bERLinPro

HZB Helmholtz Zentrum Berlin

Beam Dynamics and Optics Challenges of the Berlin Energy Recovery Linac Project

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ERL17 CERN

ERL17: 59th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs – CERN, Geneva, 20.06.2017

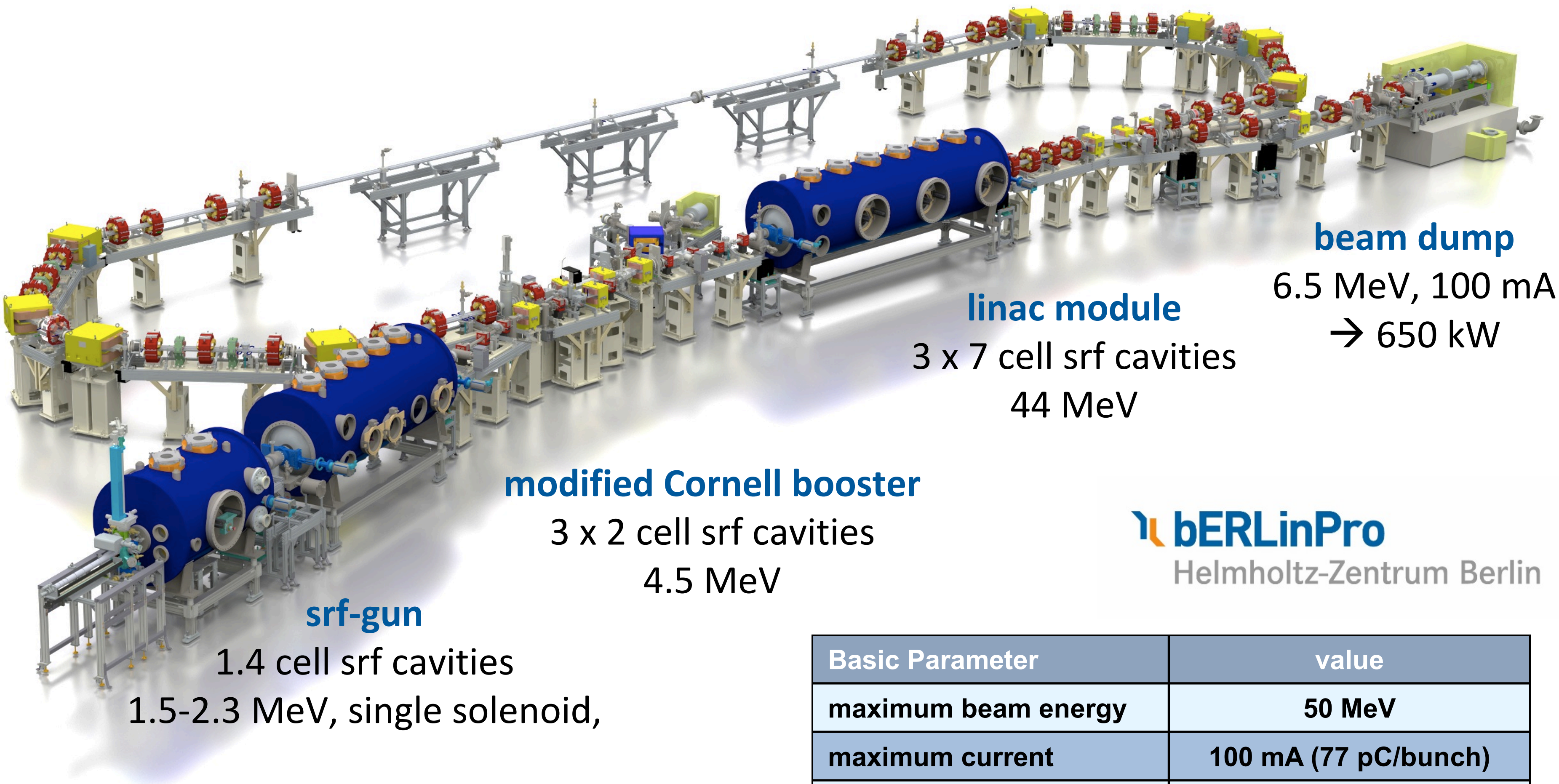
Outline

Introduction: bERLinPro

ERL Beam Dynamics & Beam Optics

- Goal Beam Parameter & Energy Recovery Issues
- Linear Beam Optics
- Nonlinear Beam Optics
- Collective Effects
  - space charge effects
  - CSR – coherent synchrotron radiation
  - BBU – beam break up

bERLinPro – Berlin Energy Recovery Linac Project



bERLinPro
Helmholtz-Zentrum Berlin

Basic Parameter	value
maximum beam energy	50 MeV
maximum current	100 mA (77 pC/bunch)
normalized emittance	< 1 mm mrad
bunch length	2 ps (~100 fs)
repetition rate	1.3 GHz
relative losses per turn	$< 10^{-5}$

bERLinPro – building: technics and accelerator hall

J. Kühn:
“Semiconductor Photocathode development for the bERLinPro photo injector”, Mon 11:15

A. Neumann:
“The bERLinPro SRF Photoinjector system”
Wed 17:25

A. Jankowiak:
“Status of bERLinPro”
Wed 08:55

Goal Beam Parameter:

1. **efficient "Energy Recovery"**
   - adjust recovery conditions: rf phase advance & path length
   - minimize losses of high current beam:
     - small transverse beam size, dispersive regions → small E-spread
     - halo: avoid, remove, transport
     - instabilities: maximize threshold currents
2. **maintain beam quality from source**
   - transport beam preserving the emittance
3. **bunch manipulation: compression**
   - increase longitudinal bunch density as far as energy spread and transverse emittance degradation allow → user experiment

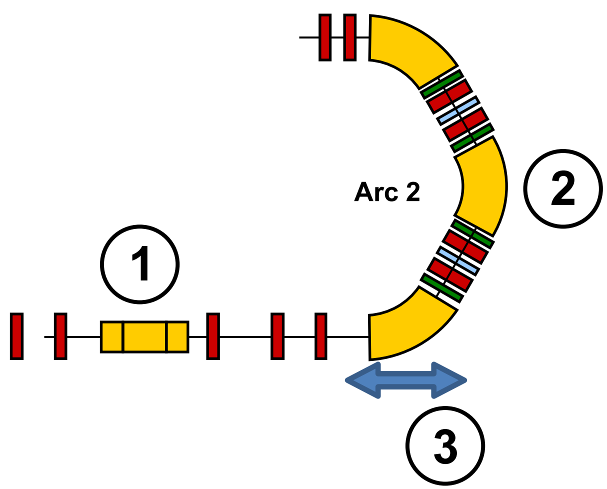
many issues known from SRs and/or Linacs

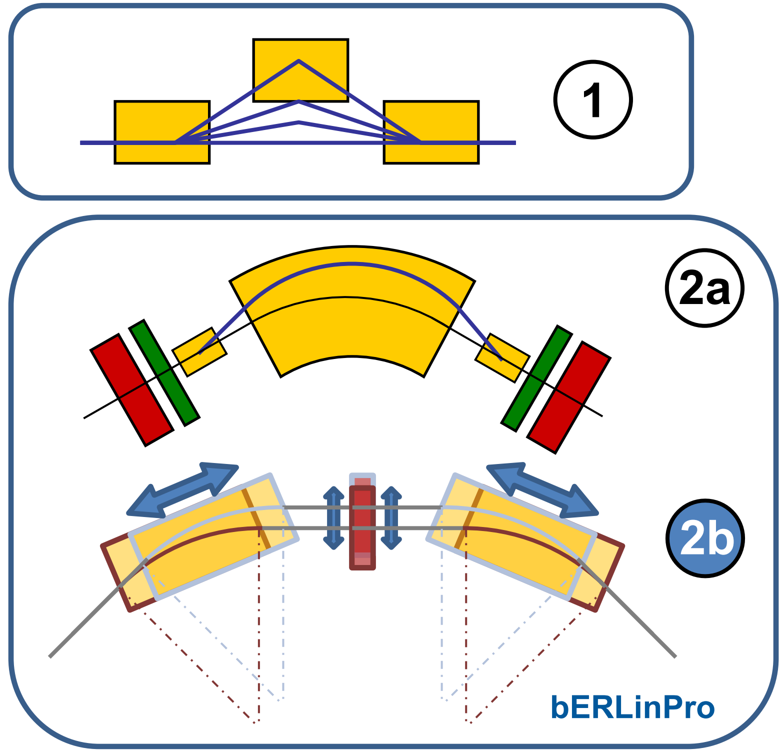
Linear and Nonlinear Beam Optics

- **energy recovery → phase advance tuning**
- **beam manipulation → short pulses in ERLs**
- **beam transport without emittance degradation & losses**
- **high power beam dump & MPS**
- **requirements for beam diagnostics & commissioning**
- **error studies → misalignments effects of magnets and cavities**
- **tolerance & acceptance studies → hardware specification**
- **halo & dark current → low losses**

