Potential of Non-Standard Emittance Damping Schemes for Linear Colliders

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1) rf wiggler & rf undulator
2) s.c. linac wiggler

presented at 9th Int'l. ATF Coll. Mtg. & APAC'04

Motivation

CLIC damping ring pushes limits of conventional design approach. It is based on arcs with TME cells & 2 straight sections with magnetic wigglers of 20-cm period (could be reduced by a factor 2-3 possibly).
Final emittances are determined by interplay of quantum excitation, radiation damping, and intrabeam scattering for design bunch population N_b=3x10^9.

Normalized rms emittance	Design goal	Achieved by present optics
longitudinal	9.8 mm	8.1 mm
horizontal	450 nm	578 nm
vertical	3 nm	8.1 nm

RF Damping

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- idea of RF wiggler & RF undulator
- parameters
- damping time
- equilibrium emittances for wigglers & undulators, including IBS
- two damping rings based on RF damping
- what can be done at the ATF?

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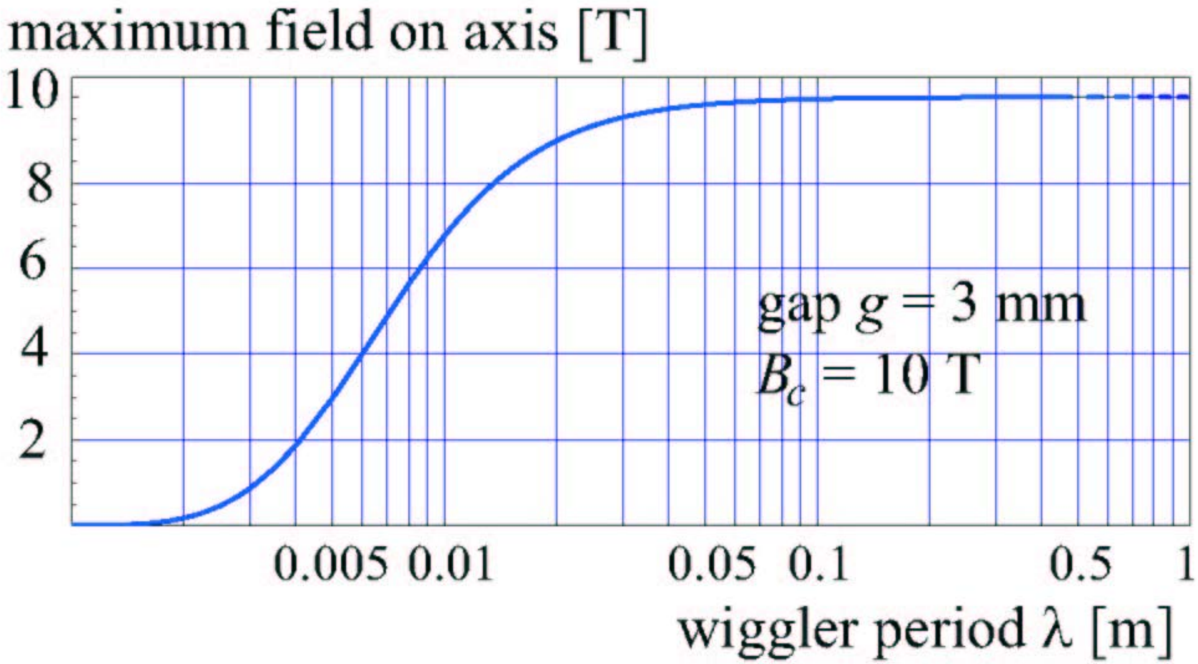
Idea of RF Wiggler

- quantum excitation and horizontal IBS growth growth rate scale as the square of the wiggler period
- radiation damping depends on magnetic field and is independent of the period
- however, for conventional, e.g., sc, magnets, maximum magnetic field is the smaller the shorter the period



example calculation for superconducting wiggler if we use RF to wiggle the beam, we can have very short periods

$$\lambda_p \sim \lambda_{rf} / 2$$

and at the same time a high magnetic field,e.g., for TE10 mode in a rectangular waveguide (disk-loaded structures may reach higher fields still)

$$\hat{B} = \sqrt{\frac{4(\omega / c + k_z)^2 \mu_0}{ba\omega k_z} P_{rf}} \quad \text{where} \quad k_z = \sqrt{(\omega / c)^2 - (\pi / a)^2}$$

Note: several authors studied the application of RF wigglers for synchrotron-light generation; a first (and so far only?) prototype was designed and built by T. Shintake and his colleagues, and operated at the KEK photon factory e^- linac around 1982/83.

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Development of Microwave Undulator

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A microwave undulator which uses transverse fields of standing microwaves the been operated successfully at the Photon Factory electron linac. The undulator consists of a long rectangular cavity with two ridges. Using a pulsed S-band microwave of 300 kW and a pulsed electron beam, the undulator radiation was observed in the visible region, and the spectral intensities were measured. The equivalent magnetic field and the period are 430 Gauss and 5.5 cm, respectively.

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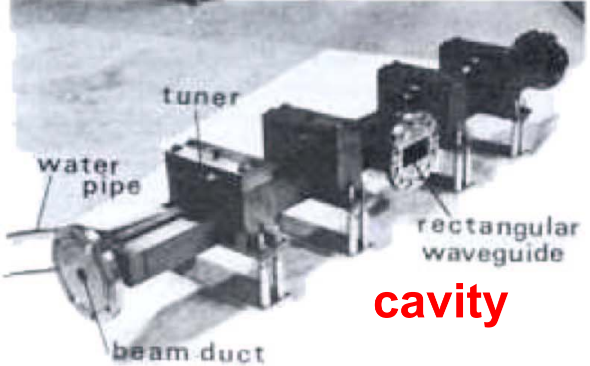
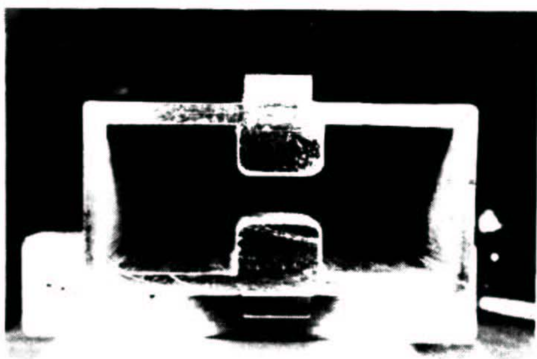
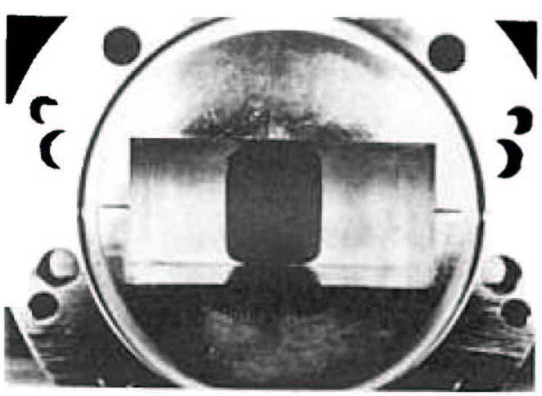


(a)



cross sectional view before welding

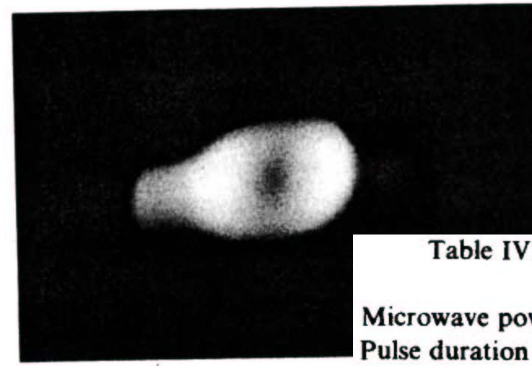
(b)



coupling hole

(c)

Fig. 5. Photographs of undulator cavity. (a) Completed cavity. (b) Cross-sectional view, before welding beam duct. (c) Coupling hole. Front is rectangular waveguide WRJ-3.

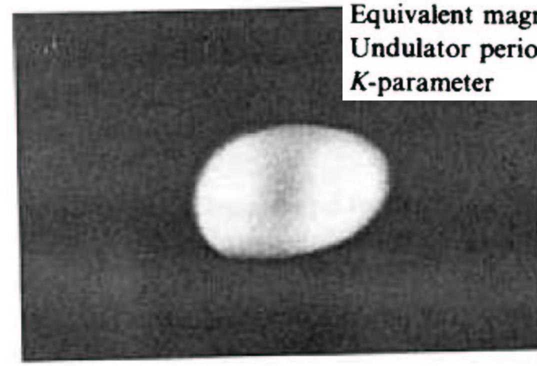


rf undulator light without filter, e^- energy 151 MeV

(a)

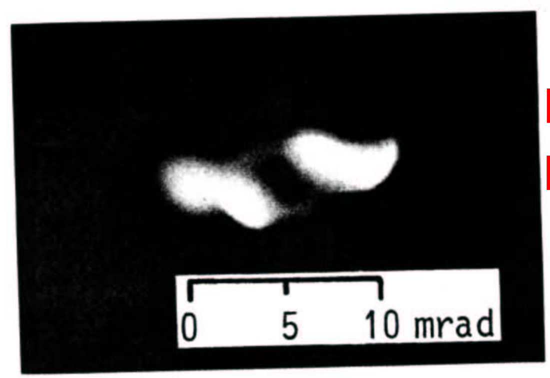
Table IV. Microwave and undulator parameters.

