Accelerator physics
R&D at a mid-scale (10-100 GeV) facility

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Strong energy frontier interest in 10+ TeV cme

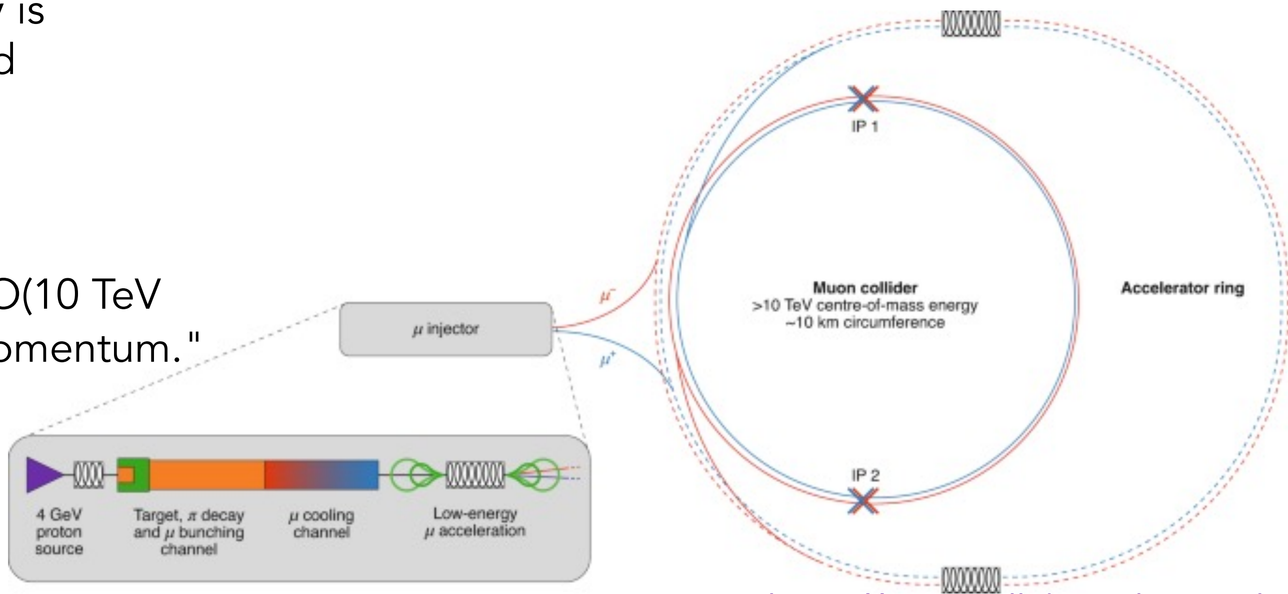
Snowmass: US particle physics community planning exercise to identify and document a scientific vision for the future of particle physics in the US. Provides input to P5 (Particle Physics Project Prioritization Panel).

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

R&D on new technologies required to reach energy frontier

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Challenging energy scale requires emphasis on

- R&D on new technologies required to provide viable options at 10+ TeV (parton cme)
  - ➢ Leptons offer clean collisions with strong physics potential
  - ➢ Similar physics is anticipated to be accessible with muon or e+e- machines
  - ➢ gamma-gamma colliders likely access significant portion of physics, analysis less complete

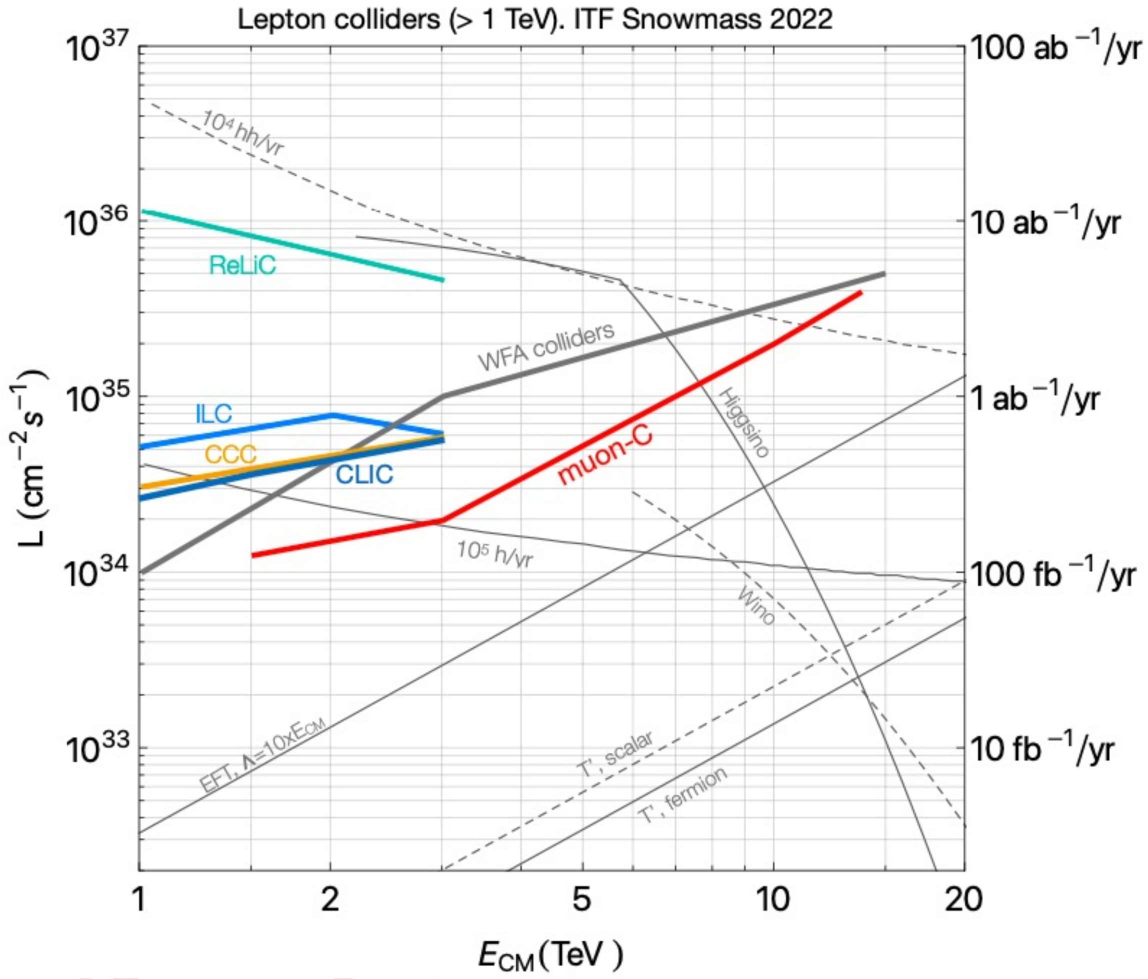
- New technologies must reduce power consumption

- With multi-decade timeline, important to leverage nearer-term applications (HEP, basic science, medicine, industry, security, etc.) to provide motivation for new test facilities for technology development

Advanced and novel accelerators (wakefield accelerators) have been focused on demonstrating and developing high-gradient plasma and structures and high-quality beams. New beam test facilities are required to test and develop auxiliary collider systems.

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.

Advantages of WFA for HEP applications:

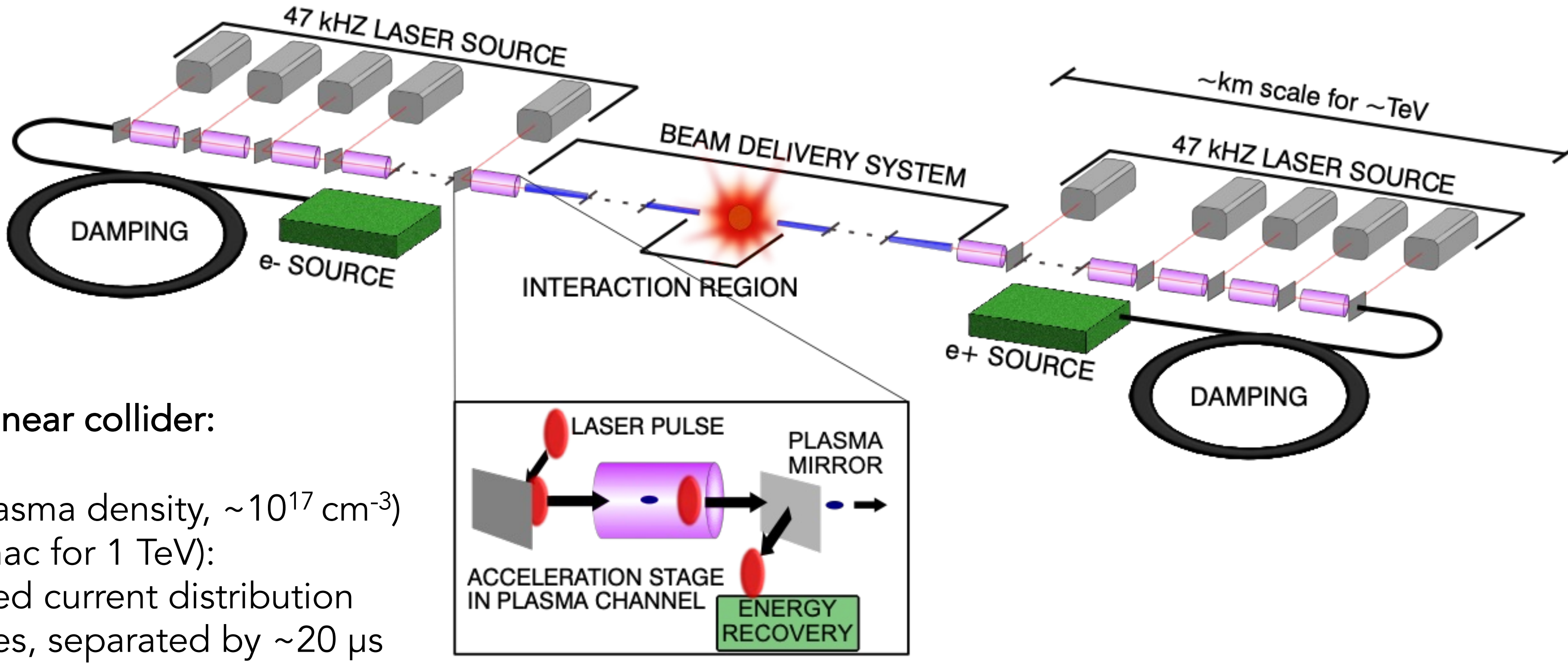
- Ultra-high gradient
- Short bunch lengths (reduced beamstrahlung and power savings)

Reduction of power consumption is main challenge of future colliders

- Use round beams to increase luminosity/power (operates in high-beamstrahlung regime at >TeV); Luminosity spectrum is degraded
- 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 toward a collider at existing test facilities

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Anticipated HEP-focused demonstrations at existing beam test facilities in the near term (circa 2025):

Some examples:

- Plasma repetition rate limits characterized @ FLASHForward
- Laser-driven staging of multi-GeV cells with high capture efficiency @ BELLA
- Beam driven 10 GeV stage with mm-mrad emittance, percent energy spread, high-efficiency @ FACET-II
- 500 MeV SWFA demonstrator module @ AWA
- and others…

FLASHForward

DESY.

