C3Demo, a cool path towards the next generation high efficient compact LINAC

GSI Accelerator Seminar

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Acknowledge to C3Demo Design Study team

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SLAC NATIONAL ACCELERATOR LABORATORY

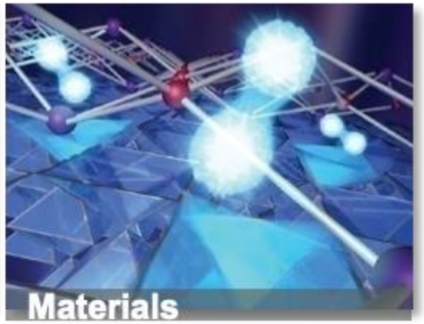
Stanford University | U.S. DEPARTMENT OF ENERGY

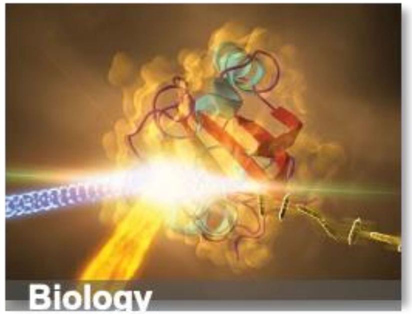
Abstract

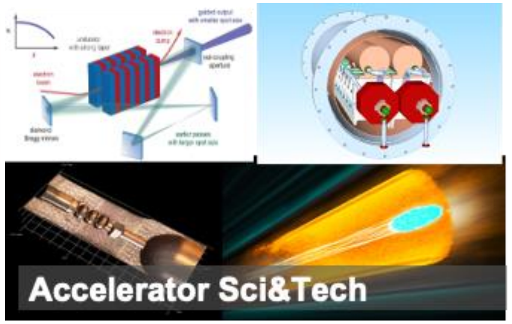
SLAC has been investigating the feasibility of hosting the demonstration of Cool Copper Collider technology as an alternative approach for high energy e+e- collider [1]. This technology is based on the breakthrough that SLAC researchers have made in pushing normal conducting RF acceleration structure towards extreme high gradient [1,3]. The ongoing design study aims for putting together a coherent plan and roadmap for addressing the required R&Ds to bring this technology towards more compact and cost-effective high energy linac. This talk will present the status along with brief introduction of accelerator R&Ds at SLAC.

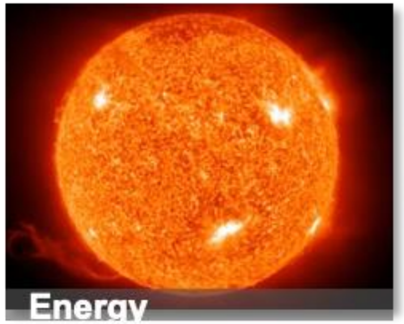
[1] E. Nanni er al, https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-217-ad-lbnf-pip2-ppd-td.pdf
[2] V. A. Dolgashev, et al, Appl. Phys. Lett. **97**, 171501 (2010); https://doi.org/10.1063/1.3505339
[1] M. Nasr, E. Nanni, M. Breidenbach, S. Weathersby, M. Oriunno and S. Tantawi, “Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature,” Phys. Rev. Accel. Beams 24, 9, (2021)

Accelerator Facilities at SLAC









Accelerator User Facility Operation

SSRL Accelerator Complex

- One of the pioneering synchrotron radiation facilities
- A 234 m 3 GeV storage ring with high brightness and low emittance electron beam to provide the synchrotron radiation for the worldwide SSRL users from a wide range of scientific fields such as biology, chemistry, material science, etc.
- High reliability and availability

LCLS, and LCLS-II

- **LCLS:** 2009 – present, ~1km long normal conducting LINAC to reach 15 GeV electron beam energy

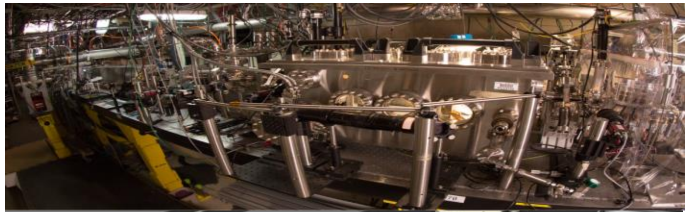
  World's first hard x-ray Free Electron Laser

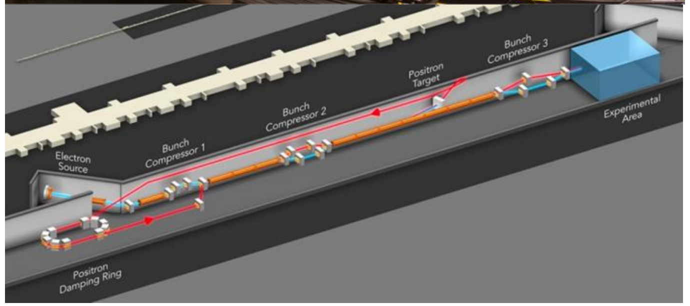
- **LCLS-II:** under commissioning now. ~500m SRF LINAC to reach 4 GeV electron beam energy

  World's first MHz X-FEL facility

FACET-II

- Powered by a 10 GeV electron LINAC, this facility provides worldwide unique capability for developing the beam driven plasma wake field acceleration, a disruptive technology that could pave the way for future collider within affordable scale
- High impact scientific program with worldwide users from universities, excellence in training students

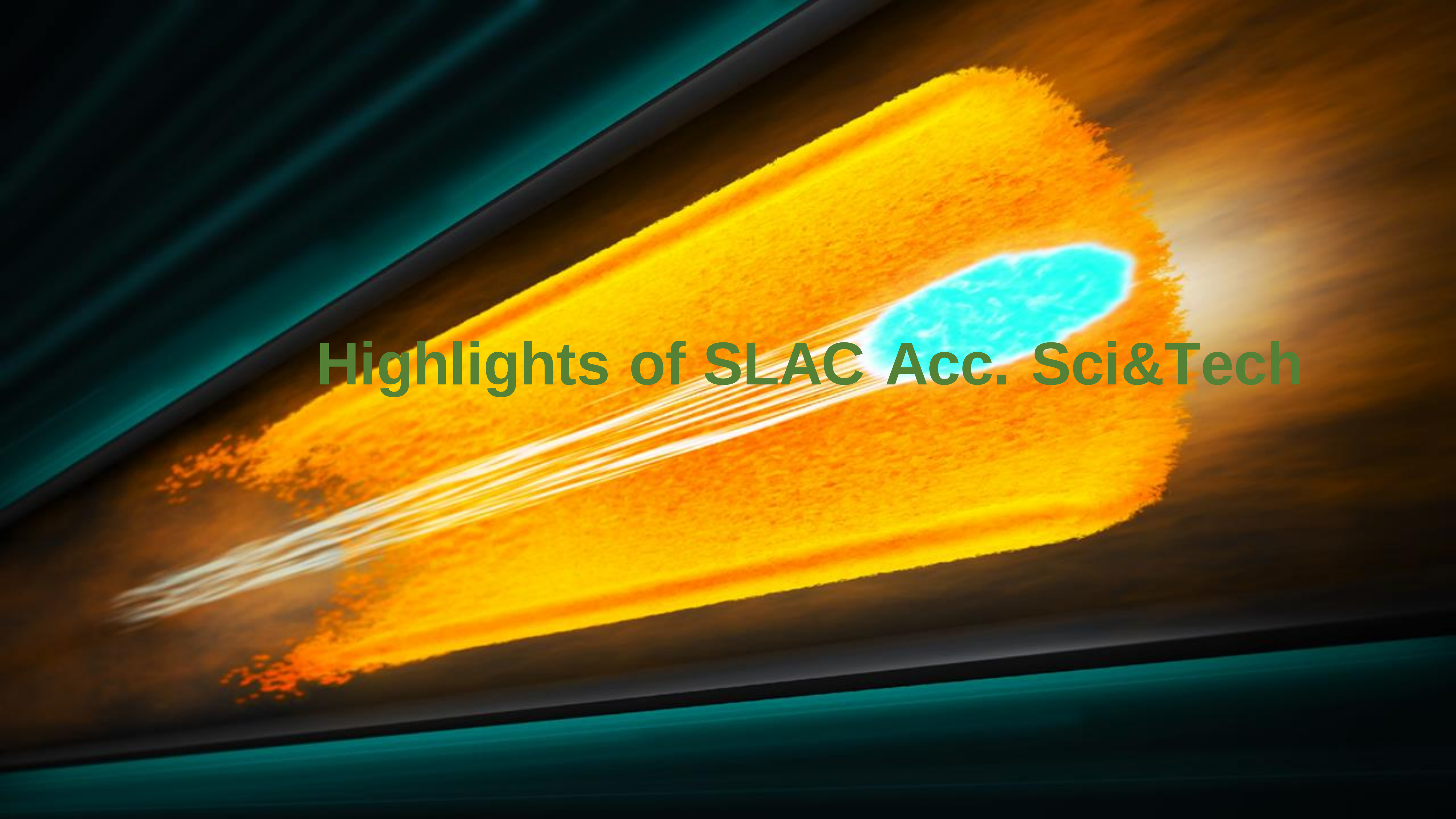




SLAC Accelerator Science Vision

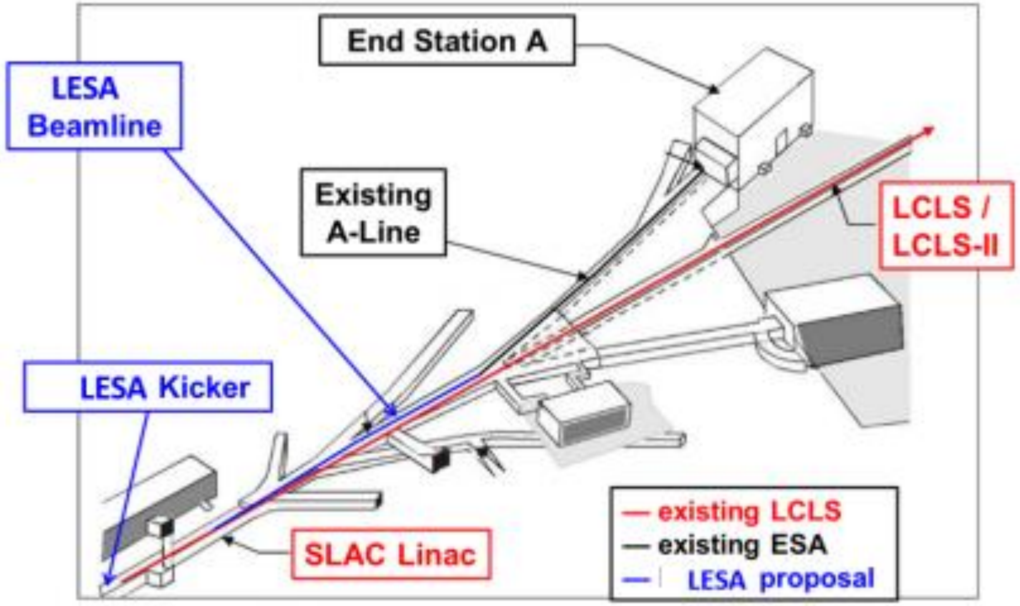
- Continue to **lead advancement of accelerator science and technology especially in the topics of**
  - beam dynamics of ultra bright, ultra fast, ultra short beams for FEL science and HEP needs
  - **RF accelerator technology, high power efficient RF sources and high gradient structures**
  - **advanced acceleration concept such as beam driven plasma wake field acceleration**
- **Operations excellence**
  - Safe and reliable operation of accelerator user facilities to maximize the science program
- **Education and outreach**
  - SLAC new staff onboarding and training
    - SLAC Particle Accelerator School
  - Student programs
    - Accelerator science programs at Stanford, both undergraduate and graduate
    - US Particle Accelerator School (USPAS), Science Accelerating Girl's Engagement (SAGE)
    - Future opportunities with Stanford, other universities and colleges

