# Plasma accelerator demonstration facility at intermediate energy

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# US Snowmass process – Energy frontier at 10+ TeV

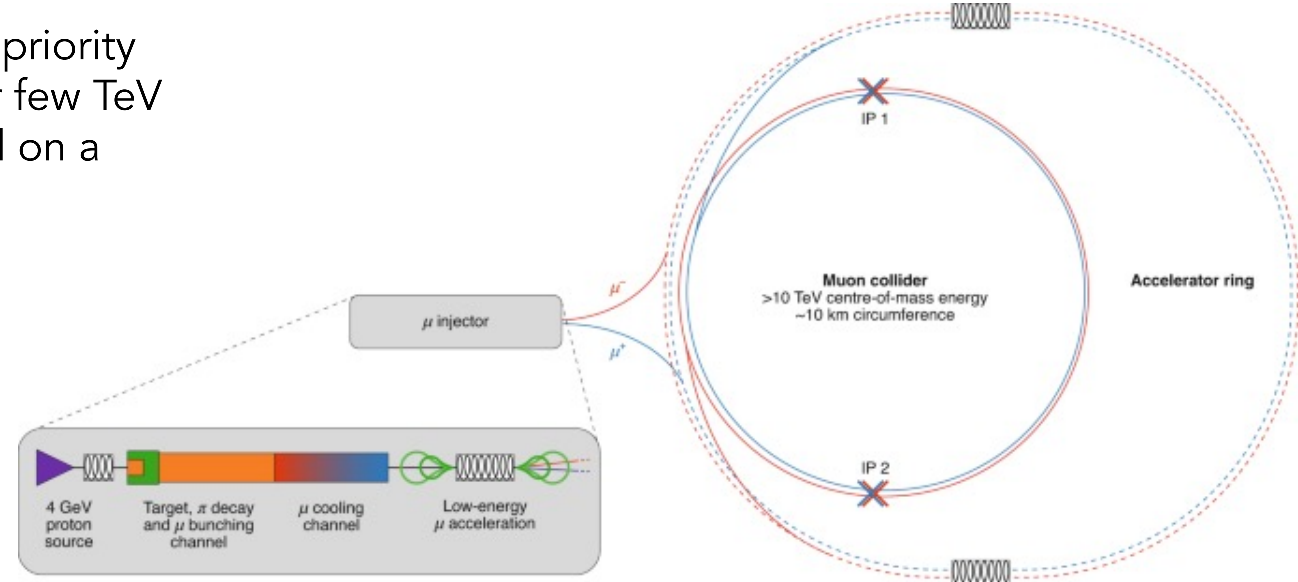
*Snowmass*: US particle physics community planning exercise to identify and document a scientific vision for the future of particle physics in the US.  Provides input to P5 (Particle Physics Project Prioritization Panel).

https://snowmass21.org/accelerator/

*Accelerator Frontier Snowmass* Report:

"While a Higgs/EW factory at 250 to 360 GeV is still the highest priority for the next large accelerator project, the motivation for a TeV or few TeV e+e− collider has diminished. Instead, the community is focused on a 10+ TeV (parton c.m.e) discovery collider that would follow the Higgs/EW Factory."

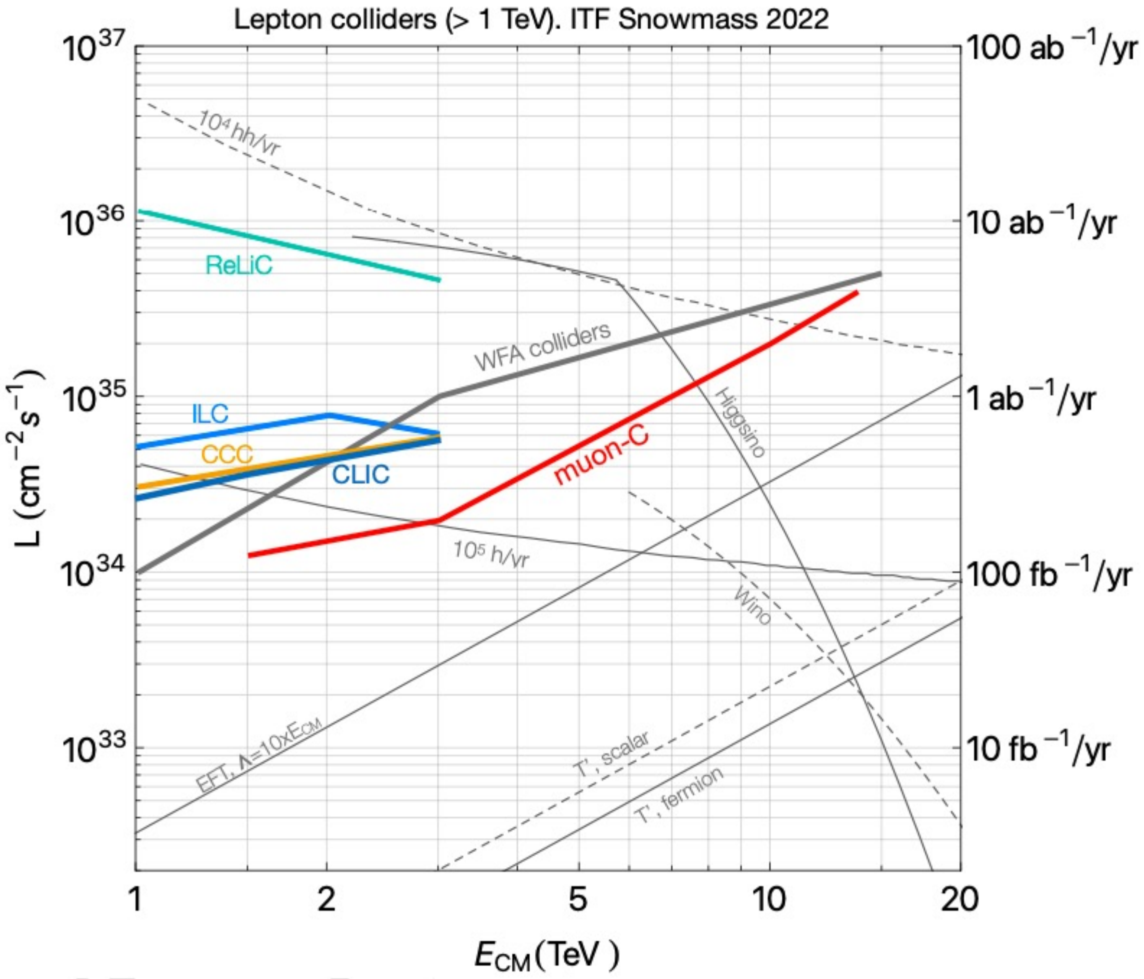
"At the energy frontier, the discovery machines such as O(10 TeV c.m.e.) muon colliders have rapidly gained significant momentum."




https://muoncollider.web.cern.ch

# Wakefield accelerator (WFA) based designs for 15 TeV

| Collider | Type |
|---|---|
| FCC-ee (0.24 TeV) | Circular |
| CEPC (0.24 TeV) | Circular |
| CERC (0.24 TeV) | Circular |
| ILC (0.25 TeV) | Linear |
| CLIC (0.38 TeV) | Linear |
| CLIC (3 TeV) | Linear |
| $C^3$ (0.25 TeV) | Linear |
| ReLiC (0.24 TeV) | Linear |
| ERLC (0.24 TeV) | Linear |
| ILC (3 TeV) | Linear |
| $C^3$ (3 TeV) | Linear |
| ReLiC (3 TeV) | Linear |
| WFA (3 TeV) | Linear |
| WFA-flat (15 TeV) | Linear |
| WFA-round (15 TeV) | Linear |




"Report of the Snowmass 2021 Collider Implementation Task Force" **arXiv:2208.06030**

Wakefield accelerators (WFAs) for 10+ TeV

- Similar high-level parameters can be achieved with LWFAs, PWFAs, and SWFAs.

