FUTURE LIGHT SOURCES, 2023

TGU FOR A STORAGE RING XFELO

20+5 TH3B3 2:50 PM

Y. LI, R.R. LINDBERG, AND K.-J. KIM

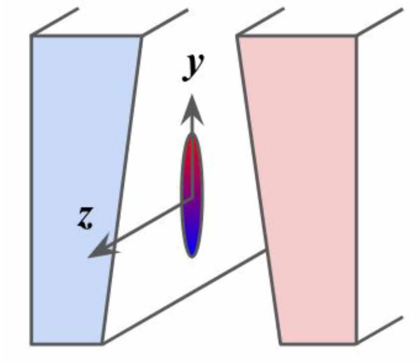
APS, ANL

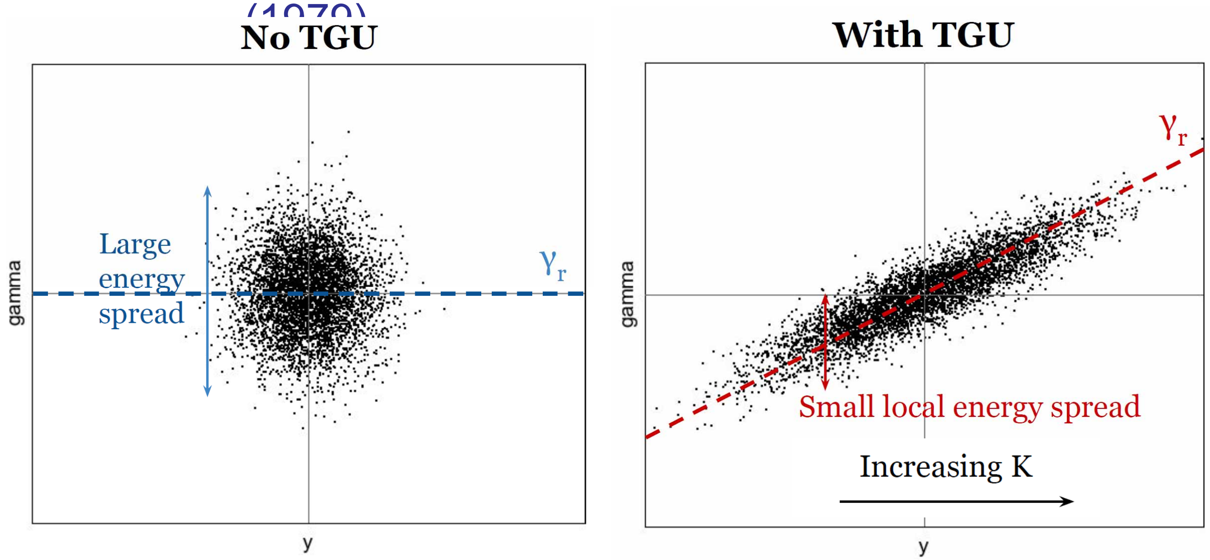
August 28-September 1, 2023

Lucerne, Switzerland

TRANSVERSE GRADIENT UNDULATOR (TGU)TO MITIGATE LARGE $\Delta\eta$ IN STORAGE RING

T. I. Smith, et al., J. Appl. Phys. 50, 4580 (1979)





- Induce $(\gamma - y)$ correlation via dispersion D

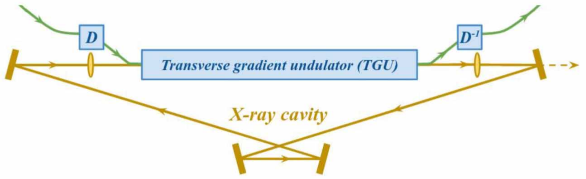
$$y_j = D\eta_j + y_{\beta j}, \qquad \eta_j = (\eta_j - \eta_0)/\eta_0$$

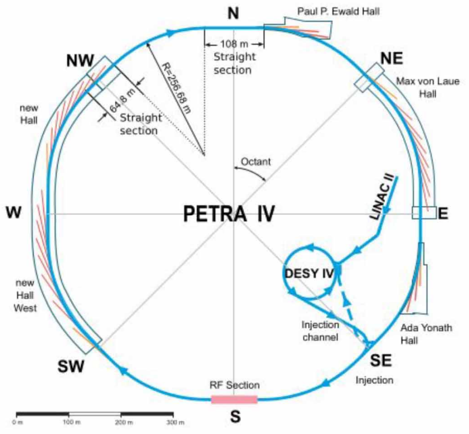
  - Uncorrelated energy spread is decreased:
    - $\sigma_\eta \rightarrow \sigma_\eta/\sqrt{1+\Gamma^2}$, TGU parameter: $\Gamma = D\ \sigma_\eta/\ \sigma_y > 1$:

