FROM RESEARCH TO INDUSTRY

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ENERGY RECOVERY LINACS

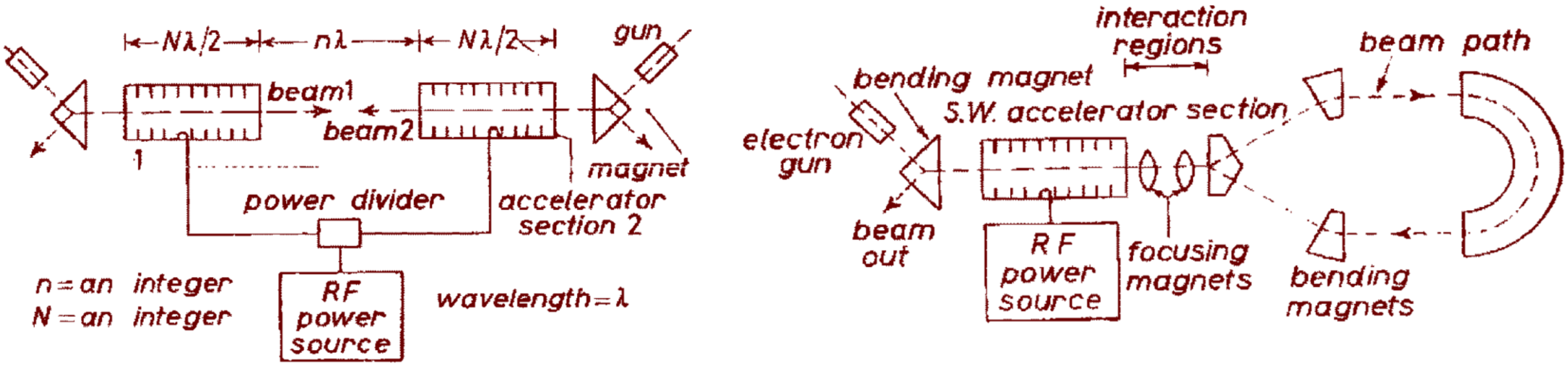
AND

HIGH INTENSITY SOURCES

A. MOSNIER

ERL CONCEPT

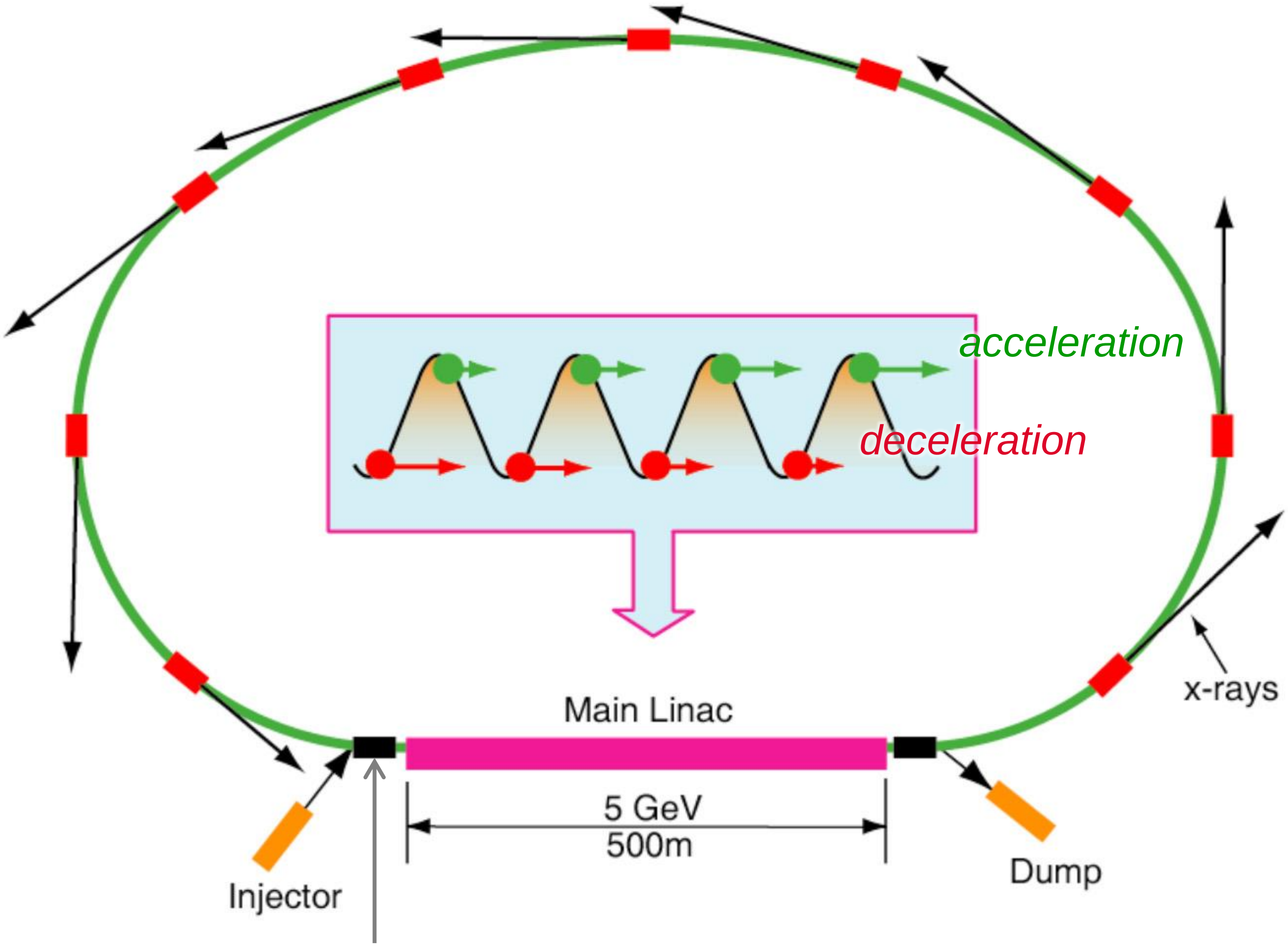
- **Storage rings**: limitations (equilibrium emittance, IBS, …)
- **Linacs**: provide the highest brightness beams (fresh particle bunch used for each interaction) But after acceleration and interaction, the beam is dumped
- **ERL**: acceleration, use of the beam, deceleration and recovery of beam energy = perfect candidate to provide continuous (energy recovery) and high brightness beams (fresh electron bunches used every turn, qualities largely determined by source)



M. Tigner: "A Possible Apparatus for Electron Clashing-Beam Experiments",
Il Nuovo Cimento Series 10, Vol. ***37****, issue 3, 1 Giugno1965*

ERL SCHEMATIC

From ERL concept (1965) to Cornell ERL study (2001)



Dogleg for return path length adjustment

ADVANTAGES OF AN ERL

☐ Relative to storage rings

- Better beam quality (emittance, polarization – maintain nonequilibrium state due to short dwell time)
- Easier to upgrade (add linac section or recirculation passes)
- Tolerate more “damage” to the beam from collisions with a beam or at target (the beam is dumped soon after)

☐ Relative to single-pass linacs

- Higher beam current possible (RF power limit removed)
- Reduced power bill (RF power recovered)
- Reduced cost of RF amplifiers (smaller RF power amplifiers)
- Reduced beam power and energy in beam dump (less shielding / activation issues)

CW SRF Linacs

CW OPERATION FOR FEL (OR HIGH DUTY CYCLE)

- ☐ **Significant interest in increasing the pulse repetition rate of FELs and so in increasing the duty cycle of the e-driver**

- ☐ **Most of projects rely on superconducting RF owing to its ability to deliver high average power electron beams**
  - with pulse frequency 10 Hz → 10 kHz → 1 MHz

- ☐ **Examples of single pass, CW operation**
  - **European XFEL @Hamburg** LP or CW operation as possible upgrade
  - **NGLS** (Next Generation Lignt Source @LBNL) FEL proposal operating in CW mode
  - **LCLS-II @SLAC** CW 4GeV SRF Linac with a bunch rate up to 1 MHz
  - **LUNEX5 @SOLEIL** includes a 400MeV SRF Linac designed for high rep'rate and possible further CW upgrade

SRF Linac (400 MeV) for high rep' rate and multiple beamlines

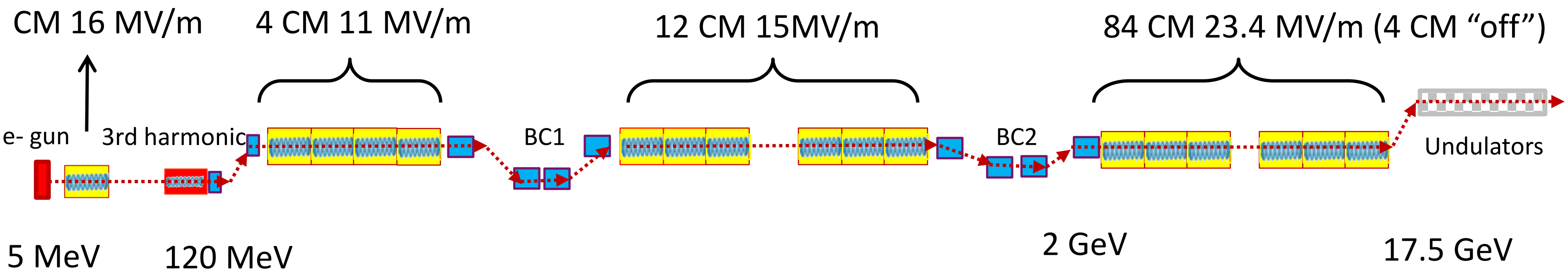
Example: LUNEX5 layout

Laser Wakefield Accelerator (400 MeV)

Pilot user experiments

POSSIBLE E-XFEL UPGRADE

XFEL cryomodule = 8 x 9-cell SC 1.3 GHz TESLA cavities
Nominal operation: Short Pulse (SP) mode → 0.65 ms bunch train 10 Hz rep rate



←------------------ Injector section (**17 CM**) -------------------------→←-- Main Linac (**84 CM**) ---→

Possible upgrade: CW or Long Pulse (LP) mode

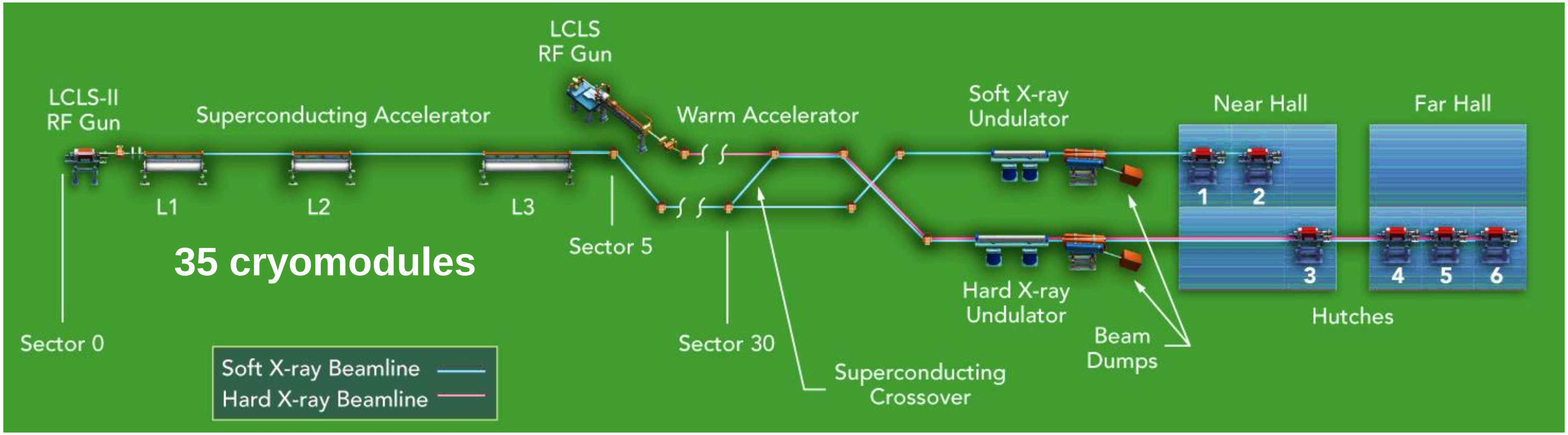
Injector section (17 CMs)
Gradients should be kept
⇒ New modified CMs allowing
CW operation up to **16 MV/m**

Main Linac (96 CMs)
12 old CMs relocated to the linac end
<Eacc> = **7.3 MV/m** limited by He pipe
⇒ ΔE = 5.8 GeV final energy = 7.8 GeV

"Prospects for CW and LP operation of the E-XFEL in hard X-ray regime" (R. Brinkmann et al.)

LCLS-II @SLAC 4 GeV SRF LINAC

Linac Acceleration and Compression (100 pC)



35 cryomodules

Linac section	Phase (deg)	Gradient (MV/m)	No. of CM's	Avail. cavities	Powered cavities
L0	~0	16.3	1	8	7
L1	-12.7	13.6	2	16	15
HL	-150	12.5	2	16	15
L2	-21	15.5	12	96	90
L3	0	15.7	18	144	135
Lf	±34	15.7	2	16	15

Average gradient **~16 MV/m**
with **Qo** ≥ **2.7 10^{10} at 2K**

CW SRF ERLs

CW OPERATION FOR ERL

In parallel, numerous Energy Recovery Linacs (ERL) based on superconducting linacs operating in CW mode planned or under construction. For example:

JLab FEL/ ERL	Light source delivers bursts at 75 MHz
Alice @Daresbury	CW ERL cryomodule developed as part of a collaboration program
ERL test facility @Beijing	(35 MeV,10 mA) to promote ERL-FEL studies at IHEP
ERL facility @BNL	ampere class 20 MeV ERLunder commissioning @Broohaven to investigate the feasability of an electron-ion collider @RHIC
cERL @KEK	ERL prototype in operation @KEK to demonstrate the recirculation of high brightness beams
bERLinPro @HZB	ERL under construction @Berlin includes SRF linac and SC photo-injector
MESA @Mainz U.	multi-turn ERL for nuclear physics
LHeC ERL @CERN	ERL test facility project to prospect e-p collider (60 GeV e^- 7 TeV p)
Cornell ERL R&D program	preparatory research launched for an ERL light source using a 5 GeV linac and high current (100 mA)

CEBAF (FOR NUCLEAR PHYSICS)

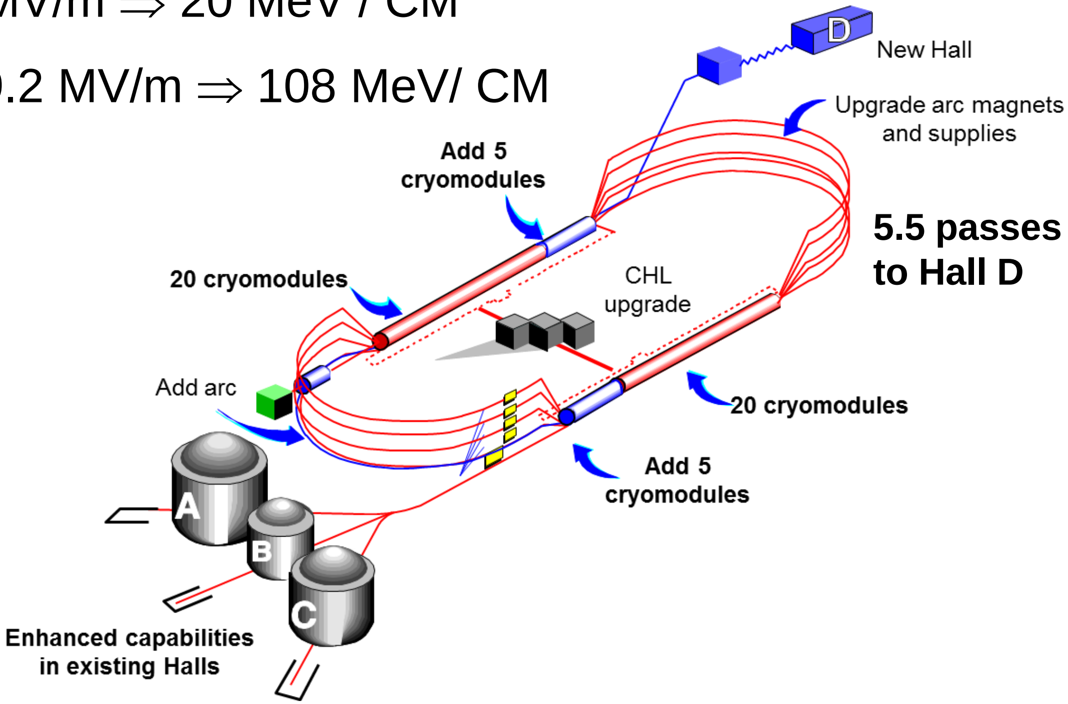
First large high-power CW recirculating e-linac based on SRF technology (1497 MHz)

Long operational experience with CW cryomodules

12 GeV upgrade (doubling the energy) → **2 x 1.1 GeV Linacs**

Initial C20 = 8 x 5-cell cavities 5 MV/m ⇒ 20 MeV / CM

Now C100 = 8 x 7-cell cavities 19.2 MV/m ⇒ 108 MeV/ CM



Results: 50 + 2 CW cryomodules commissioned

Mean maximum operating gradient – 20.4 MV/m	Dynamic heat load ≤ 35 W per cavity
Average Energy Gain = 113 MV / 108 MV	Static Heat Load ~18 W

