Low Energy RHIC electron Cooling (LEReC)
Status and Prospects

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BROOKHAVEN NATIONAL LABORATORY
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Office of Science
U.S. DEPARTMENT OF ENERGY

LEReC Project Mission/Purpose

The purpose of the LEReC is to provide luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

LEReC will be first RF linac-based electron cooler (bunched beam cooling).

To provide luminosity improvement with such new approach requires:

- ❑ **Building and commissioning of new state of the art electron accelerator**
- ❑ Produce electron beam with beam quality suitable for cooling
- ❑ Transport with RF acceleration maintaining required beam quality
- ❑ Achieve required beam position and energy stability in cooling sections
- ❑ Commissioning of bunched beam electron cooling
- ❑ Commissioning of electron cooling in a collider

LEReC design energies

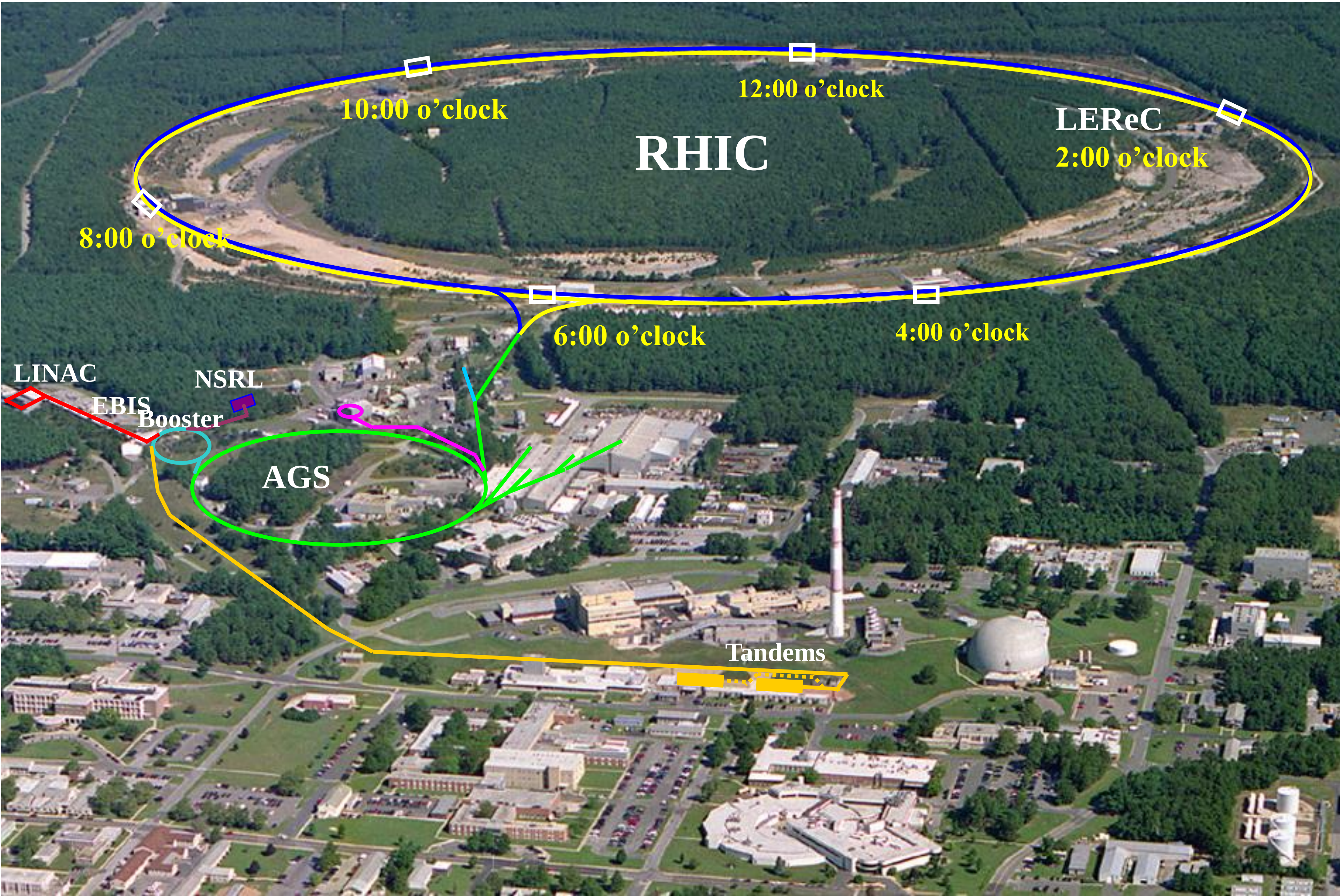
RHIC Beam Energy Scan II Physics Program
energies of interest:

$\sqrt{s_{NN}}$ = **7.7, 9.1, 11.5, 14.6, 19.6 GeV**

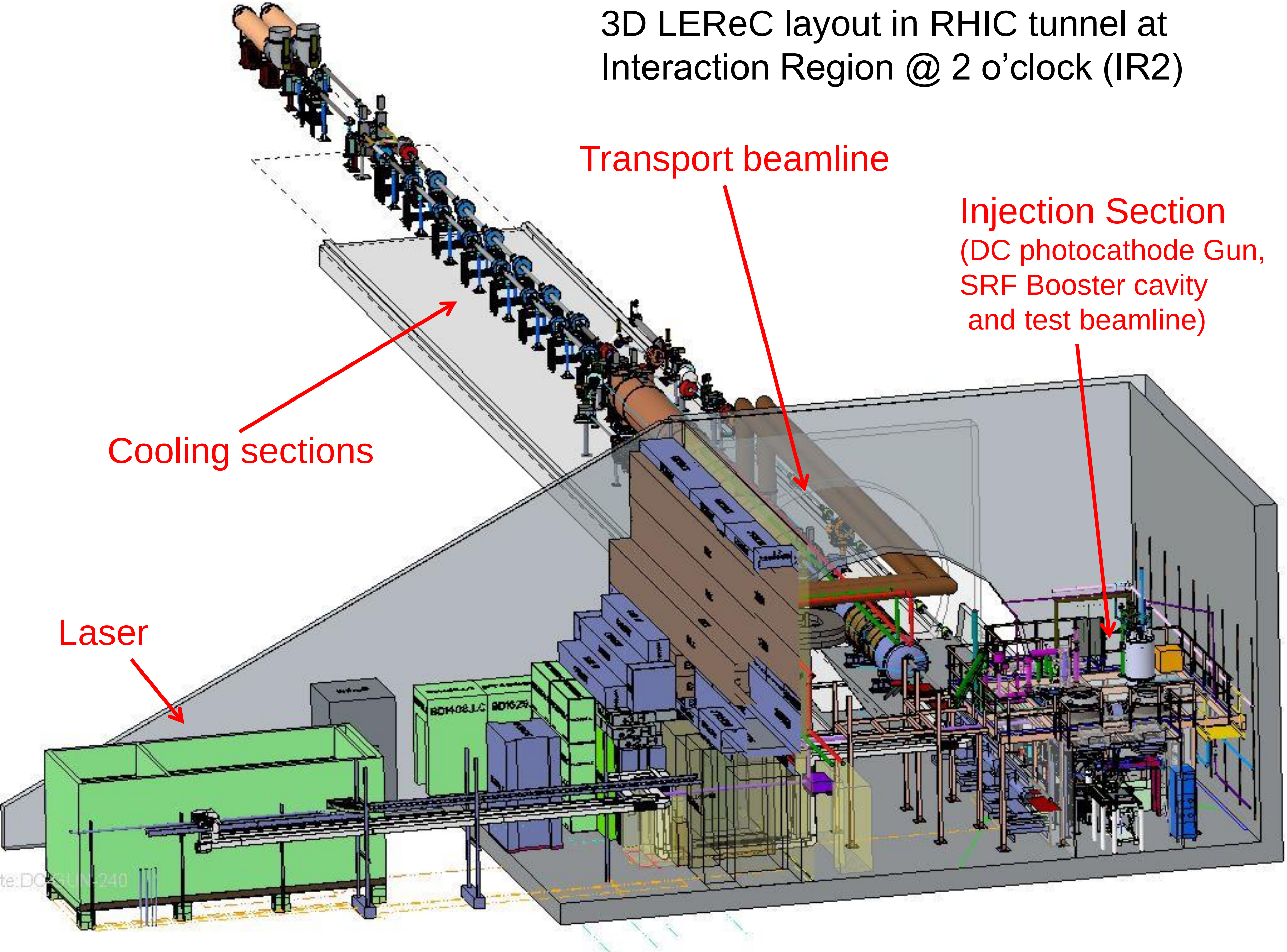
LEReC : 1.6 – 2.6 MeV
(electrons kinetic energies)

