A Possible ERL Test Facility at CERN

Erk Jensen, Ed. Ciapala
(with lots of material provided by Rama Calaga, Joachim Tückmantel and many others)

JLAB Seminar, August 2012

- The LHeC Project
- The LHeC Ring-Linac Option with ERL
- The purpose(s) of an ERL Test Facility
- Why at CERN?
- Approximate parameter range

LHeC Goal

- Collide LHC beam with electrons or positrons
  - Required lepton energy is ≥ 60 GeV
  - Luminosity of ≈10^{33} $cm^{-2}s^{-1}$
  - Polarisation
  - No interference with pp physics
  - Detector acceptance down to 1°
  - Power consumption for lepton complex ≤ 100 MW

- Study team provided CDR this earlier this year: http://arxiv.org/pdf/1206.2913v1.pdf
  - The Physics
  - Ring-ring option
  - Linac-ring option
  - Show that a solution exists, will now have to find the best solution
    - Already have a baseline and alternatives for some components
- See also http://www.cern.ch/lhec and https://indico.cern.ch/conferenceDisplay.py?confId=183282

LHeC CDR

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

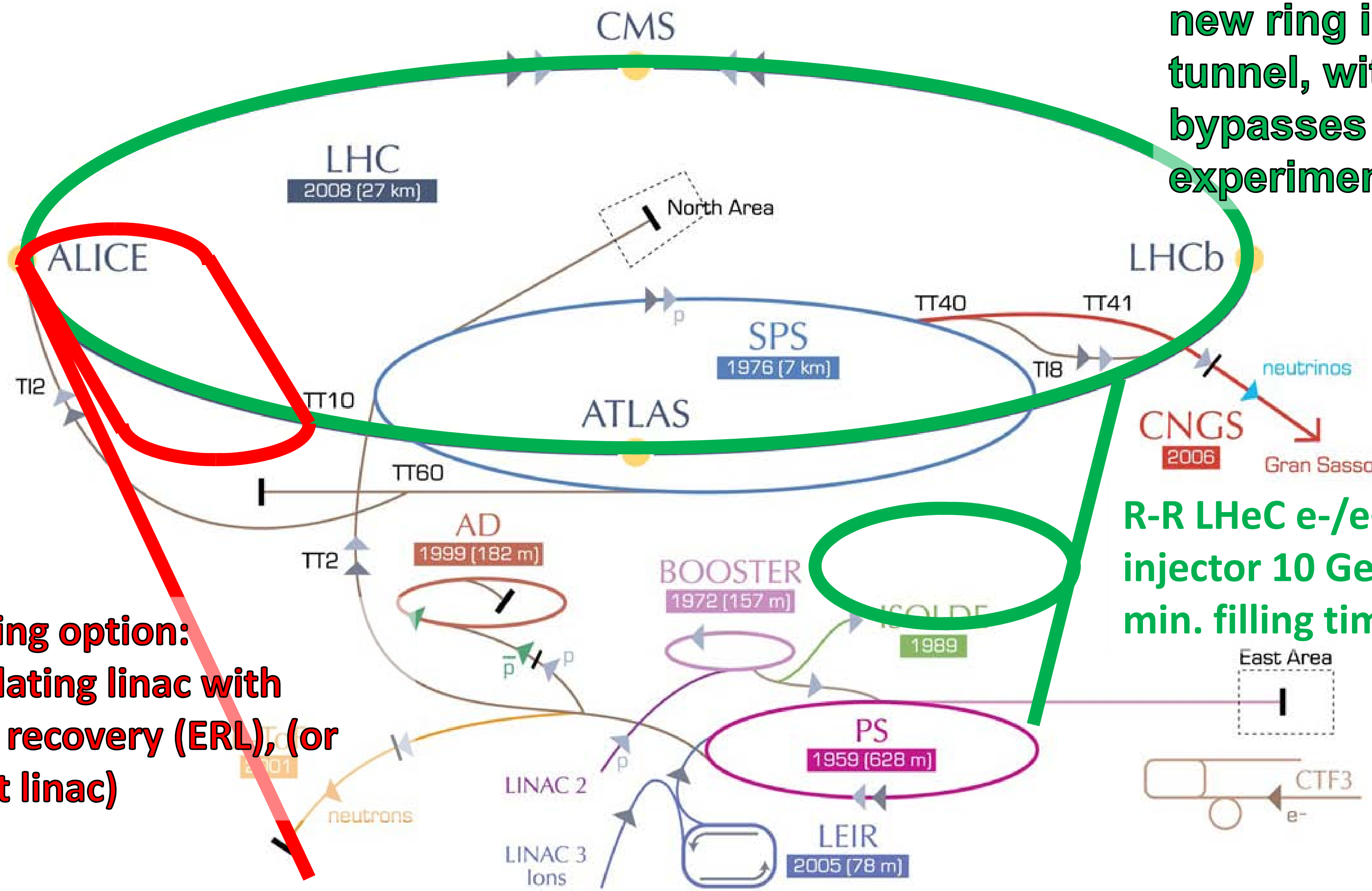
LHeC Study Group

Submitted to J.Phys. G

LHeC Study Group

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], V.Cetinkaya[01], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[16], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

LHeC Options

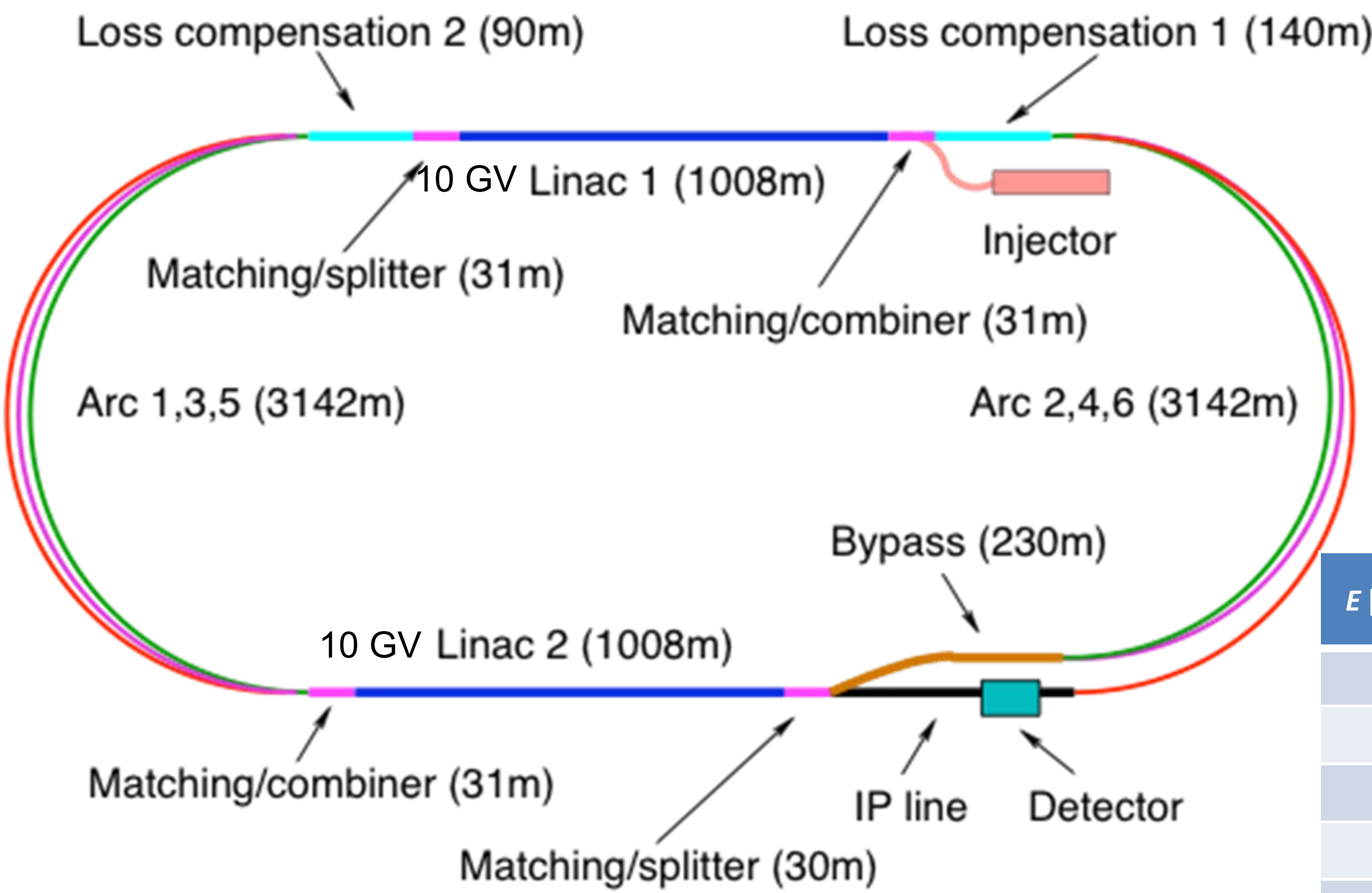


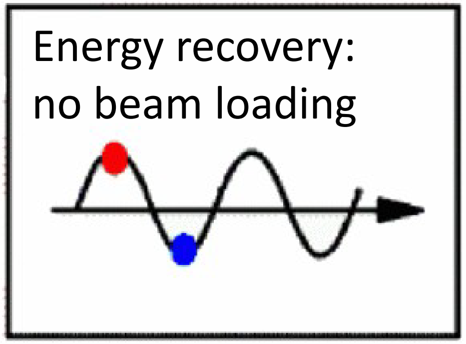
Ring-ring option: new ring in LHC tunnel, with bypasses around experiments

