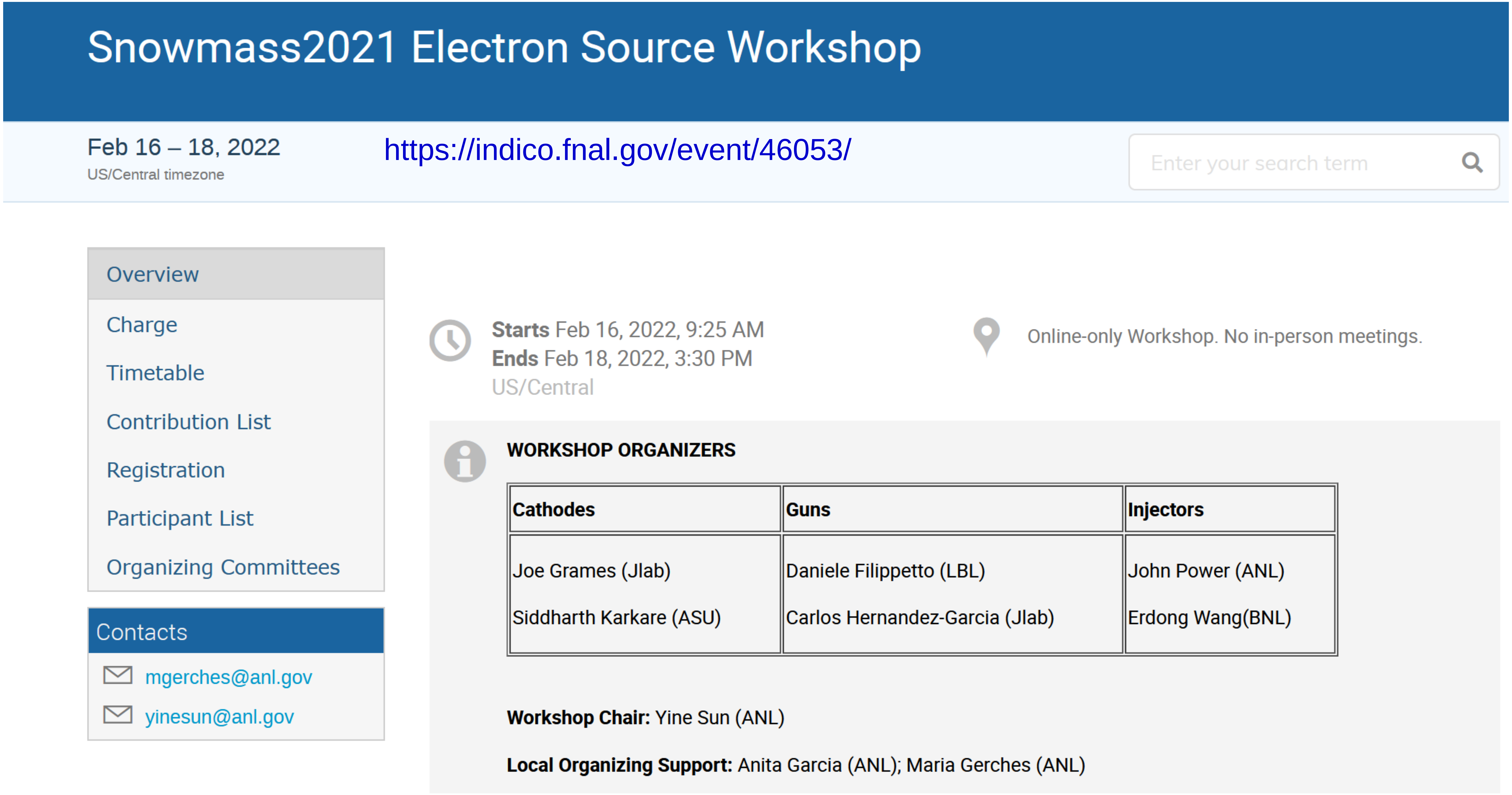
Electron Sources for Particle Accelerators

YINE SUN
Advanced Photon Source
Argonne National Lab.

Oct. 3, 2023
Photocathode Physics for Photoinjectors Workshop
Stony Brook, New York



Snowmass2021 Electron Source Workshop

Feb 16 – 18, 2022
US/Central timezone

https://indico.fnal.gov/event/46053/

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Starts Feb 16, 2022, 9:25 AM
Ends Feb 18, 2022, 3:30 PM
US/Central

Online-only Workshop. No in-person meetings.

WORKSHOP ORGANIZERS

Cathodes	**Guns**	**Injectors**
Joe Grames (Jlab) Siddharth Karkare (ASU)	Daniele Filippetto (LBL) Carlos Hernandez-Garcia (Jlab)	John Power (ANL) Erdong Wang(BNL)

Workshop Chair: Yine Sun (ANL)

Local Organizing Support: Anita Garcia (ANL); Maria Gerches (ANL)

$e^{\pm}$ Source Roadmap Working Group Report

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https://indico.fnal.gov/event/59123/

HEP Target and Sources Road Map workshop
April 11-12, 2023, Fermilab, Batavia, IL 60510

Outline

- Applications of electron sources in particle accelerators
  - High Energy Physics
  - Nuclear Physics
  - Light Sources
- The architecture of electron sources
  - Guns
  - Cathodes
  - Injectors
- Roadmap for electron source development

Applications of electron sources in particle accelerators

Electrons are widely used for different types of accelerators. In this presentation we will focus on electron injectors used in the following three areas of applications:

- Electron-Positron Colliders: High luminosity requires
  - Flat beam w/ small vertical emittance on nm level, and high average current
- Advanced accelerators
  - Sources matched to high-frequency acceleration (optical, THz)
  - Sources to produce "drive" bunch (high charge + shaped) for beam-driven wakefield acceleration in structures or plasmas.
- Accelerator-based light sources
  - Main driver for photoinjectors R&D over the last several decades
  - Photoinjectors for linac-based free electron lasers
  - High average current DC guns for ERLs

Electron Sources for High Energy Physics/Nuclear Physics

There are several types of photoinjectors for different purposes:

- Main beam injector (high brightness): provide a few hundreds of µA of polarized electrons such as in ILC, SuperKEKB etc [1]; 10s of mA for LHC -- beyond current state of art.
  - Accelerate the gun beam until it is no longer space-charge dominated (typically 100 MeV) and inject into the main accelerator. Injector must not increase the emittance generated by cathode and gun.
- Drive beam injector (High-charge bunch trains): used for beam-driven wakefield acceleration
- Secondary beam injector (e.g. e- beam to e+ beam, as baseline for KEK ILC e+)
  - 10s of mA spin polarized electrons are needed to generate µA of polarized positrons
- Electron cooling injector (High-current) for hadron cooling [2]

[1] Luca Cultrera, Spin polarized electron beams production beyond III-V semiconductors, https://arxiv.org/abs/2206.15345
[2] Xiaofeng Gu, this workshop.

An Example of Electron Sources For Colliders

- Compact Linear Collider (CLIC) Electron Beam [1]
  - Main beam: electrons need to be spin-polarized (>80%)
    - DC photoinjectors with GaAs cathode using polarized drive laser;
  - Drive beam: DC thermionic or rf photocathode gun

[2]

