# $C^3$ LINAC Demonstration Proposal

## Cool Copper Collider Workshop

Faya Wang

7 Feb. 2023

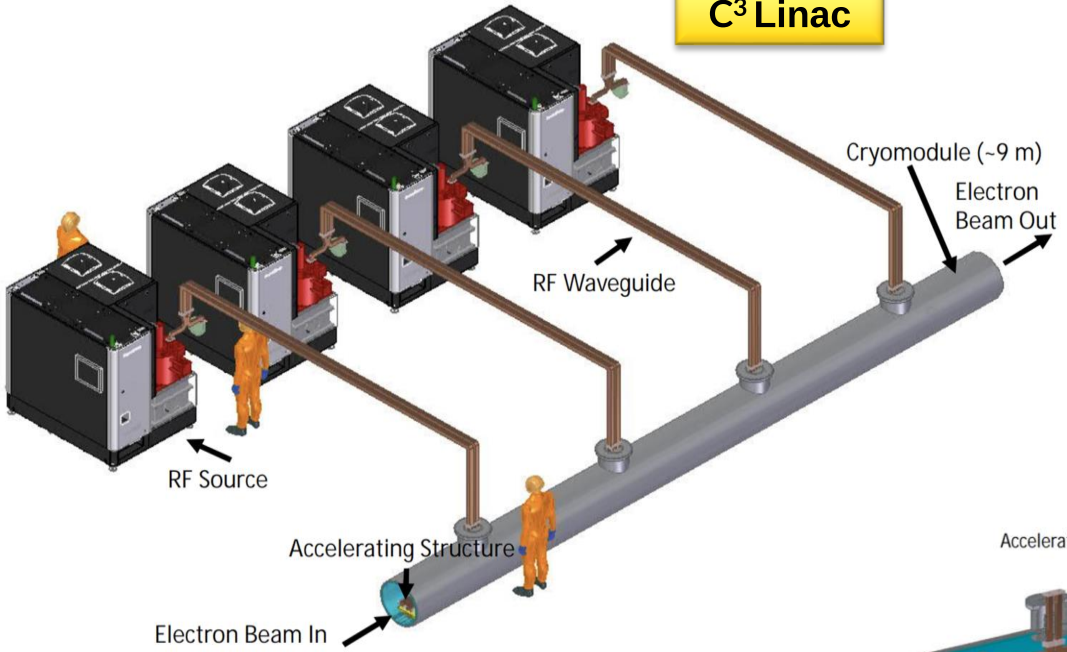
# Acknowledgement


- **SLAC: Mei Bai , Valery Borzenets , Martin Breidenbach, Anatoly Krasnykh, Carsten Hast, Xianghong Li, Zenghai Li, Emilio Nanni, Tim O'Heron, Dennis Palmer, Thomas Peterson, Alex Ratti, Tor Raubenheimer, Muhammad Shumail, Caterina Vernieri, Glen White, Juhao Wu**
- **Florida State University: Guo Wei, Kourosh Shoele**

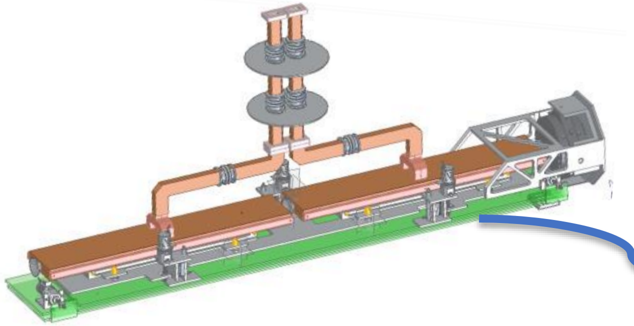
# Introduction  Staged Approach

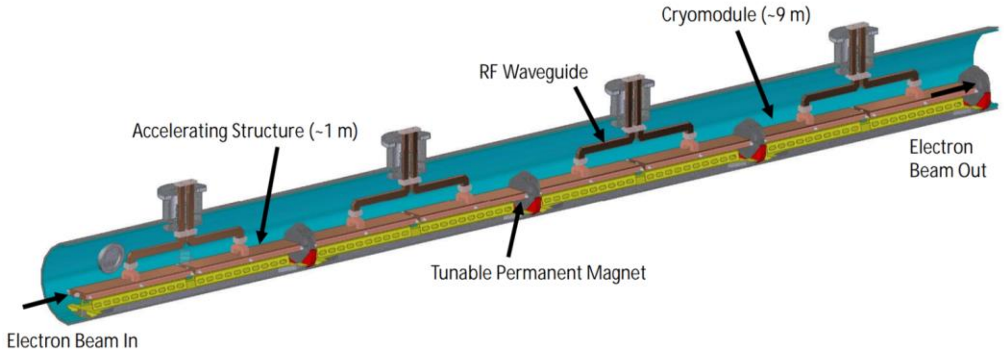
- C³ accelerator technology: Modularized linac based on liquid N2 cooled C-band cavity.
- Cryomodules (CM)s are vacuum insulated cryostats housing 4 rafts, and ha 75 cm ID and about 9 m long.
- Rafts are mechanical supporting structures consisting of 2 accelerator structures and one quadrupole magnet. They are pre-aligned at warm to 5 microns. Each raft has mechanical actuators to align one raft to the next with 5 degrees of freedom.

**C³ Linac**

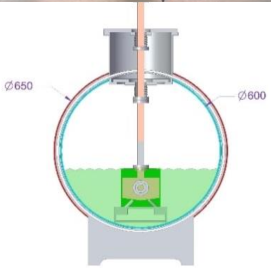



**CM & Raft**



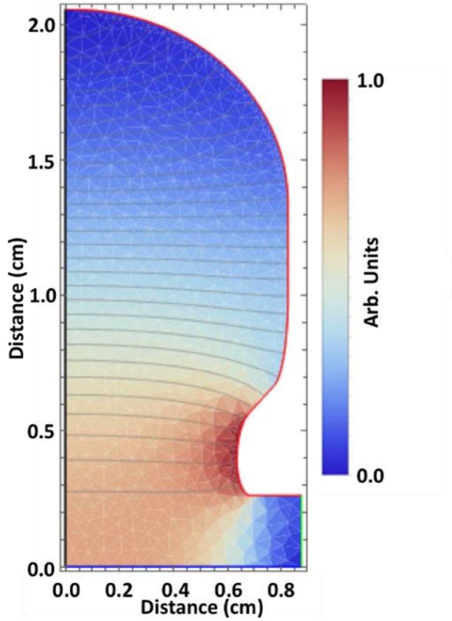



**RF Structure**

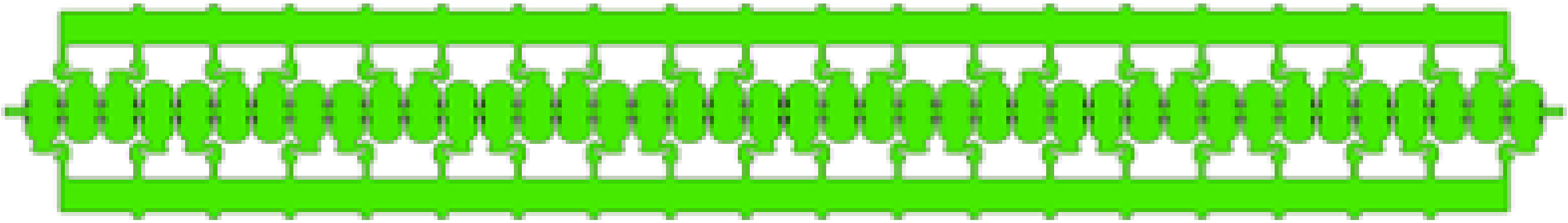


# RF Parameters – $C^3$250/550 GeV

- At $C^3$ the same LINAC can deliver 250 GeV c.o.m and 550 GeV c.o.m in 8 km




- The optimized structure can reach 300 MΩ/m at 80K.
- The accelerator beam aperture (diameter) is 5.2 mm.



- Each CM can reach up to 0.7 GeV with 4 X 50MW klystrons .

| Gradient (MV/m) | Power diss. (W) | rf flat top (ns) | Pulse compr. | Comments | Power/area (W/cm$^2$) | $\Delta T$ Cu-bulk to $LN_2$ (K) |
|---|---|---|---|---|---|---|
| 70 | 2500 | 700 | N | $C^3$ -250 | 0.393 | 2.3 |
| 120 | 2500 | 250 | N | $C^3$ -550 | 0.393 | 2.3 |
| 155 | 3900 | 250 | N | $C^3$ -550 in 7 km | 0.614 | 2.5 |
| 120 | 1650 | 250 | Y | $C^3$ -550 | 0.259 | 2.1 |

SLAC

Ref: E. Nanni et al, SLAC-PUB-17660

# RF Parameters – $C^3$250/550 GeV

- **Main linac cryogenic heat load:**
  - ~9 MW ($C^3$250, $C^3$550-8km) $\frac{250\ GeV}{70\ MeV/m} \times 2500\ W/m$

  **The LN will cool the accelerator structures by nucleate boiling with the vapor velocity near Cryoplant ~ 3m/s at a power density of 0.4 W/cm$^2$.**

  - ~14 MW ($C^3$550-7km) $\frac{550\ GeV}{155\ MeV/m} \times 3900 \frac{W}{m}$

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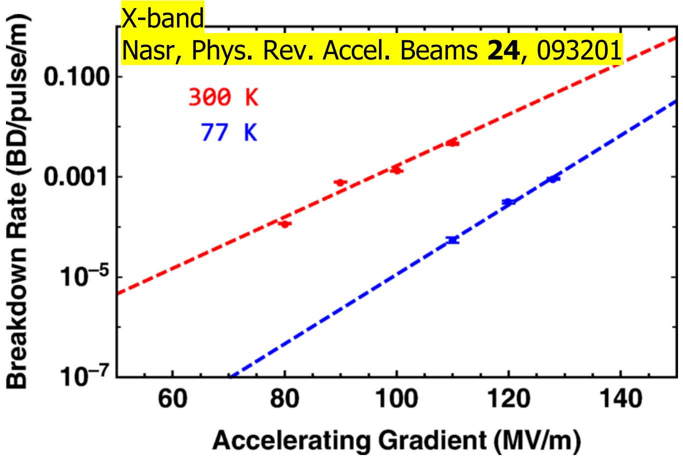
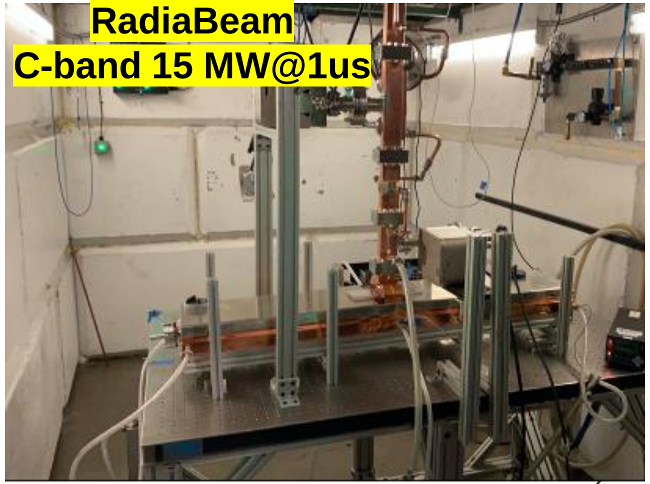
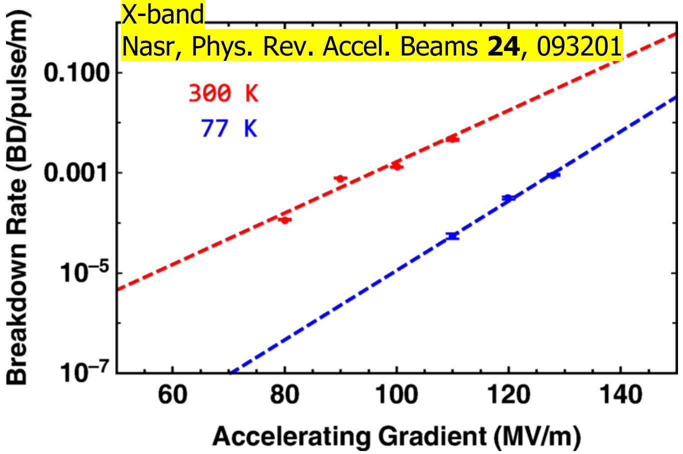
# Introduction    Staged Approach