- Remove the first order dependence on y of $\lambda_1 = \lambda_u \frac{1+K^2/2}{2\gamma^2}$ by:
  - Introducing *transverse gradient* $K(y) \approx (1+\alpha y)K_0$
  - Choosing $\alpha D = \frac{2+K_0^2}{K_0^2}$

TGU-BASED STORAGE RING XFELO

- **If there are many betatron oscillations while passing through undulator, the emittance requirement becomes too stringent**
  - N. Kroll, et al., JQE 17, 1496 (1981), J. de Phy. 44, C1-85 (1983)
- **The restriction does not apply for X-ray FELs**
  - High-gain FEL--Z. Huang, et al., PRL, 109, 20481 (2012); Y. Ding, et al., IPAC 2013
  - Low gain XFELO--R. R. Lindberg, et al., FEL 2013
- **Preliminary studies XFELOs in ultimate storage rings**
  - PEP X: R. R. Lindberg, et al., FEL 2013
  - PETRA IV: I. Agapov, XFELO Workshop, 3/24/2020
  - **Issues**
    - Need for a by-pass and fast kickers
    - Stochastic ring-FEL coupling
- **Current-enhanced e-bunches and temporal gain modulation via RF detuning at PETRA-IV could allow a non-invasive, reproducible operation**
  - Yuanshen, et al., PRAB, 26, 030702 (2023)

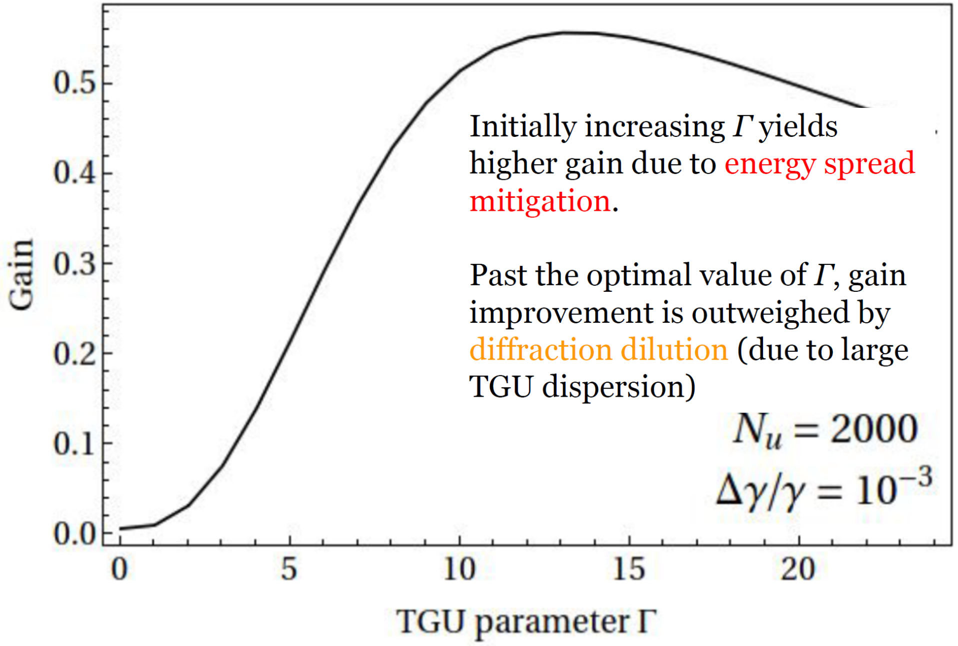




TGU GAIN FORMULA

- Generalized Madey's Theorem

$$G = \frac{G_0}{8\pi N_u L_u^2 \lambda_1^2} \int d\eta d\vec{x} d\vec{y} d\vec{\phi} d\vec{p} B_E(\vec{y}, \vec{\phi}) \times B_U(\eta, \vec{x} - \vec{y}, \vec{\phi} - \vec{p}) \frac{\partial}{\partial \eta} F(\eta, \vec{x}, \vec{p}).$$



Initially increasing Γ yields higher gain due to energy spread mitigation.

Past the optimal value of Γ, gain improvement is outweighed by diffraction dilution (due to large TGU dispersion)

$N_u = 2000$

$\Delta\gamma/\gamma = 10^{-3}$

Frequency/energy shift

$\delta = \pi N_u(\omega - \omega_1)/\omega_1$

$$G = \frac{G_0}{4\pi} \int_{-1/2}^{1/2} dz\, ds \frac{i(z-s)}{\boxed{\sqrt{\mathfrak{D}_x \mathfrak{D}_y}}} \exp\left[\boxed{-2i\delta(z-s)} - \boxed{\frac{2\tilde{\sigma}_\eta^2 (z-s)^2}{1+\Gamma^2}} - \boxed{\left(\frac{\Gamma}{1+\Gamma^2} \frac{\tilde{\sigma}_\eta}{\tilde{\beta}_y}\right)^2 \frac{(z^2 - s^2)^2}{2} \frac{\mathfrak{d}_y}{\mathfrak{D}_y}}\right]$$