R-R LHeC e-/e+ injector 10 GeV, 10 min. filling time

Linac-ring option: recirculating linac with energy recovery (ERL), (or straight linac)

ERL





E [GeV]	Energy lost (SR) [MeV]	RF power [MW]
10	0.8	0
20	14	0.1
30	70	0.5
40	230	1.7
50	550	4.0
60	570	4.2

The Beauty of the ERL

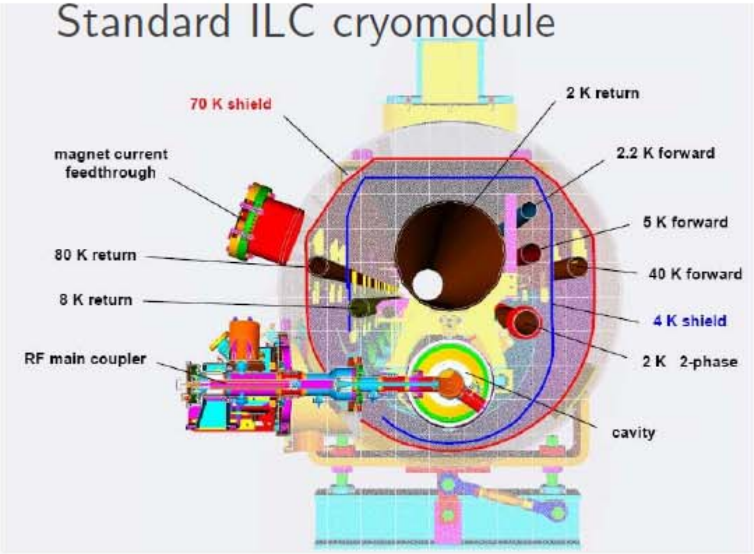
- e-beam power at IP: 384 MW (!)
- Total power consumption: 80 MW!

- Efficiency of 480%

LHeC ERL *f* Options

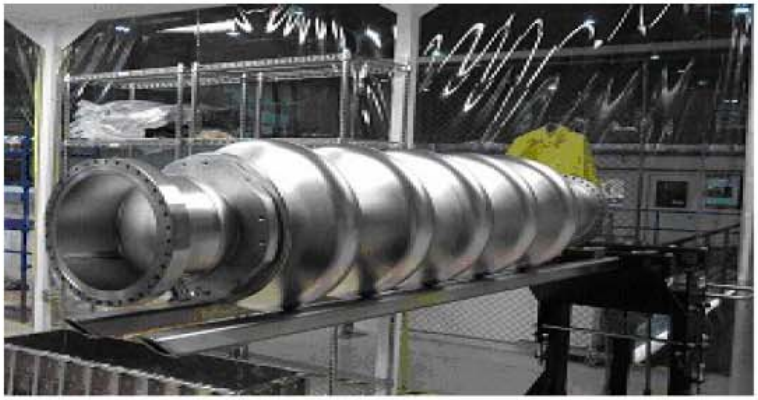
1.3 GHz

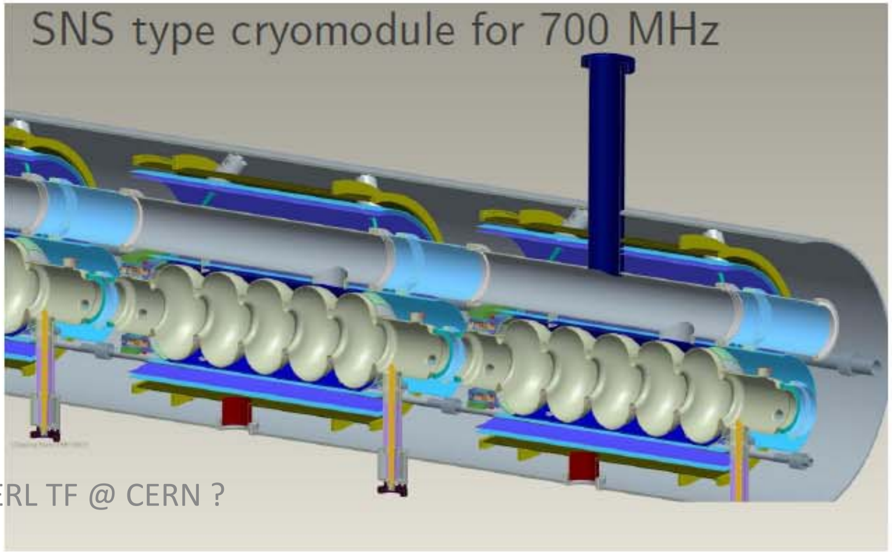
ILC Collaboration



704 MHz

ESS, eRHIC, SPL

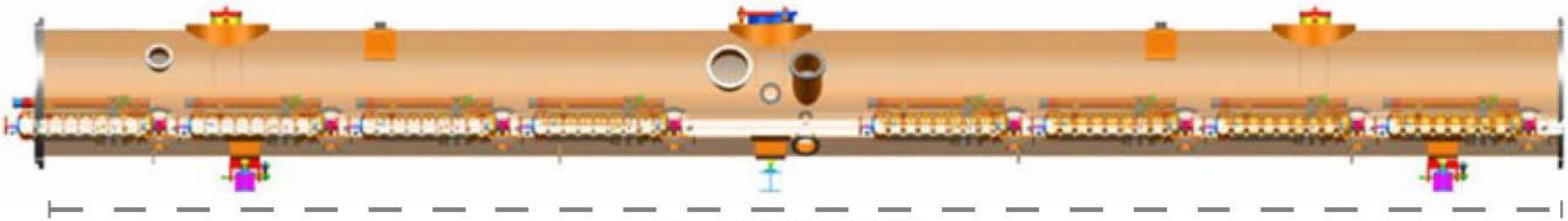




Cryomodule layout

1.3 GHz ILC Type Layout

9-cell cavities (1.53 m long), 8 per cryo-module



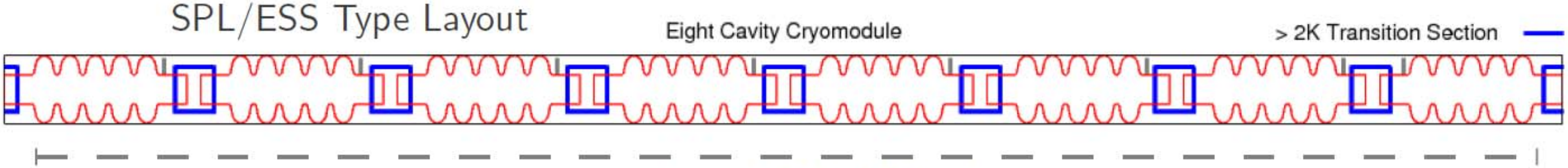
~12 m, 0.144 GeV/Module

164 CM's

704 MHz

5-cell cavities (1.6 m long), 8 per cryo-module

SPL/ESS Type Layout



~13 m, 0.144 GeV/Module

158 CM's

Approx cavity length is similar if not same

ILC type cryomodule can be utilized for both frequencies

Which frequency?

Advantages 700 MHz

- Synergy SPL, ESS, JLAB, eRHIC
- Smaller BCS resistance
- Less trapped modes
- Smaller HOM power
- Beam stability
- Smaller cryo power
- Power couplers easier

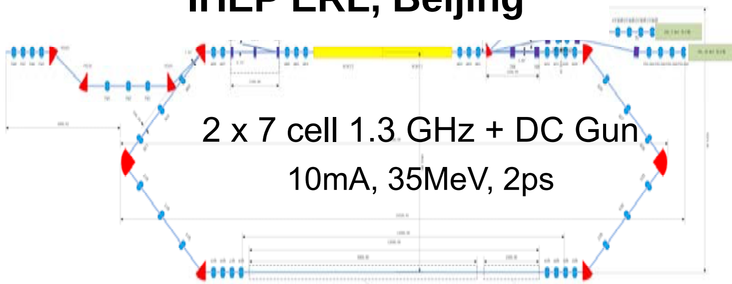
Advantages 1300 MHz

- Synergy ILC, X-FEL
- Cavity smaller
- Larger R/Q
- Smaller RF power (assuming same Q_{ext})
- Less Nb material needed

Personal preference: 700 MHz, since beam becomes unstable at higher current.