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SLAC NATIONAL ACCELERATOR LABORATORY

FACET-II

AWA

Argonne NATIONAL LABORATORY

Near- and mid-term (non-collider) applications will establish technology, and benefit future colliders:

- Compton MeV photons
- Plasma-accelerator-driven FELs
- Nonlinear QED studies
- High-brightness electron injectors
- …

New facilities coming soon to develop technology and applications

EuPRAXIA

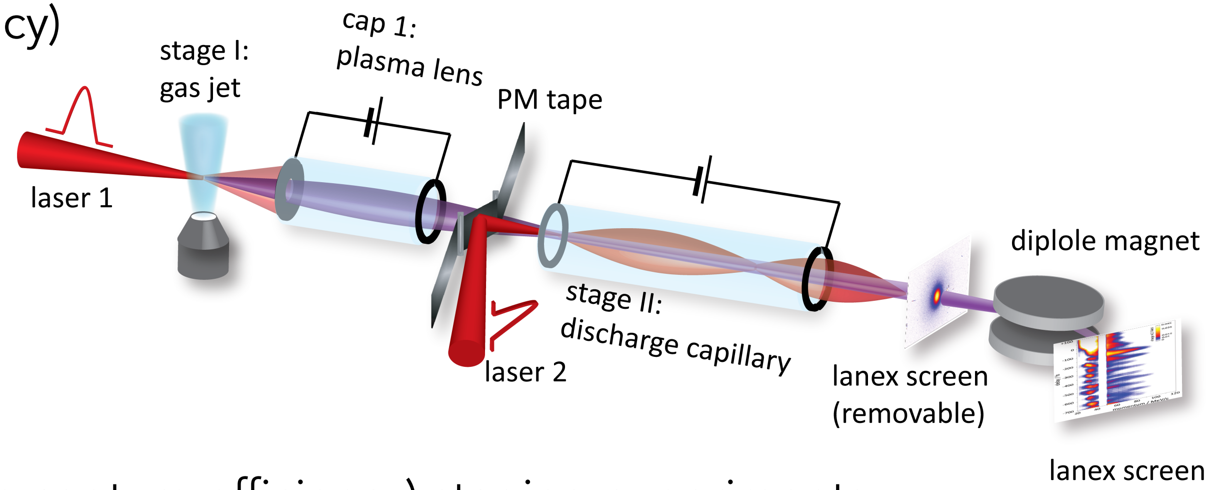
CLF central laser facility

EPAC

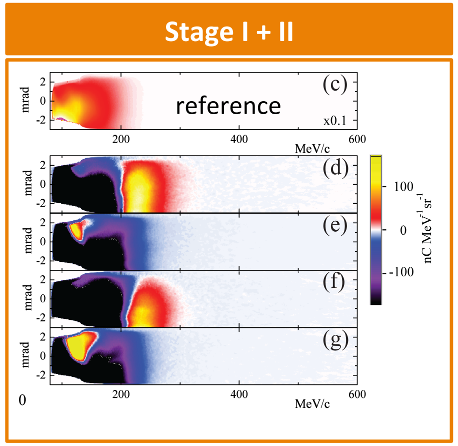
and others…

R&D on LWFA staging underway at Berkeley Lab

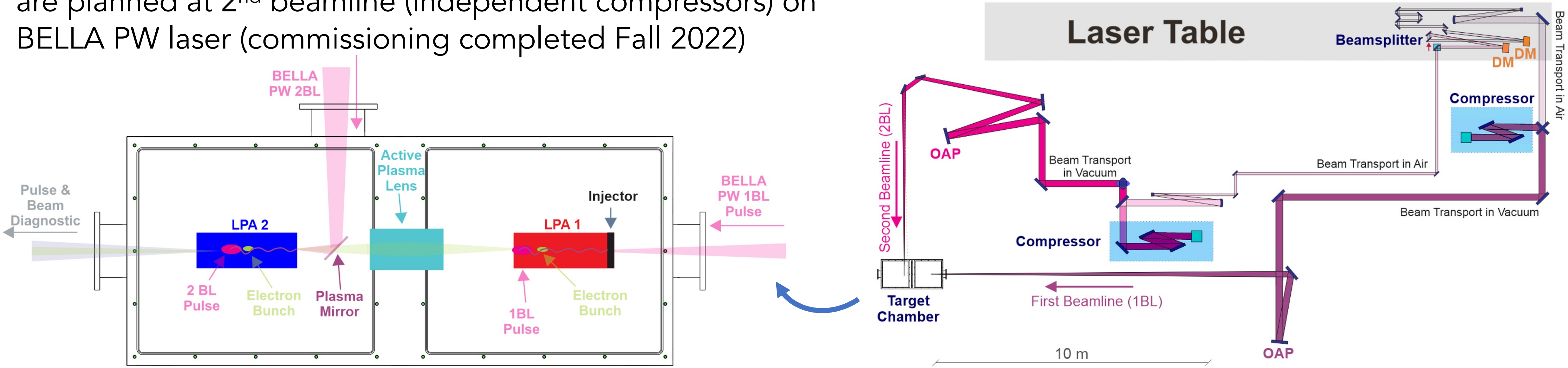
- Proof-of-principle experiment demonstrate 100 MeV energy gain (low capture efficiency)



Steinke et al. Nature (2016)



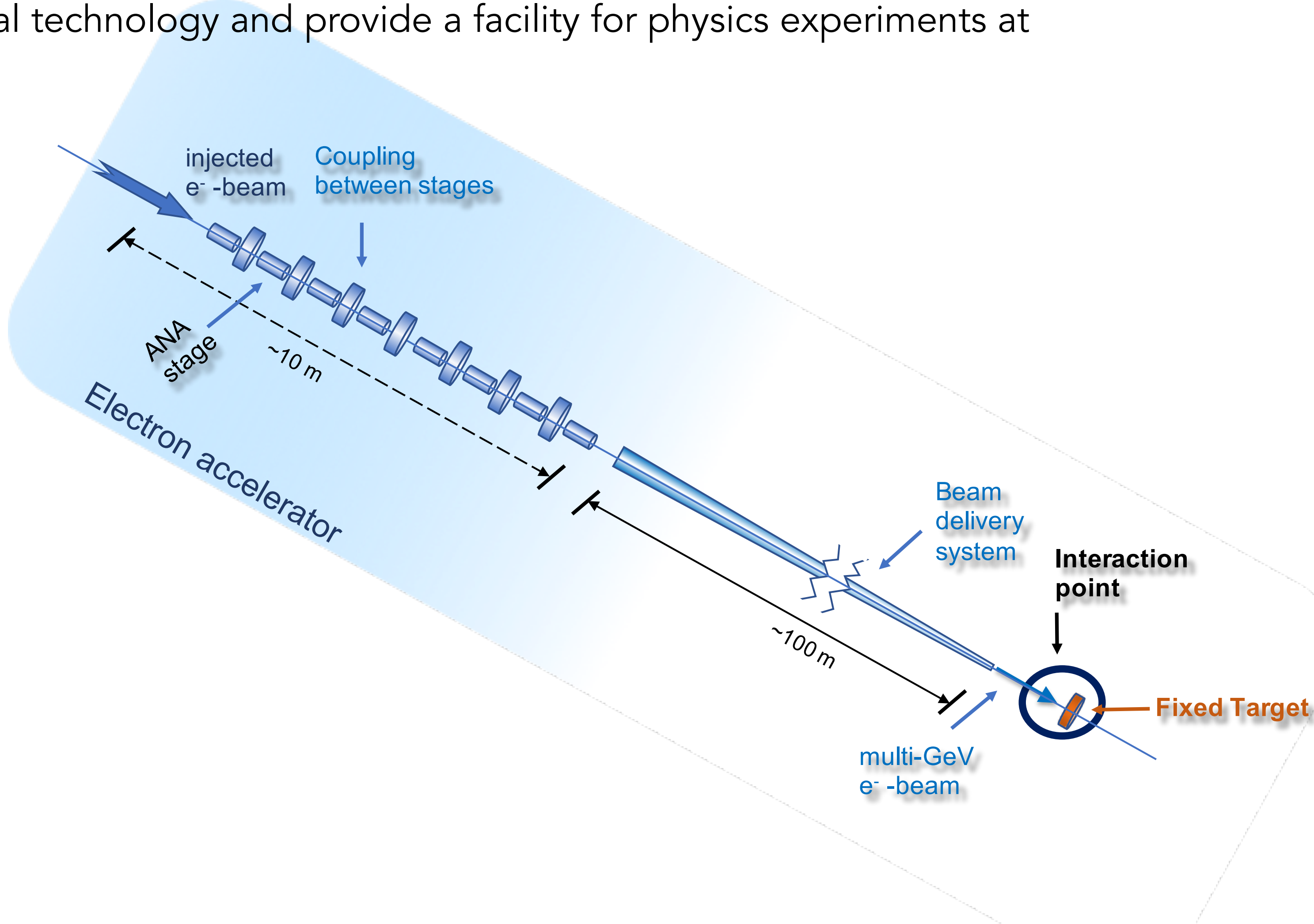
- Multi-GeV (with high capture efficiency) staging experiments are planned at 2nd beamline (independent compressors) on BELLA PW laser (commissioning completed Fall 2022)



