Layout, Optics and Beam Dynamics for the LHeC ERL

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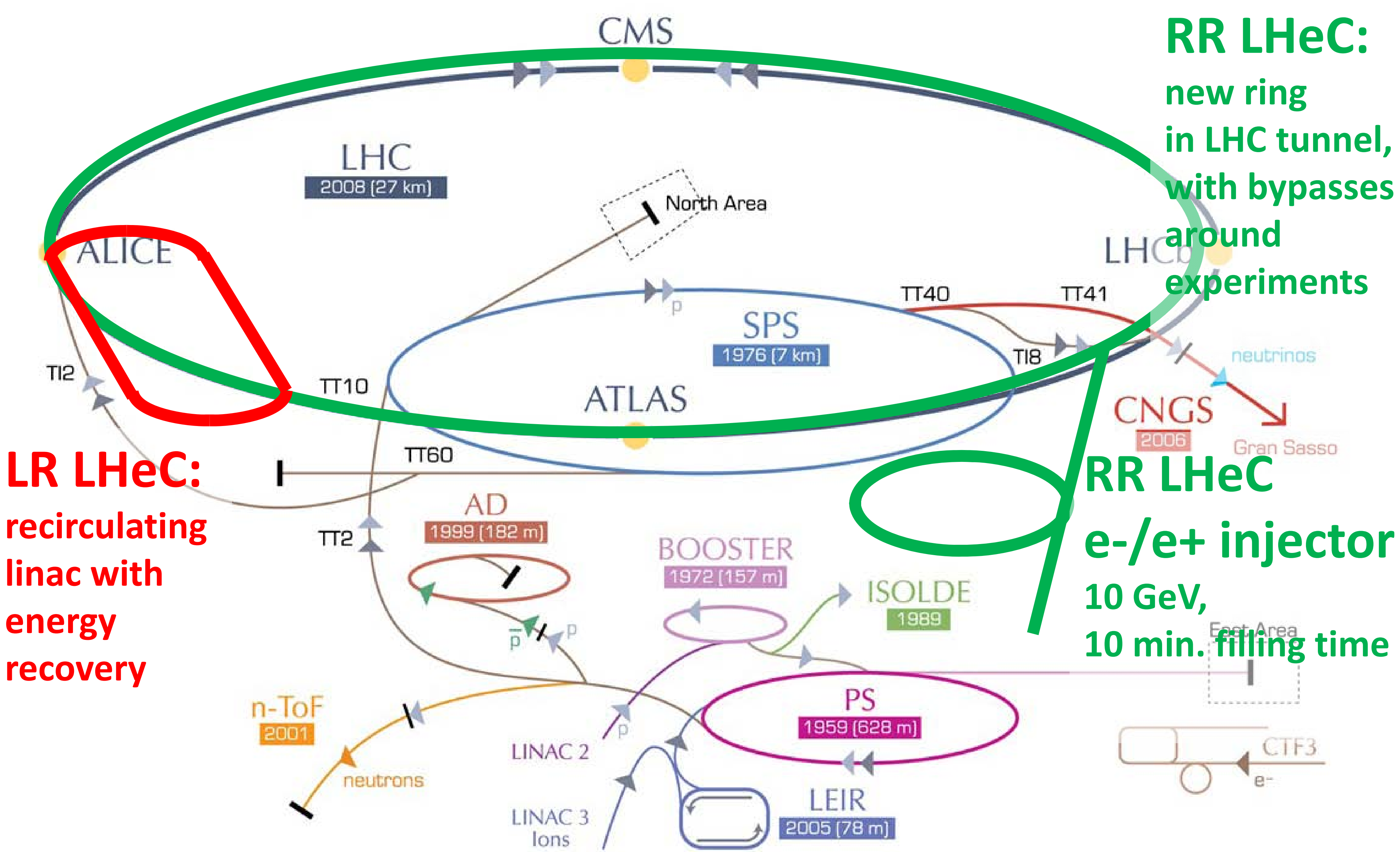
ERL2011, 18 October 2011, KEK, Tsukuba

www.cern.ch/lhec

contents

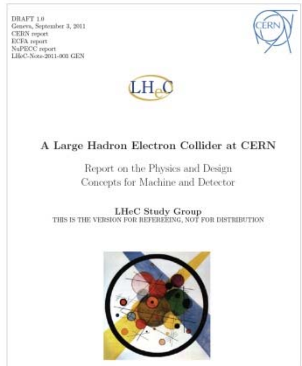
- Large Hadron electron Collider
- ERL layout & key parameters
- optics design
- beam dynamics: BBU, ion instability

Large Hadron electron Collider (LHeC)



Large Hadron electron Collider - *milestones*

- design study **since fall 2008**
- jointly **supported by CERN**, by the European Committee for Future Accelerators (**ECFA**) and by the Nuclear Physics European Collaboration Committee (**NuPECC**)
- **CDR draft** complete this summer (~600 pages)
- sent to distinguished **external referees** for review
- end of this year: **completion of CDR** including feedback from external referees; **choice between ring & linac options**
- expect **TDR by 2014**


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

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

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

performance targets

e- energy ≥60 GeV

luminosity ~10^{33} $cm^{-2}s^{-1}$

total electrical power for e-: ≤100 MW

e^+p collisions with similar luminosity

simultaneous with LHC *pp* (also *eA* || *AA*)

e^-/e^+ polarization

detector acceptance down to 1°

getting all this at the same time is very challenging;
the most challenging item is the e^+p luminosity (& e^+ rate)

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

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^*=0.1 m

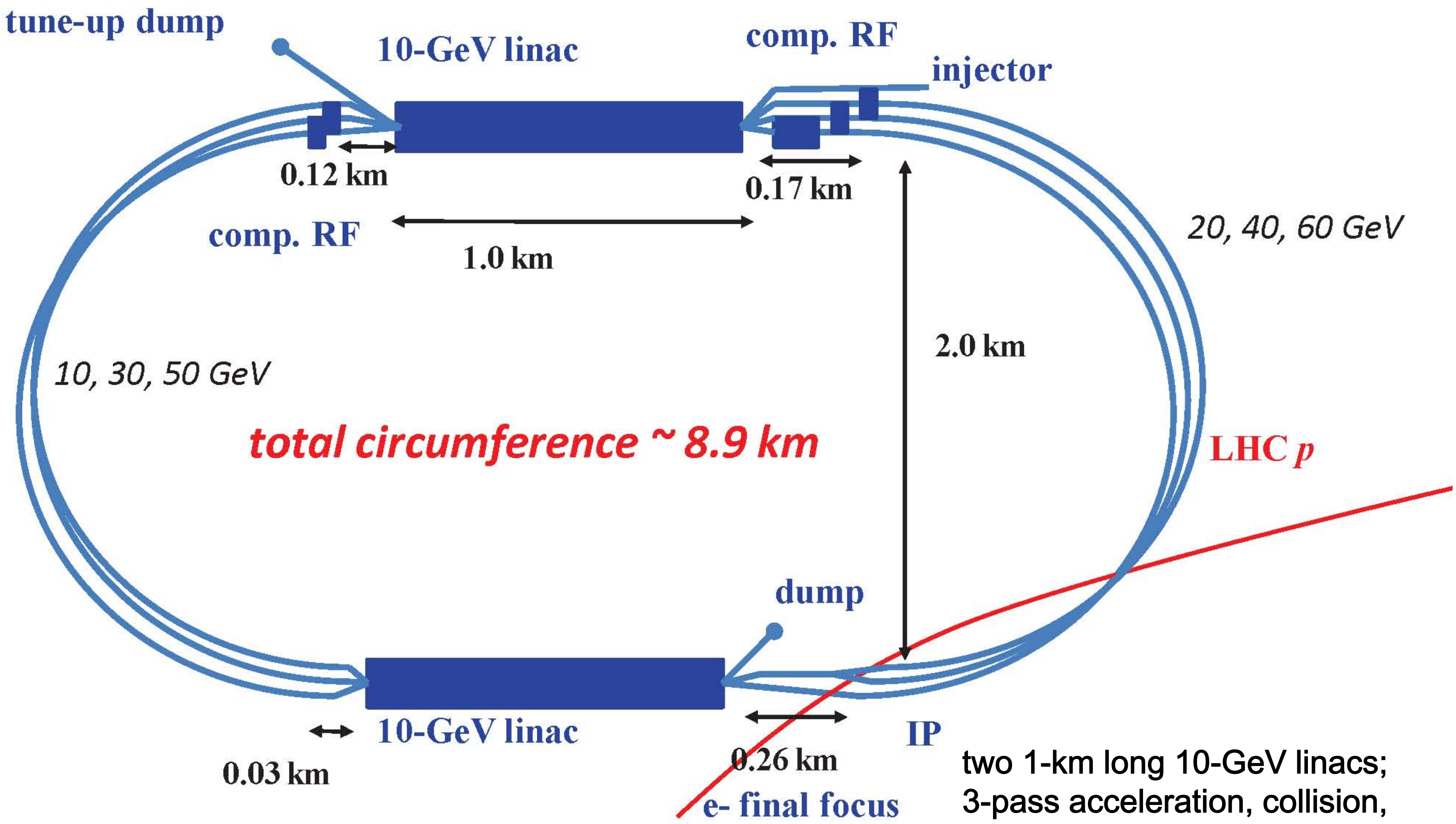
average e^-
current !

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

θ_c=0

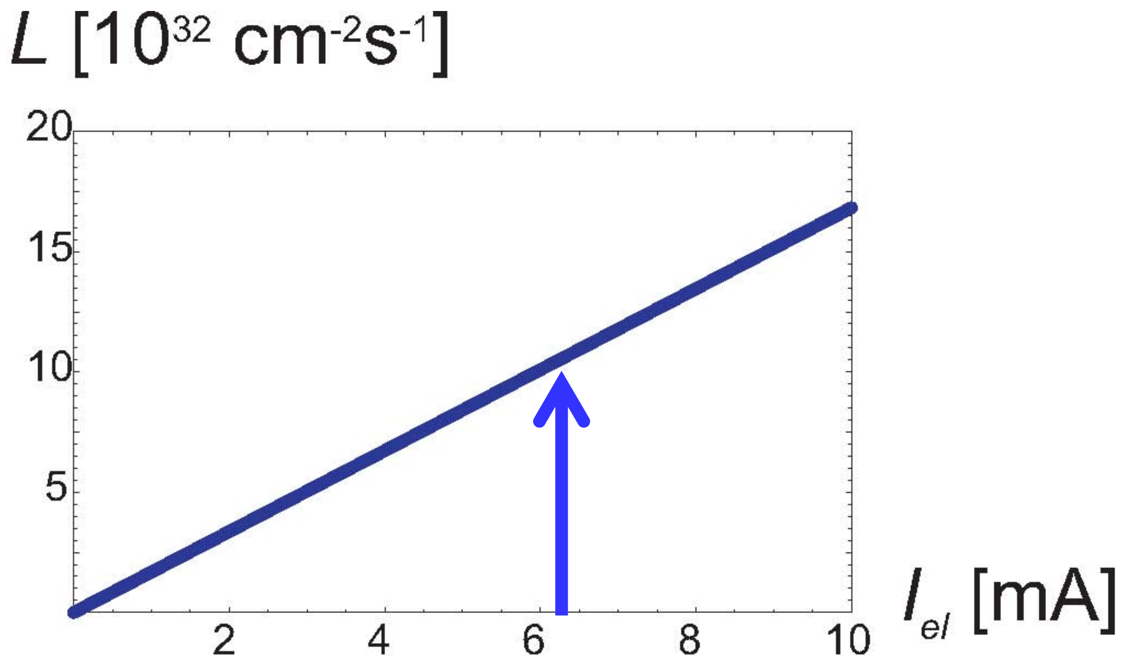
$H_{hg}\geq 0.9$

ERL configuration



two 1-km long 10-GeV linacs;
3-pass acceleration, collision,
3-pass deceleration; SR comp.;
circumference =1/3 LHC

LHeC needs ≥6 mA at 60 GeV



SC linacs can provide high average current,
e.g. with high duty factor or in cw

example design average currents:
CERN HP-SPL: ~2.5 mA (50 Hz)
Cornell ERL ~100 mA (cw)
eRHIC ERL ~ 50 mA at 20 GeV (cw)

beam power

6.4 mA at 60 GeV

→ 384 MW beam ! → ~800 MW el. power!!??

