VAriable **D**ipole for the **E**lettra **R**ing

A first proposal for the magnet design

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October, 7th 2022

This project has received funding from the European Union's Horizon 2020 Research and Innovation program under Grant Agreement No 101004730.

Outline

- From LEL 2022 in ALBA
- Quick Reminder: Why Variable Dipoles?
- Design Proposal
- Results with VADER
- Conclusions and Perspectives
- Back-Up

Outline

The Elettra 2.0 Upgrade (1)

More details about the Elettra ring can be found in the **previous presentation by E. Karantzoulis [1].**

In 2014, the Elettra leadership came up with the specifications for a new upgrade of the machine, with the following specifications [2]:

- **Main operation energy of 2.4 GeV** (assumption for the rest of the presentation)
- **Emittance reduction** by more than an order of magnitude
- Same ring circumference (260 m)
- Beam size of 60 µm in the long straight sections with zero dispersion
- Keep the same ID structure (positions, space, beam lines, etc...)

The Elettra 2.0 Upgrade (2)

A new lattice was proposed. This lattice is based on a 6-bend achromat, combined with longitudinally variable dipoles.

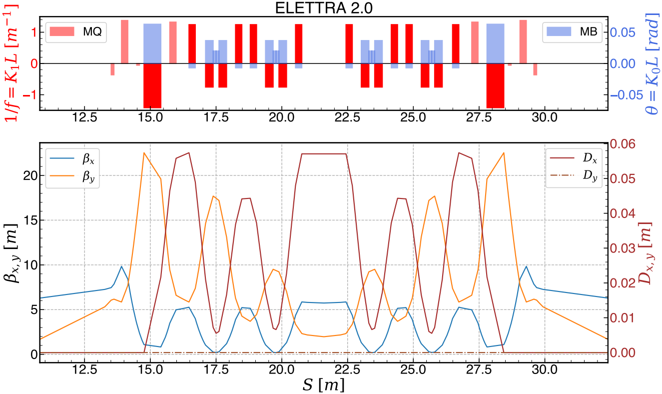

Figure: The S6BA-E cell for Elettra 2.0

Elettra 2.0 Upgrade (3)

Some machine parameters for the ELETTRA2.0 upgrade (given for an energy of 2.4 GeV):

Parameter	**Unit**	**Value**
Circumference	[m]	259.2
Geom. Emittance [1]	[pm.rad]	212
Hor./Vert. Tunes		33.26/9.18
Hor./Vert. Chroma.		-71/-68
$J_x/J_y/J_e$		1.66/1/1.34
Hor./Vert. damping times	[ms]	5.46/9.08
RF Frequency	[MHz]	499.654
Bucket length	[ns]	2

Table: Elettra 2.0 main parameters

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[1] At 2% coupling

Status as presented in LEL (1)

⇒ **What's the current status of the project?**

- A first study showed a possible emittance reduction of **about 45%**.
- First tracking studies **confirmed the computed emittances** but showed a **low dynamic aperture**

⇒ **What are the next steps to be taken?**

- Include the sextupoles in the linear design
- Replace the external dipoles by VADER to reduce further down the emittance
- Provide CIEMAT with the magnetic specifications of the VADER for the **construction of a prototype** (specs to be delivered this fall)

Status as presented in LEL (2)

We replace the LG dipoles by VADER ones and the external dipoles by simple 2-steps dipoles to control the dispersion:

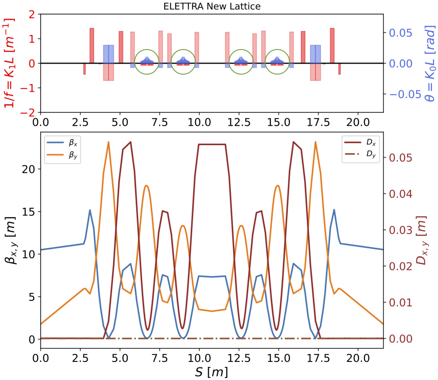

Figure: Elettra 2.0 cell with VADER dipoles.

