C^3 LINAC Demonstration Proposal

Cool Copper Collider Workshop, SLAC

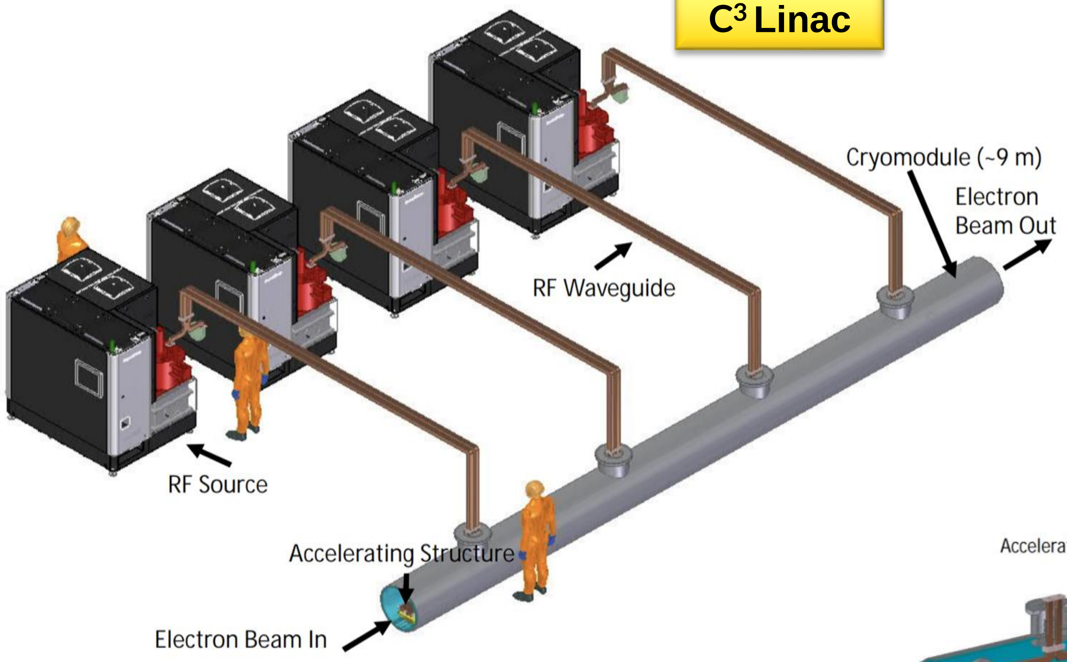
Faya Wang

13 Feb. 2024

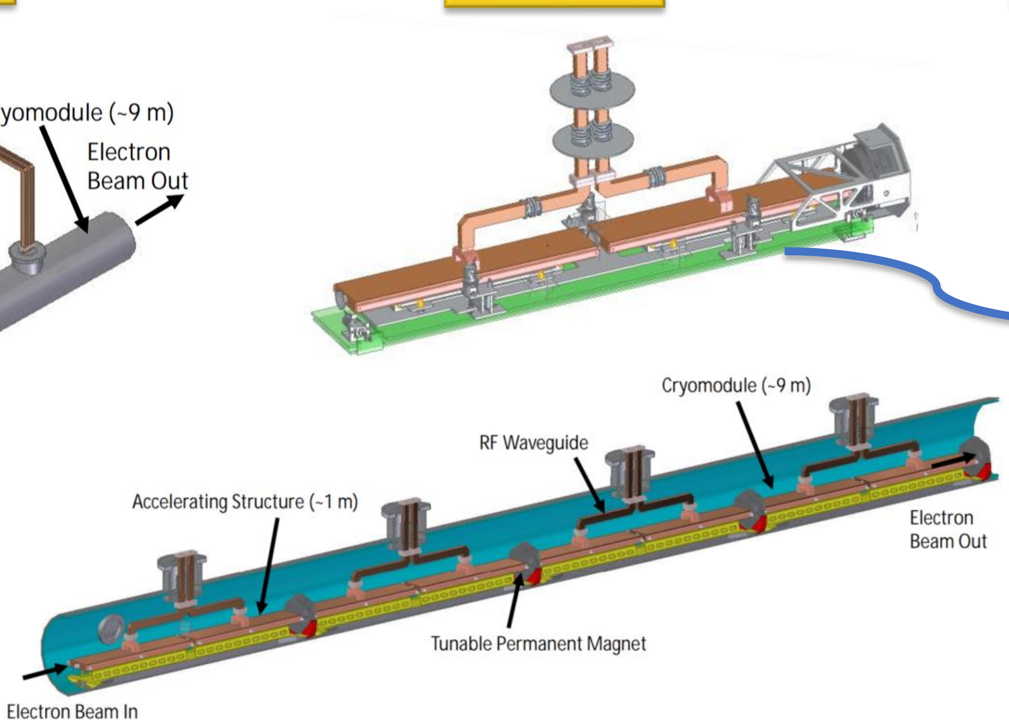
Introduction Staged Approach

- C^3 accelerator technology: Modularized linac based on liquid N2 cooled C-band cavity.
- Cryomodules (CM)s are vacuum insulated cryostats housing 4 rafts, and has 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 300K to 5 microns. Each raft has mechanical actuators to align one raft to the next with 5 degrees of freedom.

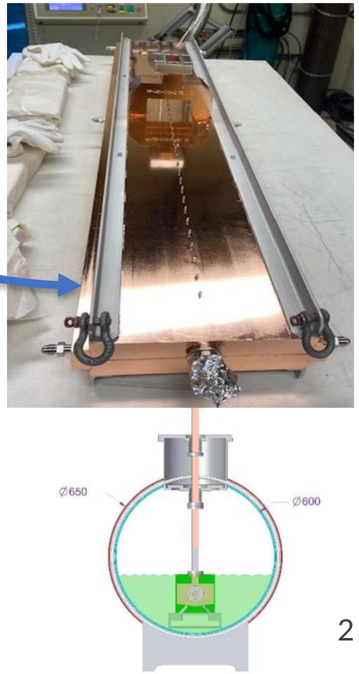
C^3 Linac



CM & Raft

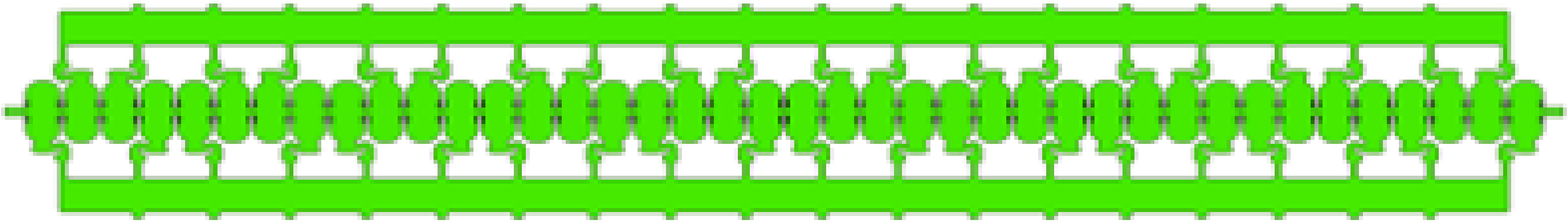


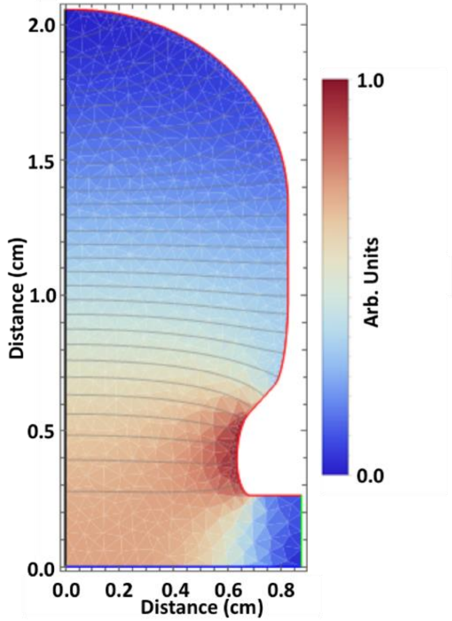
RF Structure



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 .