ERL17 McAteer: "*Dark Current and Halo Tracking in ERLs*", Thu 8:55

options:
- extra chicane 1
- inside arc 2
- moveable arc 3





recirculator passage time: $L_{Rec} / (\beta c) = (n + ½)\ T_{rf}$ ($½\ T_{rf} = 180°$ rf phase advance)

path length may change: v = f(E), misalignments & field offsets → orbit oscillations,

switch between acceleration & deceleration (n ↔ n+ ½, multi-turn ERLs)

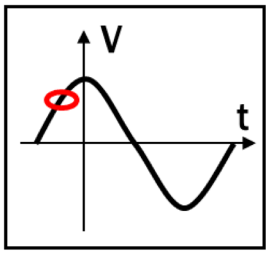
→ adjust RF frequency: f_{rf} , T_{rf} ☹

→ adjust recirculator length L_{rec}

Linear Beam Optics: beam manipulation

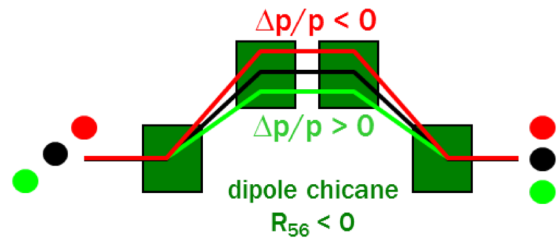
many techniques: **bunch compression**, emittance exchange, laser heater, …

1. „Off Crest" acceleration

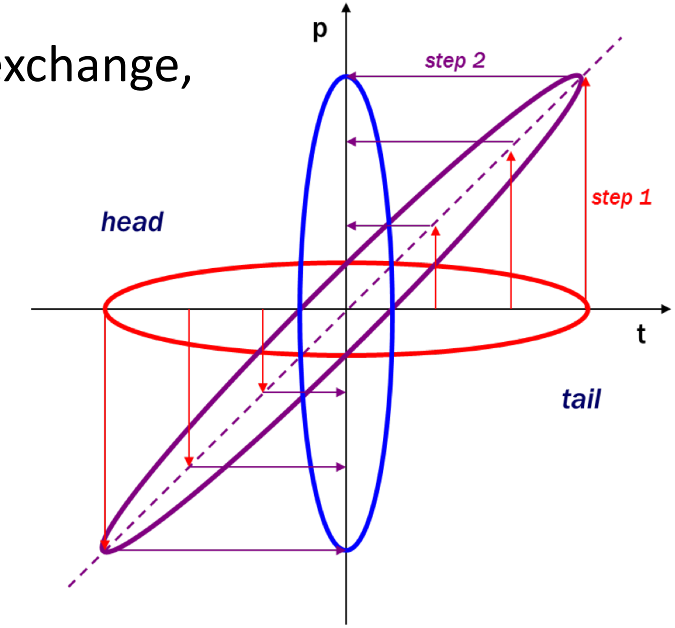


$V(t) = V_0 \cos(\omega t + \phi_0)$

2. Dispersive section: $R_{56} \neq 0$



$\Delta L = R_{56}\, \Delta p/p$



choice of bunch length / compression?

- **injector, merger**: long → reduced SC effects, short → minimize rf curvature
- **linac**: long → reduced beam loading to HOMs, short → minimize rf curvature
- **recirculator**: long → reduce SC, CSR, wakes, short → experiment / project goal

bERLinPro: 6-8 ps (laser/cath.) → 4-5 ps (merger/linac) → 2 ps (~100 fs) (recirc.)

Before deceleration: decompress bunch to restore chirp & minimize σ_E → $R_{56,Arc2} = -R_{56,Arc1}$

$R_{56,Arc2} = R_{56,Arc1}$ → inverted chirp → $\varphi_{dec} = 180° - \varphi_{acc}$ with unbalanced beam loading

Linear Beam Optics: bERLinPro

bERLinPro = one stage ERL:

Injector → Merger → Linac(acc) → Arc1 → Straight Section →

Arc2 → Linac(dec) → Splitter → Dumpline & Dump

section requirements:

injectior / merger / splitter / dumpline:

- low energy beam transport
- merge / separate low & high energy beams
- first stage of bunch compression

linac section:

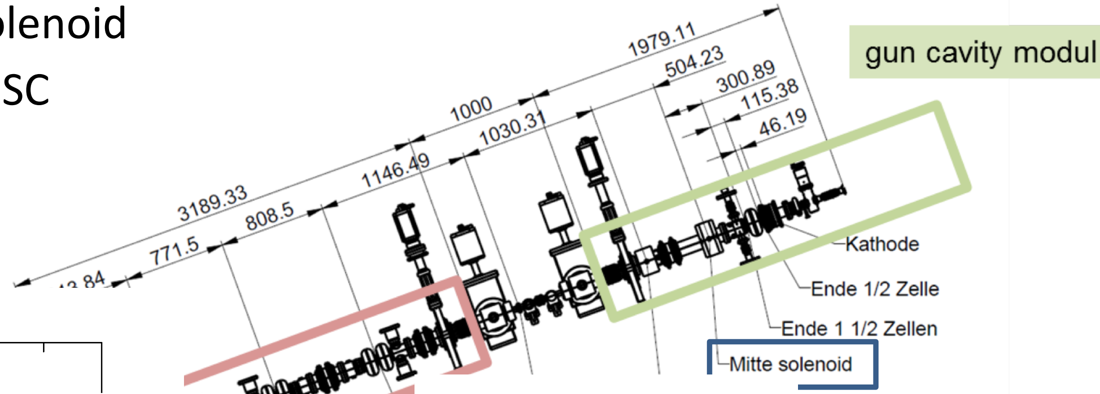
- merger / splitter chicanes
- matching to injection line, arcs and dump line

recirculator arcs & straight section:

- 2 x 180° total bending angle
- final bunch compression
- sufficient space for user experiments in the straight section

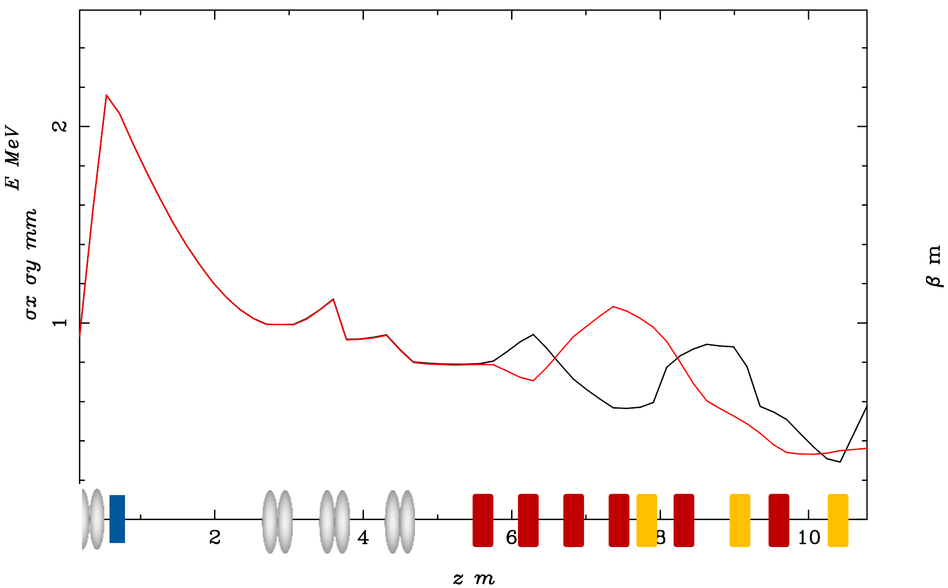
Linear Beam Optics: bERLinPro Injector

- only one magnetic element: solenoid
- beam dynamics dominated by SC
  → emittance compensation

