Beam Dynamics Meeting:

“Modelling and evidence of intra-beam scattering in high brightness electron linacs”

Giovanni Perosa/giovanni.perosa@elettra.eu

Università degli Studi di Trieste
Elettra Sincrotrone Trieste

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Beam Dynamics Meeting:

"Modelling and evidence of intra-beam scattering in high brightness electron linacs"

Prologue:

- Theory and experimental data on collective phenomena at FERMI (Elettra Sincrotrone Trieste)

Acknowledgement:

Contributions and support from: A. Brynes , P. H. Williams, A. Wolski, I. Setija, E. Roussel, N. Mirian and the FERMI team.

Special thanks to: S. Di Mitri (Elettra Sincrotrone Trieste, Univ. Trieste)

Outline

Introduction

1. Intra-Beam Scattering
2. Microbunching Instability

Modelling IBS

1. Analytical model

Model in action

1. Effect of IBS on MBI
2. Experimental evidence of IBS in SES
3. Indications of IBS effect

Conclusions

What is next…

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Intra-beam Scattering

Intra-beam Scattering

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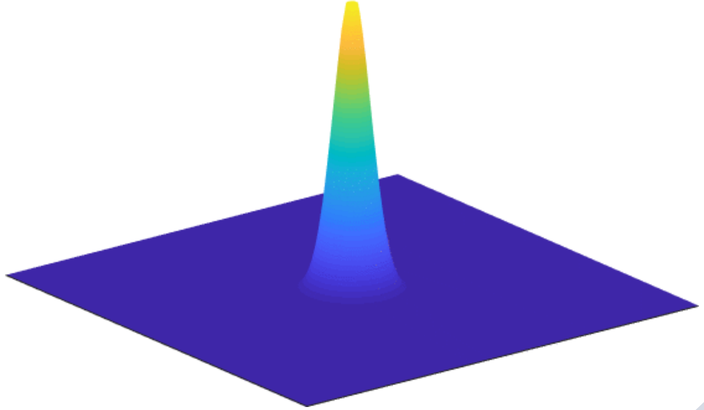


Multiple small-angle Coulomb scattering of charged particles

Emittances and energy spread growth

Main consequences in SR

- **Larger equilibrium emittances**
- **Limiting the luminosity**
- **Tendency to relax the momenta distribution to a spherical shape** (in beam reference frame)

Proportional to beam density and inversely proportional to γ^4

so…

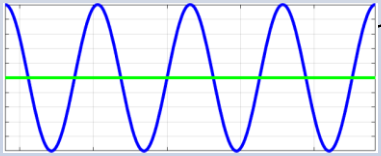
Why IBS in linac ?

Why now? Charge density of high brightness linacs driving short wavelength free-electron lasers (FELs) is large enough for IBS to become a significant effect.

Microbunching instability

From shot noise disomogeneity, modulation wavelength in the range from 1 to hundreds of μm

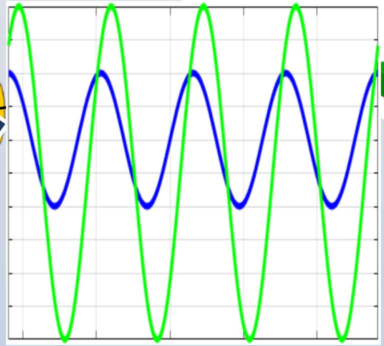
density mod.



LSC

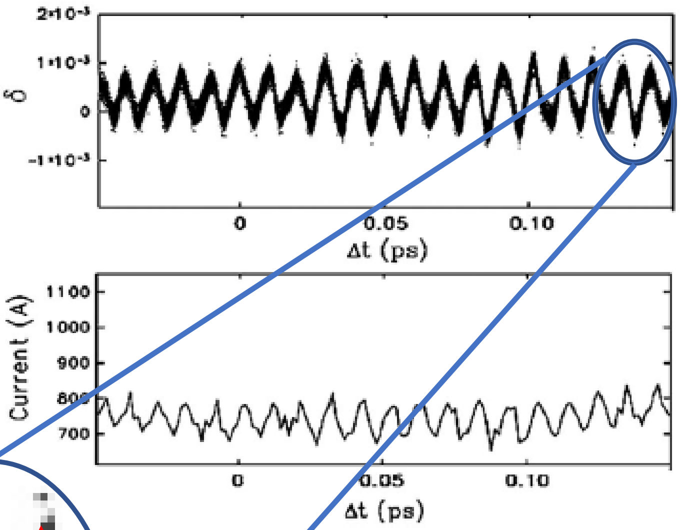
acceleration

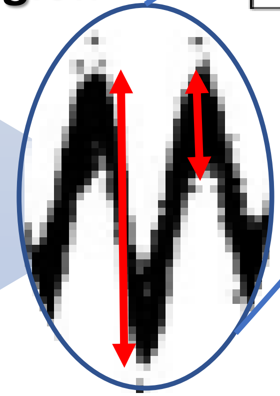
energy mod.



R_{56}, CSR

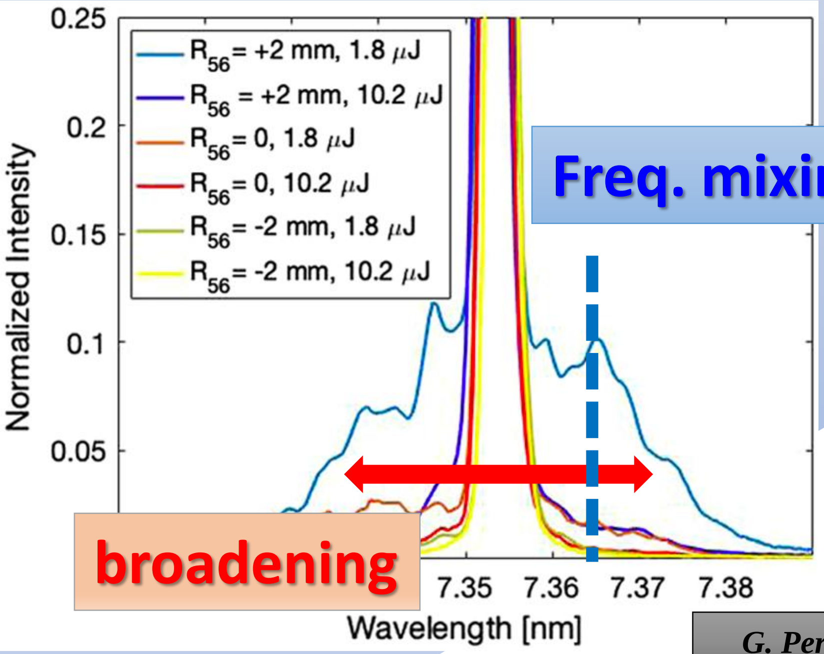
dispersive region





Simulated 30 μm wavelength, 1% amplitude at 100 MeV

S. Di Mitri S. Spampinati, PRL 112 (2014)



G. Perosa et al., PRAB 23 (2020)

Spurious harmonic content

Increased Energy Spread

Modelling IBS

Analytical model

Relative energy spread growth rate

$$\frac{1}{\sigma_\delta}\frac{d\sigma_\delta}{ds} = \frac{r_e^2 N_e [\log]}{8\gamma^2 \epsilon_n \sigma_x \sigma_z \sigma_\delta^2}$$

$$\left.\frac{1}{\sigma_\delta}\frac{d\sigma_\delta}{ds}\right|_{disp} = \frac{r_e^2 N_e [\log]}{8\gamma^2 \epsilon_n \sigma_x \sigma_z \sigma_\delta^3}\sigma_H$$

$$\frac{1}{\sigma_H^2} = \frac{1}{\sigma_\delta^2} + \frac{H_x}{\epsilon_x} + \frac{H_y}{\epsilon_y}$$

Assumptions

- Ultra-relativistic beam
- Round beam ($\beta_x = \beta_y$ …)
- Use of mean values for optics

Applications

- ✓ Straight section with constant energy
- ✓ Straight accelerating section
- ✓ Dispersive region

Microbunching instability gain

$$G(k) \cong \frac{4\pi I_0}{Z_0 I_A} Ck|R_{56}| \left| \int ds \frac{Z_{LSC}(k;s)}{\gamma(s)} \right| exp\left[-\frac{1}{2}(CkR_{56}\sigma_\delta)^2\right]$$

Landau damping

How do they couple?

Simone Di Mitri et al, New J. Phys. 22 (2020)

Analytical model

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Integrating the growth rate

$$\int_0^L \frac{d\sigma_\delta}{ds} ds \rightarrow \sigma_\delta(L)^2 - \sigma_\delta(0)^2 = f(L) \approx AL$$

Sometimes approximated to first order

Directly inserted in the gain expression

Huang-Kim MBI model

Bosch-Klemann MBI model

$$G(k) \cong \frac{4\pi I_0}{Z_0 I_A} Ck|R_{56}| \left| \int d\,s \frac{Z_{LSC}(k;s)}{\gamma(s)} \right| exp\left[-\frac{1}{2}(CkR_{56}\sigma_\delta)^2\right]$$

Can it be done directly?

$$\lambda_{crit} \propto AL_b C^2 R_{56}^2$$

The critical wavelength can be expressed as a function of A and the chicane's parameters and it is $\ll \mu$m.

MBI and IBS dynamics can be decoupled for modulations' wavelength longer than a treshold value!