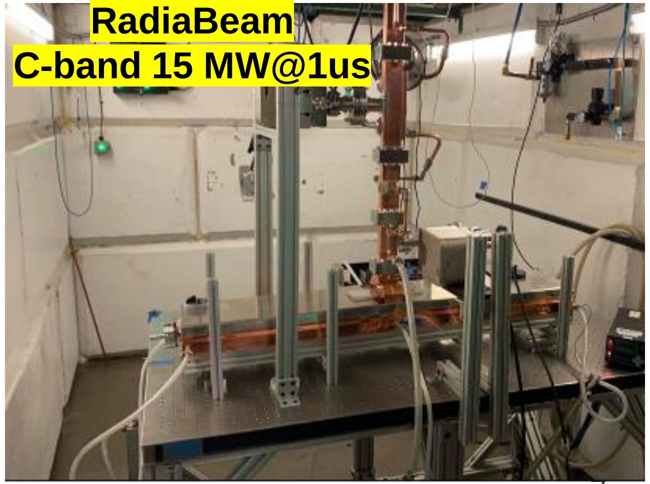
- An X-band cryogenic structure has been demonstrated at high gradient.
- The C-band has been tested at low power at SLAC and high power without beam at Radiabeam



- An X-band cryogenic structure has been demonstrated at high gradient.
- The C-band has been tested at low power at SLAC and high power without beam at Radiabeam
- C$^3$ Linac Remaining Major Risks
  - Achievable gradient and stability over C$^3$ full electron bunch train.
  - Beam emittance growth due to accelerator wakefields
  - Systematic study of alignment and vibration tolerance
  - Performance of the accelerators and the cryostat at the full cryogenic liquid and gas flow rate as expected in C$^3$.
  - A reliable cost basis for extrapolation to C$^3$ scale production.



# Introduction Staged Approach

$C^3$ Demo will focus on the 5 thrusts:

- Collider Cryogenics Design Study
- CryoModule
- Accelerator Structure
- Beam Dynamics Experimental Study
- $C^3$ Main Linac Beam Dynamics Simulation Study

# Introduction Staged Approach

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- Collider Cryogenics Design Study
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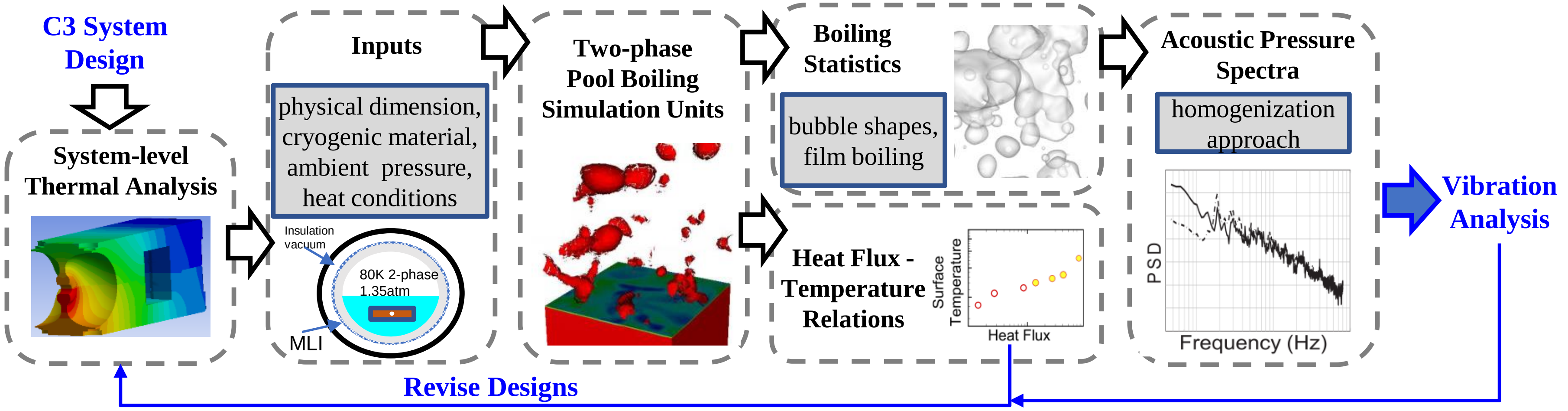
- $C^3$ Main Linac Beam Dynamics

- Vibrations due to boiling of LN
- Large scale simulation setups (from 100s to 100 meters)
- Optimizing CM and cold mass design to avoid the liquid surface turbulent flow
- Engineering procedures to eliminate possible problems from linac warm-up and cold-down process
- Instrumentation needs




SLAC

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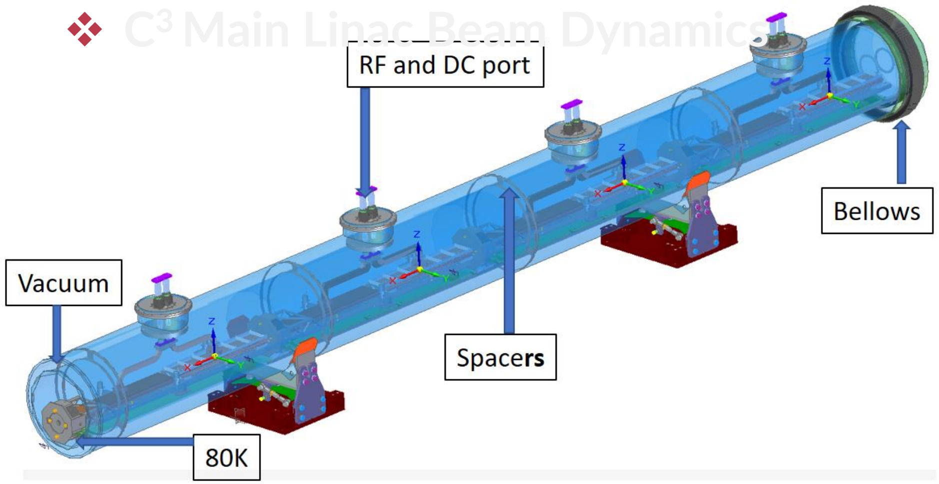


- Adequate stability of the quadrupoles and accelerators during powered operation and full $C^3$ cryogenics fluid flow rate (with margins)
- Adequate range, precision and bandwidth of the raft positioning systems
- Full $C^3$ cryogenic flow rate benchmarking with simulation
- In-situ CM vibration measurement
- In-situ pre-beam alignment ≤ 500 um
- Tunable permanent quadrupole magnets
- Waveguide transitions into the Cryomodule

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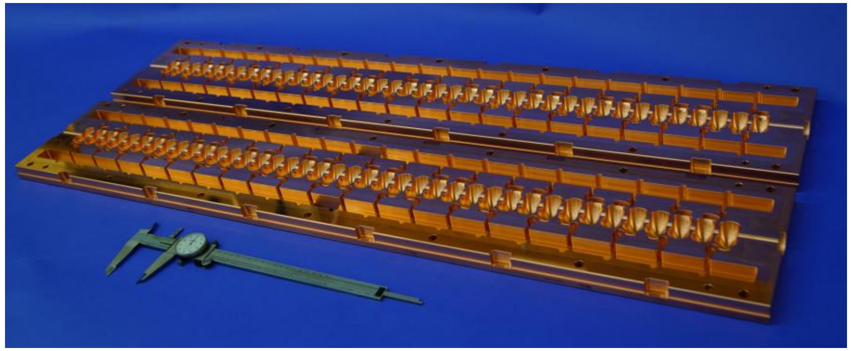
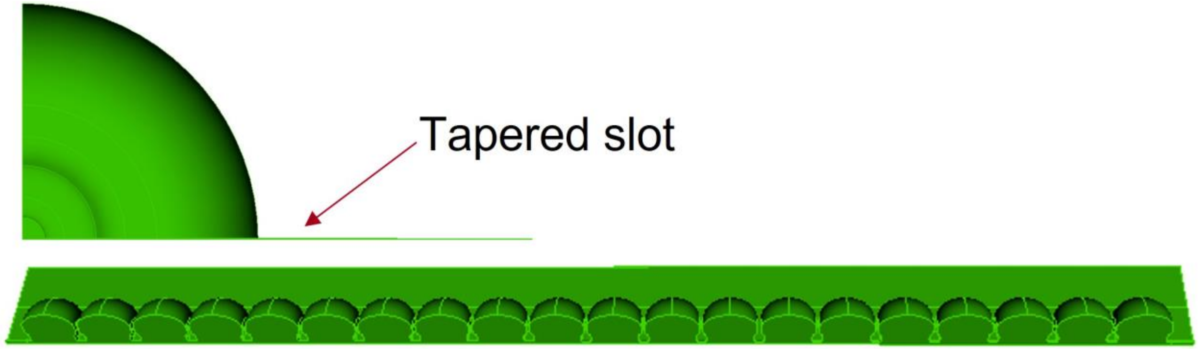
- Achievable gradient and gradient stability at the **$C^3$** equivalent beam loading
- HOM damping design and fabrication
- Integrated beam position monitor for structure alignment
- Optimization of the mechanical design for structure fabrication and tuning
- HOM detuning design

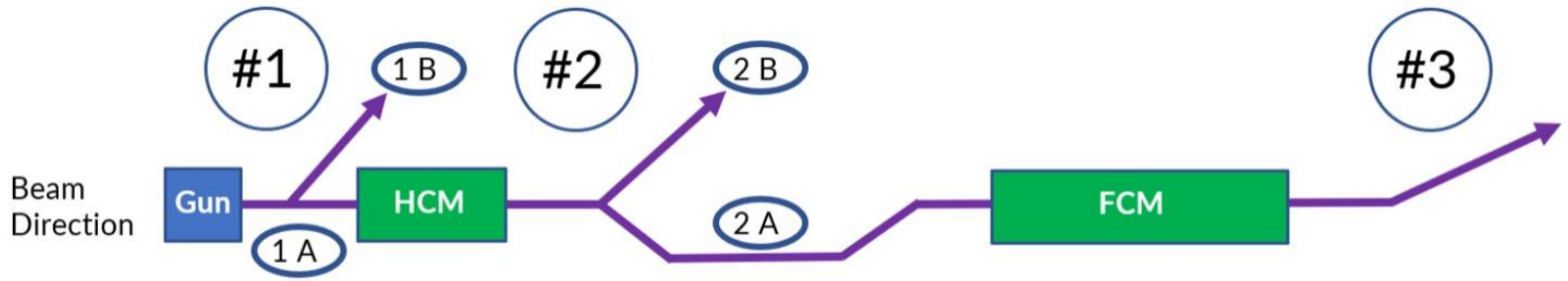




**C³ Demo will focus on the 5 thrusts:**

- Collider Cryogenics Design Study
- CryoModule
- Accelerator Structure
- **Beam Dynamics**
- C³ Main Linac Beam Dynamics

- Measure beam properties and validate wakefield model with simulations.
- Begin development of feedback loops for minimization of emittance growth.
- Develop systematic beam-based diagnostics for different stages of the Demonstrator.