Muon collider viewed as higher TRL (technical readiness level) and lower risk

Advantages of WFA for HEP applications:

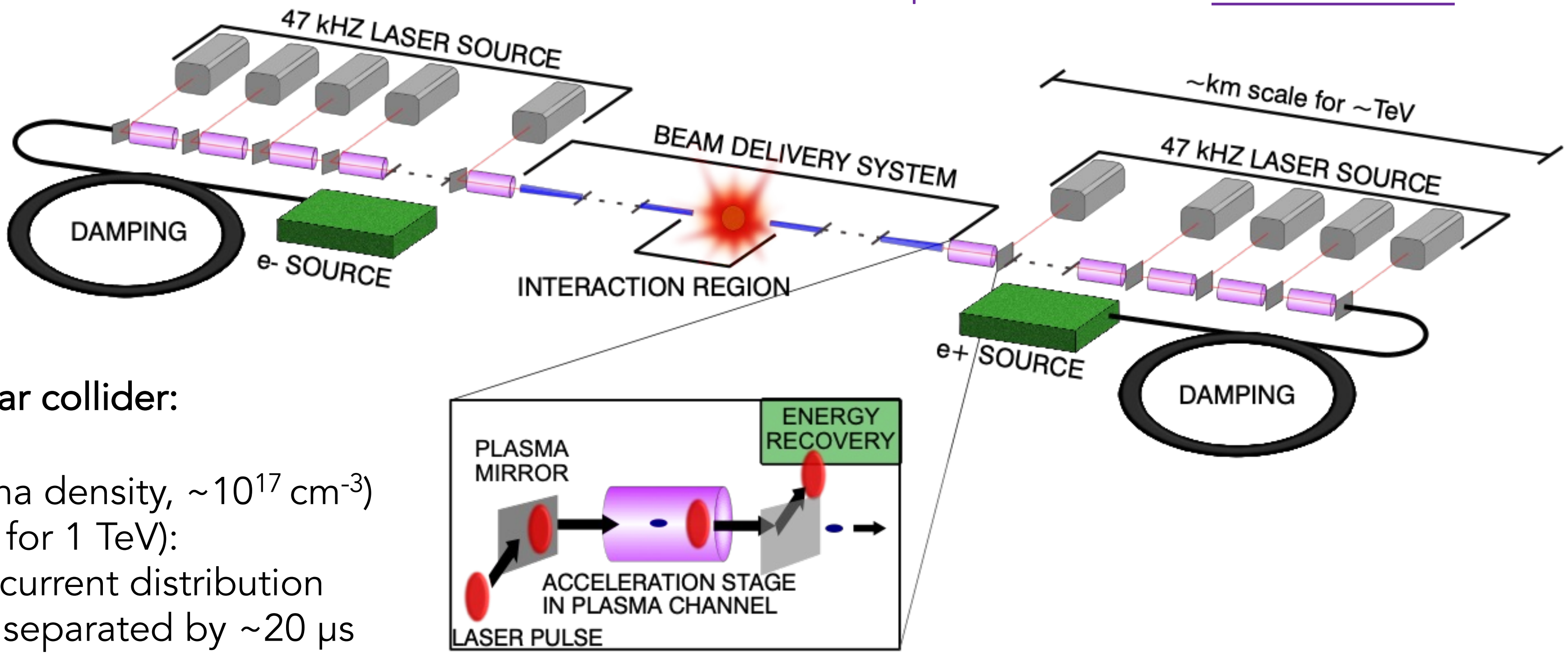
- Ultra-high gradient
- Short bunch lengths (reduced beamstrahlung and power savings)

Reduction of power consumption is main challenge of future colliders

- Use round beams to increase luminosity/power (operates in high-beamstrahlung regime at >TeV)
- Eliminate beamstrahlung using **γγ** collider (also removes need for e+)

# Example: laser-plasma-based collider concept

“Linear colliders based on laser-plasma accelerators” **arXiv:2203.08366**




Key characteristics of a laser-plasma linear collider:

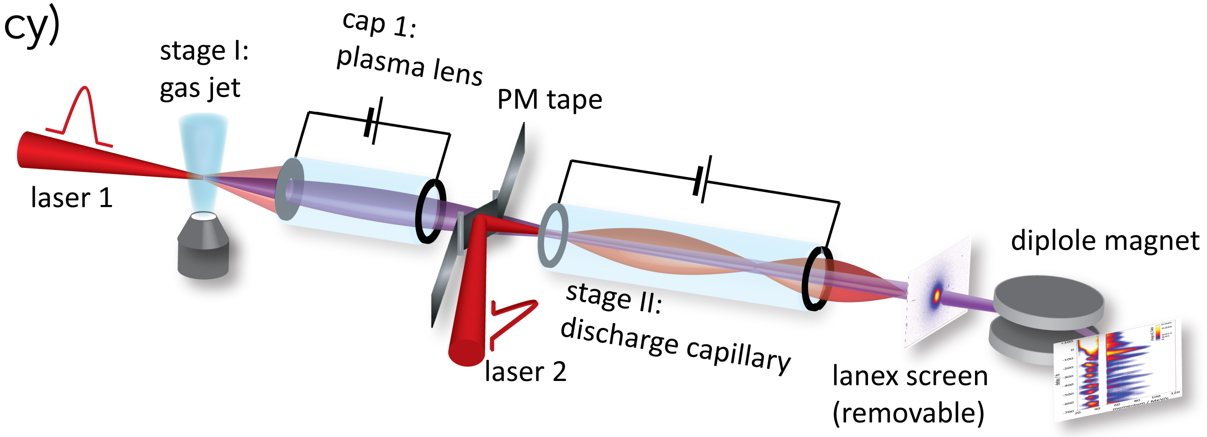
- Design (optimizing operational plasma density, ~$10^{17}$ $cm^{-3}$) yields 5 GeV/stage (200 stages/linac for 1 TeV):
- Short (8.5 μm rms) bunches; shaped current distribution
- Time structure at IP: single bunches, separated by ~20 μs (~50 kHz)

R&D in AAC community:

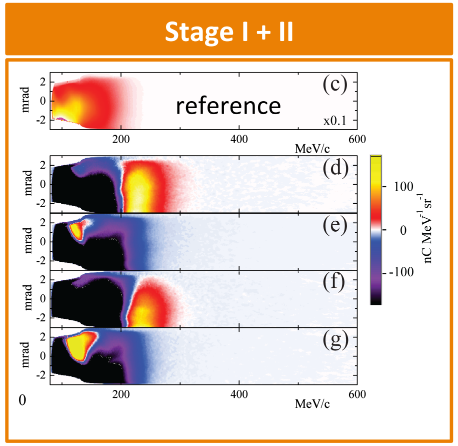
- Plasma accelerator development: controlling beam phase space; optimizing laser- and beam-plasma interaction
- Laser technology development: high-peak and high-average power lasers with high efficiency.

