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

work supported by the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579

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

LHeC

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group

THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

LHeC CDR published in
J. Phys. G: Nucl. Part. Phys. 39 075001 (2012)

http://cern.ch/lhec

LHeC

LHeC Study Group

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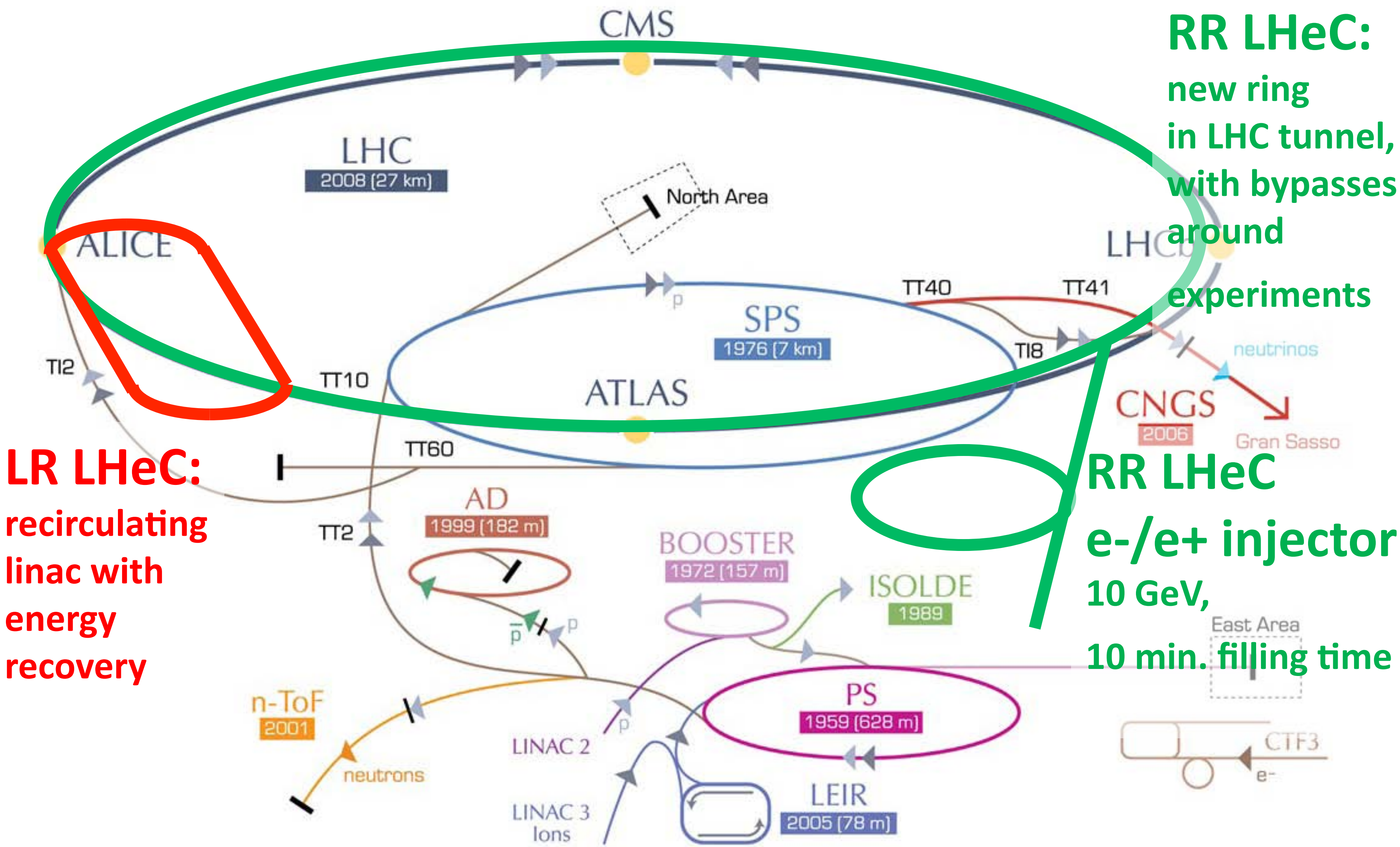
About 150 Experimentalists and Theorists from 50 Institutes
Tentative list

Thanks to all and to
CERN, ECFA, NuPECC

~600 pages

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

Large Hadron electron Collider



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

luminosity of LR collider:

(round beams)

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

H_D~1.3

D. Schulte
LHeC2010

highest proton
beam brightness “permitted”
(ultimate LHC values)

$\gamma\varepsilon$=3.75 µm

N_b=1.7x10^{11}

bunch spacing
25 or 50 ns

smallest conceivable
proton β* function:
- reduced *l** (23 m → 10 m)
- squeeze only one *p* beam
- new magnet technology Nb_3Sn

β^*_p=0.1 m

average e$^-$
current
limited by
energy
recovery
efficiency

I_e=6.4 mA

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

θ_c=0

H_{hg}≥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} cm^{-2}s^{-1}]	8	10	0.4
eN luminosity [10^{32} cm^{-2}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. $\gamma\varepsilon_{x,y}$ [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.$\gamma\varepsilon_{x,y}$ [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=1.7x10^{11} probably conservative

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

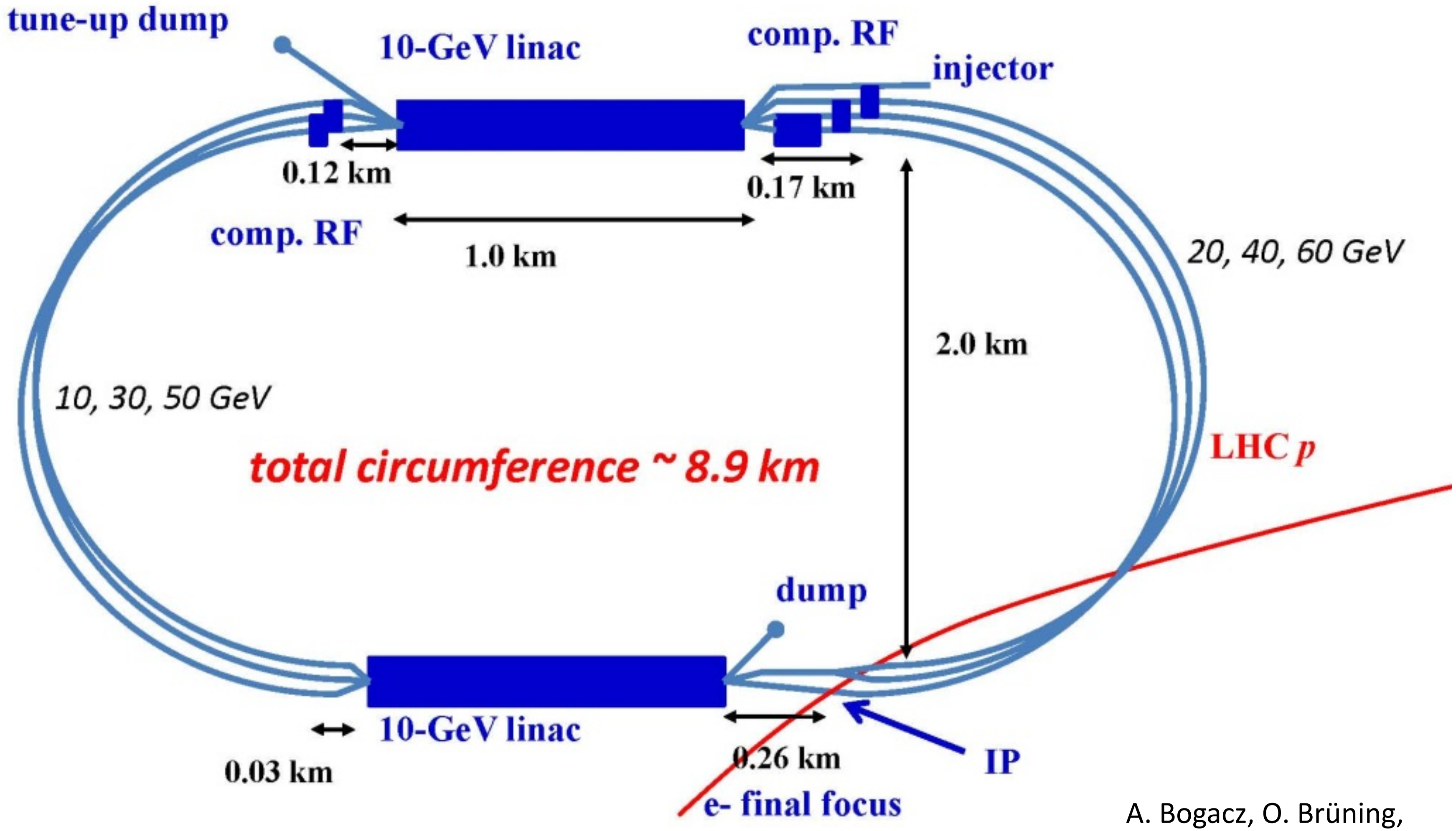
RR= Ring – Ring
LR =Linac –Ring

higher-*L* design exists

β*~0.025 m possible in IP3 or 7 using ATS optics (S. Fartoukh); + also going to 2 μm emittance (H. Damerau, W. Herr), →*L*~10^{34} cm^{-2}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

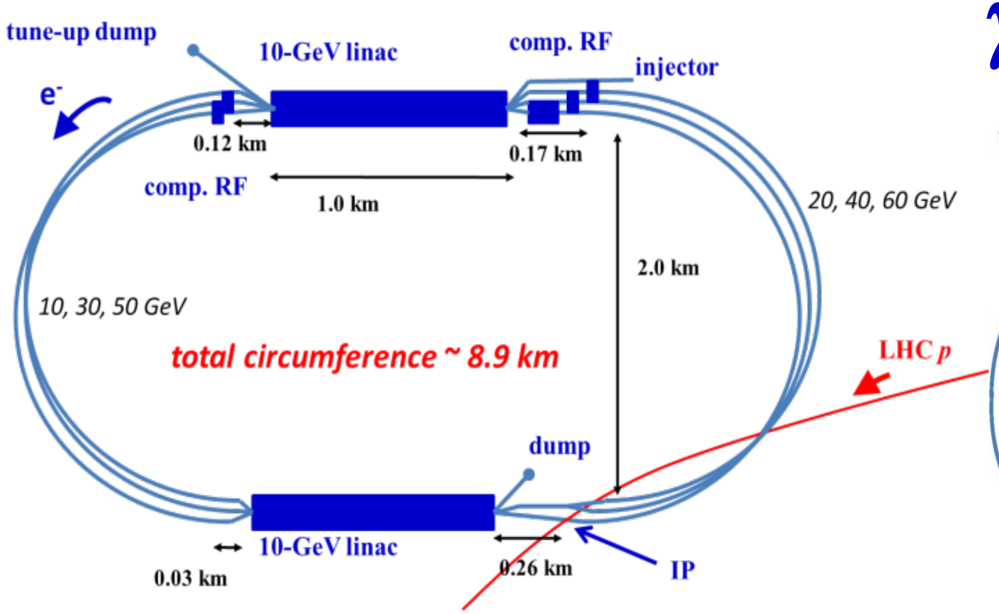


(*C*=1/3 LHC allows for ion clearing gaps)

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

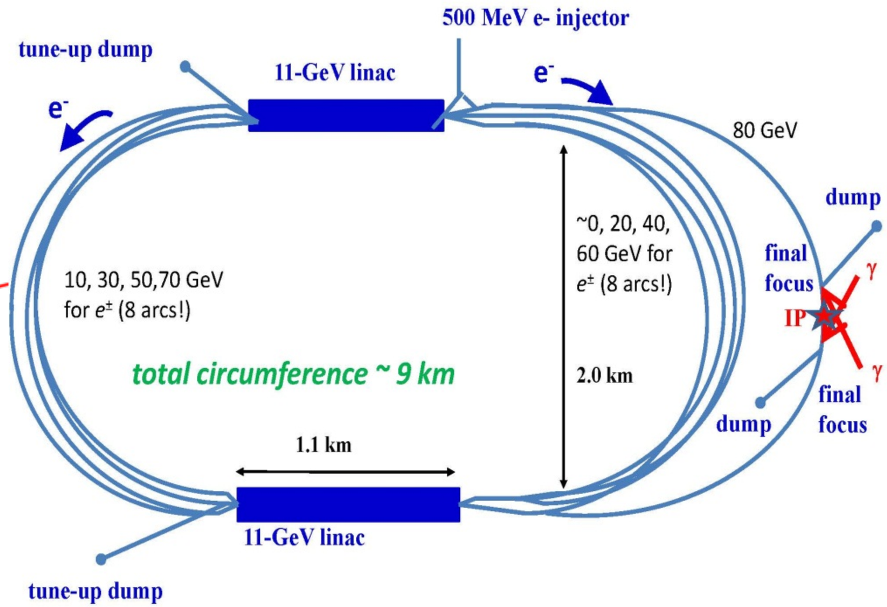
R&D for **LHeC SC linac in synergy with many future projects**: ILC, ν factory, *p*-driven plasma acceleration, and Higgs factory γγ collider

LHeC-ERL



SAPPHiRE*

γγ Higgs factory



*__S__mall __A__ccelerator for __P__hoton-__P__hoton __Hi__ggs production using __R__ecirculating __E__lectrons

collider parameters	eRHIC (ult.)		LHeC (ult).	
species	e^-	p, $^{197}Au^{97+}$	$e^{\pm}$	p, $^{208}Pb^{82+}$
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}cm^{-2}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

