RF System Design of a Polarized, High-Charge Electron Linac for the EIC Pre-Injector

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Electron-Ion Collider

Outline

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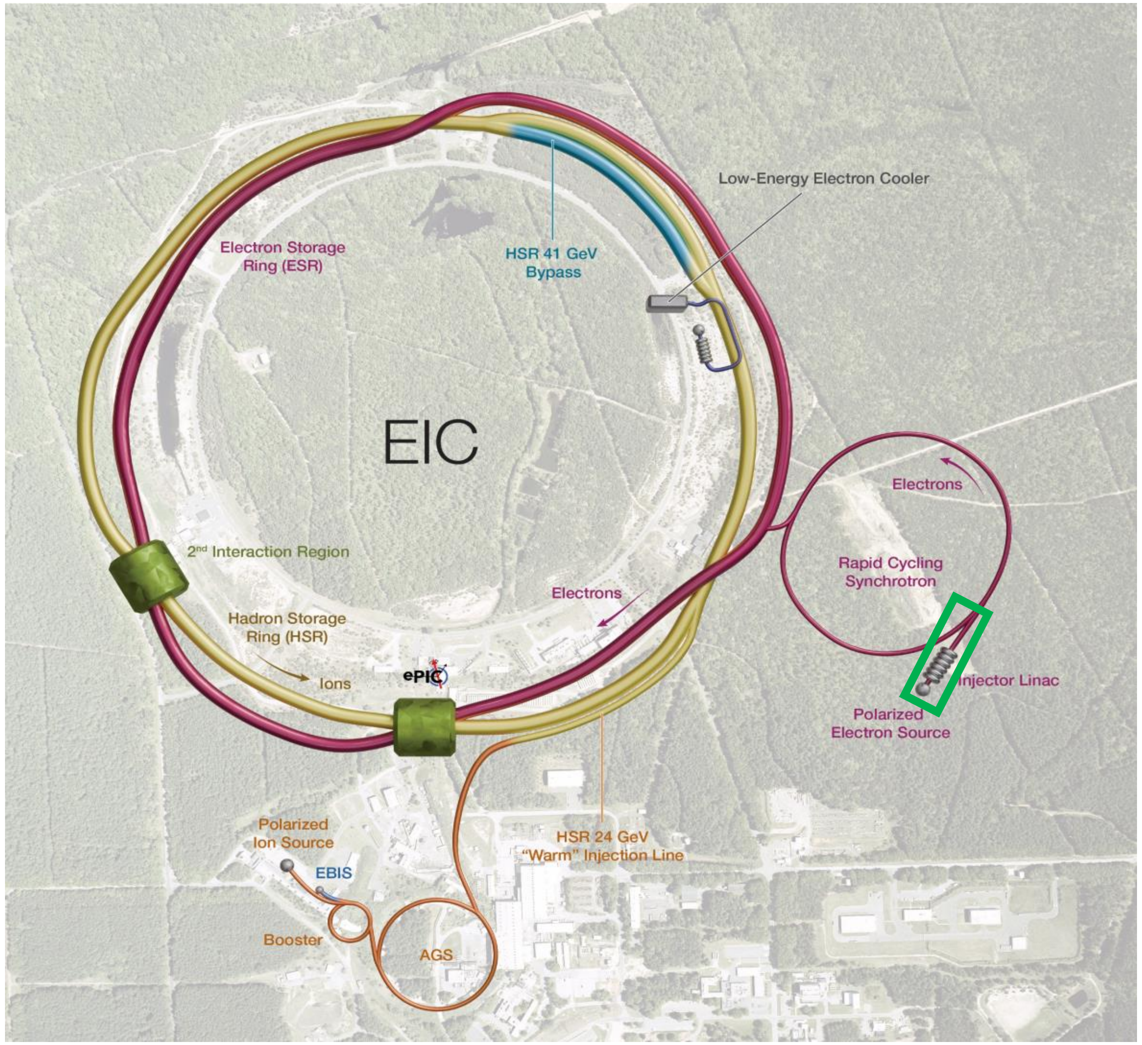


From RHIC to EIC

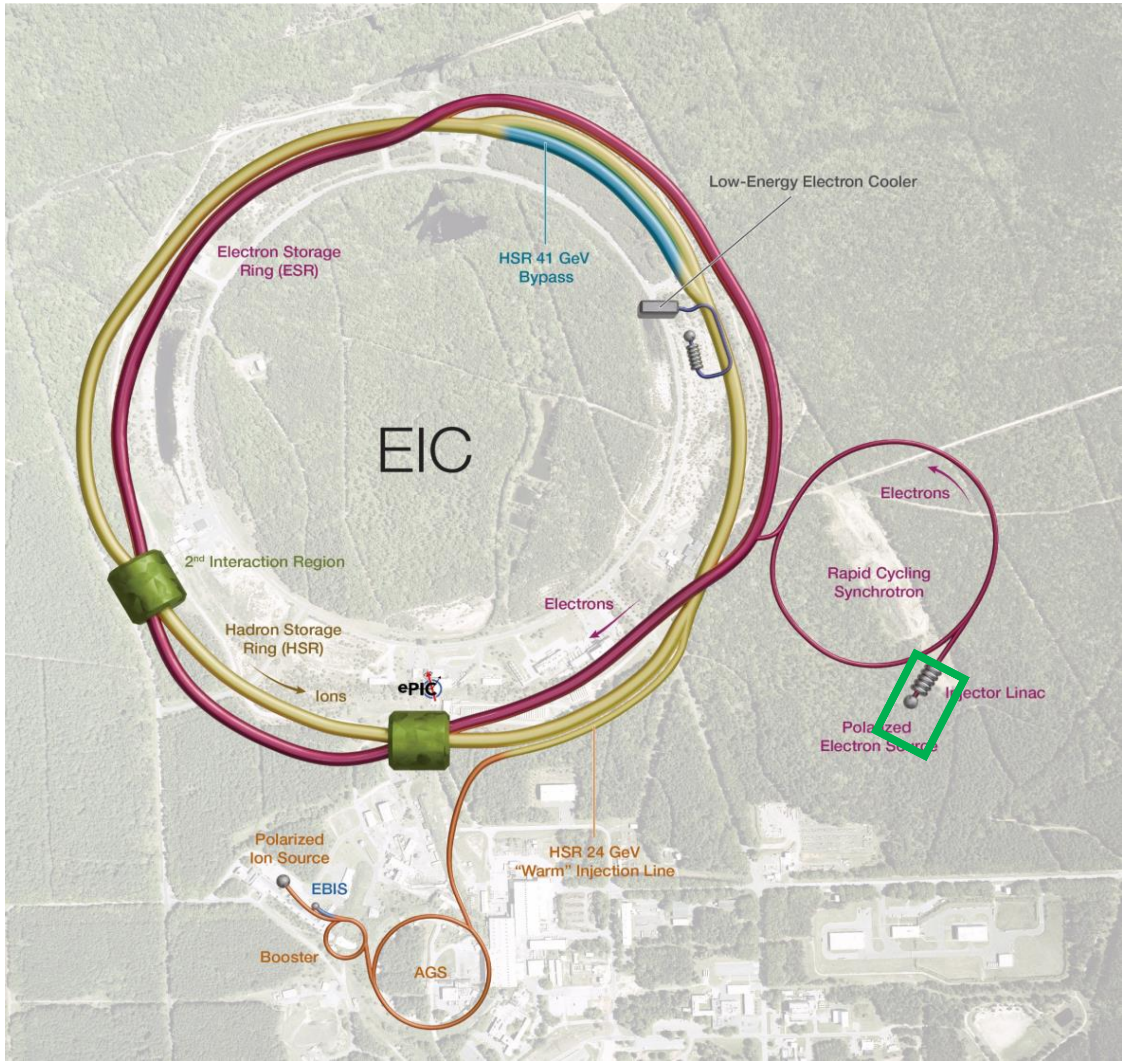
Brookhaven National Laboratory

The Relativistic Heavy Ion Collider (**RHIC**) operated for 25 years:

- the first machine in the world capable of colliding heavy ions
- the world's only machine capable of colliding high energy polarized protons.