Luminosity improvement without electron cooling (needed RHIC performance demonstrated in 2016)

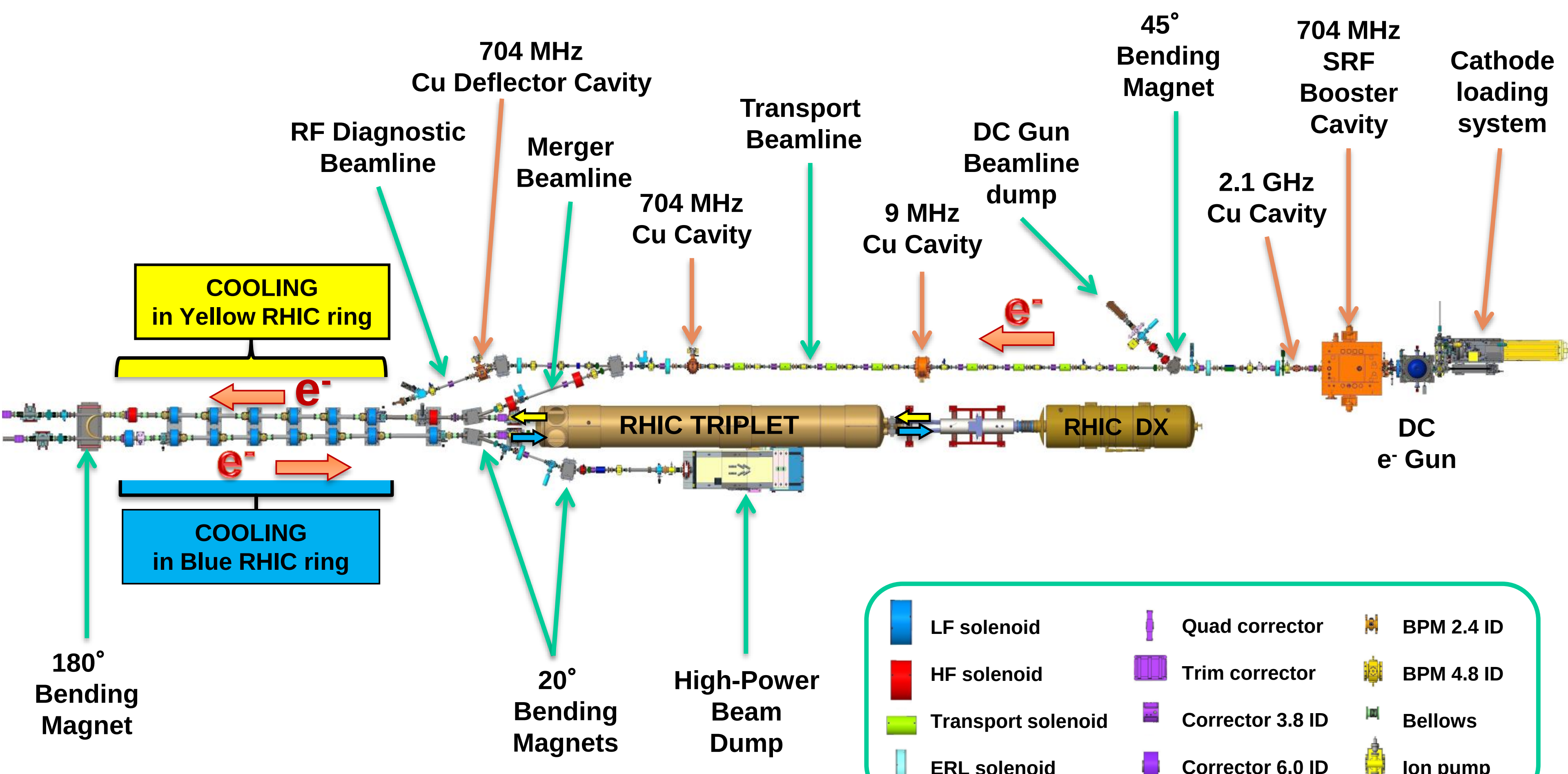
RHIC @ BNL, Long Island, New York



3D LEReC layout in RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



LEReC Accelerator Layout



* NOT to scale

LEReC electron beam parameters

Electron beam requirement for cooling			
Kinetic energy, MeV	1.6*	2	2.6
Cooling section length, m	20	20	20
Electron bunch (704MHz) charge, pC	130	170	200
Effective charge used for cooling	100	130	150
Bunches per macrobunch (9 MHz)	30	30	24-30
Charge in macrobunch, nC	4	5	5-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5
Average current, mA	36	47	45-55
RMS energy spread	< 5e-4	< 5e-4	< 5e-4
RMS angular spread	<150 urad	<150 urad	<150 urad

*CW mode at 704 MHz without macrobunches is also being considered (with even higher average current up to 85 mA)

Bunched beam electron cooling for LEReC

- Produce electron bunches suitable for cooling by illuminating a multi-alkali (CsK_2Sb or NaK_2Sb) photocathode inside the Gun with green light using high-power laser (high-brightness in 3D: both emittance and energy spread).

- The 704 MHz fiber laser will produce required modulation to overlap ion bunches at 9MHz frequency with laser pulse temporal profile shaping using crystal stacking.

- Accelerate such bunches with RF and use RF gymnastics (several RF cavities) to achieve energy spread required for cooling.

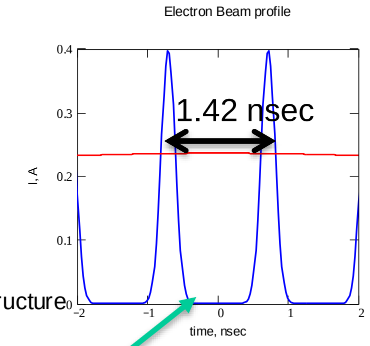
- Deliver and maintain beam quality in both cooling sections.

- Electron bunch overlaps only small portion of ion bunch. All amplitudes are being cooled as a result of synchrotron oscillations.

