

Plans for an ERL Test Facility at CERN

Frank Zimmermann

KEK WG meeting on ERL beam
dynamics, Tsukuba, 7 November 2012

many thanks to A. Bogacz, JLAB; M. Klein, U.
Liverpool; V. Litvinenko, BNL; O. Brüning,
E. Jensen, D. Schulte, A. Valloni, CERN

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two proposals for ERL-ring lepton-hadron colliders:

- **LHeC based on the LHC at CERN**
 - 7 TeV p or few TeV/nucleon heavy-ion beams
 - **adding a 60-GeV ERL with 6.4 mA current**
- **eRHIC based on RHIC at BNL**
 - 250 (325) GeV polarized p 's (& light ions) and 100 (130)-GeV unpolarized heavy ions
 - **adding a 5-30 GeV ERL with 50-220 mA current**

Large Hadron electron Collider (LHeC)

DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN



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<http://cern.ch/lhec>



A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group

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LHeC Study Group

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Tentative list

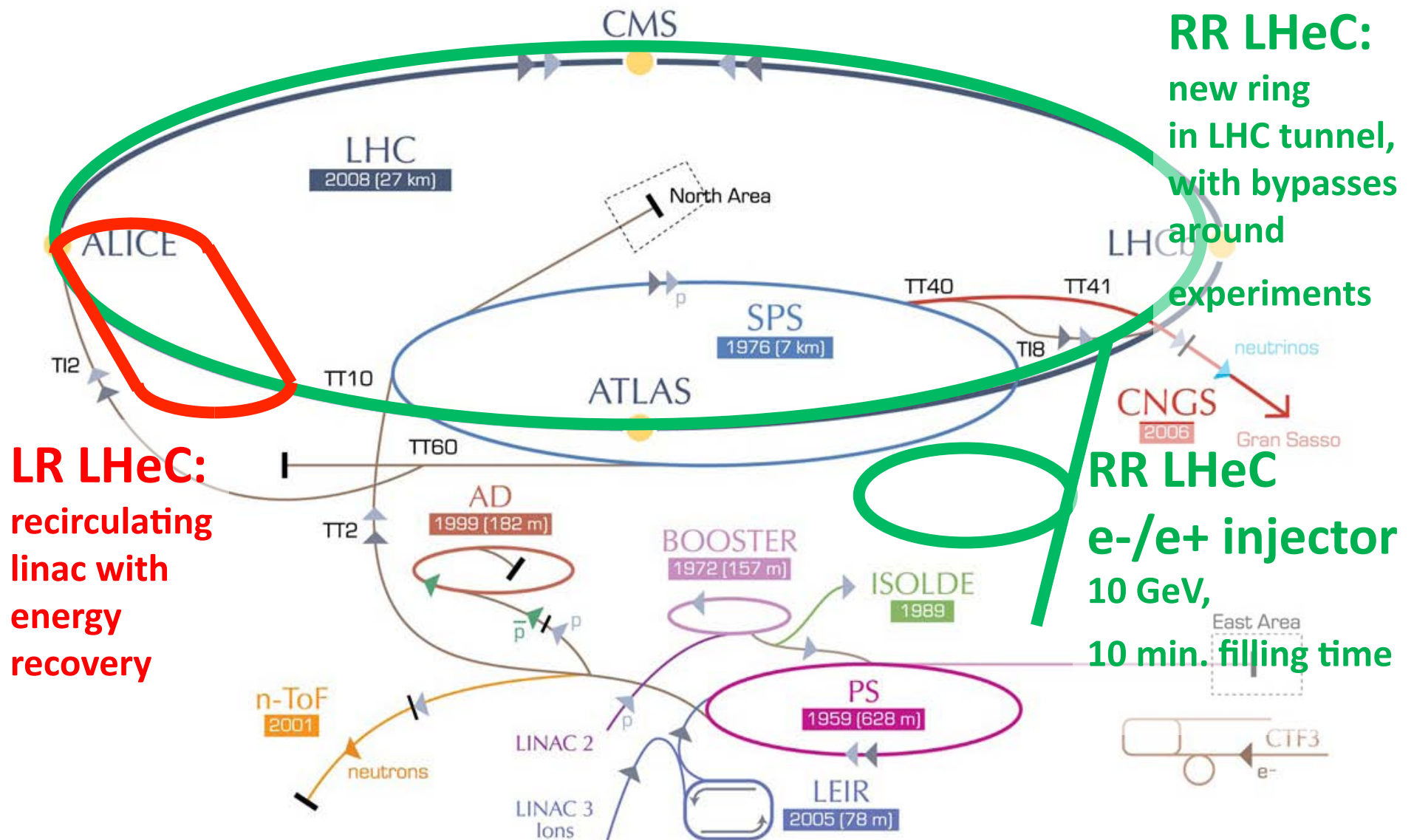
Thanks to all and to
CERN, ECFA, NuPECC

~600 pages

LHeC CDR Accelerator Part: table of contents; 4 chapters; 226 pages

III Accelerator	204
7 Ring-Ring Collider	205
7.1 Baseline parameters and configuration	205
7.2 Geometry	206
7.2.1 General layout	206
7.2.2 Electron ring circumference and e-p synchronization	206
7.2.3 Idealized ring	207
7.2.4 Bypass options	208
7.2.5 Bypass point 1	209
7.2.6 Bypasses point 5	209
7.2.7 Matching proton and electron ring circumference	209
7.3 Layout and optics	210
7.3.1 Arc cell layout and optics	210
7.3.2 Insertion layout and optics	210
7.3.3 Bypass layout and optics	211
7.3.4 Chromaticity correction	211
7.3.5 Working point	212
7.3.6 Aperture	212
7.4 Interaction region layout	226
7.4.1 Beam separation scheme	227
7.4.2 Crossing angle	229
7.4.3 Beam optics and luminosity	231
7.5 Design requirements	232
7.5.1 Detector coverage and acceptance	232
7.5.2 Lattice matching and IR geometry	233
7.6 High luminosity IR layout	234
7.6.1 Parameters	234
7.6.2 Layout of the electron lattice	234
7.6.3 Separation scheme	235
7.7 High acceptance IR layout	235
7.7.1 Parameters	235
7.7.2 Layout	237
7.7.3 Separation scheme	238
7.8 Comparison of the two layouts	238
7.8.1 Crab cavities	239
7.9 Long straight section	240
7.9.1 Dispersion	240
7.9.2 Geometry	240
7.9.3 Electron optics in the LSS	241
7.9.4 Synchrotron radiation	241
7.9.5 LHC integration	242
7.10 The non-colliding proton beam	243
7.10.1 Design elements	243
7.10.2 Solution	244
7.10.3 Summary	246
7.11 Synchrotron radiation and absorbers	247
7.11.1 Introduction	247
7.11.2 High luminosity	249
7.11.3 High detector acceptance	255
7.12 Beam-beam effects in the LHeC	262
7.12.1 Head-on beam-beam effects	262
7.12.2 Long range beam-beam effects	265
7.13 Performance as an electron-ion collider	266
7.13.1 Heavy nuclei, e-Pb collisions	266
7.13.2 Electron-deuteron collisions	267
7.14 Spin polarisation – an overview	268
7.14.1 Self polarisation	268
7.14.2 Suppression of depolarisation – spin matching	271
7.14.3 Higher order resonances	271
7.14.4 Calculations of the e^+ polarisation in the LHeC	272
7.14.5 Spin rotator concepts for the LHeC	274
7.14.6 Further work	275
7.14.7 Summary	276
7.15 Integration and machine protection issues	277
7.15.1 Space requirements	277
7.15.2 Impact of the synchrotron radiation on tunnel electronics	283
7.15.3 Compatibility with the proton beam loss system	283
7.15.4 Space requirements for the electron dump	284
7.15.5 Protection of the p-machine against heavy electron losses	284
7.15.6 How to combine the machine protection of both rings?	285
7.16 LHeC injector for the Ring-Ring option	285
7.16.1 Injector	285
7.16.2 Required performance	286
7.16.3 Source, accumulator and acceleration to 0.6 GeV	287
7.16.4 10 GeV injector	288
8 Linac-Ring Collider	290
8.1 Basic parameters and configurations	290
8.1.1 General considerations	290
8.1.2 ERL performance and layout	291
8.1.3 Polarization	299
8.1.4 Pulsed linacs	299
8.1.5 Higher-energy LHeC ERL option	301
8.1.6 γ -p/A Option	301
8.1.7 Summary of basic parameters and configurations	303
8.2 Interaction region	303
8.2.1 Layout	304
8.2.2 Optics	304
8.2.3 Modifications for γ p or γ -A	311
8.2.4 Synchrotron radiation and absorbers	311
8.3 Linac lattice and impedance	318
8.3.1 Overall layout	318
8.3.2 Linac layout and lattice	320
8.3.3 Beam break-up	326
8.3.4 Imperfections	338
8.3.5 Touschek scattering	339
8.4 Performance as a Linac-Ring electron-ion collider	339
8.4.1 Heavy nuclei, e-Pb collisions	339
8.4.2 Electron-deuteron collisions	339
8.5 Polarized-electron injector for the Linac-Ring LHeC	340
8.6 Spin rotator	342
8.6.1 Introduction	342
8.6.2 LHeC spin rotator options	342
8.6.3 Polarimetry	345
8.6.4 Conclusions and outlook	346
8.7 Positron options for the Linac-Ring LHeC	347
8.7.1 Motivation	347
8.7.2 LHeC Linac-Ring e^+ requirements	348
8.7.3 Mitigation schemes	349
8.7.4 Cooling of positrons	349
8.7.5 Production schemes	350
8.7.6 Conclusions on positron options for the Linac-Ring LHeC	356
9 System Design	357
9.1 Magnets for the interaction region	357
9.1.1 Introduction	357
9.1.2 Magnets for the ring-ring option	357
9.1.3 Magnets for the Linac-Ring option	358
9.2 Arc accelerator magnets	364
9.2.1 RR option, dipole magnets	364
9.2.2 RR option, quadrupole magnets	367
9.2.3 LR option, dipole magnets	372
9.2.4 LR option, quadrupole magnets	372
9.2.5 LR option, corrector magnets for the two 10 GeV linacs	376
9.3 Ring-Ring RF Design	377
9.3.1 Design parameters	377
9.3.2 Cavities and klystrons	377
9.4 Linac-Ring RF design	380
9.4.1 Design parameters	380
9.4.2 Layout and RF powering	381
9.4.3 Arc RF systems	383
9.5 Crab crossing for the LHeC	383
9.5.1 Luminosity reduction	385
9.5.2 Crossing schemes	385
9.5.3 RF technology	385
9.6 Ring-Ring power converters	387
9.6.1 Overview	387
9.6.2 Powering considerations	387
9.6.3 Power converter topologies	387
9.6.4 Main power converters	388
9.6.5 Insertion and by-pass quadrupole power converters	390
9.6.6 Power converter infrastructure	391
9.7 Linac-Ring power converters	391
9.7.1 Overview	391
9.7.2 Powering considerations	391
9.7.3 Linac quadrupole and corrector power converters	391
9.7.4 Recirculation main power converters	393
9.7.5 Power converter infrastructure	393
9.7.6 Conclusions on power converters	394
9.8 Vacuum	395
9.8.1 Vacuum requirements	395
9.8.2 Synchrotron radiation	396
9.8.3 Vacuum engineering issues	398
9.9 Beam pipe design	402
9.9.1 Requirements	402
9.9.2 Choice of materials for beampipes	402
9.9.3 Beampipe Geometries	403
9.9.4 Vacuum instrumentation	405
9.9.5 Synchrotron radiation masks	405
9.9.6 Installation and integration	405
9.10 Cryogenics	406
9.10.1 Ring-Ring cryogenics design	406
9.10.2 Linac-Ring cryogenics design	410
9.10.3 General conclusions cryogenics for LHeC	412
9.11 Beam dumps and injection regions	414
9.11.1 Injection region design for Ring-Ring option	414
9.11.2 Injection transfer line for the Ring-Ring Option	416
9.11.3 60 GeV internal dump for Ring-Ring Option	419
9.11.4 Post collision line for 140 GeV Linac-Ring option	421
9.11.5 Absorber for 140 GeV Linac-Ring option	422
9.11.6 Energy deposition studies for the Linac-Ring option	422
9.11.7 Beam line dump for ERL Linac-Ring option	423
9.11.8 Absorber for ERL Linac-Ring option	423
10 Civil Engineering and Services	424
10.1 Overview	424
10.2 Location, geology and construction methods	424
10.2.1 Location	424
10.2.2 Land features	426
10.2.3 Geology	426
10.2.4 Site development	426
10.2.5 Construction methods	427
10.3 Civil engineering layouts for Ring-Ring	427
10.4 Civil engineering layouts for Linac-Ring	430
10.5 Summary	430

Large Hadron electron Collider



LR LHeC:
recirculating
linac with
energy
recovery

RR LHeC:
new ring
in LHC tunnel,
with bypasses
around
experiments

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

L-R LHeC road map to $10^{33} \text{ cm}^{-2}\text{s}^{-1}$

luminosity of LR collider:

(round beams)

$$L = \frac{1}{4\pi\epsilon} \frac{N_{b,p}}{\epsilon_p} \frac{1}{\beta_p^*} I_e H_{hg} H_D$$

$H_D \sim 1.3$

D. Schulte
LHeC2010

highest proton
beam brightness "permitted"
(ultimate LHC values)

$$\gamma\epsilon = 3.75 \mu\text{m}$$

$$N_b = 1.7 \times 10^{11}$$

bunch spacing
25 or 50 ns

smallest conceivable
proton β^* function:
- reduced I^* (23 m \rightarrow 10 m)
- squeeze only one p beam
- new magnet technology Nb_3Sn

$$\beta_p^* = 0.1 \text{ m}$$

average e^-
current

limited by
energy

recovery
efficiency

$$I_e = 6.4 \text{ mA}$$

maximize geometric
overlap factor
- head-on collision
- small e^- emittance

$$\theta_c = 0$$

$$H_{hg} \geq 0.9$$

LHeC design parameters



*) pulsed, but high energy ERL not impossible

electron beam	RR	LR	LR*
e- energy at IP[GeV]	60	60	140
ep luminosity [$10^{32} \text{ cm}^{-2}\text{s}^{-1}$]	8	10	0.4
eN luminosity [$10^{32} \text{ cm}^{-2}\text{s}^{-1}$]	0.45	1	0.04
polarization for e ⁻ (e ⁺) [%]	40 (40)	90 (0)	90 (0)
bunch population [10^9]	20	1.0	0.8
e- bunch length [mm]	6	0.3	0.3
bunch interval [ns]	25	25	25
transv. emit. $\gamma\epsilon_{x,y}$ [mm]	0.59, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	45, 22	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.87	0.91	0.94
disruption enhancement	1.0	1.3	~1.0
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	100	6.4	5.4
tot. wall plug power[MW]	100	100	100

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit. $\gamma\epsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	4.0, 1.0	0.1
bunch spacing [ns]	25	25

50 ns & $N_b=1.7 \times 10^{11}$
probably conservative

design also for deuterons
(new) and lead (exists)

