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

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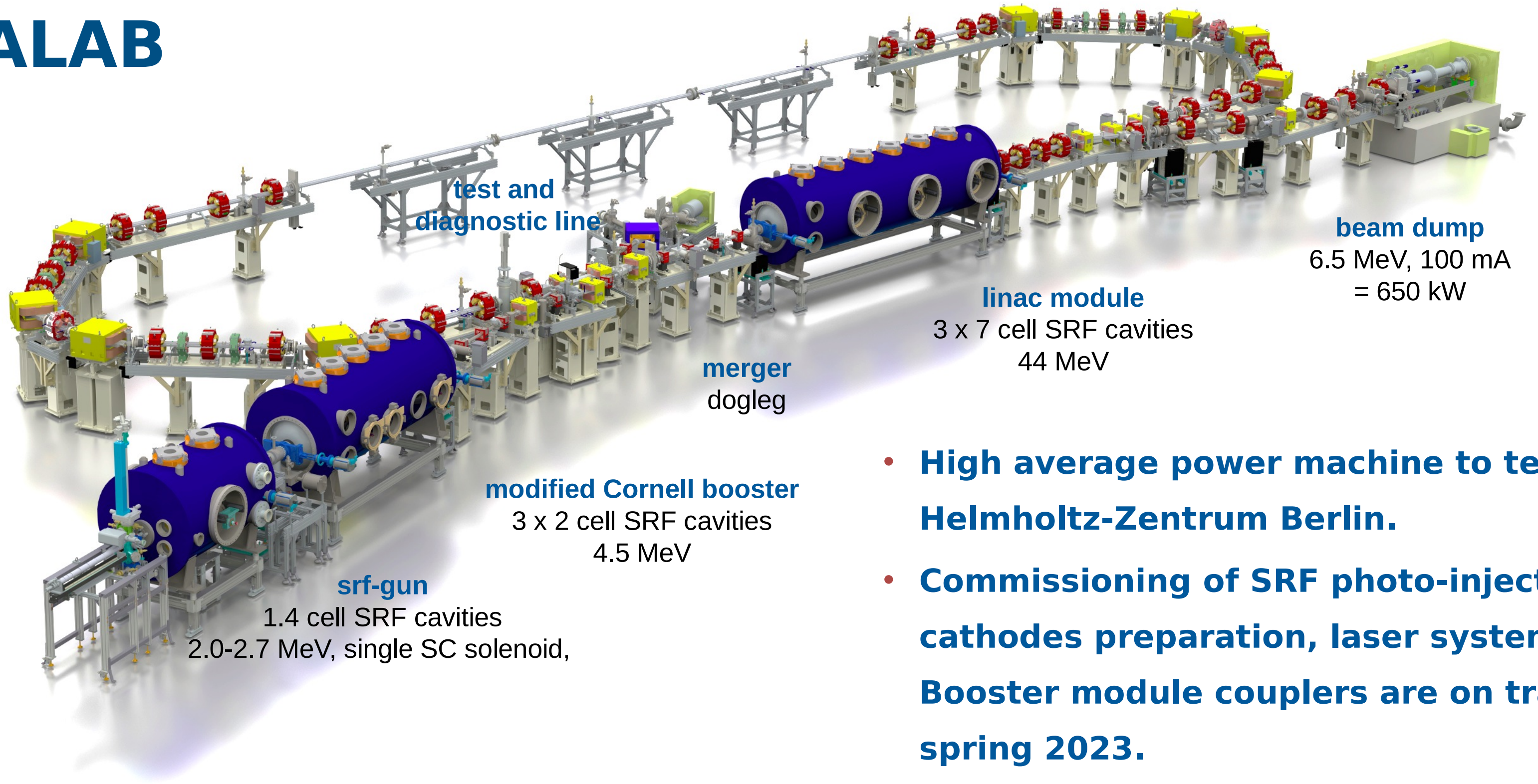
SEALAB

