Nanobeam Technologies

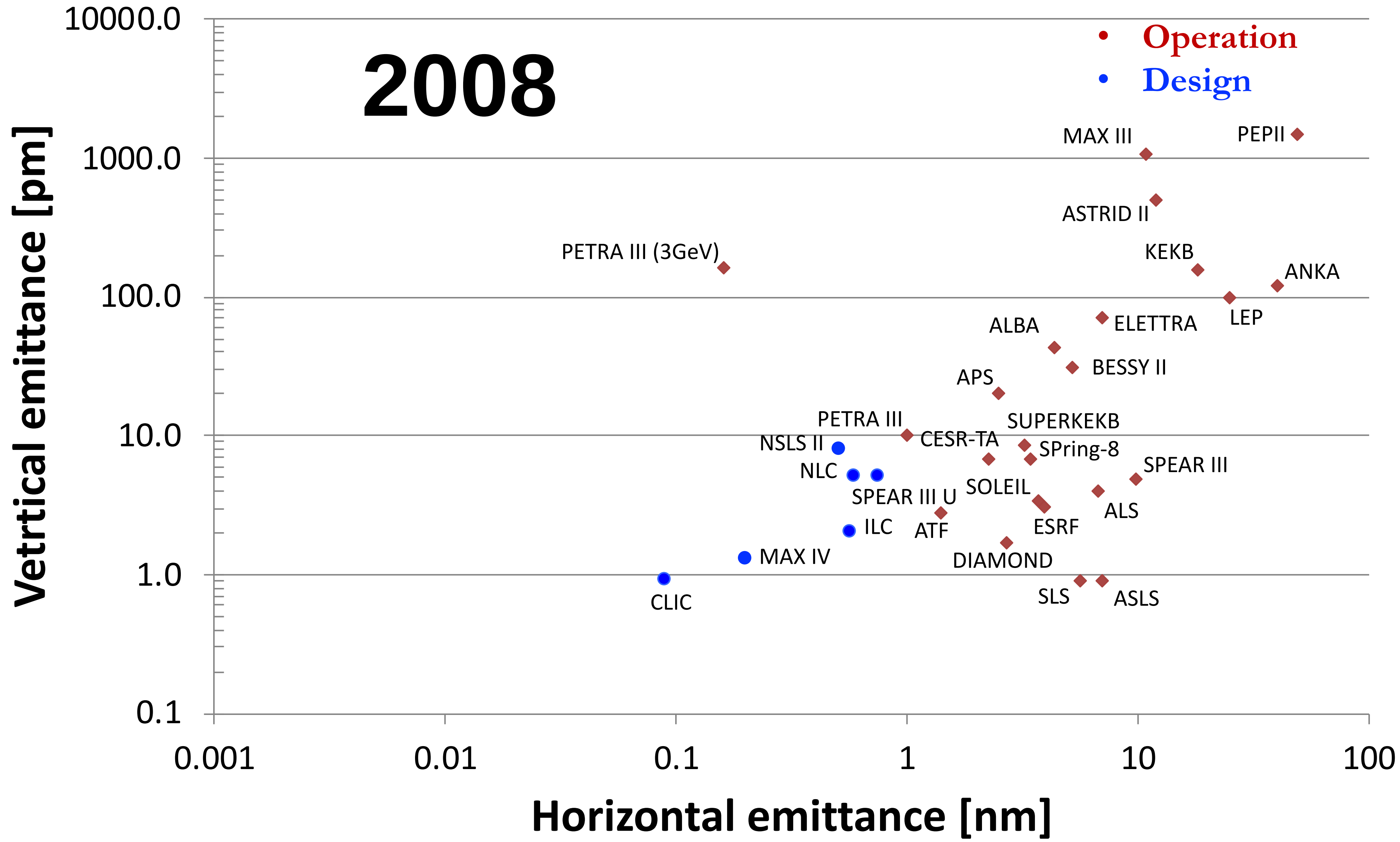
1 FEBRUARY- 3 FEBRUARY