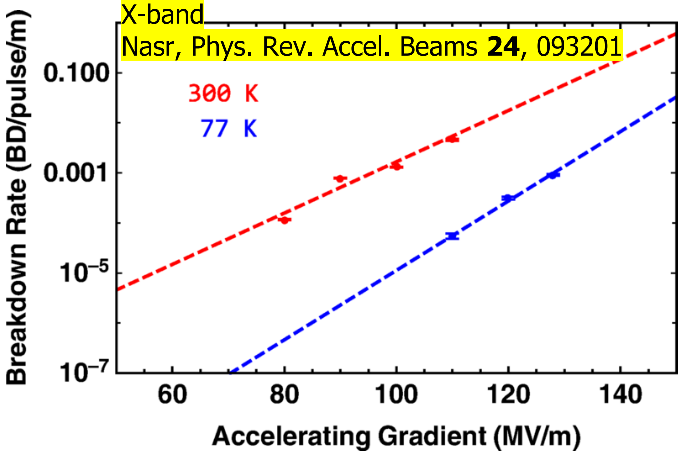
Gradient (MV/m)	Power diss. (W)	rf flat top (ns)	Pulse compr.	Comments	Power/area (W/cm^2)	ΔT Cu-bulk to LN_2 (K)
70	2500	700	N	C^3 -250	0.393	2.3
120	2500	250	N	C^3 -550	0.393	2.3
155	3900	250	N	C^3 -550 in 7 km	0.614	2.5
120	1650	250	Y	C^3 -550	0.259	2.1

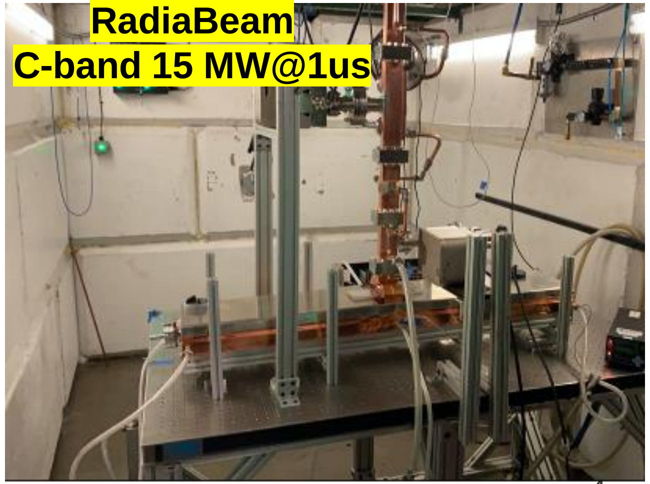
SLAC

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

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
- 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.





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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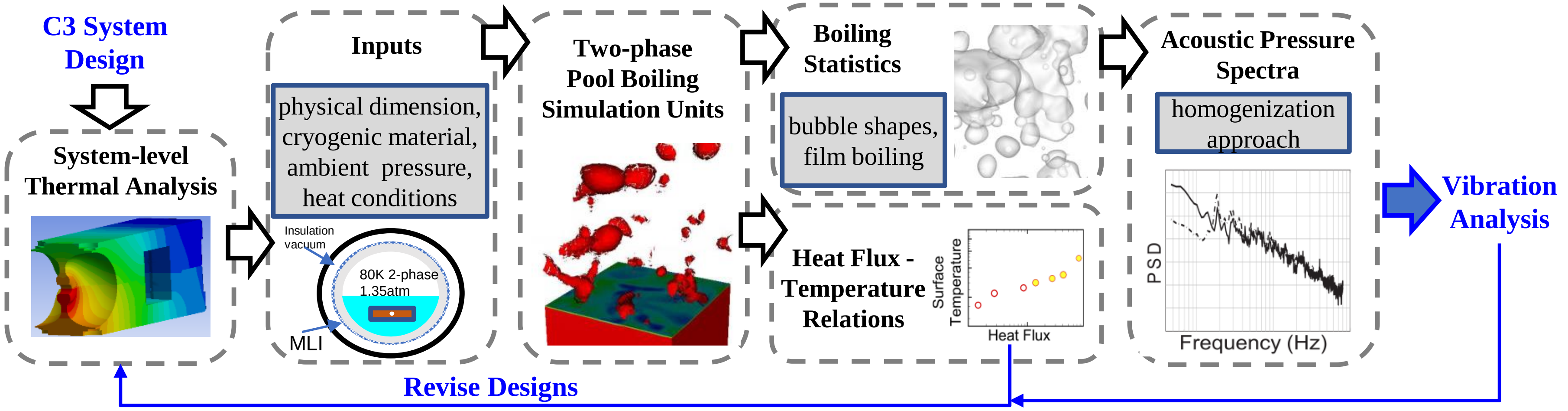
- CryoModule
- Accelerator Structure
- Beam Dynamics
- C³ Main Linac Beam Dynamics

- Vibrations due to boiling of LN
- Large scale simulation setups (from 100s to 1000 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



Introduction   Staged Approach

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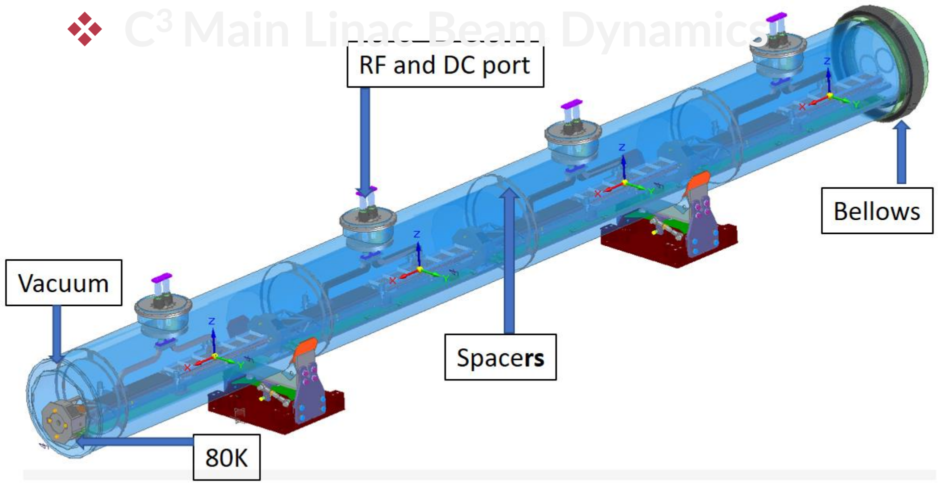
- ❖ Beam Dynamics
- ❖ C^3 Main Linac Beam Dynamics



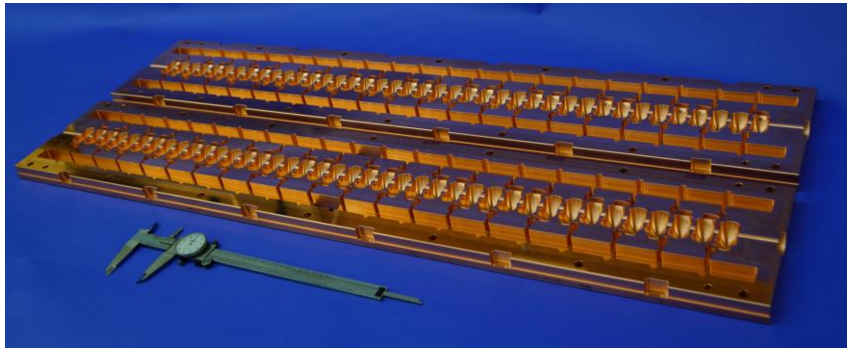
- ○ Adequate stability of the quadrupoles and accelerators during powered operation and full **C^3** cryogenics fluid flow rate (with margins)
- ○ Adequate range, precision and bandwidth of the raft positioning systems
- ○ Full **C^3** cryogenic flow rate benchmarking with simulation
- ○ In-situ CM vibration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

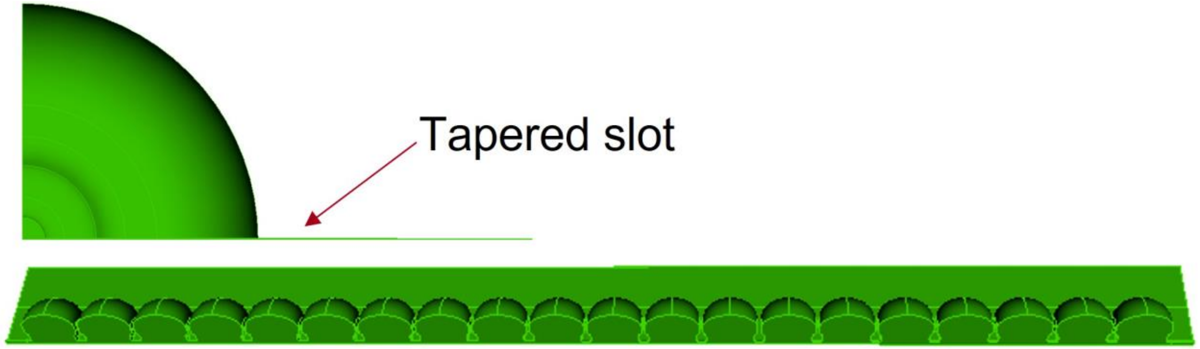
Introduction   Staged Approach

C³ Demo will focus on the 5 thrusts:

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

- Achievable gradient and gradient stability at the **C³** 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



