Efficient treatment of steady state and transient beam loading in electron linacs

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INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

Outline

- Motivation
- Steady-state beam loading for TW electron linacs
  - The Hellweg code – reduced model provides accuracy with 1000x speedup
    `https://github.com/radiasoft/rshellweg`
  - Applications and code validation
    - also see "High Efficiency Traveling Wave Linac," V. Dolgashev *et al.* (this workshop)
  - Coupled particle-field equations, including recent developments
- Proposed developments *(pending with DOE/HEP)*
  - Support of standing wave RF structures
  - Support for transient beam loading
  - Apply to transient beam loading challenges at the Argonne Wakefield Accelerator
  - Support a community resource for industry, science and education

    The Sirepo scientific gateway, `https://www.sirepo.com`
    - beta test program for Sirepo – Hellweg should begin soon
- Conclusion

Motivation

As noted in a recent e+e- collider report [1], "Electron-Positron colliders have the potential to span particle physics from precision electroweak measurements to discoveries at the Energy Frontier." The two-beam accelerator (TBA) is one of two primary concepts for the structure wakefield acceleration approach to an e+e- collider [1, 2]. Transient beam loading effects are a significant challenge for the drive beam in a TBA structure, where energy droop in roughly 50 nC electron bunch trains must be understood and compensated. This problem is being studied at the Argonne Wakefield Accelerator (AWA) (https://www.anl.gov/awa), where new algorithmic approaches are being pursued.

[1] M. C. Llatas et al. *Report of the Snowmass 2021 e^+e^--Collider Forum*. 2022. arXiv: 2209.03472 [hep-ex].

[2] C. Jing et al. *Continuous and Coordinated Efforts of Structure Wakefield Acceleration (SWFA) Development for an Energy Frontier Machine*. 2022. arXiv: 2203.08275 [physics.acc-ph].

Cross-Frontier Report Submitted to the US Community Study on the Future of Particle Physics (Snowmass 2021)

Report of the Snowmass 2021 e^+e^--Collider Forum

Maria Chamizo Llatas, Sridhara Dasu, Ulrich Heintz, Emilio A. Nanni, John Power, Stephen Wagner

September 9, 2022

Hellweg – TW linacs

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Linear accelerator for security, industrial and medical applications with rapid beam parameter variation

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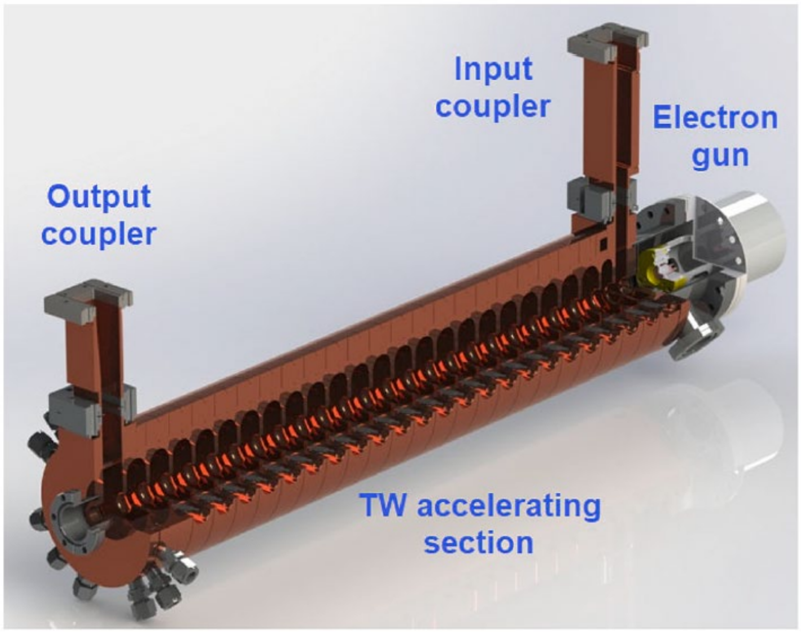
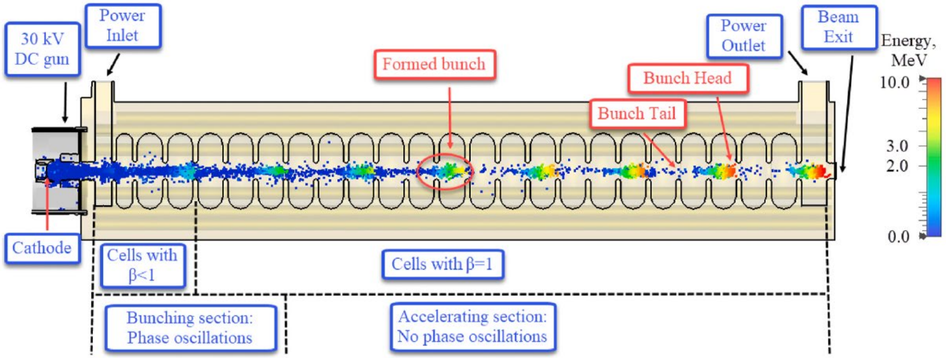