LEReC beam structure in cooling section
Example for γ= 4.1 (E_{ke}=1.6 MeV)

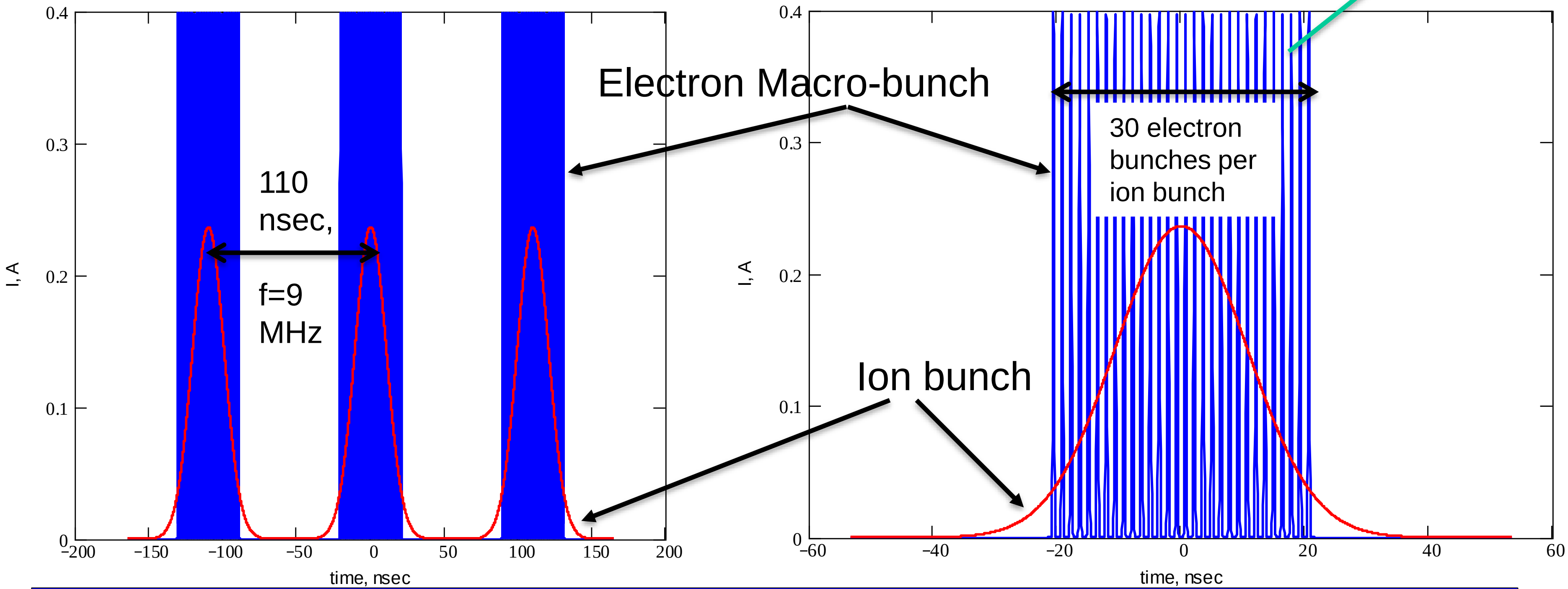
Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3.2 m

Electrons:
f_SRF=703.5 MHz
Q_e=100 pC, I_peak=0.4 A
Rms length=3 cm



LEReC Beam Structure

9 MHz bunch structure



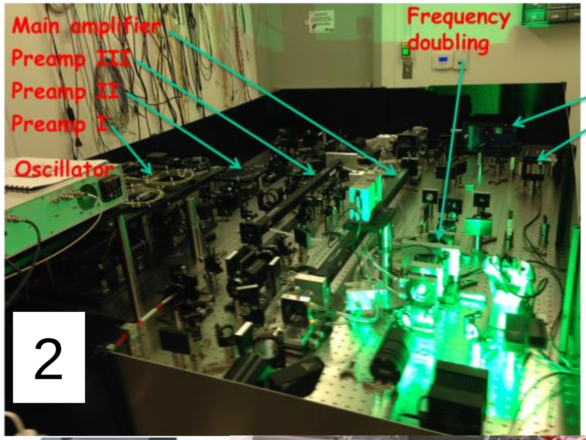
Production of bunched electron beam suitable for cooling

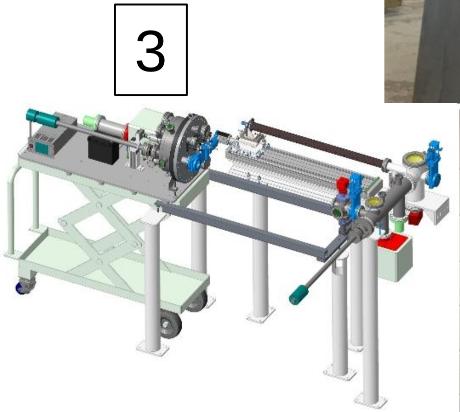
- LEReC is based on the State of the Art physics and technology:

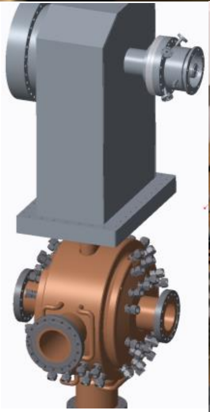
- Photocathodes
- High power fiber laser
- Laser beam shaping
- Operation of HV DC gun with high charge and high average current
- RF gymnastics and stability control to maintain energy spread of electron beam suitable for cooling.

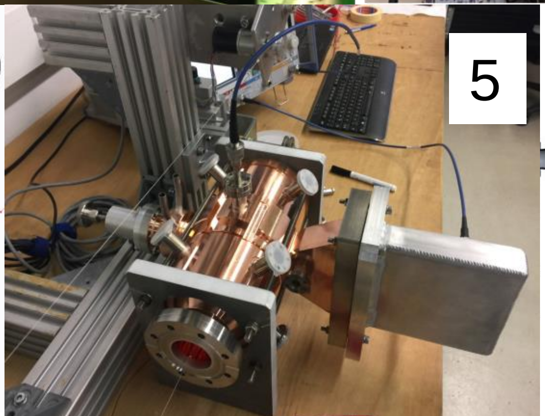
LEReC Critical Technical Systems

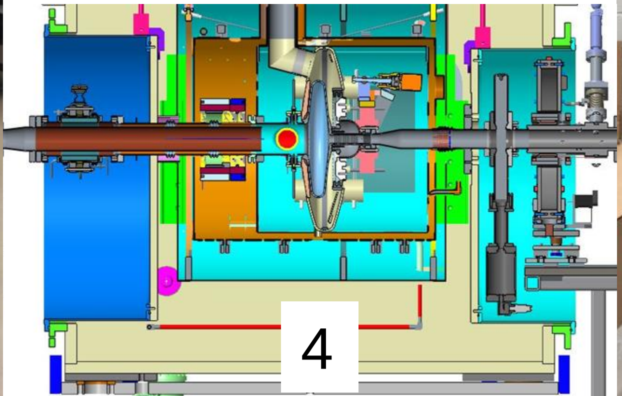
1. DC photocathode electron gun and HV PS.
2. High-power fiber laser system and transport
3. Cathode production deposition and delivery systems
4. SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities