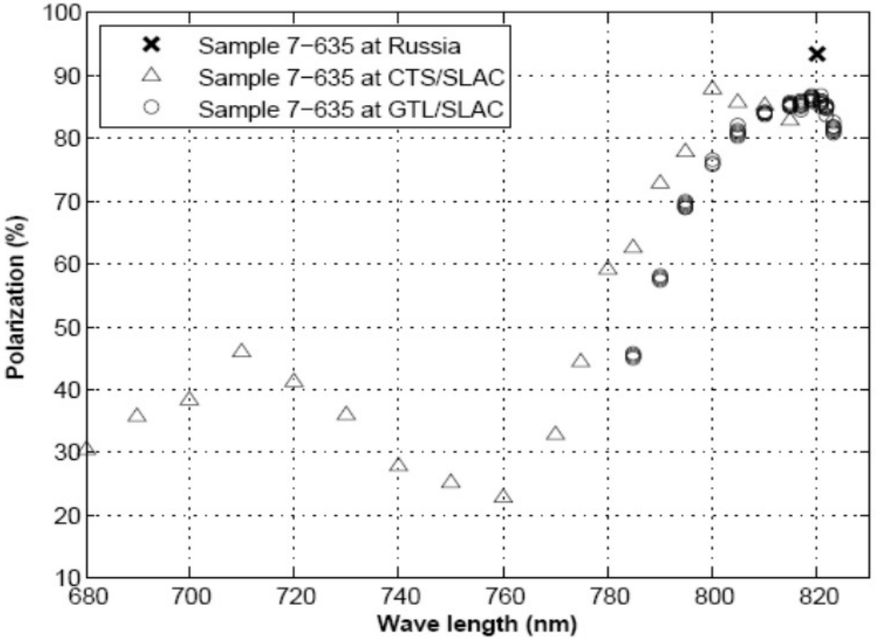
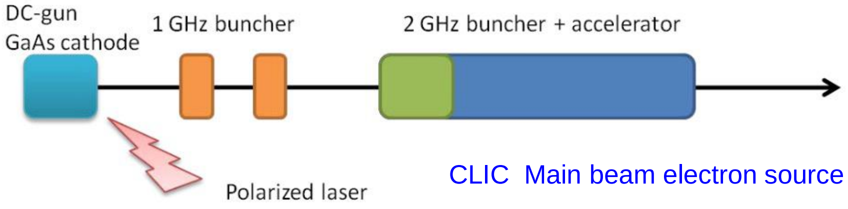
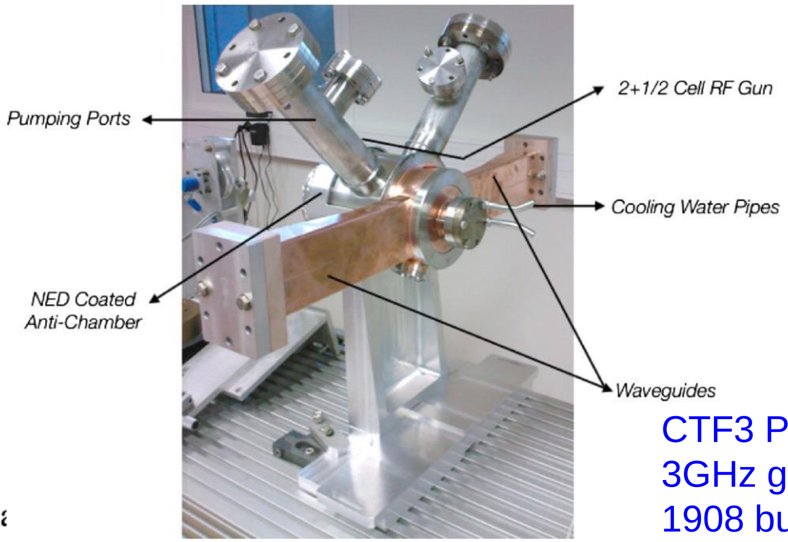


FIGURE 1. The comparison of the polarization spectrum measured at St. Petersburg in Russi
CTS/SLAC and GTL/SLAC.



CLIC Main beam electron source

[3]



CTF3 PHIN gun for drive-beam
3GHz gun, Cs2Te cathode,
1908 bunches 2.33 nC/bunch
bunch frequency of 1.5 GHz.
total charge of ~4.4 μC

[1] A. Latina, “Electron Source Requirements for Electron Colliders”, Snowmass2021 Electron Source Workshop, 2/16/2022, https://indico.fnal.gov/event/46053/
[2] F. Zhou, A. Brachmann, T. Maruyama, and J. C. Sheppard, “Polarized photocathode R&D for future linear colliders”, AIP Conference Proceedings, vol. 1149, no. 1, pp. 992–996, 2009, SLAC-PUB-13514.
[3] O. Mete et al, “Production of long bunch trains with 4.5 μC total charge using a photoinjector”, Phys. Rev. ST Accel. Beams 15, 022803

Electron Sources for Advanced Accelerators

- Small beam size over a longer distance (i.e. small beam emittance) will allow stronger interaction of electron beam.
  - Dielectric laser accelerator[1]: hundred of nm aperture size and hundreds of μm long structures, only 2.2% transmission (~11fC charge transmitted for an initial beam with 5 pC, 16x7 μm emittance, 24 keV energy spread and 60 MeV beam
  - structure-based wakefield acceleration
    - Corrugated waveguides [2]: 2-mm ID, 10-cm long
- Nano tips
  - ~10s pm emittance

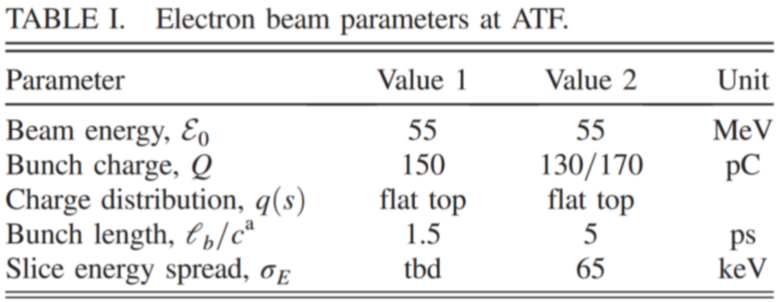
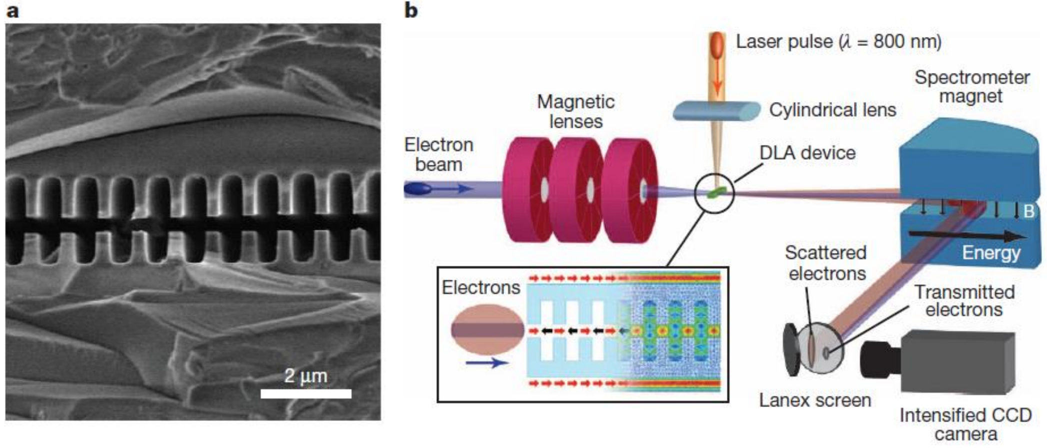


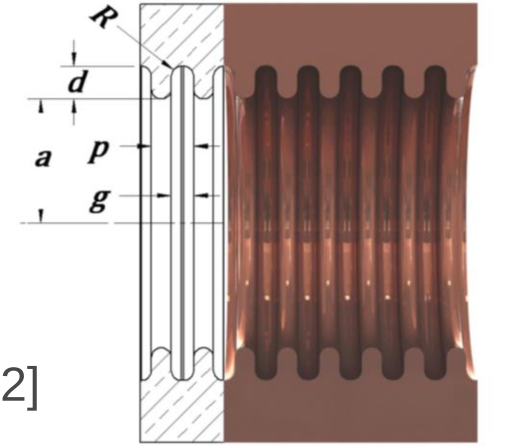
TABLE I. Electron beam parameters at ATF.

Parameter	Value 1	Value 2	Unit
Beam energy, $\mathcal{E}_0$	55	55	MeV
Bunch charge, Q	150	130/170	pC
Charge distribution, $q(s)$	flat top	flat top	
Bunch length, ℓ_b/c^{a}	1.5	5	ps
Slice energy spread, σ_E	tbd	65	keV



[1]

Figure 1 | DLA structure and experimental set-up. **a**, Scanning electron microscope image of the longitudinal cross-section of a DLA structure fabricated as depicted in Extended Data Fig. 1a. Scale bar, 2 μm. **b**, Experimental set-up. Inset, a diagram of the DLA structure indicating the field polarization direction and the effective periodic phase reset, depicted as alternating red (acceleration) and black (deceleration) arrows. A snapshot of the simulated fields in the structure shows the corresponding spatial modulation in the vacuum channel. See text for details.