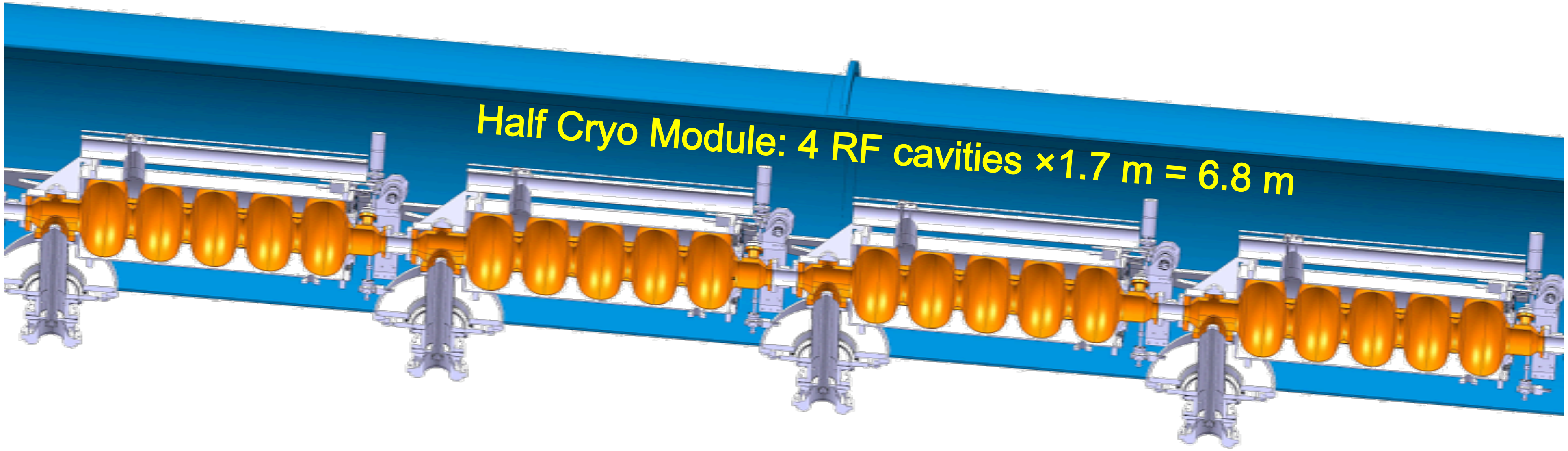
increase multi-pass BBU threshold

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:

λ = 41.557 cm

$L_c = 5\lambda/2 = 103.89$ cm

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

ΔE= 80 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

ρ=764 m (E_{max}=60 GeV), ΔE_{tot}=2 GeV

compensation with additional RF systems

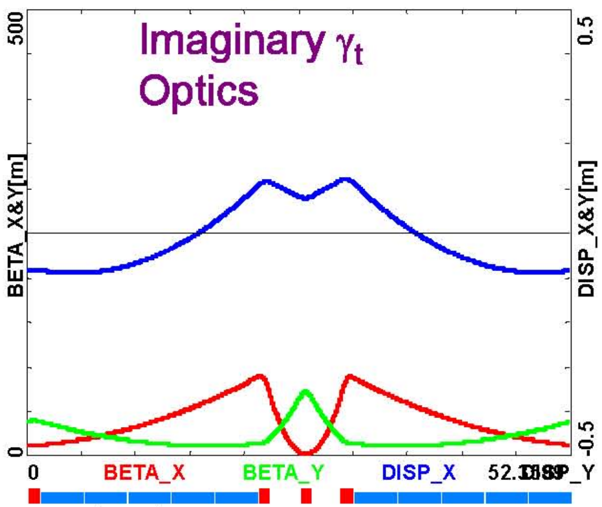
750 MV at 60 GeV (721 MHz)

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)

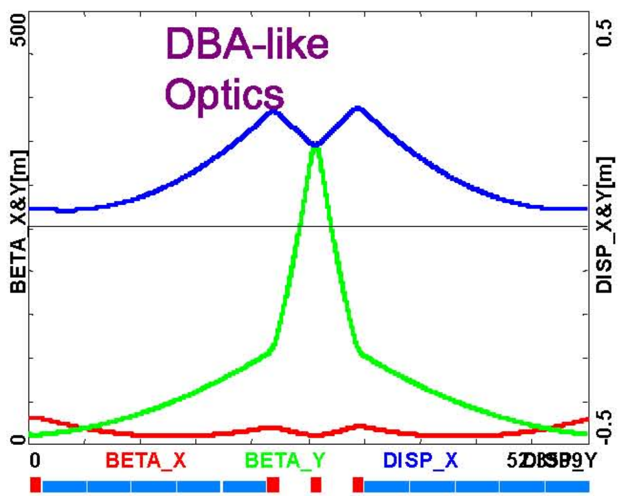
Arc 1 , Arc2



$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

limit chamber size
(>12 σ at 25 mm diameter)

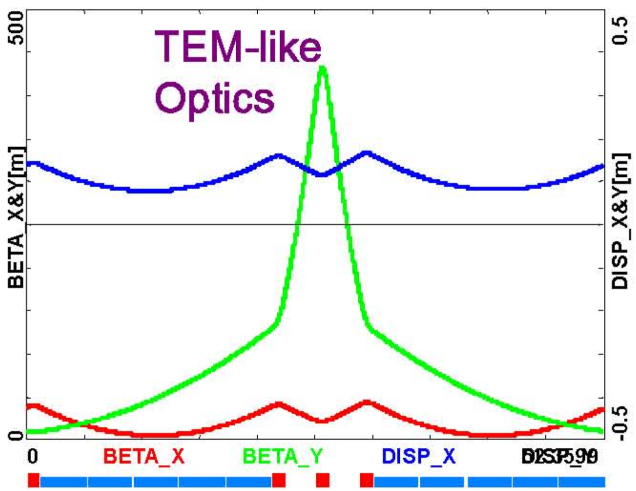
Arc 3, Arc 4



$$\langle H \rangle = 2.2 \times 10^{-3}\ m$$

Alex Bogacz

Arc5, Arc 6



$$\langle H \rangle = 1.2 \times 10^{-3}\ m$$

factor of 18 smaller than FODO

limit emittance growth

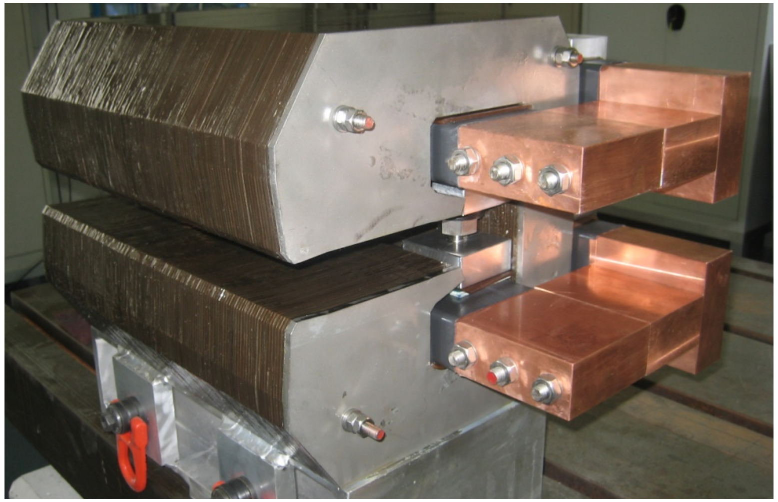
arc magnets

eRHIC dipole model

5 mm gap

max. field 0.43 T (30 GeV)

LHeC dipole model



25 mm gap

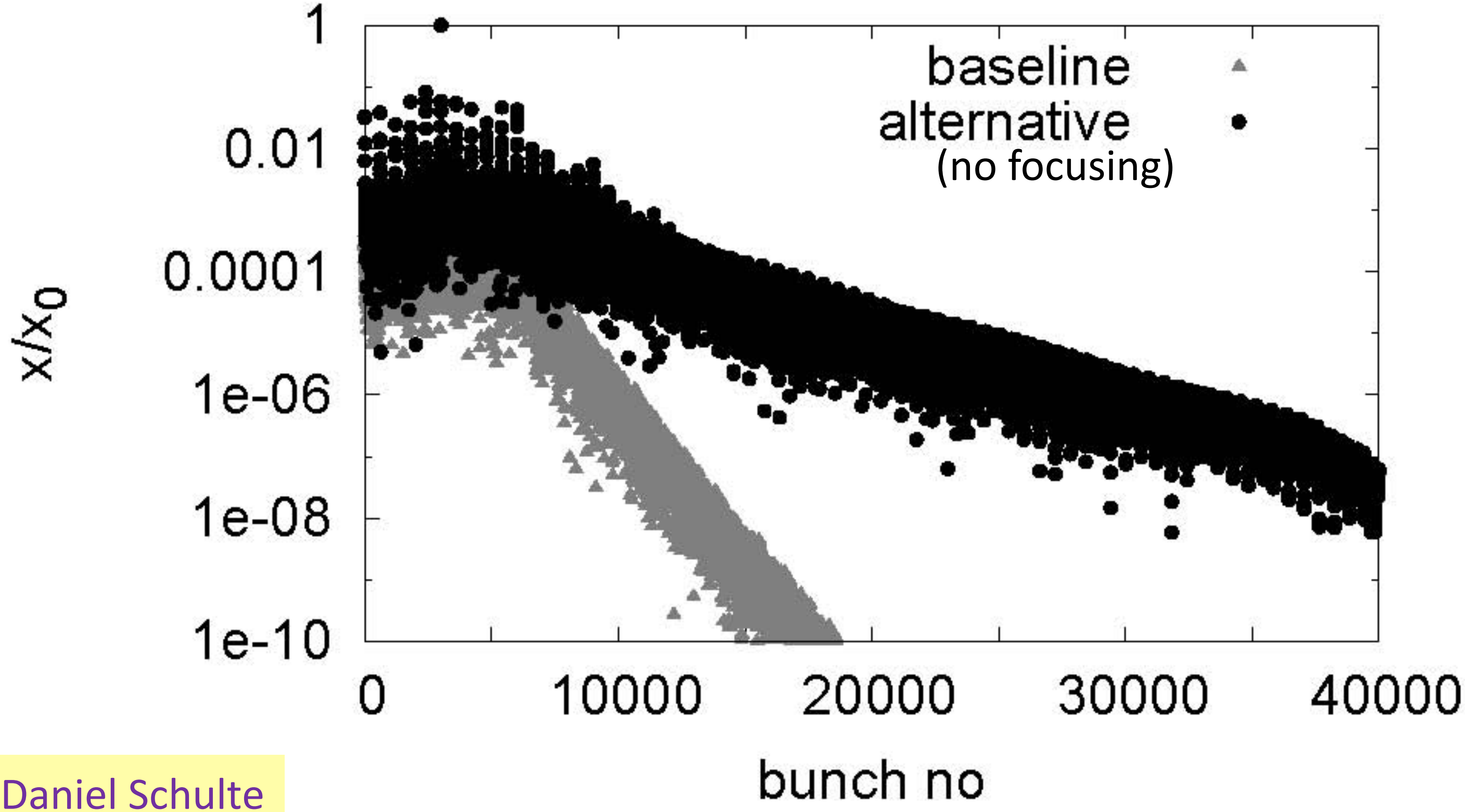
max. field 0.264 T (60 GeV)

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 ($\Delta f/f_{rms} \sim 0.1\%$) , 720 MHz

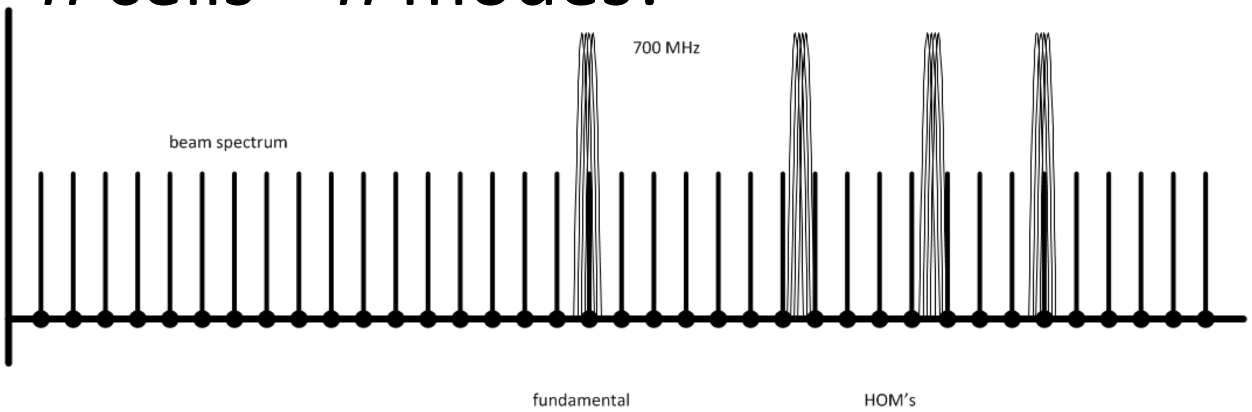


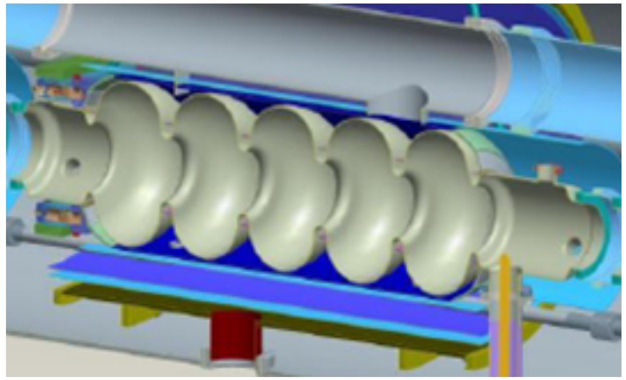
Daniel Schulte

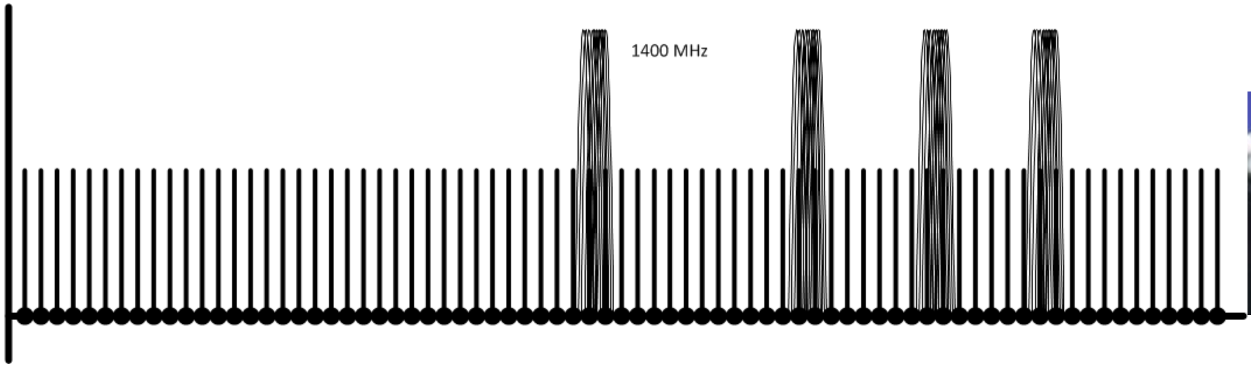
scaling 700 MHz → 1400 MHz

Erk Jensen

n cells – *n* modes!