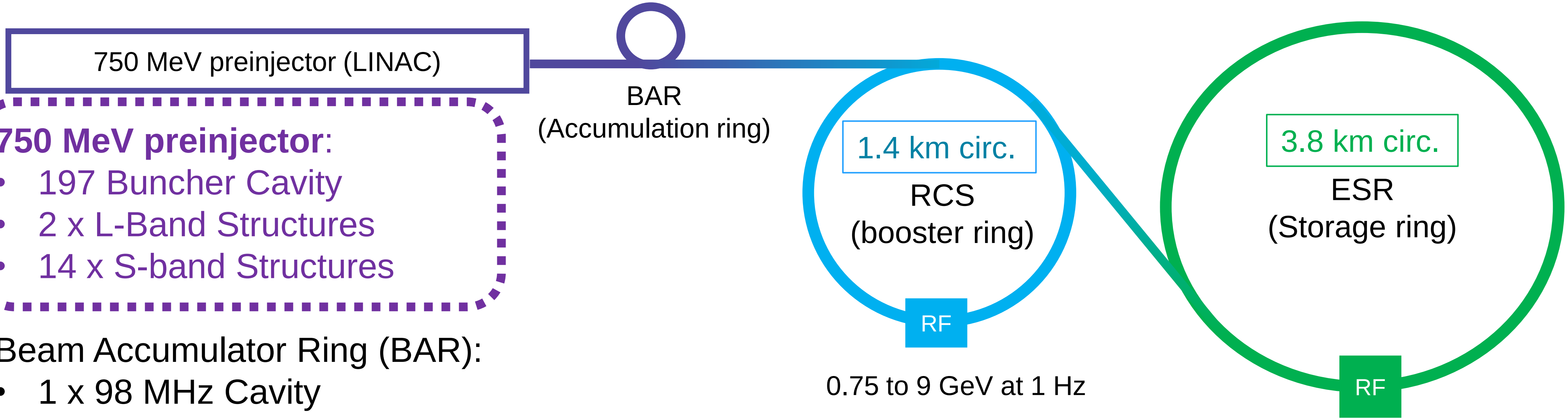
Building on RHIC's 25-year legacy, Brookhaven is moving forward with the **Electron-Ion Collider (EIC)**, the next major facility for the international nuclear physics community.

- EIC will be the only operating particle collider in the U.S. and likely the only large collider to be built in the world in the next two decades.



EIC Polarized Electron Accelerator Chain

LINAC → 1–2 nC/bunch @ 30 Hz → **BAR** accumulation → 28 nC @ 1 Hz → **RCS** → **ESR**



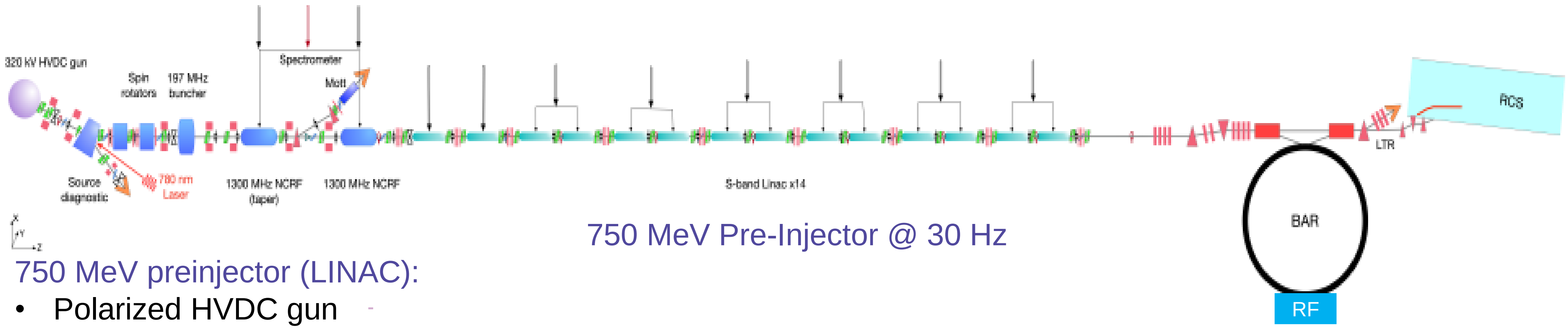
750 MeV preinjector:
- 197 Buncher Cavity
- 2 x L-Band Structures
- 14 x S-band Structures

Beam Accumulator Ring (BAR):
- 1 x 98 MHz Cavity

Rapid Cycling Synchrotron (RCS)
- 2 x 5-Cell SRF 591 MHz Cavities

Electron Storage Ring (ESR)
- 4 x 1-Cell SRF @ 591 MHz

EIC Pre-Injector & BAR RF Systems



750 MeV Pre-Injector @ 30 Hz

750 MeV preinjector (LINAC):

- Polarized HVDC gun
- Polarized laser injecting from a dipole chamber
- Two Wien filters
- 1 x 197 MHz buncher (Existing RHIC/CERN Cavity)
- 1 x 1300 MHz L-Band NCRF taper cavity (Modified from AWA cavity)
- 1 x 1300 MHz L-Band AWA cavity (Based on the AWA/LBNL cavity)
- 14 x 3 m S-band accelerating structures (Quoted from Vendor)
- 1 spin diagnostic beamline
- 1 source diagnostic beamline

PreInjector RF

BAR Cavity : 1 x 98.5 MHz (Based on HSR Bunch Splitting Cavity)

Earlier talk: E. Wang, TU1A003

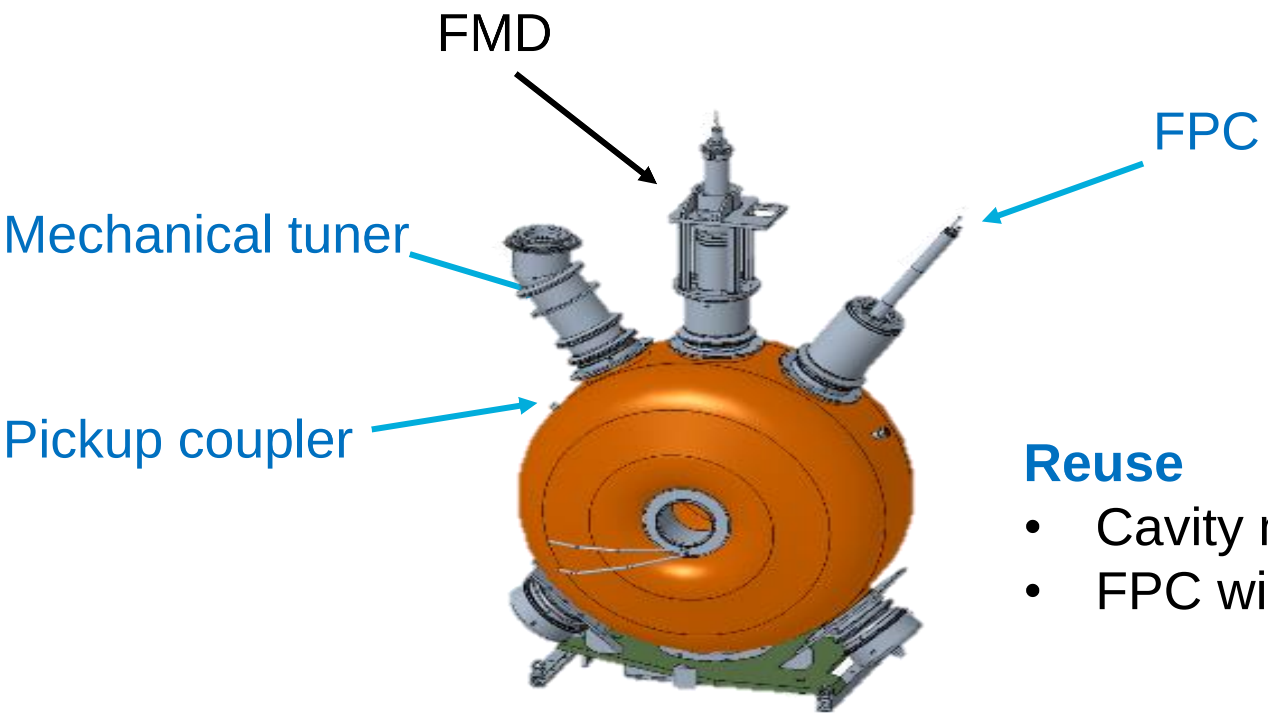
EIC Electron Injector RF Systems and Quantities

