Feasibility study of multi-turn ERL-based synchrotron light facility

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OUTLINE

- MOTIVATION
- MULTI-TURN ERL WITH TWO STAGE INJECTION
- PARAMETERS
- OPTIC ISSUES / DETAILS OF LAYOUT
- CONCLUSION

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Which new set of parameters can reach a new kind of accelerator-based light source?

Energy Recovery Linacs allow:

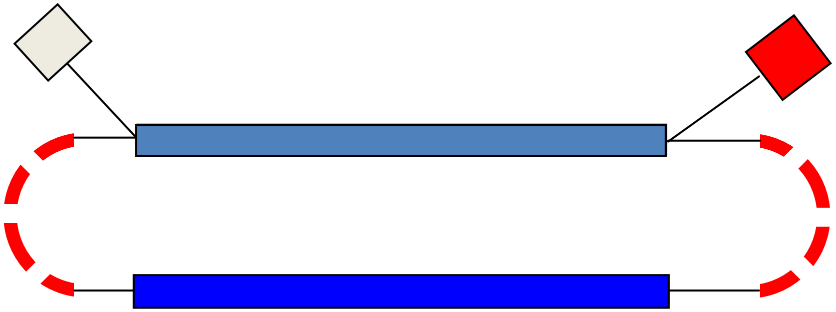
- Spectral range: ~10 keV
- reasonable flux
- high brilliance
- high peak brilliance
- high repetition rate
- full transverse coherence
- short pulses (time-resolved experiments)

- **high 6D brilliance**
- **high average current**

Combine advantages!

- high average current
- technologically mature
- energy efficient

- low emittance
- low energy spread
- long undulators
- short pulses



Like storage ring +
- low emittance
- low energy spread
- long undulators
- short pulses

