State-of-Art
Optics and Beam Transport

Ryoichi Hajima, JAERI

Outline

Components

- Merger
- Main linac
- Loop
- Bunch compressor

(Injector will be discussed in WG-1)

Phenomena

- Emittance growth by space charge and CSR
- Beam instability, BBU
- Halo formation

Beam parameters

- high average current
- small emittance
- short bunch
- stability

Design and optimization methods to obtain beam parameters as we need, without any harmful phenomena.

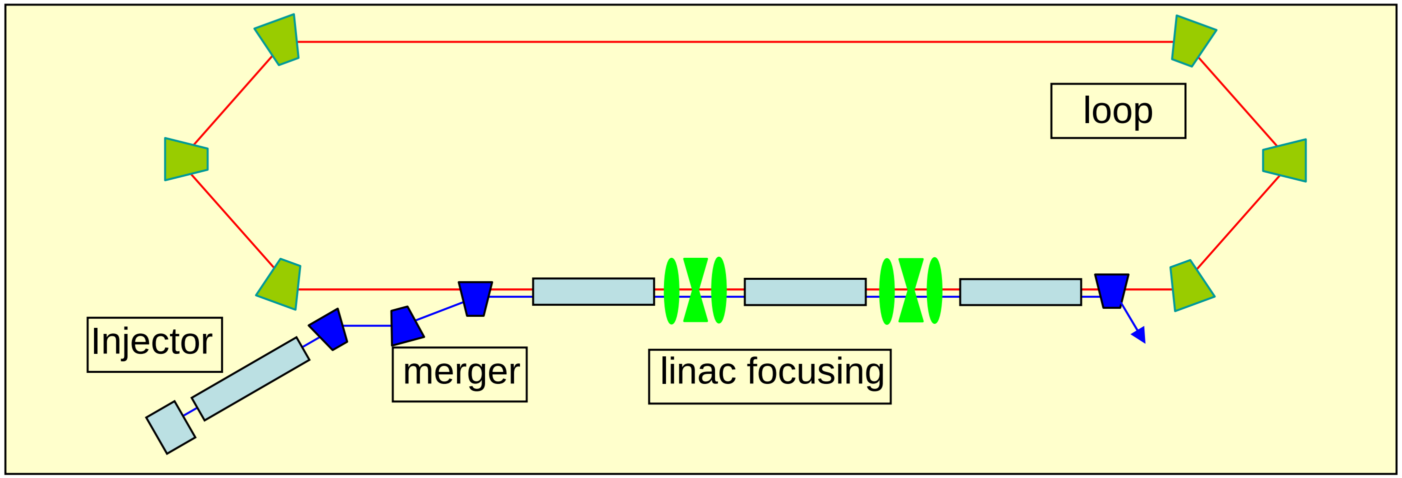
Technological challenge for each component.

Beam optics & dynamics in ERLs

Advantages of ERLs → high-average current
→ small emittance, short bunch

Beam transport design issues

- Preserving emittance through injector – merger – linac – recirc. loop
- Bunch compression scheme
- Disturbance on beam motions
  - short-range (single-bunch) disturbance = space charge, CSR, wakes
  - long-range (multi-bunch) disturbance = HOM-BBU



Merger

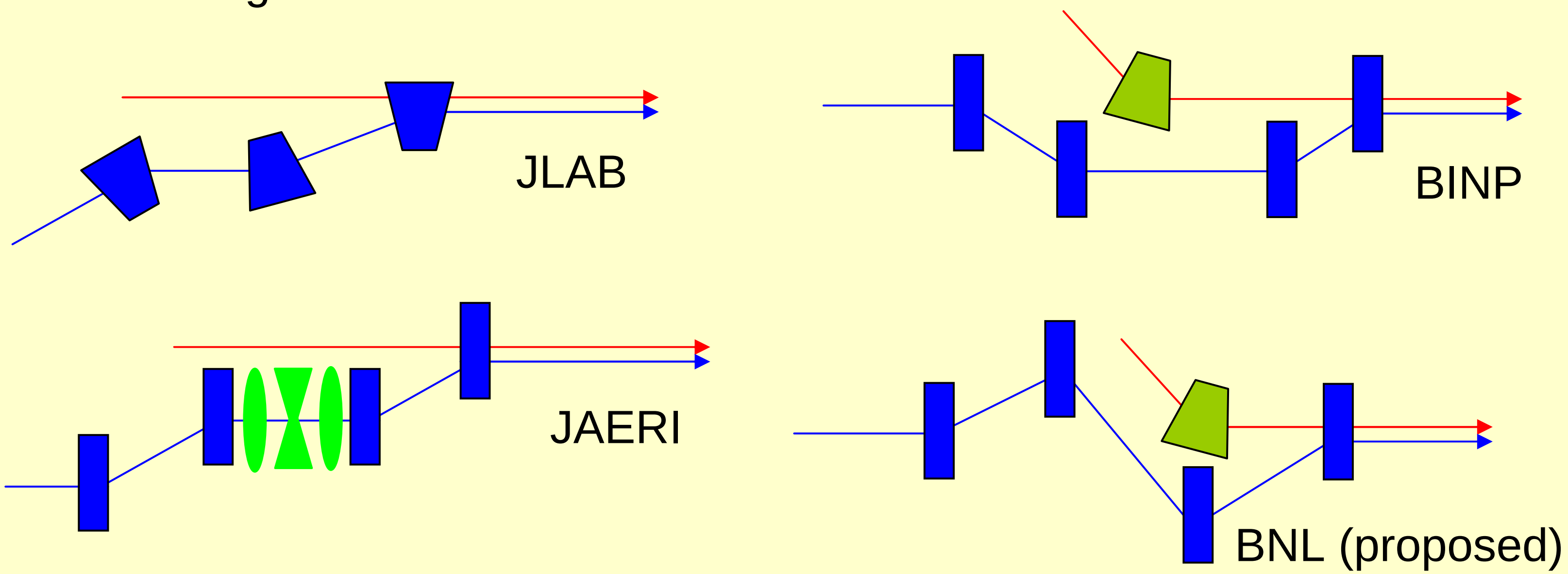
an intrinsic component of ERL.

- Energy-ratio : $E_{high} / E_{low} = 10 - 1000$
- merging two beams continuously (MHz~GHz)
- need dipole magnets, instead of a kicker