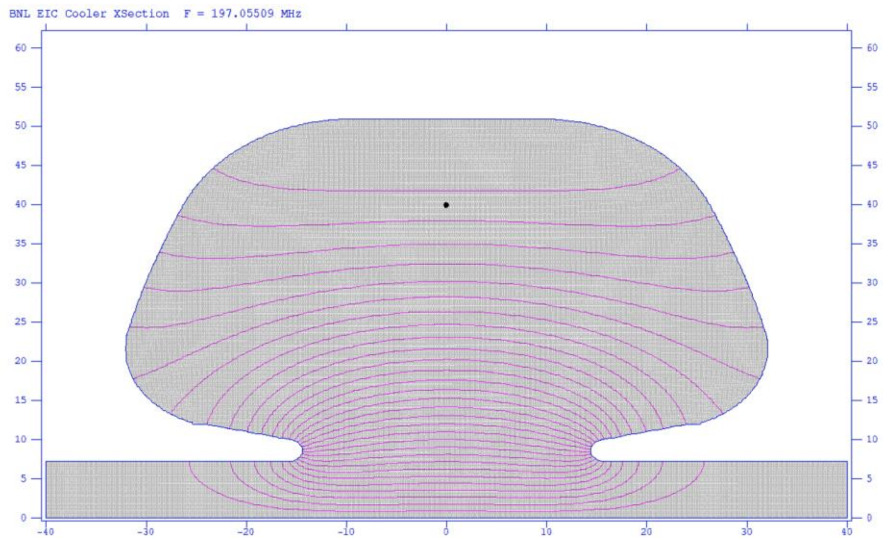
Number of RF Systems for EIN: Pre-Injector (**750 MeV LINAC**) and Beam Accumulator Ring (**BAR**) : 18 NCRF Cavities, 5 different cavity types

RF System	Frequency (MHz)	RF Function	RF Type	#Cavities	PA Type	# FPC / Cavity	# HPRF	RF Source Power
750 MeV LINAC	197	Buncher 1	Reentrant	1	SSA	1	1	10 kW
750 MeV LINAC	1300	Buncher 2 / Accel	Taper LINAC	1	KLYS	2	1	5 MW (30Hz 0.03%)
750 MeV LINAC	1300	Accel 2	AWA LINAC	1	KLYS	2	1	15 MW (30Hz 0.03%)
750 MeV LINAC	2856	Accel 3	TW	14	KLYS	2	8	40 MW (30Hz 0.01%)
BAR	98.5	Accumulate	QWR	1	SSA	1	1	120 kW

LINAC Buncher Cavity

- Bunching cavity is 197 MHz (geometry from RHIC/CERN cavity)
- Existing RHIC 197 MHz cavity design used with minor modifications





Reuse

- Cavity main body, FPC, tuner, pickup
- FPC will connect to coax (SSA RF PA)

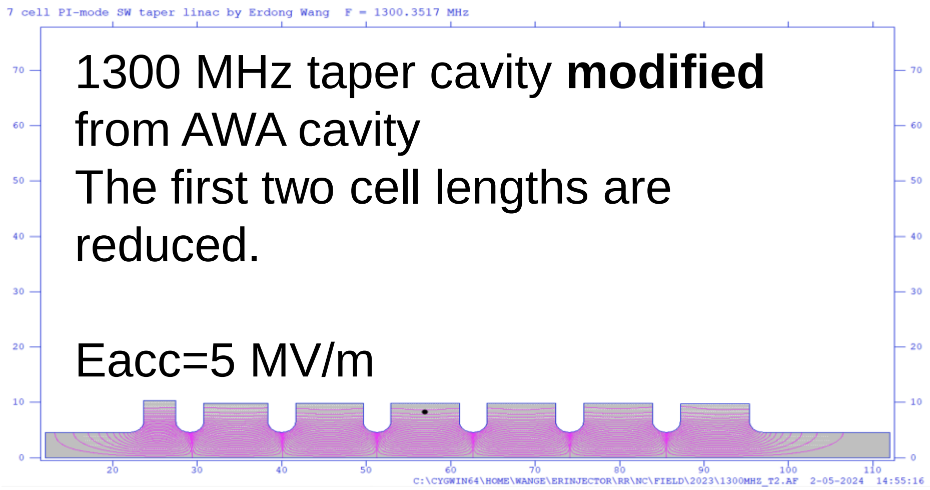
Remove

- FMD (Not required LINAC operation)

Two L-band cavities

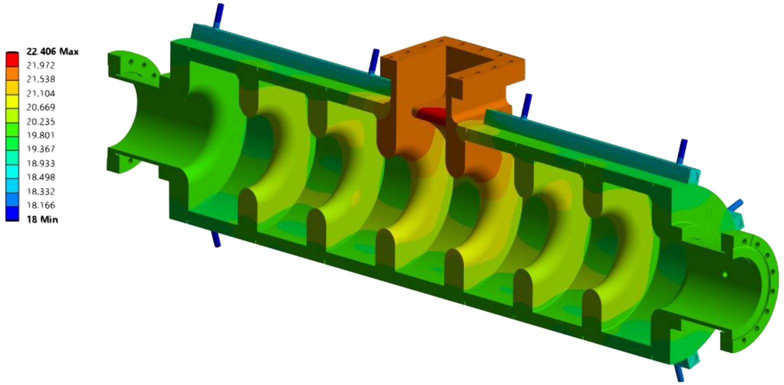
L-band **taper** cavity: Modified AWA

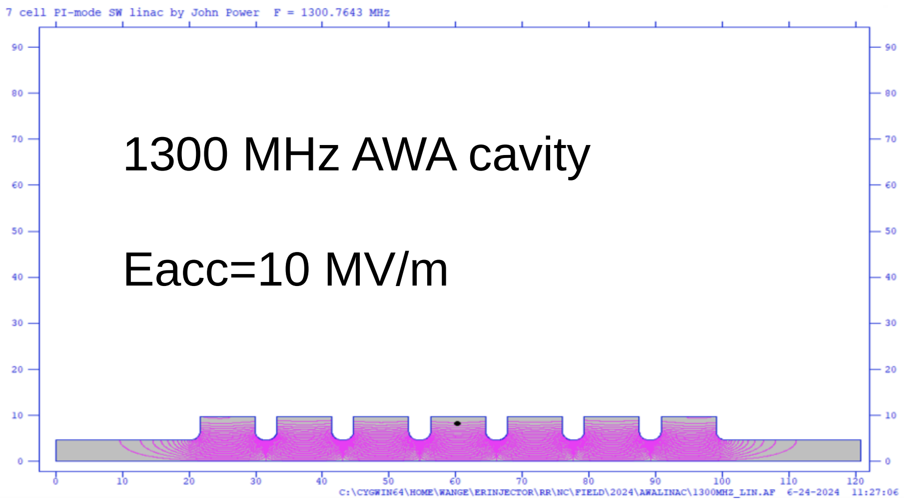
- **Boost energy to 3.5-4.5 MeV for spin measurement**
- **Velocity matching**: 320 keV with beta=0.79
- Design development **in progress**