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**C$^3$ Demo will focus on the 5 thrusts:**

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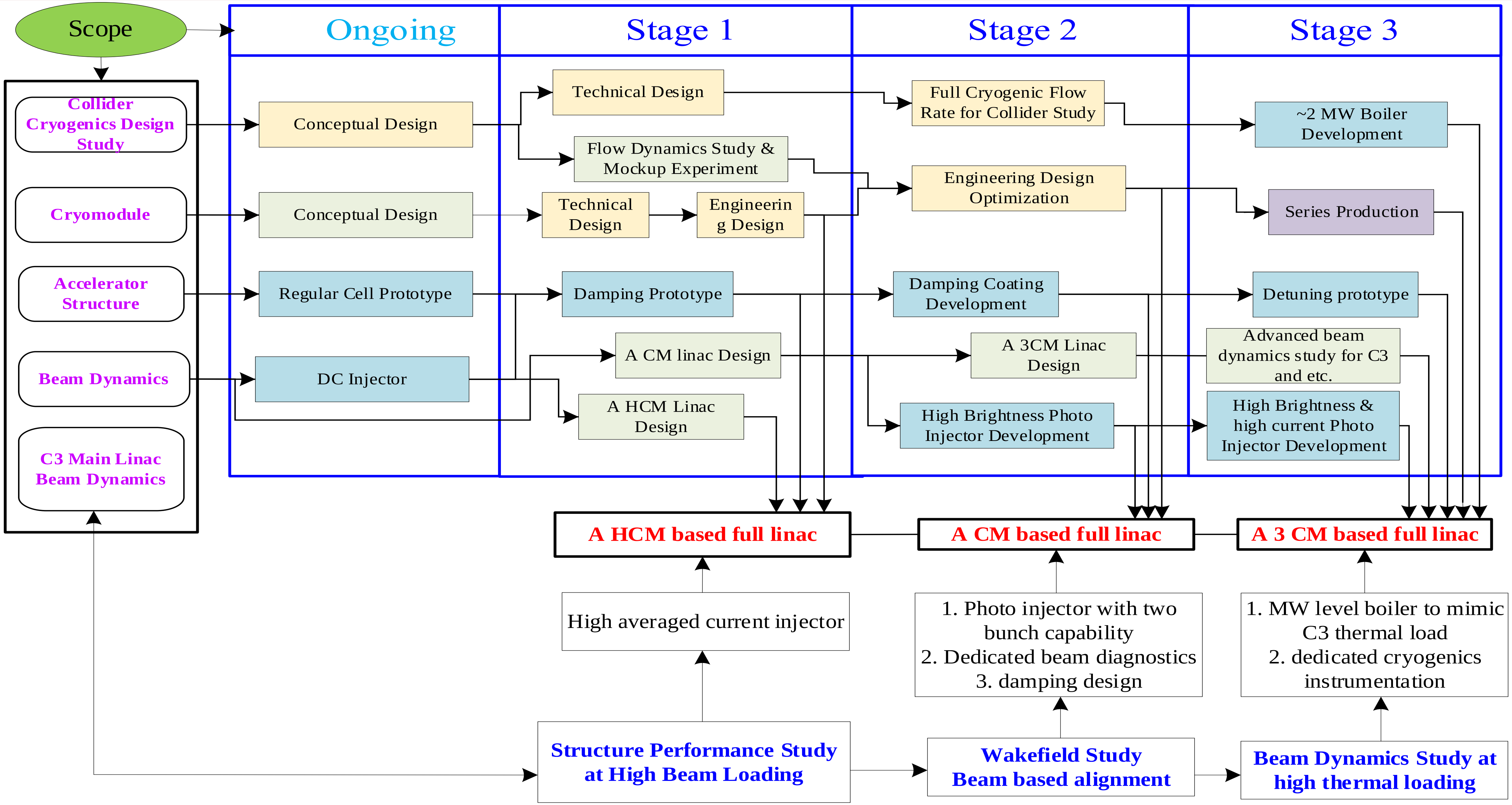
- Beam Dynamics
- C$^3$ Main Linac Beam Dynamics

- Perform emittance preservation simulation studies to determine alignment and vibration tolerances
- Investigation and optimization of lattice design, BNS damping, dispersion free steering, and wakefield corrections ect.

# Staged Approach



# Staged Approach

- Stage 1: Demonstration of $C^3$ Structure Performance at Full Beam Loading.
    - Demonstrate the accelerator structure at the full $C^3$ equivalent beam loading:
        - Unloaded and loaded at 70 MeV/m and 700 ns with 190 mA – $C^3$250
        - Unloaded and loaded gradient of 120 MeV/m and 250 ns with 300 mA - $C^3$550

# Staged Approach

- **Stage 1**: Demonstration of $C^3$ Structure Performance at Full Beam Loading.
  - **Test a $C^3$ half Cryomodule (HCM) at full $C^3$ equivalent beam loading.**
    - ✓ High current DC injector
    - ✓ HCM Linac

# Staged Approach

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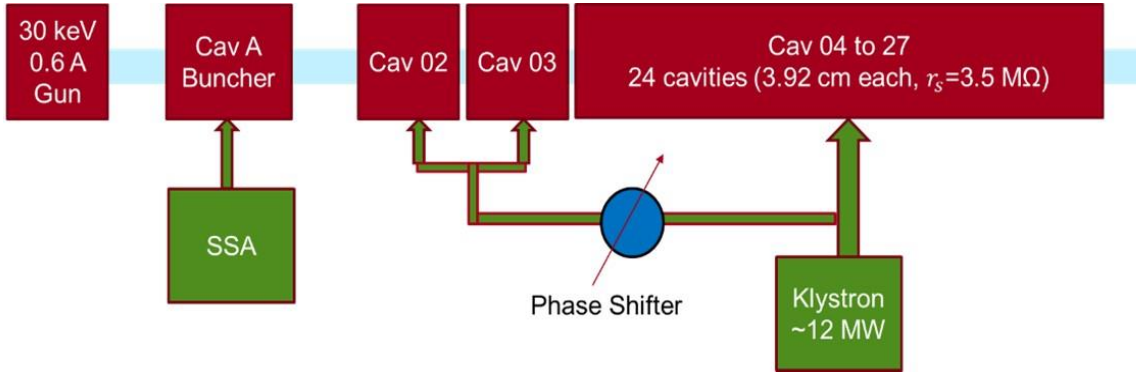
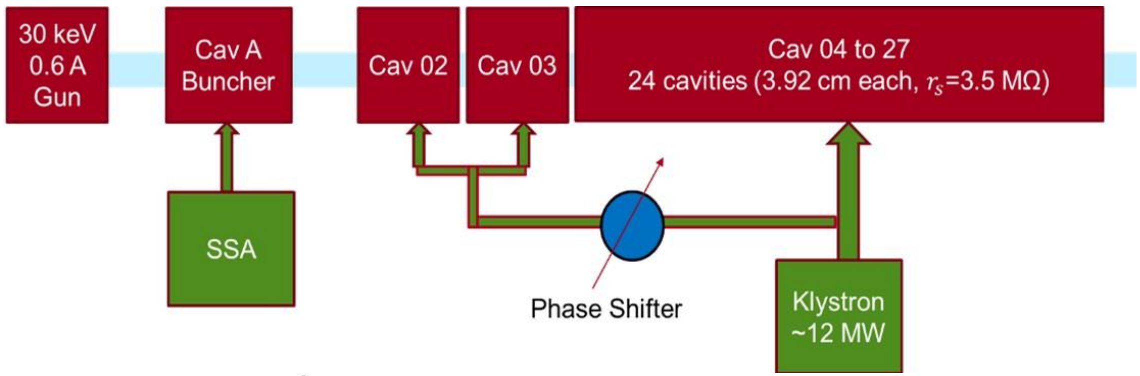
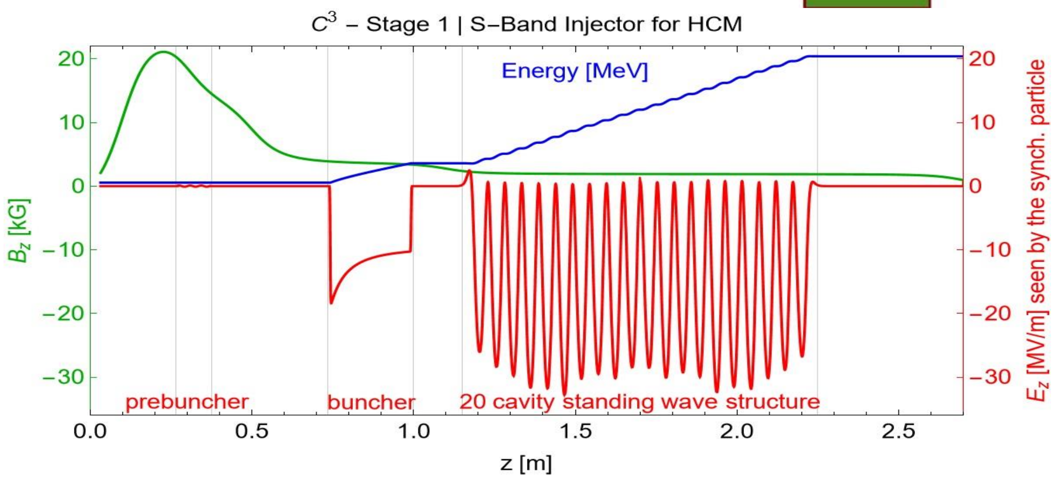