Intermediate energy ANA demonstration facility

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
- Demonstrate high rep rate operation
- Polarization studies
- Beamstrahlung studies
- Positron acceleration
- Cooling
- …

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

Electron linac at 10-100 GeV

e- Injector:

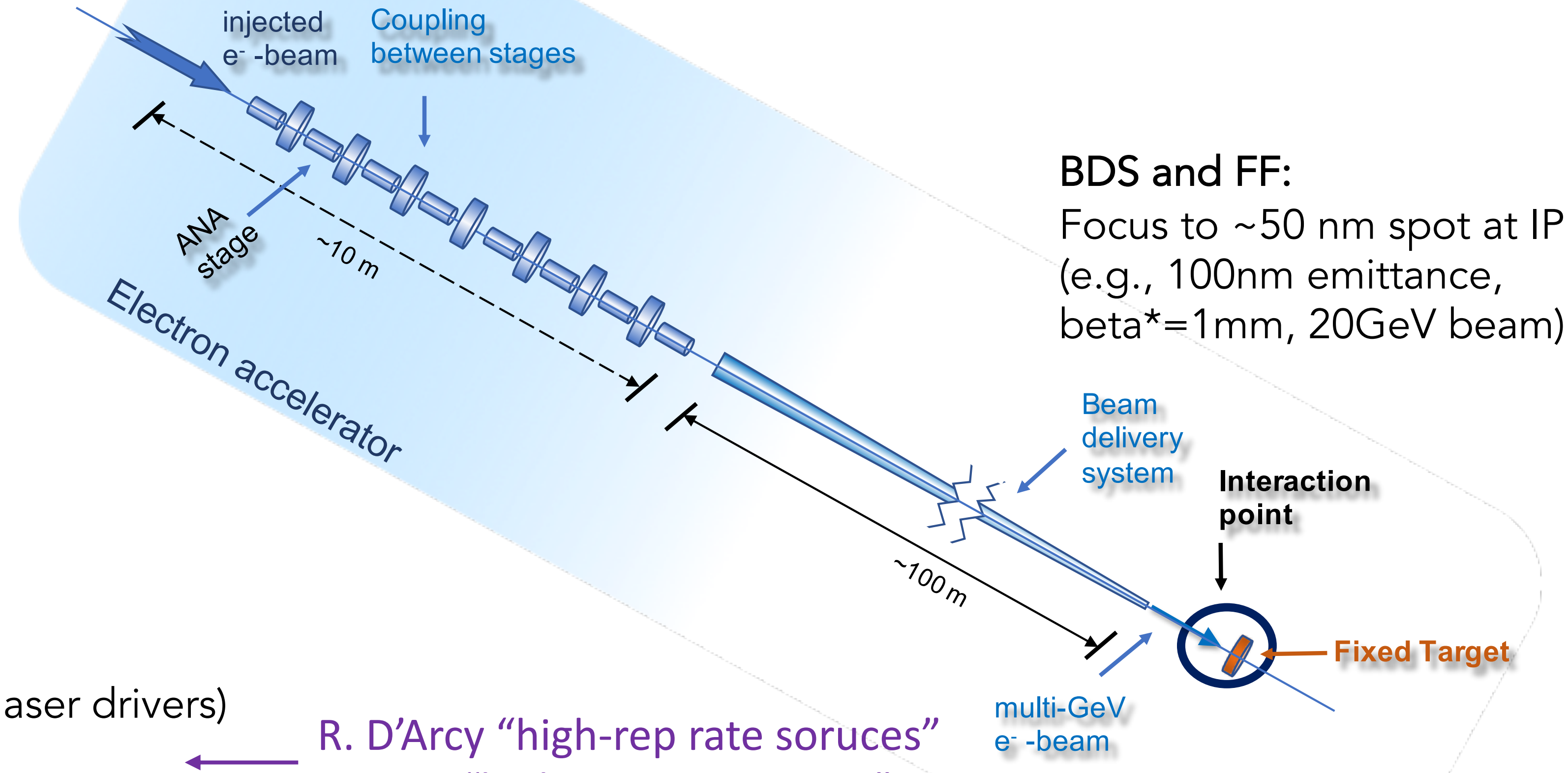
Use photo-cathode (GaAs/GaAsP superlattice) with near full e- polarization. -> study polarization preservation in plasma
Using RF photo gun methods to achieve: 0.1um normalized emittance
Develop beam current profile shaping

Bunch compressors:

tens micron beam length for plasma linacs

OR
Plasma-based injection,
density gradient or ionization injection
(plasma photocathode),
<0.1um achievable

Hidding et al., PRL (2012)
Schroeder et al., PRAB (2014)
Xu et al., PRAB (2017)



BDS and FF:

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

ANA stage R&D:

- High-rep rate coupling (plasma mirrors for laser drivers)
- High-rep rate plasma targets
- Alignment techniques to manage tolerances
  - ➢ High gradient → high frequency ($E_z \sim \boldsymbol{\omega}_p$) → (sub-)um/fs spatial/temporal scales

← R. D'Arcy "high-rep rate soruces"
B. Cros "high-rep rate targets"

← C. Lindstrom "staging tolerances"
G. White "transverse tolerances"
M. Thevenet "tolerances for emittance"

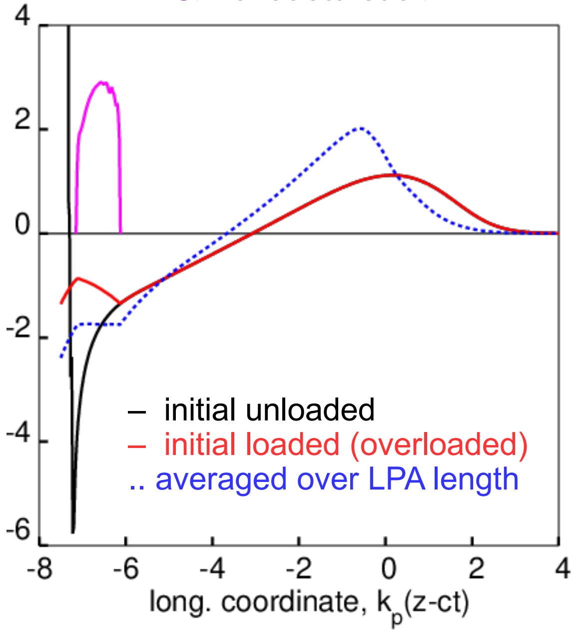
Self-guided stage providing high-gradient, high-charge, and high-efficiency acceleration

Laser: U=50 J, **λ**=0.8 um, a_0=4.5, k_pL=2.27, k_pw_0=4.02,

Plasma: n_0= 4.6x10^{17} cm^{-3}, stage length = 3.1 cm, linear taper (+74%)

Bunch: near-parabolic current profile; wake overloading to minimize energy spread [positive energy chirp imparted initially (overloading) compensated during acceleration → minimum energy spread achieved at the end of the stage]

C. Benedetti et al.

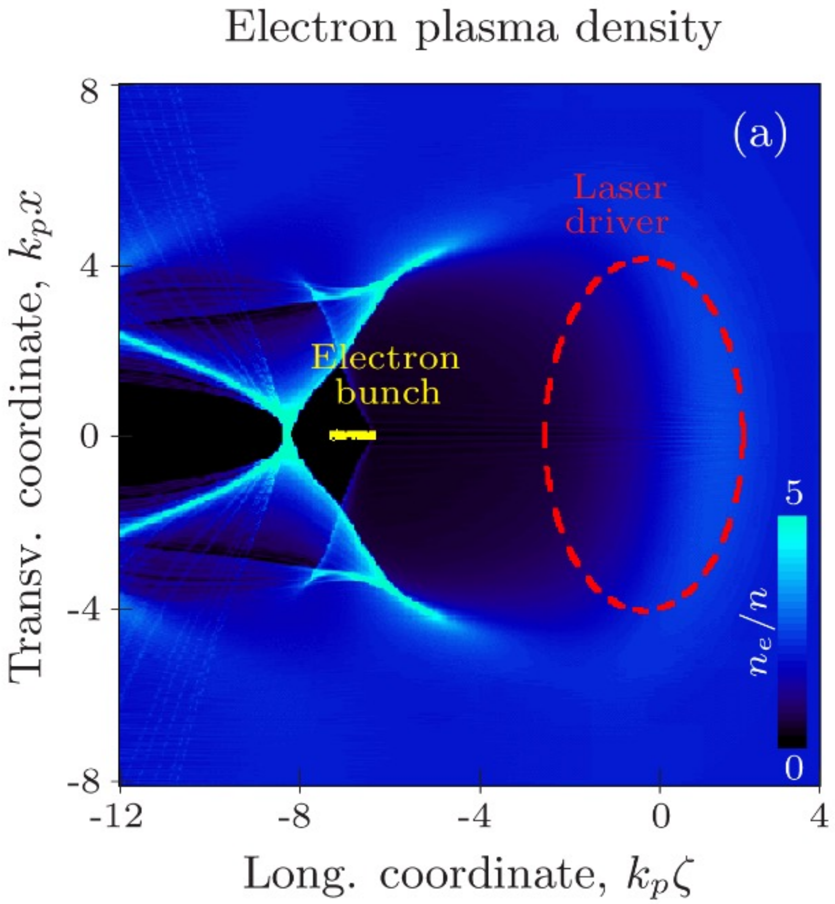


ΔW_{bunch}= 3.53 GeV (115 GV/m peak)
Energy spread = 0.09%
Q_{bunch}= 1.09 nC
Wake-to-bunch transfer = 40%
Laser driver depletion = 20%

<u>Note on transverse stability</u>:
ion motion occurs for few GeV, sub-micron emittance e-beams; mitigates hosing instability

Mehrling et al., PRL (2018)

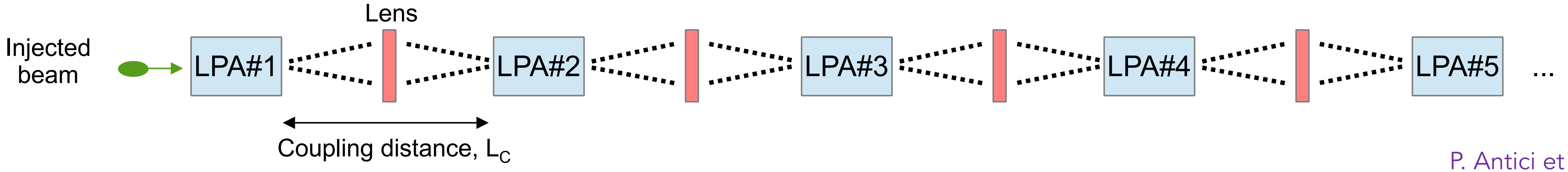
Schroeder et al., JINST (2022)

