Operating Synchrotron Light Sources with a ***High Gain*** FEL

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Re-elaborating *S. Di Mitri and M. Cornacchia, NJP 17, 113006 (2015)*

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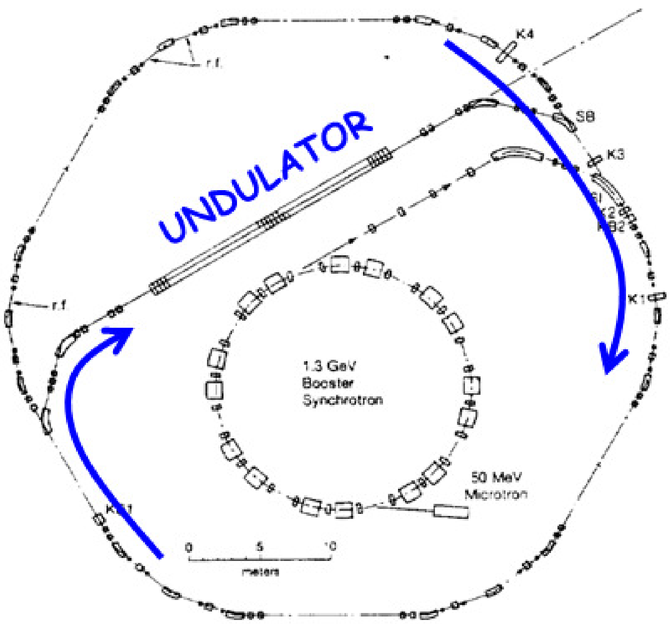
Idea and Challenges



*By-Pass figure from K.-J. Kim et al., IEEE Trans. Nucl. Sci. 32, 5 (**1985**).*

Idea:

- *Upgrade an existing storage ring to drive a high gain FEL* (i.e., mirrorless)
- $\lambda \approx$ EUV and soft X-rays
- $\langle P_{FEL} \rangle \geq 1$ W

Challenges:

- *Compatibility with multi-bunch IDs operation*
- High e-beam brightness required by FEL
- SR+FEL equilibrium state
- CSR- and MBC-instability

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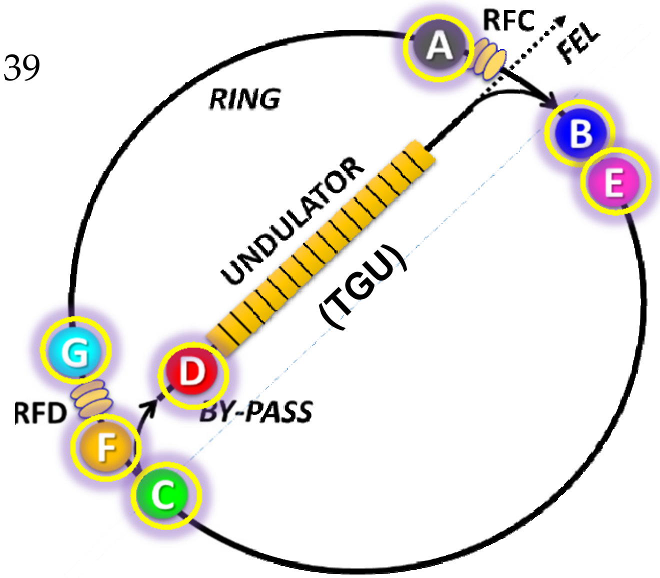
Non-Equilibrium t-Compression

A. Hofmann, ACD Note 39 (1986), *"Short bunches in PEP"*.

A. Gallo, P. Raimondi, M. Zobov, 30th ICFA Wkp (2004), *"Strong RF focusing: a possible approach to reach short bunches at the IP"*.