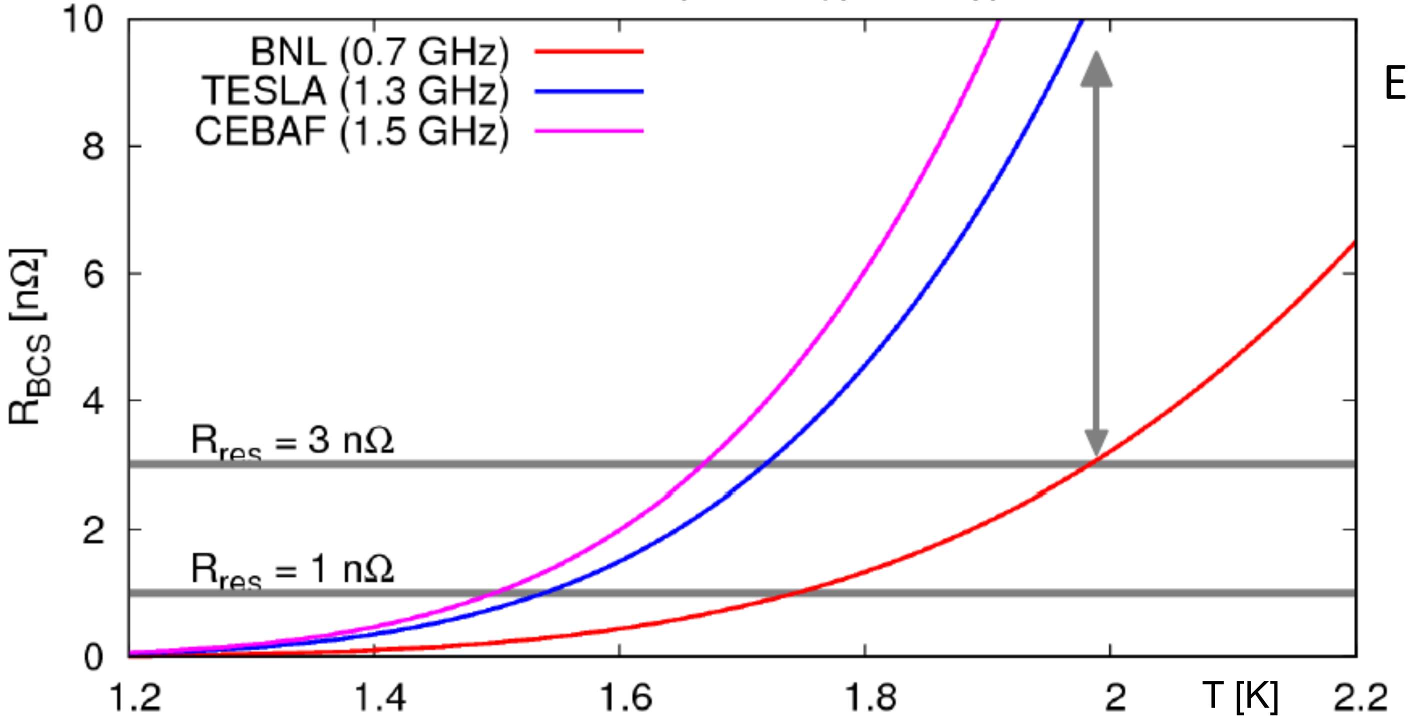


with $\frac{Z_\perp}{L} \propto f^2$ (at same offset!) plus the increased number of cells per cavity at higher *f*:

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

dynamic wall losses

$R_s = R_{BCS} + R_{res}$

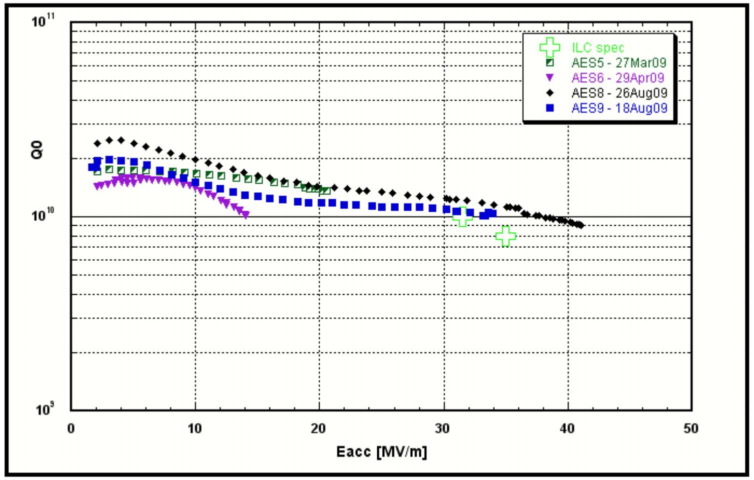


Erk Jensen

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

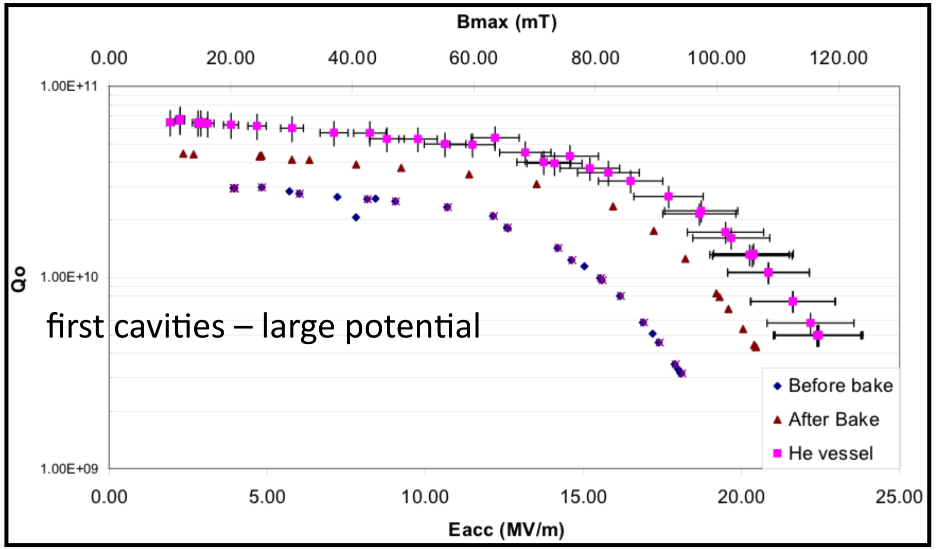
one should aim for very large Q_0

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



Erk Jensen

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



first cavities – large potential

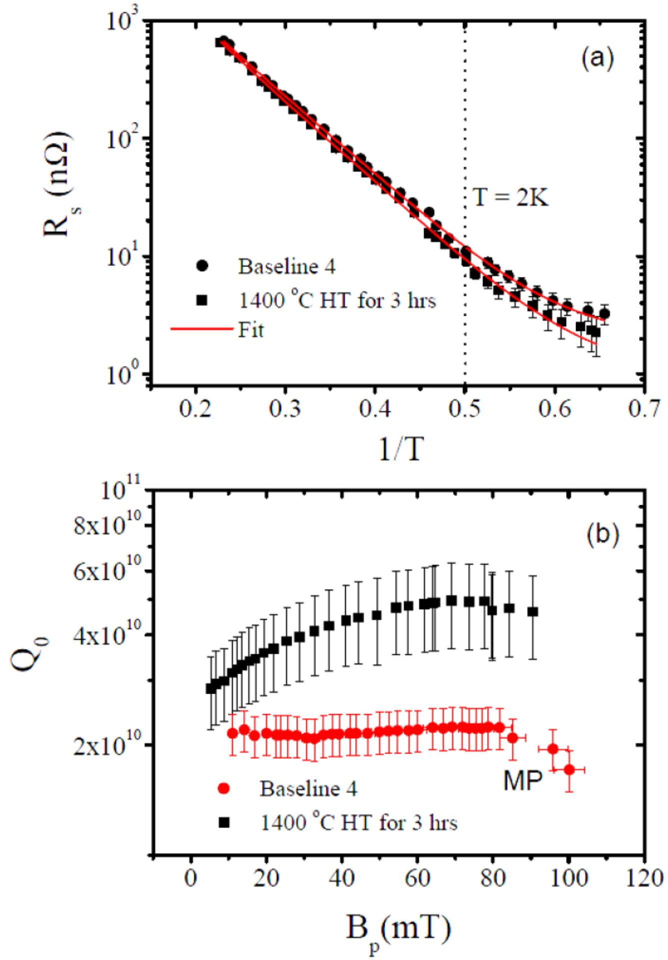


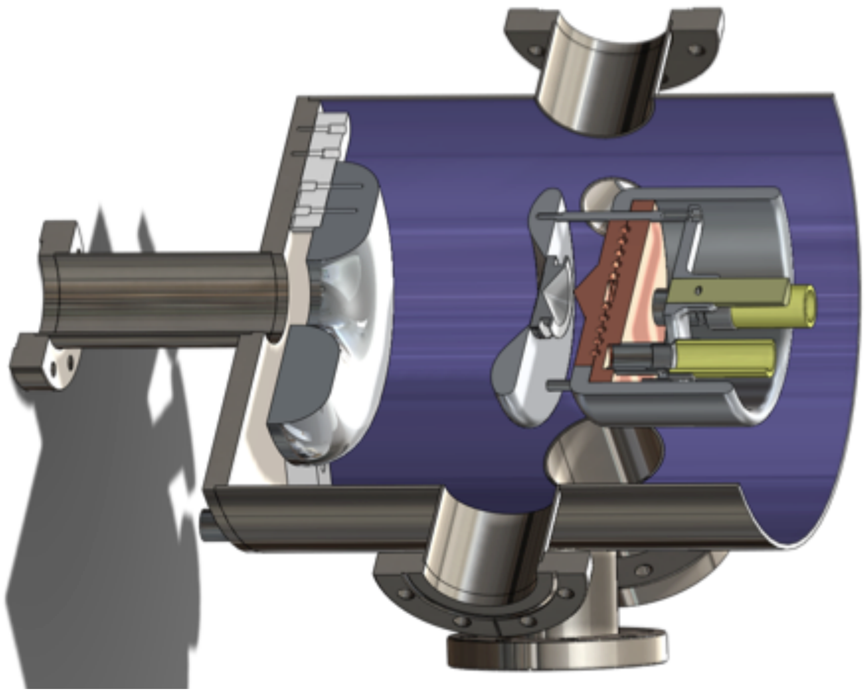
Figure 2: (a) Surface resistance R_s as a function of temperature before and after 1400 °C heat treatment. (b) Q_0 (B_p) measured at 2.0 K. The tests were limited by quench.

