Beam Dynamics of Energy Recovery Linacs

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ERL Beam Dynamics

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- Nonlinear Beam Optics
- Collective Effects
  - Space Charge effects
  - CSR – coherent synchrotron radiation
  - Geometric wakes
- BBU – beam break up
- Unwanted Beam: dark current & halo
- Ion Trapping

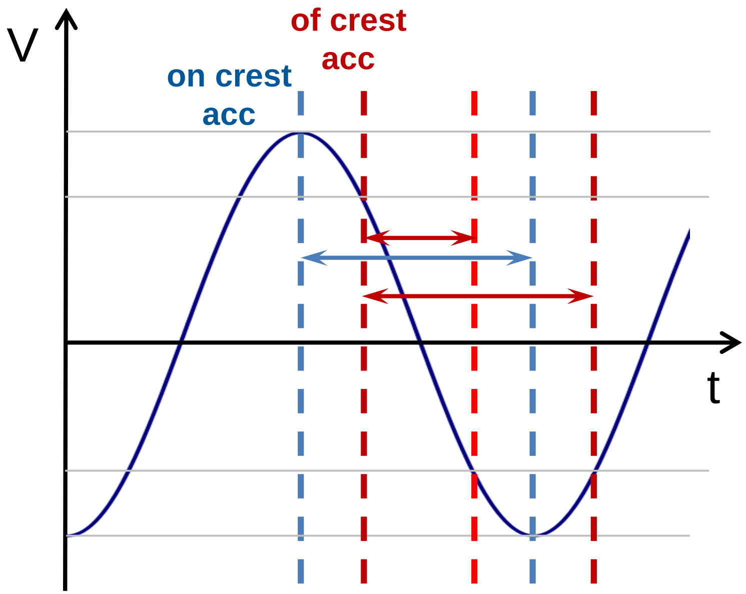
ERL Beam Dynamics: Goal Parameter & ERL Issues

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: tune for high threshold currents
2. **maintain beam quality from source**
   - transport emittance without degradation
3. **bunch manipulation: compression**
   - increase longitudinal bunch density as far as energy spread and transverse emittance degradation allow

many topics relevant for Linacs → focus here mostly on ERL specific topics

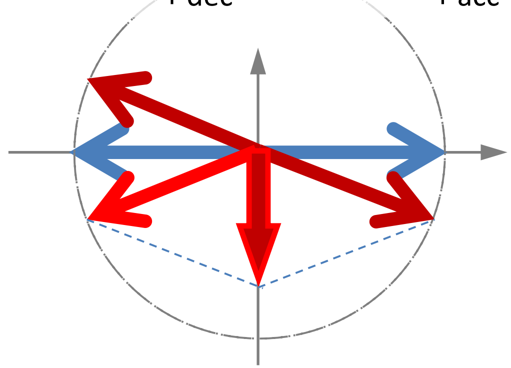
(Linear) Beam Optics: recovery of energy by passing the linac @ dec. phase



on crest: $\varphi_{dec} = \varphi_{acc} + 180°$

of crest: $\varphi_{dec} = \varphi_{acc} + 180°$

$\varphi_{dec} = 180° - \varphi_{acc}$



recirculator path length: $L_{Rec} / (\beta c) = (n + 1/2)\, T_{rf}$ → 180° rf phase advance

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

→ adjust recirculation length

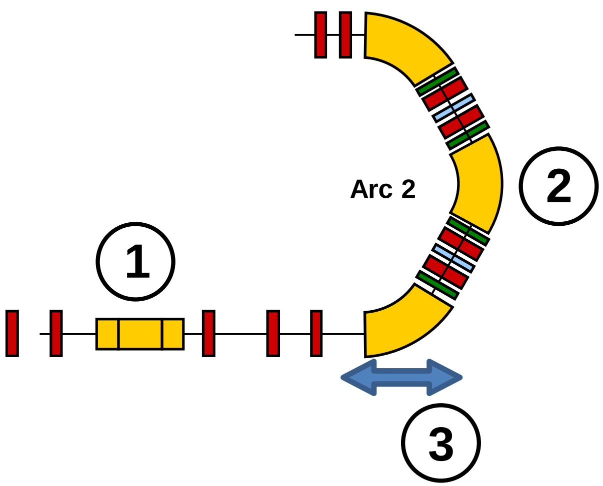
→ adjust f_{rf} : ☹

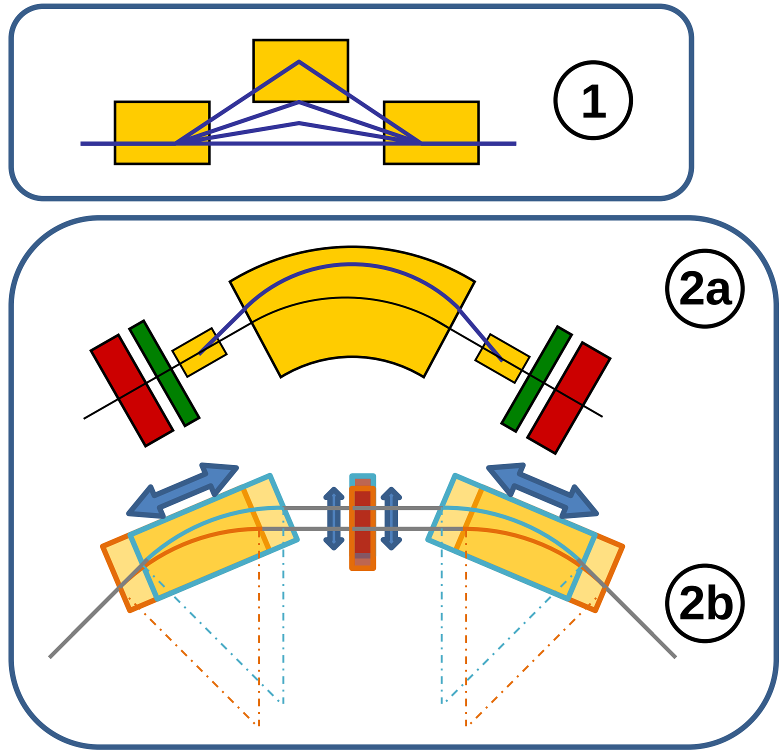
ERL Beam Dynamics: Linear Beam Optics

options: - extra chicane (1)

- inside arc (2)

- moveable arc (3)





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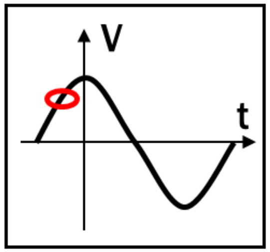
→ adjust recirculation length

→ adjust f_{rf} : ☹

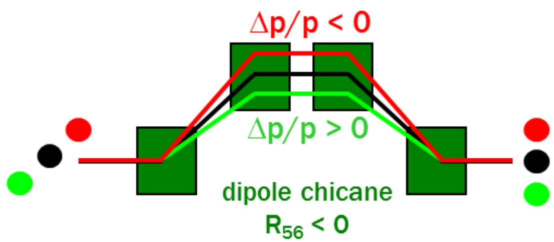
Linear Beam Optics: Bunch Compression

1. „Off Crest“ acceleration

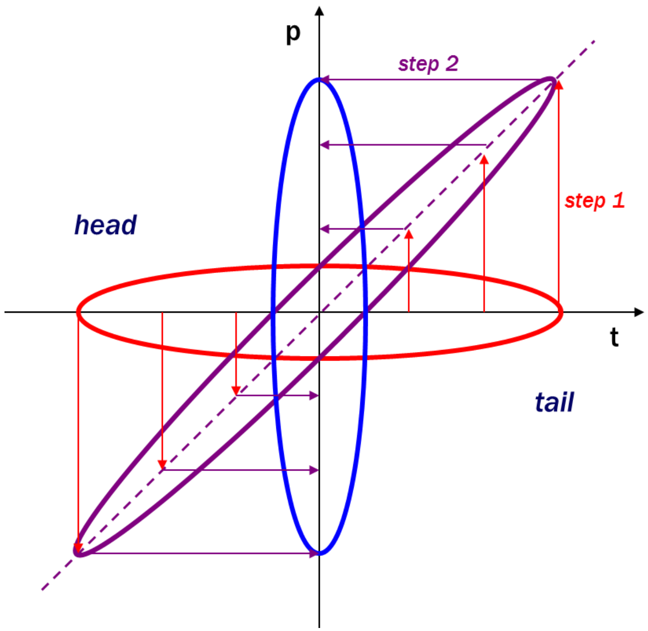


$V(t) = V_0 \cos(\omega t + \phi_0)$

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



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



ERL: bunch length @ acceleration (deceleration)?

- short: rf curvature
- long: minimize beam loading into linac HOM's

$$\sigma_{s,out}^{Pass1} = \sigma_{s,in}^{Pass2}$$

decompression: $\Delta\varphi$=180° → chirp restored → $R_{56,Arc2}$ = -$R_{56,Arc1}$

$R_{56,Arc2}$ = $R_{56,Arc1}$ → inverted chirp → $\Delta\varphi$ with unbalanced beam loading

ERL Beam Dynamics: Linear Beam Optics

Linear Beam Optics

One stage ERL = Injector → Merger → Linac(acc) → Arc1 → Straight Section → Arc2 → Linac(dec) → Splitter → Dumpline

Injectionline / Merger / Splitter /Dumpline:

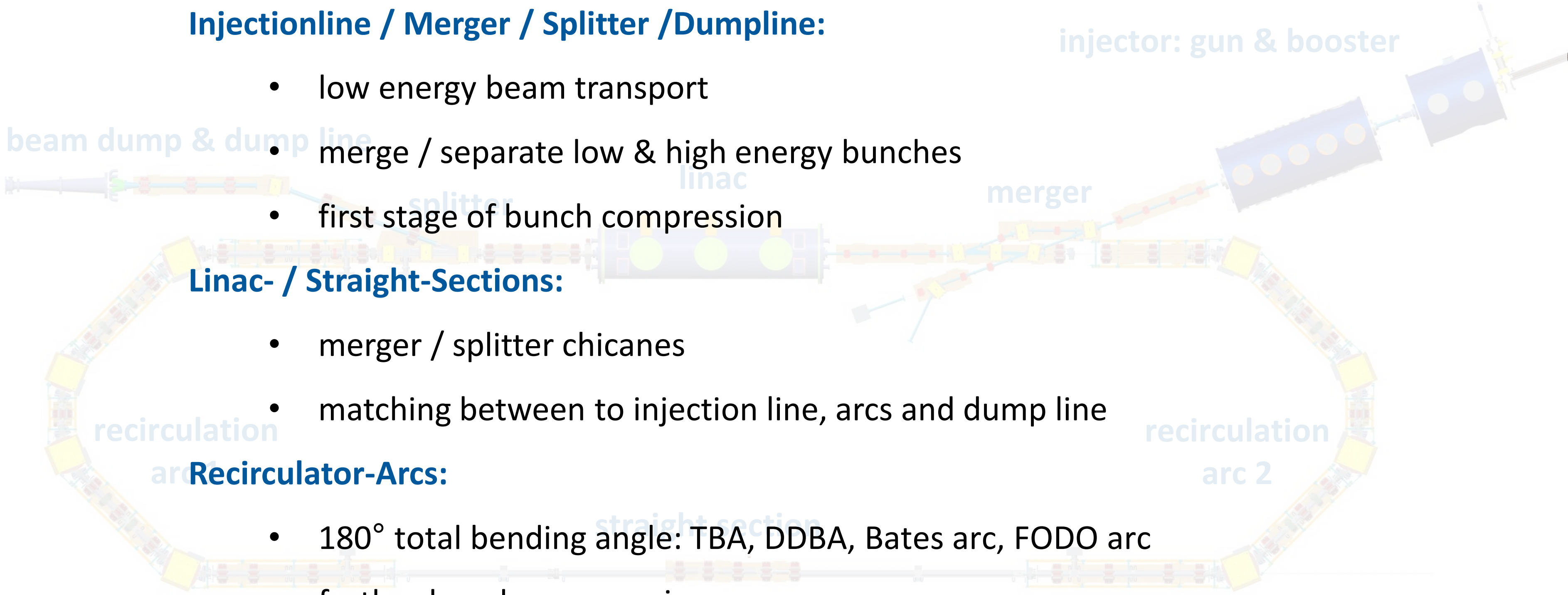
- low energy beam transport
- merge / separate low & high energy bunches
- first stage of bunch compression

Linac- / Straight-Sections:

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

Recirculator-Arcs:

- 180° total bending angle: TBA, DDBA, Bates arc, FODO arc
- further bunch compression

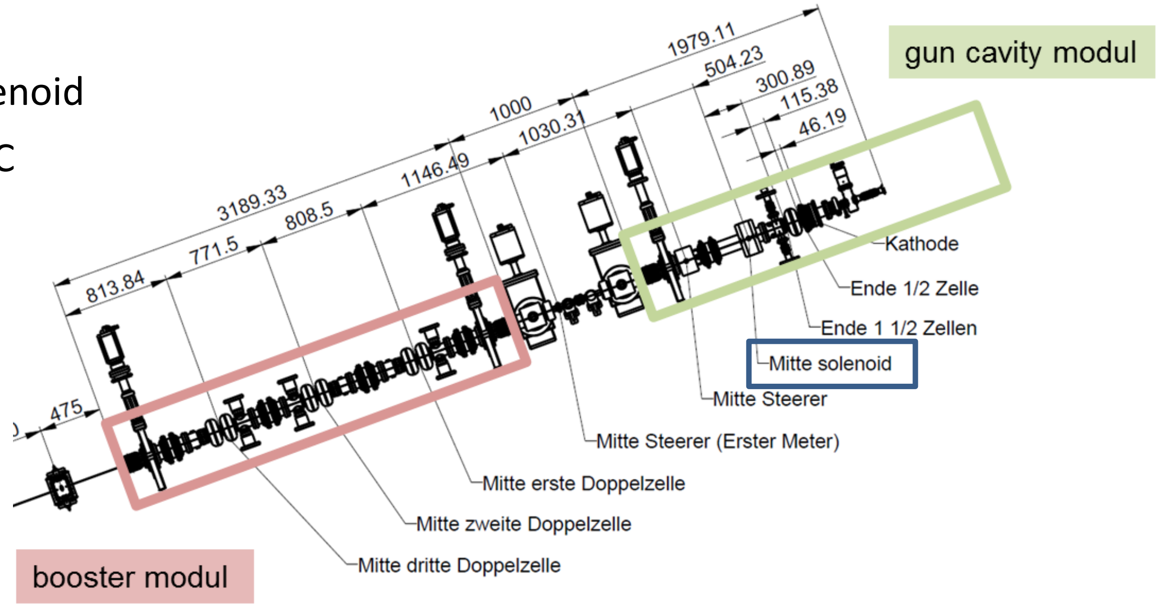


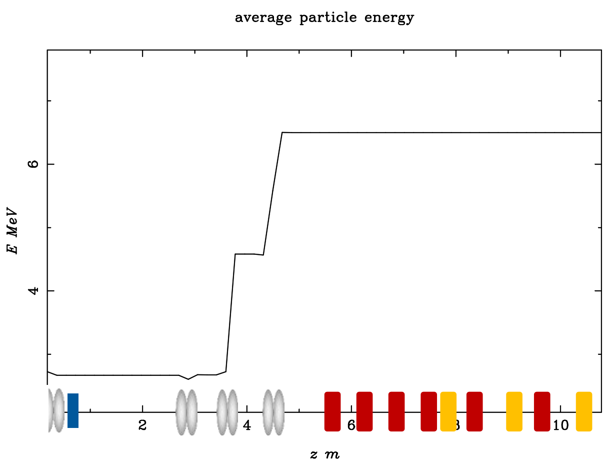
next: some design aspects on the example of bERLinPro

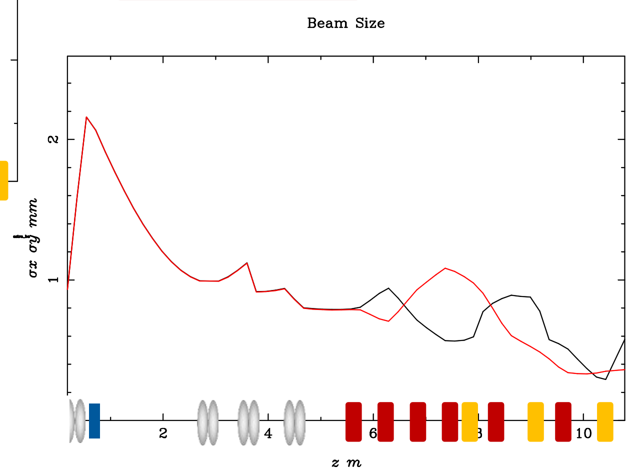
ERL Beam Dynamics: Linear Beam Optics

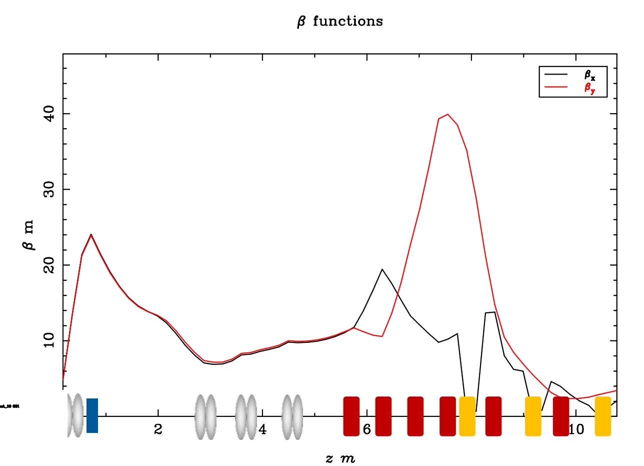
Linear Beam Optics: **Injector**

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





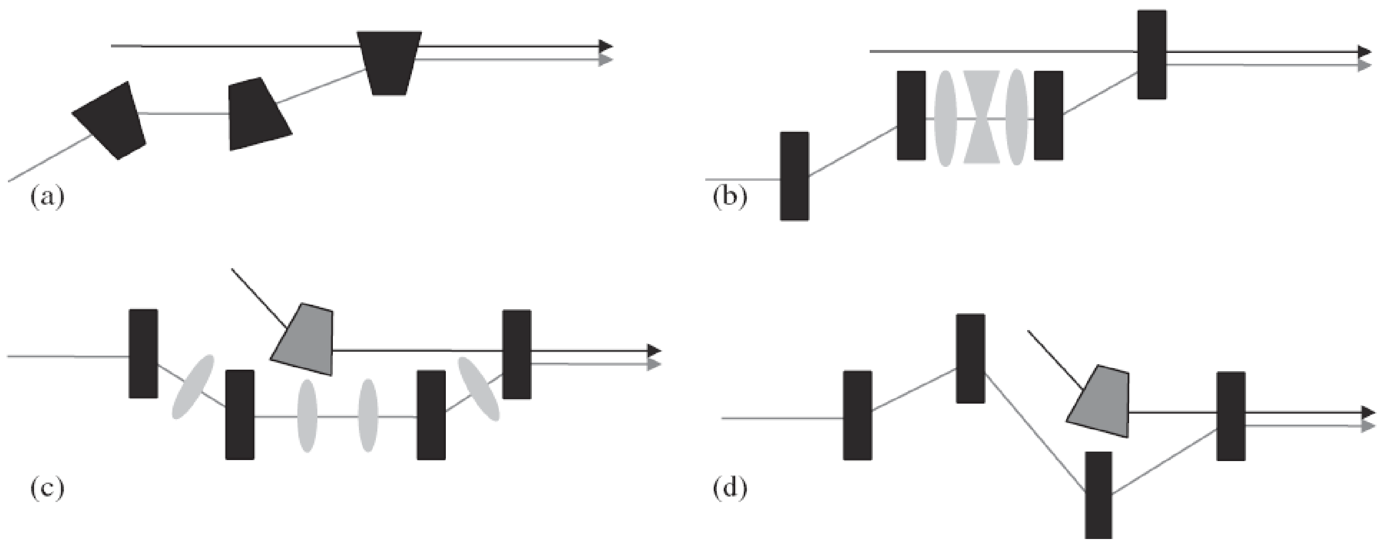




- emittance: $\varepsilon_{n,xy}$ ~1 mm mrad

Linear Beam Optics: **Merger**

R. Hajima / Nuclear Instruments and Methods in Physics Research A 557 (2006) 45–50



design considerations:

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

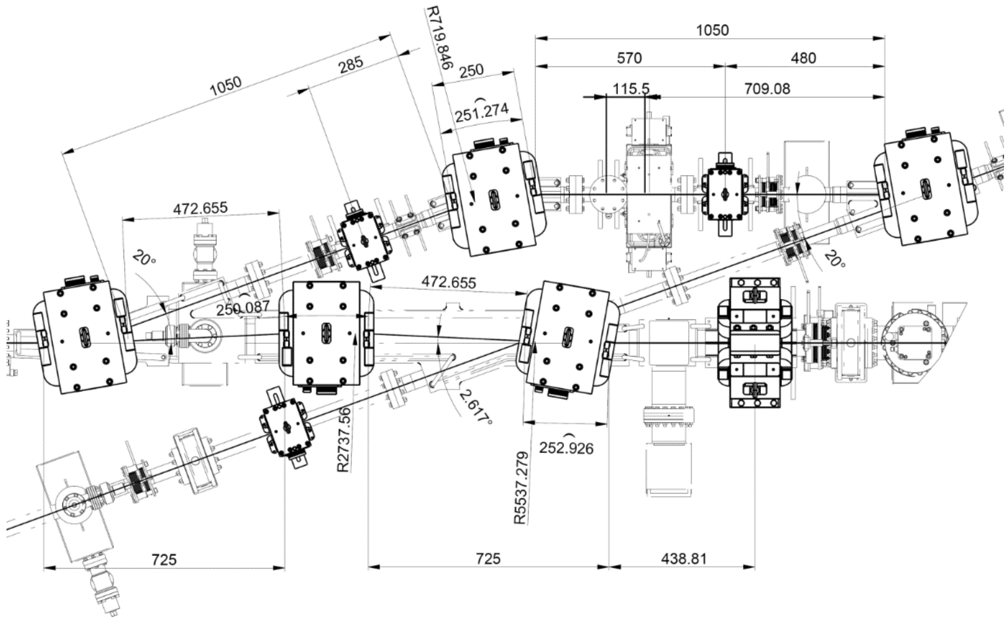
Mergers for existing and proposed ERLs:

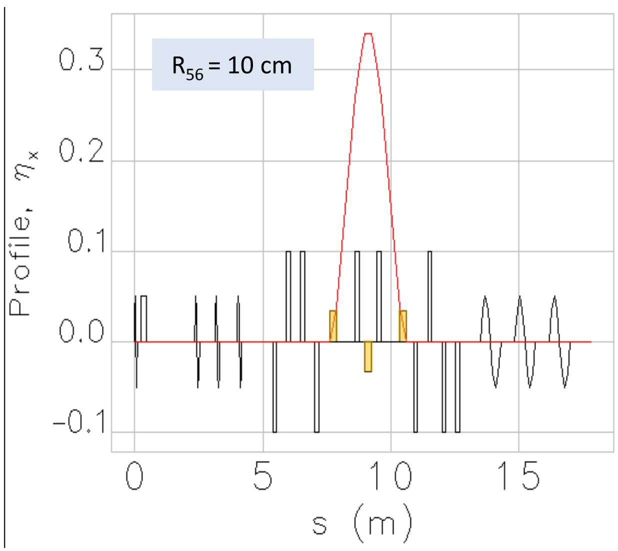
- **(a) JLAB IR-demo, IR-upgrade, Cornell ERL, Daresbury ERLP**
- **(b) JAERI-ERL**
- **(c) BINP-ERL**
- **(d) BNL-ERL (proposed)**

Linear Beam Optics: **Merger**

- beam dynamics dominated by SC
  - → emittance compensation continued
  - → beam transport in dispersive section: ε–growth
- first stage of compression
  - → rf curvature limits R_{56}

bERLinPro merger





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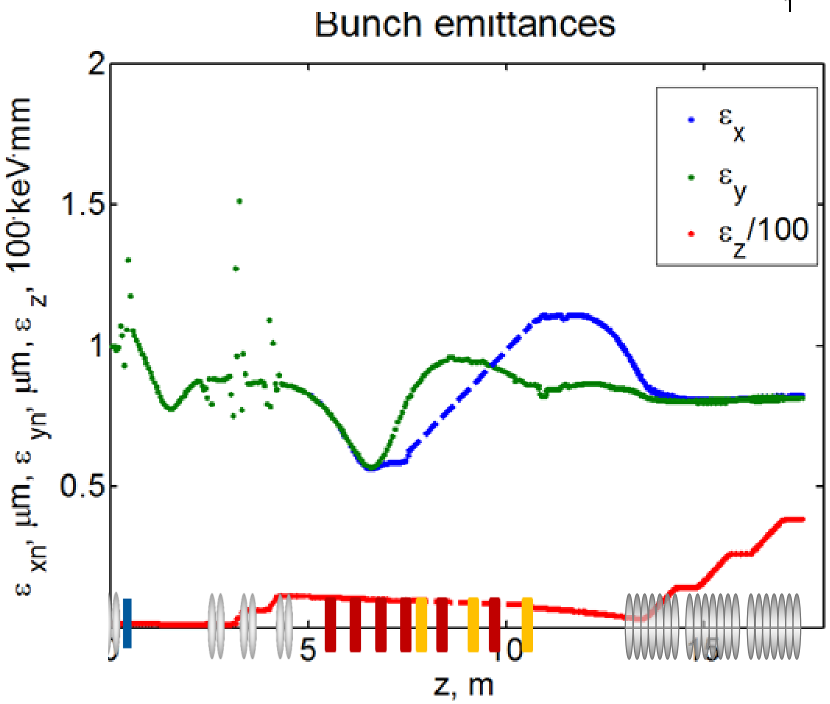
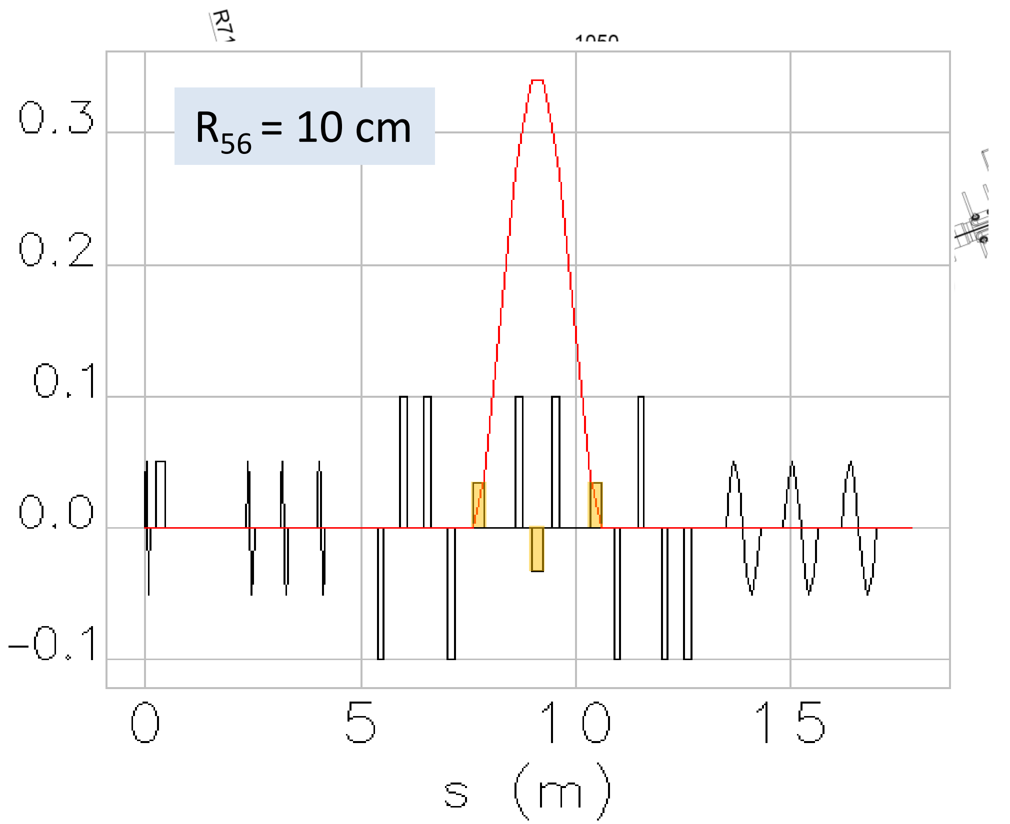


