

FFA Transport line for Laser Plasma Accelerators

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Accelerators, with dimensions from a **meter** to **kilometers**, aiming at solving the most complex issues:

- Fundamental particle physics
- Medical applications
- Industry

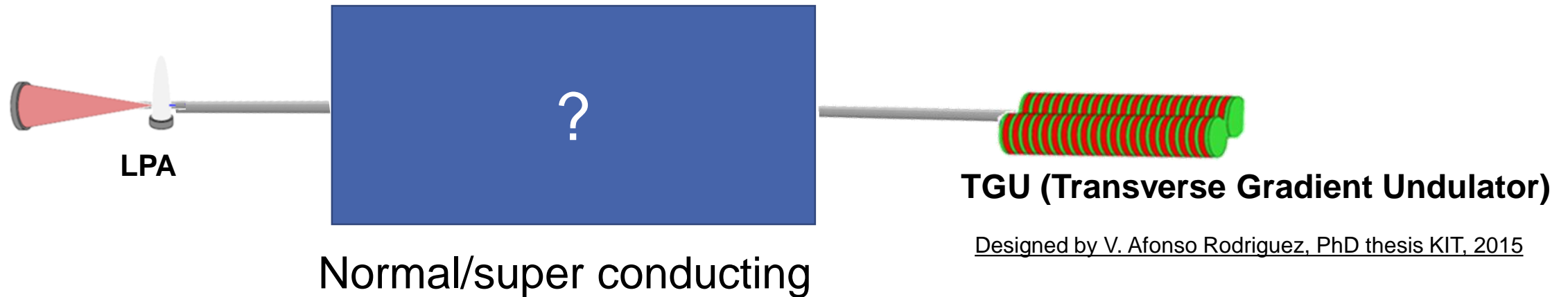
RF-based accelerators provide acceleration gradients up to **100 MeV m⁻¹** suffering limitations like electrical breakdowns and quenches in the cavities.

Aiming at **lab-scaled, ultra-compact** accelerators, like laser-plasma accelerators

Plasma medium is capable of generating and handling acceleration gradients up to **100 GeV m⁻¹**

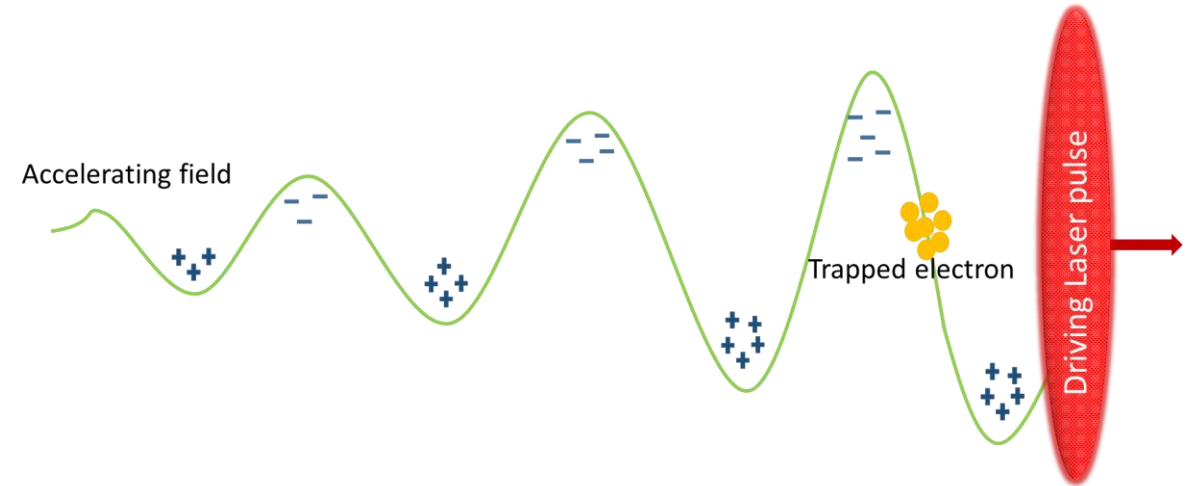
Introduction – Scope

Development of reliable **lab-scaled transport lines** employing **miniature magnets** with high-strength magnetic fields.



What is a Laser plasma accelerators (LPA)?

Laser Plasma Accelerators (LPA), electrons are accelerated in the fields of a **plasma wave** generated by a **high-power (TW) laser pulse**.



Pros

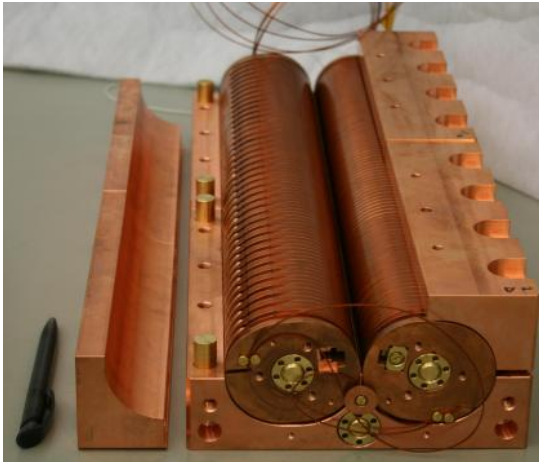
- Accelerating gradients
- Ultra-short electron bunches

Cons

- Percent energy spread
- mrad divergence

What is TGU?

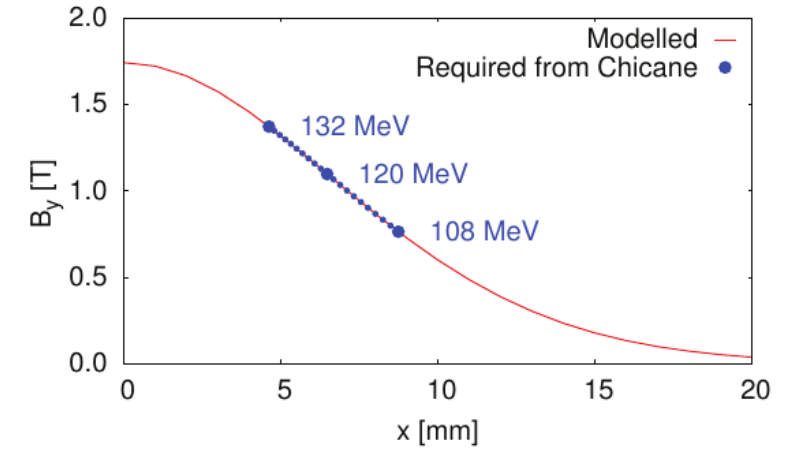
TGU



Courtesy of V. Afonso Rodriguez

■ Transverse Gradient Undulator (TGU);

- Magnetic field on a transverse plane has a gradient
- Electrons with different energy travel through different position on the transverse plane
- Radiation with a narrow spectrum

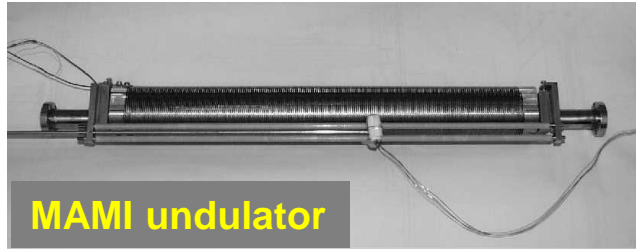


$$\lambda = \frac{\lambda_u}{2\gamma^2(x)} \left(1 + \frac{e^2 B^2(x) \lambda_u^2}{8m_0^2 c^2} \right) = const.$$

$$\lambda_u = 10 \text{ mm} , K_u = 1$$

E (GeV)	λ (nm)	Application area
0.440	10.0	EUV lithography
1.40	1.0	Soft X-ray spectroscopy
4.40	0.1	Medical imaging