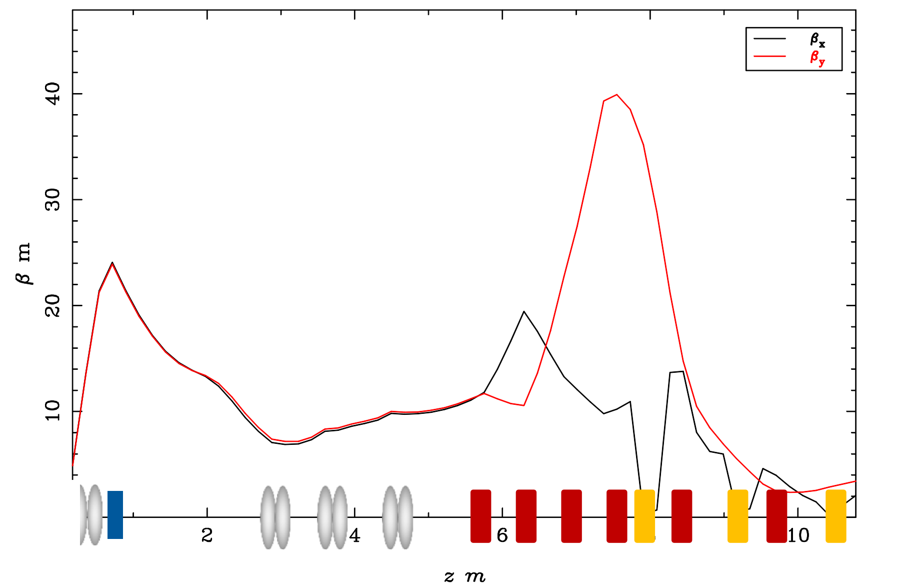


energy

rms beam size

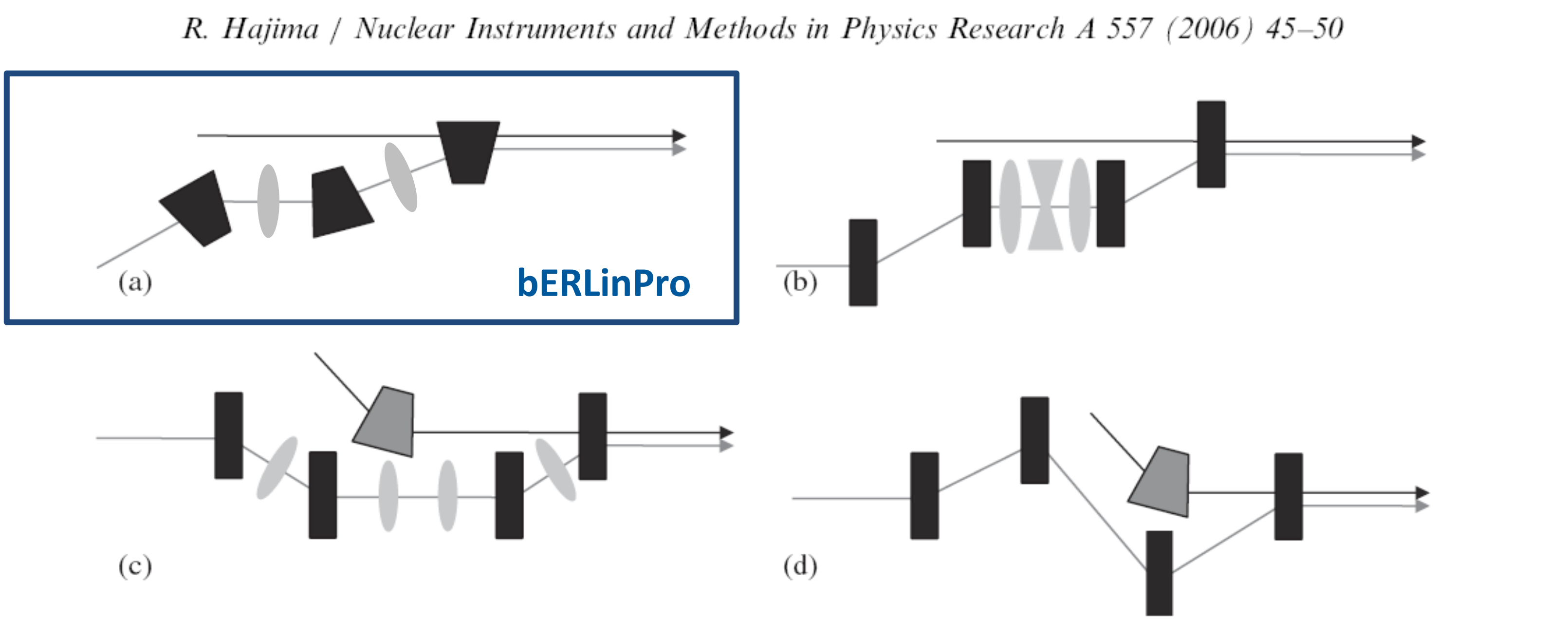


Twiss parameter



- emittance: $\varepsilon_{n,xy}$ < 1 mm mrad

Linear Beam Optics: Merger / Splitter



design considerations:

- length & hardware
- chromatic properties, R_{56} range
- SC sensitivity / ε compensation

Mergers for existing and proposed ERLs:

(a) JLAB IR-demo, IR-upgrade,
Cornell ERL, Daresbury ERLP

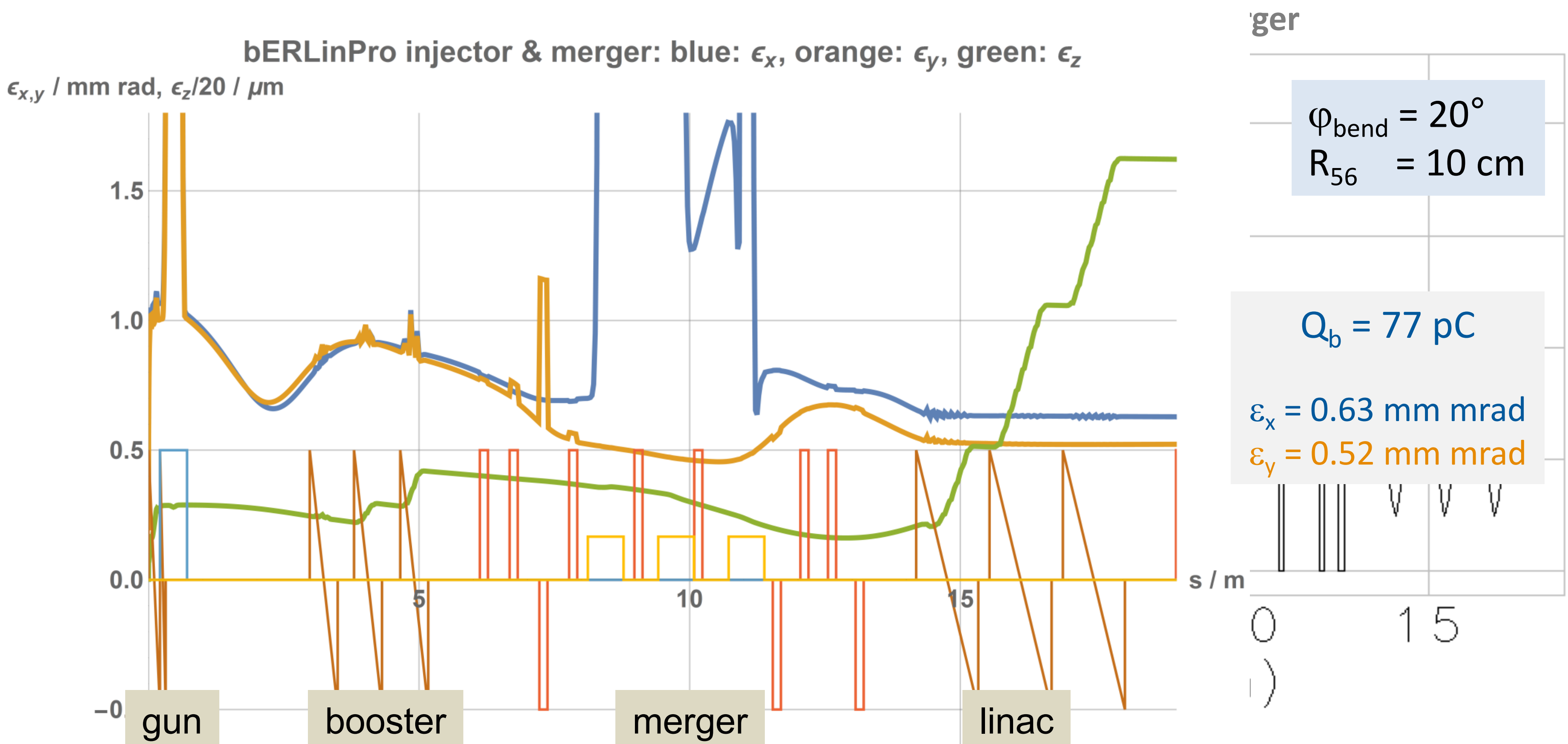
(b) JAERI-ERL

(c) BINP-ERL

(d) BNL-ERL (proposed)