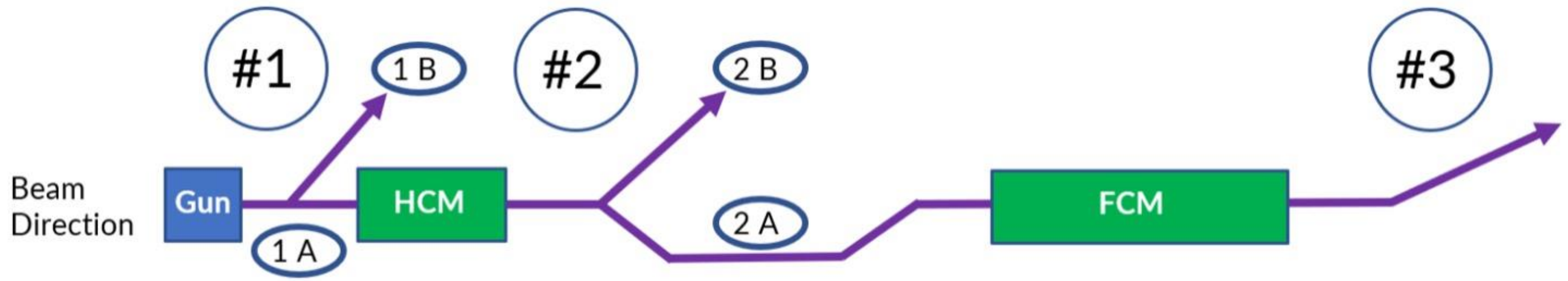


Introduction Staged Approach

C^3 Demo will focus on the 5 thrusts:

- Collider Cryogenics Design Study
- CryoModule
- Accelerator Structure
- **Beam Dynamics**
- C^3 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:

- Collider Cryogenics Design Study
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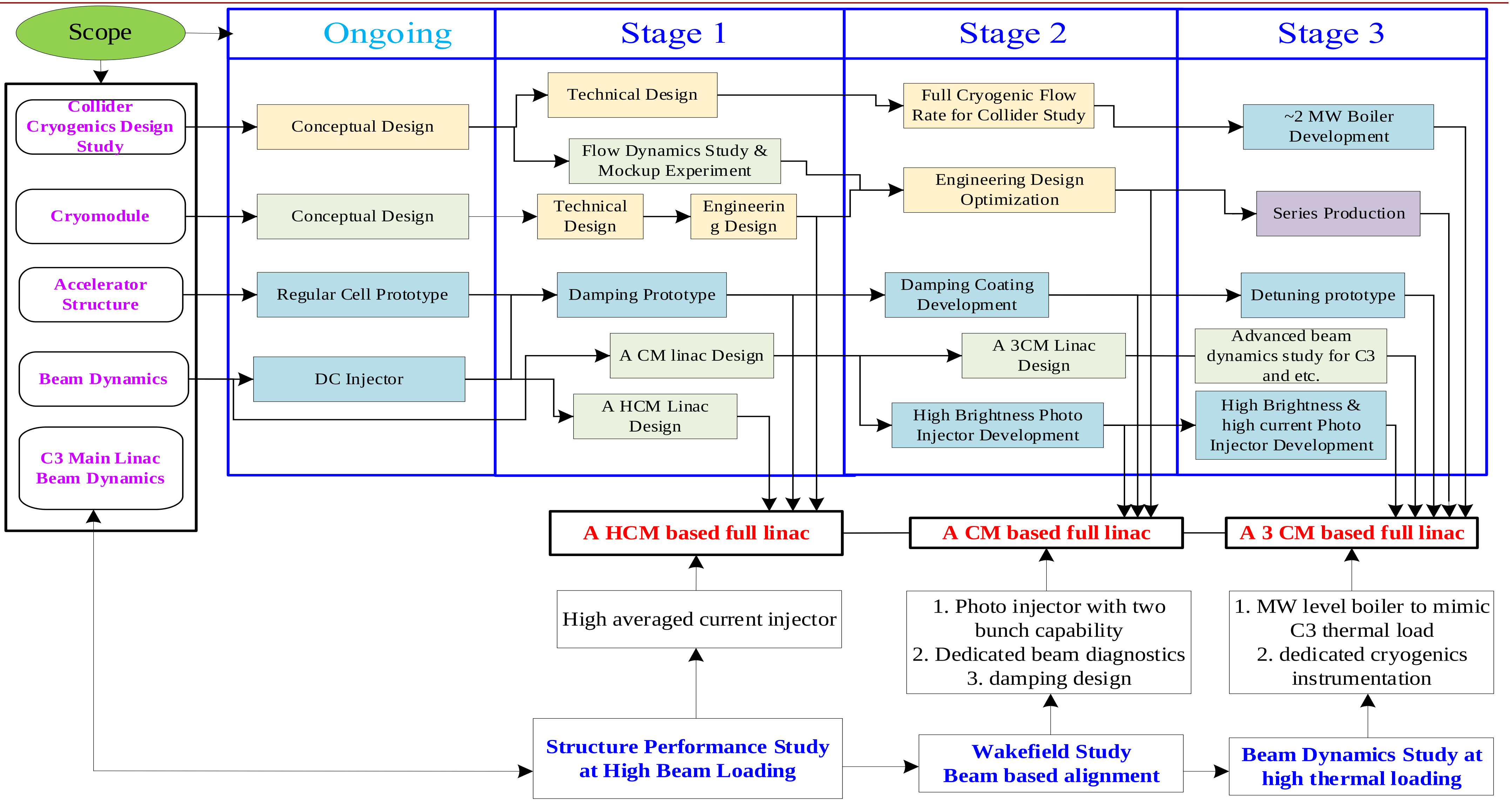
- Accelerator Structure
- Beam Dynamics
- **C^3 Main Linac Beam Dynamics**

- Perform emittance preservation simulation studies to determine alignment and vibration tolerances
- Investigation and optimization of lattice design, BNS damping, beam based alignment (1-1 steering, dispersion free steering, and wakefield corrections) ect.

Staged Approach

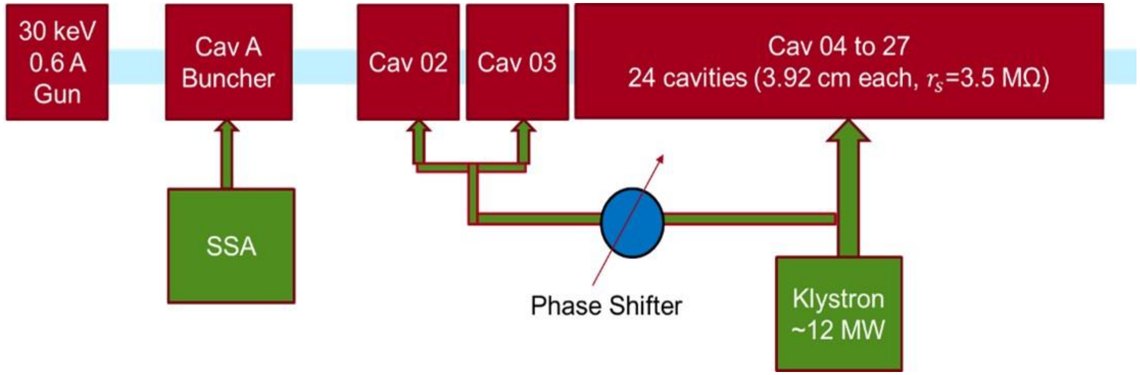


Staged Approach

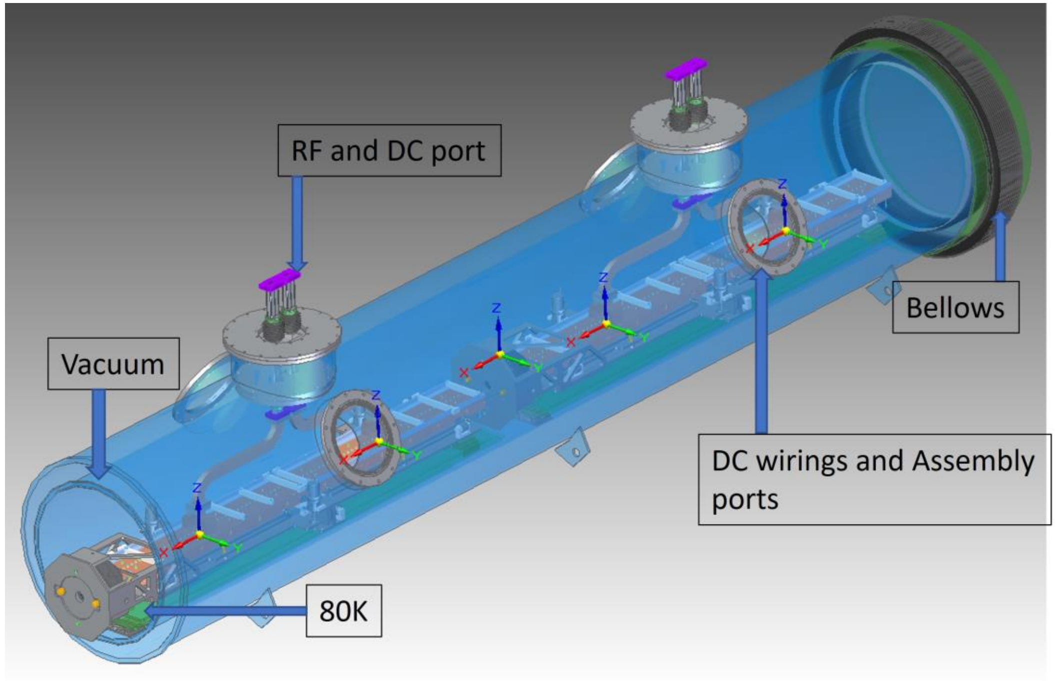
- Stage 1: Demonstration of C^3 Structure Performance at Full Beam Loading.
  - Demonstrate the accelerator structure at the full C^3 equivalent beam loading:
    - Unloaded and loaded at 70 MeV/m and 700 ns with 190 mA – $C^3$250
    - Unloaded and loaded gradient of 120 MeV/m and 250 ns with 300 mA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