Experience of superconducting IDs & magnets

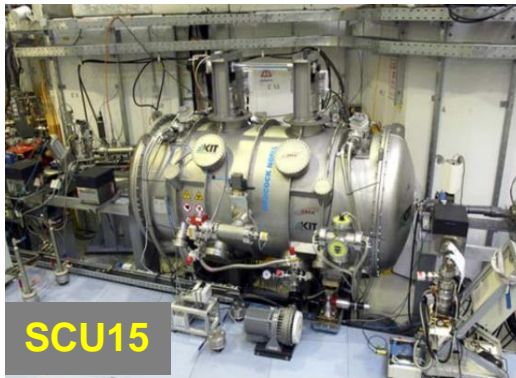


MAMI undulator

From 1990



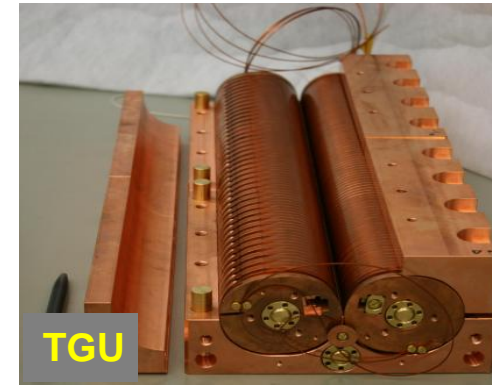
SCU14



SCU15

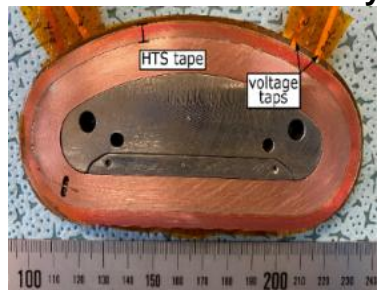


SCU20

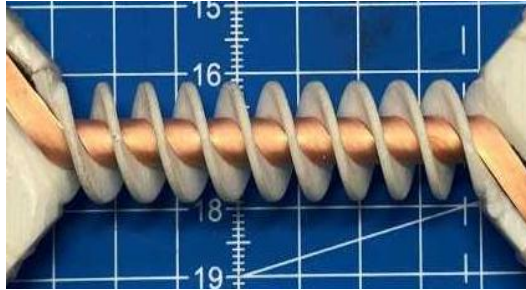


TGU

Courtesy of S. Richter



Vertical racetrack

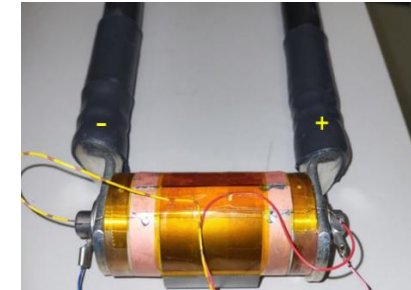


Helical

Courtesy of A. Grau



Laser-structured undulator

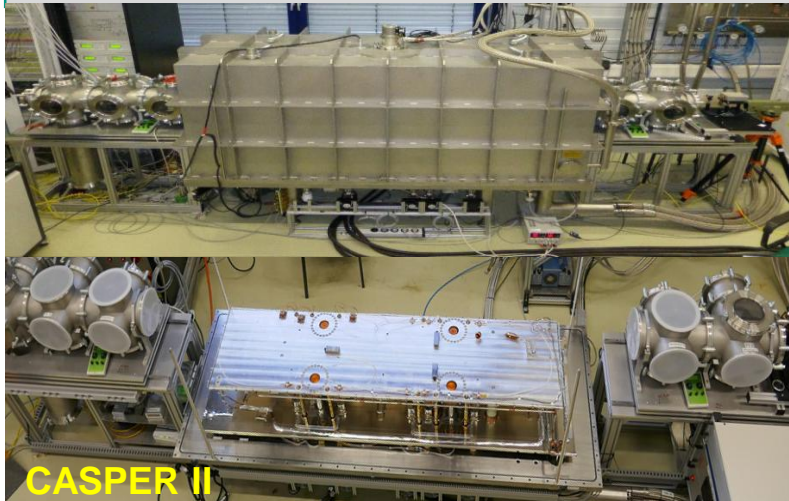


Periodic quadrupole

Now

Test facilities & technologies

Magnet characterization facilities



Winding technologies



**Laser plasma
accelerator group
established at KIT IBPT**
by Prof. M. Fuchs



Cable technologies



High temperature superconductors



LPA-based transport lines

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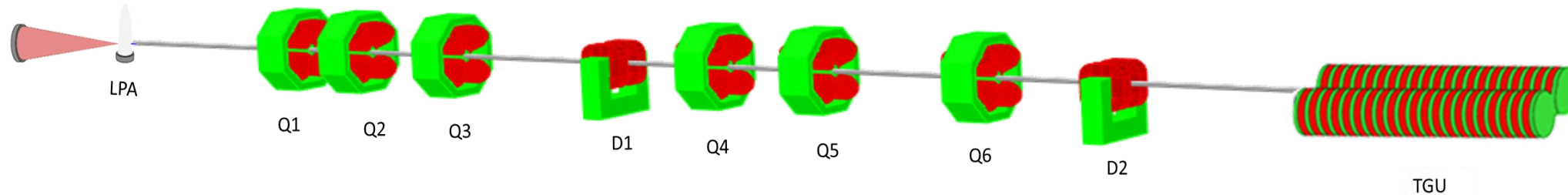
Federal Ministry of Education and Research



2.5 m NC iron-core transport line

- 300 MeV
- $g_{\max} = 80 \text{ T/m}$

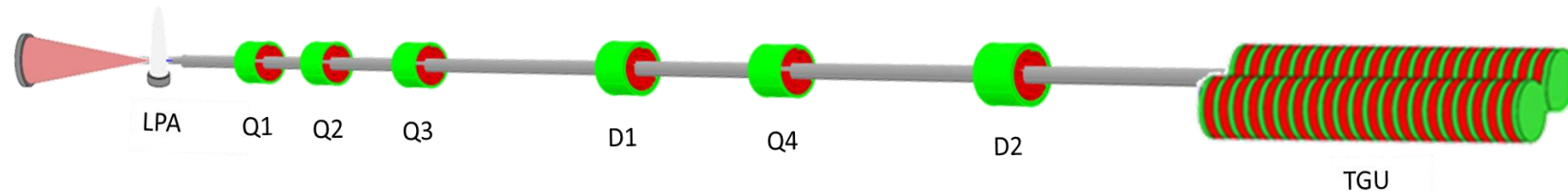
[S. Fatehi et al. IPAC21](#)
[M. Ning et al. IPAC23](#)



1.6 m HTS air-core, cosine-theta, transport line

- 700 MeV
- $g_{\max} = 500 \text{ T/m}$

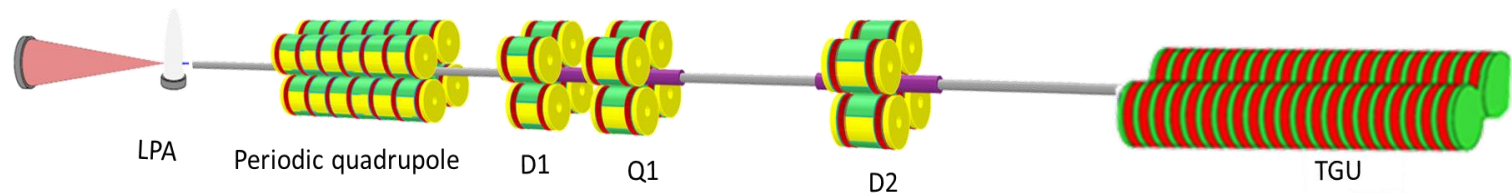
[S. Fatehi et al. IPAC21](#)
[S. Fatehi, PhD. thesis, KIT \(2023\)](#)



1.4 m HTS iron-core transport line

- 400 MeV
- Periodic magnets with $g_{\max} = 220 \text{ T/m}$

With the potential to increase energy!

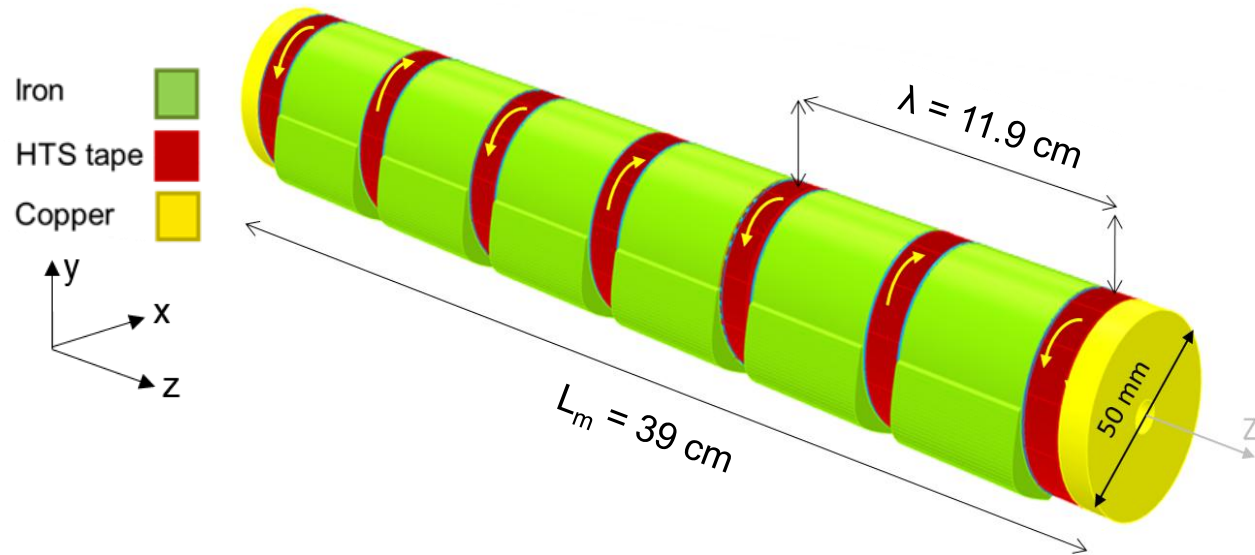


[S. Fatehi, PhD. thesis, KIT \(2023\)](#)

[S. Fatehi et al. Talk at IPAC23](#)

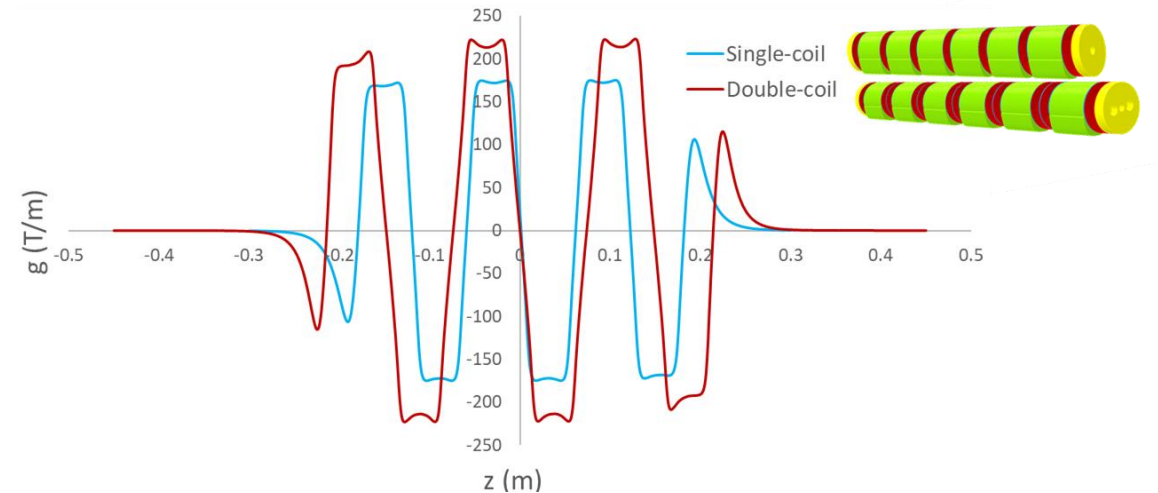
What is the periodic quadrupole?