Design consideration

Configuration
Merging energy
Emittance growth
……

various configuration

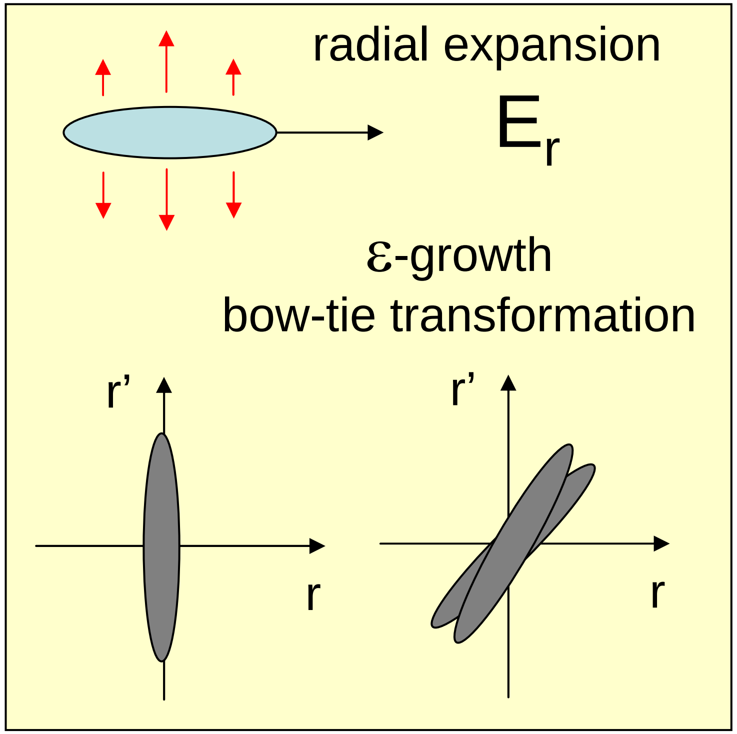


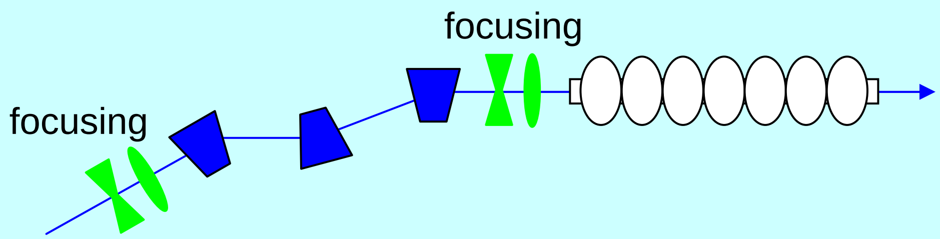
Emittance growth in a merger (1)

transverse space charge force

- injected bunches are not solid enough – still feel space charge force
- radial expansion by transverse space charge force.

$$k_p^2 = 4\pi n_b / \gamma^3 \beta^2 \qquad \text{77pC, 3ps, 5MeV} \qquad k_p \sim 0.5 m^{-1}$$

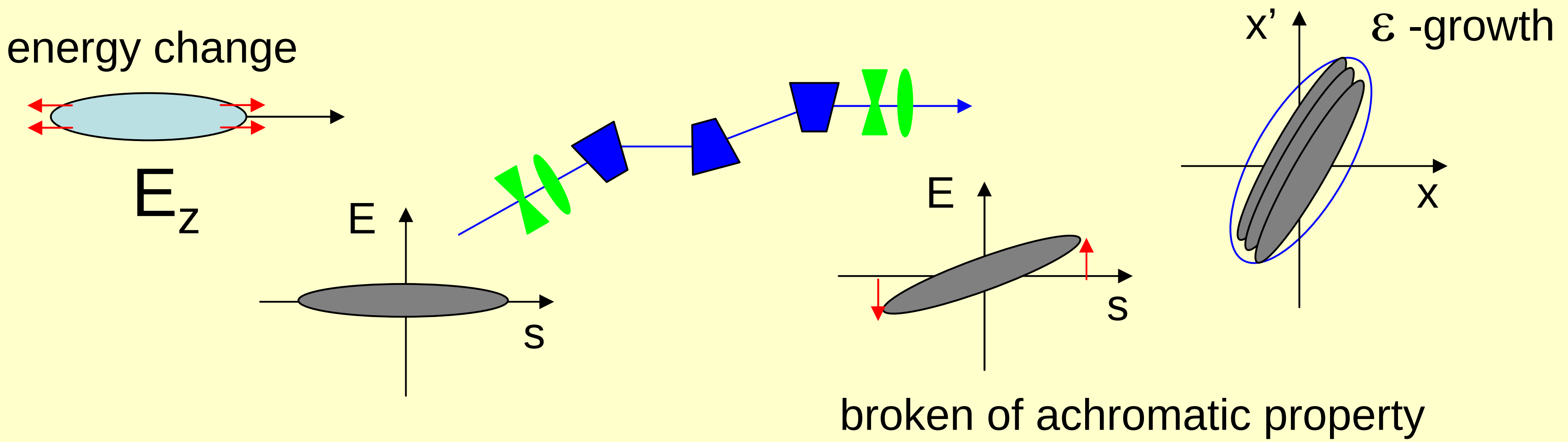




- quite different from RF-gun & solenoid.
- emittance compensation scheme must be optimized across the merger.
- dipoles introduce "x-y asymmetry"
- quadrupoles are necessary

Emittance growth in a merger (2)

longitudinal space charge force

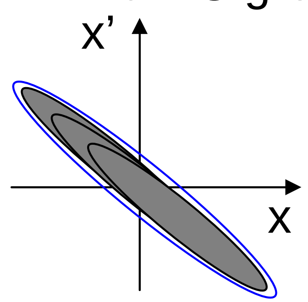


see for example, B.E. Carlsten et al., IEEE QE **27**, 2580 (1991).

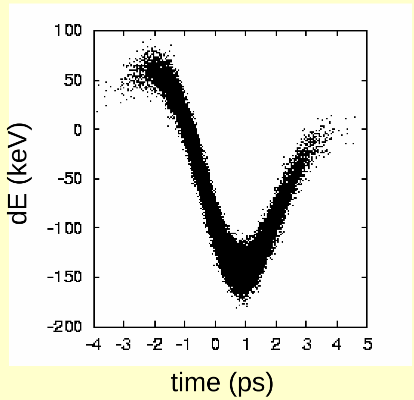
emittance compensation by envelope-matching

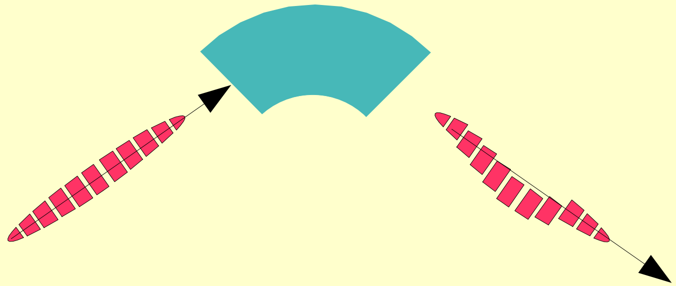
- matching the space-charge kick to the beam ellipse.
- similar to the CSR case.
- is it compatible with ε-compensation for E_r?

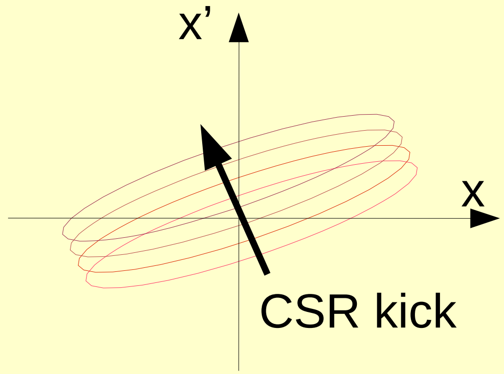
minimum ε-growth



Emittance growth by CSR







energy change in a bending path → errors in bending angle → emittance growth

- total emittance is diluted (slice emittance is preserved)
- critical for a short bunch

$$\Delta E_{ave} = -0.3505 \frac{r_e Q L_b}{e\gamma \left(R^2 \sigma_s^4\right)^{1/3}}$$

- CSR is an issue in merger and ERL-loop.