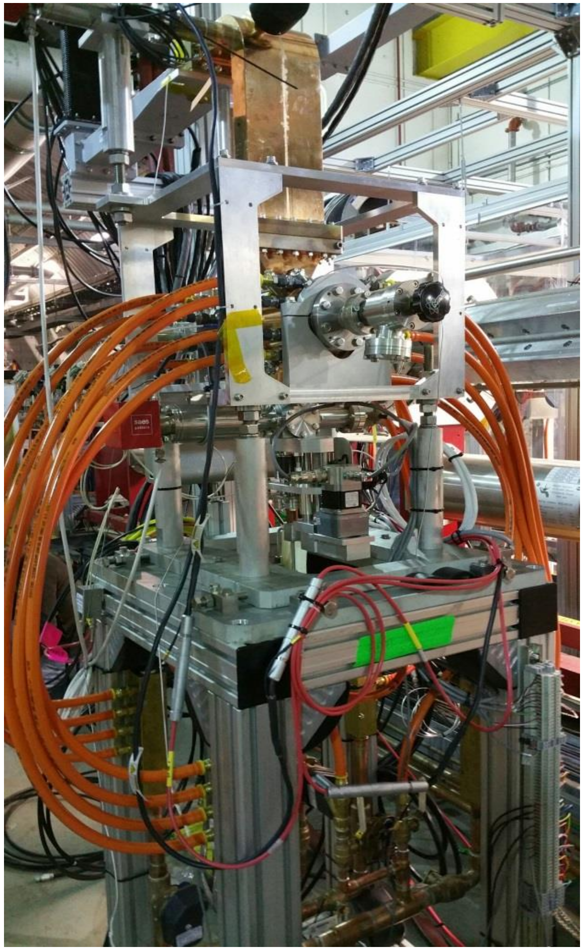






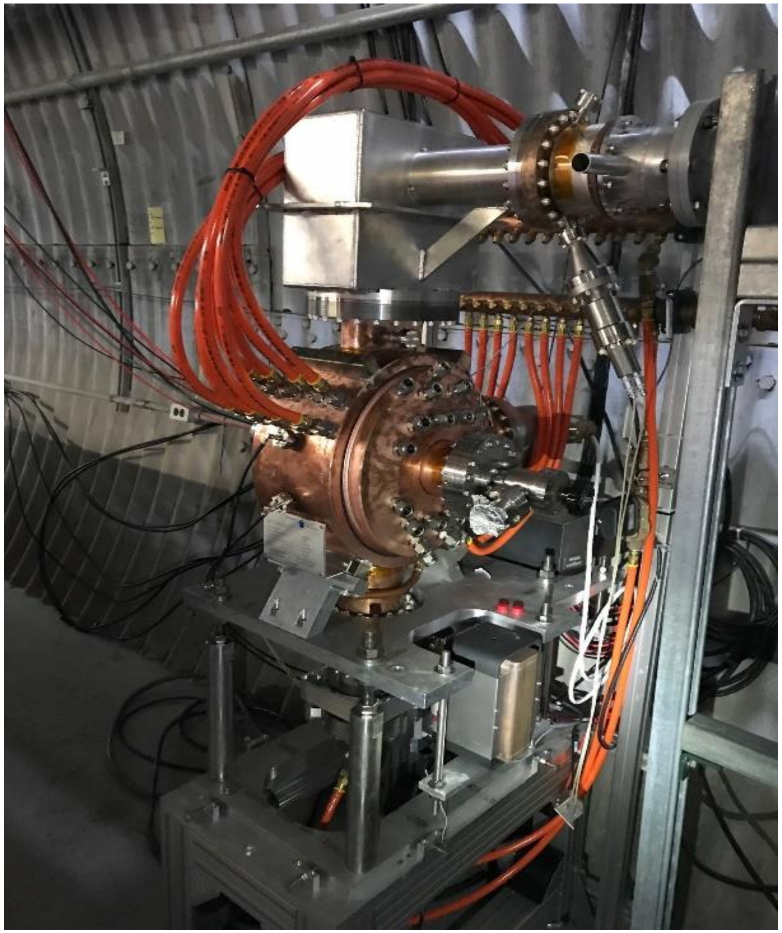
2.1 GHz warm RF cavity

RF tested to 220 kV in CW mode (design value 250kV)



704 MHz warm RF cavity

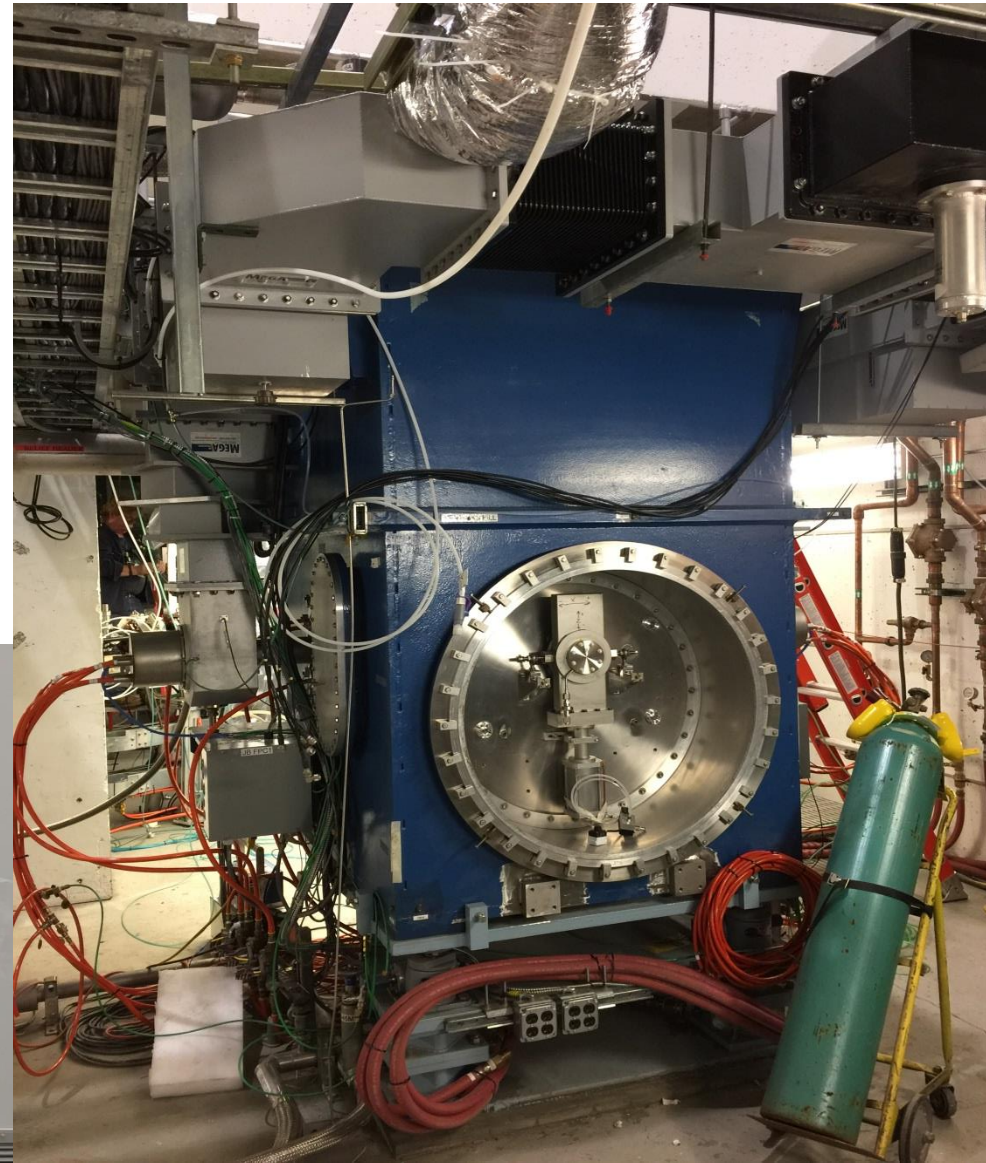
RF tested to 250kV (design value 400kV, will need 250kV for operation)