Fig. 3. Engineering design of a TW disk-loaded waveguide for the FLEX linac.

S. V. Kutsaev et al. "Linear Accelerator for Security, Industrial and Medical Applications with Rapid Beam Parameters Variation". In: *Radiat. Phys. Chem.* 183 (2021), p. 109398.



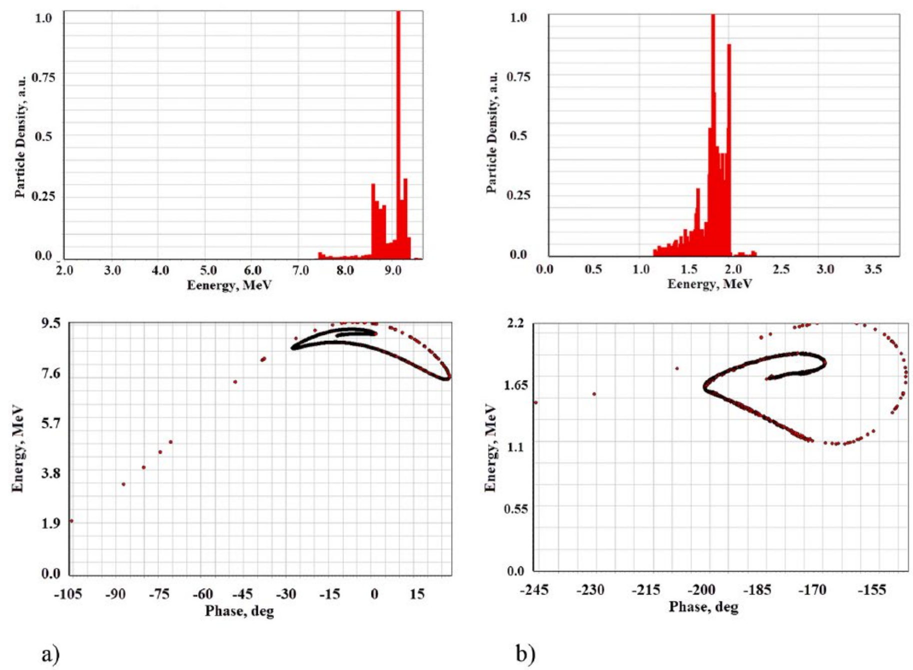


Fig. 4. Energy spectra (top) and phase portraits (bottom) of 9 MeV (a) and 2 MeV (b) bunches, simulated in Hellweg (Kutsaev, 2010; Kutsaev et al., 2019b). Note that 2 MeV bunch is in decelerating phase.

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Cloud-based design of high average power traveling wave linacs

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Hellweg is 1000x faster than CST

Table 1. Comparison of Hellweg and CST simulations.

Code	Hellweg	CST
Input current	250 mA	250 mA
Output current	124 mA	115 mA
Beam energy	9.6 MeV	9.2 MeV
Input power	4.6 MW	4.6 MW
Output power	1.73 MW	1.72 MW
Simulation time	~30 sec	~8 hrs