# R&D on LWFA staging underway at Berkeley Lab

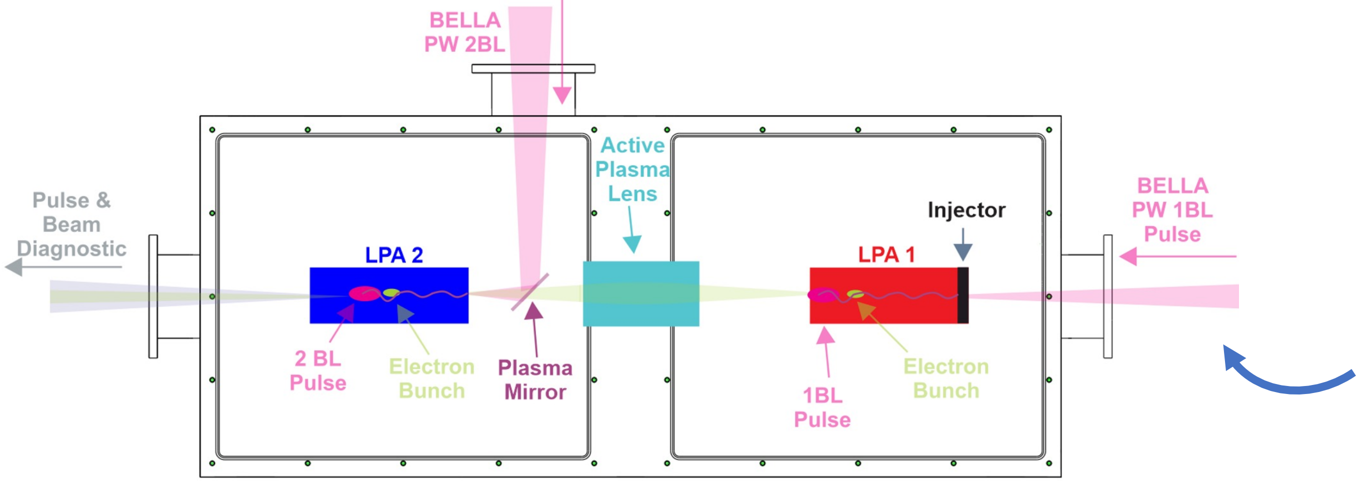
- Proof-of-principle experiment demonstrate 100 MeV energy gain (low capture efficiency)

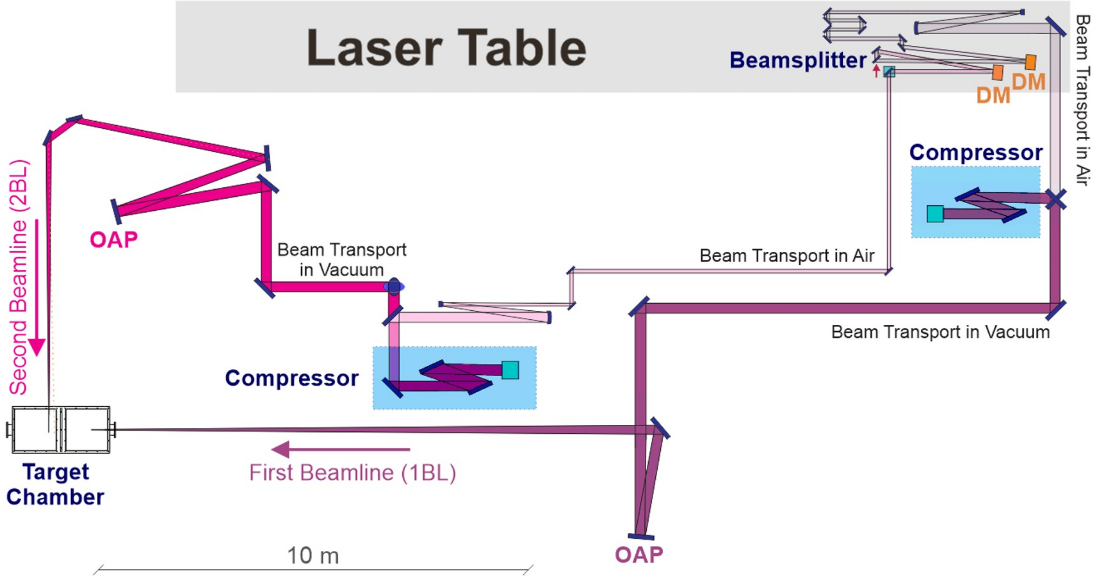



Steinke et al. Nature (2016)




- Multi-GeV (5GeV+5GeV with high capture efficiency) staging experiments are planned / commissioning 2$^{nd}$ beamline (independent compressors) on BELLA PW laser