⇒ With this new lattice, **the bare horizontal emittance is reduced down to 115 pm (-45%)**

Status as presented in LEL (3)

Particles are tracked into this lattice using the Xsuite software [3] being currently developed at CERN.

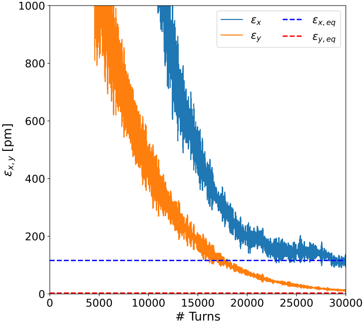

Figure: First tracking results.

- First results confirmed **the emittances computed with MAD-X**
- Particles were tracked for 30k turns: enough to see the horizontal equilibrium (about 5 damping times)
- Injection assumption: 160 nm.rad emittance at 2.4 GeV (2% coupling)

⇒ **Consistent first results!**

⇒ **DA is low and currently being optimized.**

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Why Variable Dipoles? (1)

The equilibrium horizontal emittance in a storage ring is given by [4]:

$$\varepsilon_x = \frac{C_q \gamma^2}{J_x} \frac{\langle \frac{\mathcal{H}}{|\rho|^3} \rangle}{\langle \frac{1}{\rho^2} \rangle},$$

where the *curly*-H function is defined as:

$$\mathcal{H}(s) = \gamma(s)\eta(s)^2 + 2\alpha(s)\eta(s)\eta(s)' + \beta(s)\eta(s)'^2.$$

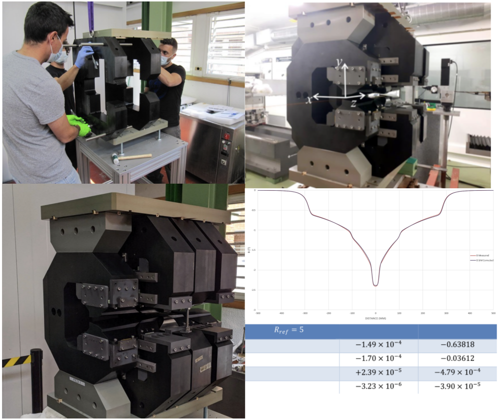
For uniform dipoles (constant ρ), minimizing the emittance consists in minimizing the $\mathcal{H}$ function. With **variable dipoles**, the emittance can be **further reduced** by minimizing the $\langle \mathcal{H}/|\rho|^3 \rangle / \langle 1/\rho^2 \rangle$ ratio.

Why Variable Dipoles? (2)

- Longitudinal variable dipoles are not a new concept (i.e., [5, 6]).
- The VADER project is highly inspired from a similar work done for the **CLIC damping rings** [4]
- Two profiles were studies: 3-steps and **trapezoidal** (in bending angle)
- Only the trapezoidal profile will be shown here

Figure: Variable dipole prototype for the CLIC DR.

Experience with the CLIC DR magnet



$R_{ref} = 5$		
	-1.49×10^{-4}	-0.63818
	-1.70×10^{-4}	-0.03612
	$+2.39 \times 10^{-5}$	-4.79×10^{-4}
	-3.23×10^{-6}	-3.90×10^{-5}

Figure: Magnet assembly in CIEMAT and magnetic measurements in ALBA (Coutesy of M. Dominguez Martinez, F. Toral, J. Marcos and V. Massana).

⇒ **Excellent field quality** and **many lessons learned** from the assembly!

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Reminder: Objective and constraints

⇒ Keep the **same S6BA-E lattice** and replace the LG dipoles by VADER dipoles.

- Objectives:
  - Implement a LG dipole with a trapezoidal profile [4] (for the bending radius).
  - Observe a clear emittance reduction.
- Constraints:
  - Keep the same **geometrical layout**.
  - Same **total bending angle** for each dipole.
  - Same **dipole length**.
- Freedoms:
  - We will change the dipole **peak field to 2.3 T** as for the CLIC DR magnet (instead of 1.8 T).
  - At the moment, we focus only on **linear optics**.