CSR studies

- Particle tracking codes
  - ELEGANT (1D CSR model) – quick calculation, easy to scanning parameters
  - TraFiC4 (3D full calculation) – includes usual SC force, needs lots of CPU time

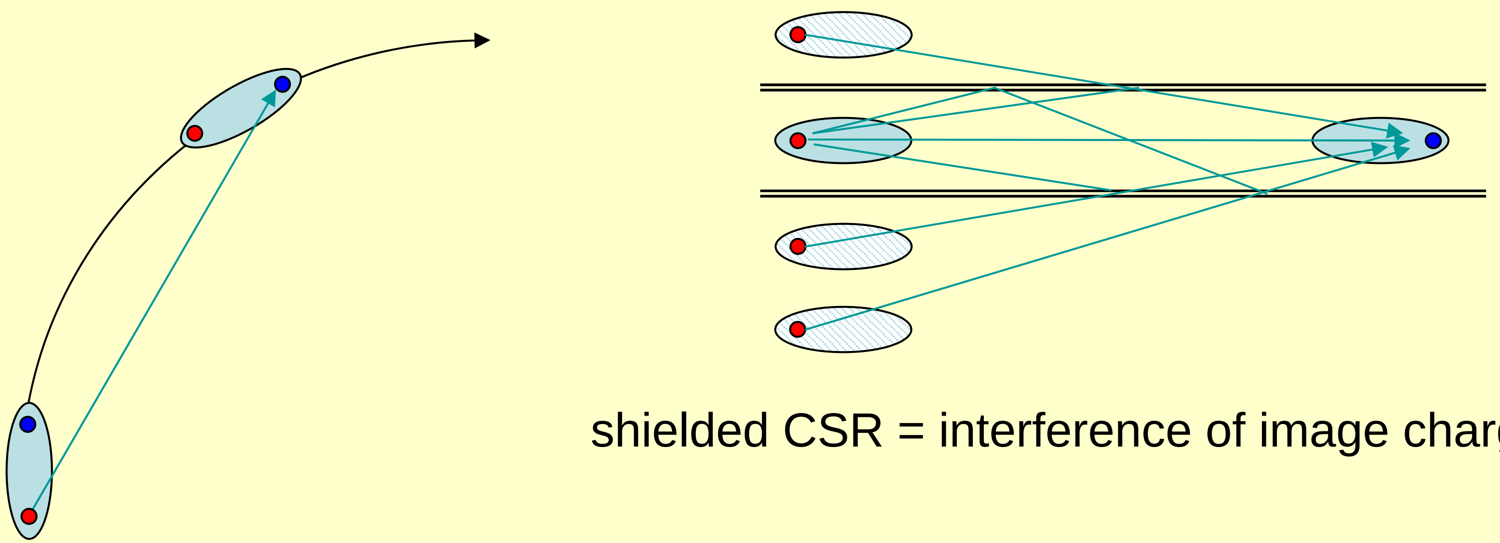
These code are well bench-marked in XFEL studies,
and also applicable to ERL-loop design.

see CSR mini-workshop http://www.desy.de/csr/

- CSR in XFEL and ERL

XFEL	ERL
bunch compressor	merger and loop (bunch compressor if exists)
no / weak shielding	no / weak / strong shielding
> 100MeV	<10MeV in a merger, >1GeV in a loop

CSR with strong shielding



CSR = tail-head radiative interaction

shielded CSR = interference of image charges

lots of image charge is necessary for particle tracking….

- using two-parallel plates model
  - shielding parameter $$\eta = \sqrt{2/3}\left(\frac{\pi R}{h}\right)^{3/2}\left(\frac{\sigma_s}{R}\right)$$

R: bending radius
h : full height of chamber
σ_s: rms bunch length

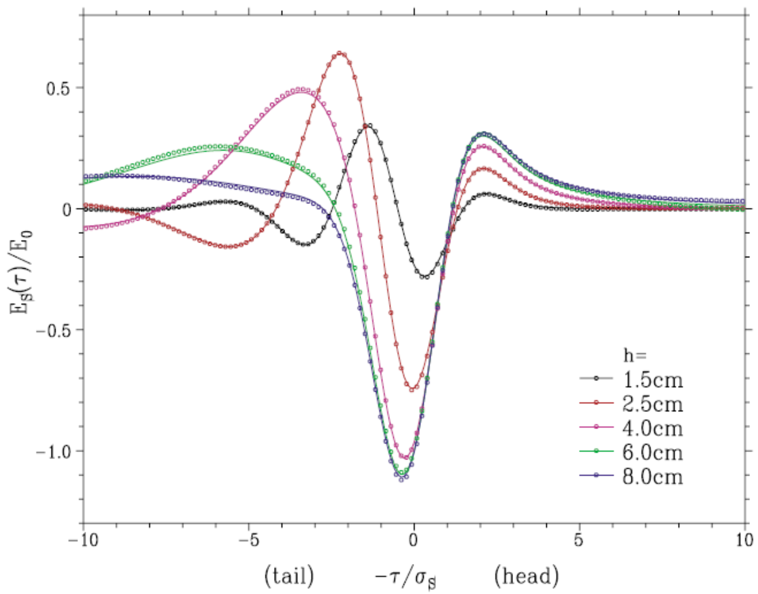
$\eta >> 1$ strong shielding regime

  - ERL light source *R*=25m, *h*=2cm, σ_s=1mm $\longrightarrow$ $\eta = 8$

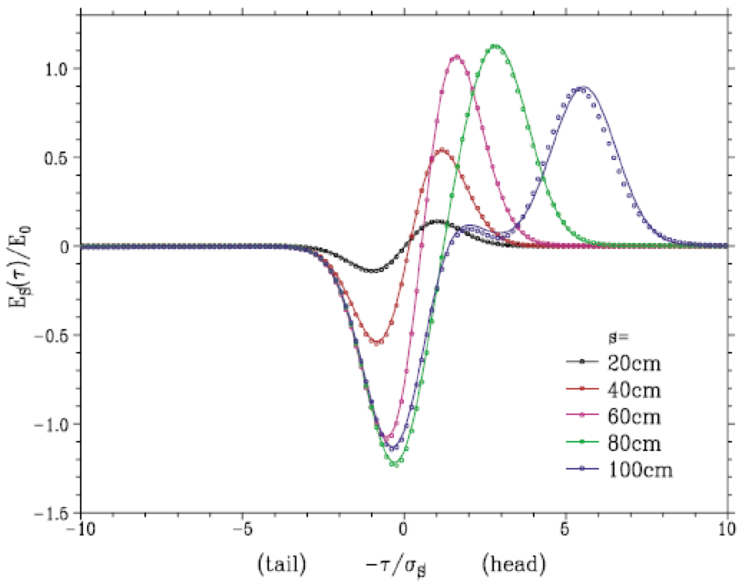
CSR calculation using mesh

T. Agoh, K. Yokoya, PRST-AB 7, 054403 (2004).

- mesh calculation of EM field in the frequency domain.
- applicable to general cases such as shielded, transient CSR with finite beam size in transverse dimension.
- also applicable to low-energy CSR (E~5MeV) after minor extension.