Beam dynamics tolerances for (Low Emittance) Rings

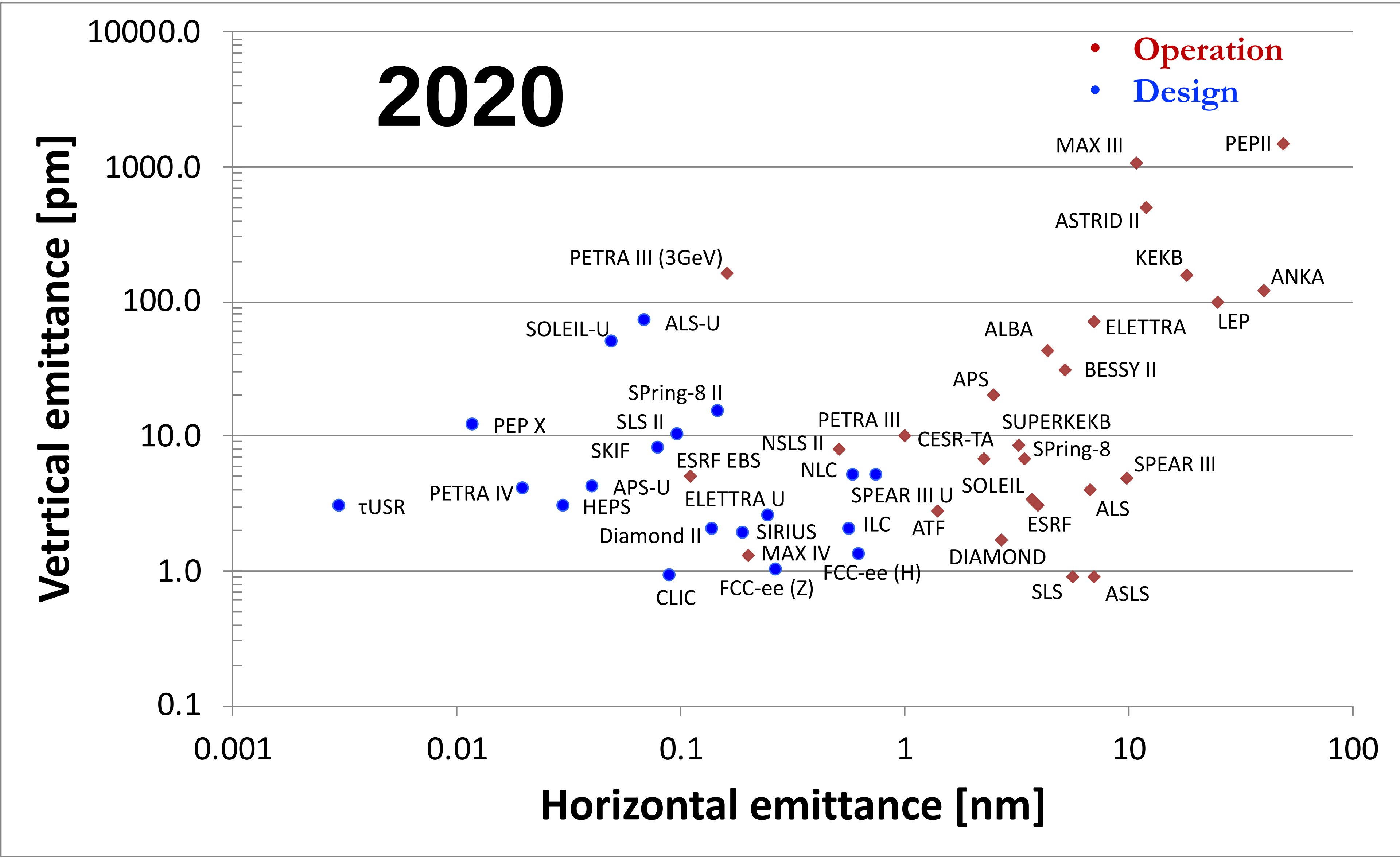
Y. Papaphilippou (CERN)