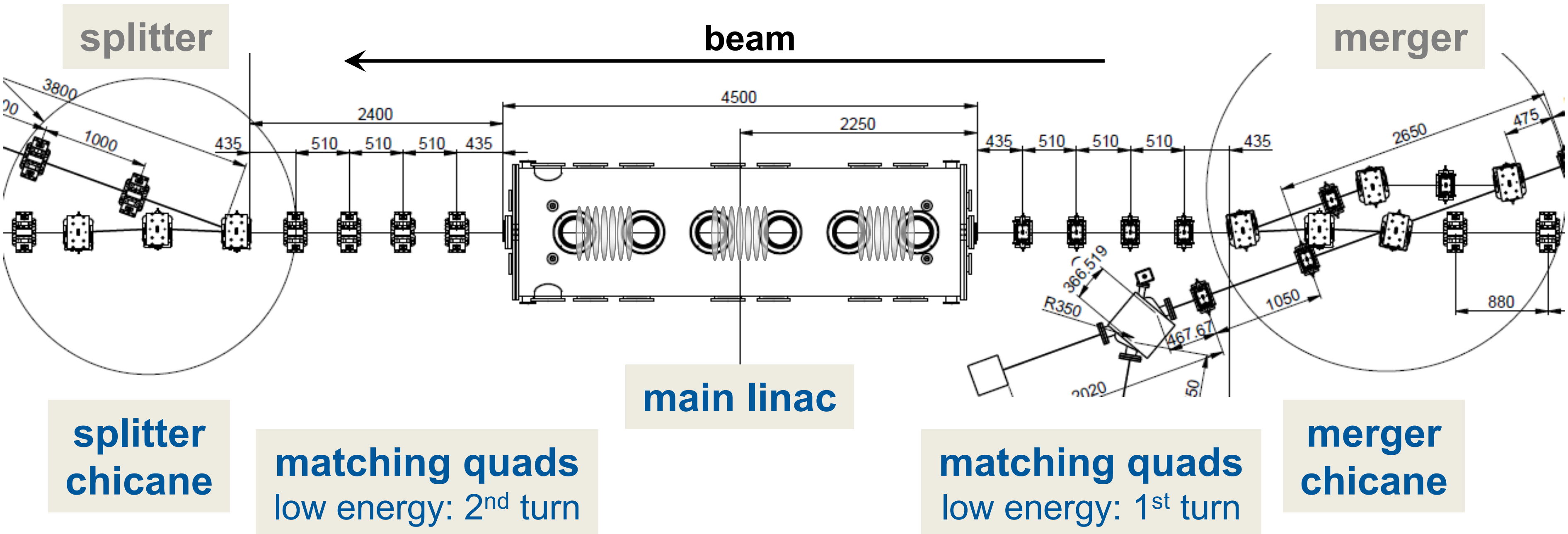
bERLinPro: merger

- beam dynamics dominated by SC
  - → emittance compensation continued
  - → beam transport in dispersive section: ε–growth (“space charge dispersion”)



Linear Beam Optics: Linac Section

- rf focusing in the linac (with few/no quads)
- two (or multi) energy beam optics: matching beam optics from merger (LE) & Arc2 (HE) and into Arc1 (HE) & Dumpline (LE)
- adjust β-function in the linac cavities for maximum BBU threshold current
- include merger and splitter chicanes for the HE beam



Linear Beam Optics: Recirculator

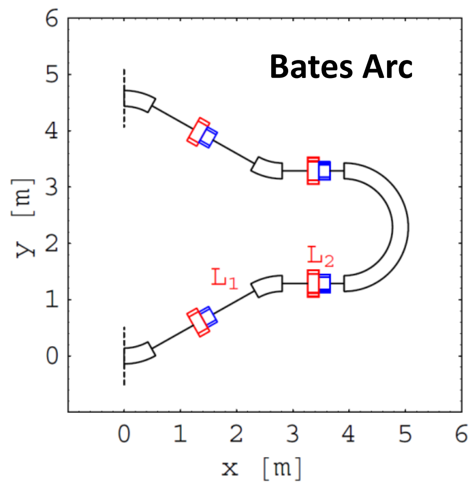
arc optics: various option also known from SR's

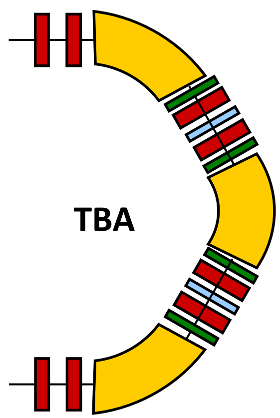
→ DBA, TBA, MBA (achromatic closed FODO)

→ Bates Arc

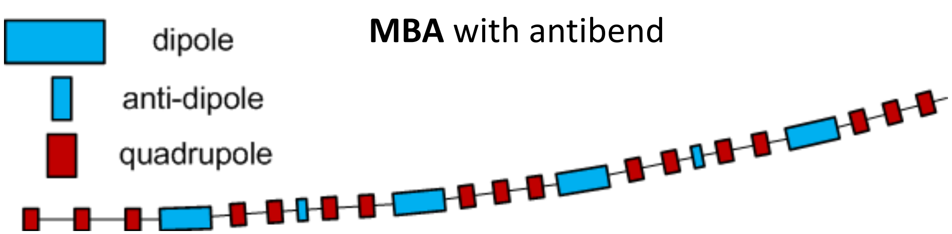
design considerations:

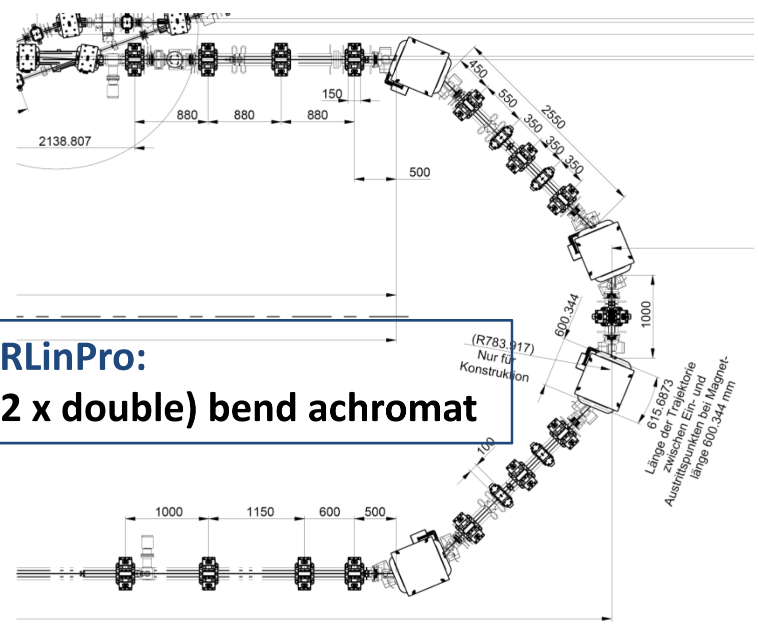
- length & hardware
- flexibility / tunability
- chromatic properties, R_{56} range
- ISR / CSR properties





MBA with antibend





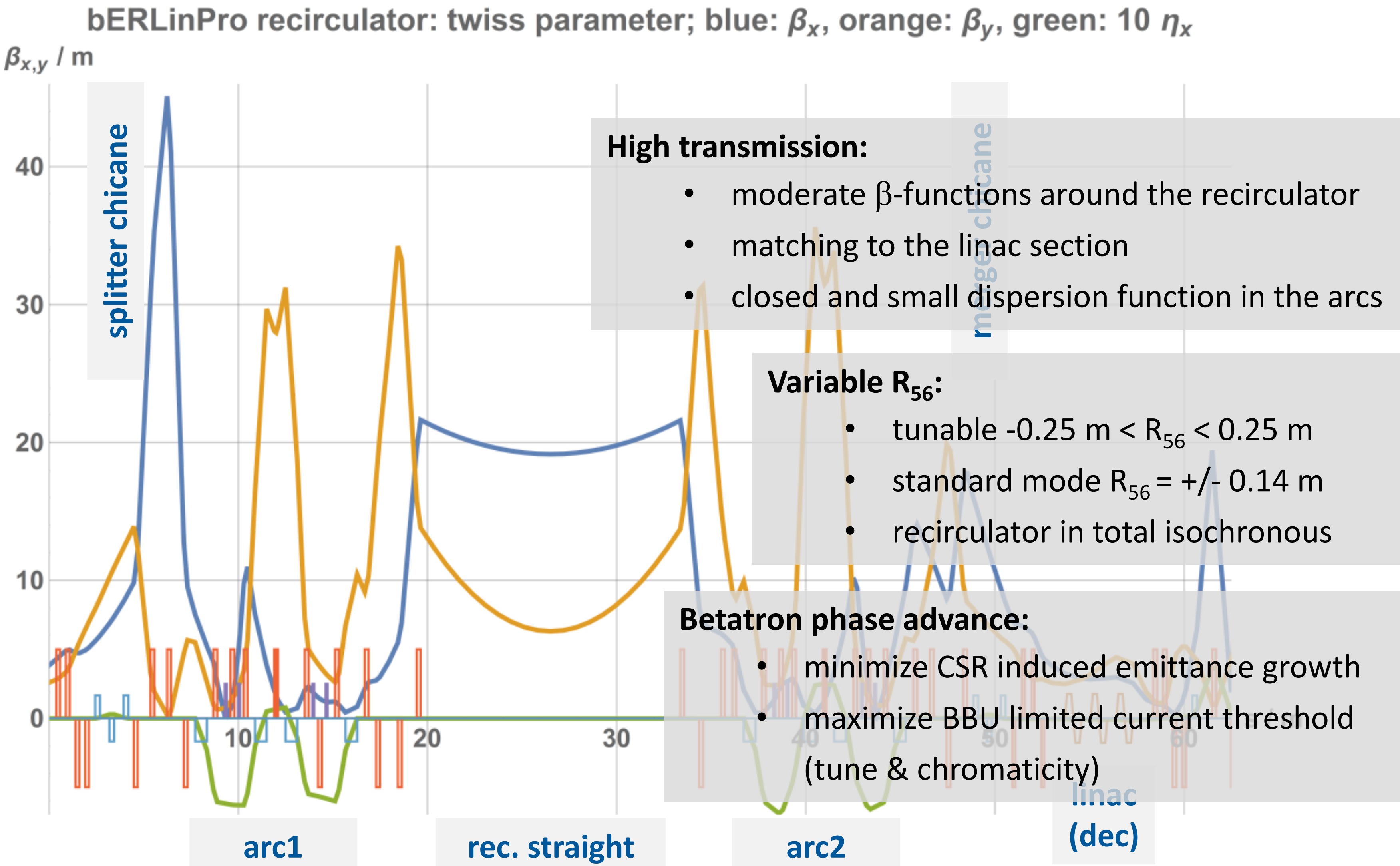
bERLinPro:
4 (2 x double) bend achromat

FSF: A. Matveenko, et al., ERL WS, 2013.