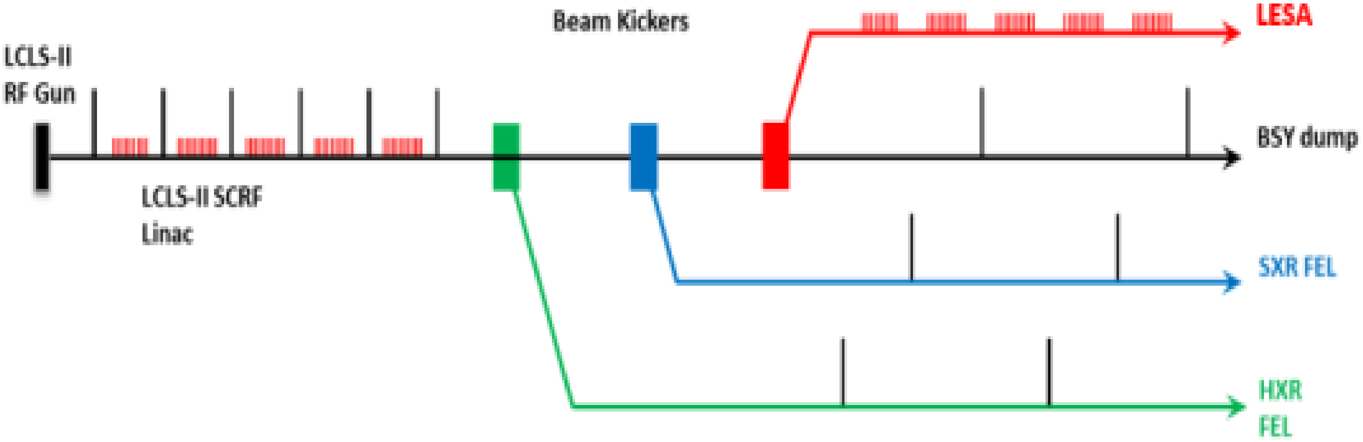
Highlights of SLAC Acc. Sci&Tech



Shining the light to dark matter: S30XL and LESA

- S30XL and LESA: to parasitically extract low current (nA) cw beam from LCLS-II/LCLS-II-HE SRF linac for beam test as well as dark sector experiments (LDMX) in End Station A (ESA)
  - Parasitic without perturbing the X-FEL program!
  - Initial phase w.o. LESA laser
    - dark current from the e-gun

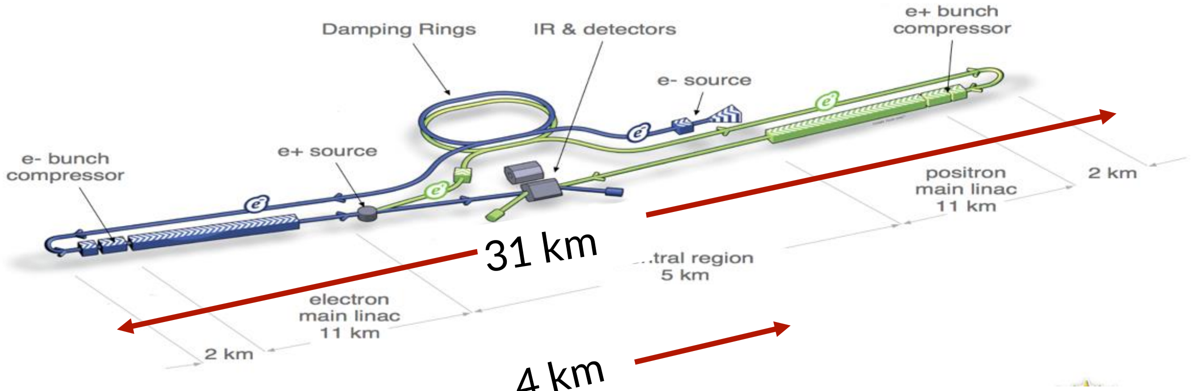




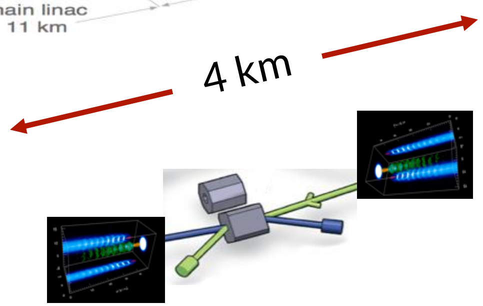
Demonstration of technology needed for TeV Linear Collider

GeV/m accelerating gradient

Today's technology LC
– a 31km tunnel:



Plasma Accelerator Technology LC:



The Luminosity Challenge:

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

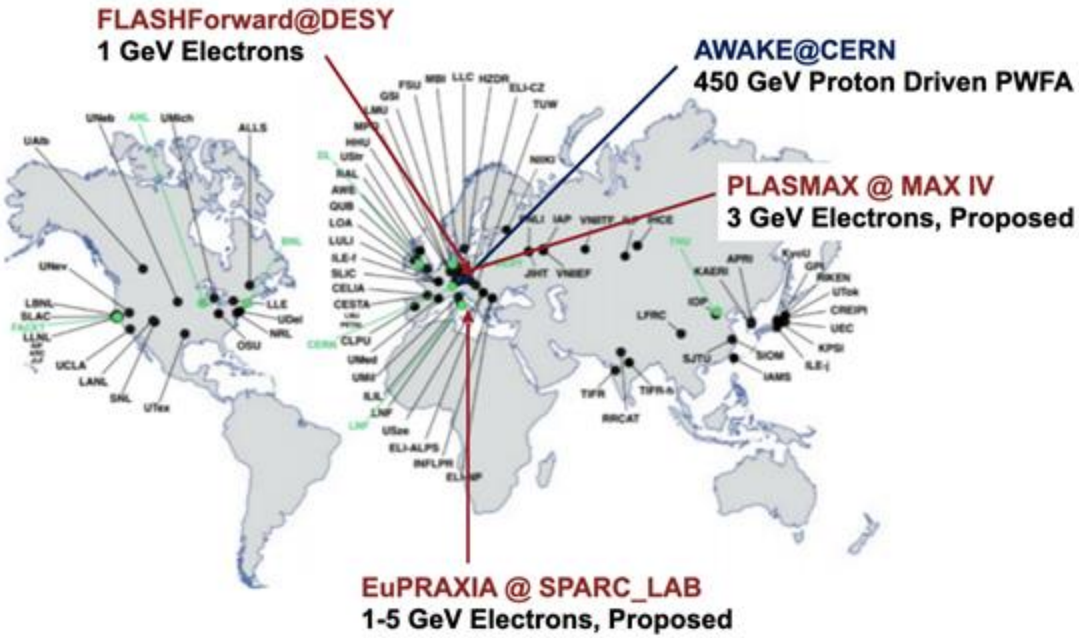
- High-efficiency
- Effective and efficient staging
- High-efficiency

...and must do it for positrons too!

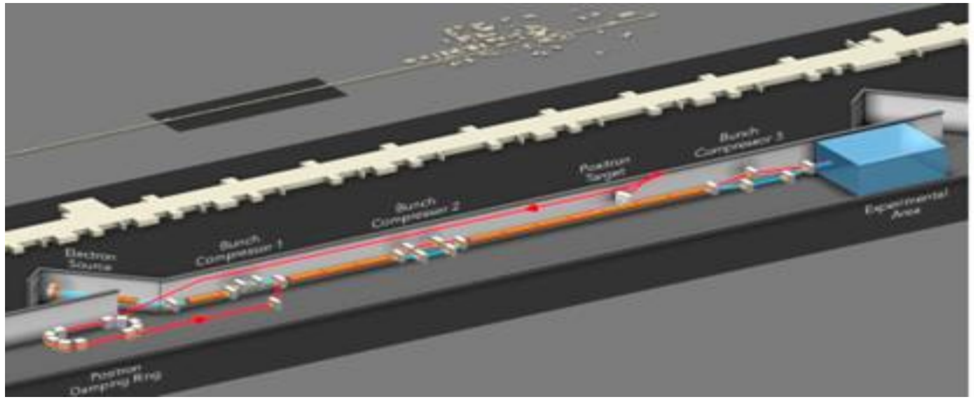
FACET-II: Advanced Acceleration Concept Program@SLAC

- One of the leading accelerator science oriented user facilities with broad program based on 10 GeV electron beams and their interaction with lasers & plasmas
  - Focus on **plasma wakefield acceleration** for HEP colliders, **ML/AI** to for beam diagnostics and control and exploiting intense beams for **gamma-ray** generation and probing **SFQED**
- Facility has recently completed its project phase and entered its scientific program. A total of 47 proposals was reviewed by its PAC, with 11 accommodated for beamtime in FY22
- All KPPs including objective KPPs are achieved or exceeded
  - 3.375nC highest peak charge!
  - 10um emittance at sector 19 emittance station
  - Sub-20um bunch length measured at XTCAV in sector 20

Description of Scope	*Units*	*Threshold KPP*	*Objective KPP*
Beam Energy	*[GeV]*	*9*	*10*
Bunch Charge (e-)	*[nC]*	*0.1*	*2*
Normalized Emittance in S19 (e-)	*[µm]*	*50*	*20*
Bunch Length (e-)	*[µm]*	*100*	*20*



B. Hidding et al, Plasma Wakefield Accelerator Research 2019–2040, arXiv:1904.09205v1



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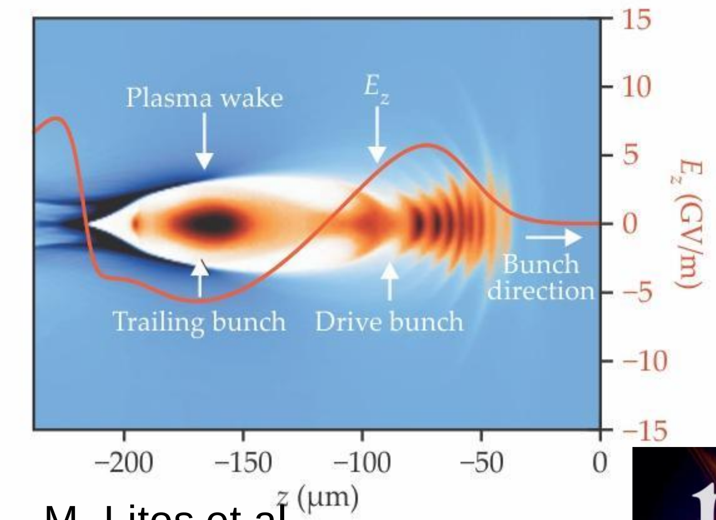
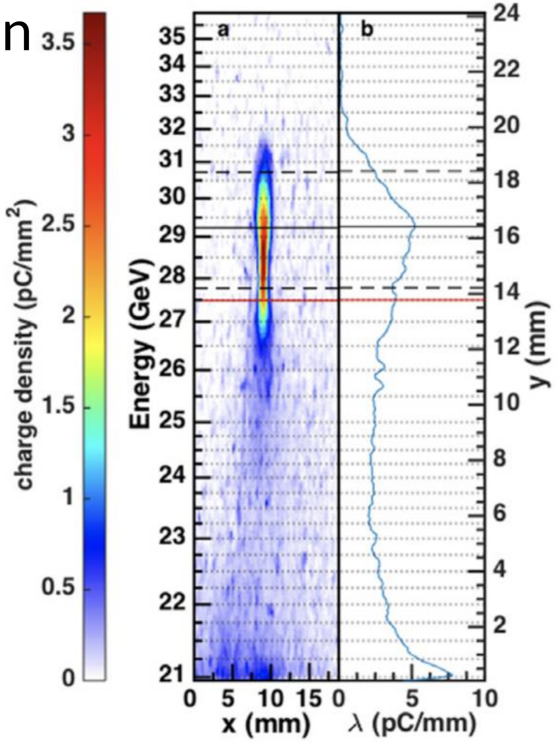
Plasma Wake Field Acceleration Concept



M. Litos et al,
Nature, 515, 92-95 (2014)

9GeV energy gain in 1.3m was achieved with electron beam!