Thanks to F. Antoniou, M. Barnes, C. Belver, A. Grudiev, P. Ferracin, S. Papadopoulou, D. Schörling, P. Zisopoulos (CERN), H. Ghasem (Diamond), L. Fajardo (LBNL), A. Bernard (KIT-ANKA), F. Torral, M. Dominguez (CIEMAT), J. Holma, M. Pont, F. Perez (ALBA), T. Mastorides (CalPoly)

Emittance targets



Emittance targets



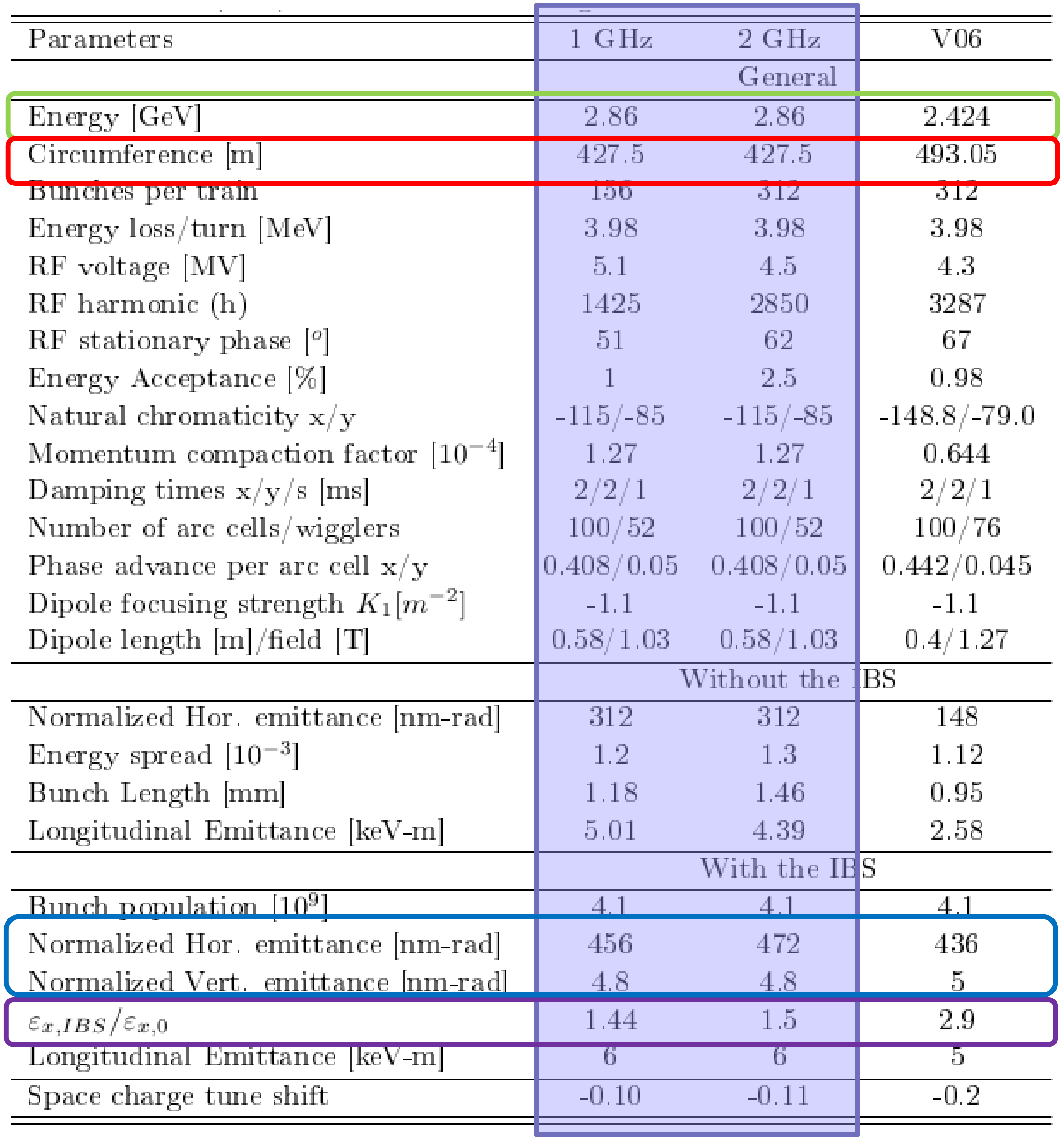
Design targets and guidelines

- Reach **horizontal emittances** <100pm, with **vertical emittance** of a few pm, ideas for round beams to reach **~10 pm** in both planes
  - Lattice design with Multi-Bend Achromats (series of TME cells), damping wigglers, innovative bedning magnets (longitudinal gradient, anti-bends,…)
- **Longitudinal emittance** free for most rings, usually enlarged for increasing lifetime, unless interest for short bunches (low-alpha operation, crab cavities) for users or downstream systems (LC DRs)
- Bunch **charge** of **~10^9-10^{10}** with structure depending on the application (**100-500 MHz** in light sources, **1-2 GHz** for damping rings)
- **Energy**: A **few GeV** depending on **users'** or **design** requirements
  - Exception e+/e- future ring colliders, i.e. **45-180 GeV**)
  - Geometrical horizontal emittance scales as **γ^2,** whereas (almost) all **collective effects mitigated** at **higher** energies
- **Circumference**: Typically a few **0.1-1 km**
  - Exception e+/e- future ring colliders 10s of km
  - Driven by the low horizontal emittance requirements ~ $\boldsymbol{\theta^3 \propto C^{-3}}$

Low emittance ring challenges and mitigations

- High-bunch brightness in all three dimensions
  - **Intrabeam Scattering** effect reduced by choice of ring energy, lattice design, wiggler technology, alignment tolerances
  - **Electron cloud** in e^+ rings mitigated by chamber coatings and efficient photon absorption
  - **Fast Ion Instability** in the e^- rings reduced by low vacuum pressure and train gaps