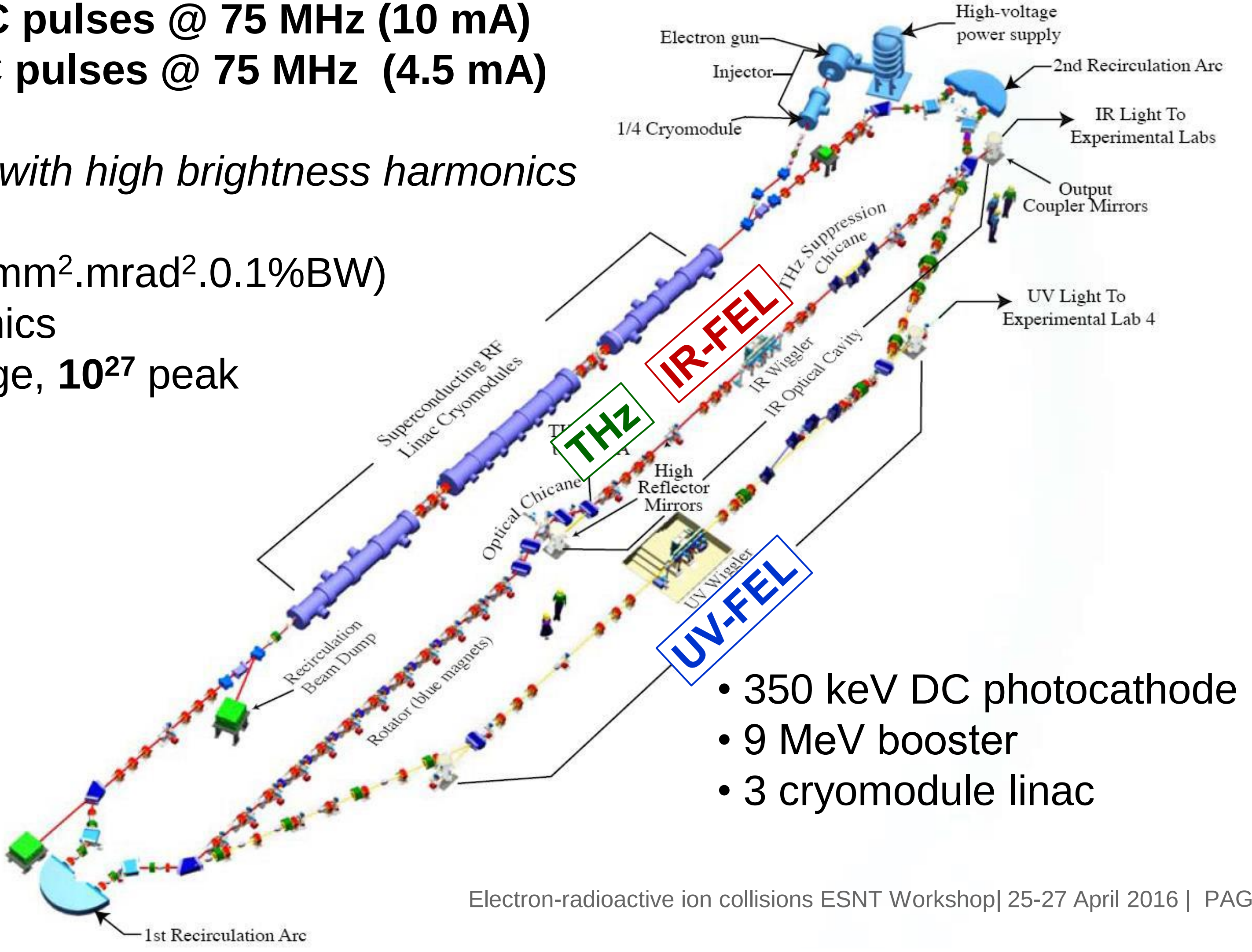
JLAB ERL LIGHT SOURCE

The first high current ERL
14 kW average power in IR

E = 135 MeV
IR : 135 pC pulses @ 75 MHz (10 mA)
UV : 60 pC pulses @ 75 MHz (4.5 mA)

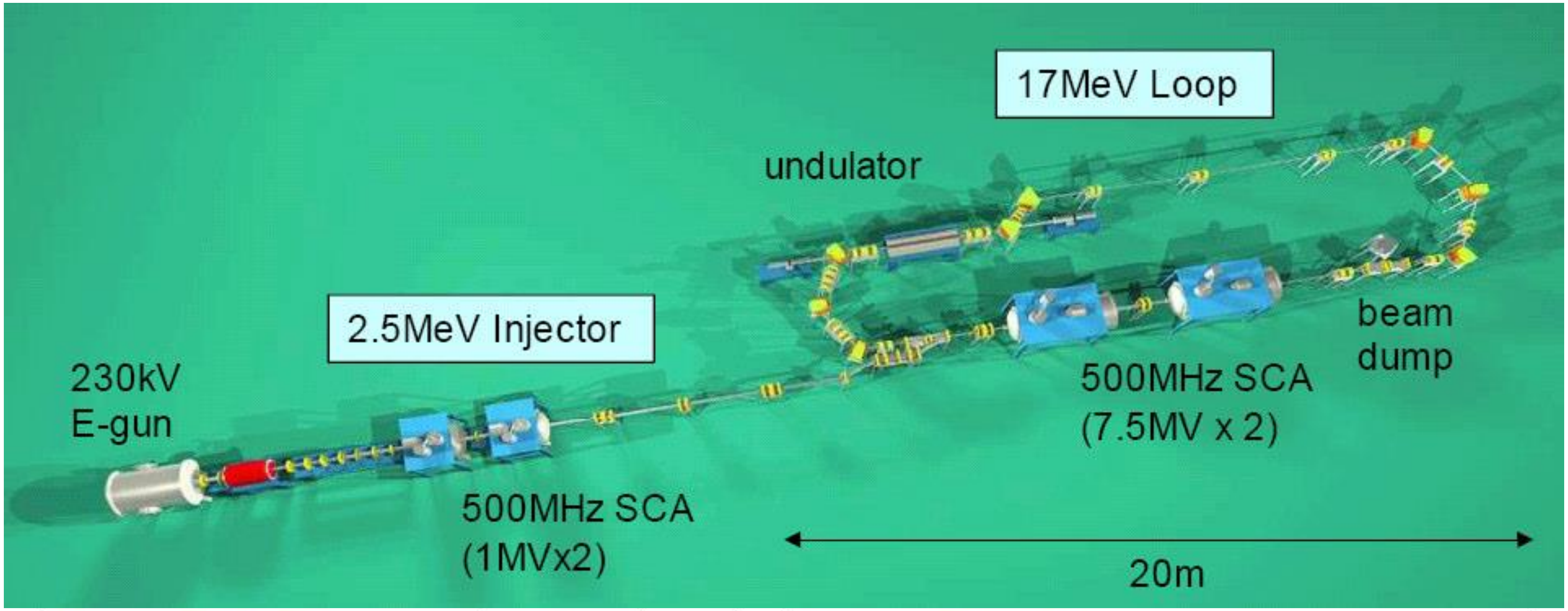
UV Lasing with high brightness harmonics

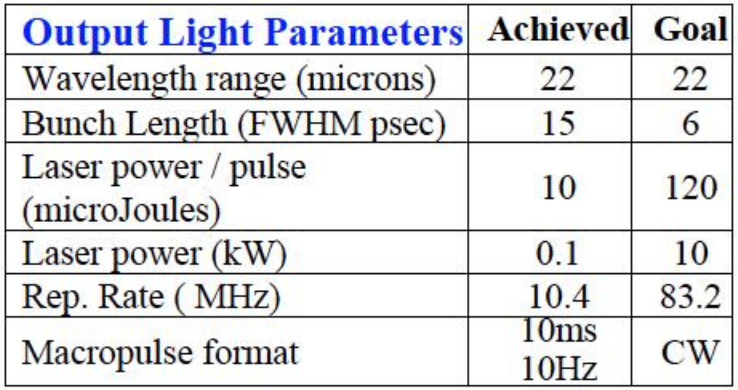
10^{23} ph/(s.mm^2.mrad^2.0.1%BW)
UV harmonics
10^{21} average, **10^{27}** peak



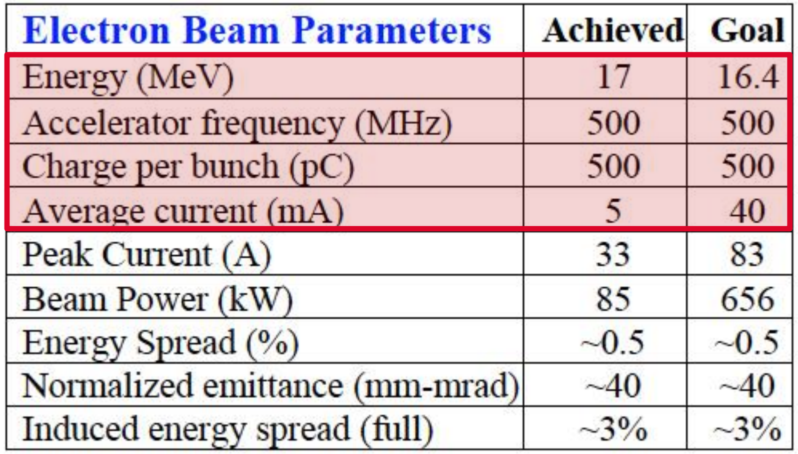
- 350 keV DC photocathode gun
- 9 MeV booster
- 3 cryomodule linac

JAERI ERL-FEL





Output Light Parameters	**Achieved**	**Goal**
Wavelength range (microns)	22	22
Bunch Length (FWHM psec)	15	6
Laser power / pulse (microJoules)	10	120
Laser power (kW)	0.1	10
Rep. Rate (MHz)	10.4	83.2
Macropulse format	10ms 10Hz	CW



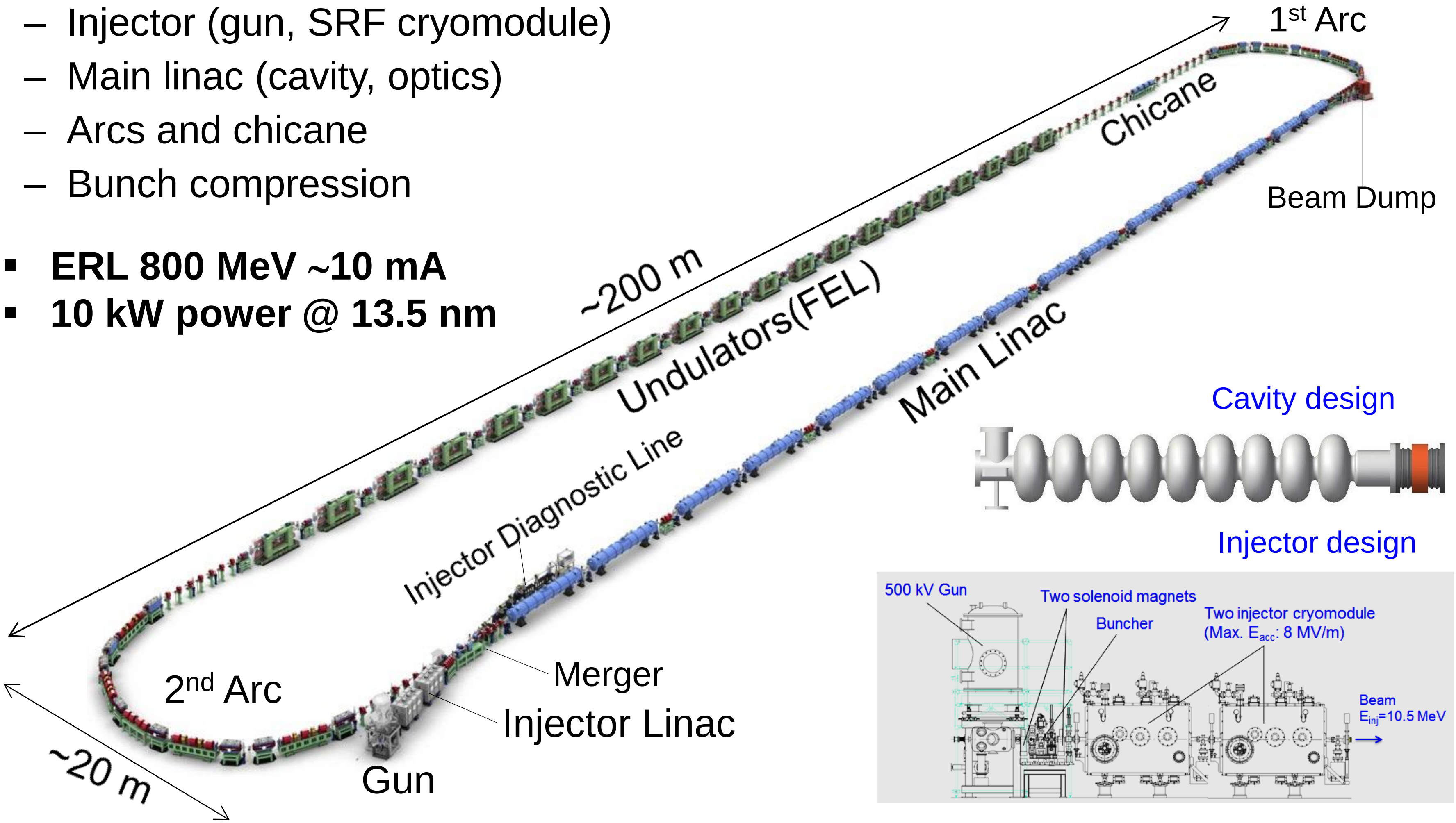
Electron Beam Parameters	**Achieved**	**Goal**
Energy (MeV)	17	16.4
Accelerator frequency (MHz)	500	500
Charge per bunch (pC)	500	500
Average current (mA)	5	40
Peak Current (A)	33	83
Beam Power (kW)	85	656
Energy Spread (%)	~0.5	~0.5
Normalized emittance (mm-mrad)	~40	~40
Induced energy spread (full)	~3%	~3%

ERL-FEL (UV SOURCE for lithography)

N. Nakamura (KEK)

- **Design of a 10-kW class ERL-FEL**
  - Injector (gun, SRF cryomodule)
  - Main linac (cavity, optics)
  - Arcs and chicane
  - Bunch compression

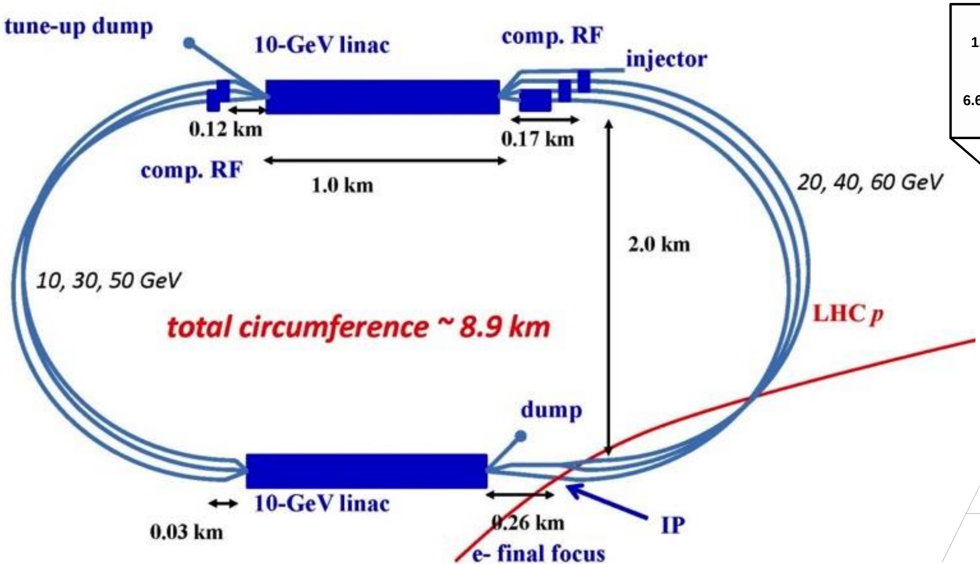
- **ERL 800 MeV ~10 mA**
- **10 kW power @ 13.5 nm**



BIG ERLS FOR ELECTRON-ION COLLIDERS

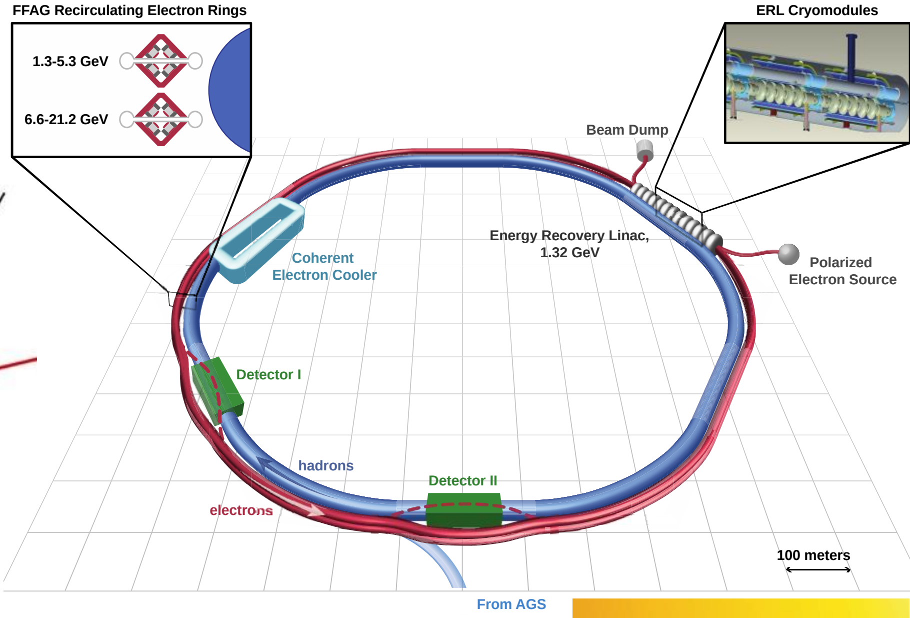
e-p collisions at CERN
LHeC Linac-Ring option

60 GeV (e) x 7 TeV (p)



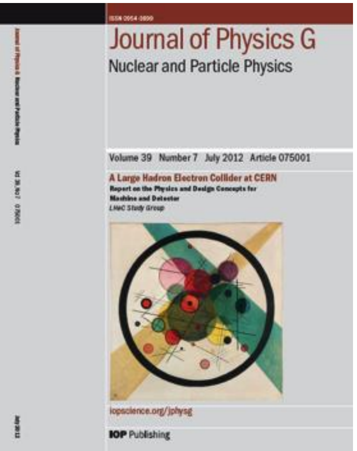
e-ion collisions at BNL
eRHIC

c.m. energy range 20 - 145 GeV



Novel FFAG lattice→16 beam re-circulations using only 2 beam transport loops

L~10^{33}-10^{34} cm^{-2}s^{-1}



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Volume 39 Number 7 July 2012 Article 075001