9 GeV Energy Gain

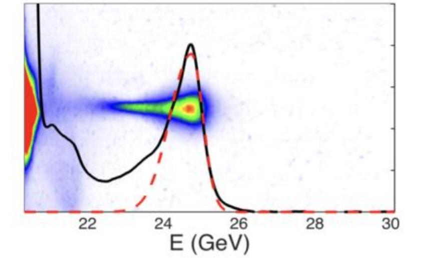


M. Litos et al,
PPCF, 515, 92-95 (2016)

Next challenge with positrons!

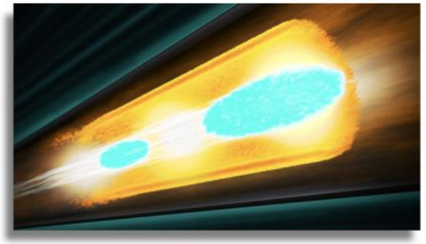
Demonstrated @ FACET

Non-linear wakes in
self-loaded regime of PWFA



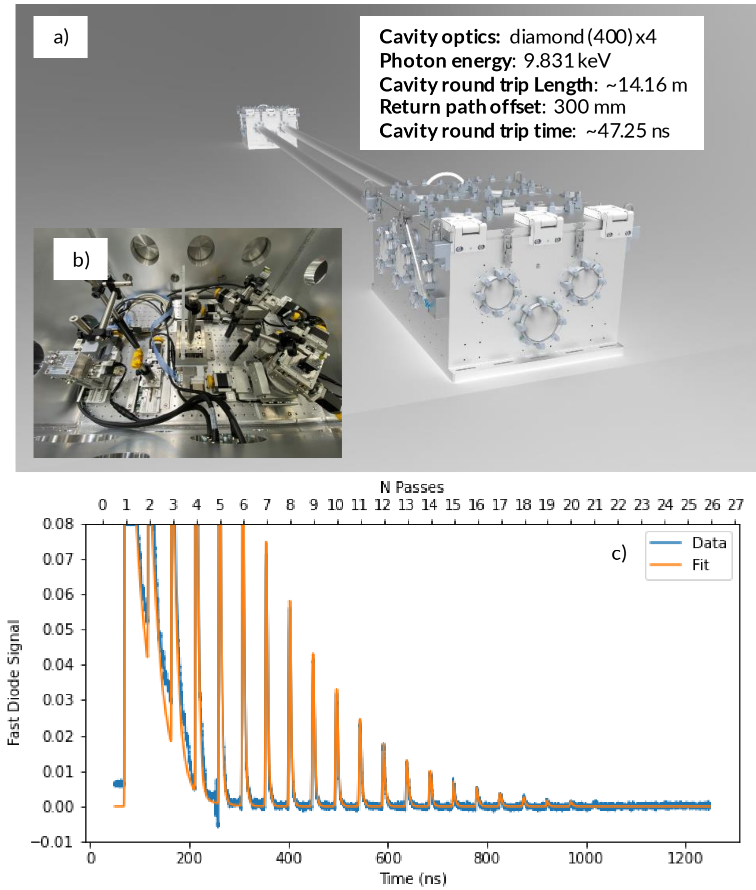
Corde et al., ***Nature*** August 2015

Hollow Channel Plasma
Wakefield Acceleration



Gessner et al., ***Nature Communications*** 2016
Lindstrom et al., ***Phys. Rev. Lett.*** 2018

Cavity based FEL



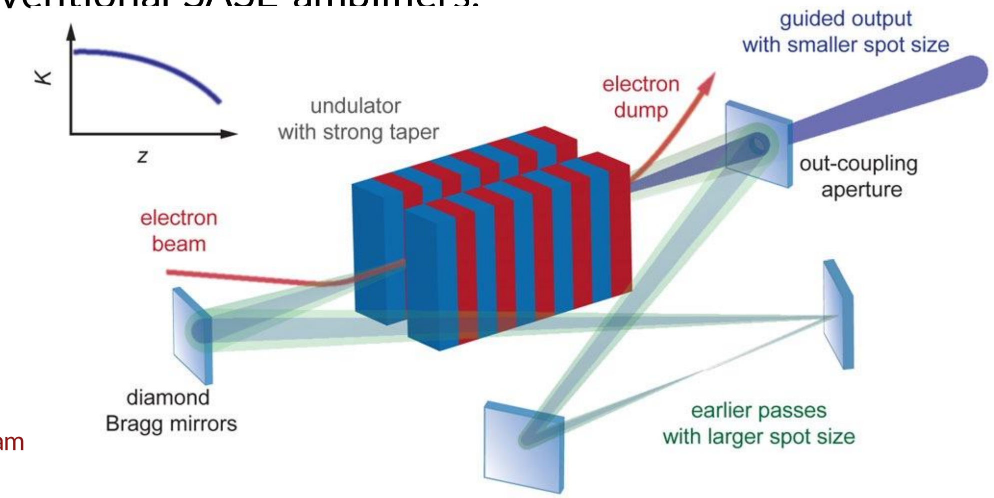
a) CAD model of the cavity, b) Photo of optics assemblies in the upstream cavity chamber, c) Typical cavity ringdown trace

Scientific Achievement

- Multi-pass storage of hard x-rays from a free-electron laser in a 14 meter rectangular cavity

Significance and Impact

- Demonstrated the feasibility of an FEL scale X-ray Bragg cavity using synthetic diamond mirrors to store and circulate hard x-ray pulses over many passes.
- Representing a major step towards realizing cavity-based X-ray free-electron lasers, which promise to push hard X-ray FEL peak and average spectral brightness 2 to 3 order of magnitude beyond conventional SASE amplifiers.

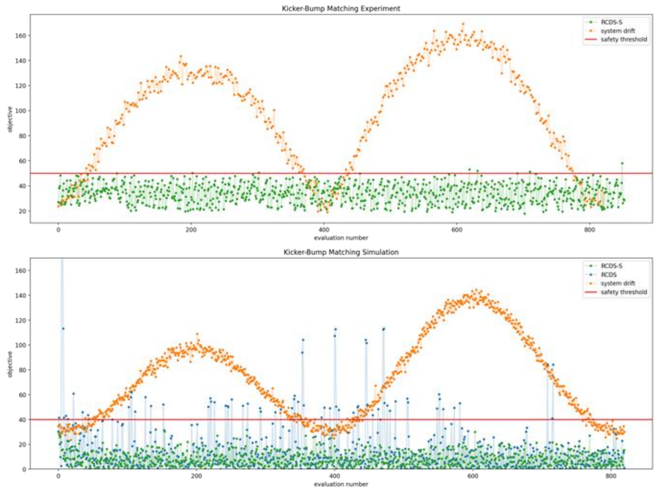


PIs G. Marcus, Z. Huang, and D. Zhu, on behalf of the SLAC CBXFEL project team

ML/AI and Robotics for Operation and Beam Diagnostics

Robust Conjugate Direction Search Algorithm

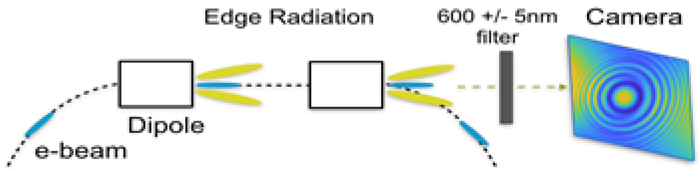
- an advanced algorithm for automatic machine tuning to compensate the machine performance drift
- Recently successfully tested at SSRL
- Can be done parasitic to machine operation, which in turn benefits the user data taking efficiency



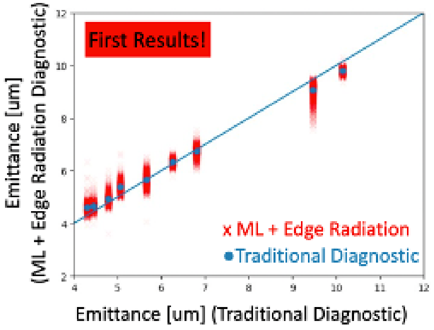
Z. Zhang, M. Song, X. Huang

Improving Accelerators with ML based non-destructive diagnostics

- Develop ML/NN based technique to measure the divergence and energy spread of the beam by analyzing the interference pattern between the radiations at the dipole edges **(B. O'Shea)**



- **1st result from this novel ML based non-destructive beam emittance measurement was obtained!**
- Its success will allow continuous monitoring of FACET-II e-beam during its operation



Remotely Operated Accelerator Monitoring (ROAM)

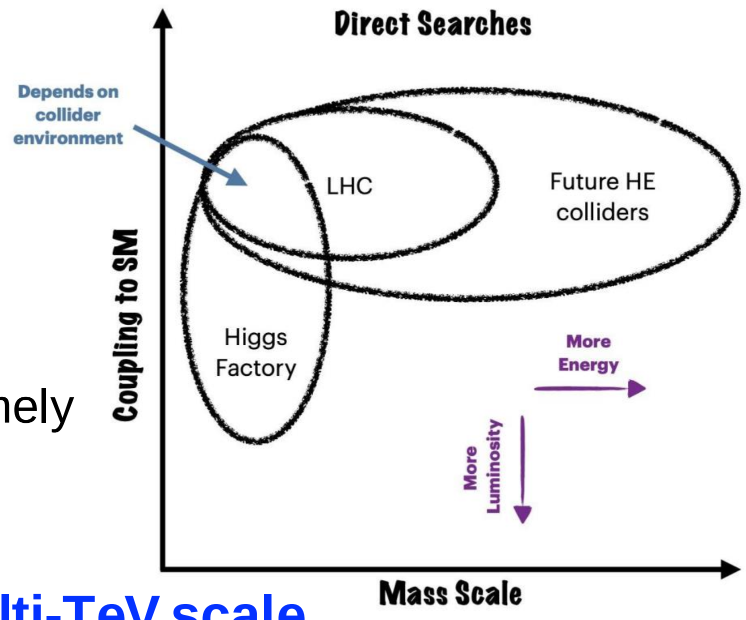
- Use off-the-shelf components and open-source robot control software framework to develop a mobile and reconfigurable sensor platform for monitoring accelerator enclosures and support buildings
- 1st phase is to the robots equipped with γ radiation detector to monitor the field emission from the LCLS-II cryomodules when in operation

A. Montironi, A. Ratti, etc

Snowmass and C3

Snowmass Energy Frontier Vision

- **The immediate future is the HL-LHC**
- **The intermediate future is an e+ e - Higgs factory, either based on a linear (ILC, C3 , CLIC) or circular collider (FCC-ee, CepC).**
  - It is important to realize at least one somewhere in the world. A timely implementation and strong US support are important



- **In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, Muon Collider)**
  - A 10-TeV muon collider and 100-TeV pp collider (FCC-hh, SppC) directly probe the ~10 TeV energy scale with different strengths that are unparalleled in terms of mass reach, precision, and sensitivity and frameworks
  - The main limitation is technology readiness. A vigorous R&D program into accelerator and detector technologies will be crucial.