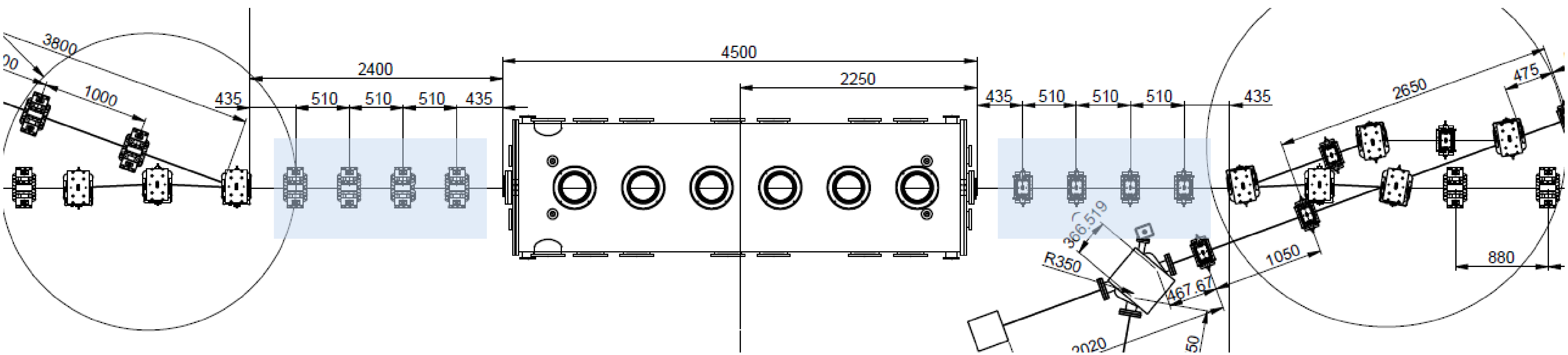
bERLinPro merger



ERL Beam Dynamics: Linear Beam Optics

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**

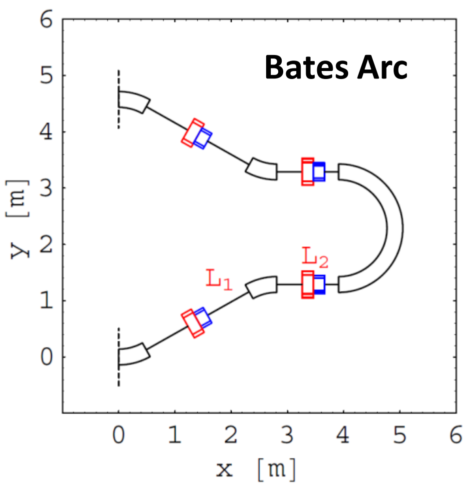
Arc Optics: various option also known from SR's

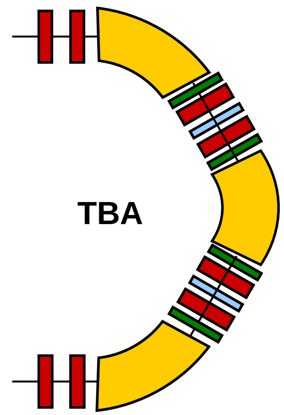
→ DBA, TBA, MBA (achromatic closed FODO)

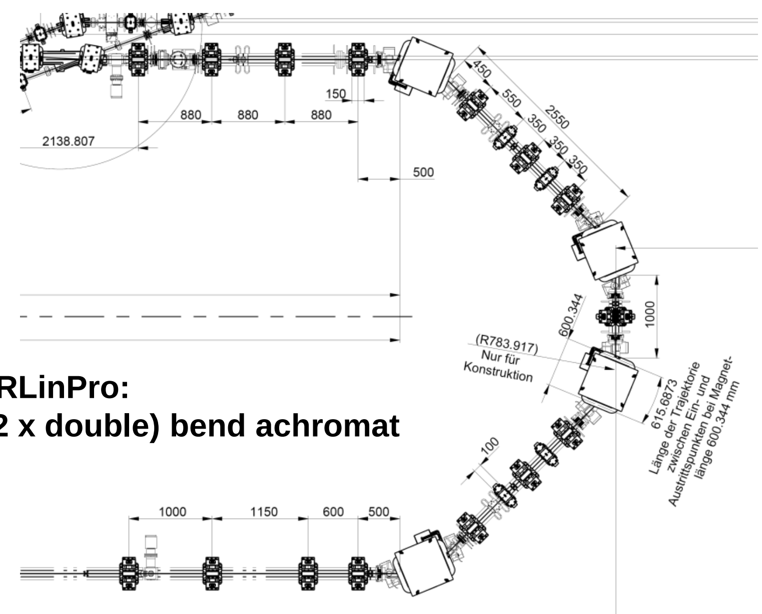
→ Bates Arc

design considerations:

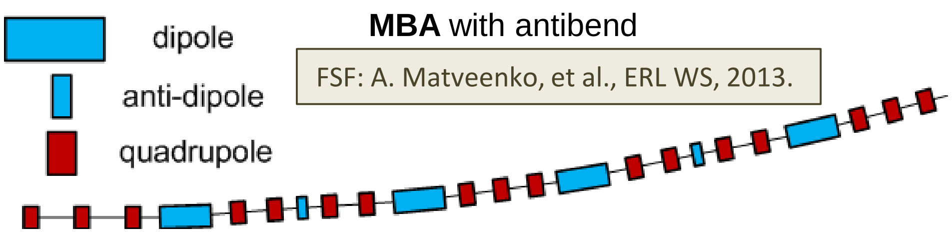
- length & hardware
- flexibility / tunability
- chromatic properties, R_{56} range
- ISR / CSR properties







bERLinPro:
4 (2 x double) bend achromat



MBA with antibend

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**

High transmission:

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

Variable R_{56}:

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

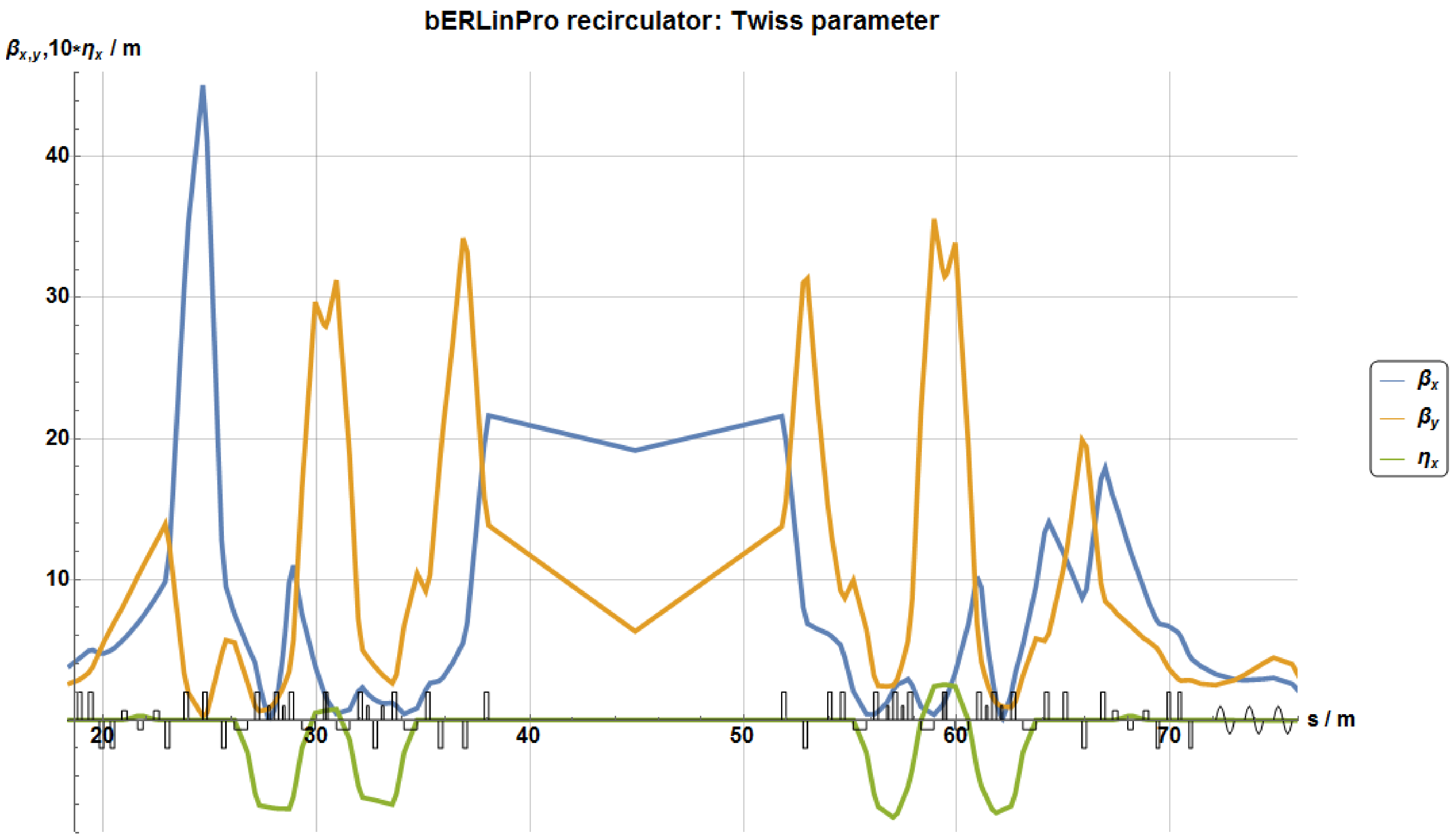
Betatron phase advance:

- minimize CSR induced emittance growth
- maximize BBU limited current threshold

difficult to meet all demands simultaneously in a small machine

ERL Beam Dynamics: Linear Beam Optics

Linear Beam Optics: **Recirculator**



Linear Beam Optics: **Dumpline**

safe disposal of the high power (MW range) beam !!!

long dumpline → vacuum: separation of outgassing dump ← → SRF Linac

beam transport into dump: minimize losses

- control β-functions: small in first part
- dogleg: dispersion closed out of it → symmetric beam with beam size decoupled from energy spread

dump high power beam: 650 kW needs to be distributed over dump surface

- static beam widening (strong increase of beta-function downstream the last quadrupole) or/and
- dynamic sweeping hor.-vert. steerer

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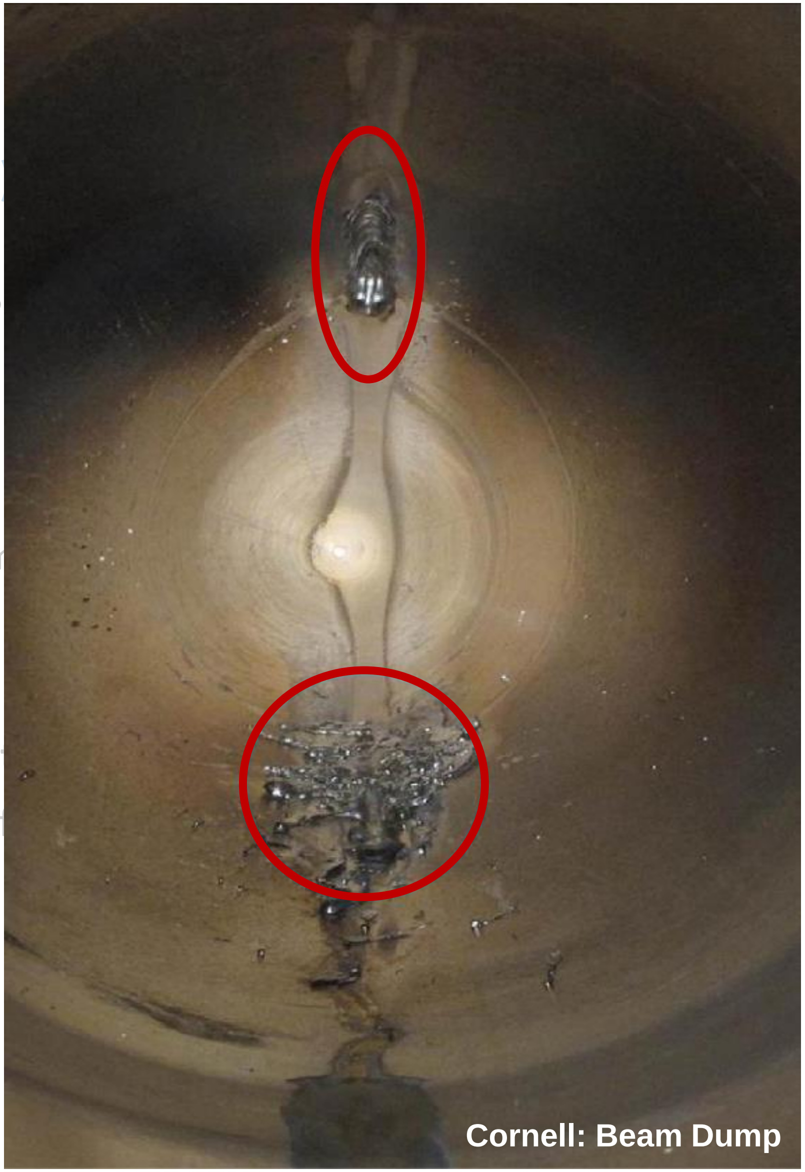
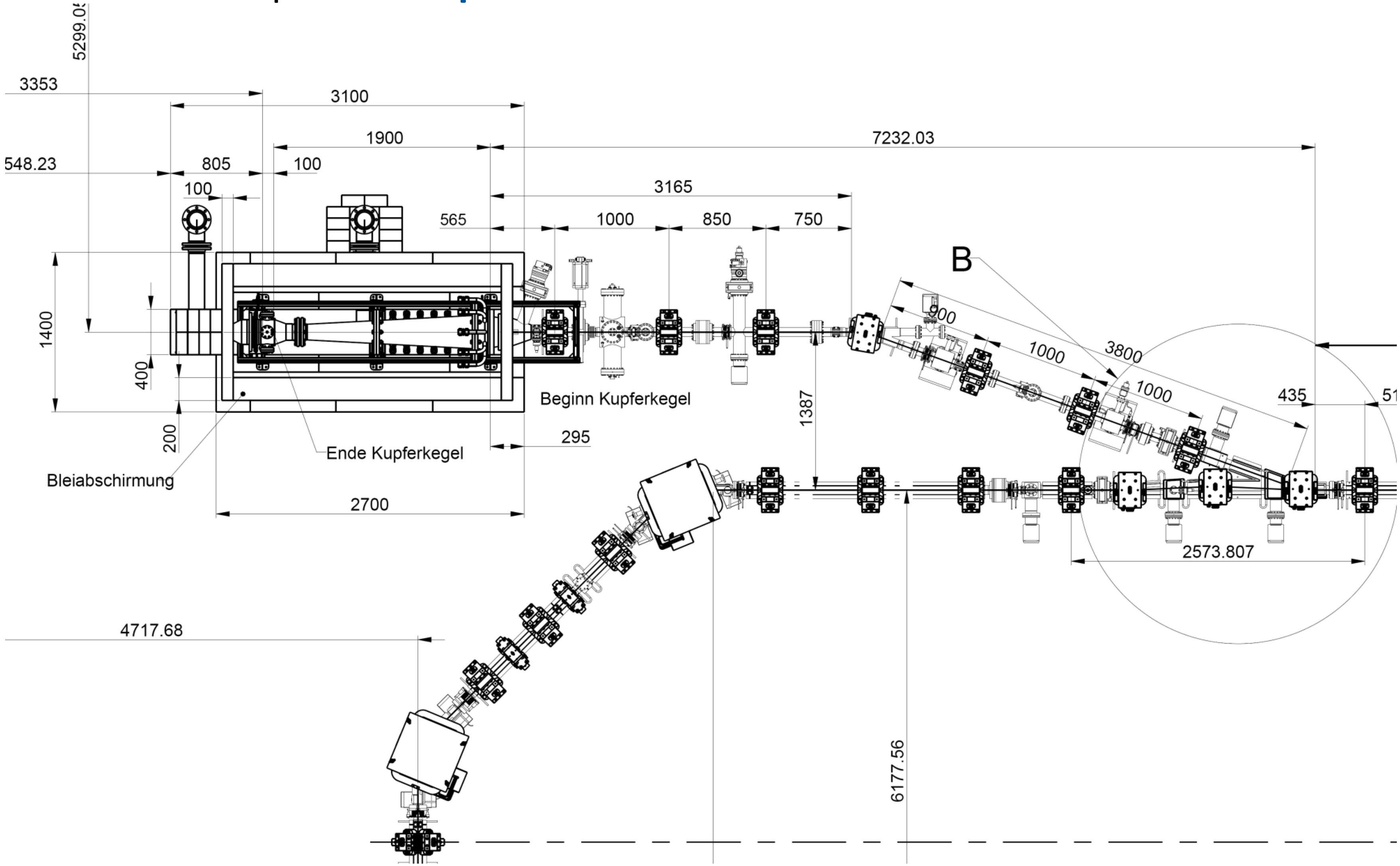
Xianghong Liu et al., "A High Average Power Beam Dump for an Electron Accelerator", Nuclear Instruments and Methods in Physics Research A 709 (2013) 37–43.

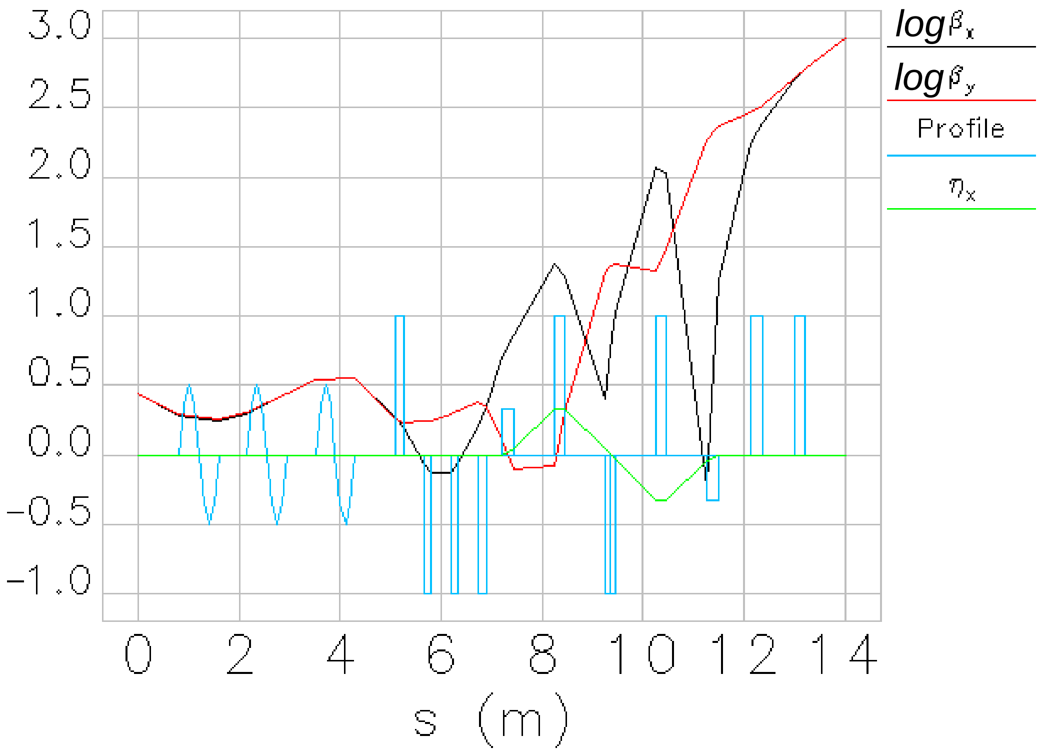


Linear Beam Optics: **Dumpline**



Linear Beam Optics: **Dumpline**

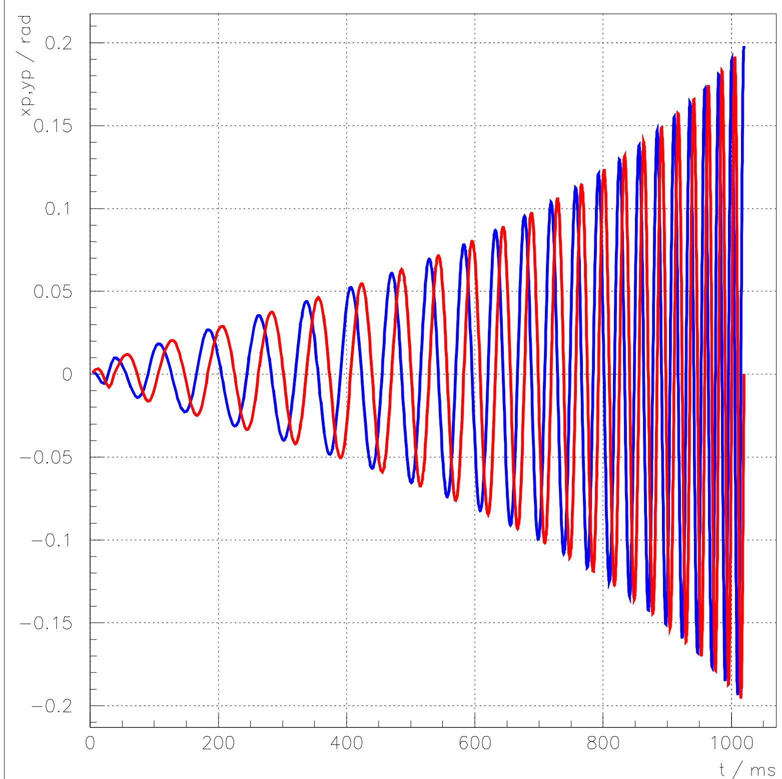
bERLinPro: Twissparameter Dump Line



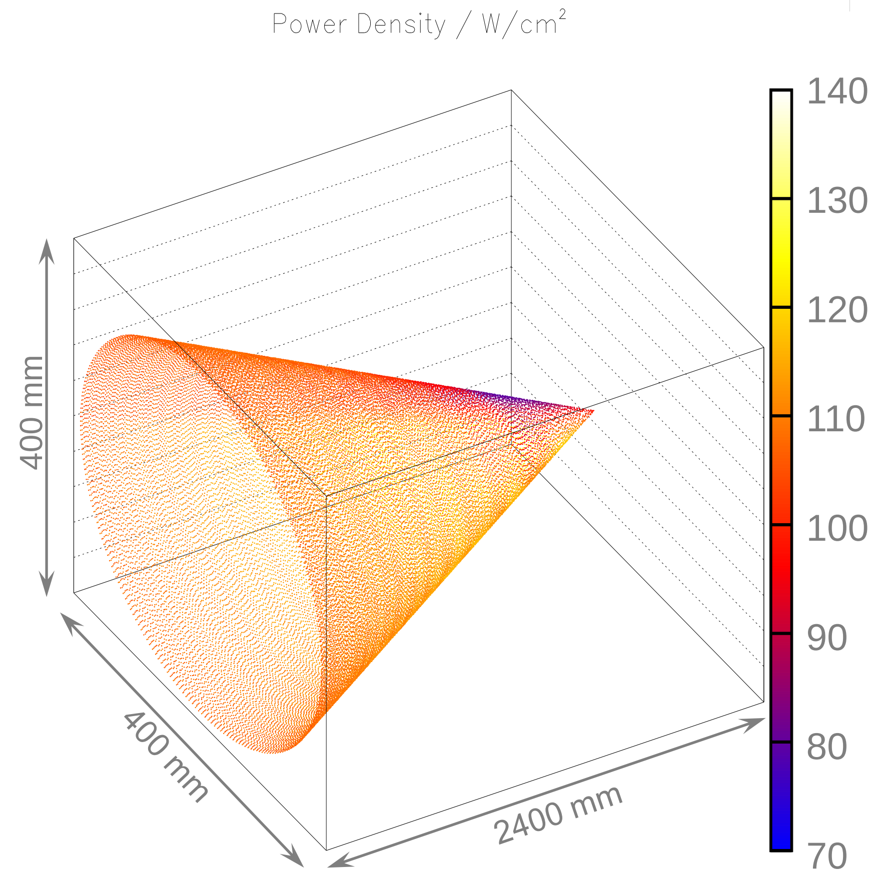
Inner copper conus of 650 kW high power dump (100 mA @ 6.5 MeV, bERLinPro)

Linear Beam Optics: **Dumpline**

bERLinPro simulations: distribution of beam power inside the dump



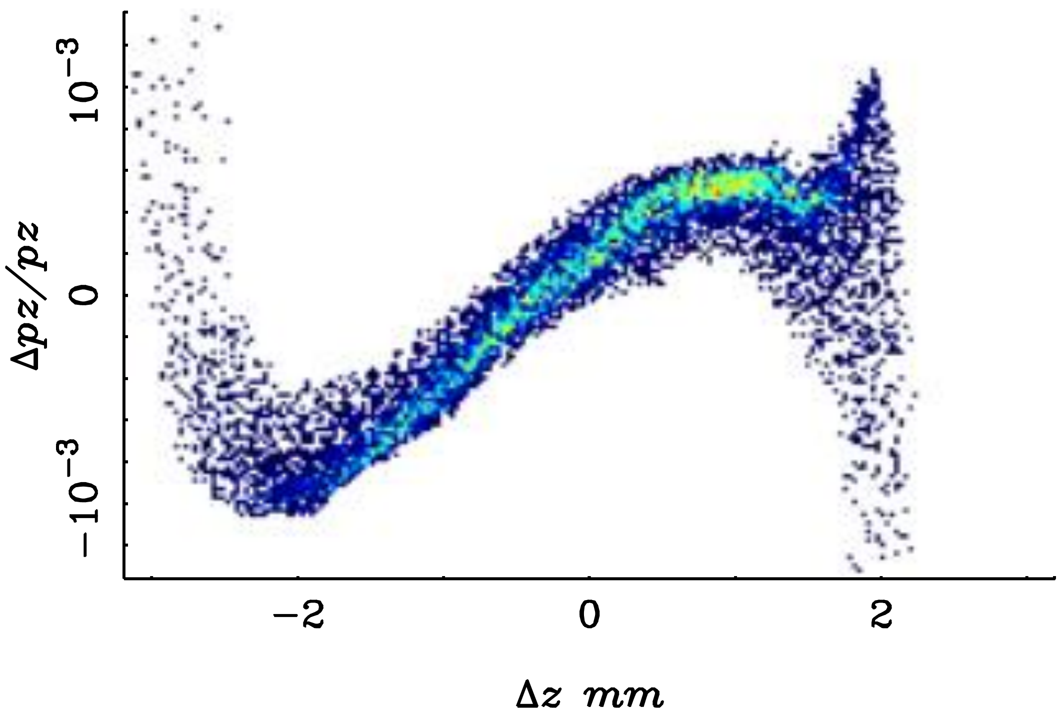
bERLinPro: transverse kick amplitude for beam "sweeping" over dump surface vs t



beam size inside dump: $\sigma_{x,y}(z)$ ~ 10…20 mm

Nonlinear Beam Optics:

- RF curvature: $E(t)=E_0 \cos(\omega t + \varphi_0)$



bERLinPro: long. phase space @ end of merger
including space charge effects too!