⇒ Replace the **external** dipoles by variable ones.

How to design a VADER? - Method 1 (1)

The problem is actually quite constrained. The trapezoidal profile is given by:

$$\rho(s) = \begin{cases} \rho_1, & 0 < s < L_1 \\ \rho_1 + \dfrac{(L_1 - s)(\rho_1 - \rho_2)}{L_2}, & L_1 < s < L_1 + L_2 = L/2 \end{cases}$$

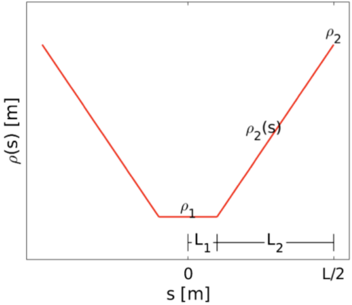


Figure: Schematic view of the bending radius profile [4]

How to design a VADER? - Method 1 (2)

We define two parameters λ and $\tilde{\rho}$ defined as:

$$\lambda = \frac{L_1}{L_2} \qquad \text{and} \qquad \tilde{\rho} = \frac{\rho_1}{\rho_2}$$

From technological constraints (cross-talk between the regions, saturation, forces...), those parameters can't be smaller than 0.04. We fix λ to this value. Then, from the bending angle of a dipole with a trapezoidal profile:

$$\theta_{trap} = \frac{L\left[\lambda(\tilde{\rho}-1) + \tilde{\rho}\ln\tilde{\rho}\right]}{\rho_1(\tilde{\rho}-1)(1+\lambda)},$$

we get $\tilde{\rho}$. Knowing the peak field, we know ρ_1 and therefore we can get ρ_2.

How to design a VADER? - Method 2

From [4], one can compute the emittance reduction factor F_{TME}, giving the emittance reduction gained from a non-uniform dipole, compared to a iso-magnetic TME cell.

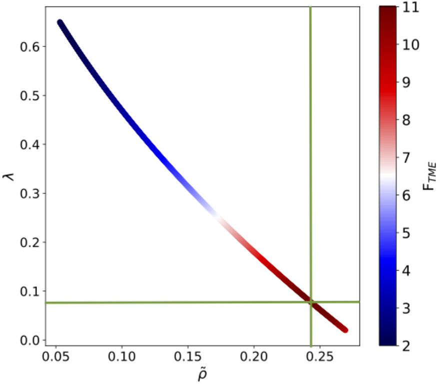


Figure: Emittance reduction factor as a function of $\tilde{\rho}$ and λ

$\Rightarrow$ **Best for $\lambda = 0.074$ and $\tilde{\rho} = 0.24$.**

Dipole Profile Proposal

We therefore obtain the following profile for the magnetic field:

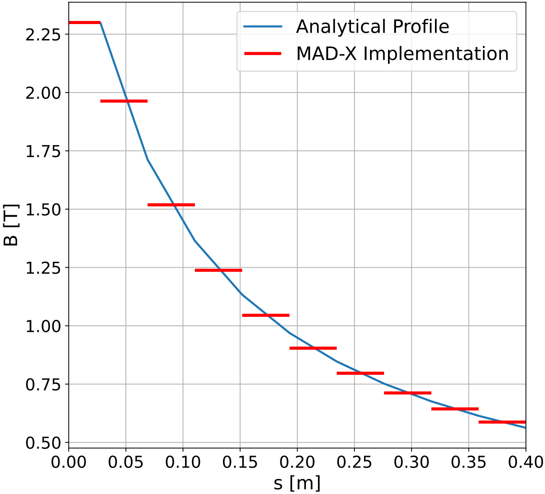


Figure: Magnetic field profile proposal for VADER.

MAD-X Implementation

Of course, such a profile cannot be implemented continuously in MAD-X (neither in real life). For the **MAD-X implementation**, we propose to decompose the **variable part** of the half-dipole in 9 slices (compromise between convergence, convenience and technical feasibility) of **constant lengths**, and **different bending angle**.