RR= Ring – Ring

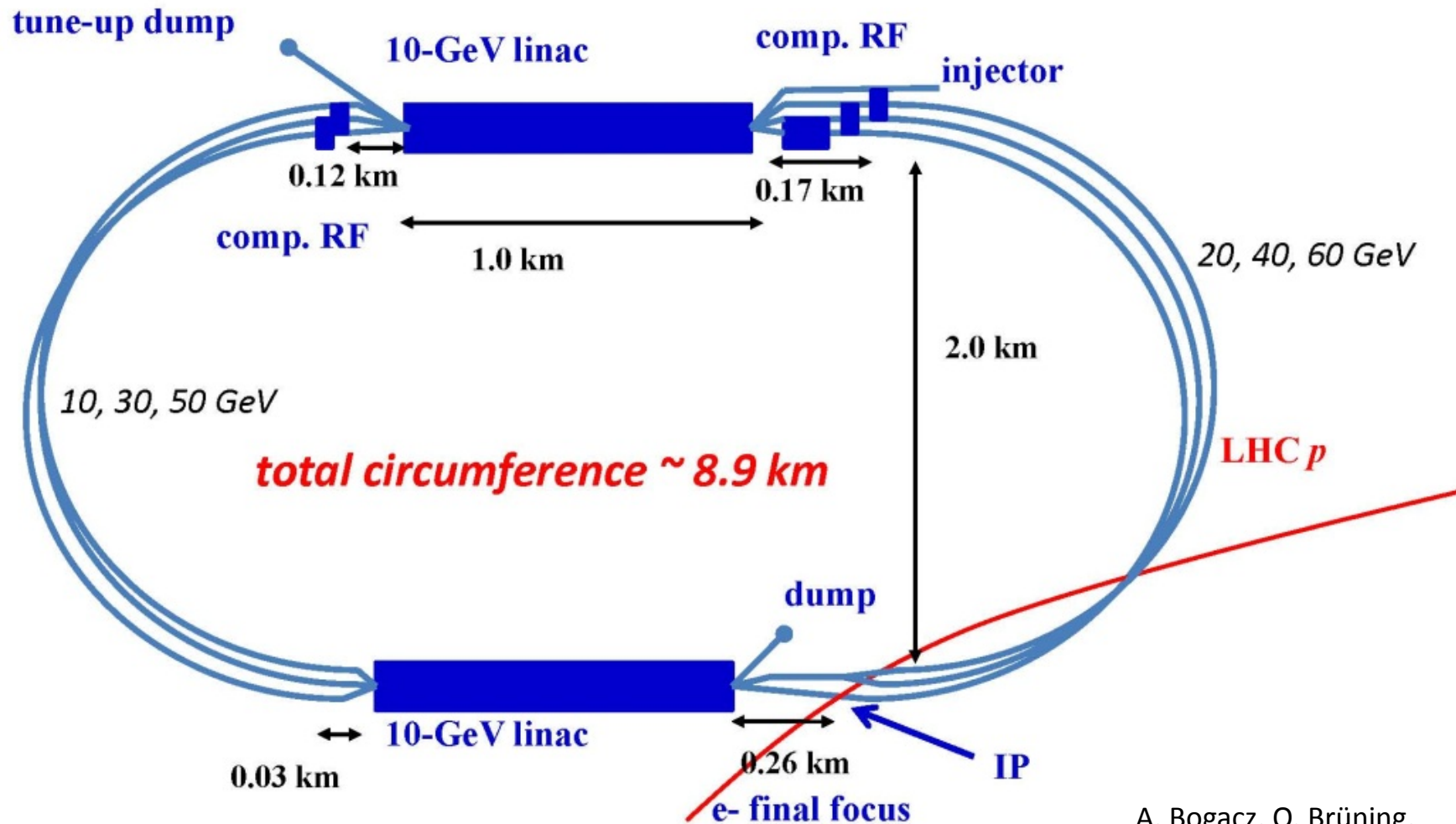
LR =Linac –Ring

higher-L
design exists

$\beta^* \sim 0.025 \text{ m}$ possible in IP3 or 7
using ATS optics (S. Fartoukh);
+ also going to $2 \mu\text{m}$ emittance
(H. Damerau, W. Herr),
 $\rightarrow L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ within reach!

LHeC ERL layout

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV
e-'s collide w. LHC protons/ions

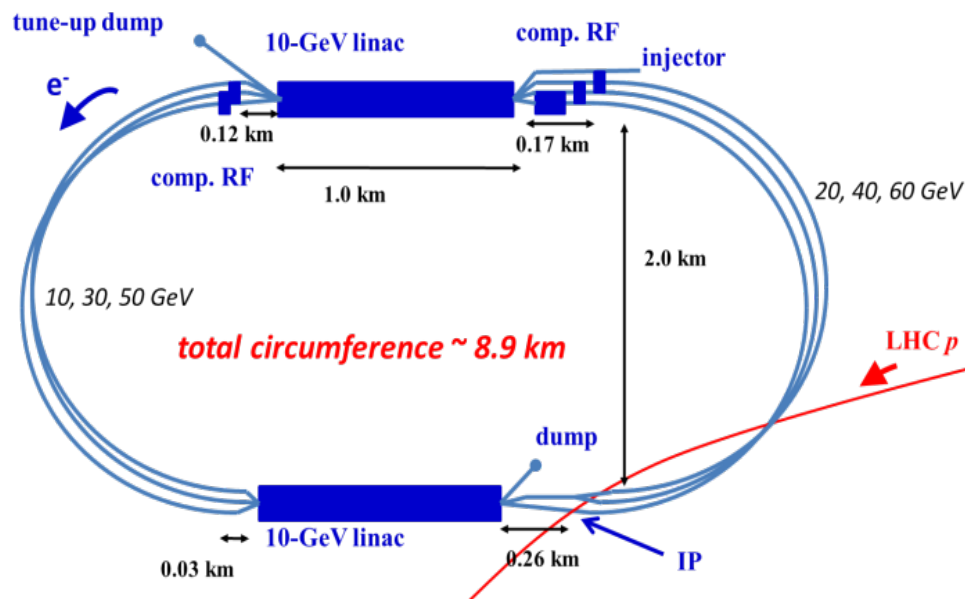


(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning,
M. Klein, D. Schulte,
F. Zimmermann, et al

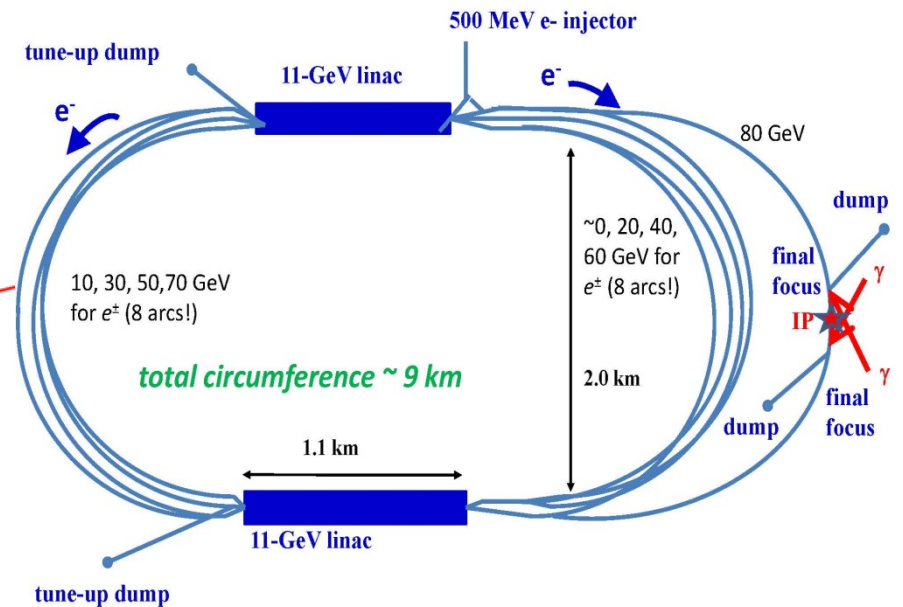
R&D for LHeC SC linac in synergy with many future projects: ILC, ν factory, p -driven plasma acceleration, and Higgs factory $\gamma\gamma$ collider

LHeC-ERL



SAPPHiRE*

$\gamma\gamma$ Higgs factory



*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

collider parameters	eRHIC (ult.)		LHeC (ult.)	
species	e^-	$p, {}^{197}\text{Au}^{97+}$	e^\pm	$p, {}^{208}\text{Pb}^{82+}$
b. energy(/nucleon) [GeV]	15 (30)	325, 130	60	7000, 2760
bunch spacing [ns]	18	18	25, 100	25, 100
bunch intensity(nucl.)[10^9]	24	400, 600	1, 4	170, 25
beam current [A]	0.22 (.01)	3.3, 2.0	0.006	0.58, 0.006
rms bunch length [mm]	2	49	0.6	75.5
polarization [%]	80	70, 0	90 (e^+ 0)	0, 0
norm. rms emittance [μm]	5.8-57	0.2,0.2 CEC	50	3.75, 1.5
$\beta_{x,y}^*$ [m]	0.05	0.05	0.12	0.1
$\sigma_{x,y}^*$ [μm]	6	6, 8	7	7
beam-beam parameter ξ_h		0.015		0.0001
lepton disruption D	52, 22		6	
CM energy [TeV]	140 (197)	88 (125)	1300	810
lum./nucl.[$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	14 (4), 8.2 (2.1)		0.1 , 0.02	

(recirculating) SC linac parameters	eRHIC (BNL)	LHeC
#linacs	2	2
length/linac [km]	0.2	1.0
energy gain / linac [GeV]	2.45	10.0
#acceleration passes	6	3
maximum final energy [GeV]	30	60
real estate gradient [MV/m]	12.45	10.0
energy gain / cavity [MeV]	20.4	20.8
cells / cavity ; cavities / linac	5 ; 120	5 ; 480
RF frequency [MHz]	703.8	721 (or 1300)
cavity length [m]	1.065	1.04
R/Q [linac Ω]	506	570
Q_0 [10^{10}]	4.0	2.5
power loss / cavity [W]	23.7	32
electrical cryopower per linac [MW]	2	10

linac features

LHeC linac 5x longer with 4x the energy gain

(cavity filling factor 0.50 vs 0.64)

eRHIC linac: no focusing

LHeC linac: ~100 quadrupoles

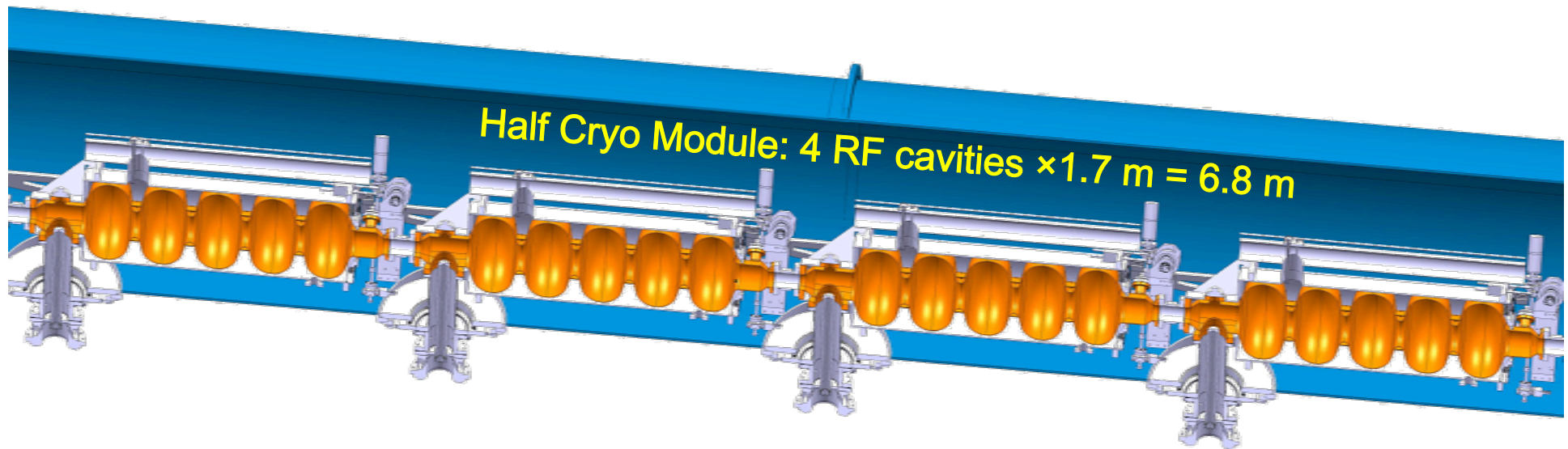
increase multi-pass BBU threshold

LHeC linac quadrupole options:

- electromagnets with indiv. powering
- clustered electromagnets
- permanent magnets

Q_0 : a key parameter !

SPL/LHeC half cryo module - layout/ specs



721.4 MHz RF, 5-cell cavity:

$$\lambda = 41.557 \text{ cm}$$

$$L_c = 5\lambda/2 = 103.89 \text{ cm}$$

grad = 20 MeV/m (20.8 MeV per cavity)

$\Delta E = 80 \text{ MV}$ per Half Cryo Module

Roland Garoby,
Maurizio Vretenar,
Daniel Schulte

LHeC electrical power budget

parameter	electrical power [MW]
total main linac cryopower	21
RF microphonics control	24
extra RF for SR losses	23
extra-RF cryopower	2
e ⁻ injector	6
arc magnets	3
total	78

design constraint: total el. power <100 MW

return arcs: energy loss from
synchrotron radiation

$$\rho=764 \text{ m } (E_{\text{max}}=60 \text{ GeV}), \Delta E_{\text{tot}}=2 \text{ GeV}$$

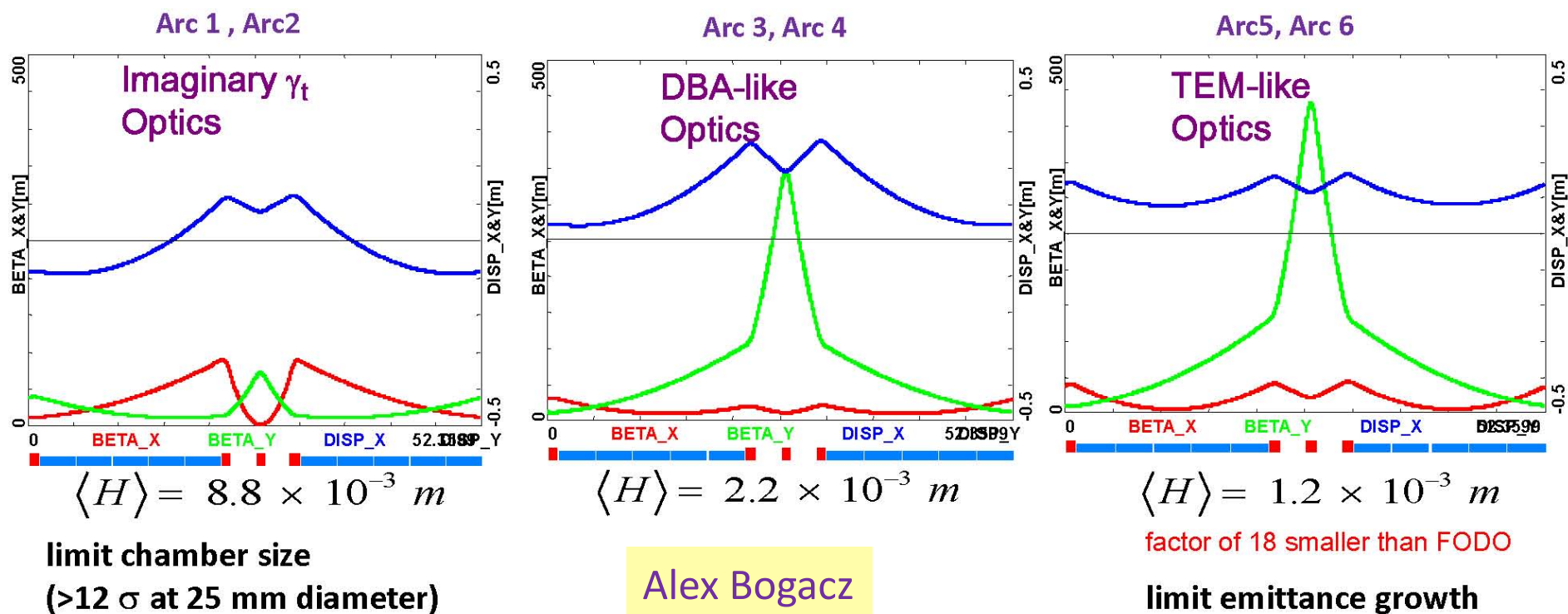
compensation with additional RF systems

750 MV at 60 GeV (721 MHz)

675 MV at lower energy (1.44 GHz)

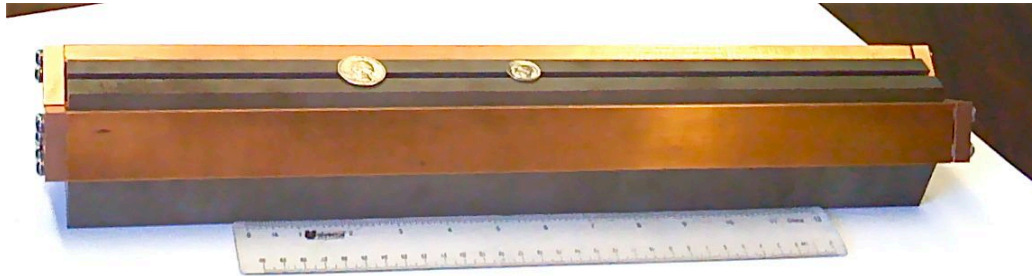
LHeC: 3 passes, flexible momentum compaction arc lattice building block: 52 m long with 2 (10) dipoles & 4 quadrupoles