G. Perosa Simone Di Mitri, Sci Rep 11 (2021)

Analytical model

Important ingredient

$$[\log] = \log\left(\frac{b_{max}}{b_{min}}\right) \approx \log\left(\frac{\theta_{max}}{\theta_{min}}\right) \approx \ln\left(\frac{\epsilon_n q_{max}}{2\sqrt{2} r_e}\right)$$

Piwinski prescription

$$\theta_{min} \approx \frac{4 r_e}{b_{max}\gamma^2 \sigma_{x'}^2} \quad \text{with} \quad b_{max} \approx \sigma_x$$

Raubenheimer prescription

$$\theta_{max} \approx \frac{\sqrt{2} q_{max}}{\gamma \sigma_{x'}} \quad \text{with} \quad q_{max} = \left[\frac{cLN_e r_e^2}{2\gamma^{3/2}\epsilon^{3/2}\sigma_z\sqrt{\beta_x}}\frac{\sigma_H}{\sigma_\delta} + \mathcal{O}(\sigma_\delta)\right]^{1/2}$$

Limit maximum scattering angle and **discard** single scattering effects to exclude **tail contribution** from the calculation.

The cutoff timescale → the time the bunch takes to travel along the section.

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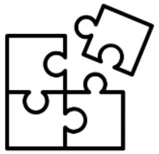
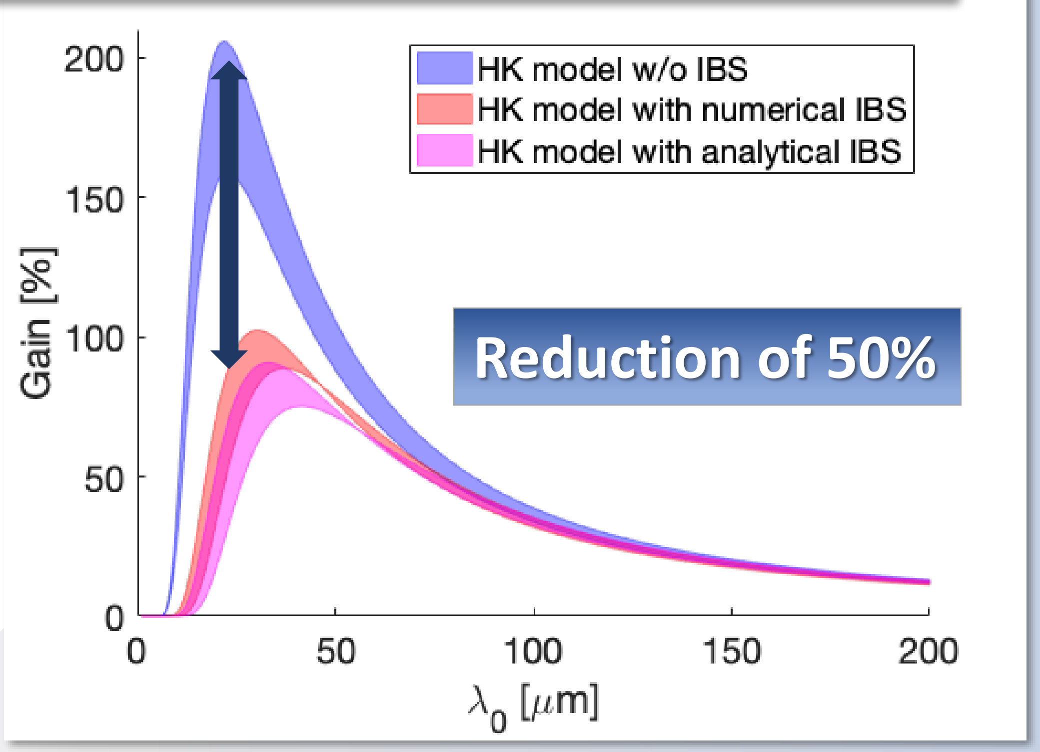
IBS in action

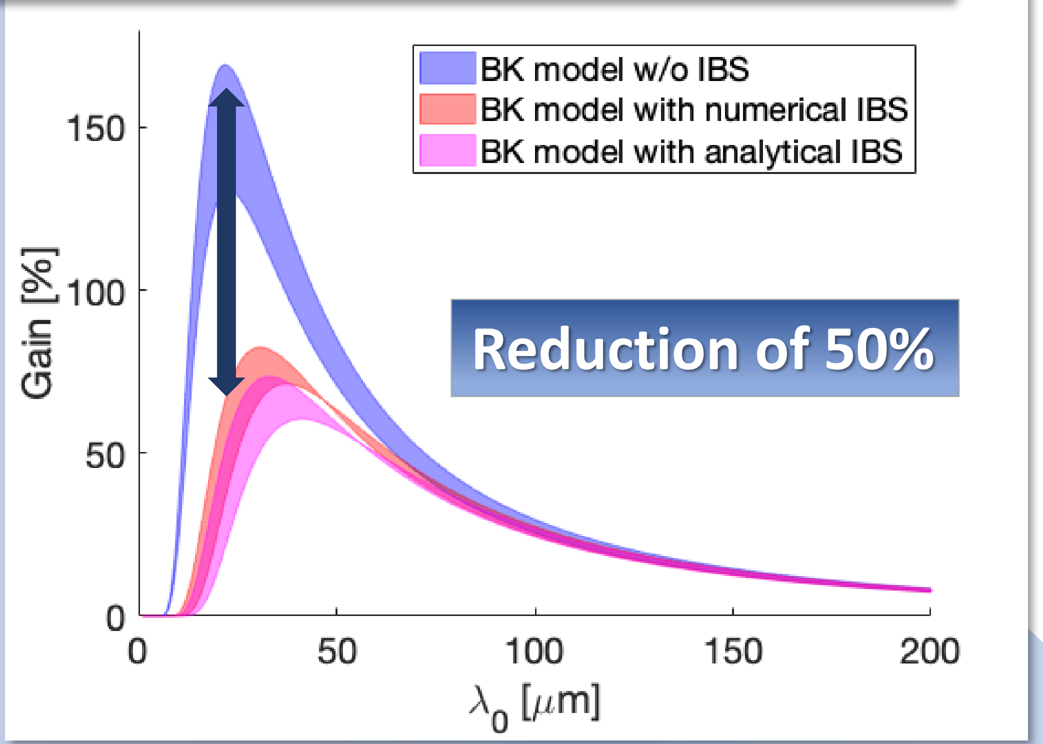


Effect of IBS on MBI

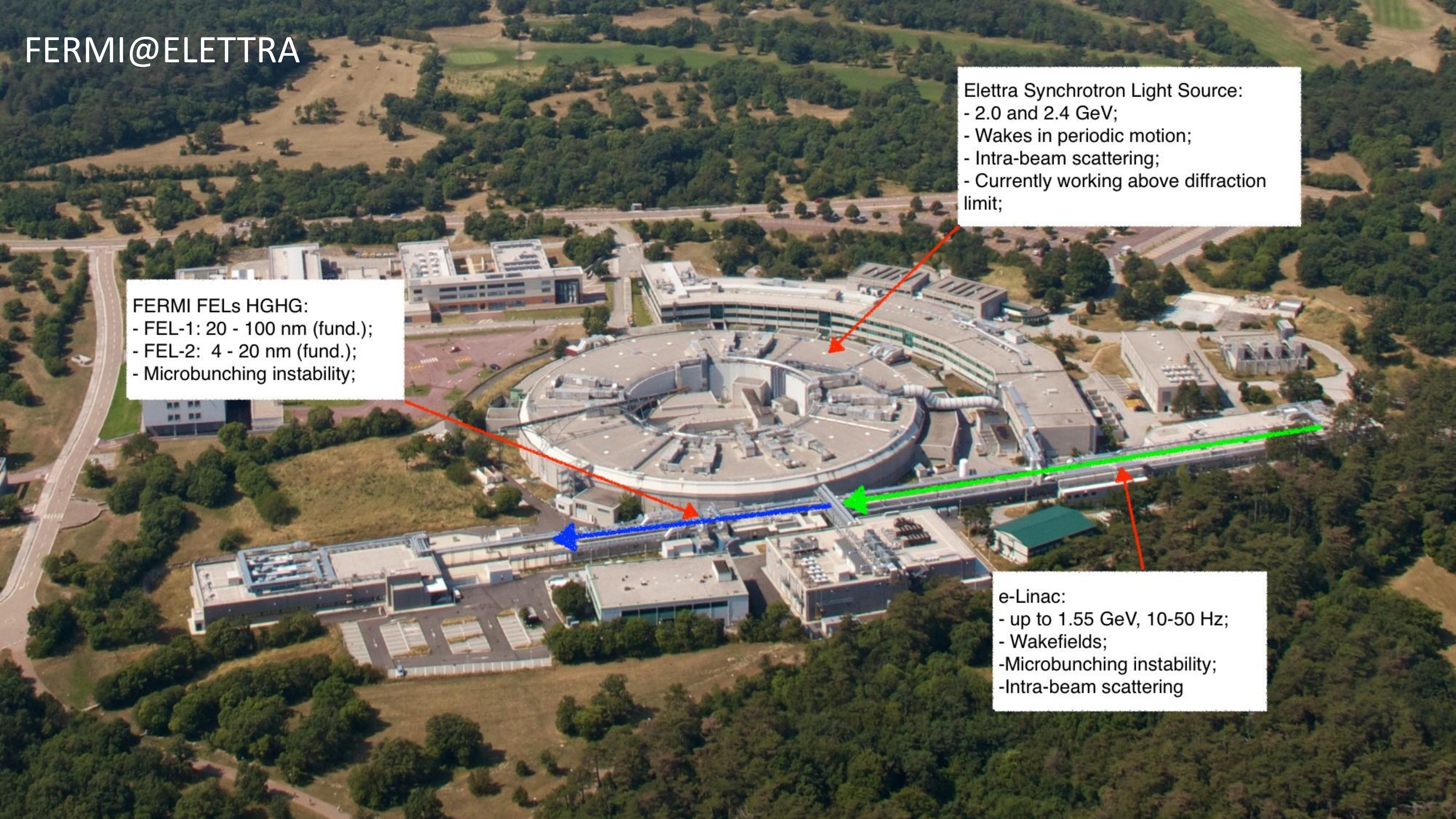
HK model: linearized Vlasov equation in integral form
Collective effects: LSC and CSR.



BK model: matrix model for longitudinal modulations
Collective effects: LSC, CSR and CER.