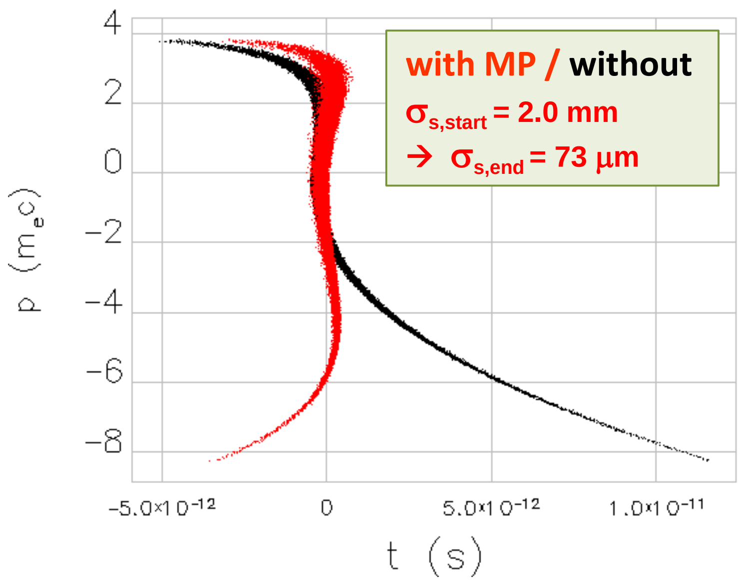
Nonlinear Beam Optics:

- RF curvature: $E(t)=E_0 \cos(\omega t + \varphi_0)$
- aberrations: geometric & chromatic

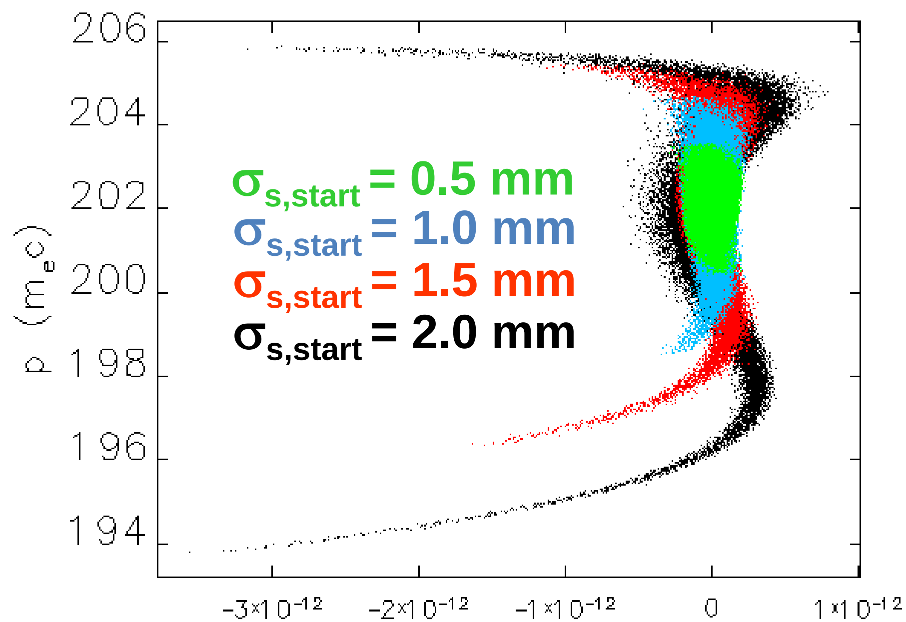
  caused and counteracted by nonlinear fields → multipole magnets

  Example: bunch compression $E(s_i) = E_0 \cos(s\, 2\pi/\lambda - \varphi_0)$ → $\delta_i = E(s_i)/E_0\cos(-\varphi_0)$

  $\Delta L_i = R_{56}\,\delta_i + T_{566}\,\delta_i^2 + U_{5666}\,\delta_i^3 + \ \ldots$



bERLinPro recirculator test: bunch compression with varying initial bunch length; linac phase, sextupole and octupole magnets optimized



ERL Beam Dynamics: Nonlinear Beam Optics

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: high current, emittance ≤ 1 mm mrad, σ_t = 2 ps

- sextupoles in first arc → counteract chromatic effects causing emittance growth
- sextupoles in second arc → reproduce longitudinal phase space to minimize energy spread of decelerated beam

Short pulse mode: $\sigma_t \leq$ 100 fs @ reduced current & degraded emittance

- sextupoles in first arc → linearize long. phase space and optimize T_{566}
- sextupoles in second arc → reproduce long. phase for deceleration (like in LEM)

optimization procedure:

1. analytical for bunch compression in SPM:

$$\delta(s) = E(s)/E_0 \cos(-\varphi_0) \rightarrow f^{-1}(\delta(s)) = s(\delta) = a_1\delta + a_2\delta^2 + a_3\delta^3 + \dots$$

beam transport in arc: $\Delta L = R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 + \dots$

full compression: $s(\delta) + \Delta L = 0$ → set: $R_{56} = -a_1$, $T_{566} = -a_2$, ...

2. **numerical optimization: Elegant → minimize goal function from tracked bunch: ε or σ_s**

Collective Effects:

- Space Charge
- Coherent Synchrotron Radiation
- Geometric Wakes

in general: interaction of wake fields with bunch

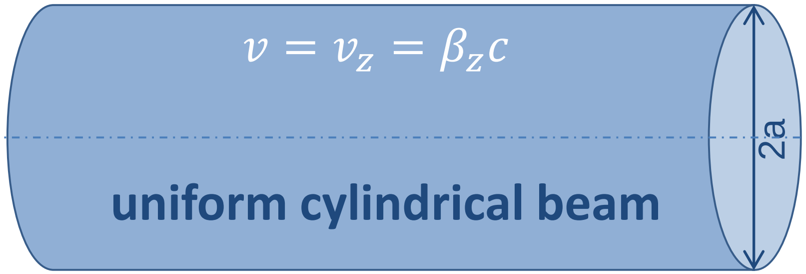
wake fields: co-propagating EM-Fields, generated by the bunch itself
or by preceding bunches

→ spatial depending forces over the bunch → degradation of beam quality

other relevant wake fields: resistive wall, surface roughness

Space Charge Forces

$$\rho = \frac{I}{\pi\, a^2\, v}$$



$$J = \frac{I}{\pi\, a^2}$$

$$\frac{1}{\mu_0\, \epsilon_0} = c^2$$

Gauss' law:

r ≤ a: $$E_r(r) = \frac{1}{r\, \epsilon_0} \int_0^r \rho(r')\, r'\, dr'$$

repulsive / defocusing

Ampere's law:

$$B_\theta(r) = \frac{\mu_0\, \beta_z c}{r} \int_0^r \rho(r')\, r' dr' = \frac{\beta_z}{c}\, E_r(r)$$

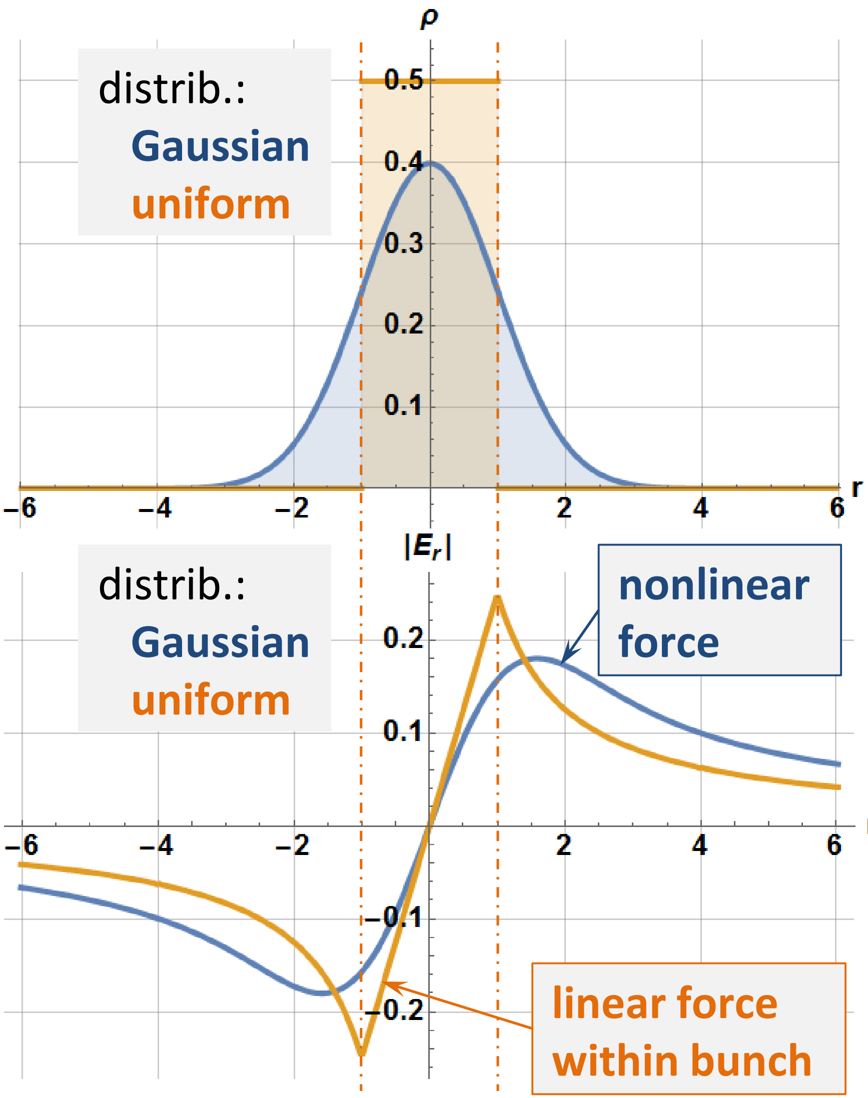
attractive / focusing

Lorentz-Force: $$\boldsymbol{F_r = e\, E_r - e\, v_z \times B_\theta = e\,(1 - \beta^2)E_r = \frac{e\, E_r}{\gamma^2}} \qquad (\beta \sim \beta_z)$$

at high energies (β ~ 1) → repulsive electric forces are compensated by attractive magnetic ones

at low energies (β < 1) → dominating repulsive electric forces → strongly defocusing

Space Charge Forces



equation of motion in free space with SC:

$$\frac{dp_r}{dt} = m_0\gamma \frac{d^2r}{dt^2} = F_r$$

uniform density distribution:

$$m_0\gamma \frac{d^2r}{dt^2} = m_0\gamma\,\beta^2c^2\frac{d^2r}{dz^2} = \frac{e\,E_r}{\gamma^2}$$

$$E_r(r) = \frac{1}{r\,\varepsilon_0}\int_0^r \rho(r')\,r'dr' = \frac{I}{2\pi\epsilon_0\beta c a^2}\,r$$

$$\rightarrow\; r'' - \underbrace{\frac{e\,I}{2\pi\epsilon_0 m_0 c^3\beta^3\gamma^3}}_{\text{perveance K}}\frac{1}{a^2}r = 0$$

with ext. focusing $\kappa(s)$

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

SC → additional focusing (quadrupole magnets)
storage rings: cause for current dep. tune shift

Space Charge Effects in ERLs

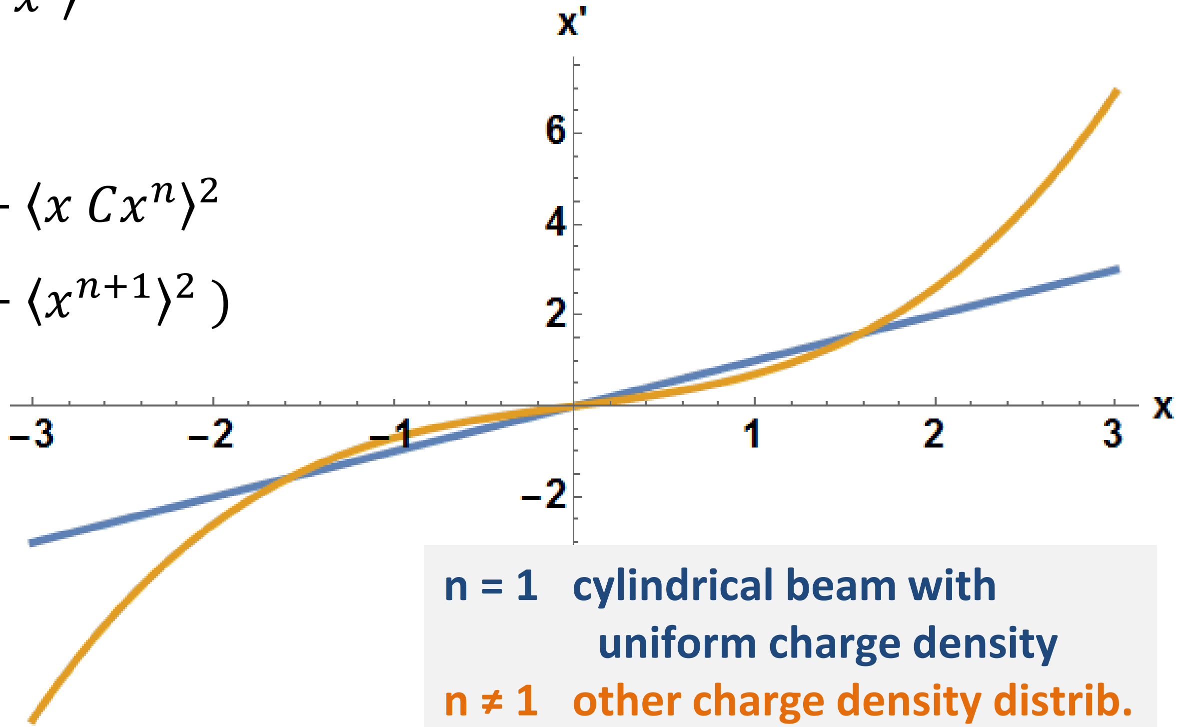
- (moderate) tune shift: minor issue in single pass devices like ERLs
- **emittance growth**
  - nonlinear SC forces → phase space nonlinearities (x-x’, y-y’, t-p)

$$\varepsilon_{x,rms}^2 = \langle x^2\rangle\langle x'^2\rangle - \langle x\, x'\rangle^2$$

$$x' = C\, x^n$$

$$\varepsilon_{x,rms}^2 = \langle x^2\rangle\langle C^2 x^{2n}\rangle - \langle x\, C x^n\rangle^2$$

$$= C^2 \left(\langle x^2\rangle\langle x^{2n}\rangle - \langle x^{n+1}\rangle^2 \right)$$



$$\boldsymbol{n = 1 \quad \rightarrow \quad \varepsilon_{x,rms}^2 = 0}$$

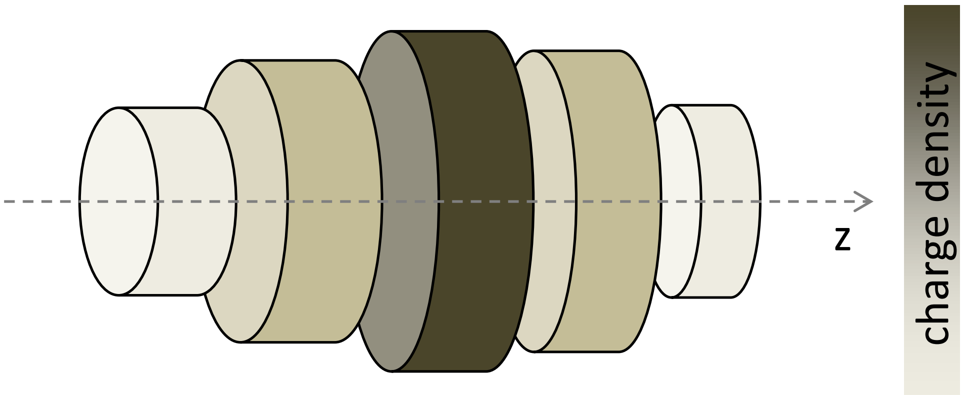
$$\boldsymbol{n \neq 1 \quad \rightarrow \quad \varepsilon_{x,rms}^2 \neq 0}$$

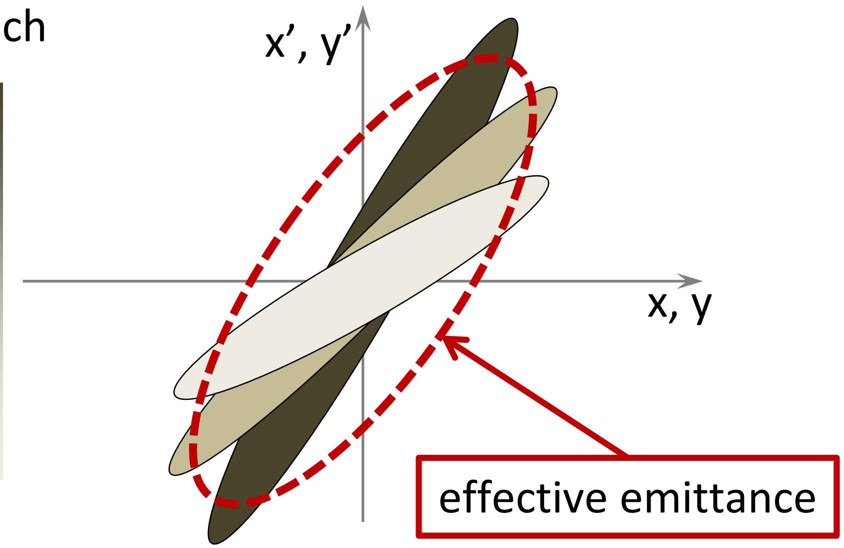
n = 1 cylindrical beam with uniform charge density

n ≠ 1 other charge density distrib. e.g. Gaussian

Space Charge 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**

$$\boldsymbol{r'' + [\kappa - K/a^2]\, r = 0}$$

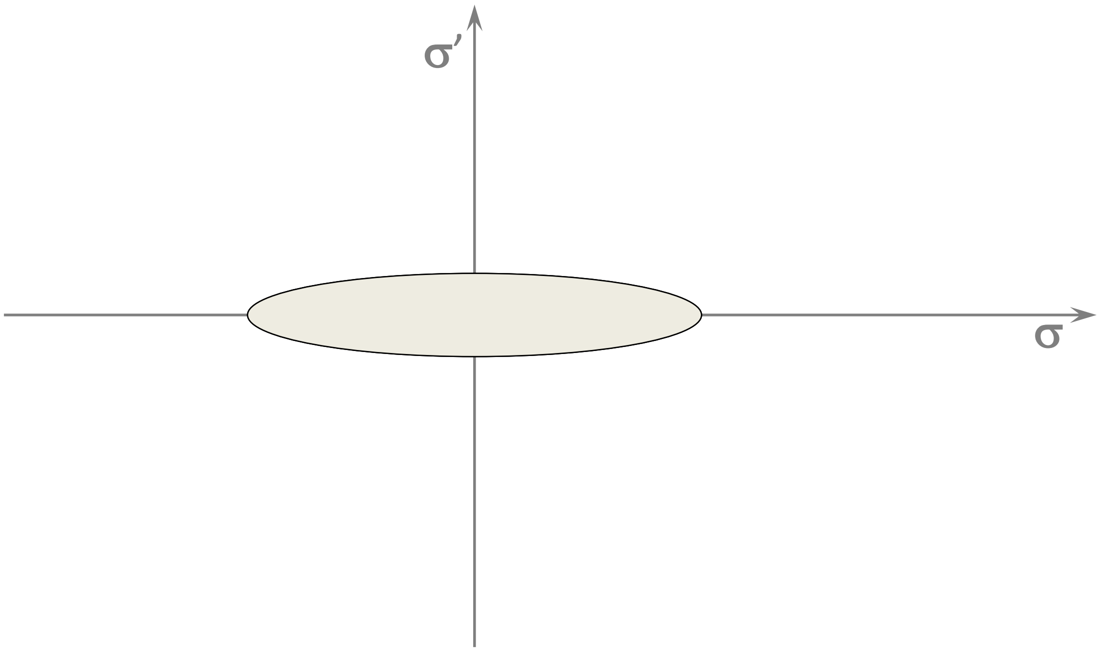
transverse slice sizes oscillate around an "reference" value
(e.g. the "invariant envelope")
→ **increase of effective (proj.) emittance**

Space Charge Effects: Emittance Compensation

paraxial beam of cylindrical symmetry and uniform charge density: envelope equation

$$\sigma'' + \sigma'\left(\frac{\gamma'}{\beta^2\gamma}\right) + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\epsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0,$$

acc. term **emit. term**



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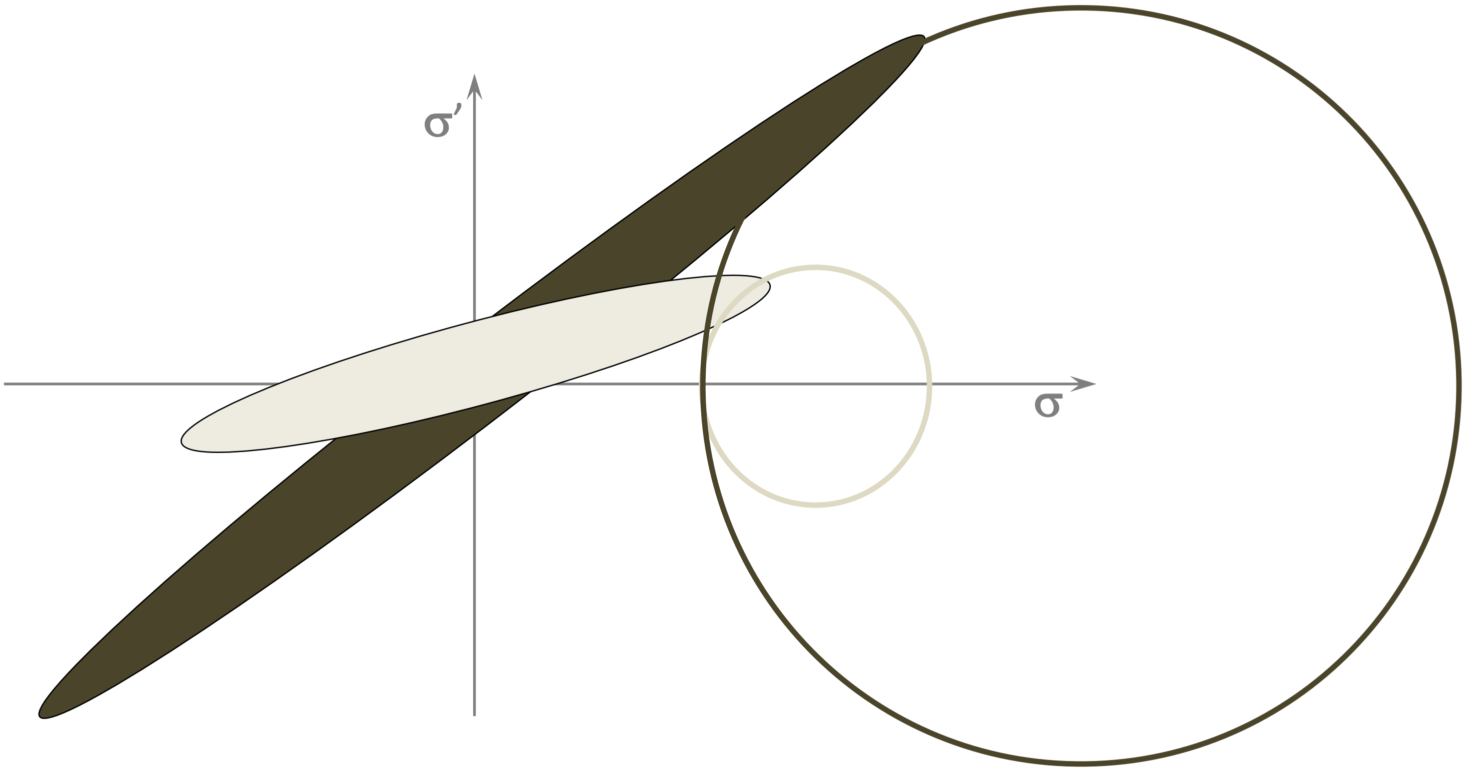
$$\sigma'' + \sigma'\left(\frac{\gamma'}{\beta^2\gamma}\right) + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\epsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0,$$

acc. term **emit. term**



Space Charge Effects: Emittance Compensation

paraxial beam of cylindrical symmetry and uniform charge density: envelope equation

$$\sigma'' + \sigma'\left(\frac{\gamma'}{\beta^2\gamma}\right) + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\epsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0,$$

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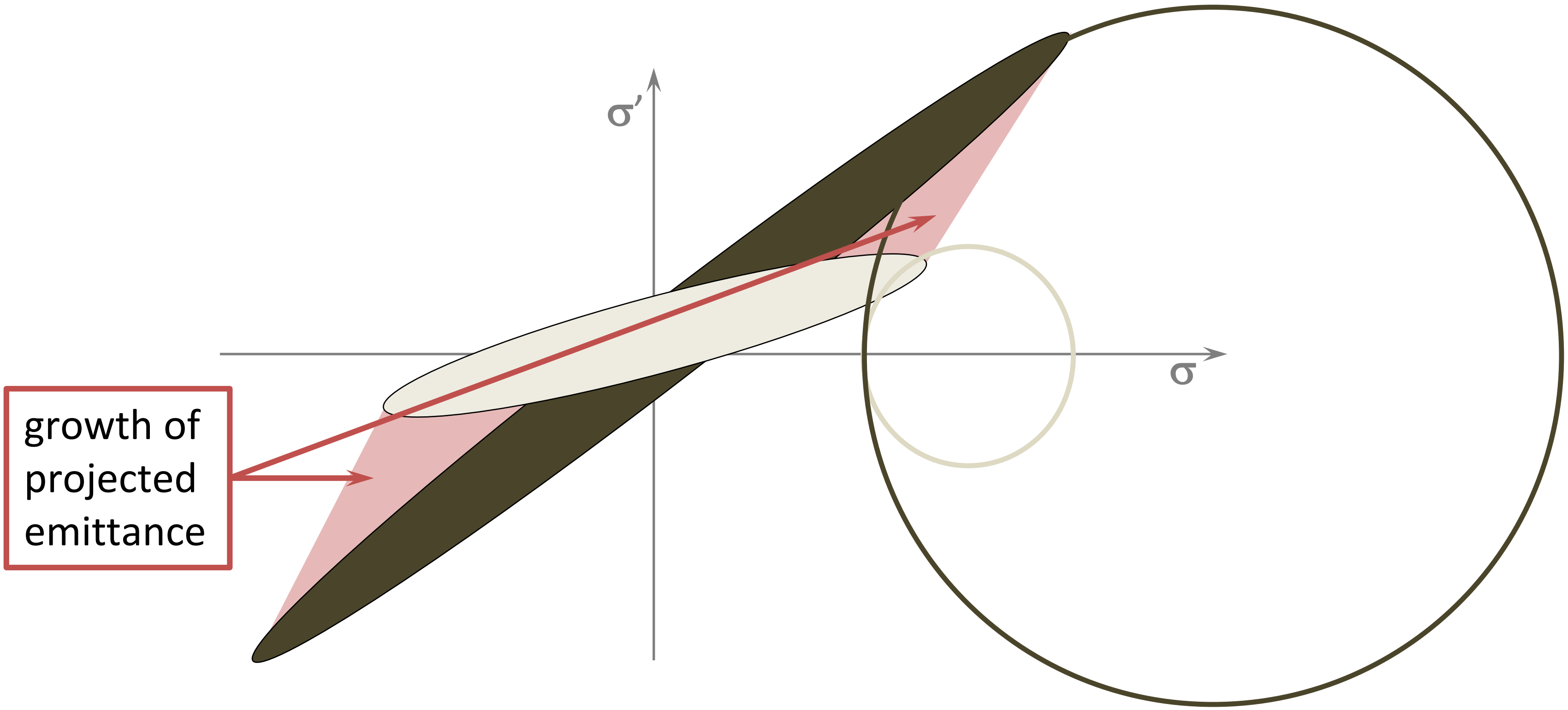