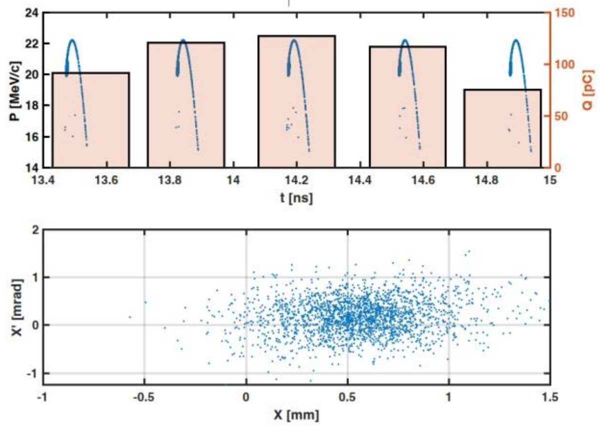
# Introduction    Staged Approach

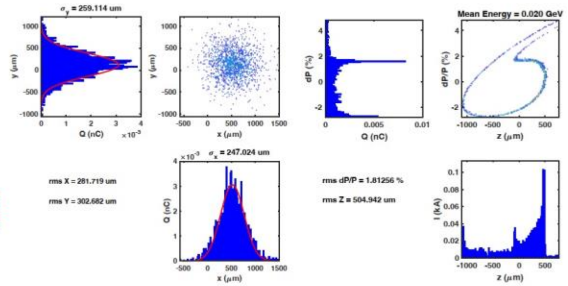
- **Stage 1: Demonstration of C³ Structure Performance at Full Beam Loading.**
  - **Test a C³ half Cryomodule (HCM) at full C³ equivalent beam loading.**

✓ **High current DC injector**    ✓ HCM Linac



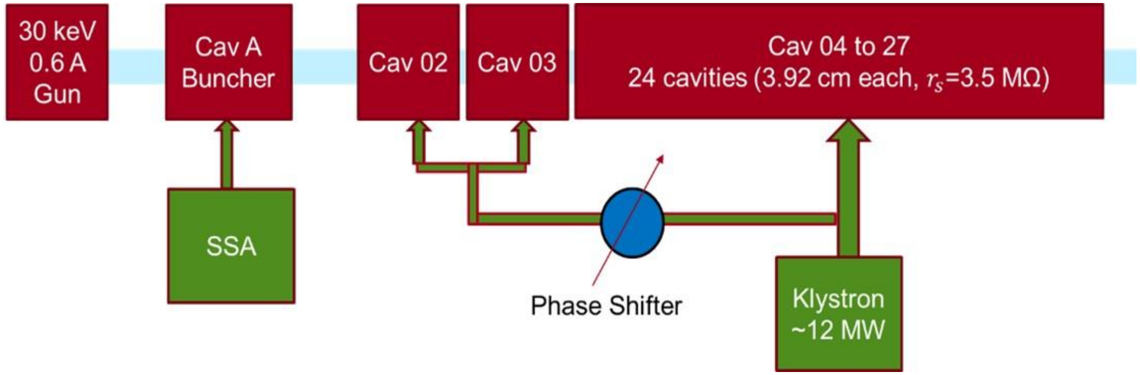



- Capture Efficiency = 61 %
- $Q_{bunch}$ = 115 pC

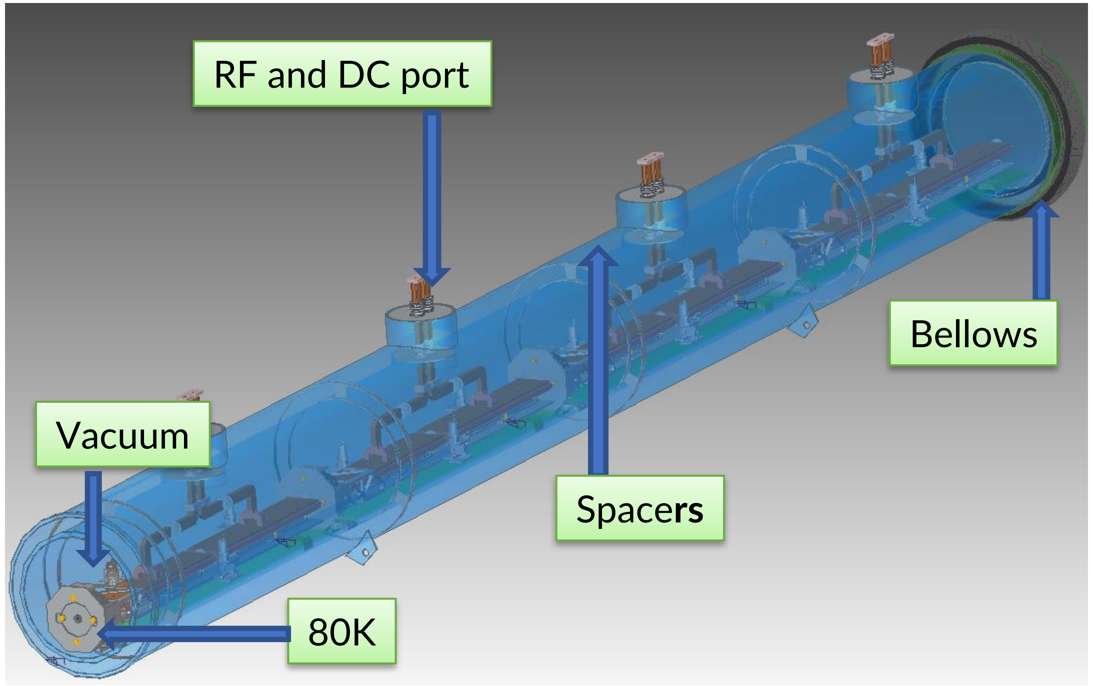
$I_{ave} \approx 330\ mA$

- **Stage 1: Demonstration of C³ Structure Performance at Full Beam Loading.**
  - **Test a C³ half Cryomodule (HCM) at full C³ equivalent beam loading.**

✓ **High current DC injector**




✓ **HCM Linac**



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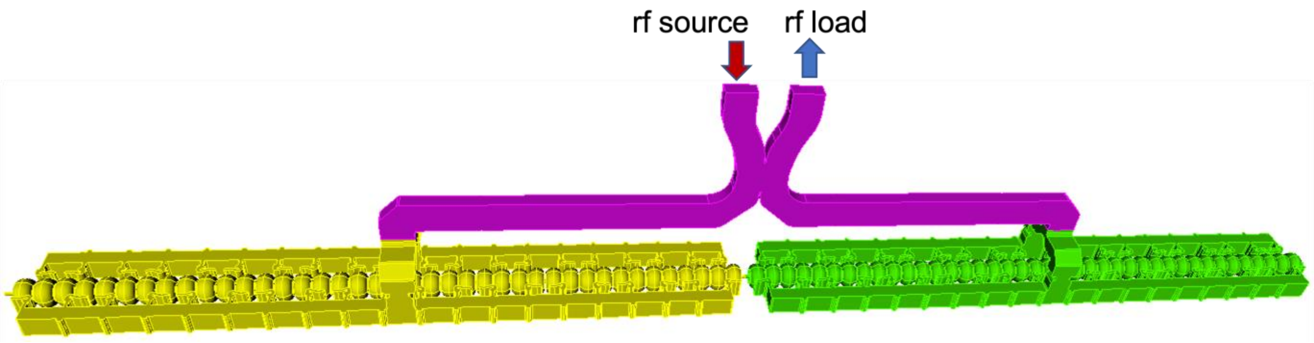
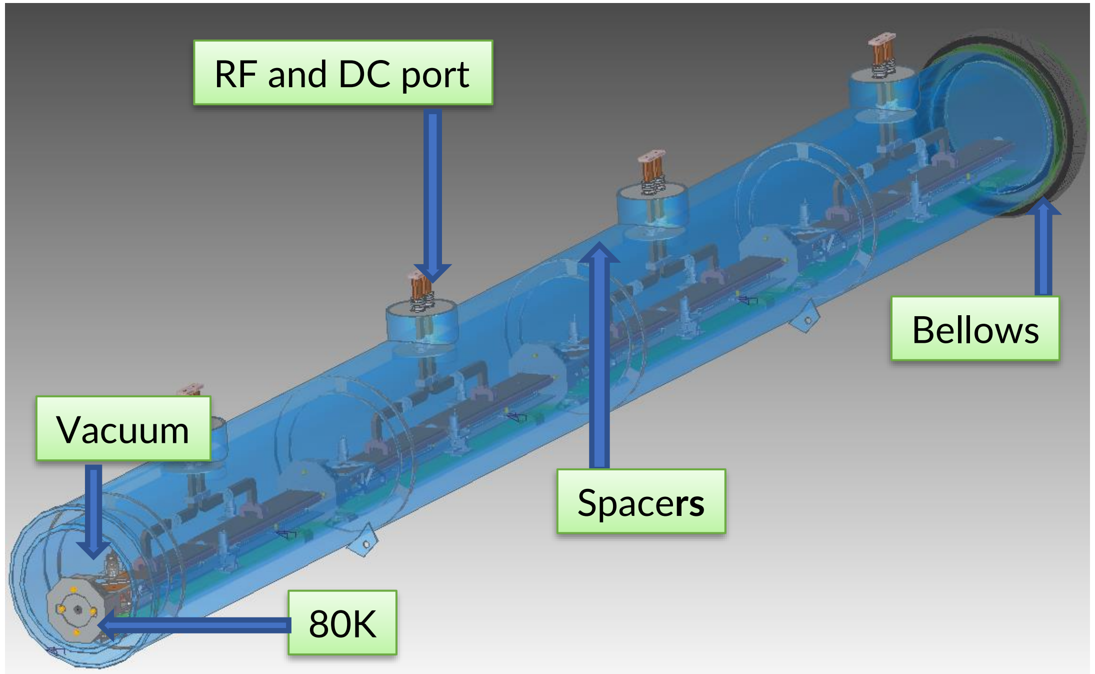