One-fourth of the optimized periodic quadrupole



$I = 1.3 \text{ kA at } 4.2 \text{ K}$

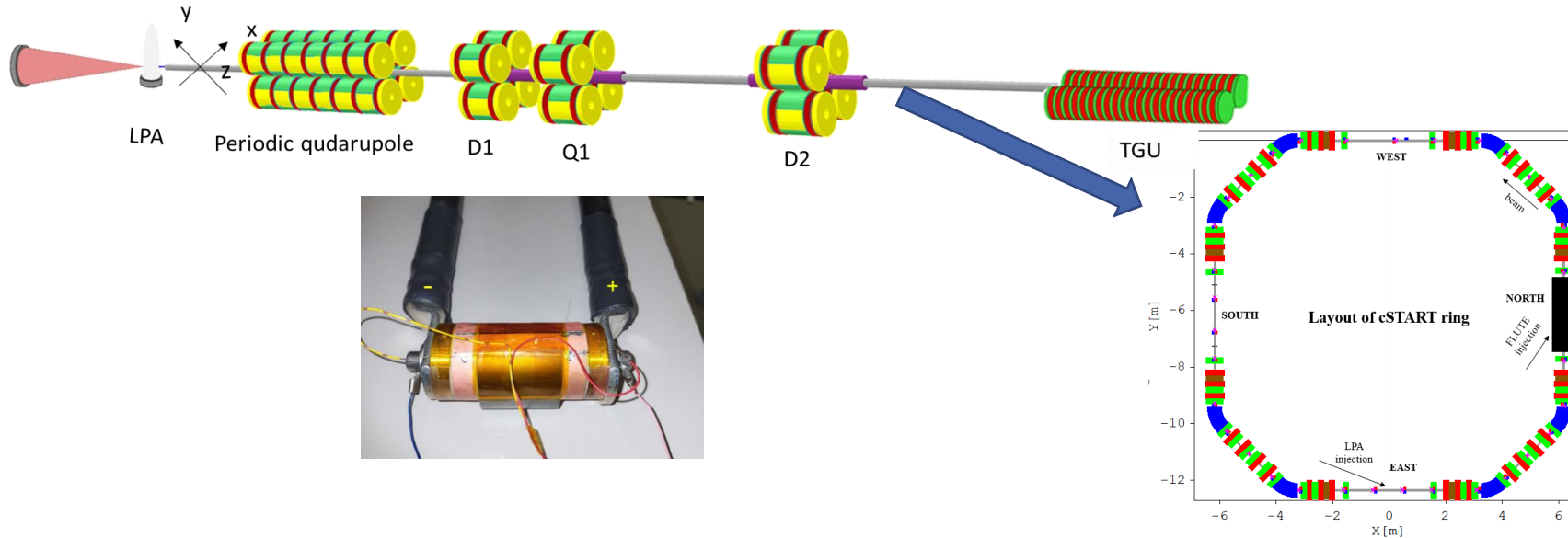
$g_{\max} = 220 \text{ T/m}$



HTS periodic quadrupole has simple **pancake coils** wound with **72 turns** of **12 mm** width ReBCO tape.

The coils carry **2000 A/mm²** current density at 4.2 K and can create a magnetic field gradient of **220 T/m** in the central plane.

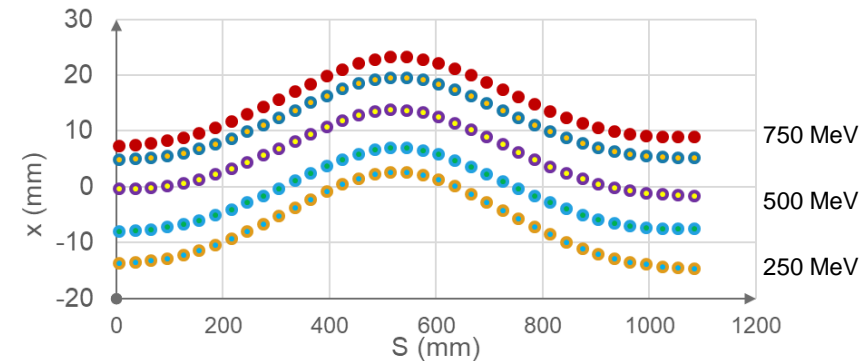
Transport large energy spread electrons to a specific target (injecting into the cSTART ring)



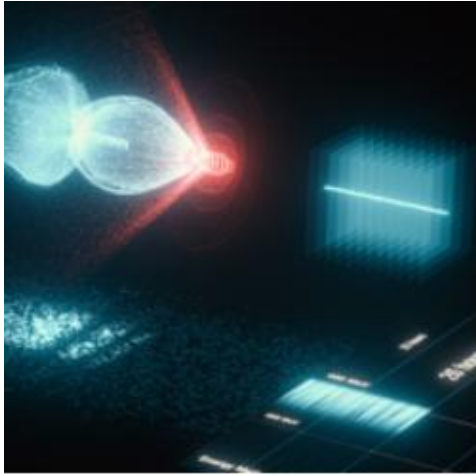
cSTART
Large energy
acceptance ring
Courtesy of Alexander Papash

Fixed field alternating gradient (FFAG)
transport section

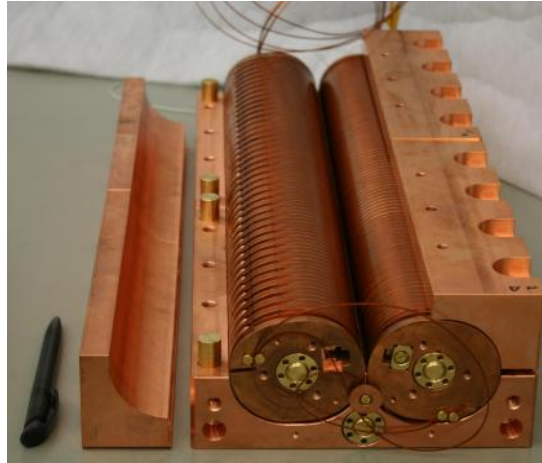
- keeping the beam optics parameters implying FFAG combined magnets



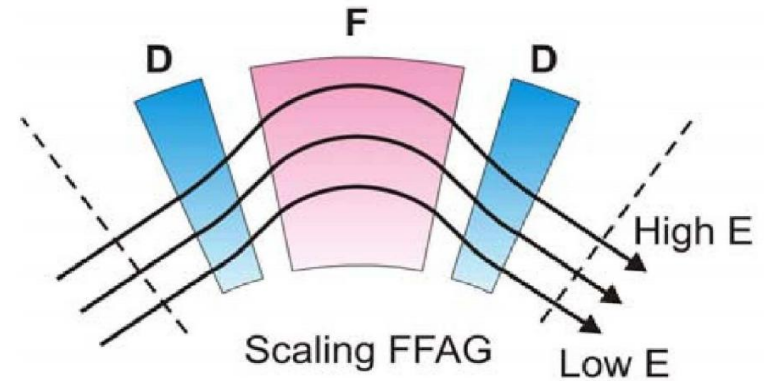
Triggering the idea of an FFA-based transport line



Credit: DESY LAB



Courtesy of V. Afonso Rodriguez

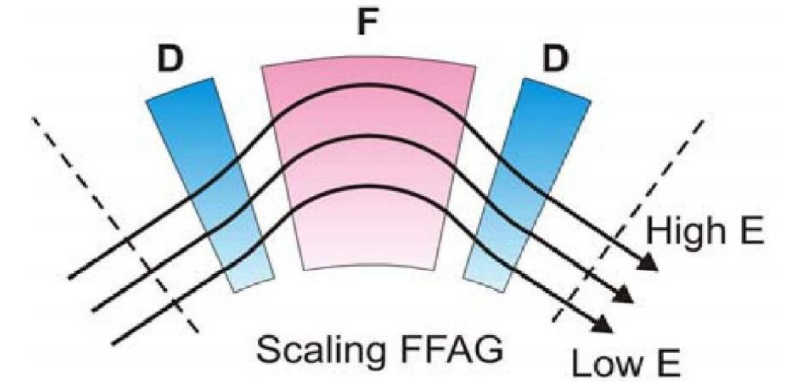


Aim : Designing a transport line for **LPA** electrons using **FFA magnets** to match the beam optics to **TGU** requirements while handling a **few percent energy spread**