or

Like linac +
- high average current
- energy efficient

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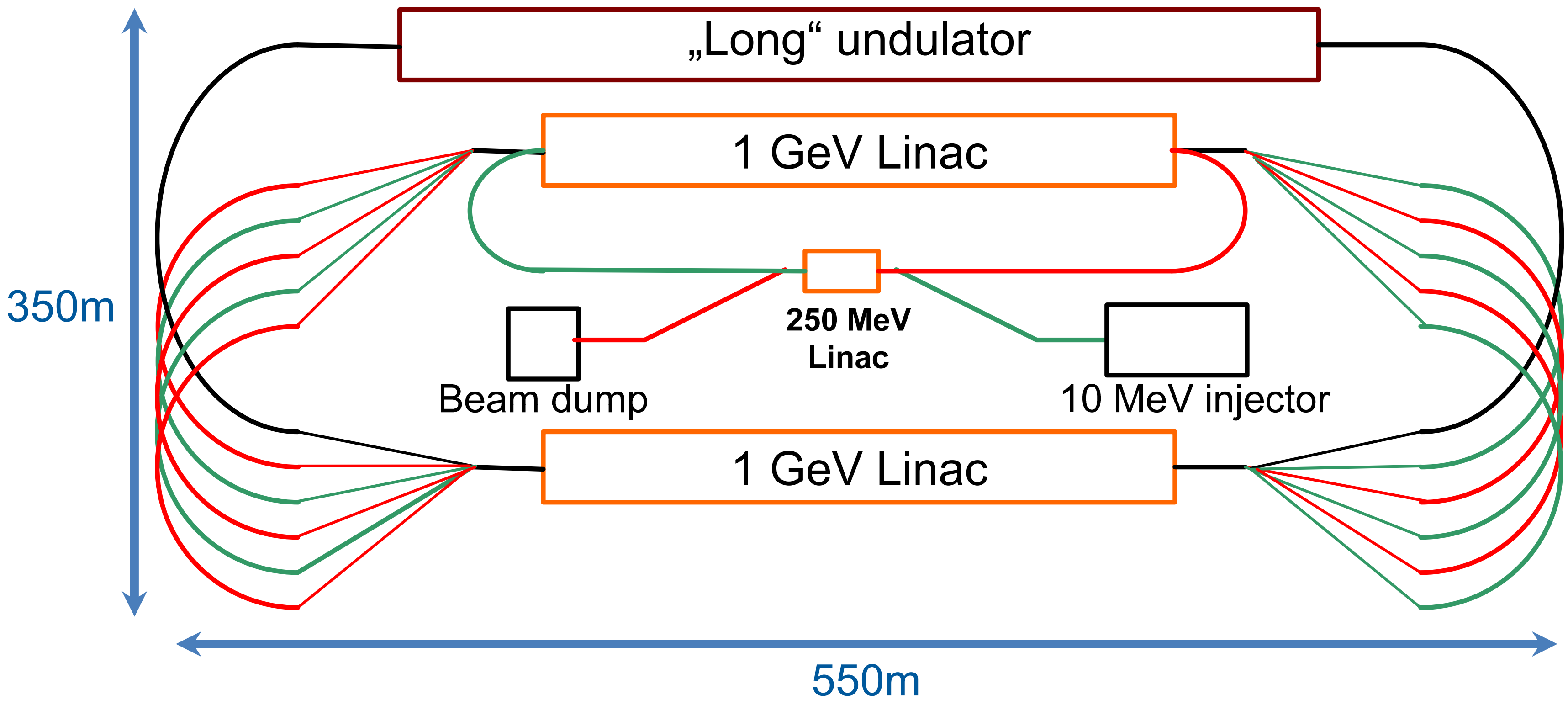
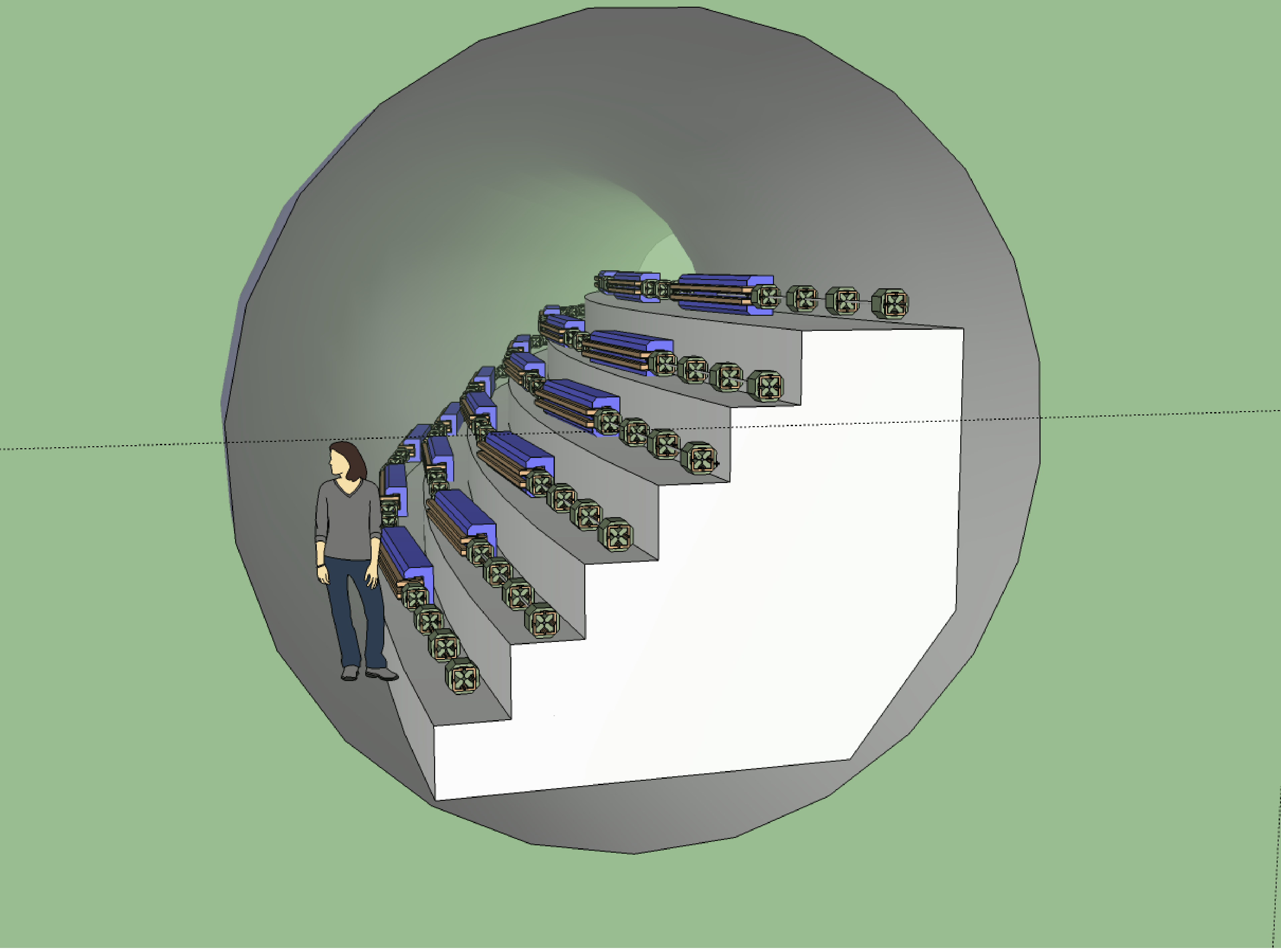
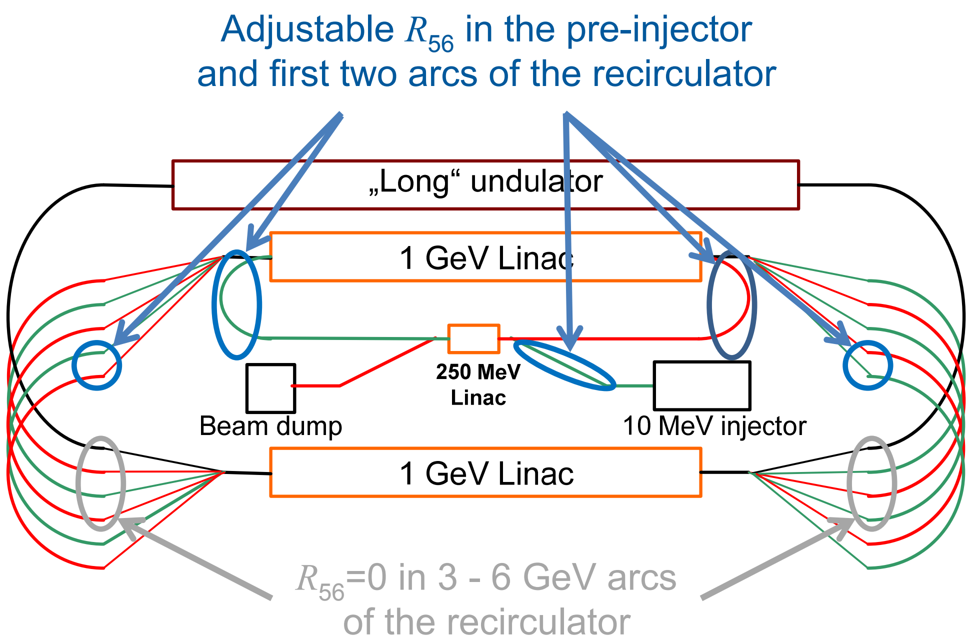
Femto-Science Factory (FSF): multi-turn, with pre-injection, splitted linac.