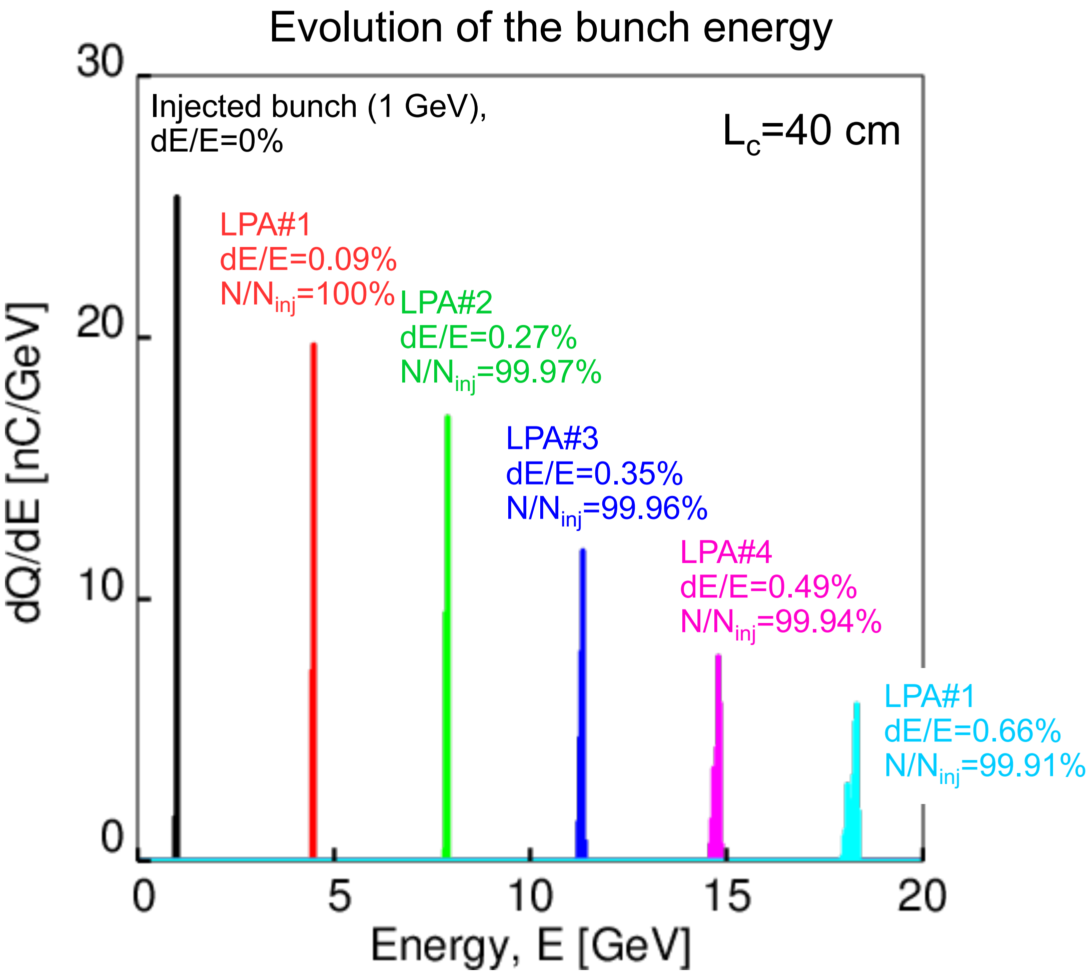


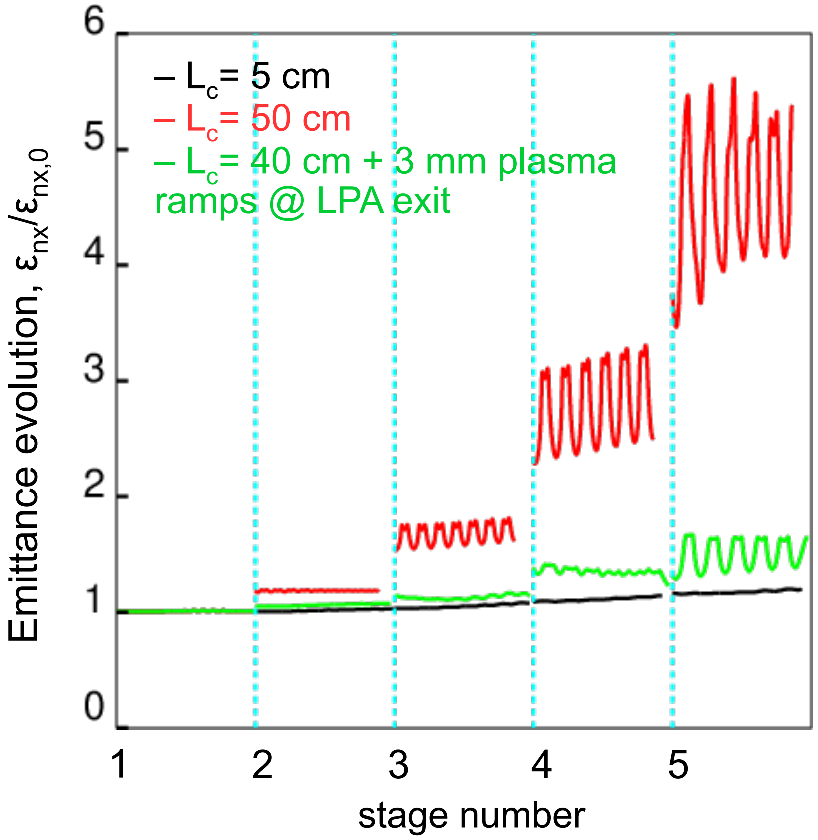
Tens of GeV linac → cascading a tens of stages

Laser plasma accelerator staging

C. Benedetti et al.







P. Antici et al., JAP (2012)
M. Migliorati et al., PRAB (2013)
C. A. Lindstrom, PRAB (2021)
Thomas & Seipt, PRAB (2022)

Emittance growth from chromaticity in drifts:

$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

Emittance preservation during staging challenging due chromatic effects:
→ emittance growth, mismatch, increase of energy spread, particle loss

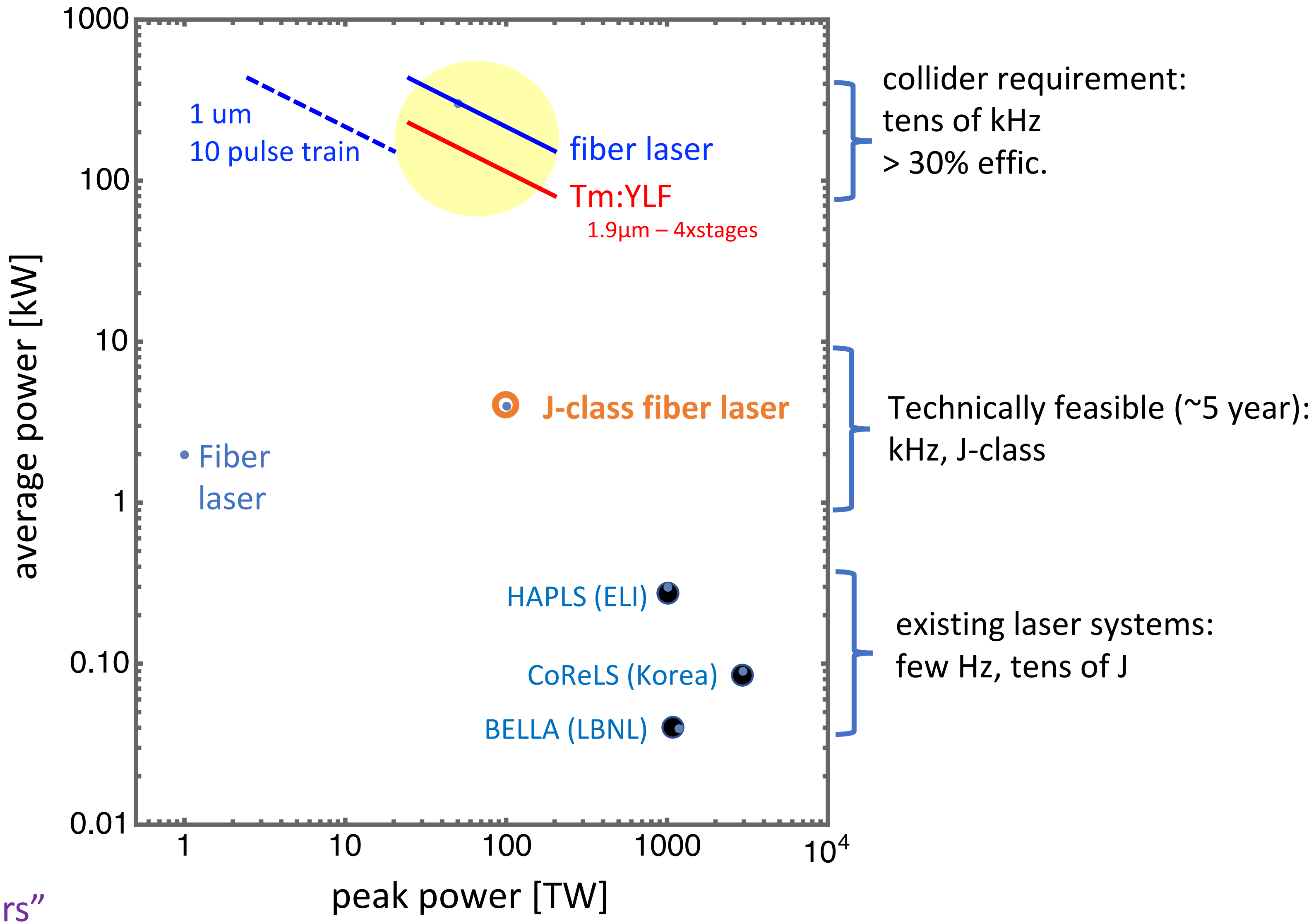
→ Staging would benefit from development of compact achromatic inter-stage transport optics (or with large chromatic acceptance)