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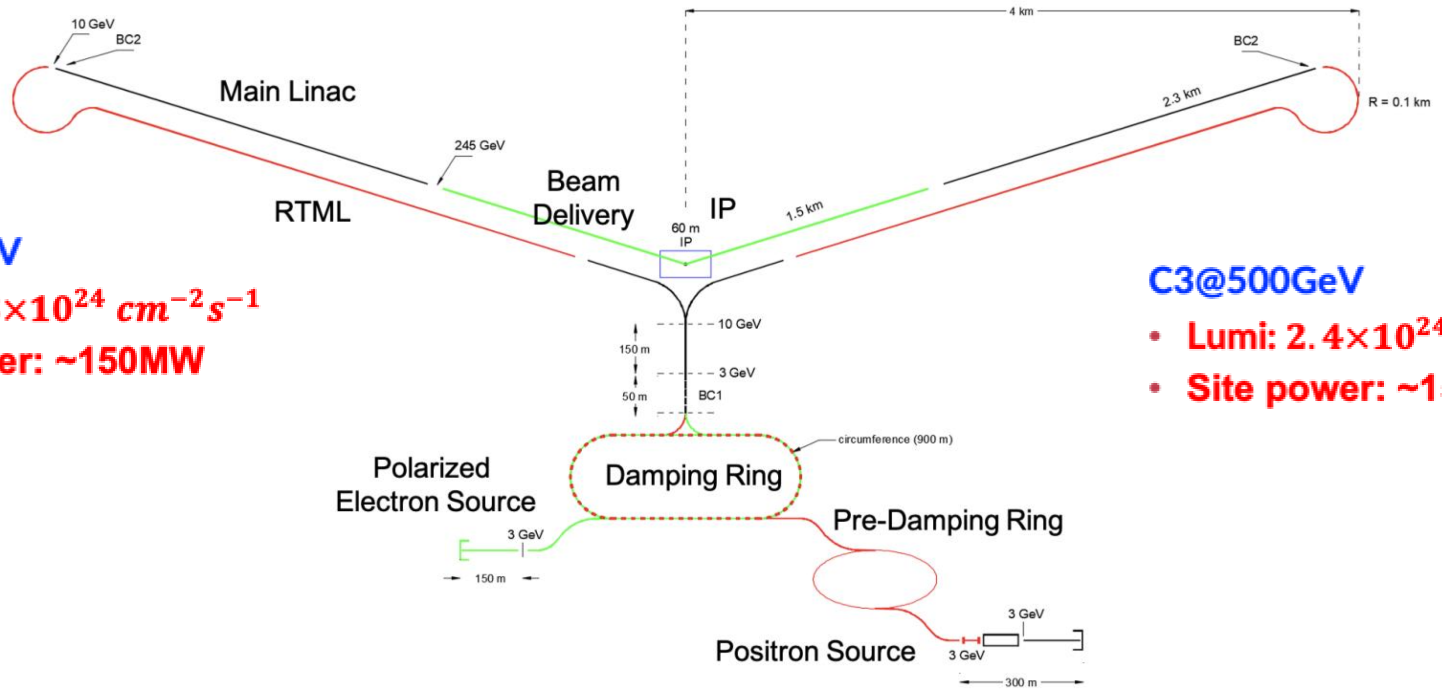
Energy Frontier Snowmass Report: https://snowmass21.org/energy/start#final_reports

C^3 (Cool Copper Collider)

- **Cool Copper Collider**, based on the novel NC RF acceleration technology developed at SLAC, provides a more compact (8km length) and potentially more cost-effective approach of realizing linear collider-based Higgs factory with possible upgrade path to reach TeV collider [SLAC-PUB-17629, arXiv:2110.15800v1]

C3@250GeV

- Lumi: $1.3\times10^{24}\ cm^{-2}s^{-1}$
- Site power: ~150MW



C3@500GeV

- Lumi: $2.4\times10^{24}\ cm^{-2}s^{-1}$
- Site power: ~150MW

- Was evaluated by the Accelerator Frontier Implementation Task Force for cost and feasibility, and is listed as a strong candidate for a US-host compact alternative e+e- energy frontier collider

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Cool Copper Collider Design Parameters

Collider	CLIC	ILC	C^3	C^3
CM Energy [GeV]	380	250 (500)	250	550
Luminosity [x10^{34}]	1.5	1.35	1.3	2.4
Loaded Gradient [MeV/m]	72	31.5	70	120
Geometry Gradient [MeV/m]	57	21	63	108
Length [km]	11.4	20.5 (31)	8	8
Num. Bunches per Train	352	1312	133	75
Train Rep. Rate [Hz]	50	5	120	120
Bunch Spacing [ns]	0.5	369	5.26	3.5
Bunch Charge [nC]	0.83	3.2	1	1
Crossing Angle [rad]	0.0165	0.014	0.014	0.014
Site Power [MW]	168	125	~150	~175
Design Maturity	CDR	TDR	pre-CDR	pre-CDR

Warm response from the community!

Cool Copper Collider Technology

Cryo-Copper for reaching high field strength

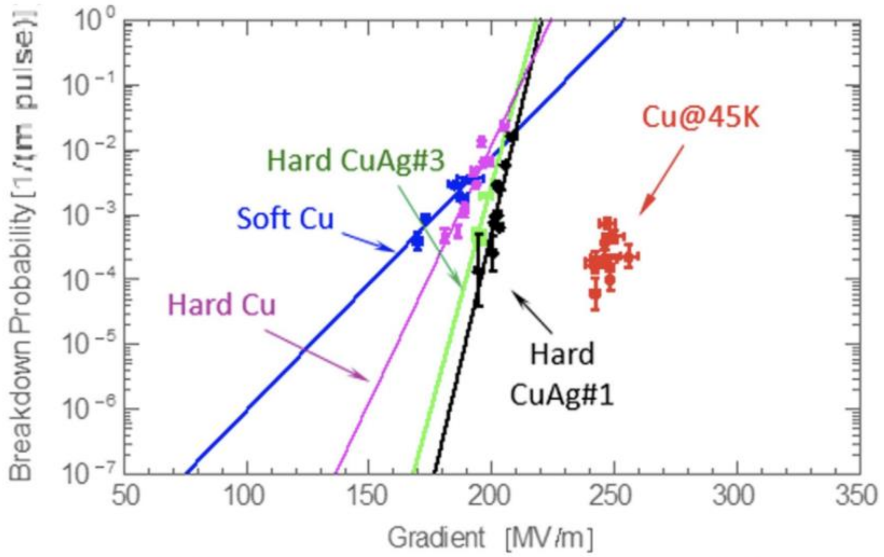
Cryogenic temperature elevates performance in gradient

- Material strength is key factor
- Impact of high fields for a high brightness injector may
- Eliminate need for one damping ring

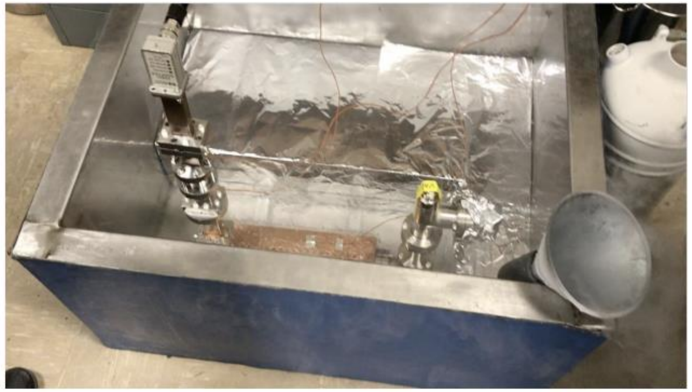
Operation at 77 K with liquid nitrogen is simple and practical

- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

E. Nanni, SLAC HEP Inst. Review, 2022



Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

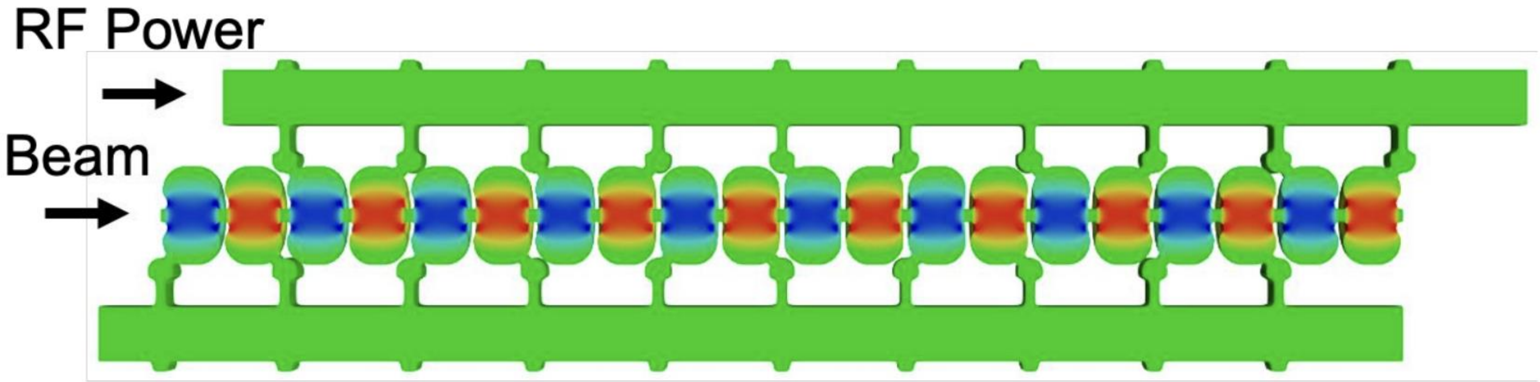


Nasr, et al. *PRAB* 24.9 (2021): 093201.

Cool Copper Collider Technology

Novel RF acceleration structure design for high efficiency operation

- RF power coupled to each cell – no on-axis coupling
- Full system design requires modern virtual prototyping



Electric field magnitude produced when RF manifold feeds alternating cells equally

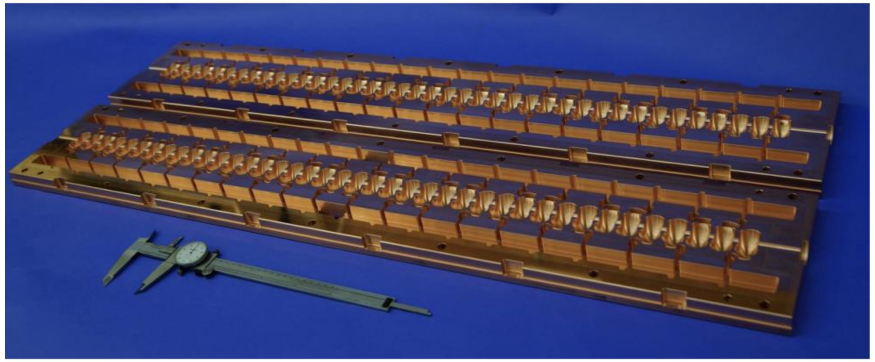
- Optimization of cell for efficiency (shunt impedance $R_s = G^2/P$ [MΩ/m])
- Control peak surface electric and magnetic fields. Key to high gradient operation

S. Tantawi, et al PRAB 23.9 (2020): 092001

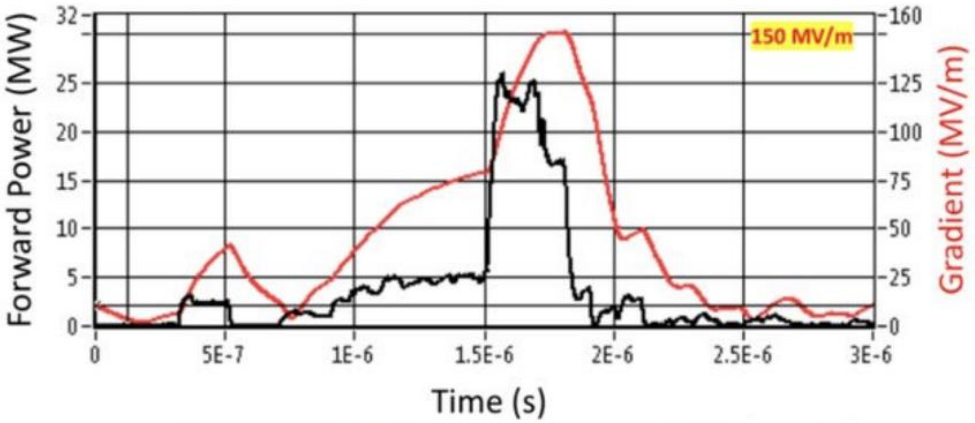
From what have been demonstrated towards collider