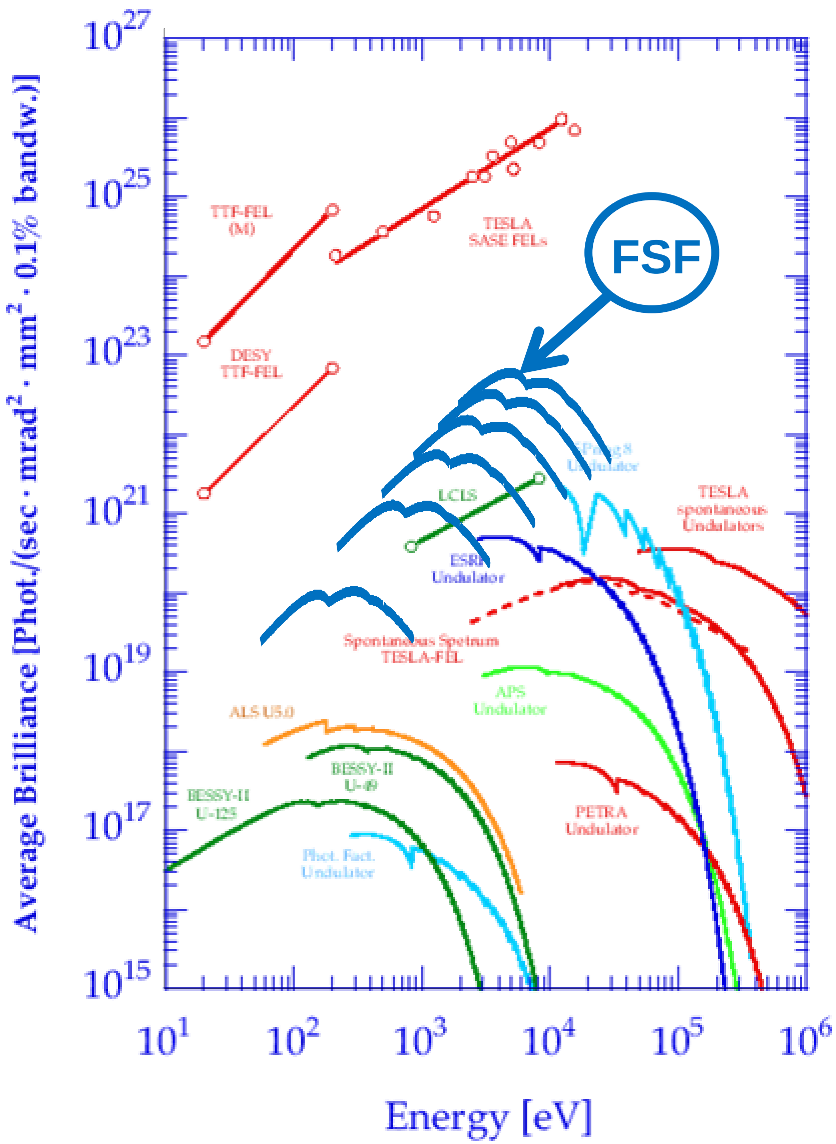


Since FSF shall be competitive with both future storage ring and linac -based light sources, it is necessary to keep the possibility to provide high average brilliance with short pulses. We propose two operation modes for 1) highest average brilliance 2) shortest bunch length. (Of course, one can think of operating with beam parameters between these extremes.) The longitudinal dispersion should be adjustable at least in some arcs to switch between the modes.



Accelerator/beam parameters	High brilliance mode	Short pulse mode
E, GeV	6	6
<I>, mA	20	5
Q, pC	15	4
$\varepsilon_{\perp n}$, μm	0.1	~0.5
$\varepsilon_{\|\|}$, keV·mm	~3	~3
τ, fs	200-1000	~10
$\langle B \rangle$, ph/s/mm²/mrad²/0.1%	$8 \cdot 10^{22}$	$\sim 4 \cdot 10^{21}$
B_{peak}, ph/s/mm²/mrad²/0.1%	10^{26}	$\sim 10^{26}$
I stage injector (no recovery)		
E, MeV	10	10
τ, fs	2000	2000
II stage injector (BERLinPro)		
E, GeV	0.25	0.25
τ, fs	200-2000	200

Accelerator/beam parameters	
Undulators	5 /arc x 6 energies x 2 arcs+1 = 61
d, cm	4
Number of periods	1000 (+ 1 with 3000)
Linacs	2 linacs x 9 cryomodules x 8 cavities x 7cell (BERLinPro type) +2 cryomodules (pre-injector)
Accelerating gradient, MV/m	17
Energy gain per linac, GeV	1
f, GHz	1,3



Type 2 undulators:
d=0.04 m
K=0..2.5
N=1000
$\delta=10^{-4}$
$B_{max}=4.85\cdot10^{22}$
γ=2000 (1 GeV),
4000 (2 GeV), …,
12000 (6 GeV).

Backgound picture (© DESY XFEL) shows the comparisson with other lightsources

Brilliance = the 6-D density of the photon beam in phase space

$$B = \frac{d^6 N_{ph}}{dV^6} \sim \frac{\dot{N}_{ph}}{4\pi^2 \sigma_x \sigma_{x'} \sigma_y \sigma_{y'} \dfrac{d\omega}{\omega}} \sim \frac{N_{ph}}{(2\pi)^3 \varepsilon_x \varepsilon_y \varepsilon_z}$$

In general, rms. bunch parameters are not the best choice to describe the beam brilliance [see e.g. I.Bazarov PRST AB 15, 050703 (2012)]. We use them for the selfconsistent comparisson with other sources.

For the undulators we consider, energy spread can lead to a widening of the radiation spectrum. This effect is important for higher harmonics. Brilliance is reduced (compared to a monoenergitic beam) by a factor

$$\frac{1}{\sqrt{1 + 8\pi (Nk\delta)^2}}$$

(this formula is a good approximation for the maximum in the spectrum, the coefficient depends on the particle distribution, here a gaussian is assumed.)