[2]

FIG. 1. Dimensions of the cylindrical corrugated waveguide: a = 1 mm, p (period) = 340 μm, g (gap) = 180 μm, d (depth) = 264 μm, R (corner radius) = 80 μm.

[1] E. A. Peralta et al, “Demonstration of electron acceleration in a laser-driven dielectric microstructure,” Nature 503, pages 91–94 (2013), https://doi.org/10.1038/nature12664
[2] A. Siy et al, “Fabrication and testing of corrugated waveguides for a collinear wakefield accelerator,” Phys. Rev. Accel. Beams 25, 021302 – Published 17 February 2022

Electron Sources for Advanced Accelerators

- Beam-Driven plasma accelerator:
  - Drive beam: synergy with injectors for light sources
  - Witness beam: uniform acceleration can be achieved via precise bunch current profile shaping
  - Examples:
    - FlashForward: FLASH FEL gun, 1.3GHz with Cs2TE cathode
    - FACET: LCLS gun, 2.856GHz with copper cathode, up to 3nC, with a few μm emittance. Bunch is compressed to achieve high peak charge (up to 10kA).
- Laser plasma [1]
  - Self-produced.

[1] Carl Schroeder, *Plasma Photocathode Injectors,* Snowmass2021 Electron Source workshop, 2/2021, https://indico.fnal.gov/event/46053/

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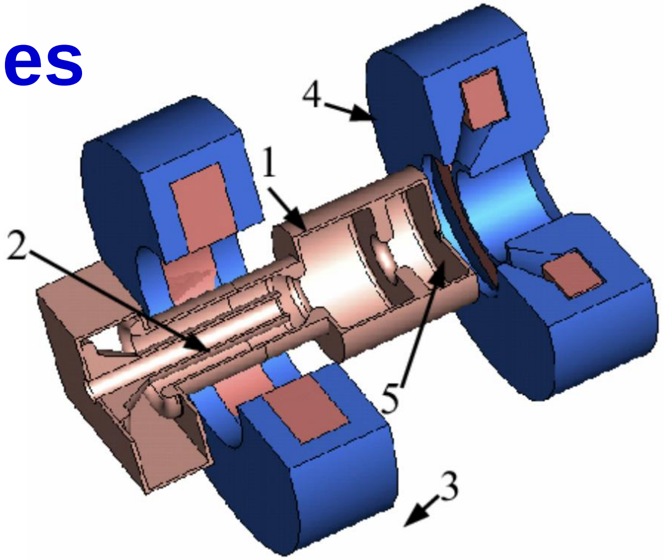
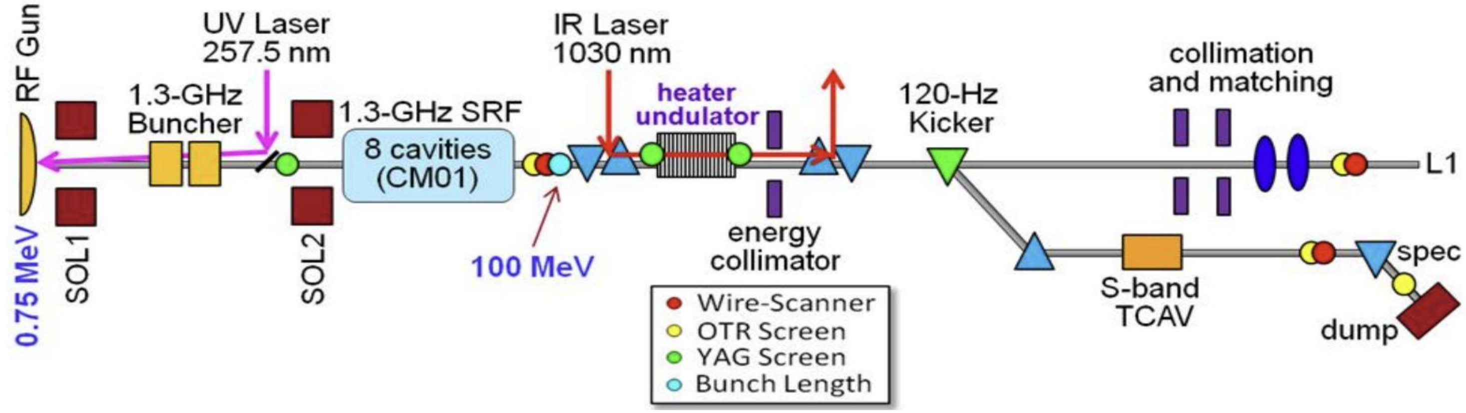
Electron Sources for Light Sources



[Courtesy M. Krassilnikov DESY]

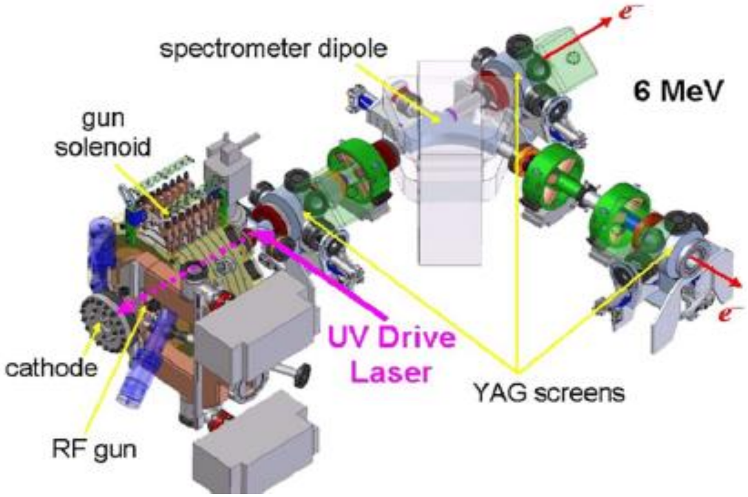
- Photoinjectors are commonly used in FELs
- Strategies to produce the required brightness:
  - Produce low peak current beam with ultra-low emittance (implement laser shaping, emittance compensation, mitigation of field asymmetries,…)
  - Accelerate beam to 100's MeV
  - Correct for nonlinearities (e.g. high-order accelerating cavities)
  - Control longitudinal emittance (laser heater to suppress microbunching instability)
  - Compress the beam to enhance the peak current (usually in a staged-compression scheme)

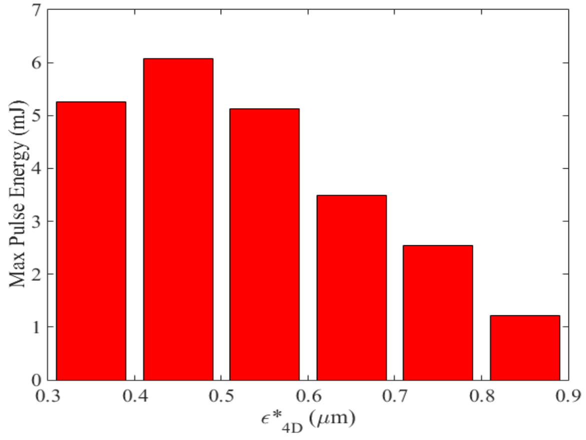


[F. Zhou, et al. LCLS-II INJECTOR PHYSICS DESIGN AND BEAM TUNING, SLAC-PUB-17124]