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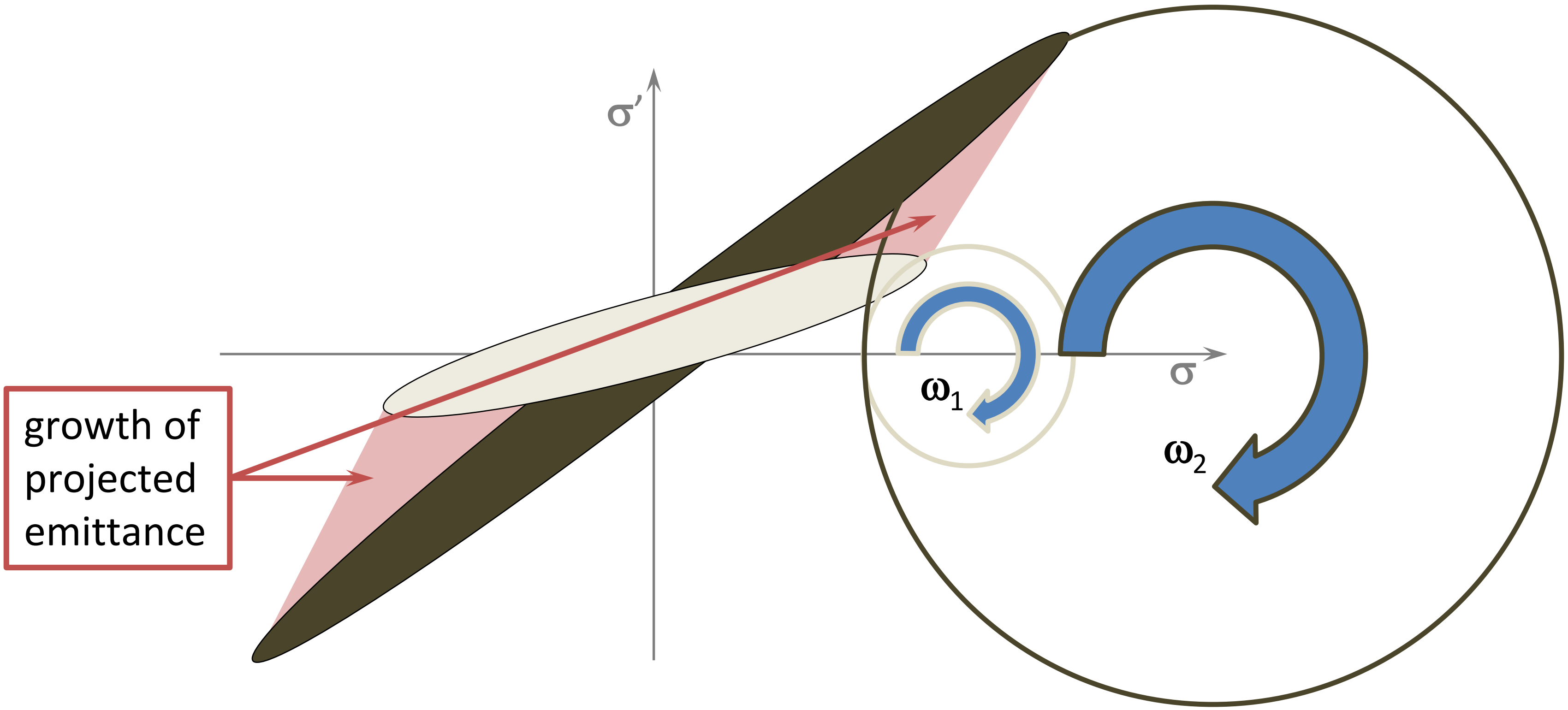

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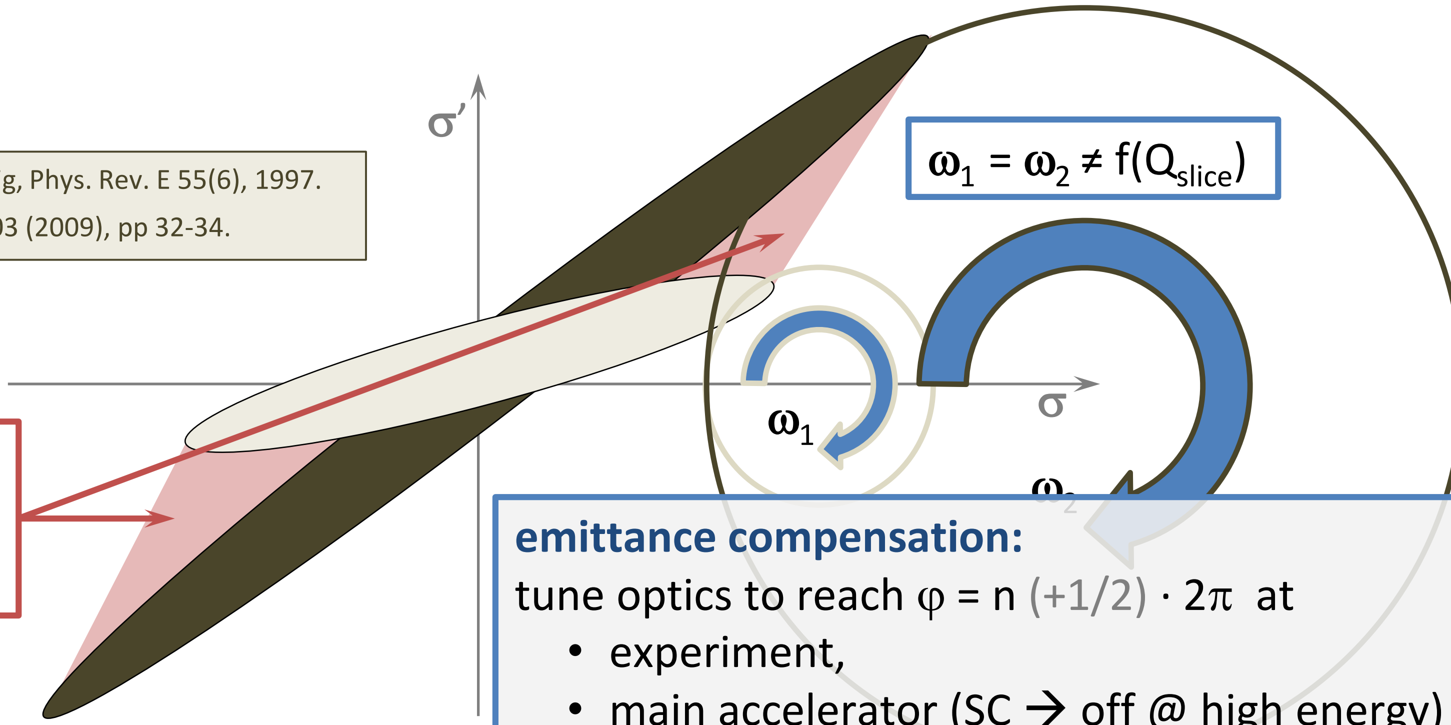
acc. term **emit. term**

L. Serafini, J. Rosenzweig, Phys. Rev. E 55(6), 1997.
S.V. Miginsky, NIM A 603 (2009), pp 32-34.



growth of projected emittance

emittance compensation:
tune optics to reach φ = n (+1/2) · 2π at
- experiment,
- main accelerator (SC → off @ high energy) or
- transition SC → emittance dominated beam

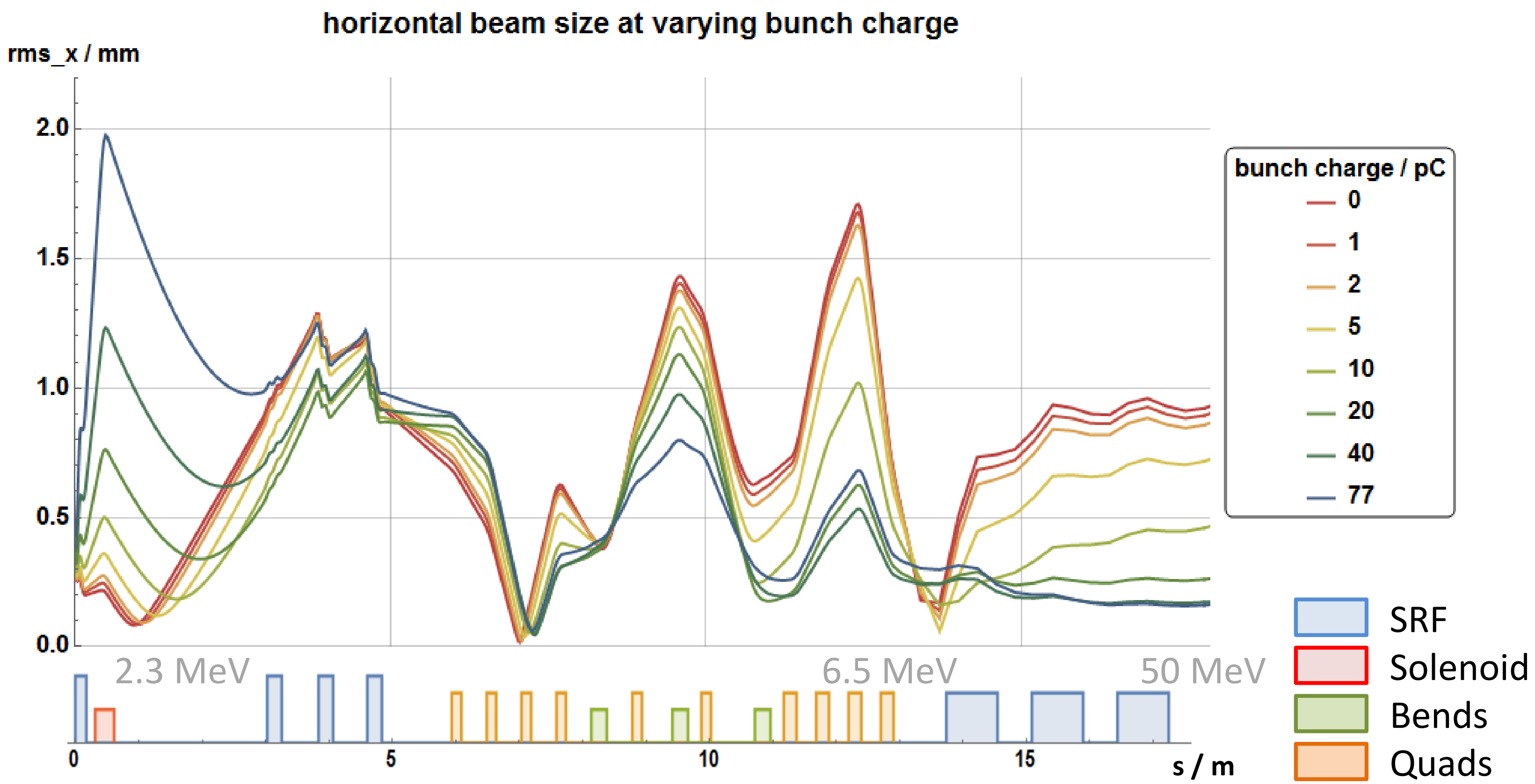
Space Charge Effects: Emittance Compensation

simulation codes for SC dominated beam transport:

ASTRA, Parmela, OPAL, GPT, HOMDYN, SCO (AM's space charge optimizer?)…

Example of SC dominated beam line with applied emittance compensation:

OPAL simulations of the bERLinPro Injector:



Space Charge Effects: Emittance Compensation

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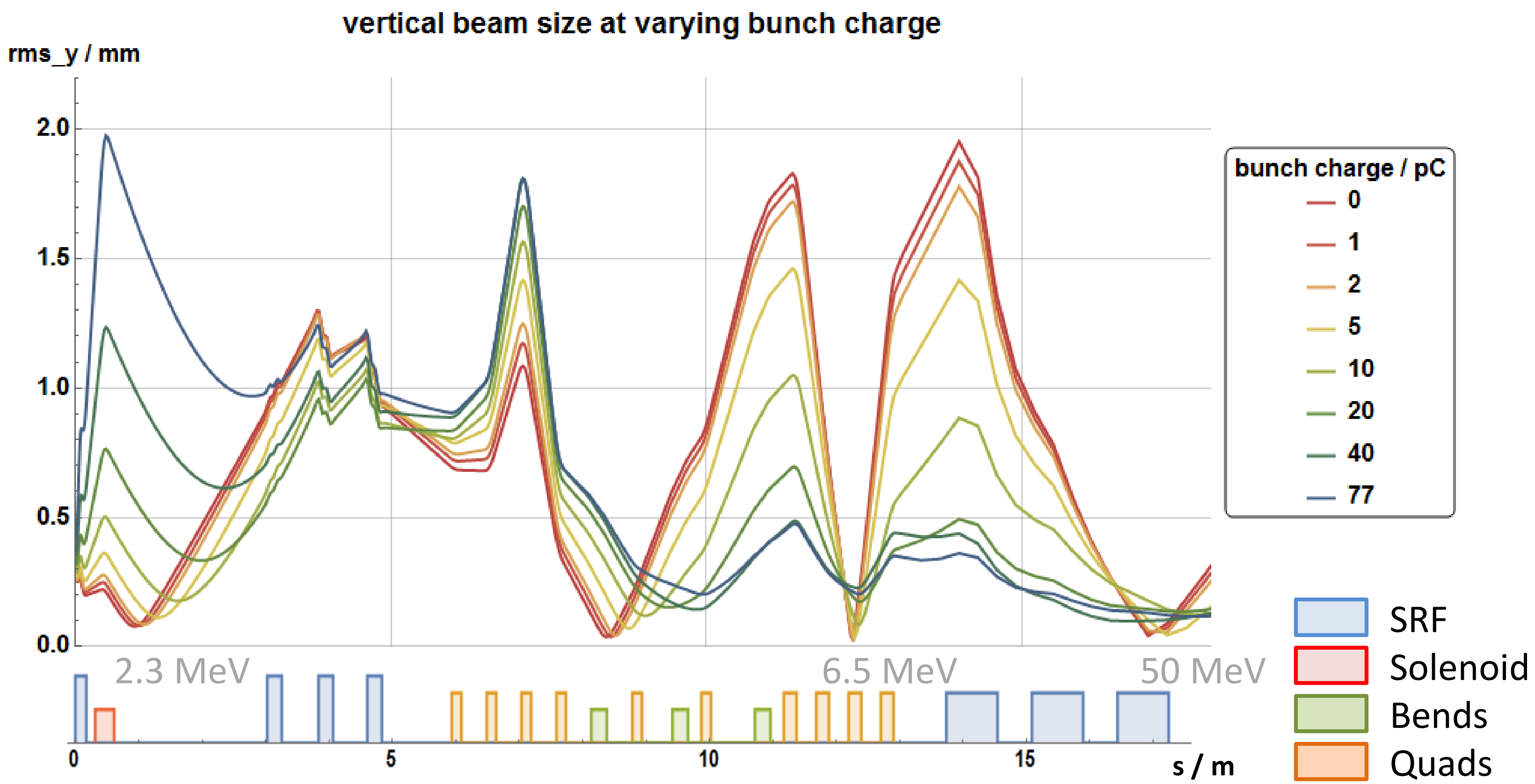
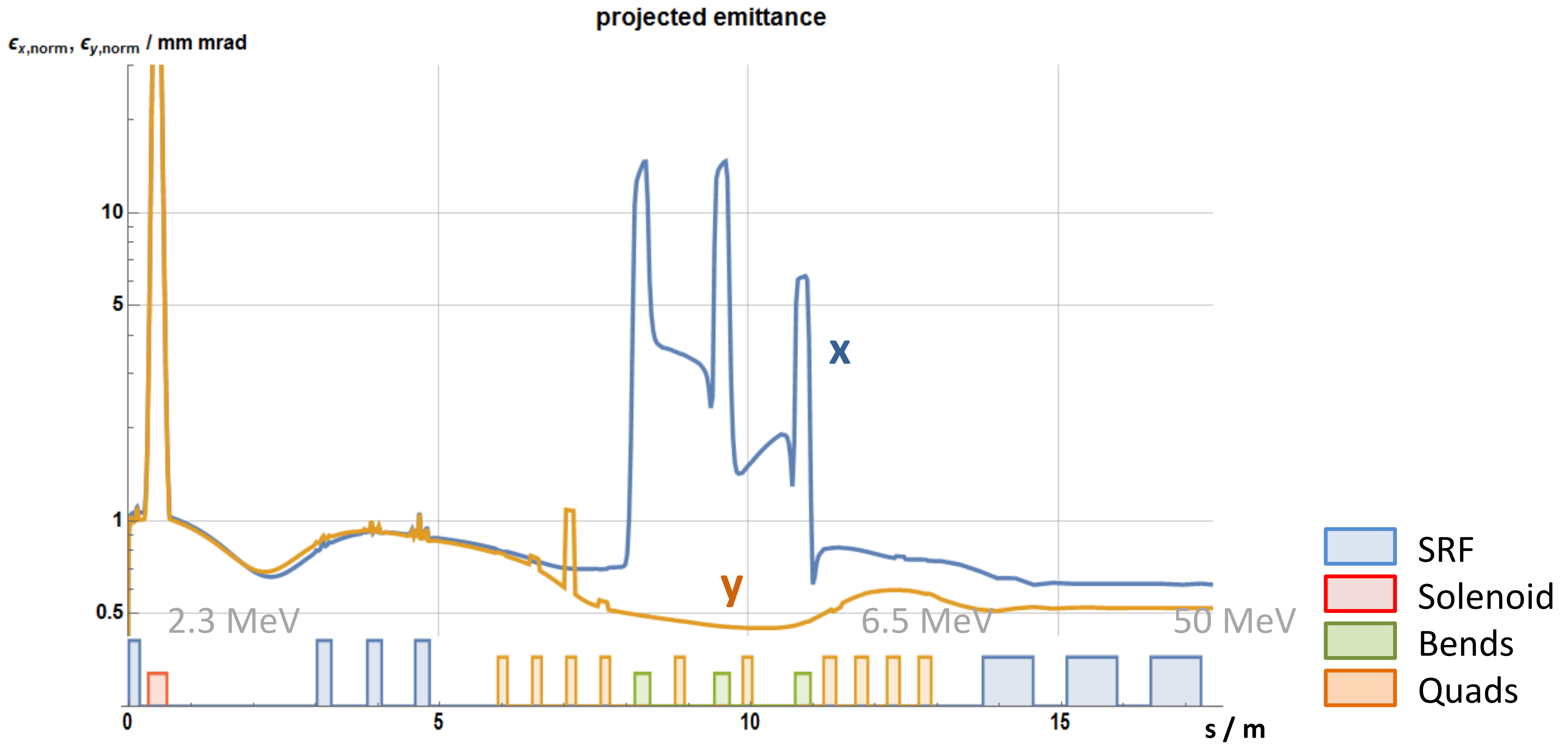


ERL Beam Dynamics: Collective Effects

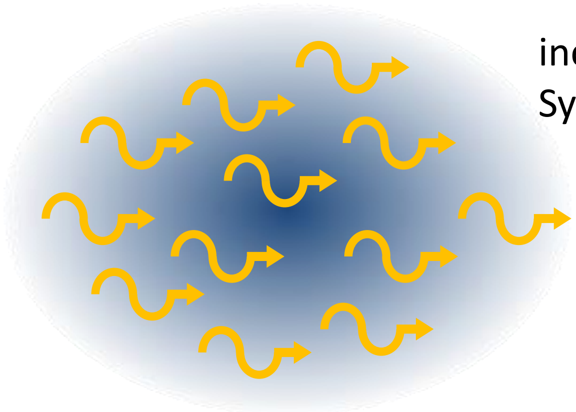
Space Charge Effects: Emittance Compensation

OPAL simulations of the bERLinPro Injector:



Only a small part of SC effects introduced here!
Not mentioned: long. SC, SC effects in ERL beam mergers, ...

Coherent Synchrotron Radiation:



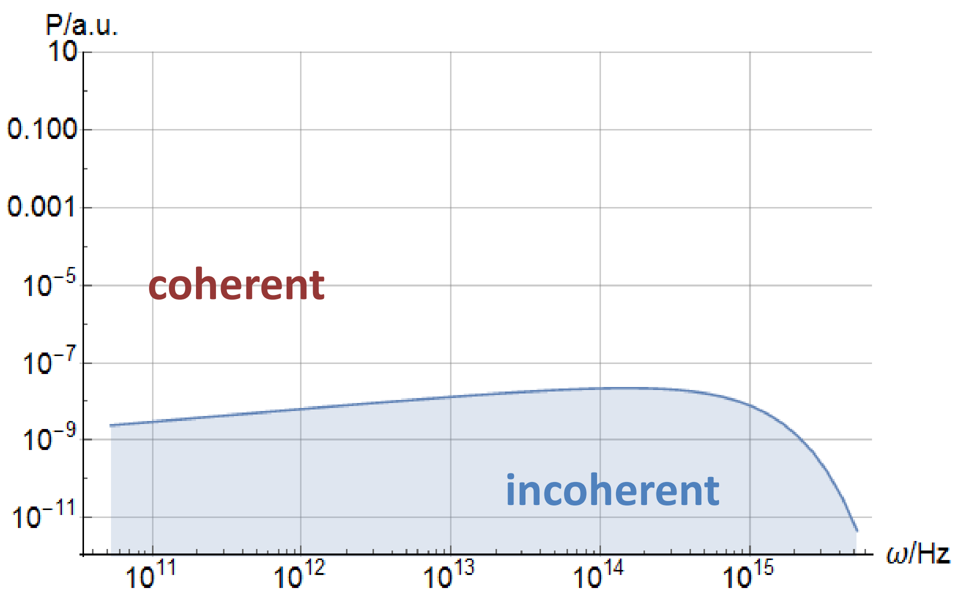
incoherent emission of Synchrotron Radiation

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

coherent emission of Synchrotron Radiation

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

$$\frac{dP}{d\omega} = P_0(\omega)\, N_e \left(1 + (N_e - 1)\, g^2(\sigma_s, \omega)\right)$$

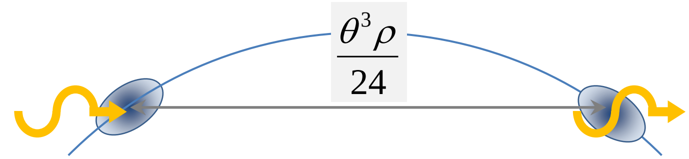


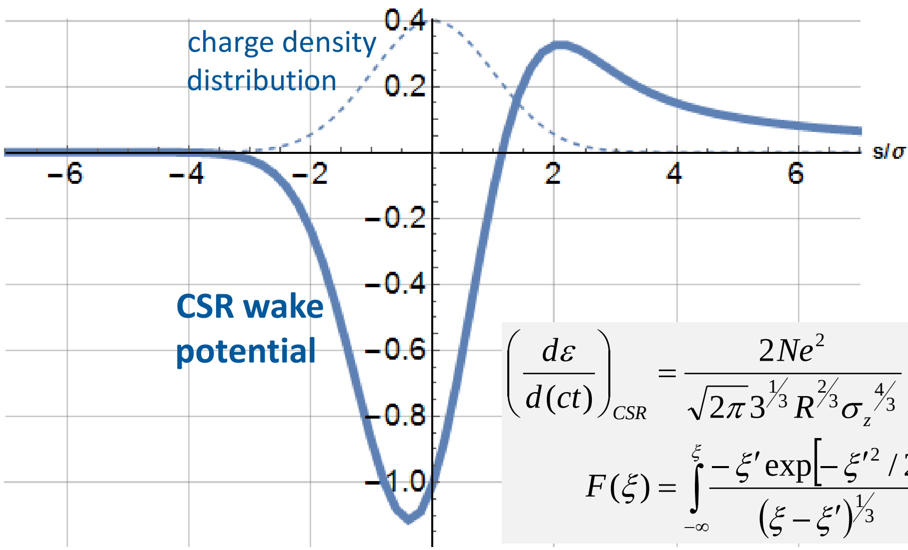
g: form factor

$$g(\sigma_s, \omega) = F(\lambda(\sigma_s, t))$$

$$g^2(\sigma_s, \omega) = \exp\left[-2\pi^2 \left(\frac{\omega \sigma_s}{2\pi c}\right)^2\right]$$

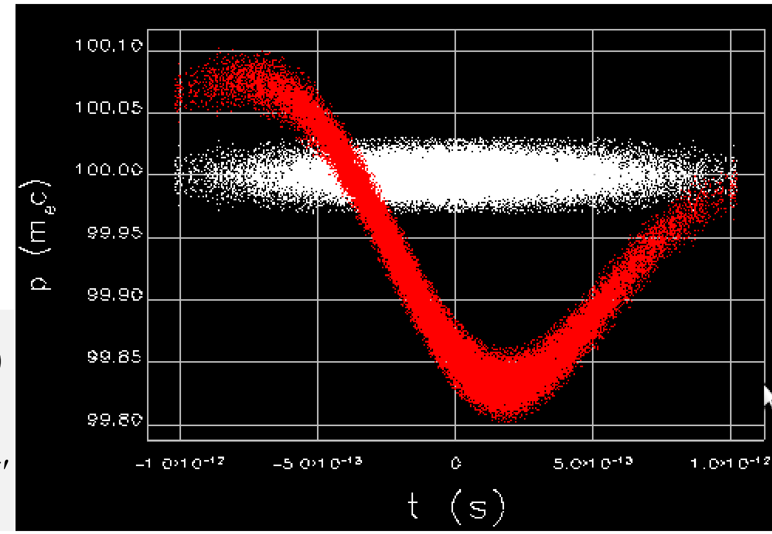
Coherent Synchrotron Radiation:





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

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



$$P_{CSR} = \frac{f_0 Q^2 R^{1/3}}{4\sqrt[3]{2}\varepsilon_0 \sigma_z^{4/3}} \left\{ 1 + N \frac{2\sqrt[3]{2}}{3\pi\sqrt{3}} \frac{\sigma_z^{1/3}}{R^{1/3}} \left[\ln\left(\frac{\sqrt{12}\sigma_z \gamma^3}{R}\right) - 4 \right] \right\}, \quad \frac{1}{\gamma} \ll \left(\frac{48\sqrt{3}\sigma_z}{R}\right)^{1/3} \le \frac{2\pi}{N}.$$

bERLinPro: LEM → P_{CSR} ~ 4.4 kW (σ_s = 2 ps, Q = 77 pC, N = 8, E = 50 MeV)

SPM → CSR power (4.4 kW from LEM) limits bunch charge: $\left(\frac{Q_{SPM}}{Q_{LEM}}\right)^2 = \left(\frac{\sigma_{SPM}}{\sigma_{LPM}}\right)^{4/3}$