  - **Space charge vertical tune-shift** limited by energy choice, reduced circumference, bunch length increase
  - Other **collective instabilities** controlled by low –impedance requirements on machine components
- Repetition rate and bunch structure
  - Fast damping times achieved with SC wigglers
  - RF frequency reduction @ 1GHz considered due to many challenges @ 2GHz (power source, high peak and average current, transient beam loading)
- Output emittance stability
  - Tight jitter tolerance driving kicker technology
- Positron beam dimensions from source
  - Pre-damping ring challenges (energy acceptance, dynamic aperture) solved with lattice design

Example: The CLIC DR CDR design



Parameters	1 GHz	2 GHz	V06
		General	
Energy [GeV]	2.86	2.86	2.424
Circumference [m]	427.5	427.5	493.05
Bunches per train	156	312	312
Energy loss/turn [MeV]	3.98	3.98	3.98
RF voltage [MV]	5.1	4.5	4.3
RF harmonic (h)	1425	2850	3287
RF stationary phase [°]	51	62	67
Energy Acceptance [%]	1	2.5	0.98
Natural chromaticity x/y	-115/-85	-115/-85	-148.8/-79.0
Momentum compaction factor $[10^{-4}]$	1.27	1.27	0.644
Damping times x/y/s [ms]	2/2/1	2/2/1	2/2/1
Number of arc cells/wigglers	100/52	100/52	100/76
Phase advance per arc cell x/y	0.408/0.05	0.408/0.05	0.442/0.045
Dipole focusing strength $K_1[m^{-2}]$	-1.1	-1.1	-1.1
Dipole length [m]/field [T]	0.58/1.03	0.58/1.03	0.4/1.27
		Without the IBS	
Normalized Hor. emittance [nm-rad]	312	312	148
Energy spread $[10^{-3}]$	1.2	1.3	1.12
Bunch Length [mm]	1.18	1.46	0.95
Longitudinal Emittance [keV-m]	5.01	4.39	2.58
		With the IBS	
Bunch population $[10^9]$	4.1	4.1	4.1
Normalized Hor. emittance [nm-rad]	456	472	436
Normalized Vert. emittance [nm-rad]	4.8	4.8	5
$\varepsilon_{x,IBS}/\varepsilon_{x,0}$	1.44	1.5	2.9
Longitudinal Emittance [keV-m]	6	6	5
Space charge tune shift	-0.10	-0.11	-0.2