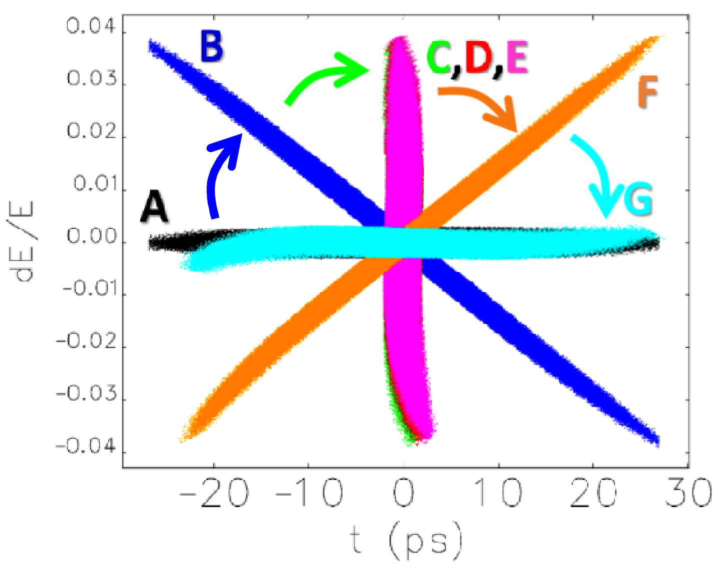


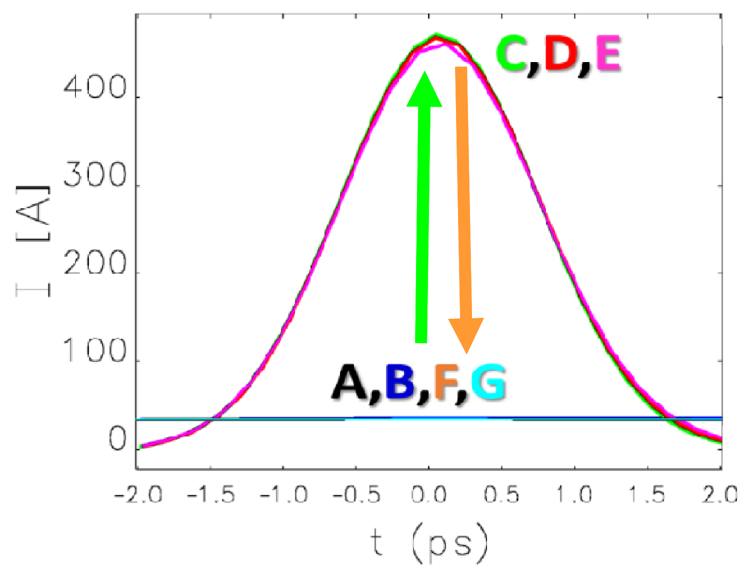
Compress the bunch duration in half turn:

$$h = \frac{1}{E_0}\frac{dE}{dz}$$ "Energy chirp"

$$C_0 = \frac{\sigma_{z,i}}{\sigma_{z,f}} = \frac{1}{|1 + hR_{56}|}$$ "Compression factor"

Beam goes back to equilibrium state.





E = 1 GeV
Q_b = 0.7 nC
$\sigma_{z,0}$ = 9 ps
C_0 = 13

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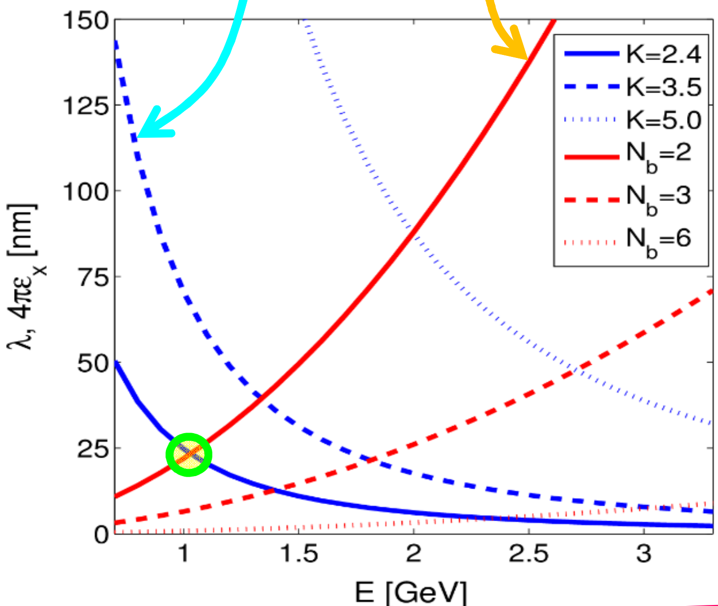
Storage Ring and RF Parameters