Diffraction dilution

$$\mathfrak{D}_{x,y} = \Sigma_{x,y}^2 + sz\, L_u^2 \Sigma_{\phi x,y}^2 - iL_u(z-s)\left[\frac{1}{4k_1} + k_1 \Sigma_{\phi x,y}^2 \Sigma_{x,y}^2\right]$$

Radiation/electron beam sizes

$$\Sigma_y^2 = \sigma_y^2 + \sigma_{ry}^2 + D^2 \sigma_\eta^2,$$
$$\Sigma_x^2 = \sigma_x^2 + \sigma_{rx}^2,$$
$$\Sigma_{\phi x,y}^2 = \sigma_{px,y}^2 + \sigma_{\phi x,y}^2.$$

TGU + energy spread

Energy spread $\tilde{\sigma}_\eta = 2\pi N_u(\Delta\gamma/\gamma)$

TGU parameter $\Gamma \equiv \frac{D\sigma_\eta}{\sigma_y}$

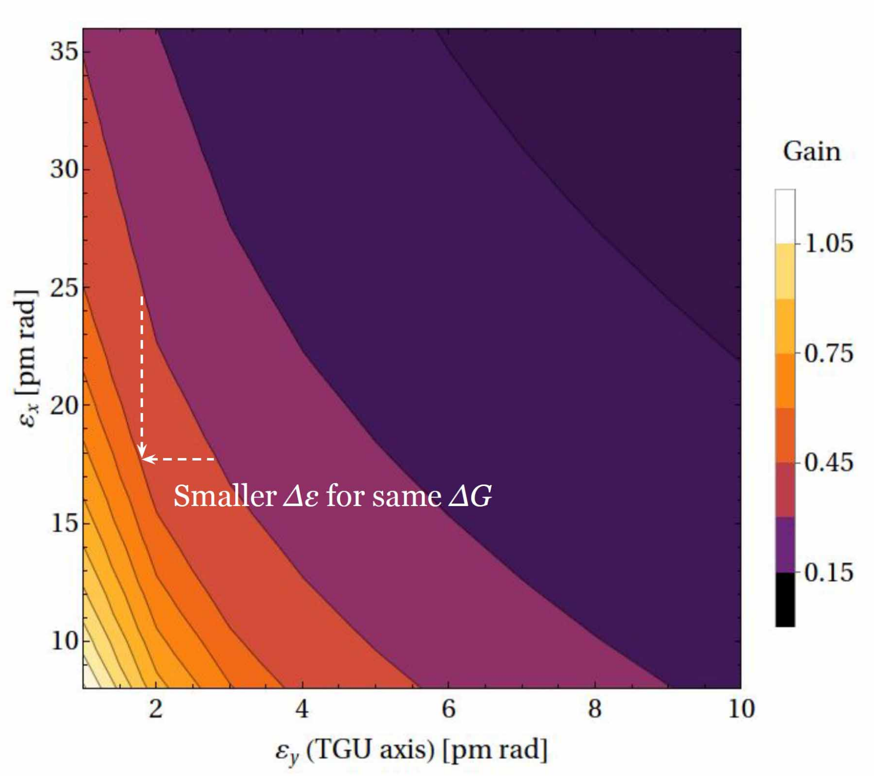
TGU parameter in denominator counteracts exponential gain suppression due to energy spread

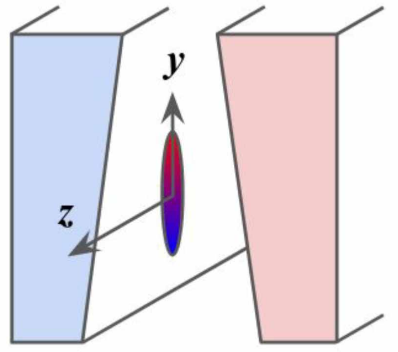
$$\mathfrak{d}_y = \Sigma_y^2 + szL_u^2 \sigma_{\phi y}^2 - iL_u(z-s)\left[\frac{1}{4k_1} + k_1 \sigma_{\phi y}^2 \Sigma_y^2\right]$$

Yuanshen, et al., PRAB, 26, 030702 (2023)

EMITTANCE OPTIMIZATION

- The transverse emittances in storage ring
  - $\varepsilon_x = \frac{\varepsilon_{x,0}}{1+\kappa_c}$, $\varepsilon_y = \frac{\kappa_c \varepsilon_{x,0}}{1+\kappa_c}$
- Vertical (y) emittance is much smaller
- Aligning the TGU axis with vertical direction yields much larger gain improvement