need for **energy recovery**! gain factor $(1-\eta_{ERL})$

→ LHeC ERL is high-luminosity baseline

RF frequency: 1.3(ILC) or ~0.72GHz

- 720 MHz requires less cryo-power (~2 times less from BCS theory) [J. Tückmantel, E. Ciapala]
- 720 MHz: fewer cells - better for trapped modes [J. Tückmantel]
- synergy with SPL, eRHIC and ESS

linac RF parameters

- Numbers from CERN RF Group differ

	ERL 720 MHz	ERL 1.3 GHz	Pulsed
duty factor	cw	cw	0.05
RF frequency [GHz]	0.72	1.3	1.3
cavity length [m]	1	~1	~1
energy gain / cavity [MeV]	18*	18	31.5
R/Q [100 Ω]	400-500*	1200	1200
Q_0 [10^{10}]	2.5-5.0	2 ?	1
power loss stat. [W/cav.]	5	<0.5	<0.5
power loss RF [W/cav.]	8-32	13-27 ?	<10
power loss total [W/cav.]	13-37 (!?)	13-27	11
"W per W" (1.8 k to RT)	700	700	700
power loss / GeV @RT [MW]	0.51-1.44	0.6-1.1	0.24
length / GeV [m] (*filling*=0.57)	97	97	56

ERL electrical site power

cryo power for two 10-GeV SC linacs: 28.9 MW

MV/m cavity gradient, 37 W/m heat at 1.8 K

700 "W per W" cryo efficiency

RF power to control microphonics: 22.2 MW

10 kW/m (eRHIC), 50% RF efficiency

RF for SR energy loss compensation: 24.1 MW

energy loss from SR 13.2 MW, 50% RF efficiency

cryo power for compensating RF: 2.1 MW

1.44 GeV linacs

microphonics control for compensating RF: 1.6 MW

injector RF: 6.4 MW

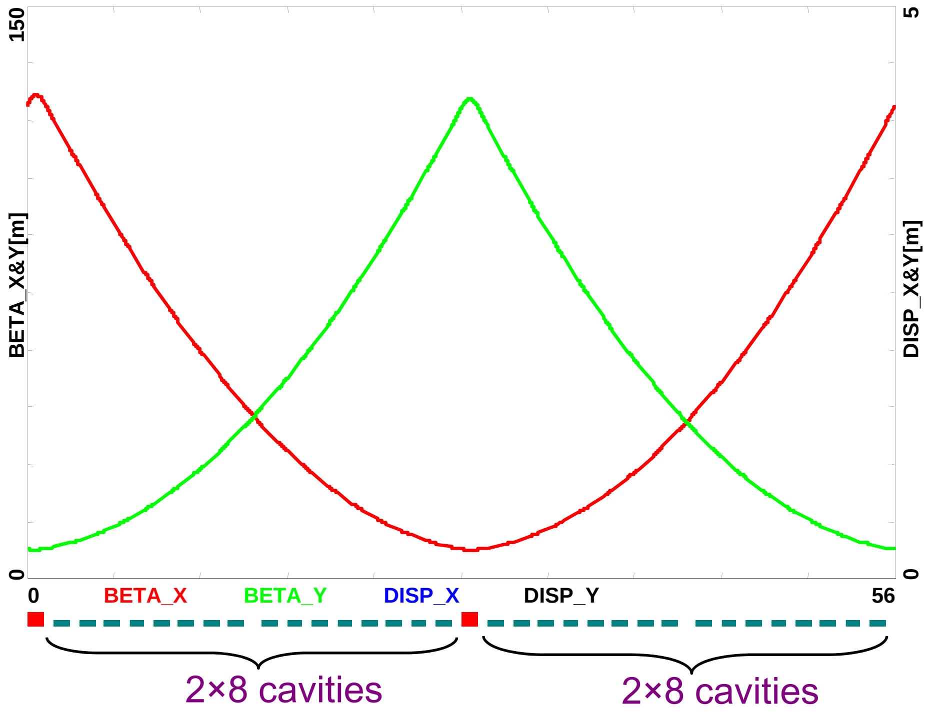
500 MeV, 6.4 mA, 50% RF efficiency

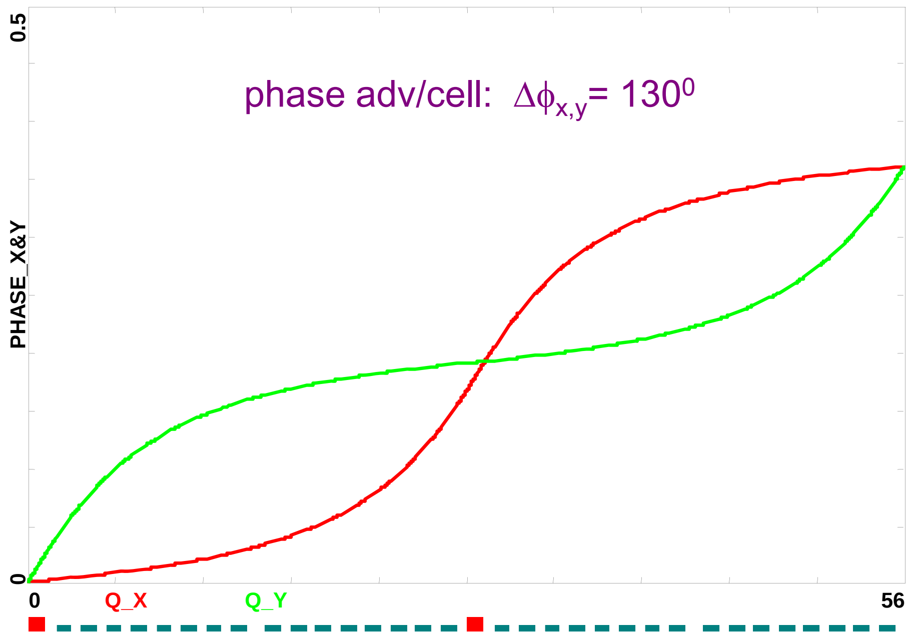
magnets: 3 MW

grand total = 88.3 MW

Linac Optics – 130^0 FODO Cell

E = 0.5 GeV





linac quadrupoles

Lq=100 cm

GF= 0.103 Tesla/m

GD= -0.161 Tesla/m

720 MHz RF:

Lc =100 cm

5-cell cavity

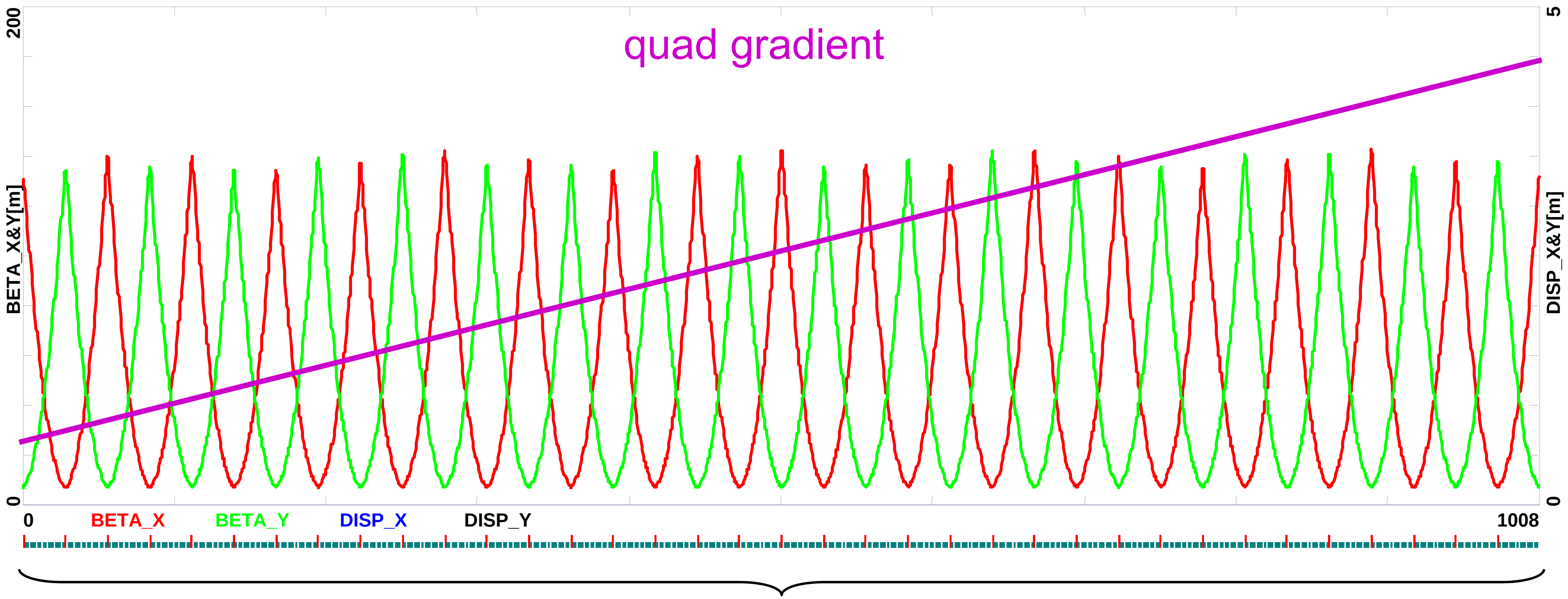
Grad = 17.361 MeV/m

ΔE= 555.56 MV

Alex Bogacz

Linac 1 – Focusing profile

E = 0.5 – 10.5 GeV



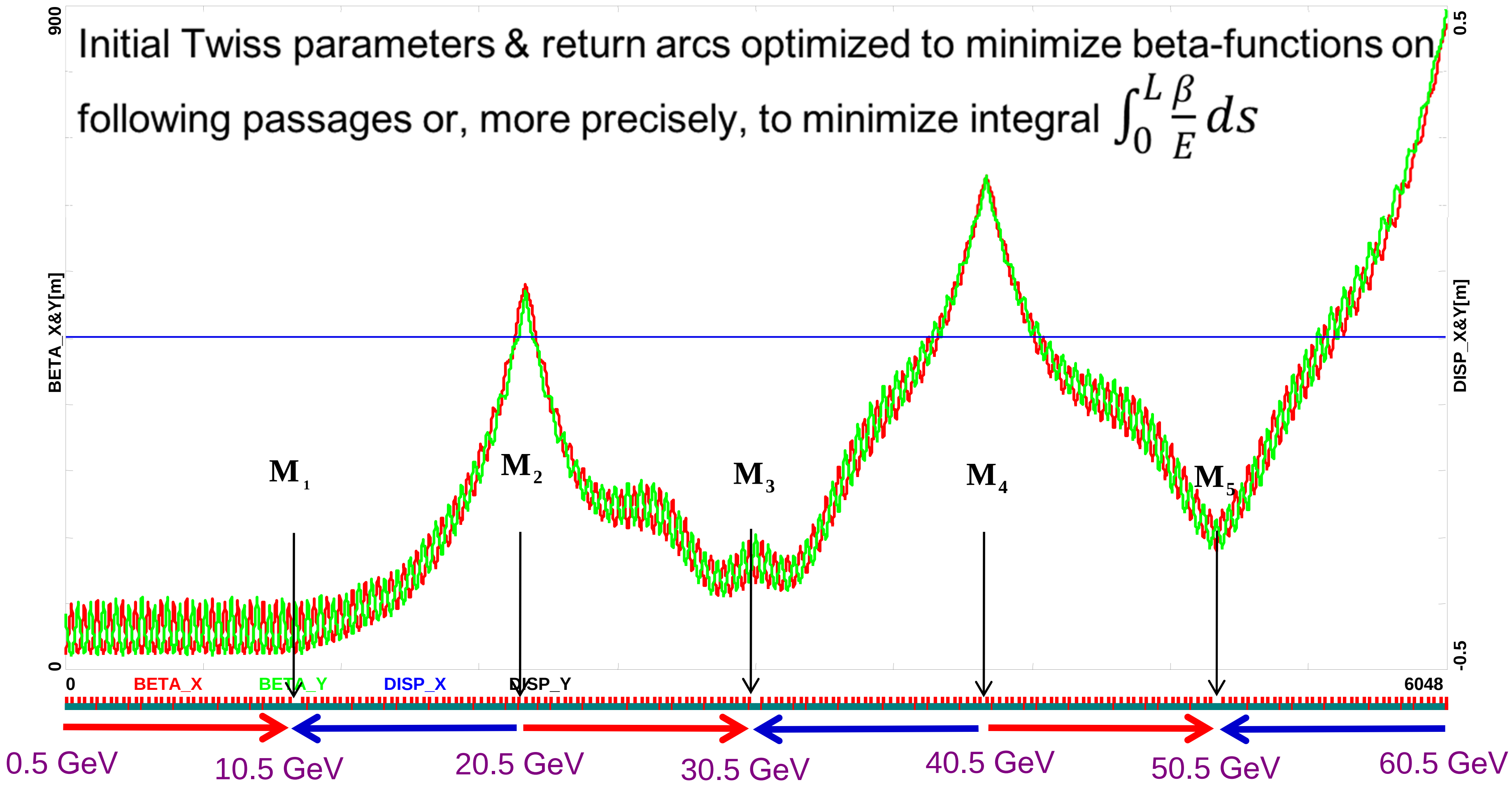
18 FODO cells (18 × 2 × 16 = 576 RF cavities)