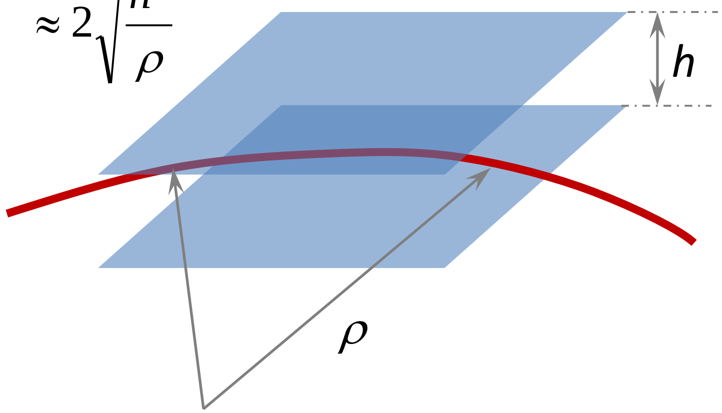
→ Q_{SPM} ~ 10 pC

Coherent Synchrotron Radiation: Countermeasures → Shielding

infinite extended parallel plates suppress THz emission for $\lambda > \lambda_{cut}$

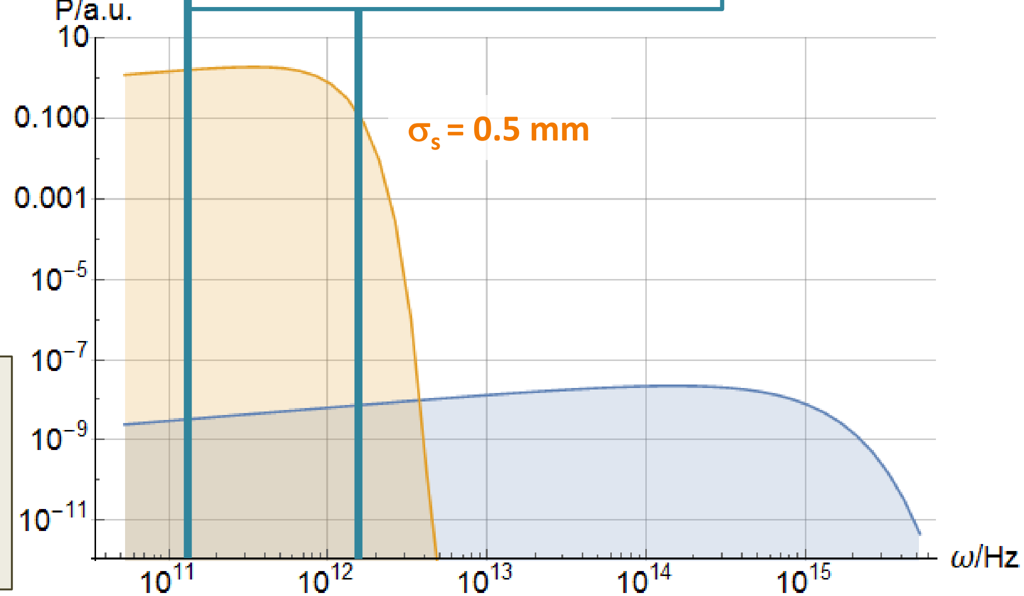
$$\lambda_{cut} = 2h\sin\theta_c \quad with \quad \theta_c = \left(\frac{3\lambda_{cut}}{2\pi\rho}\right)^{1/3}$$

$$\approx 2\sqrt{\frac{h^3}{\rho}}$$



h = 20 mm, ρ = 10.0 m
→ λ_{cut} = 1.8 mm
→ ω_{cut} = 1.05*10^{12} Hz

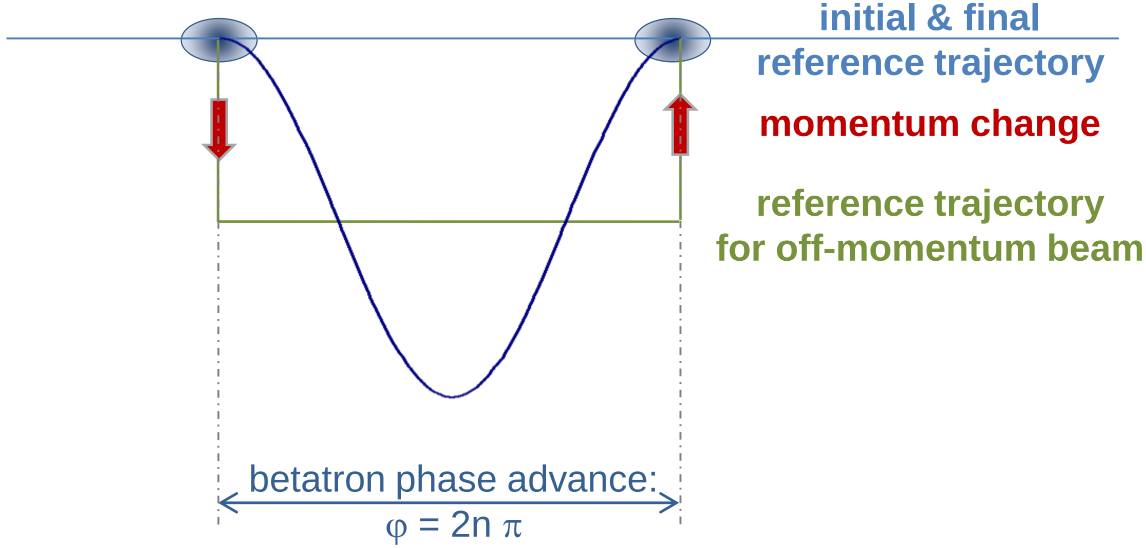
h = 40 mm, ρ = 1.0 m
→ λ_{cut} = 16 mm
→ ω_{cut} = 1.2*10^{11} Hz



J. Schwinger, Phys. Rev. 70, 798 (1946) and LBNL-39088 (1966).
J. S. Nodvick and D. S. Saxon, Phys. Rev. 96, 180 (1954)
R. Warnock and P. Morton, Part. Accel. 25, 113 (1990).
J.B. Murphy, S. Krinsky and R. L. Gluckstern, PAC 1995
Y. S. Derbenev, et al., DESY Report No. TESLA-FEL 95-05, 1995.
G. Stupakov and I. Kotelnikov, PRST-AB 6, 034401 (2003).

Coherent Synchrotron Radiation: Countermeasures → Beam Optics

- **energy modulation:** ☹ (s → -s, but crossing full compression with more CSR)
- **emittance growth:** adjust phase advance in bending plane



$\Delta p_{CSR} < 0$

→ not for CSR

Coherent Synchrotron Radiation: Countermeasures → Beam Optics

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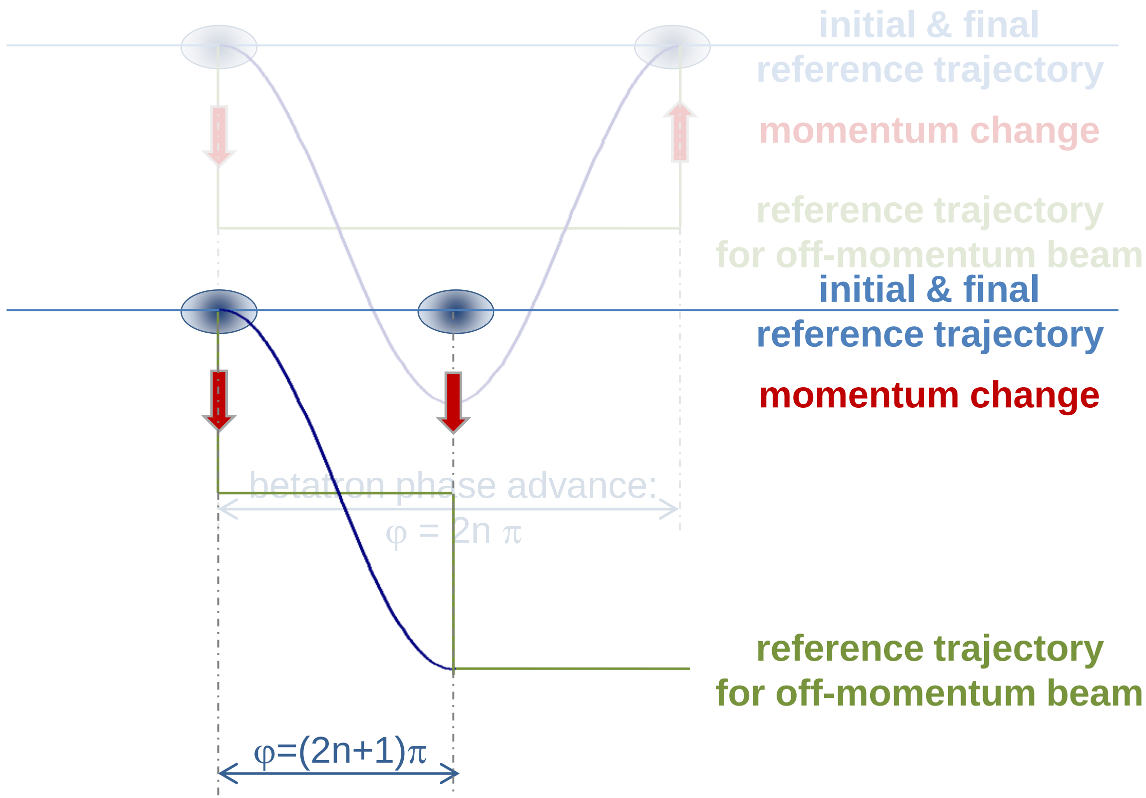
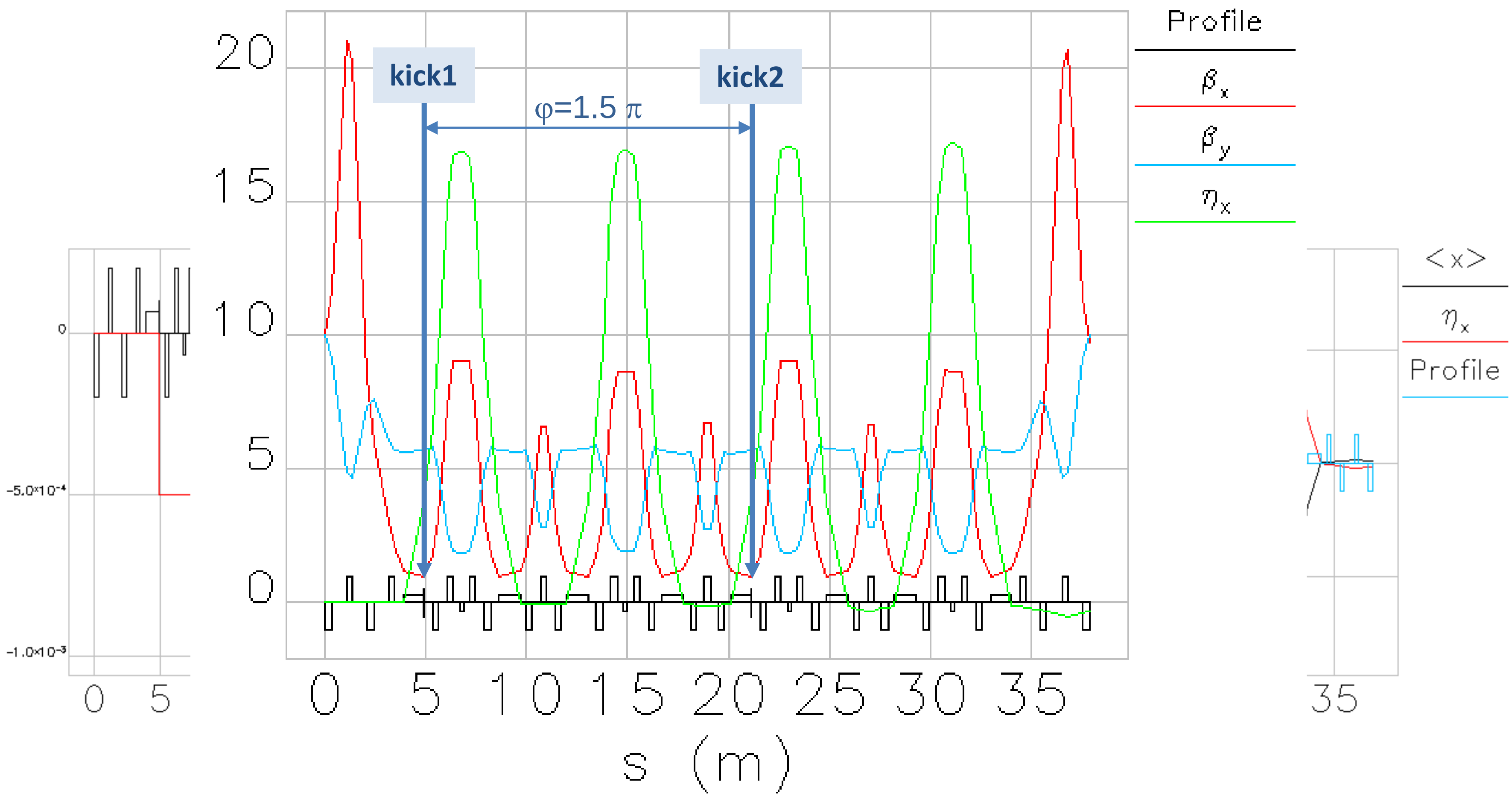


$\Delta p_{CSR} < 0$
→ not for CSR

works for CSR

Coherent Synchrotron Radiation: Countermeasures → Beam Optics

example: two energy kicks

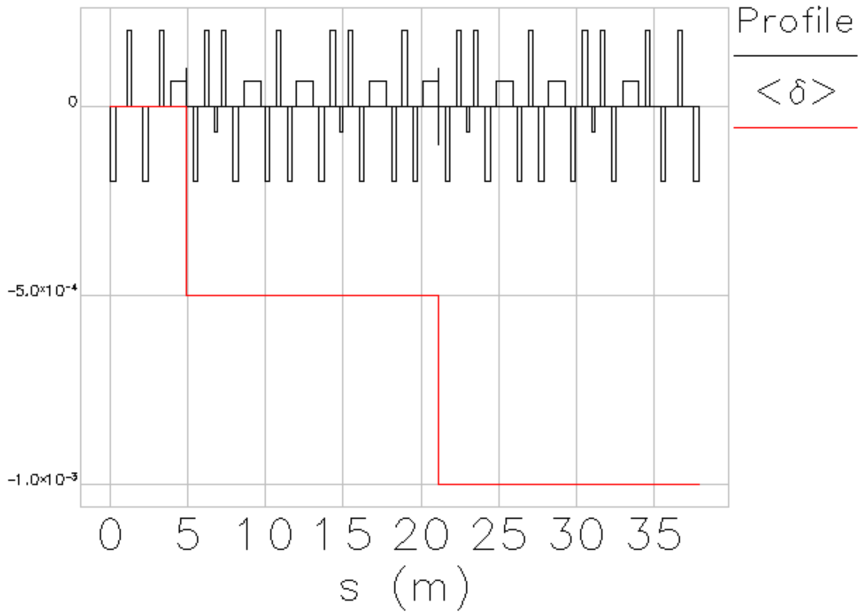


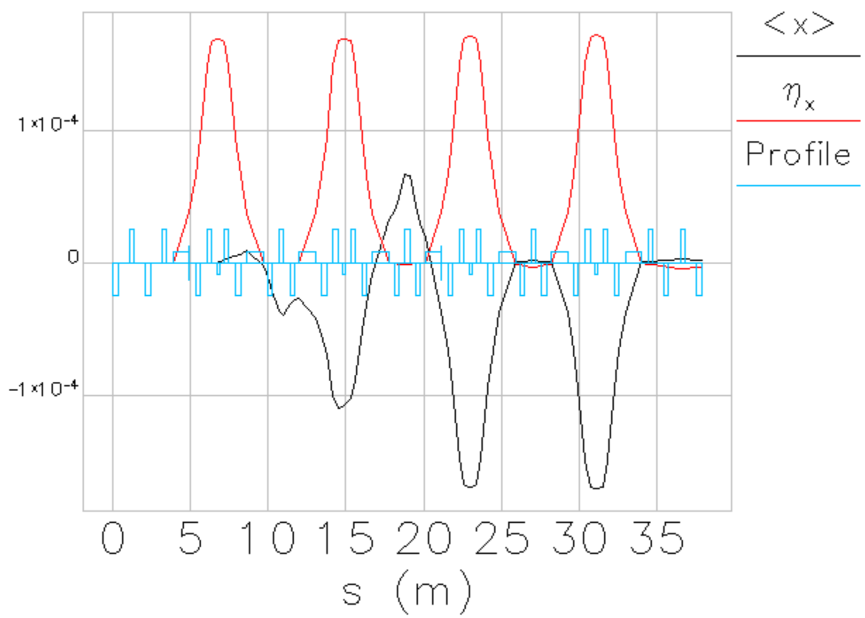
FSF arc optics (A. Matveenko et al.)

ERL Beam Dynamics: Collective Effects

Coherent Synchrotron Radiation: Countermeasures → Beam Optics

example: two energy kicks





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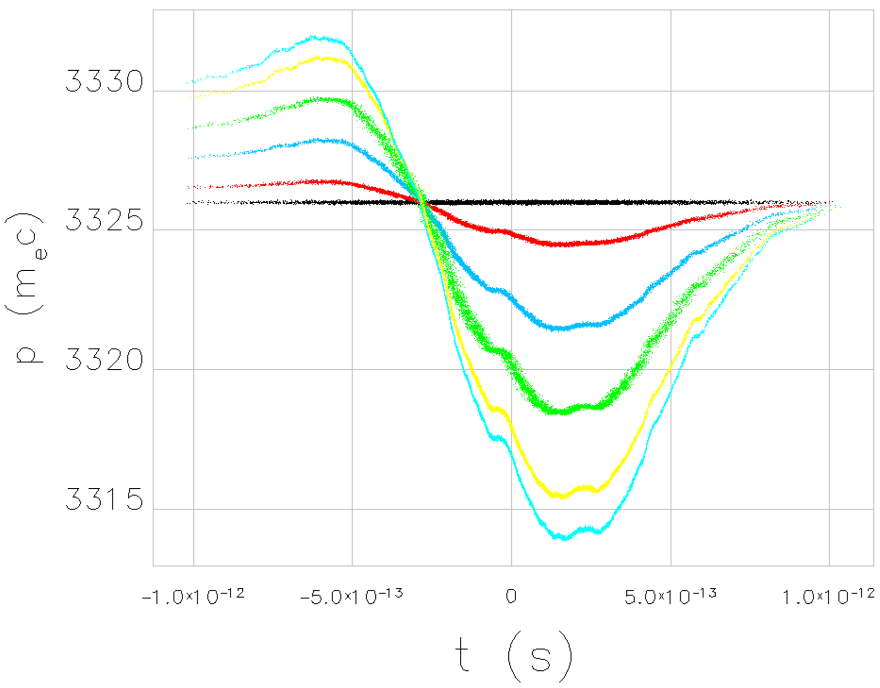
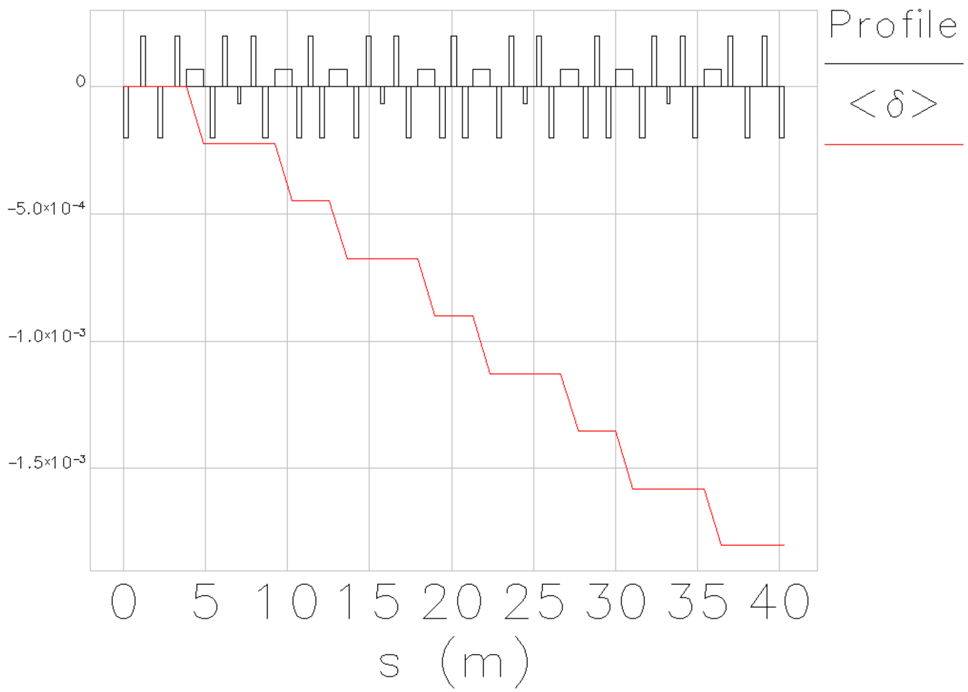
Coherent Synchrotron Radiation: Countermeasures → Beam Optics

example: CSR induced energy modulation, Q = 5 nC **(FSF optics & parameter)**





Coherent Synchrotron Radiation: Countermeasures → Beam Optics

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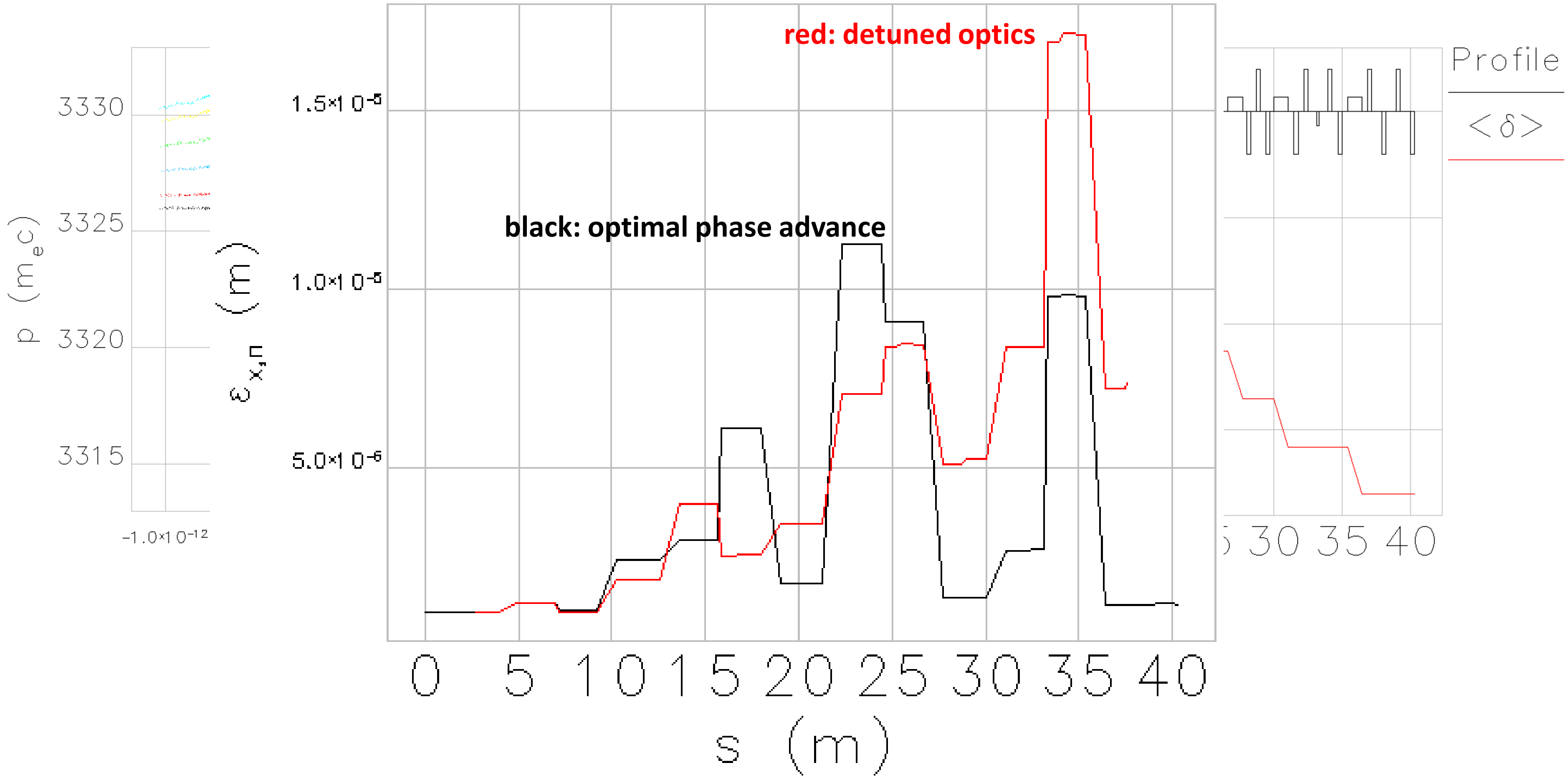


ERL Beam Dynamics: Collective Effects

Geometric Wakes:

point charge wake function:

$$W_z(s) = -\frac{1}{q}\int_{z_1}^{z_2} dz\, E_z\left(z, t = \frac{z+s}{c}\right)$$

wake potential:

$$V_z(s) = \int_{-\infty}^{s} \lambda(s')\, W_z(s-s')\, ds'$$

energy loss of full bunch:

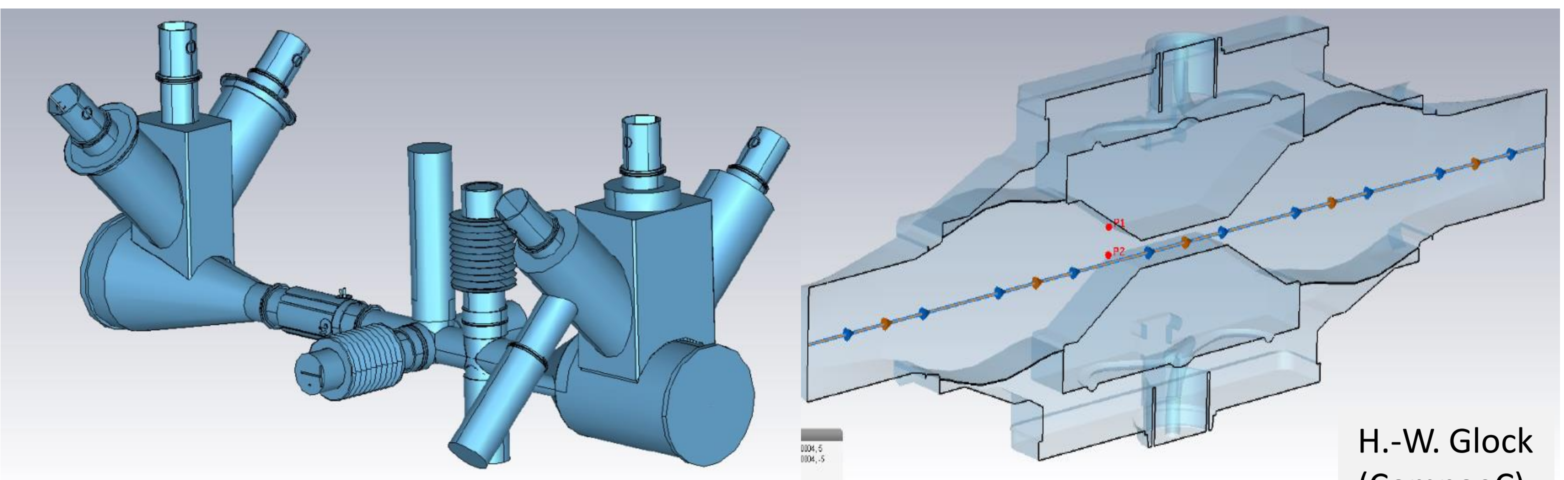
$$\Delta U = \int_{-\infty}^{\infty} \lambda(s)\, V_z(s)\, ds$$