H.L. Owen et al., "Choice of Arc Design for the ERL Prototype at Daresbury Laboratory", EPAC, Lucerne, Switzerland 2004.

Linear Beam Optics: Recirculator

Lattice design: various demands → difficult to meet all simultaneously



High transmission:

- moderate β-functions around the recirculator
- matching to the linac section
- closed and small dispersion function in the arcs

Variable R_{56}:

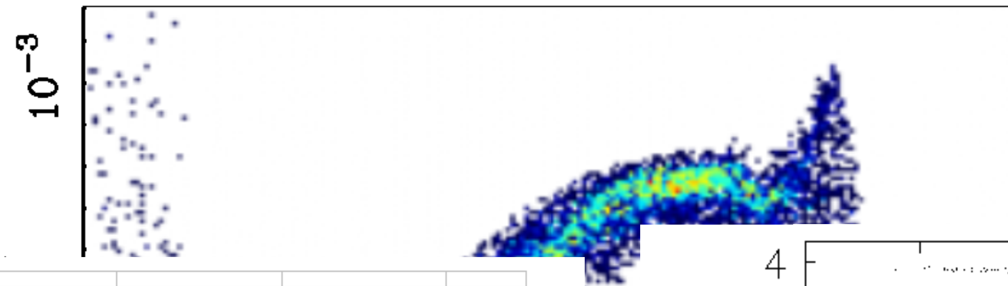
- tunable -0.25 m < R_{56} < 0.25 m
- standard mode R_{56} = +/- 0.14 m
- recirculator in total isochronous

Betatron phase advance:

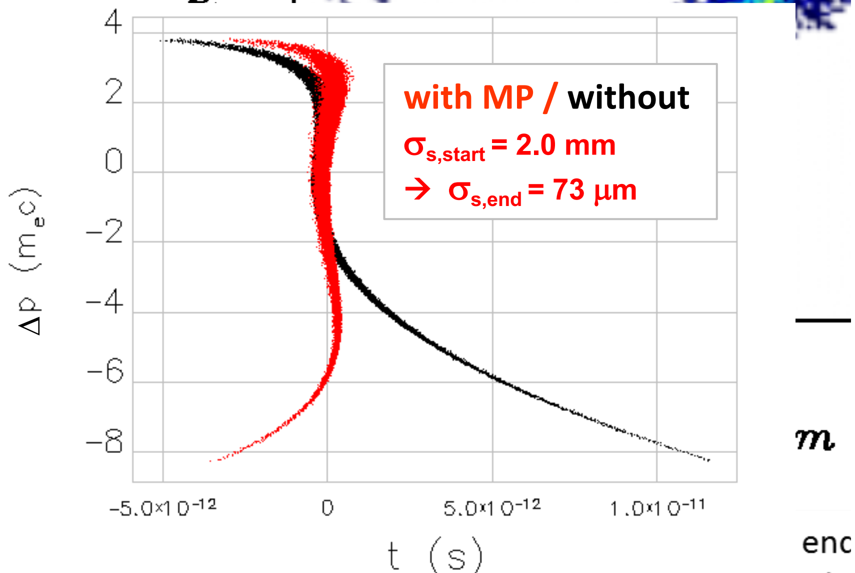
- minimize CSR induced emittance growth
- maximize BBU limited current threshold (tune & chromaticity)

Nonlinear Beam Optics

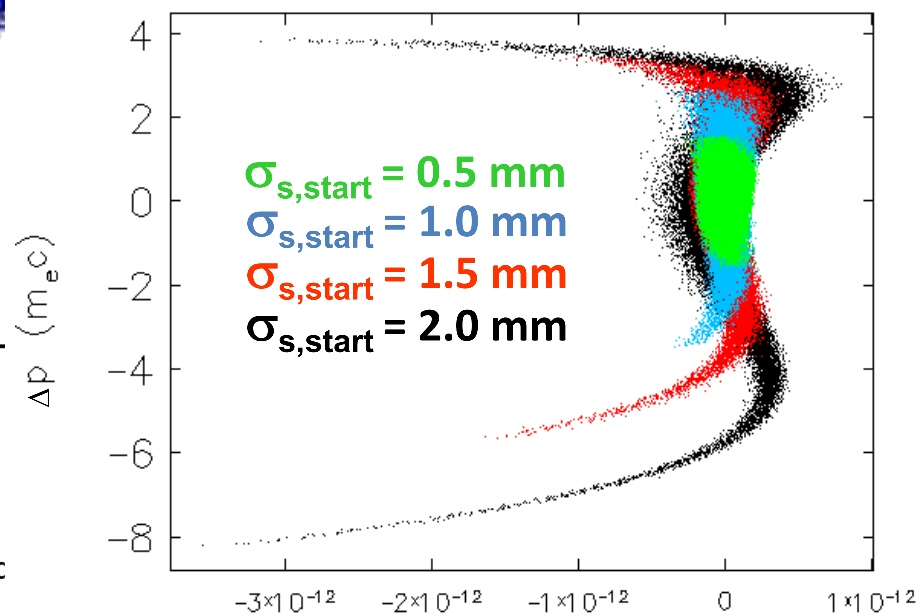
- RF curvature: $E(t) = E_0 \cos(\omega t + \varphi_0)$
- aberrations: geometric & chromatic:
  - counteracted by nonlinear fields → multipole magnets

Example: 

: rel. energy dev.



including space charge effects too!



bERLinPro recirculator: bunch compression test with and without multipole (sextupole and octupole) magnets

bERLinPro recirculator: bunch compression test with varying initial bunch length indicating the influence of the the rf curvature

Nonlinear Beam Optics

bERLinPro: two modes of operation - both require multipole magnets for nonlinear corrections

→ **four sextupole magnets per arc** (each individually powered)

Low Emittance Mode (LEM): high current, emittance ≤ 1 mm mrad, $\sigma_t = 2$ ps

- sextupoles first arc → counteract chromatic effects causing emittance growth
- sextupoles second arc → **restore longitudinal phase space** before deceleration to minimize the downstream energy spread

Short Pulse Mode (SPM): $\sigma_t \leq 100$ fs @ reduced current & degraded emittance

- sextupoles in first arc → linearize long. phase space / optimize T_{566} for **shortest bunches**
- sextupoles in second arc → **restore long. phase space** (like in LEM)

optimization procedure:

numerical optimization (Elegant) → minimize goal function from tracked bunch:

- **@ experiment (recirculator straight section): ε, σ_s**
- **after deceleration: phase space optimized to dump the beam**