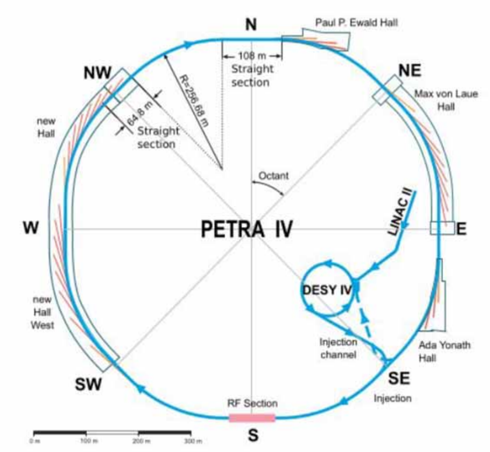
PARAMETERS

PETRA-IV parameters

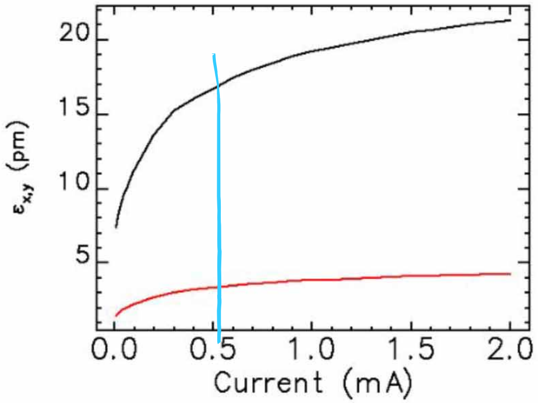
Parameter	Symbol	Value
Electron energy	E_{beam}	6 GeV
Storage ring circumference	C	2304 m
Bunch charge (non-lasing)	Q_{n}	1 nC
Bunch charge (lasing)	Q_{FEL}	4 nC
Number of lasing bunches		16
Peak current (lasing)	I_{peak}	32 A
Relative energy spread	σ_η	0.1 %
Natural emittance	$\epsilon_{x,0}$	19 pm-rad
Coupling coeff	κ_c	0.167
Emittance damping time (y)	τ_y	22 ms
Betatron function at TGU midpoint	β_x, β_y	8.2 m, 4.5 m

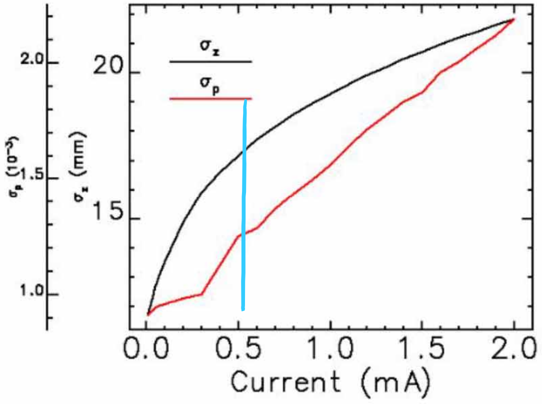
TGU parameters

Parameter[unit]	Symbol	Set A	Set B	Set C
Undulator period [cm]	λ_{u}	1.52	1.52	1.52
Number of periods	$N\text{u}$	2000	2000	2000
Undulator parameter	K_0	1.06	1.06	1.06
TGU parameter	Γ	5	12	13.3
TGU gradient [1/m]	α	85	42	42
Dispersion[m]	D	3.2	6.5	6.2
Frequency detuning	δ	4.495	2.715	2.722
Betatron function (x) [m]	β_x	6.0	6.2	8.2
Betatron function (y) [m]	β_y	8.4	14.1	4.5
Rayleigh length(x) [m]	Z_{Rx}	6.0	14.1	8.2
Rayleigh length(y) [m]	Z_{Ry}	14.8	14.1	47.5
Gain (theory)	G_{th}	0.29	0.36	0.42
Gain (sim)	G_{sim}	0.34	0.36	0.48