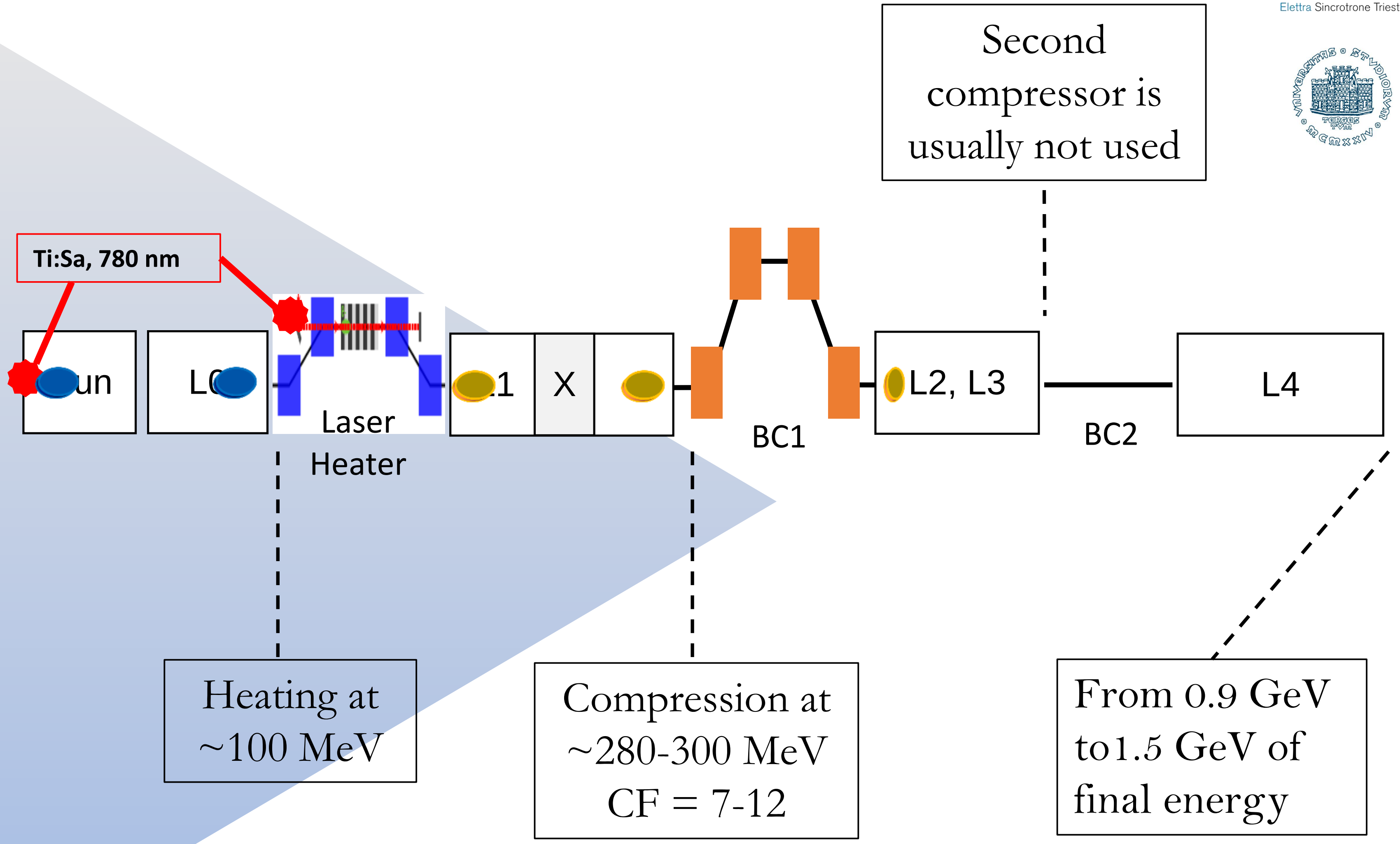


G. Perosa Simone Di Mitri, Sci Rep 11 (2021)

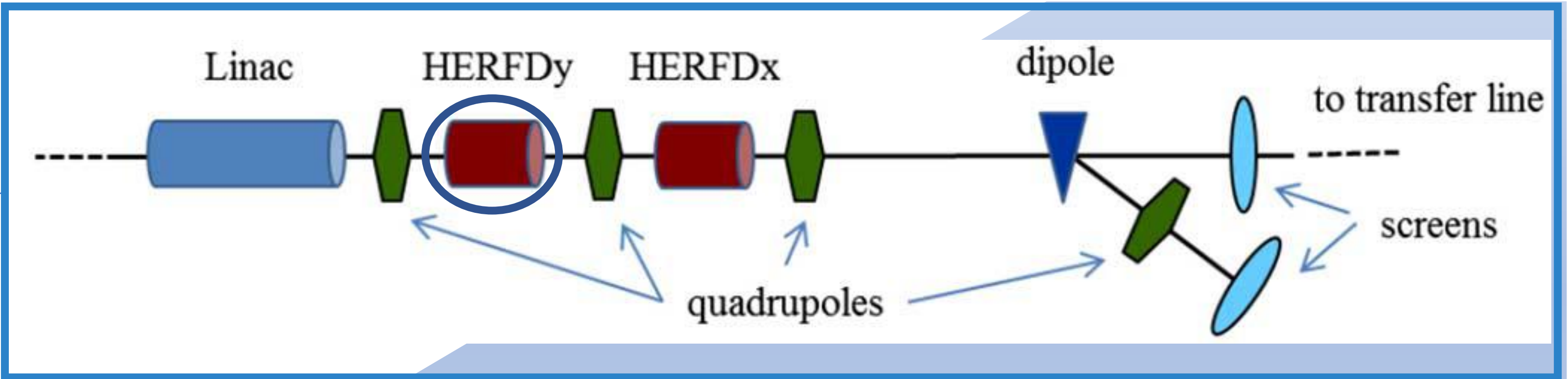

FERMI@ELETTRA
Elettra Synchrotron Light Source:
- 2.0 and 2.4 GeV;
- Wakes in periodic motion;
- Intra-beam scattering;
- Currently working above diffraction limit;
FERMI FELs HGHG:
- FEL-1: 20 - 100 nm (fund.);
- FEL-2: 4 - 20 nm (fund.);
- Microbunching instability;
e-Linac:
- up to 1.55 GeV, 10-50 Hz;
- Wakefields;
-Microbunching instability;
-Intra-beam scattering

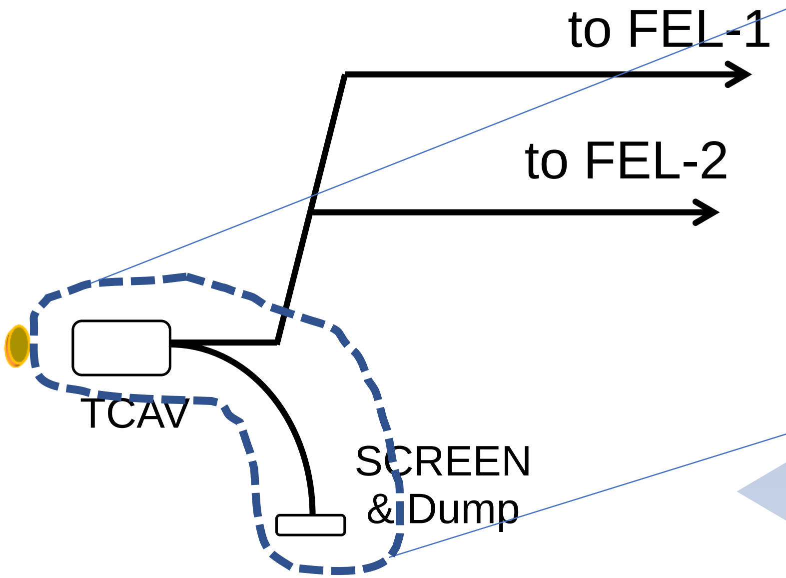
FERMI linac

Parameters	Values
Charge	500-700 pC
Emittances	1-2 mm mrad
Energy spread	100-170 keV
Peak current	500-700 A
Beam Energy	0.9 - 1.5 GeV

