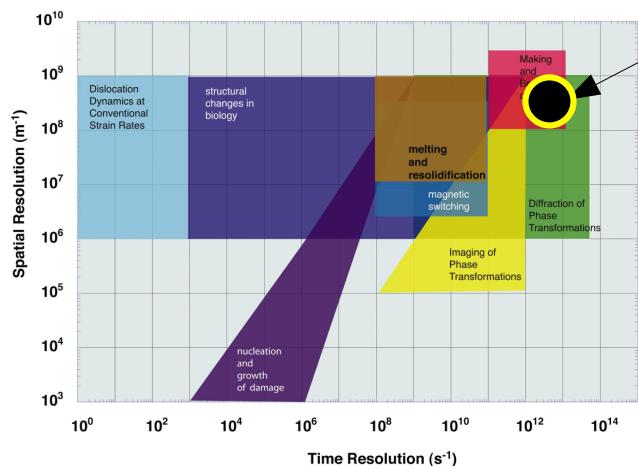
For this we use MOGA algorithms (with constrains for charge, emittance).



B. Alberdi et al., Sci. Rep. 12, 13365 (2022).

# CONCLUSIONS AND SUMMARY

- The best solutions from MOGA result in nearly linearized bunches with low ToF jitter, compromising the total linearization to reduce ToF jitter considerably.
- Even though we have unfriendly UED parameters in the beamline, playing with the RF cavities we get **time resolution of around 100fs (91fs ToF jitter and 43fs bunch length) together with 3 nm spatial resolution → This is a competitive UED machine!**
- The time-resolution is then governed by the phase stability of the additional cavities, which can be reduced with improvements in the LLRF [1]. **A factor 2 improvement in phase stability would bring the time resolution to 60fs**, lower than some dedicated UED facilities [2].



W. E. King et al., J. Appl. Phys. 97, 111101 (2005).

## OUTLOOK:

- Everything shown here are simulations and calculations, this has to be brought to reality.
- Commissioning is ongoing, first beams are expected by 2023.

[1] S. Posen, Phys. Rev. Accel. Beams 25, 042001 (2022).

[2] S. P. Weathersby, Rev. Sci. Instrum 86, 073702 (2015).