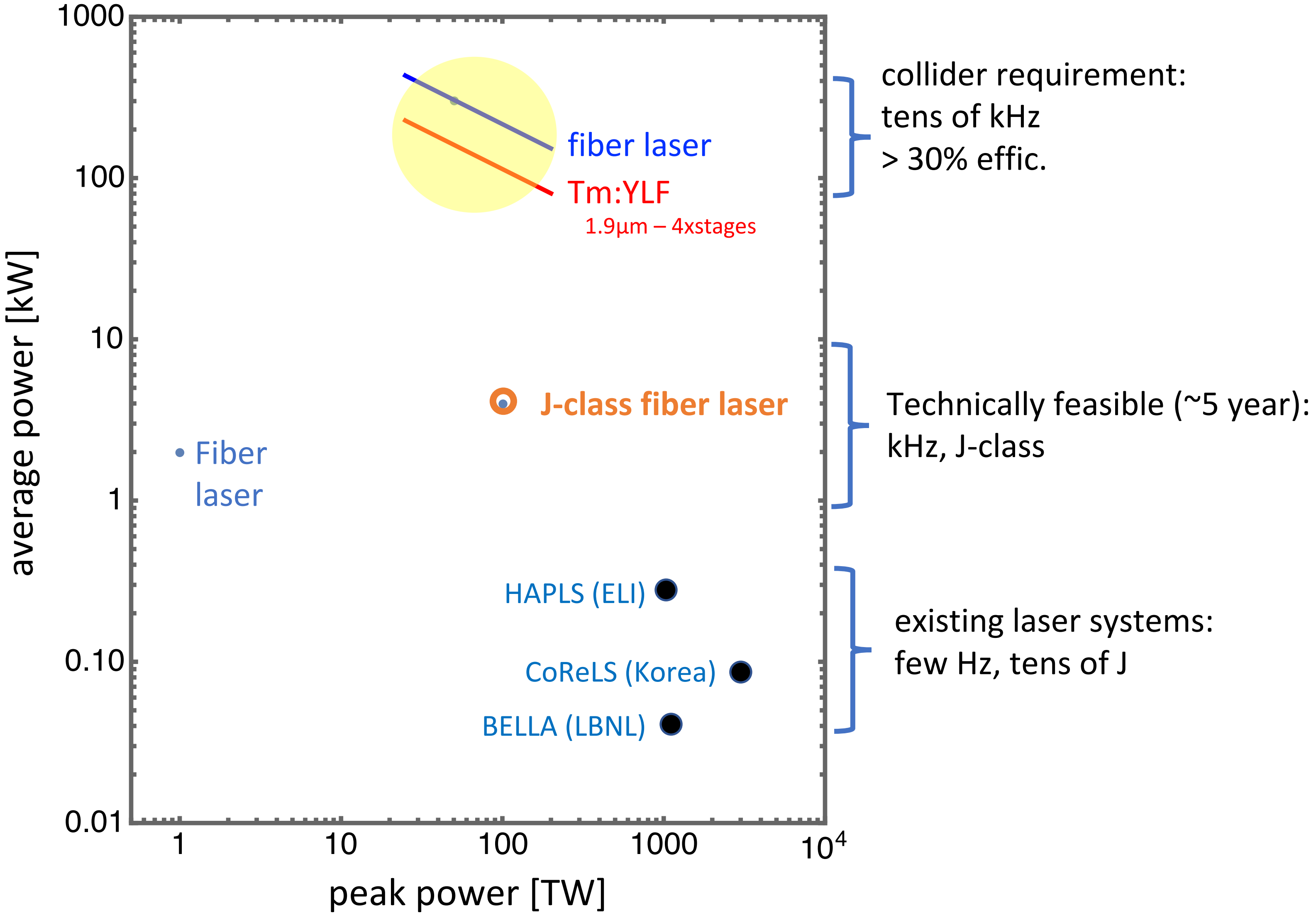


# Laser driver technology R&D required for collider

**Laser drivers:**

- Tremendous progress in recent years
- Requires R&D to reach collider parameters: ~10J, ~100fs class, ~50kHz, high wall-to-laser efficiency
- Two promising laser architectures:
  - Coherent combination of fiber lasers (1 um). ~50% wall-to-laser efficiency; R&D at Jena, Michigan, LBNL, LLNL, et al.
  - Tm:YLF (1.9 micron) – (4x as many LWFA stages). R&D at LLNL



# R&D on fiber laser combining at Berkeley Lab

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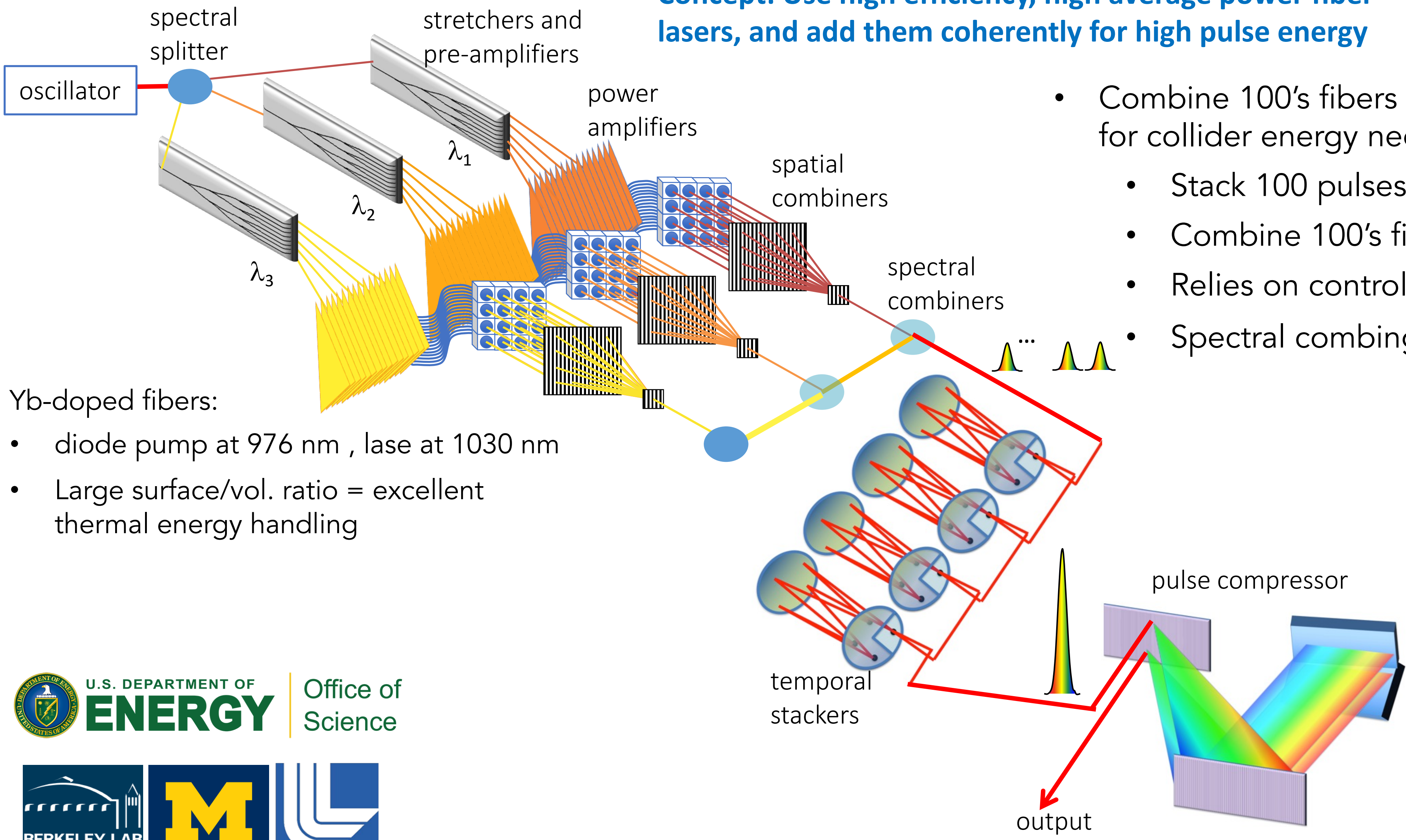


**Concept: Use high efficiency, high average power fiber lasers, and add them coherently for high pulse energy**

- Combine 100's fibers spatially x 100 pulses temporally for collider energy needs
  - Stack 100 pulses in 1 fiber to get >10mJ, sub-kW
  - Combine 100's fibers to get Joules, >100 kW
  - Relies on control of laser phase of each pulse
  - Spectral combing for ultrashort duration (10s of fs)

Yb-doped fibers:

- diode pump at 976 nm , lase at 1030 nm
- Large surface/vol. ratio = excellent thermal energy handling

- Achieved 23mJ with 3 spatial 81-pulse channels combined at 1kHz rep-rate
- Integration in FY22/23 to achieve >100mJ at 1kW