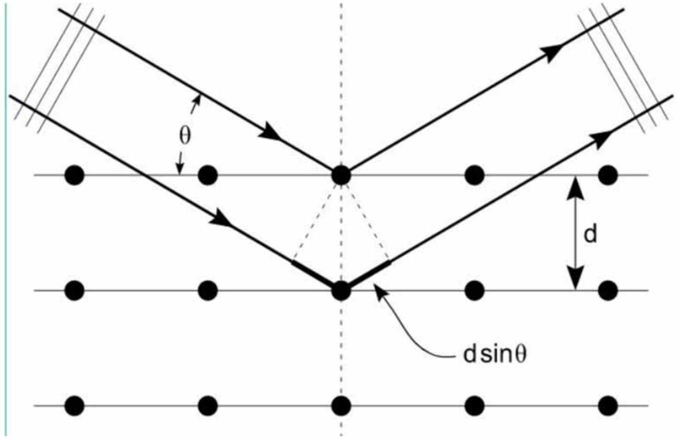
$\mathcal{E}_y = 2.7$ pm

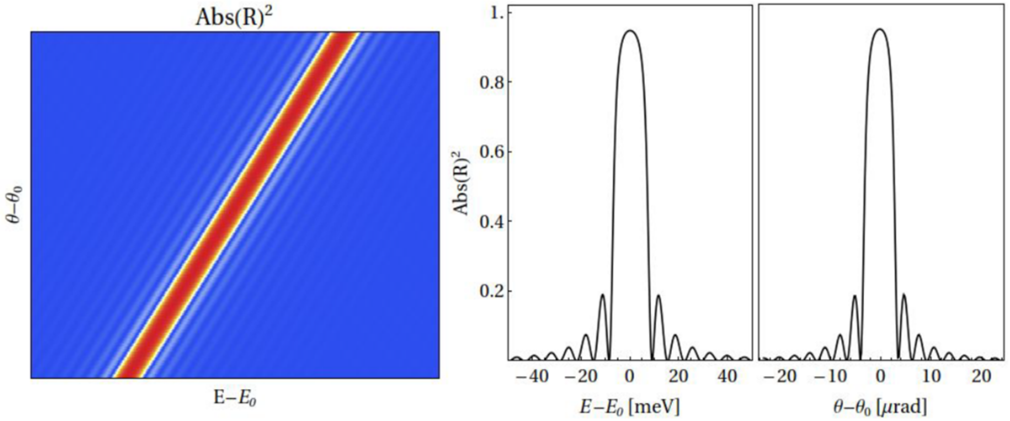




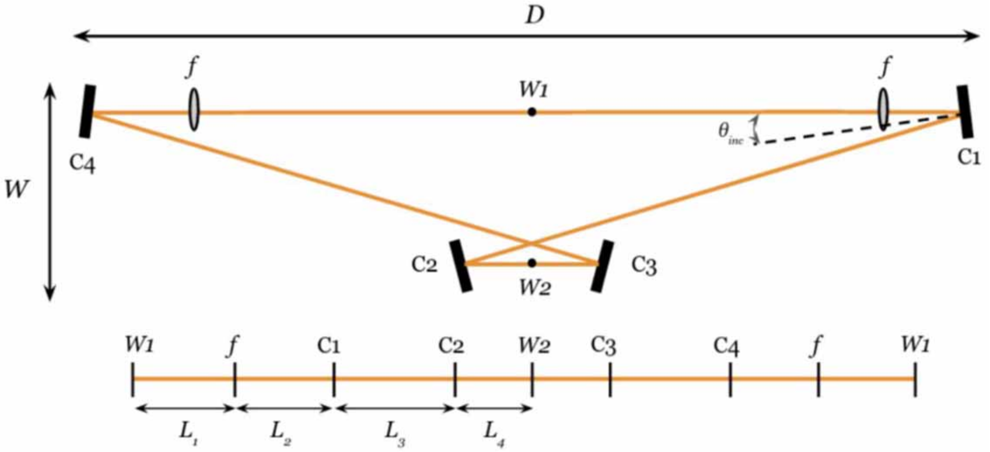
BRAGG DIFFRACTION

- $n\lambda = 2d\sin\theta$
- Diamond C(3,3,7)
  - E_0 =14.4 keV
  - $\theta_0 \equiv \frac{\pi}{2} - \theta$ =9.25°
  - ΔE =10 meV ($\frac{\Delta E}{E} = 6.9 \times 10^{-7}$)
  - $\Delta\theta = 0.5\,\mu rad$ ($\frac{\Delta\theta}{\theta_0} = 5 \times 10^{-6}$)