Microwave power	300 kW
Pulse duration	4 μsec
Repetition rate	10 pps
Peak electric field	12.8 MV/m
Equivalent magnetic field	430 Gauss
Undulator period	5.5 cm
K-parameter	0.24



vertical polarizer

(b)

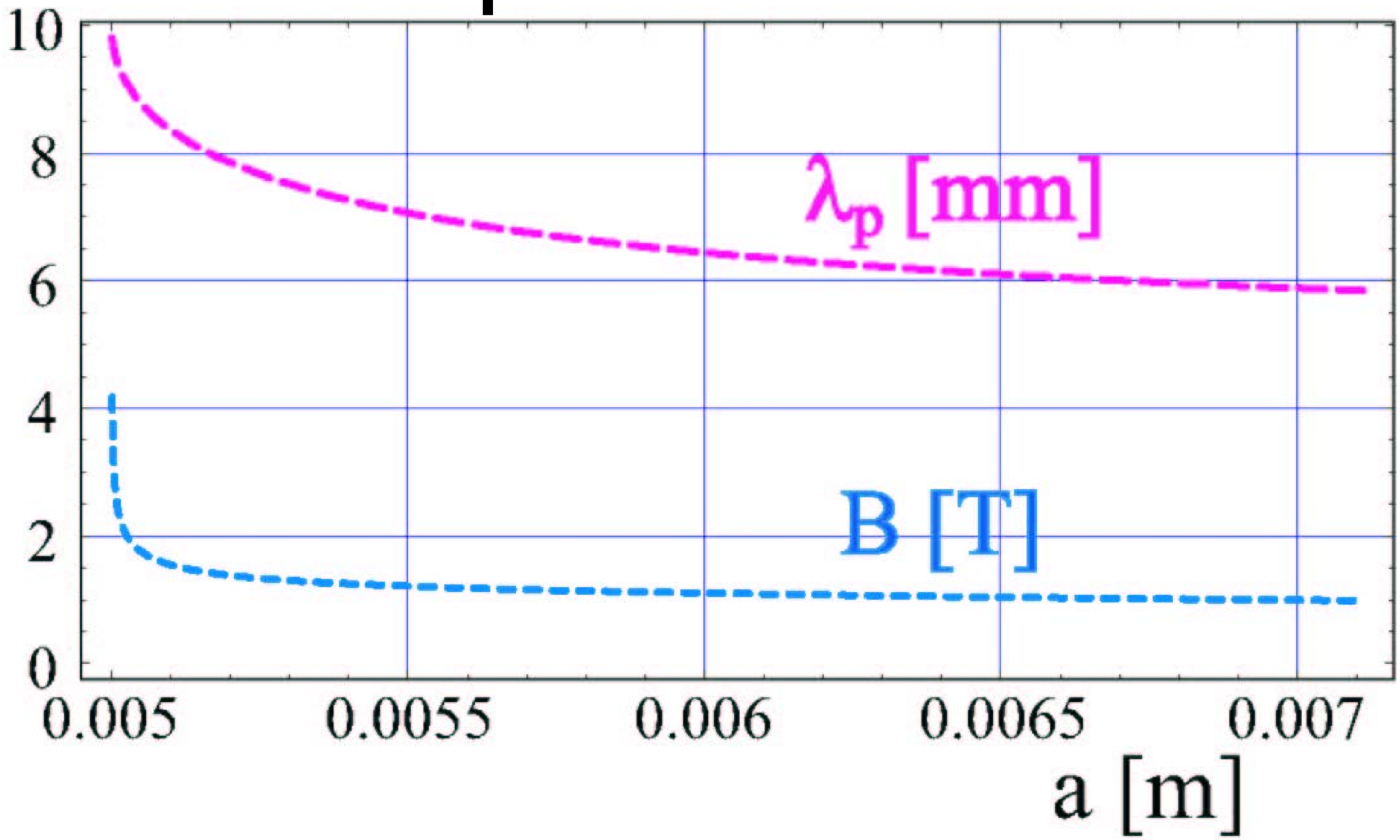


horizontal polarizer

(c)

Fig. 11. Phtographs of undulator light at beam energy of 151 MeV. (a) Without filter. Blue center and red outside are intrinsic property of undulator light. (b) With vertical polarizer. (c) With horizontal polarizer.

Example Parameters



Peak magnetic field (bottom curve) and equivalent wiggler period (top curve) for a TE10 mode at 200 MW at 30 GHz, propagating in a waveguide of height *b*=2 mm as a function of the waveguide width *a*.

Depending on the available rf power and on breakdown limits, such device may operate as an *rf undulator* rather than an as an *rf wiggler*.

The undulator regime is roughly defined by

$$\lambda_p \hat{B} < 0.01\,\mathrm{T\,m}$$

where $\hat{B}$ denotes the equivalent peak field.

Damping Time

For both wiggler and undulator, the transverse amplitude damping time is given by

$$\tau_{x,y} = 4/(aE\hat{B}^2 cR)$$

where E is the energy in GeV,

$\hat{B}$ the peak magnetic field

$$a = 2c^2 e^2 r_e/(3(m_e c^2)^3) \approx 1.3x10^{-6}\ \mathrm{GeV^{-1}m^{-1}T^{-2}}$$

and R the wiggler filling factor.

Equilibrium Emittances

- **balance of radiation damping, quantum excitation, and IBS**

- **dispersive quantum excitation and intrabeam scattering in X plane** are proportional to Sand's **curly-*H*** function, whose average value, for a sinusoidal field, we approximate as

$$\langle H \rangle \approx \beta \lambda_p^2 (e\hat{B}c)^2 / (8\pi^2 E^2)$$

- **quantum excitation in the vertical plane, and for an undulator also in X plane**, are determined by **opening angle** effect. For a wiggler, this was computed by **Hirata [SLAC AAS-Note 80 (1993)]**, for an undulator partially by **Hofmann [SSRL ACD-Note 41 (1986)]** and, considering Compton scattering off a laser rather than an rf wave, by **Huang and Ruth [PRL 80, 5, p. 976 (1998)]**

- we approximate the **excitation from IBS** by averaging **Bane's formula** [EPAC2002 Paris (2002)], itself a simplification of Part. Acc. 13, 115 (1983)].

equilibrium emittances for a **wiggler** (w/o arcs)

$$\varepsilon_{N;x} = 2\frac{b_{1,w}}{a}\beta_x\lambda_p^2\hat{B}^3 + 2\frac{b_{2,w}}{a}\beta_x\hat{B} + \frac{\lambda_p^2\beta_x^{3/4}}{\beta_y^{1/4}}\frac{2h}{aE^{7/2}}\frac{g(\alpha)}{\varepsilon_{N,x}^{3/4}\varepsilon_{N,y}^{3/4}\sigma_s}$$

$$\varepsilon_{N;y} = 2\frac{b_{2,w}}{a}\beta_x\hat{B} + \kappa\frac{\lambda_\mathrm{p}^2\beta_x^{3/4}}{\beta_y^{1/4}}\frac{2h}{aE^{7/2}}\frac{g(\alpha)}{\varepsilon_{N;x}^{3/4}\varepsilon_{N;y}^{3/4}\sigma_s}$$

$$\varepsilon_{N;s}^2 = \frac{g_w}{a}\hat{B}E^3\sigma_s^2 + \frac{f}{a}\frac{\sigma_s g(\alpha)}{\beta_x^{1/4}\beta_y^{1/4}E^{1/2}\hat{B}^2\varepsilon_{N,x}^{3/4}\varepsilon_{N,y}^{3/4}}$$

$$\kappa \approx 1\%$$

$$g_w = \frac{55}{36\sqrt{3}\pi}\frac{c^4e^3r_e\hbar}{(m_ec^2)^8} \approx 9.0\times10^{-6}\frac{1}{\mathrm{m\,GeV^4\,T^3}}$$

$$b_{1,w} = \frac{55}{288\sqrt{3}\pi^3}\frac{c^6e^5r_e\hbar}{(m_ec^2)^7} \approx 5.24\times10^{-13}\frac{1}{\mathrm{m^3\,GeV\,T^5}}$$

$$b_{2,w} = \frac{13}{36\sqrt{3}\pi}\frac{c^4e^3r_e\hbar}{(m_ec^2)^5} \approx 2.84\times10^{-17}\frac{1}{\mathrm{m\,GeV\,T^3}}$$

$$h = \frac{r_e^2N_b(\log)e^2c^2}{64\pi^2}(m_ec^2)^{1/2} \approx 6.06\times10^{-25}\frac{N_b}{10^9}\frac{\mathrm{GeV}^{5/2}}{\mathrm{T}^2}$$

$$\alpha = \sqrt{\frac{\beta_x\varepsilon_y}{\beta_y\varepsilon_x}} \quad \text{and} \quad g(\alpha) \approx \alpha^{(0.021-0.044\ln\alpha)}$$

$$f = \frac{r_e^2N_b(\log)}{8(m_ec^2)^{1/2}} \approx 1.04\times10^{-18}\frac{N_b}{10^9}\mathrm{m}^2\frac{1}{\mathrm{GeV}}$$

equilibrium emittances for an **undulator** (w/o arcs)

$$\varepsilon_{N;x} = 2\frac{b_{1,u}}{a}\beta_x\lambda_P\hat{B}^2 + 2\frac{b_{2,u}}{a}\beta_x\frac{1}{\lambda_p} + \frac{\lambda_p^2\beta_x^{3/4}}{\beta_y^{1/4}}\frac{2h}{aE^{9/2}}\frac{g(\alpha)}{\varepsilon_{N,x}^{3/4}\varepsilon_{N,y}^{3/4}\sigma_s}$$

$$\varepsilon_{N,Y} = 2\frac{b_{2,u}}{a}\beta_y\frac{1}{\lambda_p} + \kappa\frac{\lambda_p^2\beta_x^{3/4}}{\beta_x^{1/4}}\frac{2h}{aE^{9/2}}\frac{g(\alpha)}{\varepsilon_{N,x}^{3/4}\varepsilon_{N,y}^{3/4}\sigma_s}$$

$$\varepsilon_{N;s}^2 = \frac{g}{a}\frac{1}{\lambda_p}E^3\sigma_s^2 + \frac{f}{a}\frac{\sigma_s g(\alpha)}{\beta_x^{1/4}\beta_y^{1/4}E^{1/2}\hat{B}^2\varepsilon_{N,x}^{3/4}\varepsilon_{N,y}^{3/4}}$$

$$b_{1,u} = \frac{7}{30\pi}\frac{c^4e^4r_e}{\left(m_ec^2\right)^6}\hbar c \approx 1.86\times10^{-23}\frac{1}{\mathrm{GeV\,T^4m^2}}$$

$$b_{2,u} = \frac{\pi c^2e^2r_e}{\left(m_ec^2\right)^4 5}\hbar c \approx 4.6\times10^{-19}\frac{1}{\mathrm{GeV\,T^2}}$$

$$g_u = \frac{7\pi}{15}\hbar c\frac{c^2e^2r_e}{(m_ec^2)^7} \approx 8.0\times10^{-9}\frac{1}{\mathrm{GeV}^4T^2}$$

Equilibrium Energy Spread

wiggler

$$\sigma_{\delta,w} = \sqrt{\frac{55}{24\sqrt{3}\pi}\frac{\lambda\!\!\!^{-}{}_e eB\gamma}{m_e c}}$$

undulator

$$\sigma_{\delta,u} = \sqrt{\frac{7\pi}{10}\frac{\lambda\!\!\!^{-}{}_e \gamma}{\lambda_p}}$$

note that the period λ_p is smaller than for magnets, but much larger than for a laser; therefore the energy spread stays reasonable in the undulator regime