U.S. DEPARTMENT OF ENERGY | Office of Science

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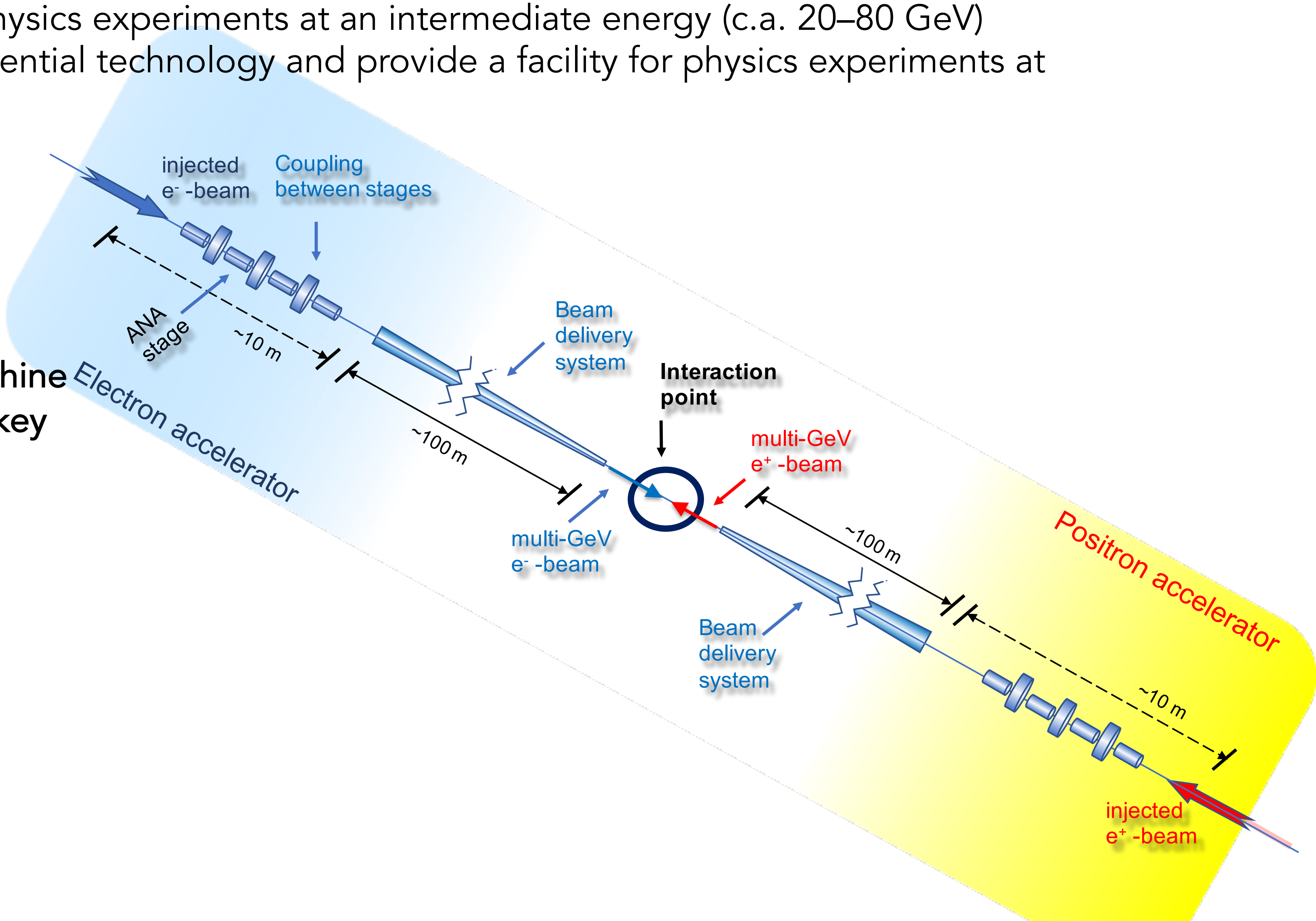
"High average power ultrafast laser technologies for driving future advanced accelerators" **arXiv:2204.10774**

# Intermediate energy demonstration

*Recommendation of AF6 (Advanced Accelerators) Snowmass Report*:

"A study for a collider demonstration facility and physics experiments at an intermediate energy (c.a. 20–80 GeV) should establish a plan that would demonstrate essential technology and provide a facility for physics experiments at intermediate energy. "



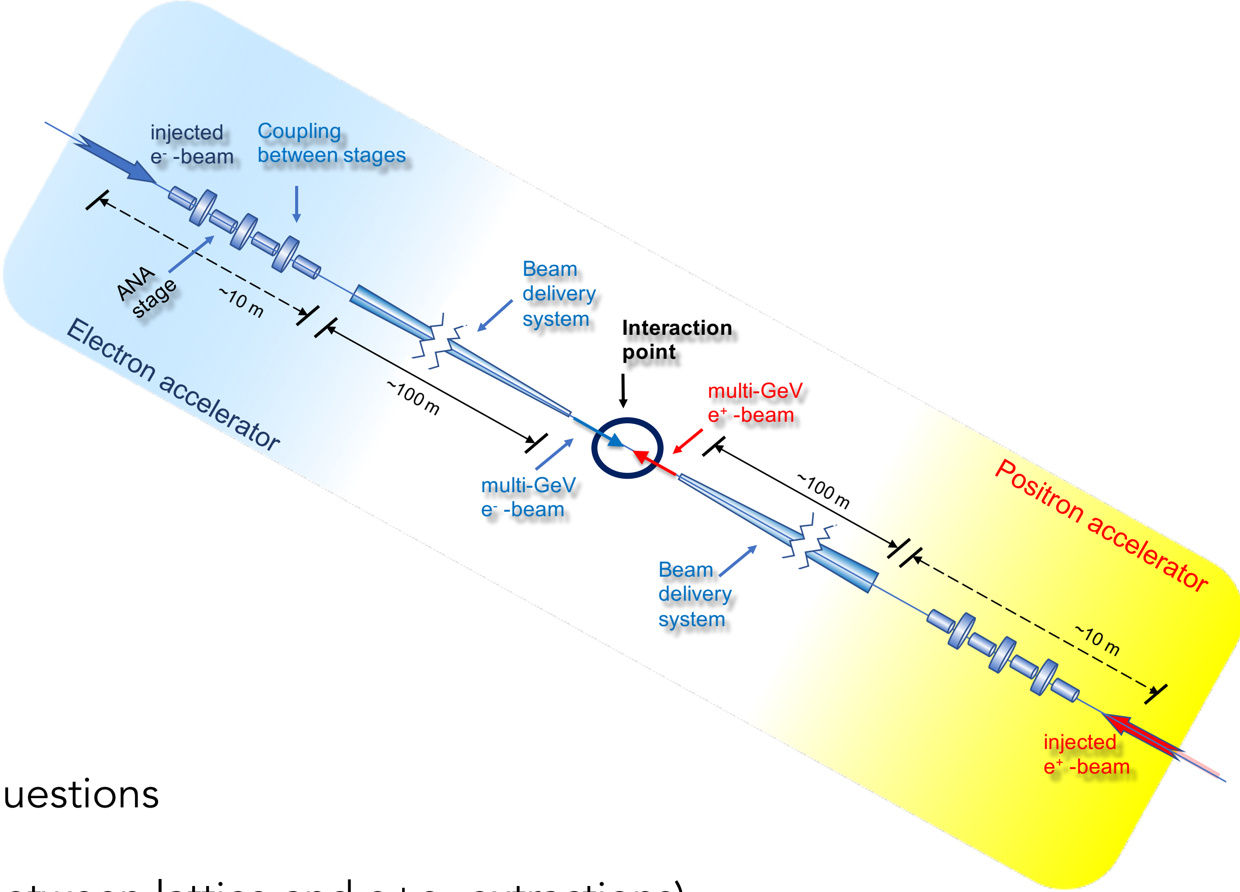

**Primary motivation for an intermediate energy machine is to test accelerator technology and demonstrate key collider subsystems.**

- Injector
- Bunch compression
- Beam delivery systems
- Final focus technology
- Develop beyond state-of-the art alignment
- High rep rate operation
- Polarization studies
- Beamstrahlung studies
- Positron generation
- Cooling
- …

"Advanced accelerator linear collider demonstration facility at intermediate energy" **arXiv:2203.08425**

# Science at intermediate energy facility

This energy range was extensively xstudied previously at, e.g., DESY-PETRA (~27 GeV com), SLAC-PEP (~29 GeV com), KEK-TRISTAN (~57 GeV com)




Why repeat measurements?

1. New detector technology has improved and new physics is possible with modern detectors and techniques (new theoretical and experimental tools).
2. Physics understanding has improved – new questions in QCD and BSM

- Use production of hadrons in e-e+ annihilation to address QCD questions
  - Precision QCD measurements:
    - Strong coupling constant measurements (discrepancy between lattice and e+e- extractions)
    - Measurements of jet substructure (synergistic with EIC program)
    - New tests of QCD factorization (and universality of hadronization effects)

Kardos et al., Eur. Phys. J. C 78, 498 (2018).