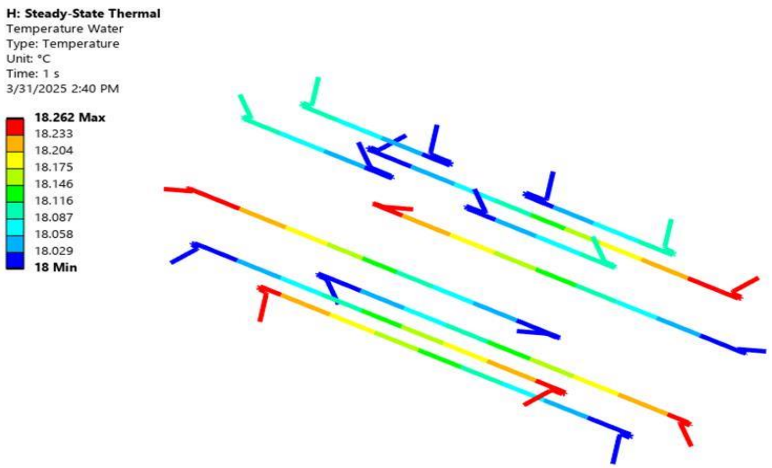
L-band **capture** cavity: AWA

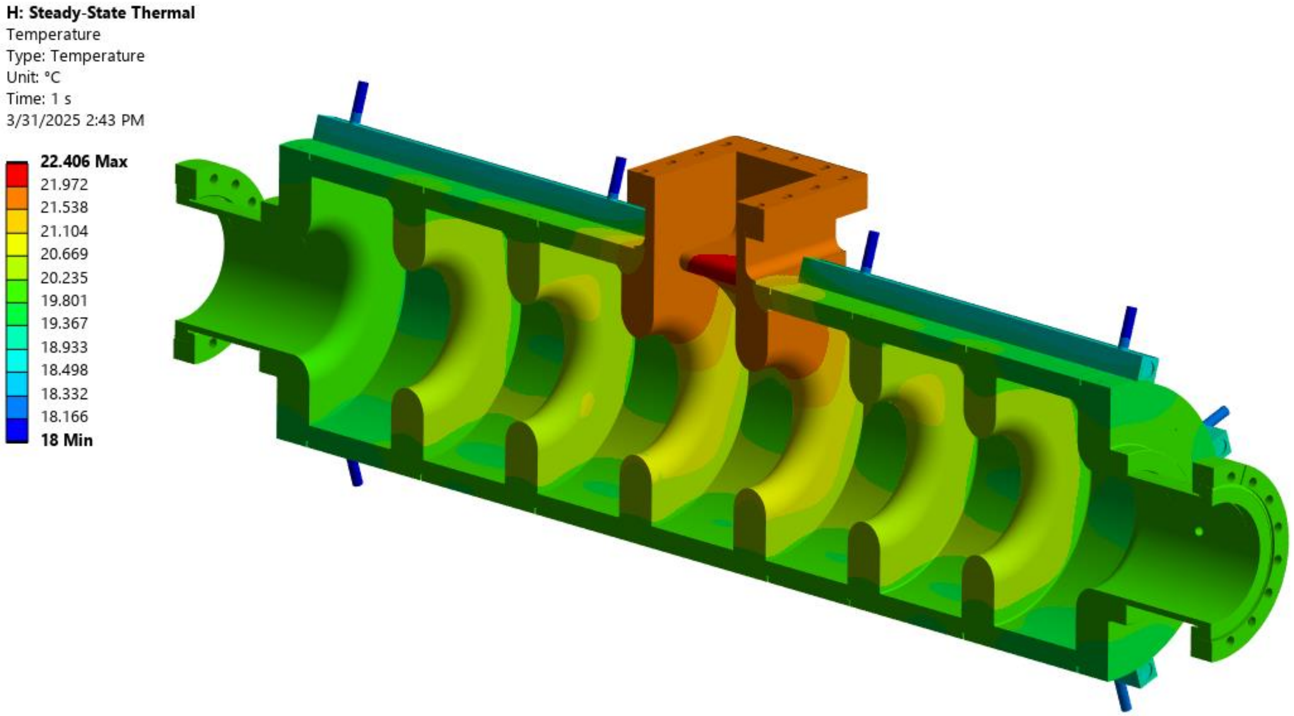
- AWA type with dual coupler set up
- **Acceleration to S-band injection energy** (13-14 MeV)
- Thermal simulation shows **30 Hz is fine**.





L-Band thermal analysis



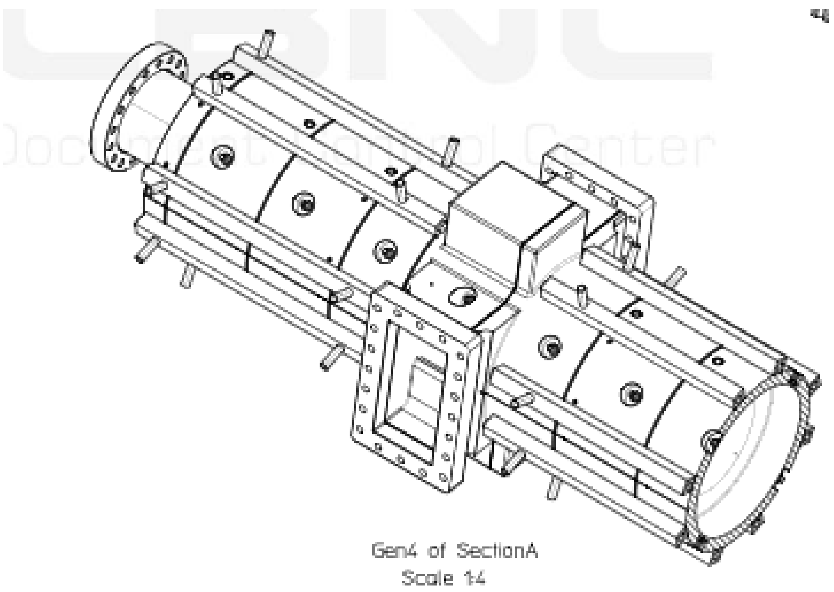


Cooling Channels	Long Cooling Chanel	Short Cooling Channel
Number of Channels	6	4
Inlet/Outlet Diameter	0.25 in	
Water Tube Diameter	0.50 in	
Average Water Diameter	0.375 in	
Total Length	35.153 in	16 in
Power Loss Per Channel	245.155 W	
Inlet Temperature	18.0 °C	
Outlet Temperature	18.2 °C	
Average Temperature	18.1 °C	
Convection Coefficient H	**14919.2417 W/(m^2·K)**	
Mass Flow Rate	**0.3006 kg/s - 4.7726 GPM**	
Flow Velocity	4.226 m/s - 13.863 ft/s	
Pressure Drop	18.62 kPa - 2.70 Psi	8.43 kPa - 1.22 Psi

- Preliminary thermal analysis assumes 30 Hz operation at 11.8 MV.
- Preliminary analysis; design assumptions are still being refined.