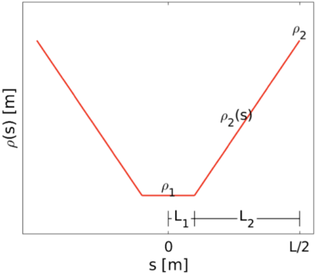
```
! Slices
VADER0       : SBEND, L = length0, ANGLE := angle0, k1 = 0;
VADER1       : SBEND, L = length_slice, ANGLE := angle_slice1, k1 := k1_vader;
VADER2       : SBEND, L = length_slice, ANGLE := angle_slice2, k1 := k1_vader;
...
! Assemble the dipole

VADER        : LINE=(VADER9, VADER8, VADER7, VADER6, VADER5, VADER4, ...);
```

Magnetic Specifications

- Good field region: +/- 6-8 mm
- Gap: 22 mm
- Gradient of about 21 T/m (except in the center)

Then, for the trapezoidal profile:

- $L_1 = 0.0276$ m / $L_2 = 0.3724$ m
- $B_{max} = 2.3$ T / $B_{min} = 0.56$ T



How to design the external dipoles? (1)

⇒ First option: analytically. Over the external dipole, the $\mathcal{H}$ function looks like:

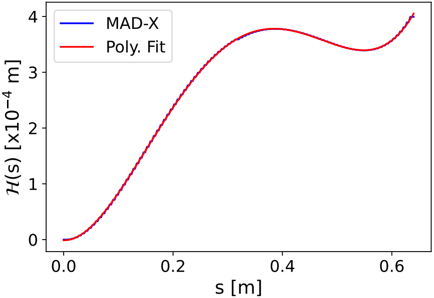


Figure: $\mathcal{H}$ function over the external dipole length

It can be approximated with a 4th order polynomial. **What to choose for $\rho(s)$?**

How to design the external dipoles? (2)

I tried with ρ as a linear function or a 2nd order polynomial:

- Integrals get very hard to compute.
- I couldn't find a *good* emittance value (knowing also that these are only 2 out of 6 dipoles.

$\Rightarrow$ **Not completely given up on that direction, but a bit blocked at the moment.**

How to design the external dipoles? (3)

Other idea ⇒ **Going fully numerical.**

- Go for 5 steps dipoles
- Get a large number of configurations such as the sum of those 5 steps gives you the correct bending angle
- Run all those configurations with the following:
  - Build the cell
  - Match such as ensuring zero dispersion in the long straights
  - Match ALFX and DPX to zero at the center of the VADER (TME conditions)
  - Build the full ring and get the emittance

To do so, we use *cpymad*, and *joblib* (parallelization), running on a CERN workstation. With 64 cores, it took about 5 hours to try 30k configurations.
⇒ Poor man approach, but still useful.

How to design the external dipoles? (4)

The best configuration (in terms of emittance) is the following:

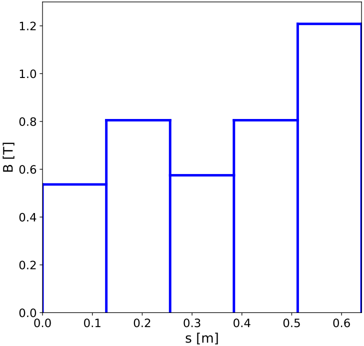


Figure: Proposal for the external dipoles

⇒ Some other solutions, probably easier to design (monotonic increase) with slightly higher emittances (few pm)

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Lattice Design

We replace the LG dipoles and the external dipoles:

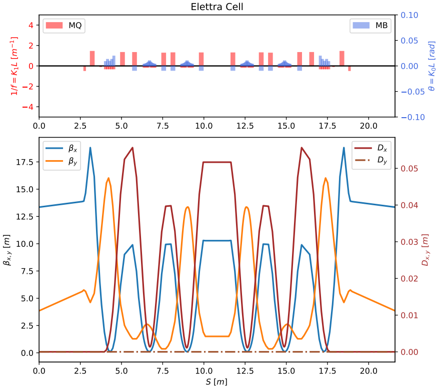

Figure: Elettra 2.0 cell with VADER dipoles.