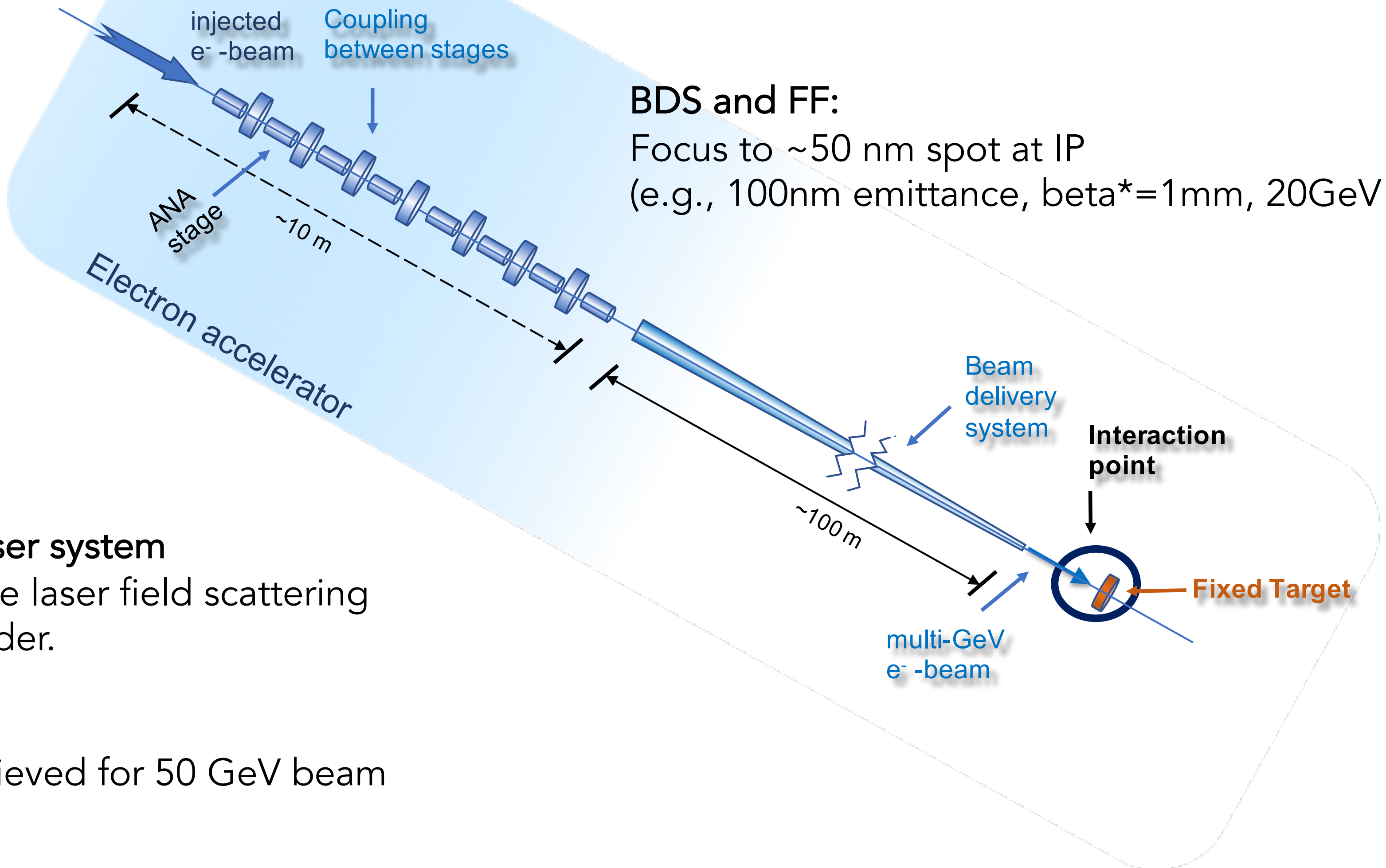
- Physics beyond standard model: search for axion-like particles, millicharged particles; dark sector studies; etc.

# Staged approach: electron linac

**e-Injector:**
Use photo-cathode (GaAs/GaAsP superlattice) with near full e- polarization. -> **polarization preservation studies**
Using RF gun methods to achieve: Q=200pC; 0.1um normalized emittance
Develop beam current profile shaping