Alex Bogacz

Linac 1 – Multi-pass ER Optics

Design with OptiM32 code (V. Lebedev et al)

Initial Twiss parameters & return arcs optimized to minimize beta-functions on following passages or, more precisely, to minimize integral $\int_0^L \frac{\beta}{E} ds$



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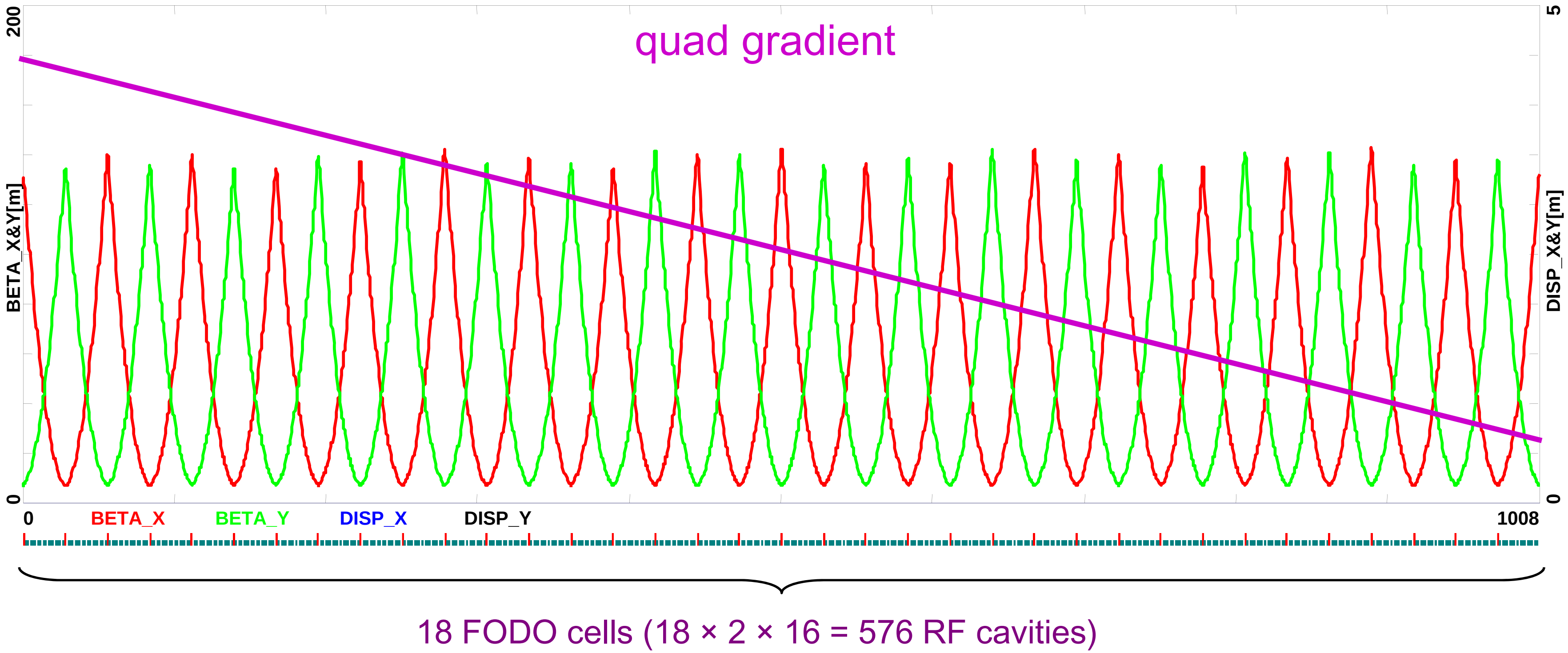
Linac 2 – Focusing profile

E = 10.5 – 0.5 GeV (ER)



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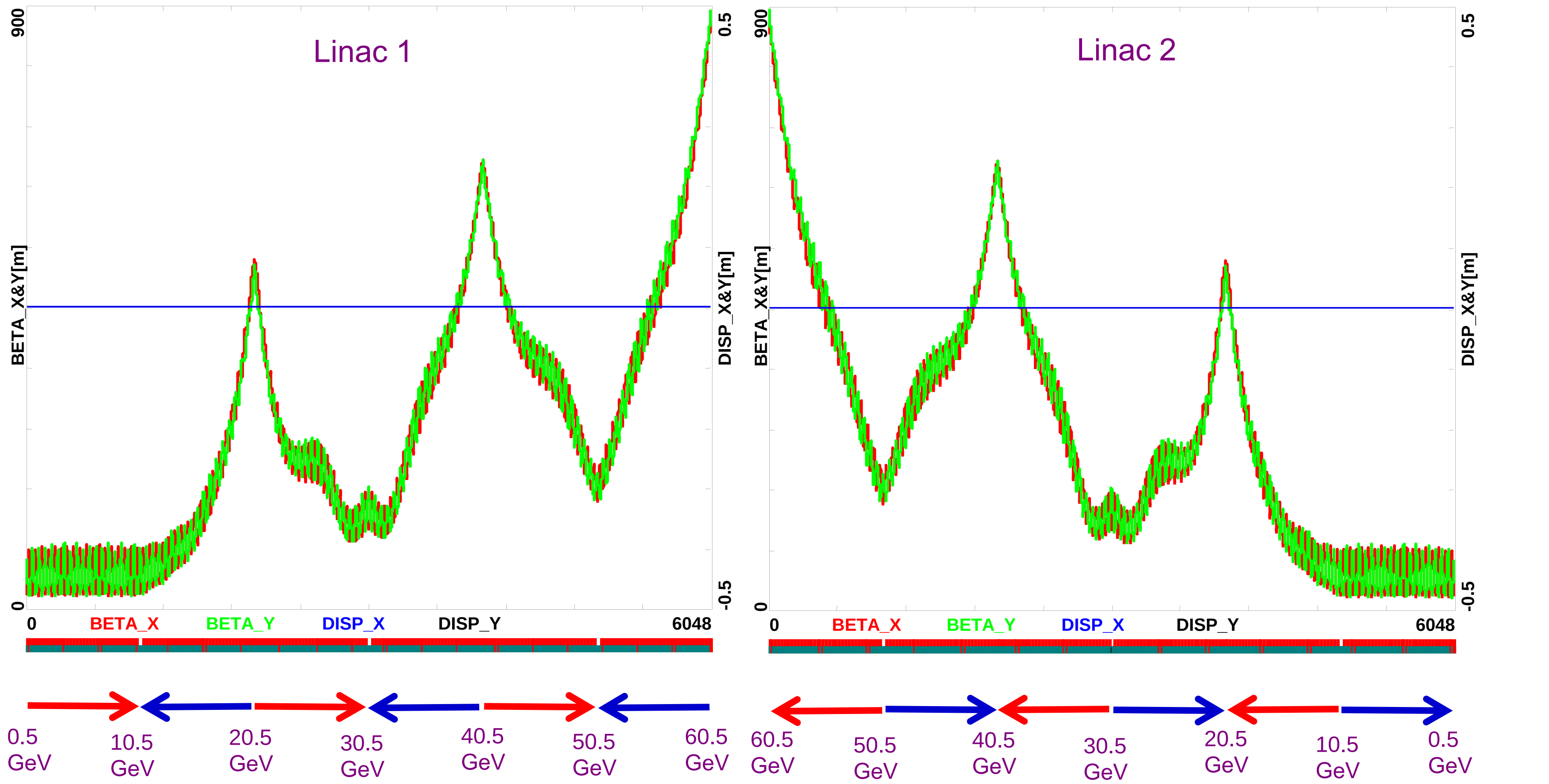
Linac 2 multi-pass optics with ER
– mirror symmetric to Linac 1 !

Daniel Schulte

Linac 1 and 2 – Multi-pass ER Optics



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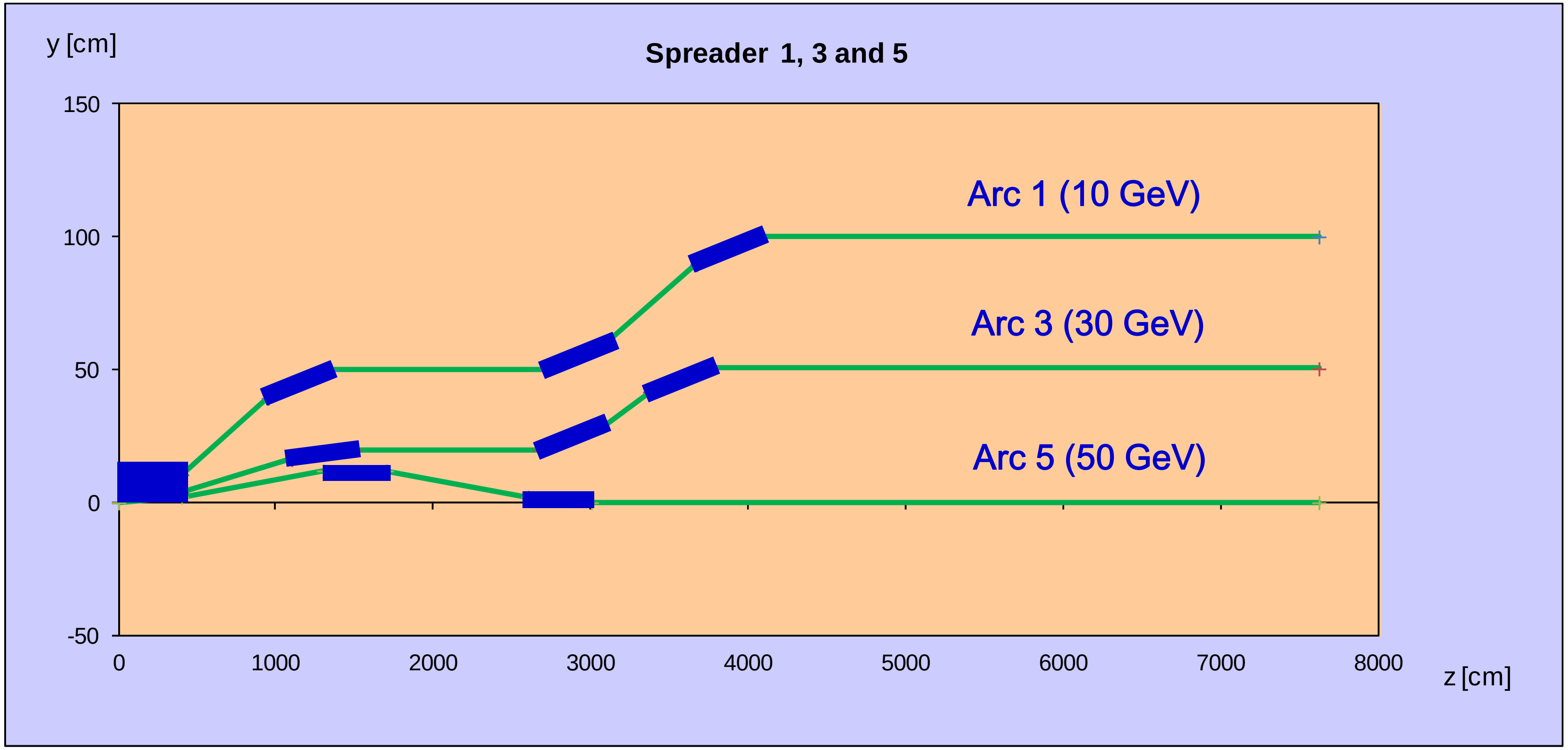
Vertical Separation of Arcs