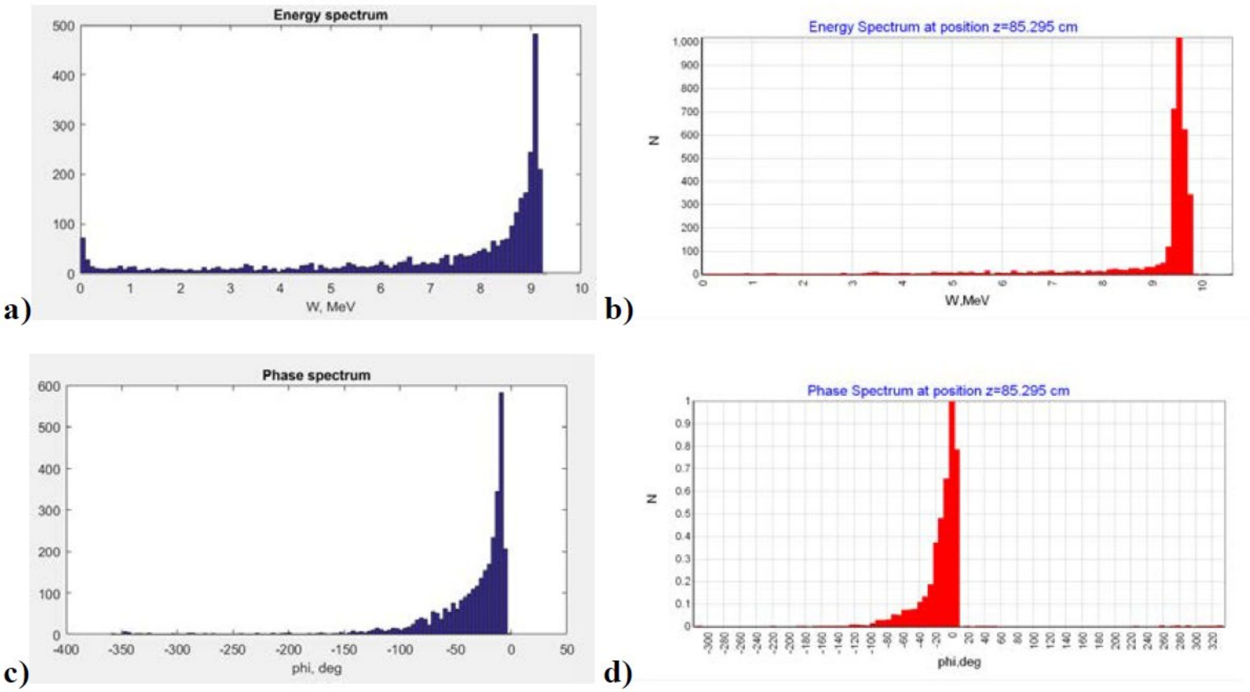

Figure 2. The simulated beam energy (a, b) and phase (c, d) spectra is presented, as generated by two codes: CST Particle Studio (a, c) and Hellweg (b, d)

Handheld MeV linac

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journal homepage: www.elsevier.com/locate/apradiso

Check for updates

Ir-192 radioisotope replacement with a hand-portable 1 MeV Ku-band electron linear accelerator