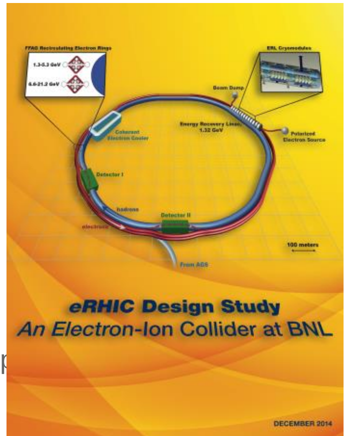
A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing



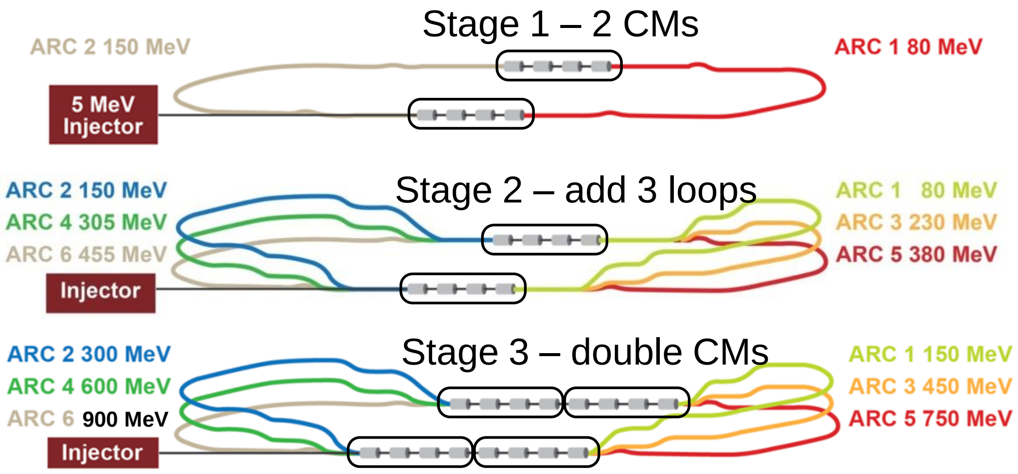
eRHIC Design Study

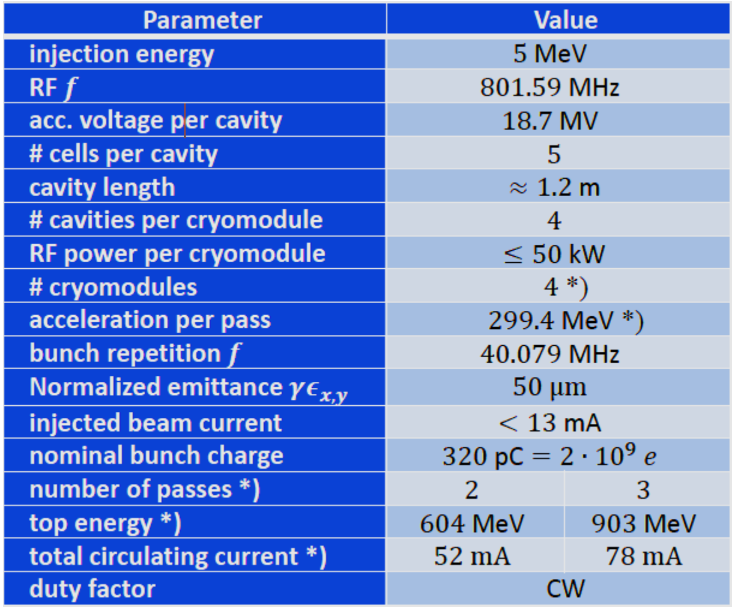
An Electron-Ion Collider at BNL

DECEMBER 2014

BUT SMALLER SCALE TEST FACILITIES NEEDED

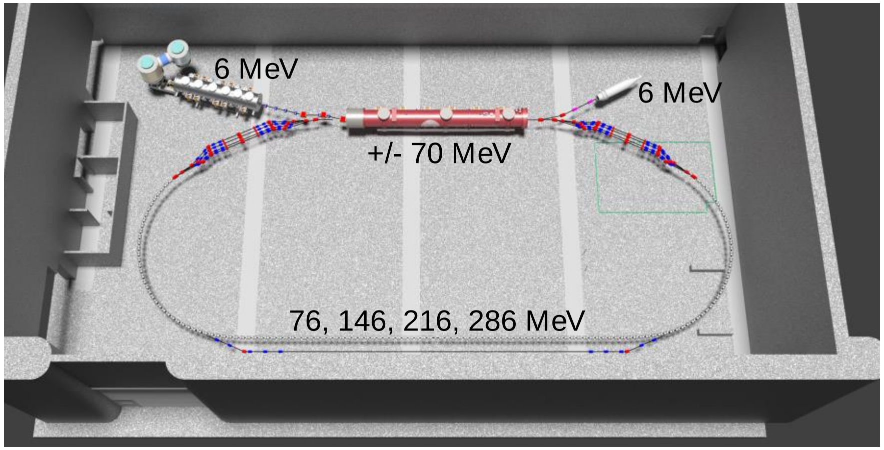
CERN ERL Test Facility (PERLE)





Parameter	Value	
injection energy	5 MeV	
RF f	801.59 MHz	
acc. voltage per cavity	18.7 MV	
# cells per cavity	5	
cavity length	$\approx$ 1.2 m	
# cavities per cryomodule	4	
RF power per cryomodule	$\leq$ 50 kW	
# cryomodules	4 *)	
acceleration per pass	299.4 MeV *)	
bunch repetition f	40.079 MHz	
Normalized emittance $\gamma\epsilon_{x,y}$	50 μm	
injected beam current	< 13 mA	
nominal bunch charge	320 pC = $2 \cdot 10^9$ e	
number of passes *)	2	3
top energy *)	604 MeV	903 MeV
total circulating current *)	52 mA	78 mA
duty factor	CW	

Cornell-BNL FFAG-ERL Test Facility (Cβ)

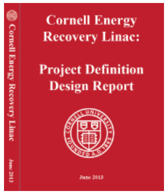


- NS-FFAG arcs, 4 passes (similar to first eRHIC loop)
- Momentum aperture of x4 as for eRHIC
- Uses Cornell DC gun, injector (ICM), dump, 70MeV SRF CW Linac
- Prototyping of essential components of eRHIC design

BIG ERLS FOR LIGHT SOURCES

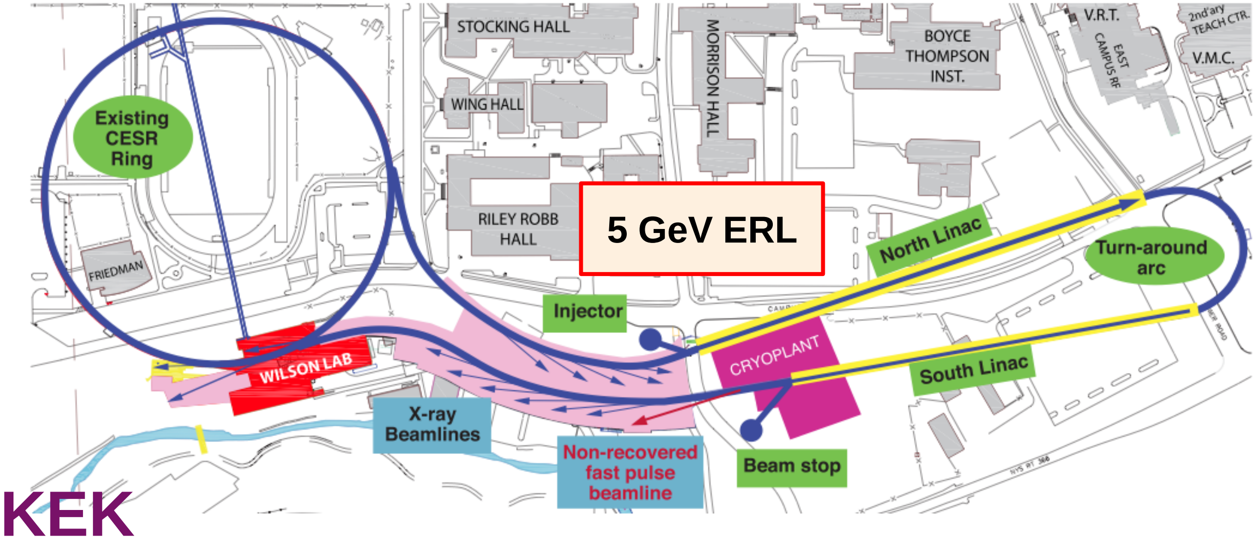
ERL Light Source at Cornell

Norm. emittance	0.1 - 0.5 mm.mrad
Beam current	25 - 100 mA
Bunch charge	19 - 77 pC
RF frequency	1.3 GHz



Cornell Energy Recovery Linac:

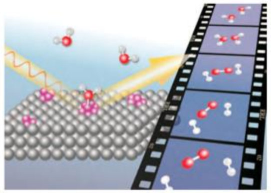
Project Definition Design Report

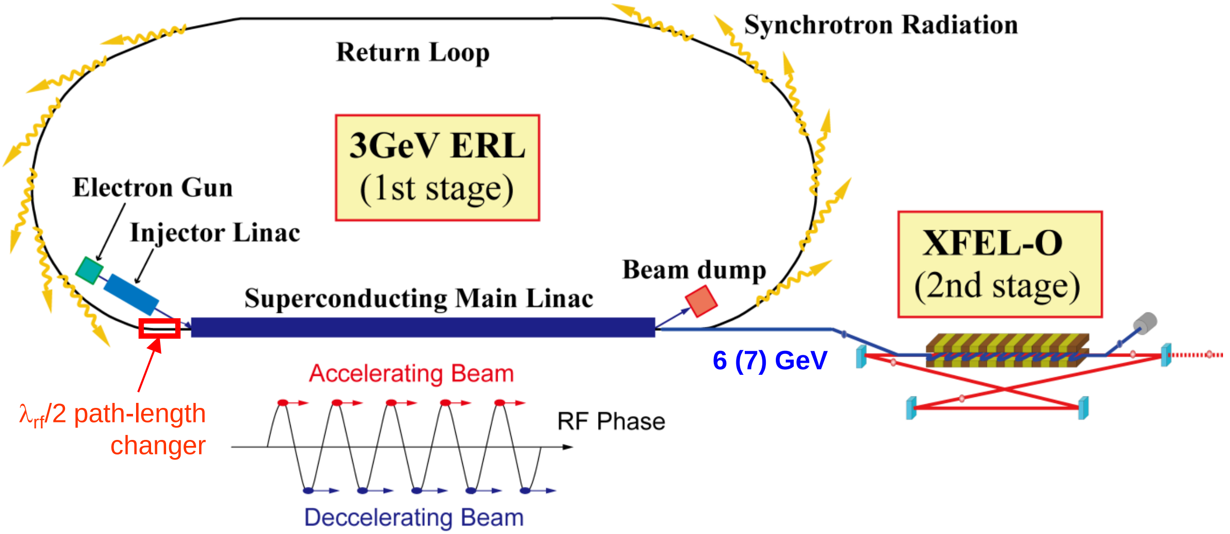


ERL Light Source at KEK

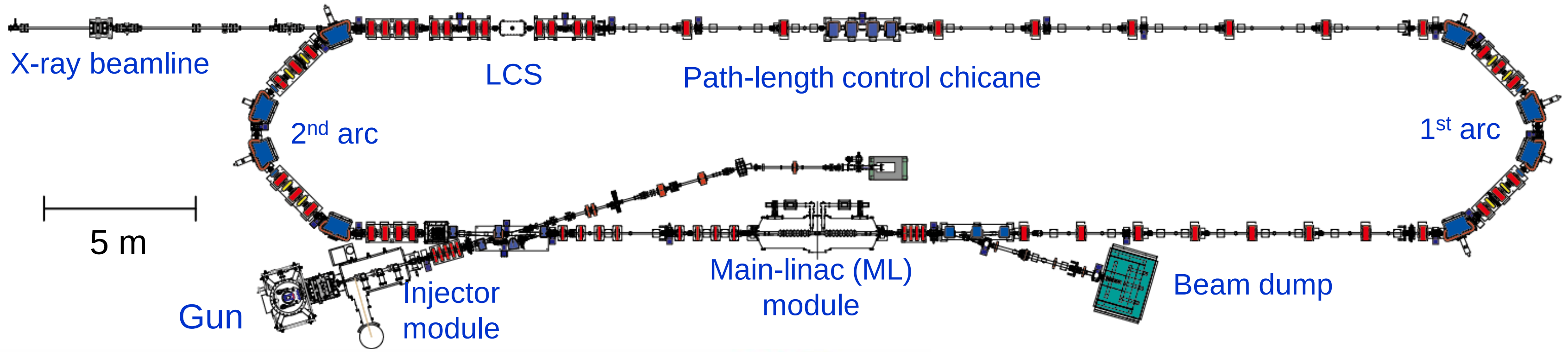
Norm. emittance	0.1 - 1 mm.mrad
Beam current	10 - 100 mA
Bunch charge	7.7 - 77 pC
RF frequency	1.3 GHz

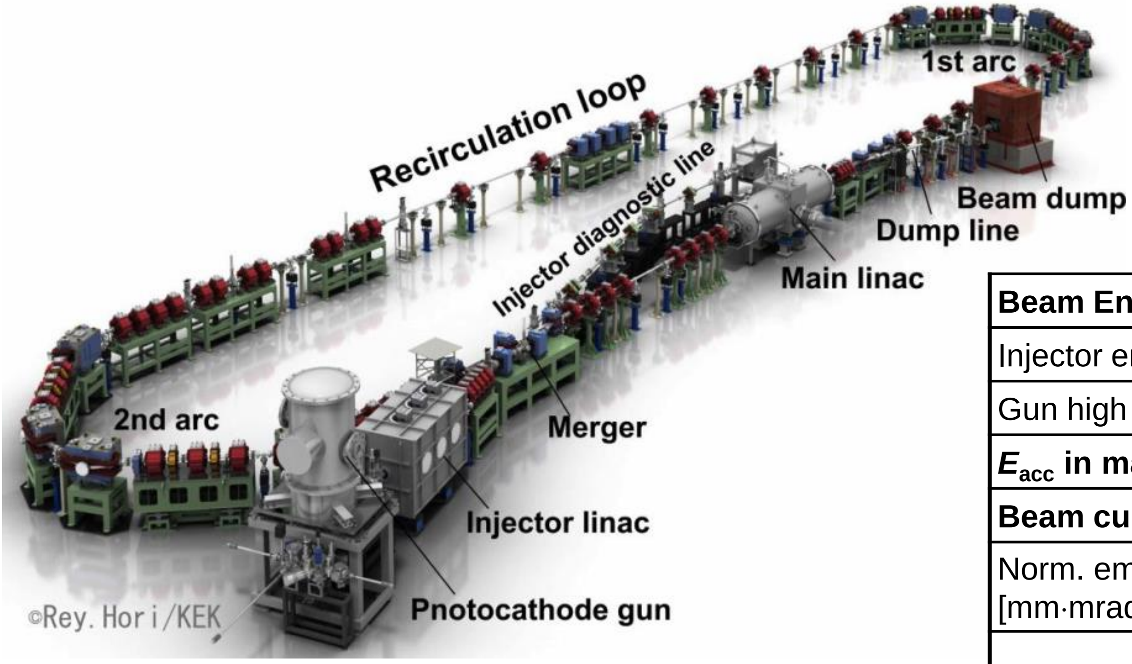
Energy Recovery Linac
Conceptual Design Report





cERL = DEMO FOR KEK 3 GeV ERL





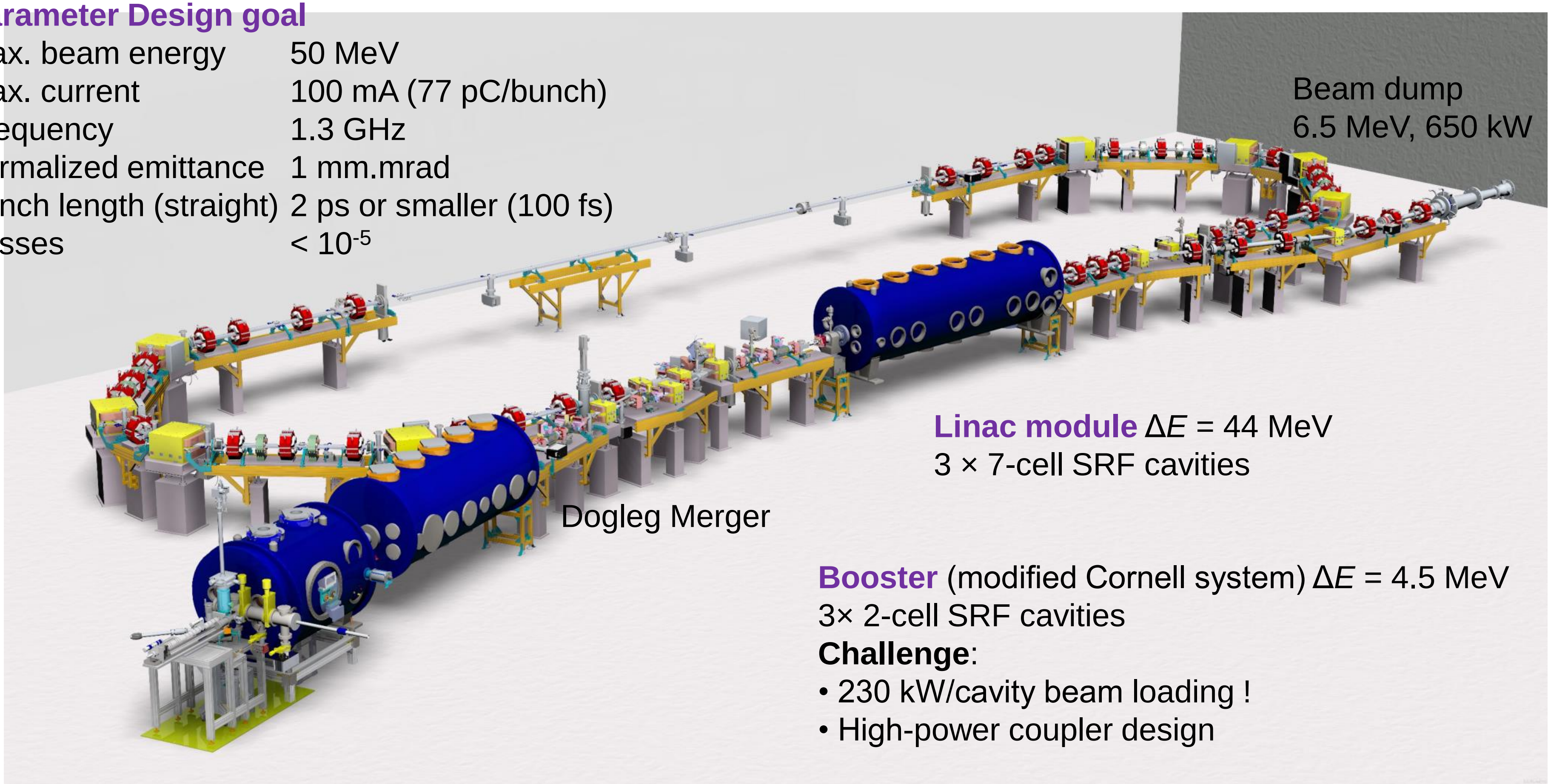
Initial goal
35 MeV 10 mA
1 mm.mrad @7.7pC