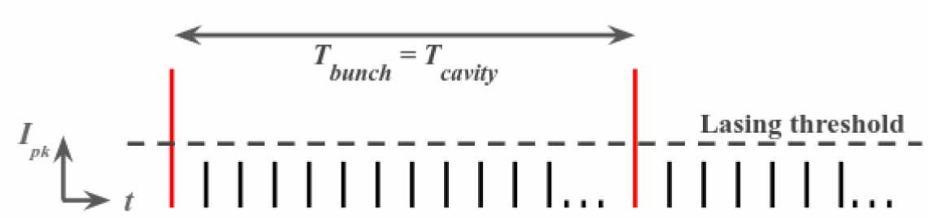
CAVITY OPTICS



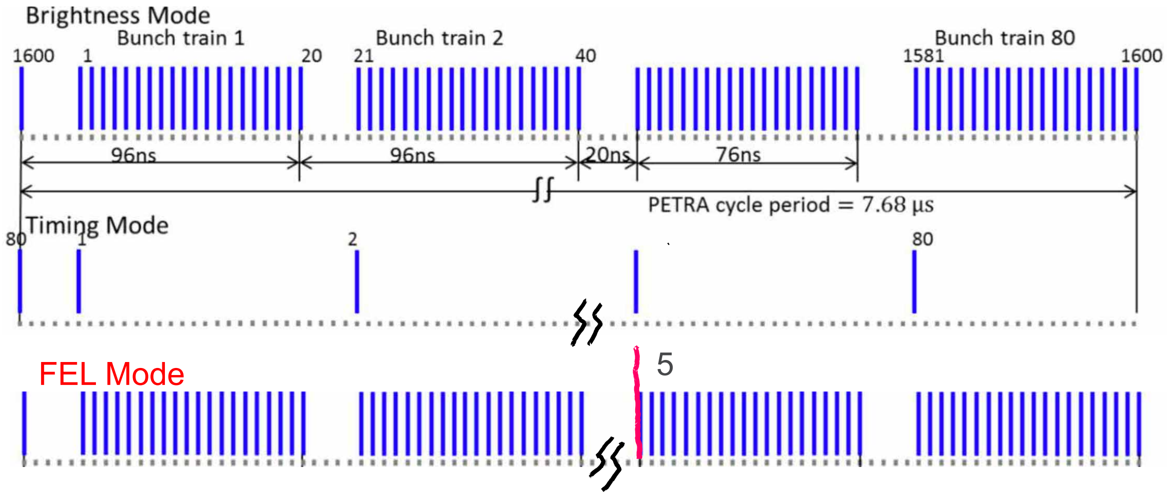
Parameter	Symbol	Value
Photon energy	$\hbar\omega_1$	14.41 keV
Angle of reflection	θ_{inc}	9.248 deg
Round trip length	L_{cav}	143.88 m
Round trip time	T_{cav}	497.92 ns
Length 1	L_1	26.63 m
Length 2	L_2	7.89 m
Length 3	L_3	36.92 m
Length 4	L_4	0.493 m
Cavity length (footprint)	D	69.04 m
Cavity width (footprint)	W	11.71 m
Focal length	f	20.42 m
Rayleigh length at W1	Z_{Rx1},Z_{Ry1}	8.09 m
Rayleigh length at W2	Z_{Rx2},Z_{Ry2}	32.37 m

- High reflectivity diamond mirror
  - C(337): $\hbar\omega$ =14.4 keV, $\theta_0 = 9.25°, \Delta\hbar\omega = 10\text{meV}$
- Beryllium compound refractive lens (CRL)
- Bowtie optical path for tuning

CURRENT-ENHANCED BUNCHES FOR FEL GAIN

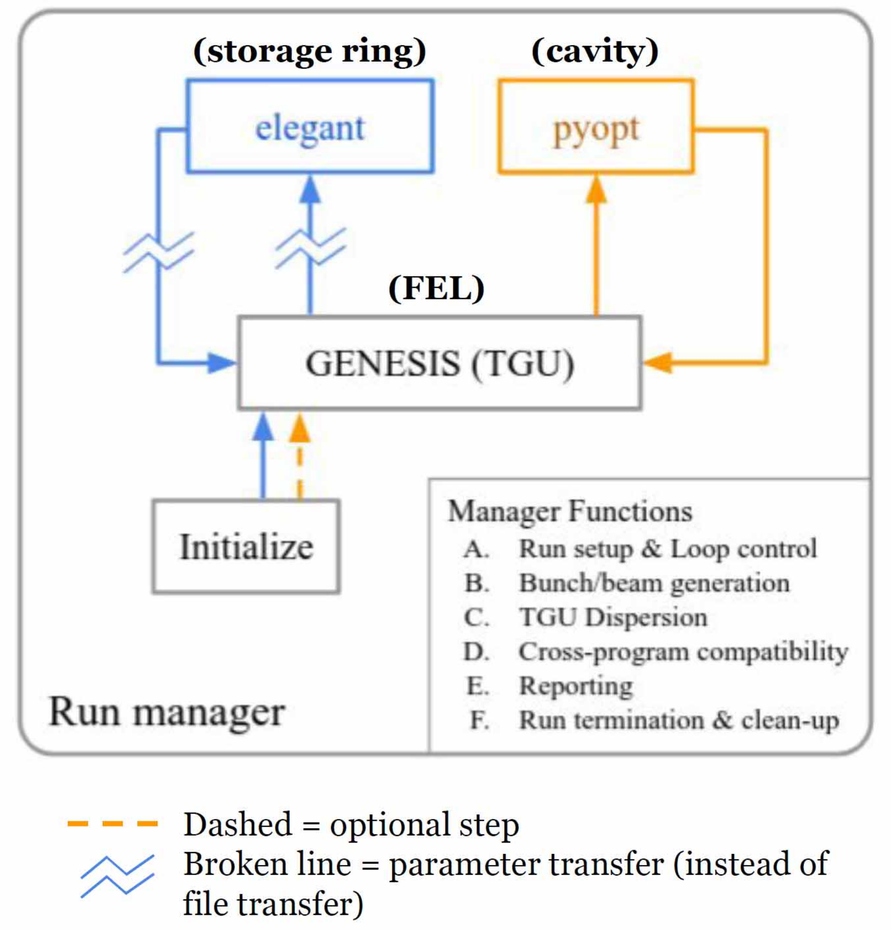


- Choose $n_{FEL} = C/L_{cav}$ equidistant bunches of higher current (4 nC, 32 A) for FEL interaction, the other of bunches (1 nC) serving the normal users
- $n_{FEL} = 16$ if every 5th in PETRA-IV bunch trains contains one FEL bunch