Scaling FFAs

$$\mathbf{B}(r) = \mathbf{B}_0 \exp(k r/r_0) \quad \text{For large } r_0 \text{ (Transport line)}$$

$$\frac{\delta k}{\delta p} = 0 \quad \text{The gradient must change so that } K \text{ remains constant with changing the energy}$$



A scaling fixed field alternating gradient (FFAG) accelerator

✓ Has a large momentum acceptance

➡ FFAG can be a candidate to be used for LPA electron beams

Design A



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Technology
Facilities Council



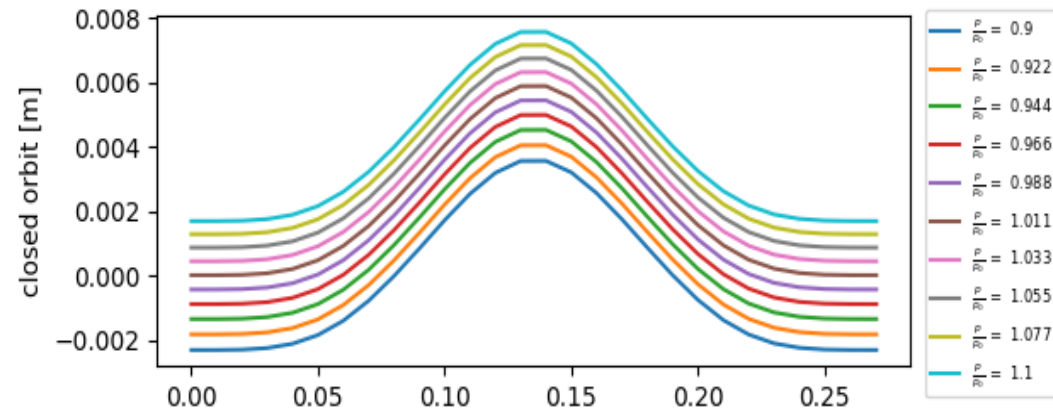
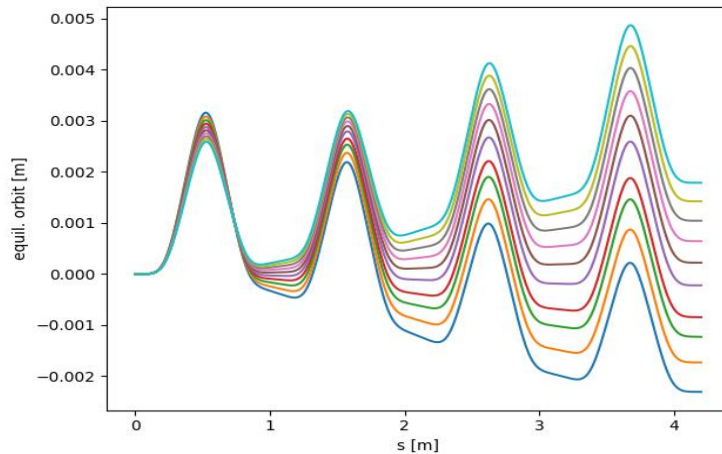
LPA

FFA dispersion creator

FFA Periodic cell

TGU

$\sigma_{x,y} = 4 \mu\text{m}$
 $\beta_{x,y} = 1.6 \text{ mm}$
 $\alpha_{x,y} = 0$
 $D = 0$



$\beta_y = 0.6 \text{ m}$
 $\beta_x = 0.2 \text{ m}$
 $\alpha_{x,y} = 0$
 $D = 20 \text{ mm}$

Design B



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Technology
Facilities Council



LPA

Matching
cell I

FFA dispersion creator

FFA Periodic cell

Matching
cell II

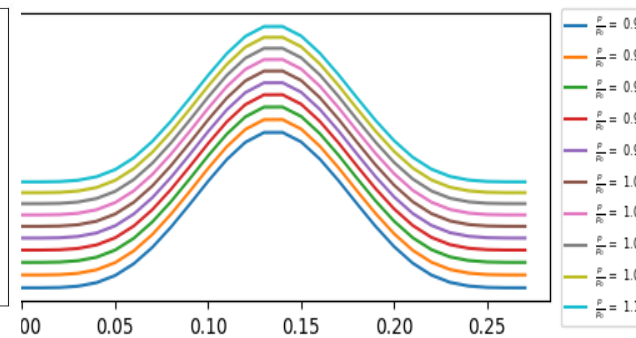
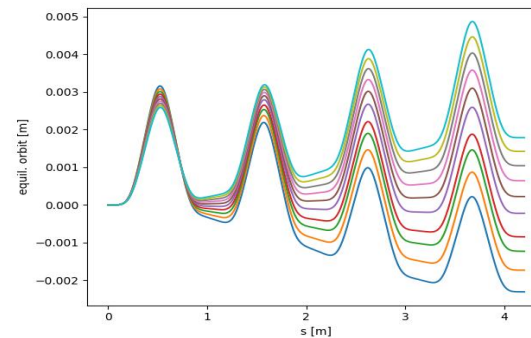
TGU

$$\sigma_{x,y} = 4 \mu\text{m}$$

$$\beta_{x,y} = 1.6 \text{ mm} \quad \text{Doublet/Triplet}$$

$$\alpha_{x,y} = 0$$

$$D = 0$$



Doublet/Triplet

$$\beta_y = 0.6 \text{ m}$$

$$\beta_x = 0.2 \text{ m}$$

$$\alpha_{x,y} = 0$$

$$D = 20 \text{ mm}$$

Design C



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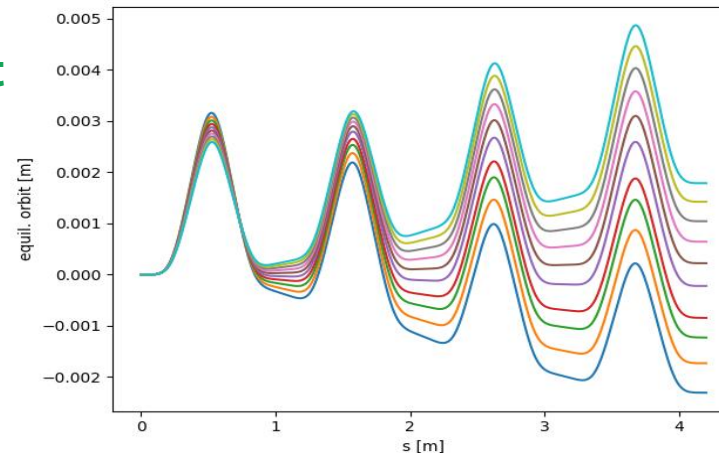
LPA

$\sigma_{x,y} = 4 \mu\text{m}$
 $\beta_{x,y} = 1.6 \text{ mm}$
 $\alpha_{x,y} = 0$
 $D = 0$

Matching
cell I

Doublet/Triplet

FFA dispersion creator



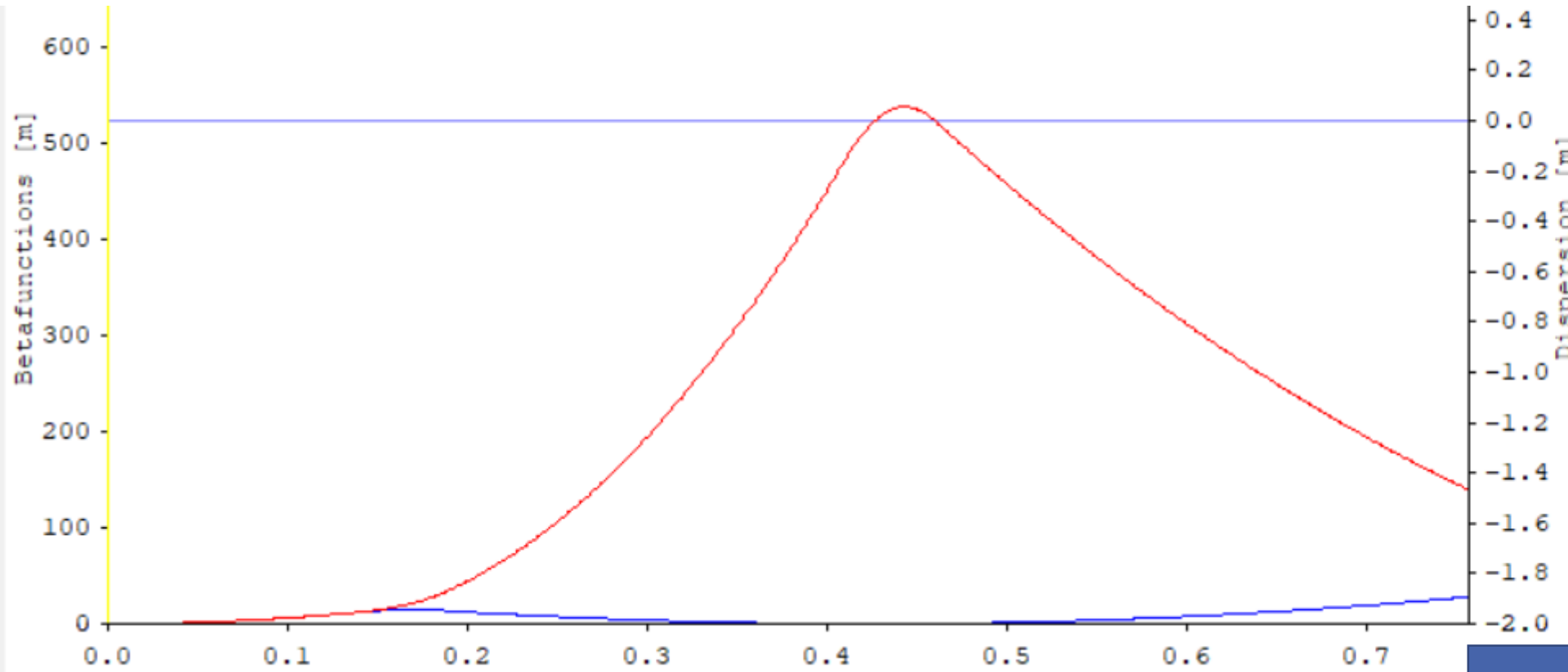
Matching
cell II

Doublet/Triplet

TGU

$\beta_y = 0.6 \text{ m}$
 $\beta_x = 0.2 \text{ m}$
 $\alpha_{x,y} = 0$
 $D = 20 \text{ mm}$