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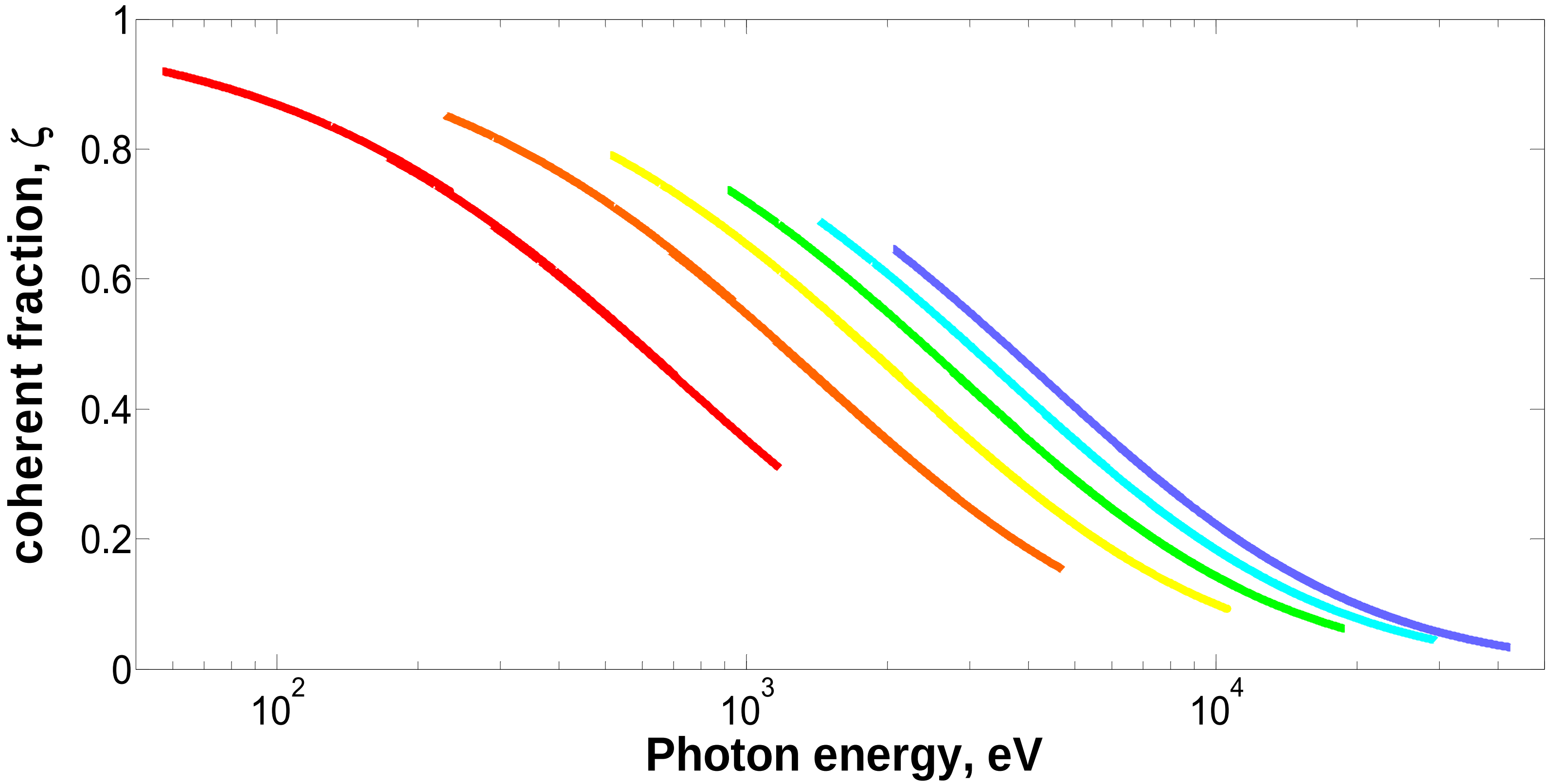
$$\sigma_x = \sqrt{\frac{\sigma_r^2}{2} + \varepsilon_x \beta_x + (\eta_x \delta)^2 + \dots} \qquad \sigma_{x'} = \sqrt{\frac{\sigma_{r'}^2}{2} + \frac{\varepsilon_x}{\beta_x} + (\eta'_x \delta)^2}$$

If emittances are small, the source is called “diffraction limited” or “spatially coherent”. The brilliance in this case is defined by the photon beam emittance.

$$if \qquad \varepsilon_x << \frac{\lambda}{4\pi} \quad \Rightarrow \quad (\sigma_x \sigma_{x'})_{\min} = \frac{\sigma_r \sigma_{r'}}{2} = \frac{\lambda}{4\pi} \qquad B_{\max} = \frac{4\dot{N}_{ph}}{\lambda^2 \frac{d\omega}{\omega}}$$

The transversally coherent fraction of the radiation is given by

$$\zeta = \frac{\lambda^2}{(4\pi)^2 \sigma_x \sigma_{x'} \sigma_y \sigma_{y'}}$$



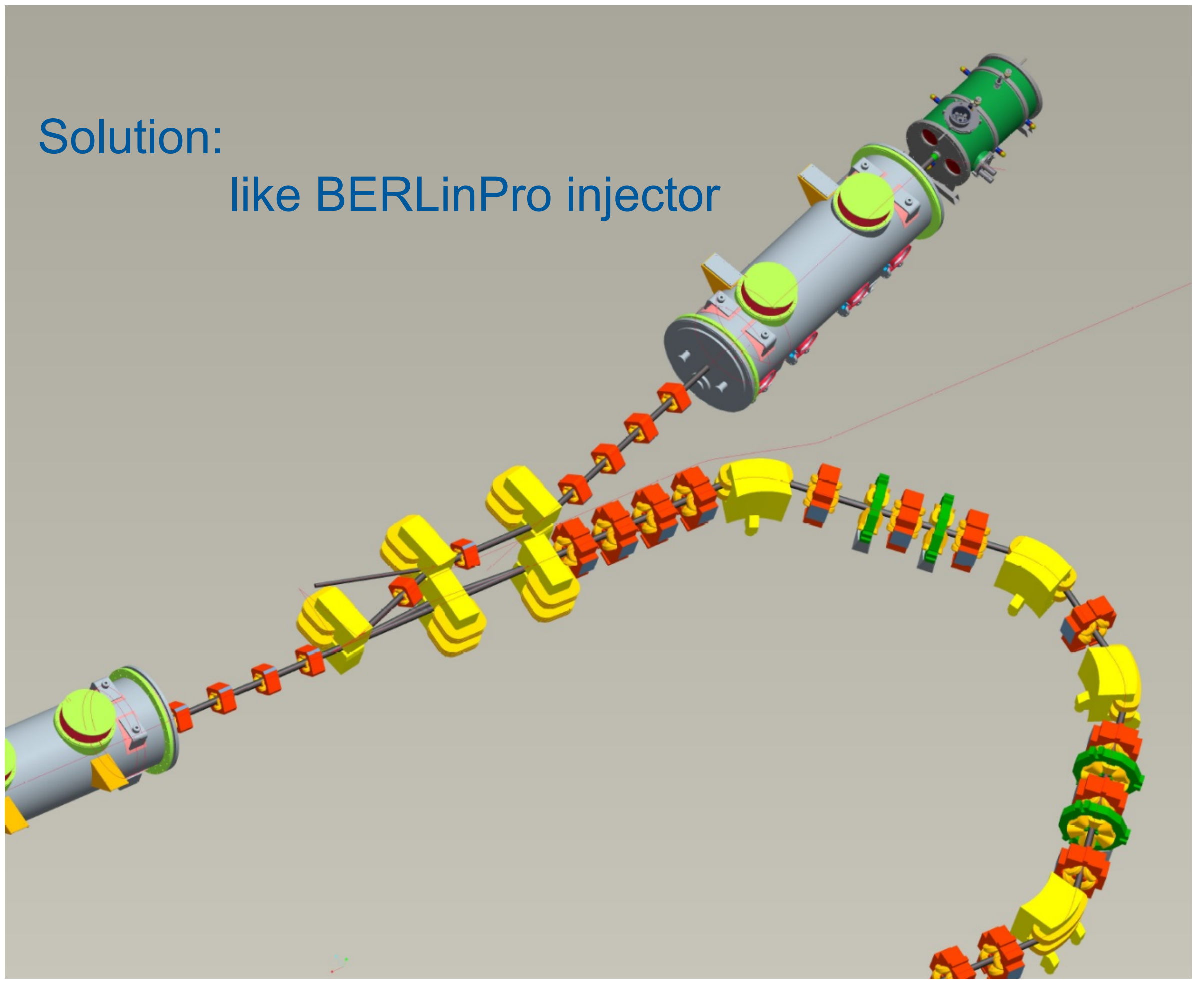
Coherent fraction of the FSF Type 2 undulator radiation at 1 (red) through 6 (blue) GeV for the photon energies covered by the first to fifth harmonics.