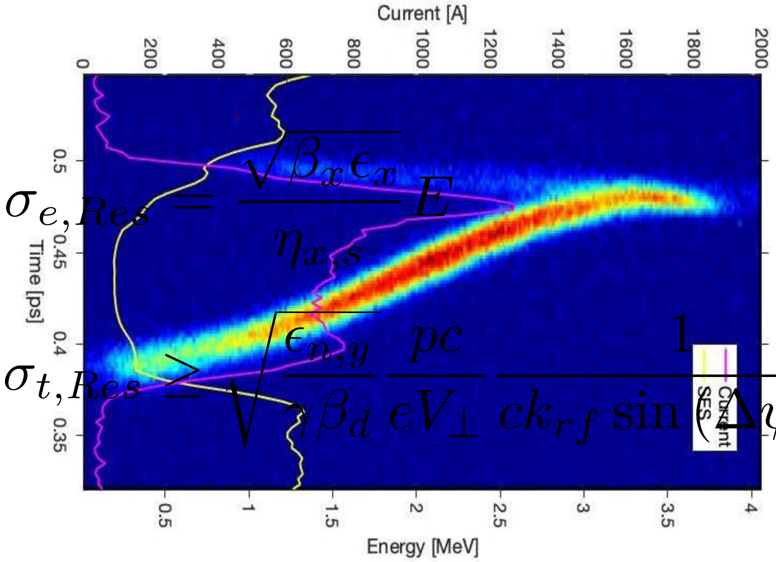


Vertical RF Deflecting Cavity



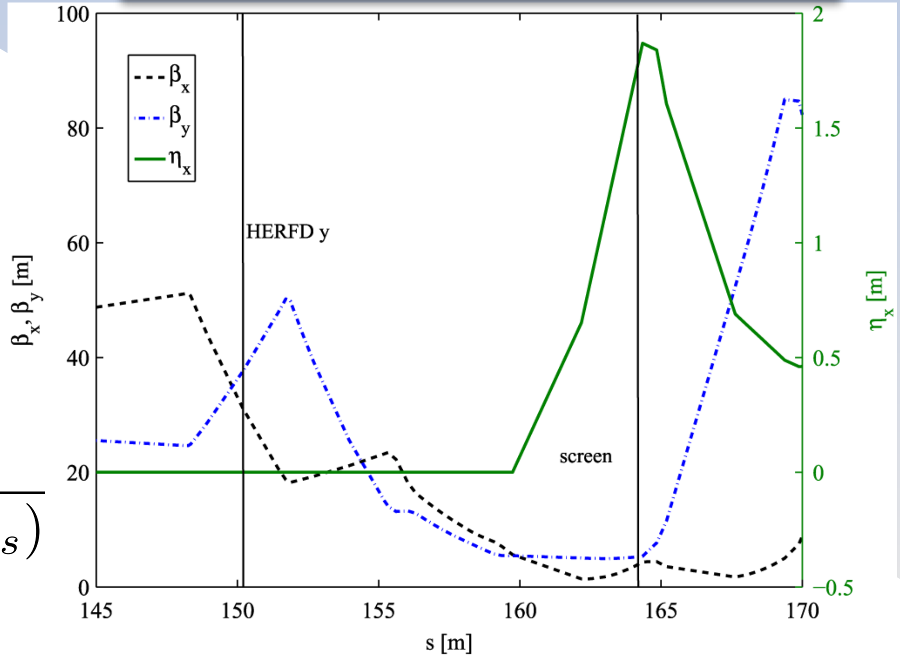


Beam optics matched to optimize time or energy resolution



$$\sigma_{e,Res} = \frac{\sqrt{\beta_x \epsilon_x}}{\eta_{x,s}} E$$

$$\sigma_{t,Res} \geq \sqrt{\frac{\epsilon_{n,y}}{\gamma \beta_d}} \frac{pc}{eV_\perp} \frac{1}{ck_{rf} \sin(\Delta\psi_{ds})}$$



Important parameters

$V_\perp$ peak voltage

k_{rf} RF wave vector

L length of the section

η_x dispersion

β at VRFD (d) and screen (s)

$\Delta\psi_{ds}$ vertical betatron phase advance from d to s

Sistematic errors

- Screen pixel size
- Beam emittance ε_y
- VRFD induced energy spread

Experimental evidence of IBS

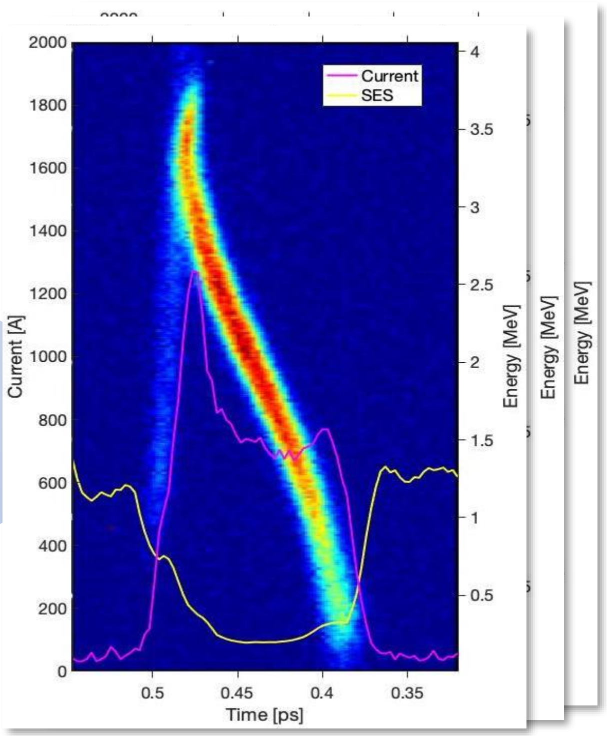
Predictions of the model:

- ☒ Compressed initial energy spread: $C\sigma_0^2$
- ☑ IBS_induced energy spread: σ_{IBS}^2
- ☑ Energy spread due to MBI: σ_γ^2

$$\sigma_E^{(no\ IBS)} = \sqrt{C\sigma_0^2 + \sigma_\gamma^2}$$

$$\sigma_E^{(model)} = \sqrt{C\sigma_0^2 + \sigma_{IBS}^2 + \sigma_\gamma^2}$$

Processing of measured data:



...

$$\sigma_E^{(meas)} = \sqrt{\bar{\sigma}^2 - \sigma_{VRFD}^2}$$

Comparison

Simone Di Mitri et al, New J. Phys. 22 (2020)

Experimental evidence of IBS

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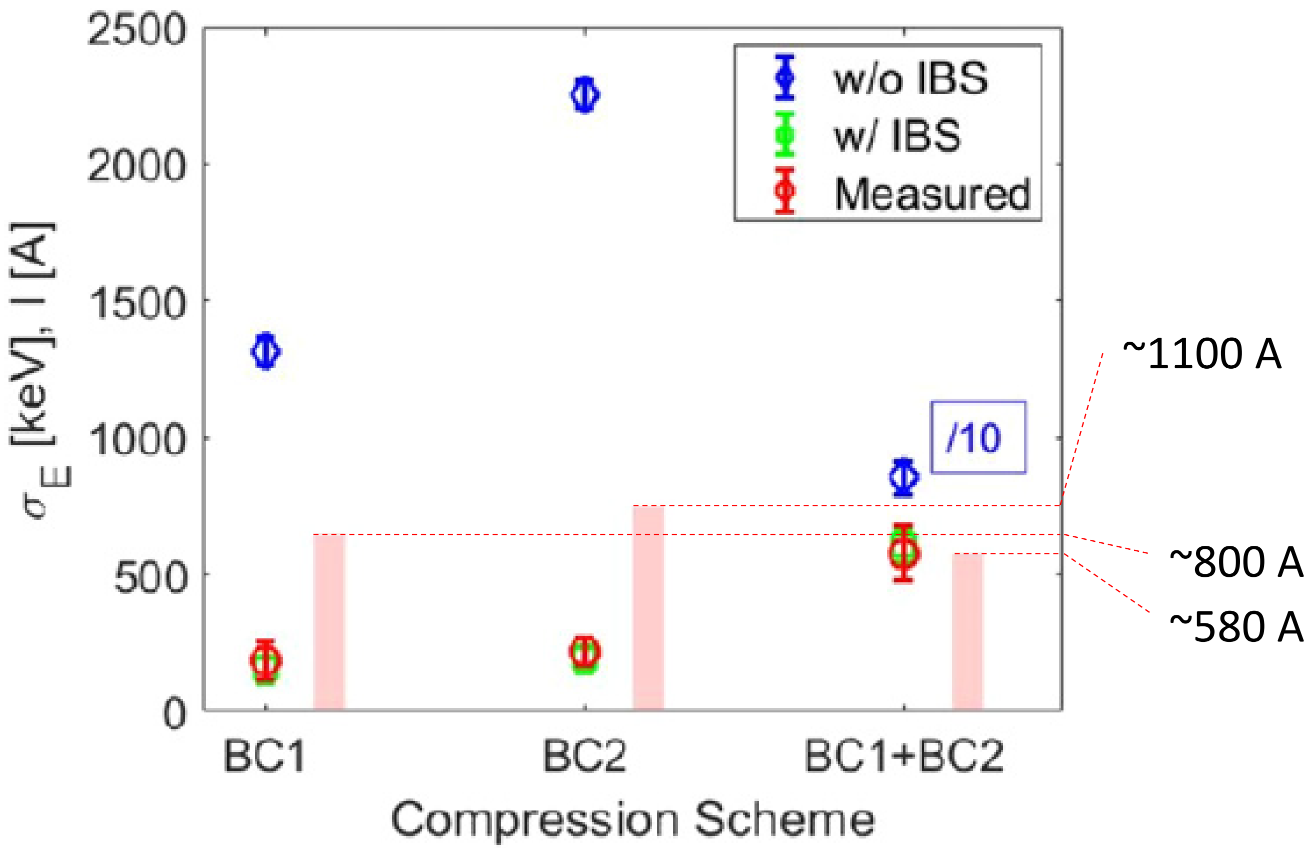
	100 pC	650 pC	Units
Initial peak current	18	60	MeV A
Initial beam energy	96	96	
Beam energy at BC1	~290	~290	
Beam energy at BC2	424–740	610	MeV
Final beam energy	713–754	900	MeV
R_{56} of BC1	−35, −42	−42	mm
R_{56} of BC2	0, −35	0	mm
Compression factor	31–45	11–19	
Normalized emittance	0.4	1.3	μm m rad
$<\beta_{x,y}>$ along the linac	7–30	7–30	
Temporal resolution	8–12	8–12	fs
Energy spread resolution	65–85	65–85	keV

Comparison between **measured SES** and the one **predicted by model** with and without IBS



Measurements for three different compressions (only BC1, only BC2 and both) and without LH

- ❖ Error bars in the data: reproducibility of the measurements in the same experimental session.
- ❖ Error bars for the model are related to optics uncertainties

Simone Di Mitri et al, New J. Phys. 22 (2020)