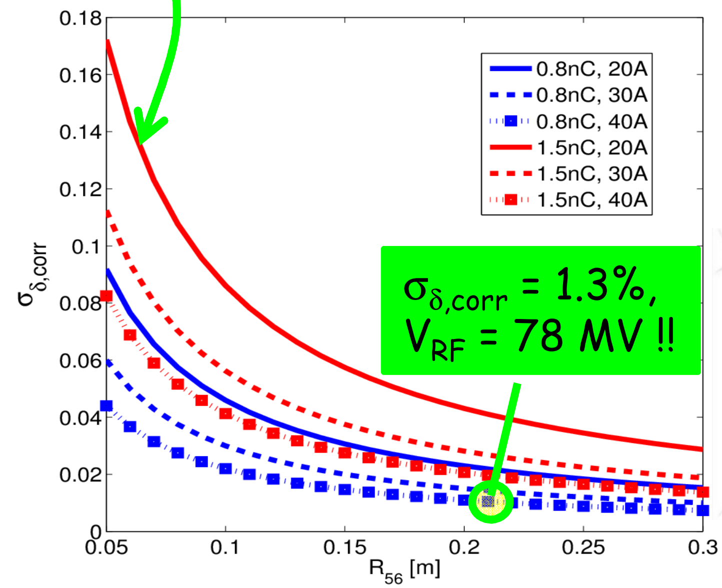
- Keep the Elettra **DBA-lattice** as it is, and lower the beam energy to match $4\pi\varepsilon_x \approx \lambda = 25$ nm.

$$\lambda \propto \frac{(1+K^2)}{E^2}$$

$$\varepsilon_x \propto \frac{E^2}{N_b^3}$$

$$\sigma_{\delta,cor} \approx \left(1-\frac{1}{C}\right)\frac{\sigma_{z,0}}{R_{56}} \approx \frac{2\pi\sigma_{z,0}}{\lambda_{RF}}\frac{e\hat{V}_{RF}}{E_0}$$





MBA-cells provide low-ε_x above 2 GeV
--> $R_{56} < 0.1$ m ($\alpha_p < 10^{-3}$)
--> Momentum acceptance > 2%
--> $V_{RF} > 50$ MV (S-band)

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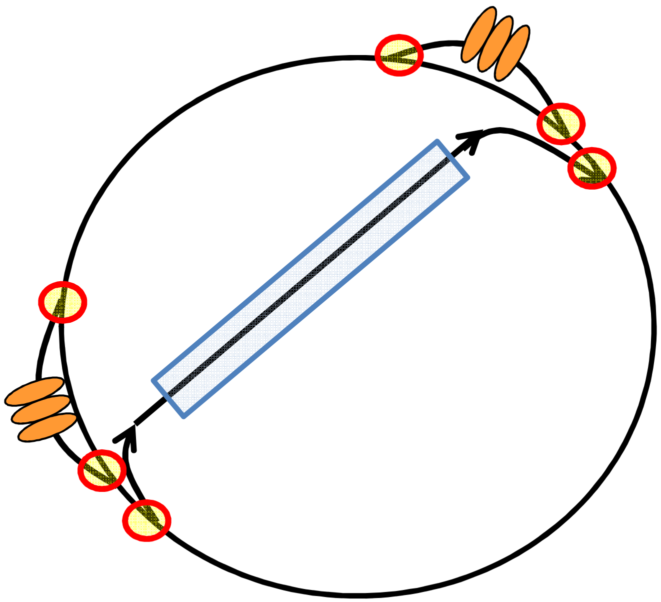
RF Linacs in a Ring ??

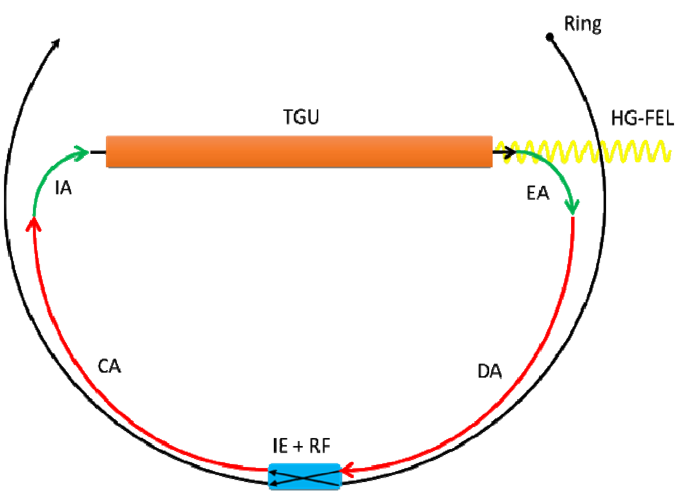


- **SC** HOMs-damped multi-cell cavities might provide E_z~20 MV/m, but they stay on for milliseconds…
- **NC** (pulsed) cavities not available (yet) with HOMs damping at <I> ~ 300 mA.