Low Energy ERL's/Test Facilities

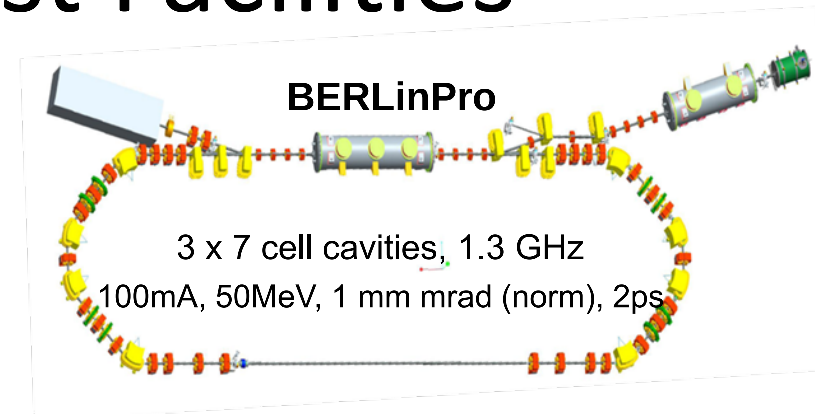
IHEP ERL, Beijing



2 x 7 cell 1.3 GHz + DC Gun

10mA, 35MeV, 2ps

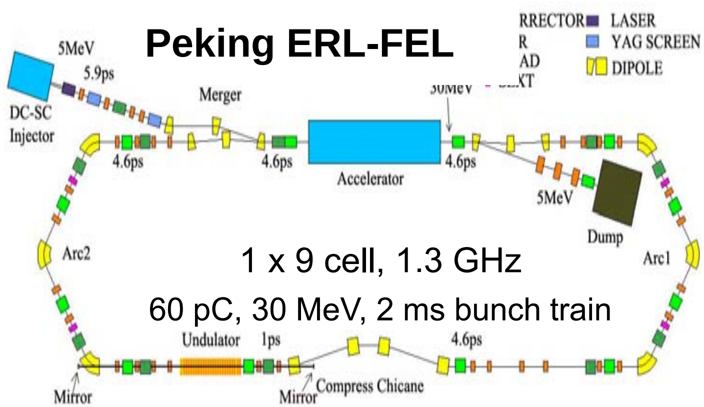
BERLinPro



3 x 7 cell cavities, 1.3 GHz

100mA, 50MeV, 1 mm mrad (norm), 2ps

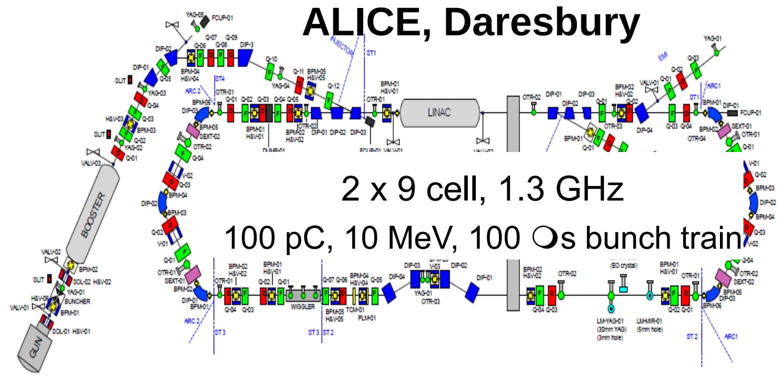
Peking ERL-FEL



1 x 9 cell, 1.3 GHz

60 pC, 30 MeV, 2 ms bunch train

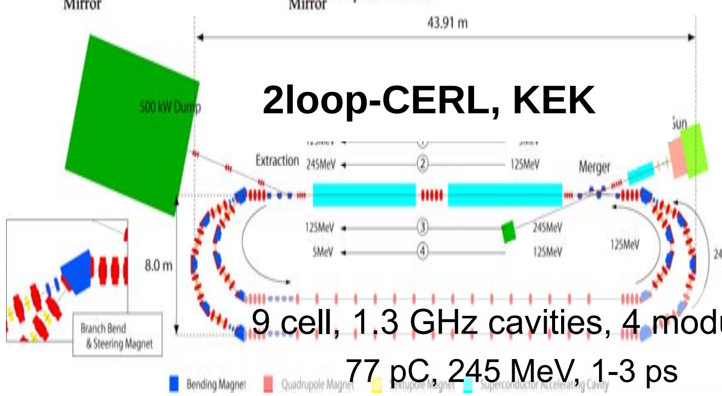
ALICE, Daresbury



2 x 9 cell, 1.3 GHz

100 pC, 10 MeV, 100 ❍s bunch train

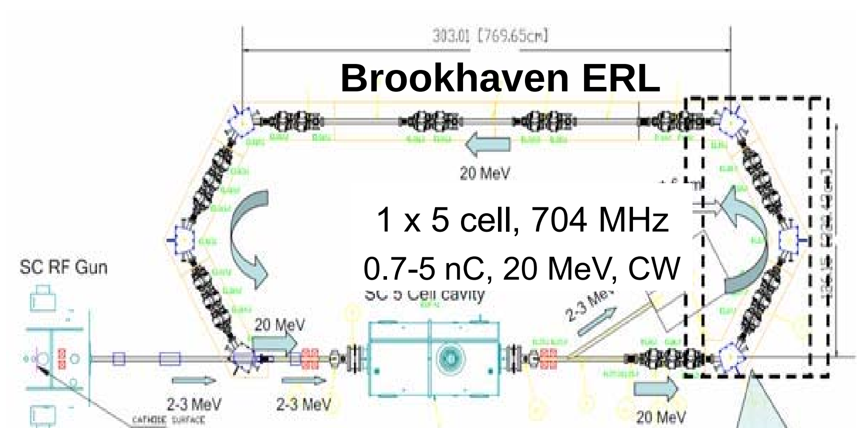
2loop-CERL, KEK



9 cell, 1.3 GHz cavities, 4 modules

77 pC, 245 MeV, 1-3 ps

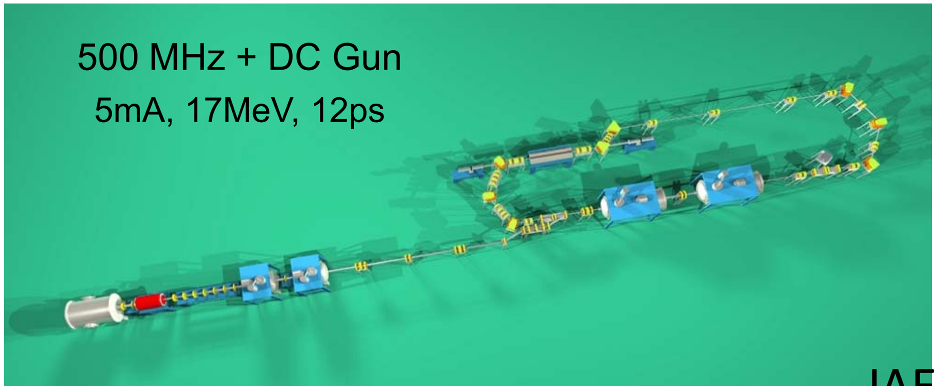
Brookhaven ERL



1 x 5 cell, 704 MHz

0.7-5 nC, 20 MeV, CW

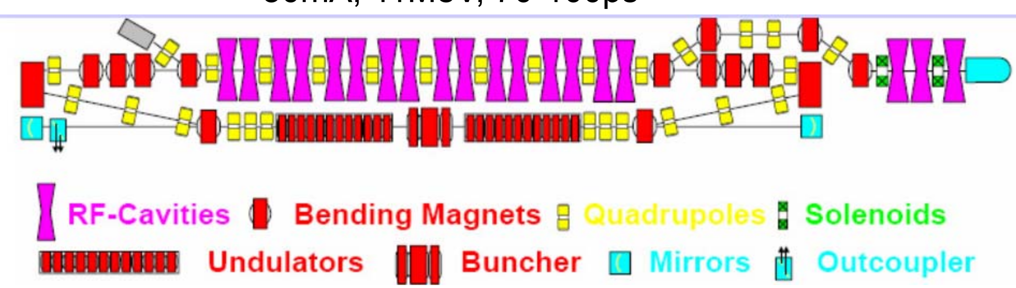
Low Energy ERL's/Test Facilities



JAERI, Tokai

Normal Conducting 180 MHz + DC Gun

30mA, 11MeV, 70-100ps



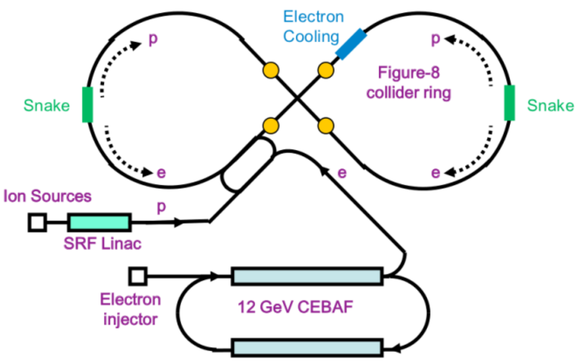
BINP, Novosibirsk

Low Energy ERL's/Test Facilities

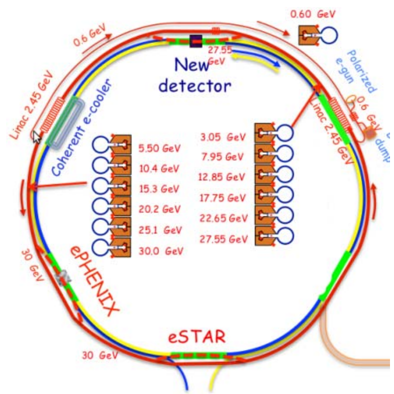
IHEP ERL-TF	HZB BERLinPro	BINP	Peking FEL	BNL ERL-TF	KEK cERL	Daresbury ALICE	JAERI
35 MeV	100 MeV	11-40 MeV	30 MeV	20 MeV	245 MeV	10 MeV	17 MeV
1.3 GHz 9 cell	1.3 GHz	180 MHz	1.3 GHz 9-cell	704 MHz 5-cell	1.3 GHz 9-cell	1.3 GHz 9-cell	500 MHz
10 mA	100 mA	30 mA	50 mA	50-500 mA	10-100 mA	13 μA	5-40 mA
60 pC	10-77 pC	0.9-2.2 nC	60 pC	0.5-5 nC	77 pC	80 pC	400 pC
2-6 ps	2 ps	70-100ps	1-2 ps	18-31 ps	1-3 ps	~10 ps	12 ps
1 pass	1-2 pass	4 passes	1 pass	1 pass	2-passes	1-pass	1-pass
Under construction	Planned / construction	operating		Under construction	Under construction	operating	operating