**Bunch compressors:**
tens micron beam length for plasma linacs

**BDS and FF:**
Focus to ~50 nm spot at IP
(e.g., 100nm emittance, beta*=1mm, 20GeV beam)

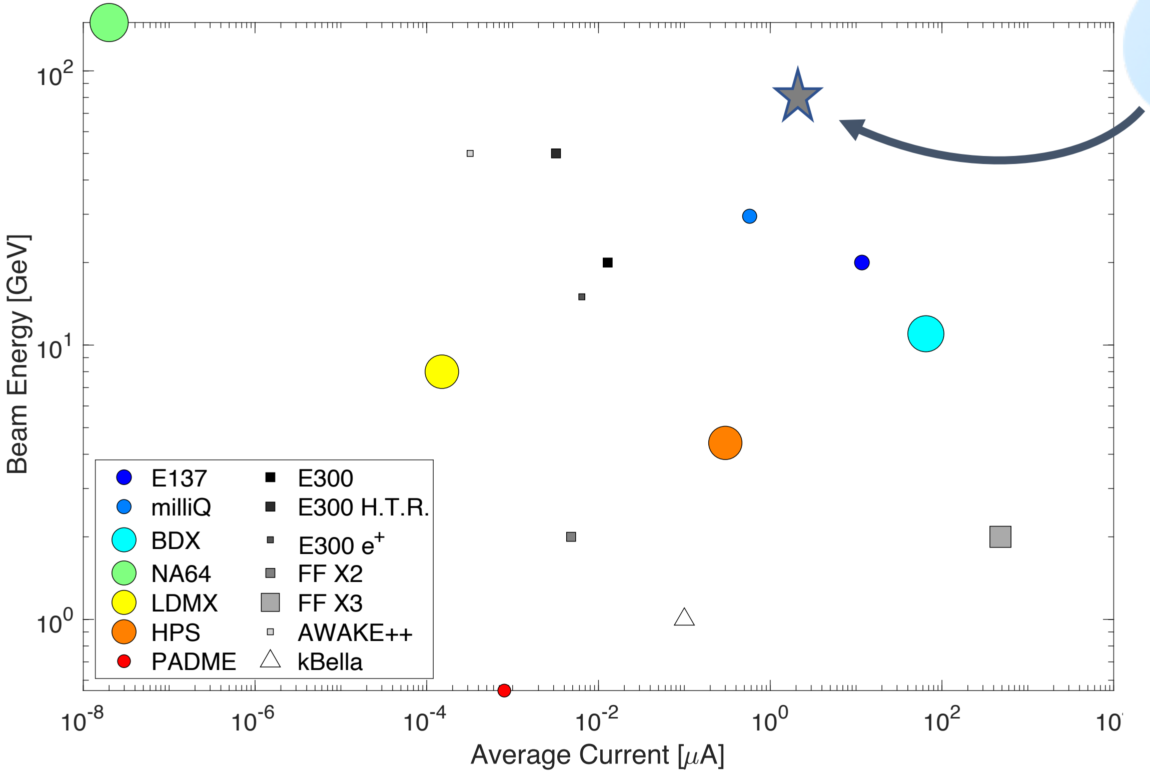


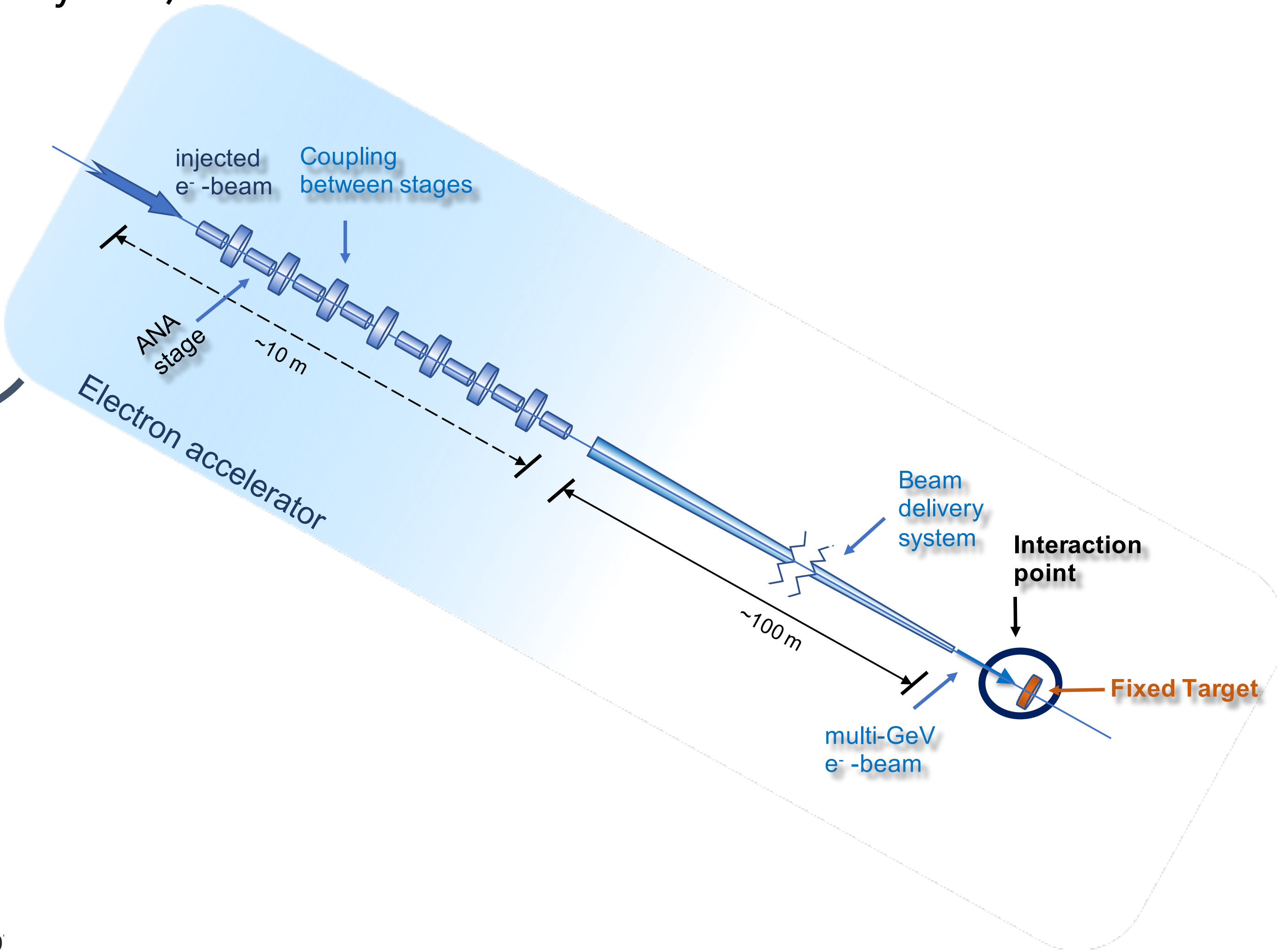

**Beamstrahlung studies using high power laser system**
Test high-beamstralung regime using intense laser field scattering with beam to mimic beam self-fields in collider.

Example:
Beamstrahlung parameter **Y**~10 can be achieved for 50 GeV beam scattering with a $10^{22}$ W/cm$^2$ laser

- Beam dump/fixed target experiments to investigate/detect rare processes, dark sector searches
- nonlinear-QED experiments (scattering with high-intensity laser)

Existing and future fixed target (beam dump) experiments:
(energy and flux determines science reach)



# Gamma-gamma collider

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"conventional" $\gamma\gamma$-collider:

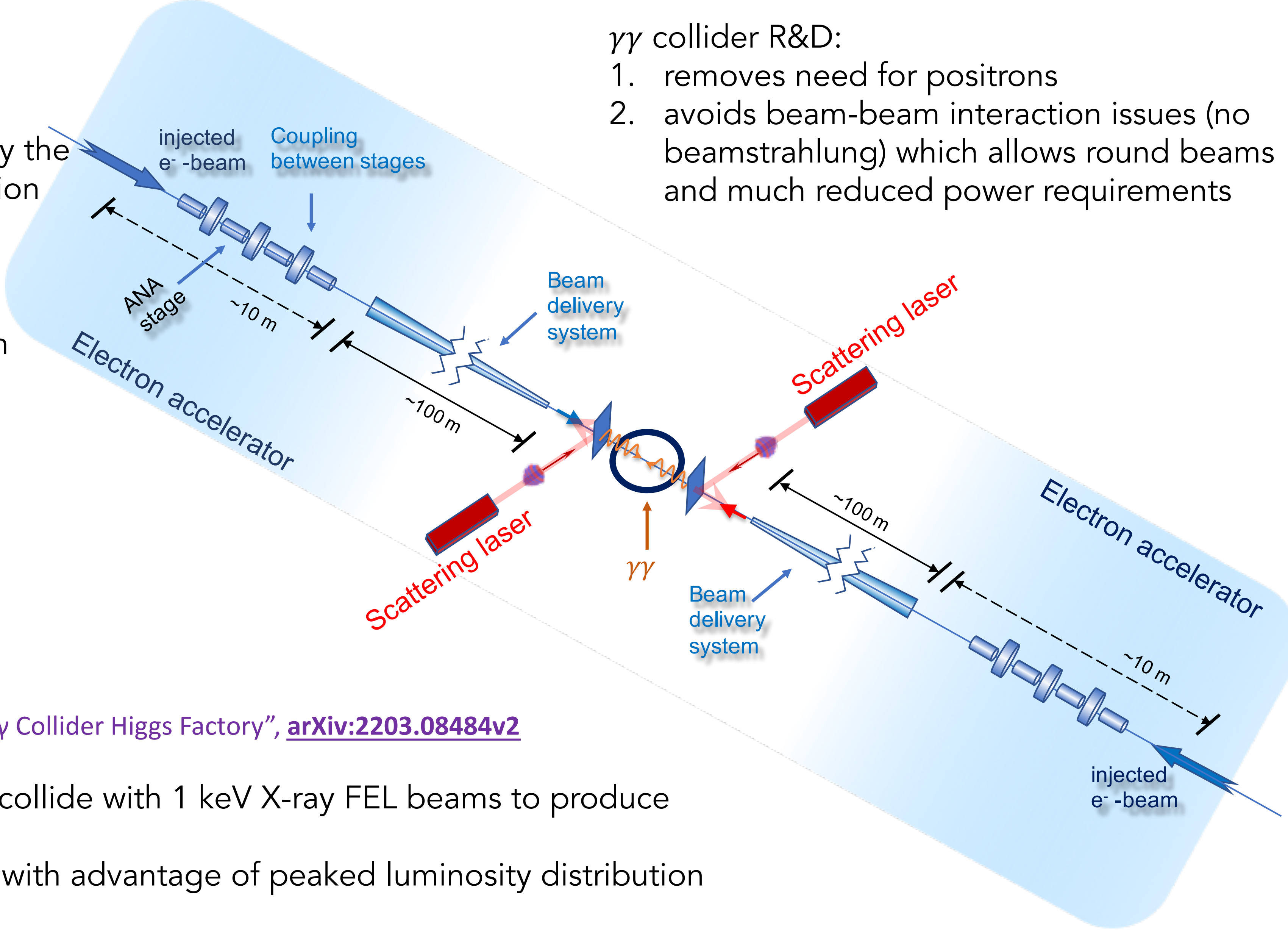
Scattering laser wavelength is determined by the absence of the high-energy photon conversion into e+e- pairs in the laser.