➢ In small rings, RF cavities should be installed in by-pass lines.

- **Strip-line kickers:** rep. rate 0.1-1 MHz , < 5 ns rise/fall time, < 100 ns flat top, ~1% stability
- RF transverse deflectors

  [T.Naito et al., NIMA 571 (2009)]
  [M.Placidi et al., NIMA 768 (2014)]



➢ For rings larger than C~500 m, *arc compressors* and *RF linacs* can be *internal* to the main ring.

- **Swap out injection**

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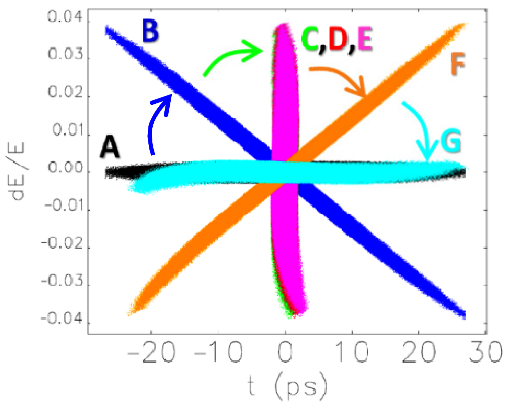
Microwave Instability

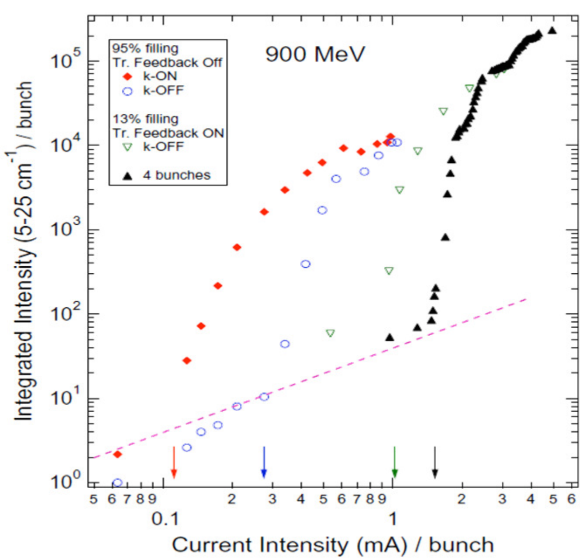
- The higher the peak current, the higher the uncorrelated energy spread ⇒ MWI is "naturally" suppressed by a factor C^2.



$$I_{th,0} \approx I_A \left(\frac{\pi R}{\lambda}\right)^{2/3} \gamma \alpha_c \sigma_{\delta,0}^2$$ Beam in SR

Compression $$\sigma_{\delta,FEL} \propto \hat{I}_{b,FEL} = C_0 \hat{I}_{b,0}$$

$$I_{th,FEL} = C_0^2 I_{th,0} \approx 100 I_{th,0}$$ Beam at FEL



$I_{th,0}$ in Elettra @ 1 GeV is > 0.3 mA/bunch.

⇒ $I_{th,FEL} \approx$ 30 mA/bunch

[E. Karantzoulis et al., IP&T 53, 2010.]

CSR-Induced ε_x-Growth

❑ *Storage Ring Lattice (DBA)*

- At least 3 families of sextupoles, for linear compression, ε_x-control and large DA.

[S. Di Mitri, M. Cornacchia, EPL 109, 62002 (2015)]