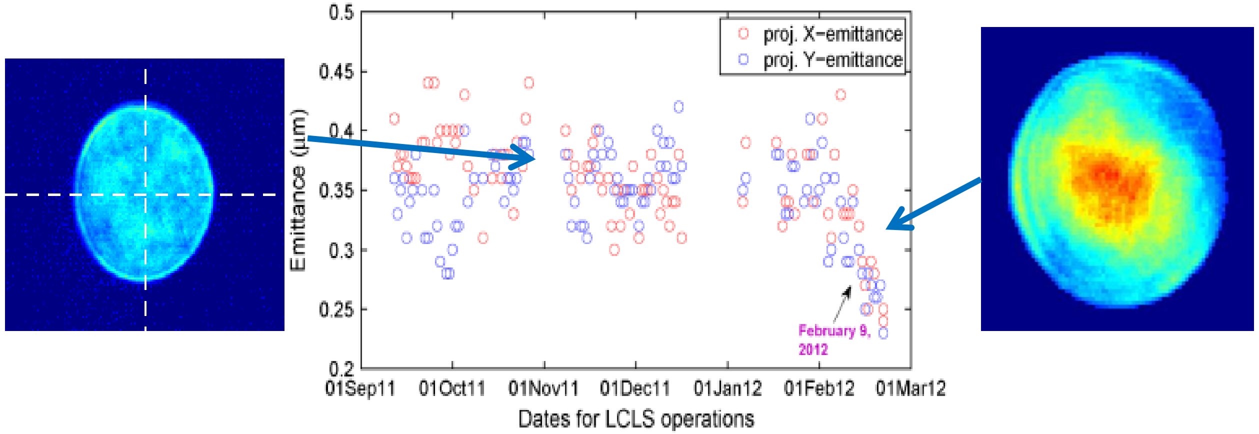
Examples of Electron Sources for Light Sources

- LCLS-I injector [1]
  - S-band NCRF Gun, 1.6-cell
  - 6 MeV gun beam energy 115 MV/m on cathode, 135 MeV injector
  - Emittance < 0.6 μm
  - Copper cathode, 250 pC bunch charge at 120 Hz rep rate
- Development over the years [2,3]:
  - Cathode cleaning for QE improvement 10^{-4}
  - Transverse drive-laser profile shaping to improve emittance
  - Correction of higher order E&M field.





Dowell et al, PRAB 2008

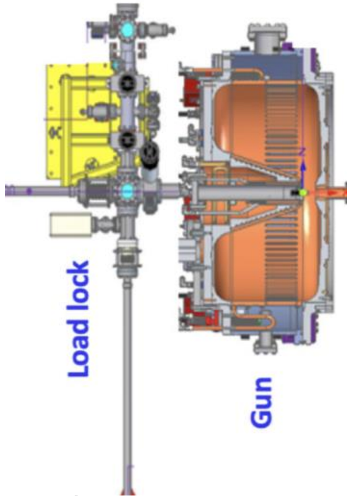


[1] F. Zhou, Snowmass2021 Electron Source workshop, 2/2022.
[3] Dowell, Zhou, and Schmerge, PRAB 21. 010101 (2018)

[2] Zhou et al., PRST-AB 15, 090703 (2012)

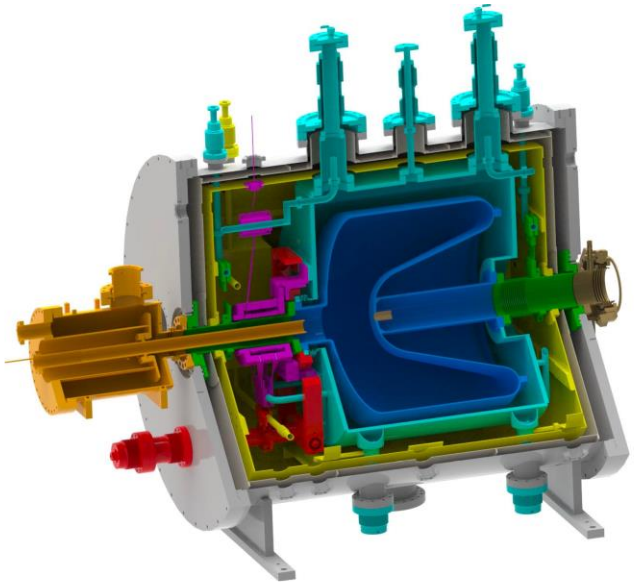
Examples of Electron Sources for Light Sources

- LCLS-II injector [1]
  - 186 MHz NCRF CW gun
  - 1.3 GHz NC buncher + 1.3 GHz SCRF accelerating structures
  - Cs_2Te cathode, 1μm/mm intrinsic emittance
  - 5-10% QE, QE lifetime 2-3 weeks for 1MHz operation
  - 50 W IR laser conversion to UV
  - Development
    - Dark current collimation
    - New gun with lower field emission
  - Supported first lasing of LCLS-II!
- LCLS-II-HE low emittance injector– SCRF gun R&D [2,3]



F Zhou, PRAB 2021

RF gun energy	750keV
Injector energy	>95 MeV
RF	CW
Repetition rate	1 MHz
Emittance (100 pC)	0.4 μm
Rms Bunch length	1mm
Peak current	>10 A



[1] F. Zhou, Snowmass2021 Electron Source workshop, 2/2022, https://indico.fnal.gov/event/46053/.
[2] J. Lewellen et al, https://accelconf.web.cern.ch/napac2022/papers/wepa03.pdf, NAPAC2022.
[3] S. H. Kim et al. https://accelconf.web.cern.ch/napac2022/papers/mopa85.pdf, NAPAC2022.

The important parameters of electron sources

- The electron source determines many essential beam characteristics which can be a make-or-break point for their applications, such as spin-polarization, lifetime of the photocathode etc.

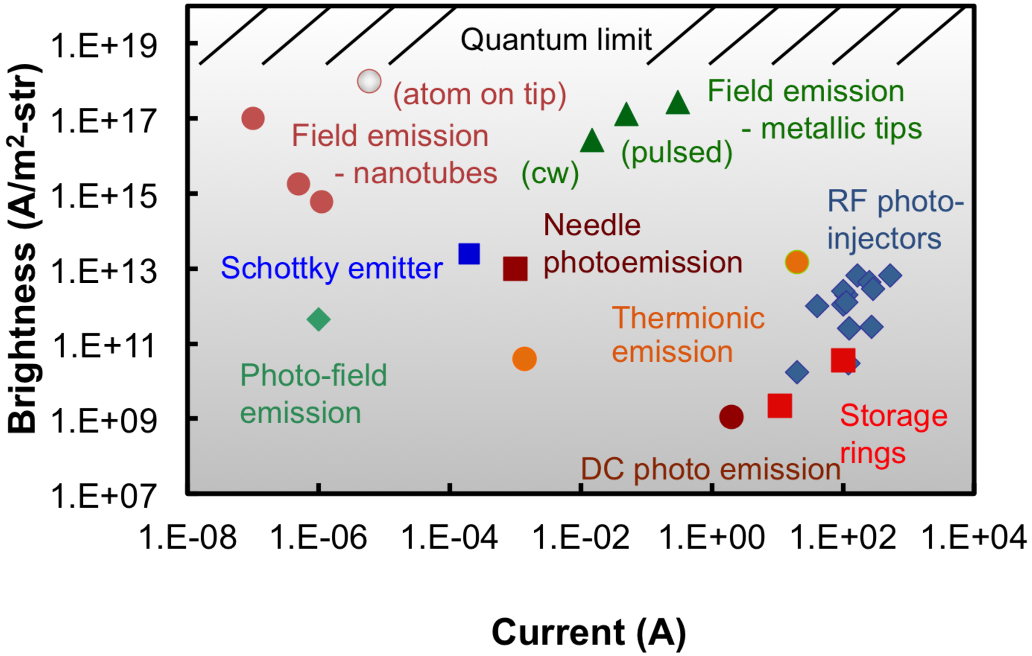
- Many applications of electron beams relate to the notion of brightness:

$$\mathcal{B} = \frac{Q \longleftarrow \text{bunch charge}}{V \longleftarrow \text{phase-space volume}}$$

  - In a linear accelerator, the electron source sets the limit of the smallest phase-space volume that can be ultimately achieved for a given amount of charge.
  - In an accelerator ring, damping effects can “cool” the phase-space, however small phase-space at the electron source mitigates injection losses or enable compact injection scheme.
  - Bunch charge, in the case of photoinjectors, is strongly related to the photocathode quantum efficiency and photocathode drive-laser power.