LHeC flexible momentum compaction cell; tuned for small beam size (low energy) or low $\Delta\varepsilon$ (high energy)



arc magnets

eRHIC dipole model



5 mm gap

max. field 0.43 T (30 GeV)

LHeC dipole model



25 mm gap

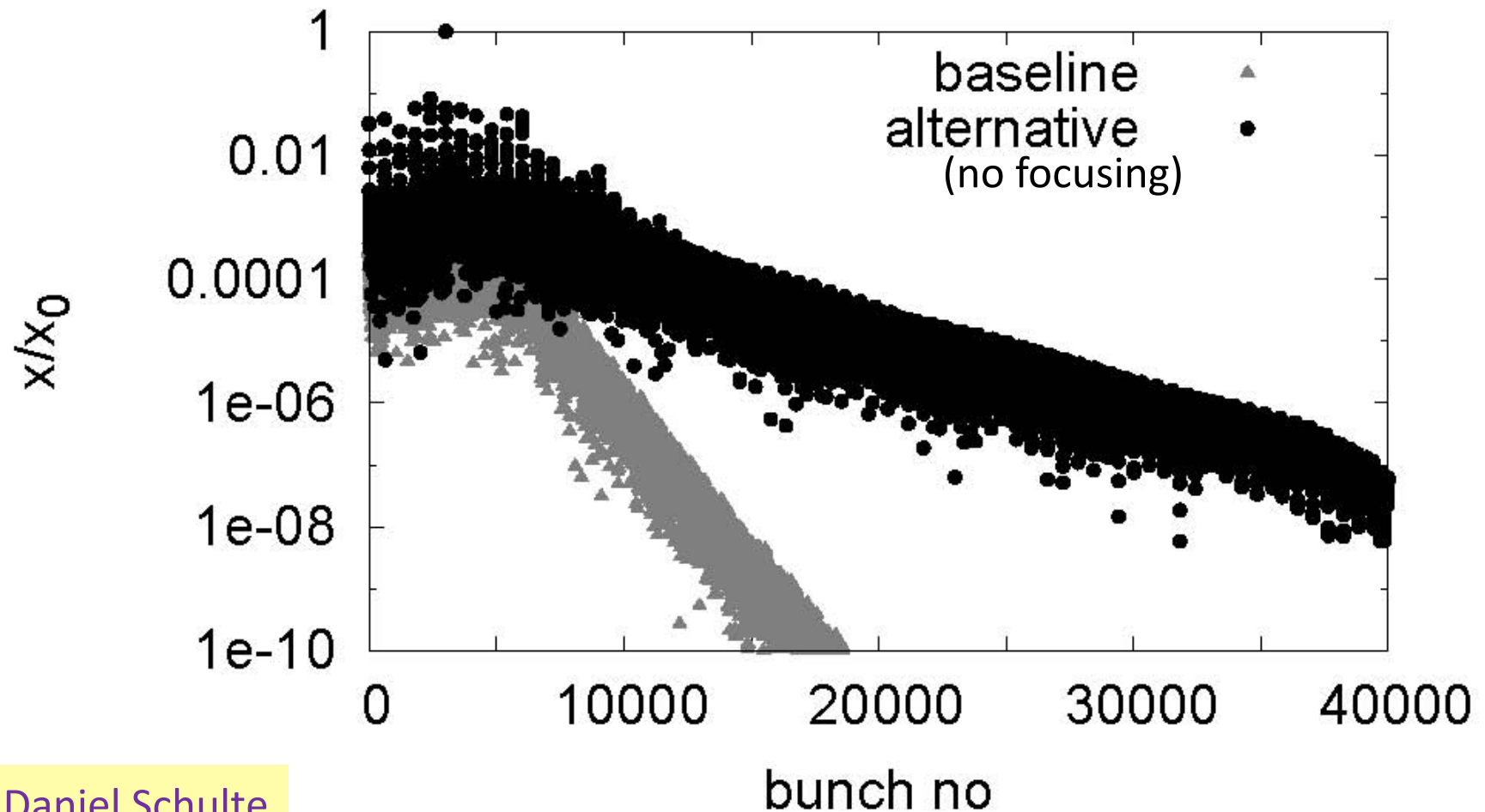
max. field 0.264 T (60 GeV)

ERL beam dynamics

- multi-pass beam break up
 - suppressed by cavity HOM damping & detuning
 - further suppression possible using correlated energy spread & arc chromaticity if needed (V. Litvinenko, PRST-AB 15, 074401 (2012))
- ion accumulation & ion instabilities
 - clearing gaps (circumference choice), excellent vacuum in warm (10^{-9} hPa) and cold regions (10^{-11} hPa)
- others: resistive wall, surface roughness, CSR, Touschek effect

LHeC ERL Multi-Pass Beam-Break Up

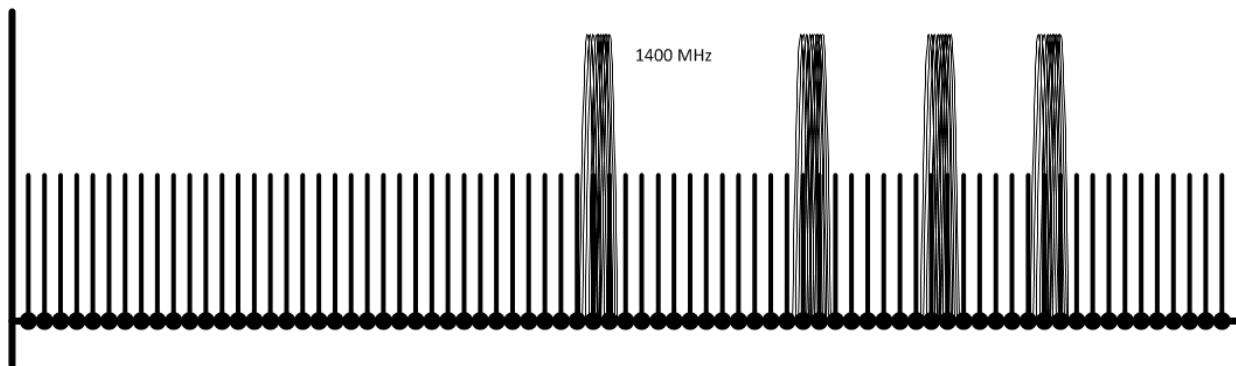
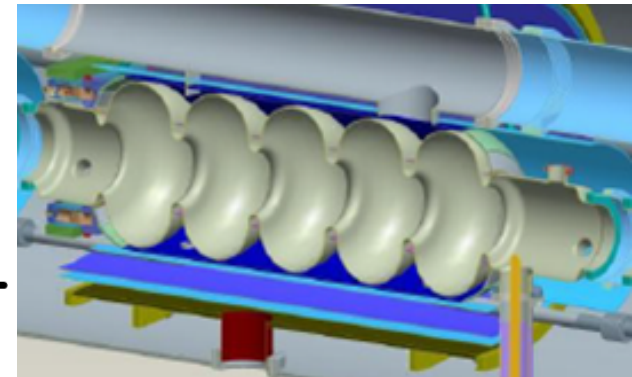
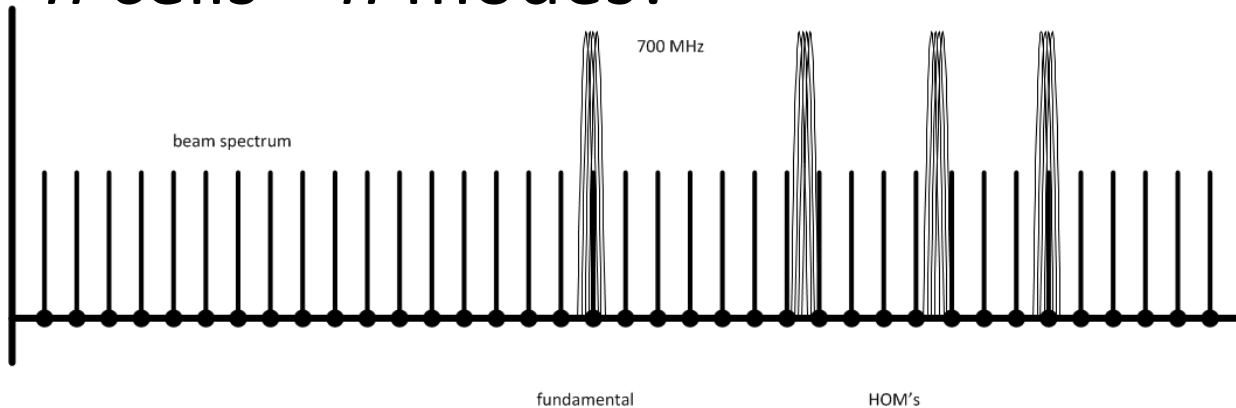
beam stability requires both damping ($Q \sim 10^5$) & detuning ($\Delta f/f_{\text{rms}} \sim 0.1\%$), 720 MHz



scaling 700 MHz \rightarrow 1400 MHz

Erk Jensen

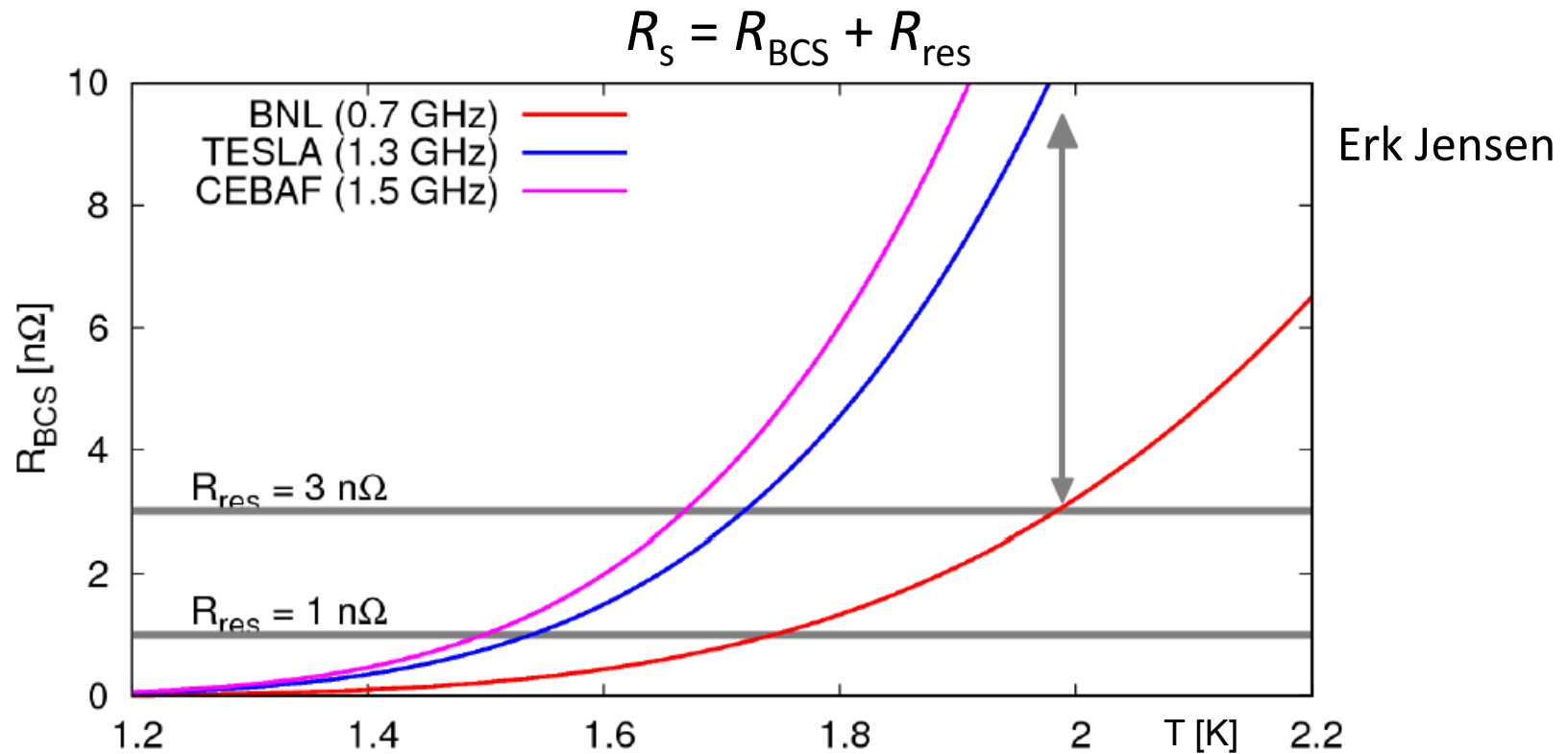
n cells – n modes!



with $\frac{Z_{\perp}}{L} \propto f^2$ (at same offset!) plus the increased number of cells per cavity at higher f :

\rightarrow **beam break-up threshold current decreases as f^{-3} !**

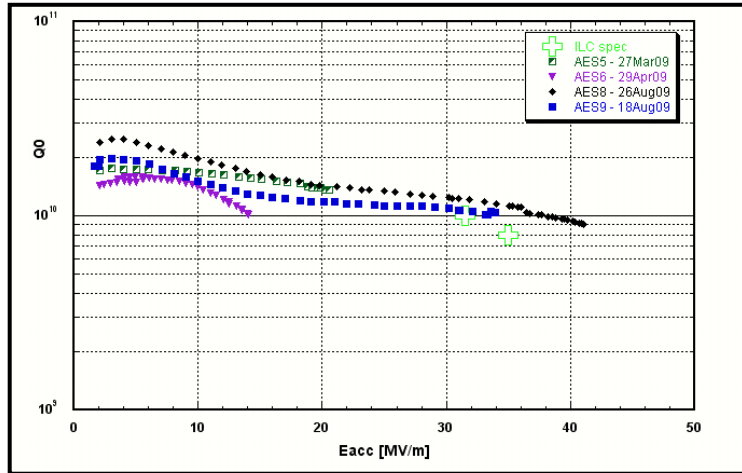
dynamic wall losses



for small R_{res} , these clearly favour smaller f

one should aim for very large Q_0

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



Erk Jensen

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

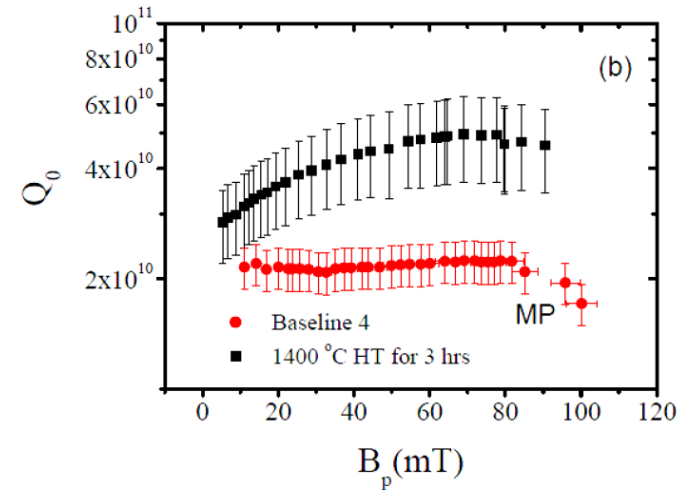
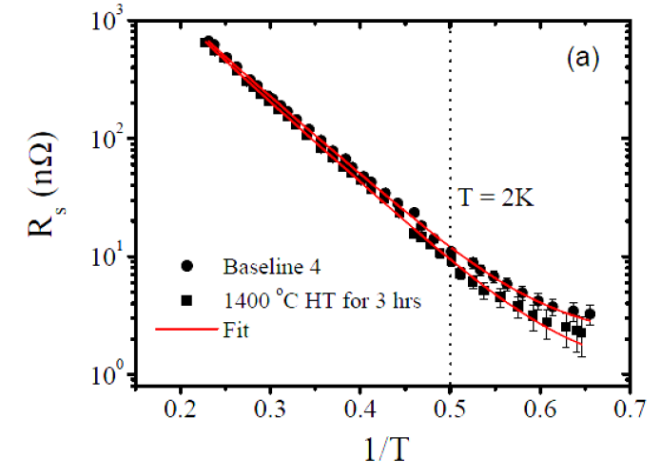
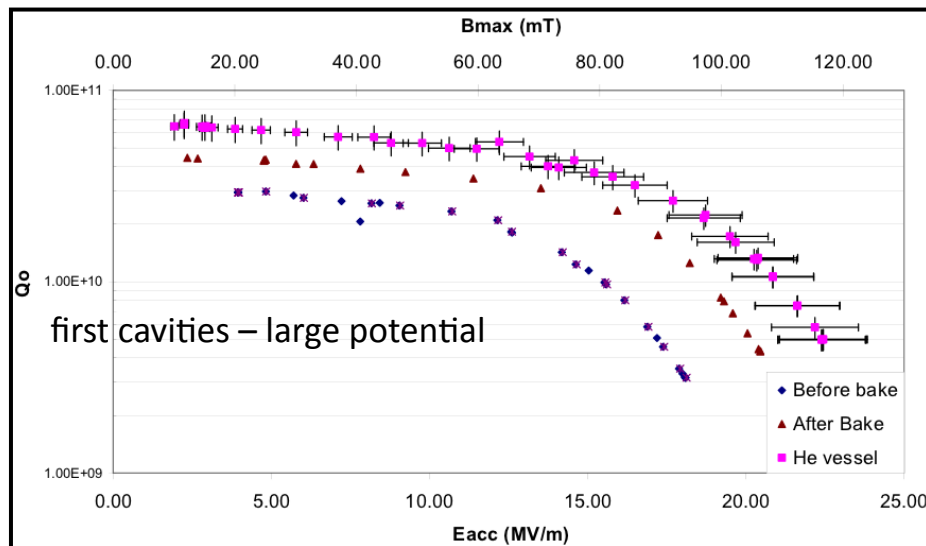