✓ HCM Linac

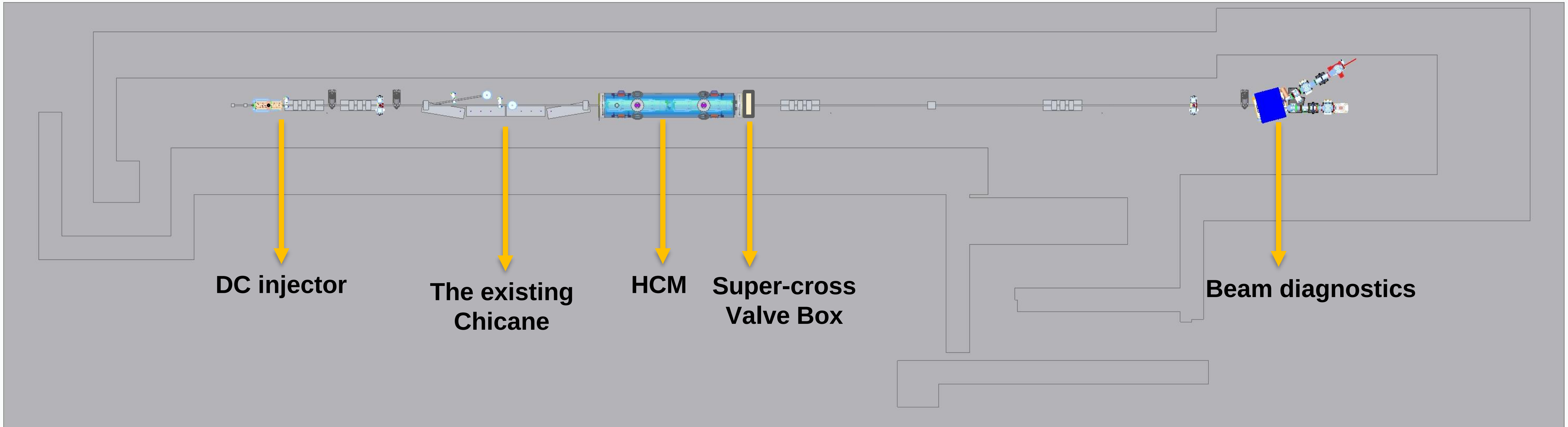



- 2x50 MW C-band RF station needed to be developed.
- About 10% rf transmission loss
- With structure match to 43% beam loading

  - 4 structure at 78 MeV/m with no beam
  - 2 structure at 111 MeV/m wo beam and 90 MeV/m with 190 mA (C3-250)
  - 1 structure at 157 MeV/m wo beam and 125 MeV/m with 300 mA (C3-550)

# Staged Approach

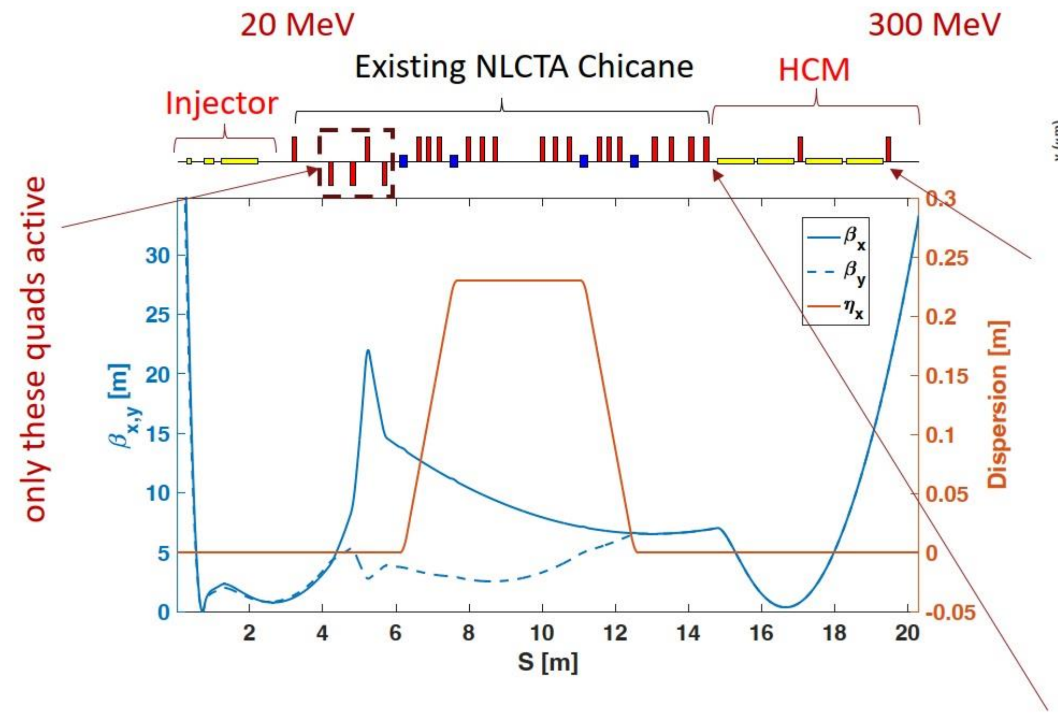
- Stage 1: Demonstration of $C^3$ Structure Performance at Full Beam Loading.
  - Test a $C^3$ half Cryomodule (HCM) at full $C^3$ equivalent beam loading at SLAC NLCTA.
  - 2x50 MW C-band rf stations will be developed with repurposing an exiting X-band station modulator.
  - The existing S-band station in NLCTA will be used to power the injector.

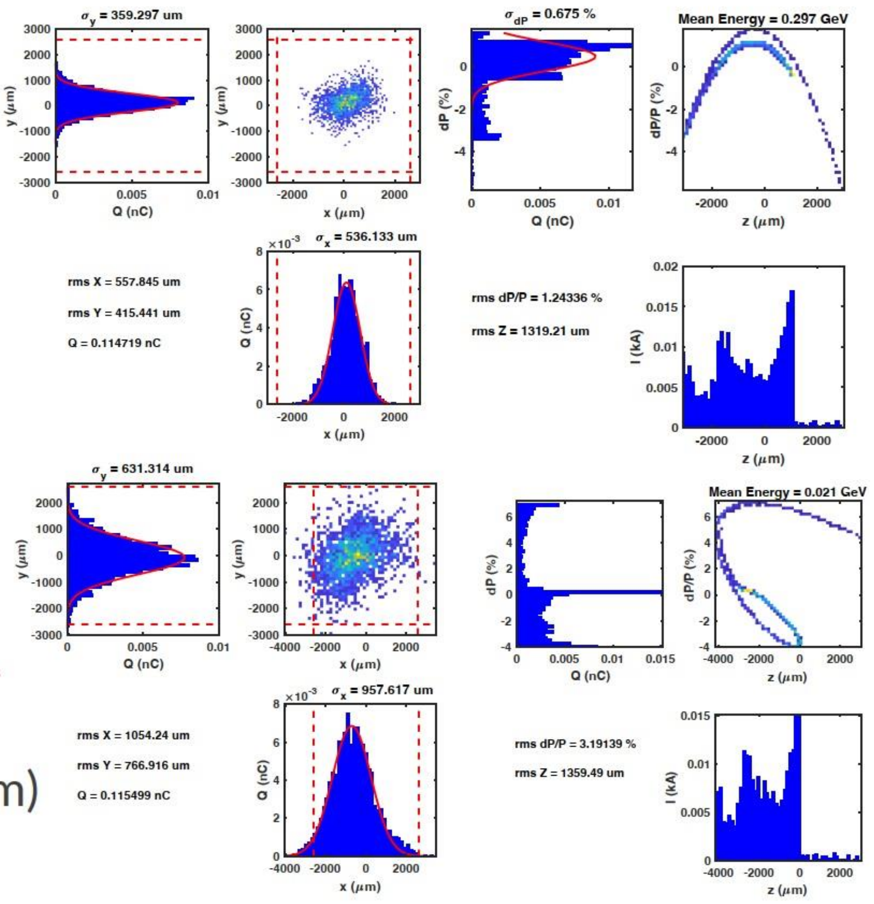



Rendering layout of the HCM (light blue block) full linac with its injector in the NLCTA bunker.

# Introduction    Staged Approach

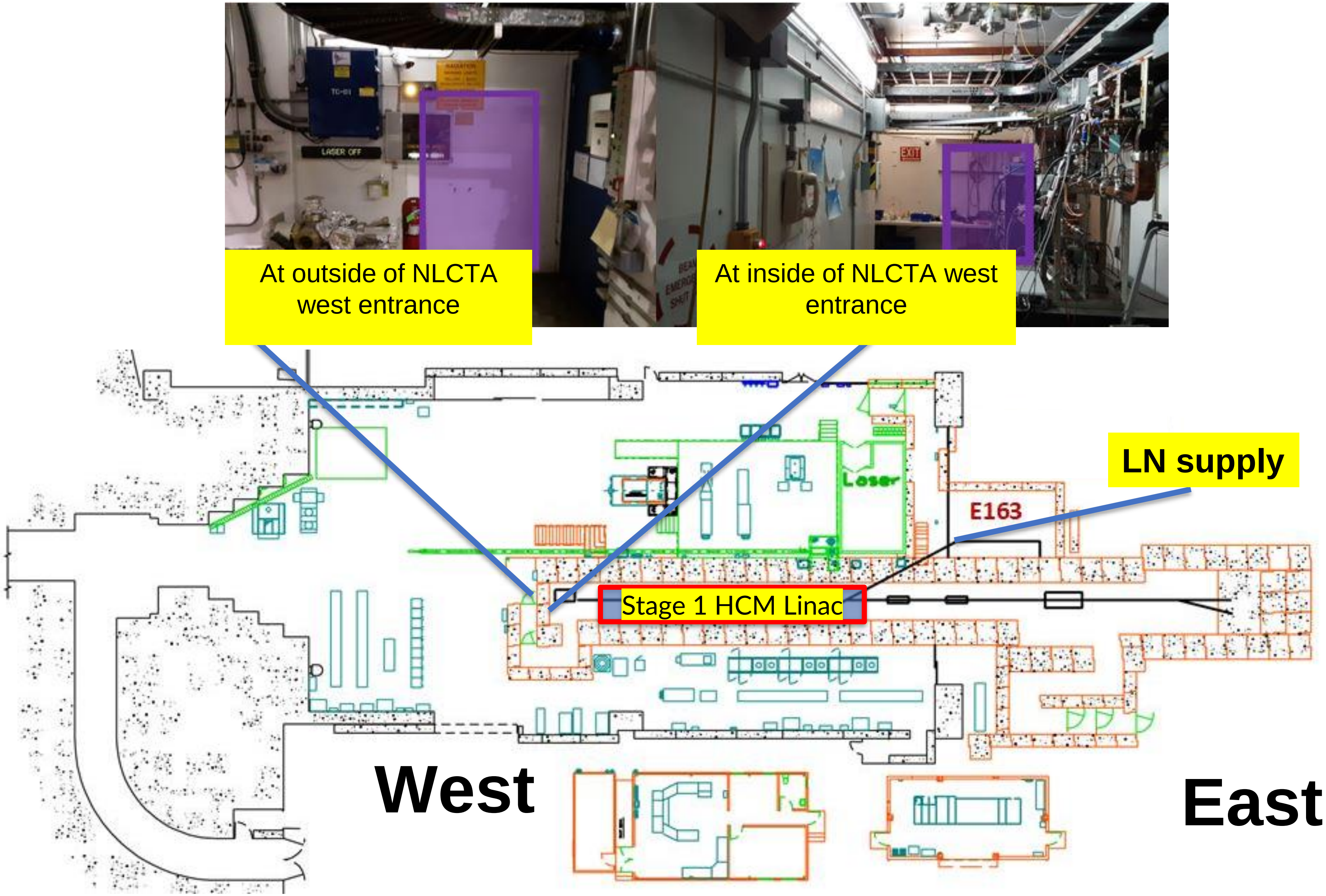
- **Stage 1**: Demonstration of $C^3$ Structure Performance at Full Beam Loading.
  - Test a $C^3$ half Cryomodule (HCM) at full $C^3$ equivalent beam loading at SLAC NLCTA.