High Energy ERL’s, EIC’s (electron-ion)

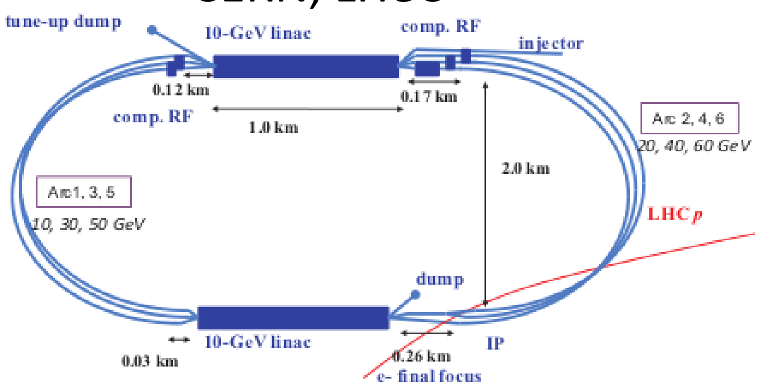
JLAB, MEIC



BNL, eRHIC

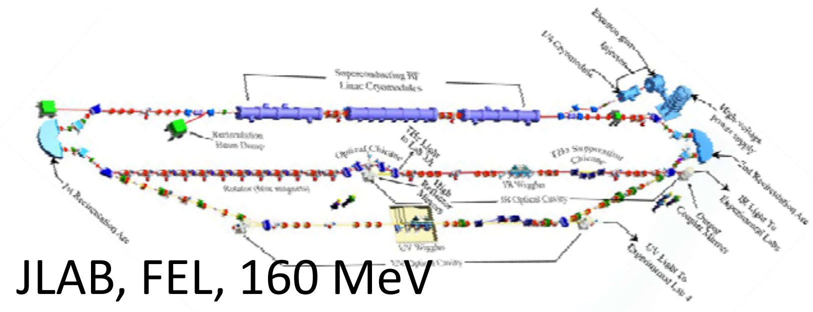


CERN, LHeC



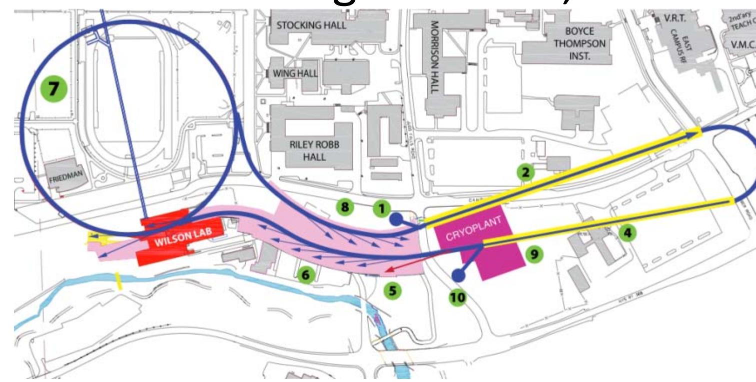
JLab MEIC	BNL eRHIC	CERN LHeC
5-10 GeV	20 GeV	60 GeV
750 MHz ? passes	704 MHz 6 passes	704 MHz 3-passes
3 A	50 mA	6.4 mA
4 nC	3.5 nC	0.3 nC
7.5 mm	2 mm	0.3 mm
Planned	Planned	Planned

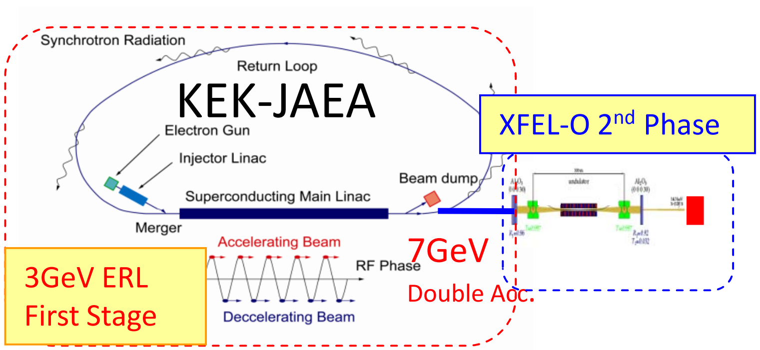
High Energy ERL's, Light sources, FEL



JLAB, FEL, 160 MeV

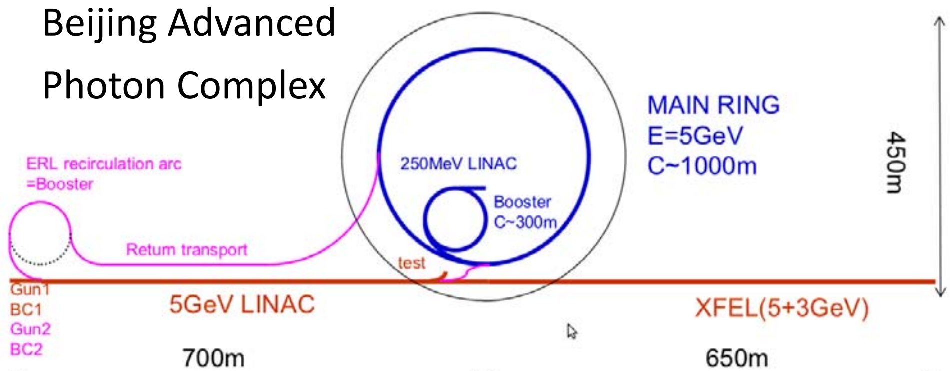
Cornell ERL Light Source, 5 GeV





Beijing Advanced

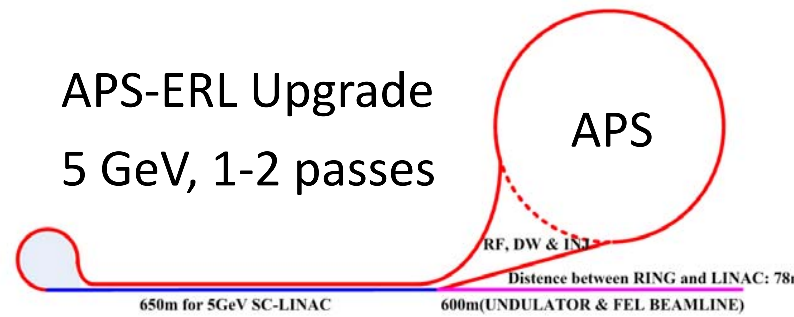
Photon Complex



600 9-cell Cavities !

APS-ERL Upgrade

5 GeV, 1-2 passes



High Energy ERL's, Light sources, FEL's

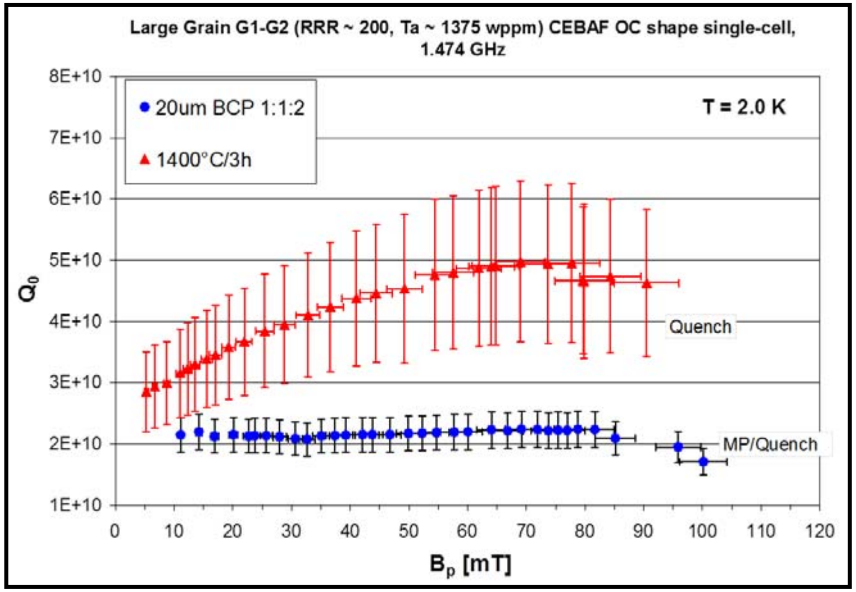
JLab FEL (IR, UV)	Argonne Light Source	Cornell Light source	Mainz, MESA ERL	KEK-JAEA Light Source	Beijing Photon Source
160 GeV	7 GeV	5 GeV	100-200 MeV	3 GeV	5 GeV
1.5 GHz	1.4 GHz 1-2 passes	1.3 GHz	? 2 passes	1.3 GHz	1.3 GHz 9 cell
10 mA	25-100 mA	100 mA	0.15-10 mA	0.01-100 mA	10 mA
135 pC	77 pC	77pC	7.7 pC	7.7-77 pC	77 pC
0.045-0.15 mm		0.6 mm	- ps	2 ps	2 ps
Operating	Planned	Planned	?	Planned	Planned