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

source e^- beam parameters

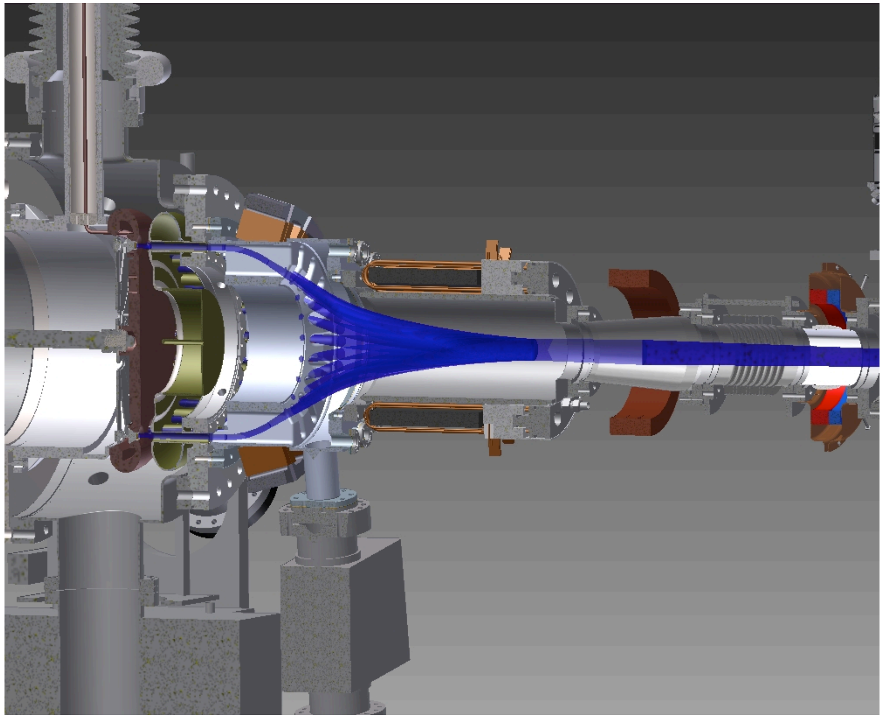
parameter	eRHIC	LHeC
e^-/bunch [10^9]	5.6, 24	1.1
charge / bunch [nC]	0.9, 3.8	0.18
rms bunch length [mm]	2	3-30
bunch spacing [ns]	18	25
average current [mA]	**50, 220**	7
bunch peak current [A]	50, 200	7-70
polarization	**85-90%, none**	>90%

eRHIC polarized electron gun - candidates



large-sized GaAs cathode gun

Evgeni Tsentalovich

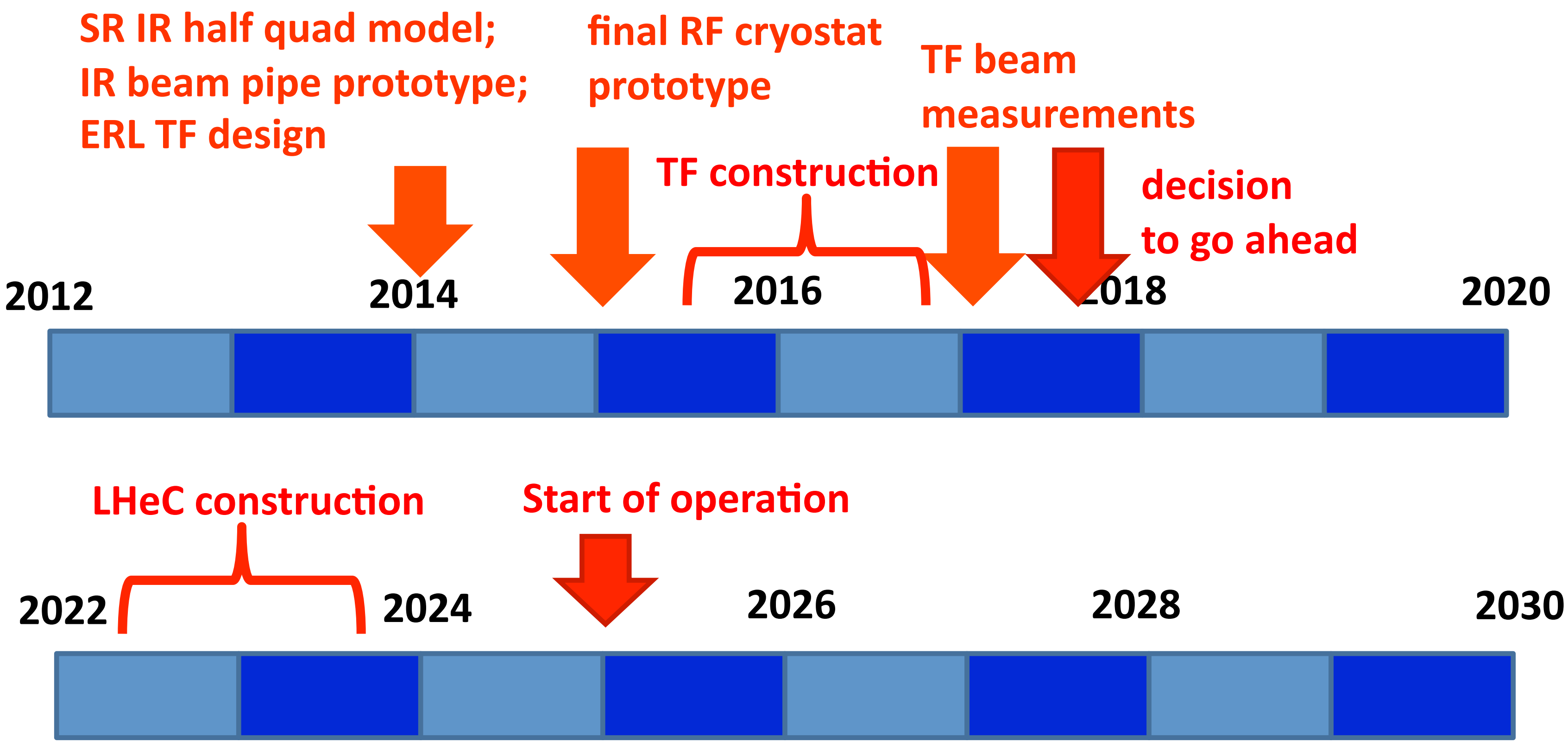


Gatling gun, combing beams from an array of 24 GaAs cathodes

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**

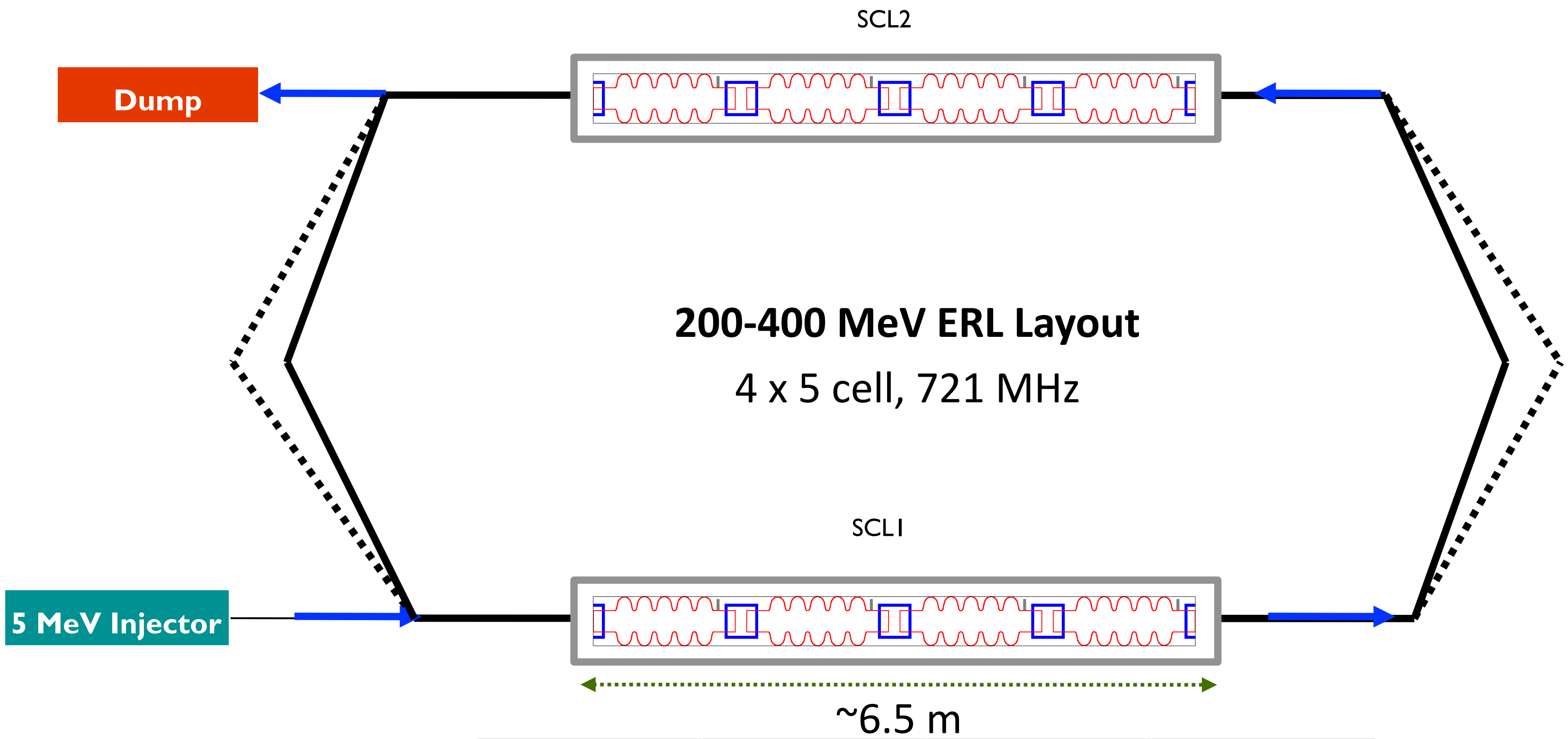


R. Calaga,
E. Ciapala,
E. Jensen,
J. Tückmantel

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

Rama Calaga

Alessandra Valloni

LINAC :

Half Cryo Module → 4 Cavities

721.44 MHz RF, 5-cell cavity:

λ = 41.557 cm

L_c = 5l/2 = 103.89 cm

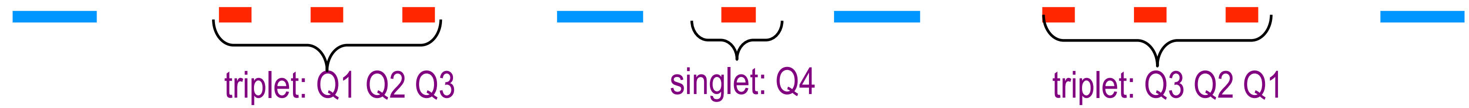
Grad = 18 MeV/m (18.7 MeV per cavity)

ΔE= 74.8 MV per Half Cryo Module

ARC 1 OPTICS : (80 MeV)

4 x 45° sector bends

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

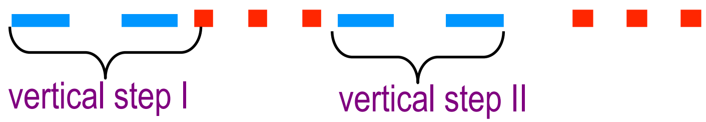


Dipole Length = 40cm B = 5.01 kG
Quadrupole Length = 10 cm
Q1 -> G[kG/cm] = -0.31 Q3 -> G[kG/cm] = -0.34
Q2 -> G[kG/cm] = 0.50 Q4 -> G[kG/cm] = -0.44

VERTICAL SPREADER OPTICS:

Spreader for Arc 1 @ 80 MeV

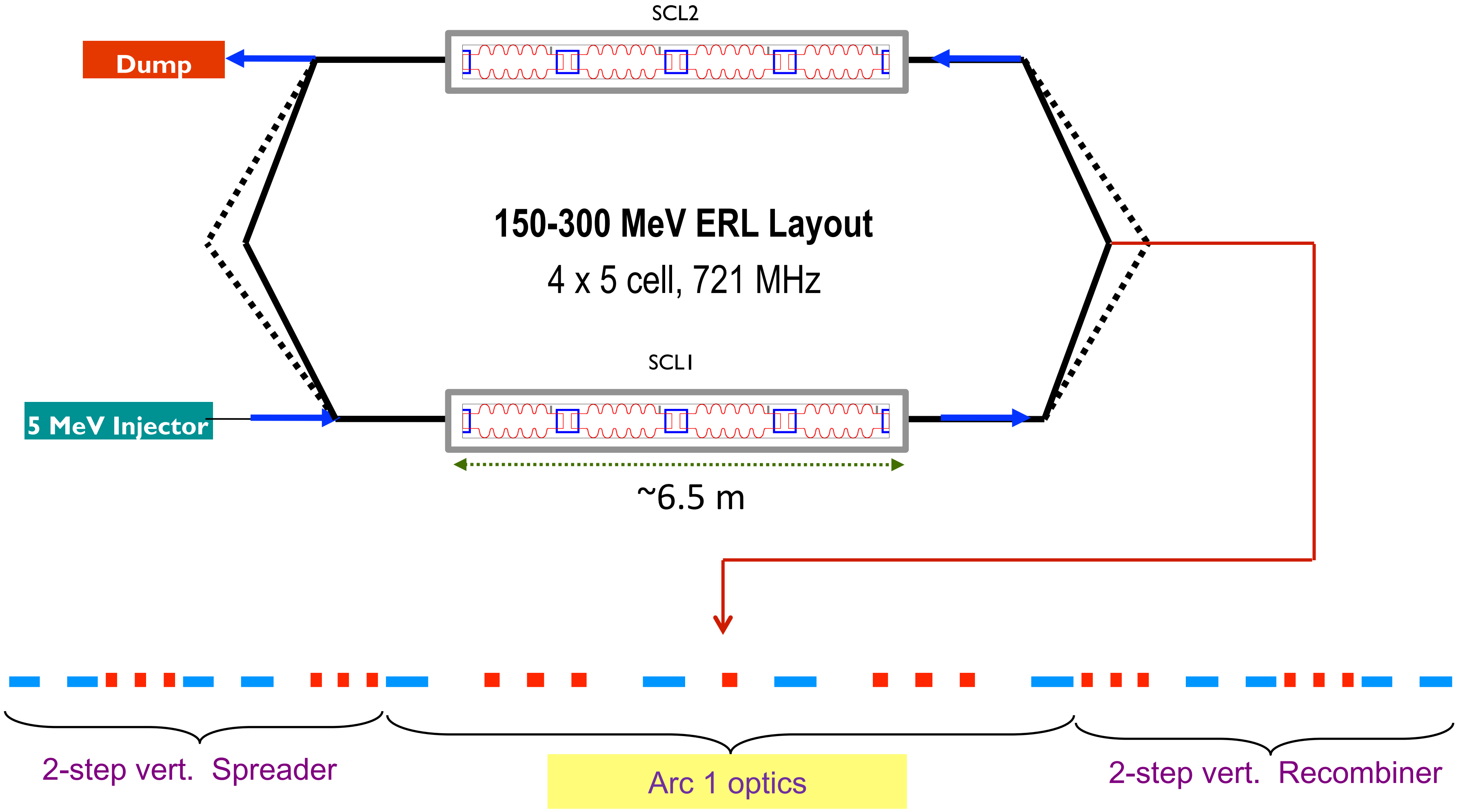
2 Vertical steps (dipoles with opposite polarity) and quads triplet for hor. and vert. focusing