- What have been demonstrated

C3 Prototype One Meter Structure



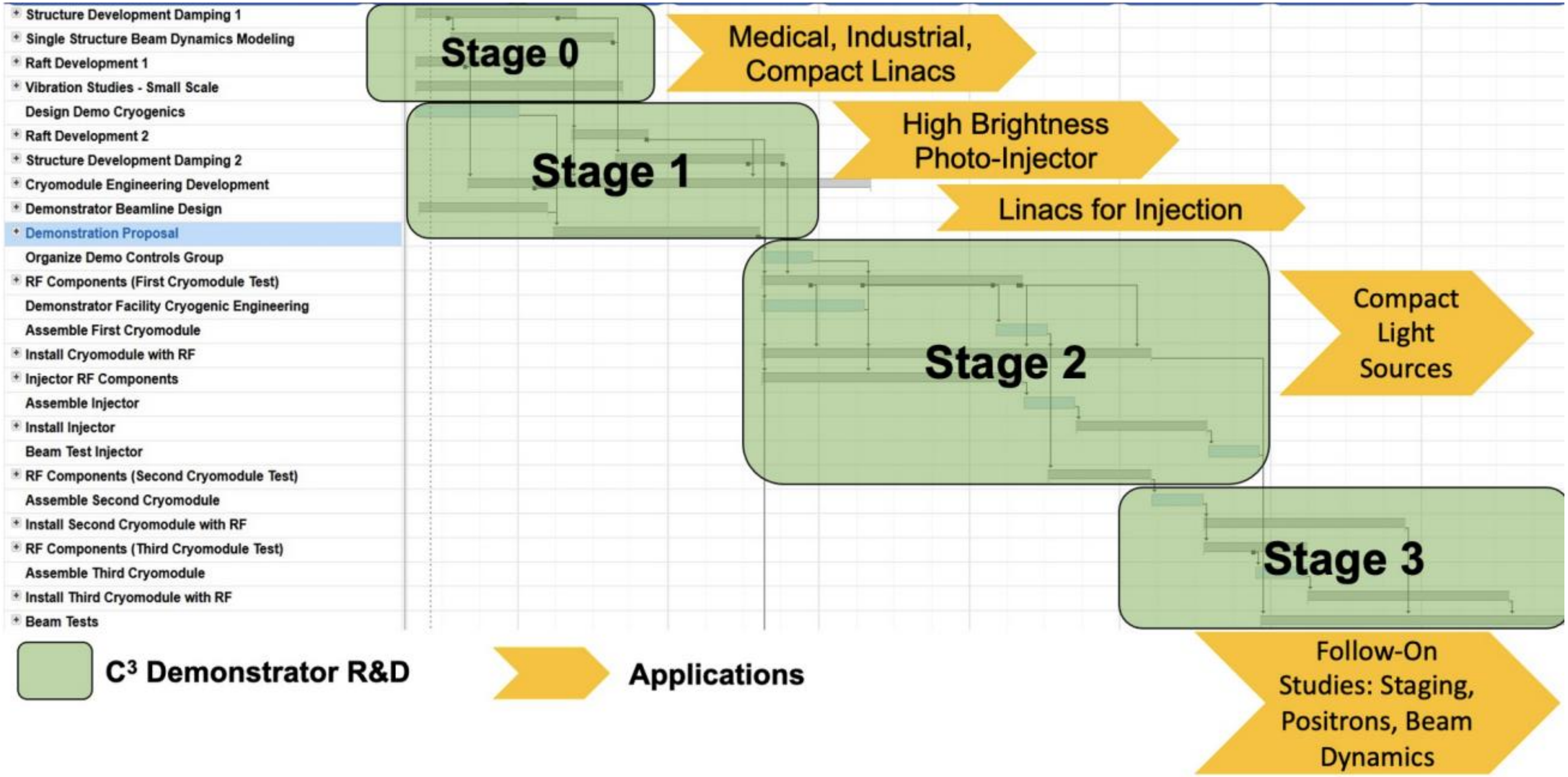
High Gradient Operation at 150 MV/m



Cryogenic Operation at X-band

- To be developed
  - Cryomodule and cryogenics
    - RF thermal loads for C3-250GeV is 2.5kWatt per acceleration section, and a total of 9MWatt of the main LINAC
  - Accelerating structure
    - Optimized RF design, wake fields damping
    - Manufacturing and industrialization
    - Thermal performance and vibration
  - Beam dynamics
    - Mitigation of wakefields and HOMs
    - Tolerance of various imperfections such as misalignment
  - High brightness RF injector

C^3 (Cool Copper Cavity) R&D Plan



[1] https://arxiv.org/pdf/2203.09076

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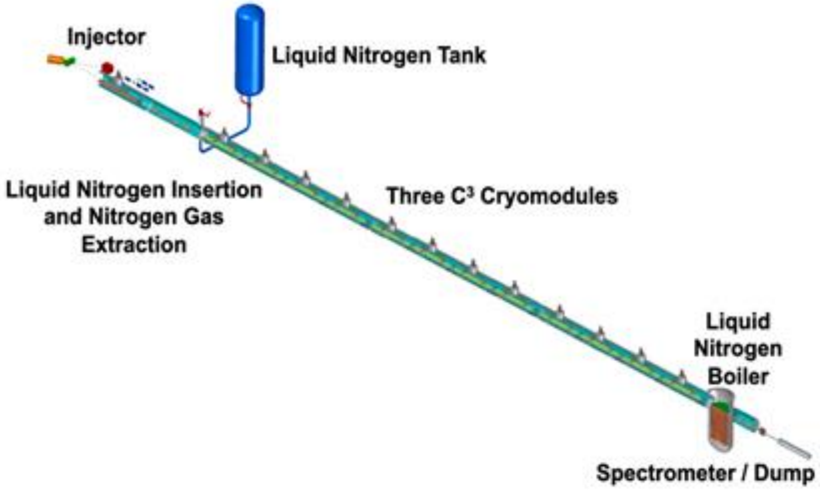
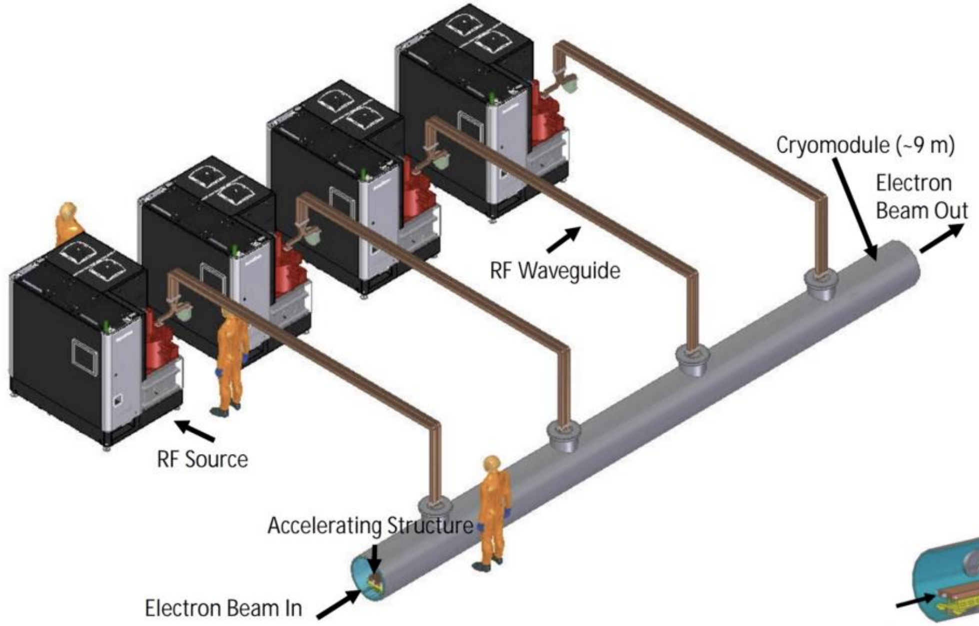
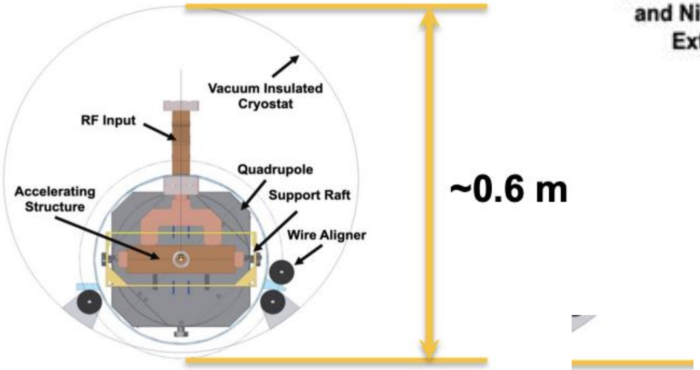
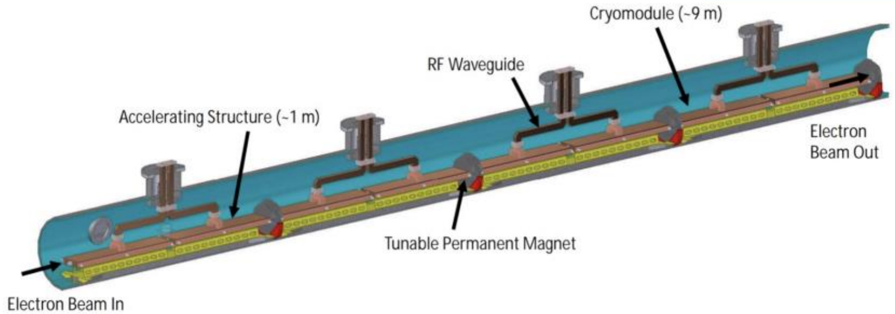
C³ (Cool Copper Cavity) Demonstration

Staged approach of R&D plan was developed and presented during the Snowmass community meeting. Colleagues from Fermilab, LANL, ANL, LBL, UCLA etc expressed interests in forming collaboration to carry out the R&D jointly