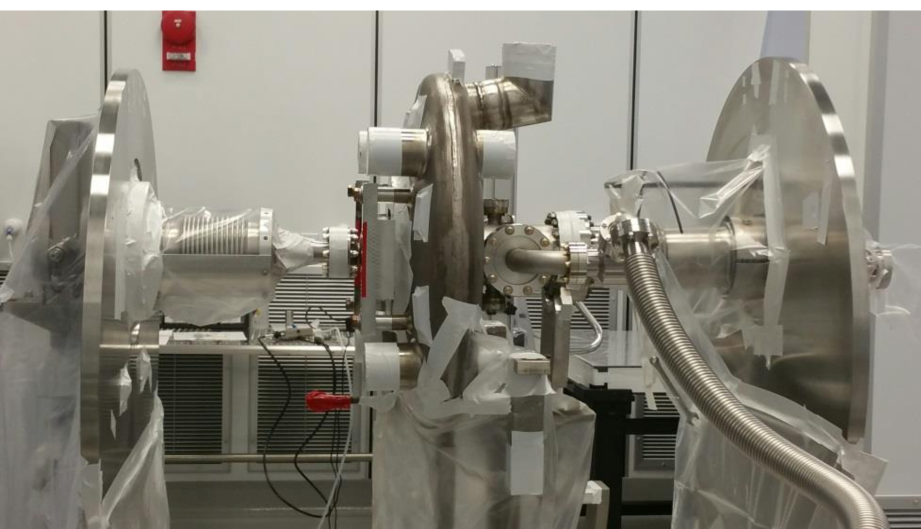
LEReC SRF booster cavity

- SRF Booster cavity conditioned to 2MV in February 2018.
- Presently commissioned with beam for lowest design energy of 1.6MeV.
- Already run significant CW electron current and power through the cavity.

Cavity inside cryostat (2017)



Cavity string assembly in clean room



Stages of LEReC Commissioning

- **Phase 1:** DC Gun tests

  (April-August 2017): DC Gun tests in temporary configuration

  (January-February 2018): DC Gun tests in final configuration

- **Phase 2** (March-September 2018): Full LEReC commissioning

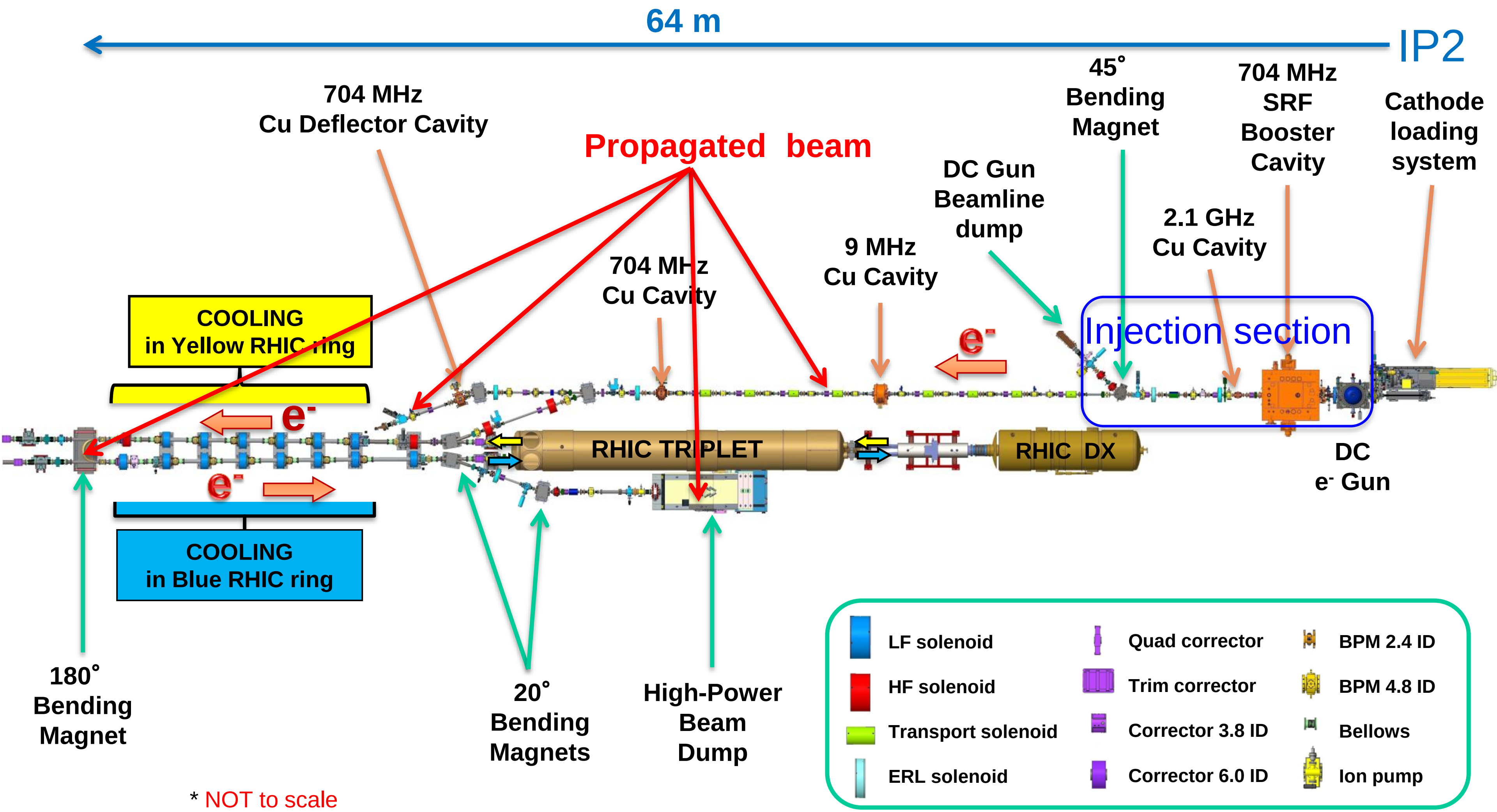
Goals: Achieve stable high-current operation of accelerator with electron beam parameters suitable for cooling.

- **Phase 3** (2018-2019): Transition to operations

Goals: Commissioning LEReC for operation at higher energies. Achieve needed stability (energy, orbit) of electron beam. Develop necessary stability feedbacks.

- **Phase 4** (2019-2020): Commissioning of cooling – requires Au ions at the same energy.