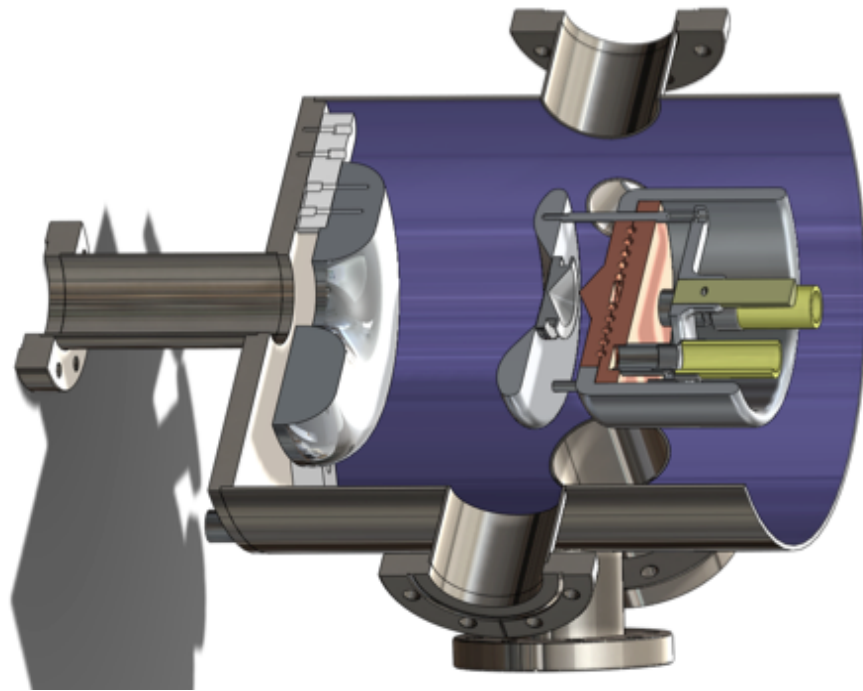
Figure 2: (a) Surface resistance R_s as a function of temperature before and after 1400 °C heat treatment. (b) $Q_0(B_p)$ measured at 2.0 K. The tests were limited by quench.

JLAB, 1.5 GHz, (Dhakal, Ciovati, Myneni 2012:
<http://arxiv.org/abs/1205.6736>

source e^- beam parameters

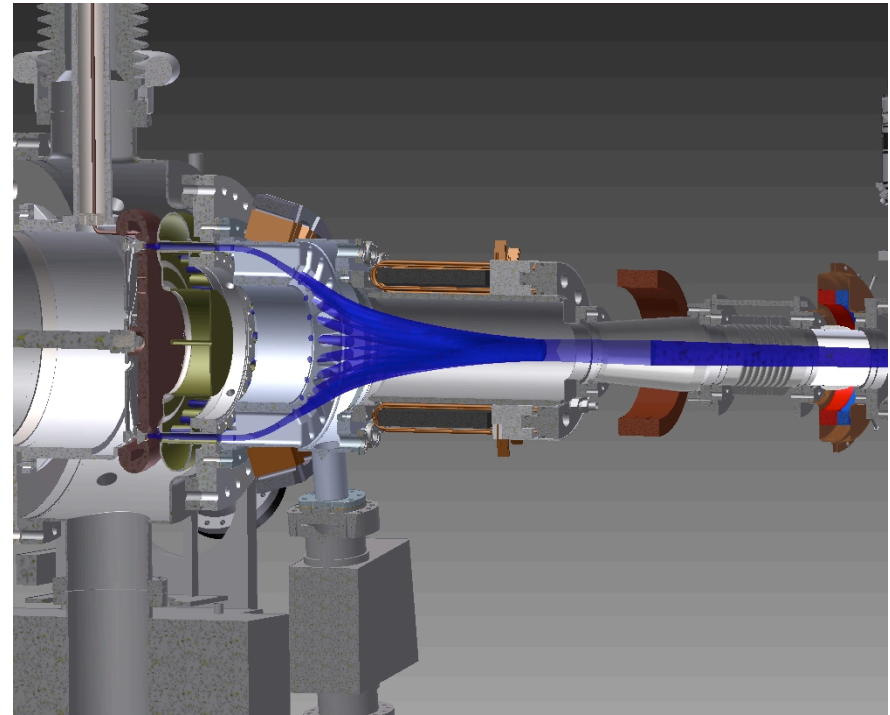
parameter	eRHIC	LHeC
e^- /bunch [10^9]	5.6, 24	1.1
charge / bunch [nC]	0.9, 3.8	0.18
rms bunch length [mm]	2	3-30
bunch spacing [ns]	18	25
average current [mA]	50, 220	7
bunch peak current [A]	50, 200	7-70
polarization	85-90%, none	>90%

eRHIC polarized electron gun - candidates



large-sized GaAs cathode gun

Evgeni Tsentalovich

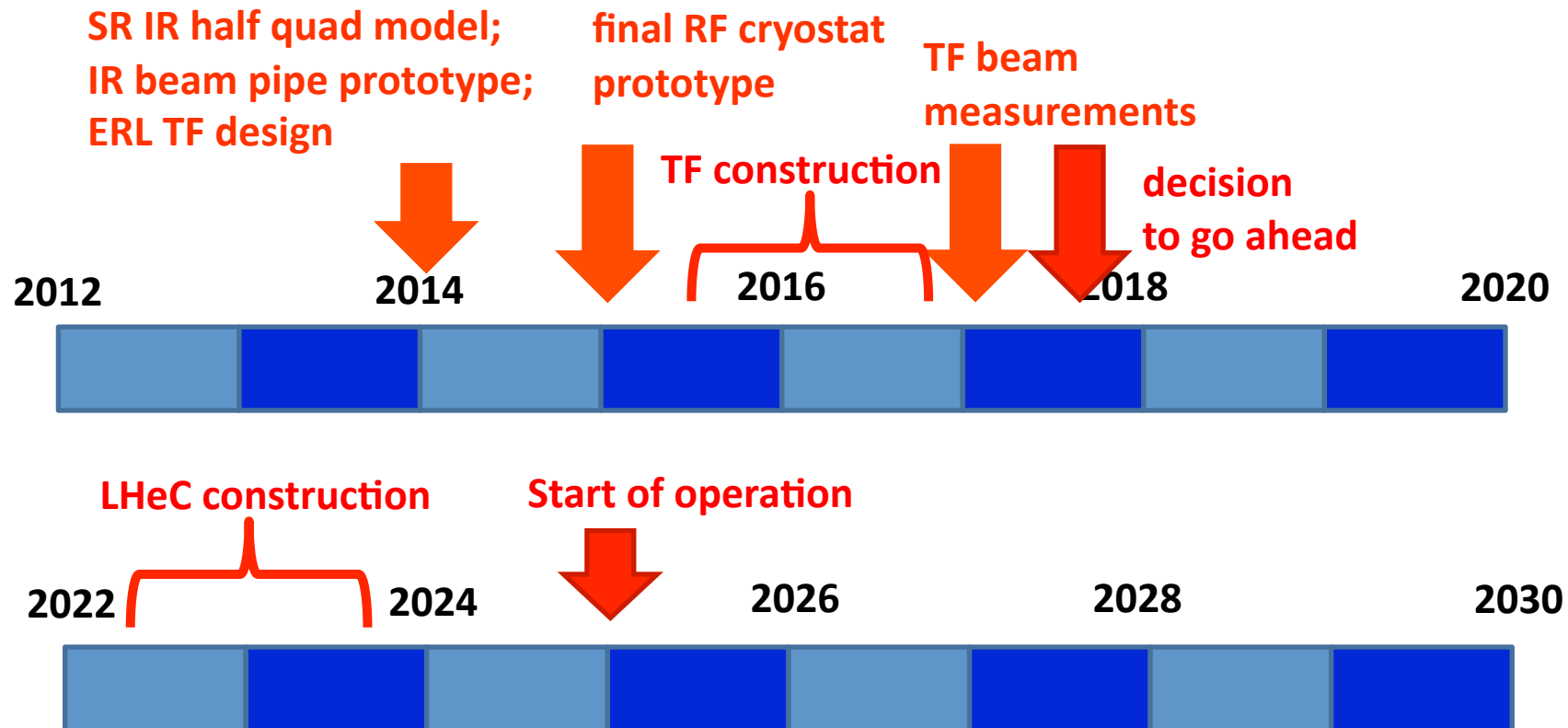


Gatling gun, combing beams from an array of 24 GaAs cathodes

Vladimir Litvinenko

LHeC R&D items & possible time line

SC IR final “half quadrupole”; IR beam pipe ;
RF cryostat including cavity & coupler ;
dedicated **LHeC ERL test facility** ; proto collaboration for **detector**



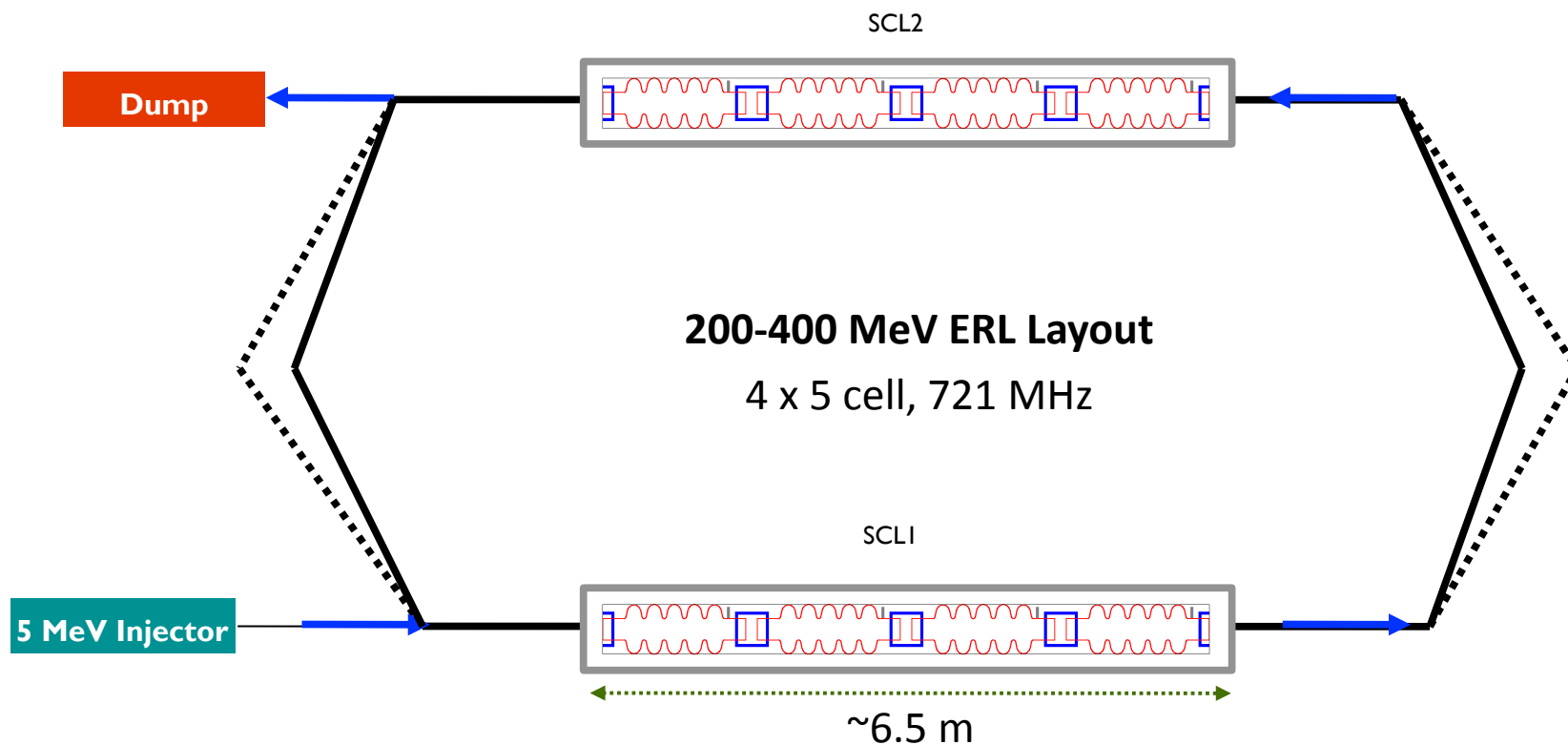
R. Calaga,
E. Ciapala,
E. Jensen,
J. Tückmantel

ERL Test Facility at CERN



- ERL demonstrator, FEL, γ -ray source, e-cooling demo
- one of the 1st low-frequency multi-pass SC-ERLs
- e-cooling (@PS/SPS energies)
- ultra-short electron bunches
- strong synergy with SPL-ESS & BNL activities
- high energies & CW (100 – 400 MeV) & CW
- multi-cavity cryomodule layout - validation + gymnastics
- MW class power coupler tests in non-ER mode (vector feedback?)
- complete HOM characterization and instability studies
- cryogenics & instrumentation test bed
- a place to work, to practice and to train people

ERL-Test Facility (TF) at CERN



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

LINAC :

Half Cryo Module → 4 Cavities

721.44 MHz RF, 5-cell cavity:

$$\lambda = 41.557 \text{ cm}$$

$$L_c = 5\lambda/2 = 103.89 \text{ cm}$$

Grad = 18 MeV/m (18.7 MeV per cavity)

$\Delta E = 74.8 \text{ MV}$ per Half Cryo Module

Alessandra Valloni

ARC 1 OPTICS : 4 x 45° sector bends

(80 MeV)

Dipole + Quads triplet + Dipole + Quad singlet + Dipole + Quads triplet + Dipole



Dipole Length = 40cm B = 5.01 kG

Quadrupole Length = 10 cm

Q1 → G[kG/cm] = -0.31

Q3 → G[kG/cm] = -0.34

Q2 → G[kG/cm] = 0.50

Q4 → G[kG/cm] = -0.44

VERTICAL SPREADER OPTICS:

Spreader for Arc 1 @ 80 MeV

2 Vertical steps (dipoles with opposite polarity) and quads triplet for hor. and vert. focusing

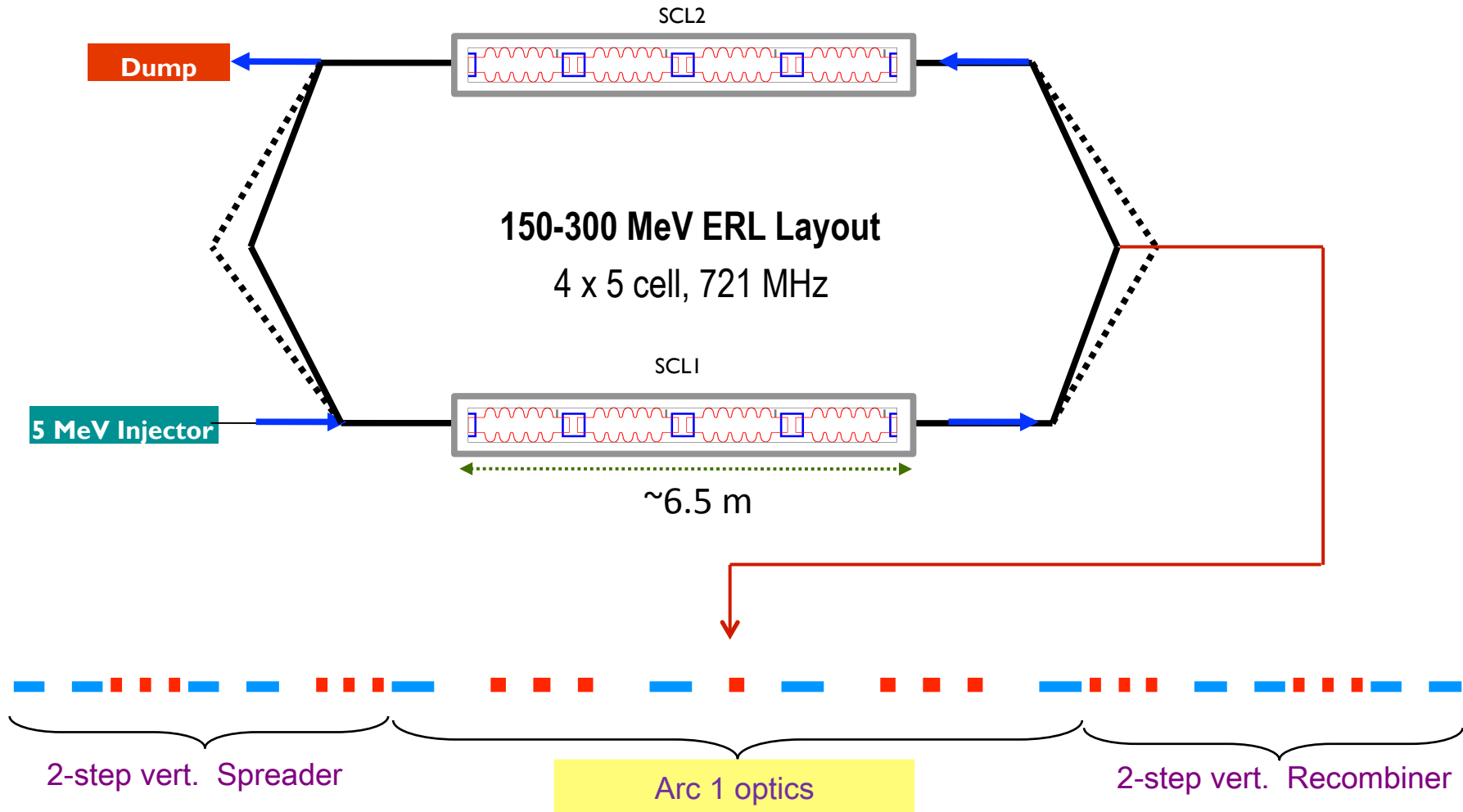


Spreader for Arc 3 @ 230 MeV

A vertical chicane plus and 2 quads doublets



ARC 1 + VERTICAL SPREADER AND COMBINER OPTICS



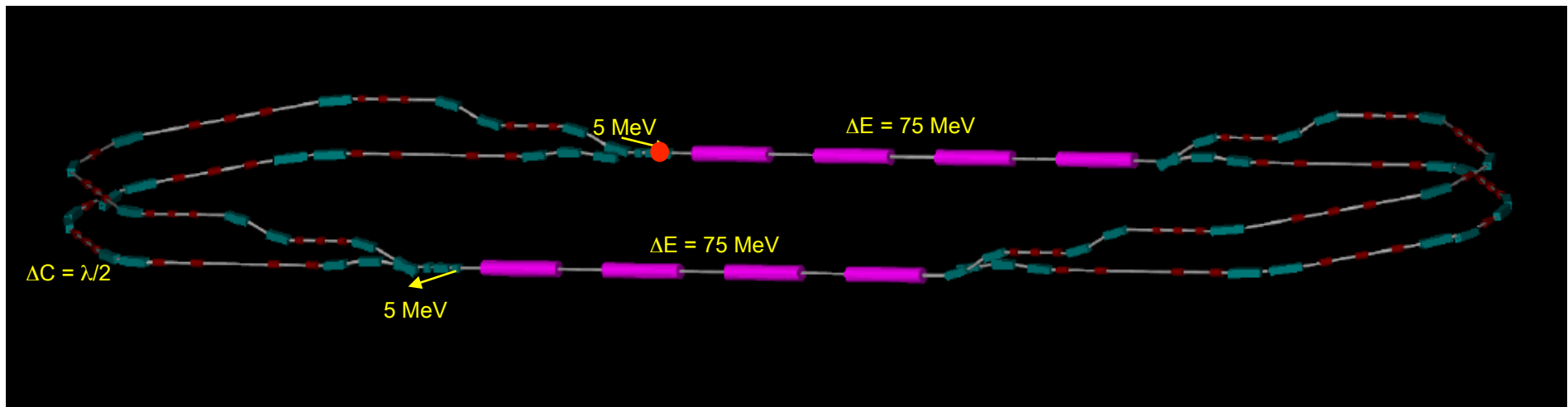
Alessandra Valloni

CERN oPAC fellow Alessandra Valloni – just started

near-term work plan:

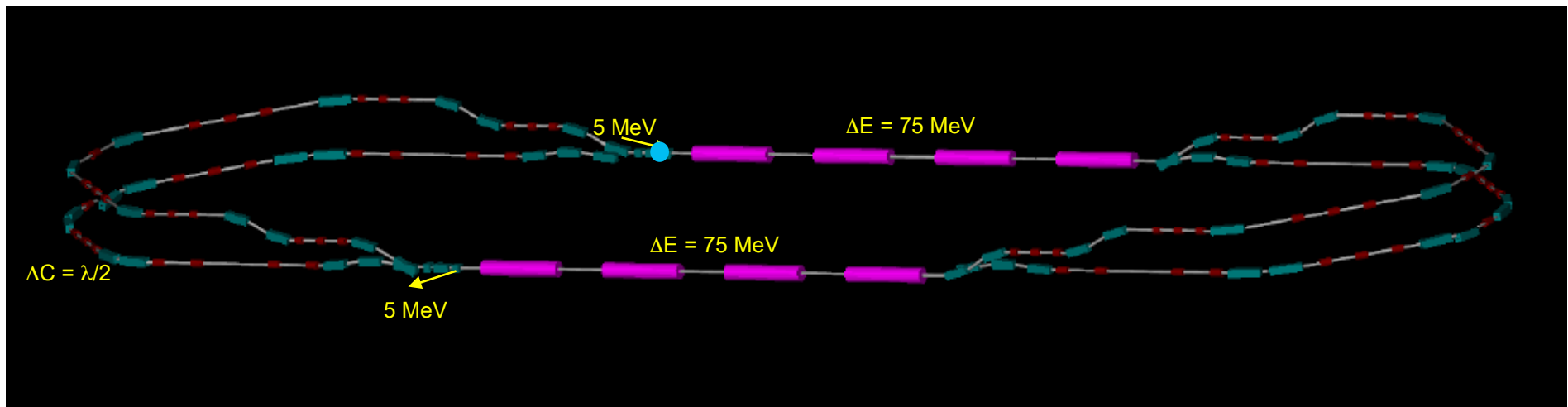
- getting comfortable with OptiM code (JLAB, FNAL)
- writing OptiM input files for ERL-TF in order to reproduce Alex Bogacz 's results for ERL-TF
- doing/understanding calculations on adverse effects in the arc optics design (cumulative emittance and momentum-spread growth due to synchrotron radiation, wake fields, ions, CSR, etc.)
- trying to understand all the beam dynamics challenges for the LHeC ERL in order to figure out parameters for the TF

ERL-TF (300 MeV) – Layout



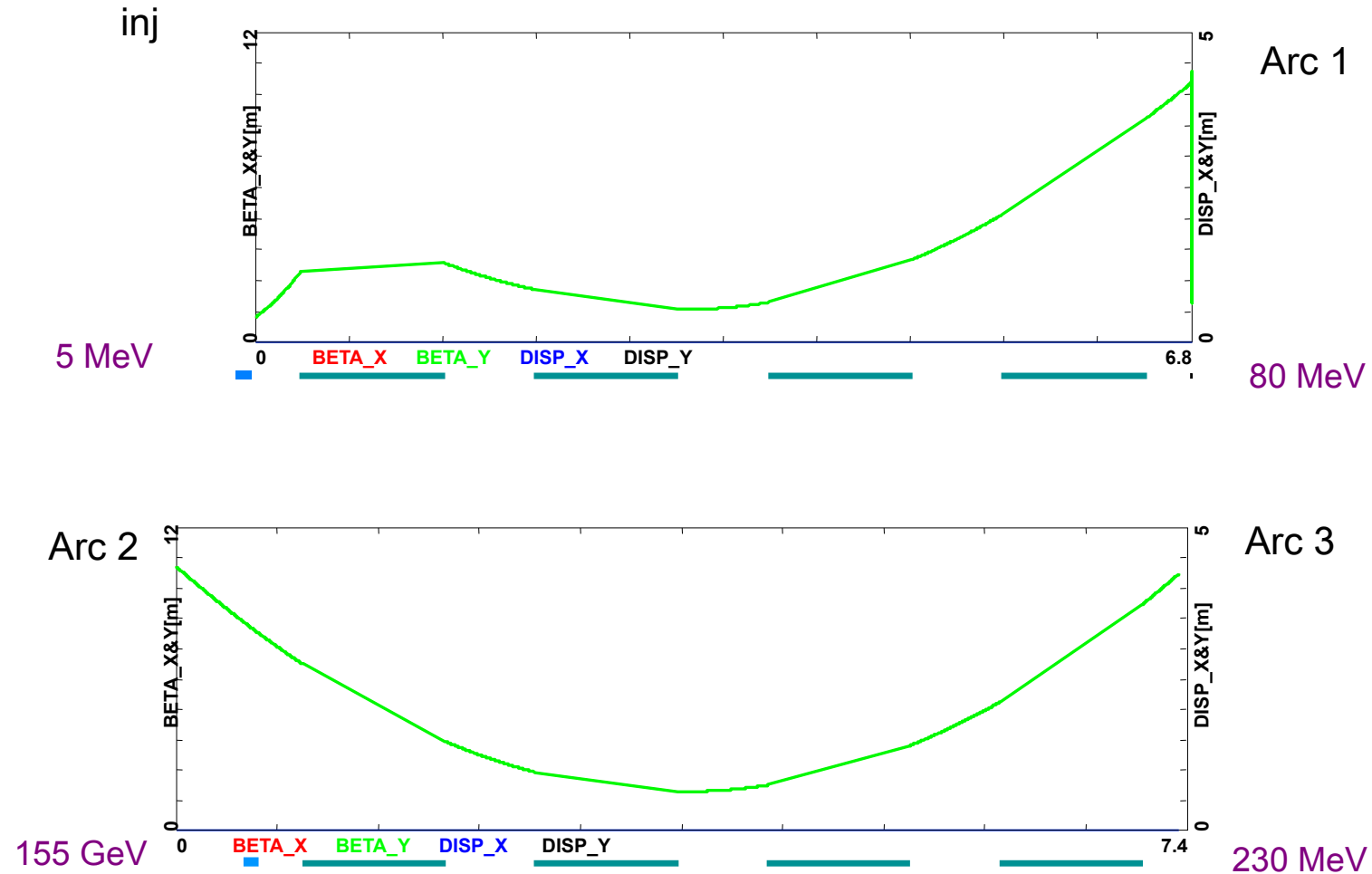
Two passes 'up' + Two
passes 'down'

ERL-TF (300 MeV) – Layout



Two passes 'up' + Two passes 'down'

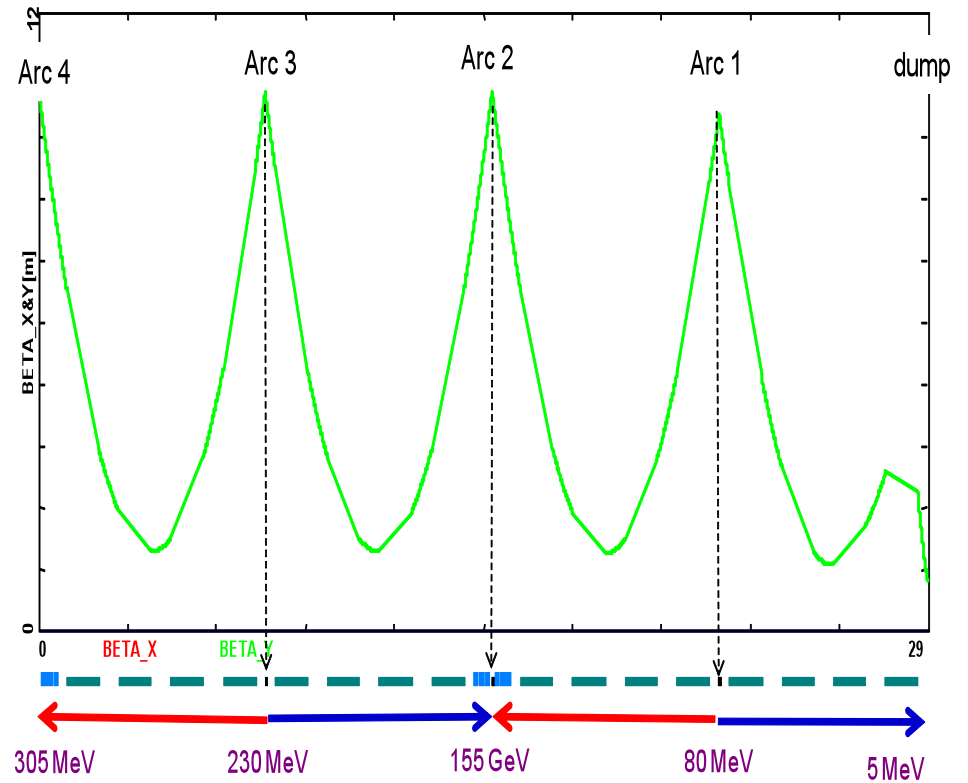
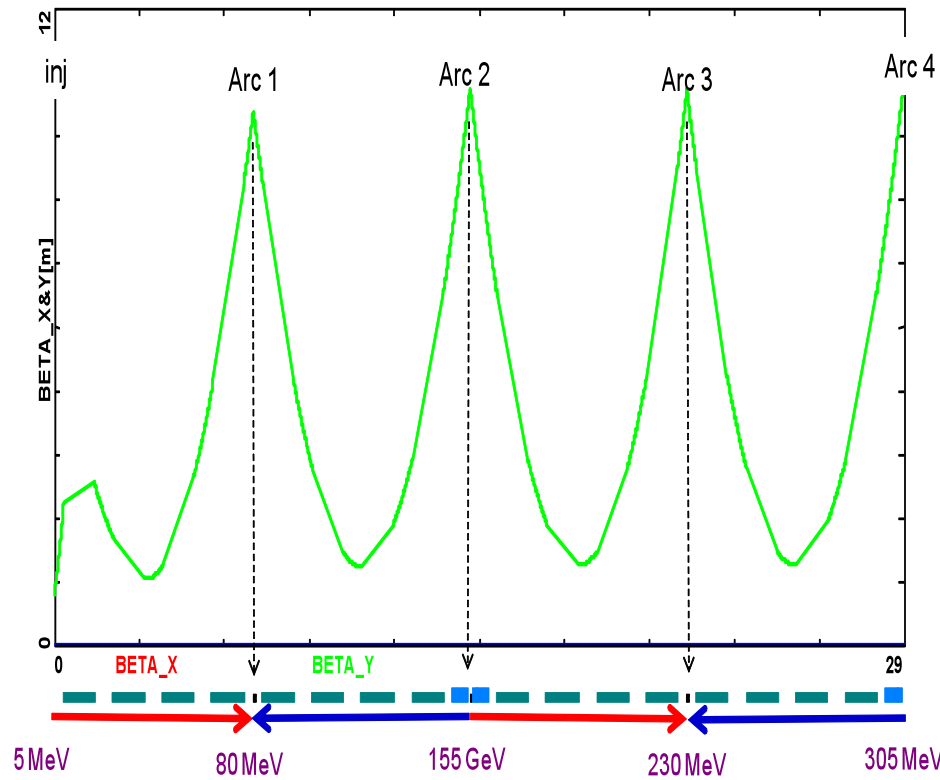
Linac 1 – Multi-pass Optics