	Design	In operation
Beam Energy	35 MeV	20 MeV
Injector energy E_{inj}	5 MeV	2.9 - 6 MeV
Gun high voltage	500 kV	390 kV
E_{acc} in main linac	15 MV/m	8.2 MV/m
Beam current	10 mA	80 μA
Norm. emittance [mm·mrad]	0.1 @7.7 pC 1 @77 pC	???
Bunch frequency	1.3 GHz	1.3 GHz (usual) 162.5 MHz (for LCS)
RMS bunch length	1-3 ps (usual) 100 fs compress.	1-3 ps (usual)
Max. heat load at 2K	80 W	80 - 100 W

in operation since 2013

BERLINPRO

Parameter	**Design goal**
max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
Frequency	1.3 GHz
normalized emittance	1 mm.mrad
bunch length (straight)	2 ps or smaller (100 fs)
Losses	$< 10^{-5}$



Beam dump
6.5 MeV, 650 kW

Linac module $\Delta E = 44$ MeV
3 × 7-cell SRF cavities

Dogleg Merger

Booster (modified Cornell system) $\Delta E = 4.5$ MeV
3× 2-cell SRF cavities

Challenge:

- 230 kW/cavity beam loading !
- High-power coupler design

SRF photoinjector, with SC solenoid, 1.5 – 2.3 MeV

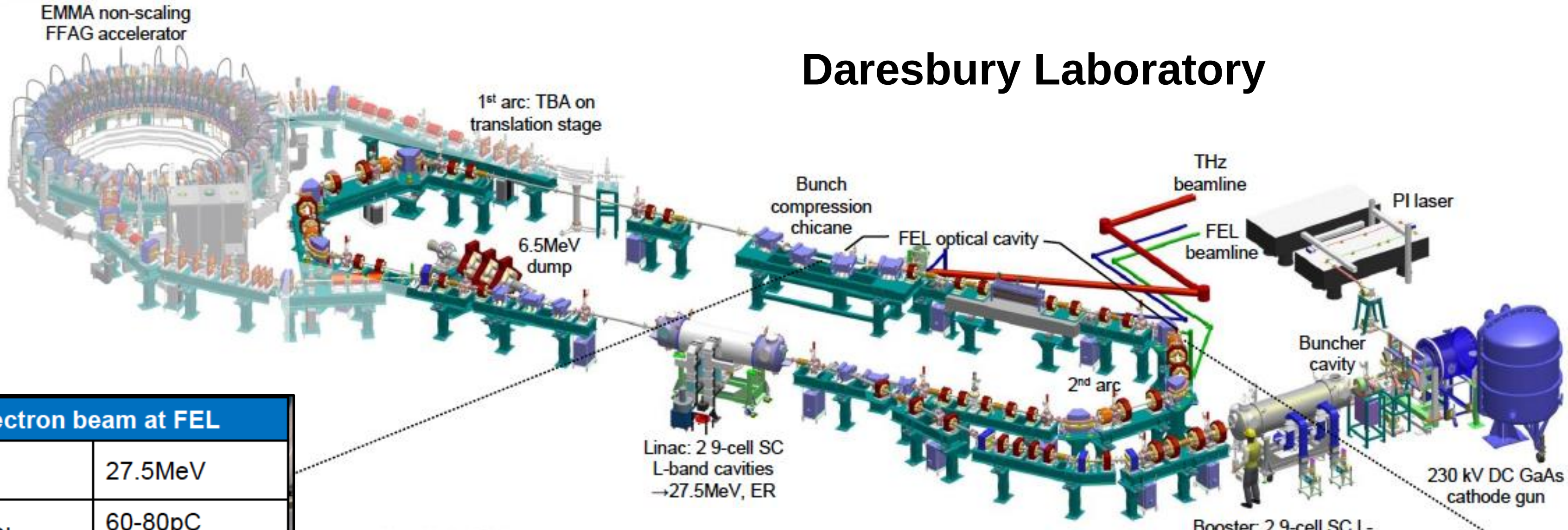
Challenge:

- 30 MV/m CW operation with CsK$_2$Sb cathode
- Cathode performance @ 100 mA
- Dark current/halo control
- Emittance compensation

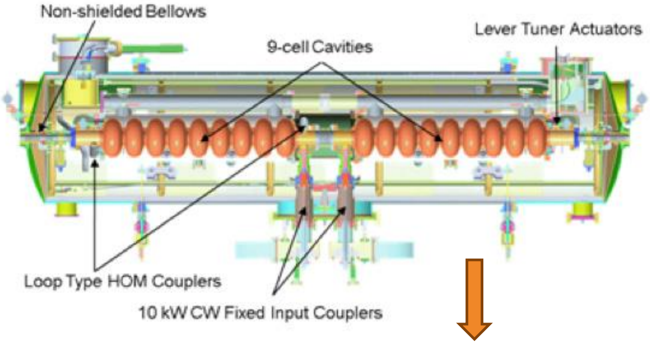
HZB (Helmholtz Zentrum Berlin)

ALICE ERL FEL

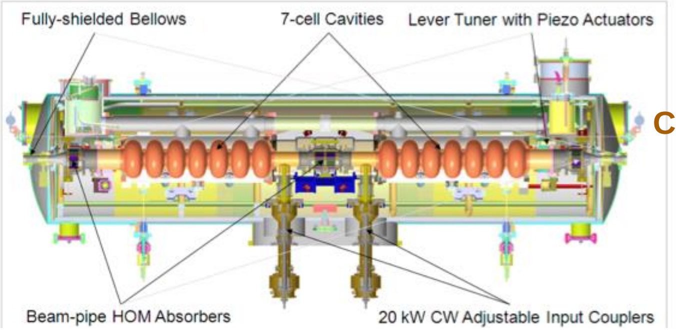
Daresbury Laboratory



Electron beam at FEL	
Energy	27.5MeV
Bunch Charge	60-80pC (@16.25MHz)
FWHM Bunch Length	~1ps
Normalised Emittance	~12 mm-mrad
Energy Spread	~0.5% rms
Repetition Rate	81.25MHz/ 16.25MHz
Macropulse Duration	≤100μs
Macropulse Rep. Rate	10Hz



Existing Cryomodule on ALICE



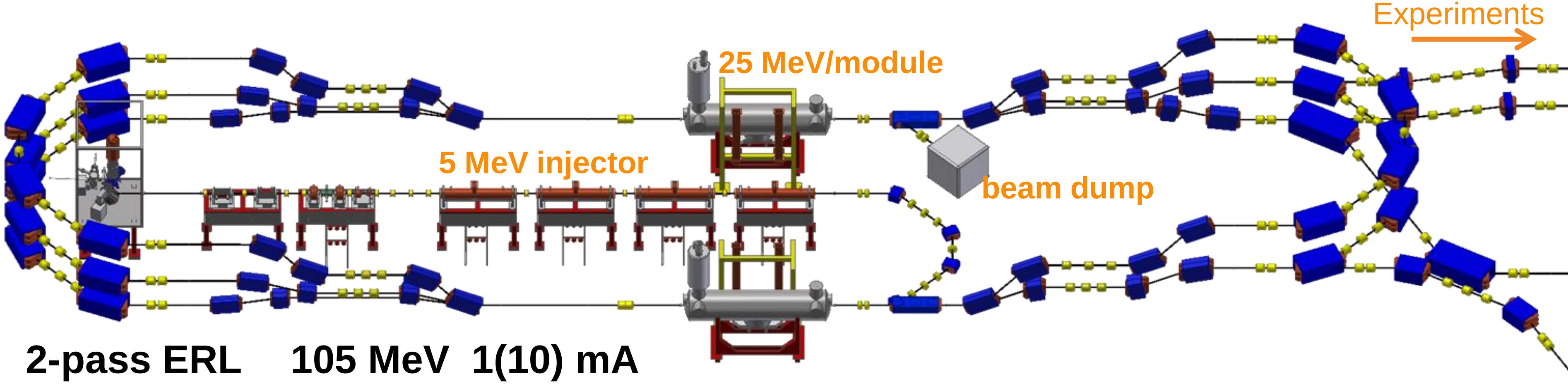
CW-ERL Cryomodule

Achieved ALICE FEL output parameters, in-vacuum immediately behind the downstream mirror:

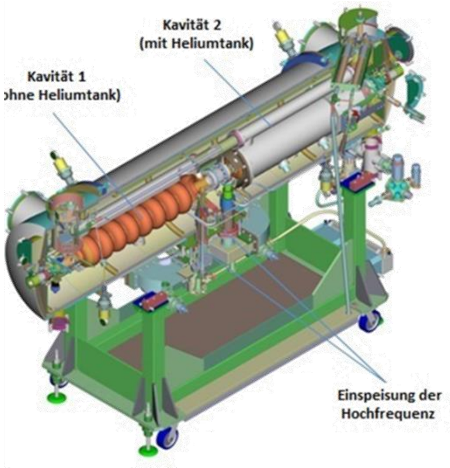
Parameter	Notation	Value
Wavelength	λ_r	5.0–8.0 μm
FWHM Bandwidth	$\Delta\lambda/\lambda$	0.9–1.8 %
Pulse Energy	E_{pulse}	$\leq$ 3.3 μJ
Peak Power	P_{peak}	$\leq$ 3.6 MW
Average Power	P_{avg}	$\leq$ 45 mW
Average Power (within macropulse)	$P_{\text{avg,pulse}}$	$\leq$ 53 W

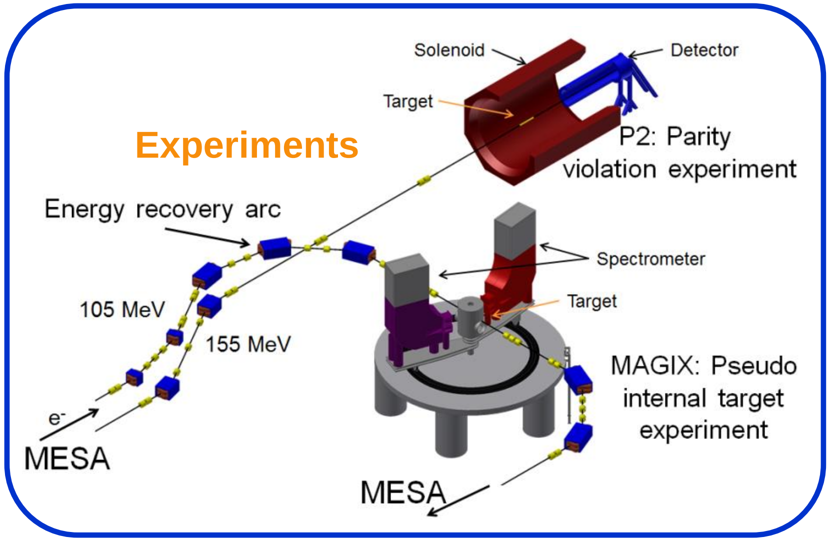
MESA FOR NUCLEAR PHYSICS (MAINZ UNIV)

D. Simon, IPAC15



2-pass ERL	**105 MeV**	**1(10) mA**
3-pass Linac	**155 MeV**	**150 µA**





2 x ELBE Rossendorf Modules
with some modifications

RELEVANT PROJECTS BASED ON CW SC LINACS

		Energy (MeV)	Rep Rate (MHz)	<Ib> (mA)	# Cryom x Cav x Cells	Freq (GHz)	Eacc (MV/m)
LINACs	LUNEX5 CW	400	0.010 - 1	0.100	3 x 8 x 9	1.3	17
	XFEL CW option	7,800	0.25	0.125	17 x 8 x 9 96 x 8 x 9	1.3	16 7.3
	LCLS-II	4,000	> 0.6	0.030	35 x 8 x 9	1.3	16
	NGLS	2,400	1	0.300	24 x 8 x 9	1.3	14
ERLs	Jlab ERL	135	75	10	3 x 8 x 5	1.5	12
	ALICE (Dares)	35	81.25	6.5	1 x 2 x 7	1.3	
	cERL (KEK)	35	1300	10-ini	1 x 2 x 9	1.3	15
	bERLinPRO	50	1300	100	1 x 3 x 7	1.3	18
	LHeC demo stage 1	150	40.1	13	4 x 4 x 5	0.802	20
	Cornell ERL	5,000	1.3	100	64 x 6 x 7	1.3	16.2

High rep rate FEL projects rely on TESLA Technology
Developed in the 90s' inherited low duty cycle from HE linear colliders designs

CW SRF Linacs Challenges

HIGH DUTY CYCLE & CW OPERATION ISSUES

❑ SRF cavities

- CW operation at high fields with low cryogenic losses ⇒ high Q_0
- Reliable operation with very low trip-rate
- Very low microphonics levels → optimized mechanical cavity design

❑ RF power system and control

- Low cost, low CW RF power input couplers
- Low cost RF power sources → High efficiency IOTs & Solid-State RF amplifiers

❑ Cryostat and Refrigeration

- Cryogenic system for high cryo-loads
- Cryostat design for excellent magnetic shielding (to preserve high Q_0)

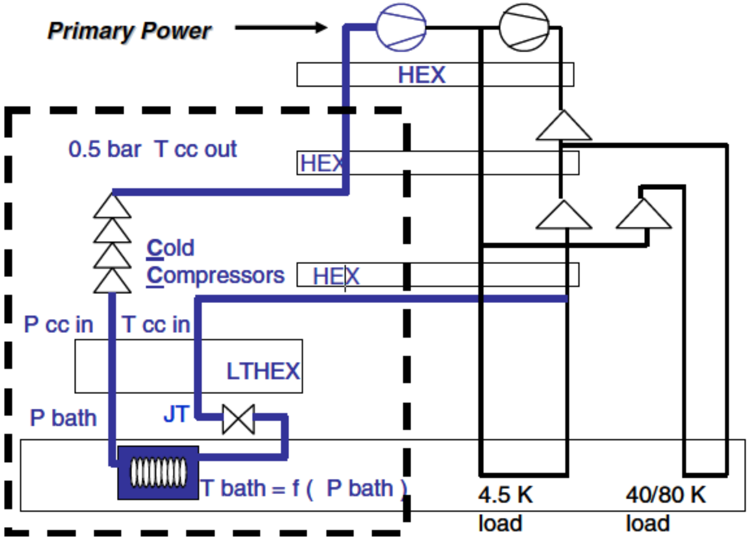
CRYOGENIC ISSUES - REFRIGERATION

- Because the resistive power dissipated in the SRF cavities is absorbed by the refrigeration system at 2K (1.8K), high duty cycle or CW operation makes the refrigeration system a major utility component

Total dissipated power for a given final energy $P_d = \frac{\Delta E}{r/Q} \times \frac{E_{acc}}{Q_0} \times d.c.$

This favors relatively low gradient E_{acc} and high Q_0

JLab CEBAF 12 GeV Upgrade 4.5K cold-box



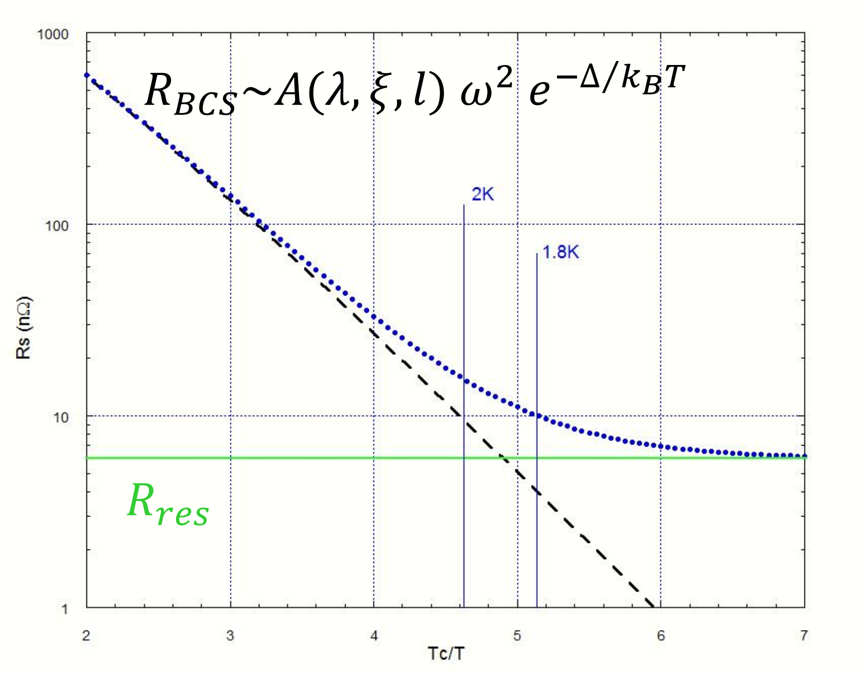
simplified flow scheme of a He refrigerator including a helium II cooling loop

TOWARDS HIGH Q0 – OPERATING TEMPERATURE

Cryogenic losses strongly depend on temperature below Tc

Optimum operating Temp ultimately set by residual resistance

Surface resistance $R_s = R_{BCS} + R_{res}$ depends on surface preparation conditions



- with cavities dominated by BCS resistance, lower Temp of the He bath is favored
- Dynamic cryogenic load reduced by a factor of ~2 if the temperature is lowered by 0.2°