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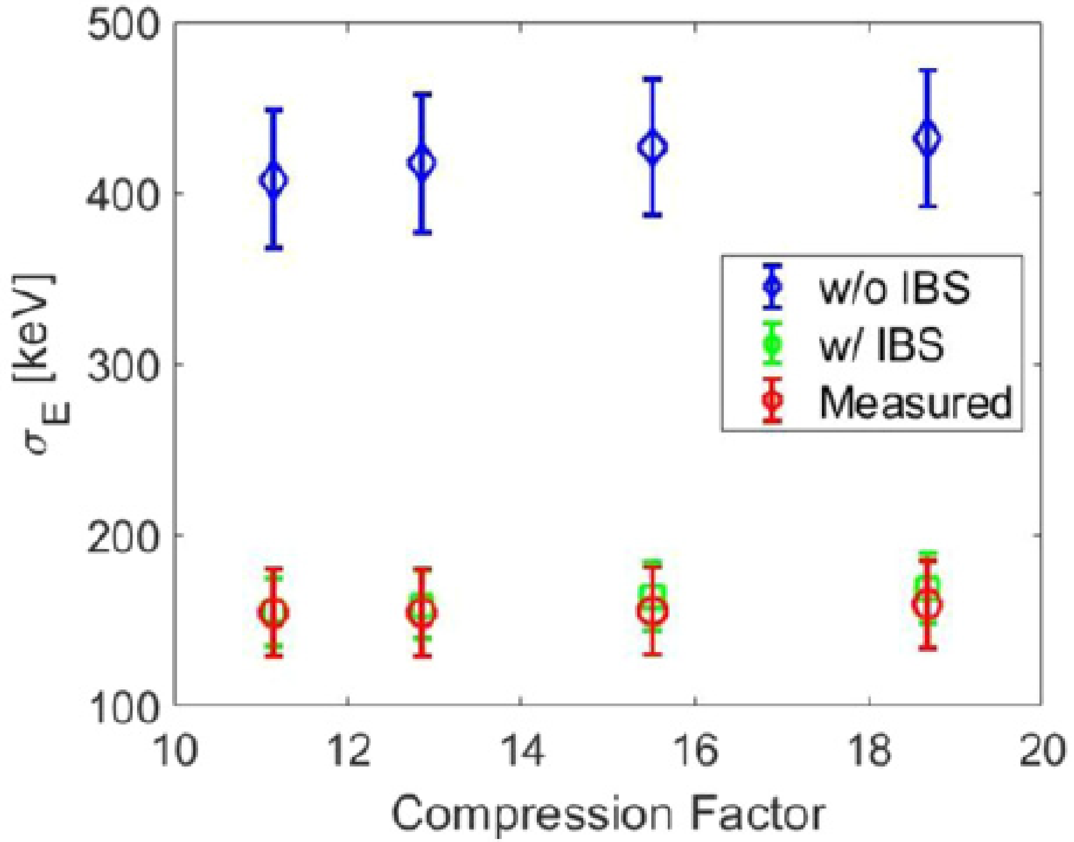


Measurements for four different single
co

❖ the

To summarize: only with the **inclusion of** the integrated **IBS** along the whole linac, it becomes possible to **reproduce the measured SES** at the end of accelerator.

❖ Error bars for the model are related to optics uncertainties

Simone Di Mitri et al, New J. Phys. 22 (2020)

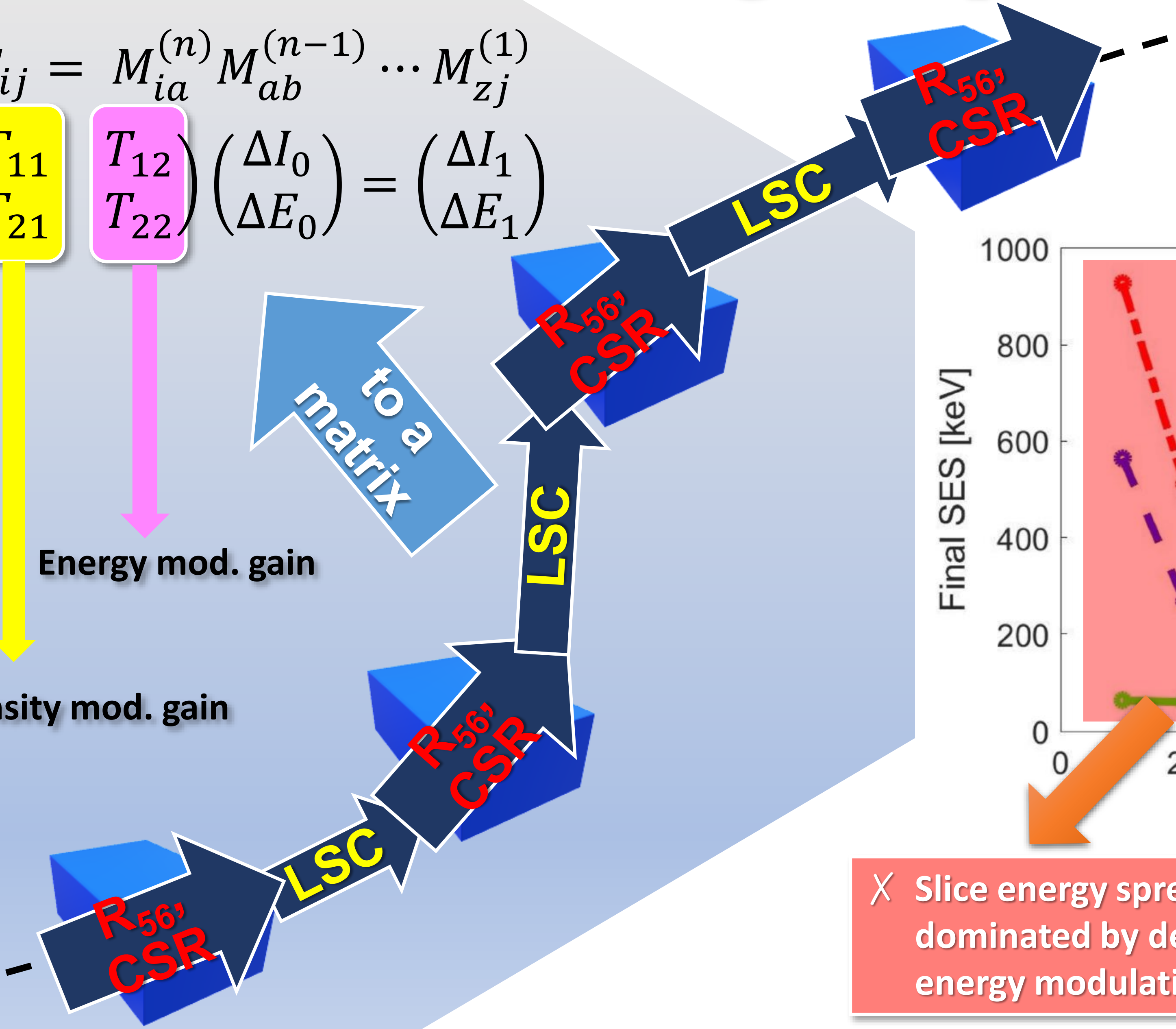
Design and predictions

$$T_{ij} = M_{ia}^{(n)} M_{ab}^{(n-1)} \cdots M_{zj}^{(1)}$$

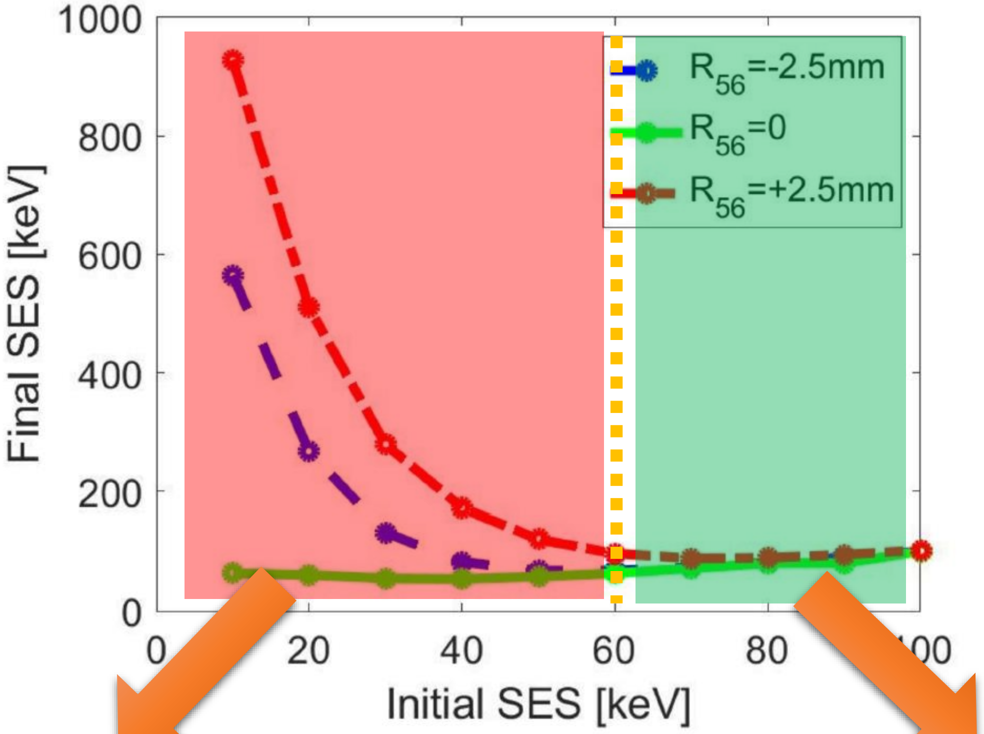
$$\begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} \Delta I_0 \\ \Delta E_0 \end{pmatrix} = \begin{pmatrix} \Delta I_1 \\ \Delta E_1 \end{pmatrix}$$