LEReC commissioning 2018 (100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)



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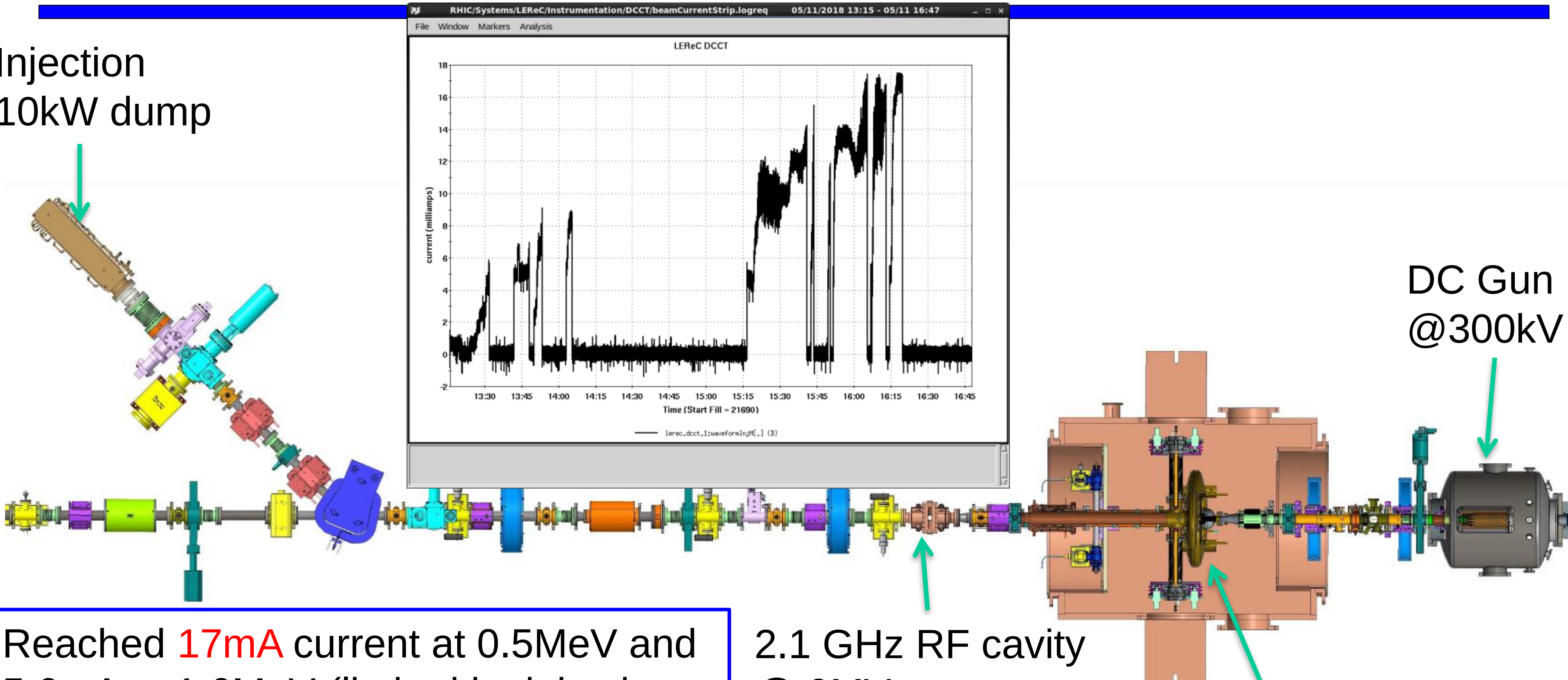
LEReC Injection section (2018)

Injection
10kW dump



DC Gun
@300kV

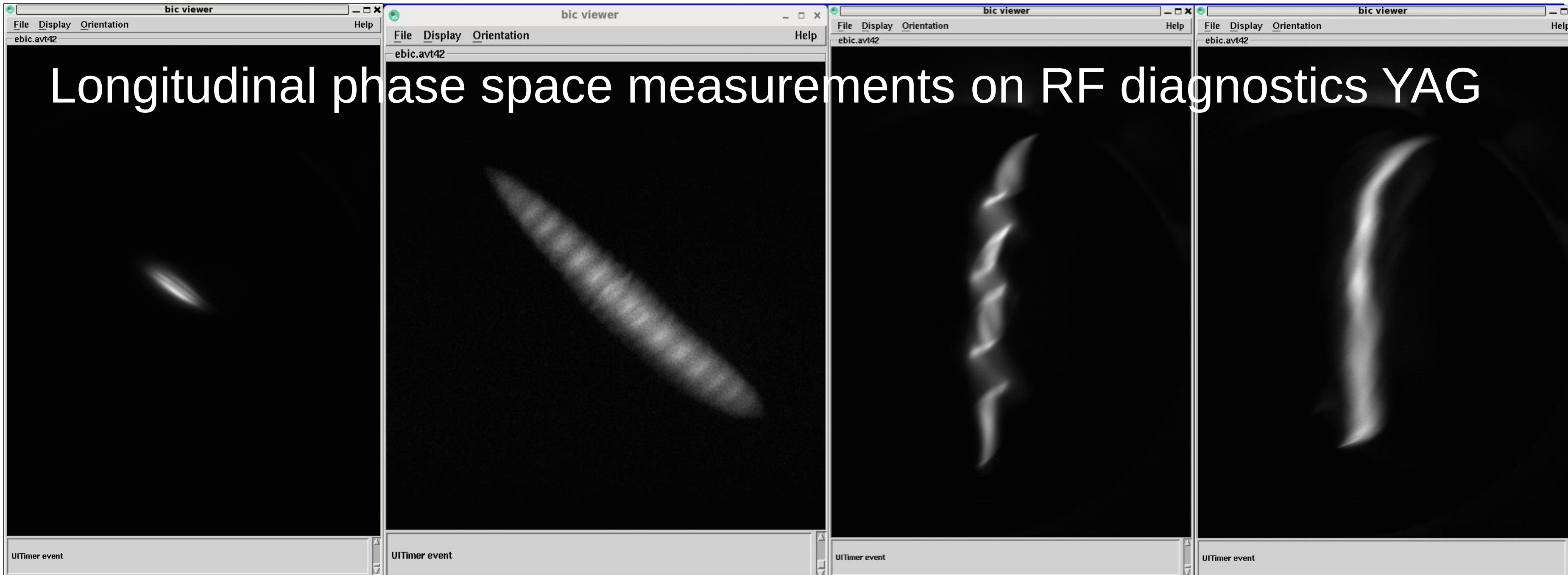
Reached 17mA current at 0.5MeV and 5.6mA at 1.6MeV (limited by injection section dump power of 10kW). Design current 30-55mA.