The architecture of electron sources

- An electron source consists of
  - An electron emission material: photocathode + photocathode drive-laser system, thermionic cathode, field emitters…
  - An electron extraction E&M field: Direct Current (DC) gun, Normal Conducting Radio-Frequency (NCRF) gun, or Superconducting Radio-Frequency (SRF) gun
  - A beam acceleration/manipulation section to:
    - Implement emittance compensation [e.g. solenoid]
    - Provide phase-space control [e.g. bunching cavity]
- The type of source generally:
  - Dictate the design of the upstream region (acceleration to ~100 MeV)
  - Impact the photocathode choice (and thus the final brightness, and ability to deliver spin-polarized beams)



[Adapted from Charles Brau, Vanderbilt U.]

Roadmap for DC Guns

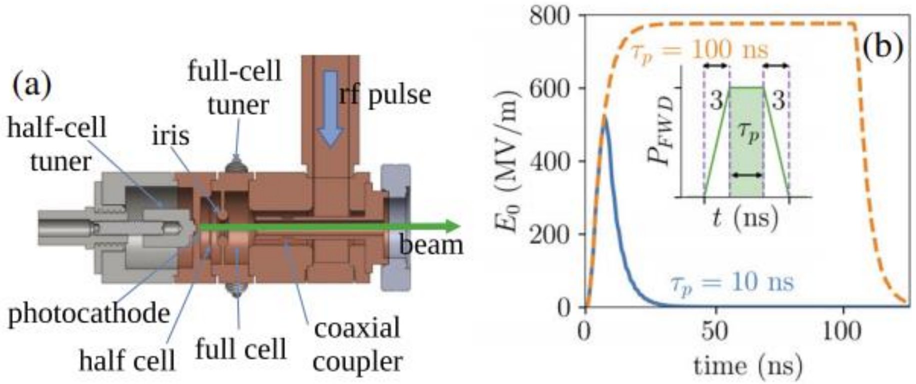
Source of choice for spin-polarized electron-bunch generation

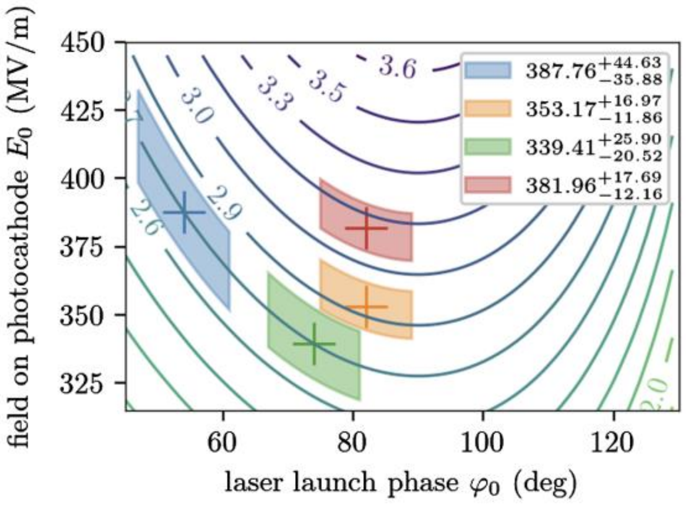
- DC guns have best vacuum (better than 10^{-11} Torr) for GaAs photocathodes and generate highest CW current
- Application to HEP– Linear collider polarized DC e-gun, polarized positron beam generation, synergies with NP
- New commercial ceramics: reliable > 400 kV operation, to reach lower emittance at very high current >100mA
- Lower outgassing materials are needed to break into the 10^{-14} Torr barrier, to create longer lifetime and greater facility operations
- ~mA polarized electron beam with > 1 kC charge lifetimes, the next vacuum frontier for GaAs superlattice dc photo-guns
- ~100 mA unpolarized electron beam with 10’s of kC charge lifetime, achieving low emittance ~ 1 μm with high charge > 1 nC

Roadmap for Normal-Conducting RF (NCRF) Guns

High-gradient for bright beams generation

- **NCRF guns reach higher gradient essential for lower emittance and higher brightness**
  - LCLS gun 100pC, emittance 150nm at 120MV/m on cathode
- Application to HEP – Linear collider unpolarized RF e-gun; synergies with NP and LCLS-II
- Achieving very high gradient >400 MV/m for very ~nsec pulse generation in the X-band frequency [1]
- Cryogenically cooled NC structures for achieving higher RF duty factor at higher gradients (C3)
- Low frequency (<200 MHz) RF structures operating in the CW regime with high gradient





[W.H. Tan, et al. PRAB 2022]

[1] W. H. Tan et al, "Demonstration of sub-GV/m accelerating field in a photoemission electron gun powered by nanosecond X-band radio-frequency pulses," Phys. Rev. Accel. Beams 25, 083402 (2022).

Roadmap for Superconducting RF (SRF) Guns

Combing DC & RF guns advantages

- **SCRF guns are promising with vacuum levels comparable to DC guns but at higher gradients**
- Application – Low emittance beams for linear colliders, very high current e- beams (pol/unpol), synergies with NP
- Integrating conventional non-SRF photocathodes to SRF guns with thermal/RF/particulate isolation for higher QE/POL
- Generation of high current > 10 mA spin polarized beams from GaAs with charge lifetime comparable to DC gun.
- Photo-cathode material choice is important as SRF cavity is sensitive to contamination, especially if the cathode is at risk of being overheated [1].

[1] Rong Xiang, Recent progress on advanced photocathodes for SC RF guns, Snowmass2021 Electron Source workshop, https://indico.fnal.gov/event/46053/

Photocathode and Drive-Laser

Cathodes can be fabricated using different materials with different characteristics[1,2].

- **Metal**
  - Copper (Cu), Magnesium (Mg), Lead (Pb)
- **Semiconductor**
  - Cesium Telluride (Cs_2Te), Alkali Antimonide (K_2CsSb), Gallium Arsenide (GaAs) and III-V semiconductors such as Gallium Nitride (GaN)[3].
- **Cathode properties:**
  - QE, lifetime, response time, thermal emittance (Mean Transverse Energy related), dark current **e**
- **Drive-laser**
  - **Wavelength, power, and shaping:**

[1] Jana Schaber, Rong Xiang a and Nikolai Gaponik, “Review of photocathodes for electron beam sources in particle accelerators,” *J. Mater. Chem. C, 2023, 11, 3162*
[2] D.H. Dowell et al., “Cathode R&D for future light sources,” Nucl. Instrum. Methods Phys. Res., Sect. A, 2010, 622, 685–697. https://doi.org/10.1016/j.nima.2010.03.104
[3] L. Cultreta et al, “Photoemission characterization of N-polar III-Nitride photocathodes as bright electron beam source for accelerator applications,” arXiv:2110.01533v1.

Challenges for Cathodes

- **Robust photocathodes/coating** for high average currents (100 mA un-pol., 20 mA pol.):
  - Frequent (daily) cathode replacements while possible are not ideal;
  - Enable operation of otherwise “delicate” materials like GaAs in “harsh” environment (RF guns) to leverage NCRF gradients.
- Increasing the QE at near threshold to leverage lower MTEs:
  - MTEs of electron is decreased at threshold as well as QE;
- **Operation at cryogenic temperatures and higher gradients**:
  - Cryo-temperatures are beneficial for producing electrons with low MTEs;
  - Leveraging cryocooled (or other) NCRF or SRF guns higher than DC accelerating gradients.
- **Exploring new promising materials and structures:**
  - Transition from bulk materials to engineered, nanofabricated structures -photocathode tailoring-;
  - Exploring new classes of materials -III-Nitrides, II-VIs, atomically ordered band-structure engineered cathodes, spin filters;

Photocathode Drive-Laser Shaping I

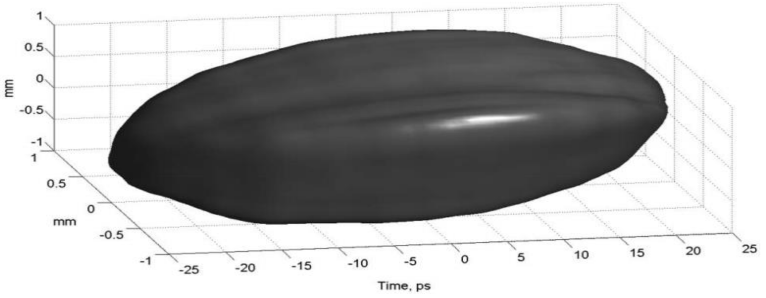
Ab-initio control of the electron bunch to conserve brightness