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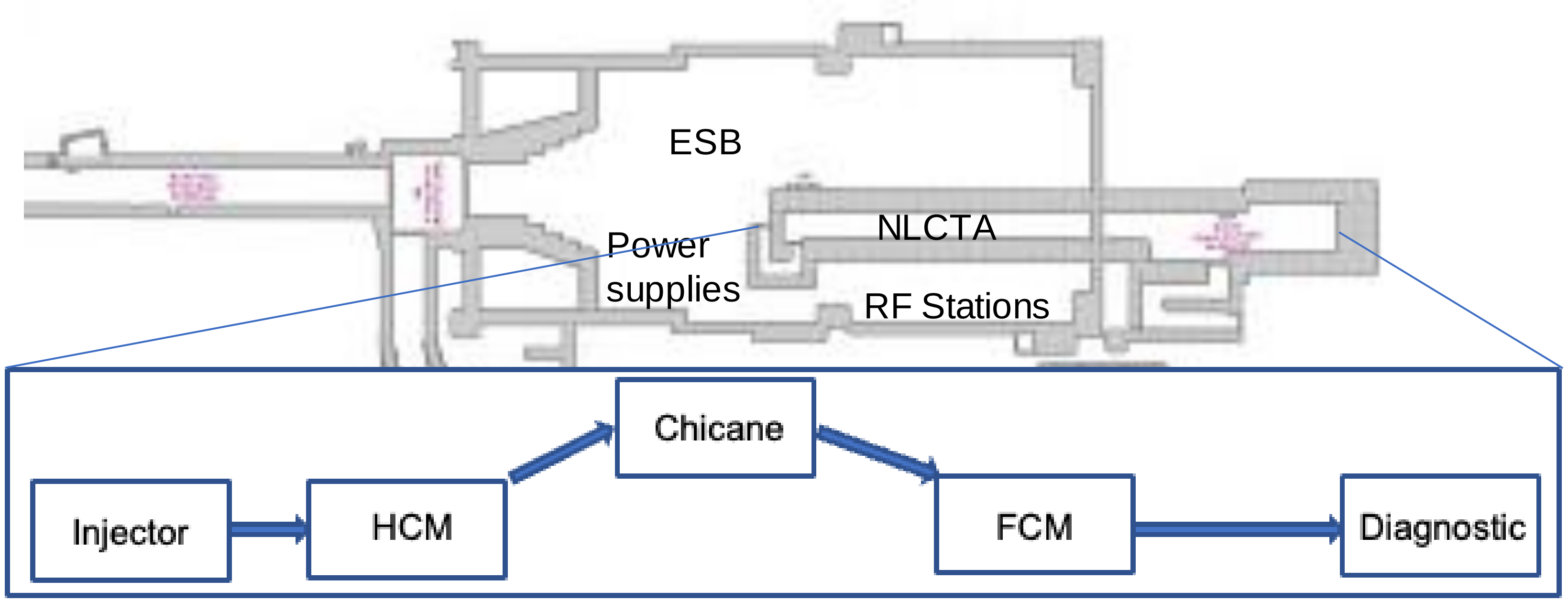
C^3 (Cool Copper Cavity) Demonstration

- A design study of a dedicated facility at SLAC NLCTA to demonstrate the technology and key parameters, such as
  - **Beam energy ~1 GeV, with ~1e-4 energy jitter**
  - **high brightness beam with 1nC bunch charge**

  is ongoing. Synergies with other applications are under investigation. The design study will also lay out R&D roadmap towards Stage 3, i.e. 3-cryomodule main LINAC



4 stages – Goals & Impact & Applications

2028- **2030**

- **3: CM scale-up demonstration for equivalent linear collider (LC) required heat-load**
  - A C^3 full linac of 3 CMs ~ 3 GeV over about 30 meters
  - ✓ Positron production
  - ✓ Muon production
  - ✓ Advanced accelerator concept study like PWFA
  - ✓ Full energy linac injector for storage ring.

2026- **2028**

- **2: CM scale-up minimum demonstration**
  - Compact high energy linac with cost-effective RF source
    -- A single CM linac with 4x50 MW klystrons of ~ 0.9 GeV over 9 meters
  - ✓ Energy booster for facilities like LCLS-X
  - ✓ Compact light sources like FEL.

2023- **2026**

- **1: CM engineering design study and prototypes**
  - Compact medium energy linac
    -- A half CM with 2x50MW klystrons ~ 0.4 GeV over 5 meters
  - ✓ Medical: VHEE therapy
  - ✓ Compact high energy (100s keV to 1MeV) Compton source
  - ✓ Lower energy injector for booster ring
  - ✓ High brightness injector feasibility

2022 - **2023**

- **0: Proof of concept for the most critical structure performance parameters**
  - Compact cost-effective low energy linac based on single rf structure
  - ✓ Security
  - ✓ Medical: linac therapy
  - ✓ Industrial: high energy CT, irradiation with electrons or x-rays

Courtesy of F. Wang

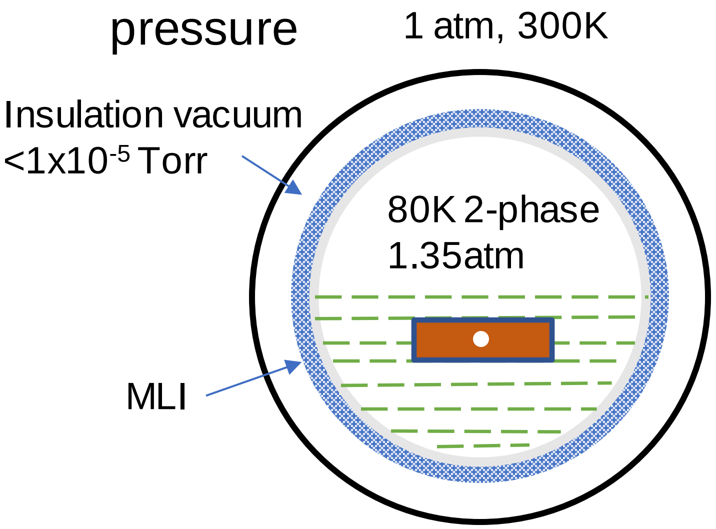
Current progress

- **Cryogenics and thermal analysis**

LN2 cryogenic system

- Nucleate boiling
- Two-phase fluid dynamics

Requires
- Proper size of the cryostat and volume of LN2 with mild flow and proper gas pressure



Schematic

SLAC

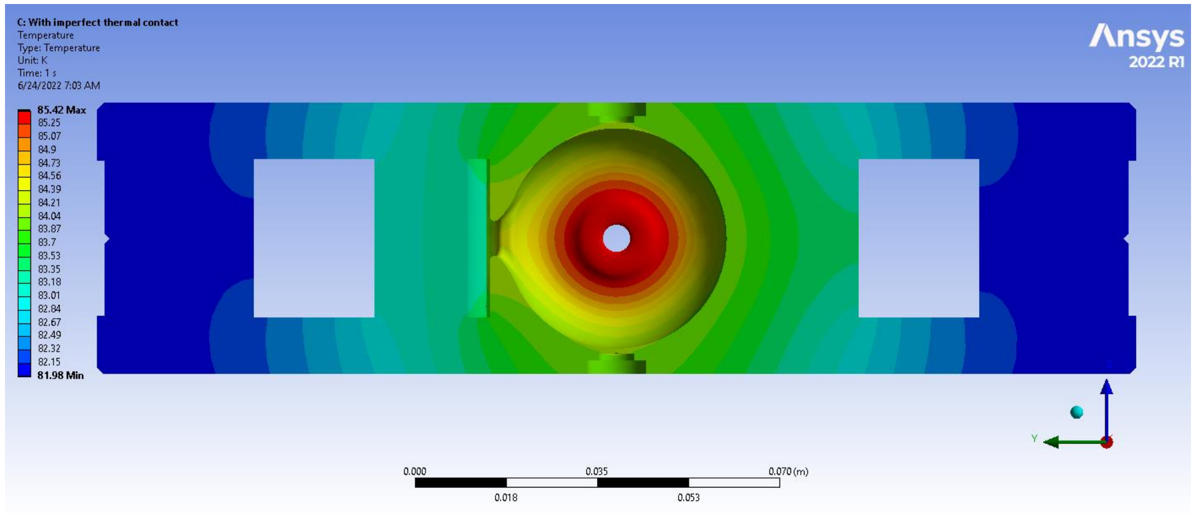
Courtesy of X. Liu, M. Breidenbach

Preliminary heat analysis

- Cavity detuning is quite sensitive to the temperature variation, i.e. ΔT=1K results in ~ 0.1MHz detuning

Requires
- LLRF feedback for keeping gradient stable
- Procedure for detuning compensation

Assuming same cooling for both sides of the structure



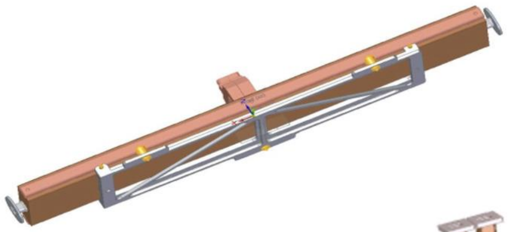
Current progress

❑ Cryomodule and Raft Design

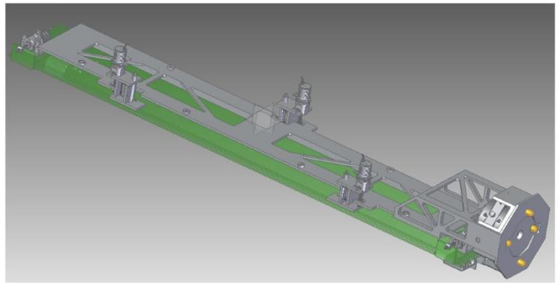
Courtesy of V. Borzenets

- Require high accuracy alignment: 5μm over 50m
  - 5 degree of freedom with 2 directions and 3 rotations with accuracy (~1μm and better) of each individual component as well as assembled rafts
- Allow active compensation and alignment of building block components
  - Using precise Phytron LAV actuators (slow) and PI PIEZO actuators (fast)
- Compensation of the thermal expansion/shrinking of components
- Structure and material design to maximize the heat exchange between copper structure and LN2 and minimizing the impact of bubbling on the LINAC structure stability