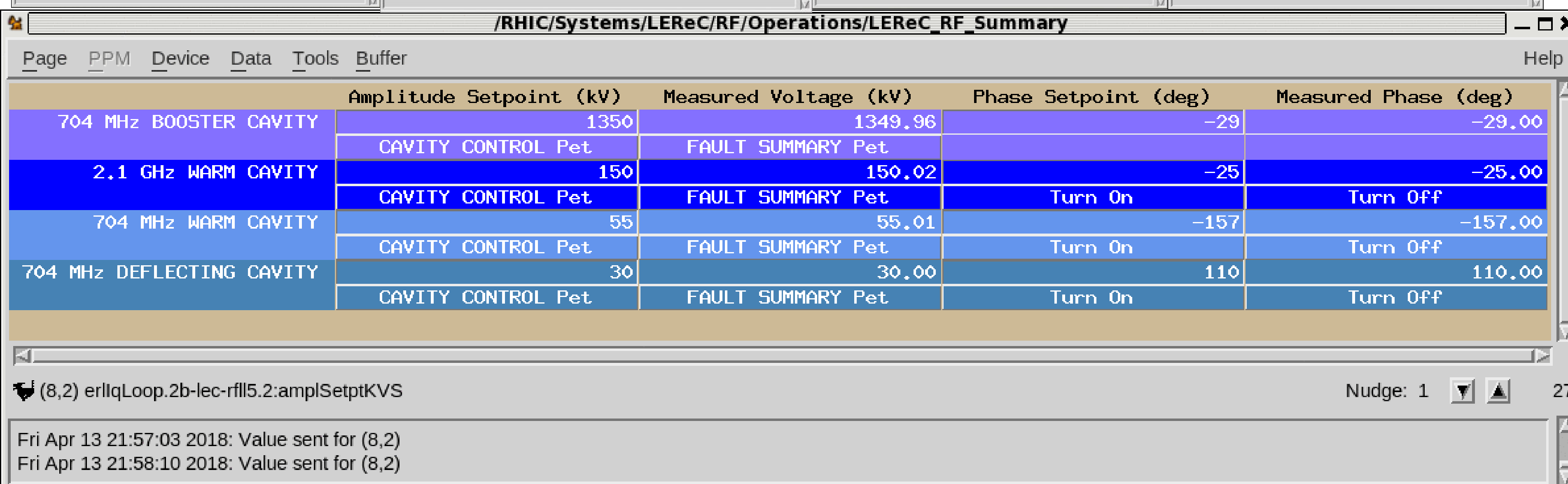
2.1 GHz RF cavity
@ 0MV

SRF Booster cavity
@ 0.2MV

7 m

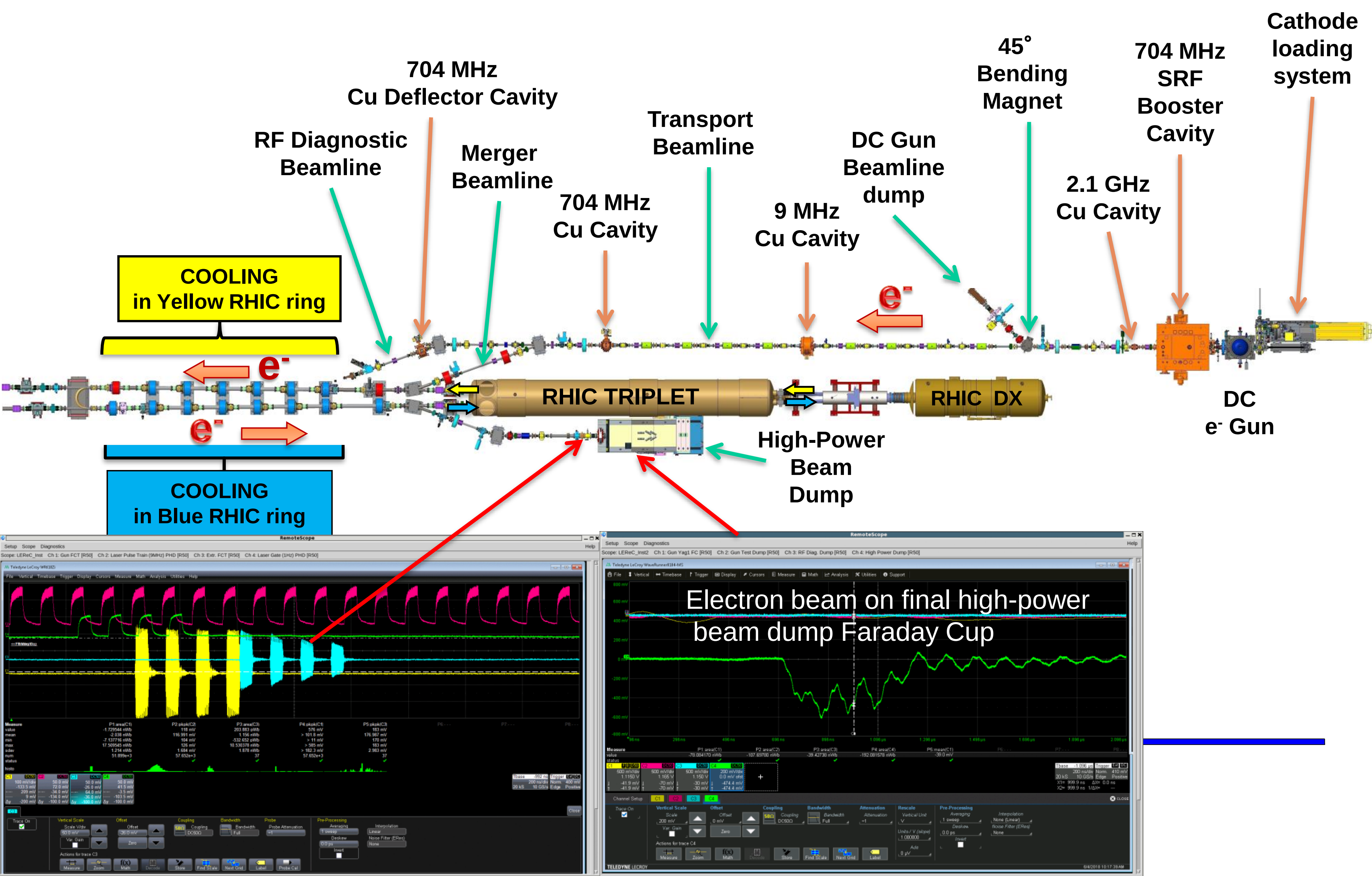
Using 4 RF cavities together (704MHz SRF Booster, 2.1GHz , 704MHz energy correction and 704MHz deflecting cavities)





	Amplitude Setpoint (kV)	Measured Voltage (kV)	Phase Setpoint (deg)	Measured Phase (deg)
704 MHz BOOSTER CAVITY	1350	1349.96	-29	-29.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet		
2.1 GHz WARM CAVITY	150	150.02	-25	-25.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet	Turn On	Turn Off
704 MHz WARM CAVITY	55	55.01	-157	-157.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet	Turn On	Turn Off
704 MHz DEFLECTING CAVITY	30	30.00	110	110.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet	Turn On	Turn Off

LEReC: beam propagated all the way to final beam dump



LEReC Commissioning progress

- Commissioning of electron accelerator is going well.
- Propagated electron beam through all beamlines, including both cooling sections and to all beam dumps (injection, RF diagnostics and high-power beam dumps).
- Achieved design bunch charge (4nC/macro-bunch) including transverse laser shaping (3mm iris).
- Commissioned (with relevant instrumentation) injection section, transport, RF diagnostics and merger beamlines in pulsed mode.
- RF cavities are synchronized and are being used for RF gymnastics and longitudinal phase space optimization.
- Started high-current CW commissioning in injection section. Reached 17mA current at 0.5MeV and 5.6mA at 1.6MeV (limited by injection section dump power of 10kW). Design operational current 30-55mA.
- We had several technical problems. Some of them are being resolved. Problems which require long time periods to be addressed will have to wait until end of commissioning in September.