Spreader for Arc 3 @ 230 MeV

A vertical chicane plus and 2 quads doublets

ARC 1 + VERTICAL SPREADER AND COMBINER OPTICS



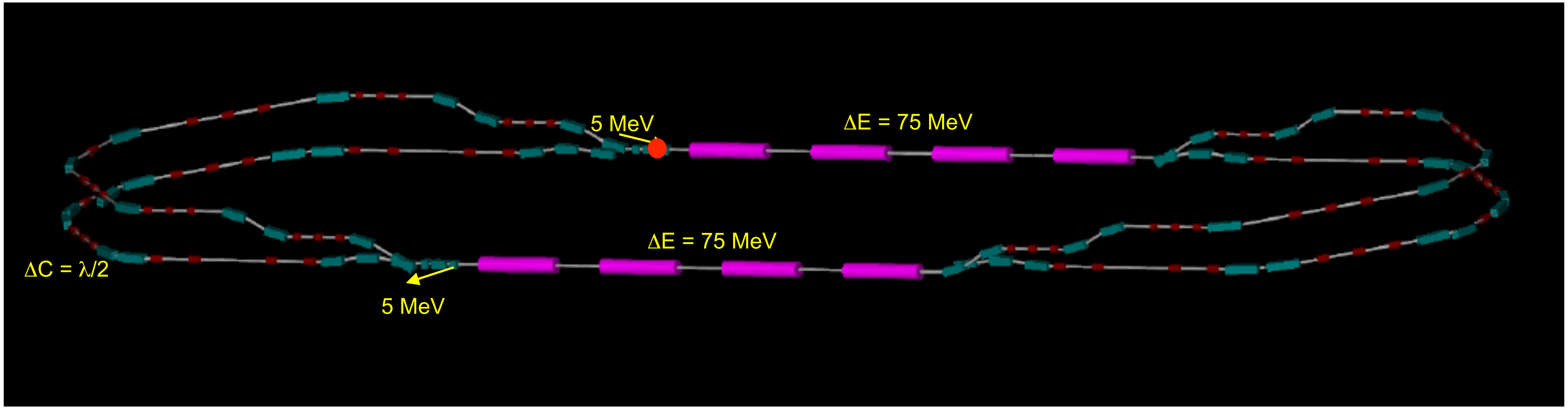
Alessandra Valloni

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

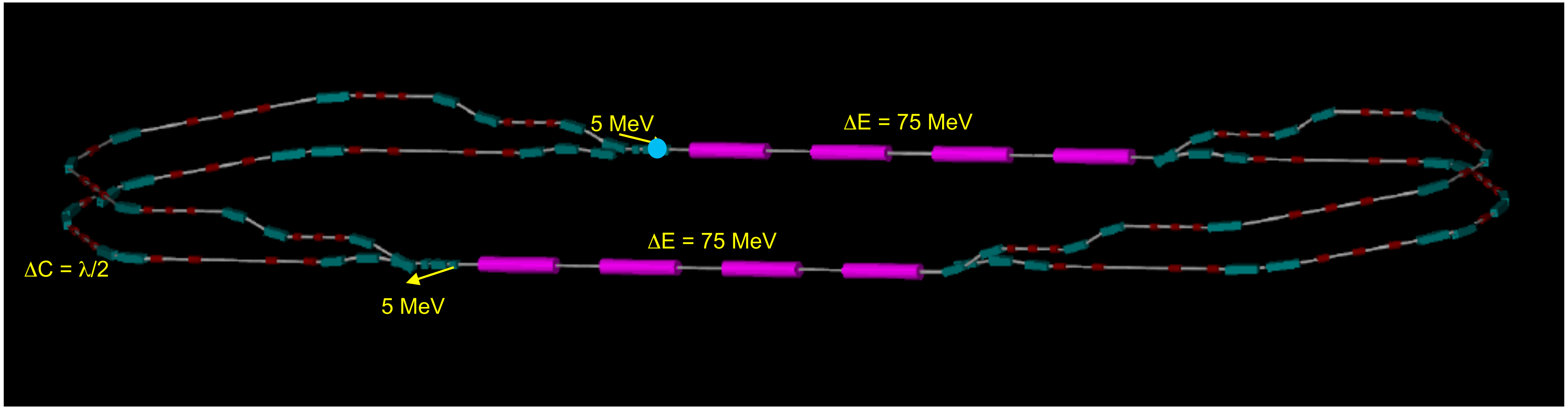
ERL-TF (300 MeV) – Layout



Two passes 'up' + Two passes 'down'

Alex Bogacz

ERL-TF (300 MeV) – Layout

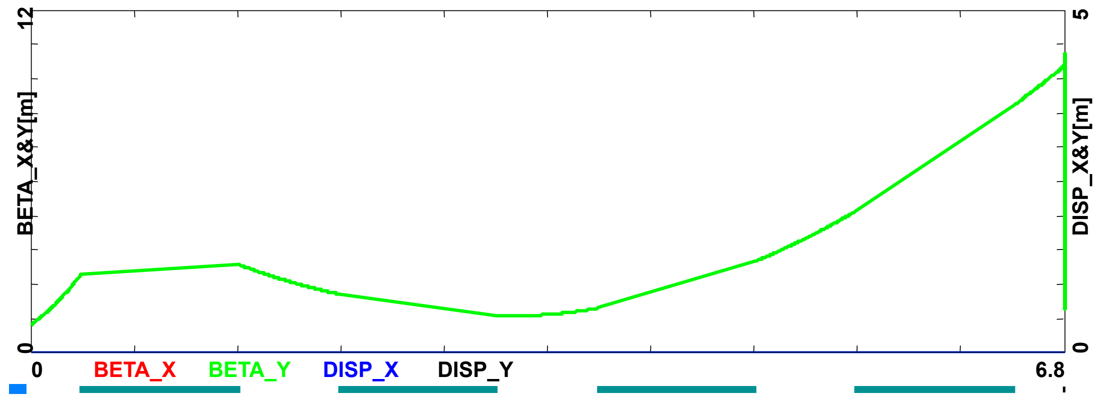


Two passes ‘up’ + Two passes ‘down’