Energy mod. gain

Density mod. gain



S. Di Mitri G. Perosa, Physics 2 (2020)



✗ Slice energy spread and LPS dominated by density and energy modulations

✓ Suppression of non-linear behaviour, region of Liouvillian behaviour

G. Perosa et al., PRAB 23 (2020)

Indication of IBS

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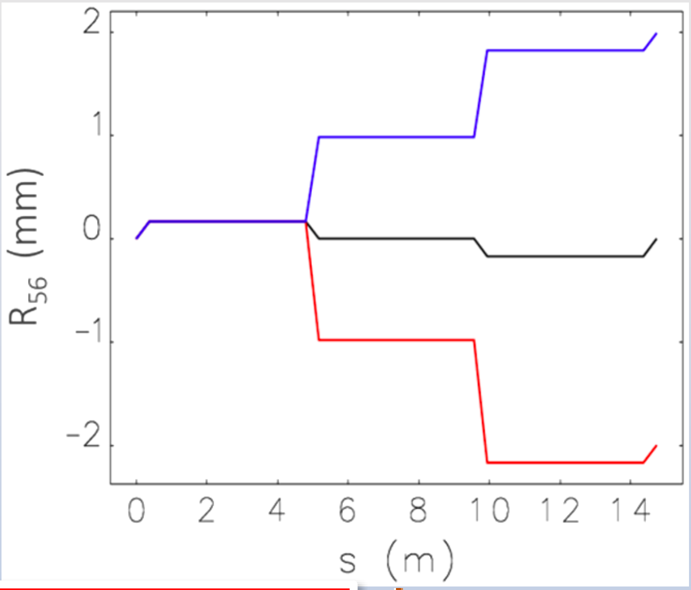
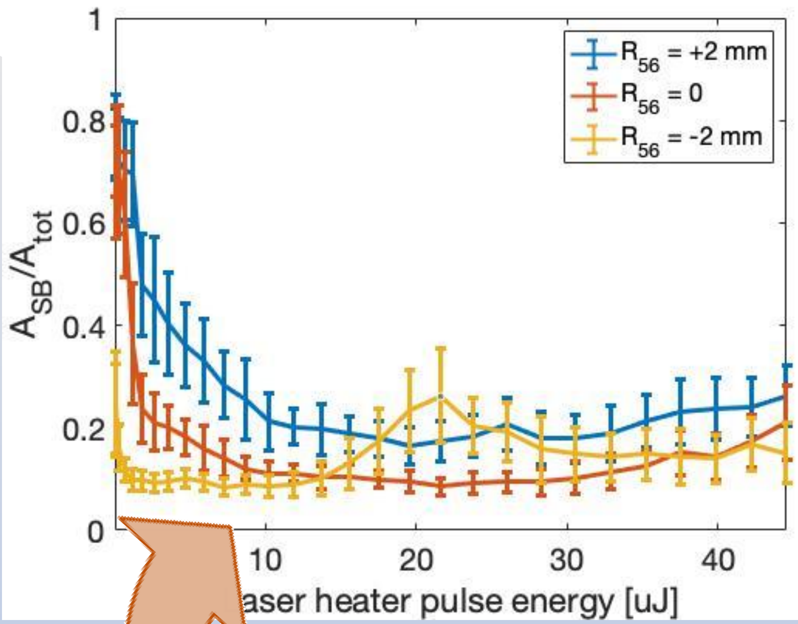
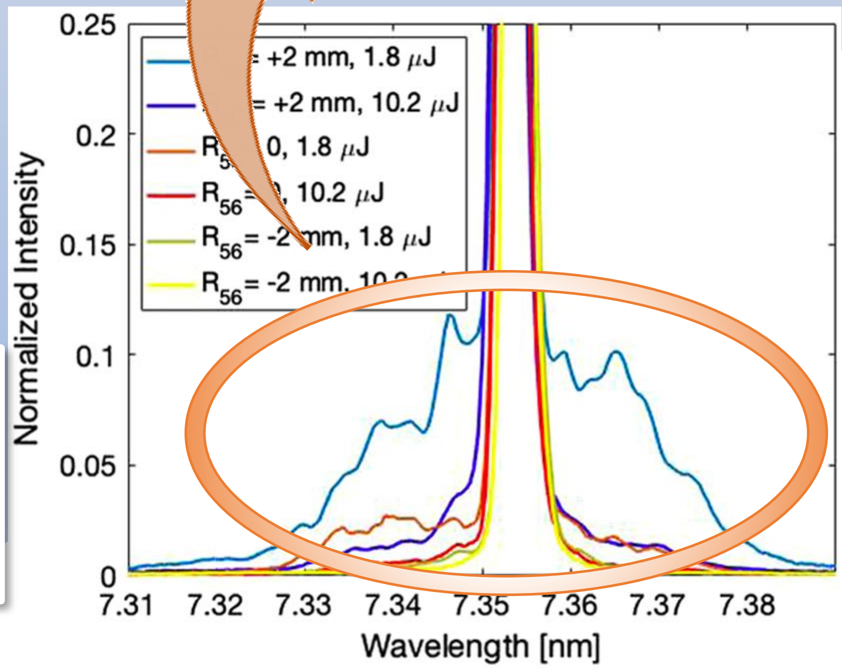


3 different optics with different values of R_{56}

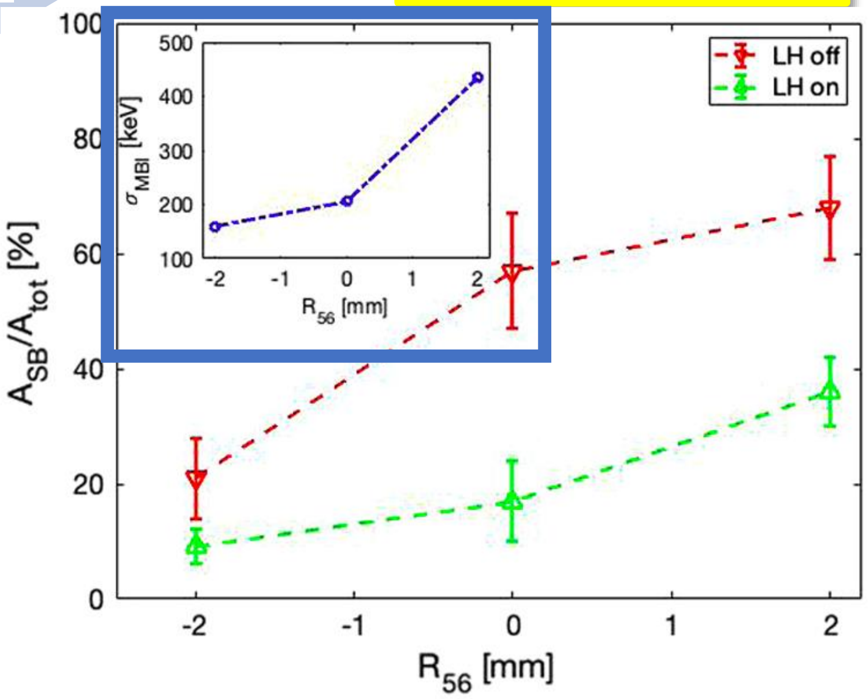


Sidebands for the 3 different optics as a function of LH uJ



Mean spectra of EEHG scheme for each optics and different LH values

Behavior of the MBI given by the model



Conclusions

In conclusion…

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- **Intra-beam scattering** is no longer a negligible effect in linacs, when dealing with a faithful characterization of microbunching instability and phase space dynamics.

- A **new derivation** of the **Coulomb logarithm** is proposed, in order to properly normalize the contribution coming from hard scattering.

- The **combination of IBS and MBI** models results in a fast and comprehensive semi-analytical tool to predict final energy spread and modulations in linacs and multi-bend transfer lines.

- This model has been **tested and benchmarked**, showing good agreement with measurements in a vast set of machine configurations.

What is next…

What is next…

1. **IBS in linac (part 2)**: the model MBI + IBS has been tested at the end of the linac
   → we want to benchmark it also in the first region of the accelerator

2. **MBI+IBS**: other authors are considering second order effect of IBS in MBI dynamics.

3. **Effect of IBS in EEHG scheme**: at very high harmonics, a simplified theory predicts an impact on EEHG performances (rigid diffusion of the bunching factor) → we want to explore deeply the theoretical aspects of IBS diffusion in EEHG.

4. **Application of IBS**: control of IBS in the accelerating sections before compression is, in theory, an additional knob to reduce MBI → is there a useful way to use IBS?

Thank you for your attention

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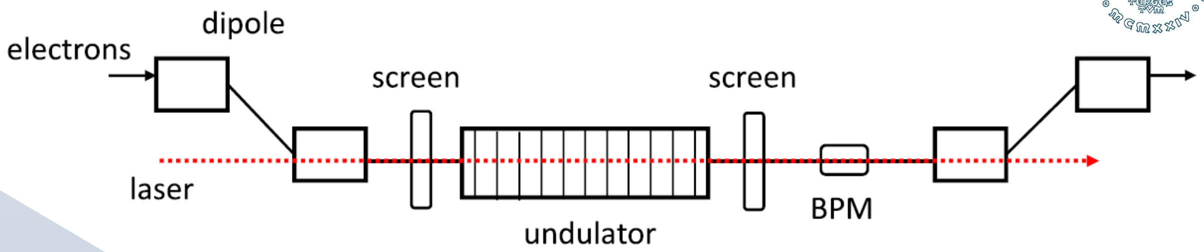
Back-up slides

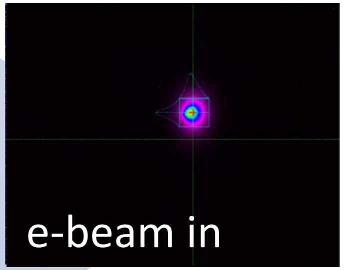
Laser Heater

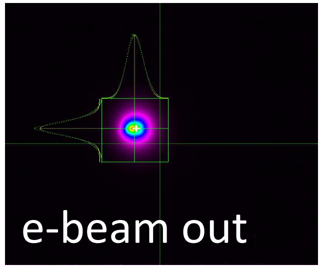
What is it?