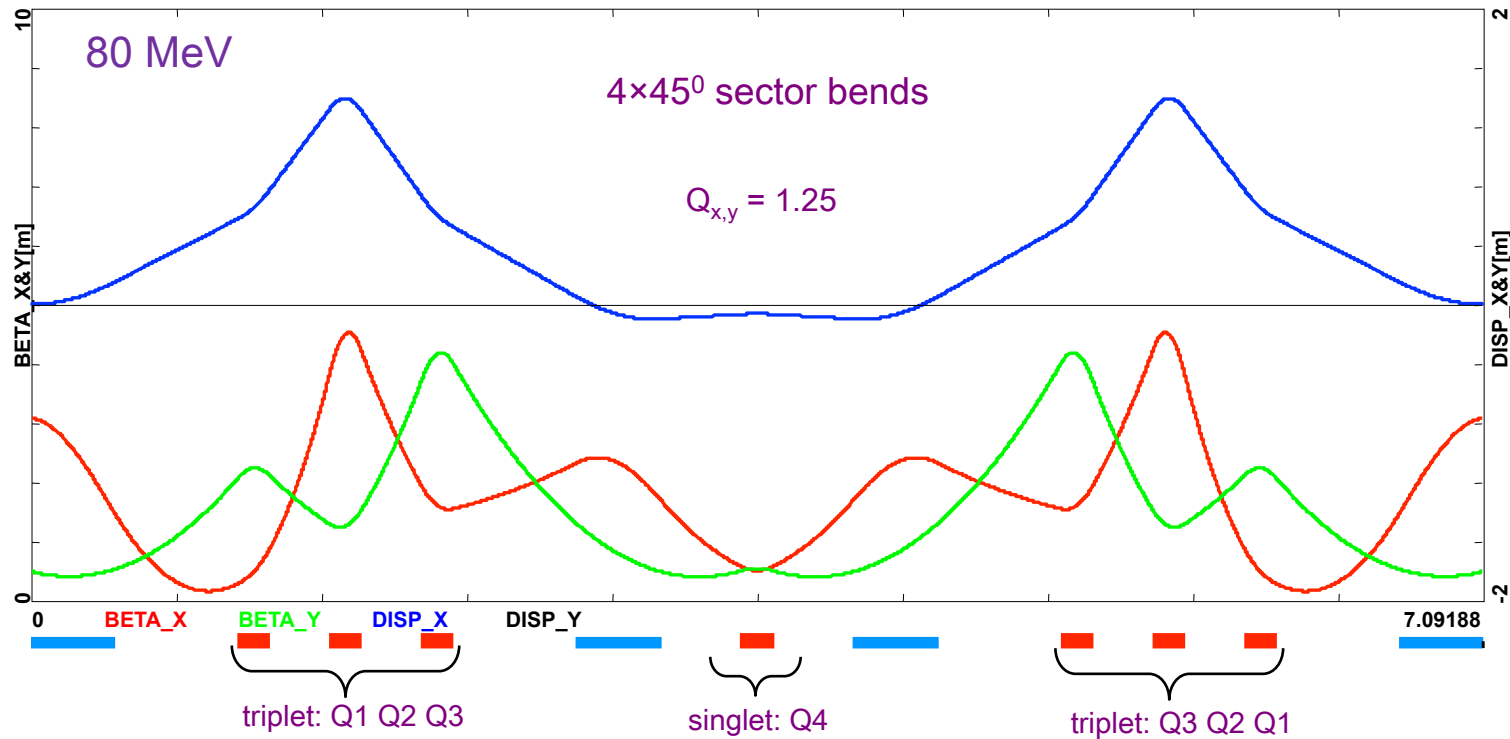
Linac 1 & 2 – Multi-pass ER Optics

Linac 1

Linac 2



Arc 1 Optics – FMC Lattice



dipoles (40 cm long)

B = 5.01 kGauss

quadrupoles (10 cm long)

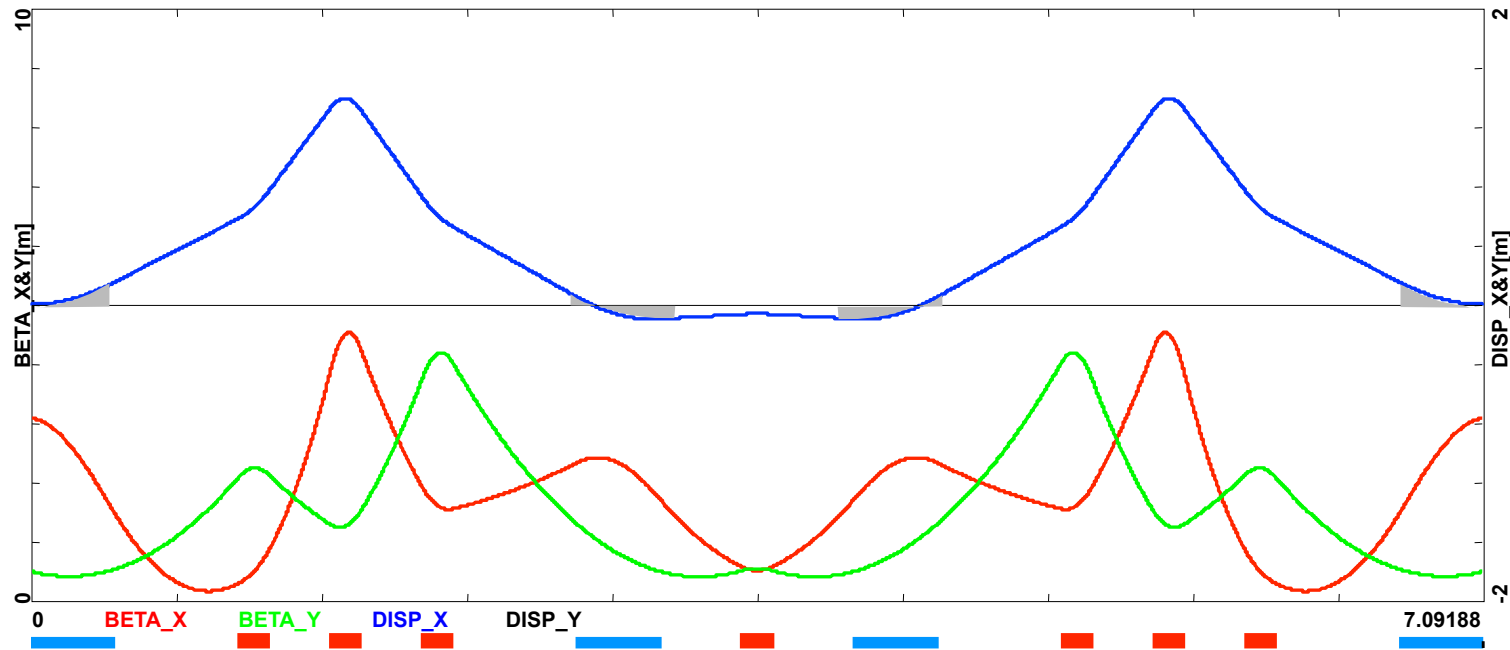
Q1 G[kG/cm] = -0.31

Q2 G[kG/cm] = 0.50

Q3 G[kG/cm] = -0.34

Q4 G[kG/cm] = -0.44

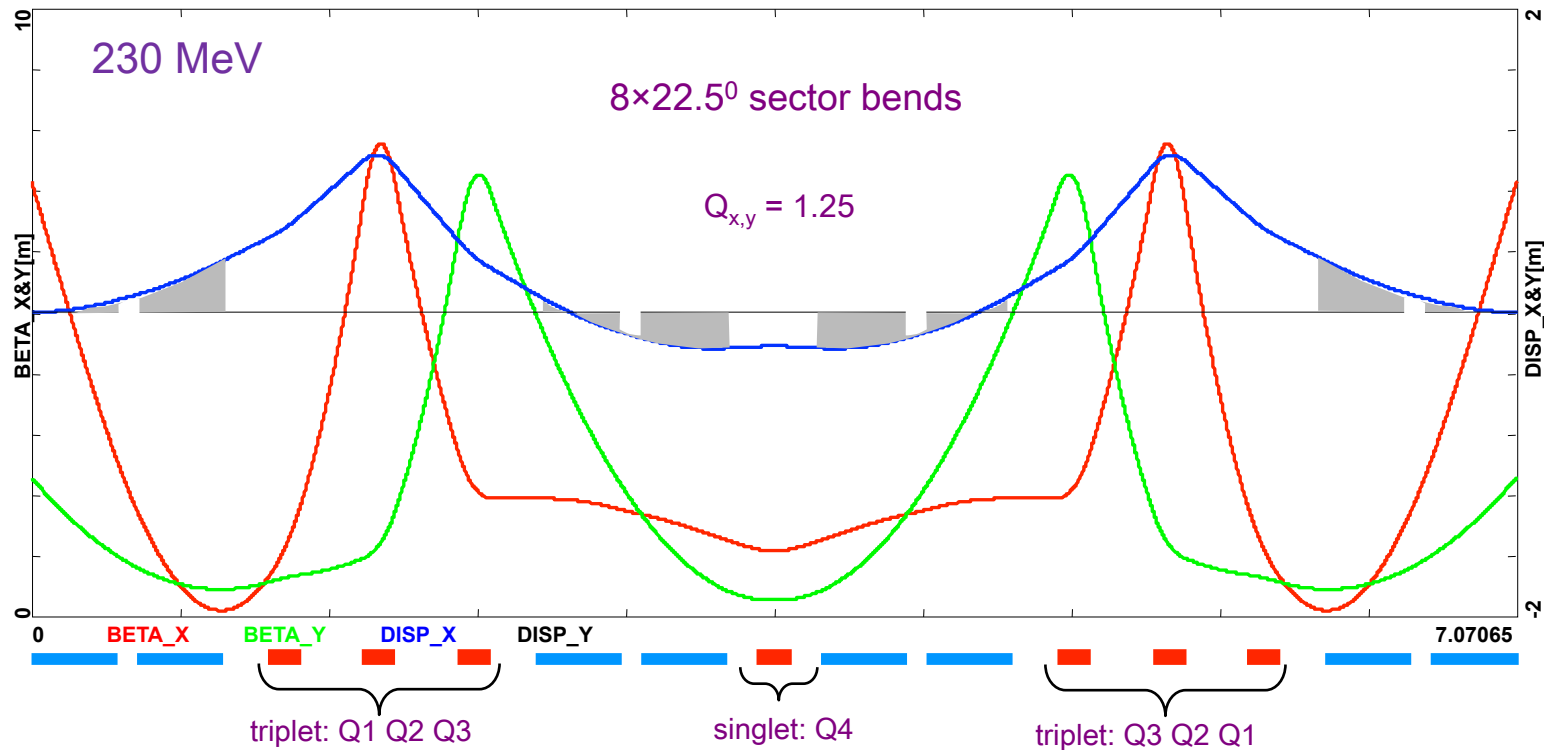
Arc 1 Optics – Isochronous Lattice



- Synchronous acceleration in the linacs \Rightarrow Isochronous optics:

$$M_{56} = I_1 = \int_0^L \frac{D}{\rho} ds \quad I_1 = 0$$

Arc 3 Optics – FMC Lattice



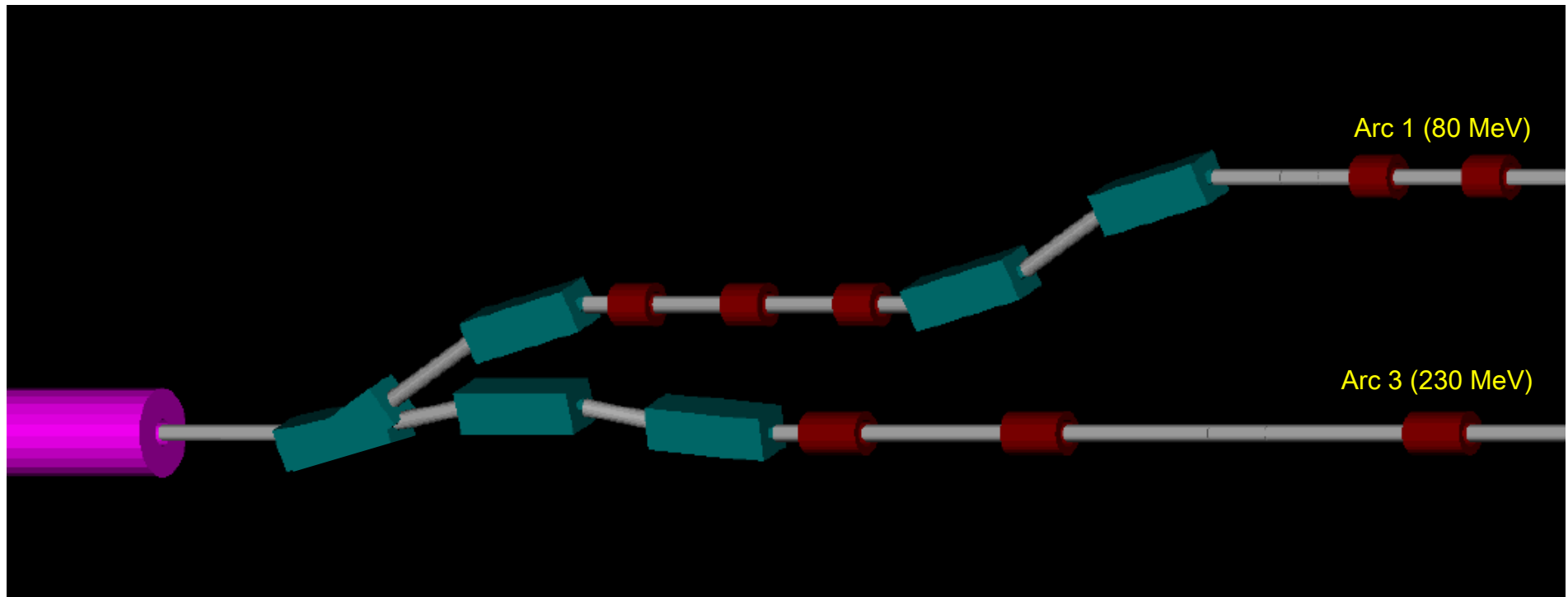
dipoles (40 cm long)

B = 7.47 kGauss

quadrupoles (15 cm long)