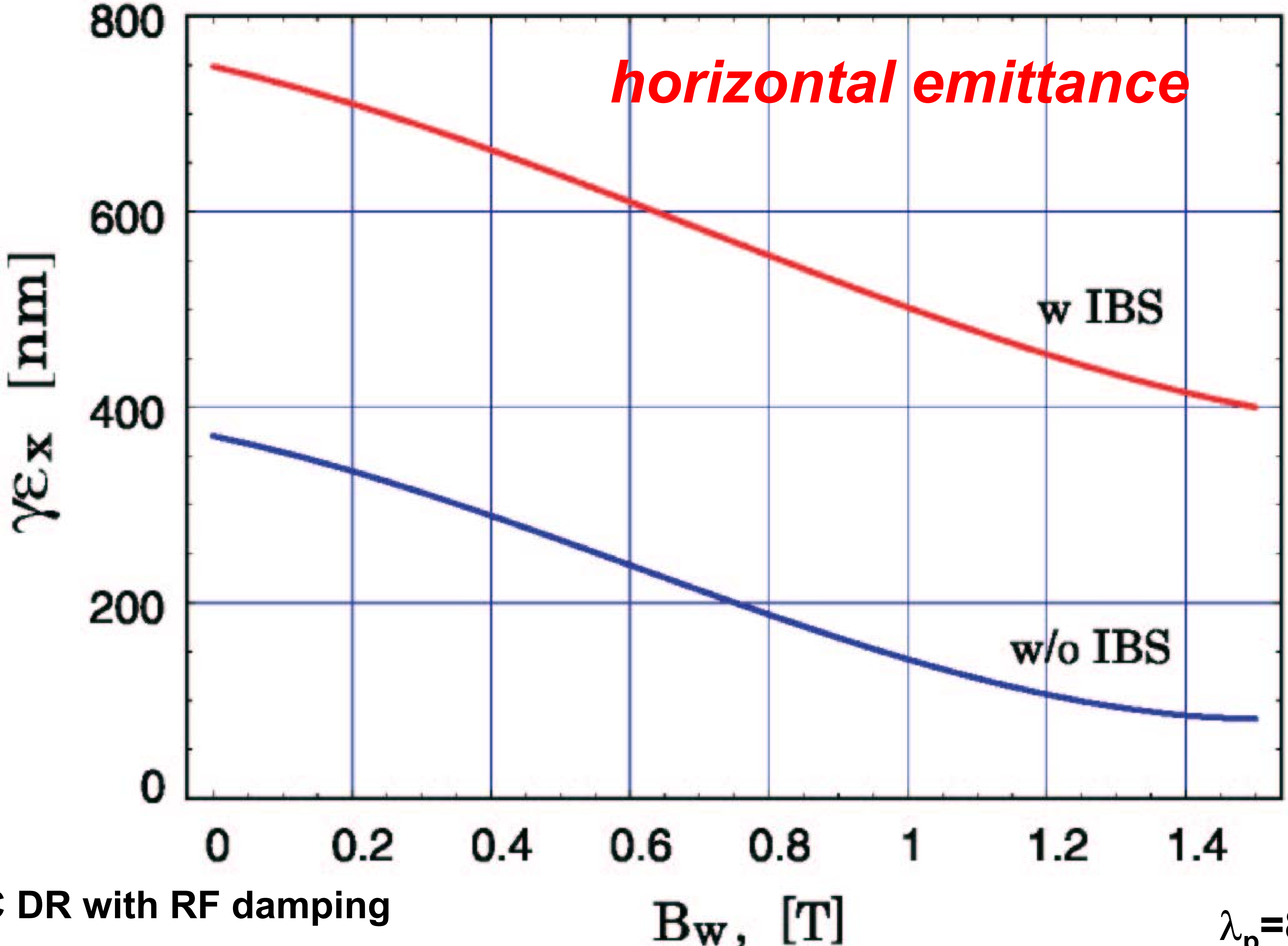
Two Example Rings

in the present CLIC damping ring design replace magnetic wigglers [160 m at 1.76 T] either by rf wigglers or by rf undulators operating at 30 GHz; here arc contributions (TME cells with 0.932-T bending field, total length 166 m, bend length 52 m) are included when computing damping times and equilibrium emittances

	RF wiggler	RF undulator		RF wiggler	RF undulator
RF power	200 MW	50 MW	E	2.42 GeV	2.42 GeV
Waveguide dimensions	2, 5.1 mm	2, 7 mm	$\tau_{x,y}$	3.36 ms	11.6 ms
Equivalent peak field	1.5 T	0.5 T	τ_s	1.68 ms	5.8 ms
RF frequency	30 GHz	30 GHz	β	5 m	5 m
Equivalent wave length	8.2 mm	5.9 mm	σ_z	2 mm	3 mm
Equivalent gradient	450 MV/m	150 MV/m	N_b	3×10^9	3×10^9
Parameter Kλ	1.14	0.27	$\gamma\varepsilon_y$ w. (& w/o) IBS	587 nm (73 nm)	924 nm (250 nm)
Circumference	357 m	357 m	$\gamma\varepsilon_y$ w. (& w/o) IBS	5.4 nm (0.3 nm)	7.1 nm (0.3 nm)
Totel undulator length	160 m	160 m	$\gamma\varepsilon_s$ w. (& w/o) IBS	10.8 mm (7.5 mm)	13.2 mm (9.5 mm)

similar or superior to conventional designs!

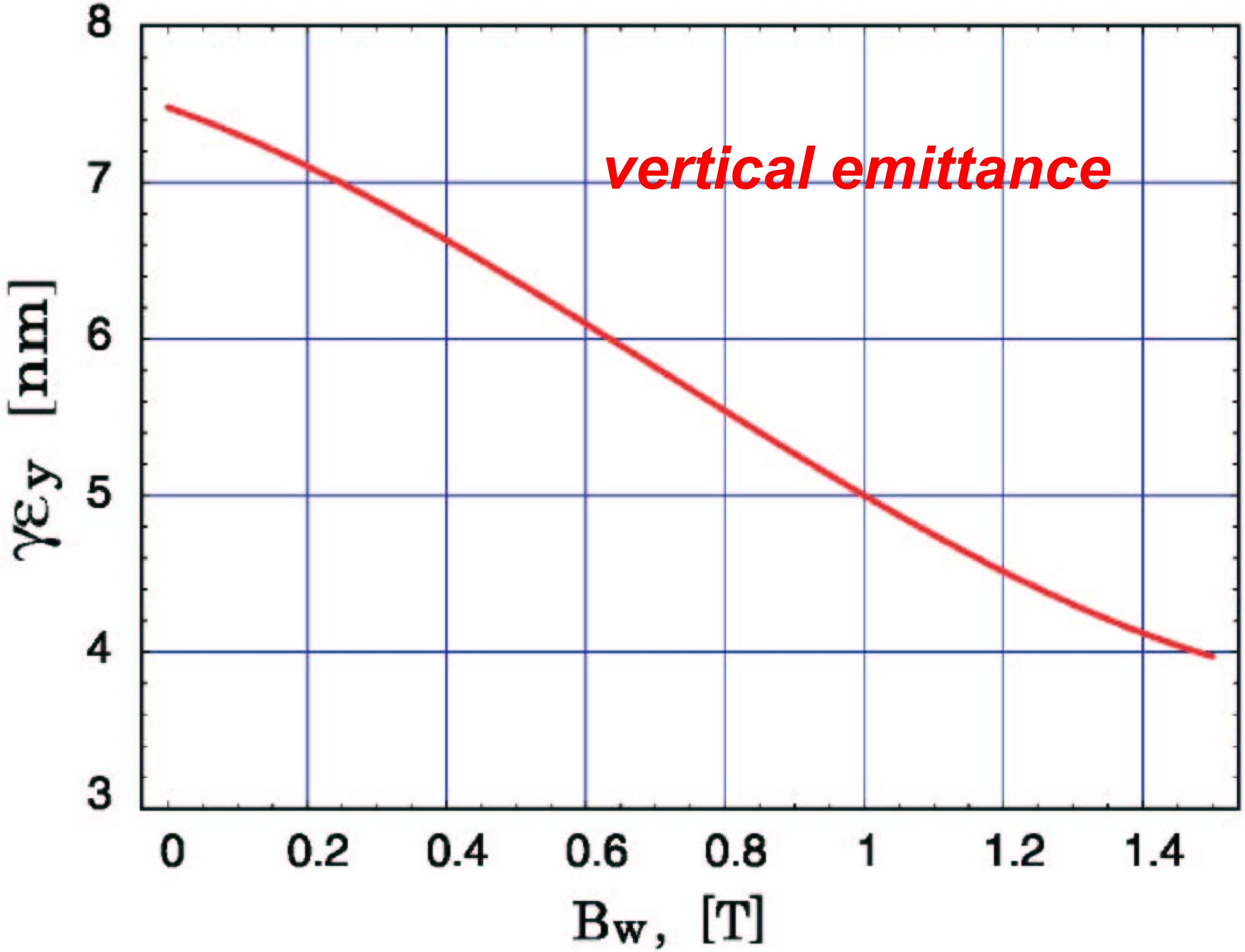
independent calculation by M. Korostelev (different bunch length & possibly differences in expressions; these results are only valid for wiggler regime)