⇒ With this new lattice, **the bare horizontal emittance is reduced down to about 100 pm (-50%)**

Dynamic Aperture Studies (1)

⇒ All the DA studies are done using **Xtrack**, developed at CERN.

⇒ First DA optimization: **tune scan**!

⇒ Then: scan the **octupoles** and the **harmonic sextupoles**.

Dynamic Aperture Studies (2)

⇒ Impact of octupoles:

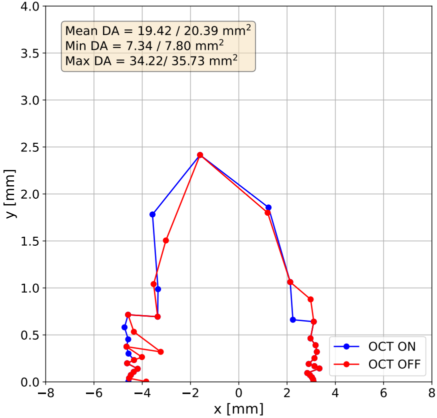

Figure: DA with octupoles ON/OFF.

Dynamic Aperture Studies (3)

⇒ Impact of sextupoles:

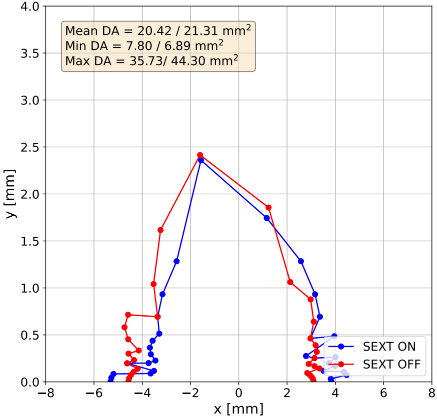

Figure: DA with harmonic sextupoles ON/OFF.

Comparison S6BA-E/VADER

Parameter	**S6BA-E**	**VADER**
Hor. Emitt. ε_x	212 pm.rad	**100 pm.rad**
Ver. Emitt. ε_y	1 pm.rad	1 pm.rad [2]
Beam size @ ID $\sigma_{x,ID}$	60 µm	35 µm
$J_x/J_y/J_E$	1.52/1/1.48	1.51/1/1.48
Q_x / Q_y	33.25/9.2	34.18/20.42
Natural ξ_x/ξ_y	-76/-52	**-140/-67**
Corrected ξ_x/ξ_y	$+1/+1$	$+1/+1$
Compaction factor $\alpha_{c,0}$	1.2×10^{-4}	**4.05×10^{-6}**
Quad. gradient	$<$ 50 T/m	$<$ 60 T/m
Mean DA	22 mm^2(err.)	21.31 mm^2(bare)

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[2] To be confirmed by tracking studies.

Known issues and next steps

- **Main issue:** low dynamic aperture
- Next steps to be taken:
    - Continue non-linear optimization
    - Use ELEGANT (probably more efficient for this kind of issues)
    - Non-linear optimizations routines from Elettra?

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Conclusions and Perspectives

⇒ **What's the current status of the project?**

- In the context of the WP7 of the I.FAST project, we are developing a **new magnet** for the Elettra 2.0 upgrade.
- The goal is to reduce further down the emittance by replacing the dipoles with **VADER** ones.
- A first study showed a possible emittance reduction of **about 50%**.
- Tracking studies **confirmed the computed emittances** but showed a **low dynamic aperture**

⇒ **What are the next steps to be taken?**

- Continue the non-linear optimization
- Benchmark with ELEGANT
- **Let's build a magnet!**

Thank you for your attention !

VAriable **D**ipole for the **E**lettra **R**ing

References I

[1] E. Karantzoulis, "Elettra 2.0 progress." `https://indico.cells.es/event/1072/contributions/1792/`. This conference.