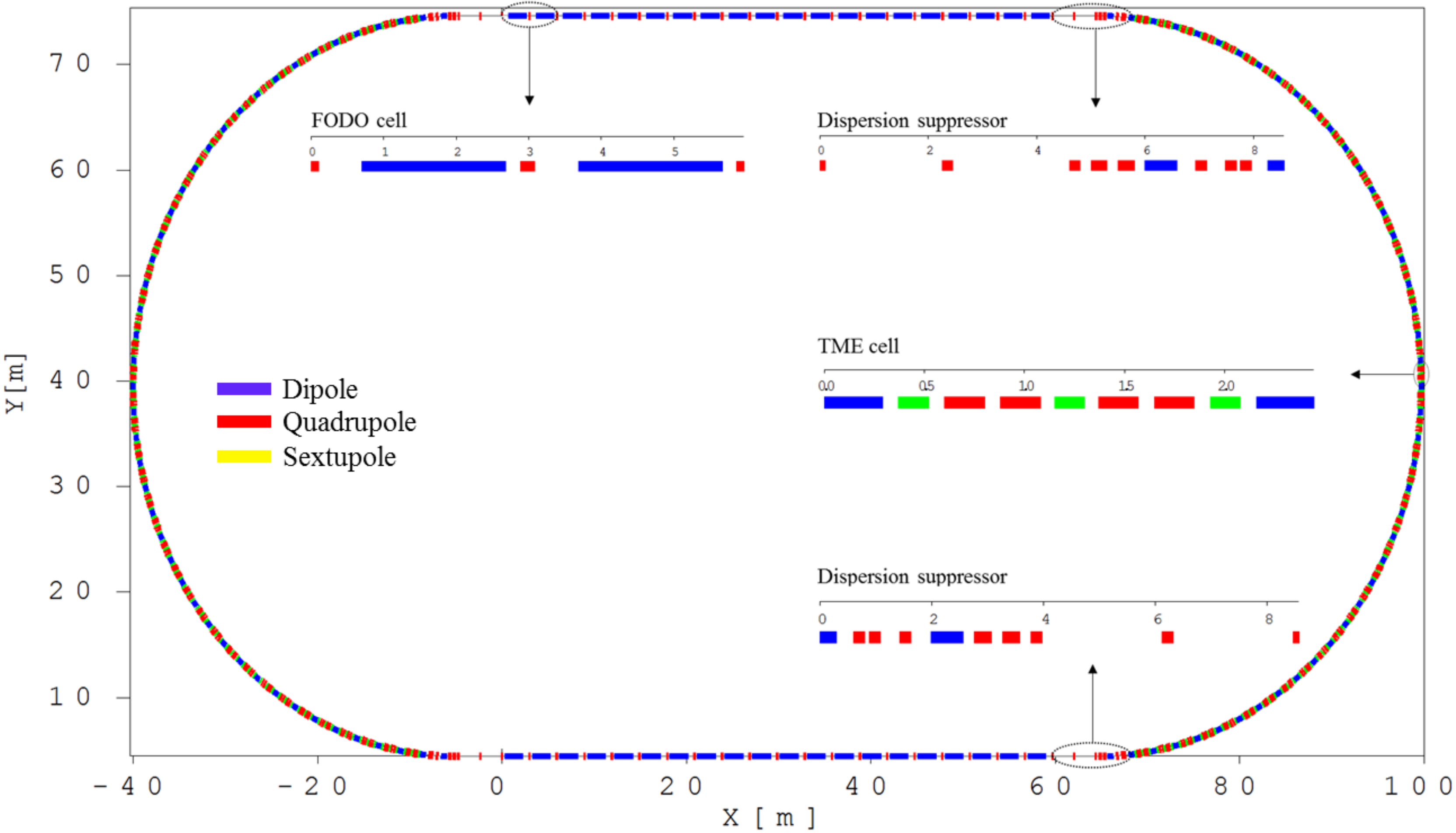
- **Performance parameters** of the CLIC DR for the **1 GHz** and **2 GHz** options in comparison to the V06
  - ☐ Increased energy (2.424→2.86 GeV)
  - ☐ Reduce the circumference by 15%
  - ☐ Ultra-low emittances in all 3 planes
  - ☐ Reduced IBS effect (from 3 to 1.5)
  - ☐ Reduced space charge tune shift (-0.2 → -0.1)
  - ☐ Lower RF stable phase (70°→51° (62°))