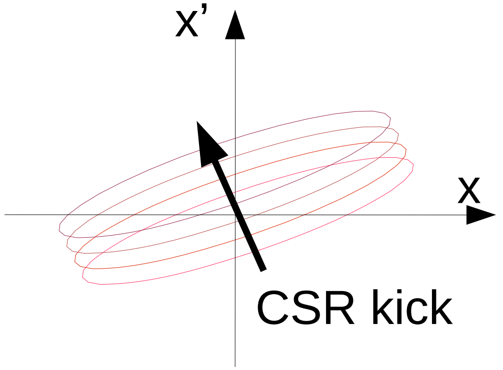
shielded CSR calculation



transient CSR calculation

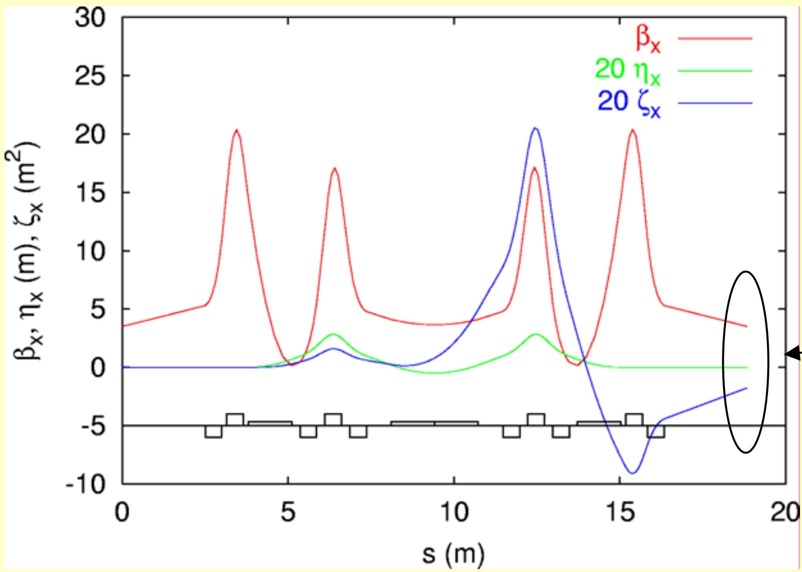
Tracking CSR effects by linear matrix

R. Hajima, JJAP 42, L974 (2003)
R. Hajima, APAC-04.



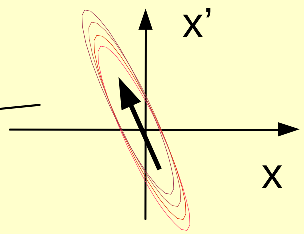
Extending the first-order transfer matrix, we can track beam ellipse displacement by CSR.

applicable to ERL-loop optimization.



CSR-dispersion (ζ,ζ')

similar to momentum-dispersion (η,η')

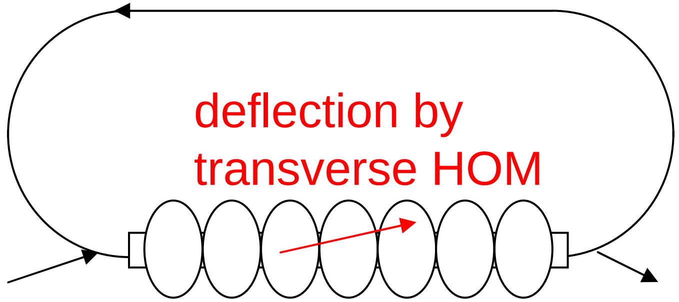


TBA cell for minimum emittance growth.

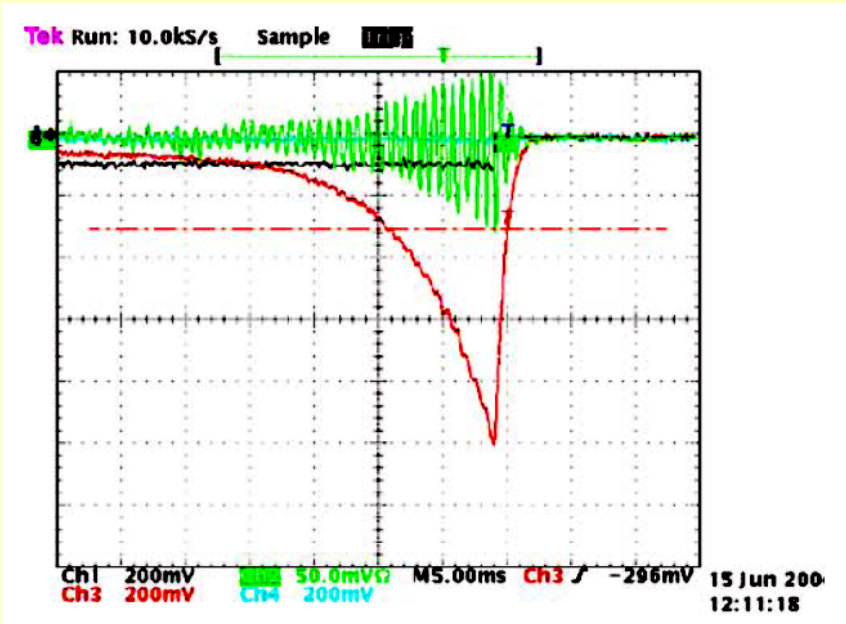
Such optimization can be easily done by matrix calculation.

Multi-bunch instability

- transverse HOM is the dominant source of multi-bunch instability in ERLs.



If the kicked bunch comes back again “in phase”, the HOM power grows exponentially and BBU occurs.

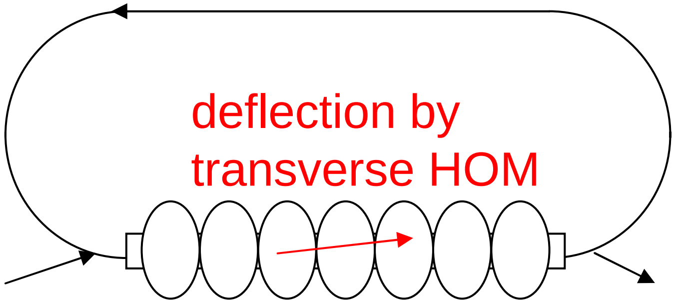


HOM-BBU observed in JLAB-ERL.

C. Tennant et al., Proc. FEL-2004, 590 (2004).

Threshold current of HOM-BBU

for a single-cavity, single-HOM, single-loop ERL,



for multi-cavity, multi-HOM cases, we need numerical simulation codes.

$$I_{th} = -\frac{2c^2}{e(R/Q)Q\omega}\frac{1}{R_{12}\sin(\omega T_r)}$$

impedance
(cavity-beam interaction)
↓
cavity design
HOM coupler

transfer matrix and phase
(amplification of deflection after recirculation)
↓
beam optics design

studies related to HOM-BBU

- simulation codes: TDBBU, MATBBU (JLAB), RBBU (JAERI), BI (Cornell)

  -- BBU code session on Tuesday

- experiment: HOM measurement with transversely oscillating beam (JLAB)

  L. Merminga, I.E. Campisi, D.R. Douglas, G.A. Krafft, J.Preble, B.C. Yunn
  Proc. PAC 2001, 173.

- theory: BBU theory for ERLs

  Georg H. Hoffstaetter and Ivan V. Bazarov
  PRST-AB 7, 054401 (2004).

- suppression: linac focusing optimization, (x, y) reflection or rotation

  R. Rand, T. Smith
  Particle Accelerators, 2, 1-13 (1980).
  C. Tennant, D. Douglas, K. Jordan, L. Merminga, E. Pozdeyev, T. Smith
  Proc. FEL-2004, 590 (2004).