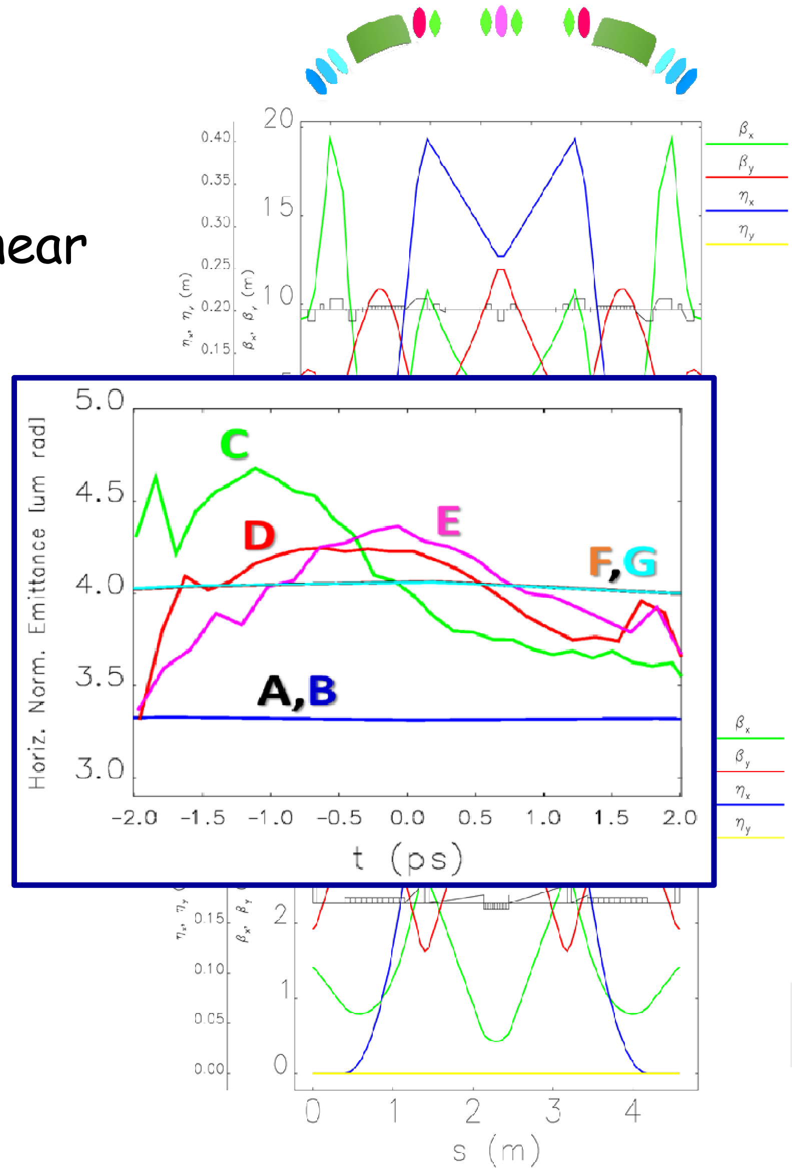
[S. Di Mitri, NIM A 806 (2016)]

❑ *Arcs to/from By-Pass*

- Isochronous achromatic lattice.
- CSR-ε_x growth is suppressed through optics "balance".

[D. Douglas et al., JLAB-ACP-14-1751 (2014)]

[S. Di Mitri et al., PRL 110, 014801 (2013)]



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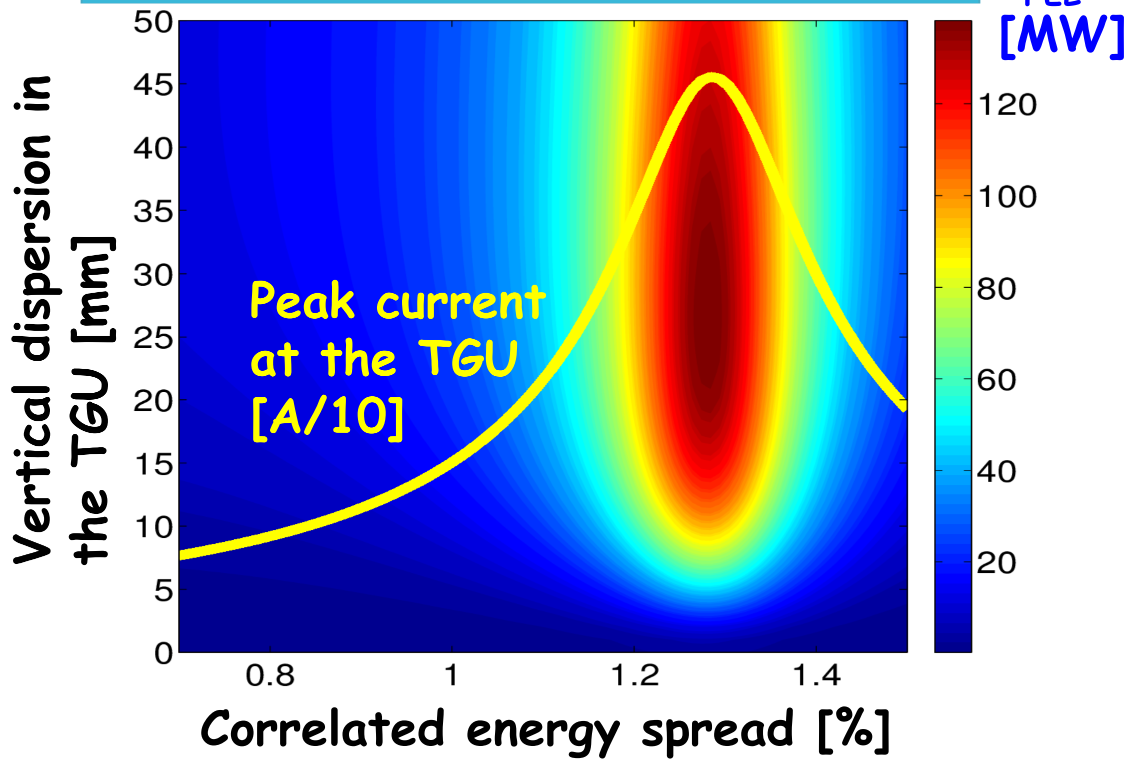
SR + SASE FEL, Single-Pass