- **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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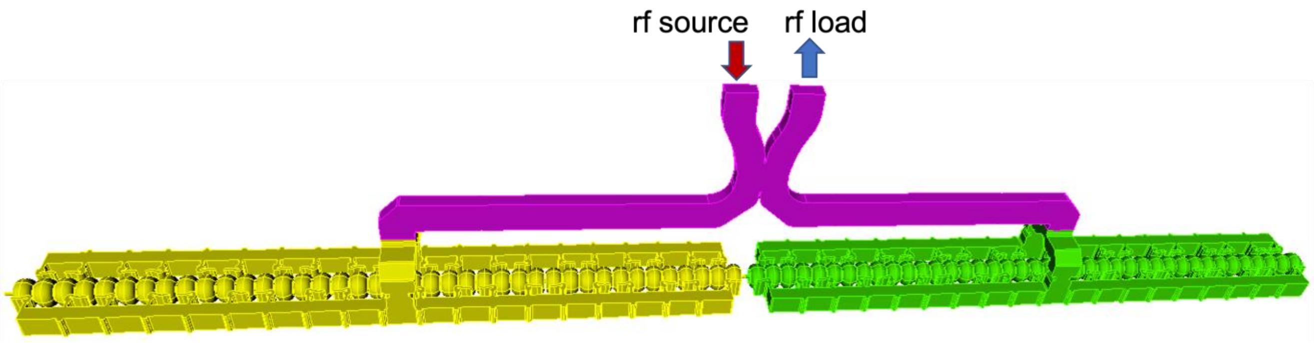
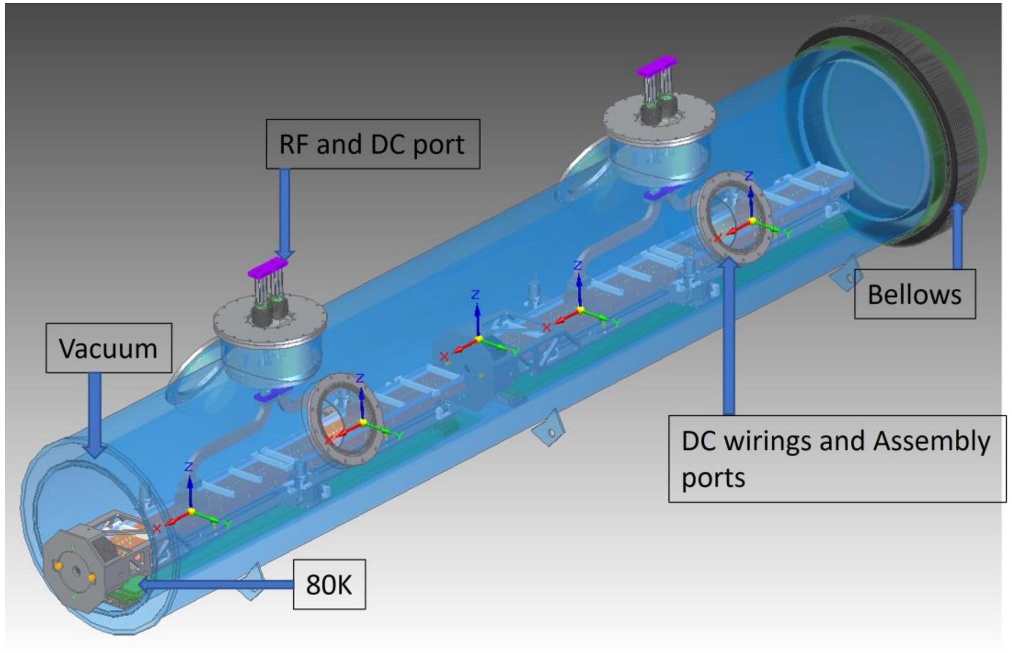


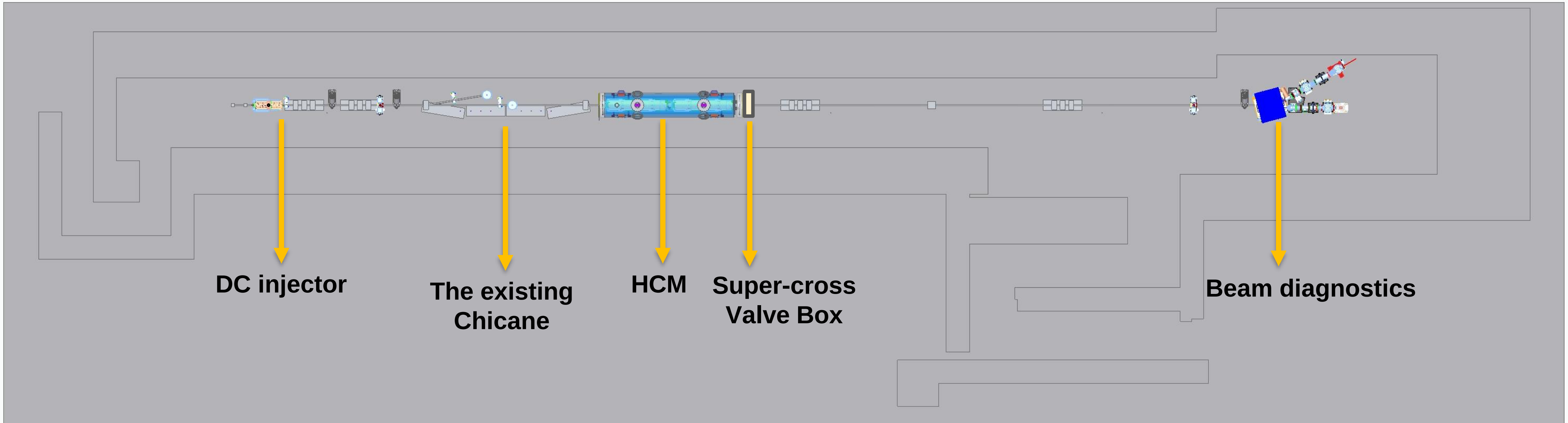
✓ HCM Linac



- 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 without beam and 90 MeV/m with 190 mA (C3-250)
  - 1 structure at 157 MeV/m without beam and 125 MeV/m with 300 mA (C3-550)

Staged Approach

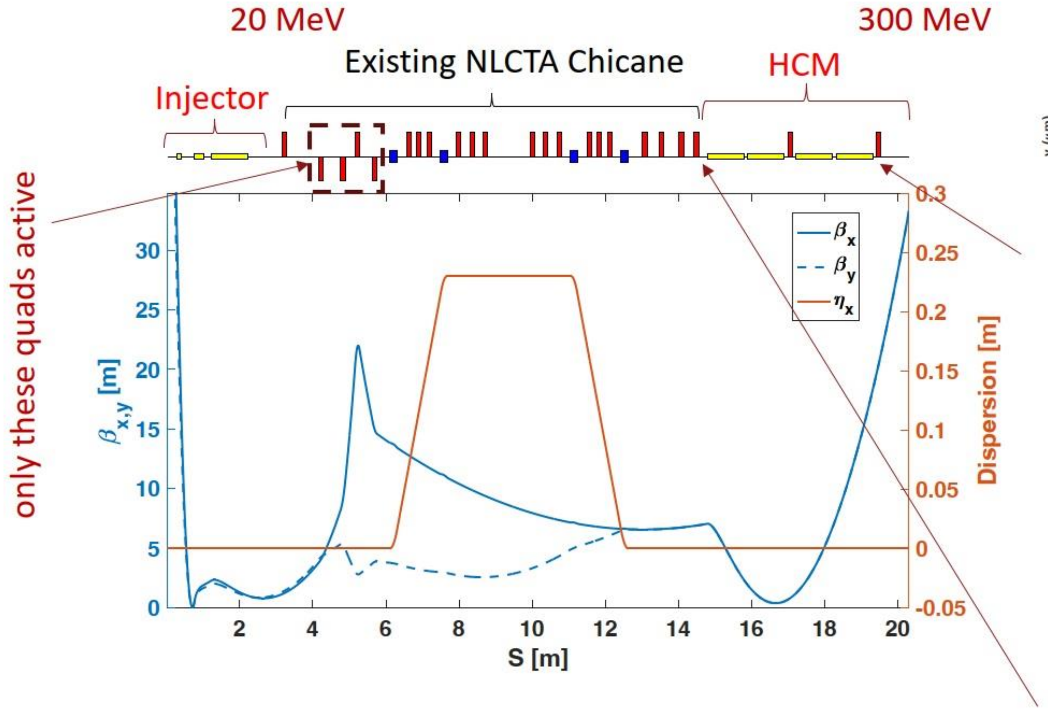
- Stage 1: Demonstration of C³ Structure Performance at Full Beam Loading.
  - Test a C³ half Cryomodule (HCM) at full C³ equivalent beam loading at SLAC NLCTA.
  - 2x50 MW C-band rf stations will be developed by repurposing an exiting X-band station modulator.
  - The existing S-band station in NLCTA will be used to power the injector.