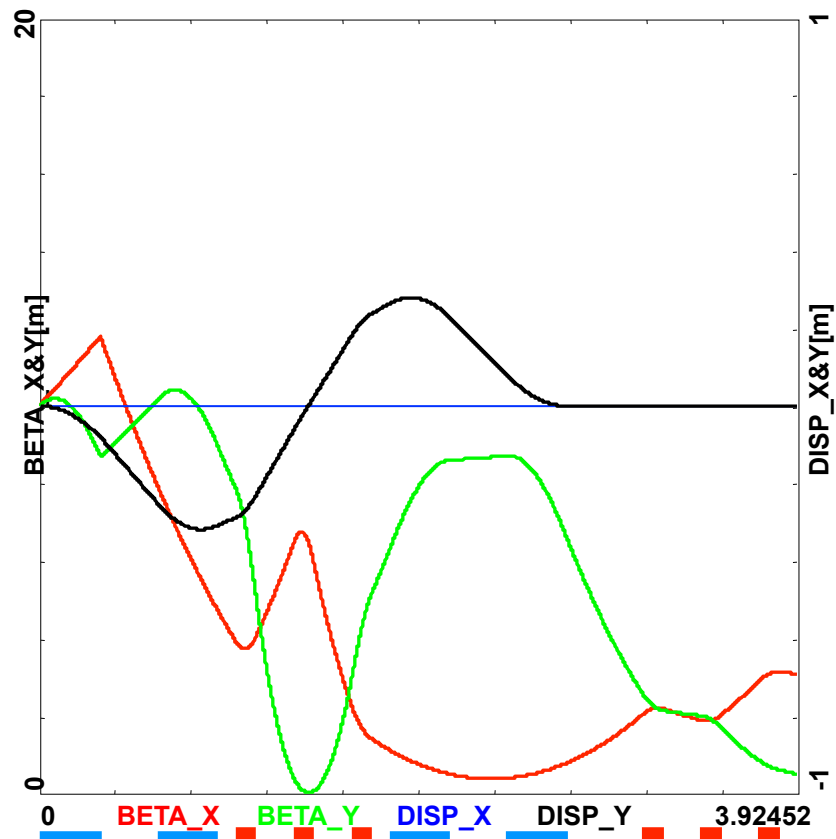
Q1	G[kG/cm] = -0.47
Q2	G[kG/cm] = 1.43
Q3	G[kG/cm] = -1.14
Q4	G[kG/cm] = -0.34

Switchyard - Vertical Separation of Arcs



Vertical Spreaders - Optics

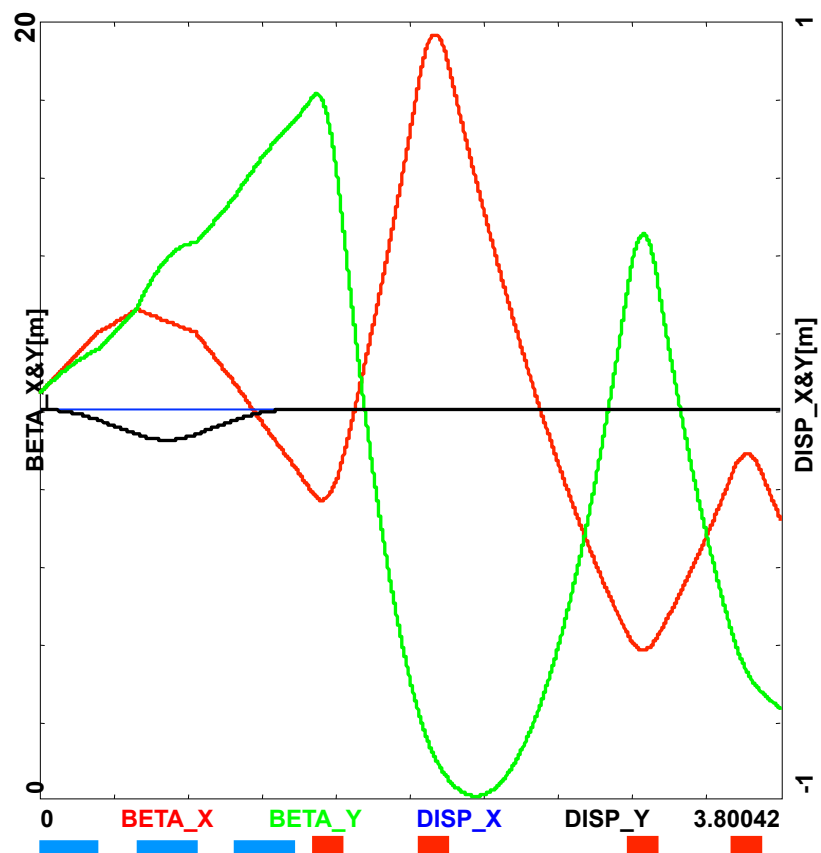
Spr. 1



vertical step I

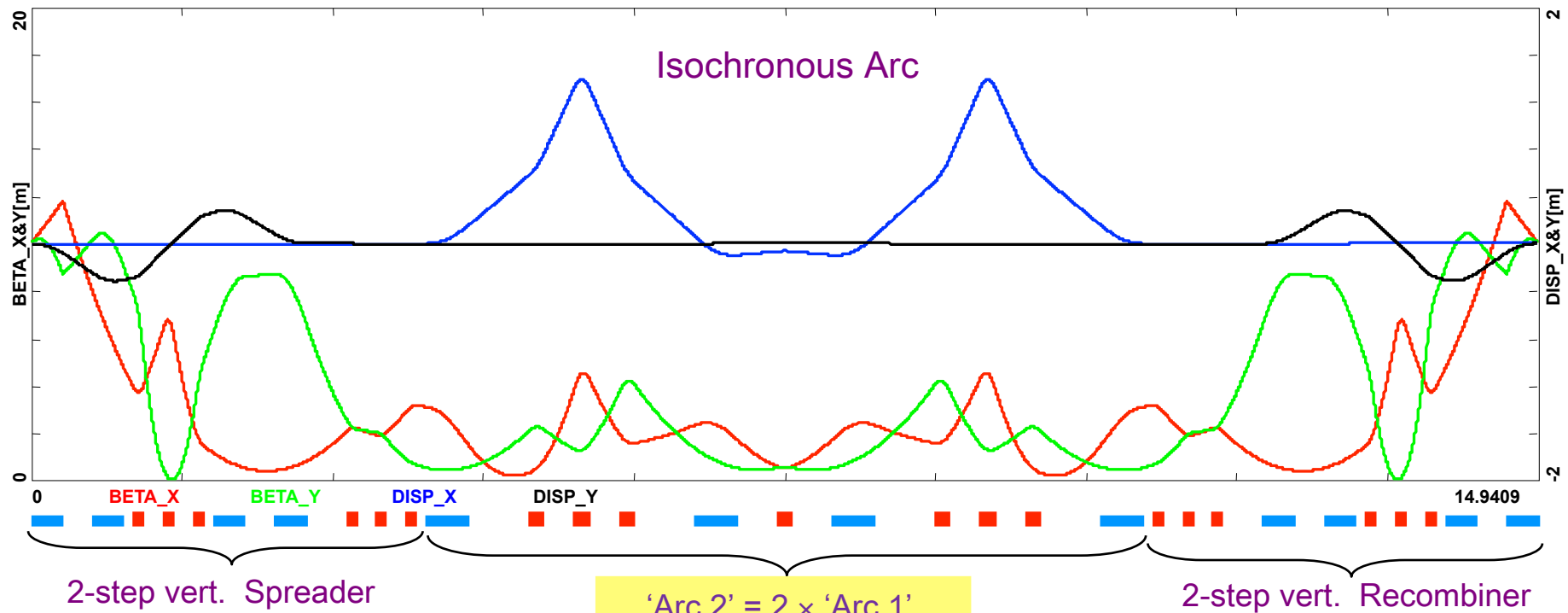
vertical step II

Spr. 3



vertical chicane

Arc 1 Optics (80 MeV)



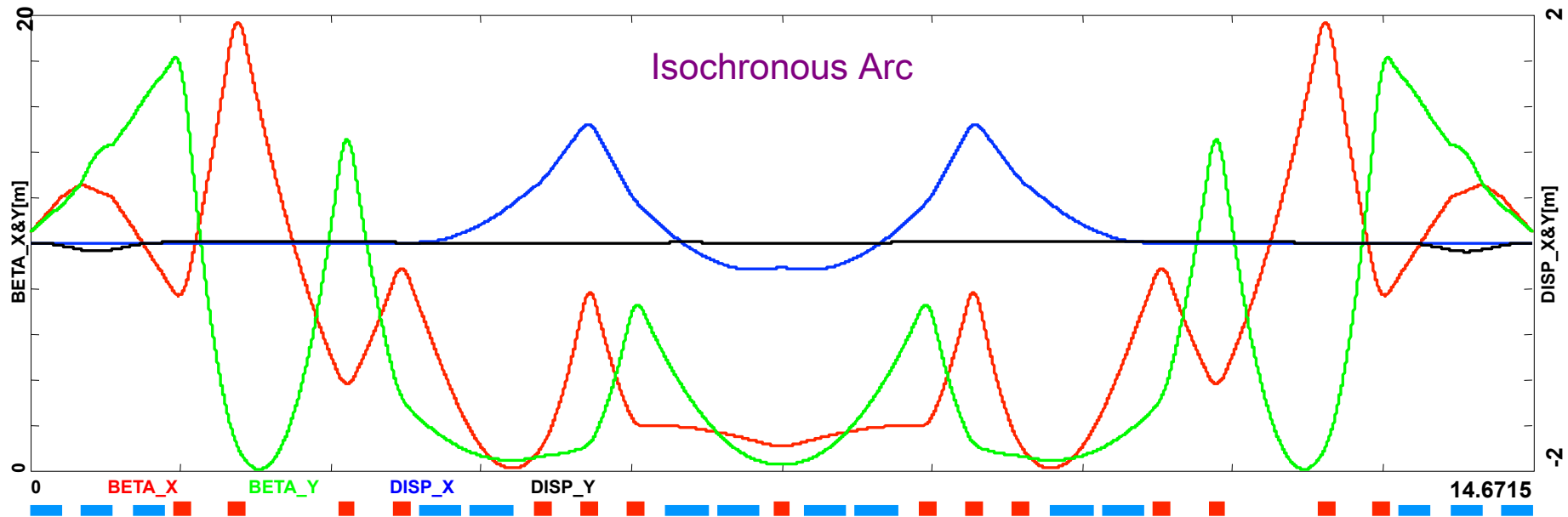
Spr. dipoles:
 30° bends (1 rec. + 3 sec.)
 Lb = 30 cm
 B = 5 kGauss

Arc dipoles :
 4×45° bends(sec.)
 Lb = 40 cm
 B = 5 kGauss

Rec. dipoles:
 30° bends (3 sec. + 1 rec.)
 Lb = 30 cm
 B = 5 kGauss

quads: Lq = 10-15 cm G ≤ 0.6 kGauss/
 cm

Arc 3 Optics (230 MeV)



Chicane vert. Spreader

'Arc 4' = $\frac{4}{3} \times$ 'Arc 3'

Chicane vert. Recombiner

Spr. dipoles:

$10^0 - 20^0 - 10^0$ bends (rec.)

Lb = 30 cm

B = 5-10 kGauss

Arc dipoles :

8×22.5^0 bends(sec.)

Lb = 40 cm

B = 5 kGauss

Rec. dipoles:

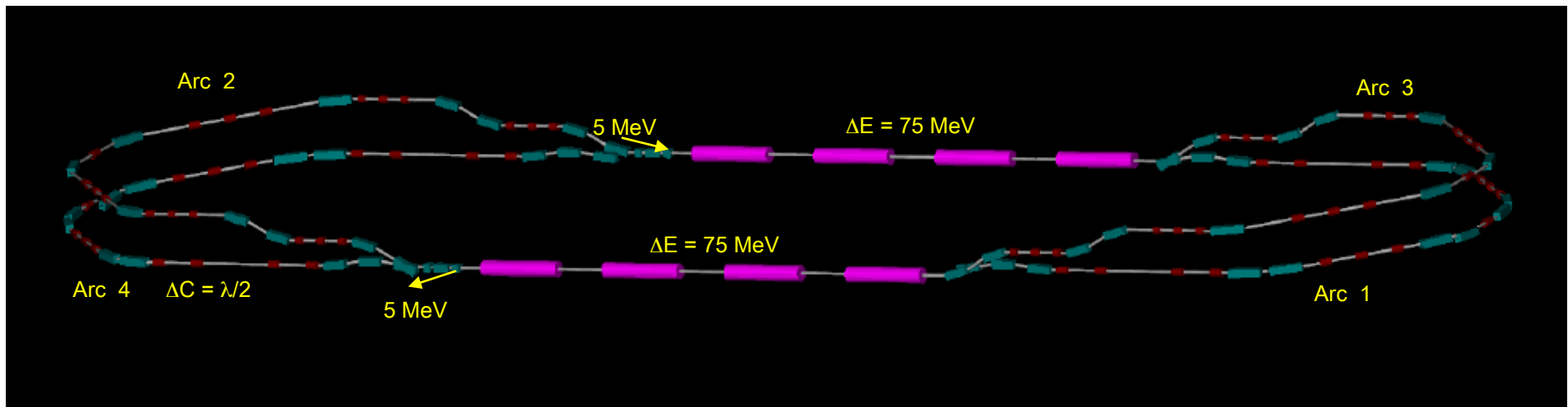
$10^0 - 20^0 - 10^0$ bends (rec.)

Lb = 30 cm

B = 5-10 kGauss

quads: Lq = 10-15 cm $G \leq 1.2$ kGauss/cm

ERL-TF Complete Lattice Design



Two passes 'up' + Two passes 'down'

CERN ERL test facility design status

- ERL-TF at CERN
 - 'Test bed' for SRF cavities at high current
- Multi-pass linac Optics in ER mode
 - Choice of linac RF – 721 MHz SRF
 - Linear lattice: 2-pass 'up' + 2-pass 'down'
- Arc Optics Choice
 - Synchronous acceleration → Isochronous arcs
 - Flexible Momentum Compaction Optics
- Complete Arc Architecture
 - Vertical switchyard
 - Matching sections: Linac-Switchyard-Arc
- 'First cut' Lattice design for ERL-TF
 - Two Linacs + Four Arcs

ERL-TF: HOM Measurements

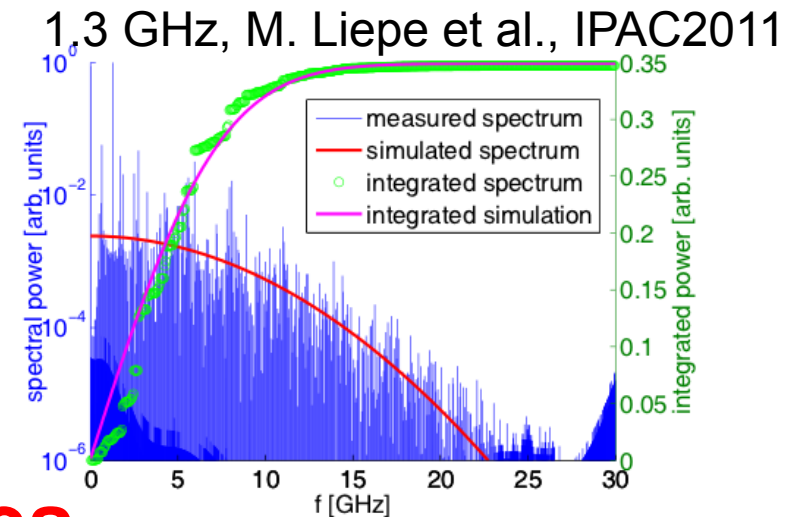
Complete characterization
of **HOMs**

Benchmark simulations

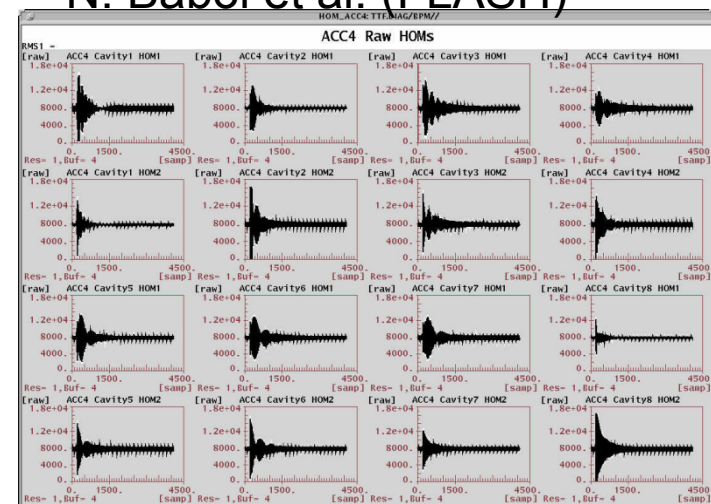
Improved **damping schemes**

Precision orbit measurement
Cavity & CM alignment

Erk Jensen



N. Baboi et al. (FLASH)



ERL-TF: RF Power

→ 5 MeV injector → $P_{\text{beam}} \sim 50 \text{ kW}$ (10 mA)
 higher power if we go to 100 mA