Linac 1 – Multi-pass Optics

inj

Arc 1

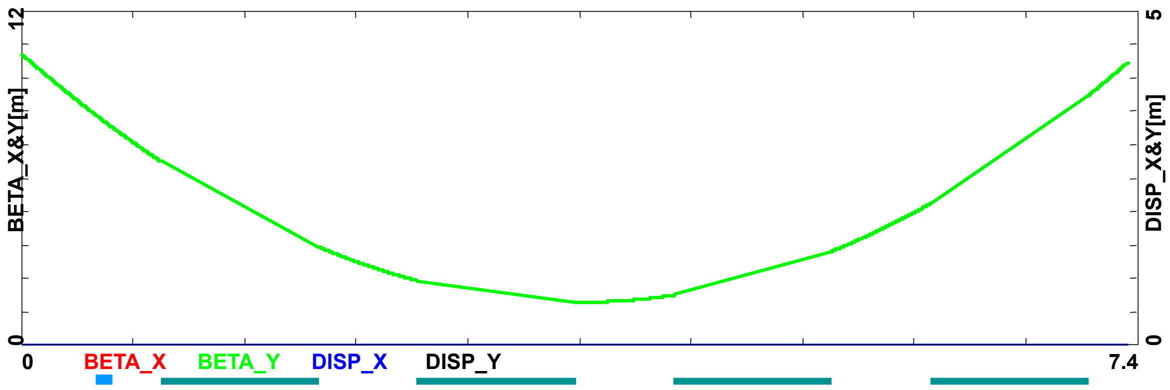


5 MeV

80 MeV

Arc 2

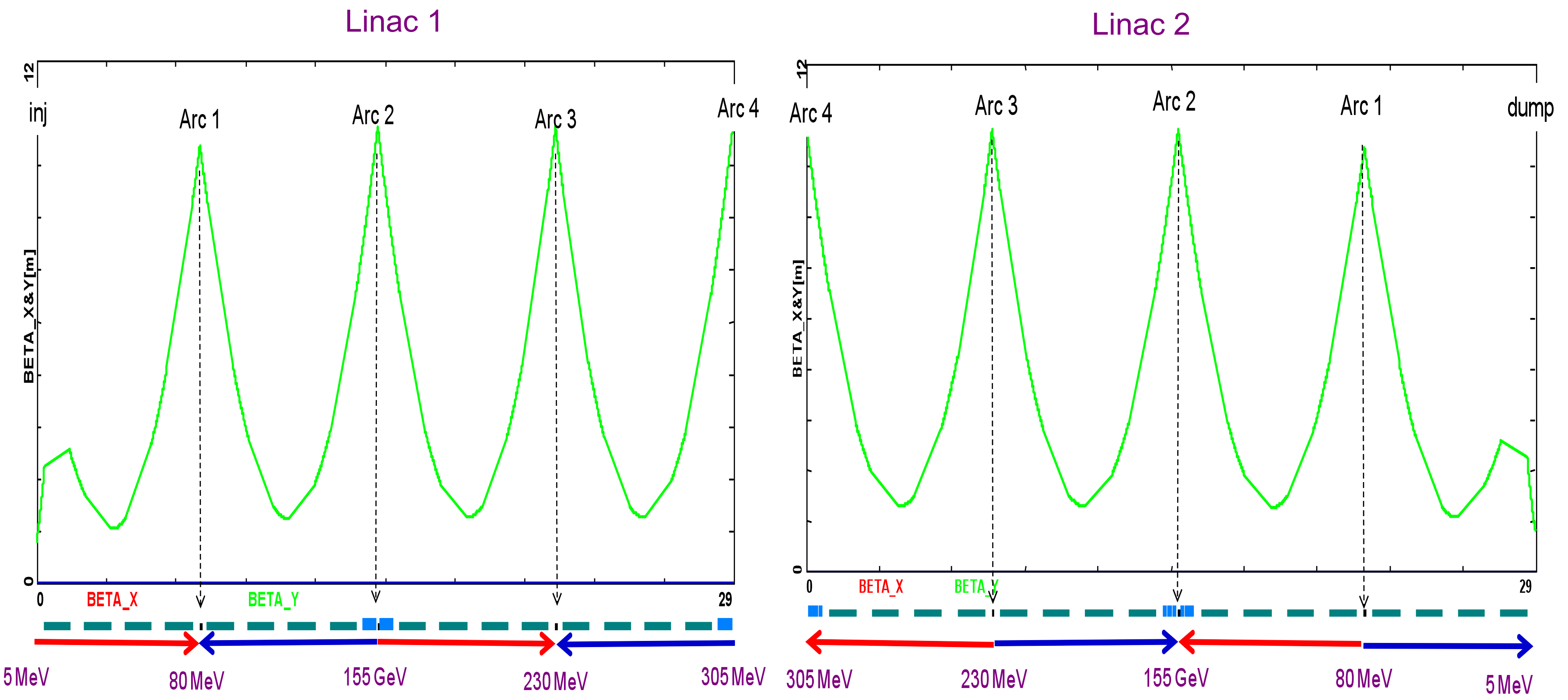
Arc 3



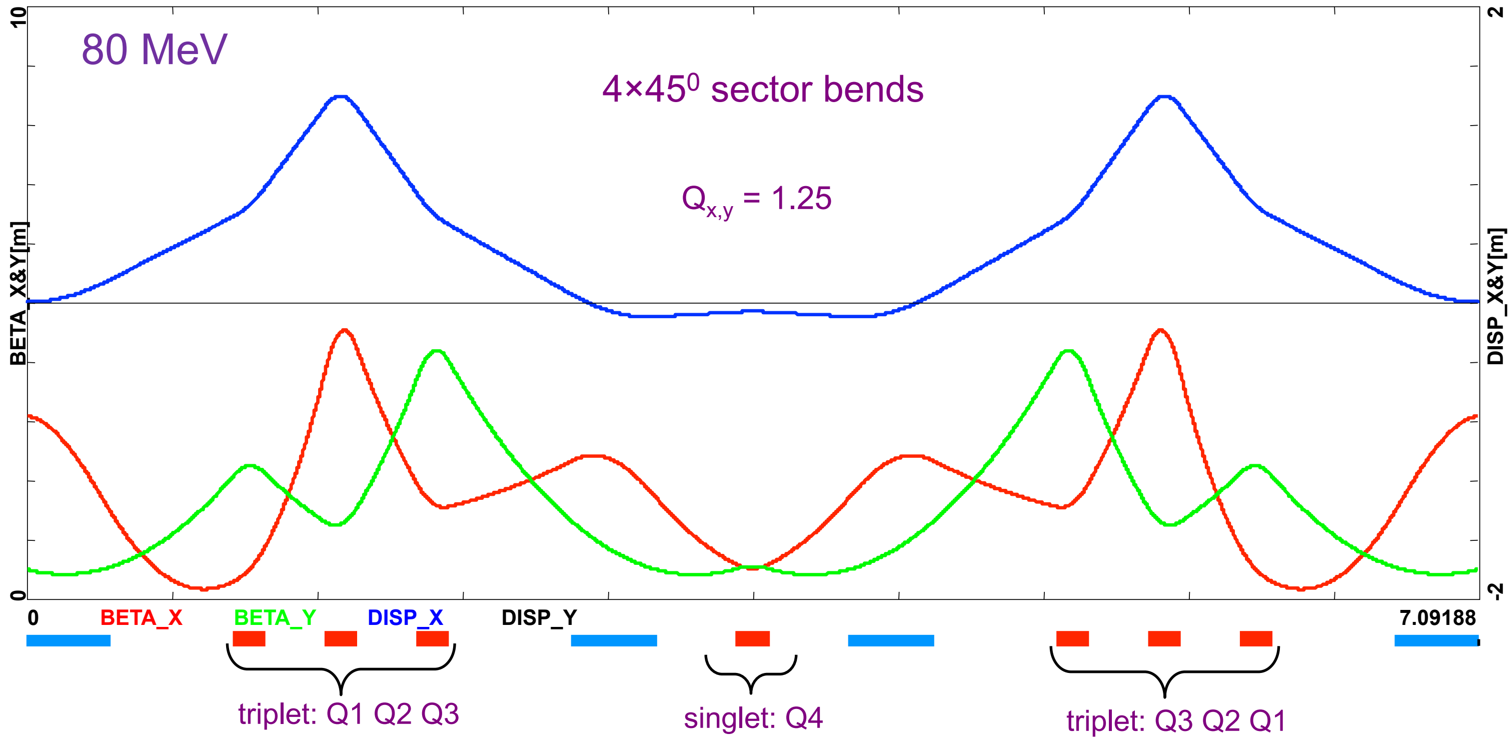
155 GeV

230 MeV

Linac 1 & 2 – Multi-pass ER Optics



Arc 1 Optics – FMC Lattice



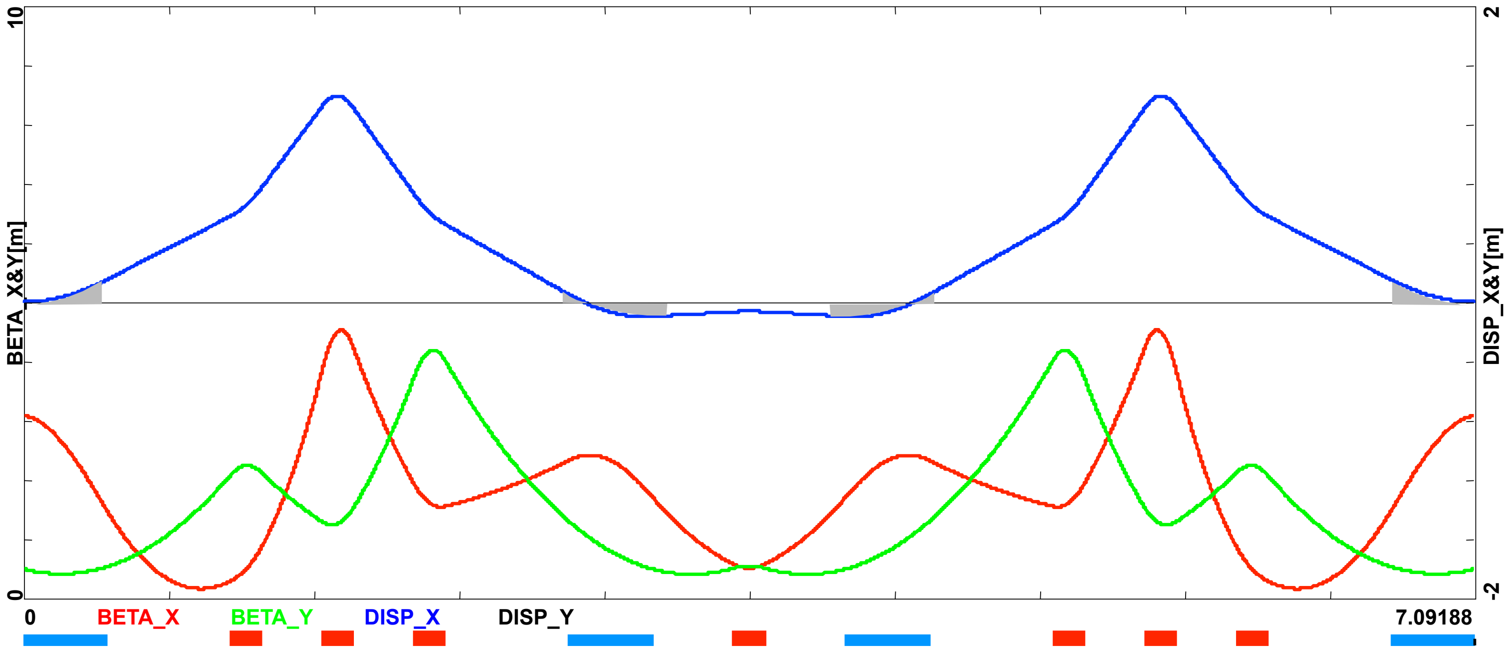
dipoles (40 cm long)

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

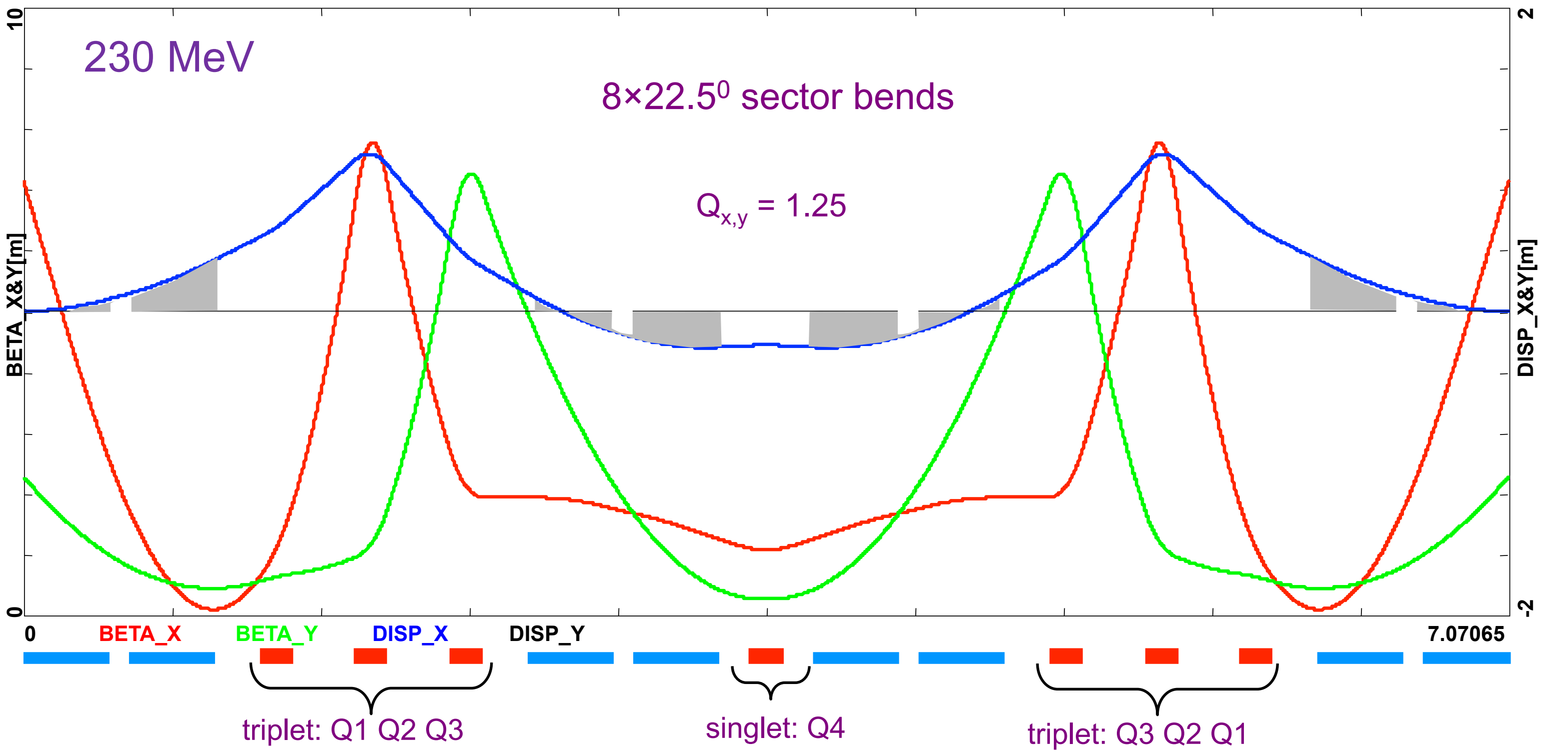
Arc 1 Optics – Isochronous Lattice



- Synchronous acceleration in the linacs ⇨ Isochronous optics:

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

Arc 3 Optics – FMC Lattice



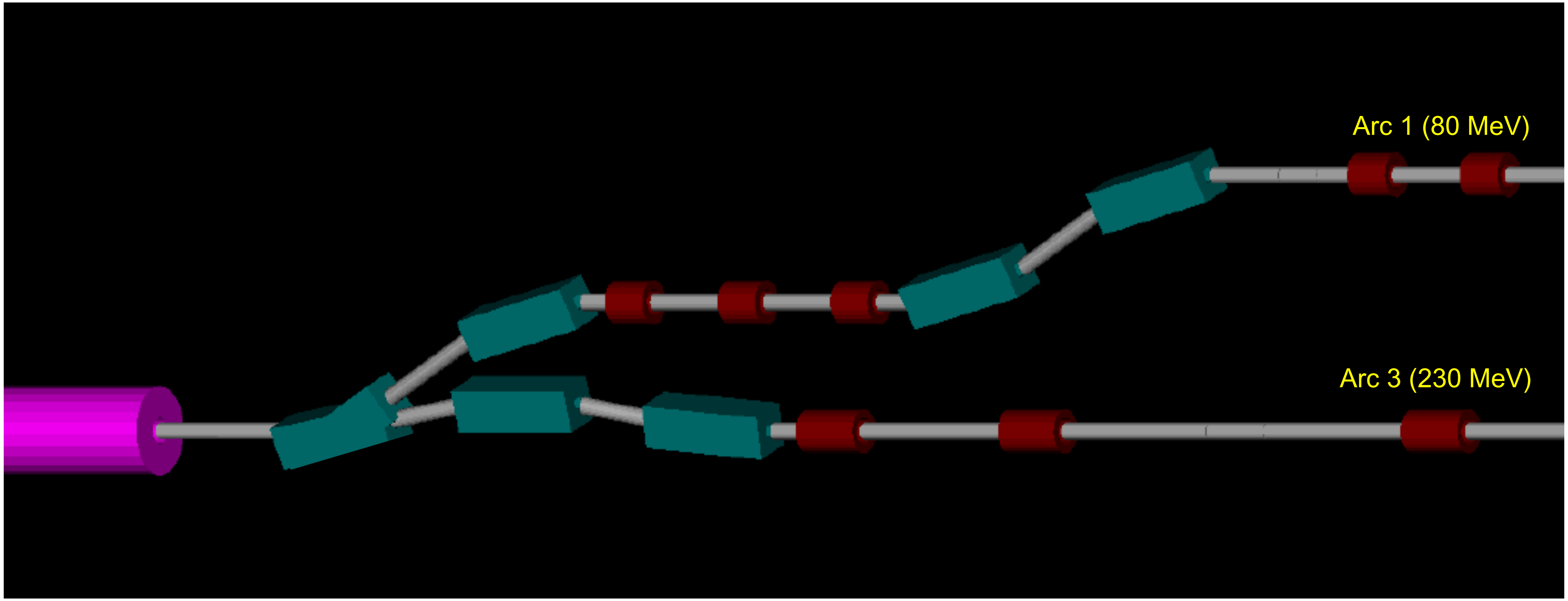
dipoles (40 cm long)

B = 7.47 kGauss

quadrupoles (15 cm long)

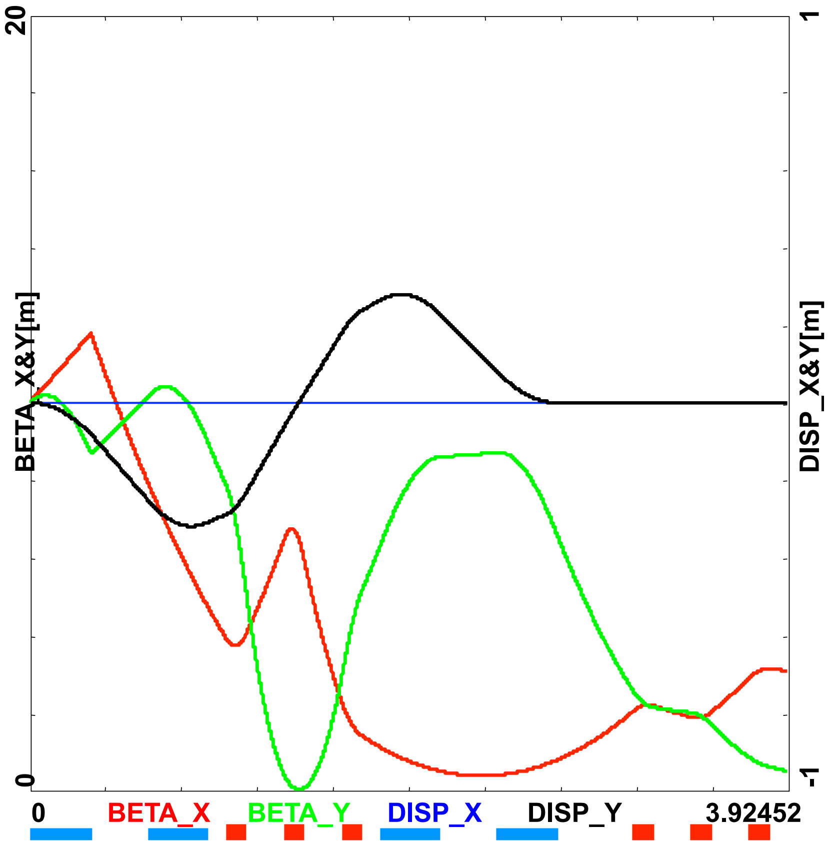
Q1	G[kG/cm] = -0.47
Q2	G[kG/cm] = 1.43
Q3	G[kG/cm] = -1.14
Q4	G[kG/cm] = -0.34