Laser driver technology R&D required for collider

Laser drivers:

- Requires significant 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

See talk by L. Corner "high-rep rate laser drivers"



R&D on fiber laser combining at Berkeley Lab

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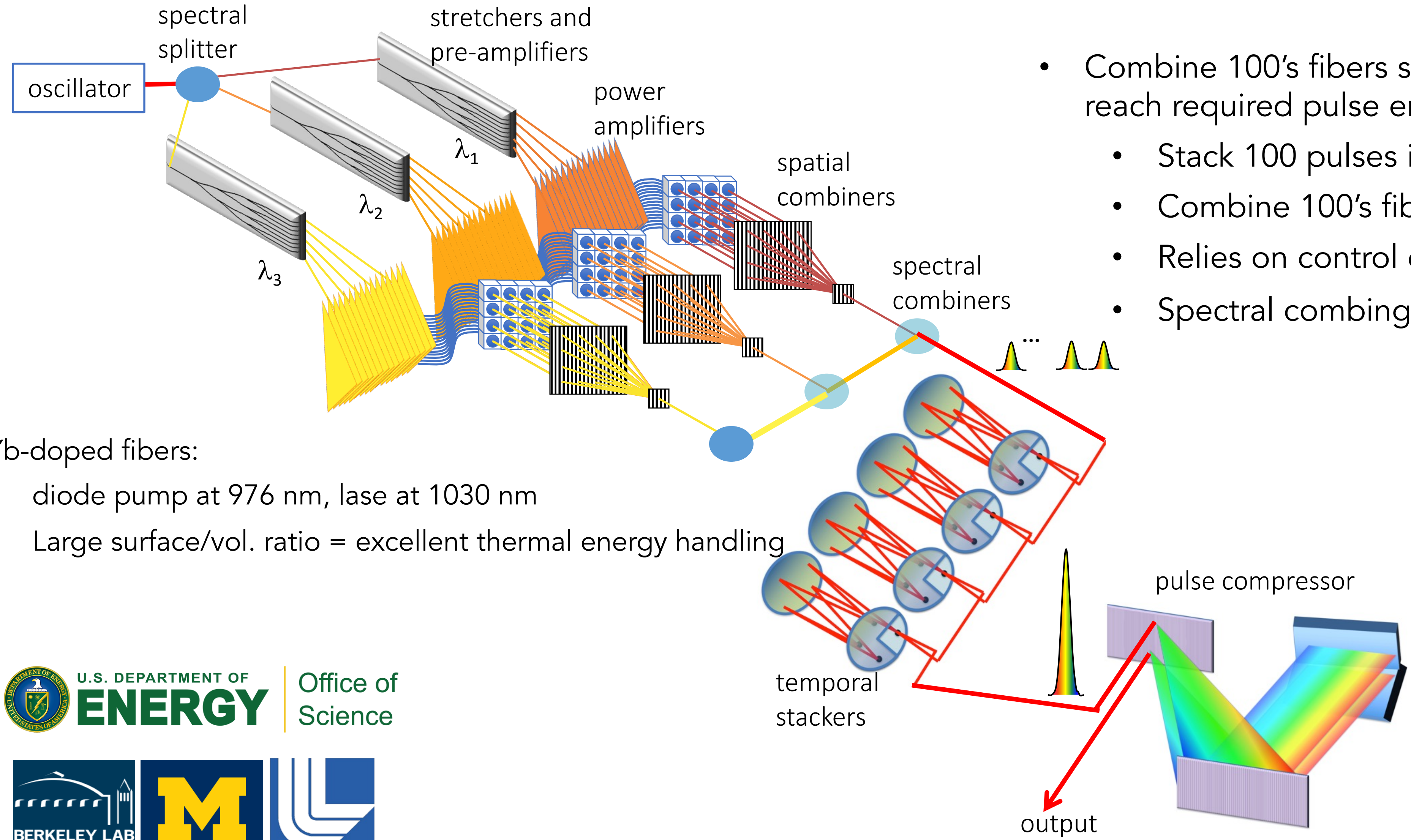
Concept: Use high efficiency, high average power fiber lasers, and add them coherently for high pulse energy



- Combine 100's fibers spatially x 100 pulses temporally to reach required pulse energy
  - 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:

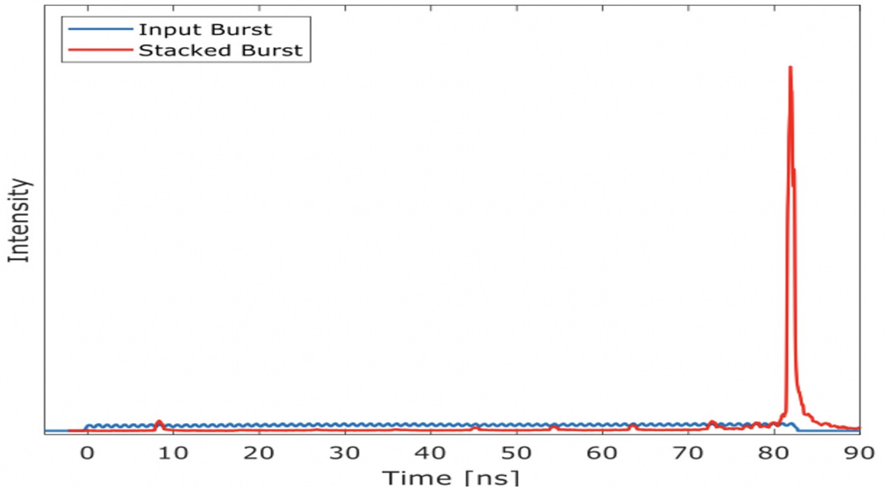
- diode pump at 976 nm, lase at 1030 nm
- Large surface/vol. ratio = excellent thermal energy handling

- Achieved 23mJ with 3 spatial 81-pulse channels combined at 1kHz rep-rate
- Integration in FY23/24 to achieve >100mJ at 1kW

U.S. DEPARTMENT OF ENERGY | Office of Science

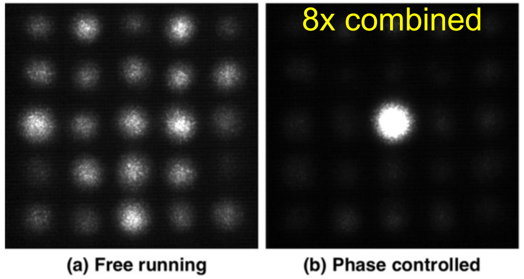
“High average power ultrafast laser technologies for driving future advanced accelerators” arXiv:2204.10774

Achieved to date on coherent combining fiber lasers

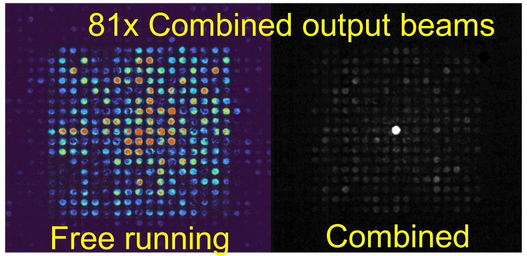


- 100 pulses can be stacked temporally to single pulse with 8 cavities
- Demo 81 pulses, and achieved full fiber energy extraction (>10 mJ) at U. Michigan

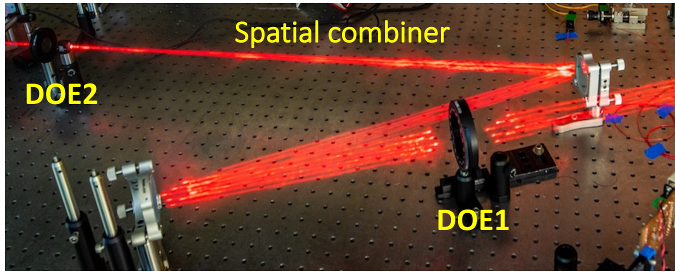
T. Zhou et al. *Optics Express* 23, 7442 (2015)