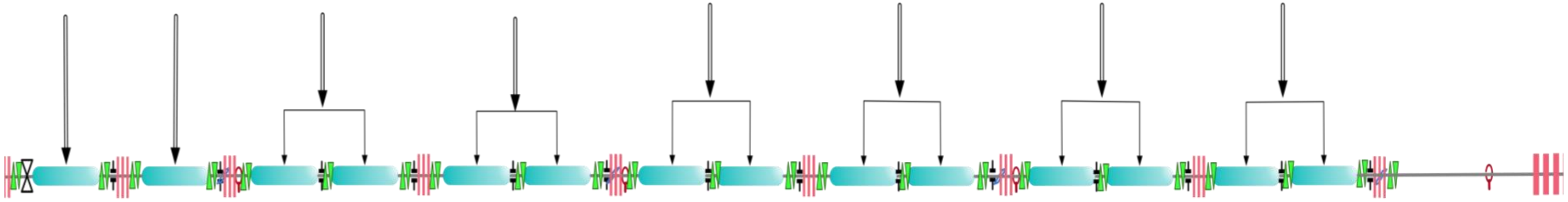
L-Band Dual coupler required

- **Dual-feed RF coupling required**
- **Minimizes transverse RF kick**
- **LBNL APEX-type coupler is a candidate design**



Linac section conceptual

- SLC-type S-band traveling-wave structures (2856 MHz)
  - Injection beam energy 13.8 MeV, output beam energy 750 MeV
  - Bunch charge : 1-2 nC
  - Seven groups, each consisting of two of 3 m structures.
  - Gradient of each cavity in operation 18.5 MV/m-21 MV/m.
  - First two structures powered individually. Possible add spare klystrons with switches to make sure stable operation.
  - One drift space after 14 units available for two more units.



S-band Linac x14

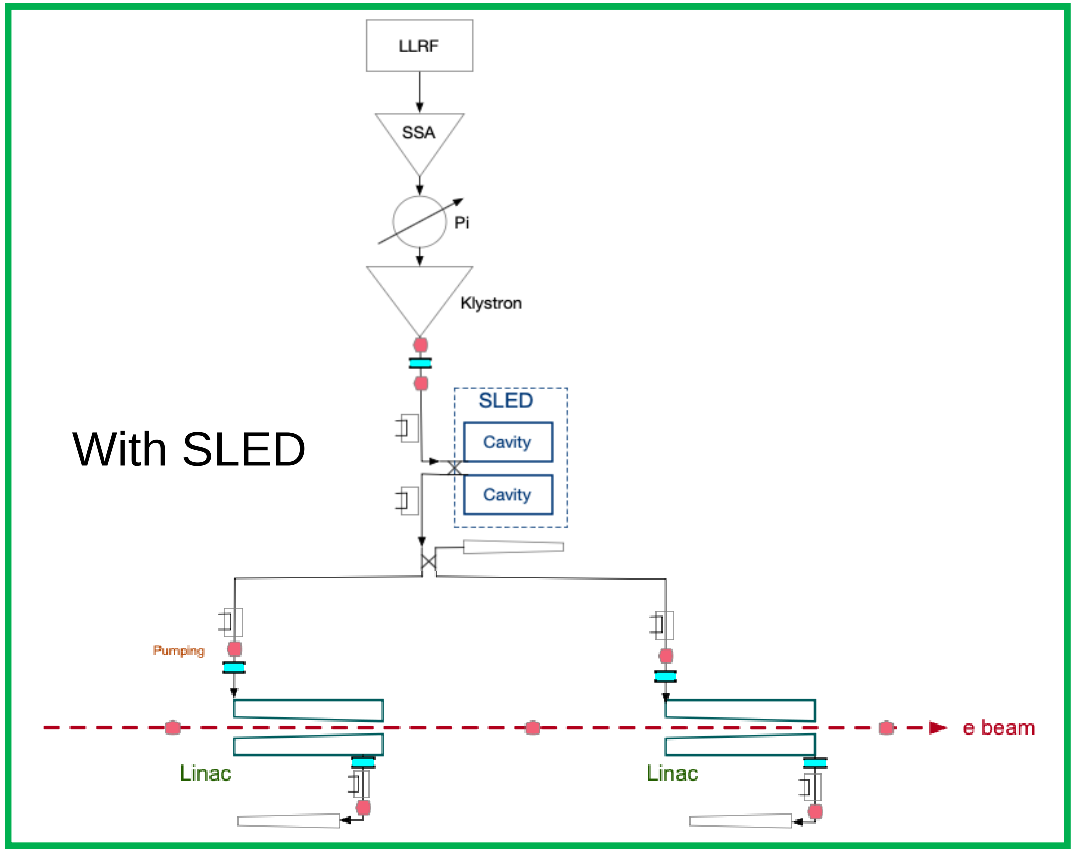
3 meter S-Band Structure Parameters

Description	S-band
Frequency(MHz)	2856
Type	TW, CG.
Structure Length	3.05
Quality factor	13,000
Rs (Mohms/m)	53
Attenuation constant	0.58
RF pulse length (us)	1
Filling Time(us)	0.85
Input peak power (MW)	33.4
Rep. rate (Hz)	30
Waveguide Length (m)	10.0
Total Transmission Loss (dB)	0.28
Transmission Efficiency	93.8%

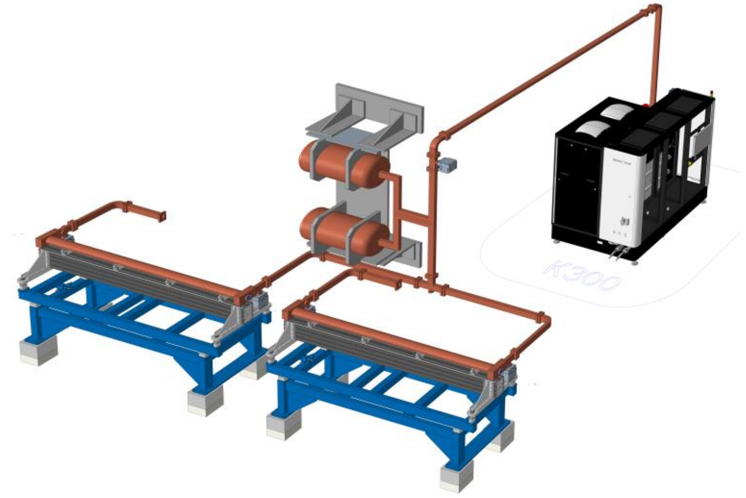
Parameter (per structure)	Nominal Operation Mode	Failure Mode
# of Structures	14	12
Energy Gain total	737 MeV	737 MeV
Gradient	**17.33 MV/m**	**20.21 MV/m**
Gain	52.64 MeV	61.42 MeV
Average power	0.75 kW	1.02 kW
Peak Power input	**25.85 MW**	**34.89 MW**

- First two structures have individual klystrons to tune the phase independently.
- The rest of the structure’s phase is controlled by the LLRF before the klystron.

Pulse Compression Reduces Klystron Peak Power



Linac power needs:	Nominal (14 x)	1 klystron fail (12 x)
Gradient	17.33 MV/m	20.21 MV/m
Power / Structure	25.85 MW	34.89 MW
Klystron Power (Nominal)	**52 MW**	**70 MW**
Klystron Power (SLED)	**< 20 MW**	**< 25 MW**



- Between two structures, the phase is fixed, pre-tuned by the length of the waveguide and deformation of the waveguide.