2K → 1.8K

Note: high quality magnetic shielding is required to prevent Q_0 spoiling due to flux trapping during cooldown → additional residual resistance ~0.35 nΩ/mG (earth's magnetic field ~500 mG)

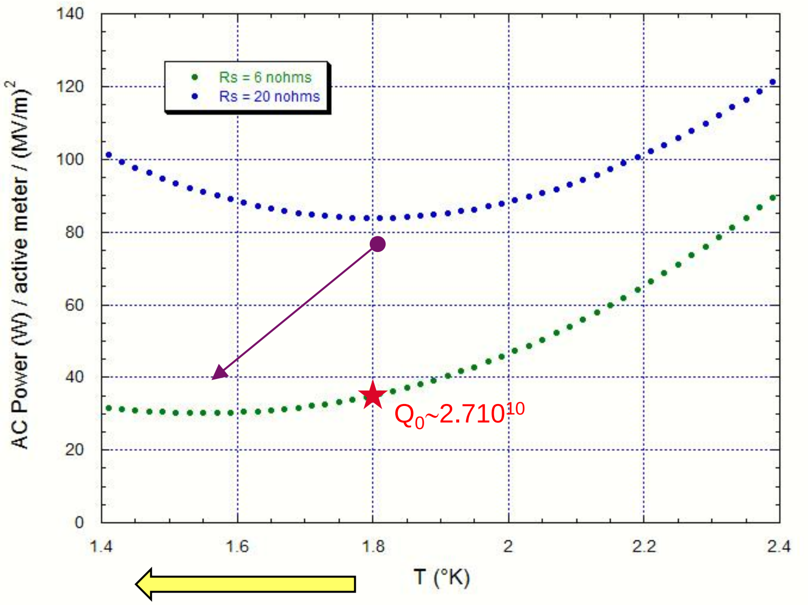
OPERATING T OPTIMIZATION - CRYOPLANT

Coefficient of Performance (COP) used to describe the cryogenic plant efficiency

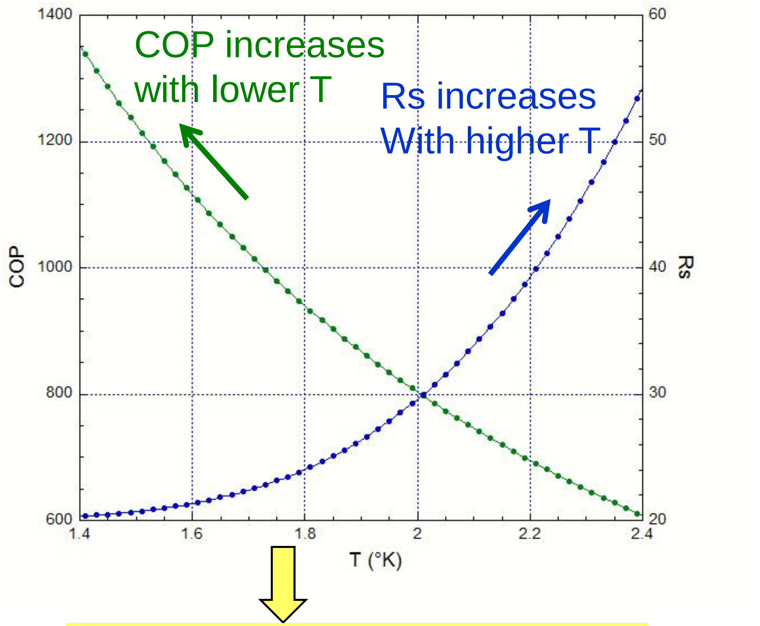
$$\eta = \frac{1}{COP} = \eta_{Carnot} \times \underset{\downarrow}{k(P,T)} = \frac{T}{T_{amb} - T}\, k(P,T)$$

Technical efficiency of refrigerator ~20% @2K
(pure isentropic Carnot cycle cannot be achieved)

Normalized primary power consumption



Note: lower T might cause instability in the cryo-system



Optimum operating Temp

- with cavities dominated by BCS resistance, lower Temp

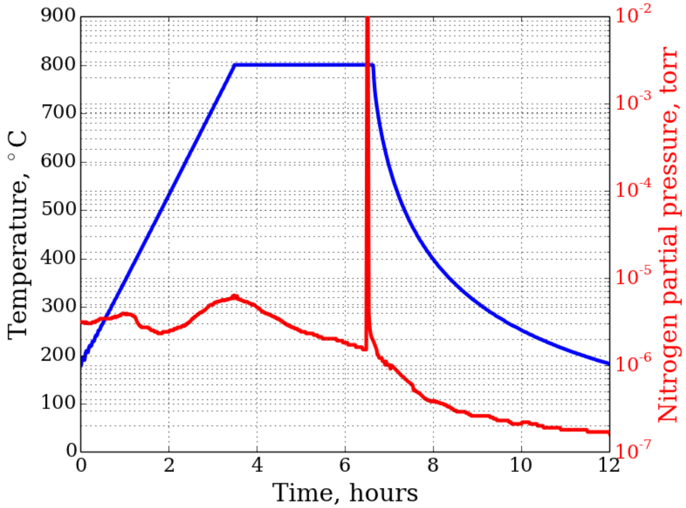
2K → 1.8K

- Another cold compressor stage required

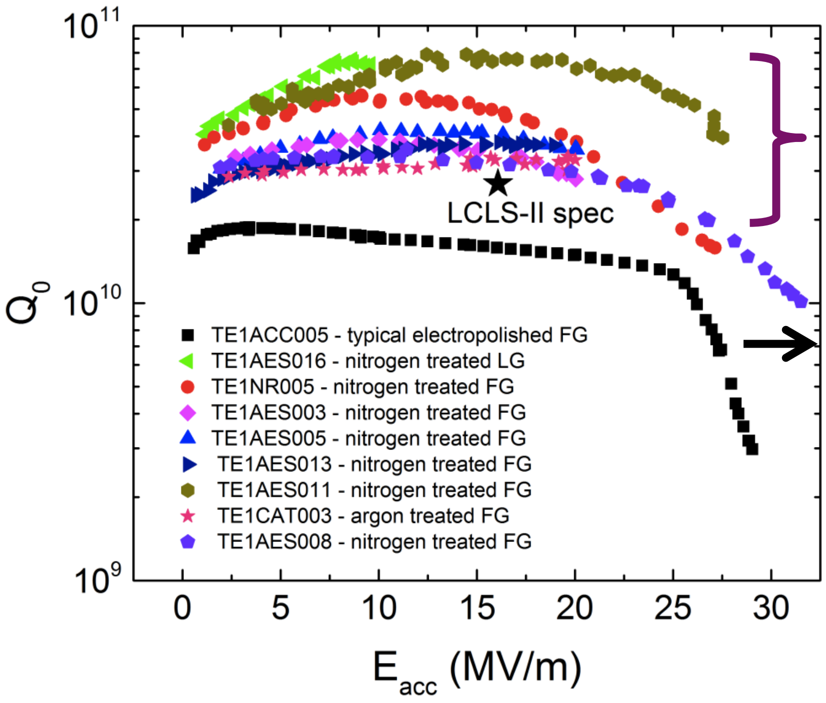
TOWARDS HIGH Q0 – NITROGEN DOPING

N-doping can drastically lower BCS losses: **Q_0 improvement up to a factor to 2-3**

A. Grassellino et al, 2013 Supercond. Sci. Technol. 26 102001



Injection of small nitrogen partial pressure at the end of 800°C degassing followed by several μms of chemistry (EP)



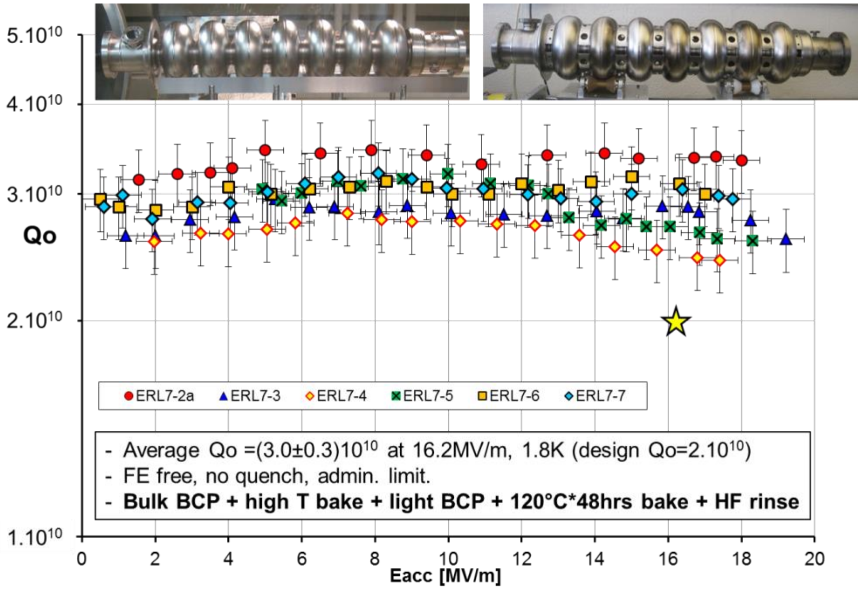
N-doping
Mean = 4.3 10^{10}
at 16 MV/m

Standard EP
+ 120C baking

Possible explanation (A. Romanenko): assuming that hydrides may be the cause of the medium and high field Q slopes, nitrogen doping may fully trap hydrogen and prevent from hydride formation

HIGH Q0 – SHIELDING & THERMAL CYCLE

Vertical Test results at 1.8K

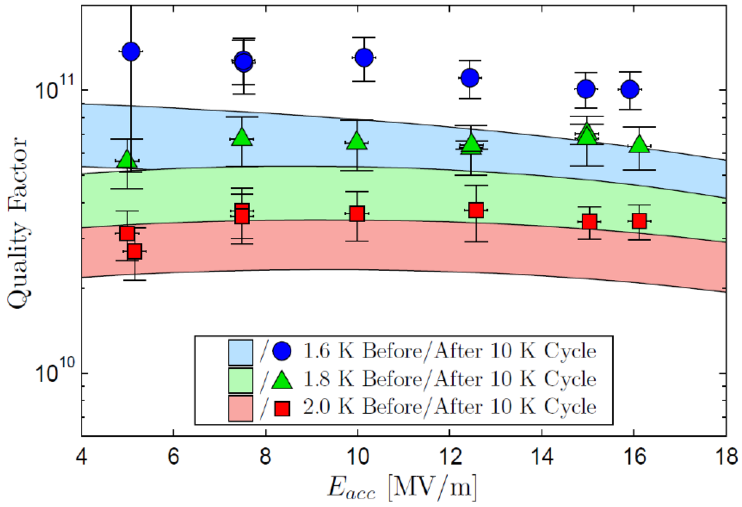


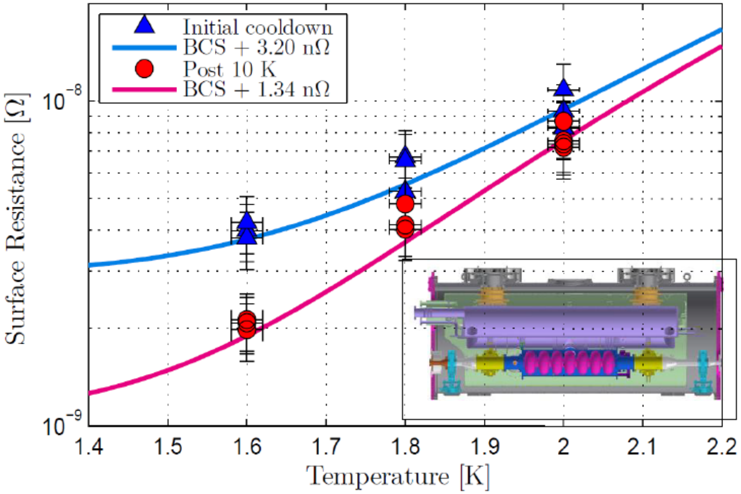
- Average Qo =(3.0±0.3)10^{10} at 16.2MV/m, 1.8K (design Qo=2.10^{10})
- FE free, no quench, admin. limit.
- **Bulk BCP + high T bake + light BCP + 120°C*48hrs bake + HF rinse**

- ➢ Better shielding in Horizontal CM
- ➢ Thermal cycle to above Tc

  Effective to reduce cavity T gradient (~0.2K) suppress flux trapping induced by thermocurrent (1.8K) Qo = 3.5 x 10^{10} ⇒ Qo = 6.0 x 10^{10}

Horizontal Test results





Additional ERL Challenges

ADDITIONAL ERL RELATED ISSUES

❑ SRF cavities

- Very low microphonics levels → optimized mechanical cavity design
- Design optimized for strong HOM damping (no trapped HOM)

❑ Higher Order Mode dampers

- Strong damping of HOMs and efficient HOM power extraction for high beam currents

❑ RF power system and control

- ~ 10 kW CW RF power
- Efficient cavity field stabilization at highest loaded Q for energy stability

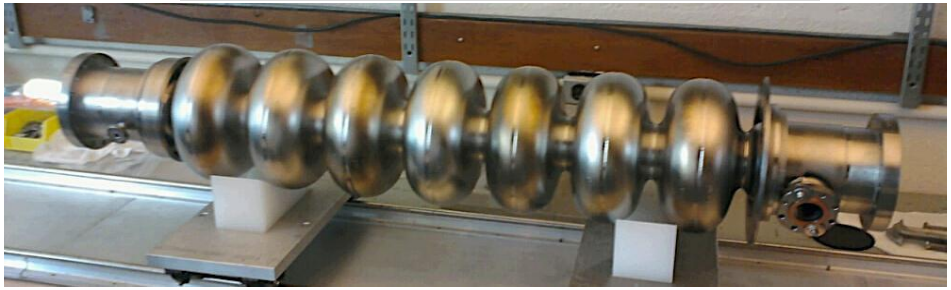
❑ Cryostat & cryoplant

- CW operation, high cryogenic load

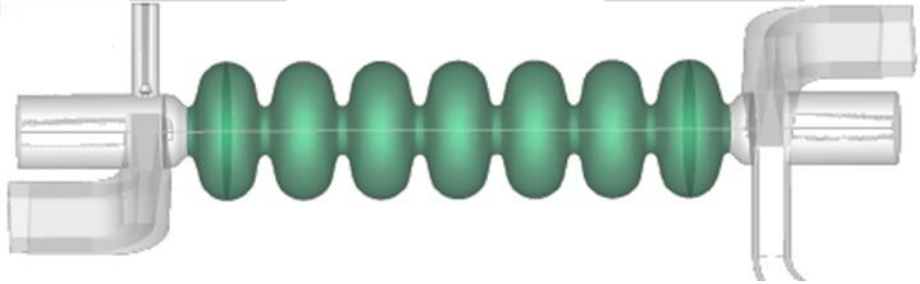
SOME ERL CAVITIES

KEK 9-cell, 1.3 GHz

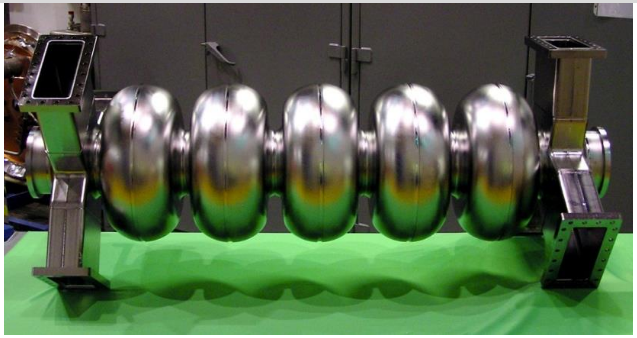
Cornell 7-cell, 1.3 GHz



bERLinPRO 7-cell, 1.3 GHz

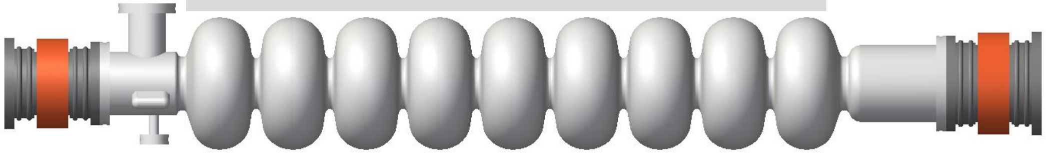


JLAB 5-cell, 748.5 MHz



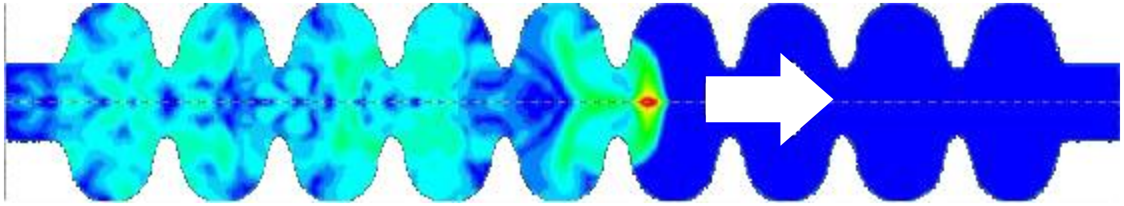
BNL 5-cell, 703 MHz

cERL 9-cell, 1.3 GHz



HOM POWER

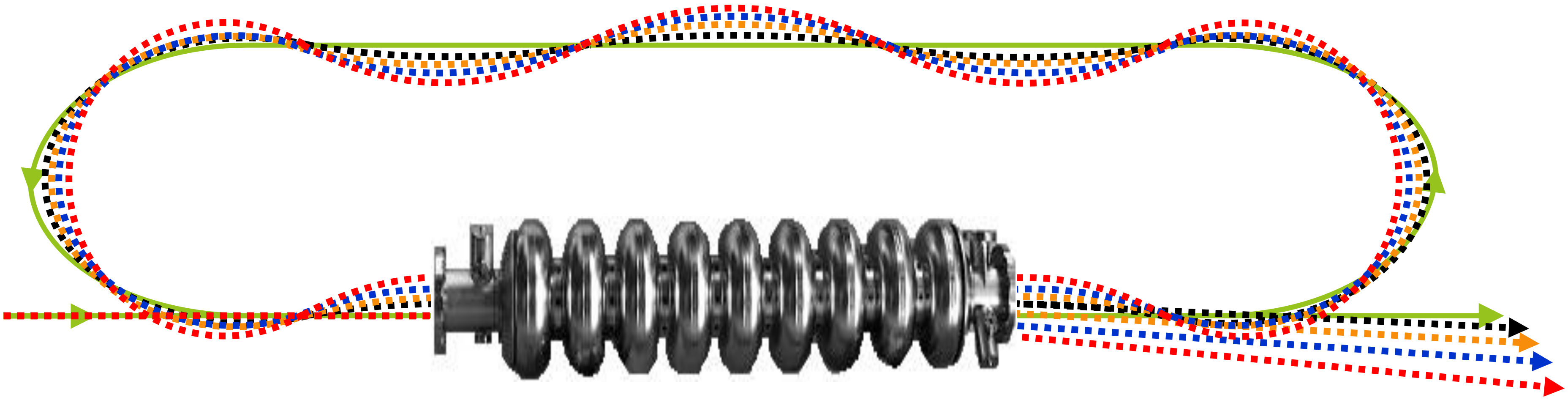
HOM power built up in a CW machine (monopole modes)