Matching cell I (doublet)

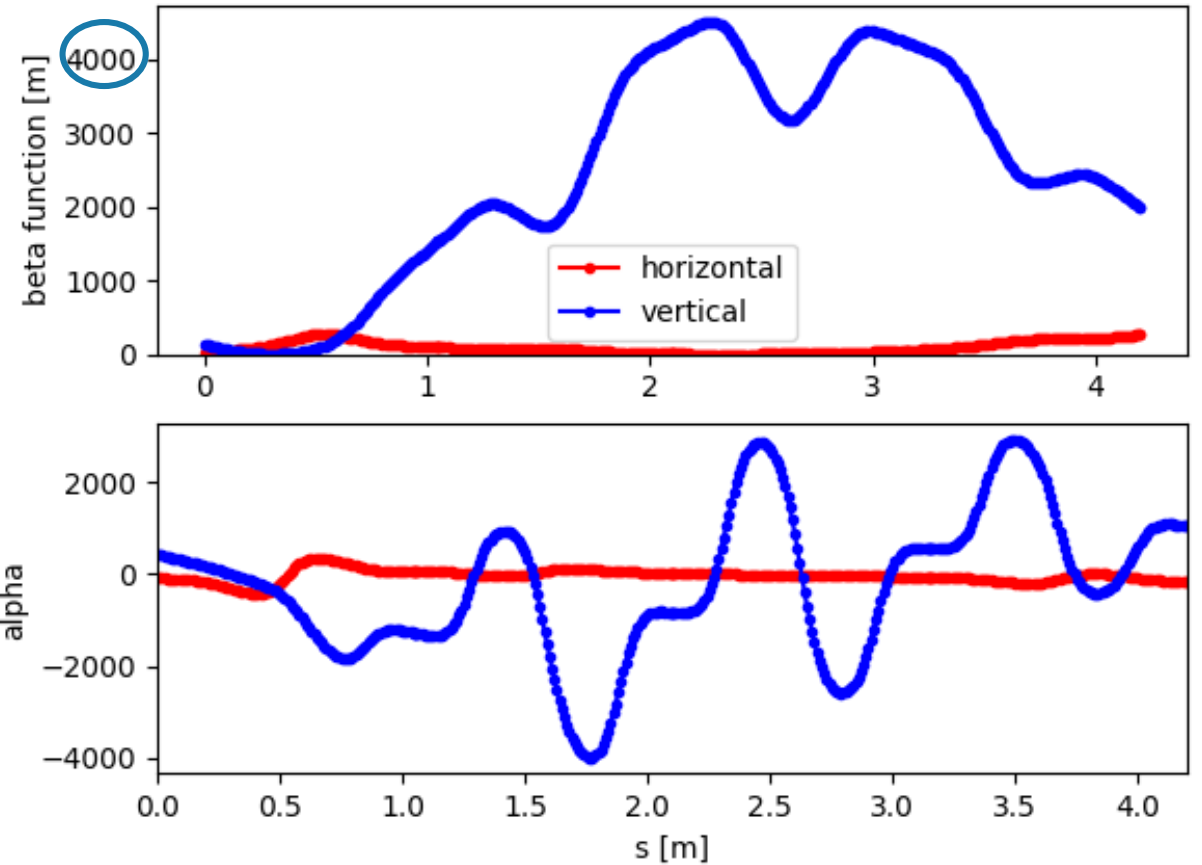
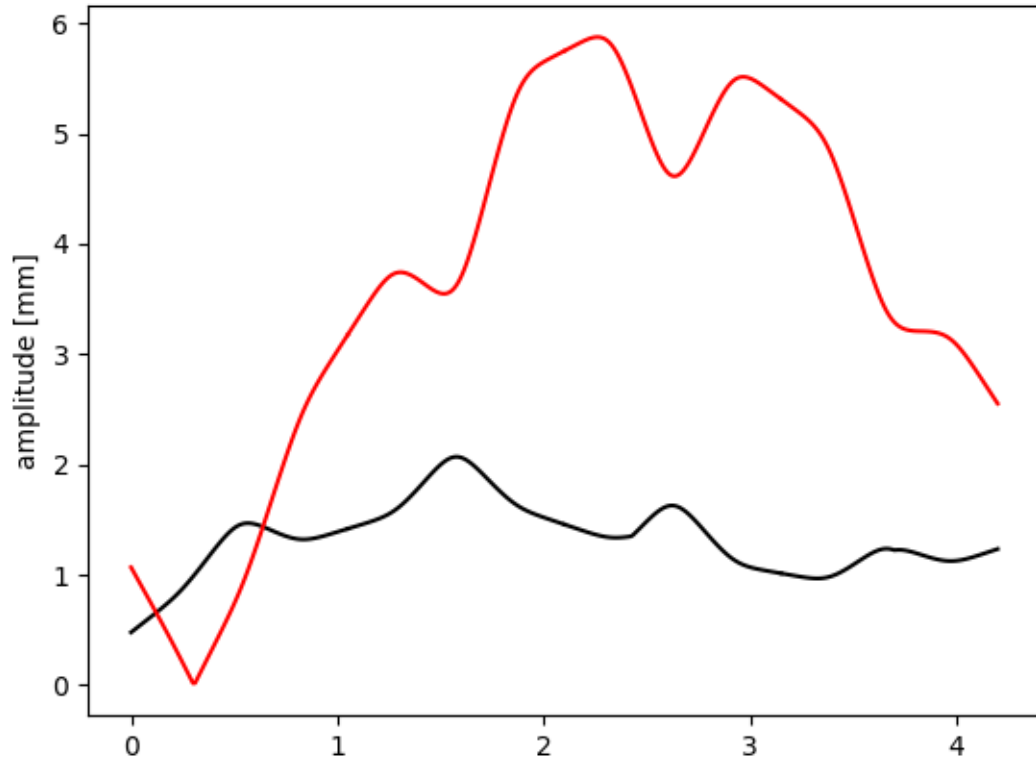


TauY	[ms]	0.000
TauE	[ms]	0.000
EmitYo	[pm rd]	0.000
Location		END
Position	m	0.757
BetaX	m	28.104
AlphaX		-85.370
BetaY	m	139.565
AlphaY		439.929
Disp.	m	0.0000
dD/ds	rad	0.0000
PhiX/2pi		0.7409
PhiY/2pi		0.2491
curly H	m	0.00000
Orbit X	mm	0.0000

LPA

FFA dispersion creator

Inserting extracted parameters as input parameters for dispersion creator

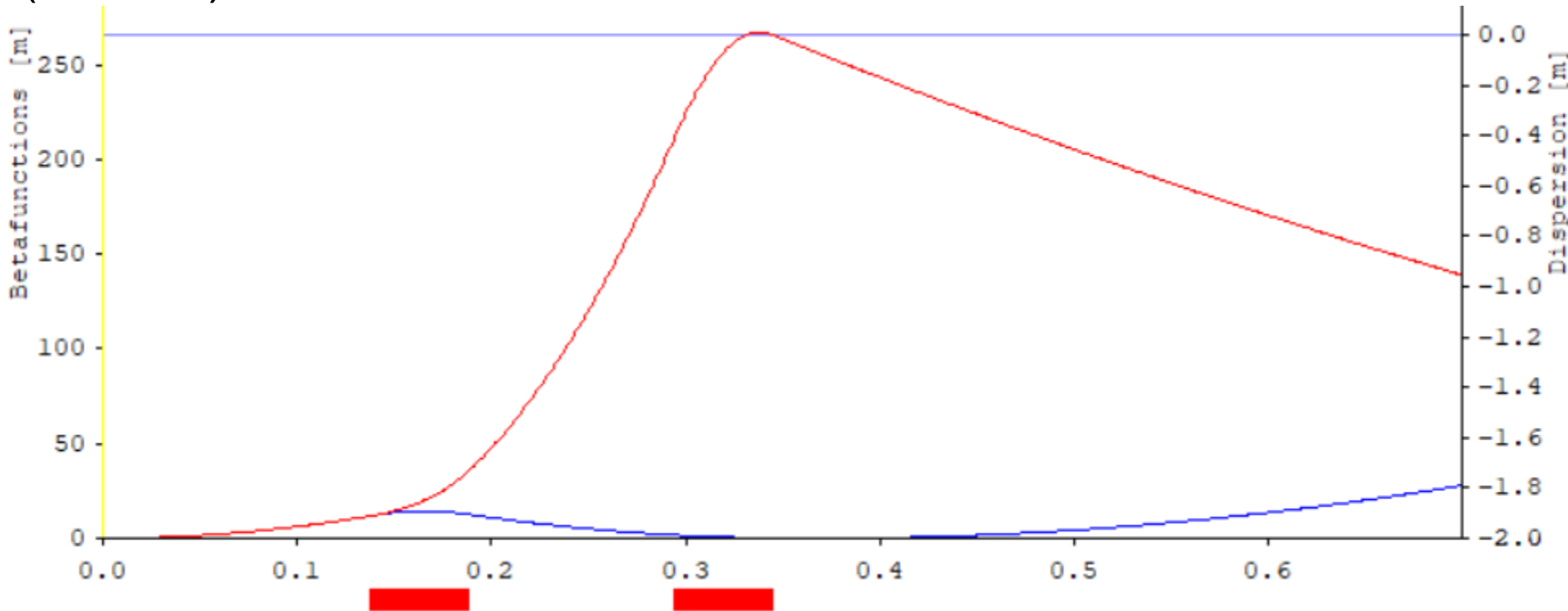


Beta values are a bit large!