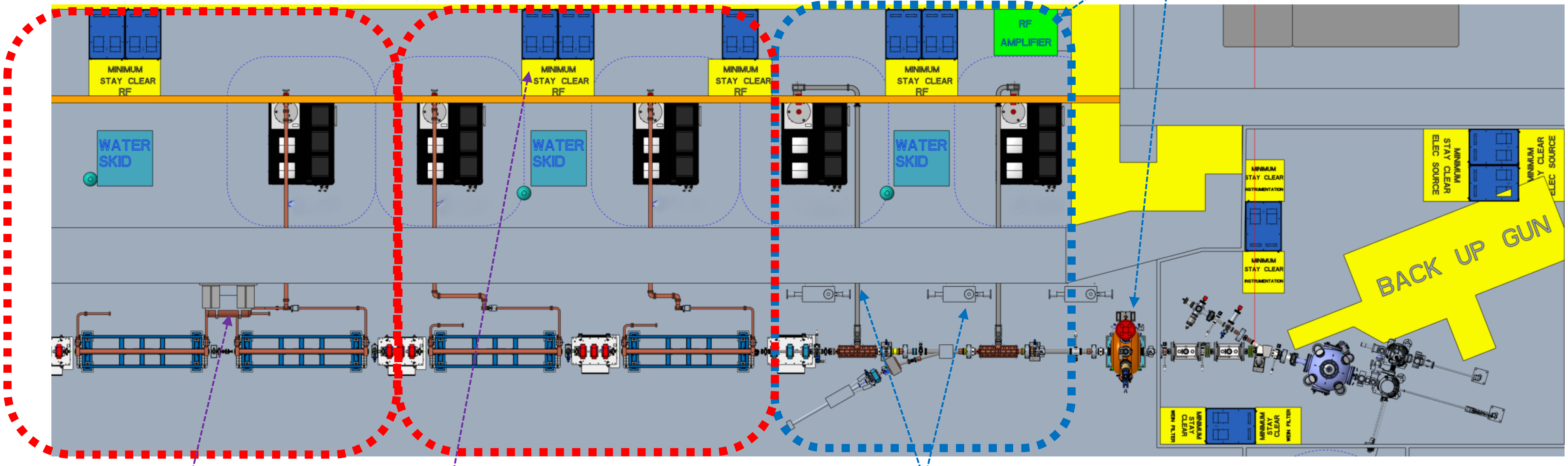
Pre-Injector Linac Conceptual Layout

1 Klystron for 2 S-Band
1 of 6

First 2 x S-Band:
1 Klystron/Cavity

2 x L-Band:
1 Klystron/Cavity

197 MHz Buncher
SSA RFPA

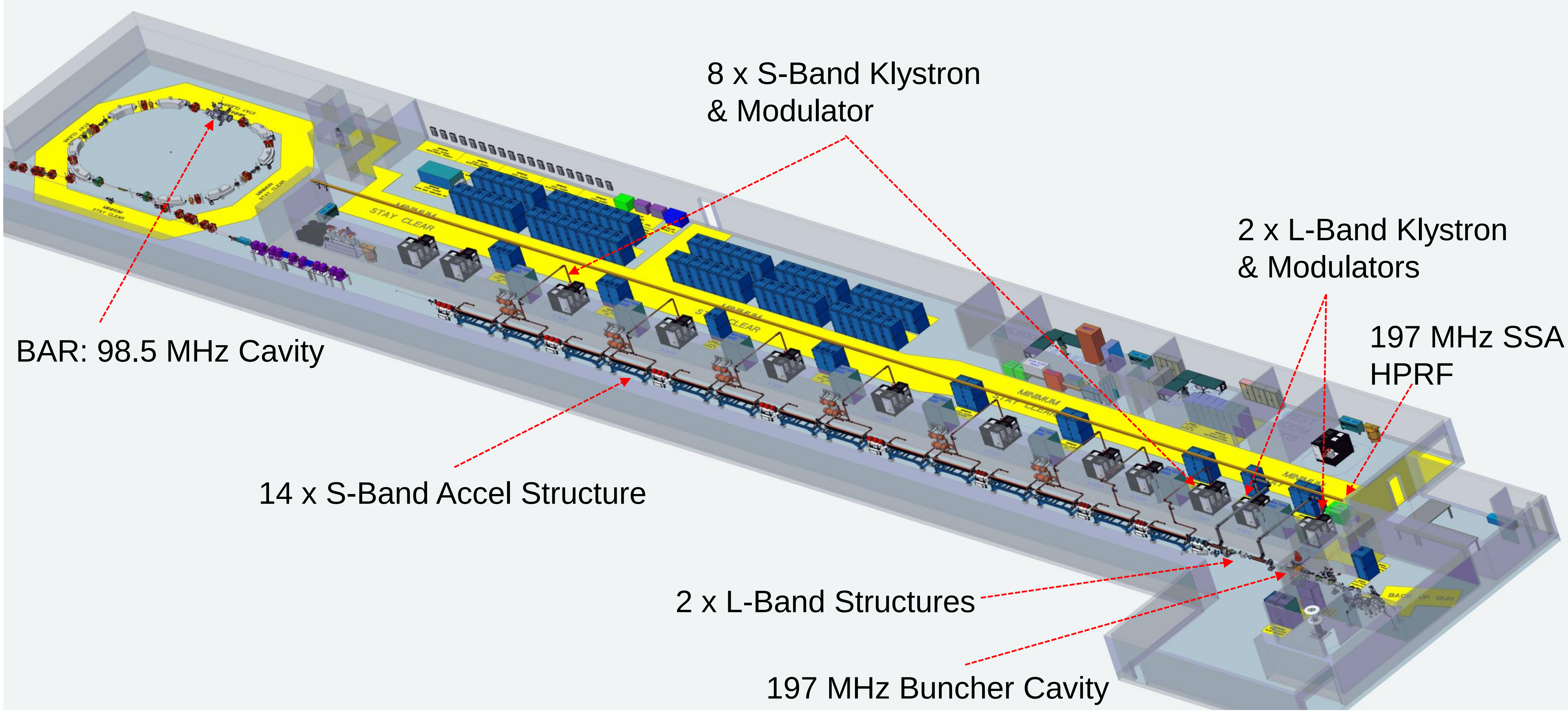


SLED

LLRF Racks
Water Skid Racks

L-Band:
SF6 Waveguide
& RF Circulator

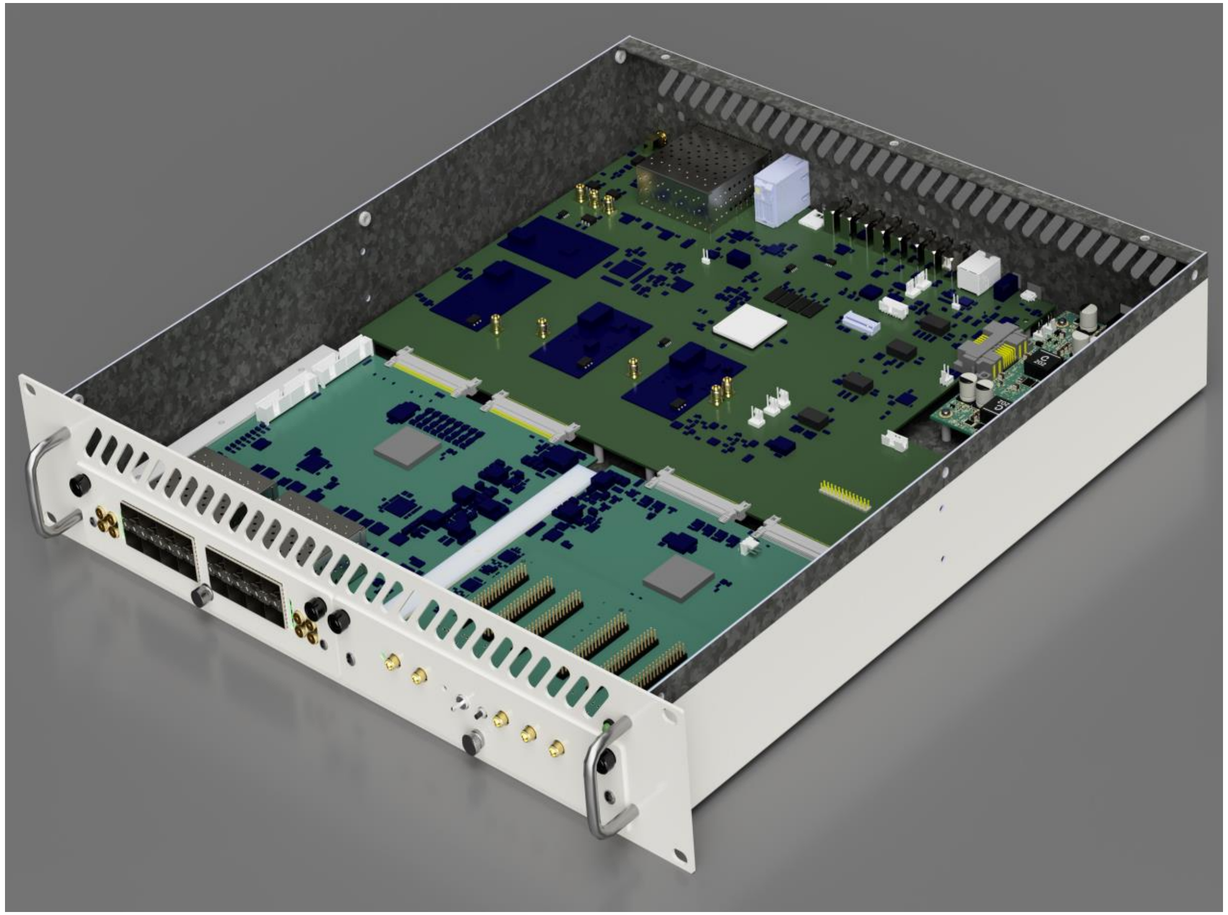
Pre-Injector & BAR Building Conceptual Layout



Low-Level RF Based on EIC Common Platform

- LLRF design is based on the EIC common platform hardware design
  - Common general-purpose carrier
  - Function-specific daughtercards
  - Common timing data link Line rate 8 Gbps
  - Standard control system interface
  - 100 MHz Master Clock

- EIC common platform hardware is an evolution of RHIC Low-level RF platform used in C-AD since 2009.
  - FPGA based carrier card
  - Gigabit serial link (deterministic / low-latency) timing and data communication
  - Function-specific daughtercards