F. Antoniou

Improving CLIC DR design

- Reviewed DR based on **recent design developments** and collaboration effort in the **low emittance rings** community (both beam dynamics and technology)
  - New **DR arc cell** (**longitudinally varying bends**) and **SC wigglers** for circumference reduction (collective effects)
  - RF frequency choice and LLRF technical development
  - Stripline kicker + pulser tests
  - SC wiggler tests and developments

CLIC DR layout



- Racetrack shape with TME arc cells and FODO straight sections filled with high field super conducting damping wigglers

Revising CLIC DR design

CDR design of the main CLIC DRs

Parameters, Symbol [Unit]	uniform
Circumference, C [m]	427.5
Norm. horiz. emittance , $\gamma\varepsilon_x$ [nm-rad] *	657

Reduce the number of arc TME cells with longitudinally variable bends

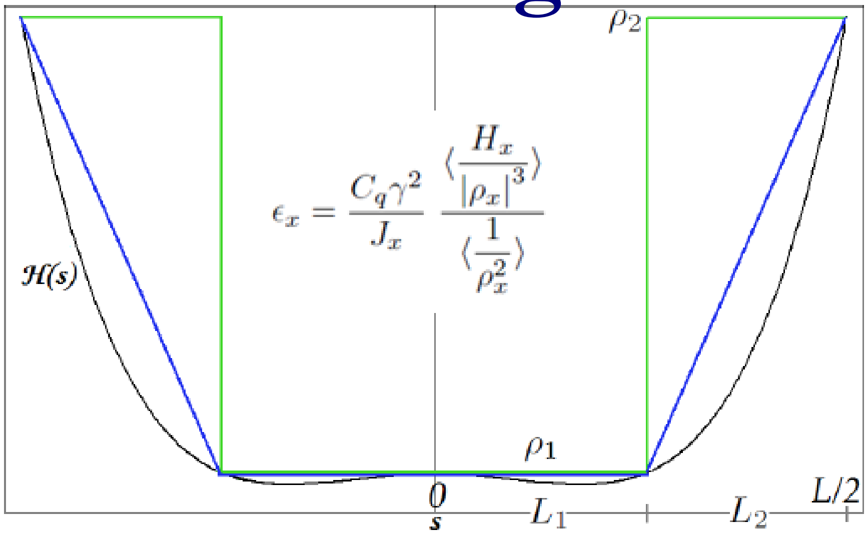
Reduce the number of wiggler using higher wiggler field

500 nm (700 nm) required output emittance

*The emittance is calculated using the Bjorken-Mtingwa formalism through MADX.
Using the Piwinski form., the original design (with the uniform dipoles) reaches the target horizontal emittance.

Longitudinally variable bends

S. Papadopoulou



$$\epsilon_x = \frac{C_q\gamma^2}{J_x}\,\frac{\langle\frac{H_x}{|\rho_x|^3}\rangle}{\langle\frac{1}{\rho_x^2}\rangle}$$

$$\rho_{st}(s) = \begin{cases} \rho_1, & 0 < s < L_1 \\ \rho_2, & L_1 < s < L_1 + L_2 \end{cases}$$

$$\rho_{\text{tr}}(s) = \begin{cases} \rho_1, & 0 < s < L_1 \\ \rho_1 + \dfrac{(L_1 - s)(\rho_1 - \rho_2)}{L_2}, & L_1 < s < L_1 + L_2 \end{cases}$$