CLIC DR with RF damping

λ_p=8 mm

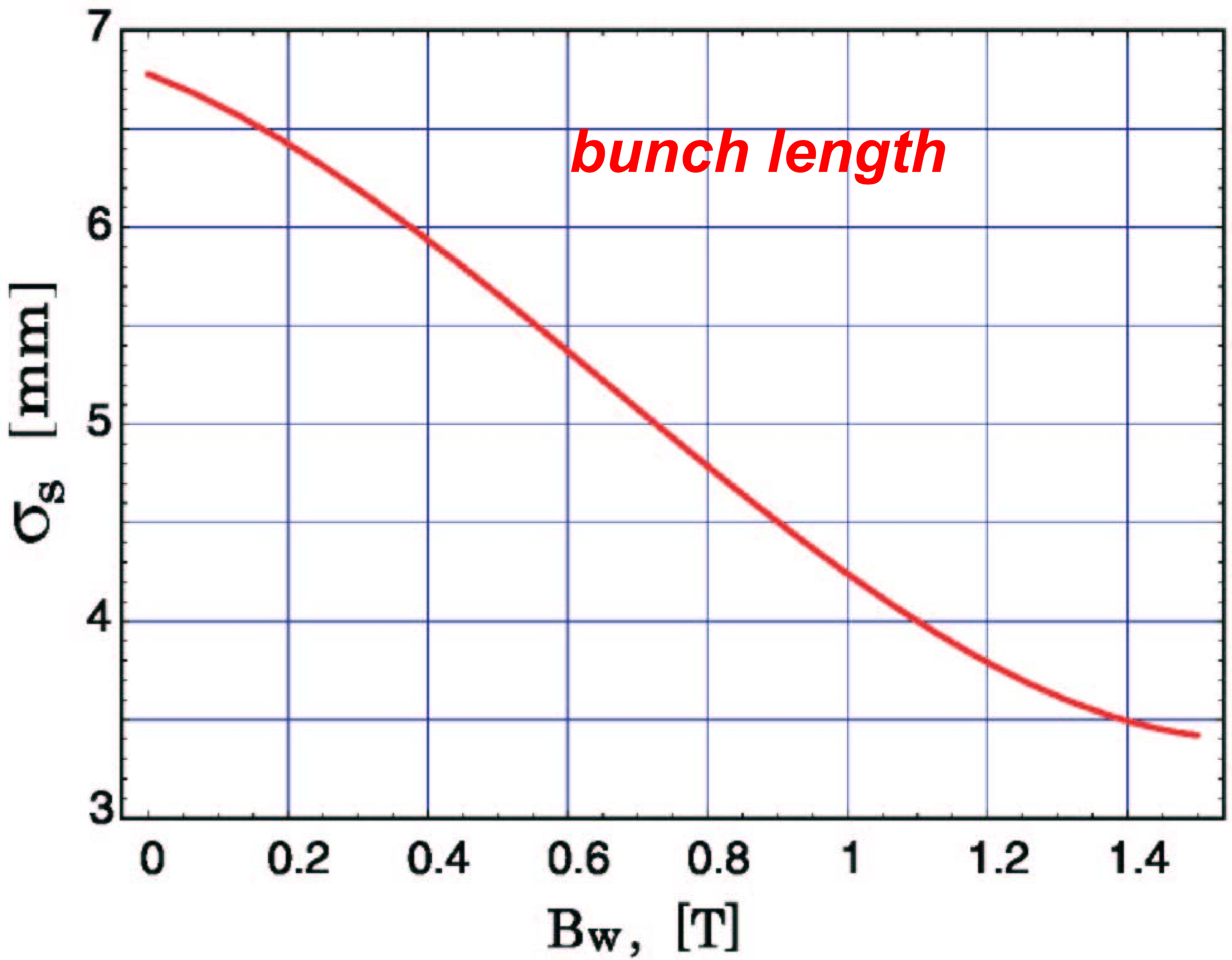
M. Korostelev



CLIC DR with RF damping

λ_p=8 mm

M. Korostelev

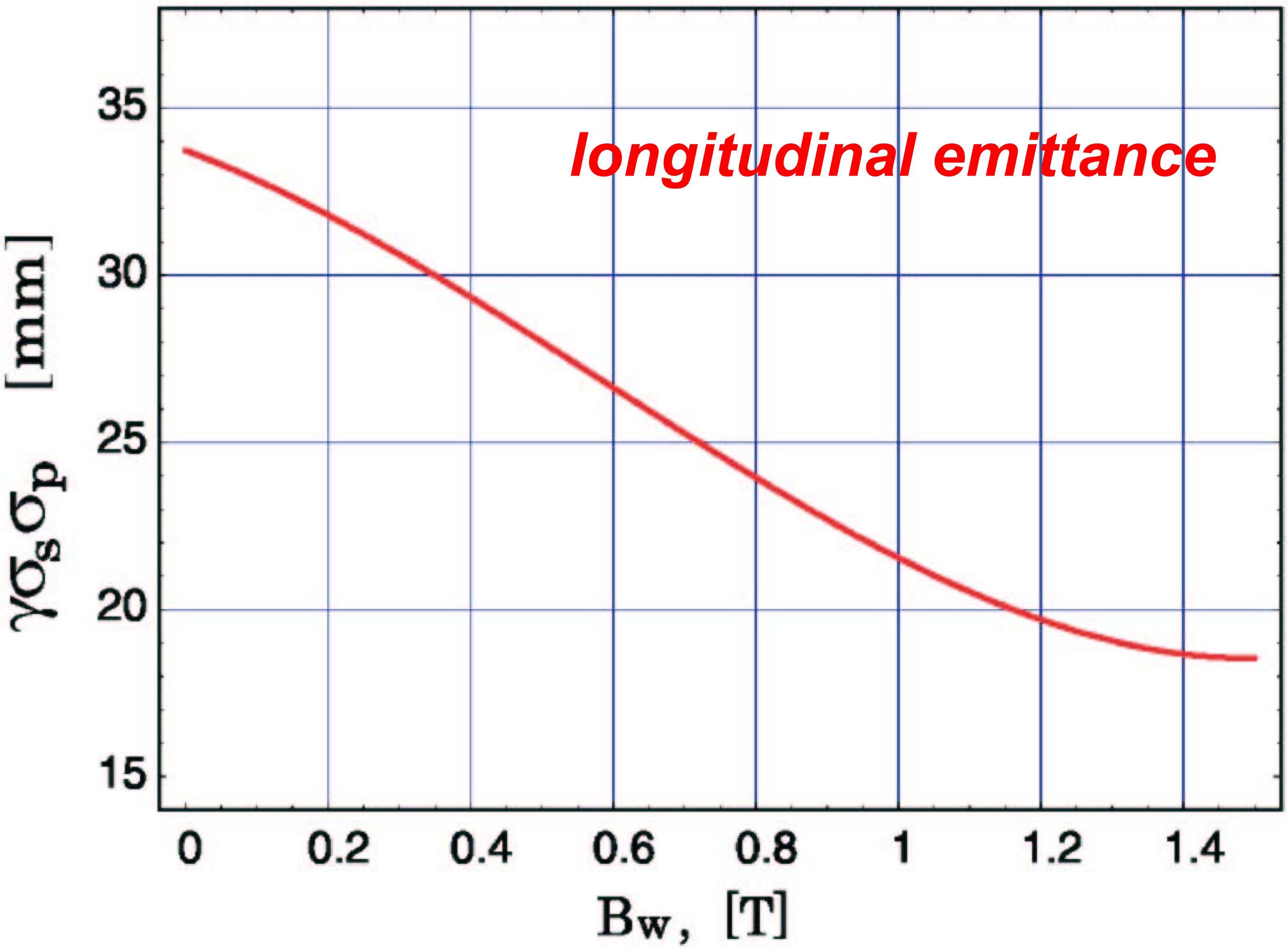


CLIC DR with RF damping

λ_p**=8 mm**

CLIC DR with RF damping

M. Korostelev



λ_p=8 mm

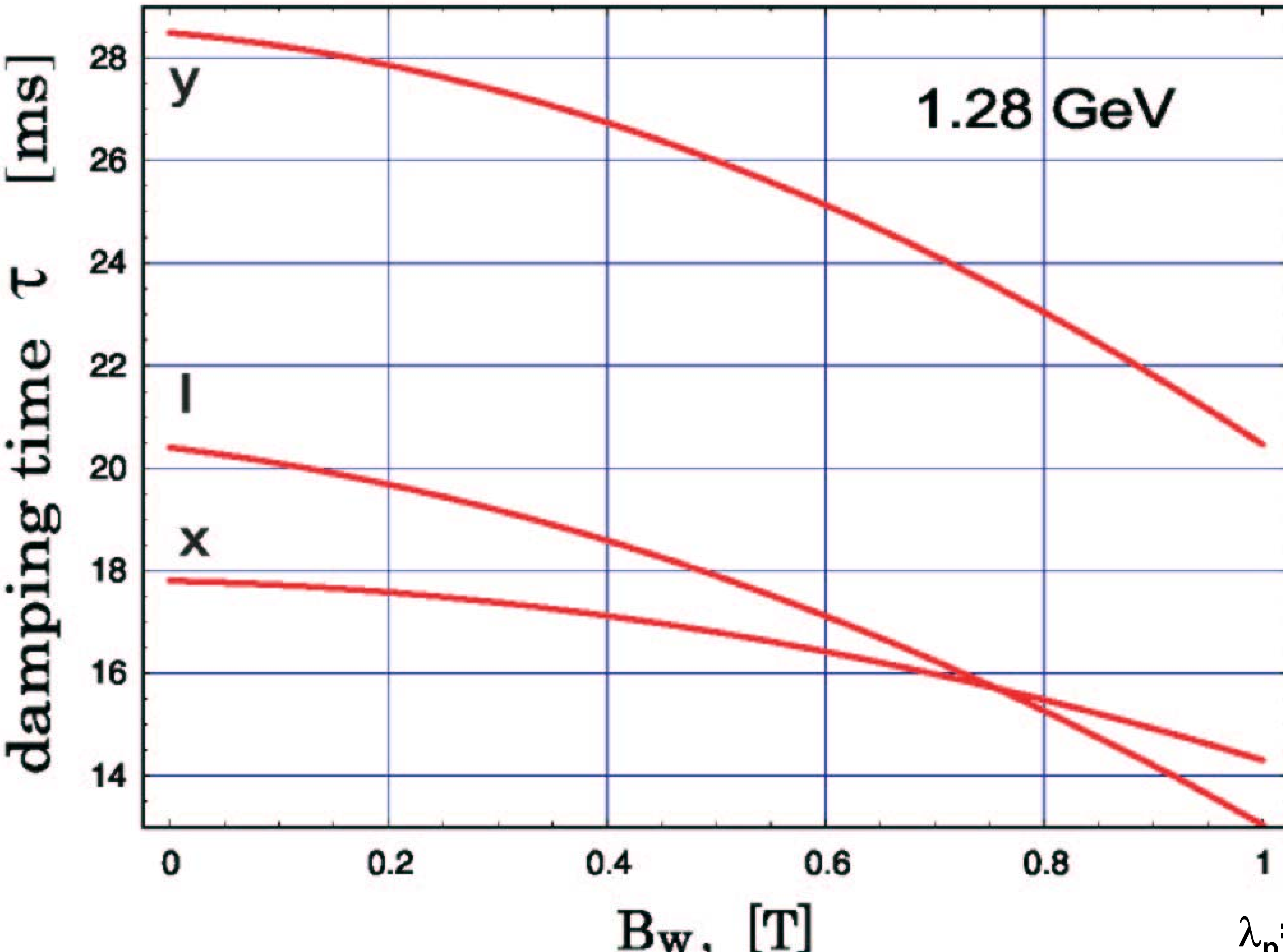
What can be done at the ATF?