Interesting, challenging R&D

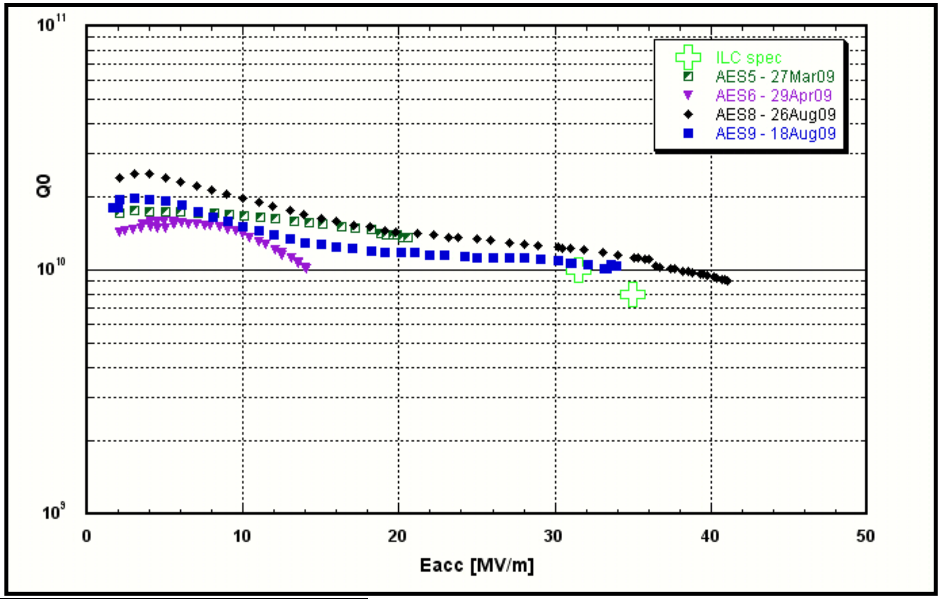
- ERL: (almost) no beam loading in steady state, so potentially small RF power.
- R&D for highest possible Q_0!
  - Technology? HiPIMMS? Ingot?
- R&D: How large Q_{ext} do you dare?
- R&D: How to get to steady state?
- influence of bunch amplitude jitter, phase jitter?
- Compensation of SR radiation loss
- failure modes

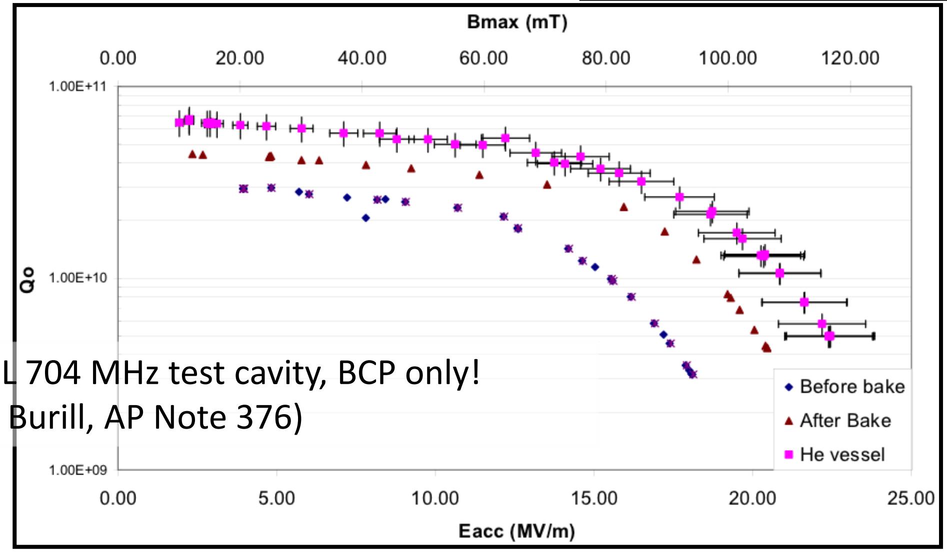
Q_0 – what is in reach?

G. Ciovati, JLAB S&T Review 2012



ILC Cavities 1.3 GHz, BCP + EP (R. Geng SRF2009)





BNL 704 MHz test cavity, BCP only!
(A. Burill, AP Note 376)

Power balance (rough estimate)

	Units	721.4 MHz	1322.6 MHz
Main linacs (no beam loading)			
R/Q	[Ω]	500	1036
Q_0 @ 2 K		4.5×10^{10}	2×10^{10}
V/cavity	[MV]	15.7	16.3
P_{RF}/cavity	[kW]	24.6	12.8
n_{cav}		1260	1318
total RF power	[MW]	31	16.9
P_{AC}	[MW]	50	28.2
Synchrotron radiation compensation			
total RF power	[MW]	10.5 MW	
P_{AC}	[MW]	18 MW	
Heat load (assuming Q_0 @ 2 K, conversion factor 600)			
P_{AC}/cav	[kW]	4.5	5
P_{AC}	[MW]	5.7	6.1
HOM's	[MW]	1.7	5.4
Static, coupler, interconnects	[MW]	3	3
0.3 GeV injector			
P_{AC}	[MW]	5	
Total P_{AC}	**[MW]**	**83.4**	**65.7**

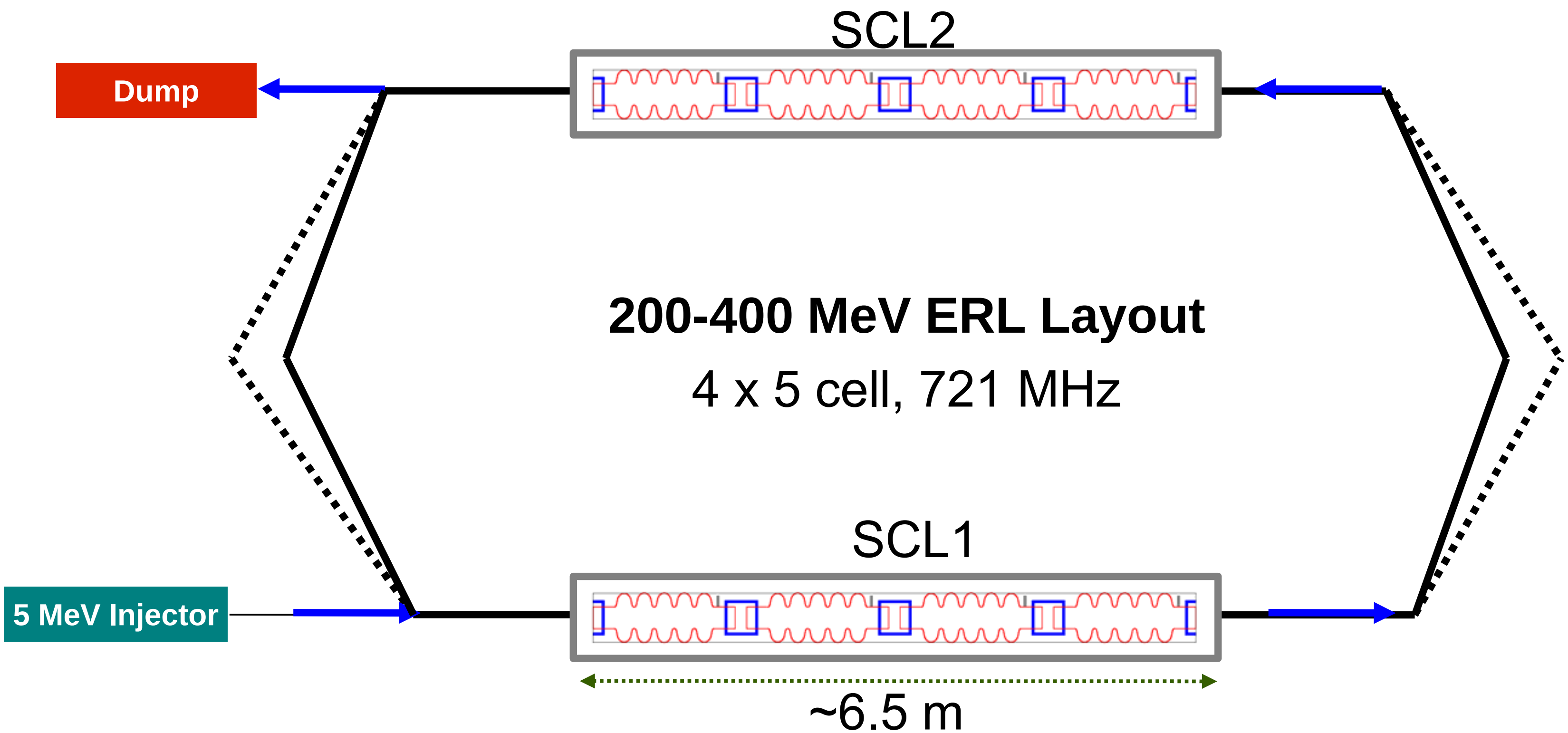
An ERL Test facility …

… could help answer some of these questions!