Modifying the Twiss parameters after the matching cell I (doublet)



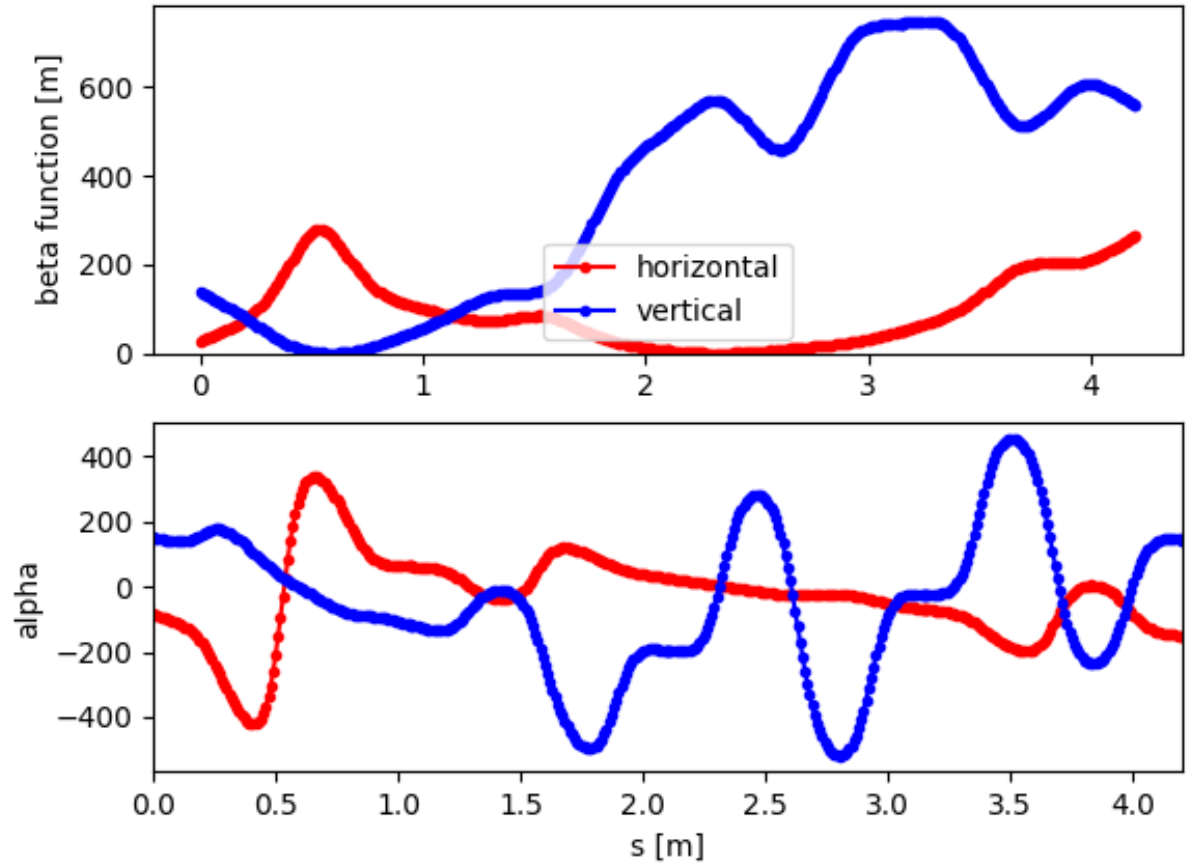
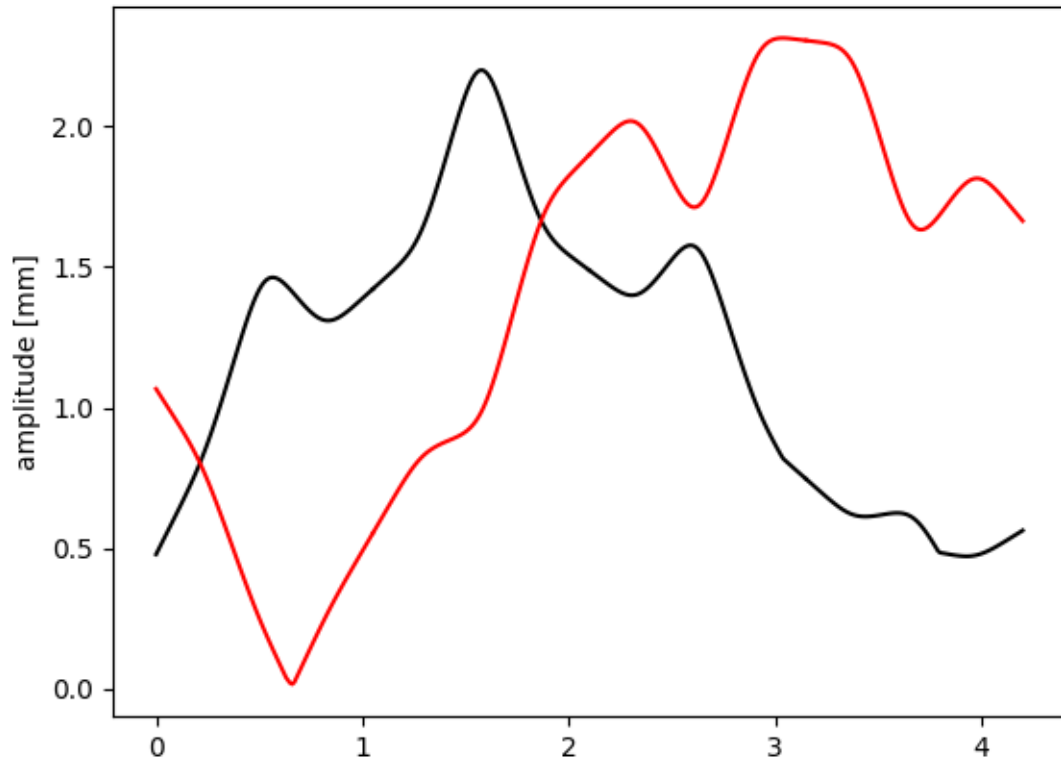
Science and Technology Facilities Council



EmitY ₀	[pm rd]	0.000
Location		END
Position	m	0.699
BetaX	m	28.000
AlphaX		-85.000
BetaY	m	139.000
AlphaY		150.000
Disp.	m	0.0000
dD/ds	rad	0.0000
PhiX/2pi		0.7418
PhiY/2pi		0.2491
curly H	m	0.00000
OrbitX	mm	0.0000
OrbitX'	mrad	0.0000