- magnetic wigglers, 24 m & 2 T, not in operation
- arc bends, 0.75 T, cover 36 m length
- there are S-band and X-band klystrons that could be used as power source, though better might be dc operation and sc rf

$$\tau_s \approx 3.2\,\mathrm{ms}\,\frac{1.28\ \mathrm{GeV\ T}^2}{E\hat{B}^2}\,\frac{1}{R}$$

- if the rf covers *R*=10% of the ring, this amounts to 32 ms at 1.28 GeV and 1-T equivalent field
- the relative contribution from rf increases for lower beam energy

ATF DR with 16-m RF damping of variable strength



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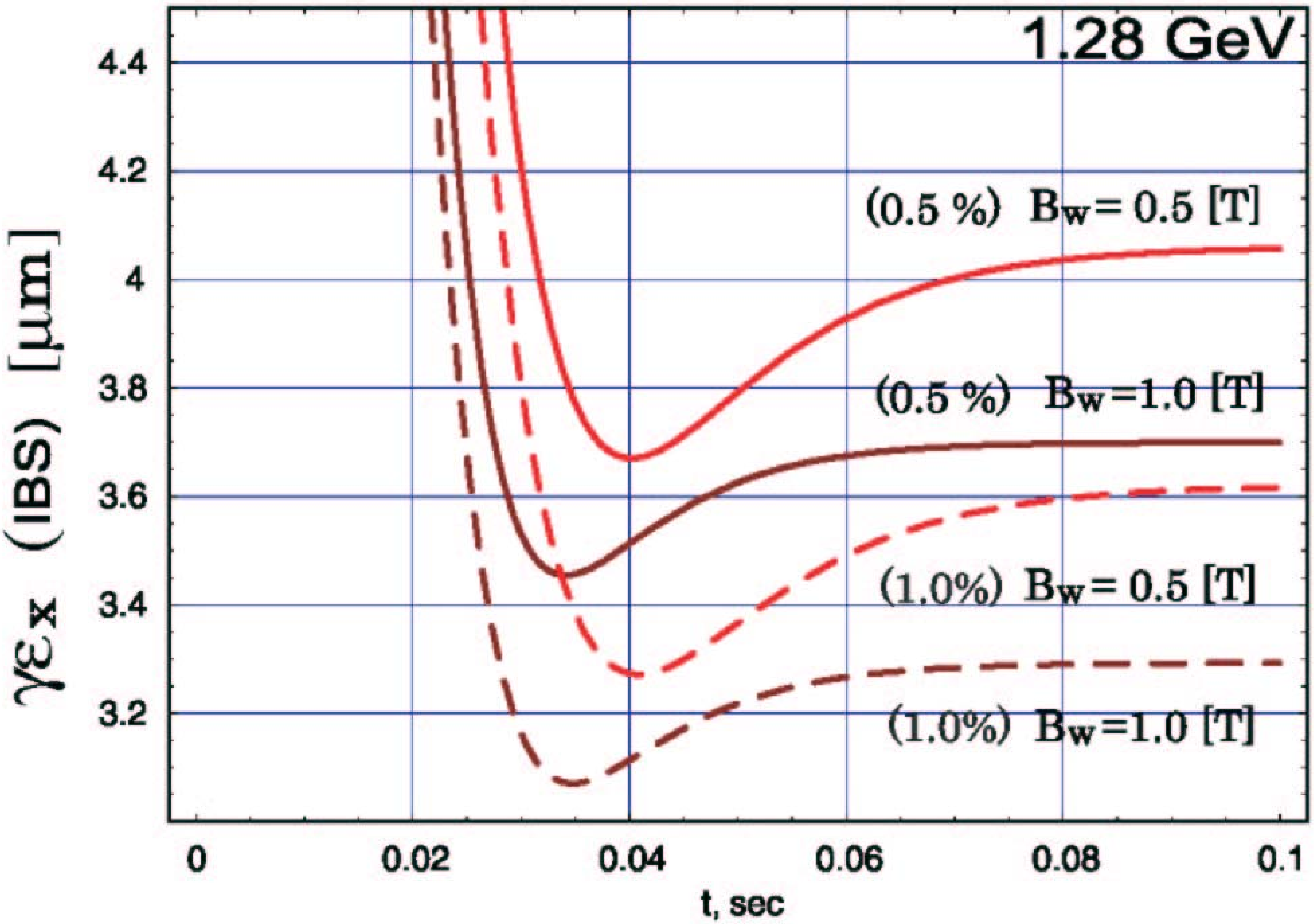
λ_p=8 mm

damping times

ATF DR with 16-m RF damping, 10^{10} e-, IBS coupling 0.5-1.0%



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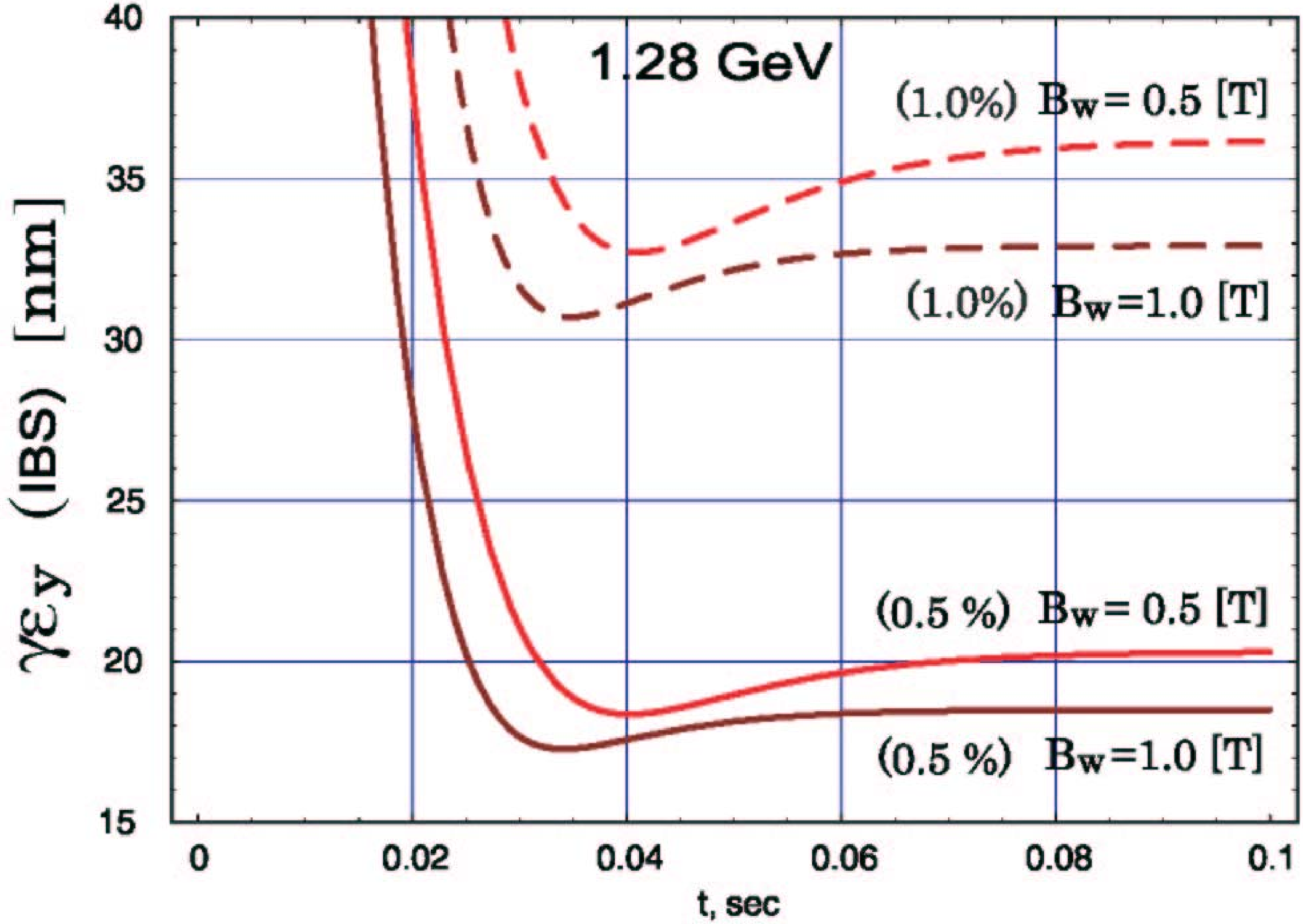
λ_p=8 mm

time evolution X

ATF DR with 16-m RF damping, 10^{10} e-, IBS coupling 0.5-1.0%



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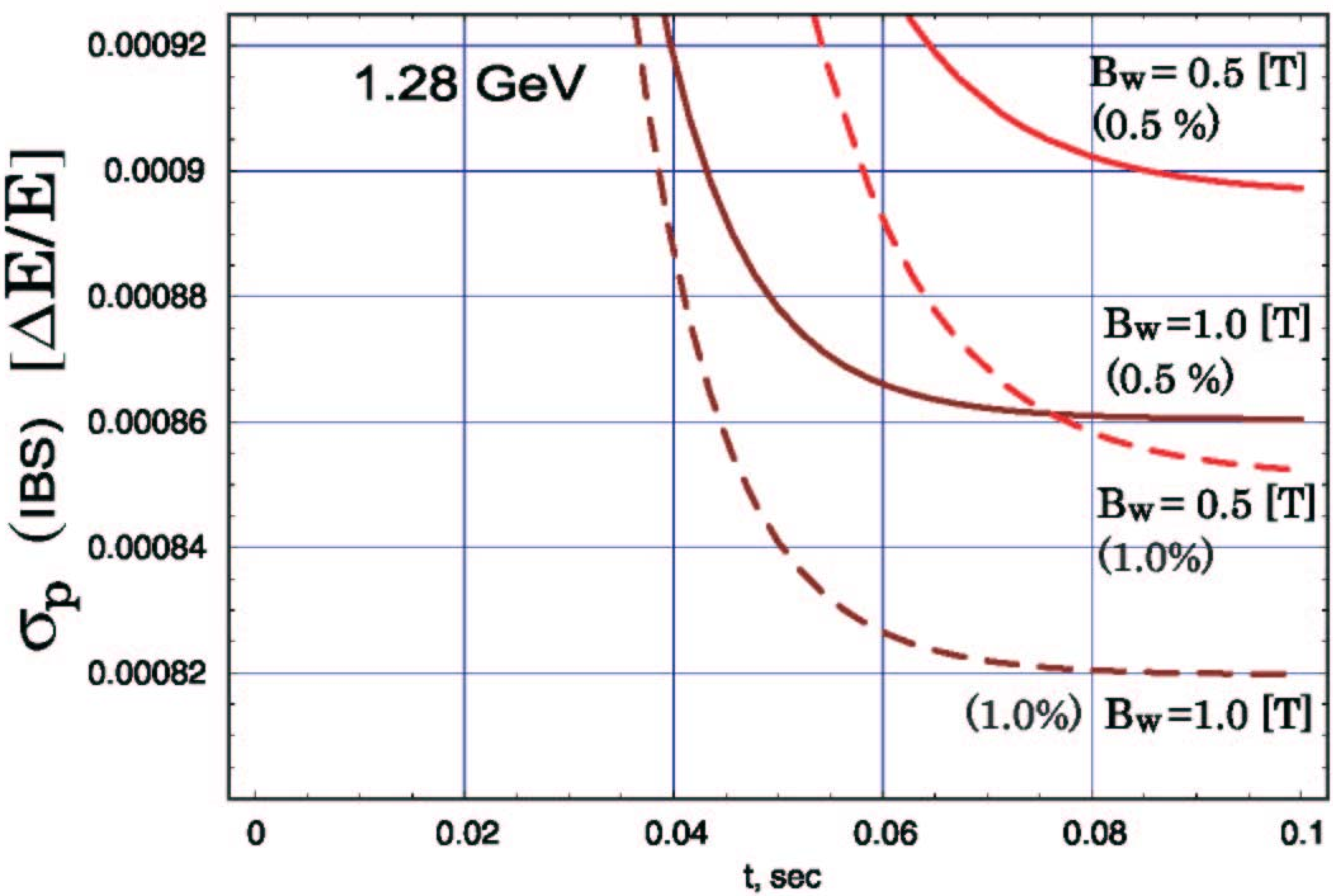
λ_p=8 mm