→ **Loss factor:** $k_{loss} = \dfrac{\Delta U}{q_b^2}$

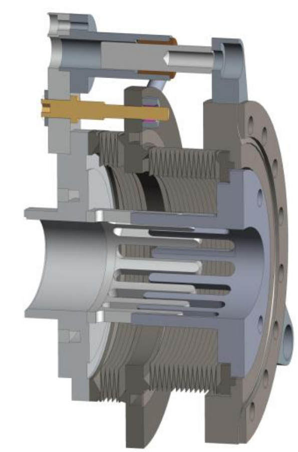
→ losses can heat / destroy chamber components

→ wakes induce energy modulation / degrade E-spread & emittance

bERLinPro: CST wake field calculations for all relevant vacuum chamber components



H.-W. Glock (CompaeC)



Geometric Wakes:

Komponente	N_1 $\sigma_t = 4.5$ ps	N_2 $\sigma_t = 2.0$ ps	N_gesamt	k / V/pC $\sigma_t = 4.5$ ps	k / V/pC $\sigma_t = 2.0$ ps	N_1 * k / V/pC $\sigma_t = 4.5$ ps	N_2 * k / V/pC $\sigma_t = 2.0$ ps	total Loss / V/pC
CSR		50	50		10		500	500
Resistive Wall		50	50		0.34		17	17
Surface Roughness		50	50		3.5		175	175
Splitter highE	0	1	1	**0.005**	**0.019**	0.000	0.019	0.019
Splitter lowE	0	1	1	**0.244**	**0.829**	0.000	0.829	0.829
dipCham_-40	0	8	8	0.041	0.139	0.000	1.114	1.114
Ventil,zSh=0.2	3	10	13	**0.053**	0.130	0.160	1.297	1.457
schlitz_03	5	28	33	**0.092**	0.150	0.461	4.198	4.659
thinSlot	7	34	41	**0.056**	0.176	0.395	5.993	6.388
erme_All	1	0	1	5.186	17.596	5.186	0.000	5.186
kontBalg	5	28	33	**0.147**	1.437	0.733	40.227	40.960
erme_Stripline	3	16	19	**0.494**	**1.909**	1.483	30.546	32.029
erme_Diag2	1	13	14	**0.226**	0.767	0.226	9.975	10.201
Koll2_10	1	0	1	6.179	20.967	6.179	0.000	6.179
Summe	26	139	165			14.824	94.197	109.021

- short bunch length → „expensive“ CST calculations → loss factors extrapolated ~ σ^{-x}

Geometric Wakes:

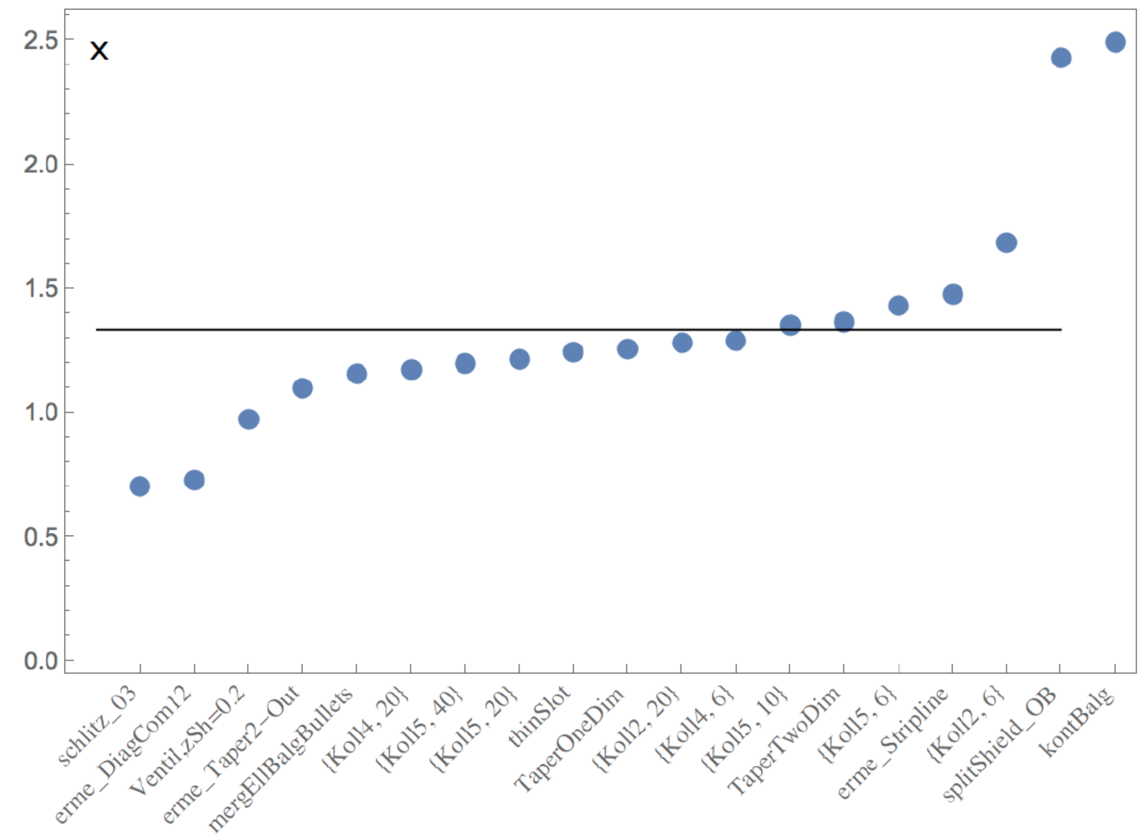
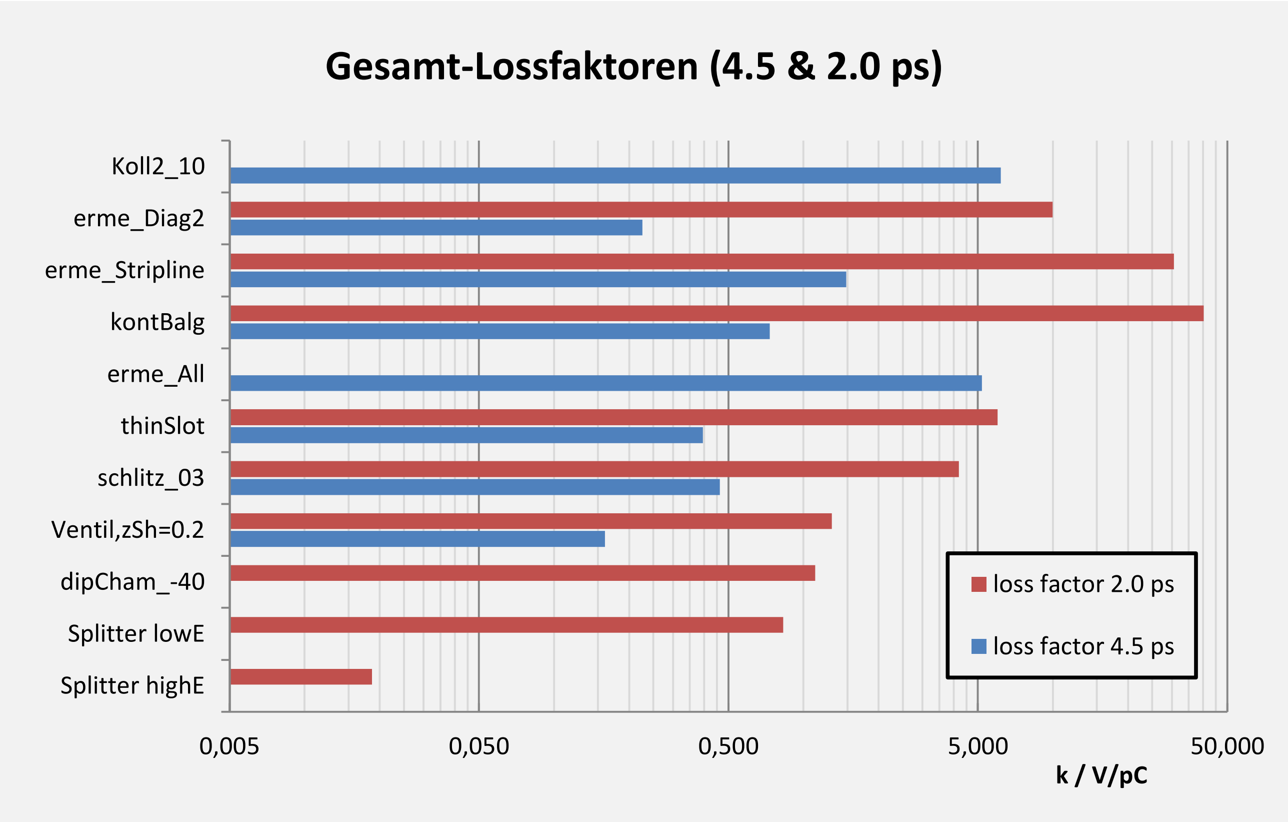


Abb. 2.3: Übersicht über die aus der Interpolation der simulierten Verlustfaktoren ermittelten Exponenten x in der Gesetzmäßigkeit $k_{loss} \sim 1/(\sigma^x)$. Die zusätzlich eingezeichnete Linie markiert den Wert x = 4/3.

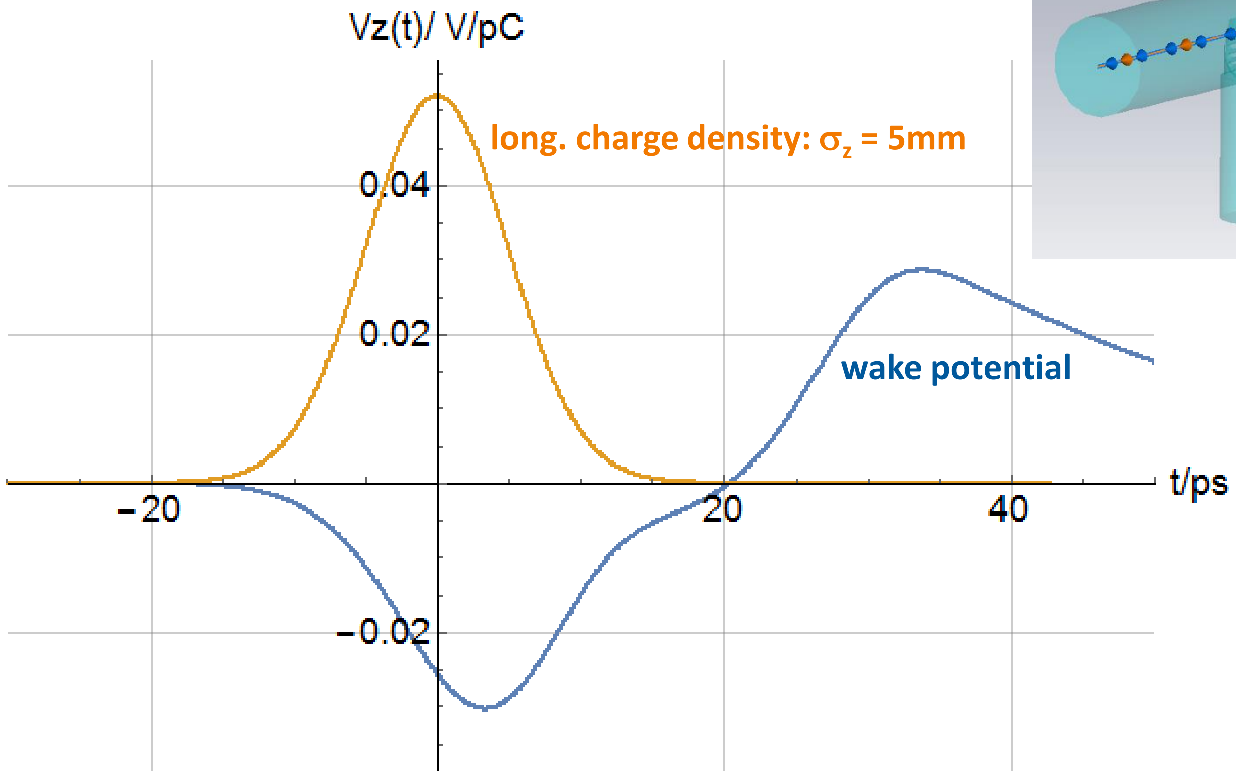
- short bunch length → „expensive“ CST calculations → loss factors extrapolated ~ σ^{-x}

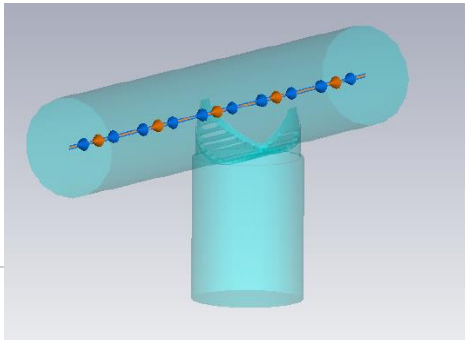
Geometric Wakes:



- short bunch length → „expensive" CST calculations → loss factors extrapolated ~ σ^{-x}
- is it a problem ? : k = 110 V/pC → $P_{total} = k\,Q_B\,I$ = 850 W,
  „first meter" & Kollimator ~ 50 W each → ☺ when equally distributed

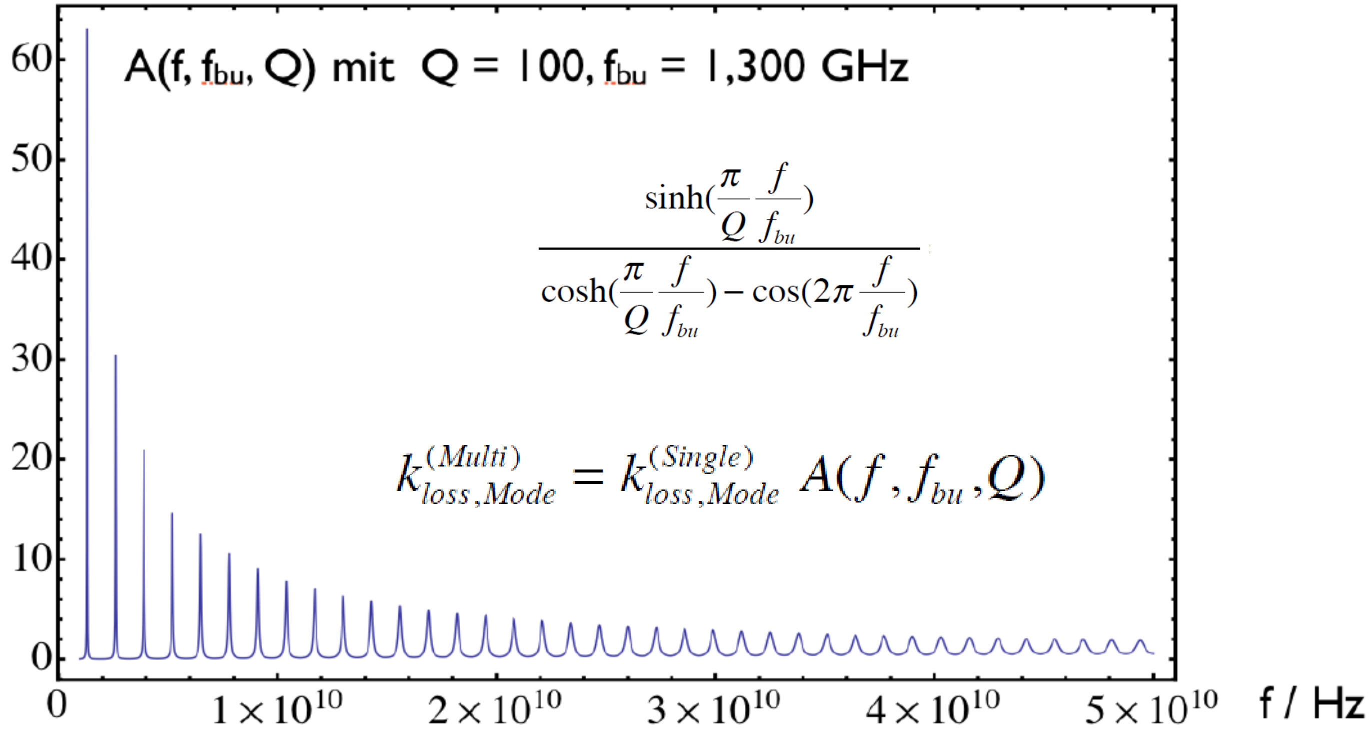
Geometric Wakes:





single bunch wake: @ high Q field from previous bunches not sufficiently damped

Geometric Wakes:



single bunch wake: @ high Q field from previous bunches not sufficiently damped

→ **in multi bunch operation: EM fields = equilibrium by beam excitation & damping**

wake field effects from realistic bunches in multi bunch operation still to be estimated

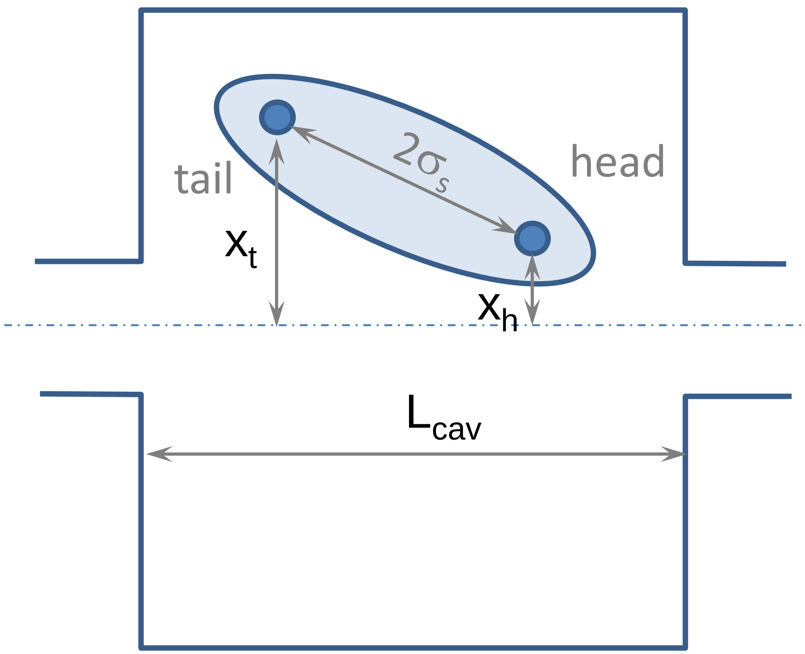
(G. Hoffstätter: Compensation of wakefield-driven energy spread in energy recovery linacs, PR ST-AB 11, 070701 (2008))

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
→ **instability & beam loss**

BBU variants:

1. **Single Bunch BBU:** head of "off-axis" bunch induces cavity wakes
→ resonant excitation of betatron oscillations of the bunch's tail



instability growth parameter:

$$\tau = \frac{x_t}{x_h} = \frac{N r_e W_\perp(2\sigma_s)}{4 k_\beta \gamma L_{cav}} L_{acc}$$

$\tau \sim 1$ → no instability
$(\tau-1) << 1$ → no emittance growth

BNS damping: tail stronger focused than head

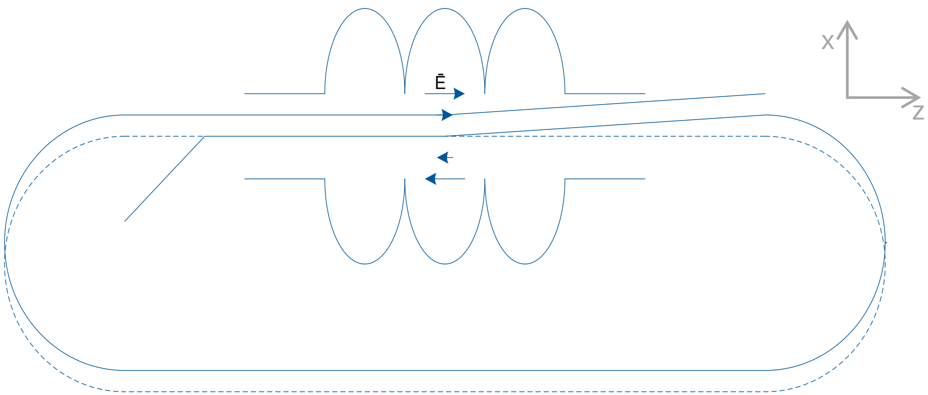
SLAC linac: SB BBU + BNS

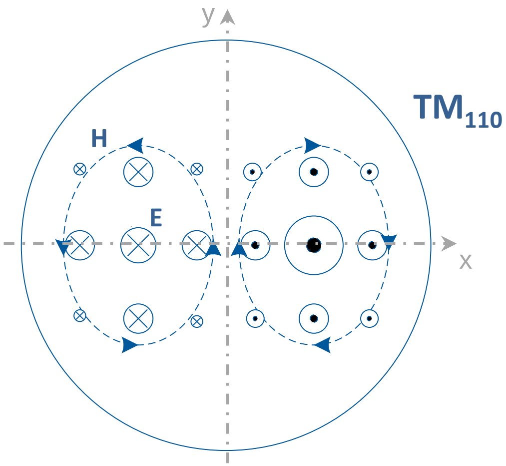
not relevant for bERLinPro

V.Balakin, A.Novokhatsky and V.Smirnov, "VLEPP: Transverse Beam Dynamics", Proc. of the 12th International Conference on High-Energy Accelerators, Batavia, Illinois, p. 119 (1983).

BBU variants:

2. Multibunch BBU: many flavours: cumulative / regenerative, transverse / longitudinal, single-/multi-cavity, single-/multiple-turn





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

1. bunch passes cavity "off axis" during accelerating passage → induce HOM voltage & transverse kick due to HOM
2. after recirculation kick transforms to an offset & HOM damp according to its Q
3. bunch passes cavity with varied offset on decelerating passage → induce HOM voltage & transverse kick due to HOM

BBU: HOM excitation exceeds HOM damping → kick strength growth up to loss

ERL Beam Dynamics: Beam Break Up

beam induced change of cavity energy:

$$\Delta U_1 = -q_b \frac{V_a}{a} \cos(\varphi)\left(x_1 \cos(\alpha) + y_1 \sin(\alpha)\right)$$

$$\Delta U_2 = -q_b \frac{V_a}{a} \cos(\varphi + \omega_\lambda T_{rec})\left(x_2 \cos(\alpha) + y_2 \sin(\alpha)\right)$$

bunch offset at 2nd passage:

$$x_2 = m_{11}x_1 + m_{12}x_1' + m_{13}y_1 + m_{14}y_1' - \frac{qV_a}{\omega_\lambda a\, p}\sin(\varphi)\left(m_{12}\cos(\alpha) + m_{34}\sin(\alpha)\right)$$

ohmic losses → damping of HOM: $P_c = \frac{V_a^{\,2}}{(\omega_\lambda / c)^2 a^2 (R/Q)_\lambda \; Q_\lambda}$

balanced HOM: $\left\langle \Delta U_1 + \Delta U_2 \right\rangle_\varphi \cdot f_b = P_c$

→ **threshold current:**

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

valid for:

- $m^* \sin(\omega_\lambda T_{rec}) < 0$
- $\omega_\lambda \neq n^* \omega_{rf}$

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

E. Pozdeyev et al.: Multipass beam breakup in energy recovery linacs, NIM-A 557 (2006) 176–188
G. Hoffstaetter et al.: Beam-breakup instability theory for energy recovery linacs, PRST-AB 7, 054401 (2004)
G. Hoffstaetter et al.: Recirculating beam-breakup thresholds for polarized higher-order modes with optical coupling, PRST-AB 10, 044401 (2007)

ERL Beam Dynamics: Beam Break Up

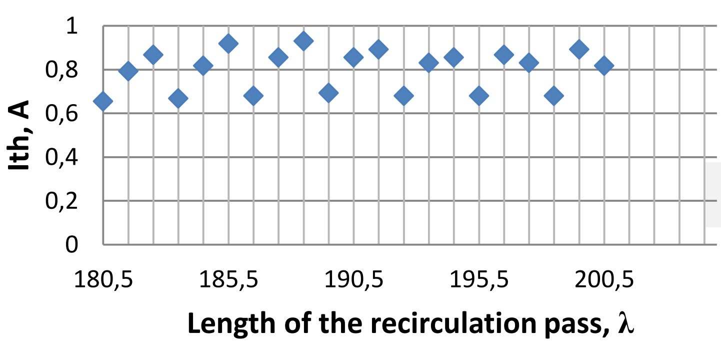
Countermeasures:

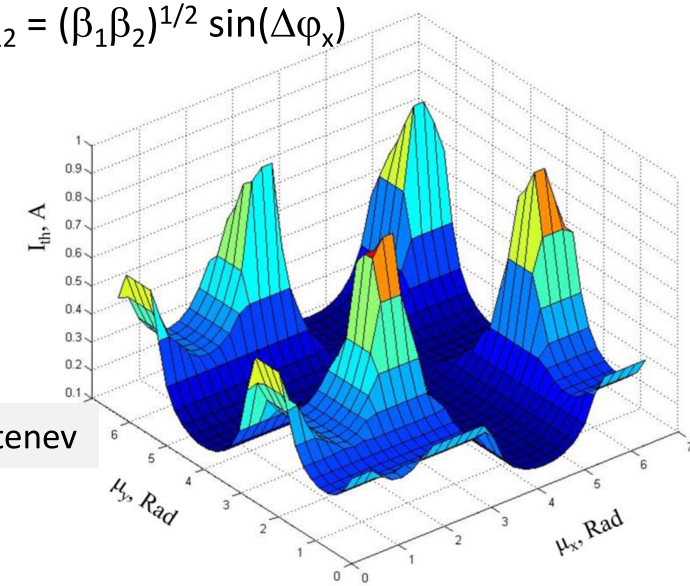
$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

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 → $m^* = m_{12} = (\beta_1\beta_2)^{1/2} \sin(\Delta\varphi_x)$

     → stable for $\Delta\varphi = n\pi$
   - adjust $\sin(\omega_\lambda T_{rec}) = 0$ for the worst HOM

     large path length change → inpractical ☹





Y. Petenev

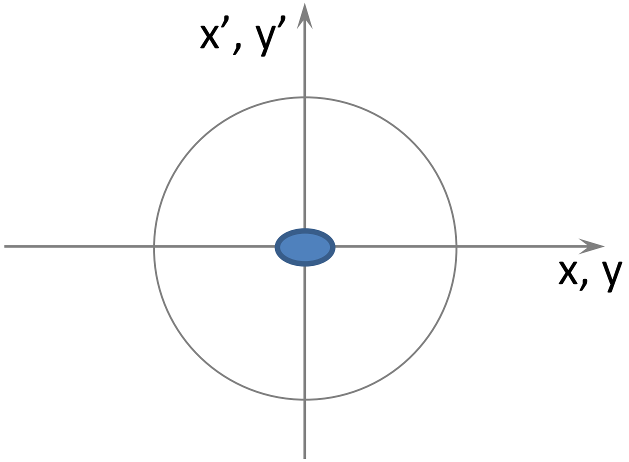
Countermeasures:

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

2. recirculator beam optics (continued):

- tune optics for **large chromaticity** ($\xi_{x,y} = dQ_{x,y}/dp$) and give bunches a high energy spread