- Produce ellipsoidal bunches to linearize the space-charge force and mitigate emittance growth

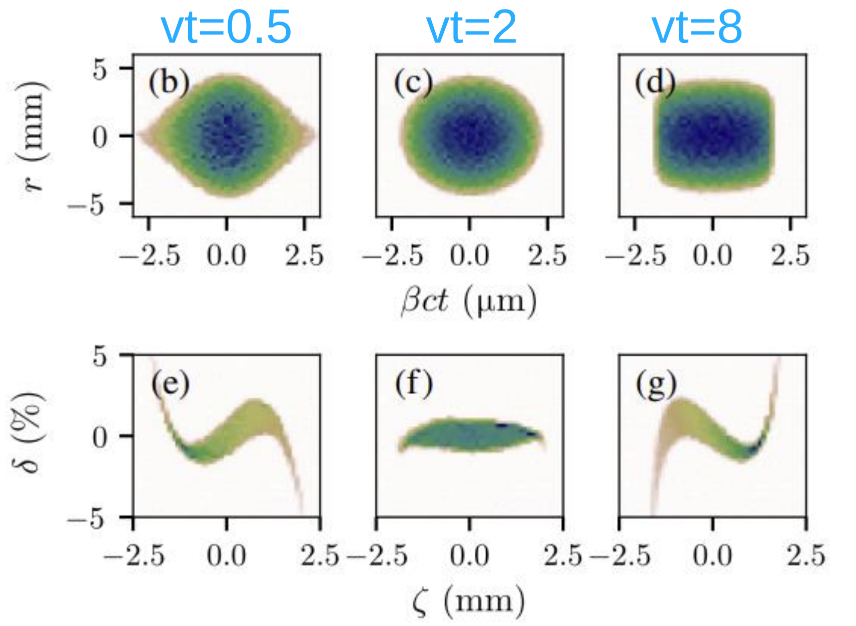
- Pre-shape the beam to control collective effects(example of Lame oval super-ellipsoids to control longitudinal phase-space ”horns”)

$$\left|\frac{x^2}{a_x^2}+\frac{y^2}{a_y^2}\right|^{\frac{\nu_\perp}{2}}+\left|\frac{t}{a_t}\right|^{\nu_t}=1$$

uniform ellipsoid laser distribution



[Mironov, et al. Appl. Opt. (2016) 10.1364/AO.55.001630

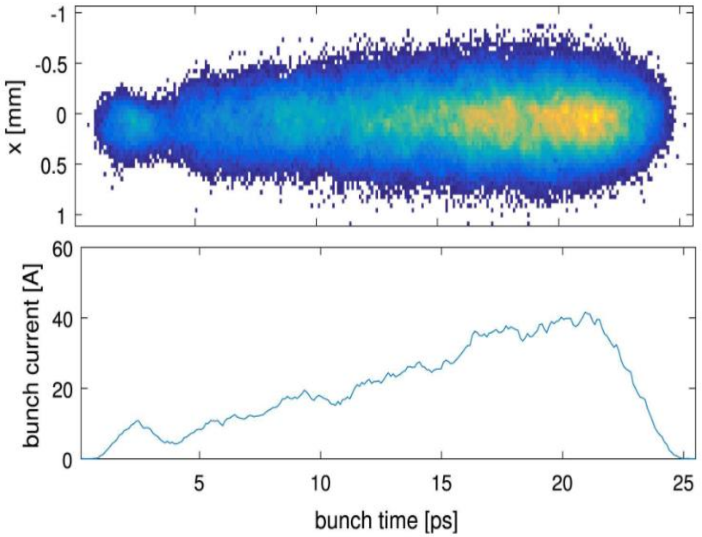


[Xu, et al. PRAB 25,044001, (2022)]

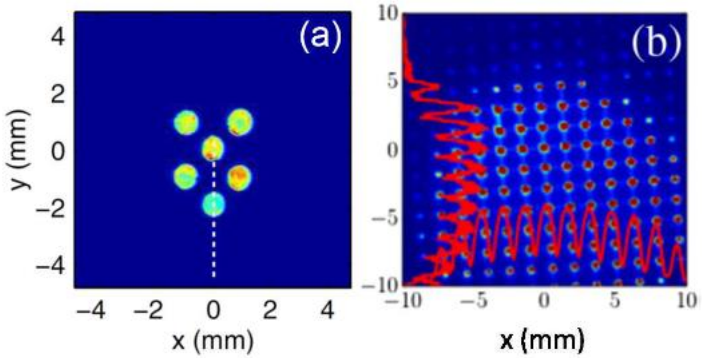
Photo-cathode Drive-Laser Shaping II

Pre-shaping for specific applications

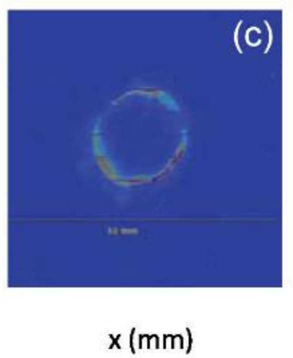
- Transverse shaping for beam focusing and injection in asymmetric structures (i.e. in wakefield accelerators)
- Segmented beam generation for coherent-radiation source
- Longitudinal beam shaping (ramped bunch)



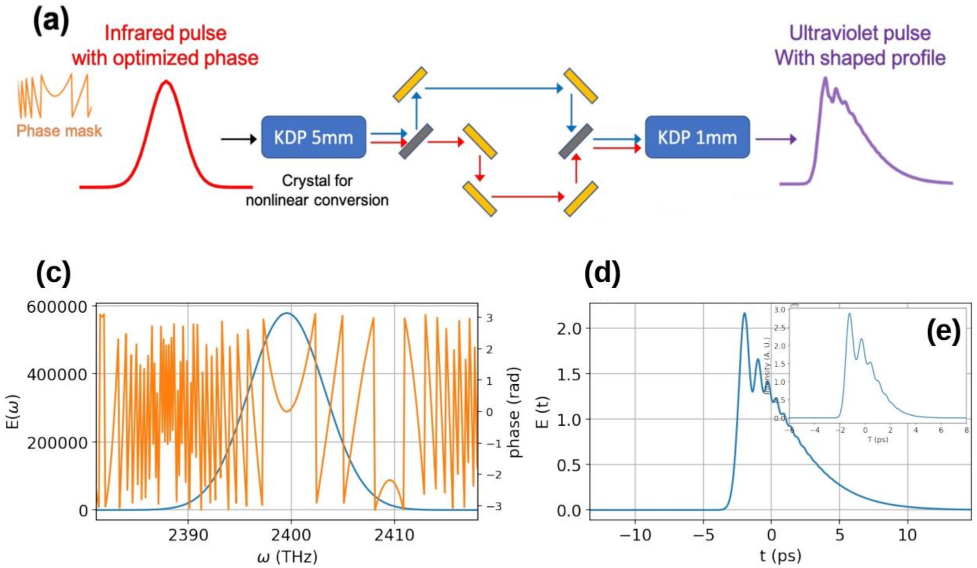
[Rihaoui, PRAB (2009)]



[Wisniewski, AAC (2012)]



[Halavanau, PRAB (2018)]