Combined eight, 100fs beams with 90% efficiency

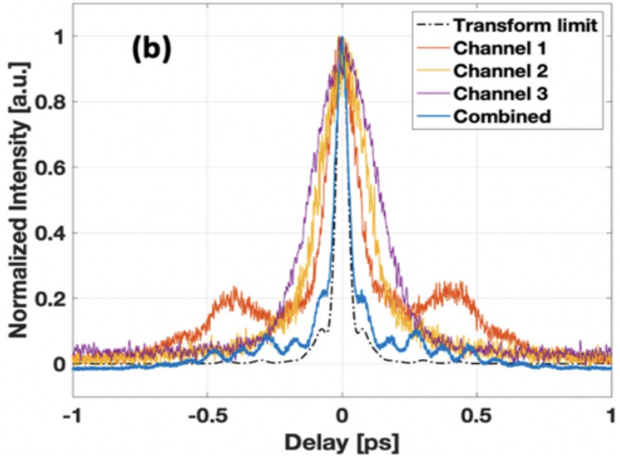


Combined 81 beams (low power, demo phase control) with single combiner



T. Zhou et al. Optics Letters 21, 4422 (2017)

In addition, must demo high power compressor, optics, & laser diagnostics



- 3 channels spectrally combine to 42 fs

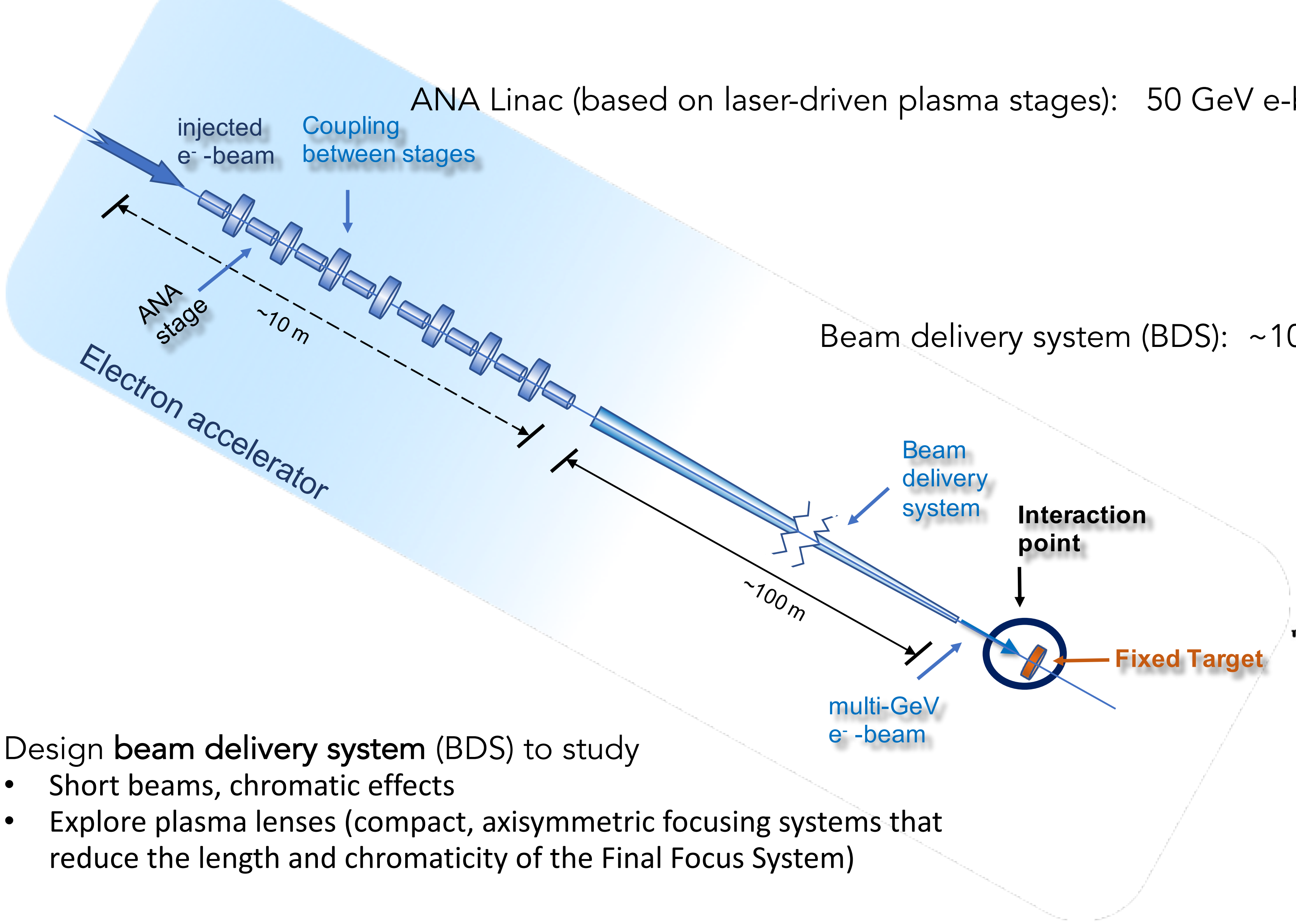
S. Chen et al. Optics Express (2023)

➢ Next step (FY23/24): 27 spatial beam, 81 temporal pulses, 3 spectral bands (200mJ, 1kW)

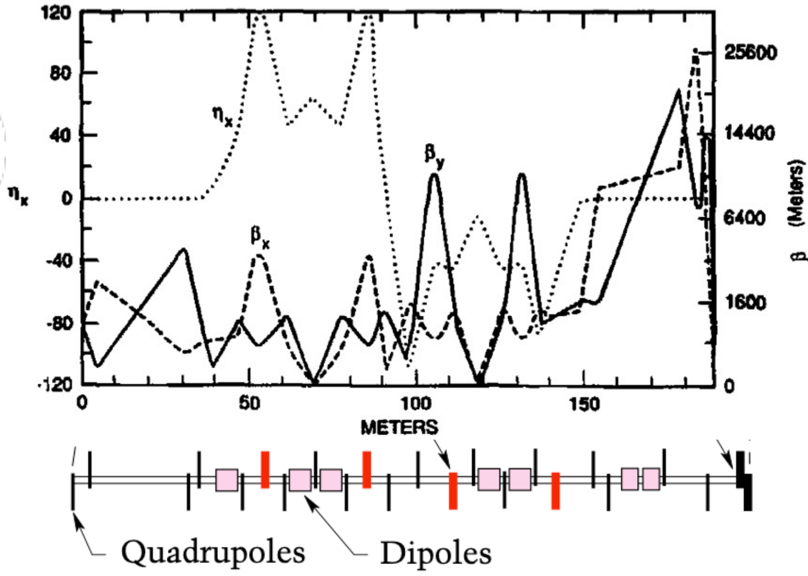
Facility footprint

ANA Linac (based on laser-driven plasma stages): 50 GeV e-beam → 15 stages → ~8m

Beam delivery system (BDS): ~100m



Example: FFTB @ SLAC
(60 nm focus of 47GeV beam)

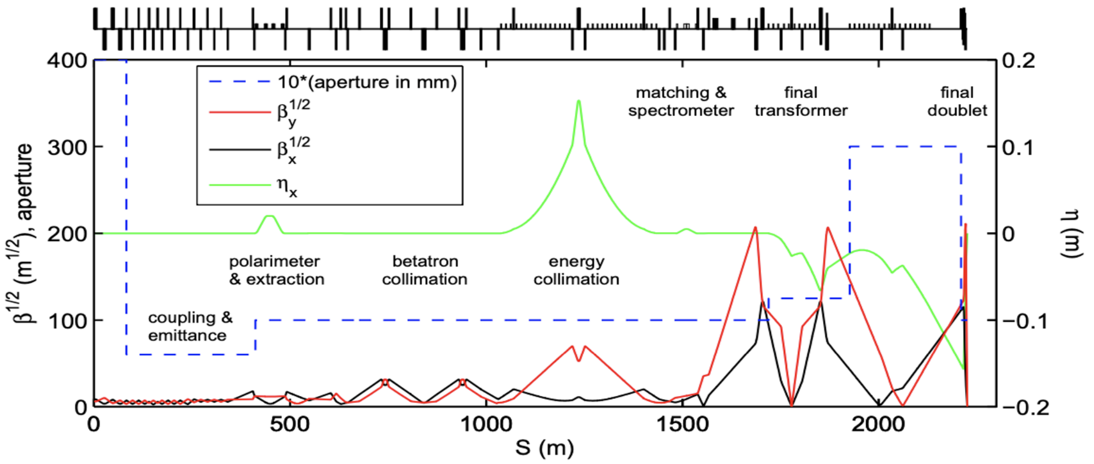


Design **beam delivery system** (BDS) to study

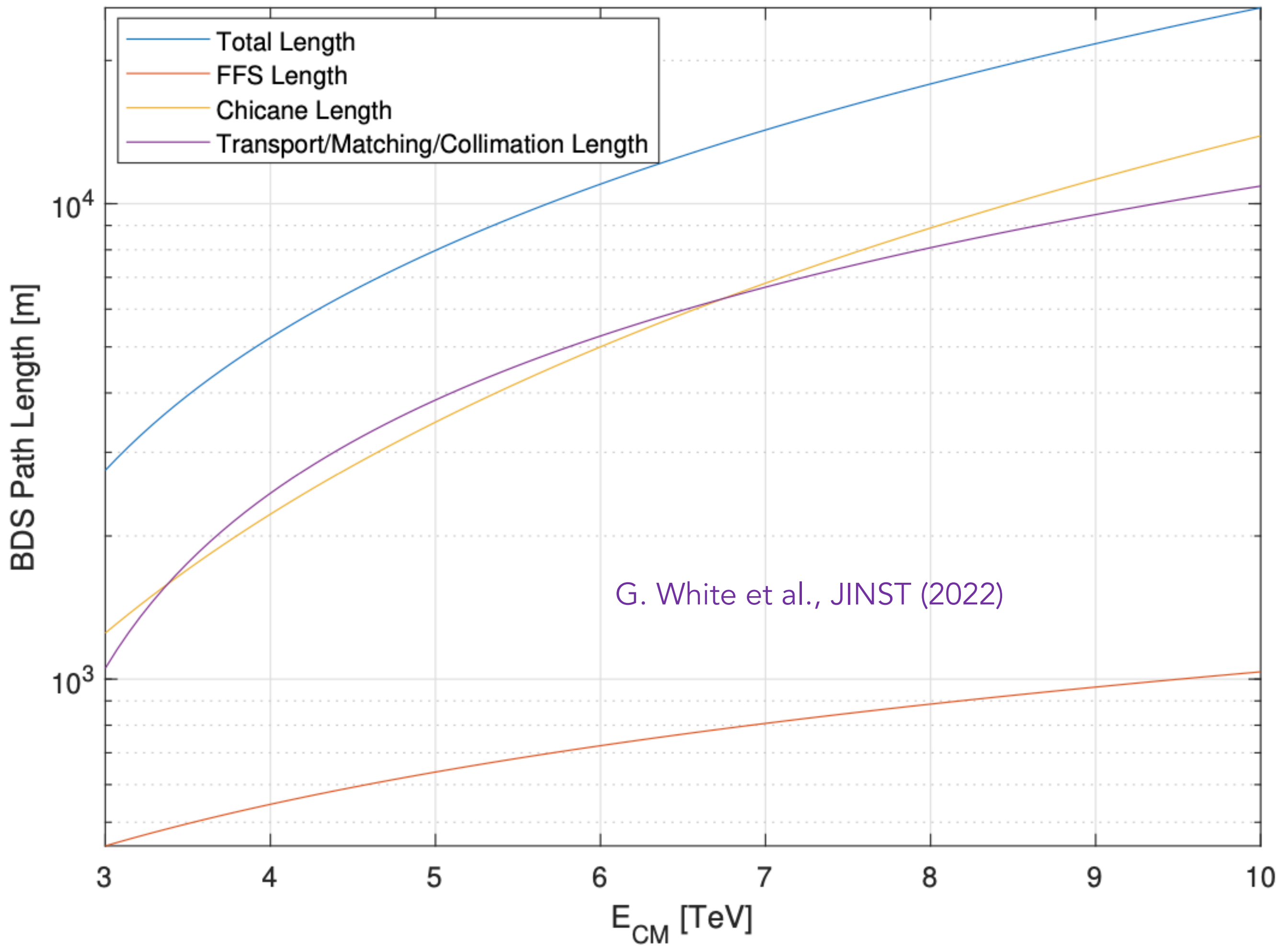
- Short beams, chromatic effects
- Explore plasma lenses (compact, axisymmetric focusing systems that reduce the length and chromaticity of the Final Focus System)

Beam delivery system R&D for future ANA colliders

ILC Beam Delivery System (BDS)



BDS energy scaling: "CLIC-style" BDS system



BDS is much longer than linac for wakefield colliders.