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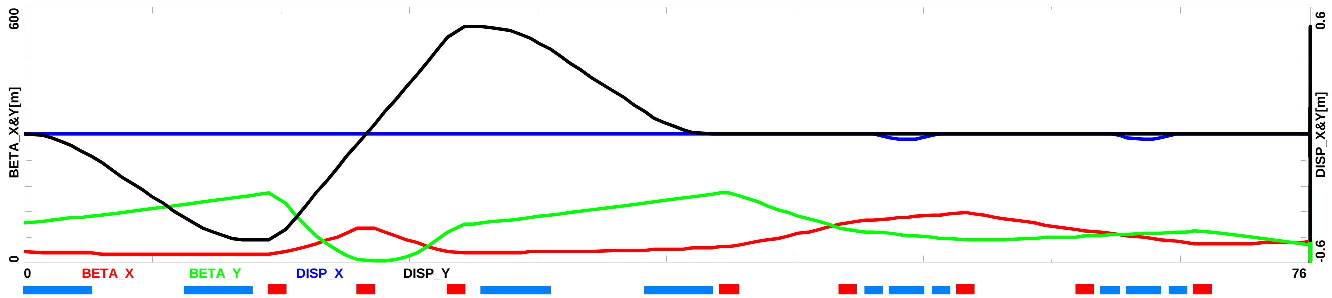
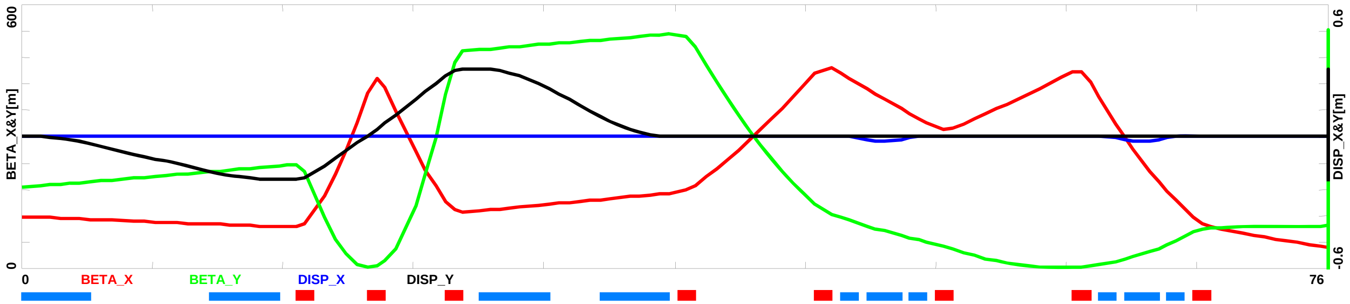
Vertical Spreaders - Optics

Spr. 1



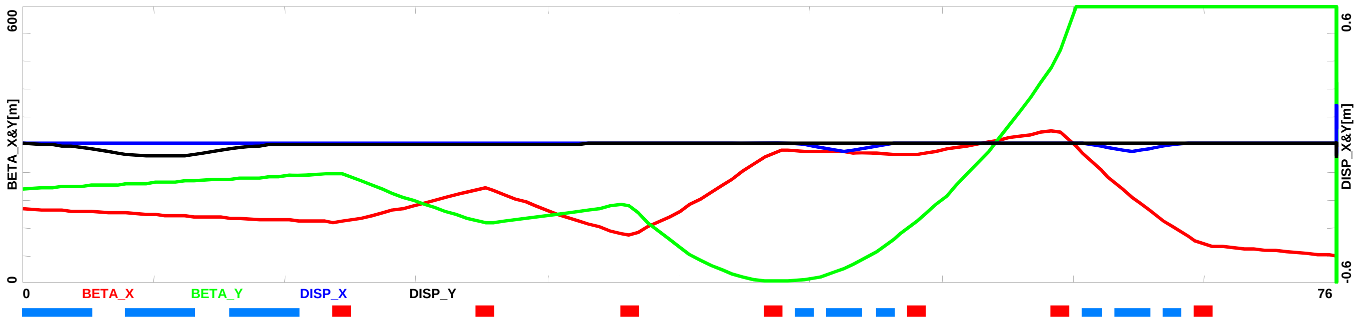
vertical step I
vertical step II
path-length adjustment ‘doglegs’

Spr. 3



vertical step I
vertical step II
path-length adjustment ‘doglegs’

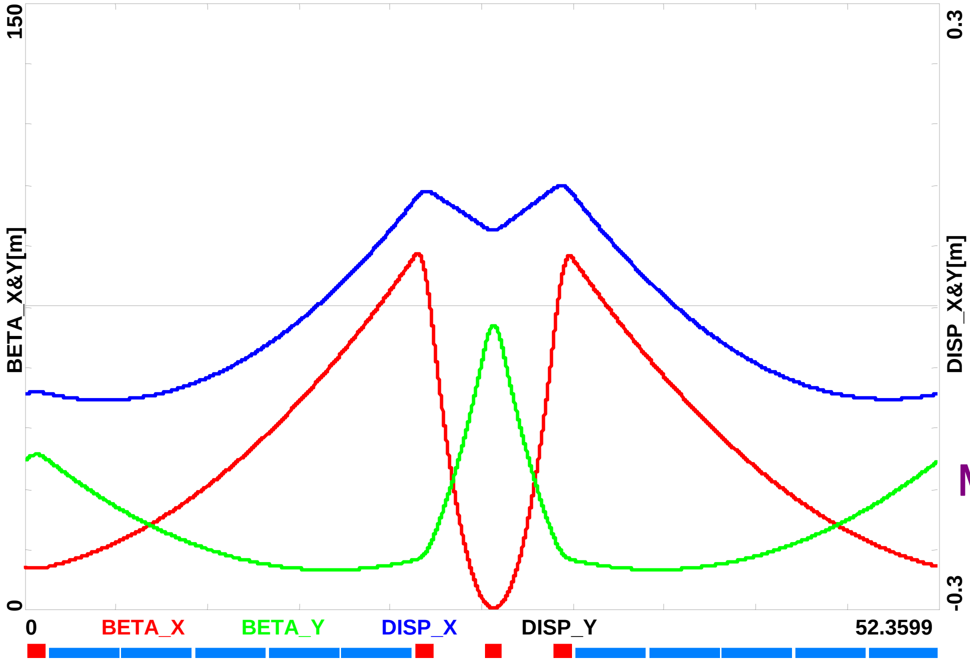
Spr. 5



vertical chicane
path-length adjustment ‘doglegs’

Alex Bogacz, Ilkyoung Shin

Arc: quasi-isochronous FMC Cell



Emittance dispersion

⟨H⟩ averaged over bends

Momentum compaction

$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

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

factor of 2.5 smaller than FODO

$$M_{56} = -\int \frac{D}{\rho}\, ds = -\theta_{bend} \langle D \rangle$$

$$M_{56} = 1.16 \times 10^{-3}\ \mathrm{m}$$

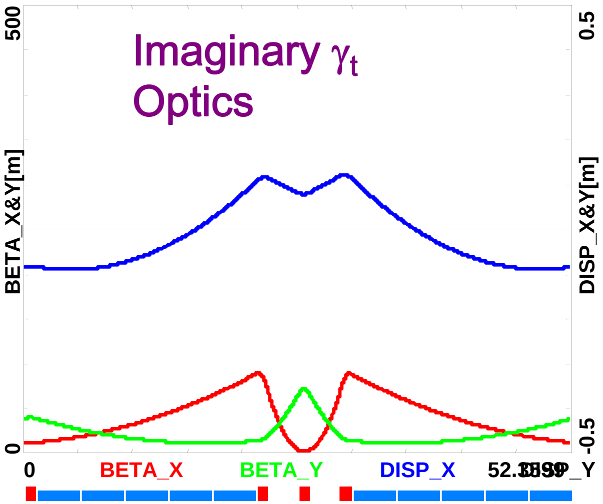
factor of 27 smaller than FODO

Alex Bogacz

Arc cells – Emittance preserving Optics

$$\Delta\varepsilon^N = \frac{4}{3} C_q \, r_0 \, \gamma^6 \langle H \rangle \frac{\pi}{\rho^2}, \qquad H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

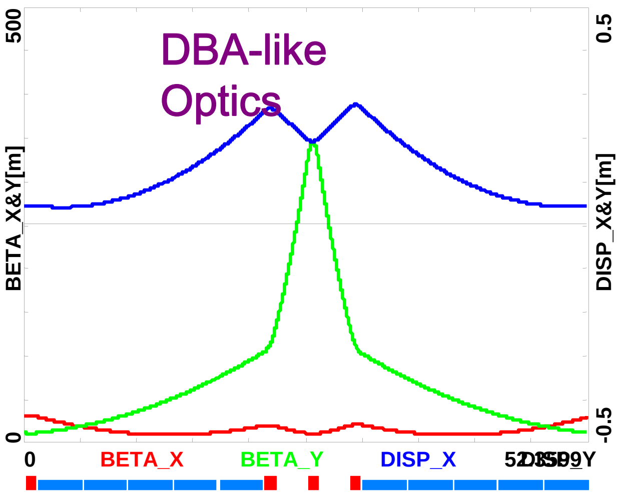
Arc 1 , Arc2



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

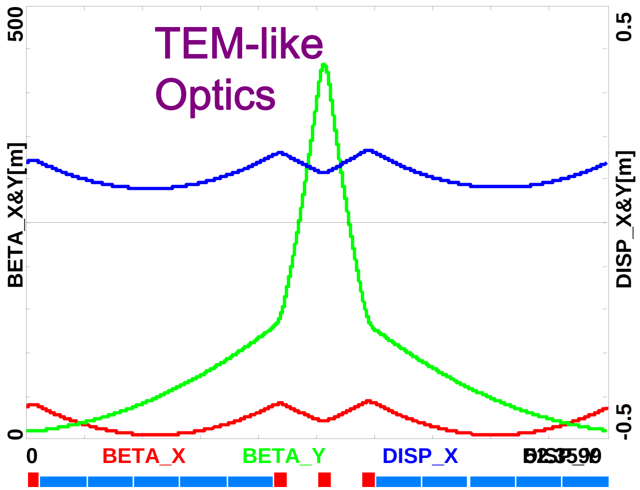
limit chamber size
(>12 σ at 25 mm diameter)

Arc 3, Arc 4



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

Arc5, Arc 6



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

factor of 18 smaller than FODO

limit emittance growth

total emittance increase (all 5 arcs): $\Delta\varepsilon_x^N$ = 1.25 × 4.5 μm rad =5.6 μm rad (~10%)

emittance growth due to disruption in the collision 15%-180% (without/with rematch the outgoing optics)

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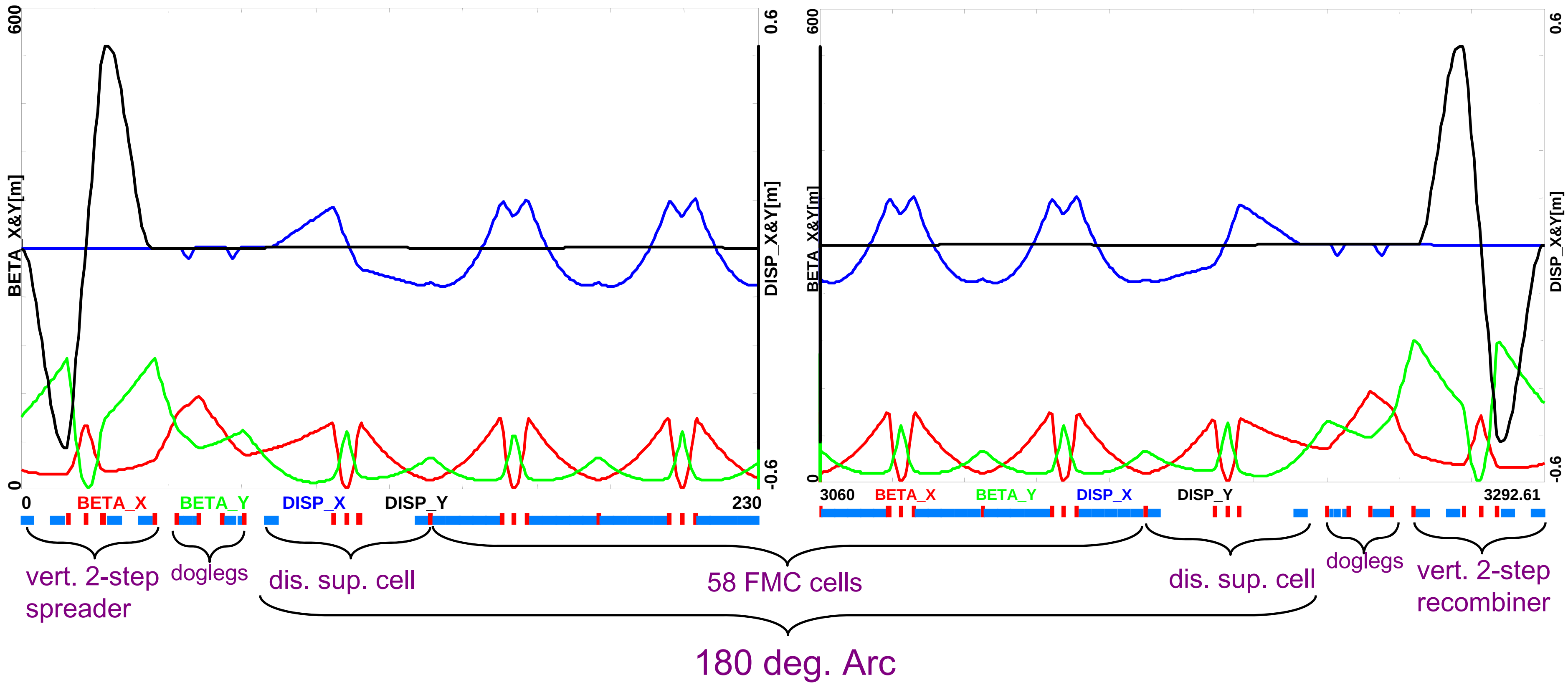
Arc 1 Optics (10 GeV)