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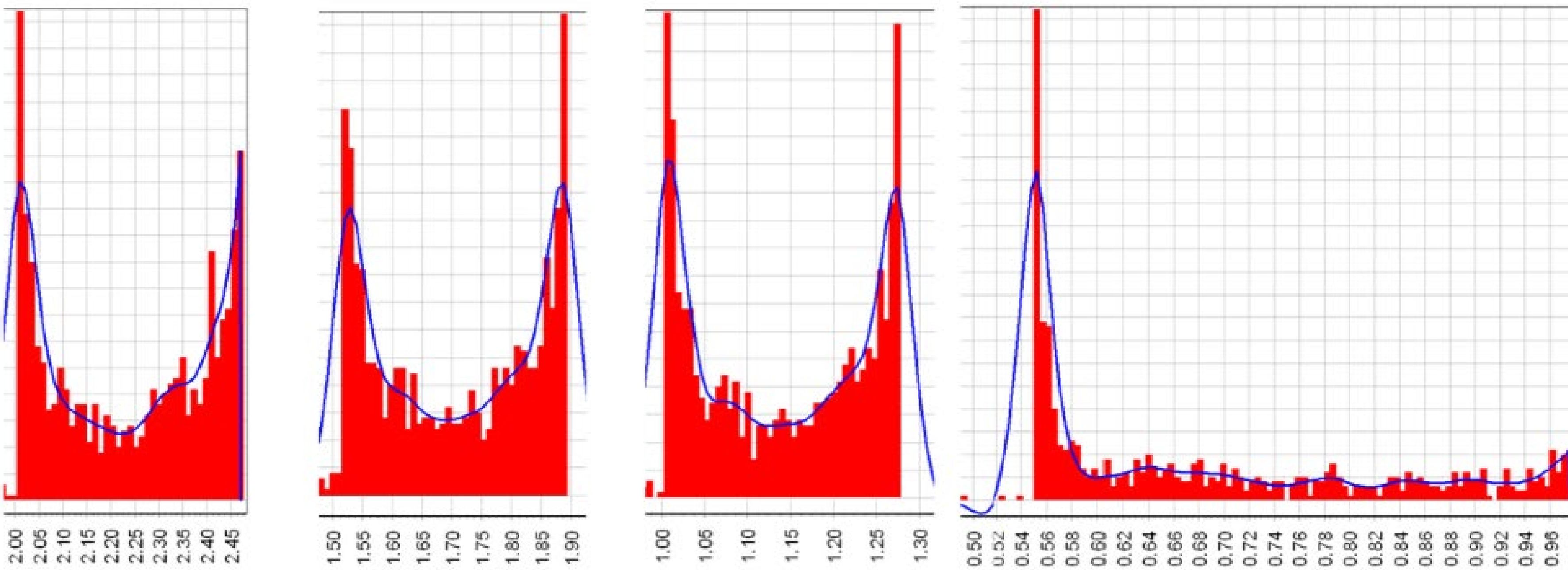

Fig. 9. The energy spectrum of the accelerated beam is shown for the nominal 2 MeV linac design, as the gun current is increased from 10 mA to 750 mA. The spectra (from left to right) correspond to the energies of 2.45 to 0.55.

The 3D Hellweg equations of motion

$$\frac{d\beta_\zeta}{d\zeta} = \frac{1}{\gamma\beta_\zeta}\Big[(1-\beta_\zeta^2)A_\zeta + \beta_\eta\left(H_\theta - \beta_\zeta A_\eta\right) - \beta_\theta\left(H_\eta + \beta_\zeta A_\theta\right) + \beta_\eta H_\theta^{ext} - \beta_\theta H_\eta^{ext}\Big]$$

$$\frac{d\beta_\eta}{d\zeta} = \frac{1}{\gamma\beta_\zeta}\Big[(1-\beta_\eta^2)A_\eta + \beta_\theta\left(H_\zeta - \beta_\eta A_\theta\right) - \beta_\zeta\left(H_\theta + \beta_\eta A_\zeta\right) + \beta_\theta H_\zeta^{ext} - \beta_\zeta H_\theta^{ext}\Big] + \frac{\beta_\theta^2}{\eta\beta_\zeta}$$

$$\frac{d\beta_\theta}{d\zeta} = \frac{1}{\gamma\beta_\zeta}\Big[(1-\beta_\theta^2)A_\theta + \beta_\zeta\left(H_\eta - \beta_\theta A_\zeta\right) - \beta_\eta\left(H_\zeta + \beta_\theta A_\eta\right) + \beta_\zeta H_\eta^{ext} - \beta_\eta H_\zeta^{ext}\Big] - \frac{\beta_\theta\beta_\eta}{\eta\beta_\zeta}$$

$$\frac{dA}{d\zeta} = A\left\{\frac{1}{2}\frac{d}{d\zeta}\left(\ln R_b - w\right)\right\} - \frac{2B}{N}\sum_{n=1}^{N} I_0\left(\frac{2\pi}{\beta_{ph0}}\sqrt{1-\beta_{ph0}^2}\,\eta_n\right)\cos\psi_n$$

$$\frac{d\psi}{d\zeta} = 2\pi\left(\frac{1}{\beta_{ph0}} - \frac{1}{\beta_\zeta}\right) + \frac{2B}{AN}\sum_{n=1}^{N} I_0\left(\frac{2\pi}{\beta_{ph0}}\sqrt{1-\beta_{ph0}^2}\,\eta_n\right)\sin\psi_n$$

$$A = \frac{E\lambda}{W_o}$$

$$H = c\frac{B\lambda}{W_o}$$

E. S. Masunov. "Bunching and Acceleration of the Intensive Beam in the Waveguide Accelerating Structure with a Presence of an External Magnetic Field". In: *Journal of Technical Physics* 49 (1979), p. 1462.