What we are working on…

- Injector design
  - Space charge limited minimal emittance optics
- Arcs
  - ISR ***and*** CSR optimized
  - Isochronous or R_{56}-adjustable
- Linacs
  - Multiple-beams suitable optics
  - BBU optimized
  - Compensation of the average energy loss (ISR, CSR, wakes)
- Spreaders/recombiners
  - ISR ***and*** CSR optimized
  - Isochronous
  - Compact
- Short pulses -enabling design (laser heater, longitudinal gymnastics, 3rd harmonic RF)

What we are working on…

Optimal injector:
•Photocathode
•Bunch compression
•Emittance compensation (2D in merger)



Optimal arc:

•Achromatic
•Isochronous (some with adjustable R_{56})
•ISR optimized (minimal emittance lattice, $I_5 = \int \frac{\left(\gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2\right)}{|\rho|^3} ds$)

$$\Delta\varepsilon = \frac{2}{3} r_e C_q \gamma^5 I_5$$

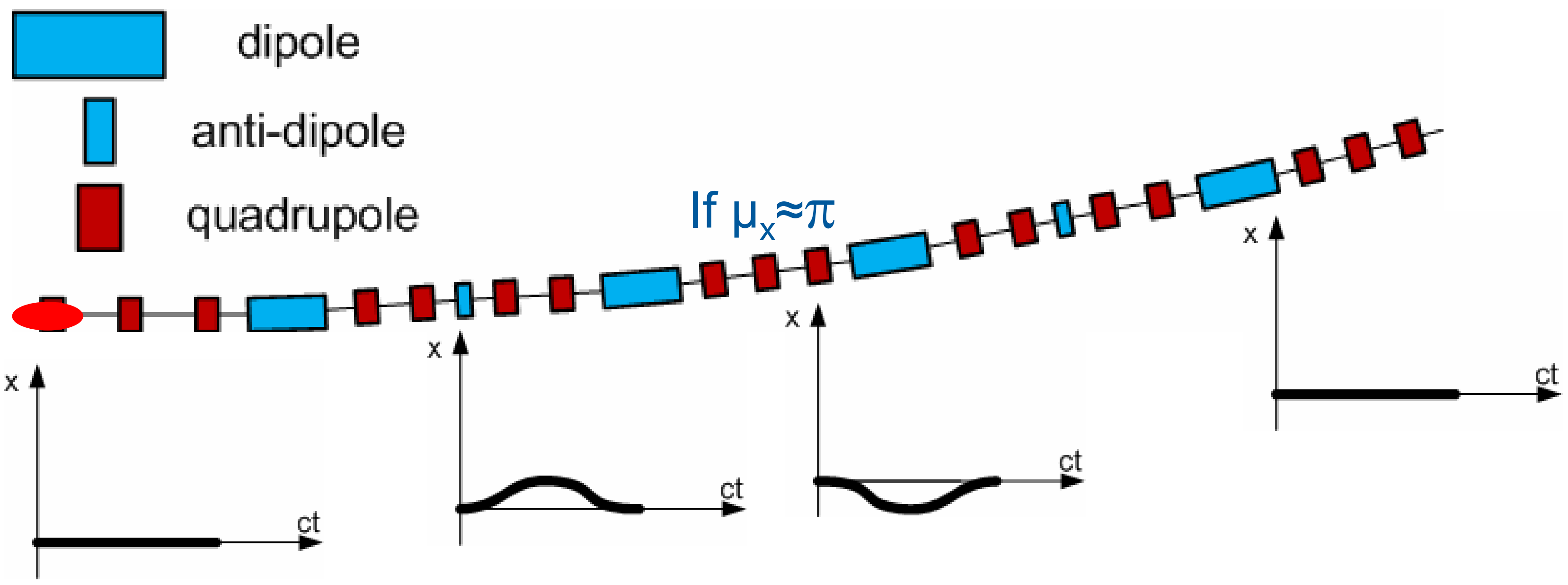
•CSR optimized (phase advance between cells)

CSR in system of identical isochronous bending cells

Consider two consecutive identical isochronous bending cell.