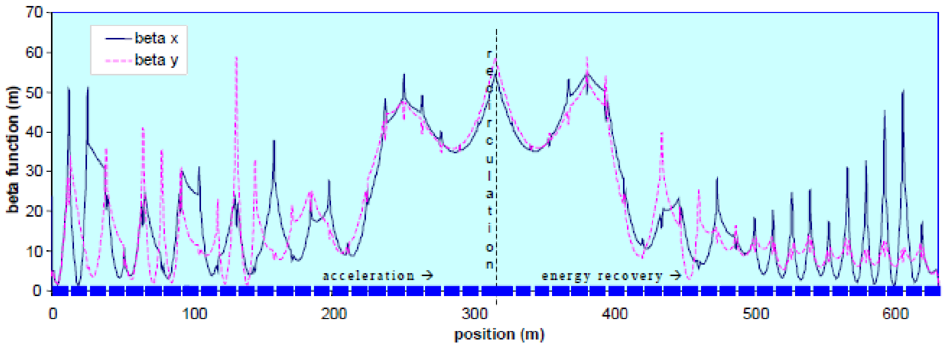
- bunch-by-bunch feedback

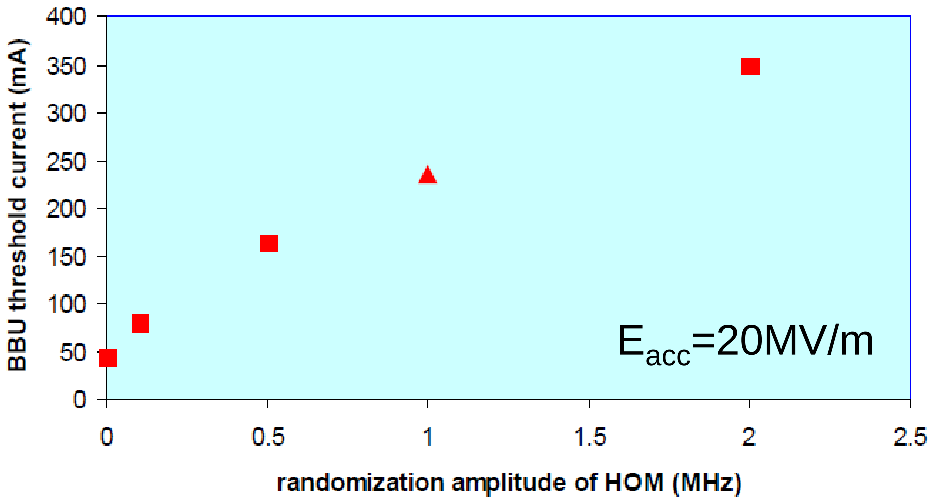
  T.Nakamura et al., Proc. EPAC 2004, 2646.

Linac focusing optimization

5GeV-ERL design study

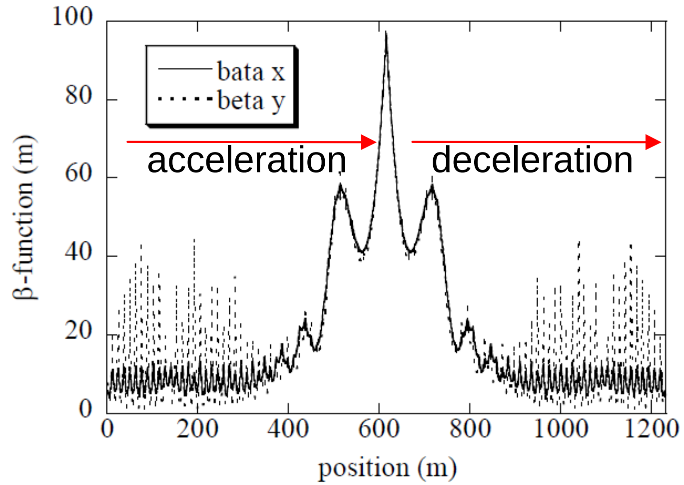
CHESS Tech-memo 01-003, JLAB-ACT-01-04

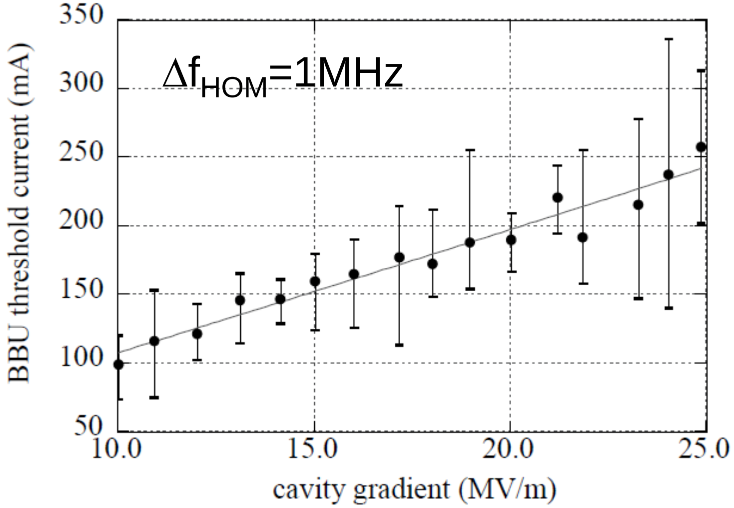




6GeV-ERL design study

R. Nagai et al., Proc. PAC-03, 3443 (2003).





HOM-BBU suppression

(x, y) reflection, rotation

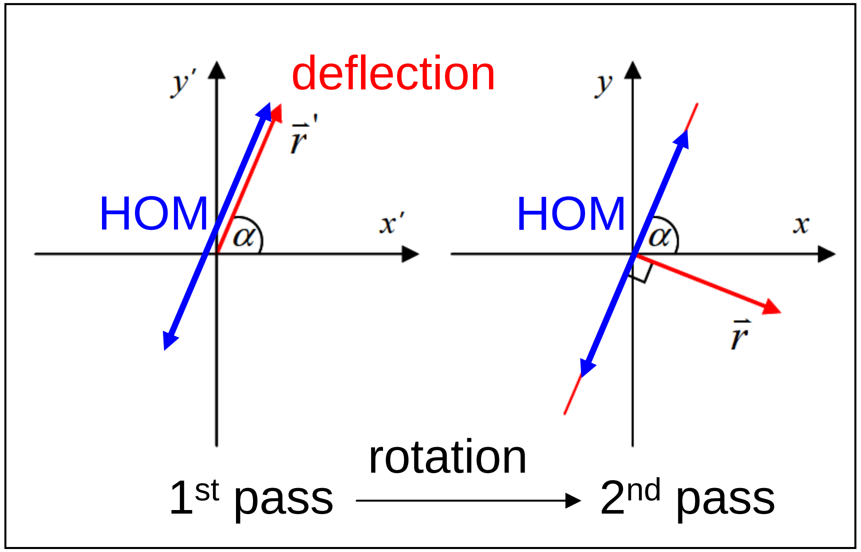
HOM-BBU can be suppressed by setting a recirculation matrix as

$$R = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{pmatrix} = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 & M \\ -M & 0 \end{pmatrix}$$

reflection rotation

such manipulation can be made using skewed-Q or solenoid.

R. Rand and T. Smith, Particle Accelerator, 2, 1-13 (1980).
C. Tennant et al., Proc. FEL-2004, 590 (2004).

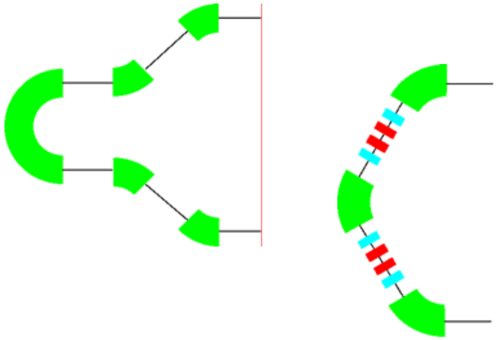


JLAB FEL upgrade driver

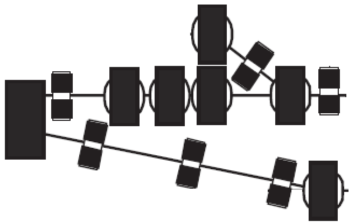
	Nominal	Pseudo-Reflection	Rotation
"Aligned"	2.83 mA	288 mA	613 mA
"Skewed"	2.87 mA	18.3 mA	208 mA

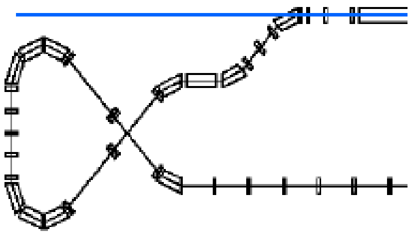
two-order higher threshold current.