S. V. Kutsaev. "Electron dynamics simulations with Hellweg 2D code". In: *Nuclear Instruments and Methods in Physics Research* 618 (2010), pp. 298–305.

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Y. Eidelman, D. L. Bruhwiler, and S. V. Kutsaev. "Ellipsoid space charge model for electron beam dynamics simulations". In: *Phys. Part. Nucl.* 52 (2021), p. 477.

Hellweg dynamics – using momentum rather than velocity

$$\frac{d(\gamma\beta_z)}{d(z/\lambda)} = \frac{Z}{M}\frac{1}{\gamma\beta_z}\left[\gamma\tilde{E}_z + (\gamma\beta_r)\tilde{B}_\theta - (\gamma\beta_\theta)\tilde{B}_r\right]$$

$$\frac{d(\gamma\beta_r)}{d(z/\lambda)} = \frac{(\gamma\beta_\theta)^2}{(r/\lambda)\gamma\beta_z} + \frac{Z}{M}\frac{1}{\gamma\beta_z}\left[\gamma\tilde{E}_r + (\gamma\beta_\theta)\tilde{B}_z - (\gamma\beta_z)\tilde{B}_\theta\right]$$

$$\frac{d(\gamma\beta_\theta)}{d(z/\lambda)} = -\frac{(\gamma\beta_r)(\gamma\beta_\theta)}{(r/\lambda)\gamma\beta_z} + \frac{Z}{M}\frac{1}{\gamma\beta_z}\left[\gamma\tilde{E}_\theta + (\gamma\beta_z)\tilde{B}_r - (\gamma\beta_r)\tilde{B}_z\right]$$

$$Z \equiv q/|e| \qquad M \equiv m/m_e$$

$$\tilde{E}_\alpha = \frac{|e|\lambda}{m_e c^2}E_\alpha \quad and \quad \tilde{B}_\alpha = \frac{|e|\lambda}{m_e c^2}cB_\alpha$$

$$\gamma = \left(1 + (\gamma\beta_r)^2 + (\gamma\beta_\theta)^2 + (\gamma\beta_z)^2\right)^{1/2}$$

- Momentum as the dynamic variable
  - necessary for ultra-relativistic electrons
- Arbitrary charge-to-mass (ion linacs)
  - structure details must be considered
- Other algorithmic aspects unchanged
  - coupling to fundamental field mode
  - ellipsoidal 'frozen' space charge model
  - 4th-order Runge-Kutta
- Benchmarking with previous version
  - complete

HELLWEG IMPROVEMENTS FOR 3D TRAVELING WAVE LINAC DESIGN WITH BEAM LOADING *

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....to appear in Proc. IPAC (2023)

Support of standing wave RF structures *(proposed)*

- TW particle-field dynamics is largely applicable to SW linacs; however…
  - need to include the discrete jump in phase between adjacent cells
  - of course, the RF transit-time factor must be included
  - also, power attenuation is very different
- Benchmarking with CST is planned

$$T = \frac{\left|\int E_z e^{ik_z z} dz\right|}{\left|\int E_z dz\right|}$$

$$\Delta W = q \int_L E_z(r,z)dz = q \sum_{m=-\infty}^{\infty} B_m(r) \int_L \cos\left[\frac{2\pi}{L}(k-m)z + \phi_0\right] dz$$

$$\int_L \cos\left[\frac{2\pi}{L}(k-m)z + \phi_0\right] dz = \begin{cases} L\cos\phi \; for \; m = k \; , \\ 0 \; for \; m \neq k \; , \end{cases}$$

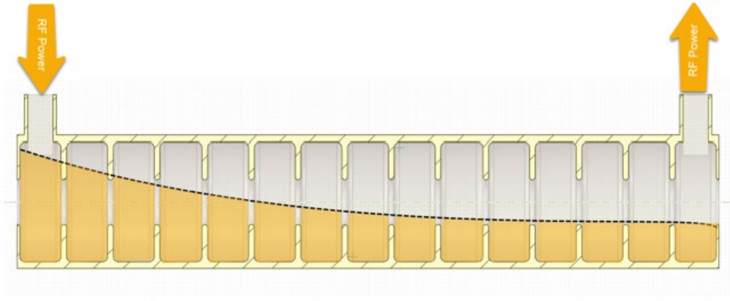


Figure 1: Power distribution mechanism in TW structures.