But also:

- Physics motivation:
  - ERL demonstration, FEL, γ-ray source, e-cooling demo!
  - Ultra-short electron bunches
- One of the 1st low-frequency, multi-pass SC-ERL
  - synergy with SPL/ESS and BNL activities
- High energies (200 … 400 MeV) & CW
- Multi-cavity cryomodule layout – validation and gymnastics
- Two-Linac layout (similar to LHeC)
  - …could test CLIC-type energy recovery from SCL2 → SCL1
- MW class power coupler tests in non-ER mode
- Complete HOM characterization and instability studies!
- Cryogenics & instrumentation test bed

- **… for CERN RF Group to re-establish practical expertise in SC-RF, train new people and get ready for the future.**

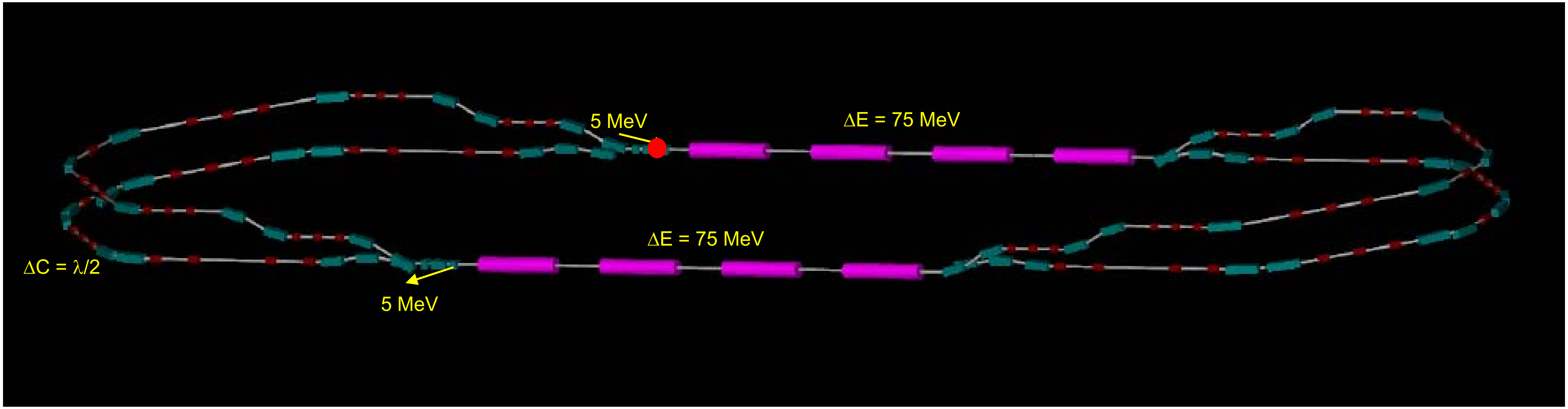


	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	721	721
Charge	[pC]	~500	~500
Rep rate		CW	CW

ERL-TF (300 MeV) – Layout

Thanks, Alex (received this morning)!

Alex Bogacz

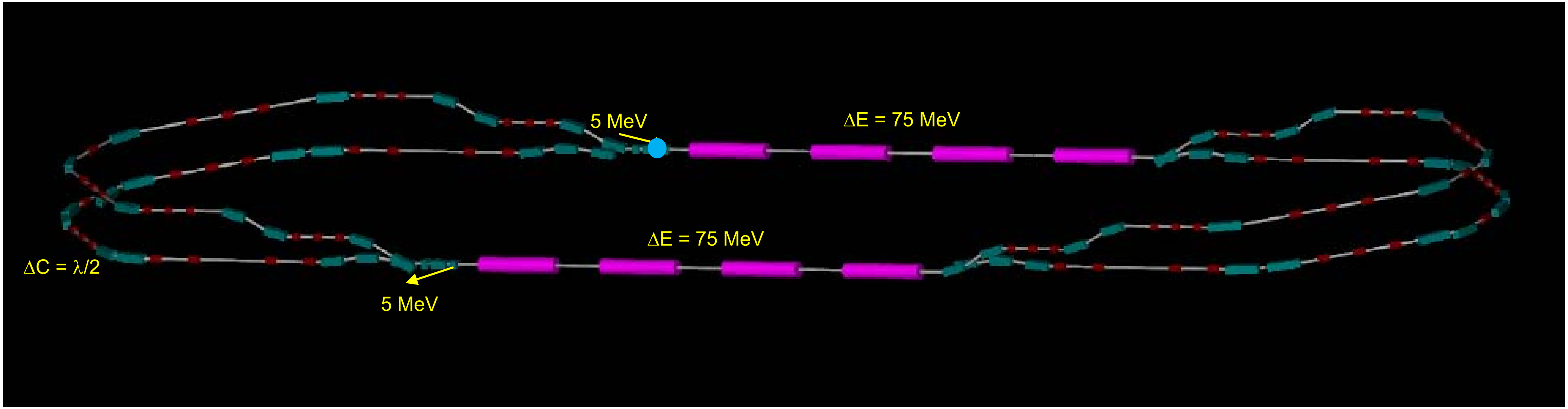


Two passes 'up' + Two passes 'down'

ERL-TF (300 MeV) – Lattice Design

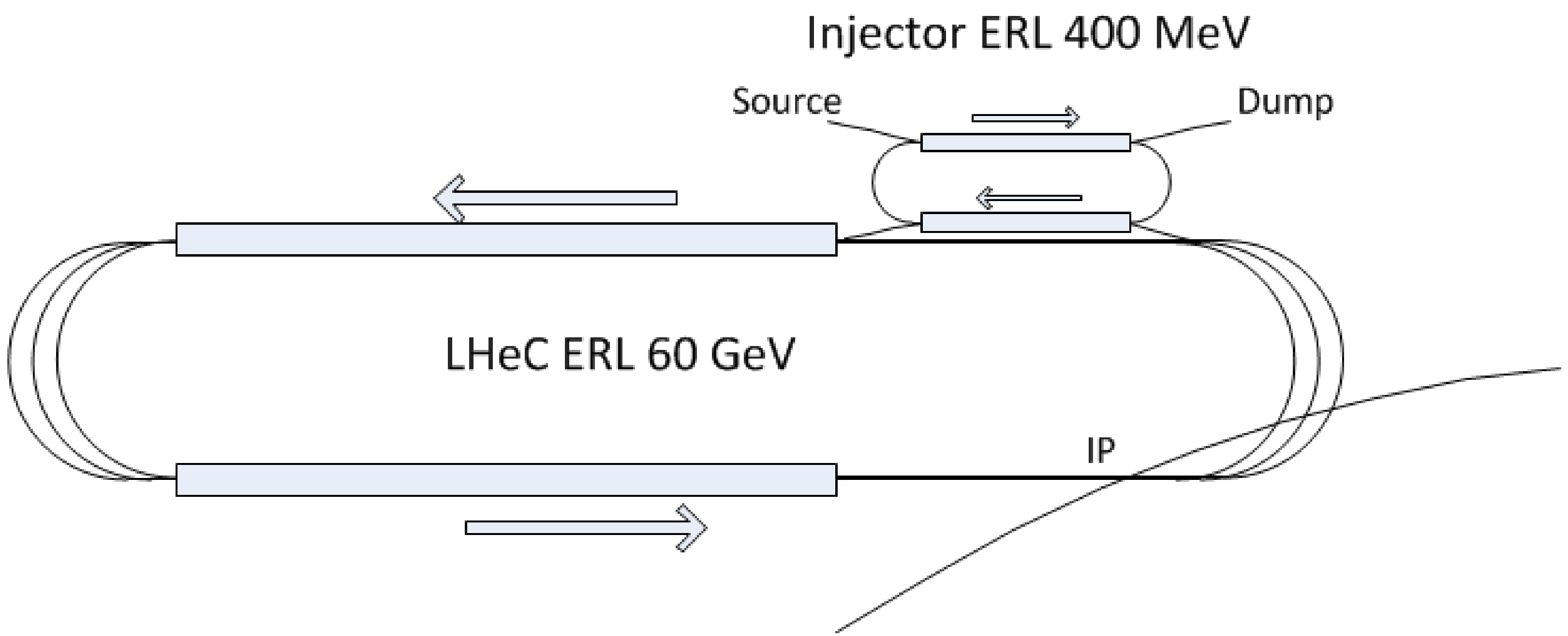
Thanks, Alex (received this morning)!

Alex Bogacz



Two passes ‘up’ + Two passes ‘down’

Could the TF later become the LHeC ERL injector ERL?