Bending radii ratio

$$\rho = \frac{\rho_1}{\rho_2}$$

Lengths ratio

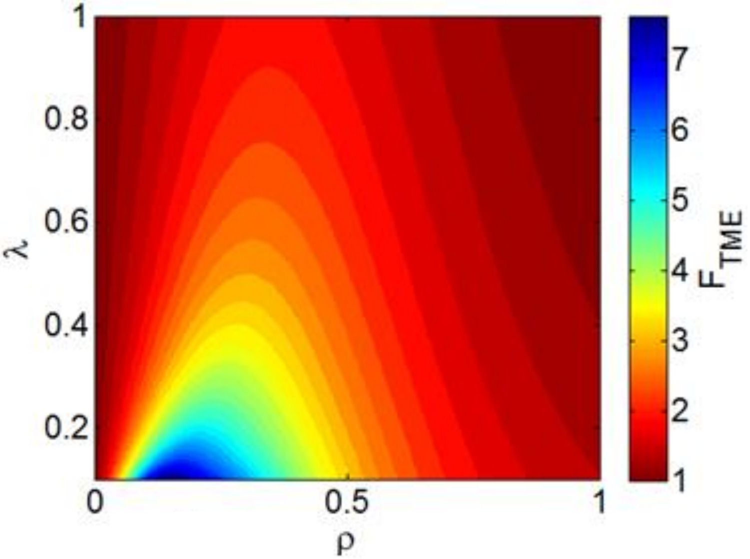
$$\lambda = \frac{L_1}{L_2}$$

Emittance reduction factor

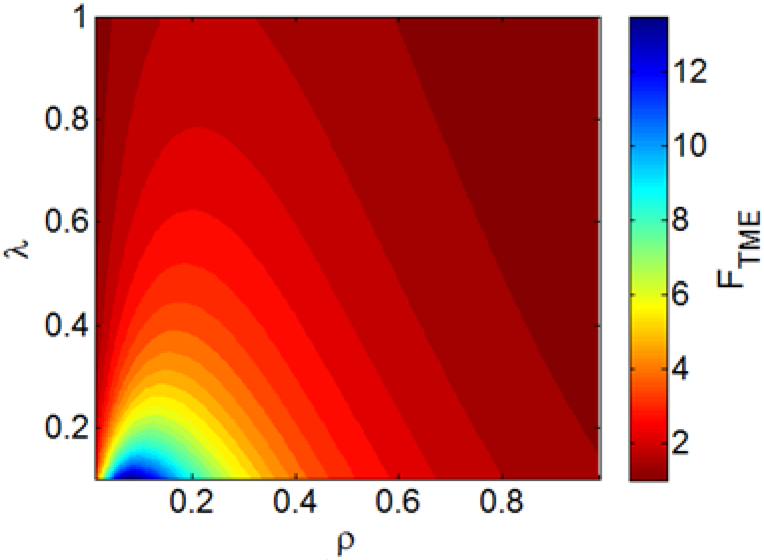
$$F_{TME} = \frac{\epsilon_{TME_{uni}}}{\epsilon_{TME_{var}}}$$

$$F_{TME} > 1$$

Step profile



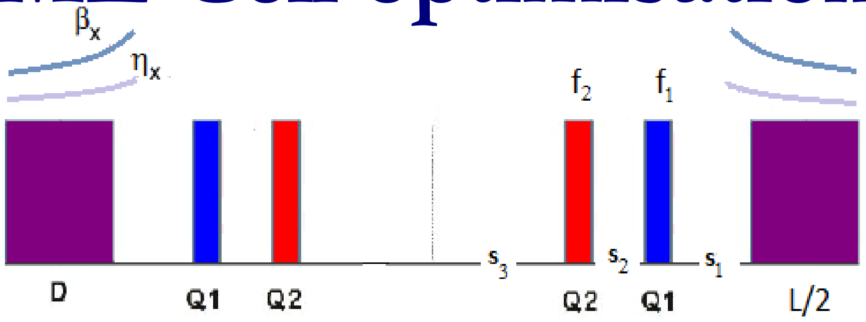
Trapezium profile



The parameterization of the emittance reduction factor F_{TME} with the bending radii ratio ρ and the lengths ratio λ, always for $\lambda > 0.1$.