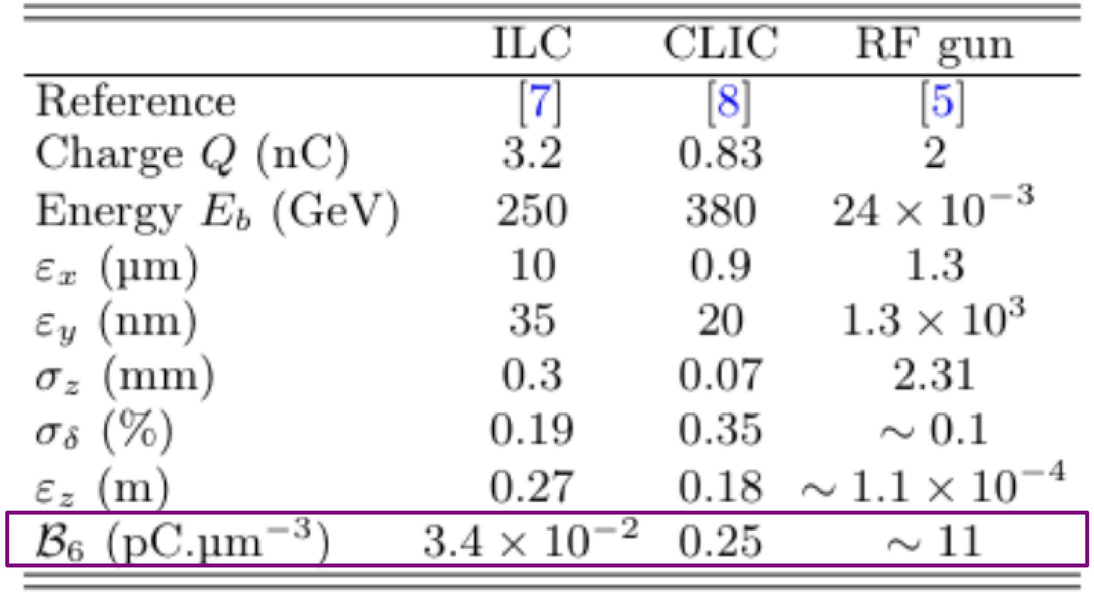
Injectors

- **Conventional injectors**
  - Emittance preservation. Preserve brighter beams from the brighter guns to the end of the injector
    - Limit space charge induced :
      - Linear: solenoids are used to compensate linear SC
      - Nonlinear: Laser shaping can be used to compensate nonlinear SC (elliptical laser distribution)
      - Eliminate double-horn current profile
    - Limit asymmetric RF fields emittance growth to 1%
      - SRF cavity coupler kicks (dipole, quadrupole)
    - Limit gun solenoid emittance growth to 1%
      - Spherical aberrations
      - Axial symmetry
  - Phase Space Partitioning. Match the beam phase space for required main linac parameters
    - Linearize longitudinal phase space
    - Preserve spin-dynamics to minimize depolarization
  - Capture. High capture efficiency of buncher (from DC gun e-, VHF gun, SRF gun)
- **Advanced injectors**
  - Develop e+/e- sources producing a phase-space volume commensurate with final emittances
  - offer a path to circumvent the DR (cost and complexity reduction)

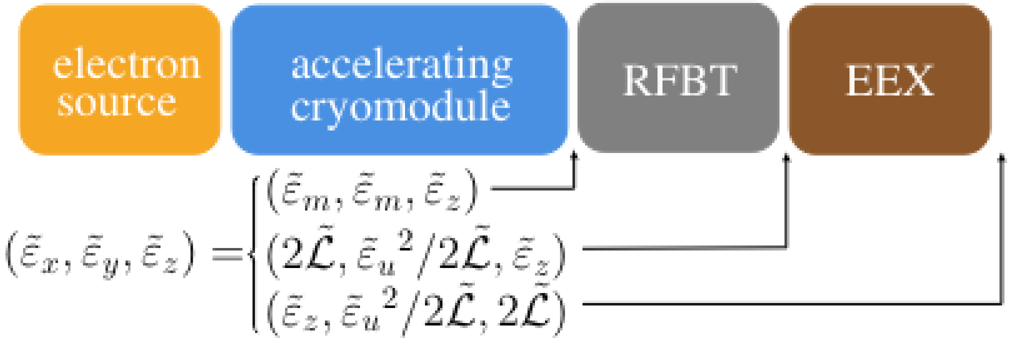
e+/e- linear collider

What a “good” source buys you?

- The 6D brightness from a state of the art photoinjector (DESY PITZ) is comparable to the one produce in LC designs
- This suggests a recipe for circumventing the damping ring
  - Produce a bright “correlated” beam
  - Use cross-plane phase-space manipulations to repartition and redistribute the beam emittance between the different degrees of freedom



	ILC	CLIC	RF gun
Reference	[7]	[8]	[5]
Charge Q (nC)	3.2	0.83	2
Energy E_b (GeV)	250	380	24×10^{-3}
ε_x (µm)	10	0.9	1.3
ε_y (nm)	35	20	1.3×10^3
σ_z (mm)	0.3	0.07	2.31
σ_δ (%)	0.19	0.35	~ 0.1
ε_z (m)	0.27	0.18	$\sim 1.1 \times 10^{-4}$
$\mathcal{B}_6$ (pC.µm^{-3})	3.4×10^{-2}	0.25	~ 11



$$(\bar{\varepsilon}_x, \bar{\varepsilon}_y, \bar{\varepsilon}_z) = \begin{cases} (\bar{\varepsilon}_m, \bar{\varepsilon}_m, \bar{\varepsilon}_z) \\ (2\tilde{\mathcal{L}}, \bar{\varepsilon}_u{}^2/2\tilde{\mathcal{L}}, \bar{\varepsilon}_z) \\ (\bar{\varepsilon}_z, \bar{\varepsilon}_u{}^2/2\tilde{\mathcal{L}}, 2\tilde{\mathcal{L}}) \end{cases}$$

[Xu, et al., *Damping-ring-free electron injector proposal for fugure linear colliders* PRAB 26, 014001 (2023)]

Injector for e+/e- linear collider

6D Emittance manipulation to generate beam with ILC-like parameters

- Initial eigen emittance

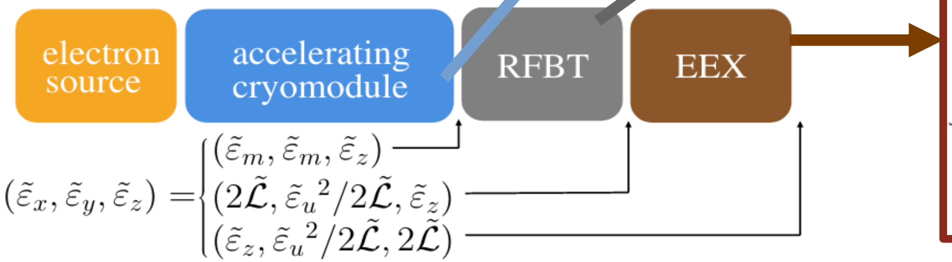
ε_-	6.84	nm
ε_+	493.4	µm

- After RFBT

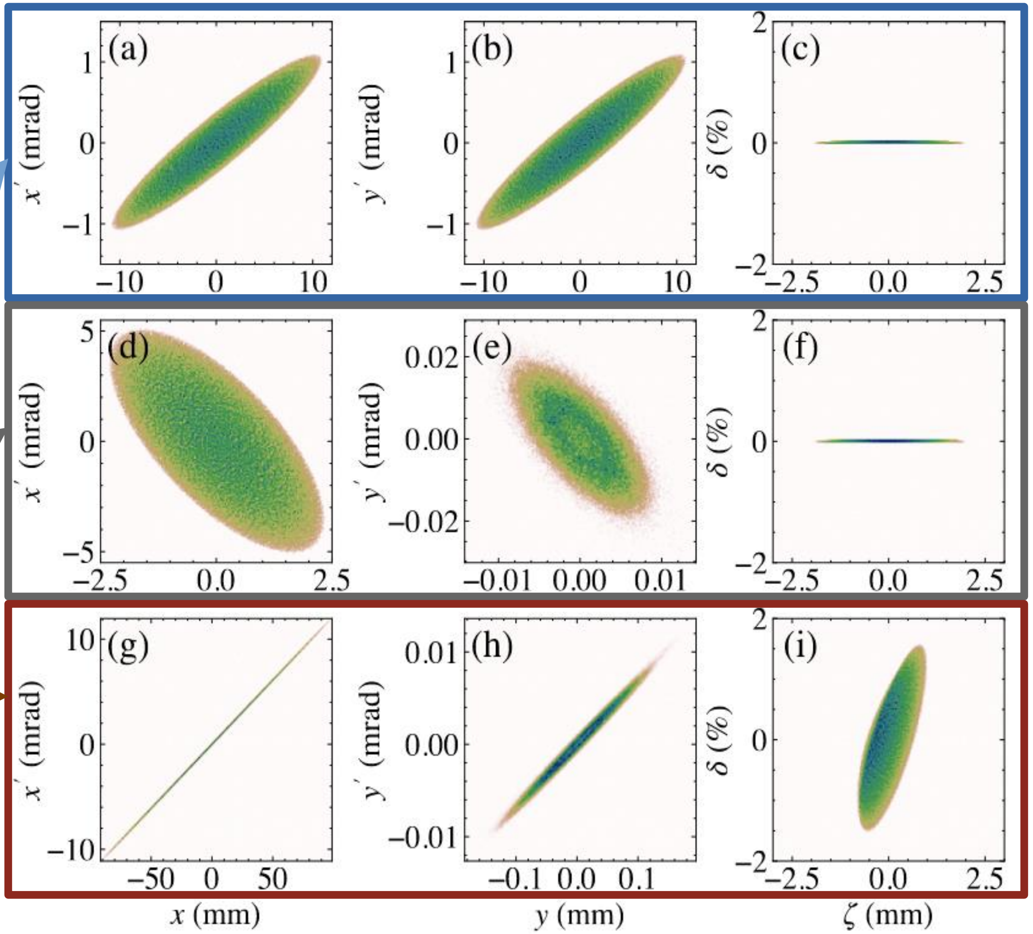
$$(\varepsilon_{x,f},\varepsilon_{y,f},\varepsilon_{z,f}) = (493.40, 7.17\times10^{-3}, 11.82)\ \mu\text{m}$$