- After **lasing once every longitudinal damping time** ($T_{FEL} \geq \tau_E \approx$ 10 ms), the beam "thermalizes" to standard SR-equilibrium state.

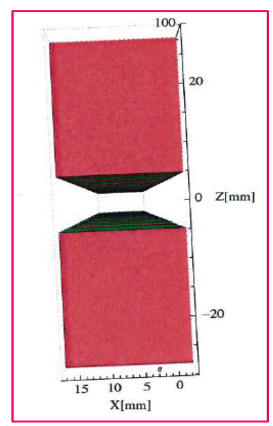
λ_u=3cm, K=3, α_{TGU}=70m^{-1}, L_u=55 m

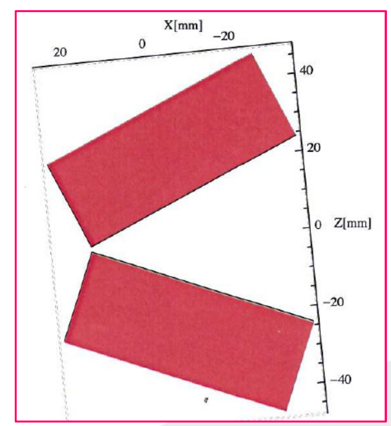


$$\rho_{TGU} = \rho_{1D} \Big/ \left[1 + \left(\frac{\eta_y \sigma_{\delta,FEL}}{\sigma_{\beta,y}}\right)^2\right]^{1/6}$$

[P. Baxevanis et al., PRSTAB 7, 020701 (2014)]

Realistic TGU designs:





$\langle P_{FEL} \rangle \approx$ 100 MW × 1 ps × 50 Hz × 400 bs. ≈ 2 W, ~10^{13} ph/pulse @ 25 nm

SR + SASE FEL, at Equilibrium

- **Lasing ~every turn** ($T_{FEL} \ll \tau_E$) imposes new equilibrium parameters, set by synchrotron radiation damping and FEL excitation.

beam energy spread at equilibrium *without* FEL

beam energy spread increases a little at every lasing

$$\frac{d\sigma_\delta^2(t)}{dt} = \frac{2\left(\sigma_{\delta,0}^2 - \sigma_\delta^2(t)\right)}{\tau_E} + \frac{1}{C_0}\frac{\Delta\sigma_{\delta,FEL}^2(t)}{T_{FEL}}$$

De-compression after lasing ***minimizes the FEL perturbation***. After every FEL loop:

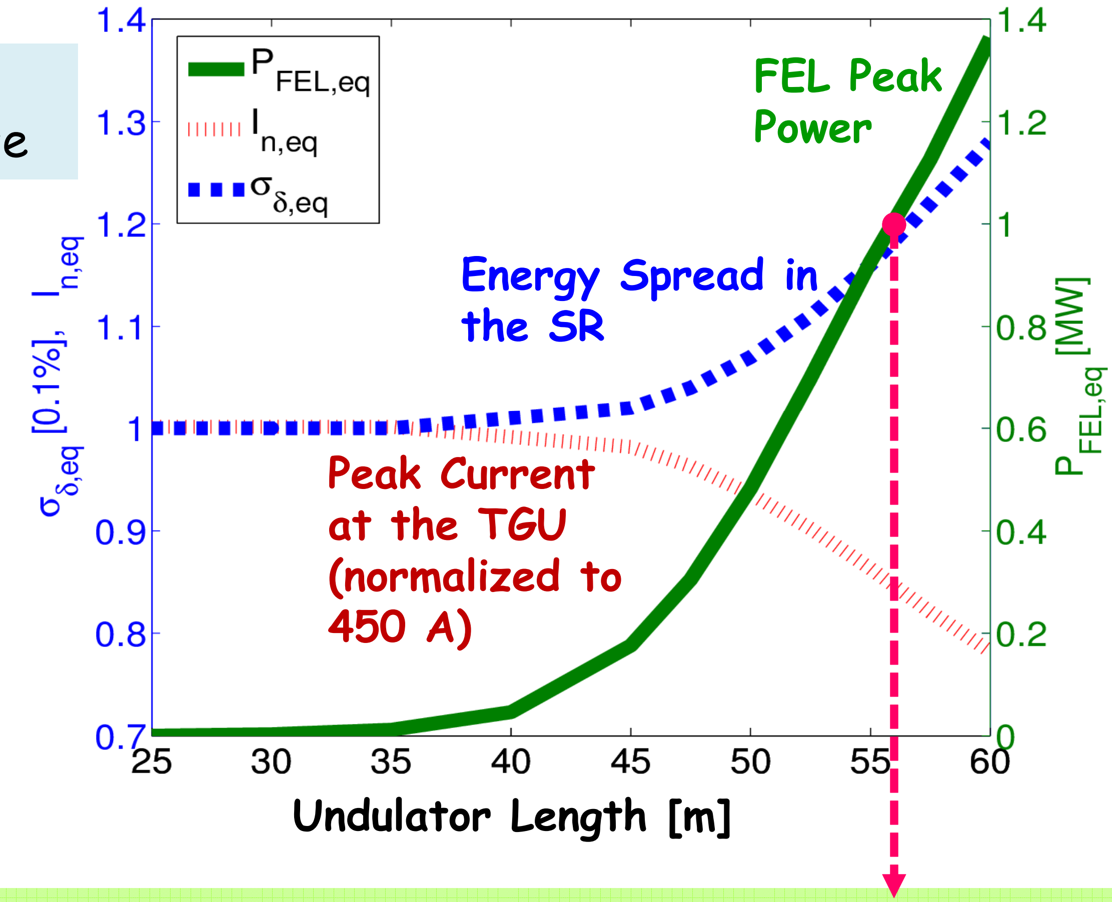
$$\sigma_{\delta,i+1} = \sqrt{\sigma_{\delta,i}^2 + \Delta\sigma_{\delta,FEL}^2 / C_0^2}$$

1. **Numerical solution** for $\sigma_\delta(t \to \infty)$, with $\Delta\sigma_{\delta,FEL}$ as a function of the undulator length *[Z. Huang et al., NIM A 593 (2008)].*
2. Approximate closed-form for $\sigma_\delta(t \to \infty)$, with $\Delta\sigma_{\delta,FEL}$ at saturation.
3. **Tracking** of the **Beam-Matrix** turn-by-turn, for arbitrary undulator length.

Numerical Solution

- The **undulator length** can be chosen to tune the FEL power vs. the beam energy spread at equilibrium. The FEL can be far from saturation.

Curves are per bunch, per pulse



E = 1 GeV
λ = 25 nm
Q_b = 0.75 nC
$\sigma_{z,0}$ = 12 ps
C_0 = 20
λ_u = 30 mm

$\langle P_{FEL} \rangle \approx 1\text{ MW} \times 1\text{ ps} \times 0.5\text{ MHz} \times 400\text{ bs.} \approx$ **200 W, ~10^{11}ph/pulse @25 nm**