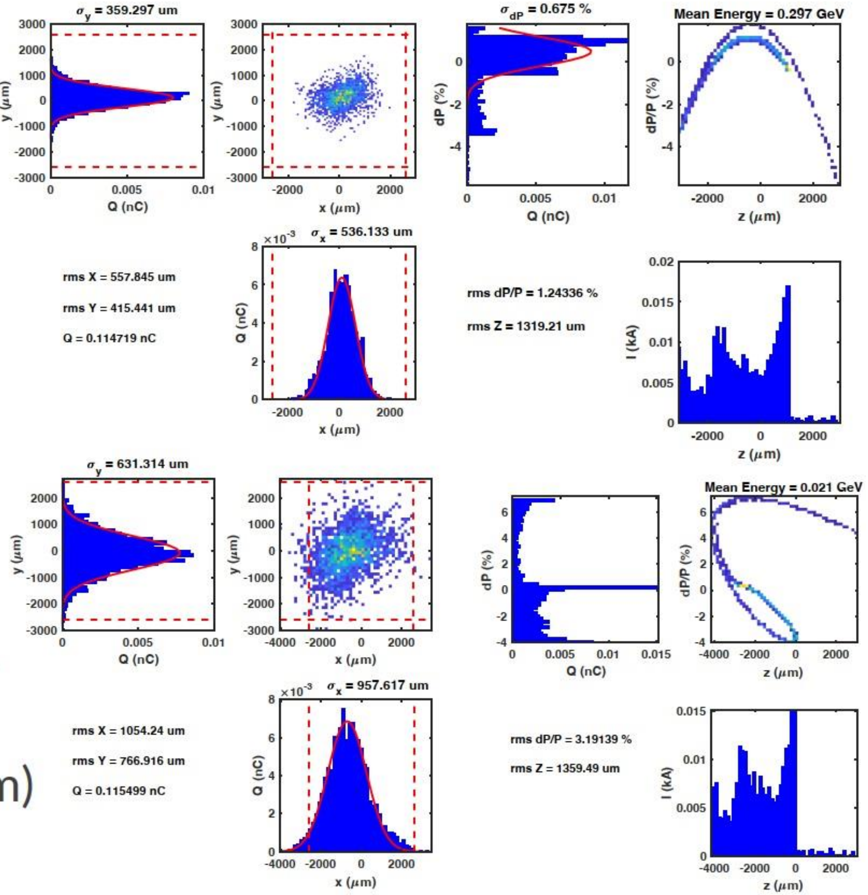


Rendering layout of the HCM (light blue block) full linac with its injector in the NLCTA bunker.

Staged Approach

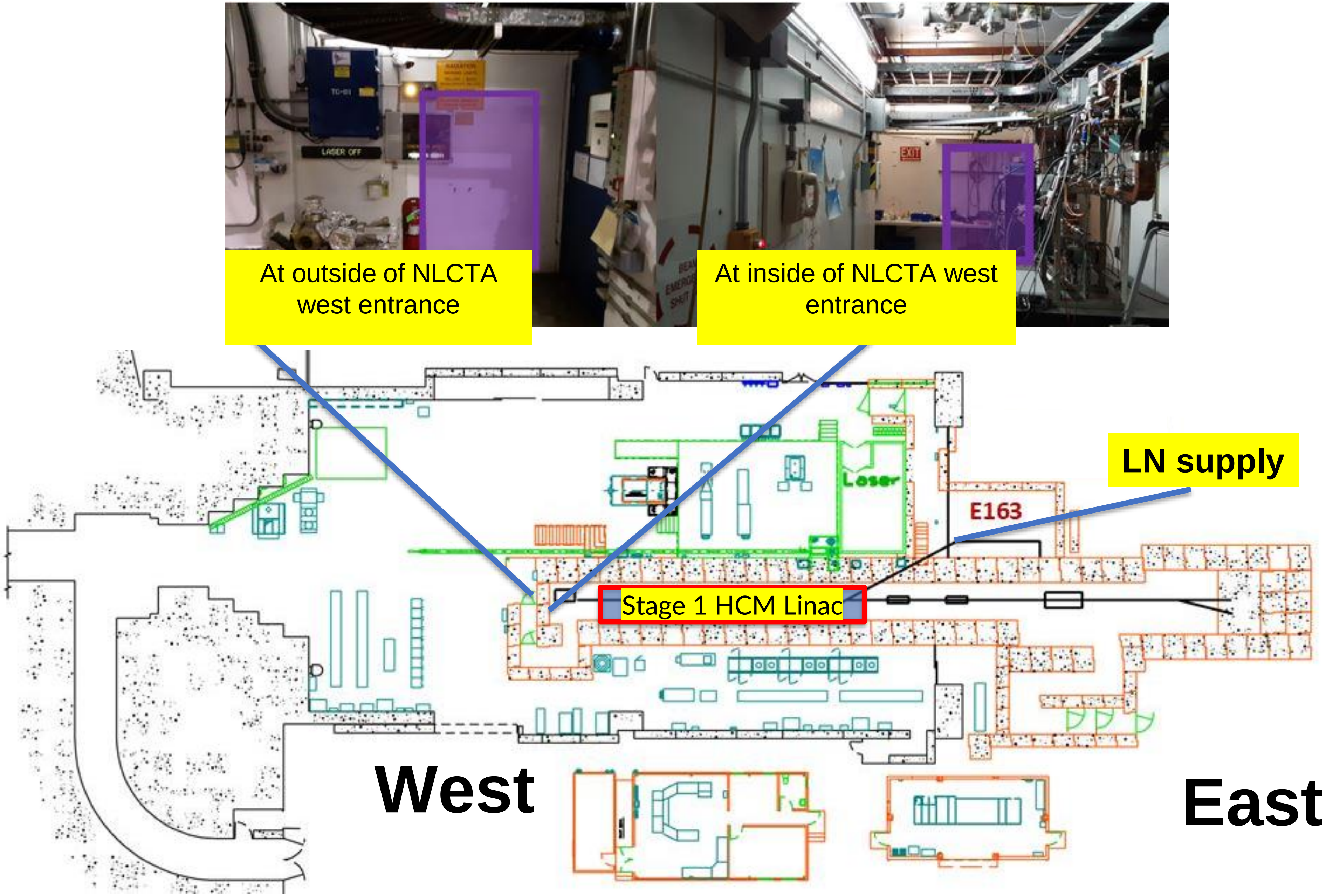
- **Stage 1: Demonstration of C^3 Structure Performance at Full Beam Loading.**
  - **Test a C^3 half Cryomodule (HCM) at full C^3 equivalent beam loading at SLAC NLCTA.**





- 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

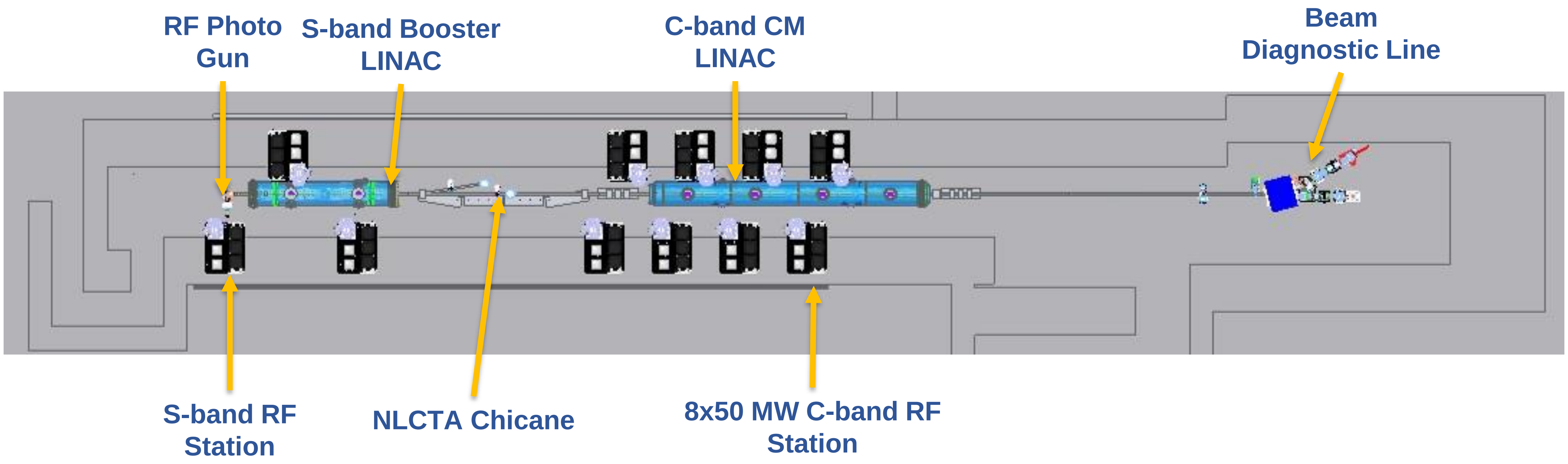
Staged Approach

- **Stage 2**: First Scale-up Demonstration of A C^3 CryoModule Linac
  - A high brightness photo injector with at least two bunches and various space
  - A large aperture S-band booster linac
  - A full C^3 CM Linac.