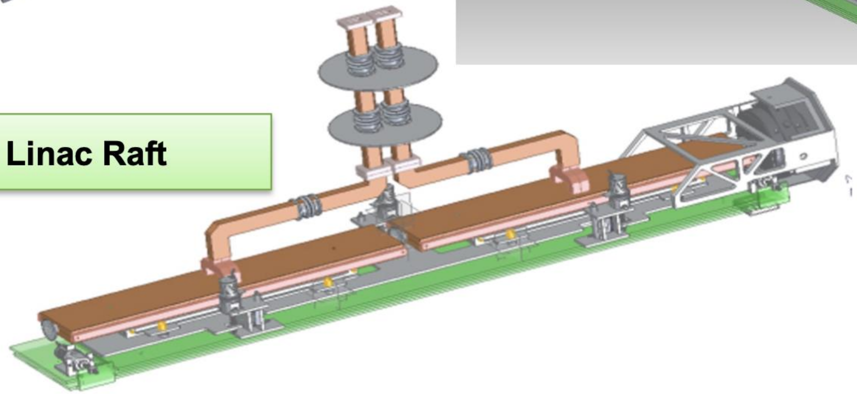
Linac alignment structure

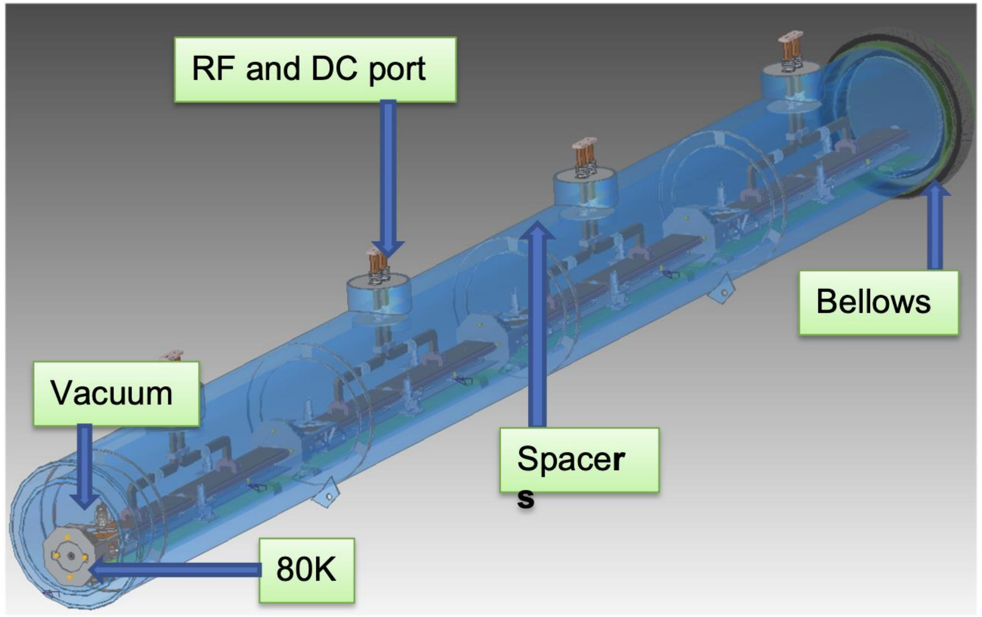


Raft mounting structure



Linac Raft

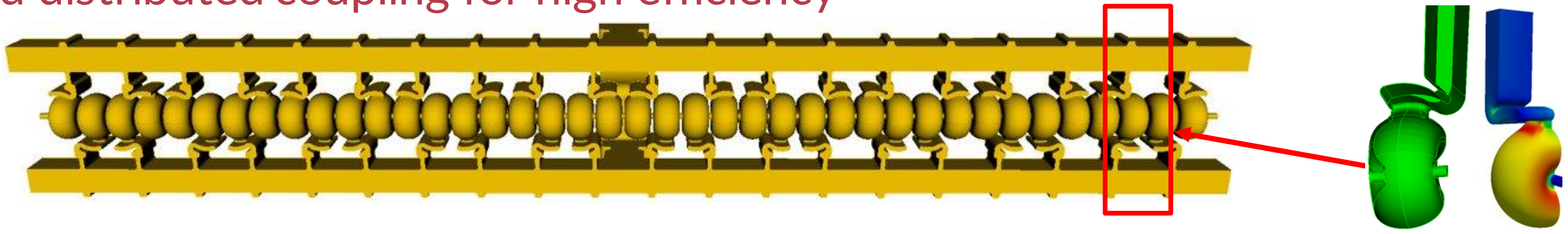




SLAC

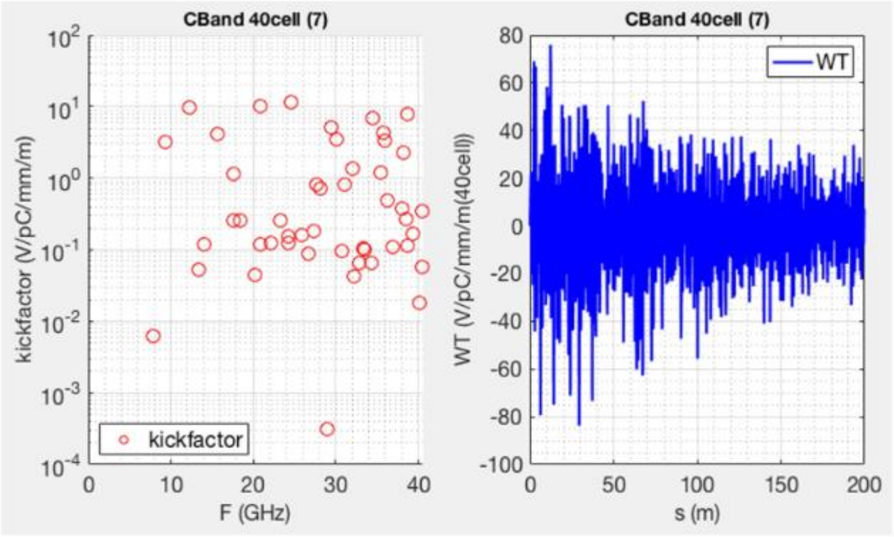
Structure

C-band distributed coupling for high efficiency

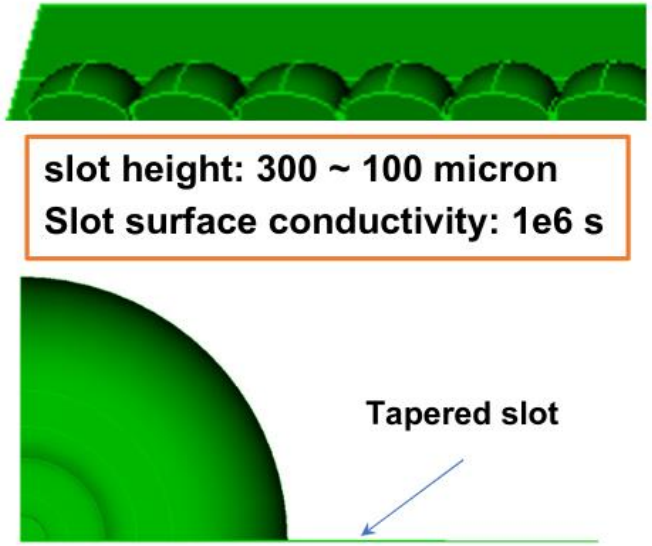


Further optimization needed for beam dynamics and long bunch train

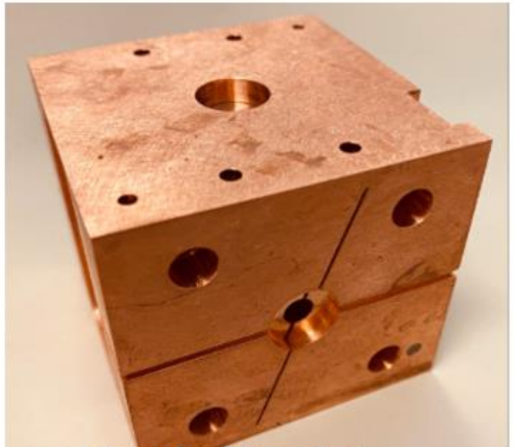
Wakefield of 1-m structure of 40 identical cells



HOM Damping Design



Damping Slot Prototype/coating



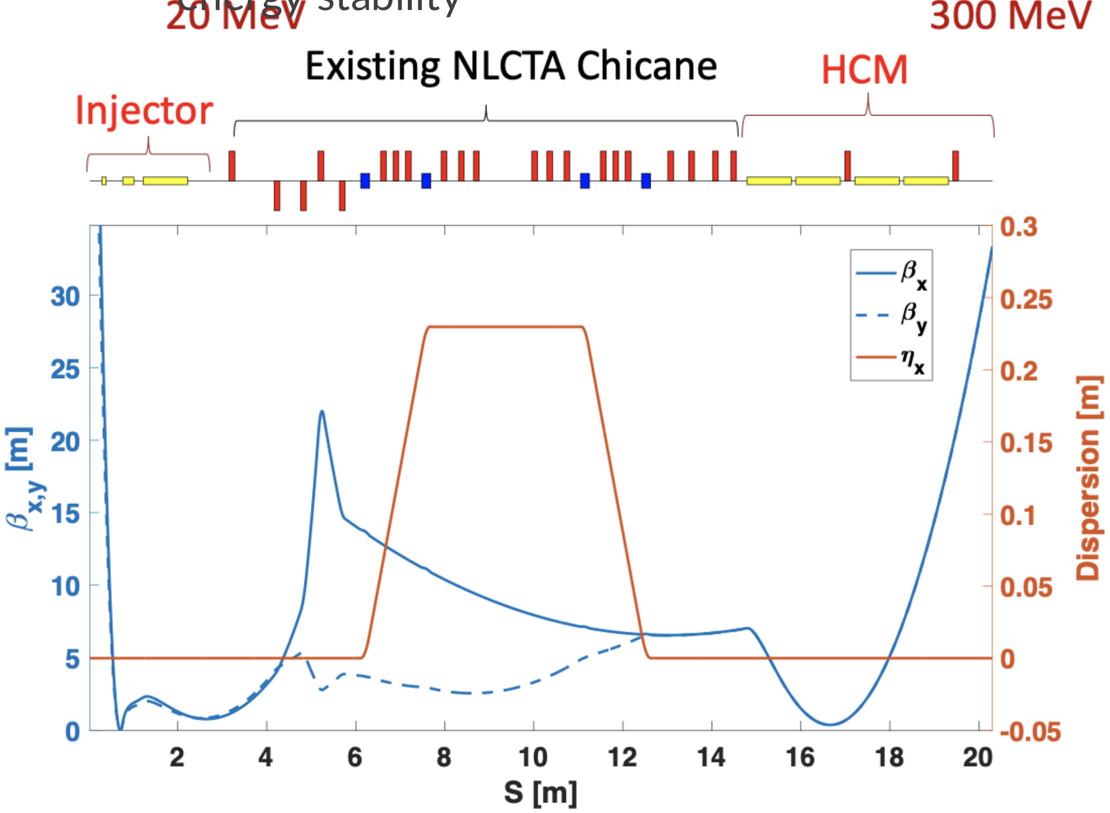
- Manufacture study
- HOM Coating study

Courtesy of Z. Li and F. Wang

C3Demo LINAC Layout

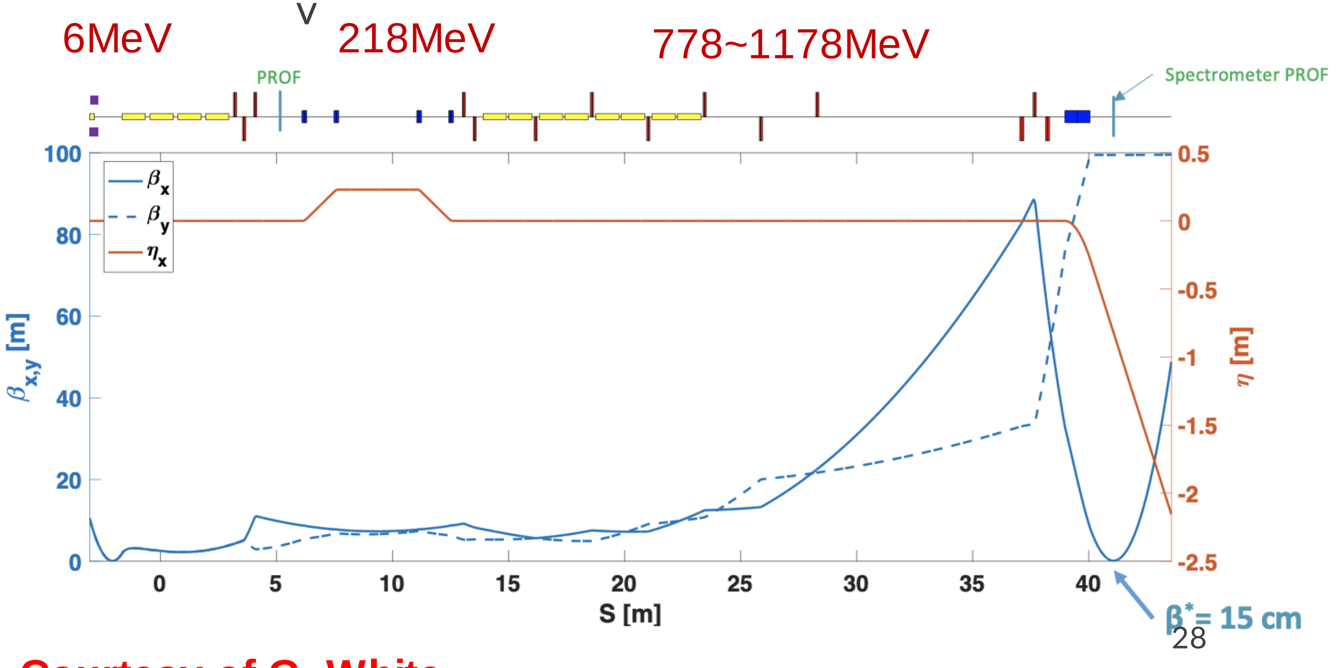
Stage 1 LINAC complex

- Injector is based on a 30keV DC gun
- characterize the HCM LINAC:
  - acceleration gradient with beam loading, evaluate beam energy stability



Stage 2 LINAC complex

- High brightness photo Injector
- HCM in stage 1 will serve as injector. Main LINAC contains 1 full cryomodule
- Beam dynamics evaluation
  - Wakefield effect on beam emittance, Toleraence on v