Design of a return loop



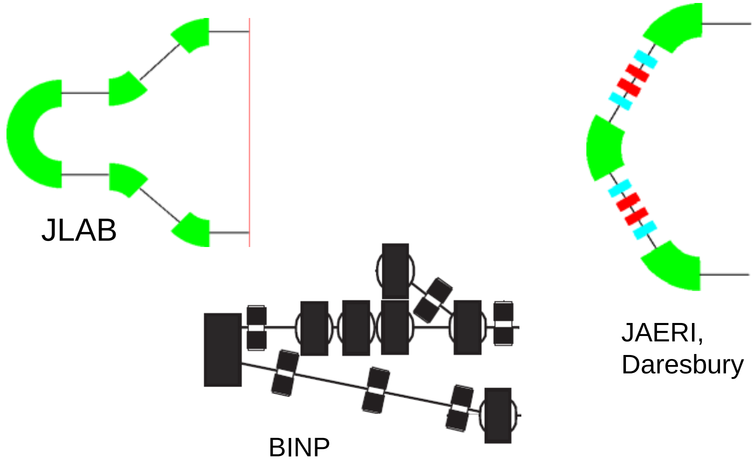
- various loops for various applications.
  - footprint,
  - energy acceptance,
  - path-length tunability,
  - bunch stretching / compression,
  - aberrations,
  - emittance growth,
  - operation flexibility …





- beam optics coupled with RF
- many studies on beam dynamics (linear and nonlinear)
- several design codes

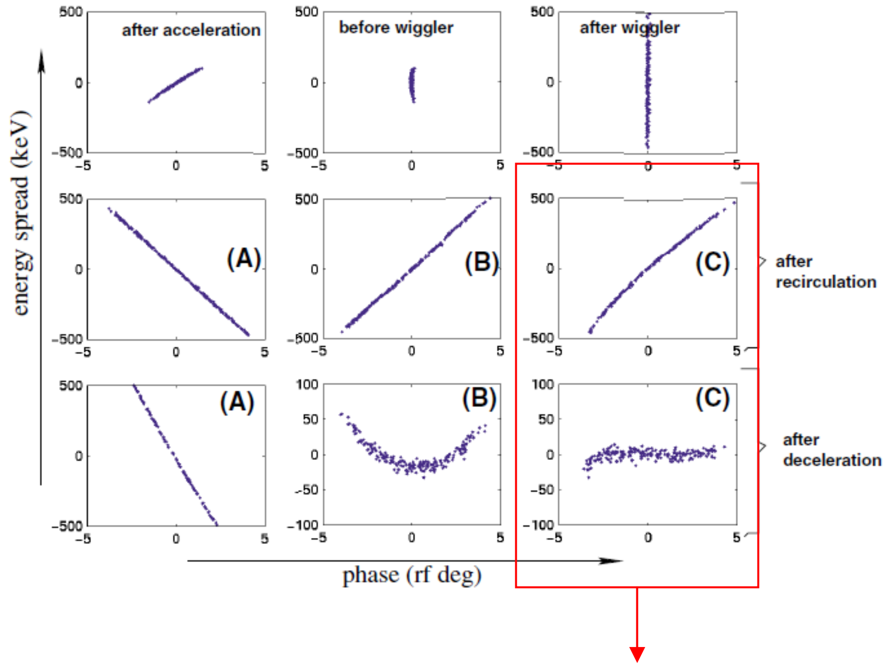
Loop design for ERL-FELs



- ΔE/E after FEL lasing 5~10%
  - large energy acceptance
  - higher-order terms
    – T_{166}, T_{266}, T_{566},
- stability against FEL lasing on/off
  - instability of fundamental mode may appear as well as HOM

L. Merminga et al.,
Nucl. Instr. Meth. A429, 58 (1999).

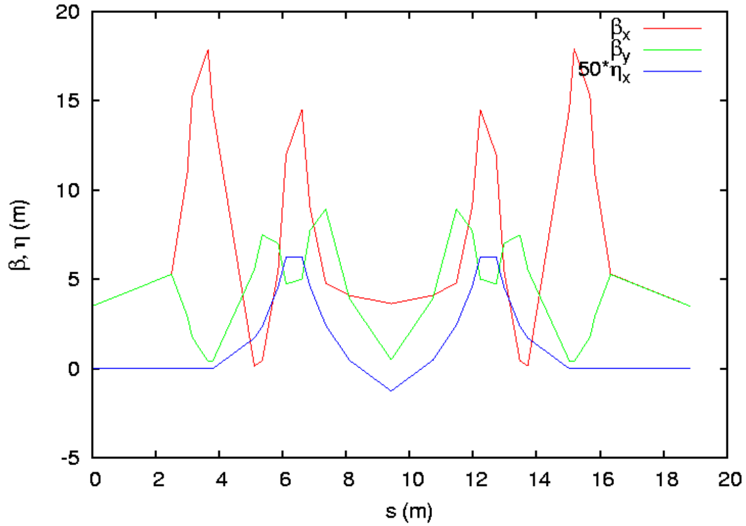
return-arc tuning at JLAB IR-demo



R56, T566 optimized for energy-compression

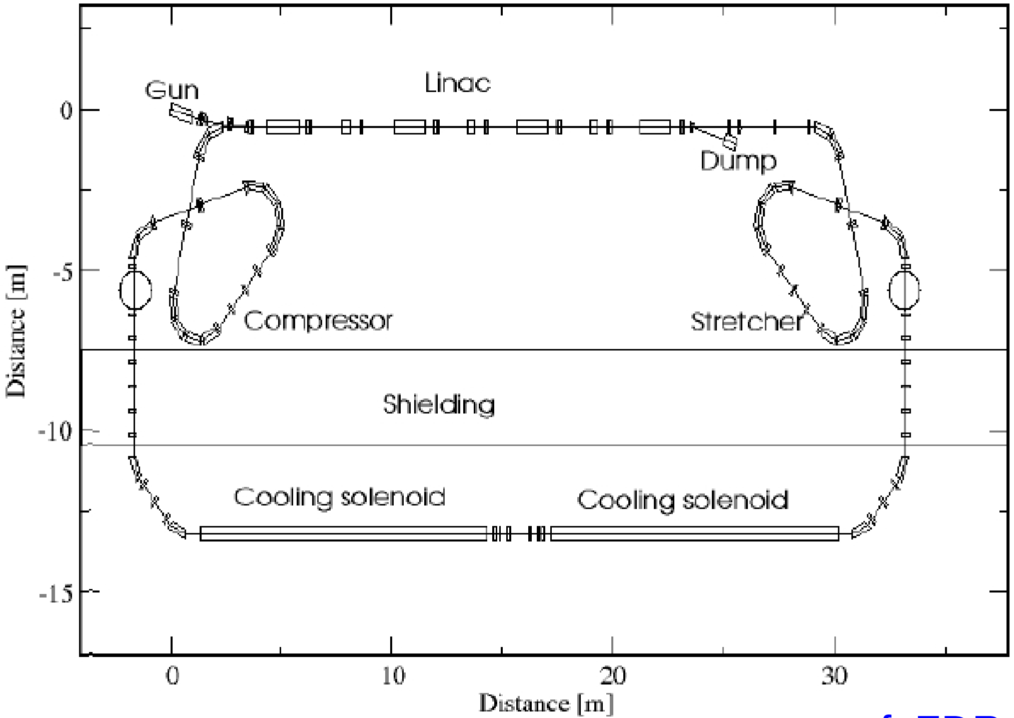
P. Piot, D. R. Douglas, and G. A. Krafft
Phys. Rev. ST-AB 6, 030702 (2003)

Loop design for ERL light sources



- achromatic cell and straight section, alternatively, similar to storage rings
- "Triple bend achromat" rather than "double bend achromat" for variable momentum compaction (switching bunch compression mode and isochronous mode).
- $\eta_x = \eta'_x = 0$ at straight sections for small horizontal beam size. (cf. non-zero dispersion is permitted in 3rd generation sources)
- emittance growth is the most critical issue.