- ☐ **Non-resonant excitation** $P = k_{loss}\, Q_b\, I_0$
  - *TESLA cavity* ***P* =260 W** for 77 pC and 2x100 mA (0.5 W for XFEL)
- ☐ **Resonant excitation** $P = (R/Q)_\lambda\, Q_\lambda\, {I_0}^2$
  HOM frequency close to beam spectrum line
  - *TESLA cavity* ***P*** **≥ 1 kW** for $Q_\lambda=10^4$ and 2x100 mA
  - 2 ps long bunches excite HOMs to ~100 GHz
- ☐ **HOM power has to be extracted (not deposited at 2K !)**
  - HOM couplers or absorbers for propagating modes
    (20% to 40% of cavity cost)

MULTI-PASS BEAM BREAK UP

Multi-pass BBU caused by Higher Order Modes field in cavities
= one of the main limitations to the beam current of ERL



- HOMs start orbit oscillations→ the returning beam then has an offset that adds energy to the HOM (feedback >0) => exponential oscillation growth
- Current threshold for a single HOM in a single cavity

$$I_{th} = -\frac{p_z c/e}{(R_\perp/Q)_\lambda\, Q_\lambda\, M_{12}\, \sin(\omega_\lambda T_r)}$$

$$R_\perp = \frac{1}{2kP}\left|\int \nabla_\perp E_z\, e^{ikz}\, dz\right|^2 \quad (\Omega/m)$$

$$M_{12} = T_{12}\cos\theta + \frac{1}{2}(T_{14}+T_{23})\sin 2\theta + T_{34}\sin^2\theta$$

$$\theta = HOM\ polarization\ angle$$

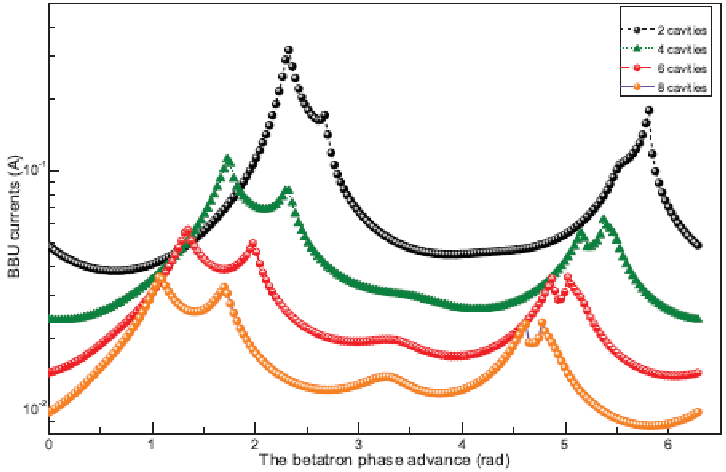
HOM coupler to damp
the added energy
$Q_\lambda < 10^4$ typically needed

Reflection or rotation section
to interchange the H and V planes betatron motion

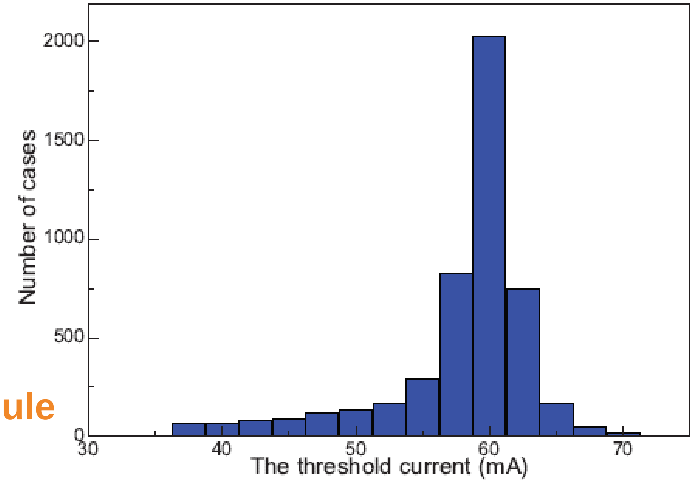
BBU WITH MULTIPLE CAVITIES

With multiple cavities and beam optics manipulation, BBU current estimate from numerical simulations

S. Chen et al, "Multi-pass, Multi-bunch Beam Break-Up of ERLs with 9-cell Tesla Cavities", IPAC2013

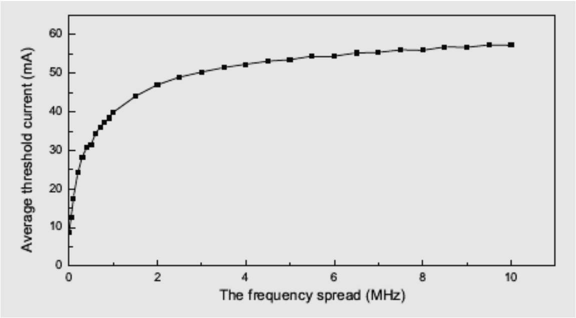


1 XFEL cryomodule



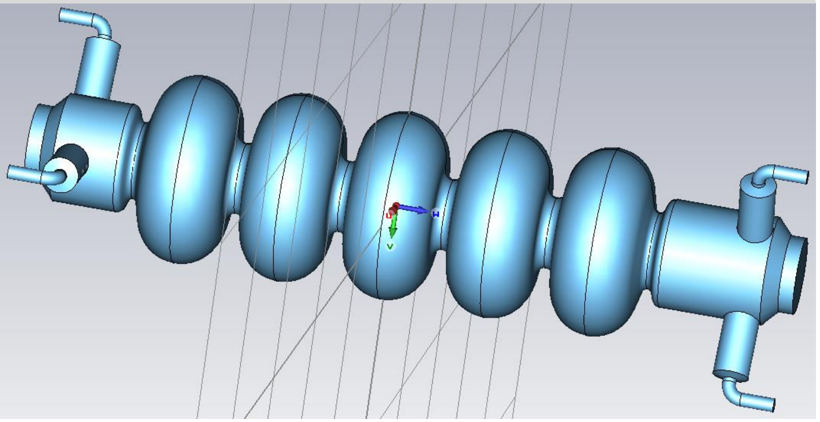
BBU current vs. betatron phase advance of recirculating loop for different cavity numbers
BBU current ↘ when number of cavities ↗

BBU current distribution with a spread in HOM frequencies (σ = 10 MHz)
BBU current ↗ with frequency spread
But reaches its limit at $\sigma \sim 5$ MHz

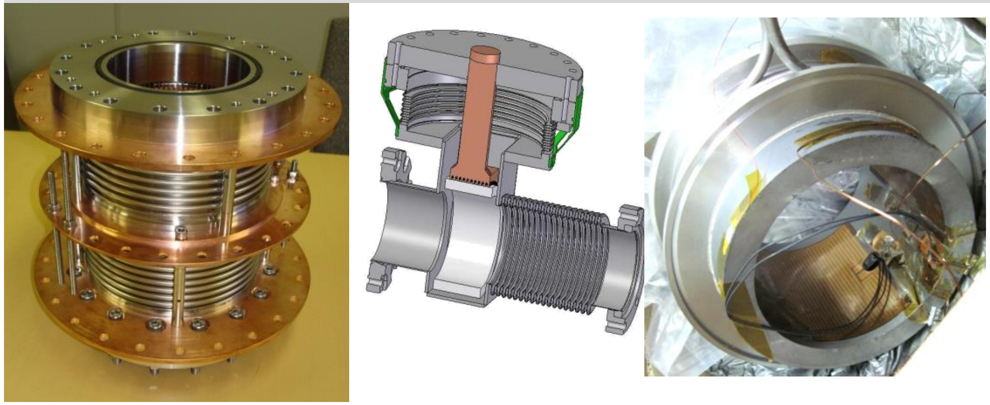


SOME HOM DAMPERS

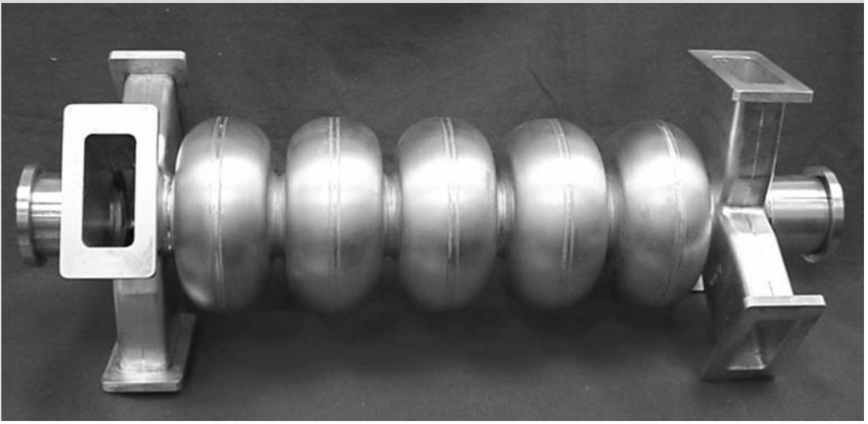
BNL 5-cell: antenna



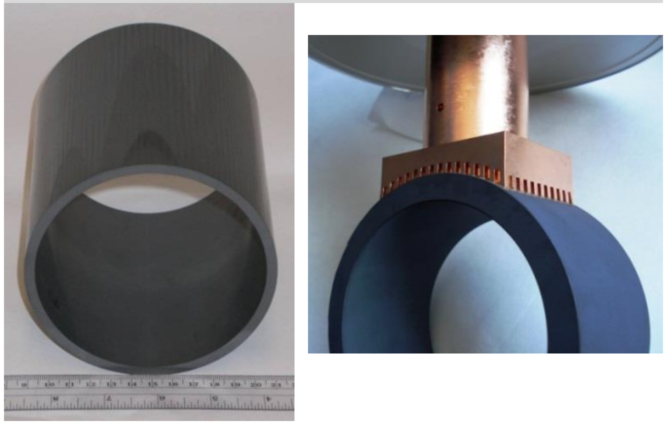
KEK, Cornell, DESY: beamline absorbers



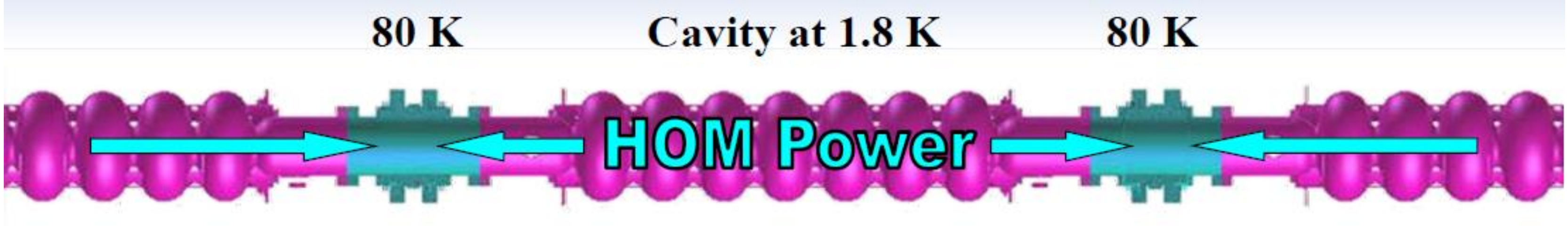
JLAB 5-cell: waveguides



RF absorber Rings

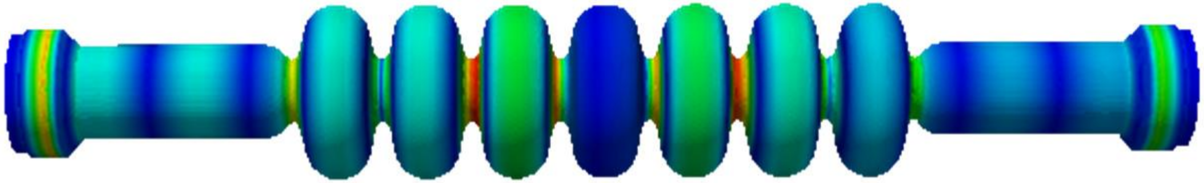


CORNELL'S ERL MAIN LINAC CAVITY 1.3 GHZ



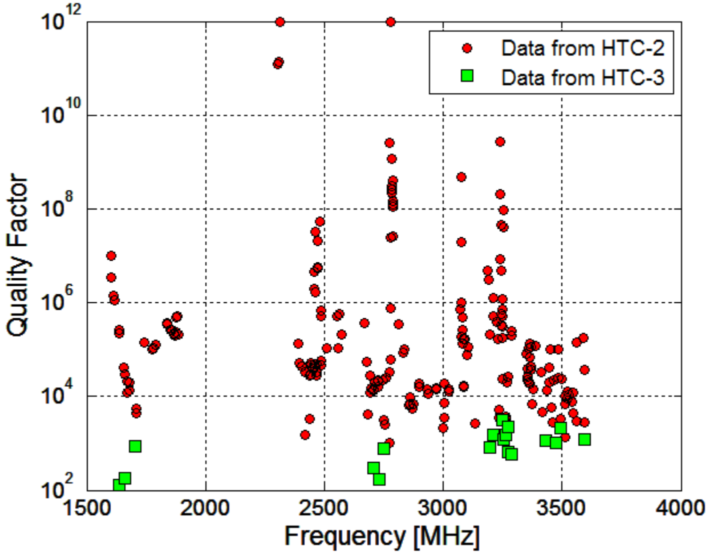
cavity shape optimized with ~ 20 free parameters

HOM damping calculated up to 10 GHz with realistic RF absorbers

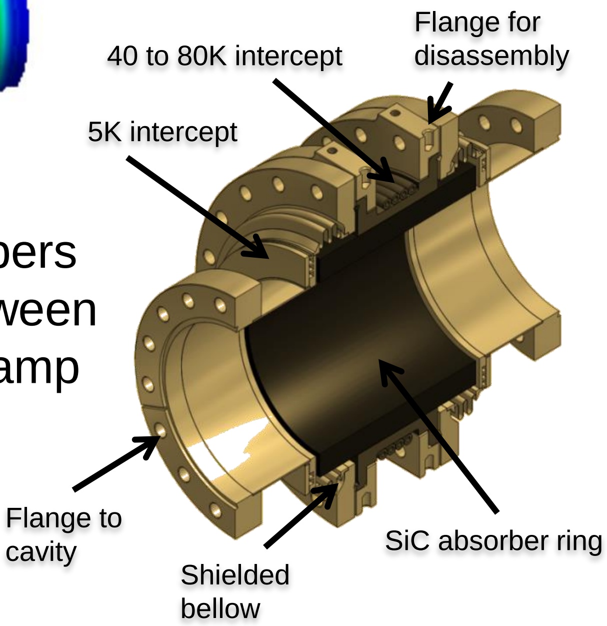


HTC-2: No HOM Absorbers

HTC-3: With HOM Absorbers



Beamline HOM absorbers in the beam pipes between the cavities strongly damp dipole HOMs $Q < 10^4$



Georg Hoffstaetter
TTC meeting, March 2014
Matthias Liepe
ICFA Workshop HOM Diagnostics & suppression in SC cavities

RF POWER REQUIREMENT - MICROPHONICS

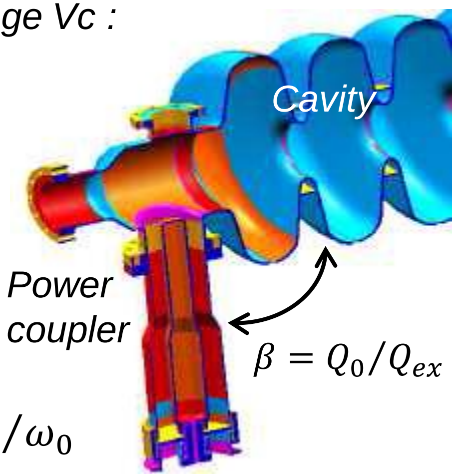
Ideally in an ERL: recirculated beam decelerated at an RF phase shifted by π relative to the accelerated beam
$\Rightarrow$ Net beam loading is zero. Required RF power to maintain a given accelerating voltage Vc :

$$P_{RF} = \frac{{V_c}^2}{R/Q\;Q_0}\,\frac{(\beta+1)^2}{4\,\beta}\left[1+\left(2\,\frac{\delta\omega}{\omega}\,\frac{Q_0}{1+\beta}\right)^2\right]$$

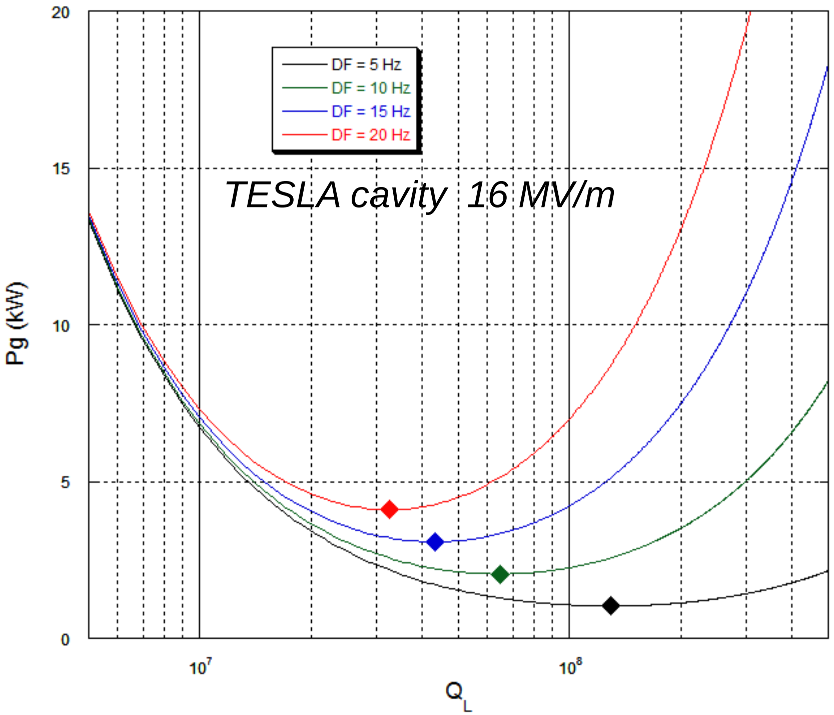
cavity wall dissipation

cavity coupling

detuning (microphonics)