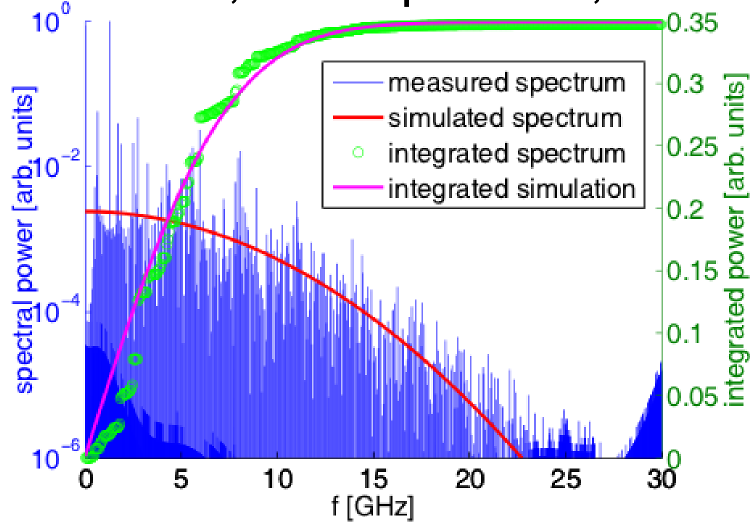
very preliminary – just an idea right now

HOM Measurements

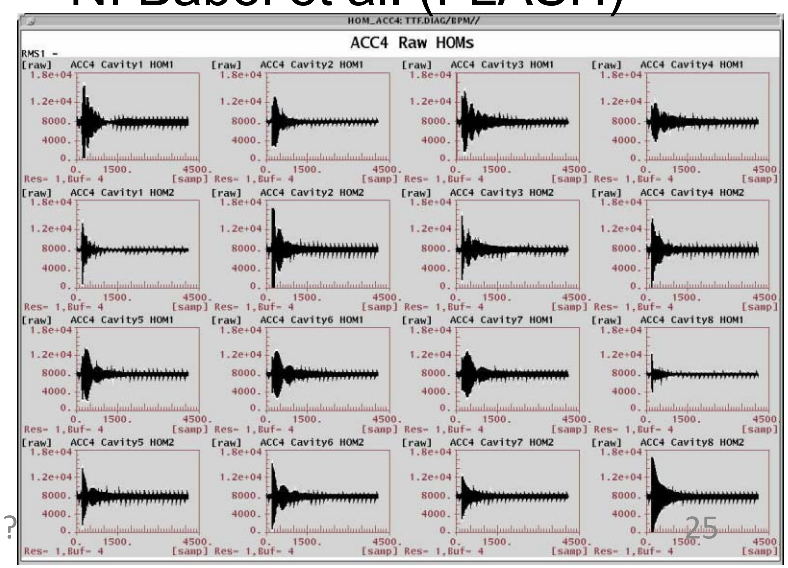
Complete characterization of HOM

- Benchmark simulations
- Improvements on damping schemes

1.3 GHz, M. Liepe et al., IPAC2011



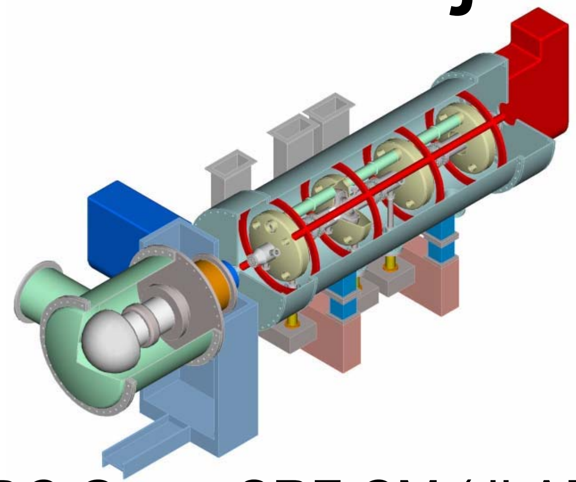
N. Baboi et al. (FLASH)



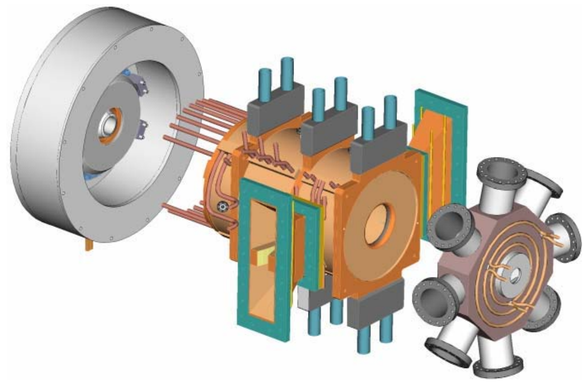
Precision measurement of orbit

- Cavity & CM alignment

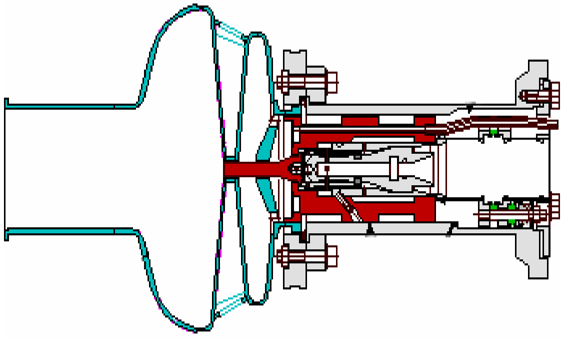
Injector R&D (~700 MHz)



DC Gun + SRF CM (JLAB-AES)

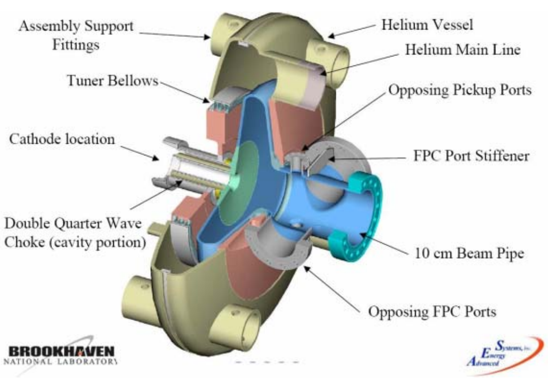


NC Gun (LANL-AES)



SRF Gun (FZR-AES-BNL)

	DC+SRF-CM	NC	SRF
Energy	2-5 MeV	?	2 MeV
Current	100 mA	100 mA	1000 mA
Long. Emit	45 keV-ps	200 keV-ps	-
Trans. Emit	1.2 µm	7 µm	< 1 µm



SRF Gun (BNL-AES)

RF Power

→ 5 MeV injector → P_{beam} ~ 50 kW (10 mA)

Will need higher powers if we go to 100 mA+

Peak detuning

→ Main LINAC

(zero beam loading)

$$P_g = \frac{V^2}{R/Q} \cdot \frac{\Delta f}{f} \qquad \{Q_{opt} = \frac{1}{2} \cdot \frac{f}{\Delta f}\}$$

	721 MHz
Q=1 x 10^6	250 kW
Q=5 x 10^6	50 kW
Q=1 x 10^7	25 kW

Commercial television

IOT @700 MHz

←

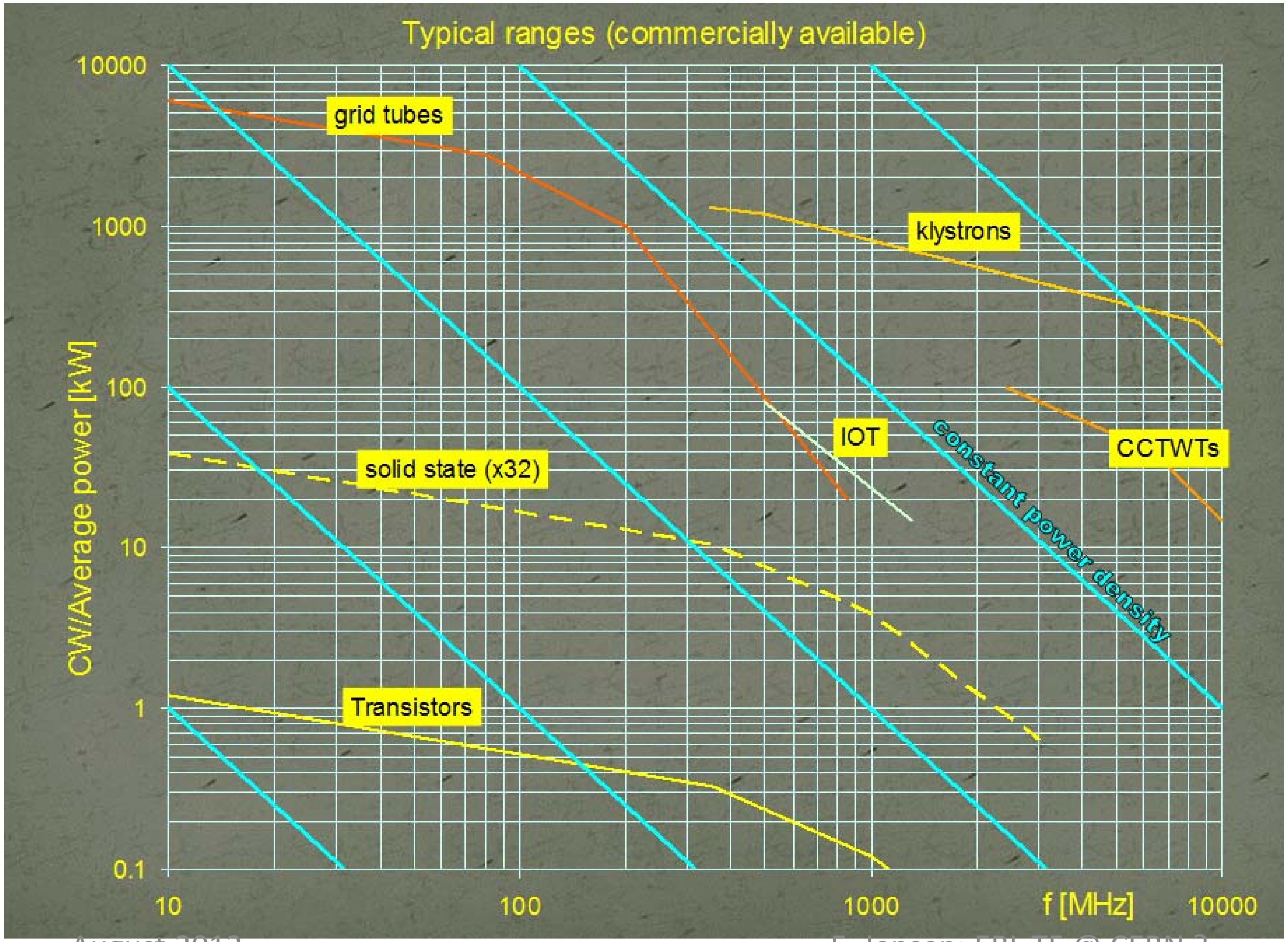
Reach steady state with increasing beam current