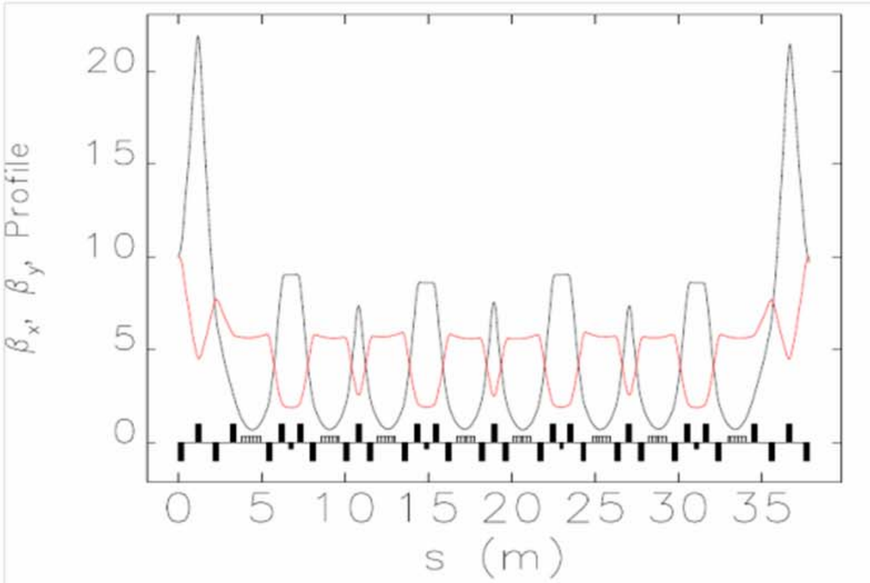
1. The longitudinal bunch shape does not change due to isochronism.
2. The longitudinal dynamic in cells is identical if CSR induced energy spread produced in one cell is small enough.

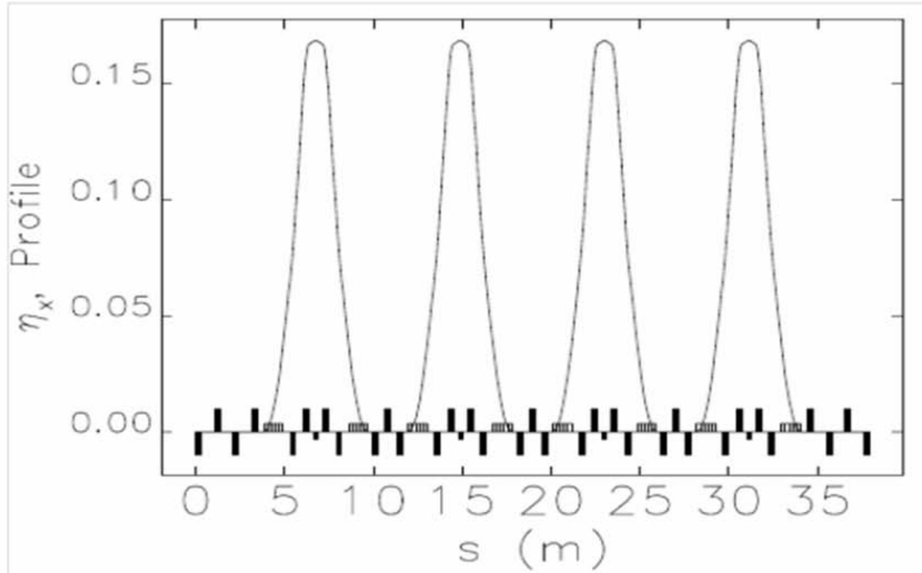
Results: 1D CSR wakes in consecutive identical isochronous bending cell also identical.



X is coordinate of slice centers

30º arc as four 7.5º bending cells

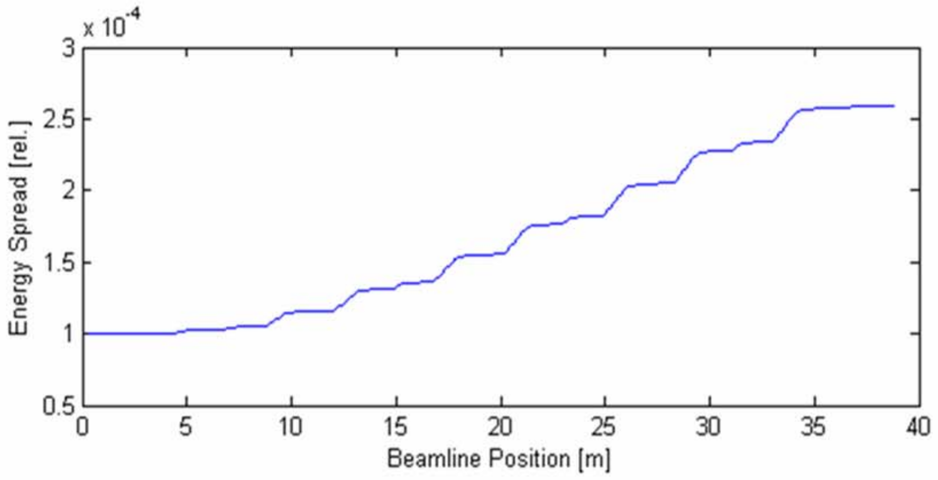


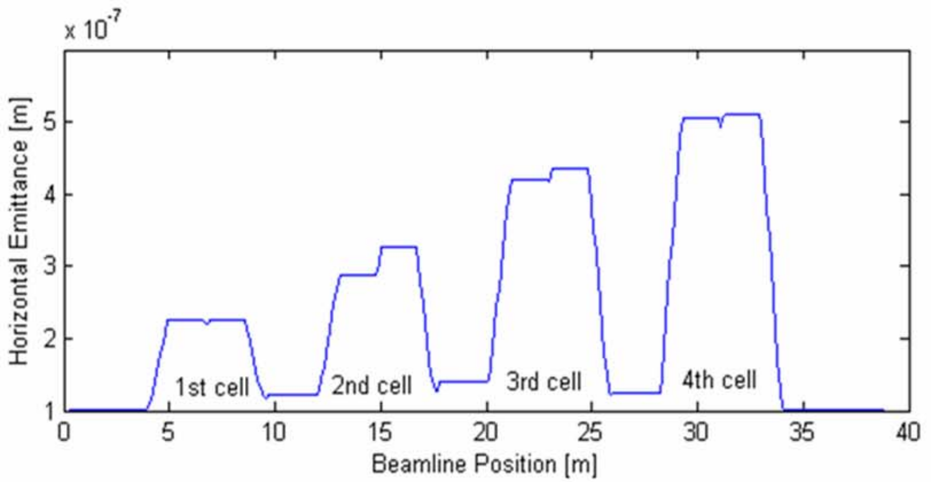


Cells optimized to minimal emittance growth due to ISR.
At 6 GeV per turn (360°) $\Delta\varepsilon_{ISR} \approx 0.05 mm \cdot mrad$
In each cell $\mu_x \approx 3\pi/2$

Bunch parametrs: σ_z=10 fs, Q=15.4 pC, ε_n=0.1 mm·mrad, E=6 GeV, δ_{rms}=10^{-4}

1D CSR (self-forces ‘projected’): N=$3\cdot10^5$, r=0.01 μm
3D CSR (self-forces ‘csr_g_to_p’): N=$2\cdot10^4$, r=0.1 μm,
All simulations give the same results.