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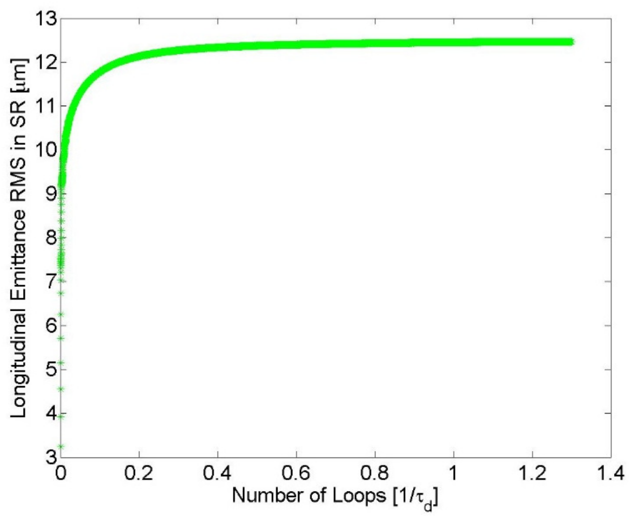
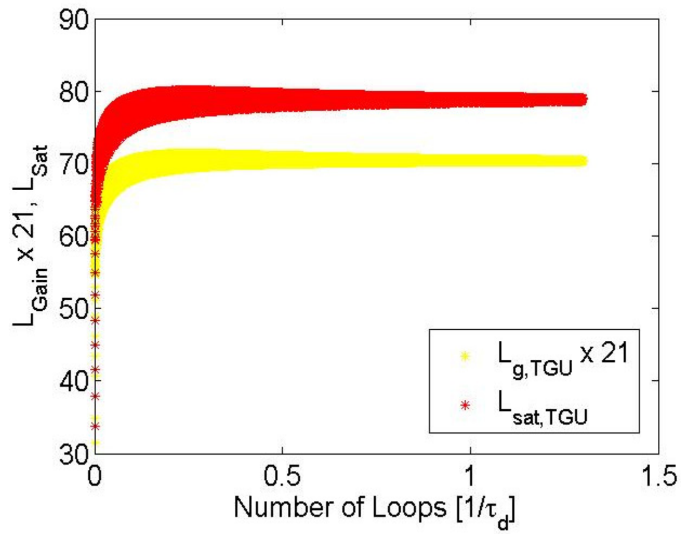
Tracking the Beam Matrix

- **Beam Matrix** through SR+FEL loop: $\Sigma_{i+1} = M\Sigma_i M^t$, where [M] describes: *bunch length compression → RF focusing → SR damping & anti-damping → SASE FEL → de-compression*





E = 1 GeV
λ = 25 nm

Q_b = 0.75 nC
$\sigma_{z,0}$ = 12 ps
C_0 = 20
λ_u = 55 mm

- **Beam transverse emittance degrades** due to emission of photons in the dispersive line of the TGU :

$$\varepsilon_{y,i}^2 \approx \varepsilon_{y,i-1}^2 \left[1 + \frac{\left(\overline{\eta}_y \sigma_{\delta,FEL}\right)^2}{\varepsilon_{y,i-1}\overline{\beta}_y} \right]$$

Efficient lasing below 10 nm looks like really challenging

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Conclusions

- ❑ ***No physical show-stoppers*** to SR-HG SASE-FEL in EUV
  - Expected ***<P_{FEL}>*** ~ ***1-100 W*** depending on the rep. rate of the extraction system (0.05 – 100 kHz).
- ❑ ***Upgrading existing 3-GeV SRs*** requires:
  - 30 – 150 m long TGU
  - 20 – 100 MV RF cavities
  - by-pass lines to host RF cavities / internal arc compressors
  - fast kickers / swap-out inj.-extr. system
- ❑ ***Emittance growth in the TGU*** is main obstacle to efficient lasing below ~10 nm
- ❑ Detailed feasibility study is on-going…

Acknowledgments

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Thank You for Your attention

Comparison of SR-FEL Studies

- **Low repetition rate HG-FEL** (lasing every τ_E or so)

	λ [nm]	#photons/ pulse	P_{pk} /pulse [MW]	$<P_{tot}>$ [W]	Compatible with ID-Beamlines ?
LBNL (1984)	40	$\sim 10^{15}$	100	0.1	NO
PEP (1998)	4	$\sim 10^{14}$	460	0.03	NO
PEPX (2013)	1.5	$\sim 10^{12}$	200	2	NO
ELETTRA (2015)	**25**	$\sim \mathbf{10^{13}}$	**100**	**2** *(400 bs)*	**YES**
FERMI FEL1	*25*	$\sim 10^{13}$	*1000*	*0.005*	*Warm Linac*

- **High repetition rate HG-FEL** (lasing every turn or so)

	λ [nm]	#photons /pulse	P_{pk} /pulse [MW]	$<P_{tot}>$ [W]	Compatible with ID-Beamlines ?
PEPX (2008)	3.3	$\sim 10^{11}$	0.2	0.7	NO
ELETTRA (2015)	**25**	$\sim \mathbf{10^{11}}$	**1**	**200** *(400 bs)*	**YES**