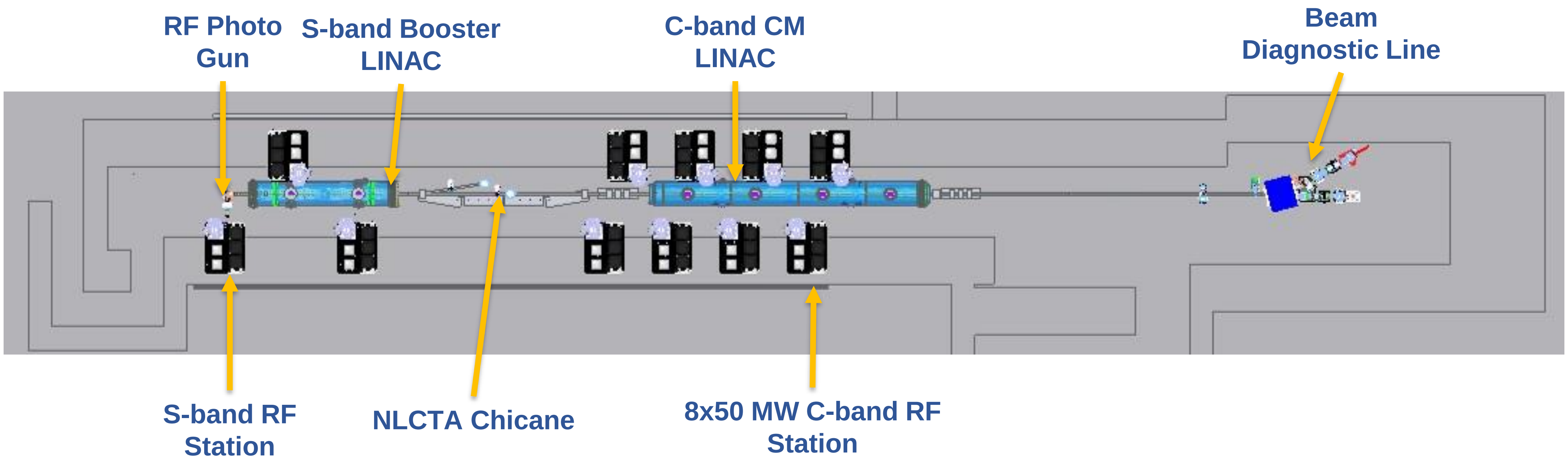
  - Production of the cryomodule assembly with in-situ pre-beam alignment ≤500 µm
  - Demonstration of the acceleration structure in the full CM LINAC reaching unloaded gradient of 155 MeV/m at 250 ns
  - Development of high brightness RF photo injector with an LCLS-like S-band RF gun and an S-band booster 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.

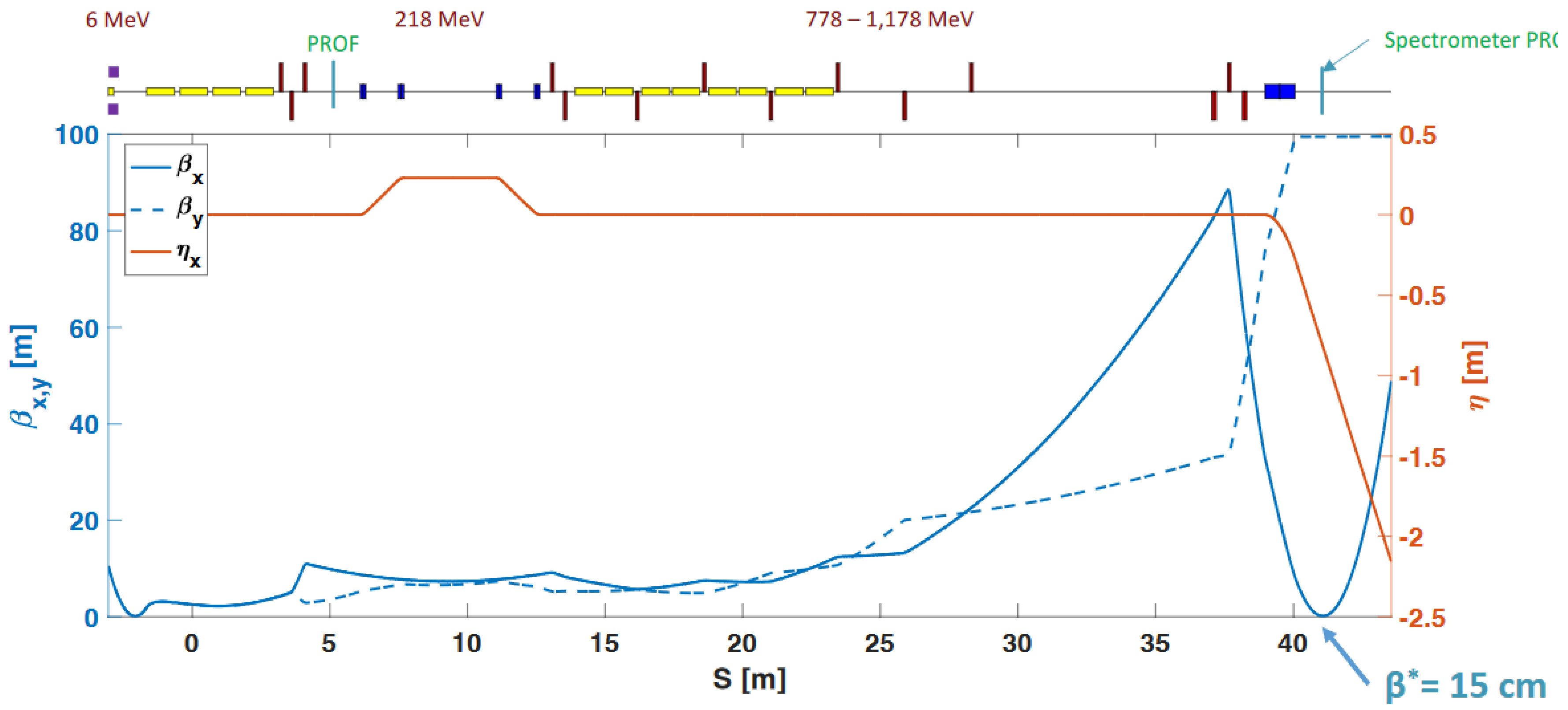


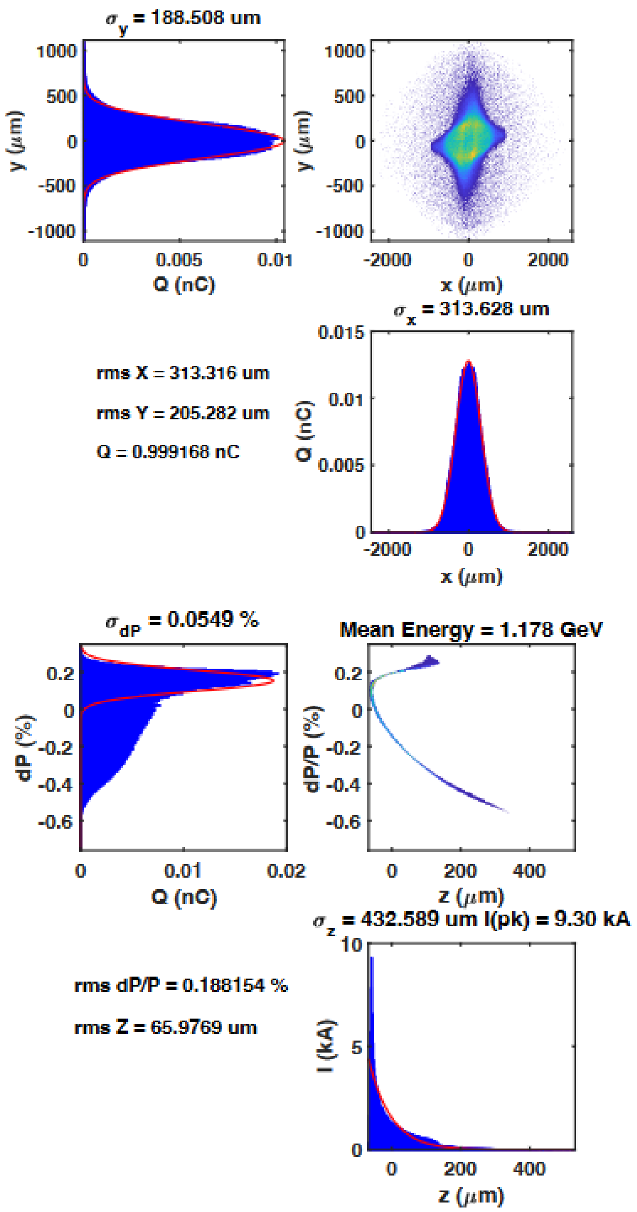
- Stage 2: First Scale-up Demonstration of A C³ CryoModule Linac
  - 8x50 MW C-band RF station will be built.
  - With zero beam loading (single electron bunch) and about 10% RF transmission loss
    - 1 klystron per structure: 8 structures at 113 MeV/m
    - 2 klystrons per structure: 4 structures at 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 GeV.**