START-TO-END MODELLING OF SRXFELO

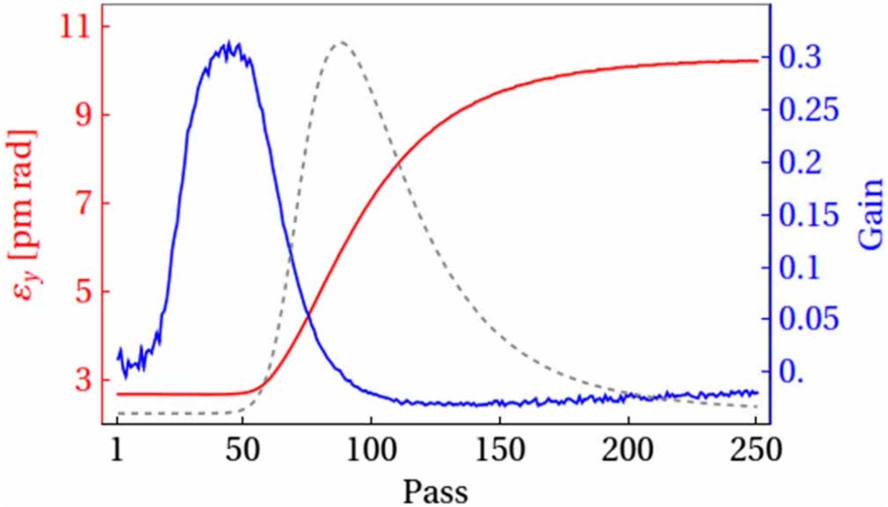
- **FEL**: GENESIS modified w/TGU
- **Storage ring**: *elegant*
- **Cavity**: Inhouse Fourier optics code “pyopt”
- Wrapper program for run management and interoperability

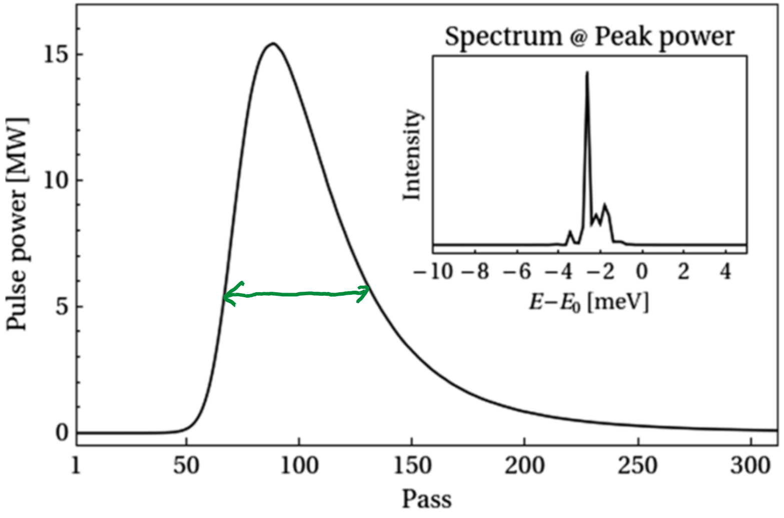


Manager Functions
A. Run setup & Loop control
B. Bunch/beam generation
C. TGU Dispersion
D. Cross-program compatibility
E. Reporting
F. Run termination & clean-up

Dashed = optional step
Broken line = parameter transfer (instead of file transfer)