time evolution Y

ATF DR with 16-m RF damping, 10^{10} e-, IBS coupling 0.5-1.0%



λ_p=8 mm

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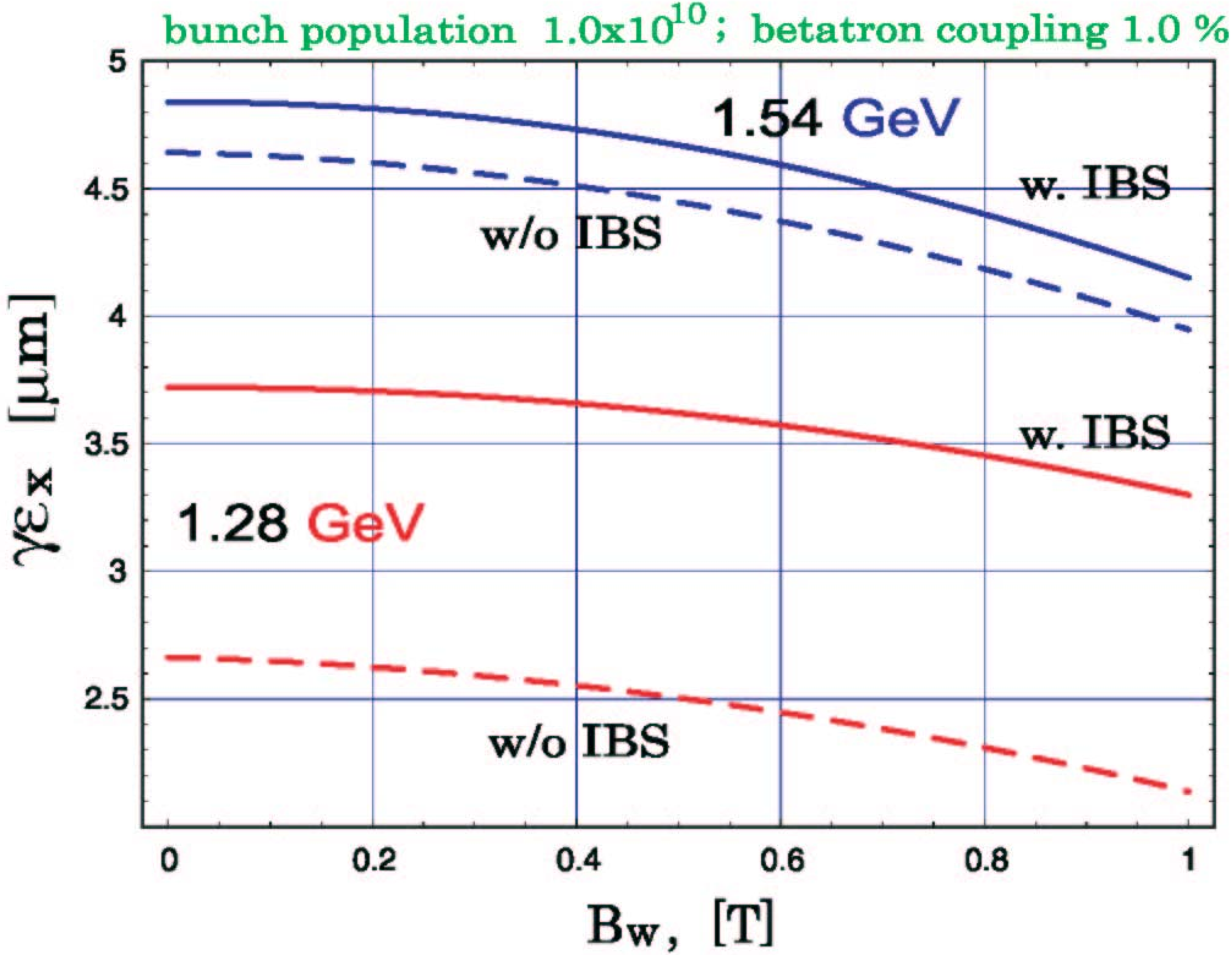
time evolution p



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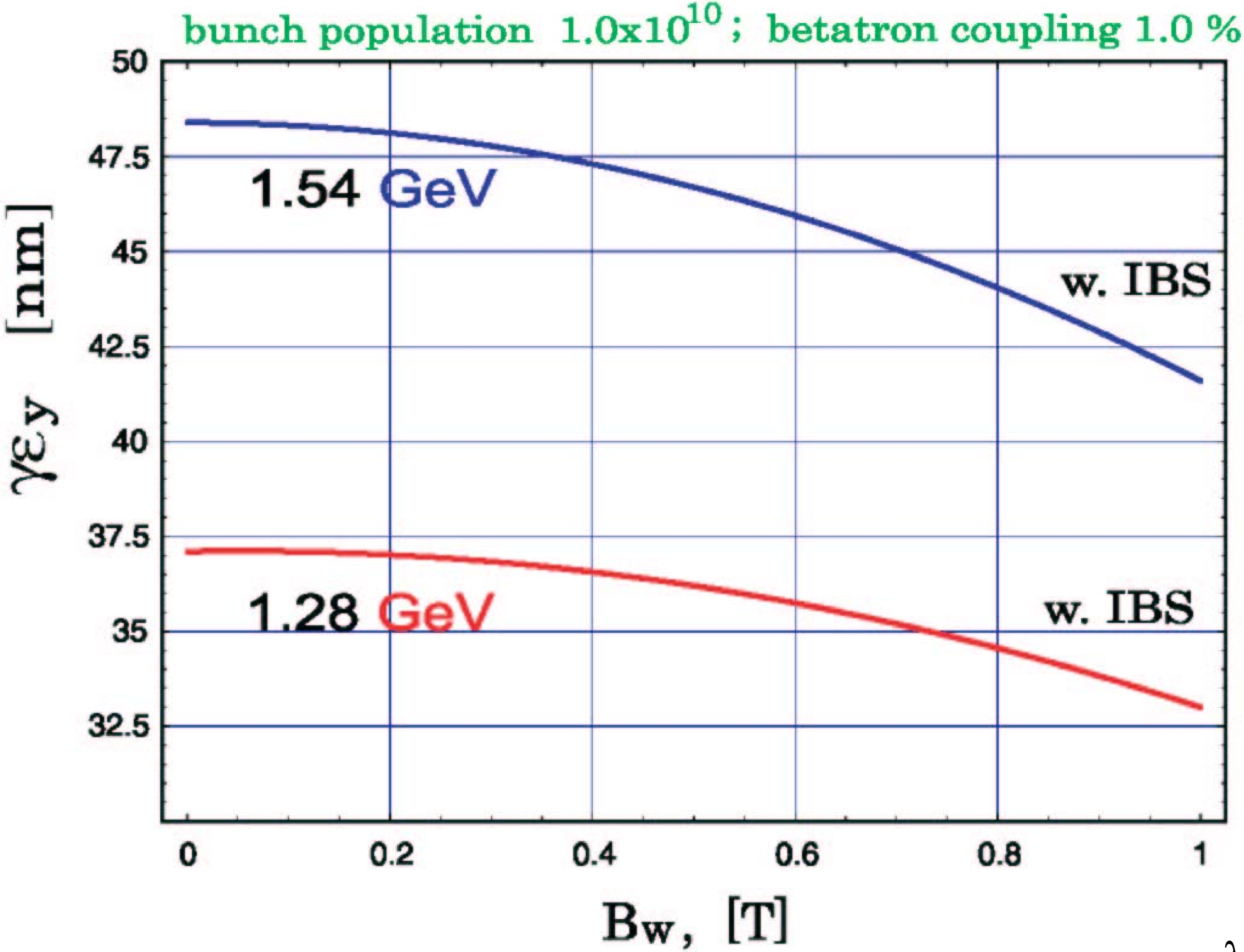
λ_p=8 mm