Cooling Commissioning

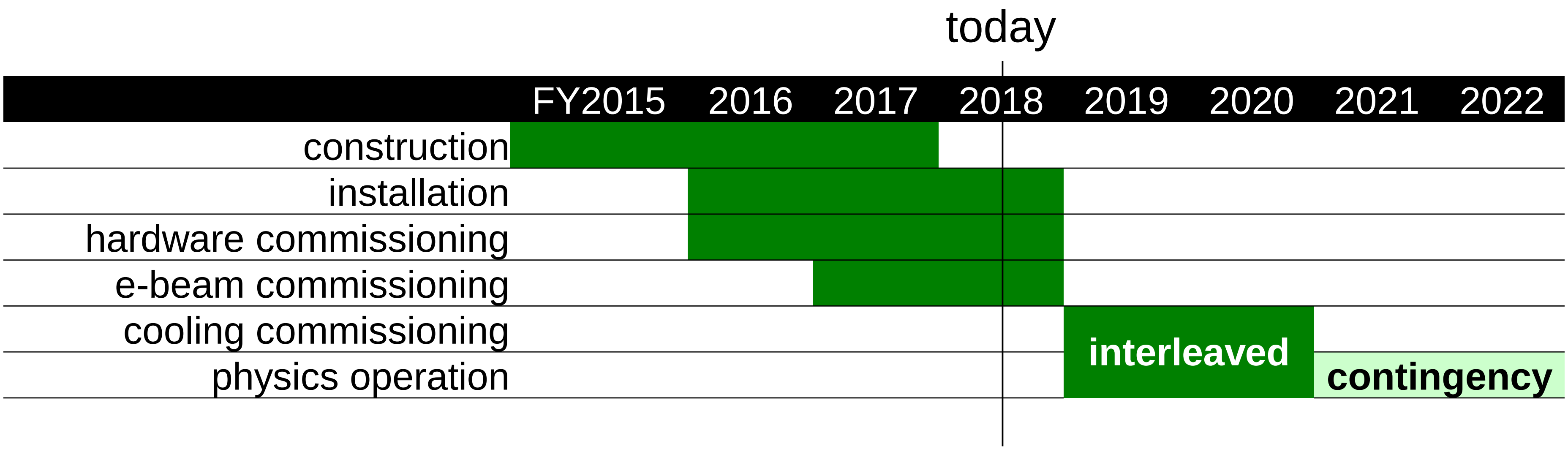
To start commissioning of cooling during Run-19, we need:

- Fully commissioned electron accelerator with all hardware problems resolved.
- Electron beam parameters required for cooling achieved.
- Required stability of electron beam in cooling sections achieved.
- Required stability of ion beam in cooling sections achieved.

Once we have Au ions in RHIC in 2019 commissioning of cooling will start and will include:

- Interaction of electron and ion beams: with e-beam parameters established (current, energy, energy spread, emittance, required stability) establish overlap between Au and electron beams in (x, y, p)
- Demonstration of bunched beam cooling
- Effects on hadron beam (cooling vs. heating)
- Effects on electron beam
- Control of ion distribution under cooling
- Cooling and beam lifetime (as a result of many effects)
- Preserve cooling performance from one cooling section to another
- Work on optimization between cooling process and luminosity improvement

LEReC Physics Integration: Overview



- Installation is complete
- Hardware commissioning is in progress
- E-beam commissioning is in progress
- Cooling commissioning interleaved with physics

LEReC Physics integration: BES-II required events

RHIC Beam Energy Scan II (BES-II) for search of critical point in QCD phase diagram

center-of-mass energy $\sqrt{s_{NN}}$	GeV	7.7	9.1	11.5	14.6	19.6
events BES-I, actual	M	4.3		11.7	24	36
events BES-II, **min goal**	M	80	100	150	200	300
events BES-II, **full goal**	M	100	160	230	300	400

General strategy to maximize integrated luminosity:

- Cooling at the 3(2) lowest energies (4x gain in L_{avg}), no cooling at the 2(3) highest energies (3x gain in L_{avg})
- Start BES-II at highest energies (machine ready w/o cooling)
- Interleave cooling commissioning with physics operation
- Finish BES-II at lowest energies (largest gain in L_{avg} and time)

Physics integration: Luminosity model (W. Fischer)

Total beam energy	GeV/nucleon	3.85	3.85	4.55	4.55	5.75	5.75	7.30	7.30	9.80	9.80
		BES-I	**BES-II**	**BES-I**	**BES-II**	**BES-I**	**BES-II**	**BES-I**	**BES-II**	**BES-I**	**BES-II**
no of colliding bunches	…	111	111	56	111	111	111	111	111	111	111
ions/bunch, initial	10^9	0.5	0.6	0.4	0.80	1.1	1.30	1.1	2.10	0.9	2.30
transverse rms emittance ε_{xy}	μm	3.3	2.5	6.7	2.5	2.5	2.5	1.7	1.7	2.5	3.5
envelope function at IP b^*	m	6.0	6.0	10.0	5.0	6.0	4.0	3.5	3.5	2.5	3.0
direct space charge tune shift ΔQ_{sc}	0.001	-36	-27	-10	-27	-46	-29	-42	-80	-13	-24
beam-beam parameter ξ/IP	0.001	-1	-1	-0.2	-1	-2	-2	-3	-5	-1	-3
initial luminosity L_{init}	**10^{24} cm^{-2}s^{-1}**	**3.1**	**6.0**	**0.35**	**15**	**33**	**60**	**100**	**369**	**80**	**330**
average / initial luminosity	%	40	84	34	117	45	100	20	16	50	40
average store luminosity L_{avg}	**10^{24} cm^{-2}s^{-1}**	**1.25**	**5.0**	**0.12**	**17.3**	**15**	**60.0**	**20**	**59**	**40**	**132**
average luminosity improvement factor	**...**		**4.0x**		**4.0x**		**4.0x**		**2.9x**		**3.3x**
time in store	%	55	65	--	65	66	65	57	65	71	65
weekly integrated luminosity L	μb^{-1}/week	0.5	2.0	--	6.8	5.0	24	8.1	23	15.0	52
total events, **min goal**	M	4.3	**80**	--	**100**	11.7	**150**	24	**200**	36	**300**
total events, **full goal**			**100**		**160**		**230**		**300**		**400**
total runing time for physics, **min goal**	weeks	4.6	9.7	--	6.0	1.4	3.2	3.4	3.5	1.4	3.2
total runing time for physics, **full goal**	weeks		12.1		9.5		4.9		5.3		4.2
BES-II (Run-19 + Run-20)											
cryo-time	weeks/run	24.0	36.0								
beam time	weeks/run	23.0									
physics time	weeks/run	22.0									
cooling commissioning time with **min goal**	**weeks**	**18.5**									
cooling commissioning time with **full goal**	**weeks**	**8.0**									

Min goals can be achieved with up to 18.5 weeks of commissioning

Max goals leave only 8 weeks for commissioning (from 48 cryo-weeks), which most likely require third year of running

Estimate (with large errors) of time needed for cooling commissioning:
Year 1: 8 weeks (to commission cooling)
Year 2: 4 weeks (to improve cooling and achieve luminosity improvement)
Year 3: 3 weeks (to further improve cooling and luminosity improvement)

Summary

- LEReC will be first electron cooler based on the RF acceleration of electron beam.
- It will be the first application of electron cooling in a collider.
- Installation of electron accelerator is complete.
- Commissioning with electron beam of full LEReC accelerator started in March 2018 and is progressing very well.
- Commissioning of cooling process will start in Run-19.