- After EEX

$$(\varepsilon_{x,e},\varepsilon_{y,e},\varepsilon_{z,e}) = (25.47, 7.26\times10^{-3}, 546.34)\ \mu\text{m}$$



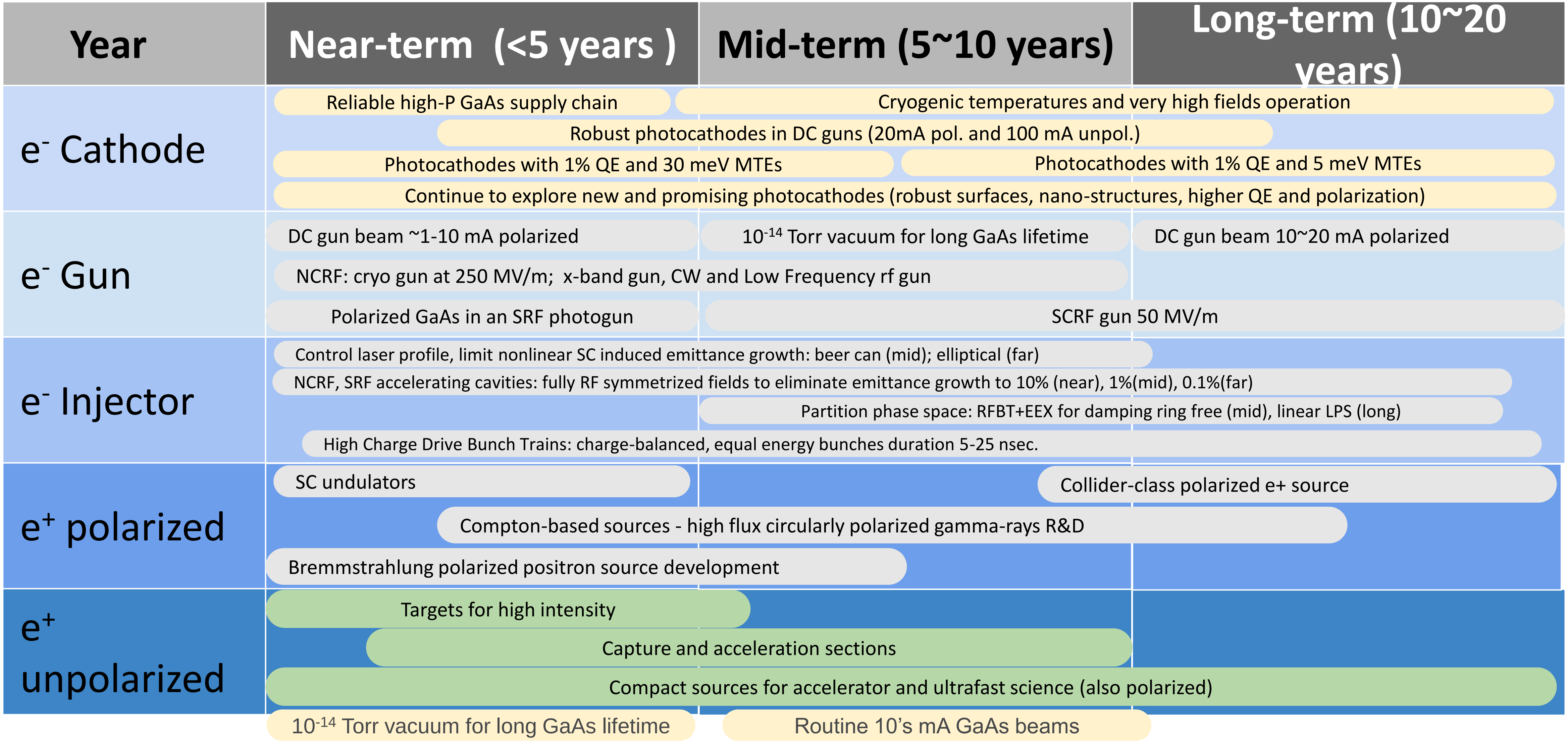
$$(\tilde{\varepsilon}_x,\tilde{\varepsilon}_y,\tilde{\varepsilon}_z) = \begin{cases}(\tilde{\varepsilon}_m,\tilde{\varepsilon}_m,\tilde{\varepsilon}_z)\\ (2\tilde{\mathcal{L}},\tilde{\varepsilon}_u{}^2/2\tilde{\mathcal{L}},\tilde{\varepsilon}_z)\\ (\tilde{\varepsilon}_z,\tilde{\varepsilon}_u{}^2/2\tilde{\mathcal{L}},2\tilde{\mathcal{L}})\end{cases}$$



[Xu, et al., PRAB 26, 014001 (2023)]

April 2023: e$^{\pm}$ Source Roadmap Working Group Report

https://indico.fnal.gov/event/59123/



Year | **Near-term (<5 years)** | **Mid-term (5~10 years)** | **Long-term (10~20 years)**

e$^-$ Cathode
- Reliable high-P GaAs supply chain
- Cryogenic temperatures and very high fields operation
- Robust photocathodes in DC guns (20mA pol. and 100 mA unpol.)
- Photocathodes with 1% QE and 30 meV MTEs
- Photocathodes with 1% QE and 5 meV MTEs
- Continue to explore new and promising photocathodes (robust surfaces, nano-structures, higher QE and polarization)

e$^-$ Gun
- DC gun beam ~1-10 mA polarized
- 10^{-14} Torr vacuum for long GaAs lifetime
- DC gun beam 10~20 mA polarized
- NCRF: cryo gun at 250 MV/m; x-band gun, CW and Low Frequency rf gun
- Polarized GaAs in an SRF photogun
- SCRF gun 50 MV/m

e$^-$ Injector
- Control laser profile, limit nonlinear SC induced emittance growth: beer can (mid); elliptical (far)
- NCRF, SRF accelerating cavities: fully RF symmetrized fields to eliminate emittance growth to 10% (near), 1%(mid), 0.1%(far)
- Partition phase space: RFBT+EEX for damping ring free (mid), linear LPS (long)
- High Charge Drive Bunch Trains: charge-balanced, equal energy bunches duration 5-25 nsec.

e$^+$ polarized
- SC undulators
- Collider-class polarized e+ source
- Compton-based sources - high flux circularly polarized gamma-rays R&D
- Bremmstrahlung polarized positron source development

e$^+$ unpolarized
- Targets for high intensity
- Capture and acceleration sections
- Compact sources for accelerator and ultrafast science (also polarized)

10^{-14} Torr vacuum for long GaAs lifetime

Routine 10's mA GaAs beams