equilibrium X



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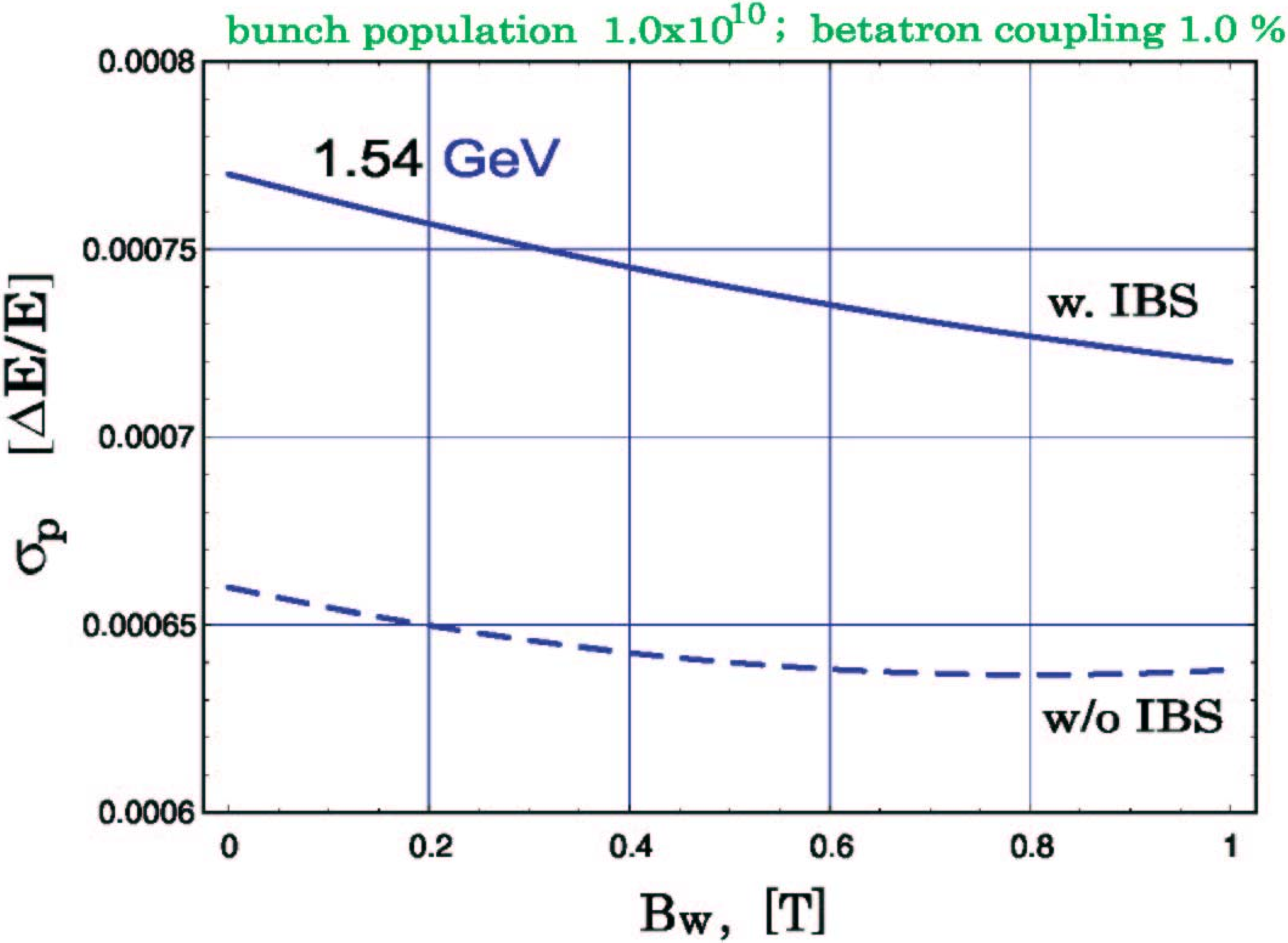
λ_p=8 mm

equilibrium Y



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λ_p=8 mm

equilibrium p

Possible Goals for ATF

- demonstrate, for the first time, damping from rf wiggler in a storage rings
- further reduce the ATF emittances
- study, for the first time, the beam distribution that results from undulator radiation as compared to regular bending-magnet or wiggler radiation
- gain experience with this type of device

SC Wiggler in Linac

H.H. Braun, M. Korostelev*, F. Zimmermann

- second approach to reach small emittance
- advantages: no arcs contributing to quantum excitation, IBS is negligible
- disadvantages: additional linac length & additional linac rf power
- first proposed for VLEPP (with much larger emittances) N.Dikansky, A.Mikhailichenko, EPAC’92 (1992).
- fast damping requires high field → s.c.

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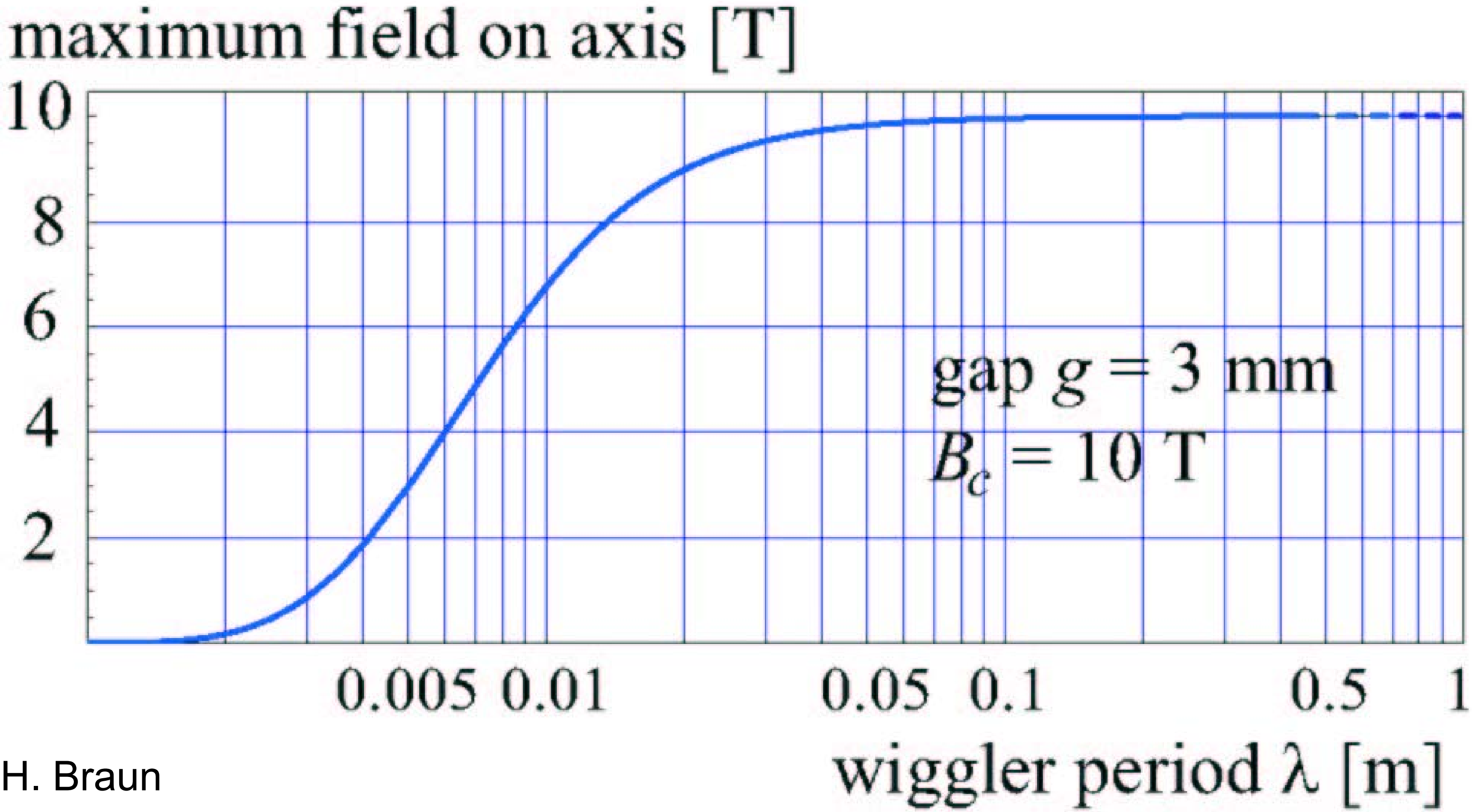
$$B_y = B_0 \cosh\left(\frac{2\pi}{\lambda} y\right)\cos\left(\frac{2\pi}{\lambda} z\right), \quad B_z = B_0 \sinh\left(\frac{2\pi}{\lambda} y\right)\sin\left(\frac{2\pi}{\lambda} z\right)$$

maximum field on axis: $B_{max} = \sqrt{2} B_c / \sqrt{1 + \cosh(2\pi g / \lambda)}$



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undulator → small period λ~1 mm

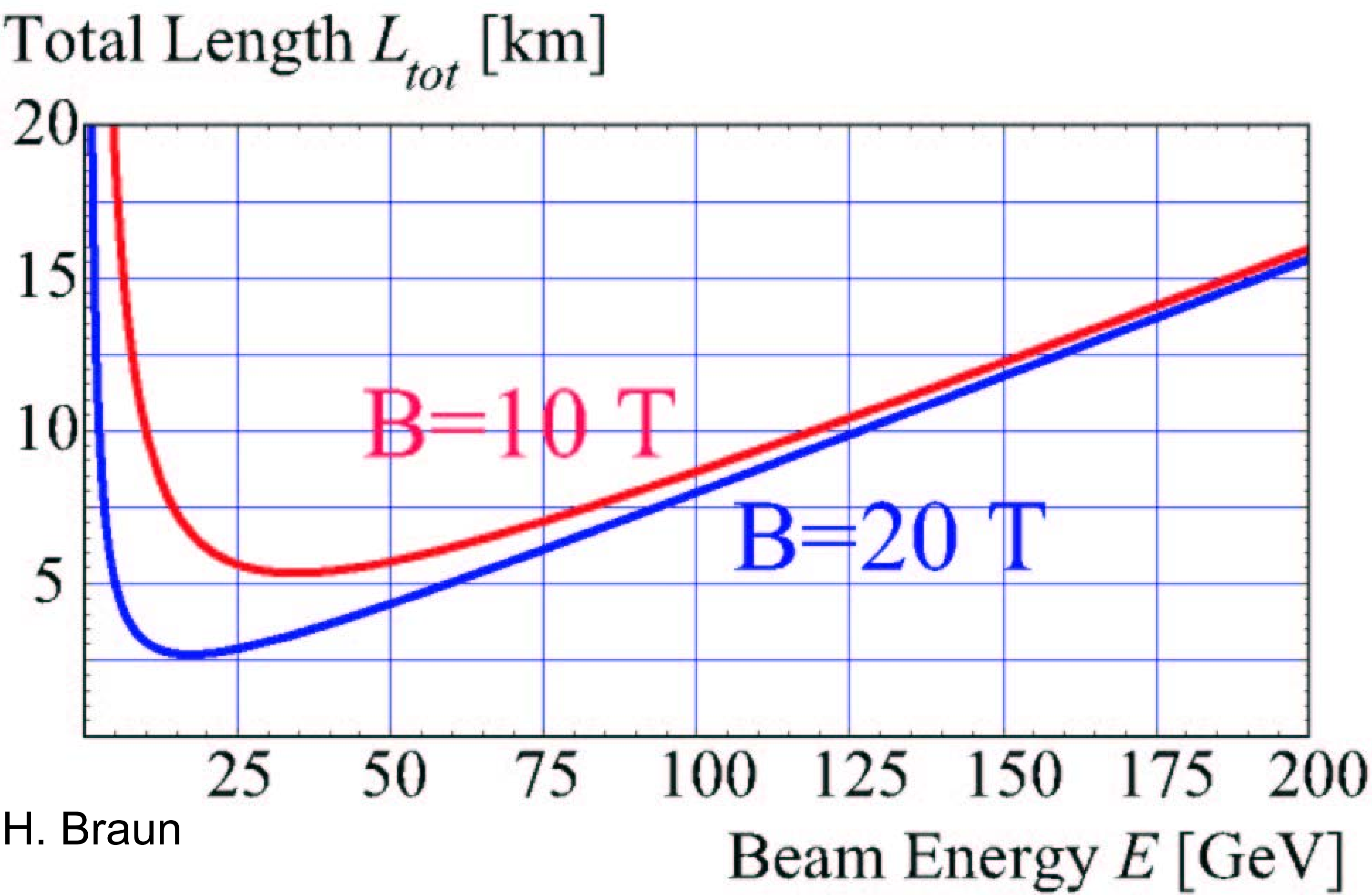
10 T → g<100-200 μm

impractical!