Switchyard - Vertical Separation of Arcs



Vertical Spreaders - Optics

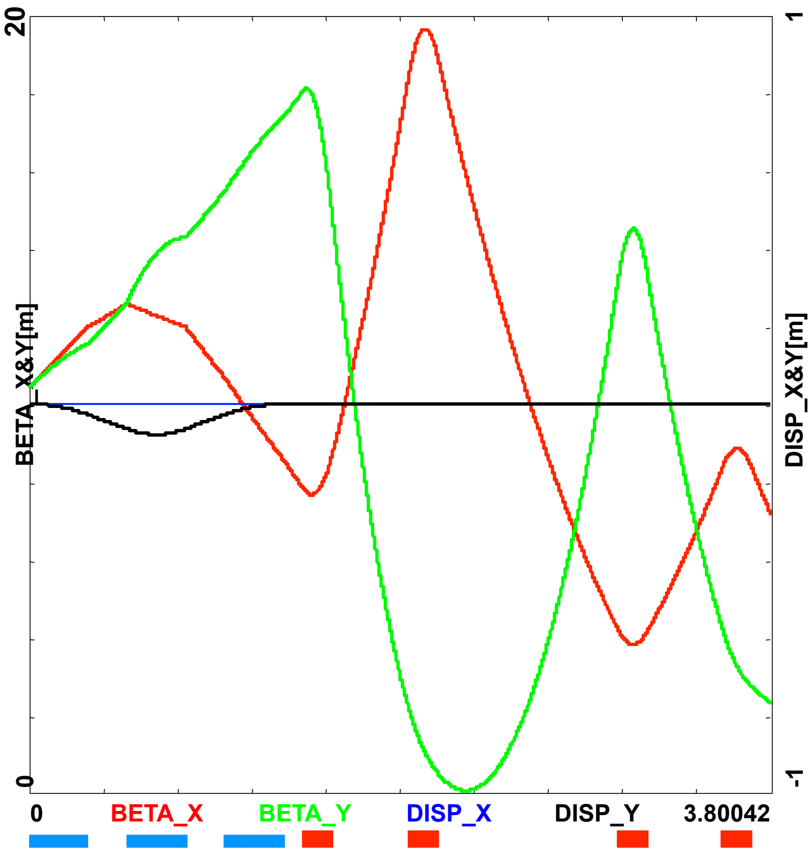
Spr. 1



vertical step I

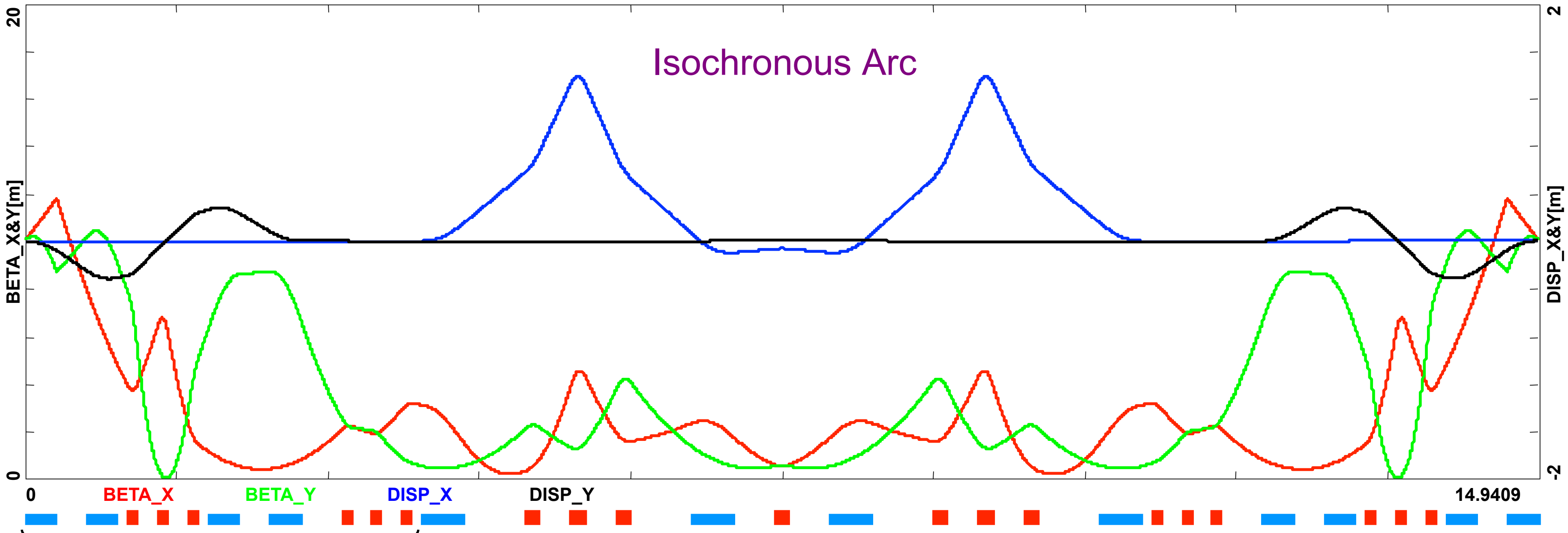
vertical step II

Spr. 3



vertical chicane

Arc 1 Optics (80 MeV)



2-step vert. Spreader

'Arc 2' = 2 × 'Arc 1'

2-step vert. Recombiner

Spr. dipoles:

30^0 bends (1 rec. + 3 sec.)

Lb = 30 cm

B = 5 kGauss

Arc dipoles :

4×45^0 bends(sec.)

Lb = 40 cm

B = 5 kGauss

Rec. dipoles:

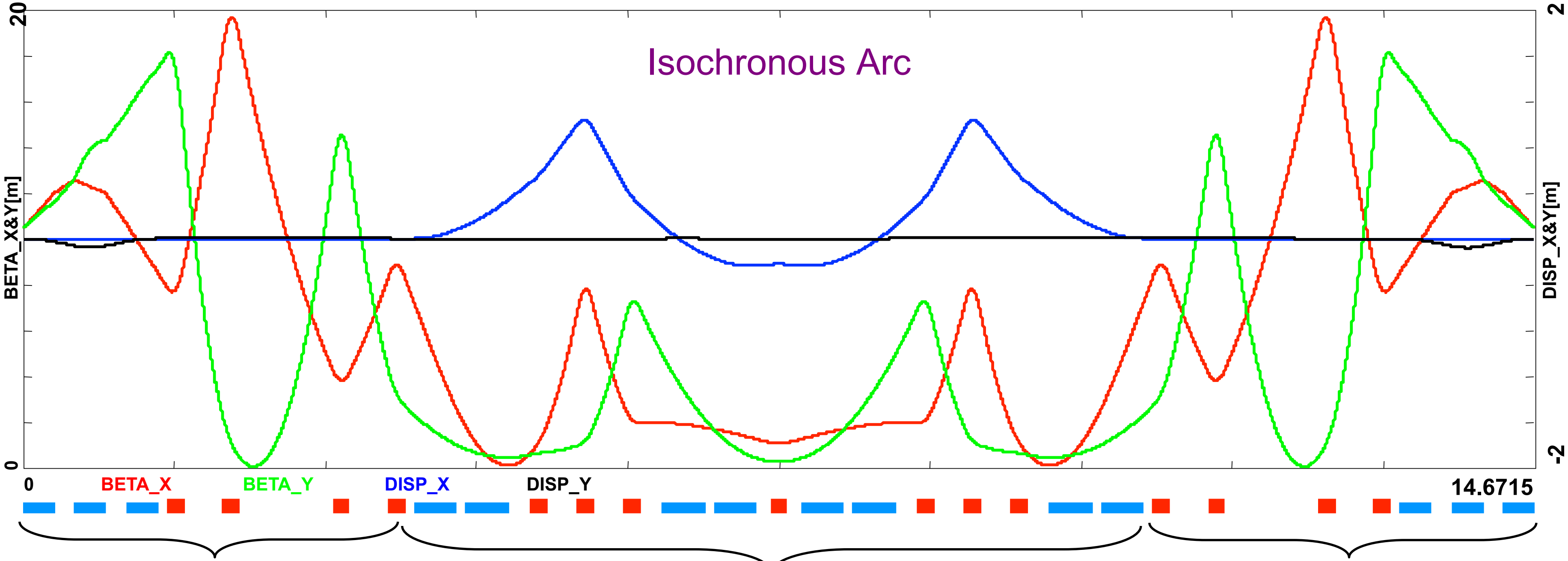
30^0 bends (3 sec. + 1 rec.)

Lb = 30 cm

B = 5 kGauss

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

Arc 3 Optics (230 MeV)



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:

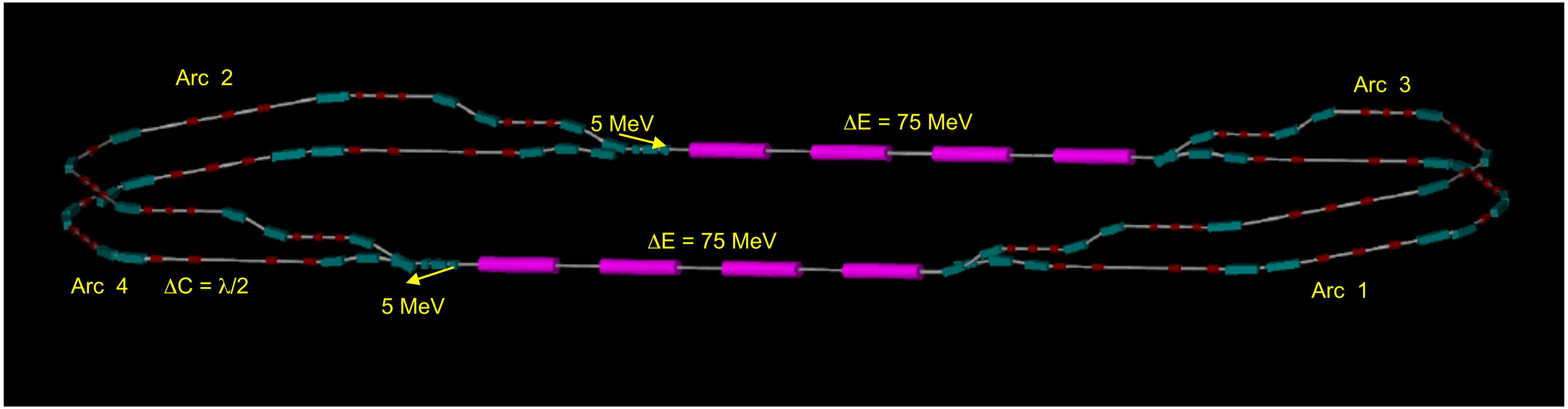
10^0 -20^0 -10^0 bends (rec.)

Lb = 30 cm

B = 5-10 kGauss

quads: Lq = 10-15 cm G ≤ 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**

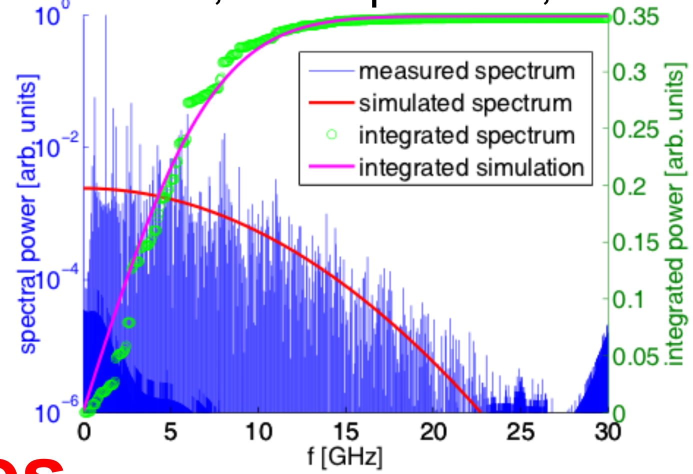
Benchmark simulations

Improved **damping schemes**

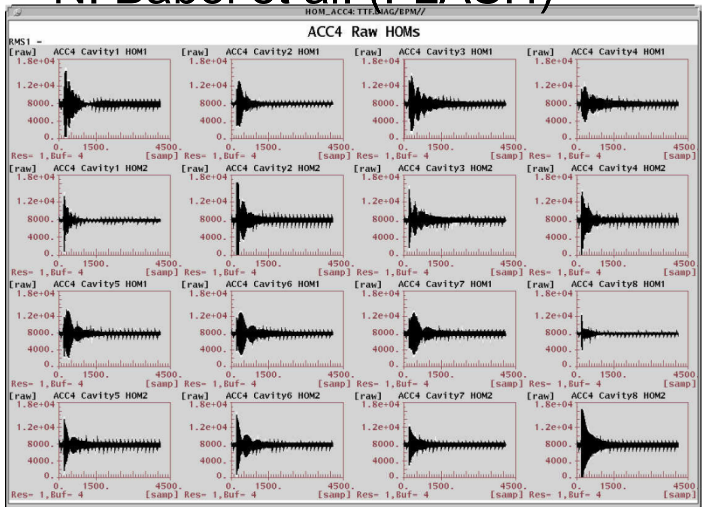
Precision orbit measurement

Cavity & CM alignment

1,3 GHz, M. Liepe et al., IPAC2011



N. Baboi et al. (FLASH)



Erk Jensen

ERL-TF: RF Power

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

→ Main LINAC
(0 beam loading)