- Combined BNL/JLAB effort

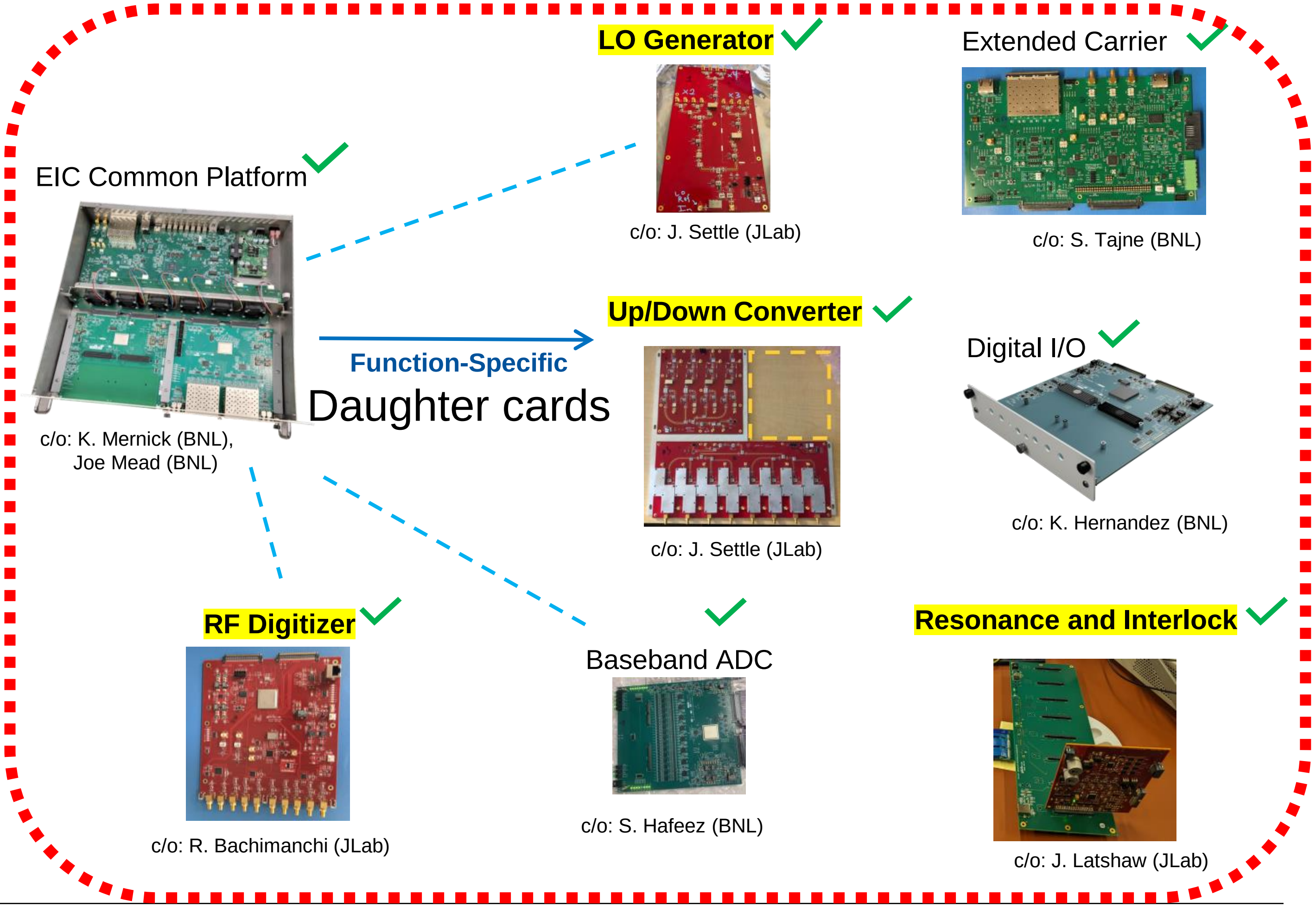
LLRF Controls – Modular and Scalable

EIN Low-Level RF (Common Platform)
Common Hardware + System Level Customization
- RF Digitizer
- Up/Down Converter
- LO Generator
- Resonance Interlock

- **Hardware designs are complete**
- **Firmware & software development is well advanced**

One common hardware platform supports:
Field Control • RF Measurement • Timing & Synchronization • Resonance Control • Machine Protection

Function-specific daughtercards provide system customization



✓ **= Hardware developed / under test**

EIN RF Systems Supported:
197 MHz | 1.3 GHz | 2.856 GHz | 98.5 MHz

EIC RF Stability Requirements vs State of the Art

Beam-dynamics studies indicate RF stability tolerances that are **within demonstrated state-of-the-art performance**. Facilities operating at the same frequencies have achieved substantially tighter amplitude and phase regulation.