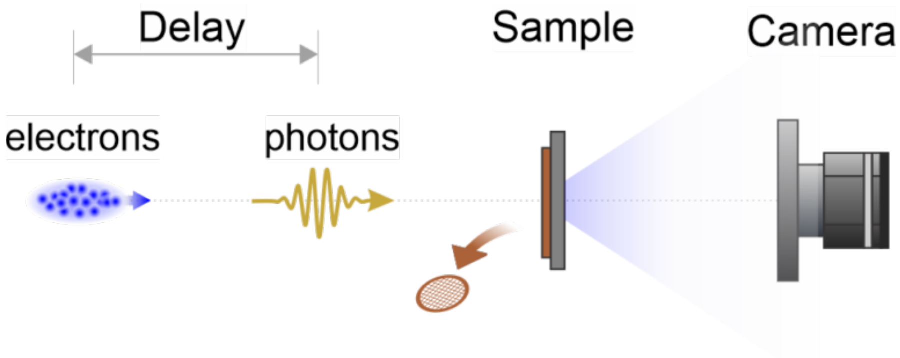


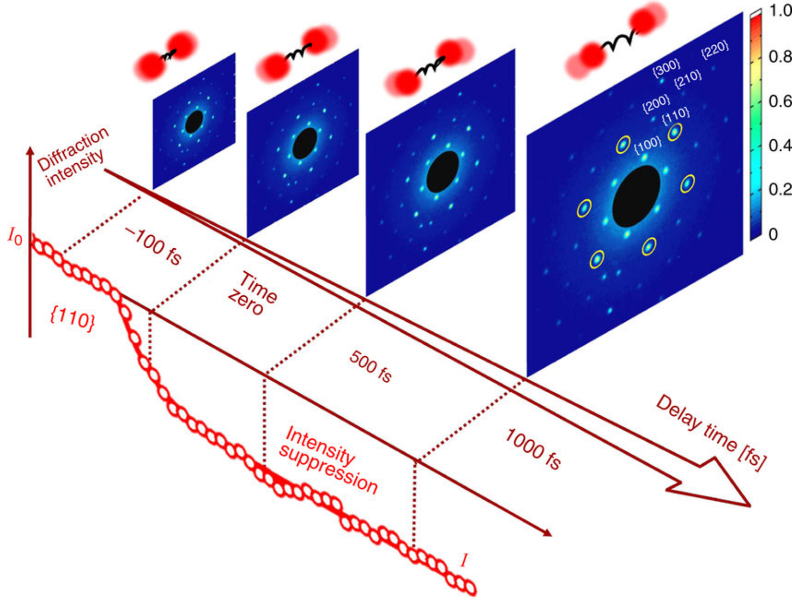
- **High average power machine to test ERL technologies and applications in Helmholtz-Zentrum Berlin.**
- **Commissioning of SRF photo-injector on-going: high quantum efficiency cathodes preparation, laser system, high-power RF conditioning of SRF. Booster module couplers are on track to allow first 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





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

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.

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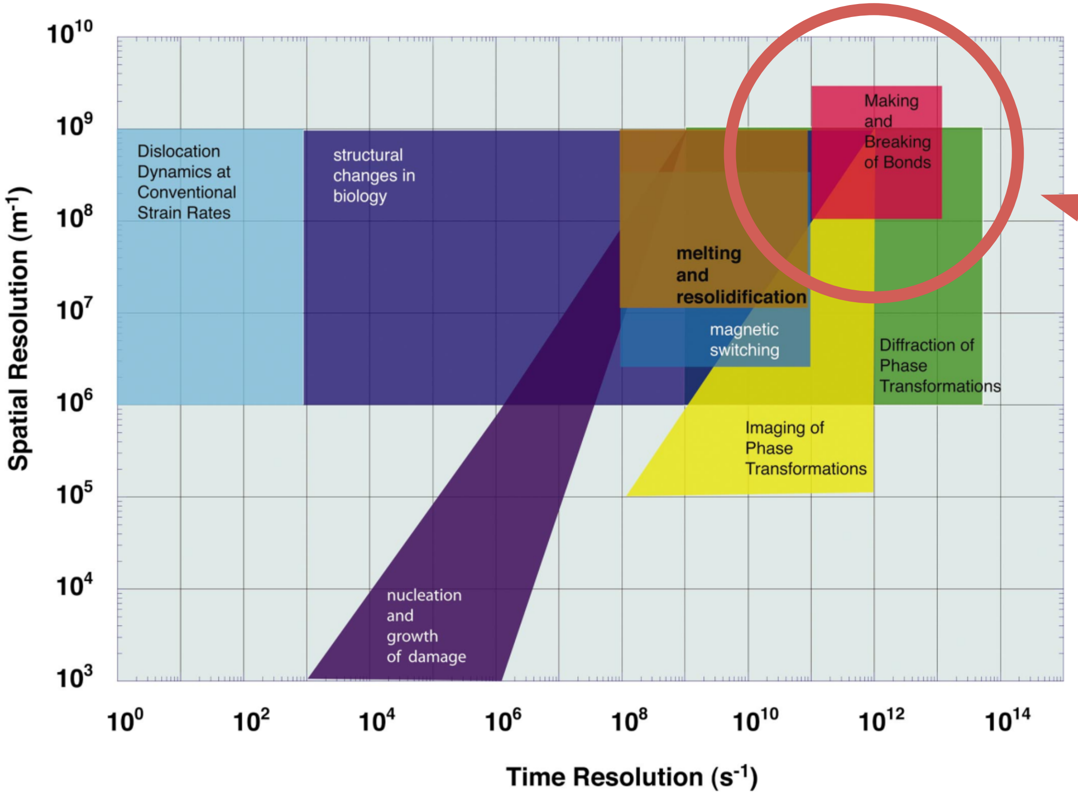
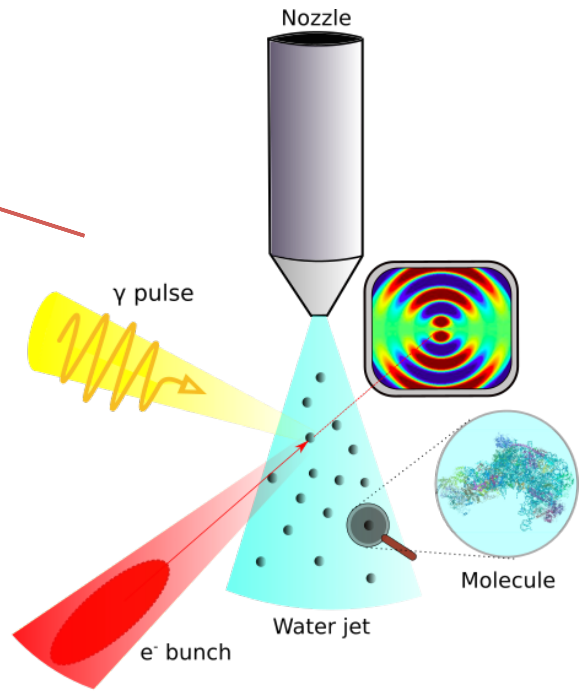
ULTRAFAST ELECTRON DIFFRACTION – GOAL?