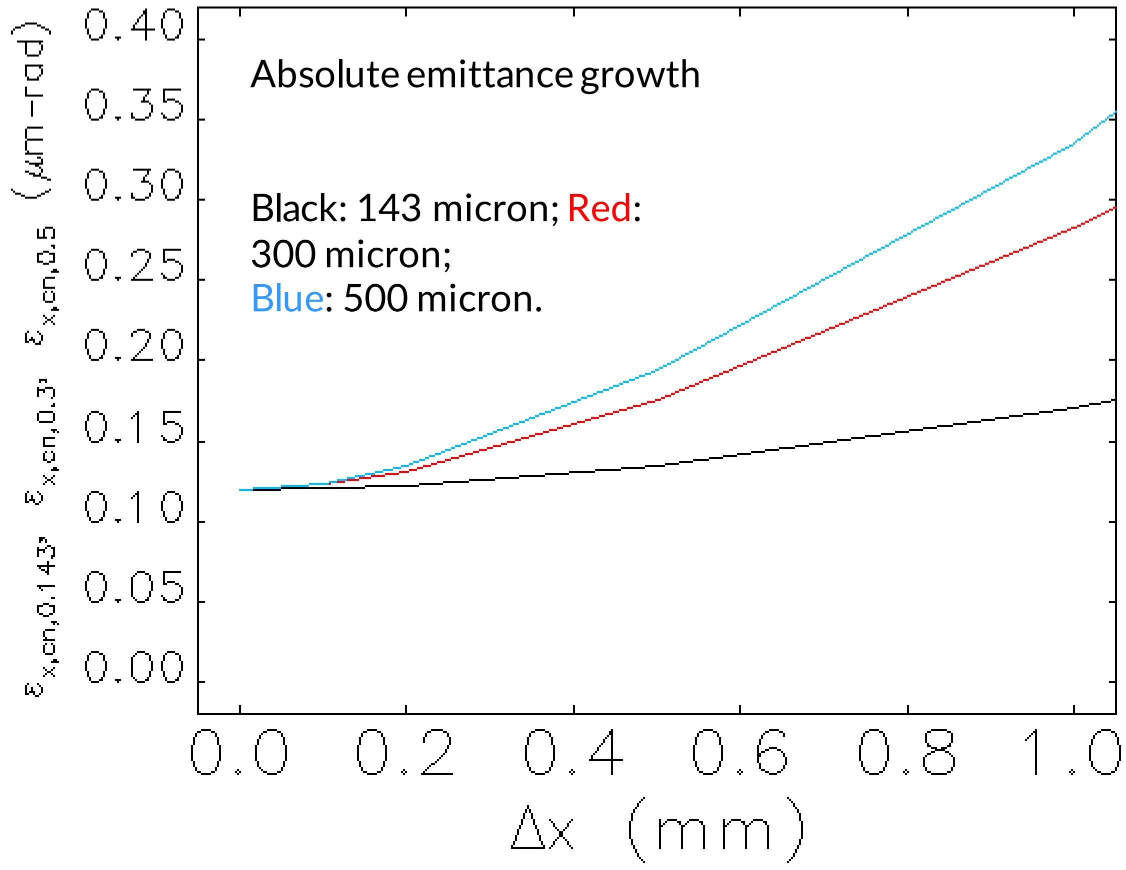


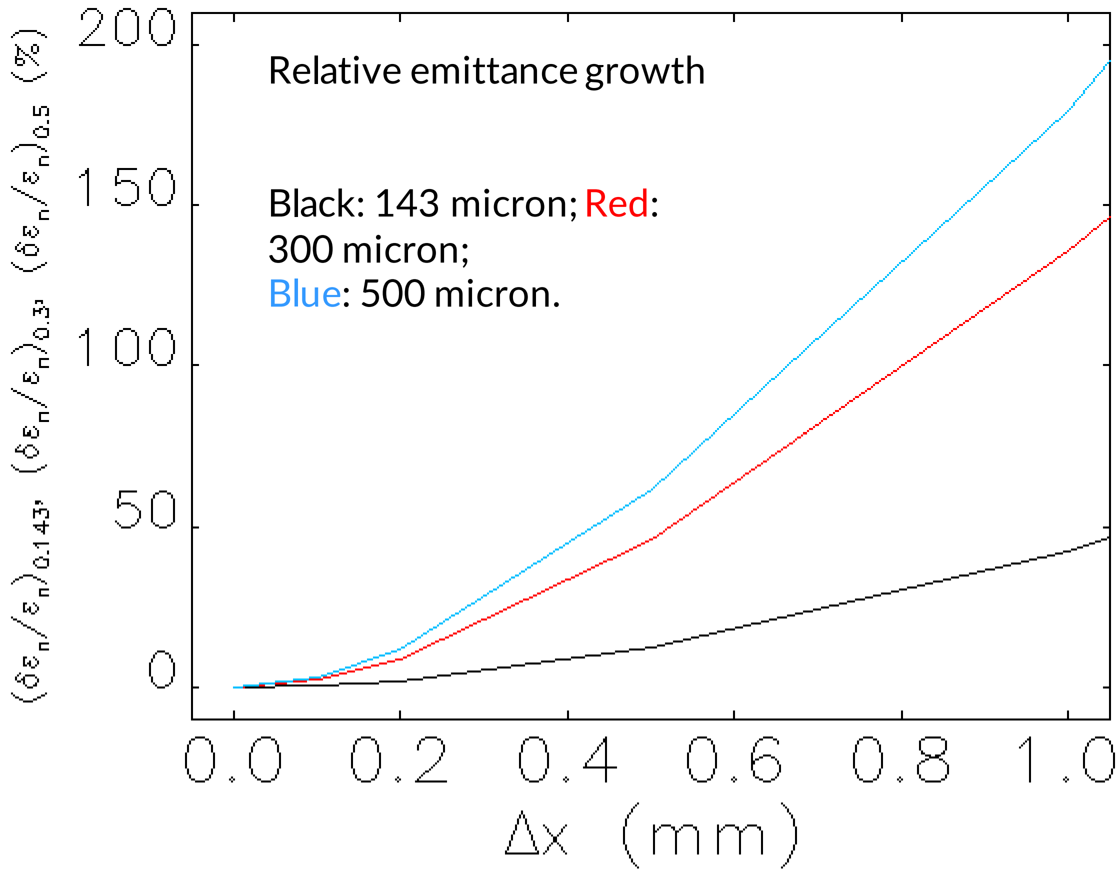
Courtesy of G. White

Initial Normalized Emittance: 0.12 μm-rad

- Wakefield effects: transverse $(x - x')$ due to offset Δx (up to 1 mm)
    - Short accelerator → long bunch: comparing 0.143 μm, 300 μm, and 500 μm

Courtesy of J. Wu





Initial Normalized Emittance: 0.12 or 1.5 μm-rad

- For initial of 0.12 μm-rad
  - A **200-micron** offset for an electron bunch length of **300 micron** might be a good parameter set with details in the table
  - If stay with a **100-micron** offset, we can use a **1 mm** electron bunch length
- For initial of 1.5 μm-rad
  - A **500-micron** offset for an electron bunch length of **556 micron** might be a good parameter set with details in the table
  - A **200-micron** offset, we can use a **1.112 mm** electron bunch length

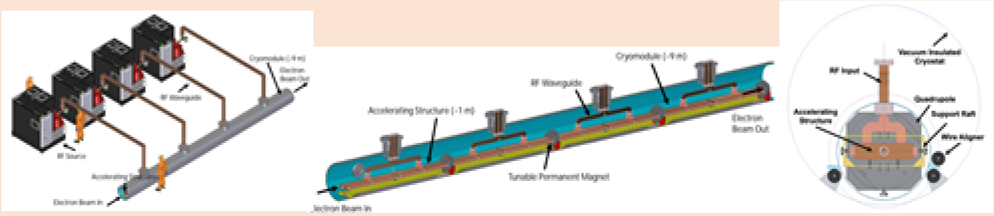
Courtesy of J. Wu

Electron bunch length (μm)	Absolute emittance (μm-rad) for different offset (μm)				Relative emittance growth (%) for different offset (μm)			
	100 (μm)	200 (μm)	500 (μm)	1000 (μm)	100 (μm)	200 (μm)	500 (μm)	1000 (μm)
143 (μm)	0.121 (μm-rad)	0.122 (μm-rad)	0.135 (μm-rad)	0.171 (μm-rad)	0.5 (%)	2.1 (%)	12.2 (%)	42.6 (%)
300 (μm)	0.123 (μm-rad)	**0.131** (μm-rad)	0.175 (μm-rad)	0.283 (μm-rad)	2.4 (%)	**8.8** (%)	46.0 (%)	135.7 (%)
500 (μm)	0.124 (μm-rad)	**0.134** (μm-rad)	0.194 (μm-rad)	0.336 (μm-rad)	3.2 (%)	**12.1** (%)	61.5 (%)	179.7 (%)
556 (μm)	1.506 (μm-rad)	1.521 (μm-rad)	**1.616** (μm-rad)	1.917 (μm-rad)	0.4 (%)	1.3 (%)	**7.7** (%)	27.7 (%)
1000 (μm)	**0.139** (μm-rad)	0.184 (μm-rad)	0.374 (μm-rad)	0.751 (μm-rad)	**15.7** (%)	53.3 (%)	210.2 (%)	523.3 (%)
1112 (μm)	1.536 (μm-rad)	1.616 (μm-rad)	2.091 (μm-rad)	3.270 (μm-rad)	1.9 (%)	7.2 (%)	38.7 (%)	117.0 (%)

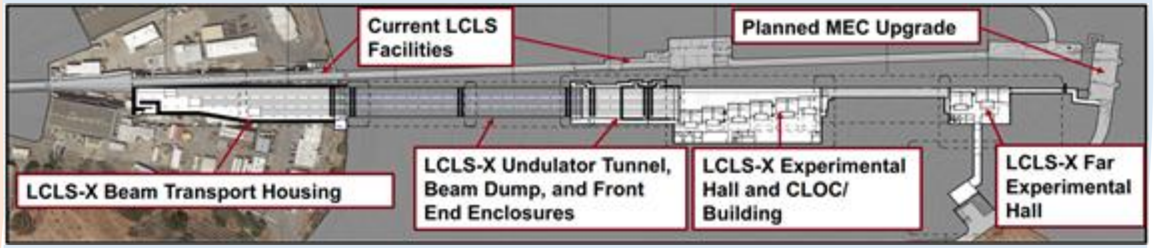
Synergies with LCLS-X

C3 Demonstration

- To demonstrate modularized linac technology based on liquid N2 cooled c-band acceleration cavity
- Each cryomodule (CM) is about 9 m long and has 4 rafts. Each raft has 2 accelerator structures and one quadrupole magnet. **Each cryomodule (CM) can reach up to 1 GeV**.



LCLS-X



- Revolutionary step of X-FEL towards user capability
- The unique combination of SRF based LCLS II and normal conducting based LCLS provides the rare opportunity for SLAC to map the wide range of X-FEL science, from high-repetition rate of soft X-ray and hard X-ray to extreme hard x-ray at low repetition rate

Synergies

- Cryo copper cavity technology for beyond current state-of-art high brightness gun/photo injector for reaching very hard x-ray. If successful, can further expand the current LCLS user capability. Such a low emittance photon injector at higher charge intensity could also pave the way for cost-saving of LC by eliminating damping ring for e- beam.
- C3-based compact LINAC to match electron beam energy for individual undulator beamline at non-high rep rate
- Advanced beam dynamics and techniques of high brightness electron beams

Summary

- SLAC has been the hub of innovation for accelerator science and technology especially in the area of ultra bright fast beams as well as advanced acceleration concept research
- The research of pushing normal conducting RF acceleration for very high gradient and high efficiency has led to the concept of Cool Copper Collider, an alternative compact energy frontier linear collider
- Ongoing design study aims to develop the roadmap for demonstrating the Cool Copper Collider as a vital accelerator technology for future energy frontier linear collider. This will then be evaluated by the HEPAP P5 panel for the next decadal HEP strategy
- Synergies with other fields are also explored

Thank you