System / facility	Frequency	Amplitude stability (% RMS)	Phase stability (deg RMS)	Basis / comparison
EIC L-band	**1300 MHz**	**0.20%**	**0.10°**	**Beam-dynamics error assumption (1σ)**
European XFEL	1300 MHz	< 0.01%	< 0.01°	Demonstrated overall RMS field stability
EIC S-band TW	**2856 MHz**	**0.20%**	**2.0°**	**Beam-dynamics error assumption (1σ)**
PAL-XFEL S-band	2856 MHz	~0.02%	~0.03°	Measured S-band RF stability (RMS)

TAKEAWAY **The present EIC tolerances do not require unprecedented RF regulation; same-frequency XFEL systems demonstrate significant performance margin.**

Sources: European XFEL/DESY LLRF: overall RMS field stability better than 0.01% amplitude / 0.01° phase at 1.3 GHz. PAL-XFEL IPAC2015: RMS klystron FWD RF ~0.02% / ~0.03° at 2856 MHz. EIC values: current beam-dynamics error assumptions.

Summary

1 INJECTOR REQUIREMENT

750 MeV normal-conducting linac

1–2 nC per bunch at 30 Hz

BAR accumulation
→ **28 nC per bunch at 1 Hz**
for RCS injection

2 RF ARCHITECTURE

197 MHz buncher
+ 2 L-band structures
+ 14 × 3 m S-band structures

Proven RF technologies
adapted to EIC requirements

3 KEY DESIGN FOCUS

L-band tapered cavity design is in progress in collaboration with LBNL

S-band Klystron topology selected and optimized for performance, reliability, and cost

4 PROJECT STATUS

Design progressing toward
project baseline

Early hardware development
and validation are underway

☆ **A scalable, reliability-driven RF architecture based largely on**
proven accelerator technology.

Acknowledgements

- Erdong Wang & Qiong Wu for their tremendous support and guidance

- BNL RF Team

  Alex Zaltsman, Binping Xiao, Carlos Ramirez, Geetha Narayan, Kevin Mernick, Arshdeep Singh Samson Mai, Mark Hoffmann Wallner, Michael Sowinski, Silvia Verdu Andres, Robert Lambiase and many others

- JLab RF Team

- BNL NSLS-II RF Team

Thank You!

Questions?

Backup

S-Band Linac Klystron Topology Choice

M=number of structure per Klystron

Four HPRF topology options were evaluated (February 2026 mini-workshop).
Options 1 and 3 were shortlisted; **Option 1** was selected.

1-2 nC case	With Sled Option:1	With Sled Option:2	Without Sled Option:3	Without Sled Option:4
RF structure/klystron	M=2	M=4	M=2	M=1
Klystron Power (#)	40 MW (7+1)	80 MW(4+1)	80/100 MW(7+1)	40 MW (14+1)
Gradient	18.5-22MV/m	16-22 MV/m	18.5-22 MV/m	18.5-22 MV/m
structure input power	34-38 MW	34-38 MW	34-38 MW	34 MW
Number of units	14	16	14	14
Major Mat. cost (K+M+S)	13.2	12.9	12.8	19.5
Example	CERN (16.5 MV/m) MAXIV (16-19)	Electtra_S_HG(22-25 MV/m) PAL_r(20.8 MV/m)	SwissFEL Inj.(up to 20) Electtra_C(13 MV/m) PAL_L1(20MV/m)	SLS (18MV/m) PAL_L0(22.5 MV/m)

Considering construction and test front end section

- Motivation: The time between preinjector building/utility ready to preinjector construction/commissioning is very tight. We are considering the construction the front-end up to 1st section of sband linac using existing ATF-II bunker, before the EIC linac building ready.
- It can solve the challenges of test area and get experience for the team, such as high voltage RF test, Wien filter beam test, beam diagnostics and commissioning; control system.

We have:

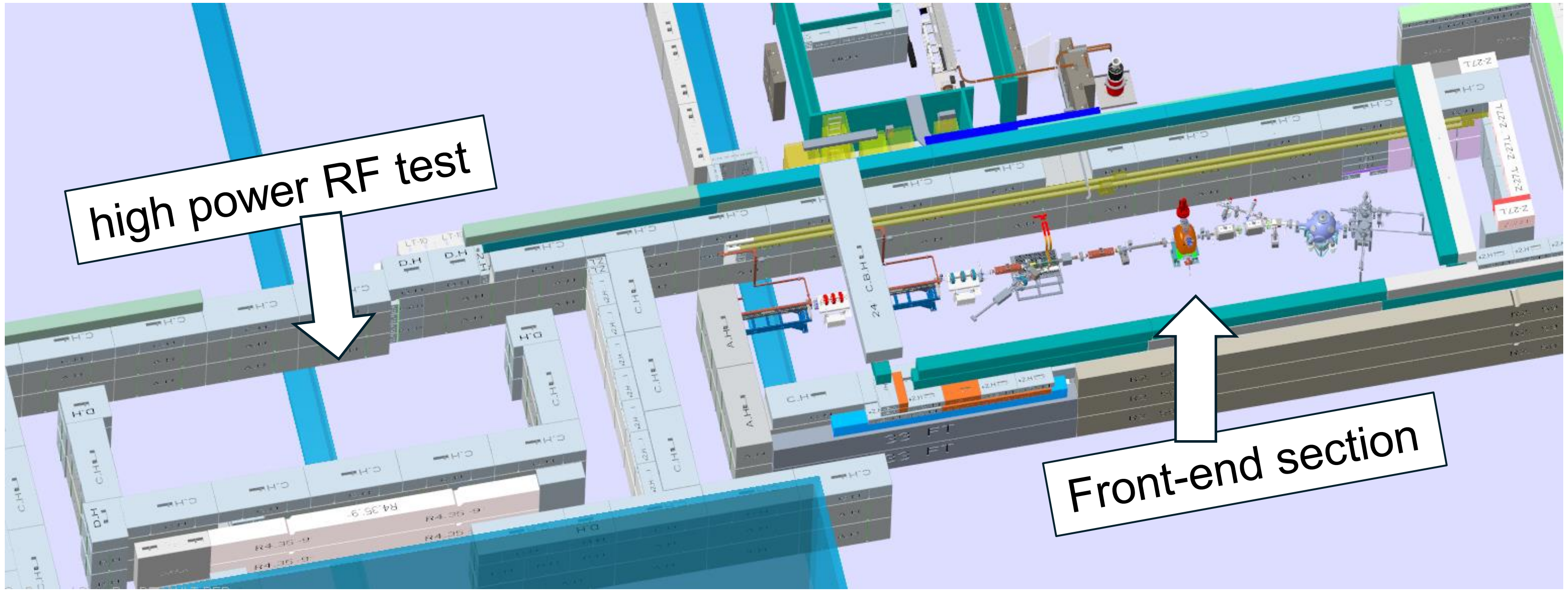
HVPS/Gun/Cathode system
Low gradient Sband cavity
197 MHz Buncher
Gun diagnostics

To be purchased:

RF source
Optics
Beamline components

To be developed:

Wien filter
Mott polarimeter



Amplitude And Phase Stability Required

```
# cell1300 RF phase error parameters
cell1300_rf_phase_sig: 0.1
cell1300_rf_phase_bound: 0.2
cell1300_rf_phase_mean: 0.0

# cell1300 RF amplitude error parameters
cell1300_rf_amp_sig: 0.002
cell1300_rf_amp_bound: 0.004
cell1300_rf_amp_mean: 0.0

# cell197 RF phase error parameters
cell197_rf_phase_sig: 0.05
cell197_rf_phase_bound: 0.1
cell197_rf_phase_mean: 0.0

# cell197 RF amplitude error parameters
cell197_rf_amp_sig: 0.001
cell197_rf_amp_bound: 0.002
cell197_rf_amp_mean: 0.0

# trwave RF phase error parameters
trwave_rf_phase_sig: 2
trwave_rf_phase_bound: 4
trwave_rf_phase_mean: 0.0

# trwave RF amplitude error parameters
trwave_rf_amp_sig: 0.002
trwave_rf_amp_bound: 0.004
trwave_rf_amp_mean: 0.0
```