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



Needed for molecular UED:

- Spatial resolution > 10^8 m^{-1}.

$$\epsilon_{n,\perp} \sim 10\text{nm} - \text{rad}$$

- Time resolution > 10^{13} 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

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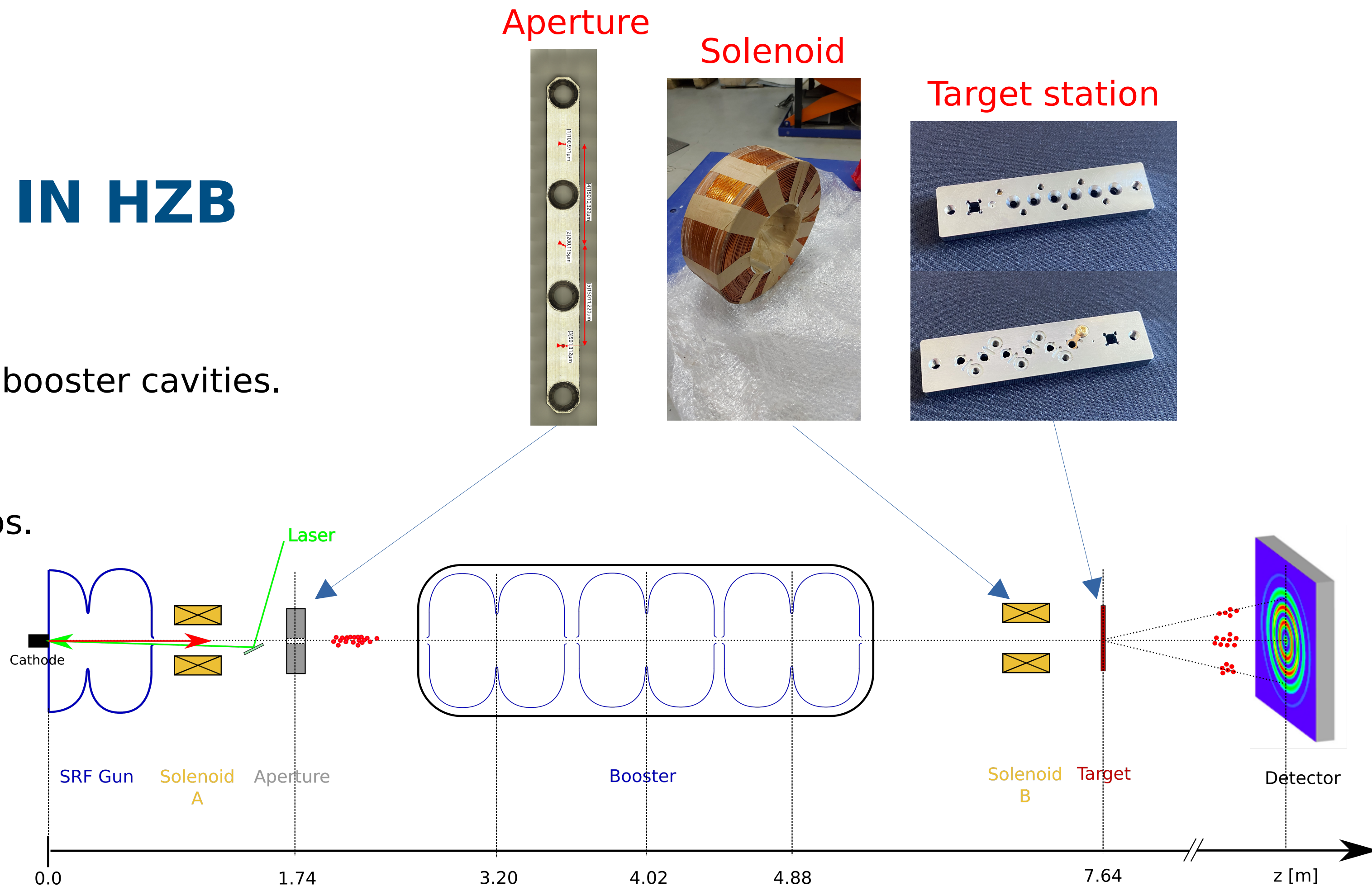
THE SRF PHOTOINJECTOR IN HZB

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.