→ *use wiggler*

total length of the damping part of the linac is

$$L_{tot} = 2\log\left(\varepsilon_{initial} / \varepsilon_{final}\right)\left[E / G + 1/(a\hat{B}^2 E)\right]$$



example values:
$\gamma\varepsilon_{initial}$=1 μm,
$\gamma\varepsilon_{final}$=3 nm,
G=0.15 GeV/m,

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total accelerating voltage required

$$V_{tot} = \log\left(\varepsilon_{initial} / \varepsilon_{final}\right) E / e$$

minimum length at energy where acceleration & damping equally long

$$E_{optimum} = \sqrt{G / a} / \hat{B} \approx 340 \text{ T GeV}/\hat{B}$$

total length at optimum energy per main linac

$$L_{tot} = 4 \log\left(\varepsilon_{initial} / \varepsilon_{final}\right) / \sqrt{aG} / \hat{B} \approx 52 \text{ km T}/\hat{B}$$

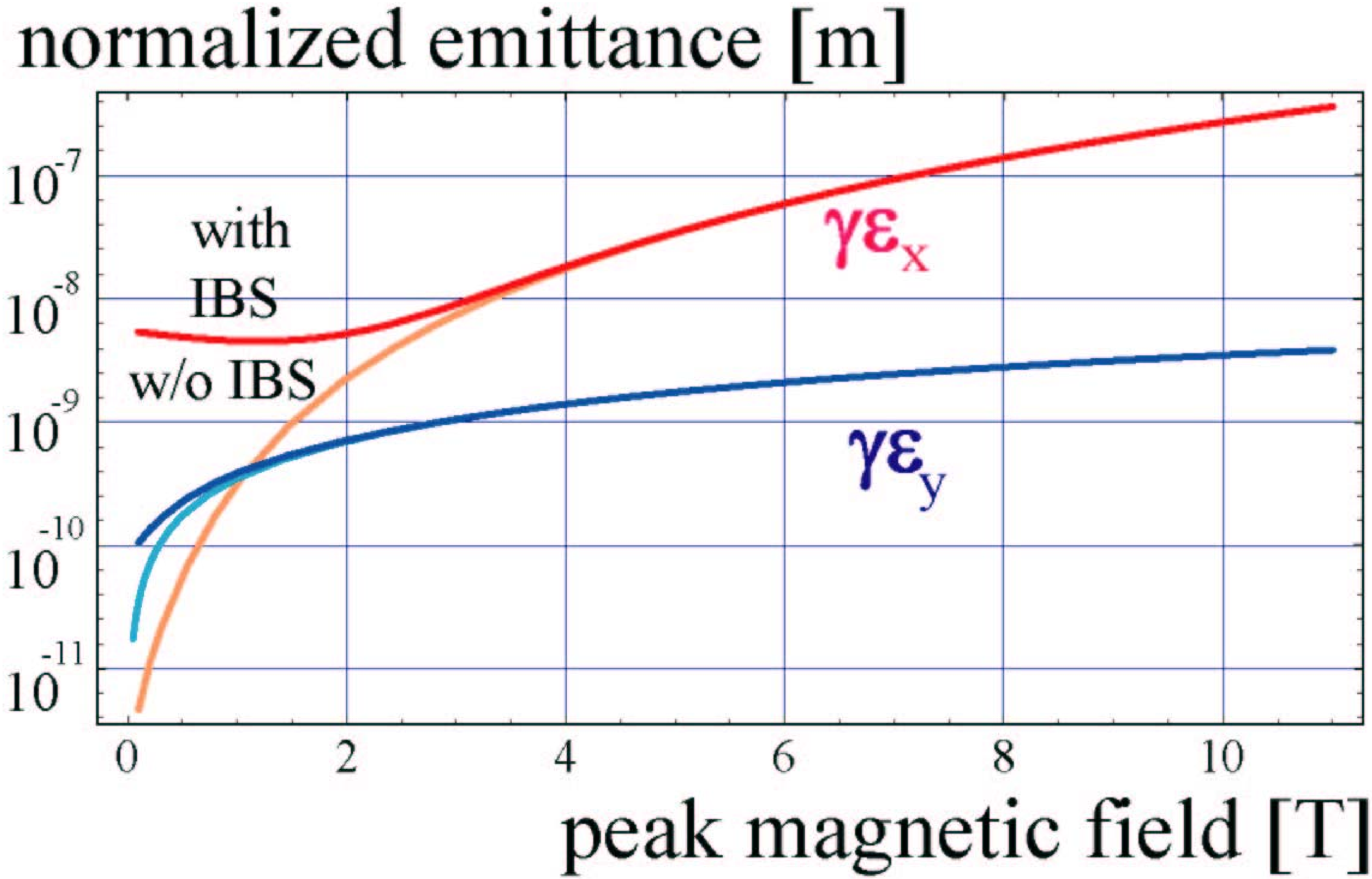
total voltage at optimum energy per main linac

$$V_{tot} = \log\left(\varepsilon_{initial} / \varepsilon_{final}\right) \sqrt{G / a} / (\hat{B} e) \approx 1.94 \text{ TV T}/\hat{B}$$

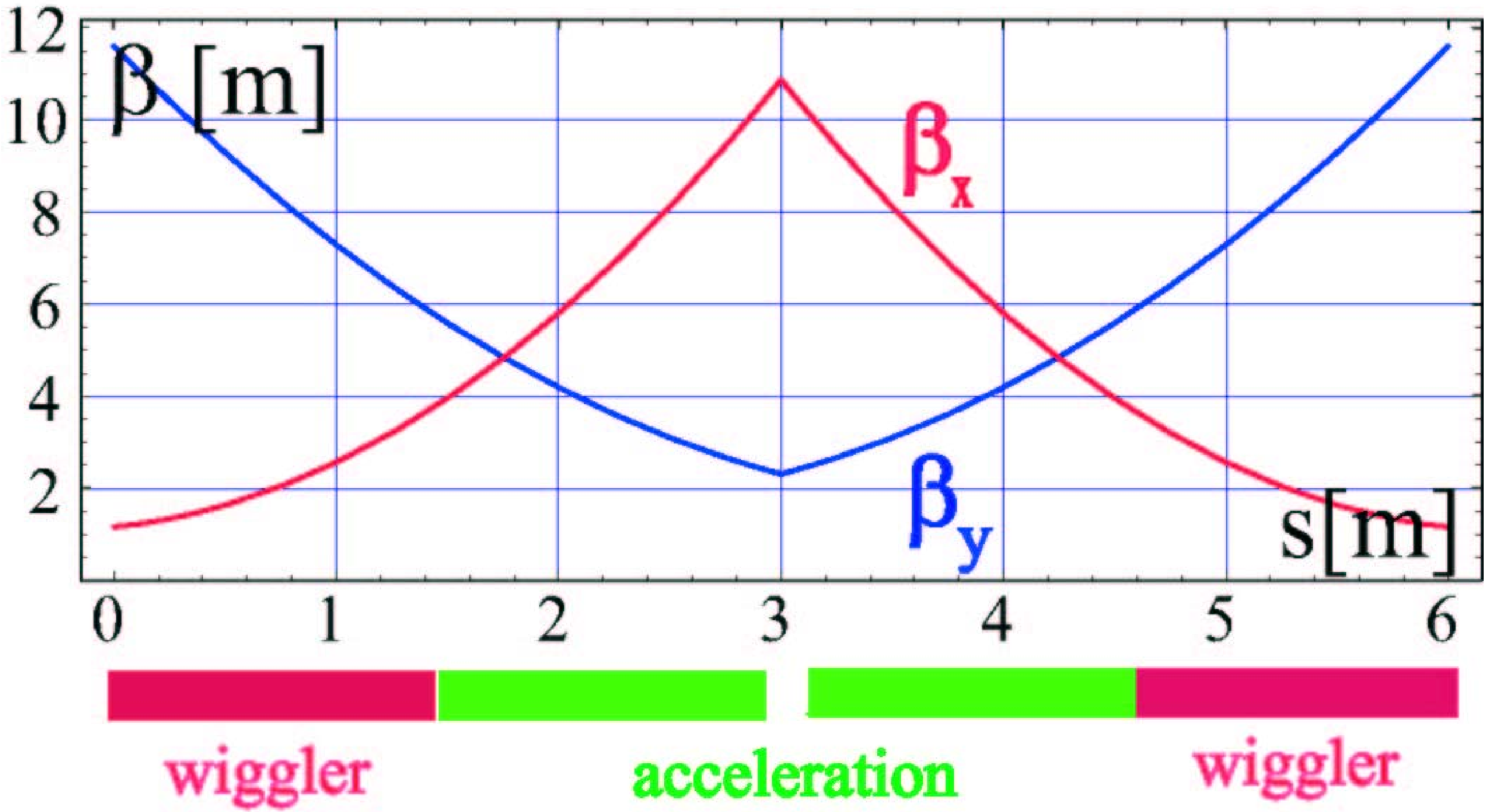
example parameters for s.c. wiggler linac

Average beam energy	34 GeV
Peak magnetic field	10 T
Wiggler period	1.5 cm
Accelerating gradient	150 MV/m
Total length of wiggler/addt'l. acceleration	2.6, 2.6 km
Average beta functions in wiggler	8, 1.5 m
Transverse damping time	1800 m/*c*
Equilibrium horizontal norm. emittance	595 nm
Equilibrium vertical norm. emittance	2.77 nm

dependence of equilibrium emittance on wiggler peak field w.&w/o IBS; emittances proportional to β at wiggler



FODO cell length of 6 m could accommodate two 1.4-m long CLIC accelerating structures and 2 wiggler units. The example optics below yields $\langle \beta_{x,y} \rangle \approx 2.2, 8.4\ \mathrm{m}$ average beta–functions at the wiggler. Quadrupoles could be 20 cm long, with 4-mm radius, 1.2-T pole-tip.



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Conclusions

We have explored two alternative approaches to produce a brilliant low-emittance beam, namely

(1) use of rf wigglers or rf undulators instead of magnetic wigglers in the damping ring, and

(2) integration of s.c. wigglers into the linac.

Both of these approaches may come close to the CLIC target parameters.