RF Power

Use of IOTs ~ 50-100 kW at 700 MHz

High efficiency, low cost

Amplitude and phase stability



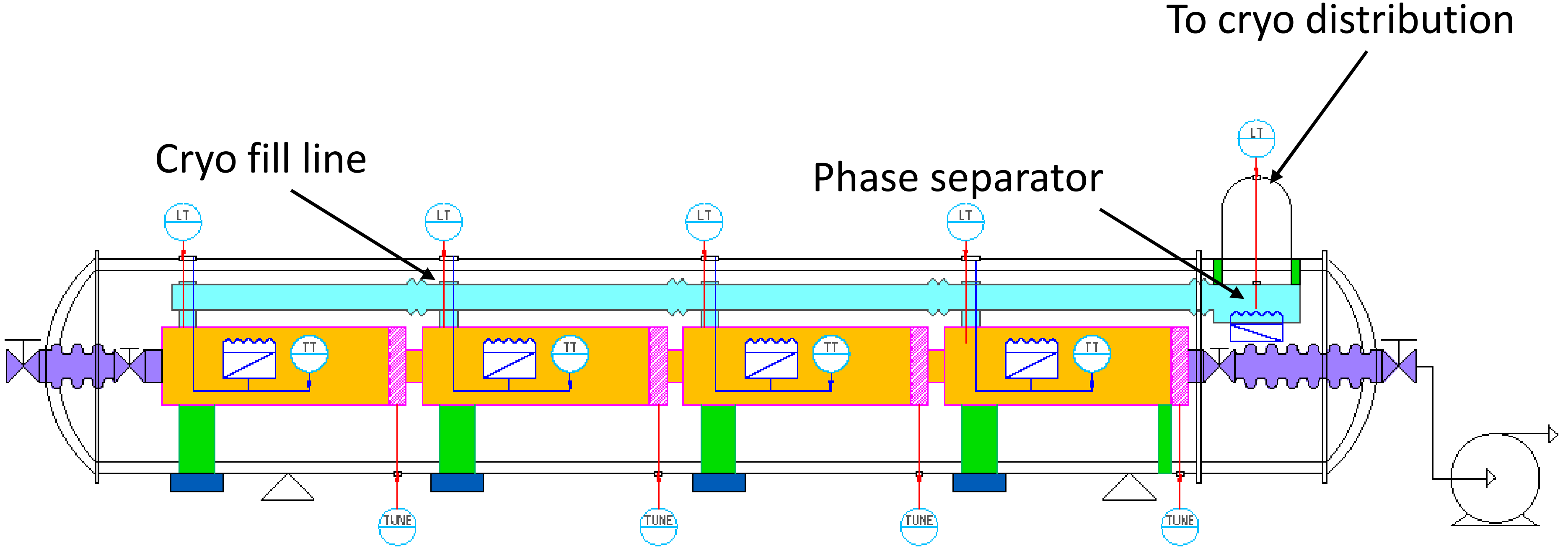
50 kW TV Amplifier, BNL

At 700 MHz

Cryogenic System

Can use the SPL like cryo distribution system

No slope at the C-TF → the distribution line can be in center ?



V. Parma, Design review of short cryomodule

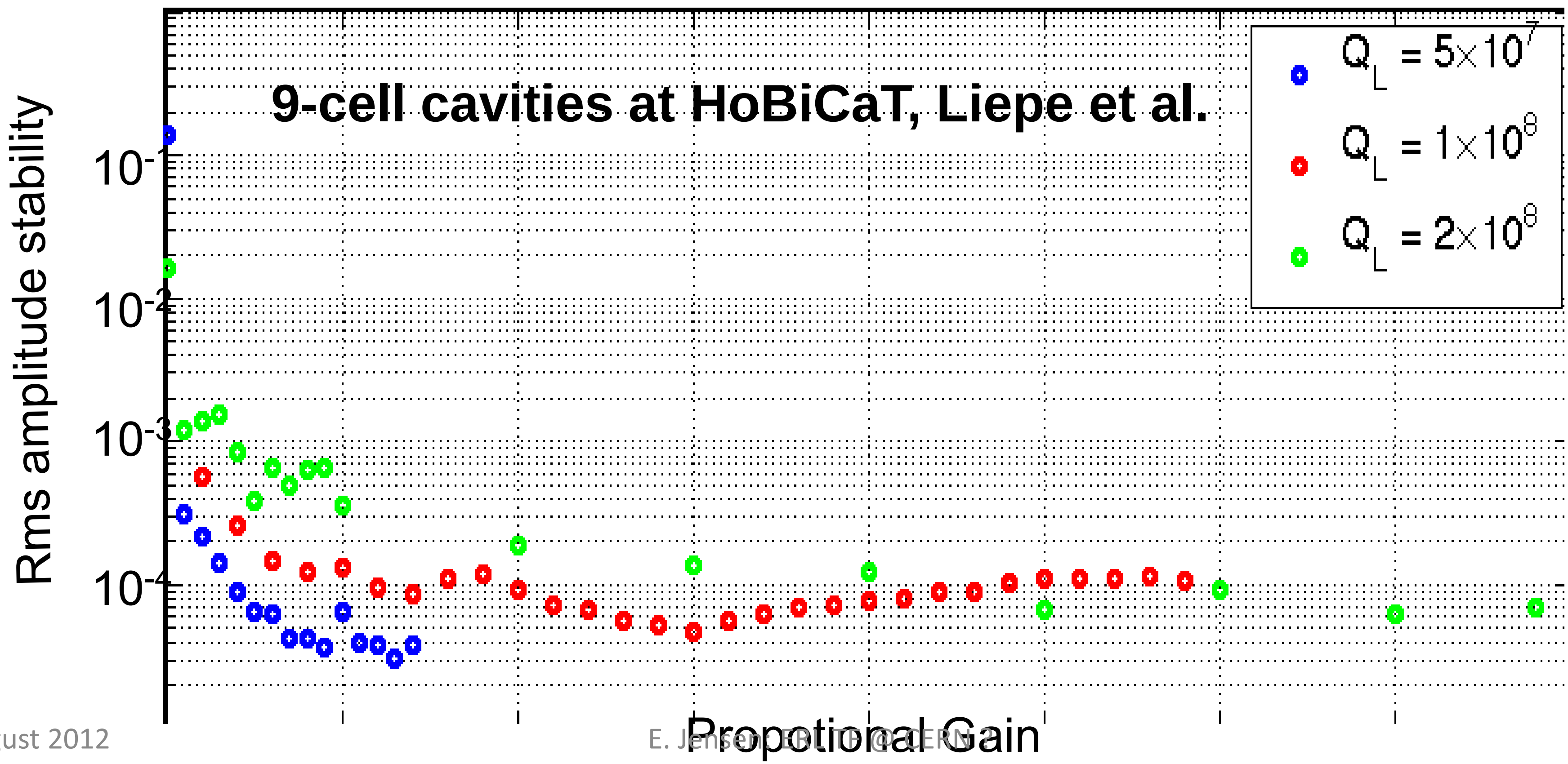
RF Controls

Development of digital LLRF system (Cornell type ?)

Amplitude and phase stability at high Q_0 ~ 1 x 10^8

Reliable operation with high beam currents + piezo tuners

In case of failure scenarios: cavity trips, arcs etc..



RF Failures

Slow failures (for example: power cut)

Q_{ext} is very high → perhaps need to do nothing …

Fast failures (coupler arc)

If single cavity → additional RF power maybe ok

Reduce beam currents or cavity gradients gradually

If entire LINAC → lots of RF power

Perhaps play with 2-LINAC configuration for safe extraction of high energy beam

Timeline & Costs

If:

SPL R&D CM can be used, then very fast turn-around (cheap option)

Else:

3-4 years of engineering & development (SRF + beam line)

The costs should be directly derived from SPL CM construction (< 5 MCHF ?)

Do we need high power couplers ?

R&D of HOM couplers

Will be needed for probing high current & CW

<u>Key question: where to place the ERL-TF to have maximum flexibility ?</u>