- Q=115pC, $\gamma\varepsilon_{x,y}$ (90%) = 3.7 x 3.3 μm-rad
- 3 pC collimated on HCM aperture (r=2.6mm)

- Stage 1 will use NLCTA as it is.




SLAC

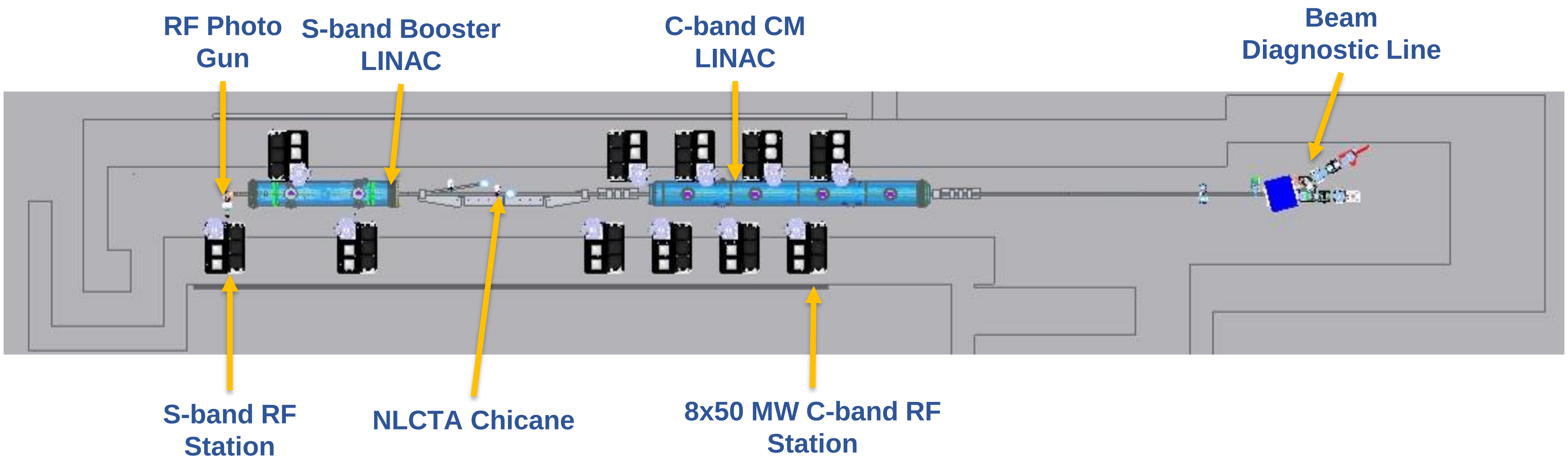
# Introduction    Staged Approach

- Stage 2: First Scale-up Demonstration of A C³ CryoModule Linac
  - A high brightness photo injector with at least two bunches and various space
  - A large aperture S-band booster linac
  - A full C³ CM Linac.

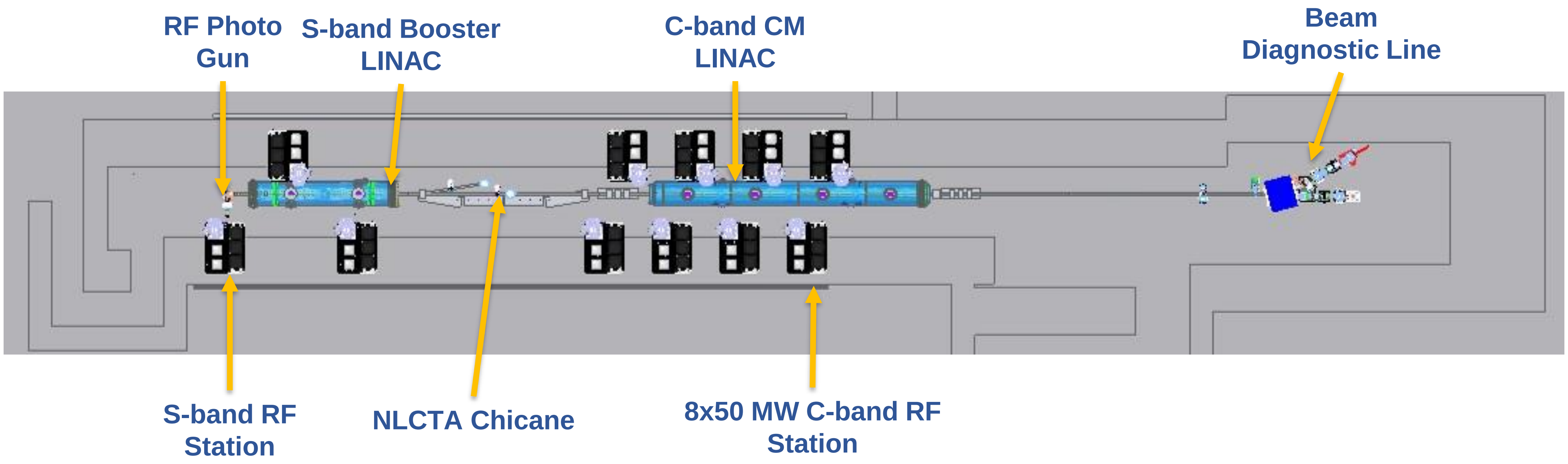
  - Production of the cryomodule assembly with in-situ pre-beam alignment ≤500 µm
  - Demonstration of the acceleration structure in the full CM LINAC reaching unloaded gradient of 155 MeV/m at 250 ns
  - Development of high brightness RF photo injector with an LCLS-like S-band RF gun and an S-band booster LINAC re-using the Stage 1 HCM cryostat
  - Evaluation of cryomodule LINAC beam performance in the presence of wakefields, and benchmarking with the beam simulation

# Staged Approach

- **Stage 2**: First Scale-up Demonstration of A $C^3$ CryoModule Linac
  - A high brightness photo injector with at least two bunches and variable bunch space
  - A large aperture S-band booster linac: repurpose the stage 1 half CM with 4x1m S-band structures
  - A full $C^3$ CM Linac.