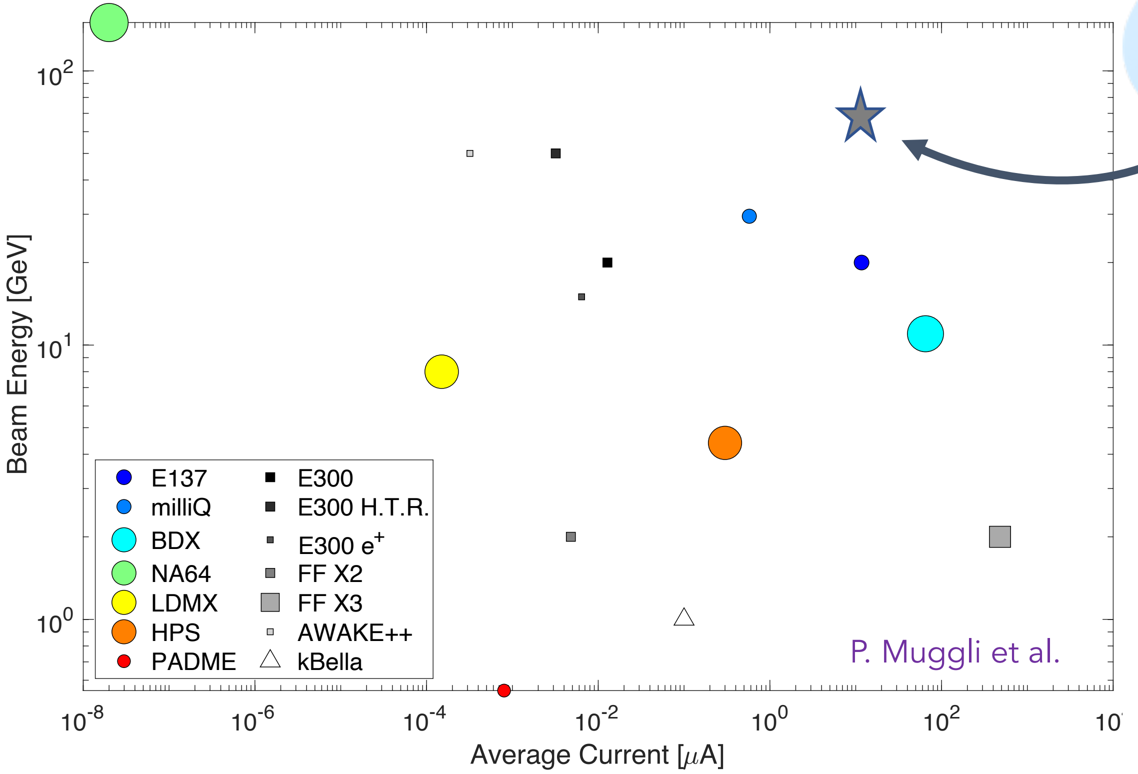
- R&D is needed!

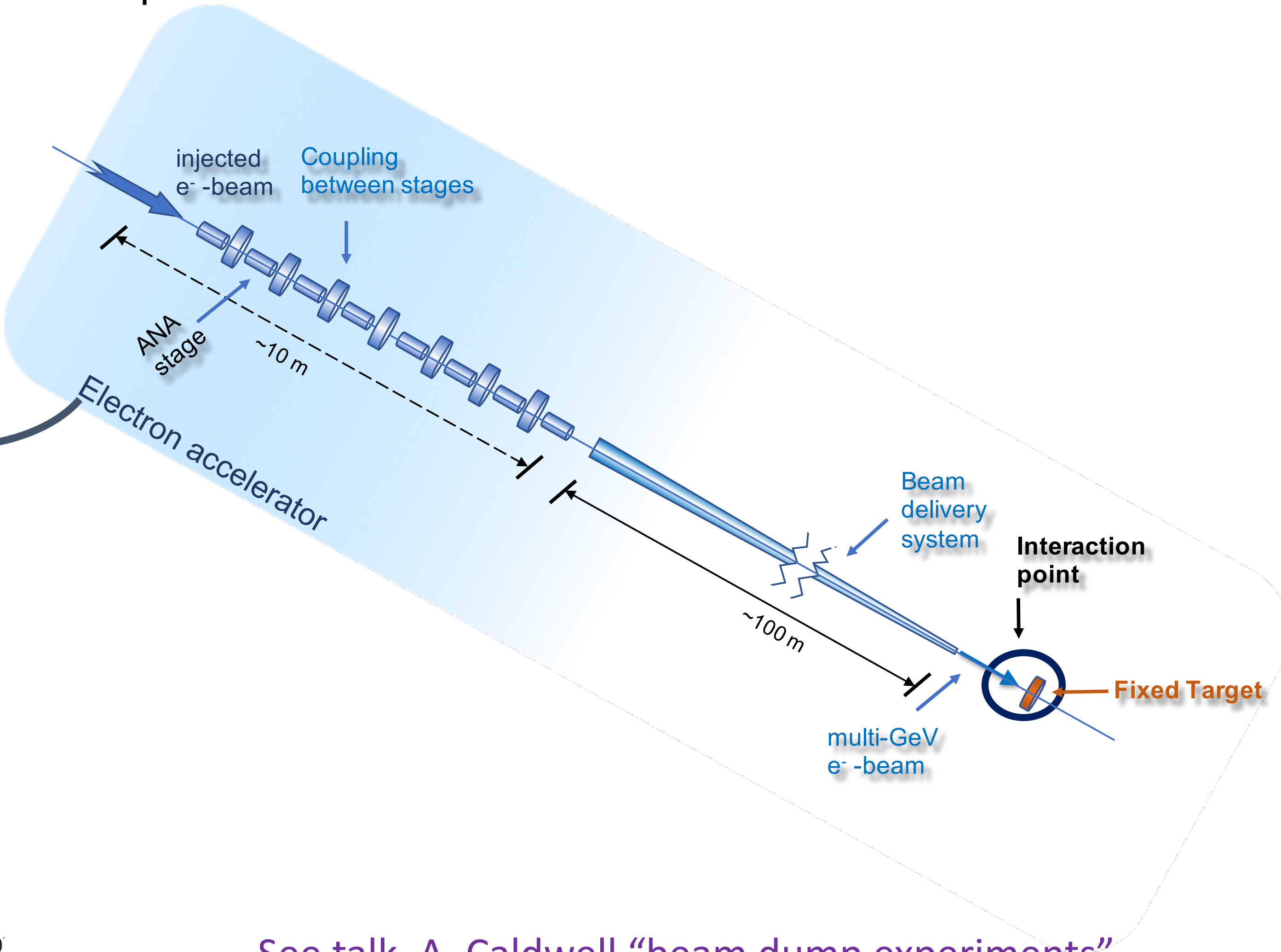
Beam dump / fixed target experiments

With single electron linac:

- Beam dump/fixed target experiments to investigate/detect rare processes, dark sector searches

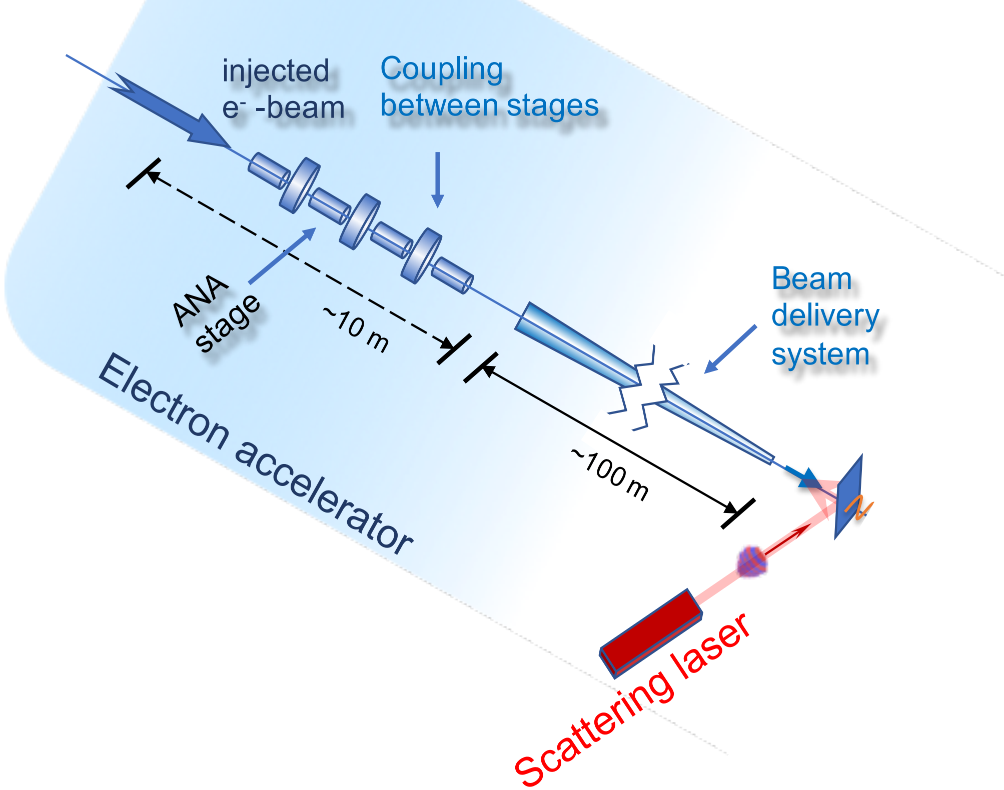
Existing and future fixed target (beam dump) experiments:
(energy and flux determines science reach)





See talk, A. Caldwell “beam dump experiments”

Beamstrahlung studies at mid-scale facility



High-power (multi-PW),
high-intensity laser system

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

Mid-scale energy facility allows exploration of nonlinear QED with quantum parameter >>1 to access SF-QED interaction regimes.