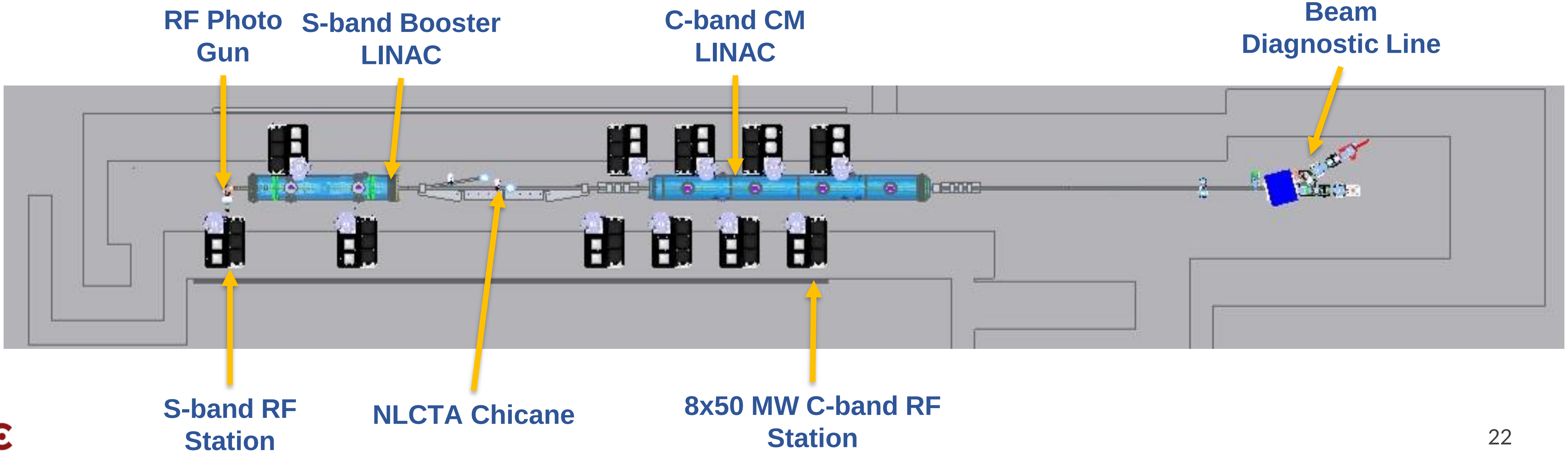


SLAC

Staged Approach

- Stage 2: First Scale-up Demonstration of a Full C³ 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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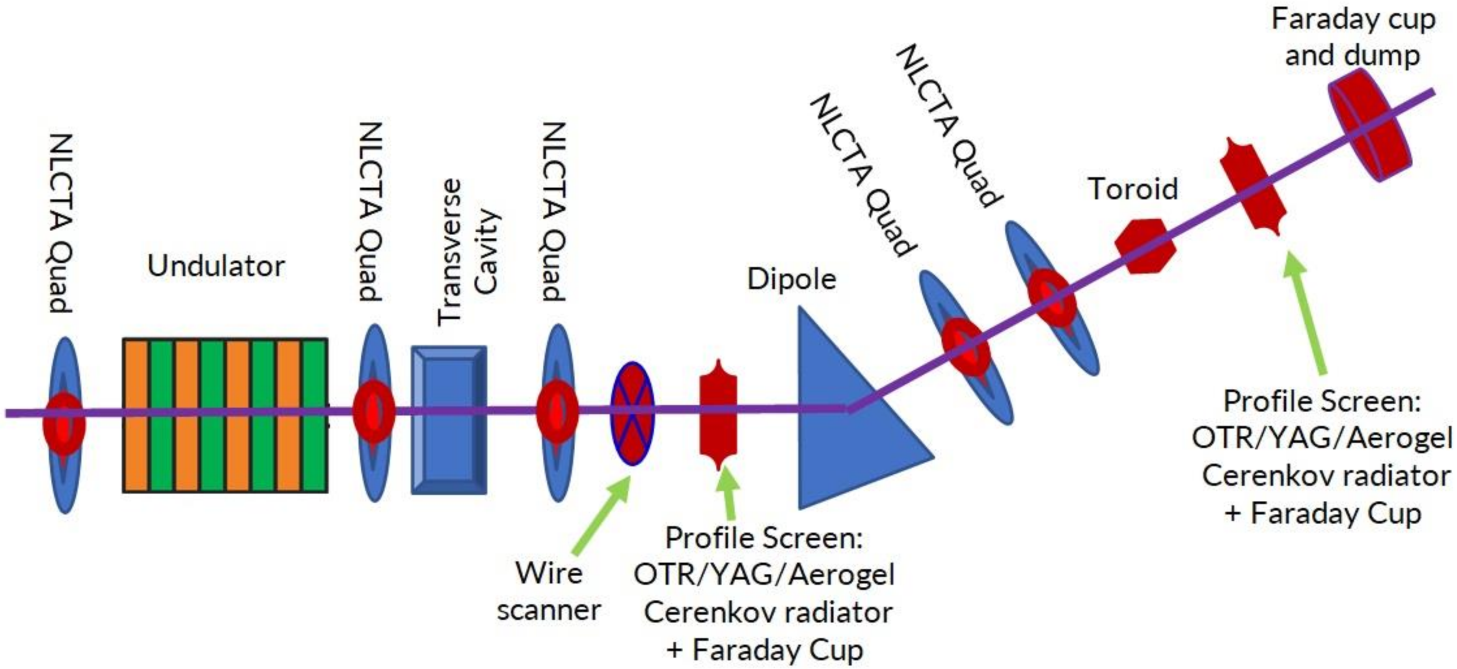
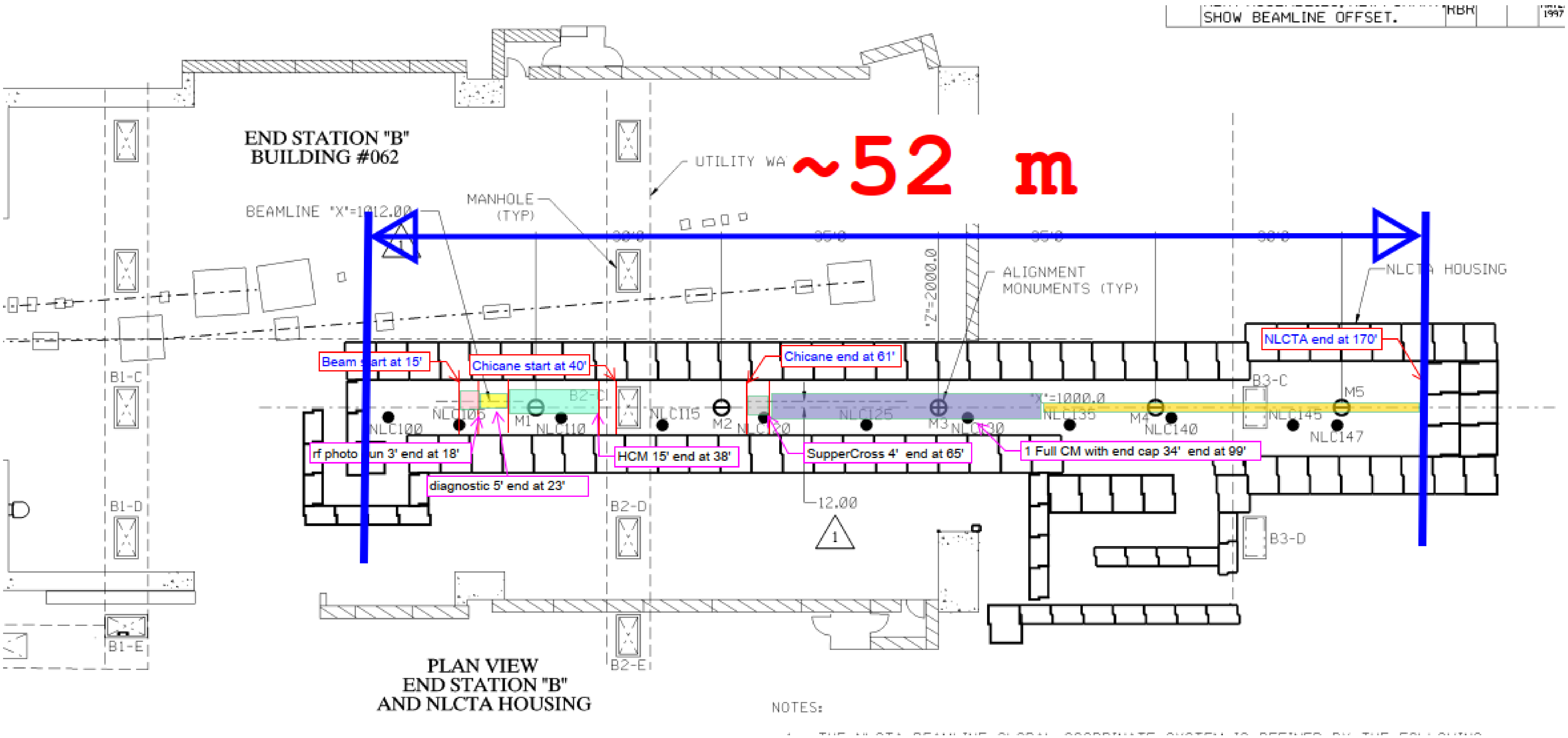
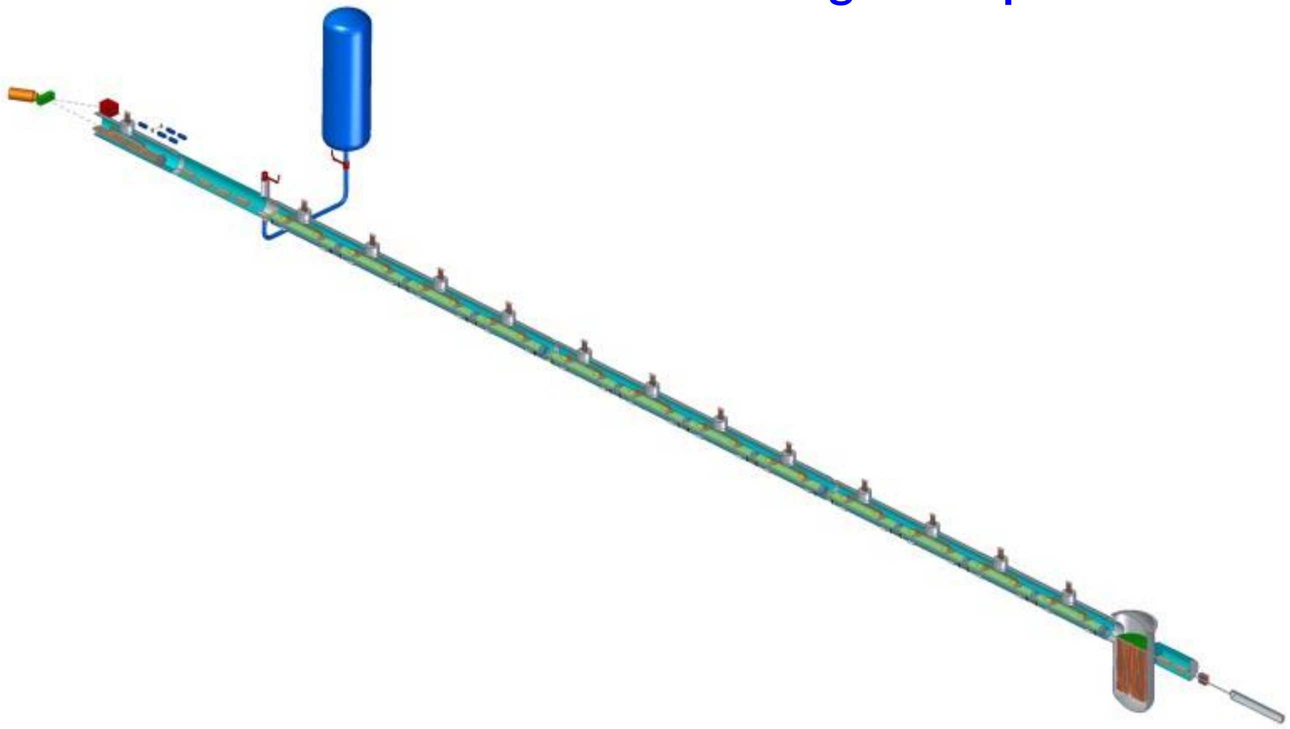