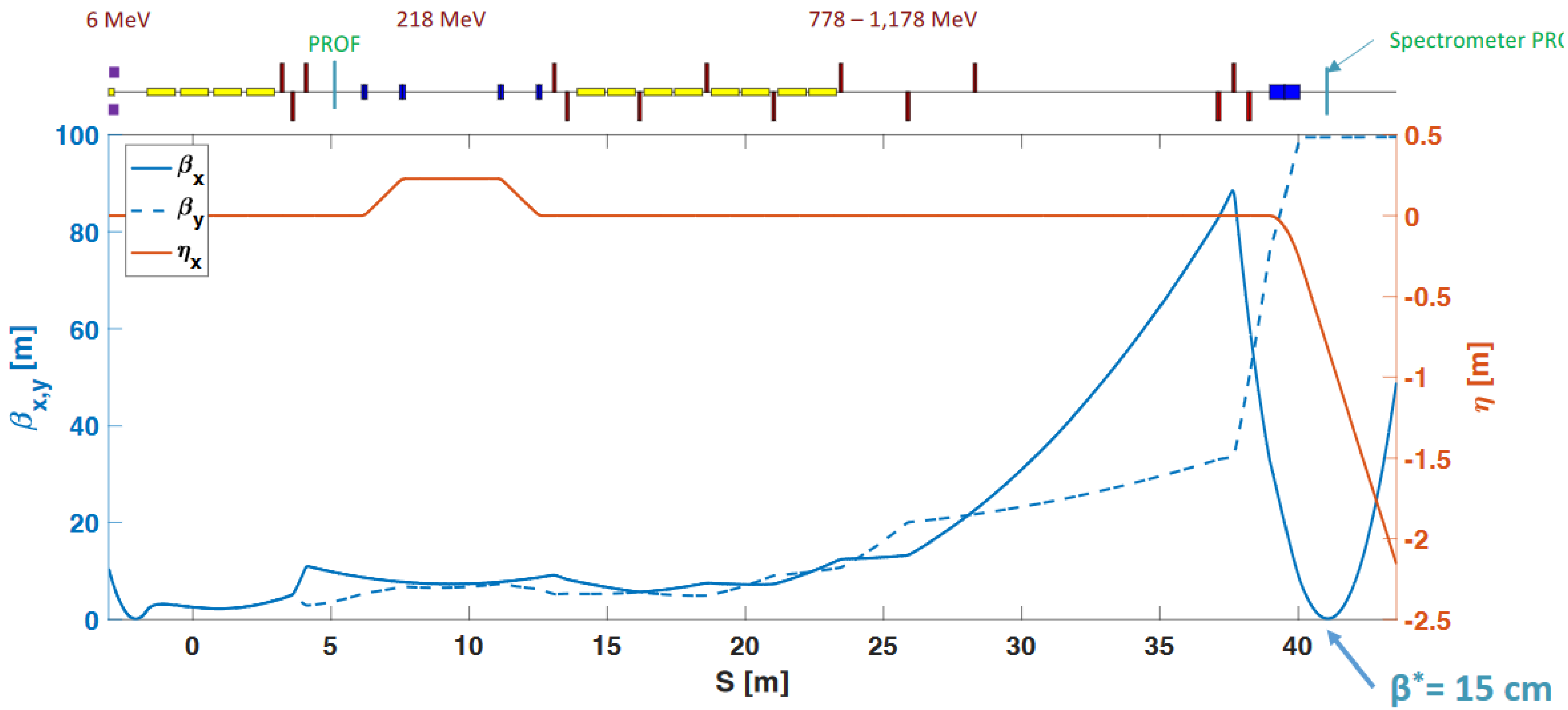


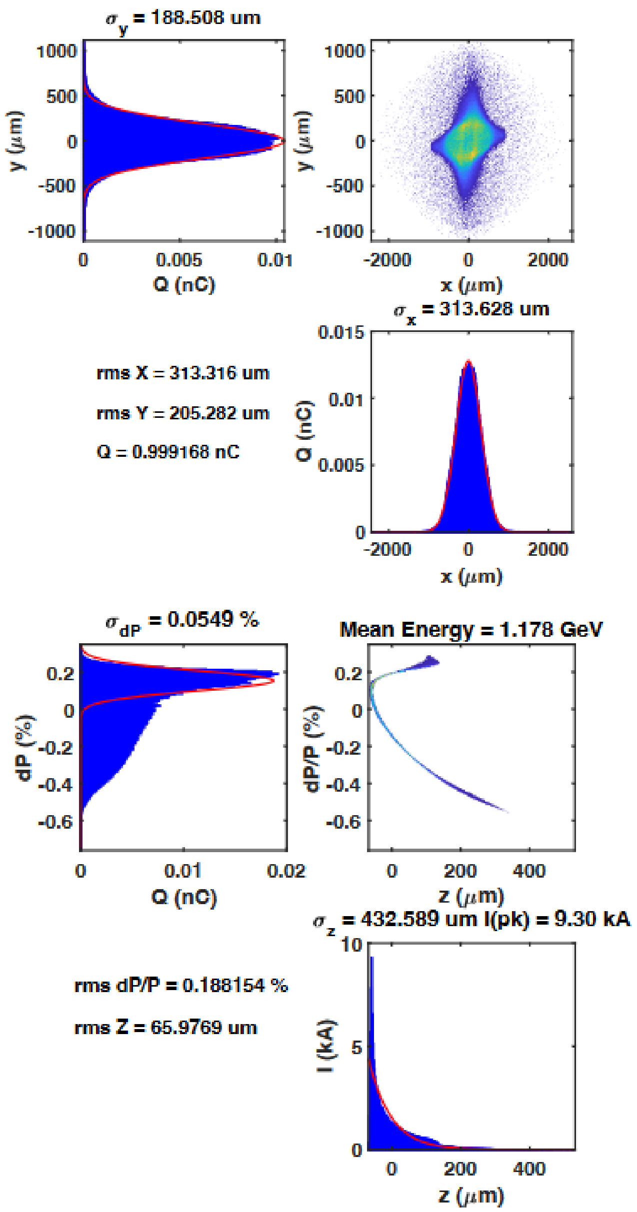
- **Stage 2**: First Scale-up Demonstration of A $C^3$ CryoModule Linac
  - 8x50 MW C-band RF station will be built.
  - With zero beam loading and about 10% RF transmission loss
    - 1 klystron per structure: 8 structures at 113 MeV/m
    - 2 klystrons per structure: 4 structures at 160 MeV/m



# Staged Approach

- **Stage 2**: First Scale-up Demonstration of A C³ CryoModule Linac
  - **The preliminary simulation shows a 1nC beam of 2µm.rad emittance is possible at a final energy of 1.2 MeV.**

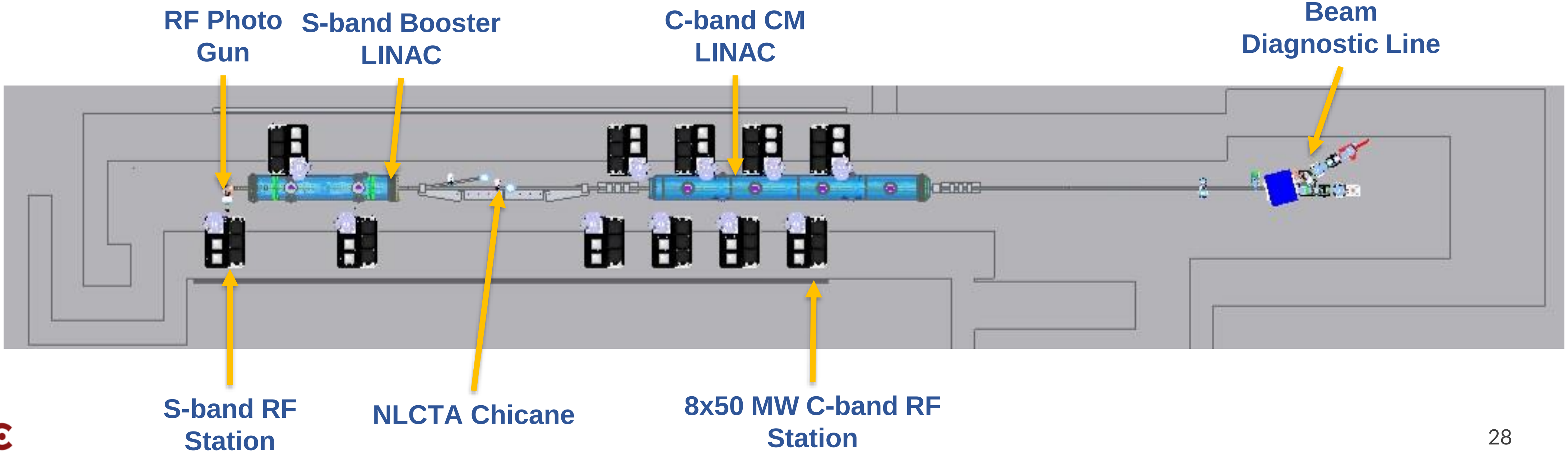


# Staged Approach

- Stage 2: First Scale-up Demonstration of a Full $C^3$ CryoModule
  - Beam diagnostics at the LINAC end: Long range wakefield and longitudinal short range wakefield

| Quantities | Devices |
|---|---|
| Energy and Energy spread | Dipole + screen/wire scanner |
| Charge | Faraday cup and beam dump, toroid |
| Beam size and beam position | Profile screens/wire scanner and NLCTA Quad package |
| Emittance and wakefield effects | Coherent undulator radiation and profile screen/wire scanner |
| Bunch length | Transverse deflecting cavity |



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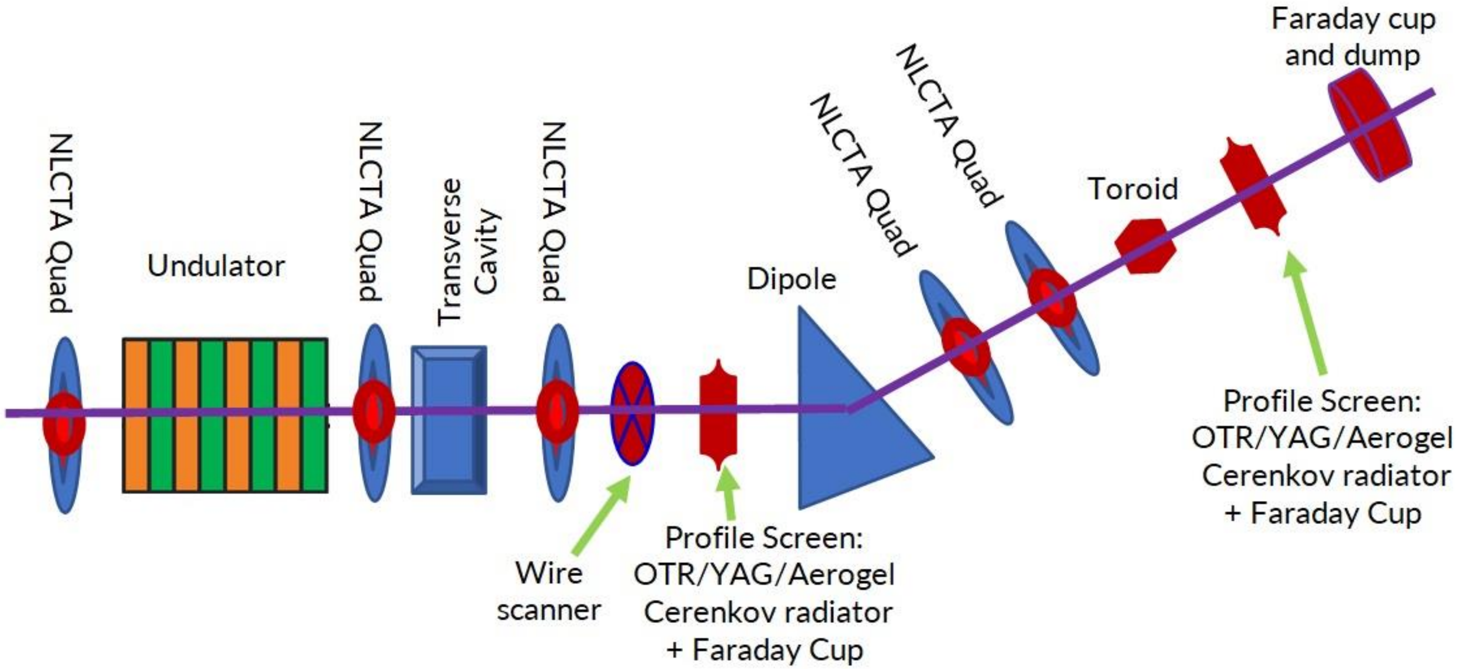
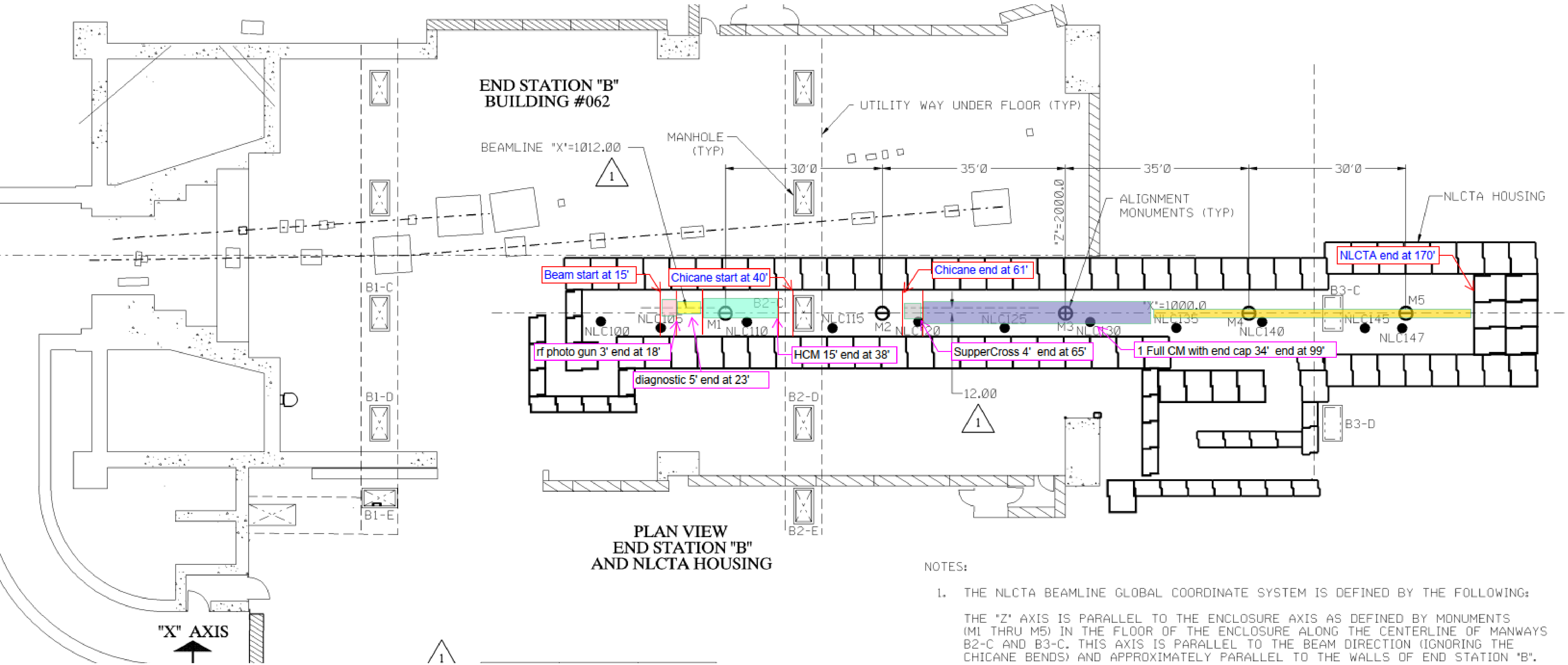





NOTES:

1. THE NLCTA BEAMLINE GLOBAL COORDINATE SYSTEM IS DEFINED BY THE FOLLOWING:

THE "Z" AXIS IS PARALLEL TO THE ENCLOSURE AXIS AS DEFINED BY MONUMENTS (M1 THRU M5) IN THE FLOOR OF THE ENCLOSURE ALONG THE CENTERLINE OF MANWAYS B2-C AND B3-C. THIS AXIS IS PARALLEL TO THE BEAM DIRECTION (IGNORING THE CHICANE BENDS) AND APPROXIMATELY PARALLEL TO THE WALLS OF END STATION "B".