[2] E. Karantzoulis and W. Barletta, "Aspects of the elettra 2.0 design," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 927, pp. 70–80, 2019.

[3] "Xsuite." `https://xsuite.readthedocs.io/en/latest/`.

[4] S. Papadopoulou, F. Antoniou, and Y. Papaphilippou, "Emittance reduction with variable bending magnet strengths: Analytical optics considerations and application to the compact linear collider damping ring design," *Phys. Rev. Accel. Beams*, vol. 22, p. 091601, Sep 2019.

[5] C.-x. Wang, "Minimum emittance in storage rings with uniform or nonuniform dipoles," *Phys. Rev. ST Accel. Beams*, vol. 12, p. 061001, Jun 2009.

References II

[6] R. Nagaoka and A. F. Wrulich, “Emittance minimisation with longitudinal dipole field variation,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 575, no. 3, pp. 292–304, 2007.

[7] “I.FAST website.” `https://ifast-project.eu/home`.

[8] “ARIES website.” `https://aries.web.cern.ch`.

Outline

A Word About I.FAST

Innovation **F**ostering in **A**ccelerator **S**cience and **T**echnology

"I.FAST aims to enhance innovation in the particle accelerator community, mapping out and facilitating the development of breakthrough technologies common to multiple accelerator platforms."[7]

⇒ European collaboration targeting the development of **new and innovative** ideas in accelerator physics (**following** of the ARIES project [8])

The Work Package 7

The I.FAST project is divided in **14 Work Packages**, each of them having several tasks. The VADER project is part of the WP7.

- WP7 corresponds to *High brightness accelerators for light sources* and is coordinated by **R. Bartolini** (DESY).
- The VADER project corresponds to the task 7.3, *Variable Dipole for the upgrade of the ELETTRA storage ring*, coordinated by **Y. Papaphilippou**.
- This task is shared with **Elettra**, **KYMA** and **CIETMAT** (responsible for the construction of a prototype).

iFAST

Why Variable Dipoles? (1)

The equilibrium horizontal emittance in a storage ring is given by [4]:

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- Longitudinal variable dipoles are not a new concept (i.e., [5, 6]).
- The VADER project is highly inspired from a similar work done for the **CLIC damping rings** [4]
- Two profiles were studies: 3-steps and **trapezoidal** (in bending angle)
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Figure: Variable dipole prototype for the CLIC DR.

Experience with the CLIC DR magnet

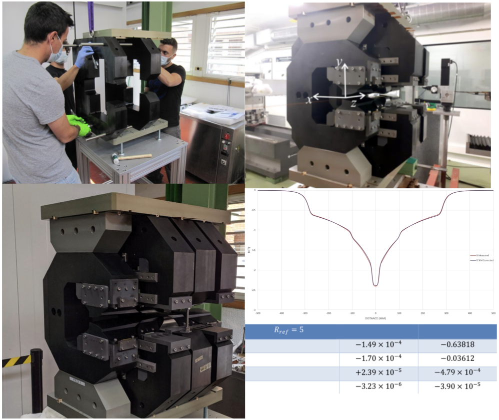

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Figure: Magnet assembly in CIEMAT and magnetic measurements in ALBA (Coutesy of M. Dominguez Martinez, F. Toral, J. Marcos and V. Massana).

⇒ **Excellent field quality** and **many lessons learned** from the assembly!

First Tracking Results

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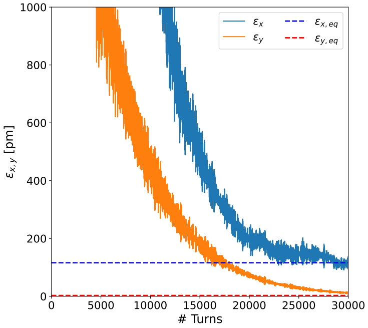

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- Injection assumption: 160 nm.rad emittance at 2.4 GeV (2% coupling)

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