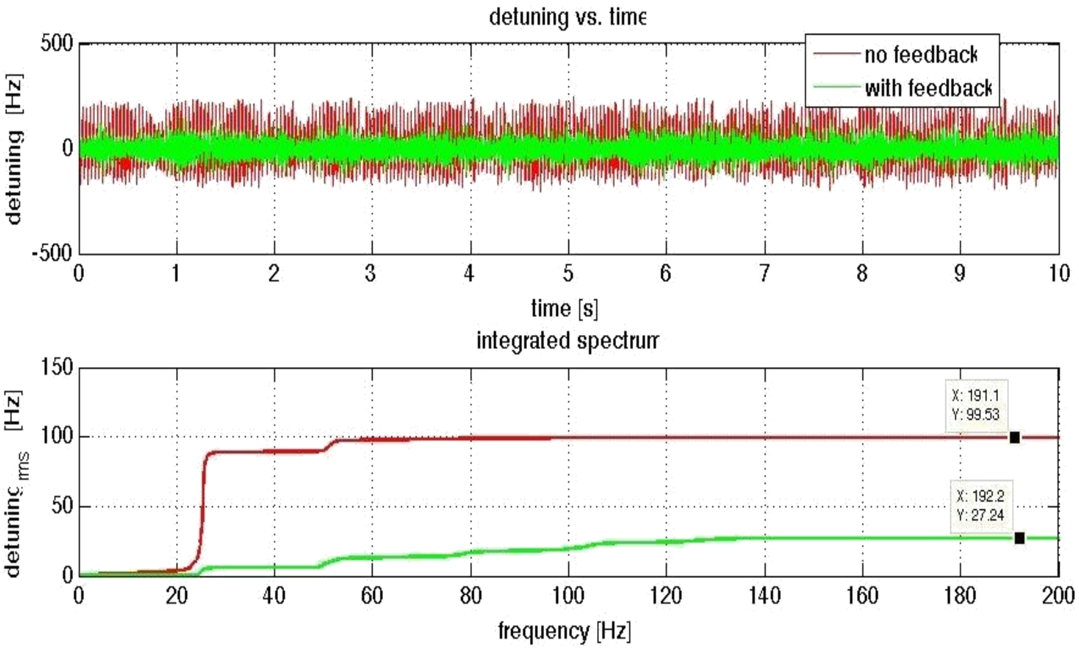
- Optimal coupling $\beta^2 = 1 + (2Q_0\,\delta\omega/\omega)^2$
- Gives minimal power $P_{RF} = P_d \times \frac{1}{2}\left(1+\sqrt{1+(2Q_0\,\delta\omega/\omega_0)^2}\right) \approx P_d\,Q_0\;\delta\omega/\omega_0$

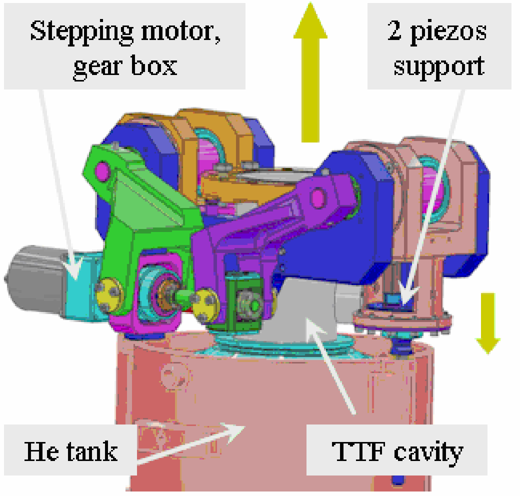


- ➢ ERL → No effective beam loading so could operate at $Q_L \sim 1\text{x}10^8$
- ➢ Microphonics as low as possible → mechanical design (dF/dP sensitivity)
- ➢ Level of microphonics should be properly predicted to optimize the coupling
- ➢ any beam return time error results in an effective beam current $I_{eff} \approx -i\,I_{acc}\,\delta\phi$ → increase of the required RF power

ACTIVE MICROPHONICS COMPENSATION

- Tests on Cornell injector module showed an rms detuning reduction of a factor 3-4 by active microphonics control
- efficiency limited by transverse mechanical modes (tuner action in axial direction)

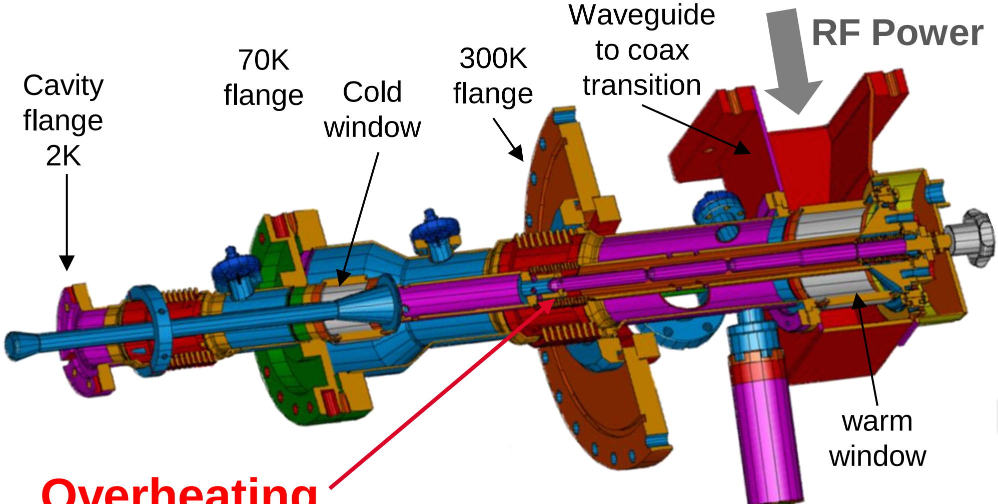




Saclay tuner equipped with fast piezo stacks

CW POWER COUPLER

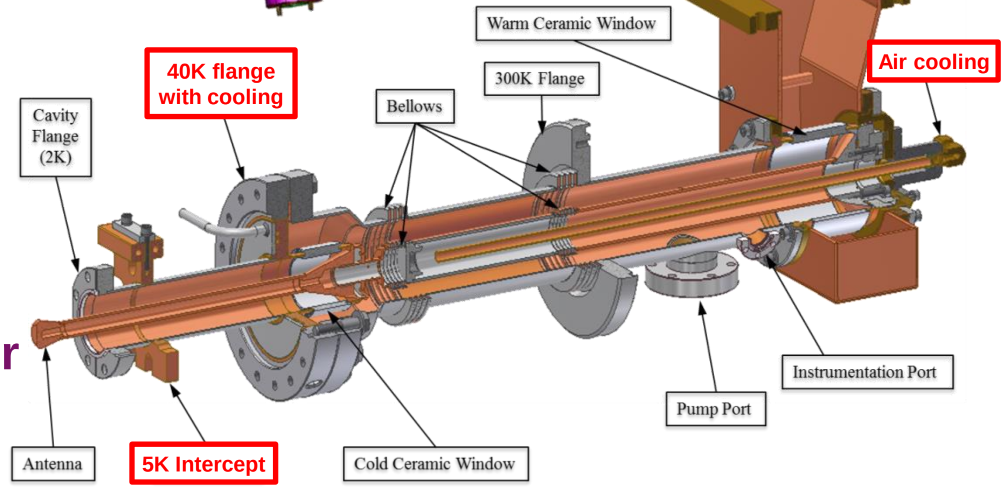
XFEL short pulses
high peak power, low average power



XFEL coupler
(TTF3 design)

Overheating
in center conductor

high duty cycle / CW FELs
low peak power, high average power

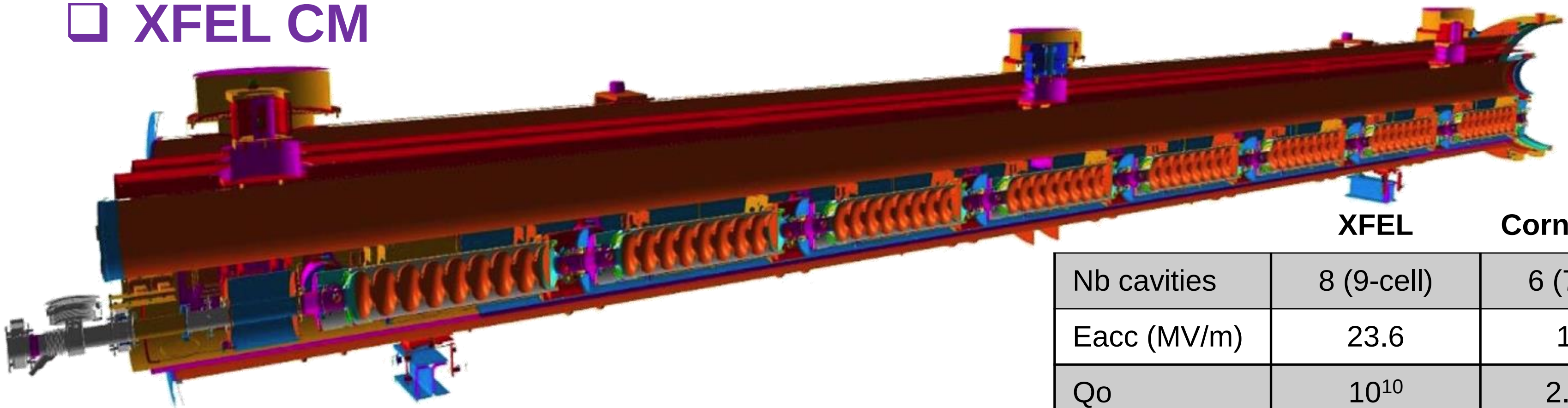


Ex. Cornell ERL design
(main Linac)

CRYOMODULE DESIGN

Most of the projects based on TESLA (XFEL) module designed for short pulses and convert it to CW

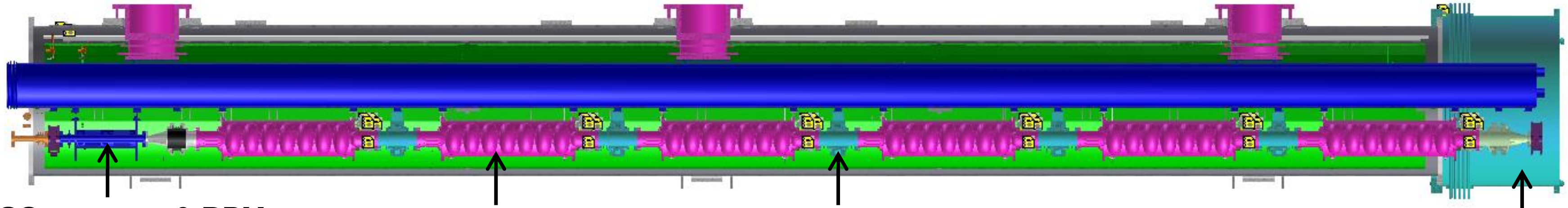
❑ XFEL CM



All components suspended from the He Gas Return Pipe supported by 3 support posts

	XFEL	Cornell ERL
Nb cavities	8 (9-cell)	6 (7-cell)
Eacc (MV/m)	23.6	16.2
Qo	10^{10}	2.10^{10}
rf duty cycle	1.4%	100%
Temperature	2K	1.8K
Coupling Qex	$4.6\ 10^{6}$	$6.5\ 10^{7}$

❑ Cornell ERL main linac CM



SC magnets & BPMs

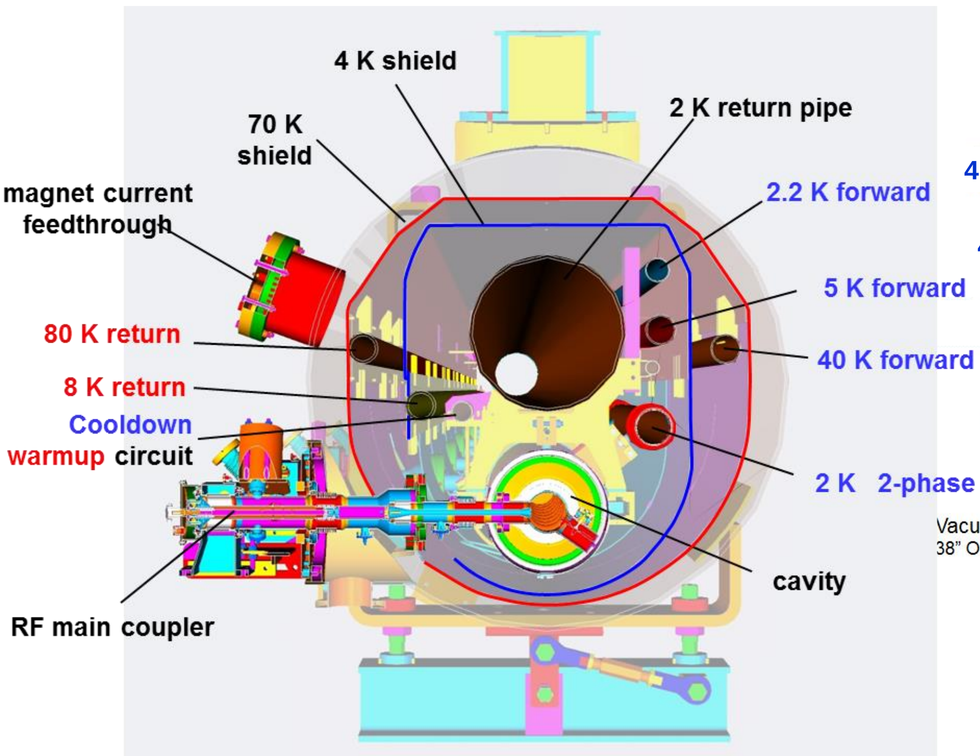
7-cell cavity

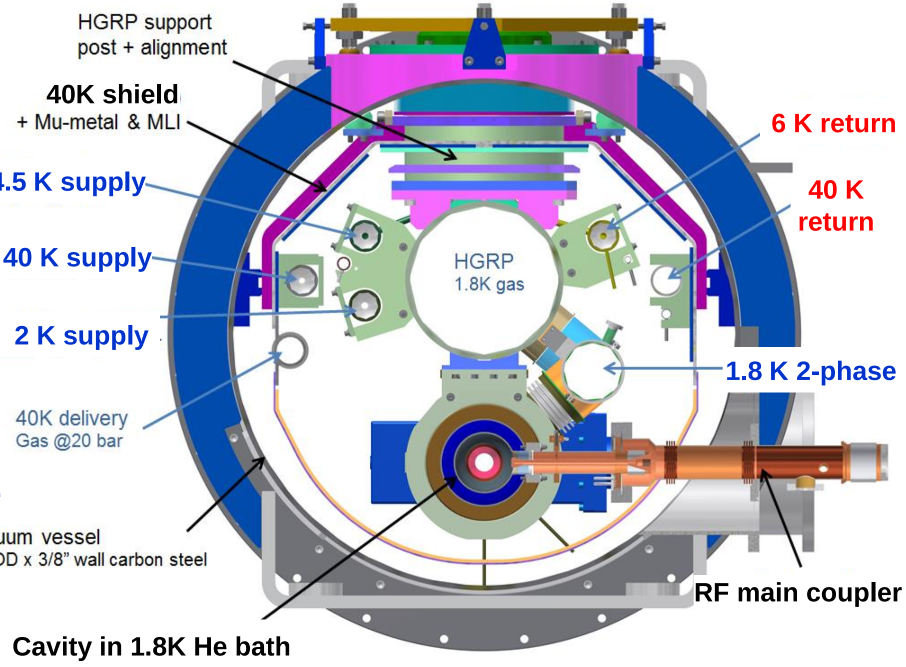
Beamline HOM absorber

Intermodule unit

nominal length: 9.8 m

XFEL / CORNELL ERL CRYOSTATS





- **Design for up to ~ 80 W per cryomodule at 1.8 K**

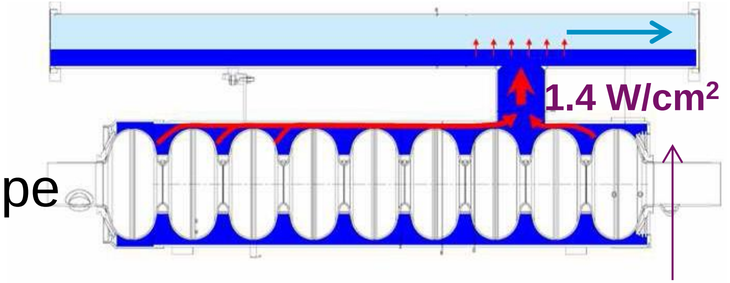
- **Design for up to 20 W per cryomodule at 2 K** (limited by 2K pipe diameter)
- Also allow for possible 1.8 K operation with lower heat load ~15 W / module at 1.8 K

1 line for 2K supply	subcooled liquid @1.2 bar	• 2K helium bath for cavities via 2K-2 phase line • pre-cool gas for cool-down • 90% heat load from RF losses in the cavities
2 lines for 4.5-6K	3.0 bar He liquid Single phase flow	• Thermal intercept for HOM absorbers and couplers • 2/3 dynamic heat load
3 lines for 40-80K	20 bar He gas	• Thermal intercept for HOM absorbers and couplers • 40K thermal shield • 90% heat load from HOM