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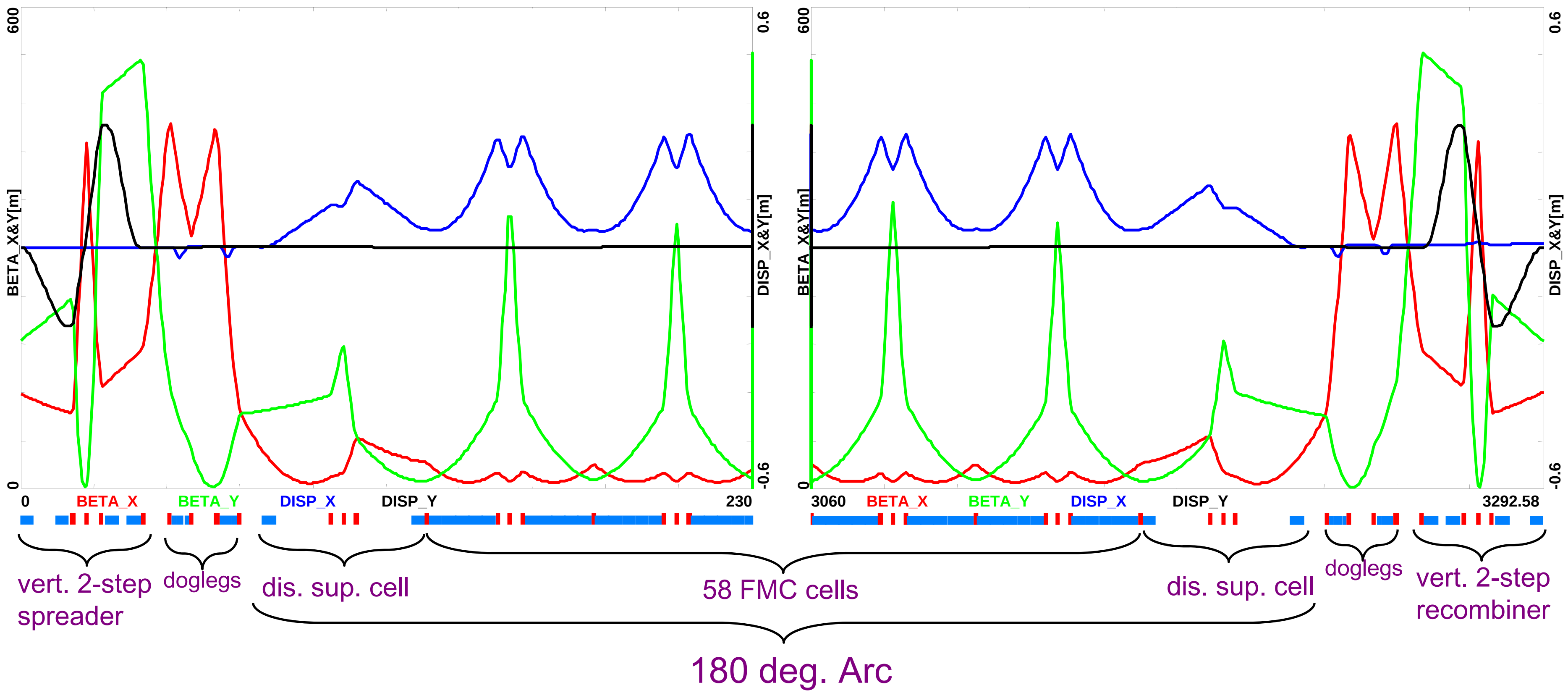
Arc 3 Optics (30 GeV)



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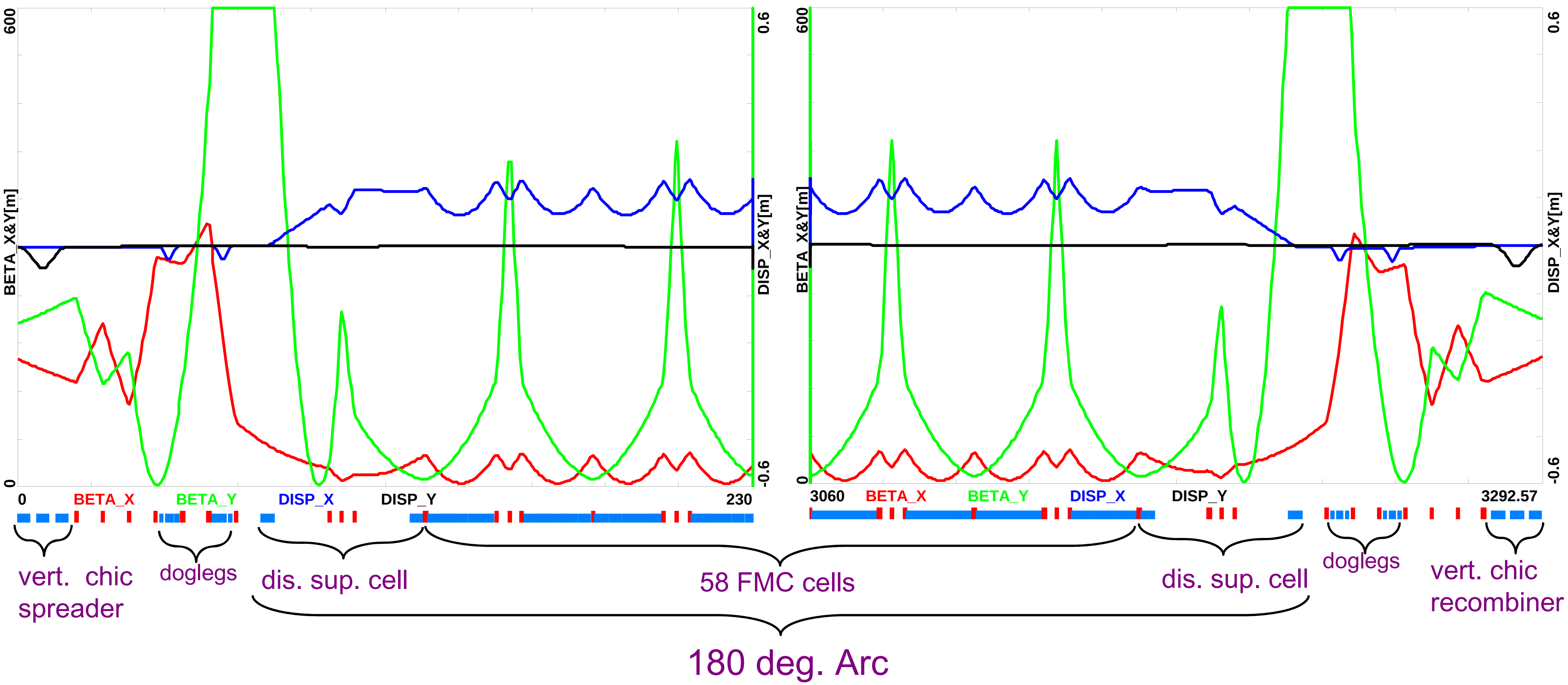
Arc 5 Optics (50 GeV)



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LHeC beam parameters

	protons	electrons (ERL)
beam energy [GeV]	7000	60
Lorentz factor γ	7460	117400
normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
geometric emittance $\varepsilon_{x,y}$ [nm]	0.50	0.43
IP beta function $\beta^*_{x,y}$ [m]	0.10	0.12
rms IP beam size $\sigma^*_{x,y}$ [μm]	7	7
rms IP divergence $\sigma'_{x,y}$ [μrad]	70	58
beam current [mA]	≥430	6.6
bunch spacing [ns]	25 or 50	50
bunch population	$1.7\text{x}10^{11}$	$2\text{x}10^{9}$
crossing angle	0.0	

beam-beam effects

protons

- **head-on tune shift:** $\Delta Q=0.0001$ *tiny*
- **long-range effect:** *none*

  36 σ_p separation at s=3.75 m
- **emittance growth** due to **e-beam position jitter**

  p kick 10 nrad ($\sim 10^{-4}\sigma^{*\prime}$) for 1σ offset,

  e- turn-to-turn random orbit jitter ≤ 0.04σ

  [scaled from K. Ohmi, PAC'07;
  see also D. Schulte, F. Zimmermann, EPAC2004]

can we achieve this stability?

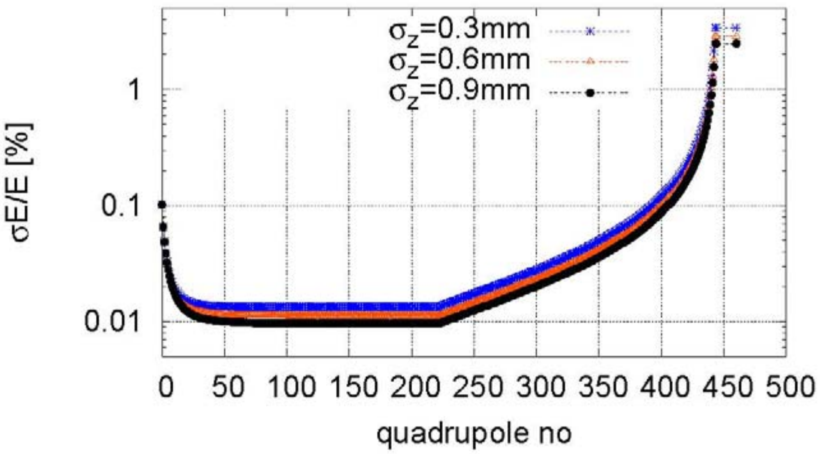
electrons

- **disruption** $D_{x,y}\approx 6$, $\theta_0\approx 600\ \mu$rad ($\approx 10\sigma^{*\prime}$) *large*

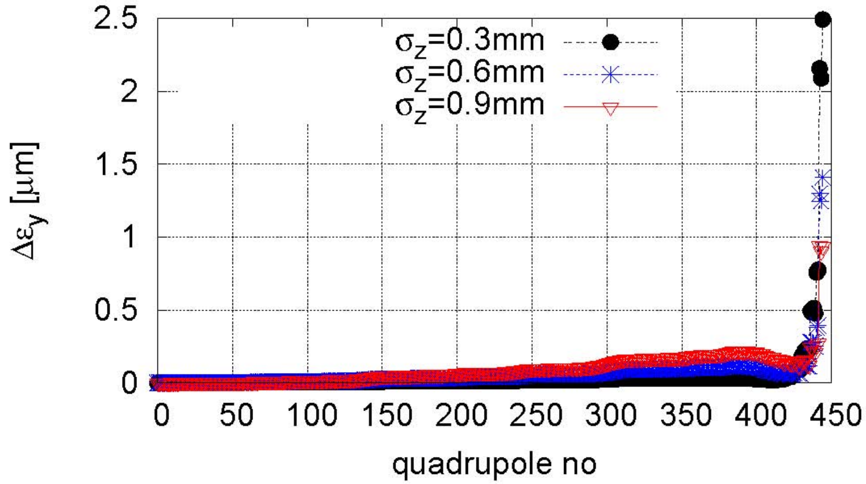
  180-15% emittance growth (un-/matched)

Single-bunch wake field effects

simulations with **PLACET code**; wake fields scaled from ILC/TESLA cavities to lower frequency and larger iris aperture



RMS energy spread along the linacs; initial uncorrelated RMS energy spread 0.1%; three different bunch lengths ; spread if 0.01-0.02% at collision point, 0.1-0.2% at final arc, and ~4% at beam dump



single bunch beam-break-up with initial offset $x = \sigma_x$

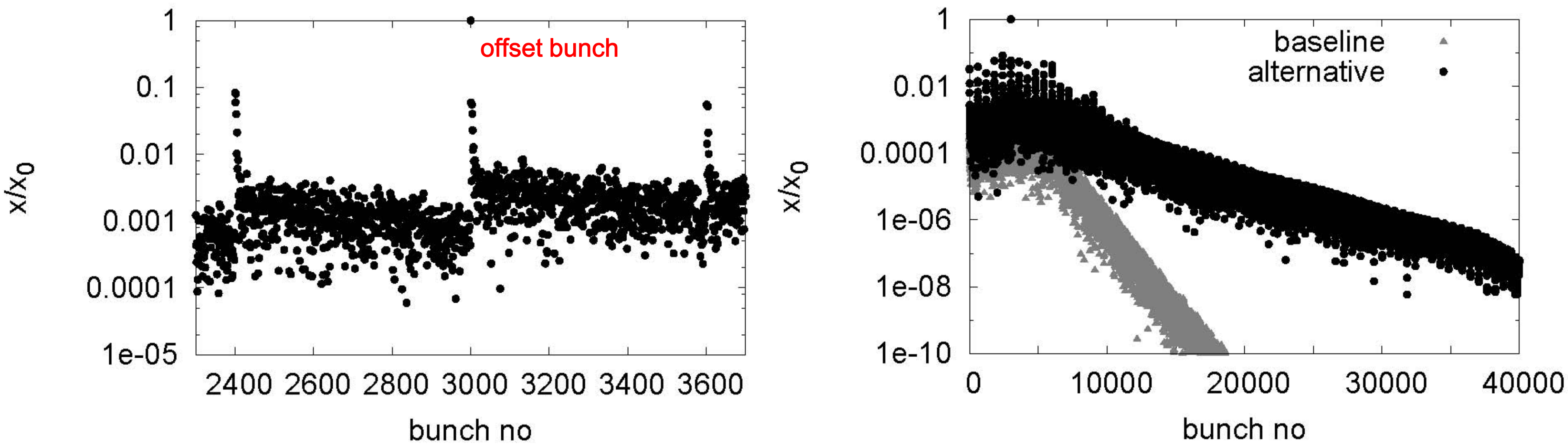
Daniel Schulte

Multi-bunch transverse wake field effects

new CERN code simulates multi-bunch effect for recirculation & ER: point-like bunches, a number of dipole wake field modes, cavity-to-cavity mode frequency spread; in the simulation a single bunch of a long train is offset by one unit ; arcs replace by simple transfer matrices (no chromaticity)

wake-field modes calculated for the SPL cavity design, assuming Q = 10^5 for all modes, comparable to the larger Q-values found in TESLA cavities; a random variation of the transverse mode frequencies of 0.1% (~1 MHz) equal to the ILC target

beam remains stable in our baseline design, and even in an alternative lattice (designed by BNL colleagues) with no focusing in the linacs