LPA

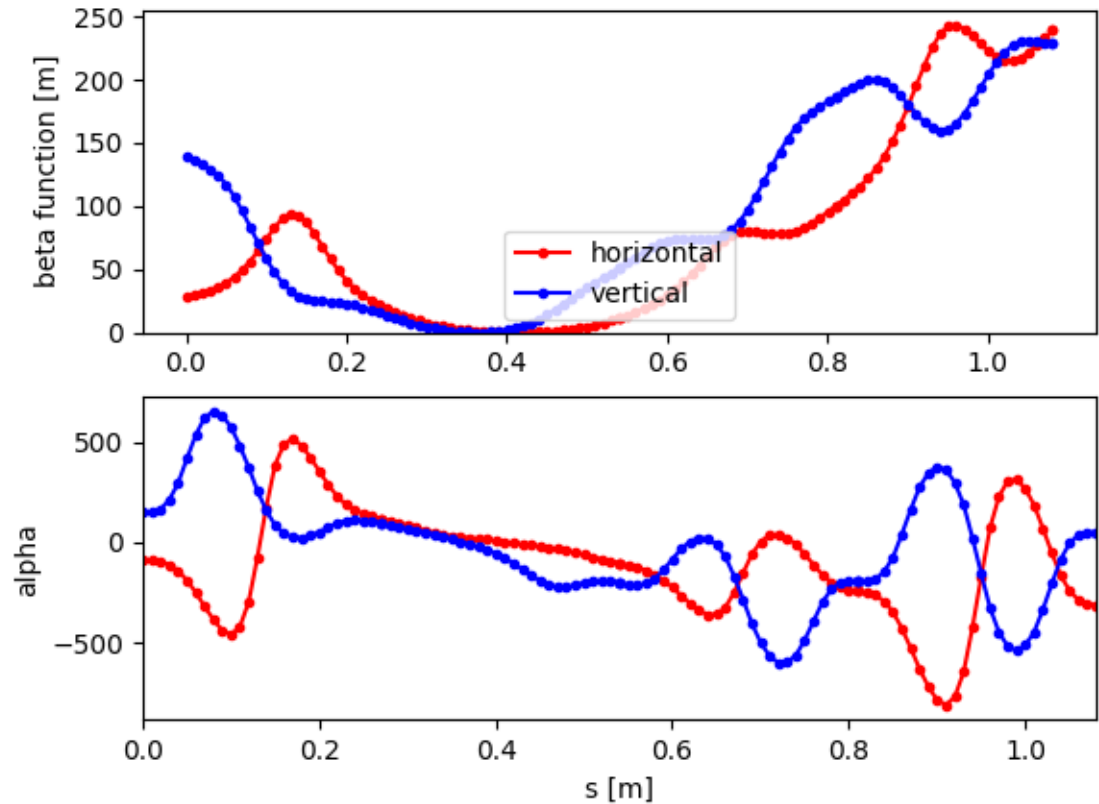
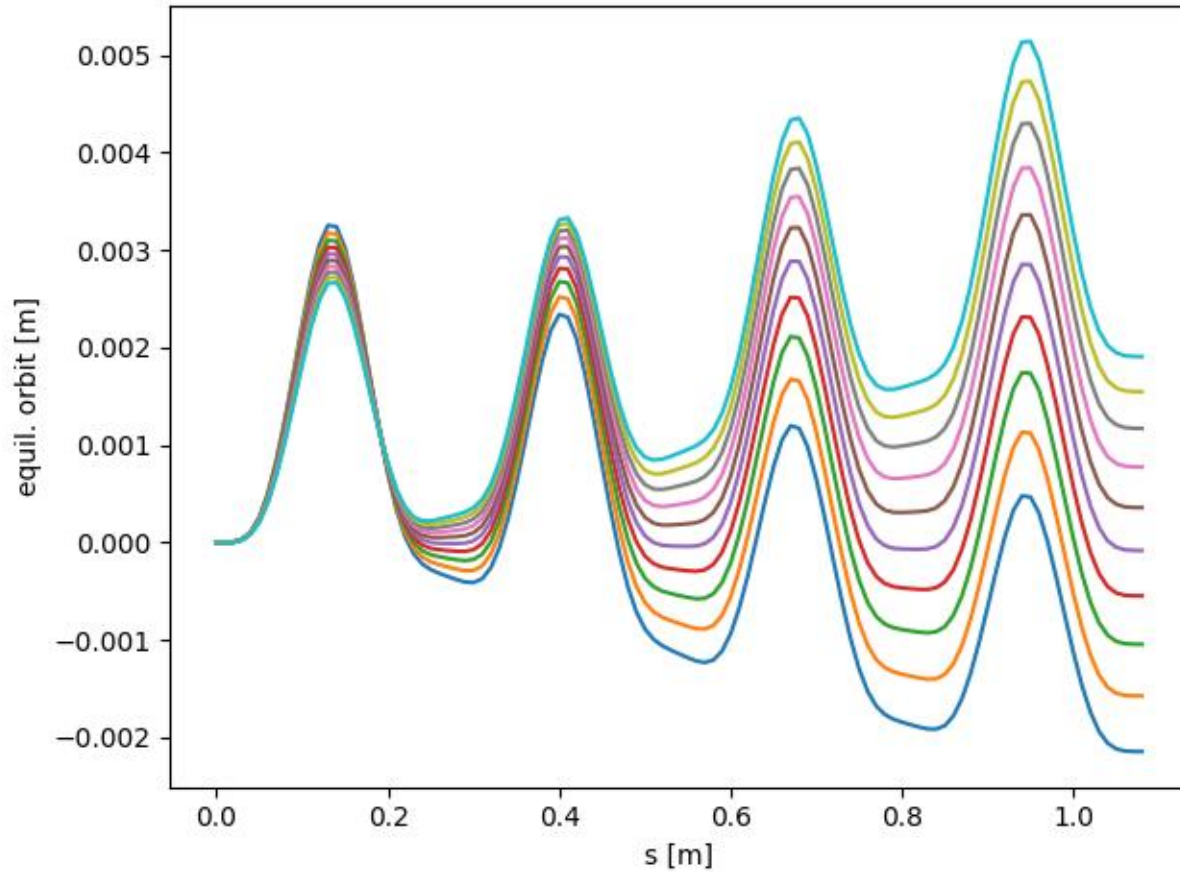
FFA dispersion creator



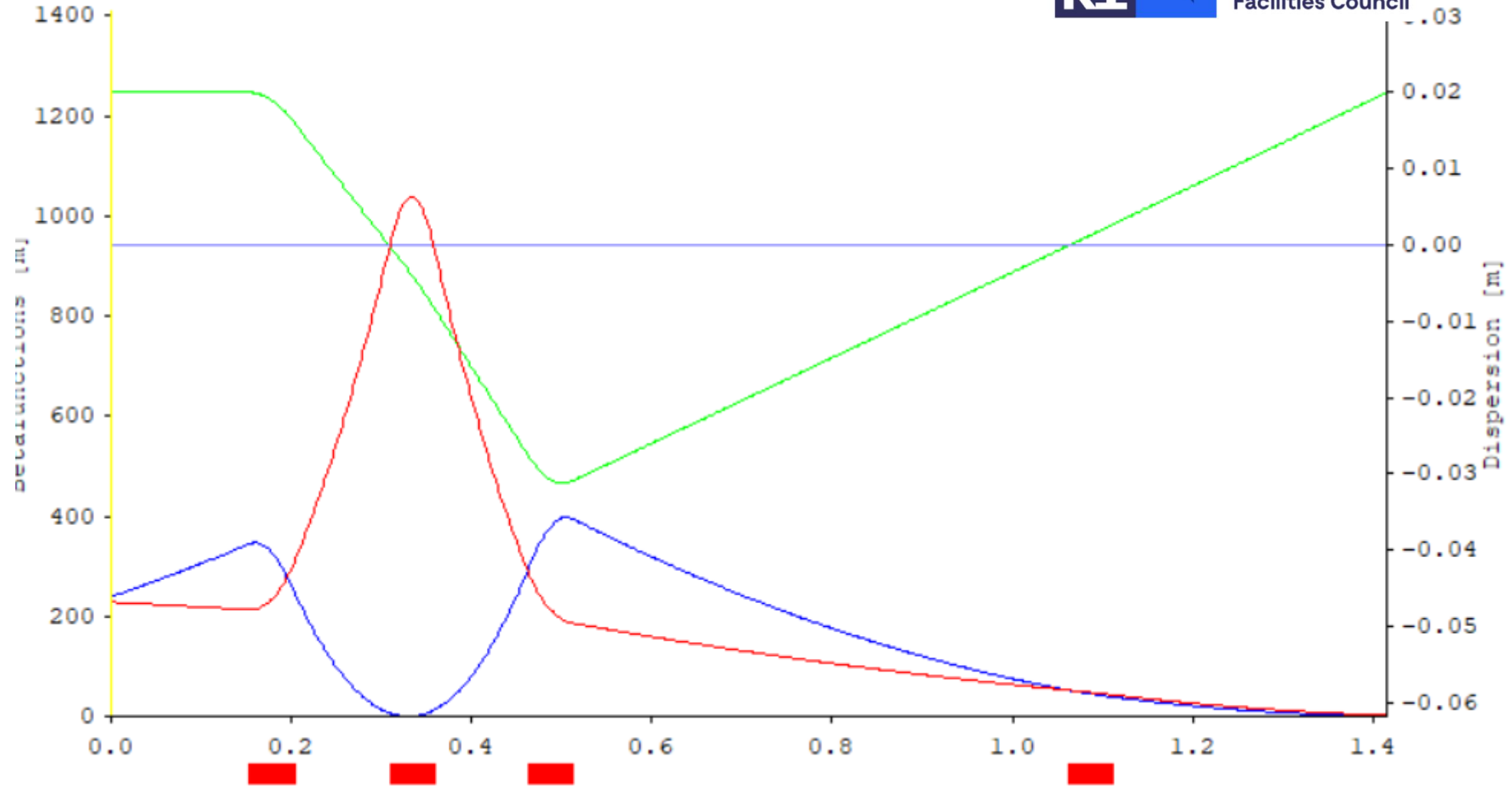
Decreasing the length of the 4-cell dispersion creator (from 4 m to 1 m)