Loop design for an e-cooler



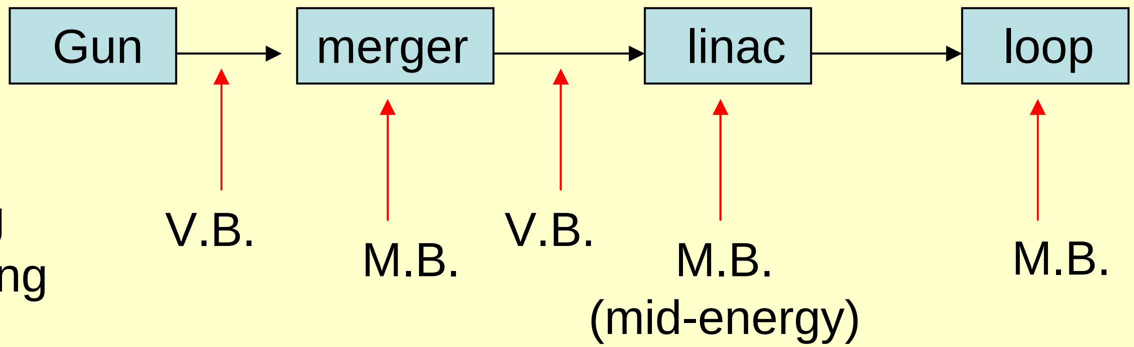
ref. ZDR electron cooling for RHIC

- stretcher & compressor for a long-bunch in the cooling section.
- superconducting solenoid with very accurate axial field.
- "magnetized beam", finite canonical angular momentum

Bunch Compression

- initial bunch length at the gun --- property of cathode, gun, drive laser
- bunch length at the linac --- acceptable HOM power, energy-spread
- final bunch length at the loop --- how short we need ?

possible locations for BC

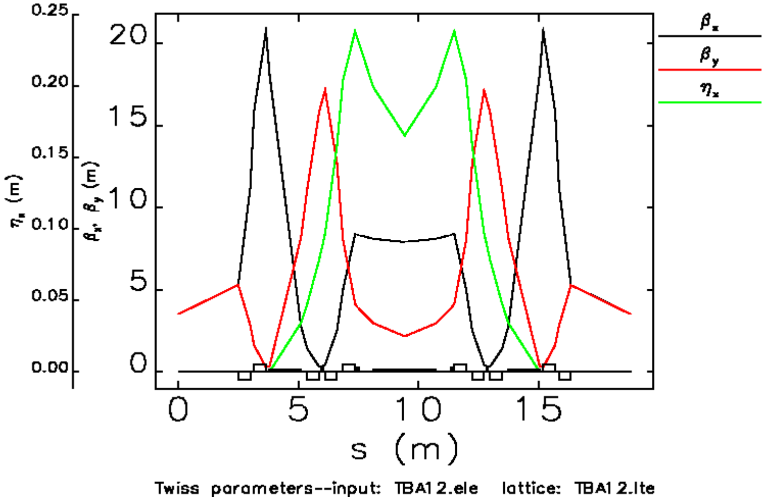


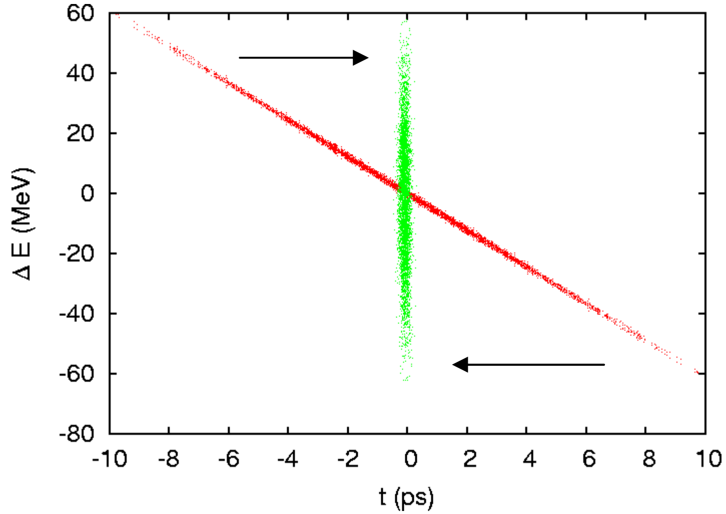
VB=velocity bunching
MB=magnetic bunching

we need to pay attention to

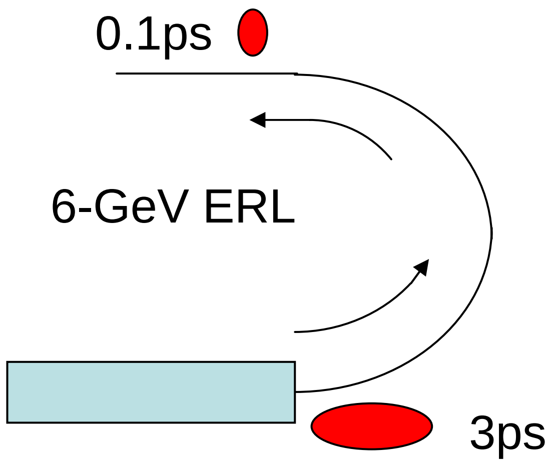
- emittance growth during bunch compression (CSR, SCF)
- residual energy spread at the loop
- HOM-power loading in the linac
- path-length consistency for two beams

Bunch compression during an arc





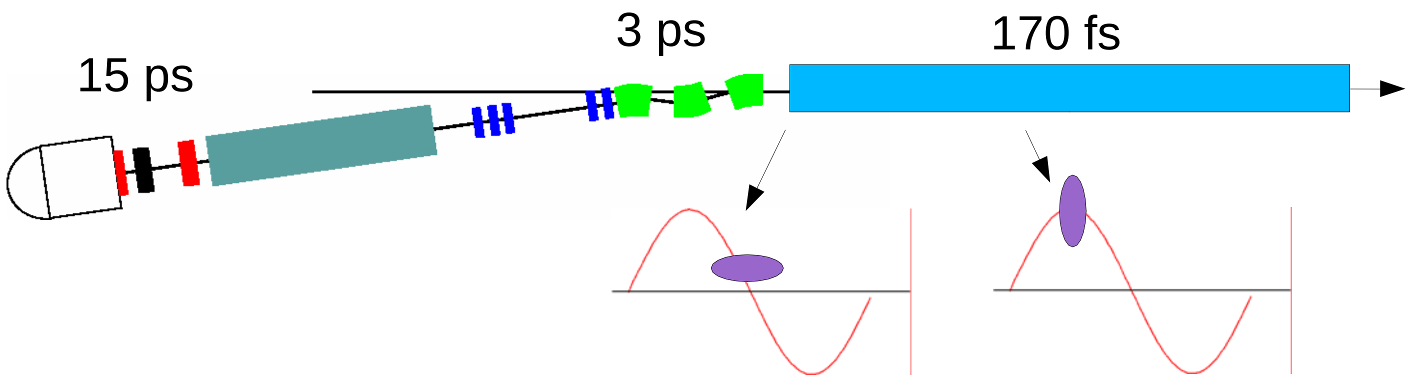
ρ=25m, R_{56}=2cm / cell, 12-deg-TBA-cell x 15