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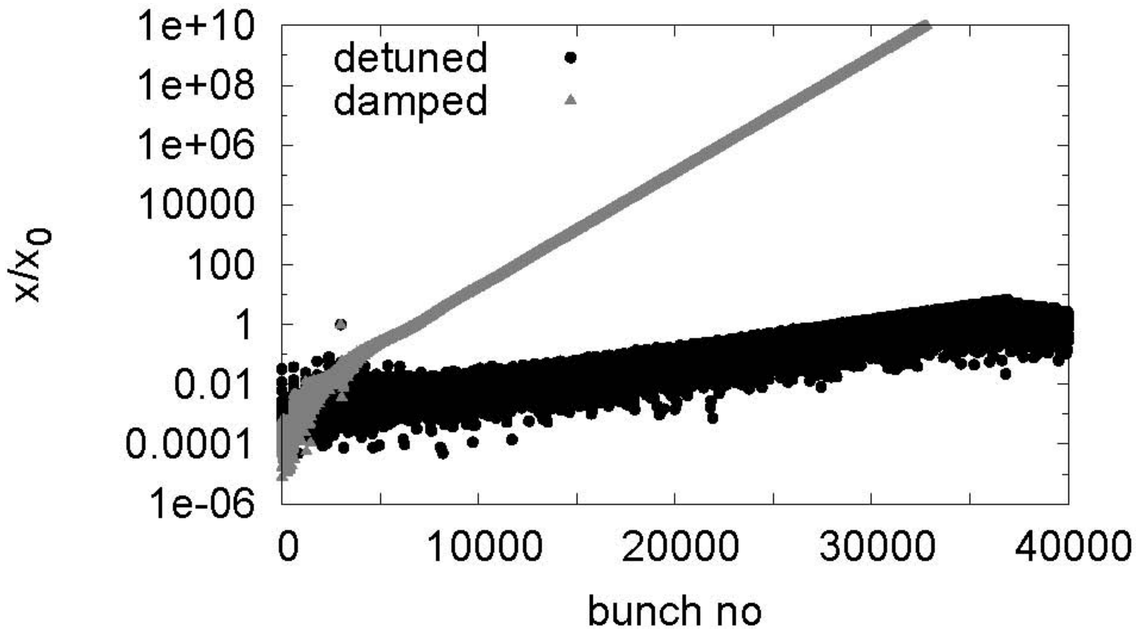
Multi-bunch transverse wake field effects

f[GHz]	k[V/pCm^2]	f[GHz]	k[V/pCm^2]
0.9151	9.323	1.675	4.160
0.9398	19.095	2.101	1.447
0.9664	8.201	2.220	1.427
1.003	5.799	2.267	1.377
1.014	13.426	2.331	2.212
1.020	4.659	2.338	11.918
1.378	1.111	2.345	5.621
1.393	20.346	2.526	1.886
1.408	1.477	2.592	1.045
1.409	23.274	2.592	1.069
1.607	8.186	2.693	1.256
1.666	1.393	2.696	1.347
1.670	1.261	2.838	4.350

dipole modes of SPL cavity design



multi-bunch beam break-up for the SPL cavities; in one case only damping, in the other case only cavity-to-cavity mode detuning is present – the beam is unstable in both cases

Daniel Schulte

Multi-bunch transverse wake field effects - conclusions from CERN studies

- One has to **ensure that transverse higher order cavity modes are detuned from one cavity to the next**. While this detuning can naturally occur due to production tolerances, one has to find a method to ensure its presence. This problem exists similarly for the ILC.

- **Damping of the transverse modes** is also required.

- Further studies can give more precise limits on the maximum required Q and minimum mode detuning.

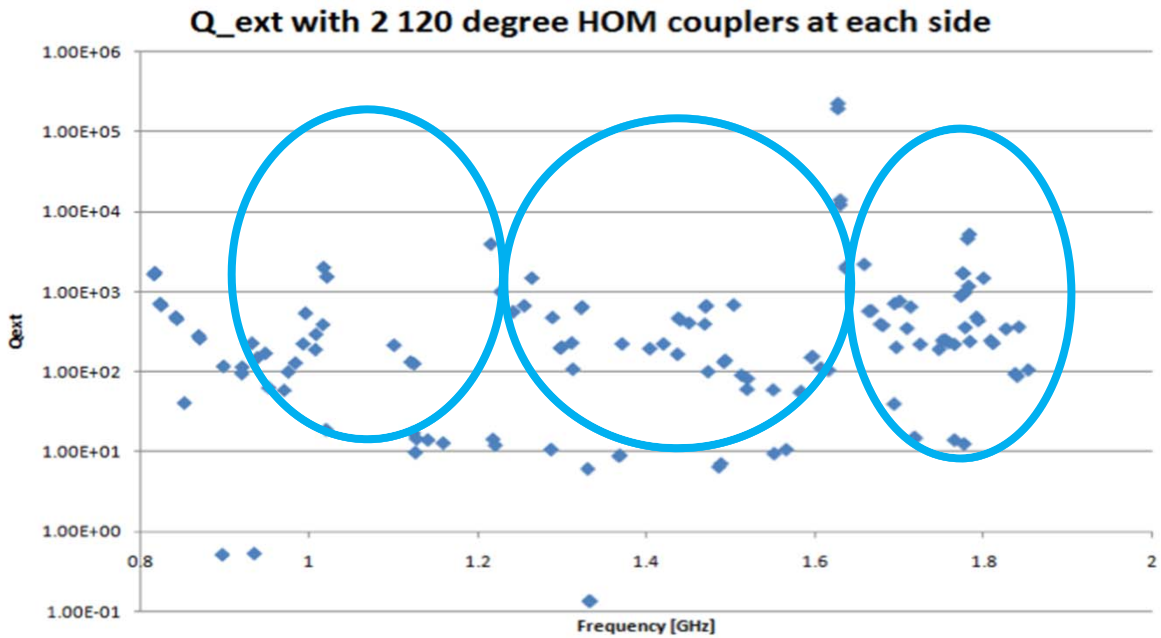
Daniel Schulte

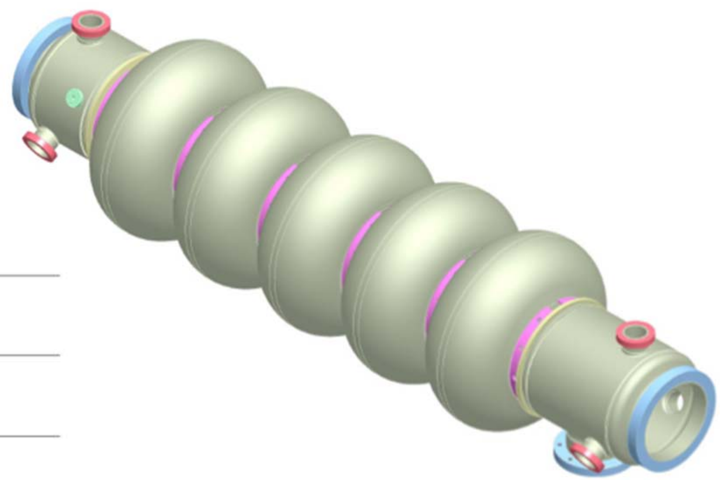
JLAB multi-pass BBU Studies

Ilkyoung Shin

- Multipass BBU due to the transverse higher order modes (HOMs)
  - Performed with **TDBBU code** using HOM data of BNL3 5-cavity (703 MHz)
  - HOM frequencies are randomly distributed with a full width of 2 MHz

Frequency[MHz]	Q_l	R/Q[Ohm]
1003	1×10^6	32
1337	1×10^6	32
1820	1×10^6	32

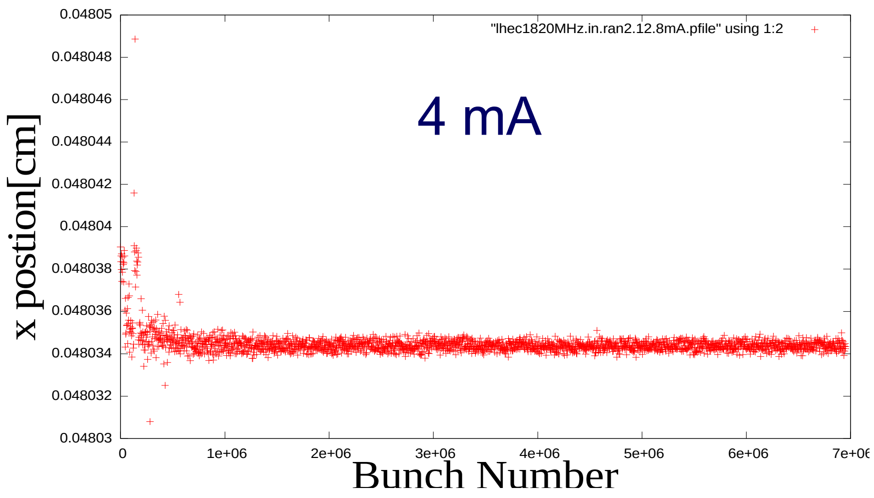


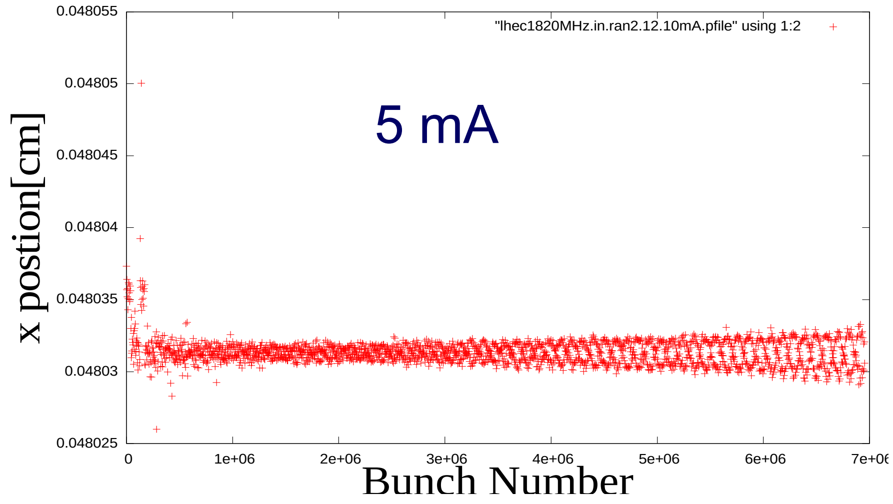


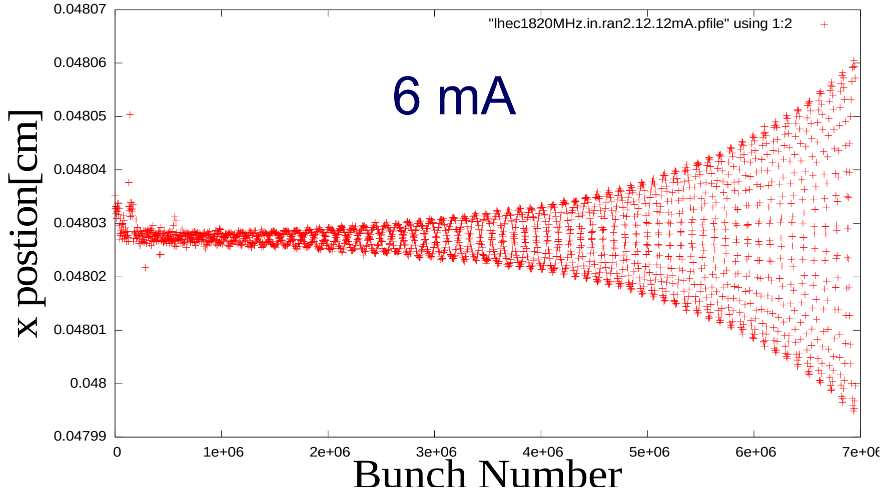
Sergey Belomestnykh

R/Q – k relation?