SHOW BEAMLINE OFFSET.
END STATION "B"
BUILDING #062
UTILITY WA
~52 m
BEAMLINE "X"=1012.00
MANHOLE (TYP)
ALIGNMENT MONUMENTS (TYP)
NLCTA HOUSING
NLCTA end at 170'
Beam start at 15'
Chicane start at 40'
Chicane end at 61'
rf photo gun 3' end at 18'
diagnostic 5' end at 23'
HCM 15' end at 38'
SupperCross 4' end at 65'
1 Full CM with end cap 34' end at 99'
NLC100
NLC105
NLC110
NLC115
NLC120
NLC125
NLC130
NLC135
NLC140
NLC145
NLC147
M1
M2
M3
M4
M5
B1-C
B1-D
B1-E
B2-D
B2-E
B3-C
B3-D
"Z"=2000.0
"X"=1000.0
12.00
PLAN VIEW
END STATION "B"
AND NLCTA HOUSING
NOTES:

Staged Approach

- 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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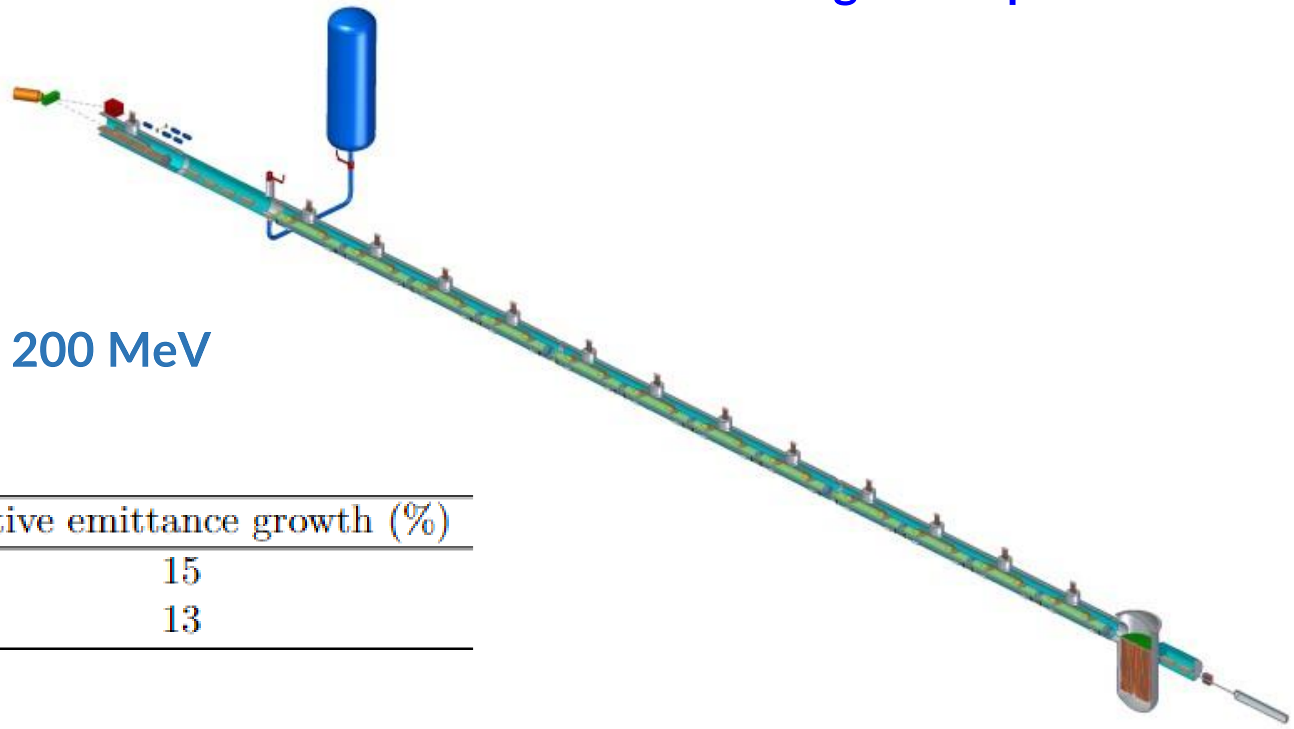

- 3 CM LINAC at 70 MeV/m
- Injected bunch of 1nC, 1.5 umrad, and 200 MeV
- Final beam energy 1.7 GeV

Bunch length (rms, μm)	Off set (μm)	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

Synergies and Impact

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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?