# Staged Approach

- **Stage 2**: NLCTA refurbishment will be required.

- **Site preparation**:

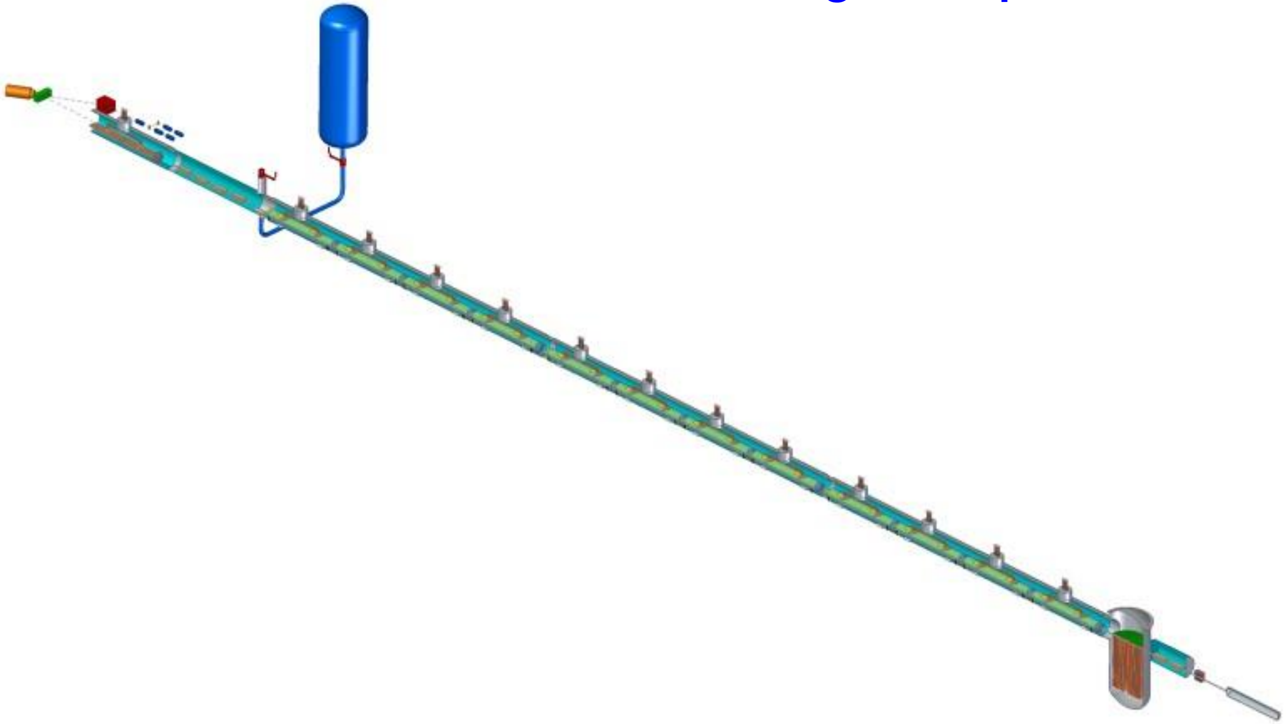
  a) The NLCTA bunker enclosure and its roof will be cleaned out.

  b) The current control racks for the current S-band and the X-band station 0 &1 will be removed.

  d) Drilling 11 penetrations on the bunker roof for the C-band RF waveguide, and installation of support structures for the 11 RF stations.

- **Utilities**: installation of 480V AC power and low conductivity water (LCW) distribution for 11 RF sources on the NLCTA roof, ventilation for N2 gas, electronic racks, and cables. 480V power is available from a nearby sub-station. LCW is available from 2 pressure limiting locations inside and outside ESB.

- Stage 3: Integrated Demonstration Towards the $C^3$ main LINAC
  - Cryogenics performance study at the $C^3$ full flow rate
  - Mapping out of transverse short range wakefield
  - Structure and magnet pre-beam alignment in each CM as well as between through multiple CMs



3.5 cryomodule LINAC with a ~ 2 MW boiler

# Staged Approach

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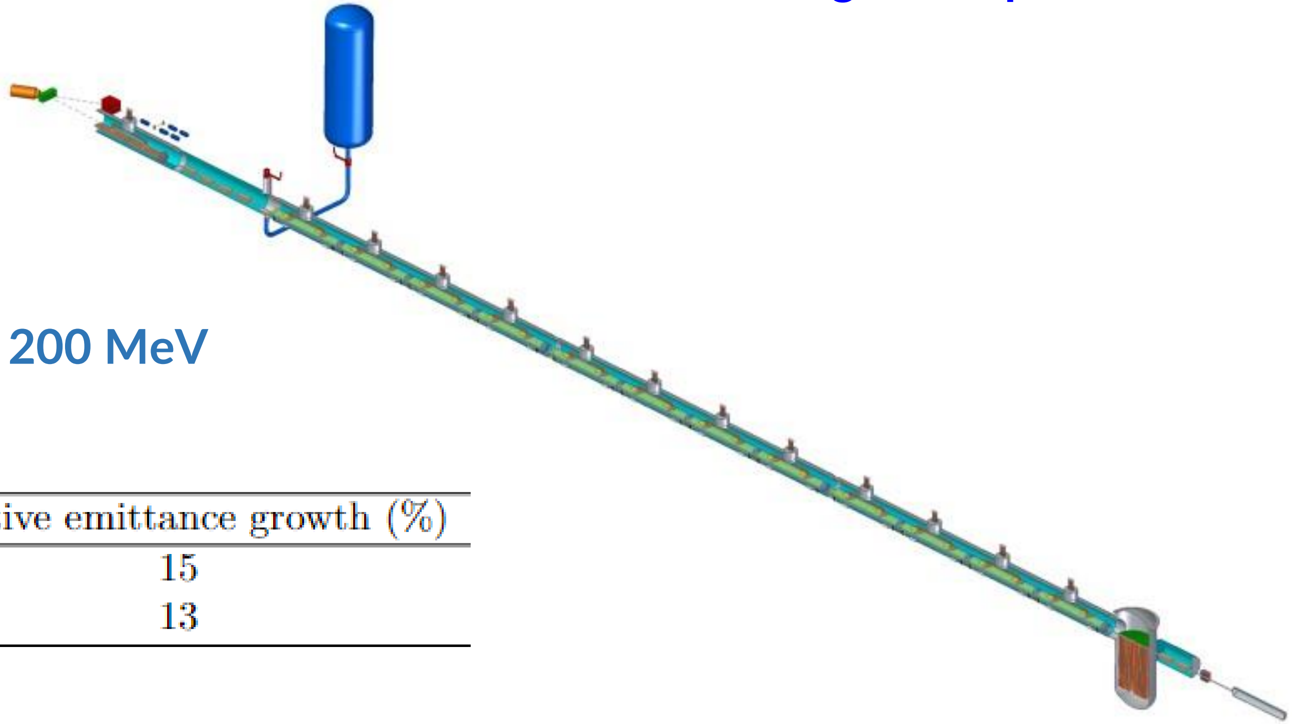

- 3 CM LINAC at 70 MeV/m
- Injected bunch of 1nC, 1.5 umrad, and 200 MeV
- Final beam energy 1.7 GeV

| Bunch length (rms, $\mu$m) | Off set ($\mu$m) | Relative emittance growth (%) |
|---|---|---|
| 556 | 500 | 15 |
| 1112 | 200 | 13 |

3.5 cryomodule LINAC with a ~ 2 MW boiler

- **Stage 3: Integrated Demonstration Towards the $C^3$ main LINAC**
  - **The full stage 3 facility requires ~ 70m bunker.**
  - **The NLCTA will have to be extended by ~ 20m to host the full stage 3 LINAC.**

| Site | pros | cons |
|---|---|---|
| NLCTA at SLAC | continuation of Stage 1&2 | needs extension of current bunker |
| IR12 at SLAC | ample space of exisitng tunnel with shielded large high bay area and control room on either side | these infrastructures were de-actived since the end of BarBar program. Will require investment to re-establish |
| FAST at Fermilab | well established operational accelerator infrastructure including cryogenic system | difficult to leverage the investment of Stage 1 and Stage 2 |
| LINAC Extension Area (LEA) at ANL | ample footprint with reasonable infrastructure help to deepen synergy with AWA and APS | possibility for PWFA R&D is not yet clear |

# Synergies and Impact

✓ Advanced accelerator concept study like staging PWFA

✓ Full energy linac injector for storage ring.

Stage 3: 3½ CM

- A 3 CM LINAC ~ 2.7 GeV reach over about 30 meters
  - ✓ Independent energy tunning of beamlines in an x-ray FEL undulator farm
  - ✓ Compact and cost-effective x-ray FEL.

Stage 2: 1½ CM

- A single CM linac with 8x50 MW klystrons of ~ 0.9 GeV over ~9 m
  - ✓ Medical: VHEE therapy
  - ✓ Compact high energy (100s keV to 1MeV) Compton source
  - ✓ Lower energy injector for booster ring
  - ✓ High brightness injector feasibility

Stage 1: ½ CM

- A half CM with 2x50MW klystrons – 0.32 GeV over 5 m

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# Synergies and Impact

- ✓ Advanced accelerator concept study like staging PWFA
- ✓ Full energy linac injector for storage ring like CHESS injector (6GeV)

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# C$^3$Demo Timeline

# Summary

- The overall objective of this proposal is to mature the RF and cryomodule technology and complete the beam dynamics investigation for the $C^3$ main LINAC.
  - design and analyze the main LINAC cryogenics
  - complete the design and construction of the cryomodules
  - demonstrate the accelerating structure with beam and wakefield damping
  - investigate the $C^3$ main LINAC machine and beam dynamics performance.
- The $C^3$ Demonstration R&D Plan will
  - provide key inputs for the conceptual design of **the $C^3$ Higgs Factory.**
  - **open up significant new scientific and technical opportunities based on the $C^3$ accelerator technology.**

# Thank you so much!

## Questions?