CSR induced transversal emittance can be cancelled

Optimal linac optics and pre-injection:

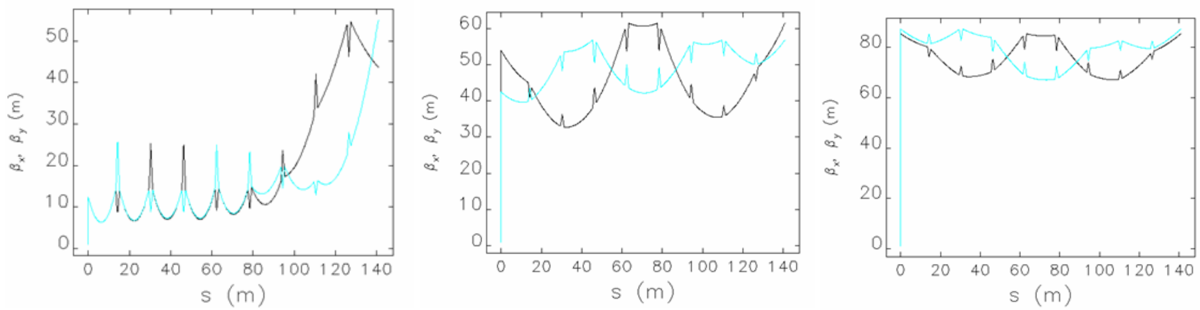
•BBU optimized (minimal β-functions at *all* energies)

•Difficulties:

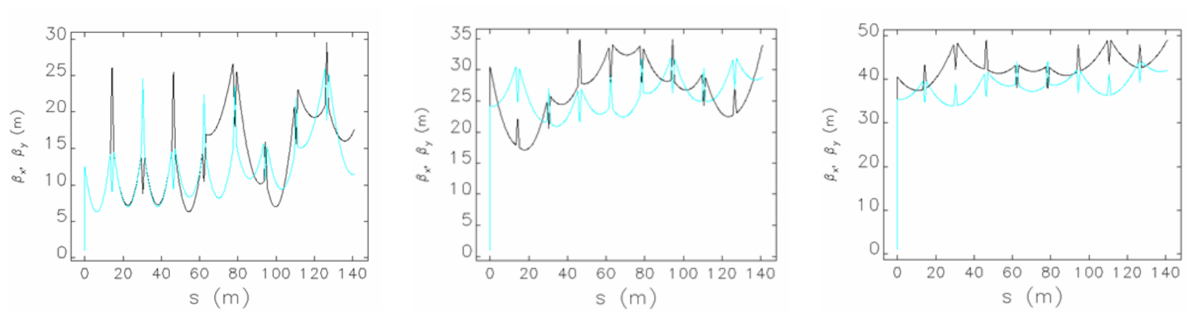
- Multiple beams (with different energies) through the same optic
- Quite high „natural“ β-functions

1st linac

1st pass | 2nd pass | 3rd pass



2nd linac



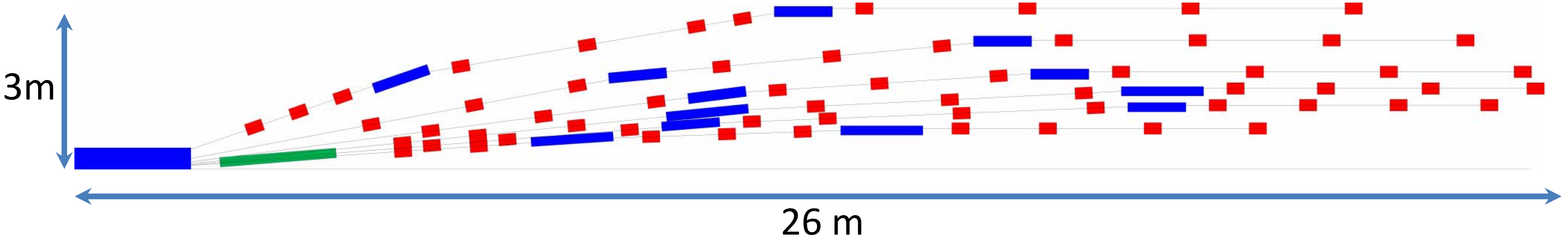
See the talk of Y.Petenev on Tuesday for details

Spreaders:

- Achromatic
- Isochronous
- ISR optimized (minimal I_5)
- Compact

- Difficulties:
  - Low β-functions are needed for low I_5, contradicts with „natural“β-functions of linacs
  - Low dispersion is necessary for low I_5, contradicts with the beamline separation
  - A „Lambertson septum -like“ separation magnet for 4, 5, and 6 GeV beam lines is pursued, coupled optics is complicated to optimize

Spreader (vertical plane)



R_{56}=0 D_y=0 D'_y=0

$\beta_{in,out} \approx$ 50÷100 m $\beta_{max} \approx$ 300 m

$$I_5 = \int \frac{\left(\gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2\right)}{|\rho|^3} ds \longrightarrow \min$$

Start-to-end simulation: longitudinal emittance recovery, transversal emittance preservation.