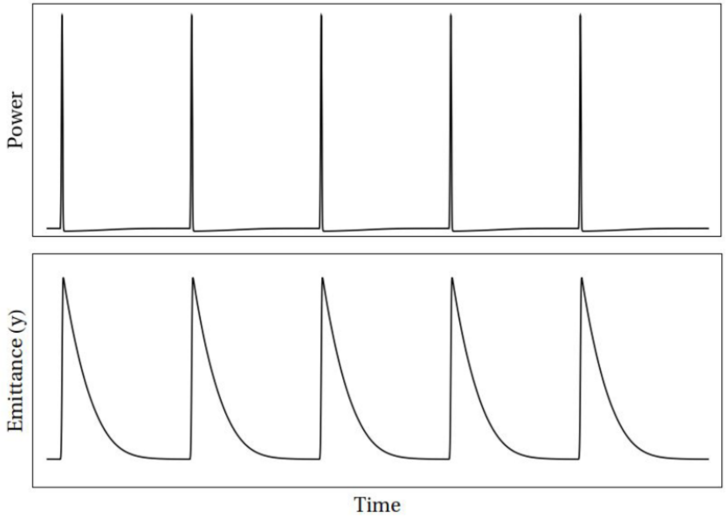
SRFELO EVOLUTION AND MACRO-PULSE





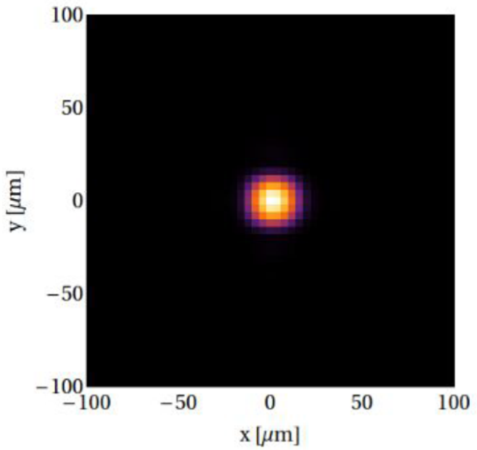
- Start-up with spontaneous emission→ Exponential growth of intra-cavity X-ray power → Degradation of electron beam emittance ε_y → X-ray power peaks when gain crosses zero, then declines due to cavity loss
- An FEL macro-pulse is formed, containing ~ 100 micro-pulses separated by 0.48 μs
- After the macro-pulse died out and the-beam emittance is sufficiently damped, another macro-pulse can make a fresh start
- The macro-pulse separation is random [M. Billardon, PRL 65, 713, 1990]

GAIN-MODULATION FOR PERIODIC AND REPRODUCIBLE MACRO-PULSE SEQUENCE

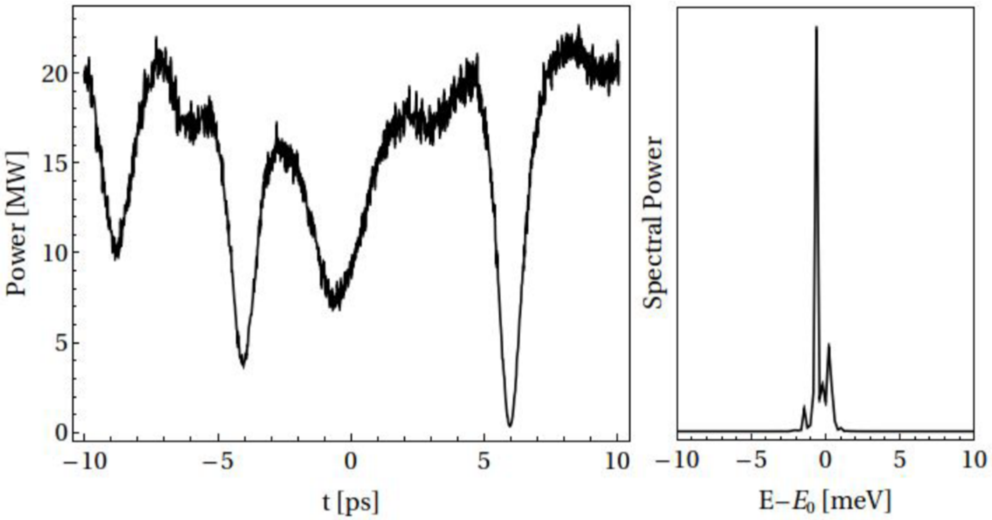


- **"On" state for macro-pulse: FEL lasing and emittance growth**
    - Duration ~ ΔT_{macro}~50μs
- **"Off" state: Switch off FEL and let electron emittance damp**
    - Duration ~3 $\tau_y = 66\ ms$
        - Duty factor $\sim 10^{-3}$
        - Macro-pulse repetition rate ~ 15 Hz
- **FEL can be switched off by**
    - **Transverse displacement**
        - Issue: need fast kickers of < 10 ns rise time
    - **Longitudinal displacement or "detuning" by RF frequency change**
        - **Displace one ΔT_{micro} during ΔT_{macro}** → $\frac{\Delta f}{f} = \frac{\Delta T_{micro}}{\Delta T_{macro}} = 5 \times 10^{-6}$
        - S.F. Mikhailov, et al, IPAC 2015

MICRO-PULSE CHARACTERISTICS



- **Transverse**
  - Diffraction limited Gaussian mode (slightly larger horizontal width due to crystal angular filtering)
- **Temporal**
  - Length ΔT_{micro} =125 ps (FW of e-beam)
  - Consists of *M*~ 40 coherent regions each ~ 3 ps long
  - Spectral width $\hbar\sigma_{\omega}{\sim}0.4\ meV$
- **Power**
  - Pulse power ~ 15 MW
  - 0.75 MW output (5% coupling)
  - 4×10^{10}photons



CONCLUSIONS

- With TGU and enhanced FEL bunches, an XFELO appears feasible in large ultimate storage rings, e.g., PETRA-IV
- With temporal gain modulation with RF frequency detuning, the output is reproducible, periodic, and non-invasive

- Thank Peifan Liu for discussion on RF detuning for DukeFEL