CHANGES COMPARED TO XFEL CM

- **Larger 2-phase 2K helium pipe** for the high CW gas load
  - → Increase from 72 mm to 90-100 mm
- **Larger nozzle** from He vessel to 2-phase pipe for the high CW heat load
  - → Increase from 55 mm to 70-100 mm

Vapor velocity limit in the 2-phase line to avoid instabilities → **5 m/s**

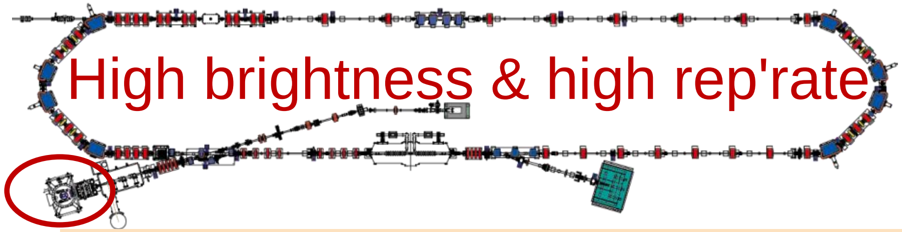


heat flux limit for heat transport by saturated helium II through a vertical pipe to the surface

- **Separate liquid baths for each cryomodule**
  - → Include a JT valve in each cryomodule for the high CW heat load
- **No 5K thermal radiation shield (dynamic losses dominant)**
- **tuner design with access ports** for repair/replacement of piezos, motors, and/or mechanism
- **Low peak/High average power coax RF input coupler per cavity**
- **Beamline HOM absorbers** for strong brodband damping of HOMs (high current and recirculation loops)

High brightness and High rep' rate sources

HIGH REP RATE PHOTO-INJECTORS SUMMARY



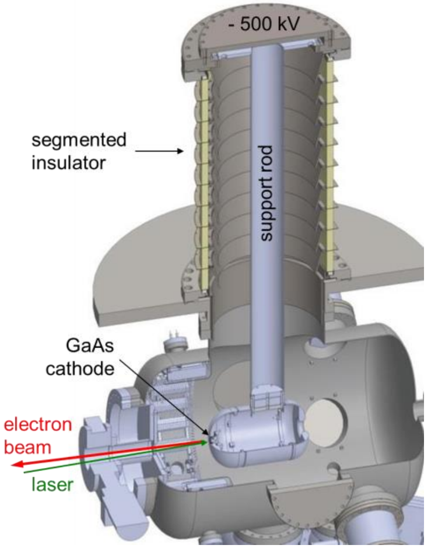
High brightness & high rep'rate e-guns required

$$\epsilon_n \propto \sqrt{\frac{kT_{\perp}(meV)}{E_{cath}(MV/m)}}$$

short + high charge bunches (pC to nC) → photocathode (vacuum ~10^{-10} mbar)
small emittance → high electic field on cathode + emittance compensation solenoid

High DC field

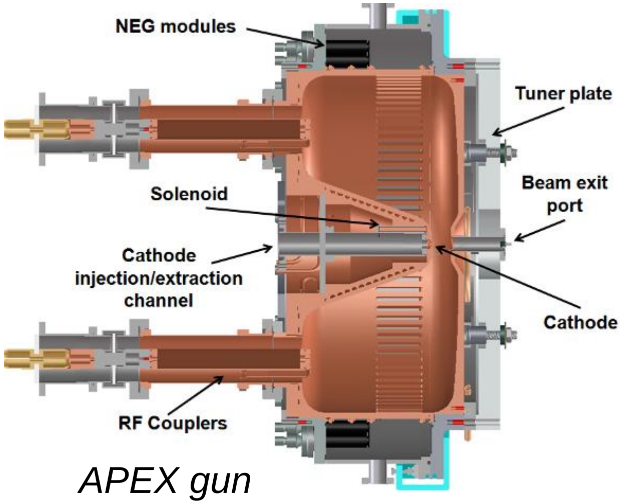
To achieve very high dc voltage
limited by field emission & breakdown



500 kV JAEA DC Gun, 160 mm gap
5.8 MV/m on photocathode
10 mA

NC RF gun

to evacuate the high heat load
(low frequency) keep good vacuum

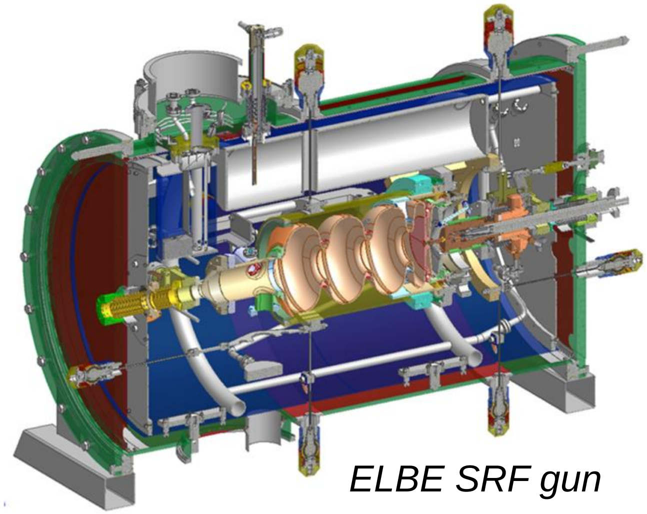


APEX gun

Berkeley 186 MHz CW RF gun
745 keV, **20 MV/m** at cathode
300 µA, 300 pC current

SRF cavity

to operate SC cavity with
NC photocathode inside



ELBE SRF gun

Potential for highest fields >30 MV/m
3½ TESLA cell + SC choke filter
Limited to 10 MV/m due to FE

ERL SUMMARY

- ❑ **Cost-driver = cryogenic load (CW SRF linacs)**
  - MW-scale cryoplants (ex: JLab Cryoplant 2x4.6 kW @2K)
- ❑ **Medium Gradient @16MV/m and $Q_0 > 2\times10^{10}$ (to limit cryo load)**
  - new methods: N-doping, thermal cycling…
- ❑ **CW cryomodule design with Power ~ 100 W @2K**
  - With low microphonics (low df/dp cavities)
  - With Q_0 preserved (efficient magnetic shielding)
- ❑ **Cavity design for strong HOM damping & broadband dampers**
- ❑ **Operation at high Q_L** (5.10^7 to $>10^8$) **with excellent field stability**
- ❑ **Numerous CW SRF linacs under development**
  - CW FELs (XFEL CW option, LCLS-II, LUNEX5, …)
  - ERLs (JLab ERL, ALICE, cERL, Berlinpro, LHeC demo, Cornell ERL, …)
- ❑ **High brightness photo-injectors**
  - DC field, NC RF, or SRF gun (R&D still neded)

END

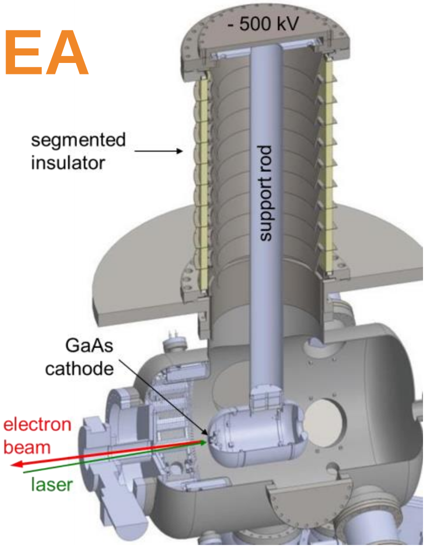
DC GUNS

DC gun challenges

Low emittance and high current

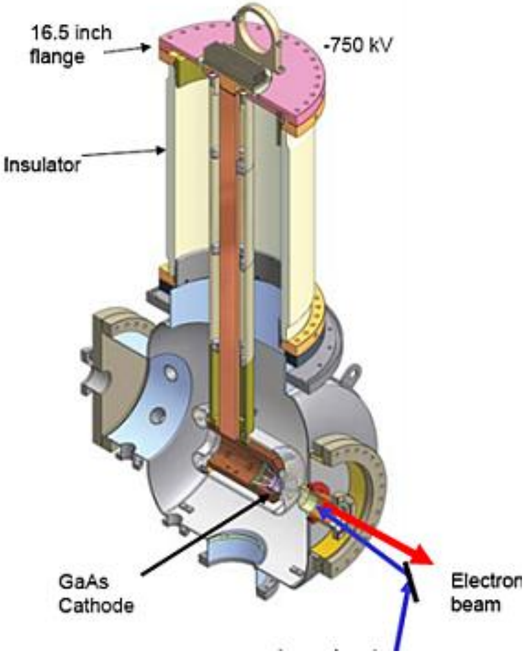
- High extraction voltage 500 kV
- High accelerating gradient on photocathode
- Cathode lifetime
  (backscattered ions bombardment)

JAEA



500 kV DC Gun
16 cm gap

CORNELL



350 kV DC Gun
10 cm gap

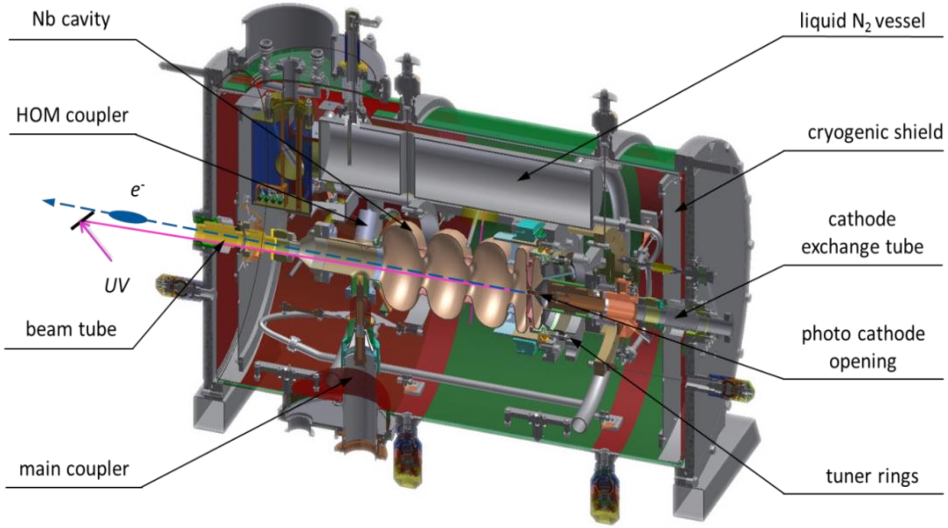
SRF PHOTO-CATHODE GUNS

SRF gun challenges

Potentially very powerful injector : CW operation + high field + UHV simultaneously but not demonstrated to date

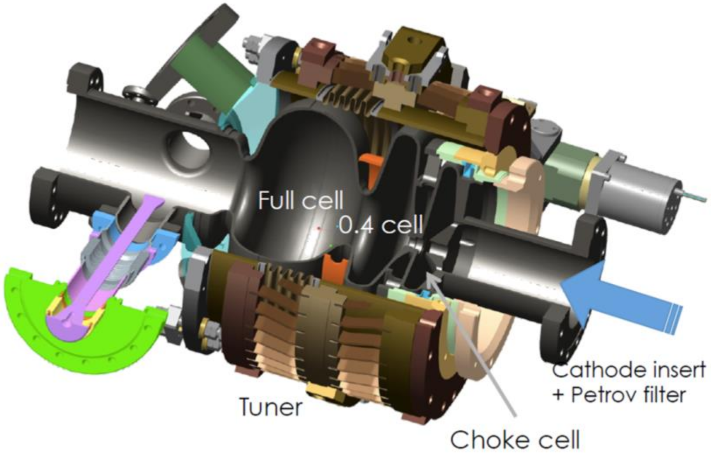
- normal conducting cathode in the SRF cavity → **cooling issues**
- Operating a cathode at high field → **field emission issues**

Development @ HZ Berlin



1.3 GHz, 3½ TESLA cell + SC choke filter
Cs_2Te photocathode
But limited by field emission

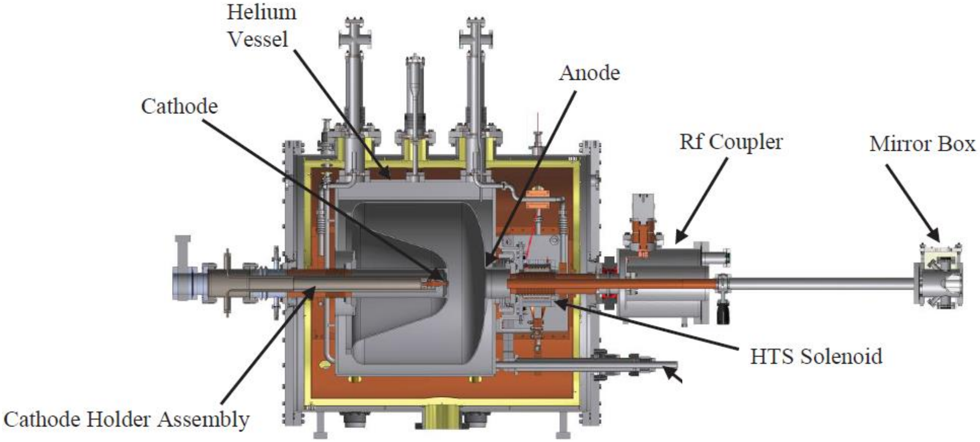
Development @ HZ DR



1.3 GHz, 1.4-cell cavity
CsK_2Sb photocathode
Reasonable longevity & vacuum requirements
QE and laser wavelength (green)

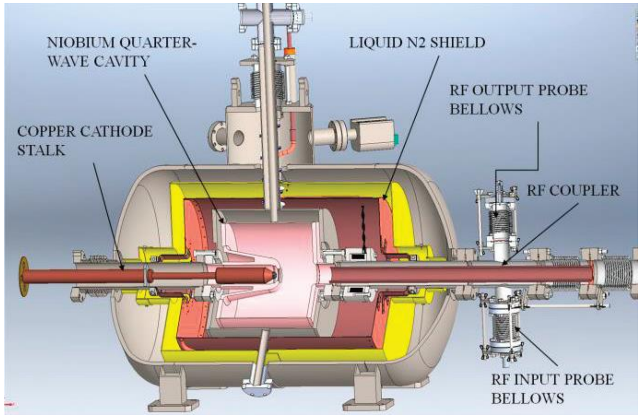
QWR SRF GUNS

Wisconsin



- Cathode field: 40 MV/m
- 200 MHz 4 MeV
- 200 pC, rep rate 5 MHz
- CsK_2Sb photocathode

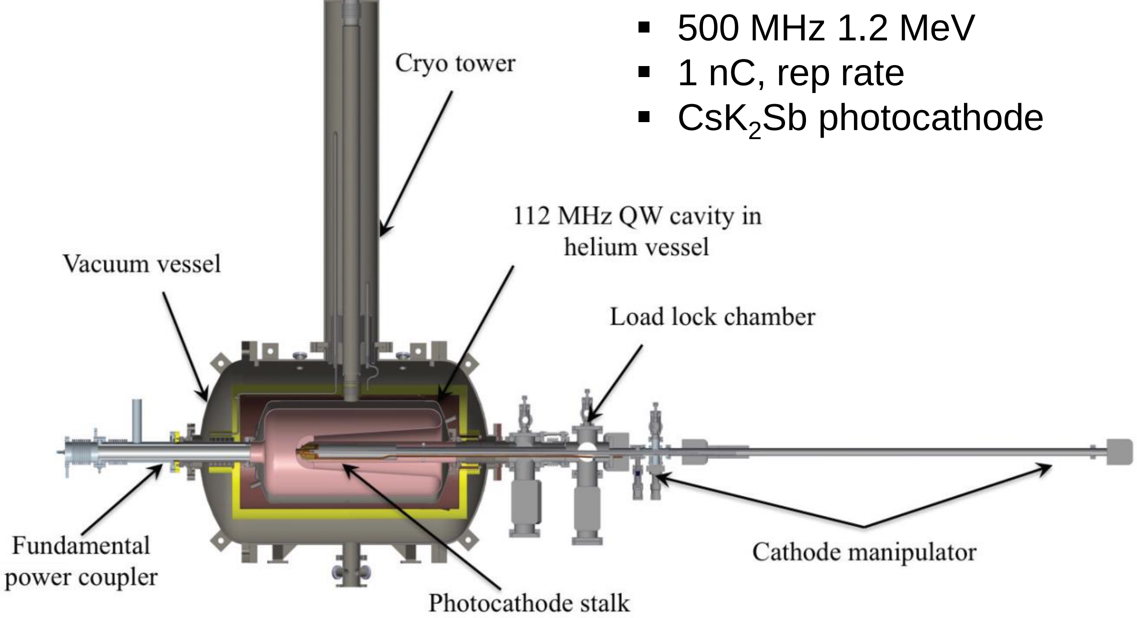
Naval Postgraduate School (Monterey)



- 500 MHz 1.2 MeV
- 1 nC, rep rate
- CsK_2Sb photocathode

BNL

- 112 MHz 2 MeV
- 1-5 nC, rep rate 78 kHz
- CsK_2Sb photocathode



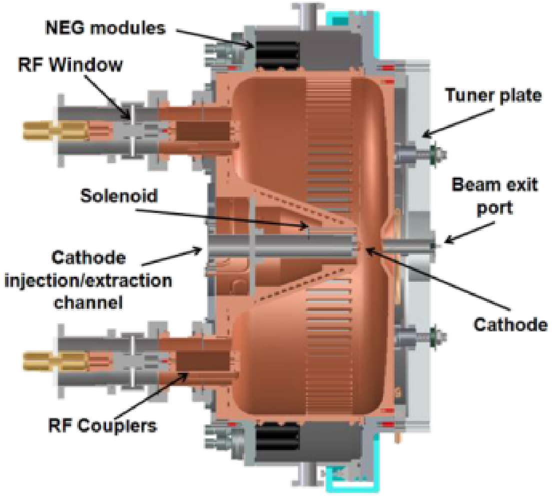
NC CW RF GUN

NC gun challenges

- Heat load at high field → **cooling issues**
- Very high vacuum required (specially with CsK_2Sb)

APEX Gun Advanced Photoinjector EXperiment (LBNL)

The Berkeley normal-conducting scheme satisfies all the LBNL FEL requirements simultaneously.



J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

Frequency	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0 (ideal copper)	30887
Shunt impedance	6.5 MΩ
RF Power @ Q_0	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-10}-10^{-9} Torr

- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.