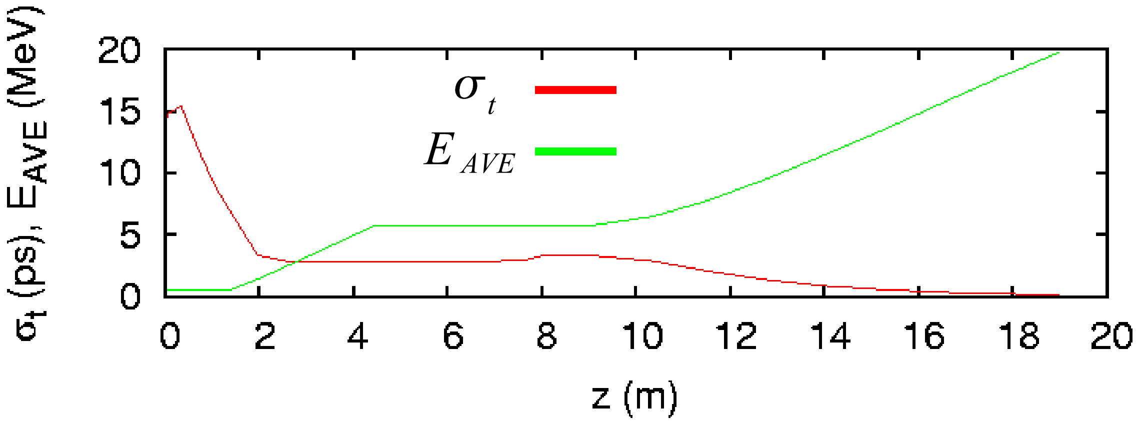


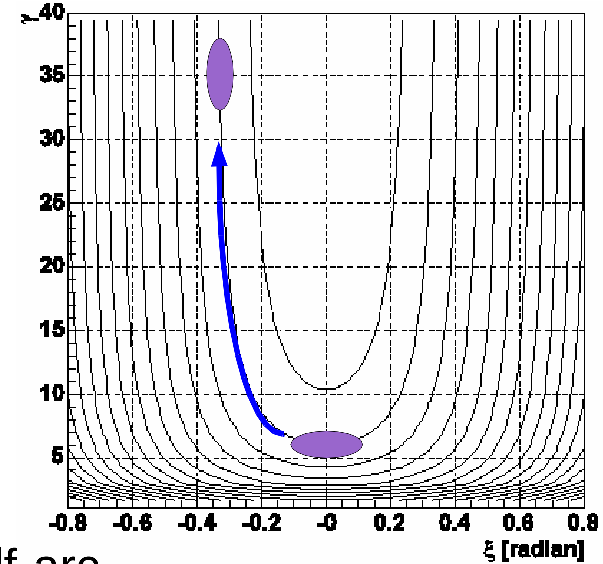
σ_t=3.3ps → 100fs σ_E/E = 0.34%

- fairly linear compression with second-order correction by sextupoles
- however, relatively large energy spread remains, emittance growth by CSR effects exist.

Velocity bunching in a main linac





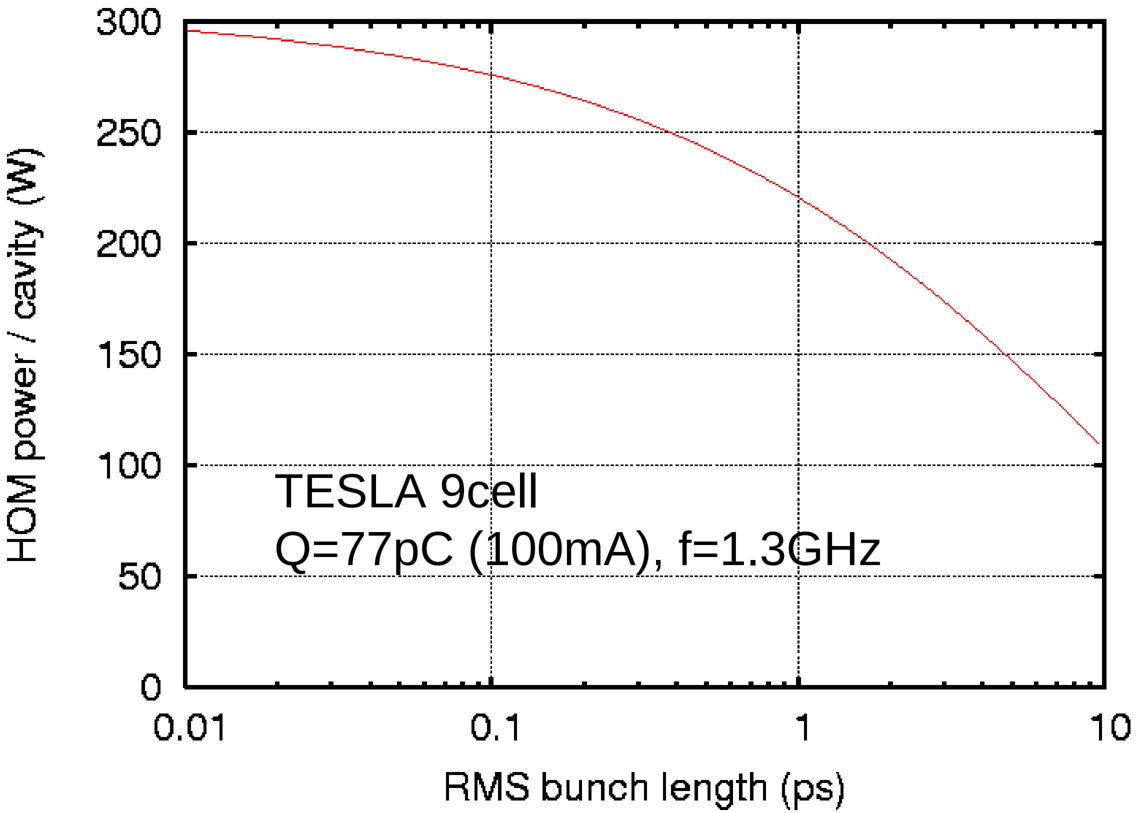


σ_t = 15ps → 3ps → 170fs (after 9-cell x 8-cavity)

- smaller energy spread than compression in a half-arc
- average current is restricted by imperfect energy-recovery
  --- 5mA for typical design.

details are presented at WG2 session.

HOM power VS bunch length

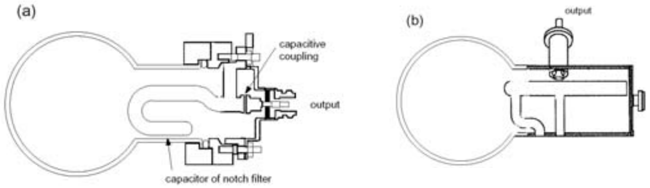


- HOM power ~ 200W is two-order larger than TESLA design.
- limitation of average current

HOM extraction

HOM coupler

TELSA 9-cell HOM power ~ 2W/cavity



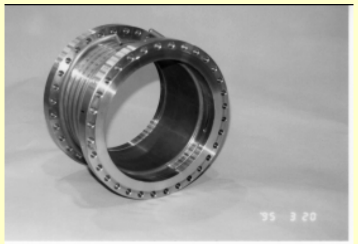
HOM coupler

Phys. Rev. ST-AB 3, 092001 (2000)

how to extract HOM with higher power?

on-axis HOM absorber

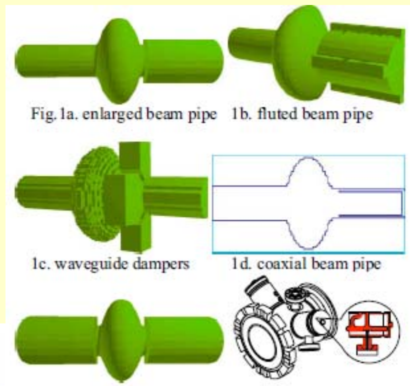
used in storage rings
P ~ 10kW



T. Tajima, SRF-1993

HOM damped cavity

R. Rimmer, PAC-2003.



and more …

- multi-loop and cascade configuration
- multiple merger
- attention to beam-wall interaction – may dilute emittance
- cavity shape and HOM coupler for high-average current
- timing jitter propagation from the gun to the end
- beam halo formation and protection
- cooling of beam pipes (CSR radiation)