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

Peak detuning

	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

Erk Jensen

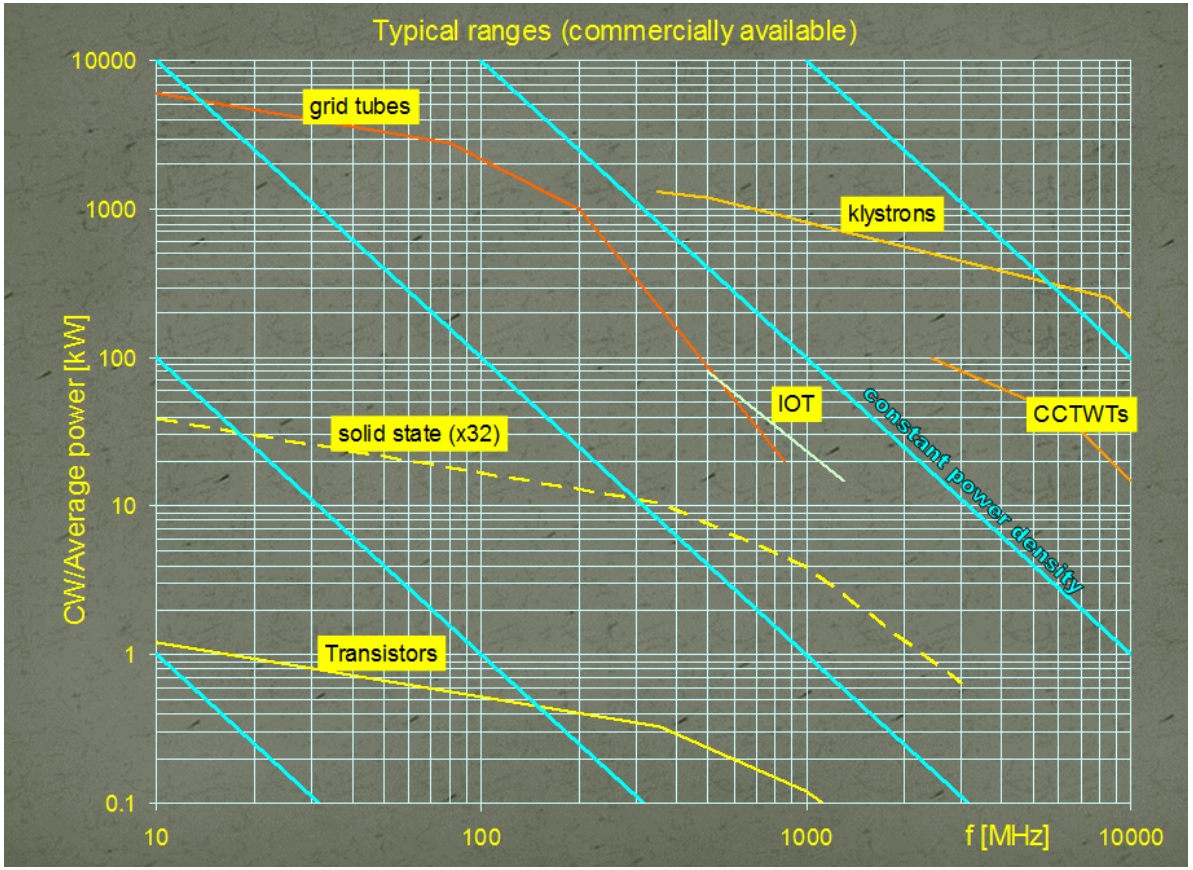
RF Power

Erk Jensen

use of IOTs ~ 50-100 kW at 700 MHz

high efficiency, low cost

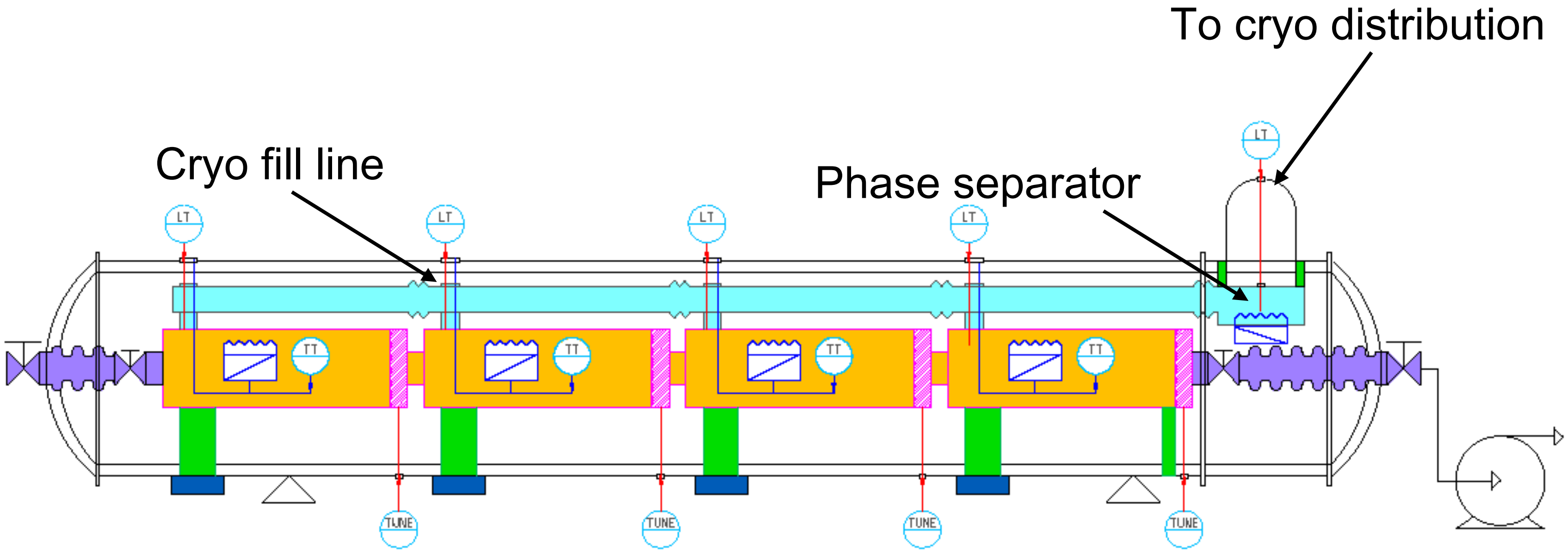
amplitude and phase stability



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

Erk Jensen

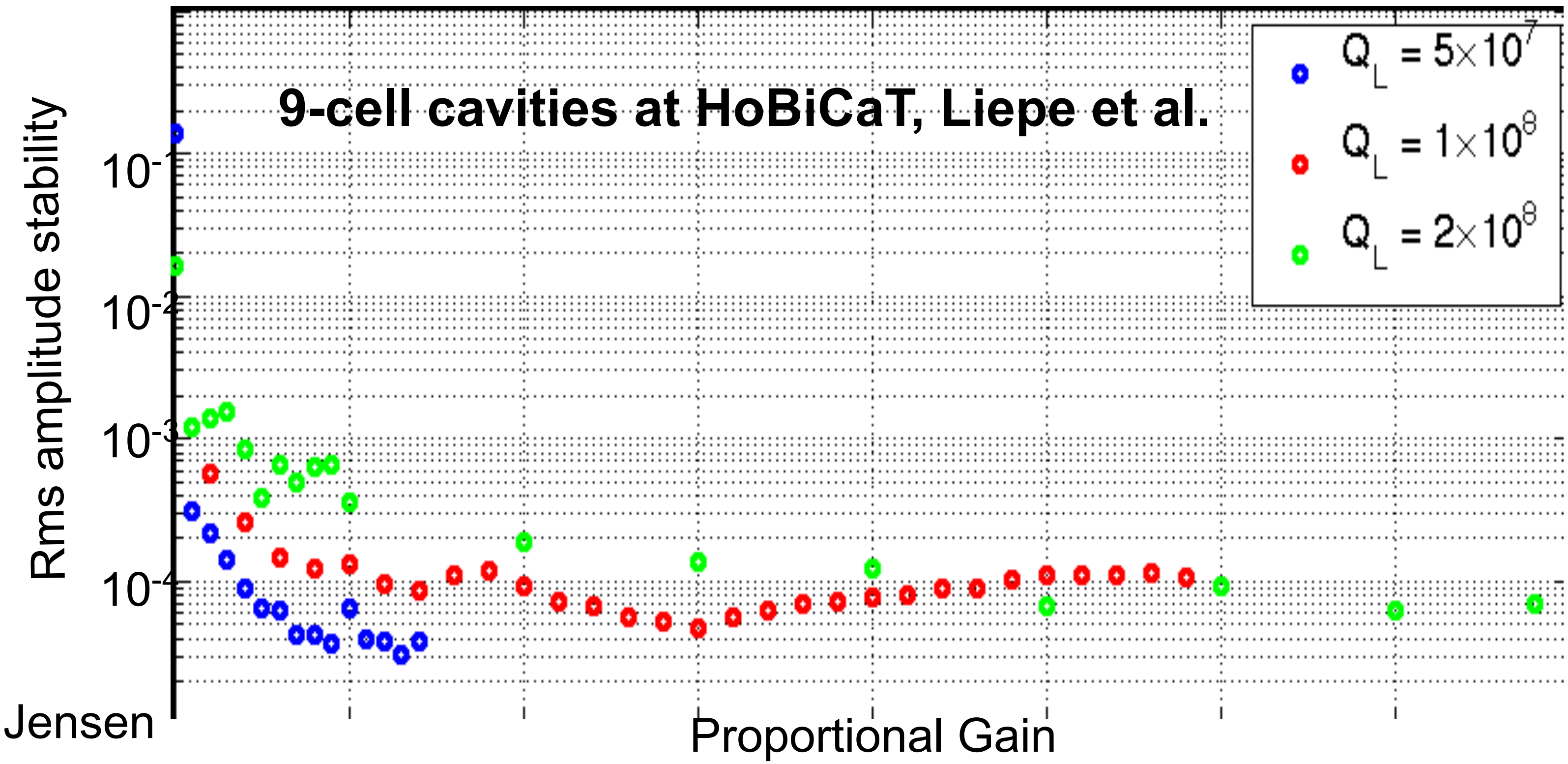
RF Controls

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.



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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

Erk Jensen

Timeline & Costs

Erk Jensen

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 ?)

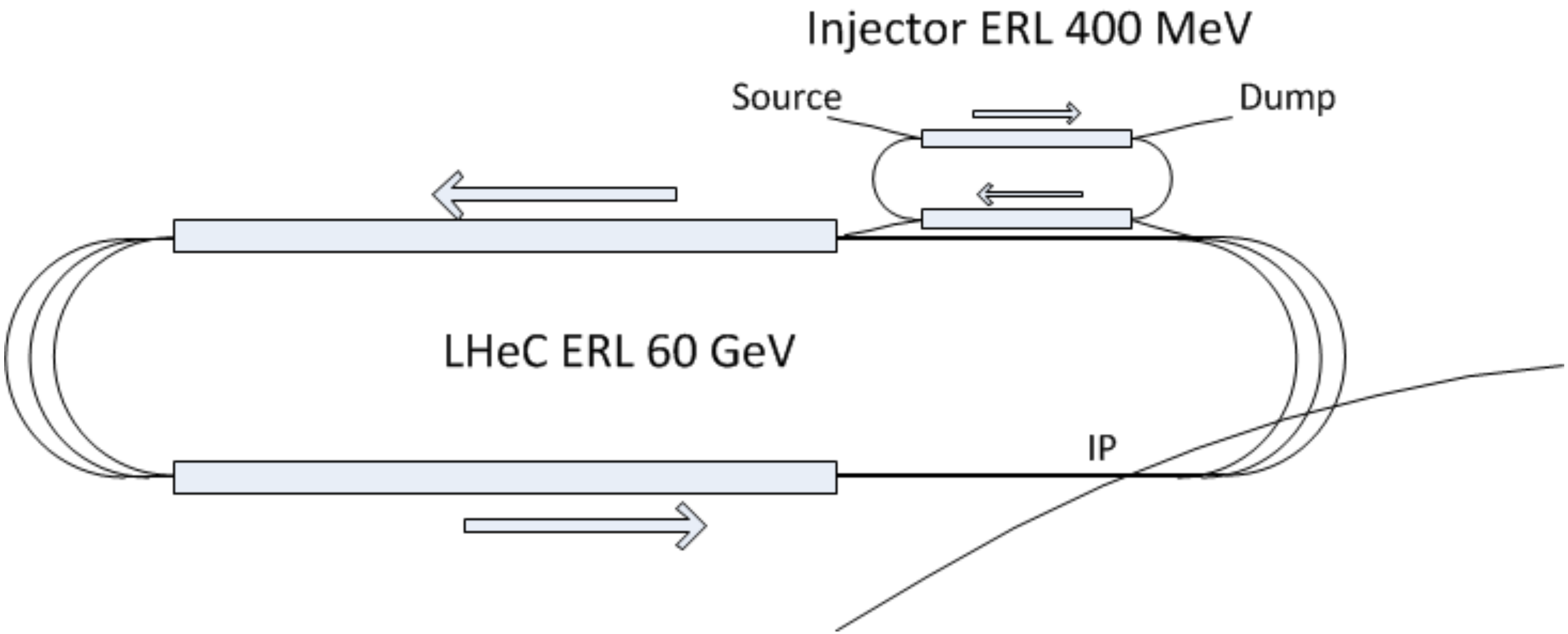
Do we need high power couplers ?

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

Alessandra Valloni

- Computer code for linear and non-linear optics calculations

- Code developed by V. Lebedev; used a 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