TDBBU Simulation – Stability Threshold







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threshold current ~ 5mA

TDBBU Simulation Results –varying Q

- $Q_l = 10^4$: threshold current = 40 mA

Frequency[MHz]	Q_l	R/Q[Ohm]
1003	1×10^4	32
1337	1×10^4	32
1820	1×10^4	32

- $Q_l = 10^5$: threshold current = 22 mA

Frequency[MHz]	Q_l	R/Q[Ohm]
1003	1×10^5	32
1337	1×10^5	32
1820	1×10^5	32

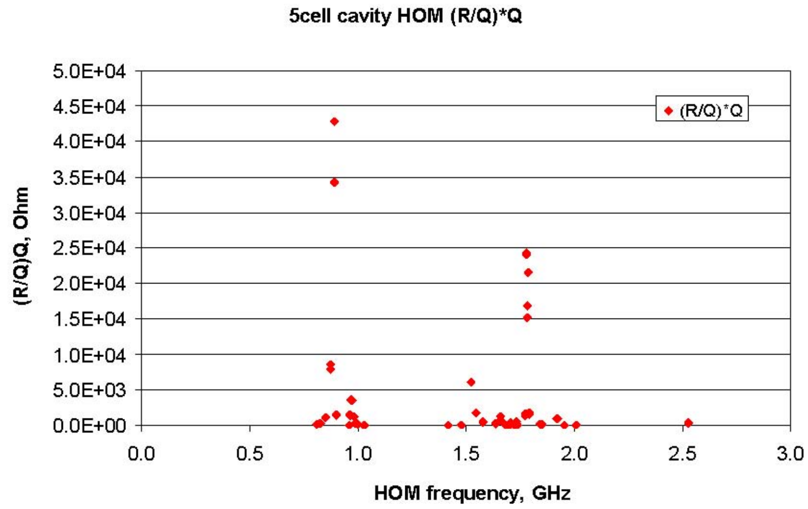
- $Q_l = 10^6$: threshold current = 4.5 mA

Frequency[MHz]	Q_l	R/Q[Ohm]
1003	1×10^6	32
1337	1×10^6	32
1820	1×10^6	32

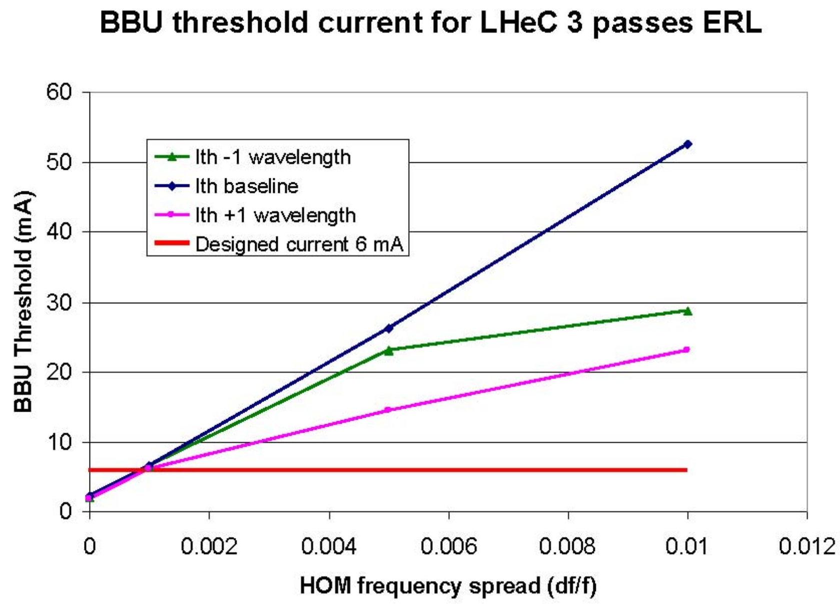
Ilkyoung Shin

BNL multi-pass BBU Studies

f, Hz	R/Q, Ohm	Q,	(R/Q)*Q
8.92E+08	57.181	7.5E+02	4.3E+04
8.89E+08	57.181	6.0E+02	3.4E+04
1.78E+09	3.3927	7.2E+03	2.4E+04
1.78E+09	3.3927	7.1E+03	2.4E+04
1.78E+09	5.1167	4.2E+03	2.1E+04
1.78E+09	5.1167	4.2E+03	2.1E+04
1.78E+09	1.6975	9.9E+03	1.7E+04
1.78E+09	1.6975	9.0E+03	1.5E+04
8.73E+08	47.013	1.8E+02	8.6E+03
8.72E+08	47.013	1.7E+02	7.8E+03



70 dipole High Order Modes (HOMs) based on simulation and measurements of **BNL 5-cell cavity**. Each HOM has either 0 or 90 degrees polarization

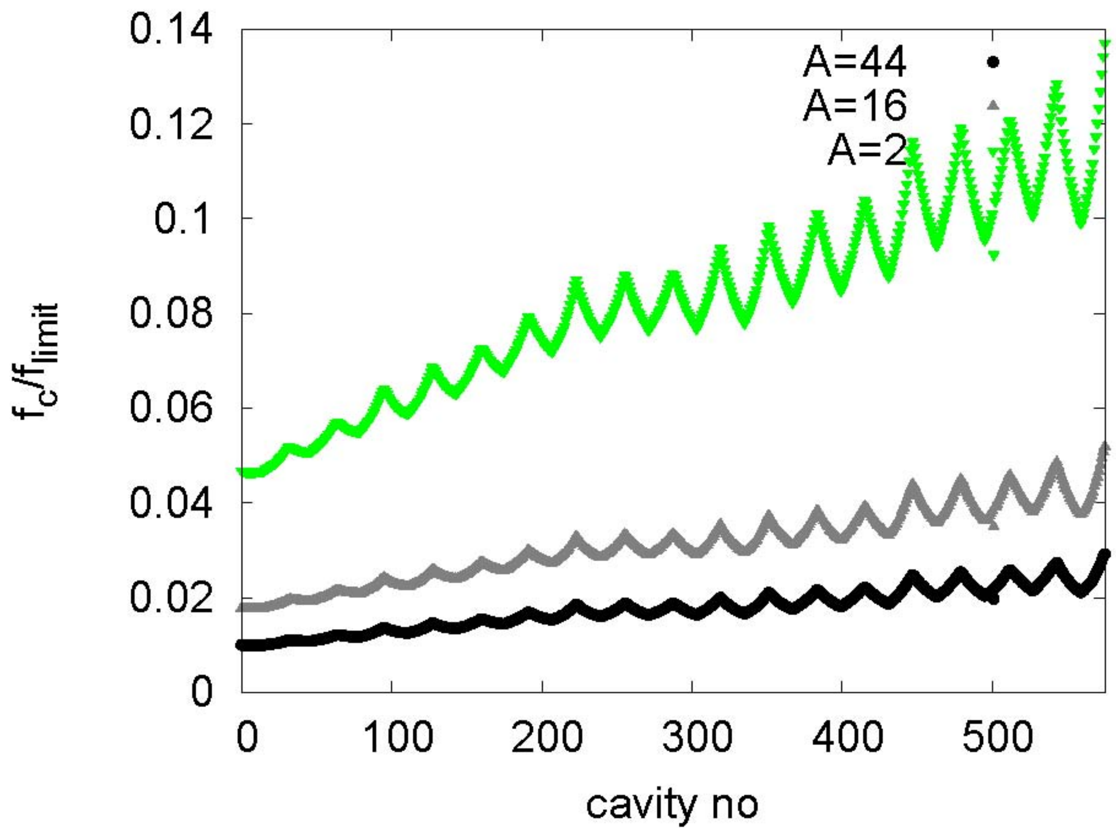


0.5% spread of HOM frequency is sufficient to reach 12 to 25 mA threshold current for different path lengths. **In all scenarios practical scenarios with HOM rms frequency spread above 0.2% (~2 MHz) threshold current > 6 mA**

Ions in the linac

- Ions change the optics & beta function
- Ions can also drive BBU

ions, even light ones, are always trapped by the beam



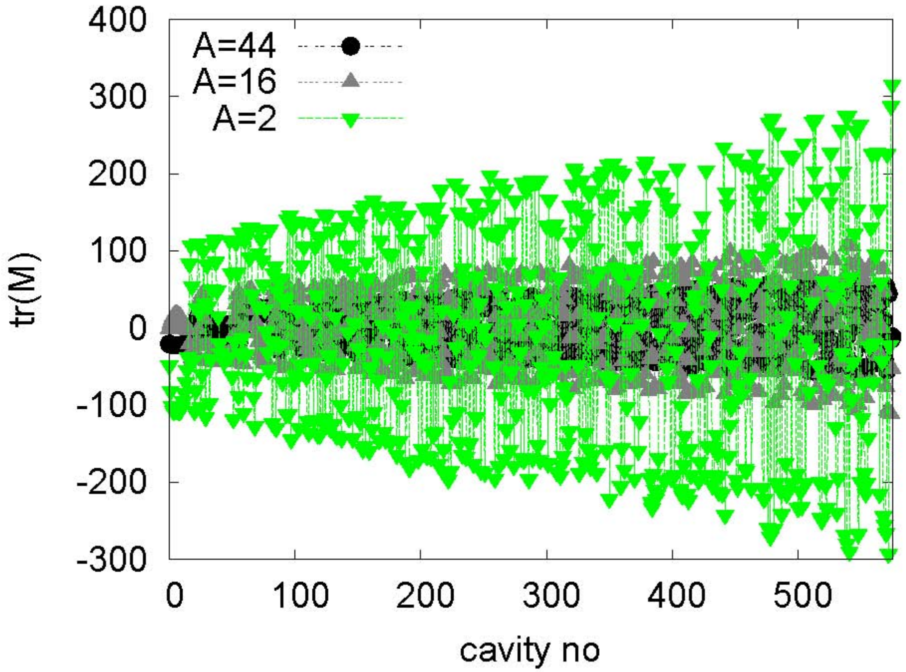
Daniel Schulte

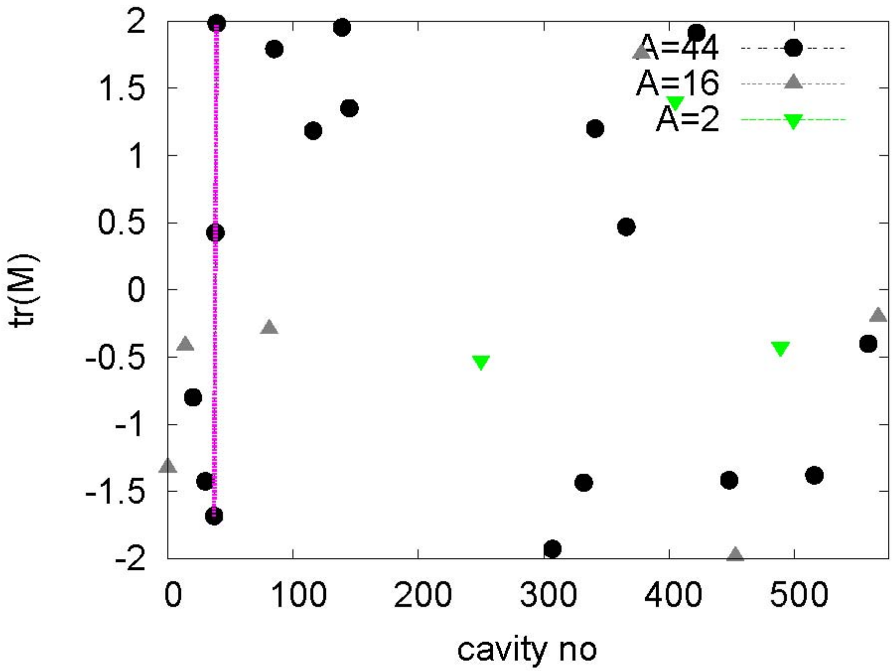
Ion countermeasures

- excellent **vacuum quality** to slow down the ion build-up
- **clearing gaps** during which the ions drift away from the beam orbit; the **gaps of different turns must fall into the same location to avoid beam loading** during the gap and **to ensure that the gaps are fully empty**; we also chose the time for one **round trip equal to integer fraction of the LHC round trip** time LHC = mcycle, to ensures that each LHC bunch will either always collide with an electron bunch or never.