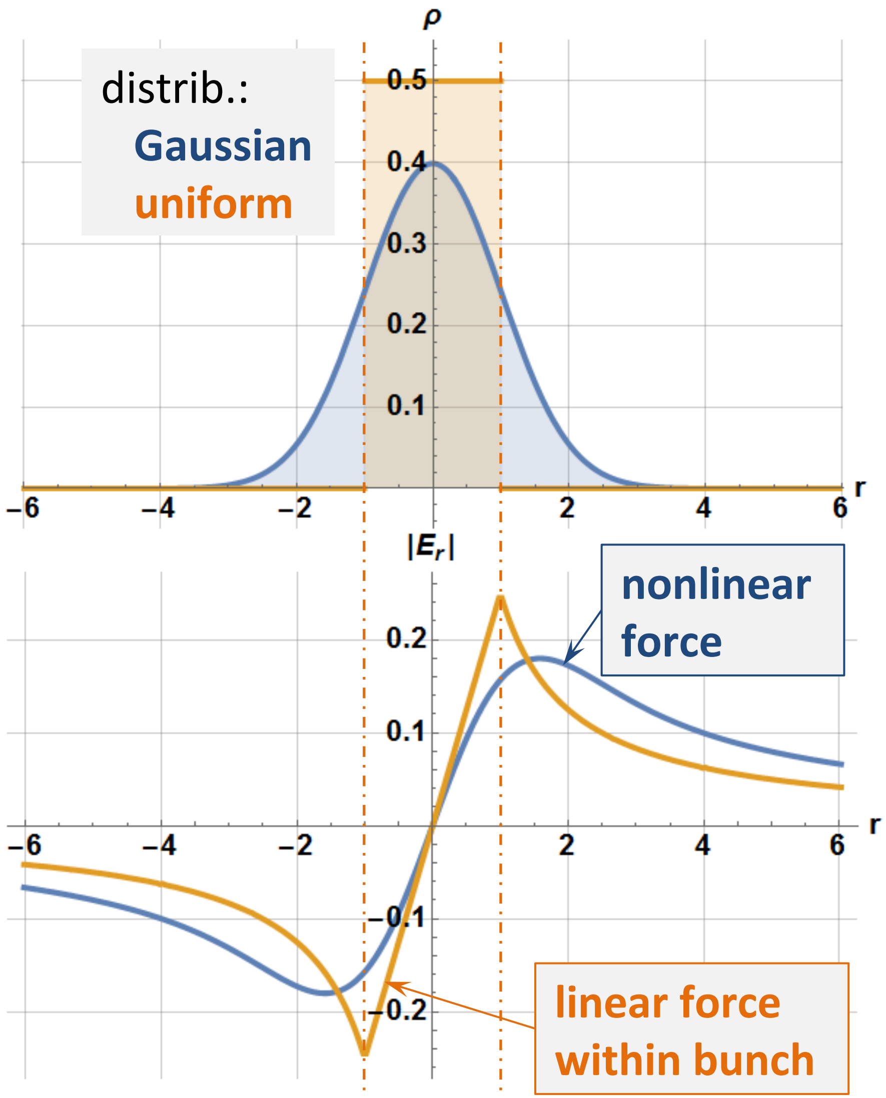
→ low ε, σ_E & no linear / nonlinear chirp

Collective Effects:

- Space Charge
- Coherent Synchrotron Radiation
- Beam Break Up
- Geometric & other wakes
- Ion Trapping

Collective Effects: Space Charge

Fields & Forces



eqn. of motion:

$$r'' + \kappa(s)\,r \; - K(s)/a^2\,r = 0$$

SC: perveance K=f(I,γ), a: (round) beam size
ext. focusing: $\kappa(s)$

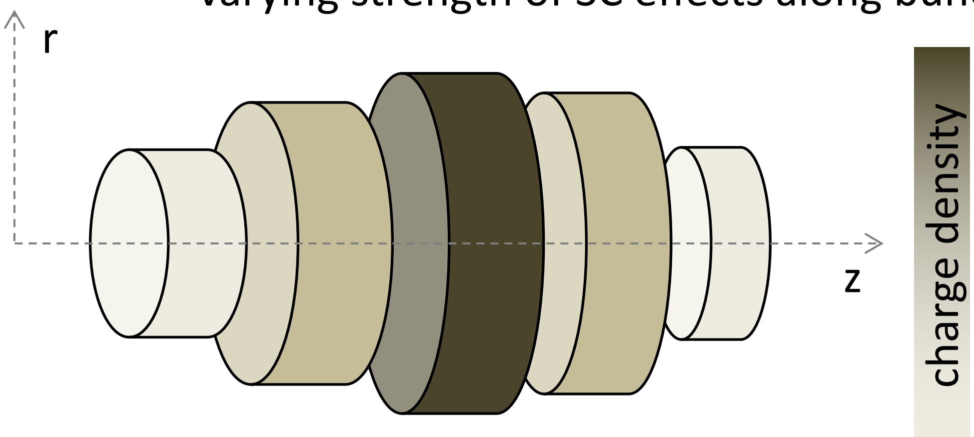
→ SC: defocusing forces in the bunch

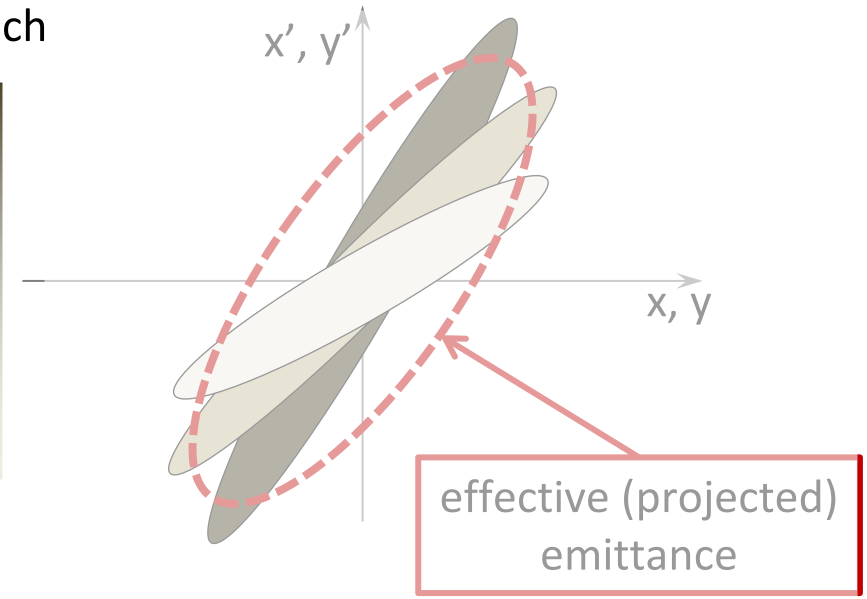
least degradation due to SC:

- radial force as linear as possible
  → uniform radial charge density distribution
- no variation of K(s) along bunch
  → K = const
  → flat top, long. charge density distribution

SC Effects in ERLs

- (moderate) tune shift: minor issue in ERLs
- **emittance growth**
  - nonlinear SC forces → phase space nonlinearities (x-x’, y-y’, t-p)
  - varying strength of SC effects along bunch





bunch: longitudinally sliced

each slice with individual

- charge & charge density
- transverse size & divergence → ε
- energy & energy spread

→ **individual SC forces**

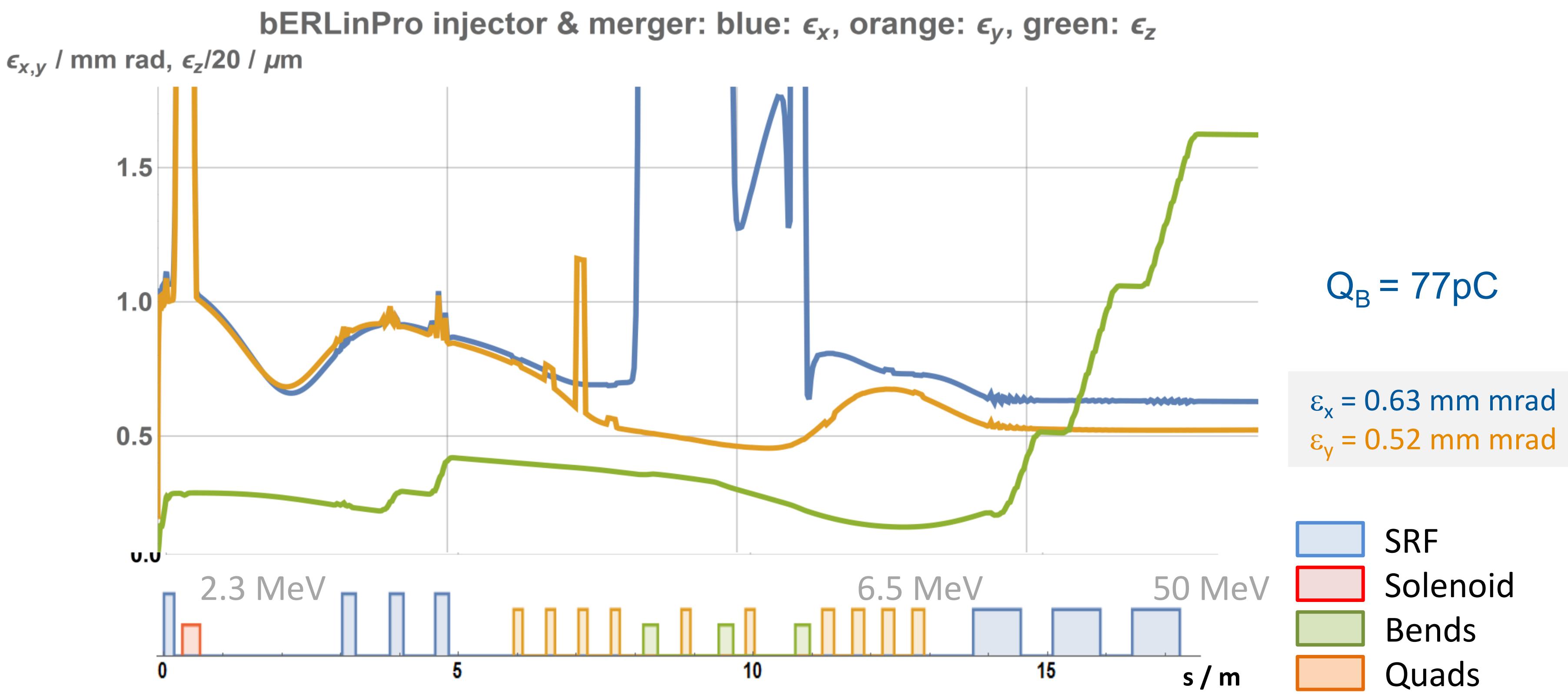
emittance compensation:
realign slices to minimize projected emittance