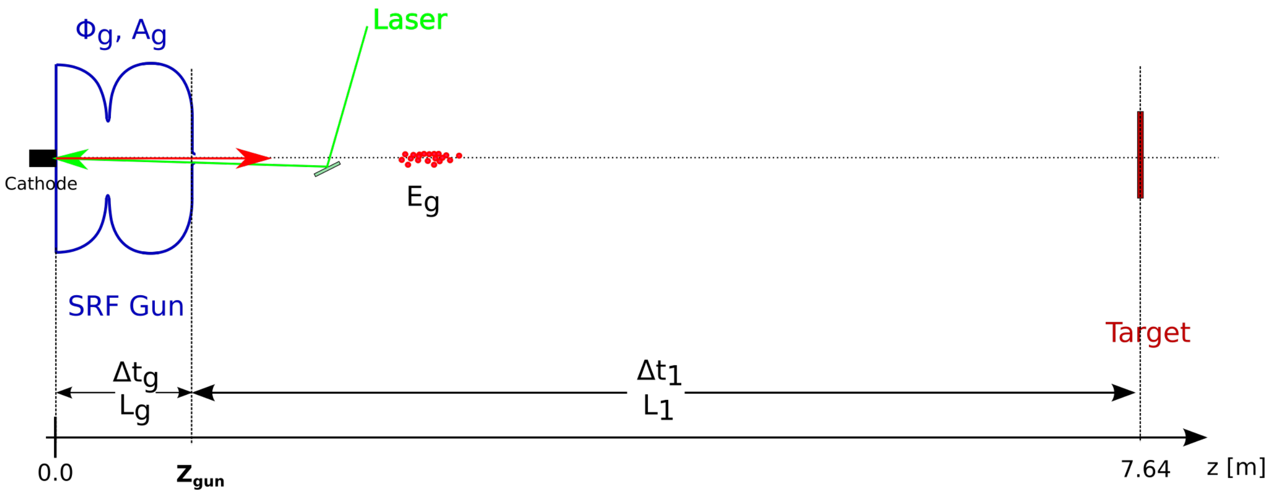
Not every parameter is ideal for UED!!

- 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	$\sim 6\,\mathrm{MeV}$	$\sim 3\,\mathrm{MeV}$
Q_{bunch}	77 pC	50 fC
$\Delta t_{\mathrm{bunch}}$	ps	fs
$\epsilon_{\perp,n}$	µm rad	nm rad
Repetition rate	1 MHz	1 MHz

TIME OF FLIGHT JITTER



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	σ_L
RF Phase [°]	0.05	σ_ϕ
RF Amplitude	$1 \times 10^{-4} \cdot \mathrm{V}$	σ_A

Timing jitters in the gun can be combined:

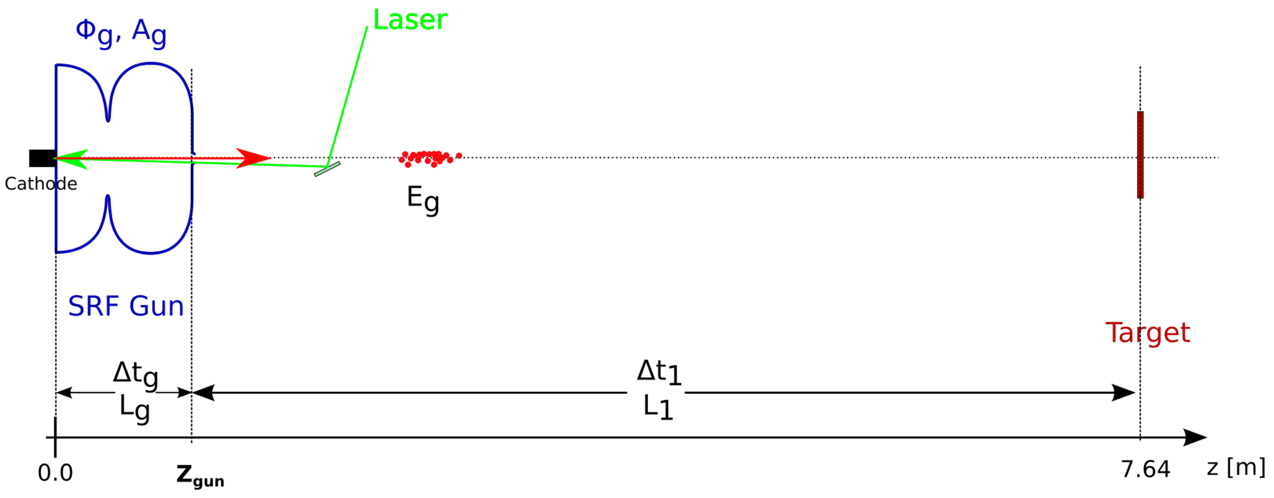
$$\sigma_{RL} = \sqrt{(\sigma_\phi/w)^2 + \sigma_L^2} \sim 320\text{fs}$$