Laser Heater is a composed of a laser and a short undulator embedded in a 4-dipole chicane:

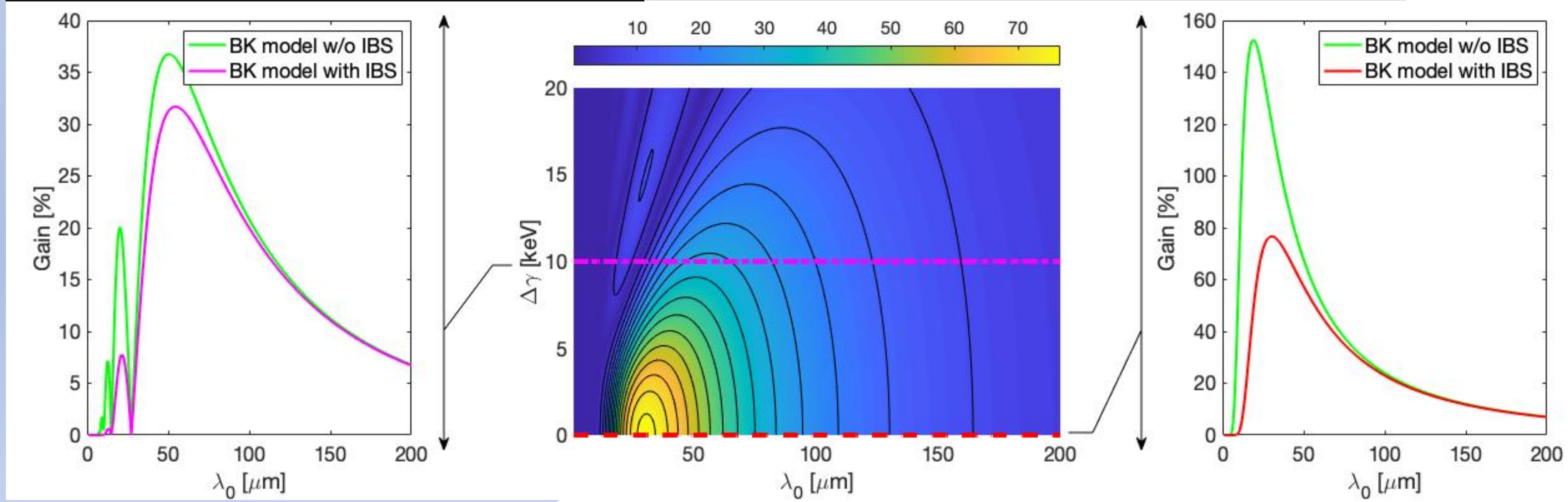
- **UV laser-electrons collinear superposition**
- **Smearing of the laser-induced modulations in the second half of the chicane**







G. Perosa Simone Di Mitri, Sci Rep 11 (2021)



Why?

To induce uncorrelated energy spread, for suppression of MBI via energy Landau Damping

Experimental evidence of IBS

Processing of measured data: for each row of an image, the width of the energy profile is calculated with different processing → W

For each image, we pick the minimum value of the width function along the bunch → min(W) = σ

For each set of images (usually 20 images), we determine the mean value and the standard deviation of the minimum of the «width slice function» → $\bar{\sigma}$

We subtract from this value the induced energy spread of the cavity

$$\sigma_E^{(meas)} = \sqrt{\bar{\sigma}^2 - \sigma_{VRFD}^2}$$

Predictions of the model: the slice energy spread at the end of the linac is determined computing the following terms:

- ❑ Compressed initial energy spread: $C\sigma_0^2$
- ❑ Energy spread induced by IBS in each section: σ_{IBS}^2
- ❑ Energy spread due to MBI: σ_γ^2

$$\sigma_E^{(model)} = \sqrt{C\sigma_0^2 + \sigma_{IBS}^2 + \sigma_\gamma^2}$$

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$$\sigma_E^{(model)} = \sqrt{C\sigma_0^2 + \sigma_{IBS}^2 + \sigma_\gamma^2}$$

- ✓ **The initial energy spread** is «gauged» and verified with GPT simulations
- ✓ **IBS-induced SES** is estimated with our model (next chapter)
- ✓ **MBI-related SES** is estimated using the expression

I_0 is the initial current

G is the gain after the compressor

Z is the LSC impedance integrated along a section length

$$\sigma_\gamma^2 = \frac{2ec}{I_0} \int d\lambda \frac{|G(\lambda) Z_{LSC}^{int}(\lambda)|^2}{\lambda^2}$$

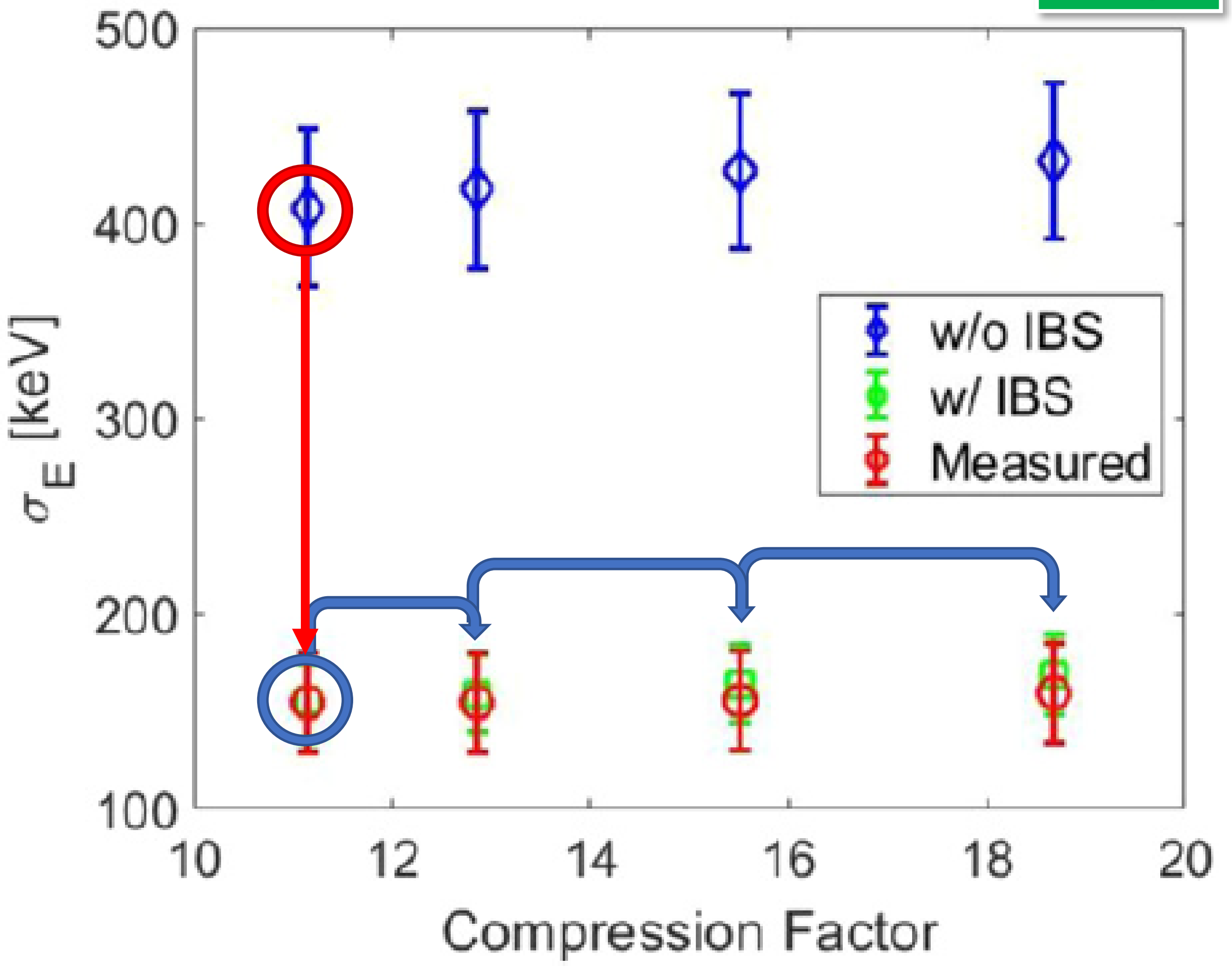
Experimental evidence of IBS

$$\sigma_E^{(model)} = \sqrt{C\sigma_0^2 + \sigma_{IBS}^2 + \sigma_\gamma^2}$$

- We "gauge" the initial energy spread in order to match the measured data for a single point
- We use the same value to check the other data
- We repeat the procedure without IBS
- We compare the found values with a simulation of GPT

N.B: in order to match measured and predicted data w/o IBS, σ_0 must be increased, reaching «unphysical» level

650 pC



Simone Di Mitri et al, New J. Phys. 22 (2020)