  → similar to landau damping



phase advance
at recirculation

ERL Beam Dynamics: Beam Break Up

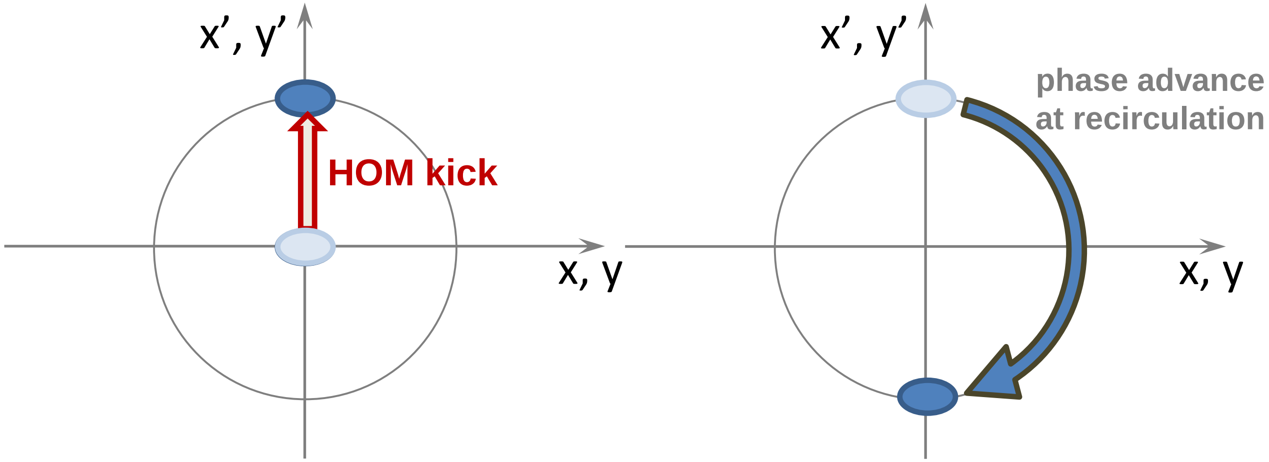
Countermeasures:

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

2. recirculator beam optics (continued):

- tune optics for **large chromaticity** ($\xi_{x,y} = dQ_{x,y}/dp$) and give bunches a high energy spread

  → similar to landau damping



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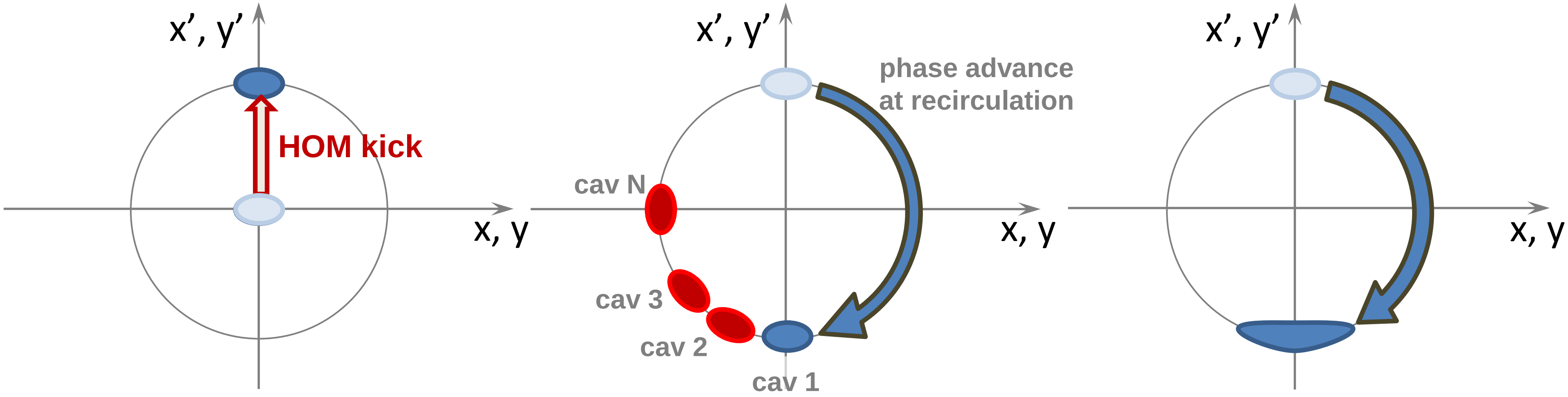

medium ξ & σ_p

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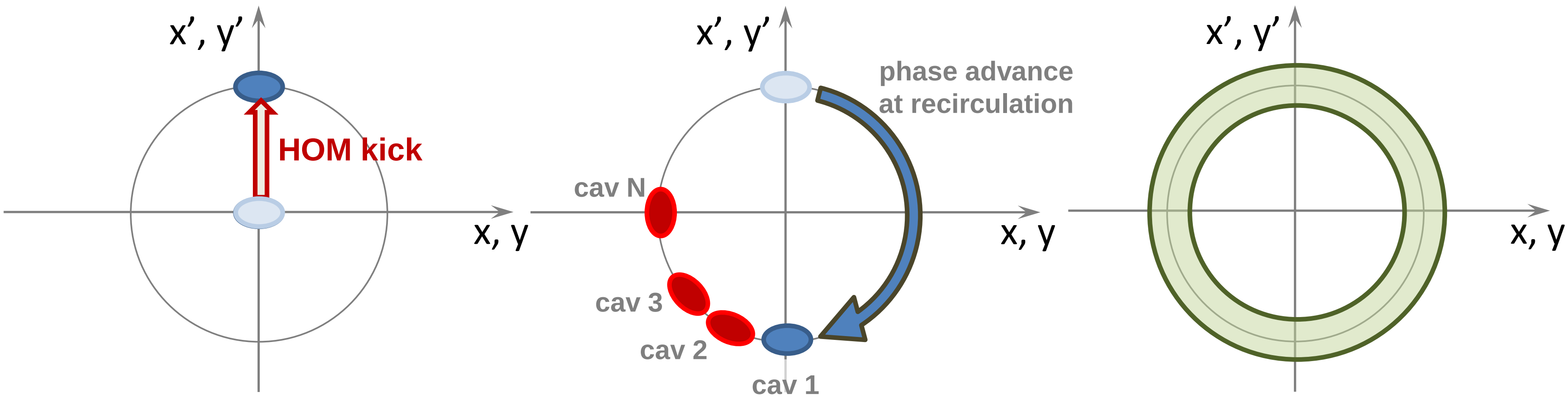


(very) large ξ & σ_p

drawback: large chromaticity by strong sextupoles → nonlinearities may cause emittance dilution

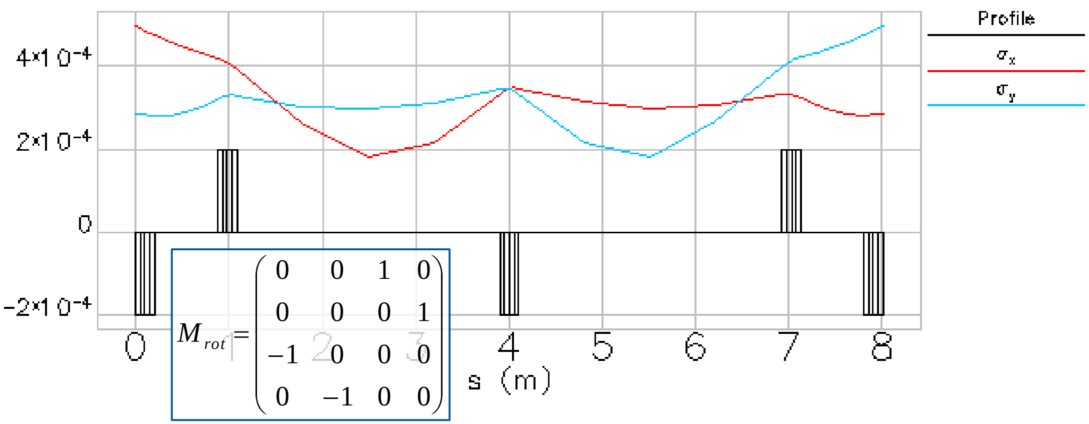
Vladimir N. Litvinenko, "Chromaticity of the lattice and beam stability in energy recovery linacs", PRST-AB 15, 074401 (2012)

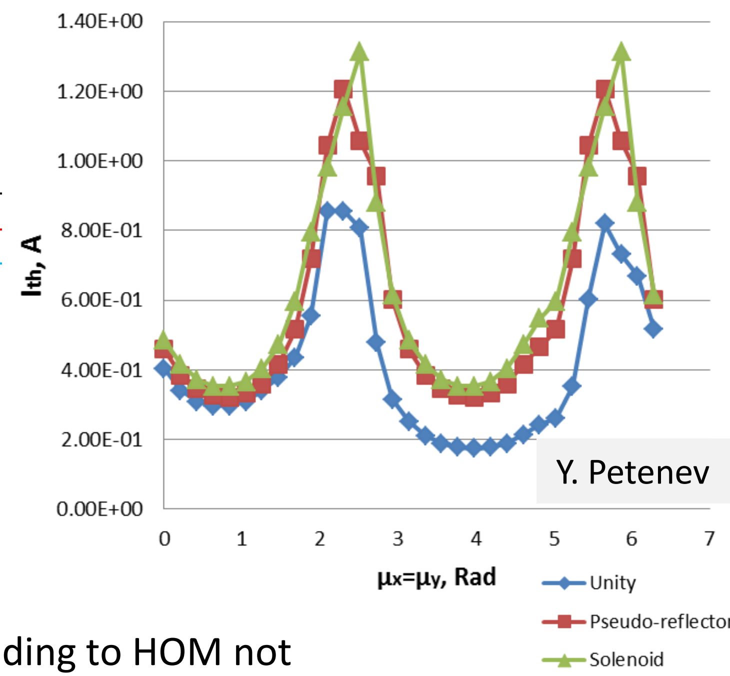
ERL Beam Dynamics: Beam Break Up

Countermeasures:

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

2. **recirculator beam optics (continued):**
   - coupled beam transport: switching of planes $M=((M_x,0),(0,M_y)) \rightarrow M=((0,M_{yx},0),(0,M_{xy}))$ $m_{12}=0 \rightarrow$ horizontal HOM kick transforms to vertical offset $\rightarrow$ HOM not further excited by the oscillatory part of x_2
   - $\rightarrow$ two options: solenoid (low energy), rotator





3. **energy / momentum:** kick strength = f(E), beam loading to HOM not

ERL Beam Dynamics: Unwanted Beam

Unwanted Beam

Halo

generated by / together with wanted beam

- scattered particles (residual gas, IBS)
- laser stray light on cathode
- laser: limited extinction ratio
- … (?)

moving together with wanted beam at design rf phases → same energy, no dispersive separation

Dark Current

generated independently of wanted beam (laser off)

- field emission in rf cavities
- ghost pulses from laser
- … (?)

beside Dark Current from the gun → lower energy than wanted beam → lost in dispersive regions

UBW 2012: https://indico.helmholtz-berlin.de/conferenceDisplay.py?confId=2

Unwanted Beam

Amount:

- not reliably predictable for most sources

Loss positions:

- with initial beam parameter (place of origin, momenta) loss position along the machine can be calculated for the various generation processes → loss probability (to be weighted with unknown loss current ☹)

source	generating process	loss positions	amount
Halo	scattered Particles		
	stray light – laser halo		
Dark Current	field emission gun cath & plug		
	field emission booster & linac		

UBW 2012: https://indico.helmholtz-berlin.de/conferenceDisplay.py?confId=2

ERL Beam Dynamics: Unwanted Beam - Halo

Halo: **1. residual gas scattering**

2. intra beam scattering → Touschek losses

3. laser stray light from cathode

according to storage rings:

$$\frac{dN}{dt} = c\, n\, \sigma_{gas}\, N$$

$$\sigma_{gas} = \sigma_{ke} + \sigma_{ki} \qquad n = n_Z \frac{1}{kT} p$$

$$\sigma_{ke} = \frac{2\pi r_e^2 Z^2}{\gamma^2}\left(\frac{1}{\theta_x^2} + \frac{1}{\theta_y^2}\right),$$

inelastic contributions:

$$\sigma_{ki} = 4\alpha r_e^2\, Z^2 \left[\frac{4}{3}\left(\ln\frac{1}{A^{\parallel}} - \frac{5}{8}\right)\ln\left(\frac{183}{Z^{1/3}}\right) + \frac{1}{9}\left(\ln\frac{1}{A^{\parallel}} - 1\right)\right]$$

residual gas species Z : 7.000000
atoms per molecule : 2
electrons per bunch : 4.8124998E+08
Temperature / K : 300.0000
res. gas presure / Pa : 5.0000000E-07
/ mbar: 5.0000000E-09

Case : BERLinPro rec

gamma = 97.84736
app_x = 2.0000000E-02
app_y = 2.0000000E-02
max_beta_x = 40.00000
max_beta_y = 20.00000
mean_beta_x = 15.00000
mean_beta_y = 12.00000
Circum = 55.00000
density of residual gas 1/m**3 : 2.4143045E+14
cross section (ke only) : 5.3624196E-25
loss rate : -1.8691530E+07
Tau / min : 0.4291160

Loss per turn = dNdt * T_Umlauf: -3.4

rel loss per turn : -7.1205832E-09

ERL Beam Dynamics: Unwanted Beam - Halo

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atoms per molecule : 2
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Temperature / K : 300.0000
res. gas presure / Pa : 5.0000000E-07
/ mbar: 5.0000000E-09

Case : BERLinPro injector

gamma = 12.72016
app_x = 2.0000000E-02
app_y = 2.0000000E-02
max_beta_x = 40.00000
max_beta_y = 40.00000
mean_beta_x = 15.00000
mean_beta_y = 12.00000
Circum = 15.00000
density of residual gas 1/m**3 : 2.4143045E+14
cross section (ke only) : 4.0796093E-23
loss rate : -1.4220099E+09
Tau / min : 5.6404909E-03

Loss per turn = dNdt * T_Umlauf: -71

rel loss per turn : -1.4774129E-07

Loss per turn = dNdt * T_Umlauf: -3.4

rel loss per turn : -7.1205832E-09

ERL Beam Dynamics: Unwanted Beam - Halo

Halo:
1. residual gas scattering
2. **intra beam scattering → Touschek losses**
3. laser stray light from cathode

$$n_B = \frac{N_B}{V_B}$$

$$V_B = (4\,\pi)^{3/2}\,\sigma_x\,\sigma_y\,\sigma_l$$

$$\frac{\mathrm{d}N_B}{\mathrm{d}t} = \frac{\sqrt{\pi}\,r_0^2\,c\,n_B}{\gamma^2 {A^{\parallel}}^3}\,D(\epsilon)$$

$$D(\epsilon) = \sqrt{\epsilon}\left[-\frac{3}{2}e^{-\epsilon} + \frac{\epsilon}{2}\int_{\epsilon}^{\infty}\frac{\ln u}{u}e^{-u}\,\mathrm{d}u + \frac{1}{2}\left(3\epsilon - \epsilon\ln\epsilon + 2\right)\int_{\epsilon}^{\infty}\frac{e^{-u}}{u}\,\mathrm{d}u\right]$$

$$\epsilon = \left(\frac{\beta_x\,A^{\parallel}}{\gamma\,\sigma_x}\right)^2$$

BERLinPro injector:

Energy / MeV	6.5
momentum acceptance / %	1.0 , 0.5
circumference / m	15
value of D-function	0.3
lost electrones per turn and bunch	3 , 26
rel. loss per turn	7E-9 , 5E-8

BERLinPro recirculator:

Energy / MeV	50
momentum acceptance / %	0.5
electrons per bunch	5E8
norm. transverse emttance / rad m	1.0E-6
$<\beta_x>$ / rad m	15
$<\beta_y>$ / rad m	12
circumference / m	55
value of D-function	0.3
lost electrones per turn and bunch	12
rel. loss per turn	2.5E-8

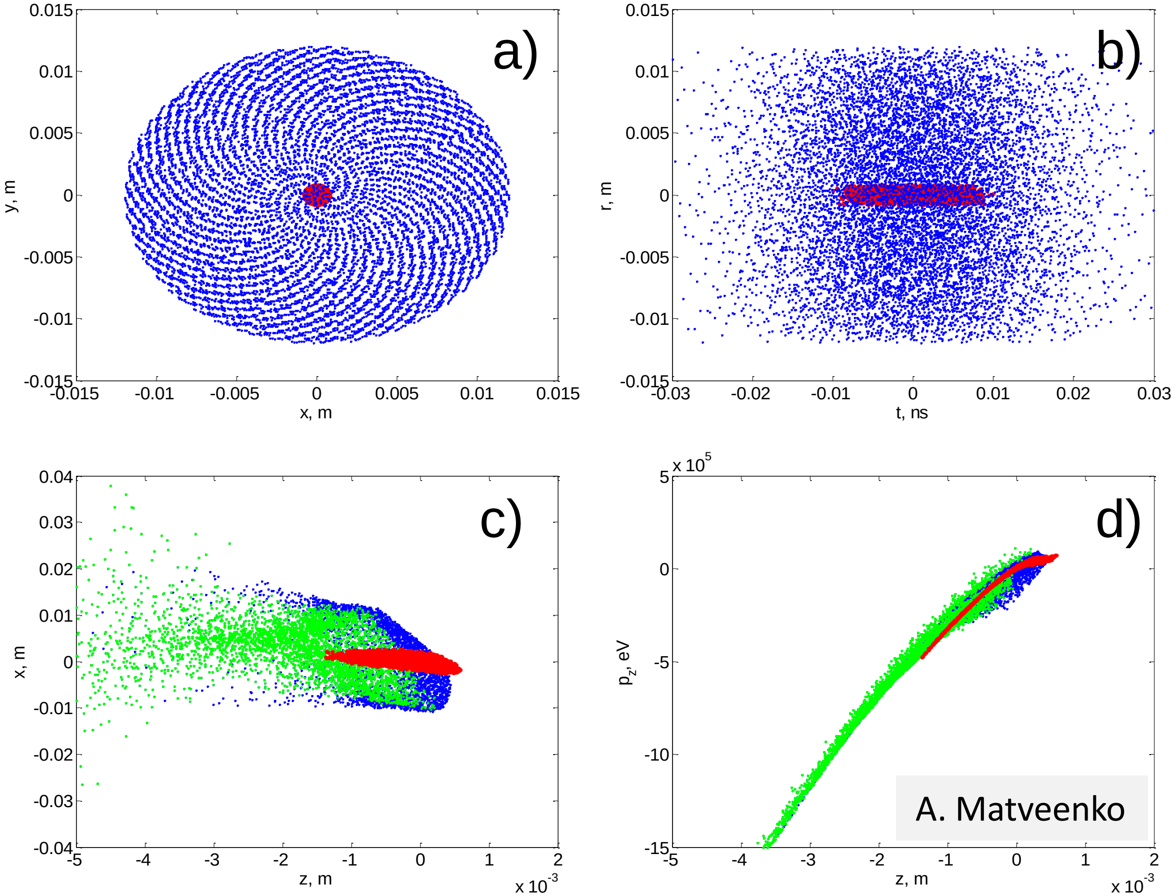
careful treatment of the longitudinal acceptance $A^{\parallel}$ at the varying ERL energies

ERL Beam Dynamics: Unwanted Beam - Halo

Halo: 1. residual gas scattering

2. intra beam scattering → Touschek losses

3. **laser stray light from cathode**



<u>Beam halo modeling:</u>
particle distribution from ASTRA.

red – active beam particles,
blue – passive halo particles,
green – particles lost in collimators.

Initial distribution on the cathode in
a) *x-y* plane,
b) *x-t* plane.

Particle distribution after the merger section in
c) *x-z* plane,
d) *p_z-z* plane.

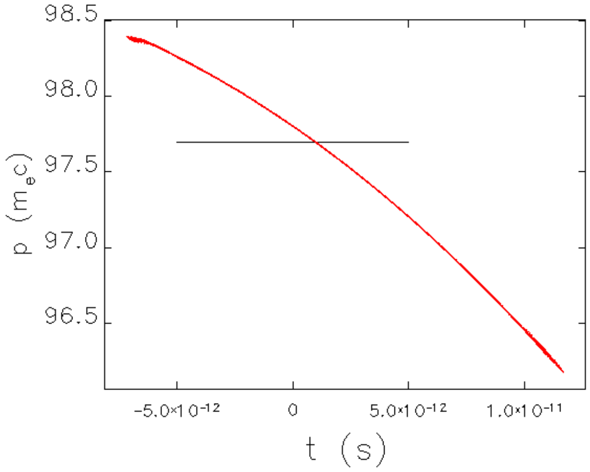
→ Collimation of large fraction of halo particles, but not 100%.

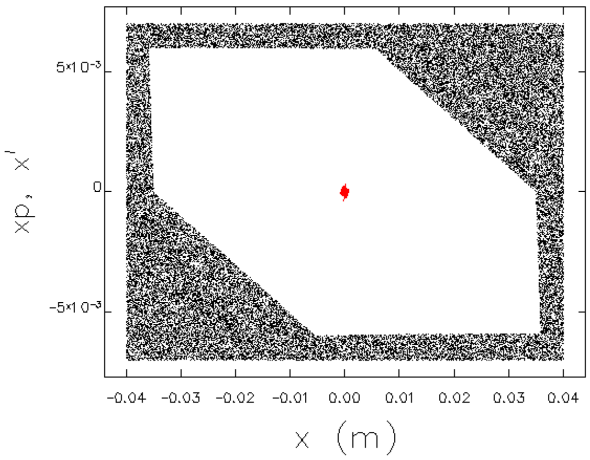
bERLinpro: one testing collimator in the merger section

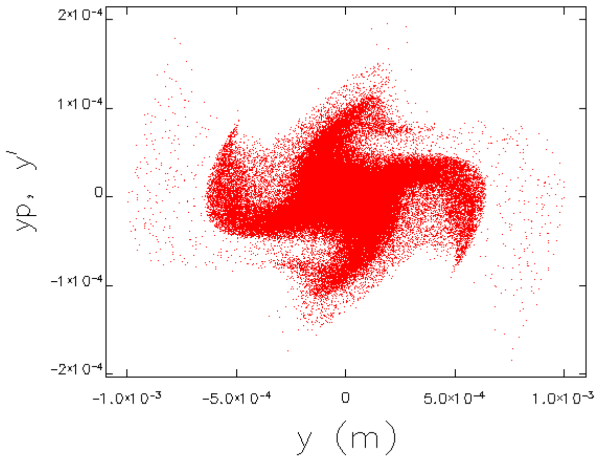
ERL Beam Dynamics: Unwanted Beam - Halo

Halo: remaining beam downstream the collimator → transport without losses

→ optimize acceptance of beam optics (linear & non-linear), JLab







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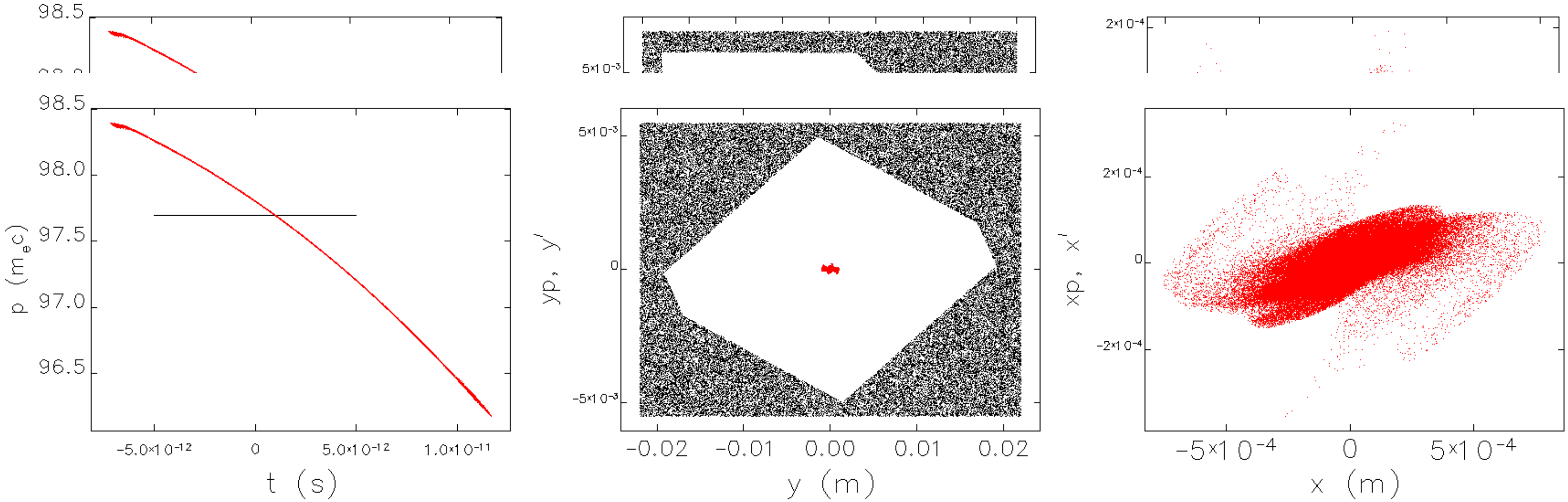

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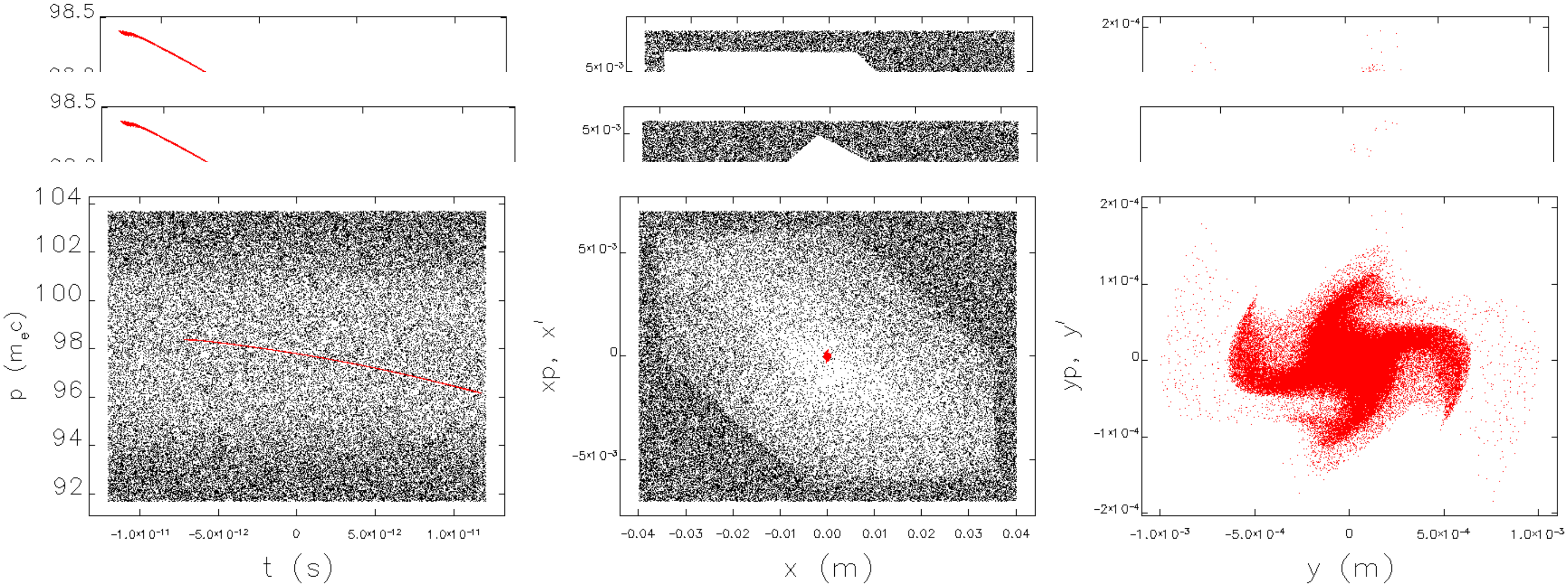


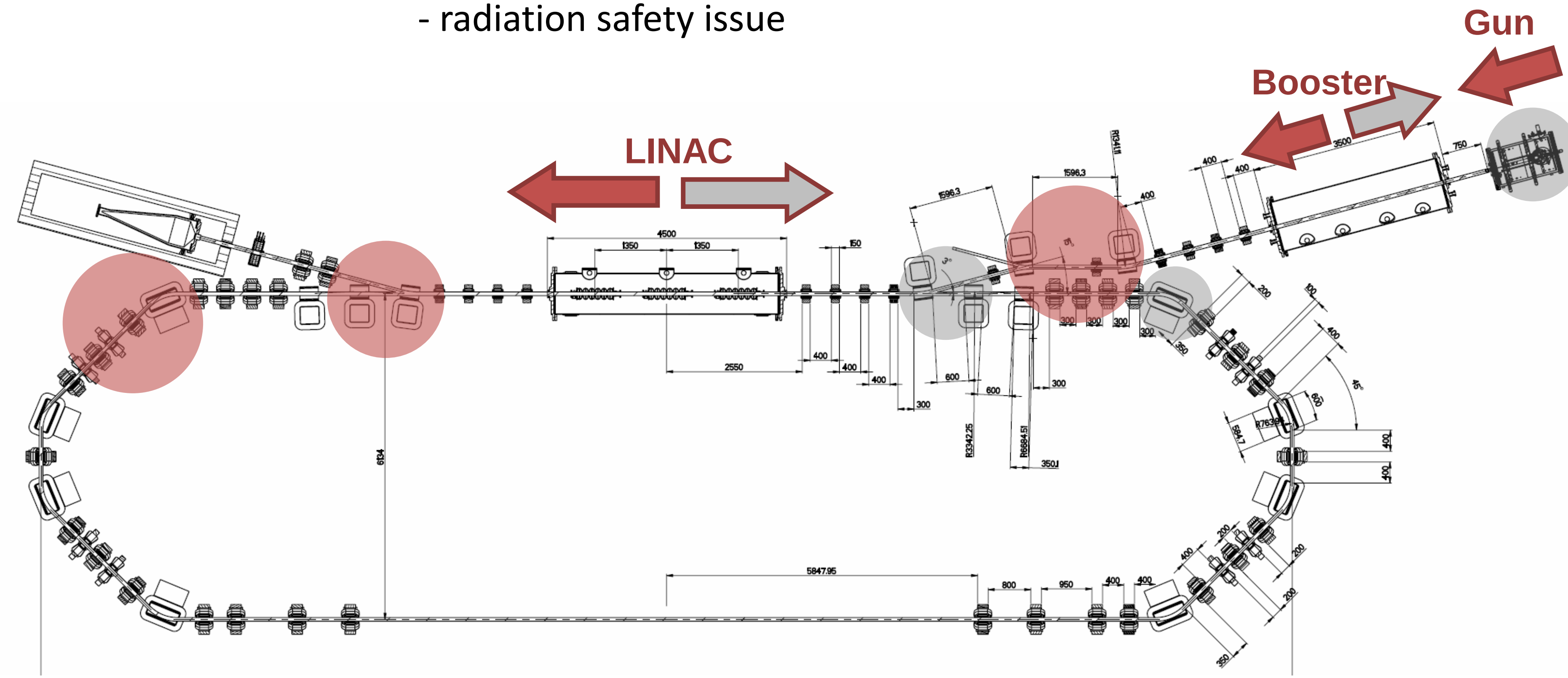
recirculator only – not optimized

optimization by adjusting quadrupole and sextupole magnet strengths

→ quadrupoles: reduce maxima of beta-function
→ sextupoles: reduce nonlinear influence on maxima of beam size: $T_{1,n}$, $T_{3,n}$

ERL Beam Dynamics: Unwanted Beam

Dark Current: - consuming rf power (linac)
- MPS relevant: μA @ tens of MeV → $10^2 \ldots 10^3$ W/??
- radiation safety issue



- dark current from booster (E_{max} = 4.5 MeV → ΔE > 30%) will be lost in merger
- dark current from linac (E_{max} = 44 MeV → ΔE > 13%) will be lost in the 1st arc bend

Only dark current from gun will potentially reach the recirculator!