→ Main LINAC
 (0 beam loading)

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

Peak detuning

	721 MHz
$Q=1 \times 10^6$	250 kW
$Q=5 \times 10^6$	50 kW
$Q=1 \times 10^7$	25 kW

commercial television
 IOT @700 MHz



reach steady state with
 increasing beam current

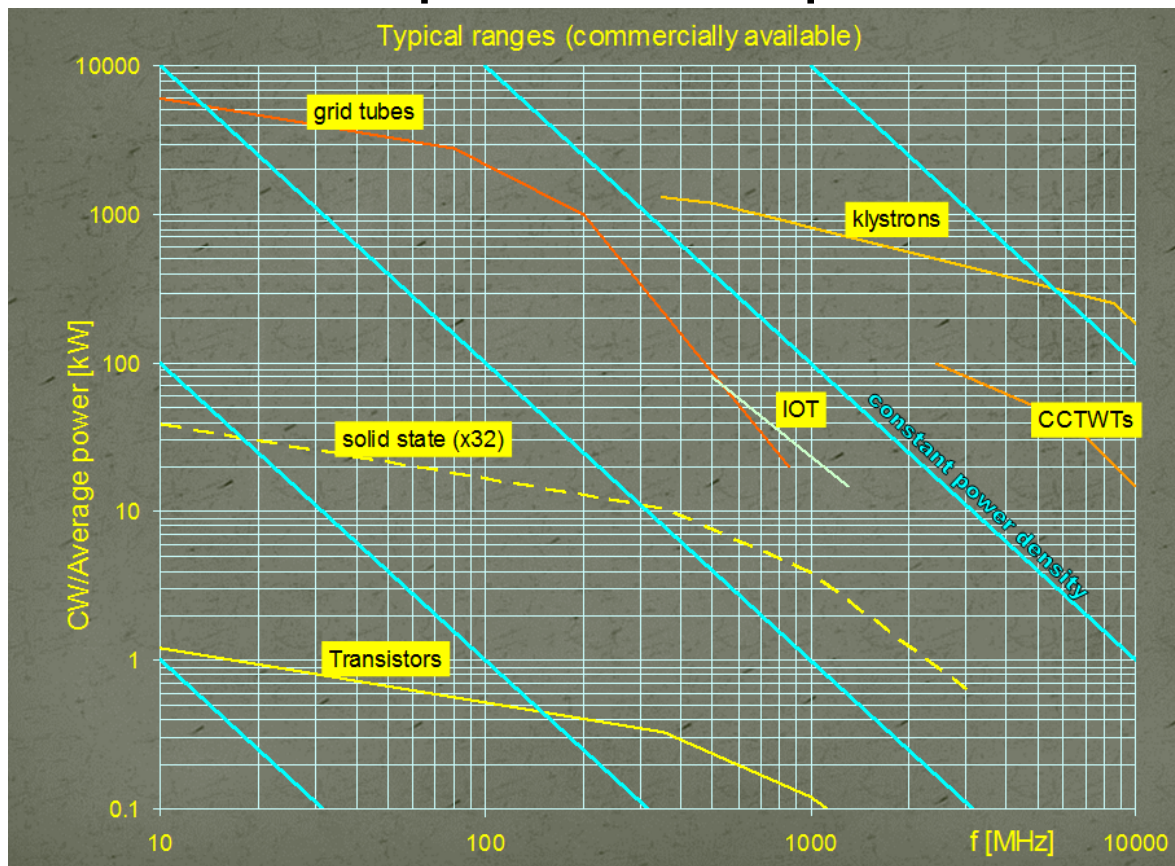
RF Power

Erk Jensen

use of IOTs ~ 50-100 kW at 700 MHz

high efficiency, low cost

amplitude and phase stability

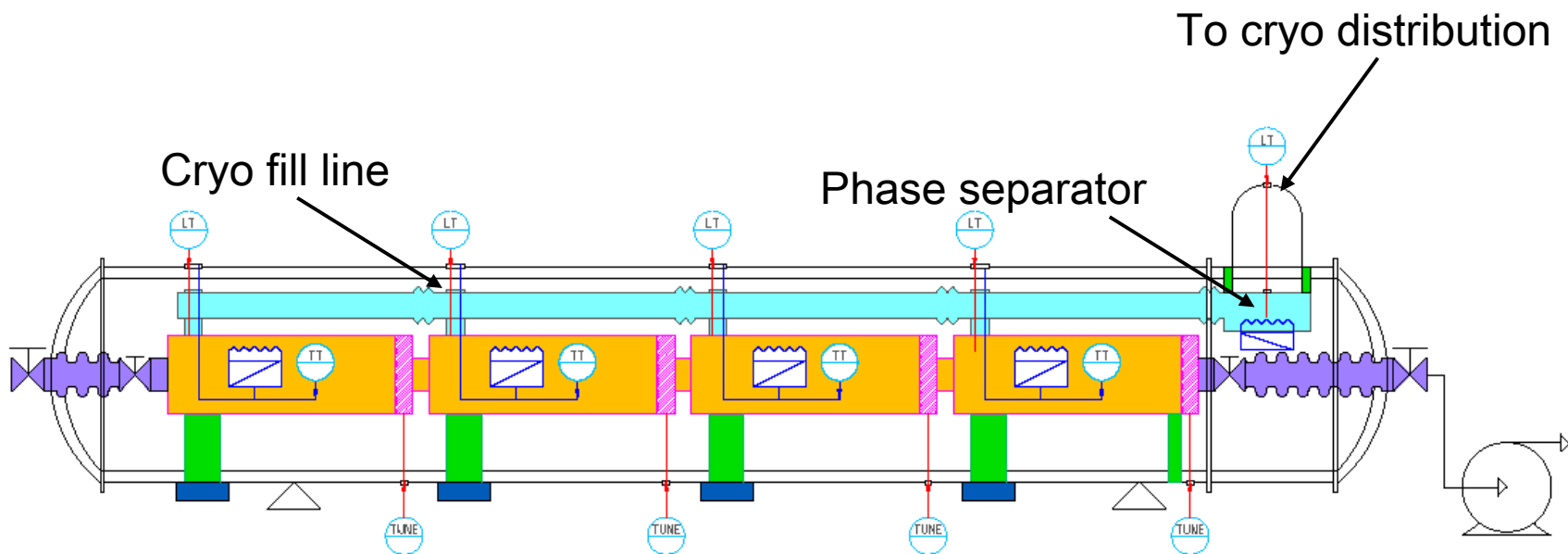


50 kW TV Amplifier,
BNL, at 700 MHz



Cryogenic System

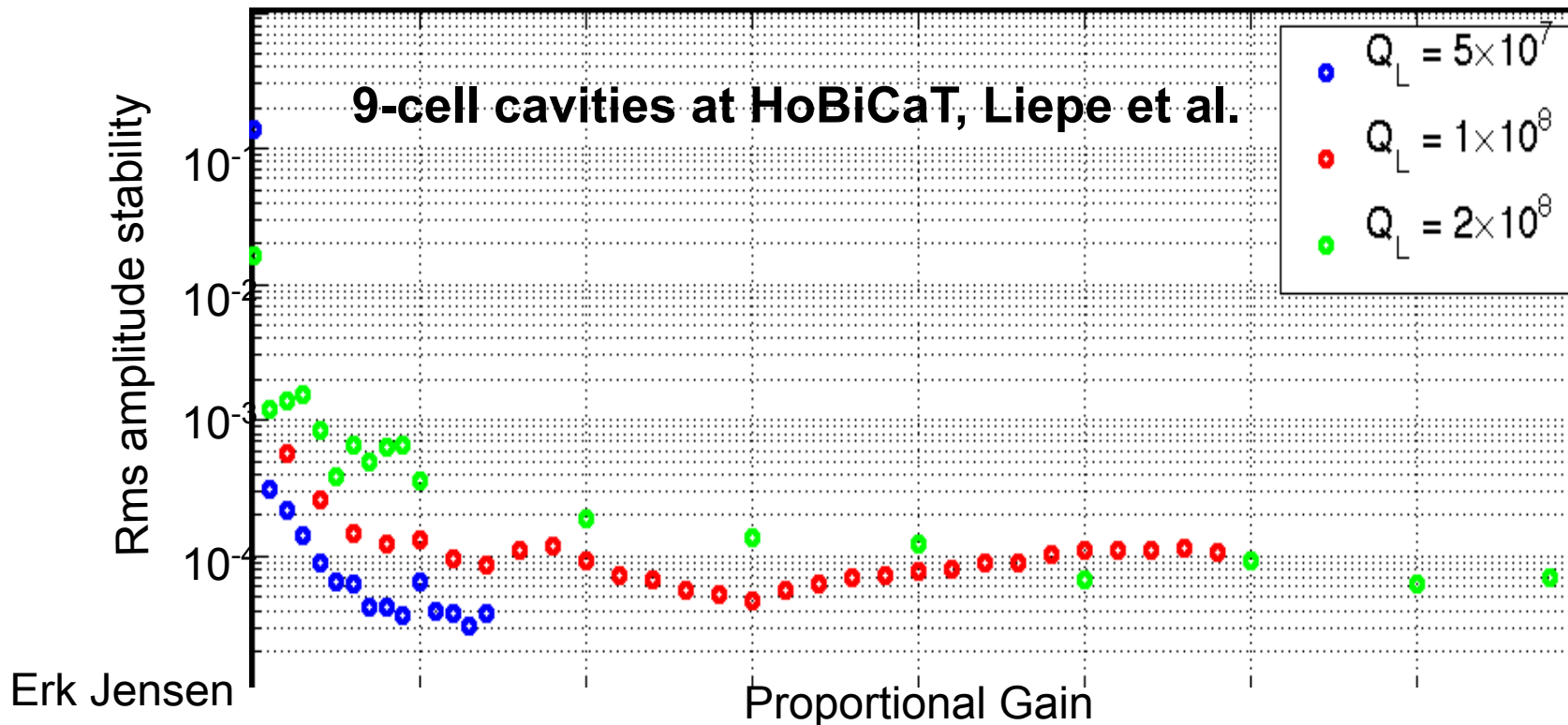
we can use SPL like cryo distribution system



V. Parma, Design review of short cryomodule

RF Controls

development of digital LLRF system (Cornell type ?) ;
amplitude and phase stability at high $Q_0 \sim 1 \times 10^8$
reliable operation with high beam currents + piezo tuners ;
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 may be 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).

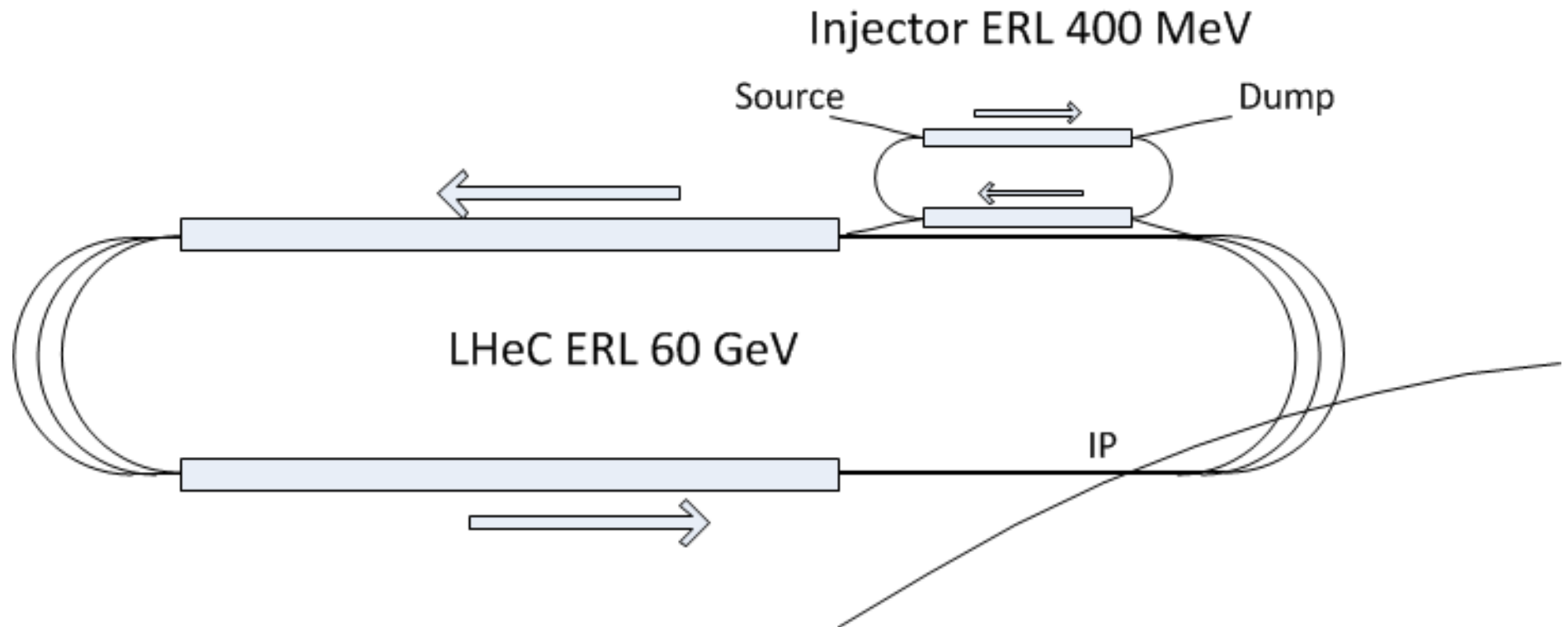
The costs should be directly derived from SPL CM
construction (< 5 MCHF ?)

Do we need high power couplers ?

R&D of HOM couplers needed for probing
high current & CW

Key question: where to place the ERL-TF to
have maximum flexibility ?

could the LHeC TF later become the LHeC ERL injector ERL?



Rama Calaga & Erk Jensen

*it might be nice to also have some
ERL collaboration with KEK*

near term plan

CERN-CI-JLAB meeting at Daresbury
end of January/early February 2013

topics:

- collaboration planning
- use of CI ALICE ERL for initial studies?
- choice of frequency 721 MHz or 1.3 GHz

thank you for your attention!

for more details:

- LHeC web site <http://cern.ch/lhec>
- LHeC CDR, J.Phys.G:Nucl.Part.Phys. 39, 075001 (2012)
- eRHIC web site <http://www.bnl.gov/cad/eRhic>
- ICFA Beam Dynamics Newsletter No. 58, special issue on future electron-hadron colliders, August 2012

back-up slides

OptiM

- Computer code for linear and non-linear optics calculations
- Code developed by V. Lebedev; used at JLAB and FNAL
- OptiM assists with linear optics design of particle accelerators (calculations are based on 6x6 transfer matrices), but it is also quite proficient with non-linear optics, tracking and with linear effects due to space charge
- It computes the dispersion and betatron functions (for both uncoupled and X-Y coupled particle motions), as well as the beam sizes, the betatron phase advances, etc. The values can be plotted or printed along machine circumference or computed at the end of lattice or at any element
- It can also fit parameters of accelerator elements to get required optics functions
- It offers a wide choice of elements that allows designing both circular and linear accelerators, along with recirculators
- It can perform computations not only at the reference orbit but also at a closed orbit excited by machine errors, correctors or energy offset. In this case the program first finds a new "reference" orbit then expands nonlinear terms for machine elements and then performs computations. One can then perform both linear optics computations and non-linear tracking relative to this new orbit