Experimental evidence of IBS

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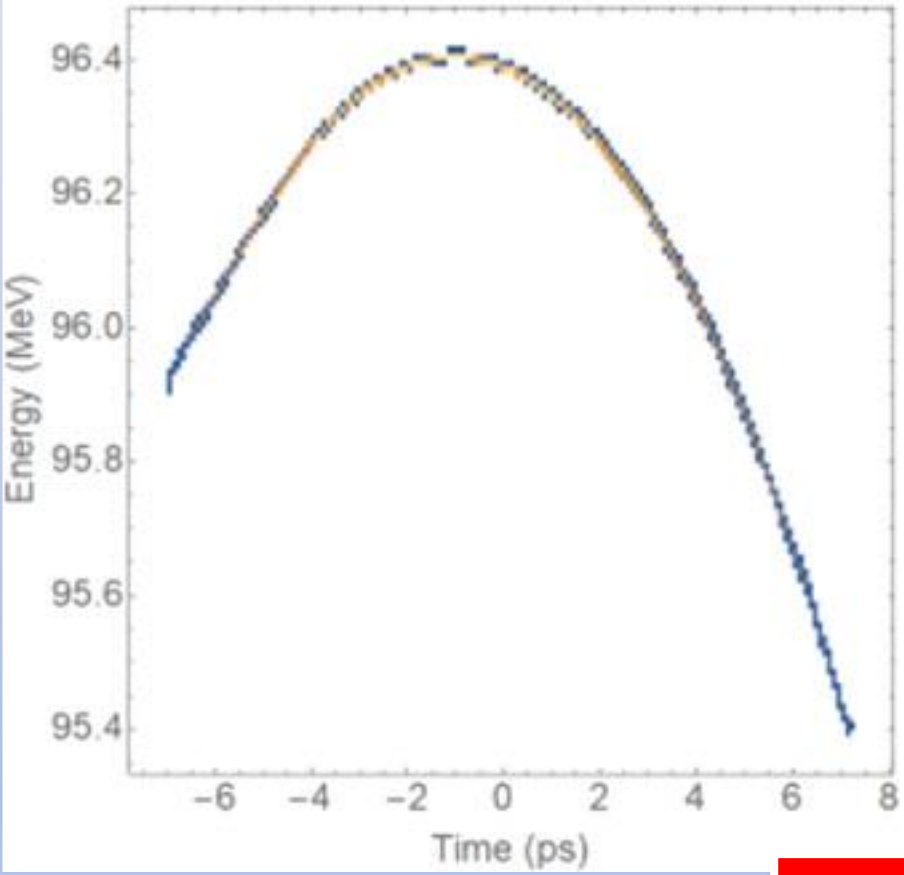
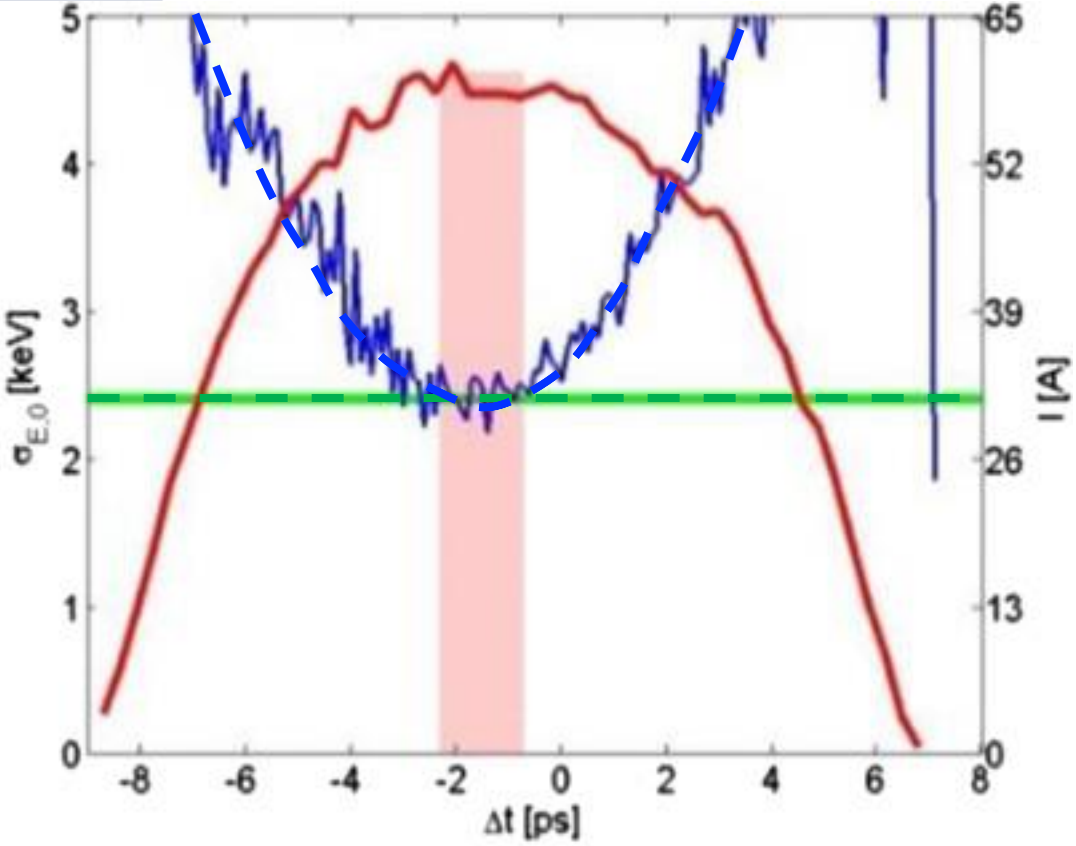


650 pC



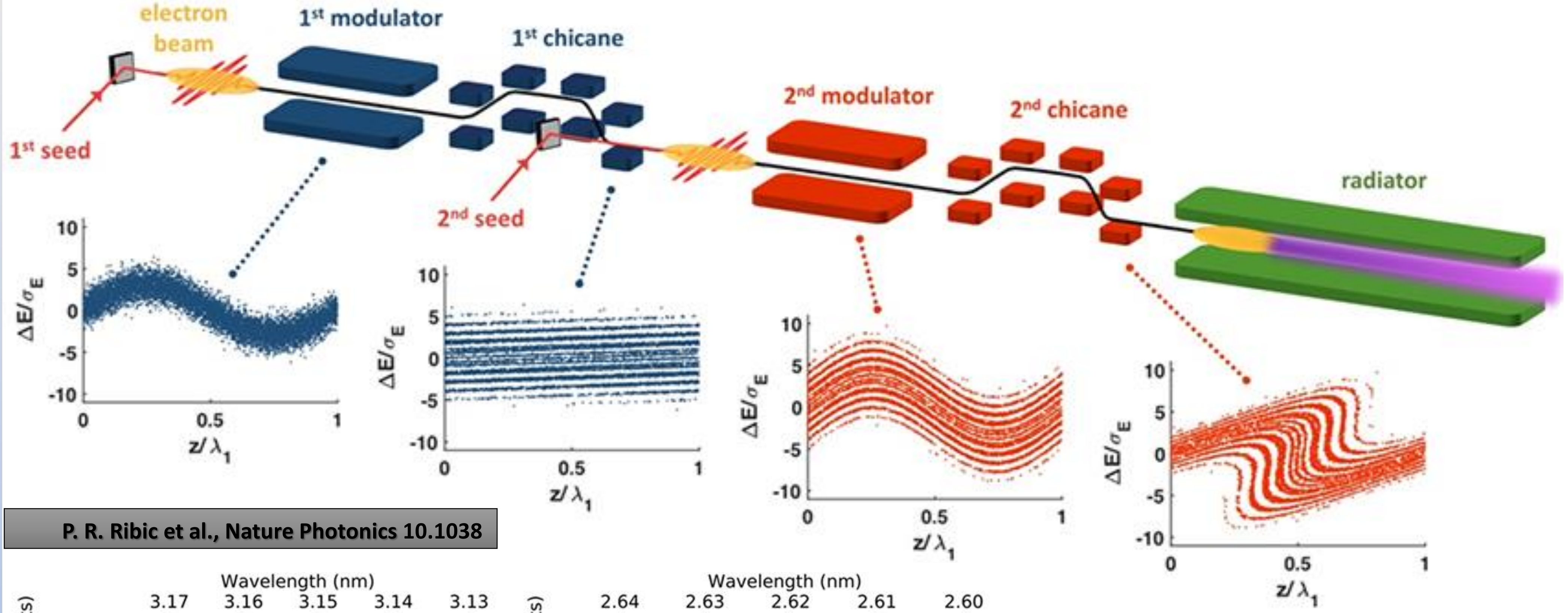
----- initial SES used in the model

----- initial SES predicted by GPT

The value used in basence of IBS is ~6uJ, well above the level shown here!

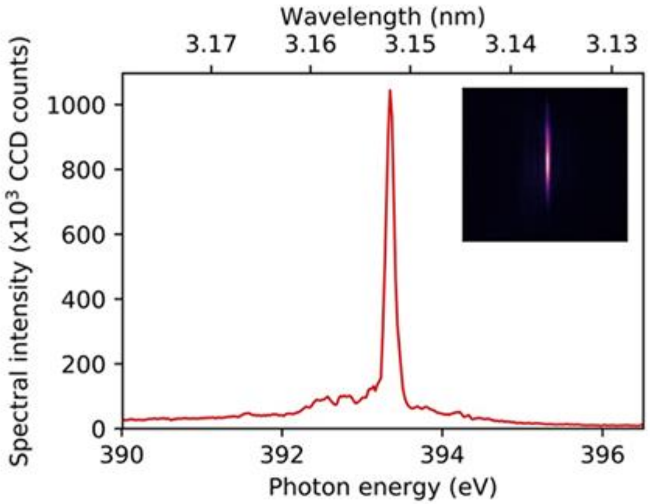
Simone Di Mitri et al, New J. Phys. 22 (2020)

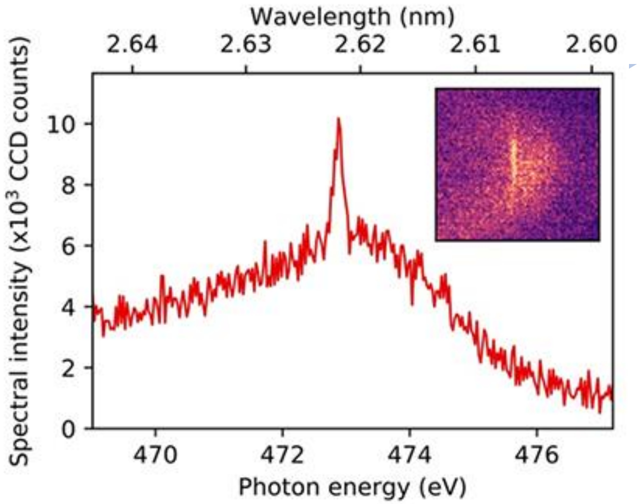
Echo-enabled harmonic generation



Down to 2.6 nm, i.e. h = 101

P. R. Ribic et al., Nature Photonics 10.1038





- ✓ Shaping by 2 seed laser require less seed energy
- ✓ Requires a much weaker energy modulation
- ✓ Is less sensitive to beam's imperfections