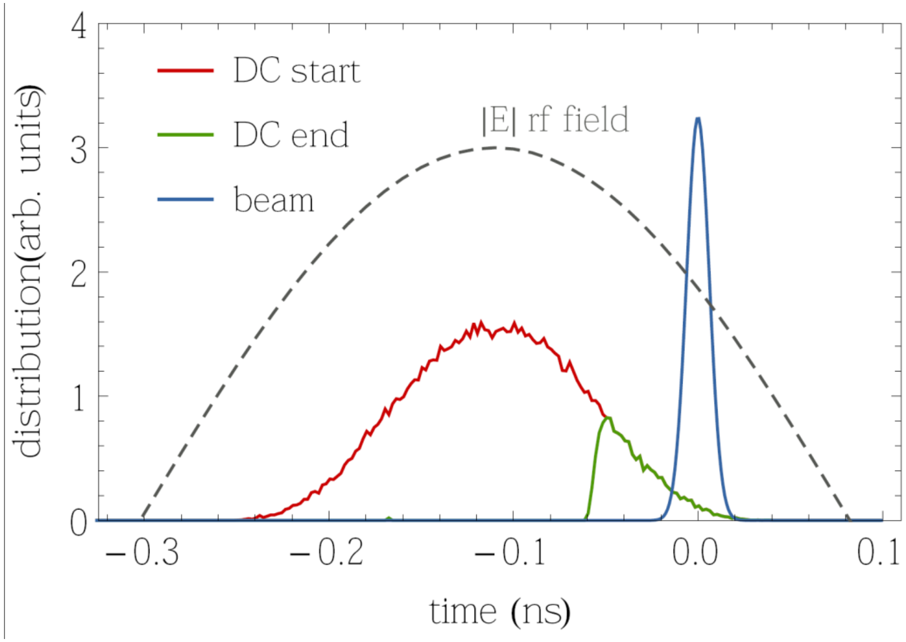
Dark Current: field emission from gun cathode

Field Emission from gun cathode

- Fowler Nordheim: φ = 1.9 eV, β = 200, E_{max} = 30 MV/m
- tracking trough merger incl. SC of reference bunch
- x-y apertures in booster & merger → loss distribution

$$j(E) = \frac{A_{FN}(\beta_{FN}E)^2}{\varphi} \exp\left(-\frac{B_{FN}\varphi^{\frac{3}{2}}}{\beta_{FN}E}\right)$$

E – electric field, φ – work function



S. Wesch

ERL Beam Dynamics: Unwanted Beam

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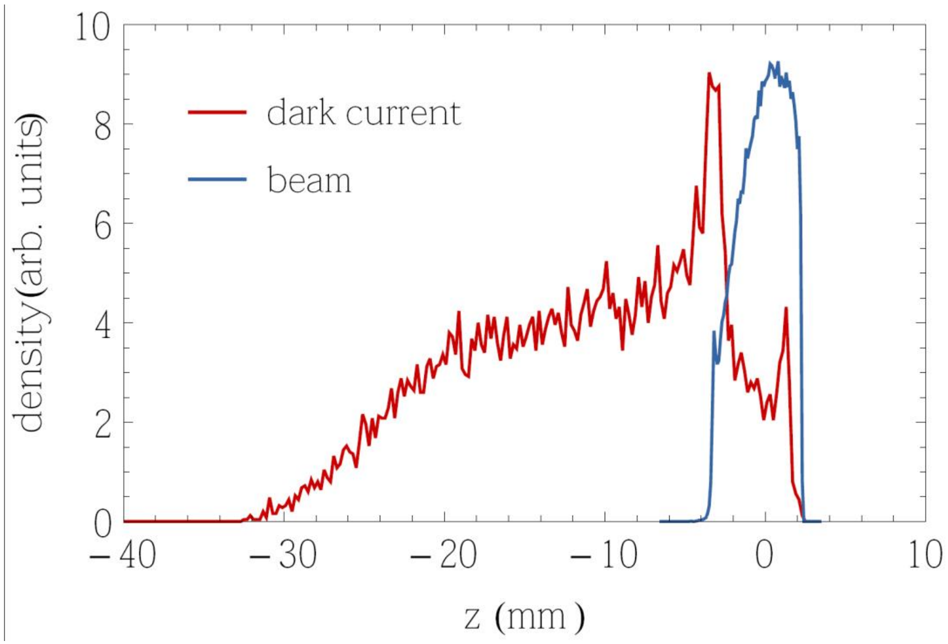

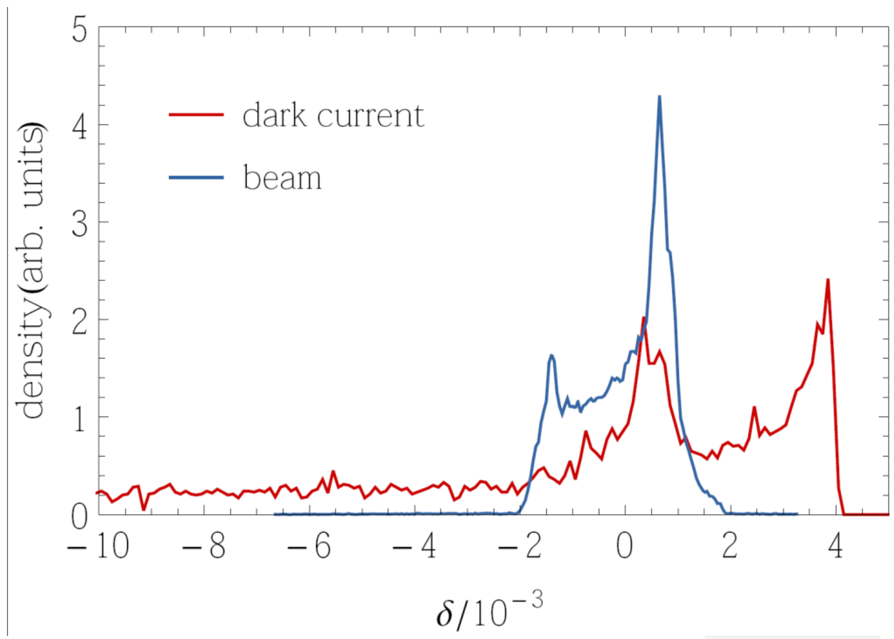

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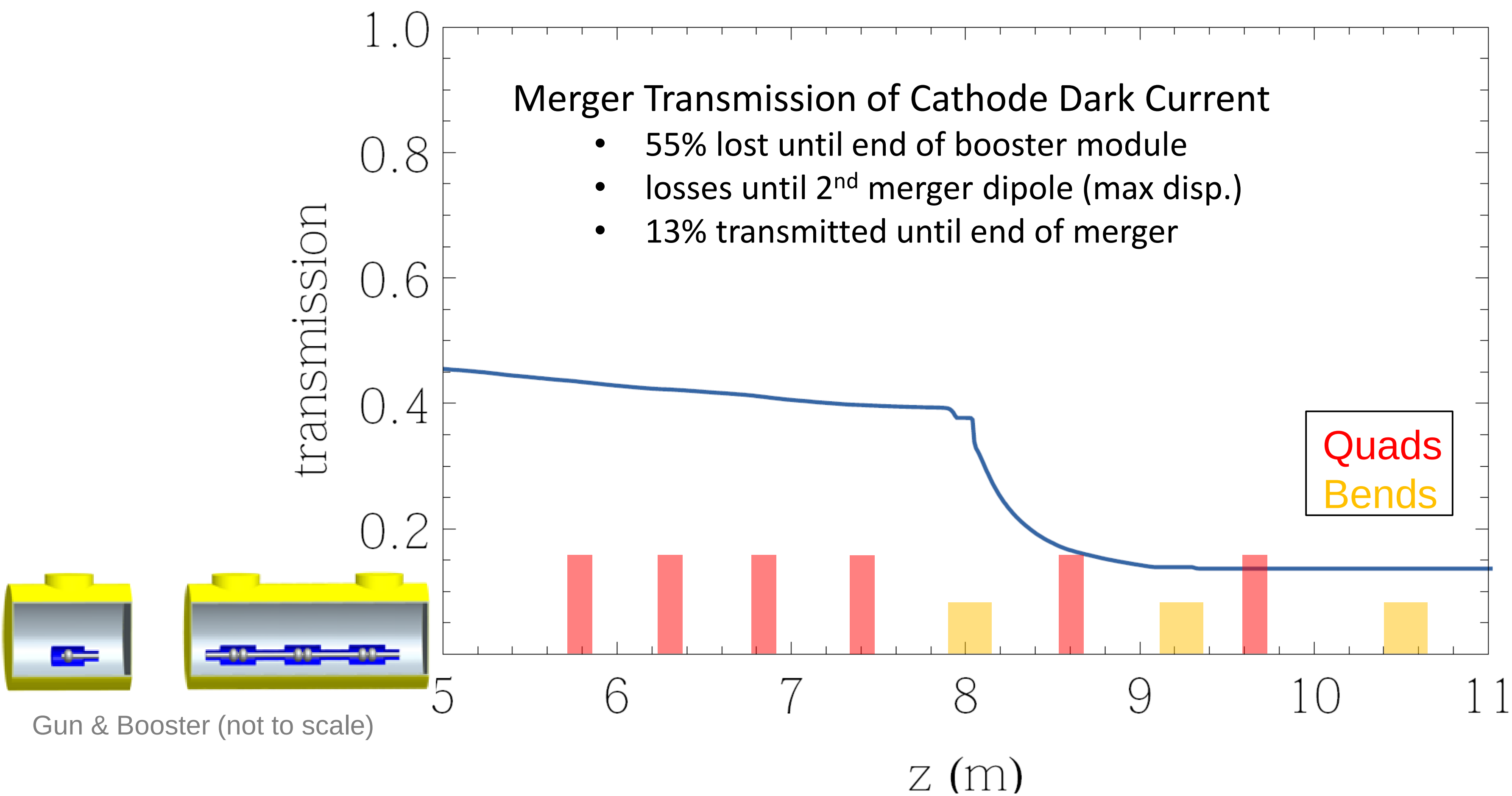

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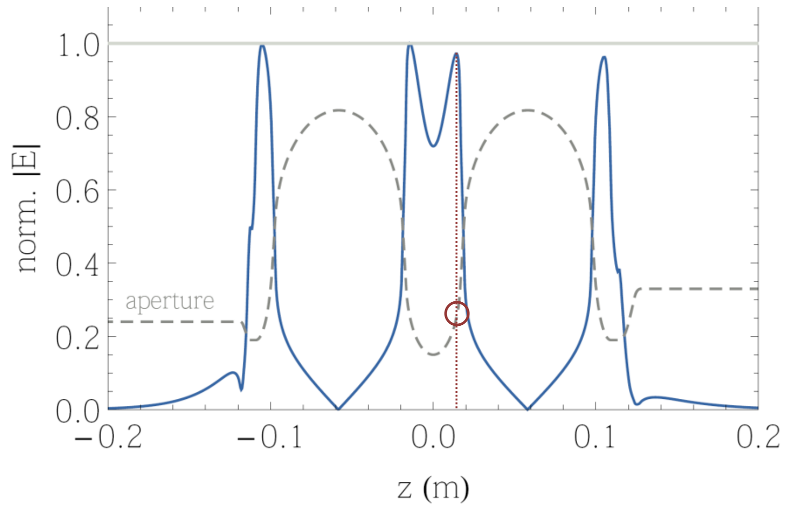
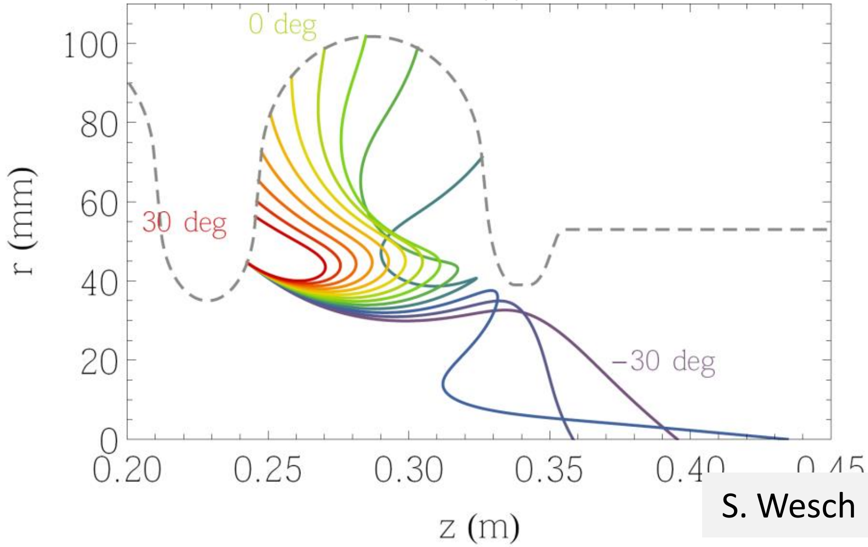
Dark Current: field emission from booster cavity

Dark current simulations booster cavity:

- calculate trajectories of field emitted electrons inside cavity (2D – cylinder symmetry assumed)
- current weighting according to Fowler-Nordheim: I=f(|E|(t), Φ, β, A)

Simulation: - $|E|_{max} = E_{max,on\_axis}$ = 20MV/m
- FN parameter: β=100, Φ_{Nb} = 4.3 eV
- emission phase: -30 … +30 degree
- emission point: max. cavity wall field





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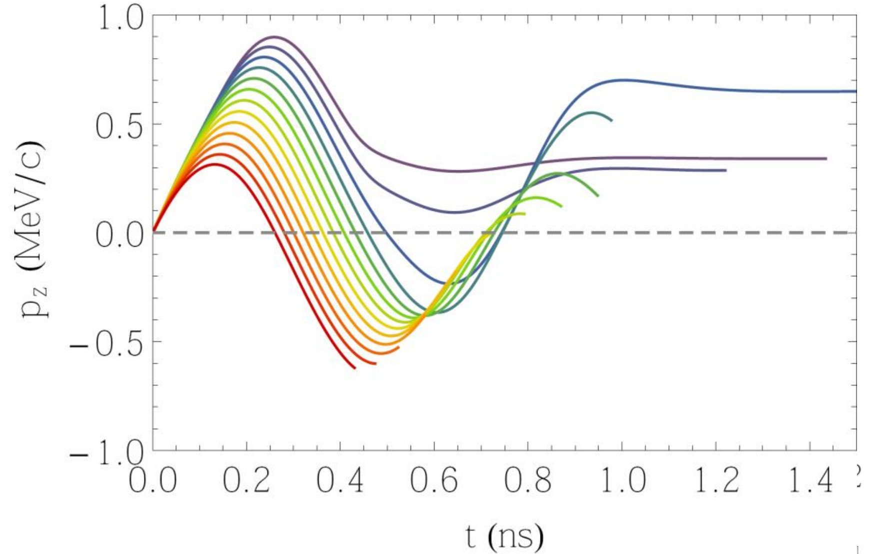

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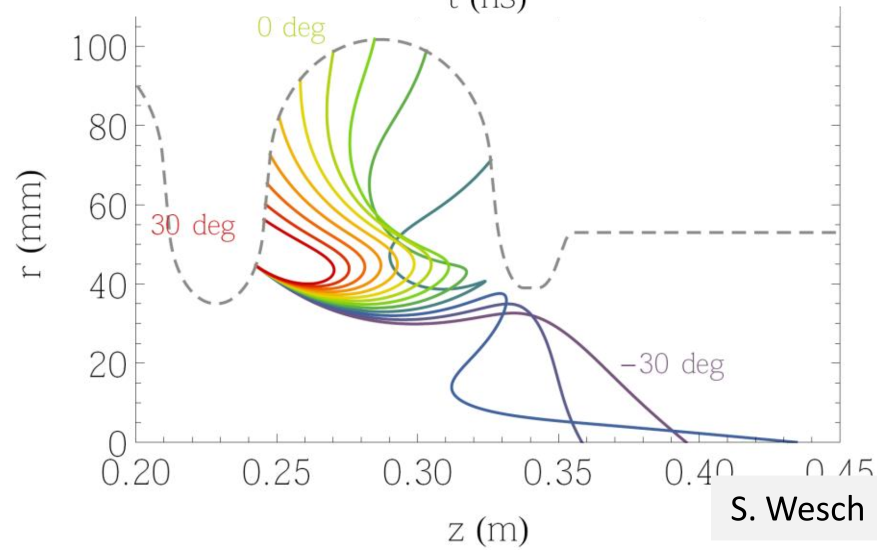


Extended Simulations:

- emission from various points on the cavity wall & collect parameters of escaping electrons to track them downstream the machine
- equivalent study for gun cavity

L.Fröhlich PhD Thesis, "Machine Protection for FLASH and the European XFEL", University Hamburg, 2009.

S. Wesch

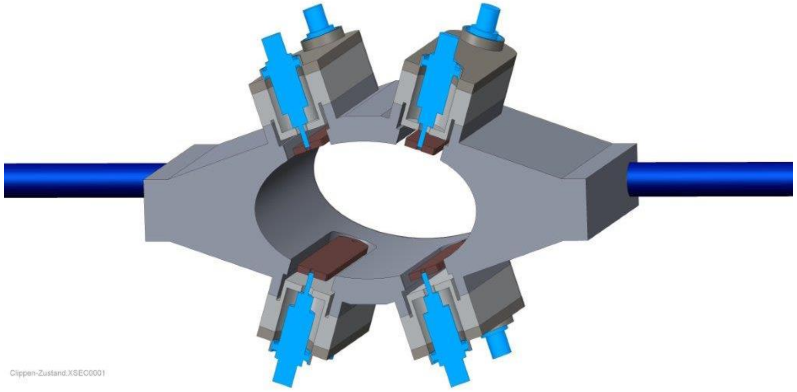
Ion Trapping: electric potential of high current beam attracts & traps residual gas ions

trapped ions leading to:

- **additional focusing → disturb beam optics**
- **increased pressure → increased losses (radiation)**

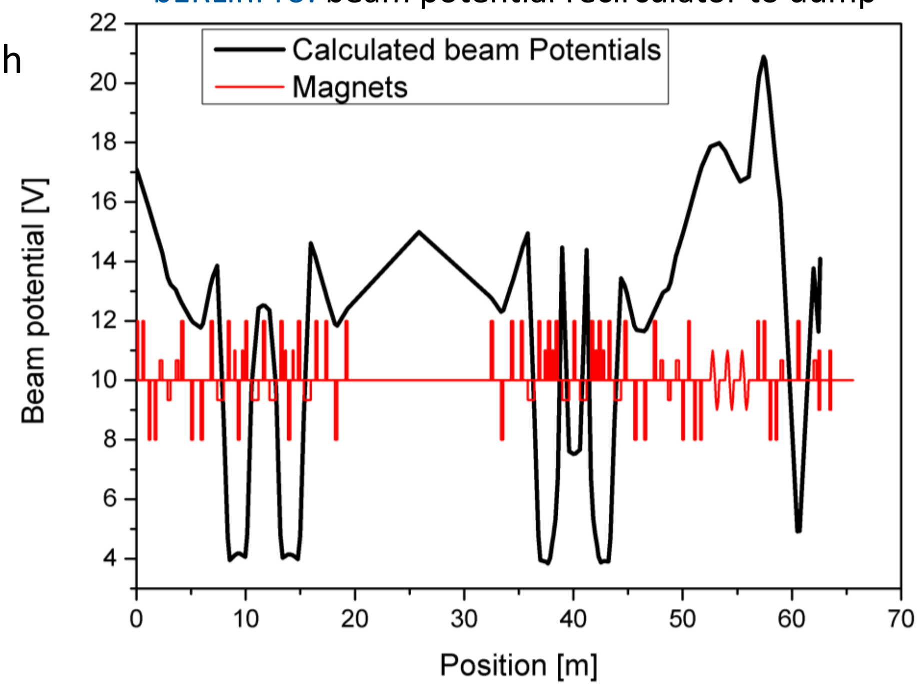
Countermeasures:

- bunch gap: reduced current / increased bunch charge → ε growth, stability of rf systems
- low pressure: ~ 10^{-10} mbar → $$$
- clearing electrodes (static, dynamic)



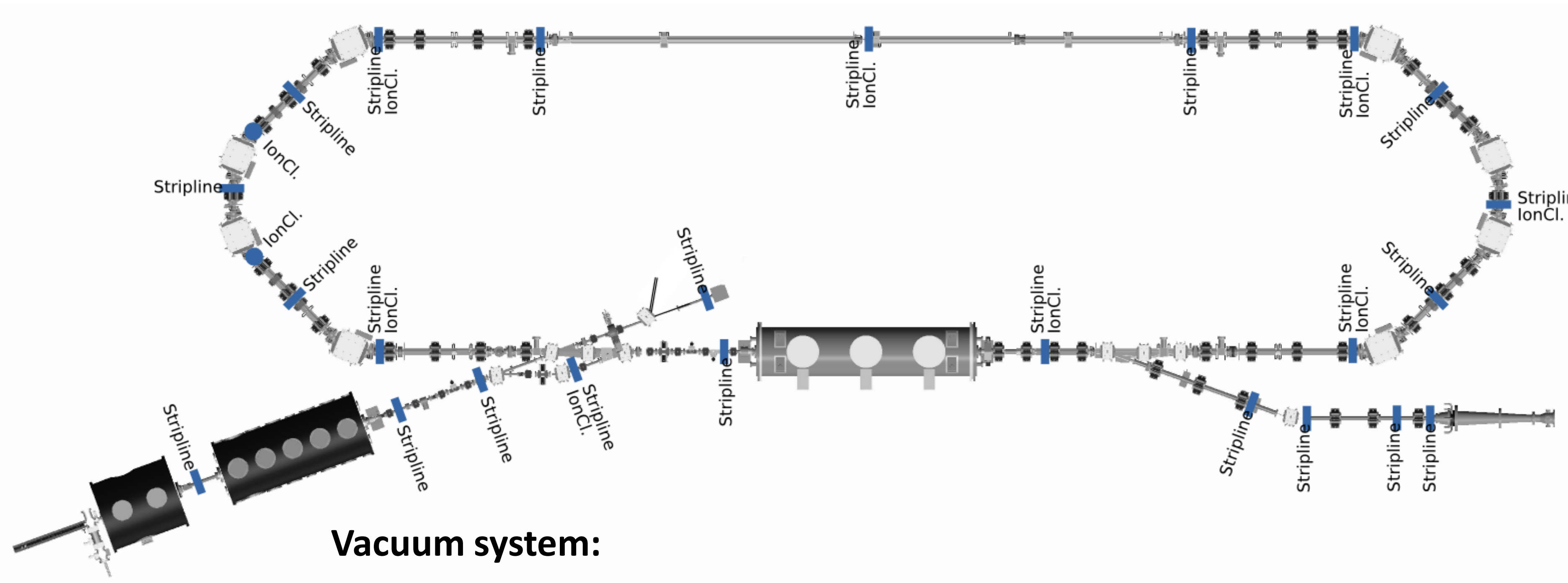
bERLinPro: Stripline BPMs with HV connectors

bERLinPro: beam potential recirculator to dump



G. H. Hoffstaetter, M. Liepe, NIM A 557 (2006) 205–212.
G. Pöplau et. al, Phys. Rev. ST Accel. Beams 18, 044401 (2015).

Ion Trapping: bERLinPro vacuum system & clearing electrodes



Vacuum system:

- ~ 3000 l/s pumping speed (vacuum pumps)
- NEG coating in all straight recirculator chambers, dipole chambers ?

Clearing electrodes:

- 8 shared beam position stripline monitors with HV: **"Stripline IonCl."**
- 2 extra "Button-devices" exclusively for cleaning