See next talk, M. Zepf “Non-linear QED”

Two electron linacs: gamma-gamma collider

<u>"conventional" $\gamma\gamma$-collider</u>:

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

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

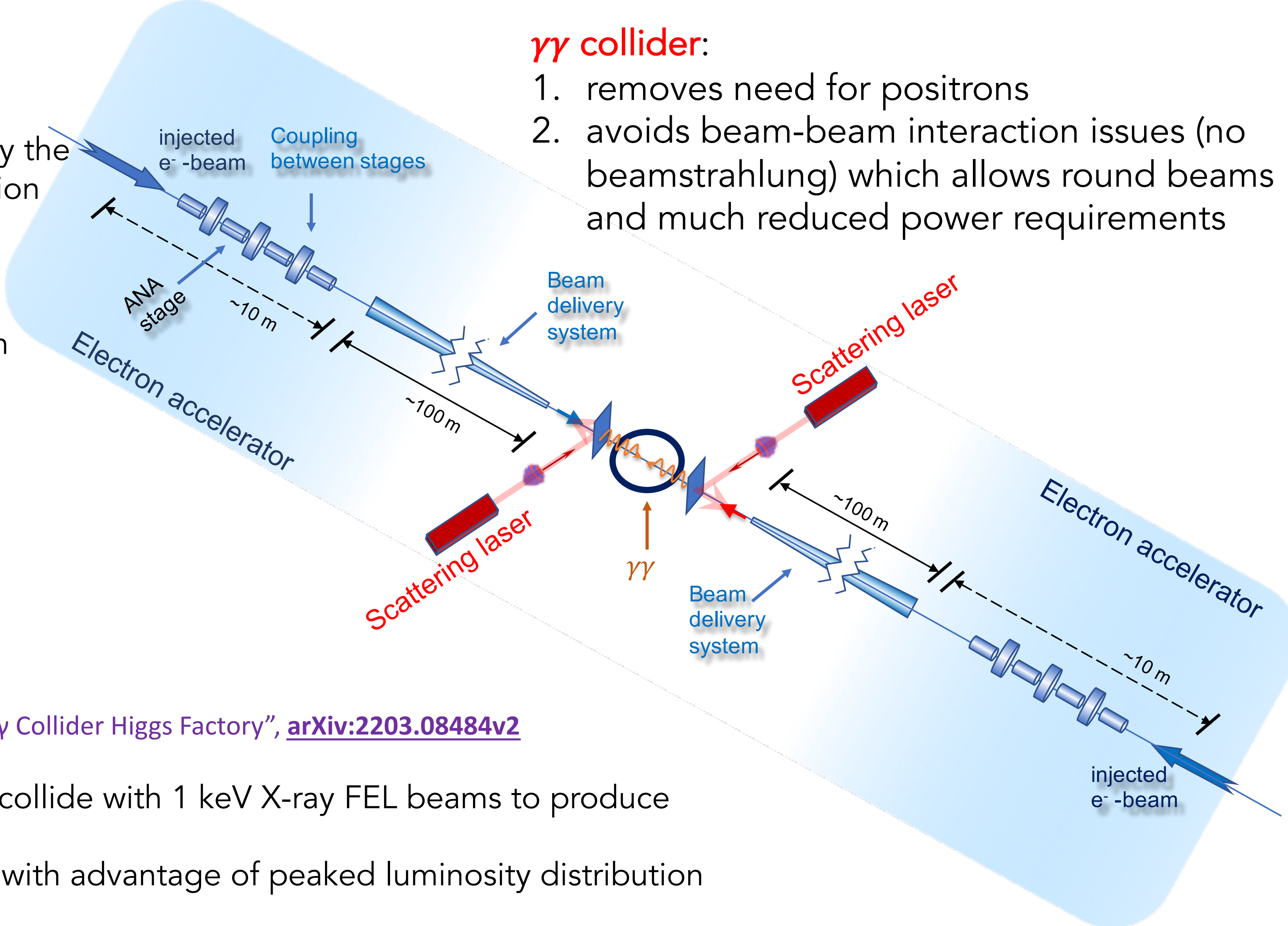
Laser wavelength to avoid e+e- pair creation (and maximize photon energy ~0.82U$_b$):

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

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

$\gamma\gamma$ collider:

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



<u>X-FEL $\gamma\gamma$-collider</u>: "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

e+e- collider demonstration facility

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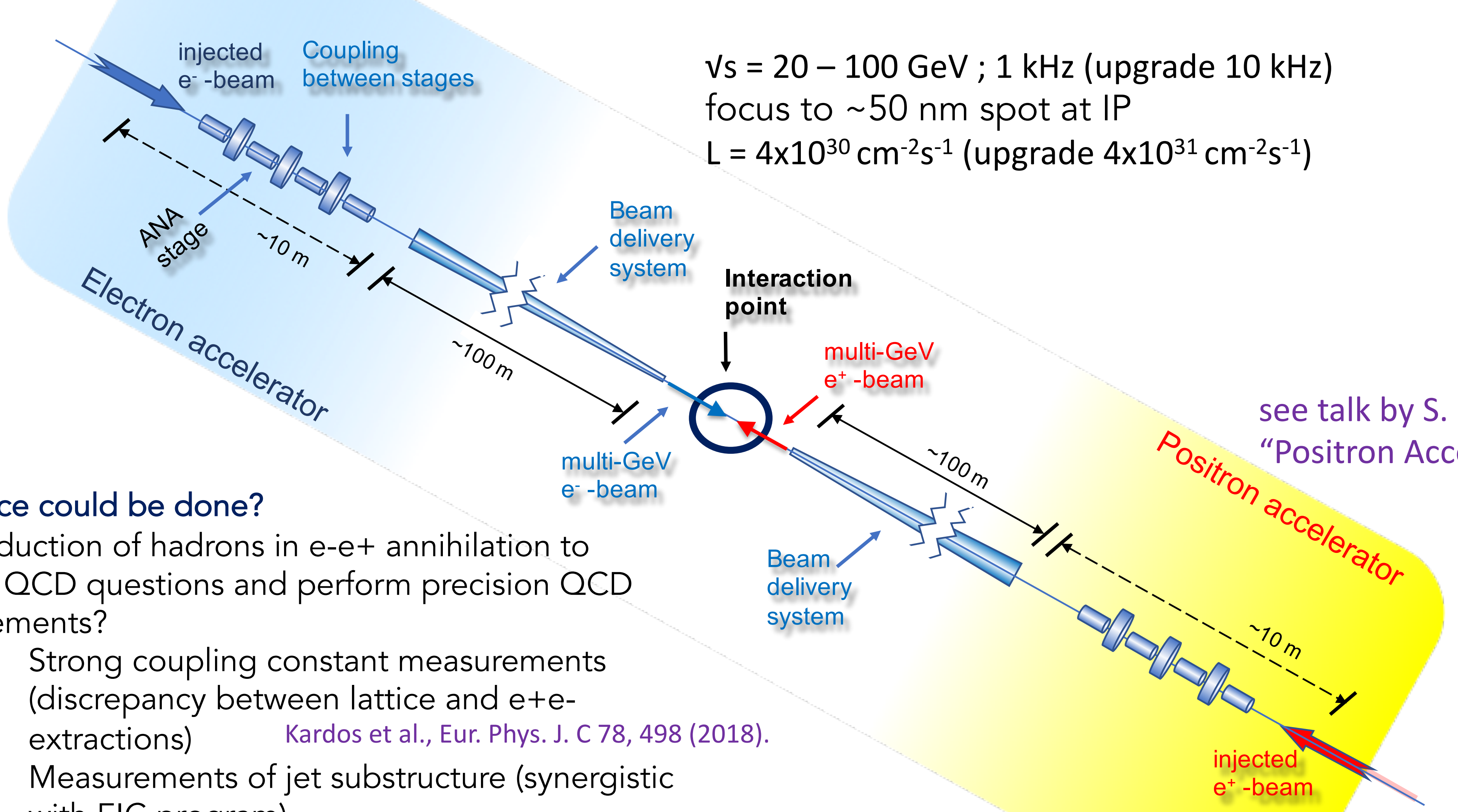
$\sqrt{s}$ = 20 – 100 GeV ; 1 kHz (upgrade 10 kHz)
focus to ~50 nm spot at IP
L = 4×10^{30} $cm^{-2}s^{-1}$ (upgrade 4×10^{31} $cm^{-2}s^{-1}$)



see talk by S. Diederichs
"Positron Acceleration"

What science could be done?

- Use production of hadrons in e-e+ annihilation to address QCD questions and perform precision QCD measurements?
    - Strong coupling constant measurements (discrepancy between lattice and e+e- extractions) Kardos et al., Eur. Phys. J. C 78, 498 (2018).
    - Measurements of jet substructure (synergistic with EIC program)
    - New tests of QCD factorization (and universality of hadronization effects)

- Requires e+ source (tens of GeV e- beam)
- Requires e+ damping ring for cooling before linac

Staged approach for mid-scale facility

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	collision	Plasma accelerator:
~10 years 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) *e*-polarized L= 4×10^{30} $cm^{-2}s^{-1}$ (upgrade 4×10^{31} $cm^{-2}s^{-1}$) Higher luminosity (~10^{32} $cm^{-2}s^{-1}$) without polarization
~20 years Significant R&D required	*γ e- , γγ*	√s = 16 – 80 GeV; 1 kHz (upgrade 10 kHz) L~2×10^{30} $cm^{-2}s^{-1}$ (upgrade ~2×10^{31} $cm^{-2}s^{-1}$) Development of scatter laser source (e.g., FEL)
	e+ e-	√s = 20 – 100 GeV; 1 kHz (upgrade 10 kHz) e+ plasma acceleration R&D required Development of e+ source; damping ring

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

50 kHz
L = 10^{34} $cm^{-2}s^{-1}$ (upgrade to 10^{35} $cm^{-2}s^{-1}$)

Conclusions

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- 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 1-10GeV, low average power).
- To develop technology for collider application, there is a need for a mid-scale (10-100 GeV) facility to test key collider systems.
  - Main motivation is advanced accelerator R&D
  - Opportunities science

Thank you