Collective Effects: Space Charge

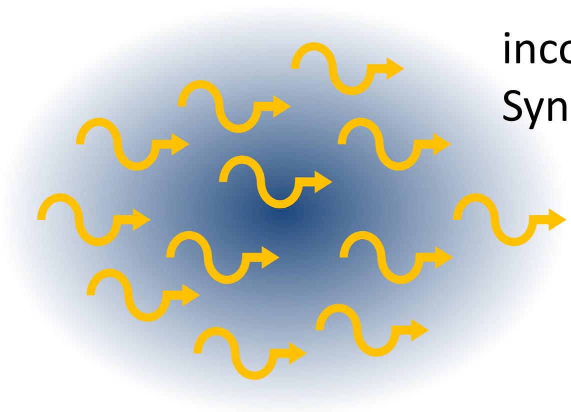
bERLinPro: simulations & optimization of SC dominated beam transport → ASTRA, OPAL
for 2D - emittance compensation: SCO*

*SCO: A. Bondarenko, A. Matveenko, "Emittance Compensation Scheme for the BERLinPro Injector",IPAC 2011, San Sebastian

space charge at current ramping = increase of bunch charges at 1.3 GHz bunch rep-rate



Collective Effects: Coherent Synchrotron Radiation



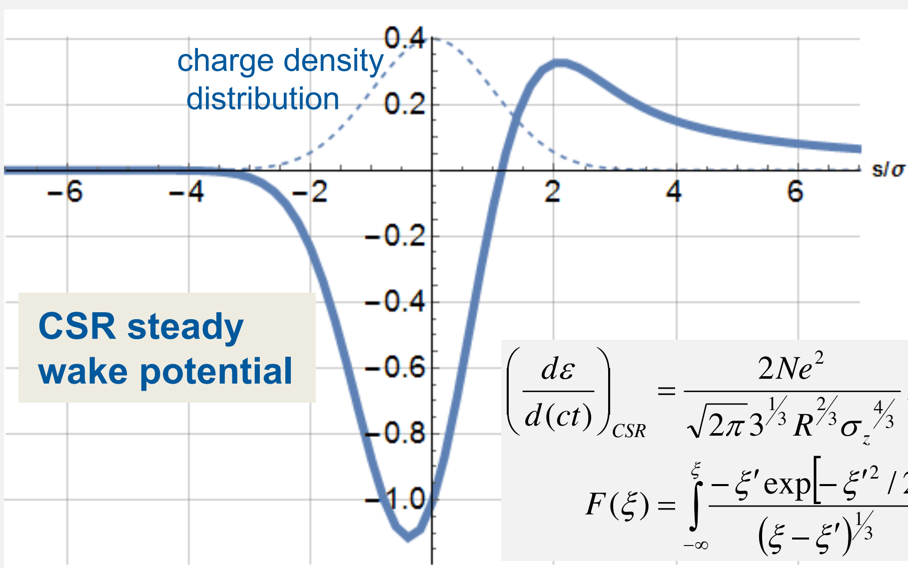
incoherent emission of Synchrotron Radiation

$$\sigma_s >> \lambda_{Ph}$$

$$\frac{dP}{d\omega} = P_0(\omega)\, N_e$$

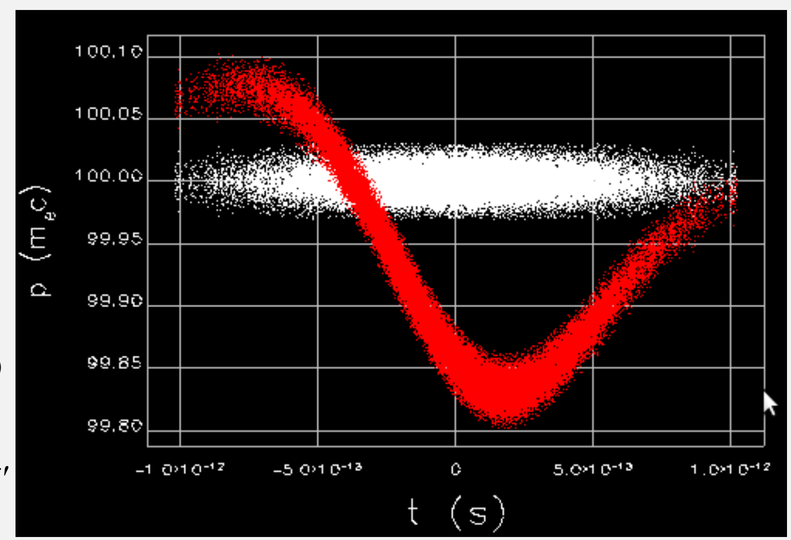
coherent emission of Synchrotron Radiation
→ CSR

$$\sigma_s <\approx \lambda_{Ph}$$

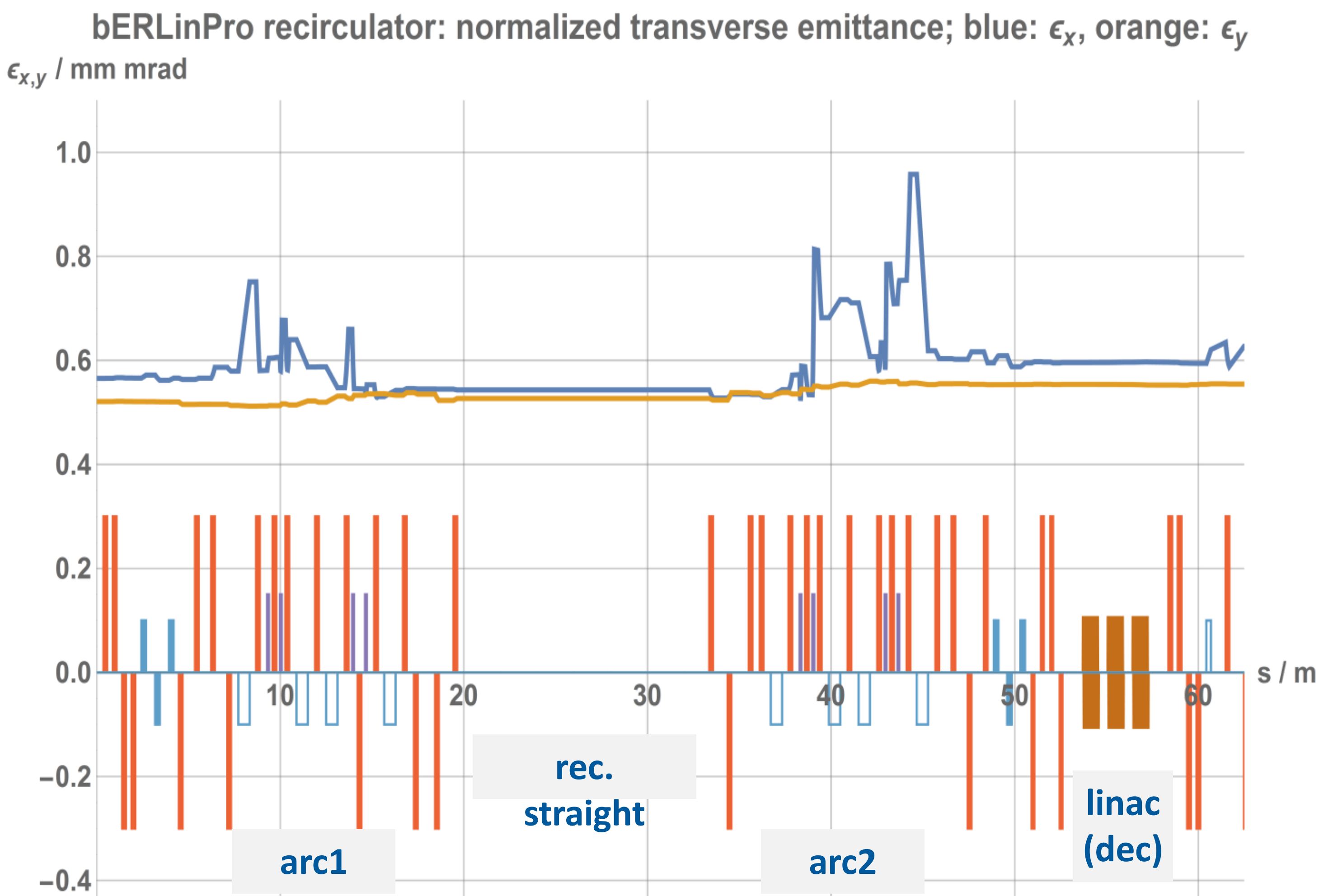


$$\left(\frac{d\varepsilon}{d(ct)}\right)_{CSR} = \frac{2Ne^2}{\sqrt{2\pi}\, 3^{1/3} R^{2/3} \sigma_z^{4/3}} F(\xi)$$

$$F(\xi) = \int_{-\infty}^{\xi} \frac{-\xi' \exp\left[-\xi'^2/2\right]}{(\xi-\xi')^{1/3}}\, d\xi'$$