  Choices: cycle = 1/3 LHC, single gap =1/3cycle ~10 μs
- **clearing electrodes** to extract the ions. They would apply a bias voltage that lets the ions slowly drift out of the beam.

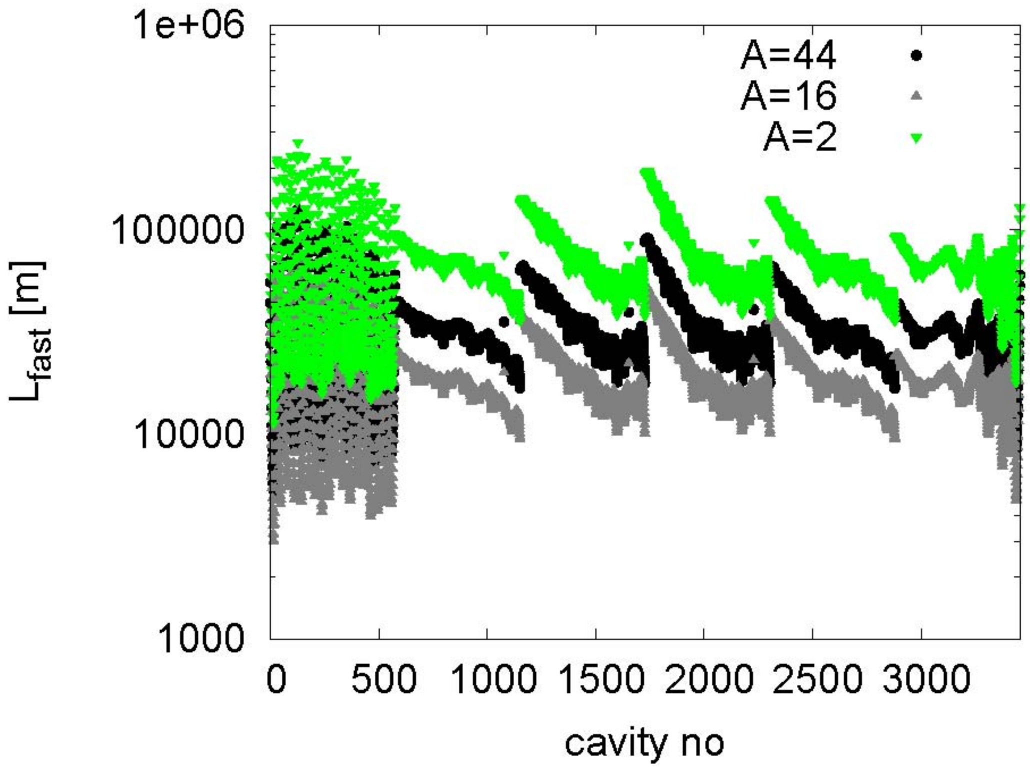
Ion trapping with clearing gap





trace of the transfer matrix for H^+_2 , CH^+_4 and CO^+_2 ions in presence of clearing gap.; values above 2 or below -2 indicate that the ions will not be trapped.

Ion instability with clearing gap



instability length of the beam-ion instability in the linacs assuming a very conservative partial pressure of 10^{-11} hPa for each gas

beam travels about 12 km in total through linacs

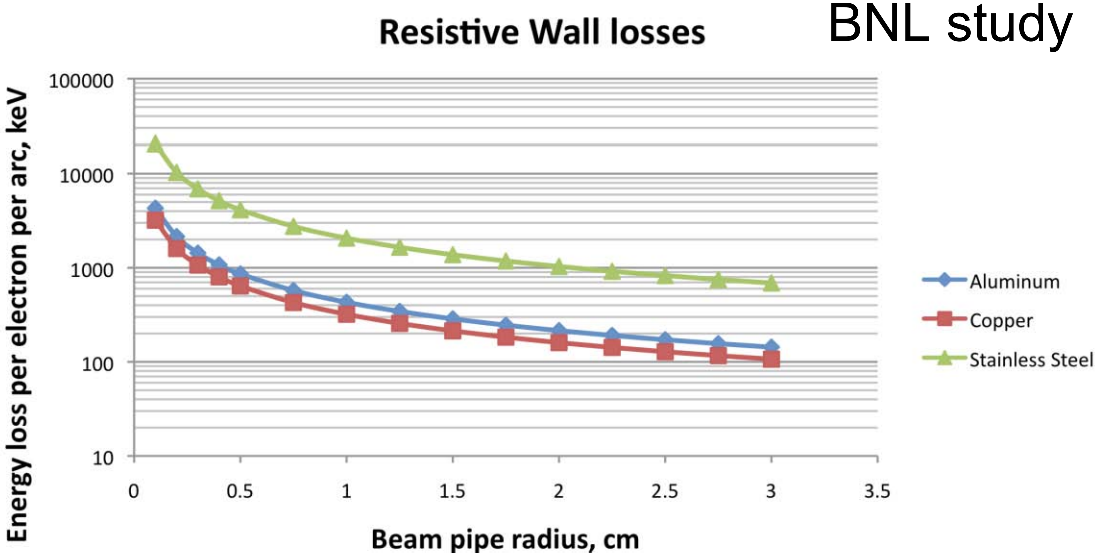
in linacs < 10^{-11} hPa OK

for arcs: pressure < 10^{-9} hPA sufficient

Resistive wall & CSR

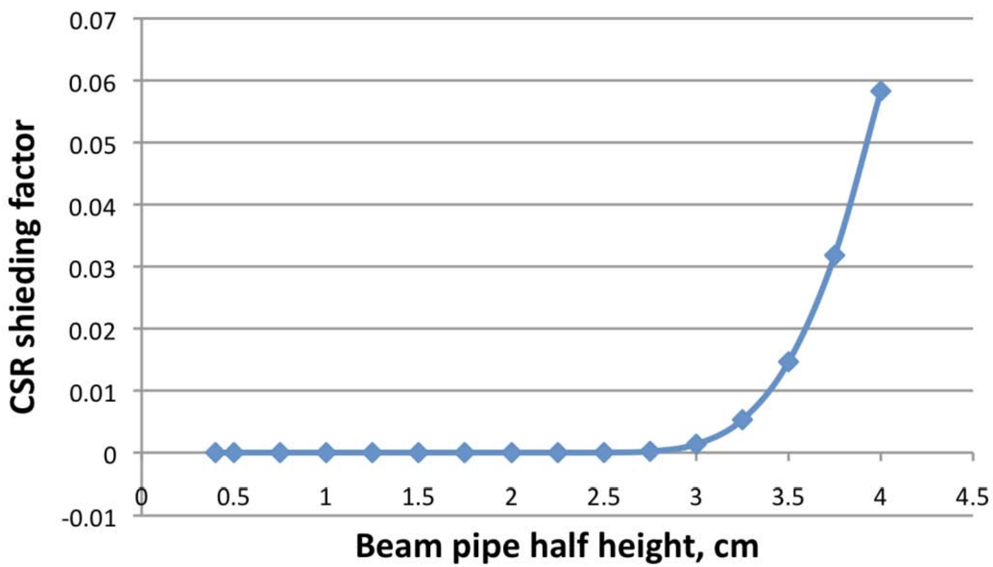
BNL study

For Al pipe radius ~ 2 mm: **additional 24 MeV RW energy loss** and similar energy spread due to resistive wall. << **2.05 GeV SR loss** ;
correlated energy spread comparable to 35 MeV RMS uncorrelated spread induced by SR.

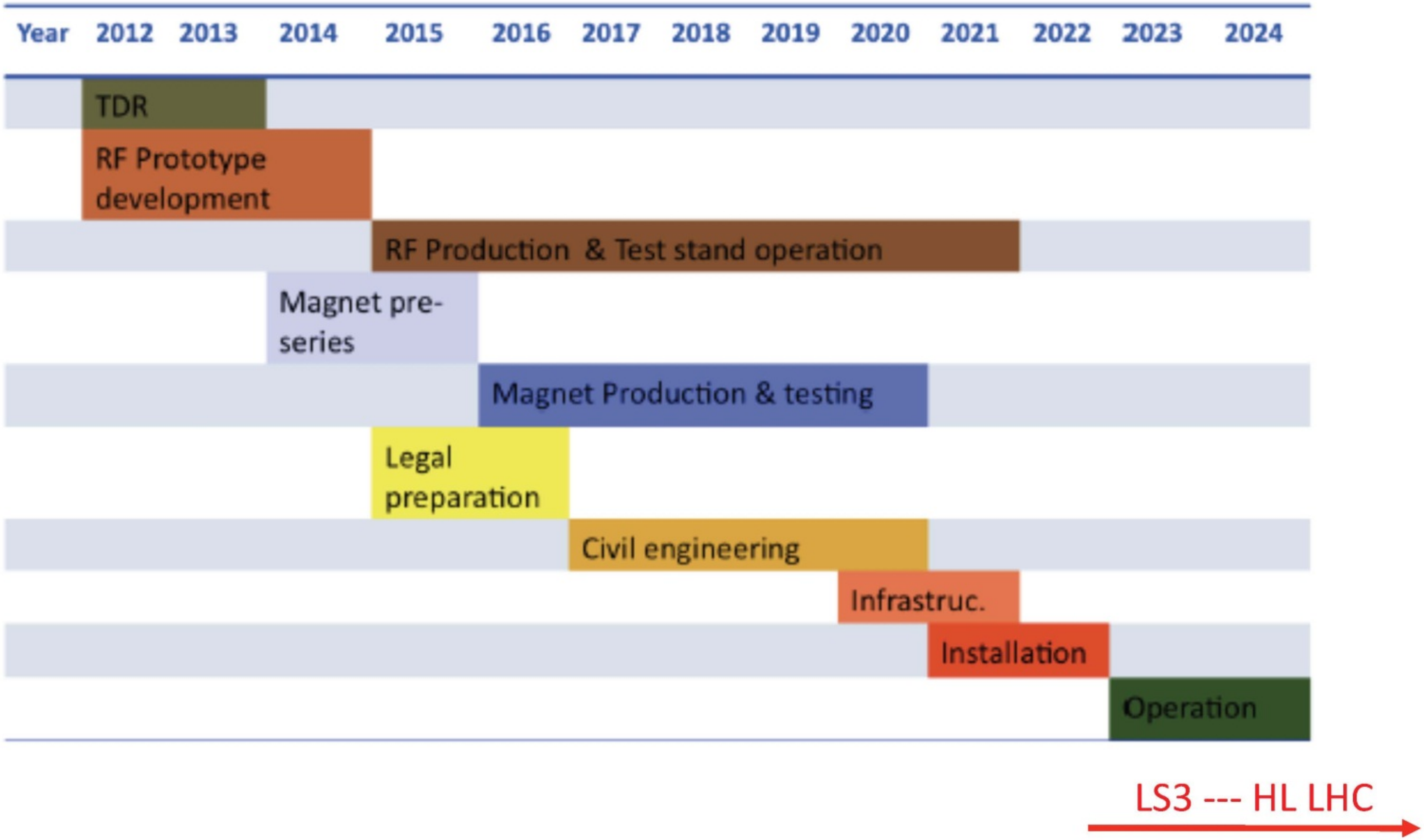


Without shielding, the beam will loose 1.4 MeV per arc due to Coherent Synchrotron Radiation (CSR). Total induced correlated energy spread ~12 MeV.

In any case, the **CSR will be strongly suppressed by the walls of the vacuum chamber.**



LHeC Tentative Time Schedule



We base our estimates for the project time line on the experience of other projects, such as (LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL)

M. Klein, IPAC'2011

Conclusions

- High luminosity Linac-Ring option – ERL
- Multi-pass linac Optics in ER mode
  - Choice of linac RF & Optics – 720 MHz SRF & 130^0 FODO
  - Linear lattice: 3-pass 'up' + 3-pass 'down'
- Arc Optics Choice – Emittance preserving lattices
  - Quasi-isochronous lattices ; Flexible Momentum Compaction
  - Acceptable **emittance dilution**, momentum spread & **aperture**
- Multi-pass BBU studies under way……
  - Worst case - BNL-3 cavity modes & TDBBU: 5 mA threshold
  - More stable: SPL cavity modes with damping and detuning
- Ion instability
  - Circumference chosen to allow gaps in the bunch trains

a few references

LHeC Study Group, "*A Large Hadron Electron Collider at CERN*," Draft CDR, LHeC-Note-20011-003 GEN, 3 September 2011

S.A. Bogacz, O. Shin, D. Schulte, F. Zimmermann, "*LHeC ERL Design and Beam-Dynamics Issues*," Proc. IPAC'2011, San Sebastian, 4-9 Setember 2011, TUPC054, p. 1120

Y. Hao, D. Kayran, V.N. Litvinenko, V. Ptsitsyn, D. Trbojevic, N. Tsoupas, "*ERL Option for LHeC*," CERN-LHeC-Note-2010-010 ACC

https://cern.ch/lhec

thank you for your attention!