$$x = 4\, U_b\, \boldsymbol{\omega}/m_e^2 < 4.8$$

Laser wavelength to avoid e+e- pair creation (and maximize photon energy ~$0.82U_b$):

$$\boldsymbol{\lambda}[\mathrm{um}] > 4\, U_b[\mathrm{TeV}]$$

Example: $\boldsymbol{\lambda}$=0.2 um for 50 GeV e-beam




$\gamma\gamma$ collider R&D:

1. removes need for positrons
2. avoids beam-beam interaction issues (no beamstrahlung) which allows round beams and much reduced power requirements

X FEL $\gamma\gamma$-collider: "XCC: An X-ray FEL-based γγ Collider Higgs Factory", **arXiv:2203.08484v2**

**γγ** Higgs factory: 62.8 GeV electron beams collide with 1 keV X-ray FEL beams to produce colliding beams of 62.5 GeV photons.

- New regime of operation: x=1000, with advantage of peaked luminosity distribution

# Staged approach for intermediate energy facility

| | collision | Plasma accelerator: |
|---|---|---|
| ~10 years<br>Modest R&D required | *e-* fixed target / high-intensity laser | 10 – 50 GeV; 1 kHz (upgrade 10 kHz) |
| ~15 years | *e- e-* | √s = 20 – 100 GeV ; 1 kHz (upgrade 10 kHz)<br>*e*-polarized<br>L= $4x10^{30}$ $cm^{-2}s^{-1}$ (upgrade $4x10^{31}$ $cm^{-2}s^{-1}$)<br>Higher luminosity (~$10^{32}$ $cm^{-2}s^{-1}$) without polarization |
| ~20 years<br>Significant R&D required | $\gamma$ *e-* , $\gamma\gamma$ | √s = 16 – 80 GeV; 1 kHz (upgrade 10 kHz)<br>L~$2x10^{30}$ $cm^{-2}s^{-1}$ (upgrade ~$2x10^{31}$ $cm^{-2}s^{-1}$)<br>Development of scatter laser source (e.g., FEL) |
| | *e+ e-* | √s = 20 – 100 GeV; 1 kHz (upgrade 10 kHz)<br>e+ plasma acceleration R&D required<br>Development of e+ source; damping ring |

*e+e-* (or $\gamma\gamma$)
√s = 1 TeV (upgrade to 3 TeV, 15 TeV)

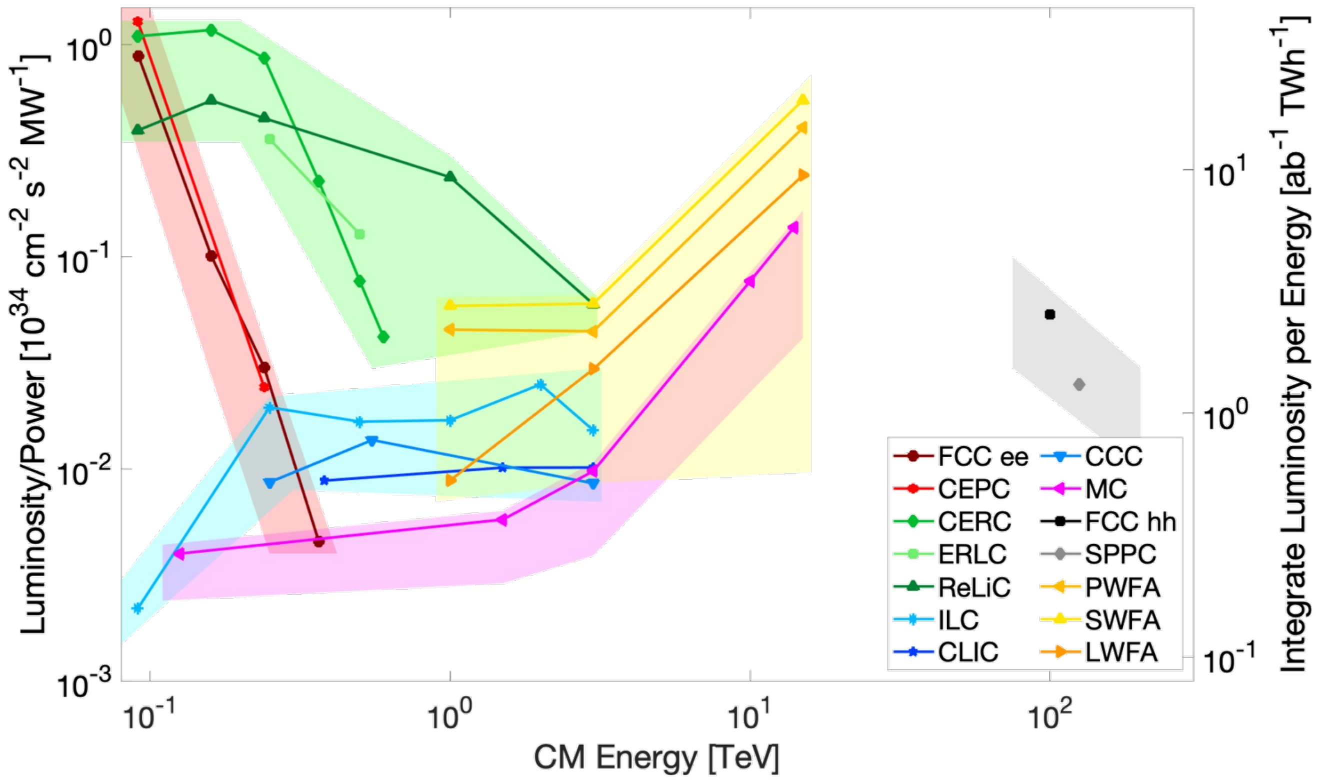
50 kHz
L = $10^{34}$ (upgrade to $10^{35}$)

# Conclusions

- Energy frontier particle physics community desires 10+ TeV cme
- Wakefield accelerators (LWFA, PWFA, SWFA) have made tremendous progress, but current beam test facilities are not focused on collider systems R&D (and acceleration at current facilities limited to ~10GeV).
- To develop technology for collider application, there is a recognized need for an intermediate energy (20-100 GeV) facility to test key collider systems.
  - Main motivation is advanced accelerator R&D
  - Opportunities for QCD and BSM physics studies


Thank you

# Back up



Luminosity/Power [$10^{34}$ cm$^{-2}$ s$^{-2}$ MW$^{-1}$]
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
CM Energy [TeV]
Integrate Luminosity per Energy [ab$^{-1}$ TWh$^{-1}$]
$10^1$
$10^0$
$10^{-1}$
FCC ee
CEPC
CERC
ERLC
ReLiC
ILC
CLIC
CCC
MC
FCC hh
SPPC
PWFA
SWFA
LWFA