Collective Effects: Coherent Synchrotron Radiation



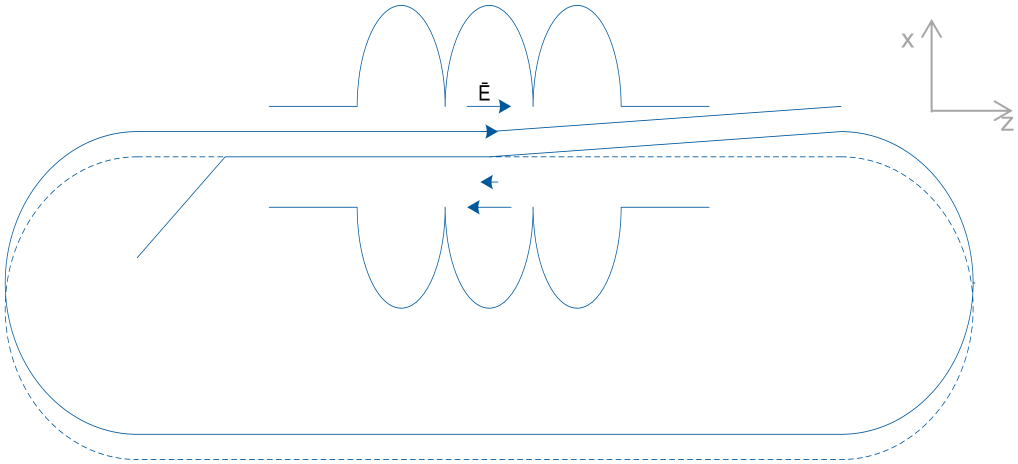
bERLinPro: 1D-simulations → CSR no major issue

limited tune adjustment range → optics not optimized with respect to CSR

ERL Beam Dynamics: Beam Break Up

Beam Break Up: resonant interaction of short & long range cavity wake fields with the generating bunch or subsequent bunches

if HOM excitation exceeds HOM damping → kick strength rapidly increases → instability & beam loss



various BBU variants: single bunch BBU, multi bunch BBU (cumulative / regenerative, transverse / longitudinal, single-/multi-cavity, single-/multiple-turn)

ERL Beam Dynamics: Beam Break Up

regenerative transverse BBU
(single cavity, single turn, one mode):

$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

Countermeasures:

$$m^* = m_{12}\cos^2(\alpha) + (m_{14} + m_{32})\sin(\alpha)\cos(\alpha) + m_{34}\sin^2(\alpha)$$

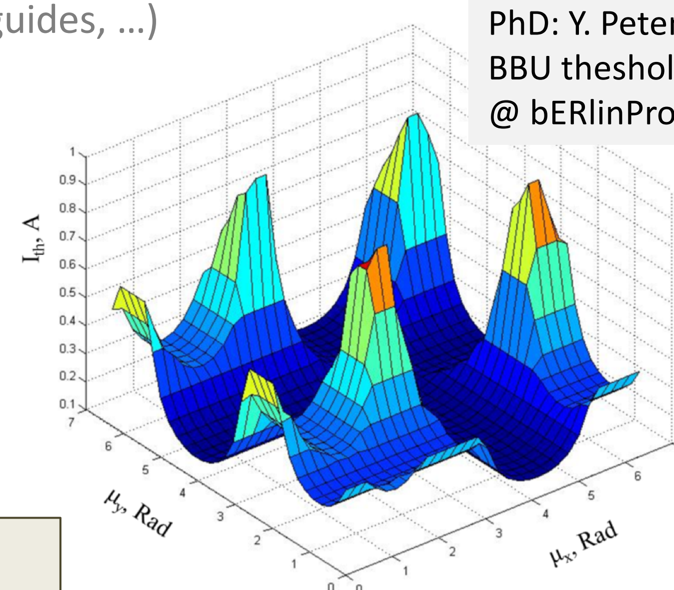
1. **cavity design:**
   - HOMs: small R/Q, varying ω_λ at fixed ω_0 → multi cavity BBU thresholds increase
   - no HOM on a fundamental's harmonics: $\omega_\lambda \neq n^*\omega_{rf}$
   - low Q for HOM → HOM dampers (ferrites, waveguides, …)
2. **recirculator beam optics:**
   - for α=0 & uncoupled beam transport

   → $m^* = m_{12} = (\beta_1\beta_2)^{1/2}\sin(\Delta\varphi_x) = 0$ for $\Delta\varphi = n\pi$
   - adjust $\sin(\omega_\lambda T_{rec}) = 0$ for the worst HOM

     large path length change → inpractical ☹
   - large chromaticity → similar to Landau damping

     strong sextupoles

PhD: Y. Petenev
BBU thesholds
@ bERlinPro



Vladimir N. Litvinenko, "Chromaticity of the lattice and beam stability in energy recovery linacs", PRST-AB 15, 074401 (2012)

ERL Beam Dynamics: Beam Break Up

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(single cavity, single turn, one mode):

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Countermeasures:

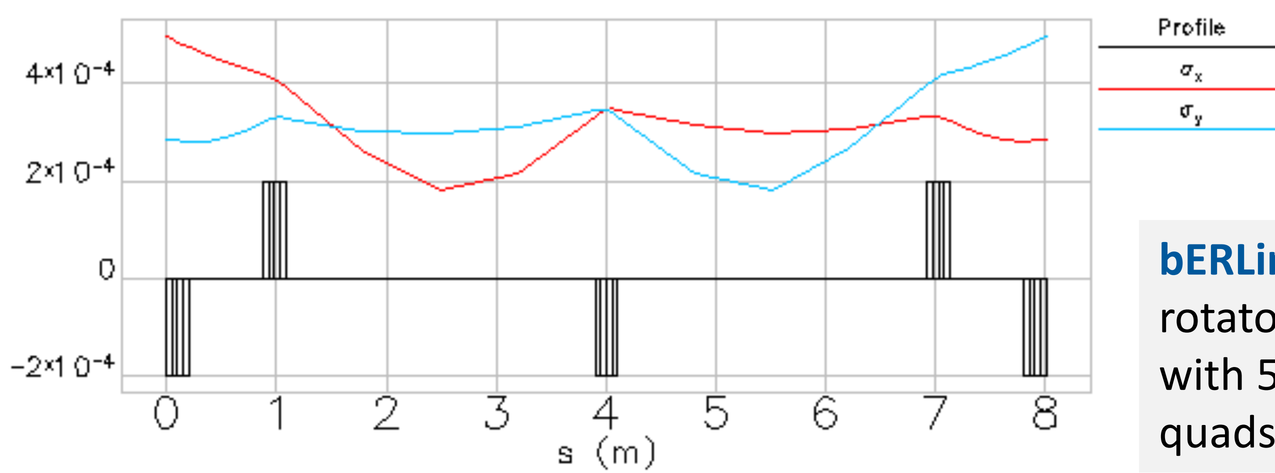
$$m^* = m_{12}\cos^2(\alpha) + (m_{14}+m_{32})\sin(\alpha)\cos(\alpha) + m_{34}\sin^2(\alpha)$$

2. recirculator beam optics (continued):

- coupled beam transport: switching of planes X↔Y: $m_{12}=0$ → horizontal HOM kick transforms to vertical offset → polarized HOM not further excited,

  two options: solenoid (low energy) or **skew quadrupole based rotator**

$$M_{rot} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$



bERLinPro:
rotator concept with 5 skew quads prepared

Thanks …

… to the bERLinPro Optics & Theory group:

J. Knedel, B. Kuske, D. Malyutin, A. Matveenko, M. McAteer & C. Metzger-Krauss

… to the bERLinPro team

M. Abo-Bakr, W. Anders, A. Büchel, K. Bürkmann-Gehrlein, P. Echevarria, A. Frahm, H.-W. Glock, F. Glöckner, F. Göbel, B. Hall, S. Heling, H.-G. Hoberg, A. Jankowiak, C. Kalus, T. Kamps, G. Klemz, J. Knedel, J. Knobloch, J. Kolbe, G. Kourkafas, J. Kühn, B. Kuske, J. Kuszynski, D. Malyutin, A. Matveenko, M. McAteer, A. Meseck, C. Metzger-Kraus, R. Müller, A. Neumann, N. Ohm-Krafft, K. Ott, E. Panofski, F. Pflocksch, J. Rahn, M. Schmeißer, O. Schüler, M. Schuster, J. Ullrich, A. Ushakov, J. Völker

… to all supporting colleagues @ HZB and from other Accelerator-Laboratories

… for your attention!