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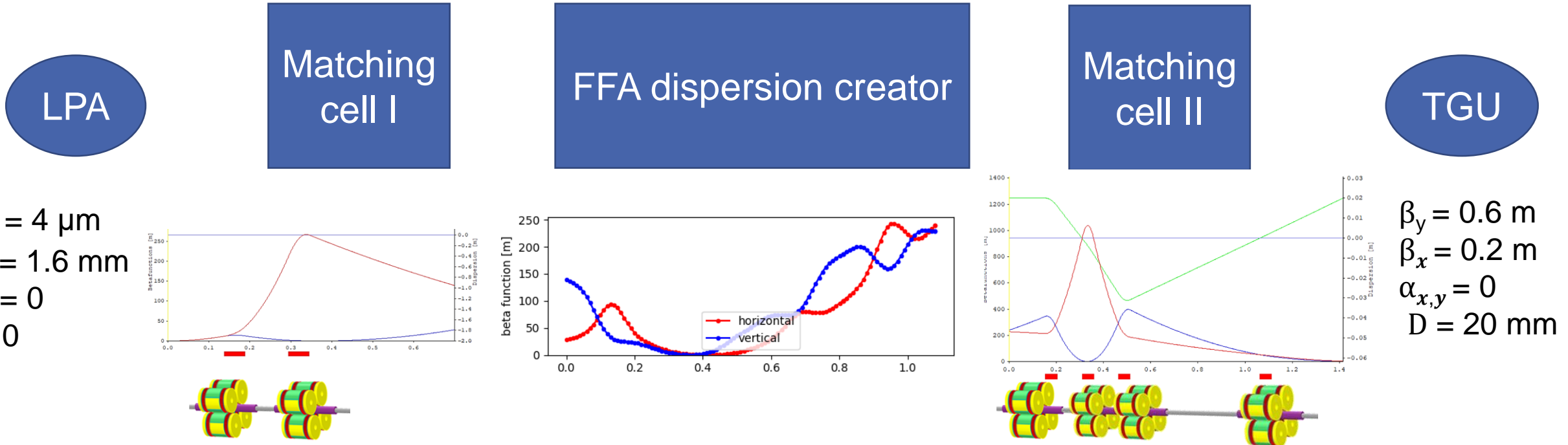
Matching cell II



Summary

A compact **2.6 m** transport line for **LPA electrons** is designed

- Using **FFA magnets** as the core element to create dispersion
- Combined with **two matching cells** based on **HTS periodic quadrupoles**
- Fulfilling the required optics for injection into the **TGU**



Conclusion

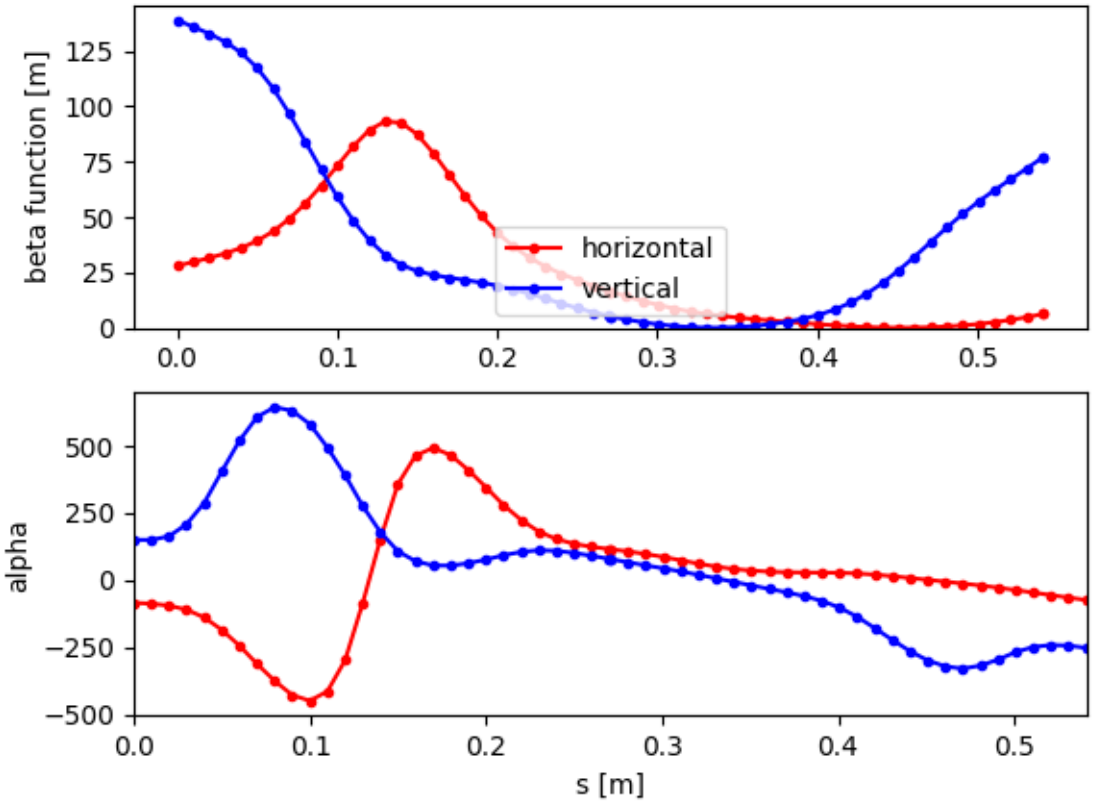
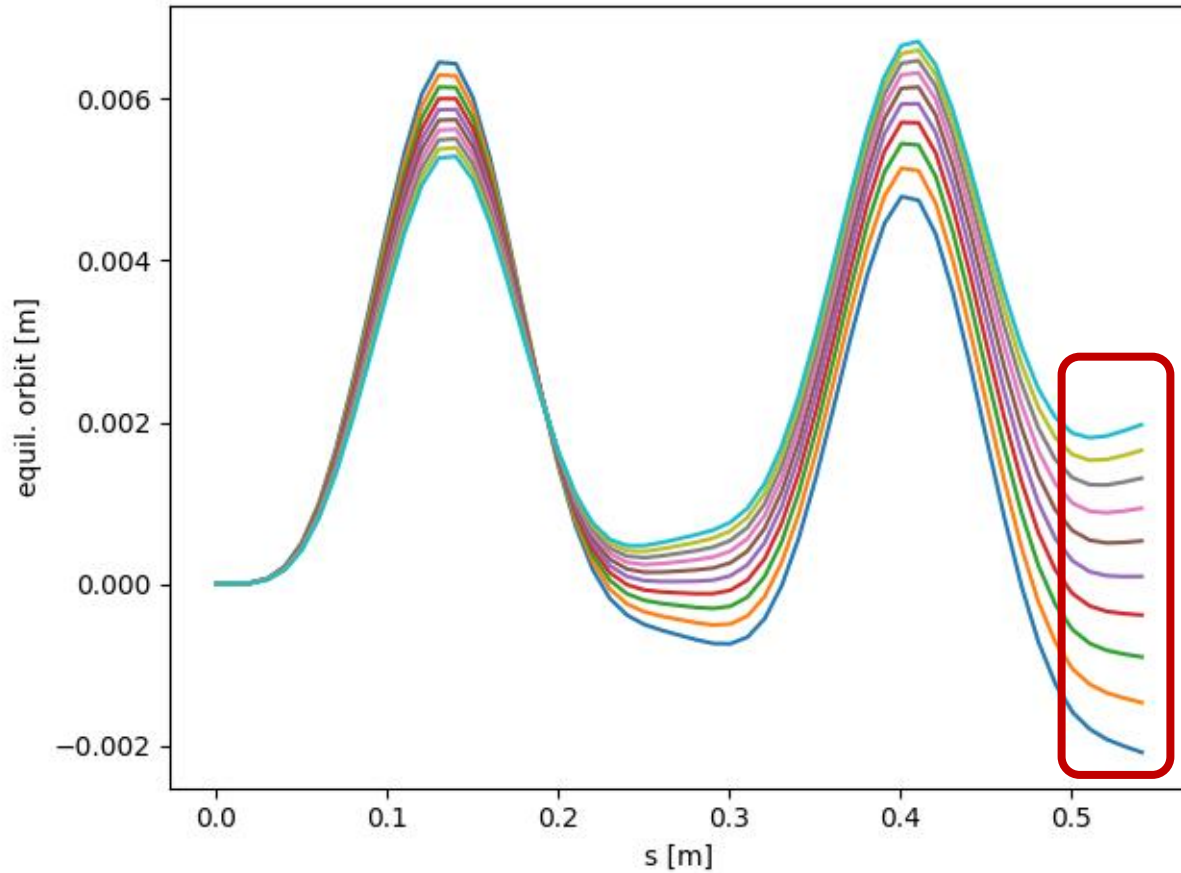
The study represents an initial step toward demonstrating the feasibility of FFA-based dispersion management for LPA-driven light sources

Next steps

- Trying to keep the dispersion gradient at the TGU center at zero, $D' = 0$, omitting the Matching cells. If FFA dispersion creator alone provides the required beam optics parameters for the TGU
- Designing a 2-cell dispersion creator to achieve a shorter transport length
- Adopting periodic quadrupole magnets, so that they reproduce the nonlinear FFA field and replace the conventional FDF/FDDF structures

Thanks for your kind attention!

2-cell dispersion creator



Why are we interested in HTS magnets?

Normal conducting (NC) coils

Cu-OFHC (Oxygen-Free High Thermal Conductivity Copper)

Low Temperature Superconducting (LTS) coils

Nb -Ti (Niobium - Titanium)

Nb₃Sn (Niobium - Tin)

High Temperature Superconducting (HTS) coils

ReBCO (Rare-earth Barium Copper Oxide)

HTS has **higher critical temperature (T_c)** and **critical current (I_c)**

- ✓ LTS magnetic fields at higher temperature *i.e.* lower cooling cost.
- ✓ Higher magnetic fields at low temperatures.