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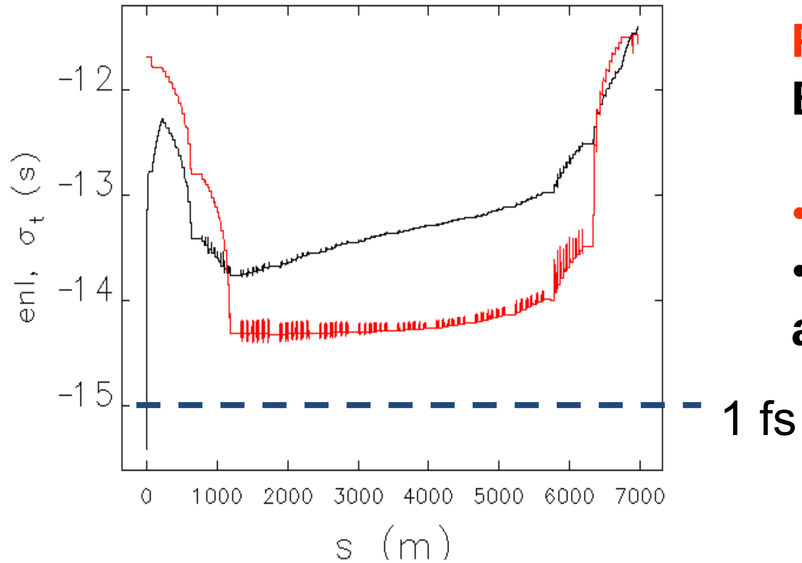
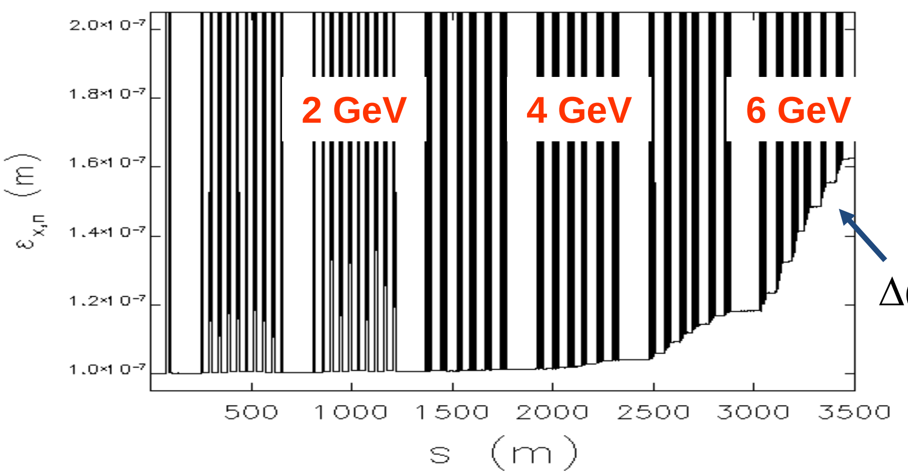


Red: bunch length
Black: longitudinal emittance

- **< 10 fs bunch length is feasible (1 pC)**
- **Longitudinal „emittance recovery“ in 1 and 2 GeV arcs**



ISR effects

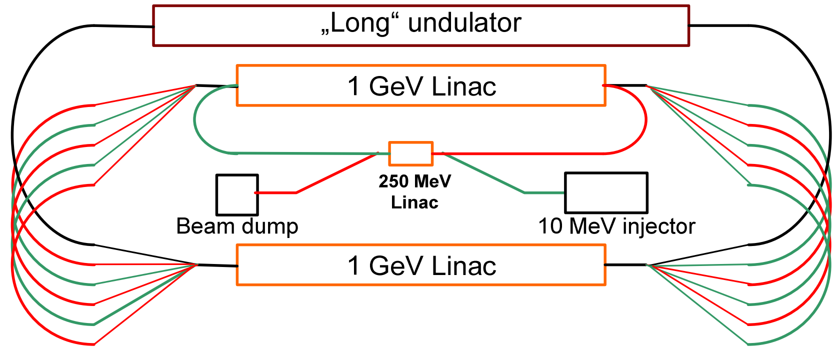
$\Delta(\gamma\varepsilon_{isr}) \sim 4\text{x}10^{-8} E^6 I_5$
$= 0.05$ mm mrad

See the talk of T.Atkinson on Wednesday for details

FSF Capabilities

• High pulse repetition rates (up to 1.3 GHz).
• Very high average brightness, several orders of magnitude greater than third-generation rings.
• Pulse durations ranging from tens of femtosecond to some picoseconds.
• High temporal coherence
• High transverse coherence (approaching diffraction limit).
• Control of time duration of the pulses.
• Excellent spectral resolving power.
• Output photon energy (including harmonics) extending throughout the soft X-ray region, from ~50 eV to ~50 keV.
• Polarization control.
• Multiple independent beamlines supporting a large user community.

Conclusion



6 GeV multi-turn ERL driver

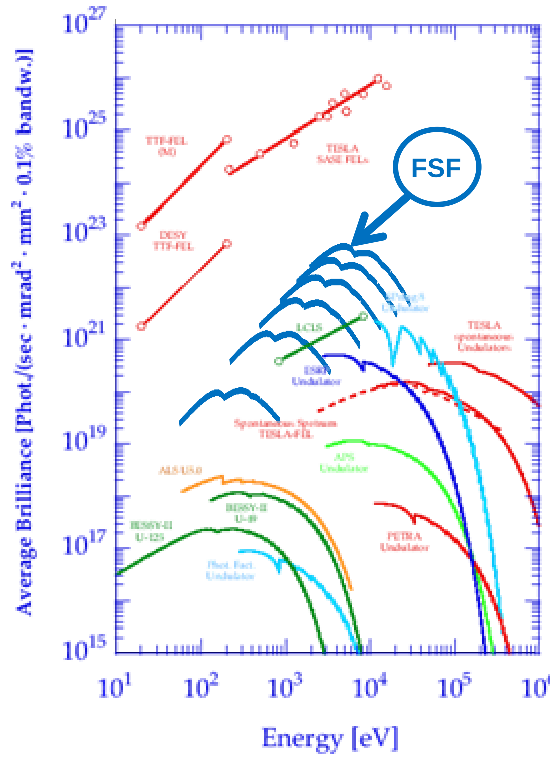
for a synchrotron light source

with

•0.1 mm·mrad normalized emittance

•diffraction limited at 1 Å wavelength

•10 fs rms bunch lenght



seems feasible.