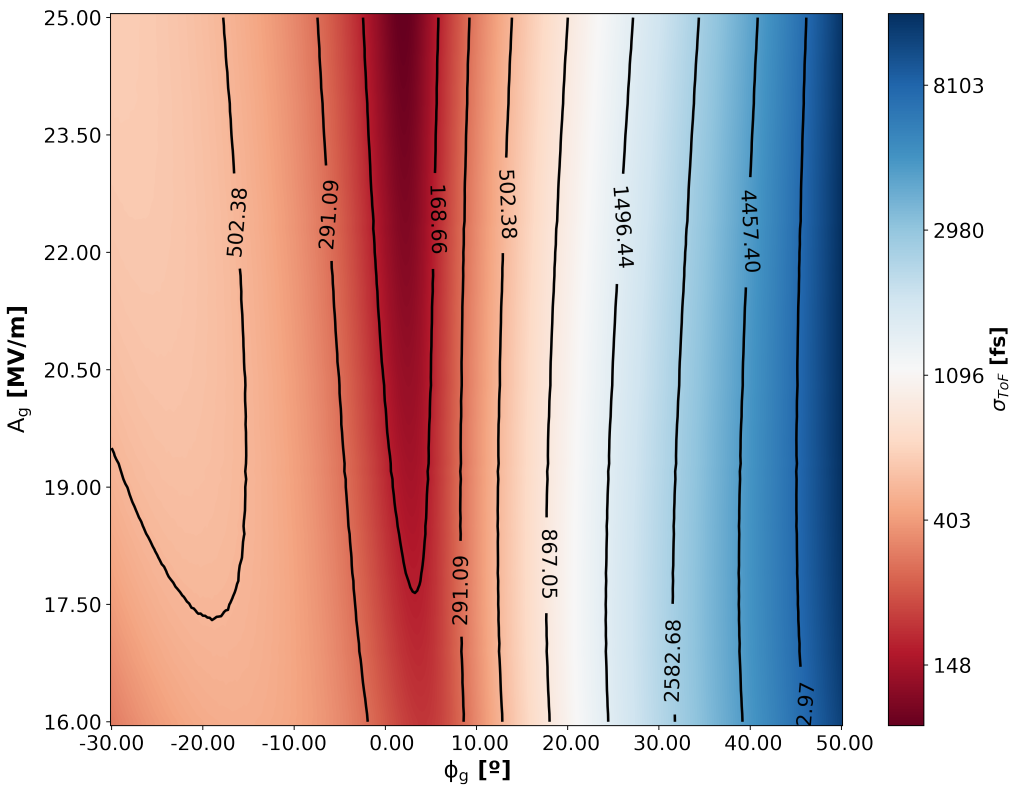
We develop an analytical model of the time of flight jitter:

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

$$\sigma_{ToF}^2 = \left(\frac{\partial t_g}{\partial A_g} - \frac{L_1}{m_0c^3(\gamma_g^2 - 1)^{3/2}}\left(\frac{\partial E_g}{\partial A_g}\right)\right)^2 \sigma_{A_g}^2 + \left(\frac{\partial t_g}{\partial \phi_g} - \frac{L_1}{m_0c^3(\gamma_g^2 - 1)^{3/2}}\left(\frac{\partial E_g}{\partial \phi_g}\right)\right)^2 (\omega\sigma_{RL})^2$$

TIME OF FLIGHT JITTER





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

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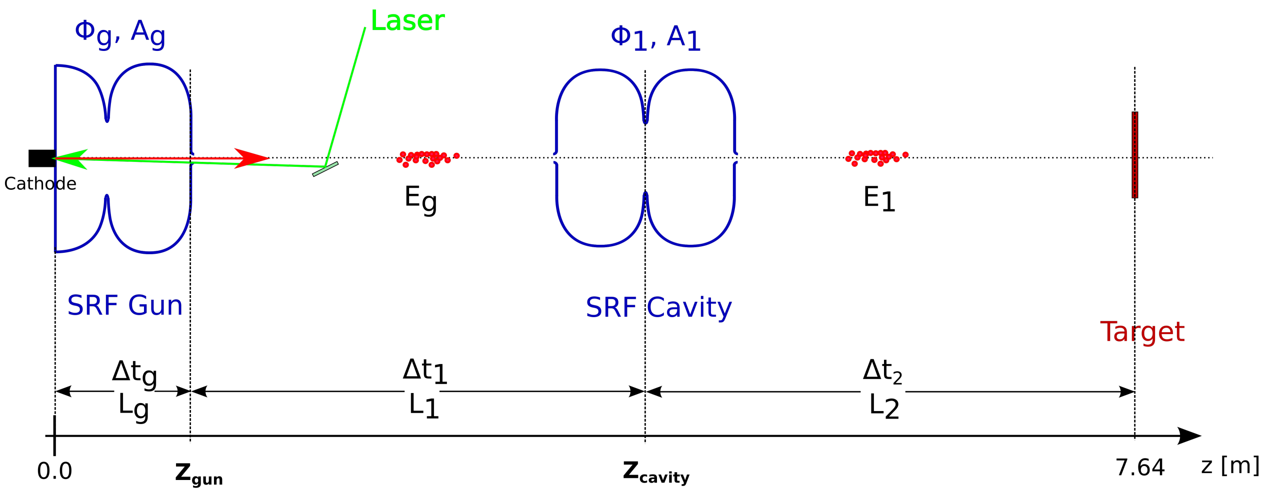
TIME OF FLIGHT JITTER – FURTHER CAVITIES



Energy gain after a booster cavity:

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

Where: $\Delta t = t_g + t_1$

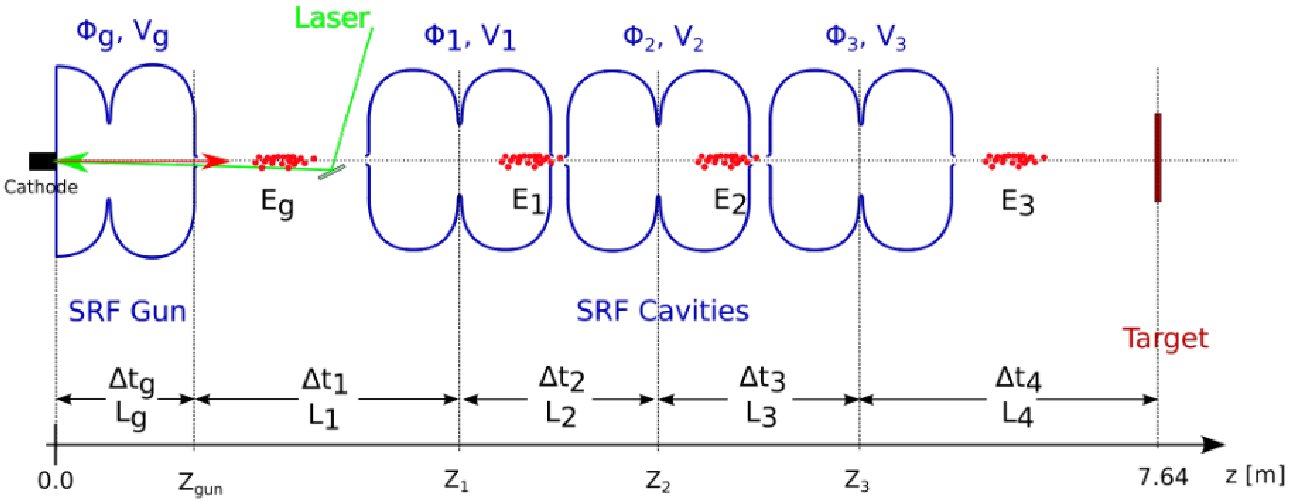
Which depend on the energy at/after the gun.