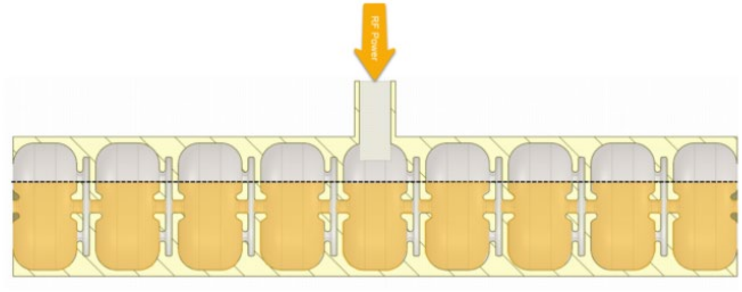
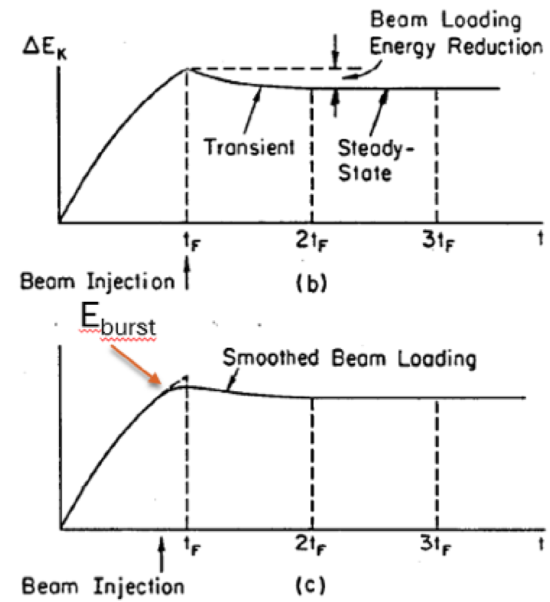


Figure 2: Power distribution mechanism in SW structures.

Support for transient beam loading *(proposed)*

- Transient effects persist for an RF filling time t_F
  - equally true for TW and SW structures
  - time-dependent correction factor will be applied
    - factor roughly tracks the function describing fill time
    - equations well known, but details vary with structure
- Compensation of transient beam loading
  - TW linac operators partially compensate the problem
    - see figure to the right →
  - in SW structures, all cavities are simultaneously loaded
    - transient effects are significant in AWA drive linac
    - 8 bunch train with ~50 nC
    - one thought: bunch-to-bunch variation of RF phase
- Extensive benchmarking with CST will be required!
- Validation via comparison with AWA experiments will also be necessary



Hellweg as an open source framework *(proposed)*

- Software development goals
  - support both Windows and Linux users
  - command line support for optimization & ML
  - reduced models for fast, interactive computing
  - interoperability with other linac & gun codes
  - *retain simplicity & ease of use*

- Further improve the Sirepo-Hellweg GUI
  - essential for education, industrial customers
  - instantaneous collaboration for distributed teams
  - interoperability between GUI and command line

Sirepo

https://sirepo.com

Conclusion

The central challenge for HEP is reducing the cost of a future collider, and finding synergies with other accelerator users is a key way to ease burden to the HEP budget. Electron accelerators are ubiquitous instruments employed throughout society and makeup the vast majority of the nearly 30,000 accelerators in operation across the globe today. ...electron accelerators are uniquely positioned to leverage these global efforts thus opening a viable path to a linear collider.

M. C. Llatas et al. *Report of the Snowmass 2021 e^+e^--Collider Forum*. 2022. arXiv: 2209.03472 [hep-ex].

- Synergy with industry, science & education via the Hellweg code
- Hellweg is a powerful reduced-model code for linac design
  - in production use for industrial TW linacs that are being built and used
    - users are actively supported *(see V. Dolgashev presentation, this workshop)*
  - steady-state beam loading is automatically included
    - 1000x faster than CST, with quantitative agreement
- Hellweg capabilities are being generalized
  - support ion linac design, as well as very high energy electron linacs
  - support standing wave structures and transient effects *(proposed)*