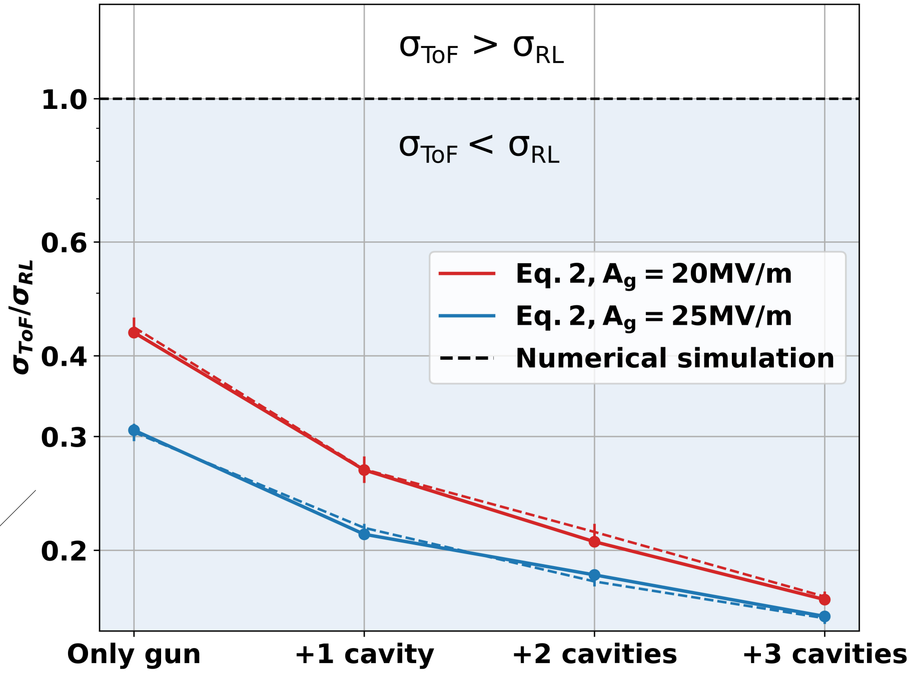
- One can then calculate E_1, t_2 and express the ToF = $t_g + t_1 + t_2$ as a function of all cavity parameters in the beamline and the previously simulated derivatives of the gun flight time and energy. Then:

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

This can be extended to an arbitrary number of cavities

TIME OF FLIGHT JITTER – SRF PHOTOINJECTOR





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

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

Second constraint: Emission close to on-crest!

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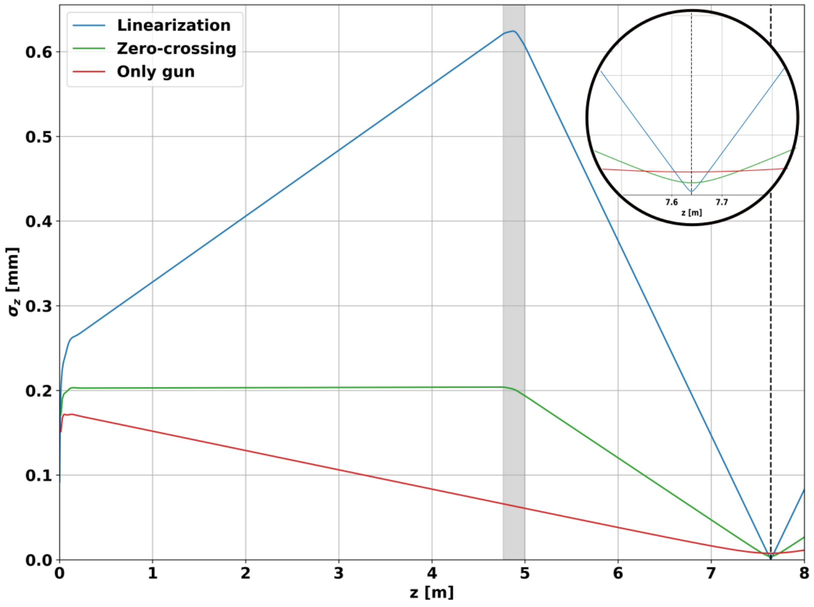
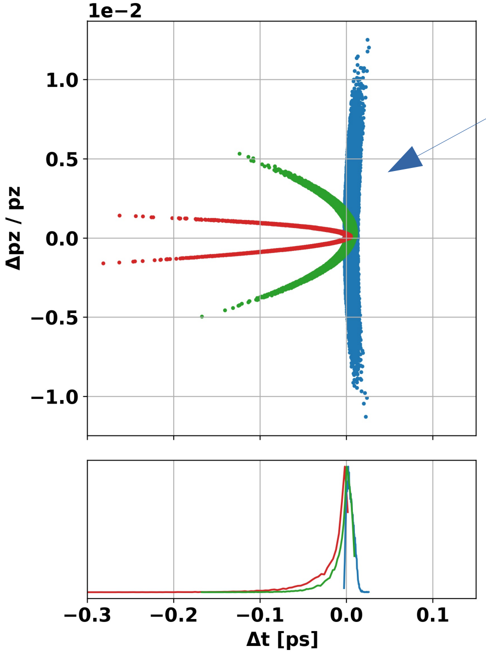
BUNCH COMPRESSION – NO SPACE CHARGE

First, study a very simple case to achieve the shortest bunch possible at the target.

- Initial condition is 1ps laser pulse at the cathode, no space-charge forces for the moment.





Linearization [1] using stretcher mode provides the shortest bunch at target.

	Gun		Booster cav.		Target @ 7.64 m	
	ϕ_g [°]	A_g [MV m^{-1}]	ϕ_b [°]	A_b [MV m^{-1}]	τ_{bunch} [fs]	τ_{jitter} [fs]
Direct compression	-7.41	20.0	X	X	26.7	354.8
Zero crossing	0.0	20.0	0.0	4.09	14.2	120.47
Linearization	14.5	20.0	-32.11	4.48	4.2	228.2

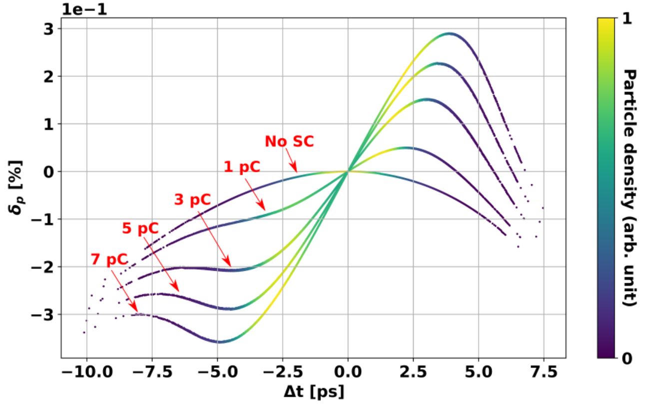
However, the emission from the gun needs to be done far from the on-crest phase, which increases the ToF jitter → We want to emit close to on-crest!

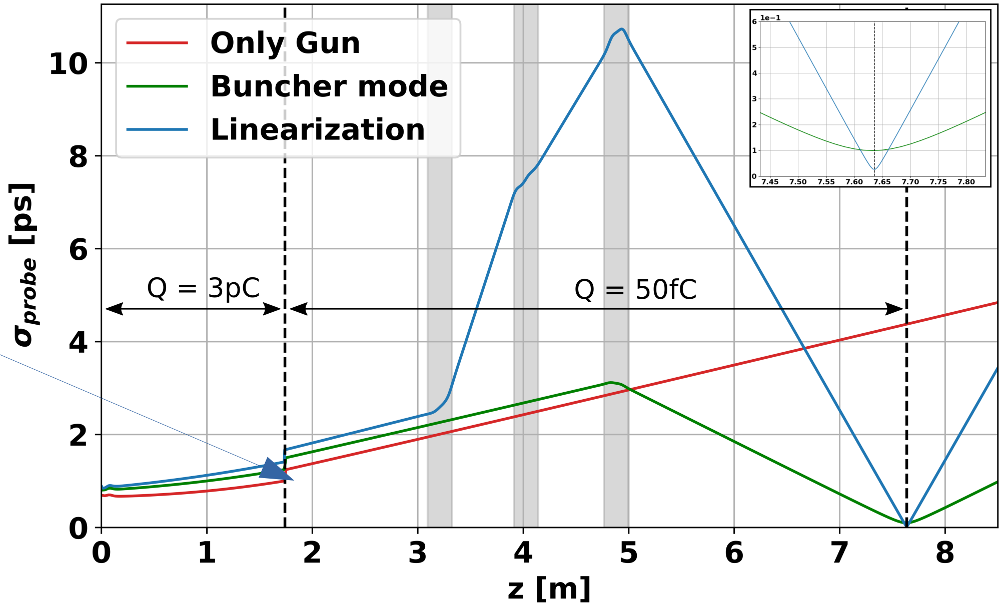
[1] B. Zeitler et al., Phys. Rev. ST Accel. Beams 18, 120102 (2015)

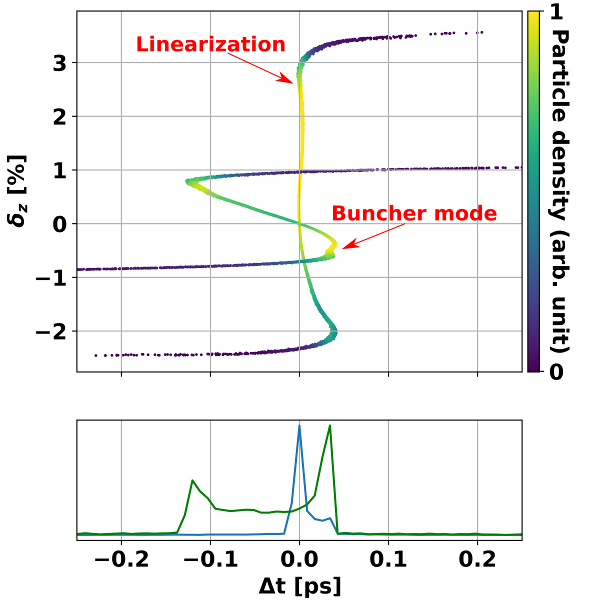
BUNCH COMPRESSION – SPACE CHARGE

Constrain 1 Constrain 2 Constrain 3

- Space charge is added now.
- We want: Collimation for emittance reduction, close to on-crest emission for jitter surpression and compression at the same time!







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

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MOGA OPTIMIZATION OF TIME RESOLUTION

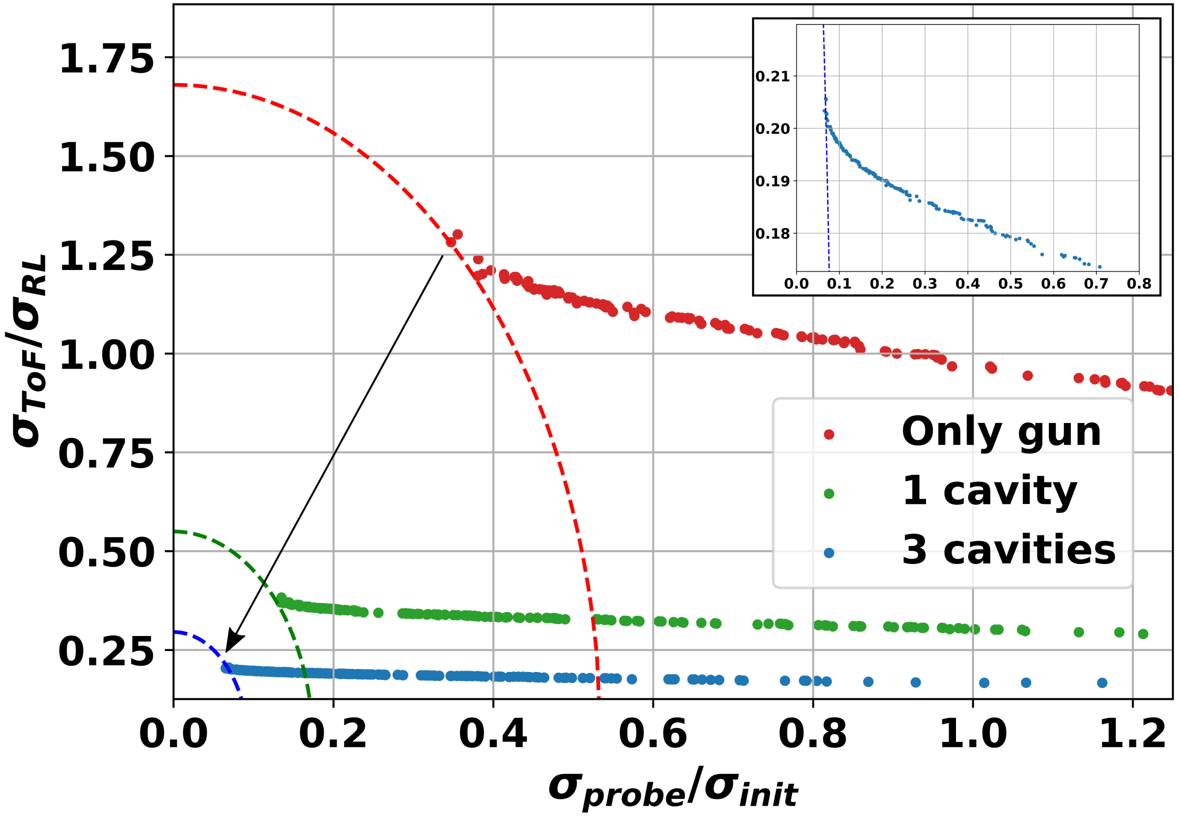
So we have achieved:

- **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 benefitial for the ToF jitter. Hence:

- Find trade off: compression ↔ ToF jitter
- Find the compromise that reduces the overal 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).

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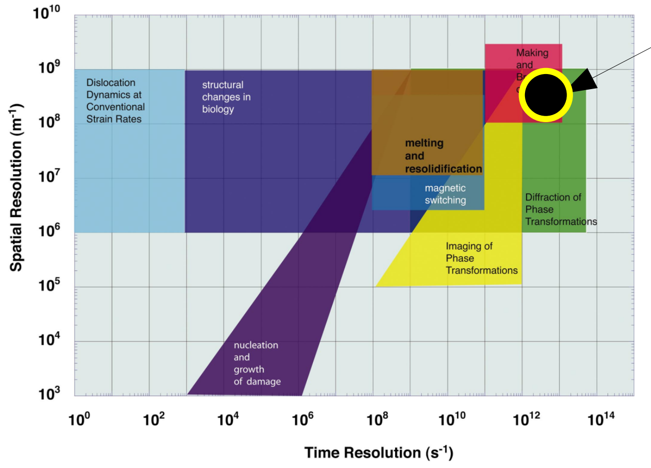
CONCLUSIONS AND SUMMARY

- 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].

!



We are here!

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.
- Commisioning 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).