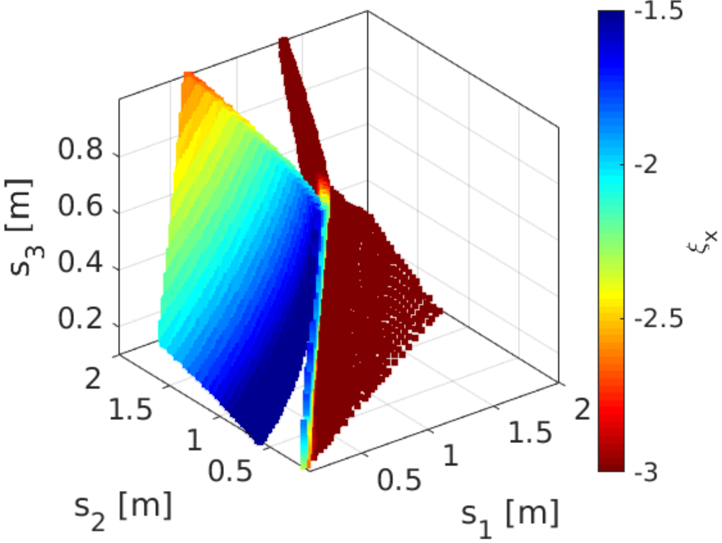
TME Cell optimisation

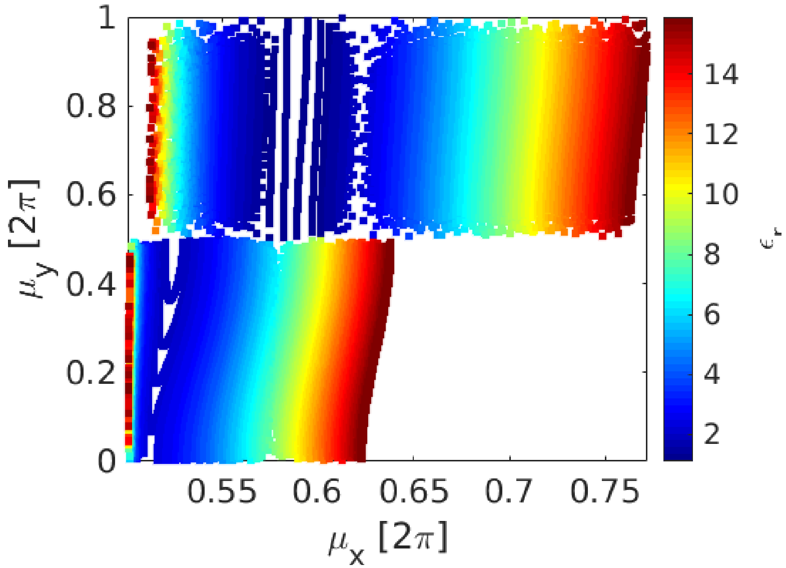
S. Papadopoulou



$$\frac{\epsilon_{var}}{\epsilon_{uni}} < 1 \Rightarrow \frac{\epsilon_{var}}{\epsilon_{uni}} = \frac{\epsilon_{r_{var}}\epsilon_{TME_{var}}}{\epsilon_{r_{uni}}\epsilon_{TME_{uni}}} = \frac{\epsilon_{r_{var}}}{\epsilon_{r_{uni}}}\frac{1}{F_{TME}} \Rightarrow \boxed{\frac{\epsilon_{r_{var}}}{\epsilon_{r_{uni}}} < F_{TME}}$$

With the variable bends, lower emittances are reached, providing flexibility to reduce the number of TME cells, for reaching target emittance in a shorter ring.





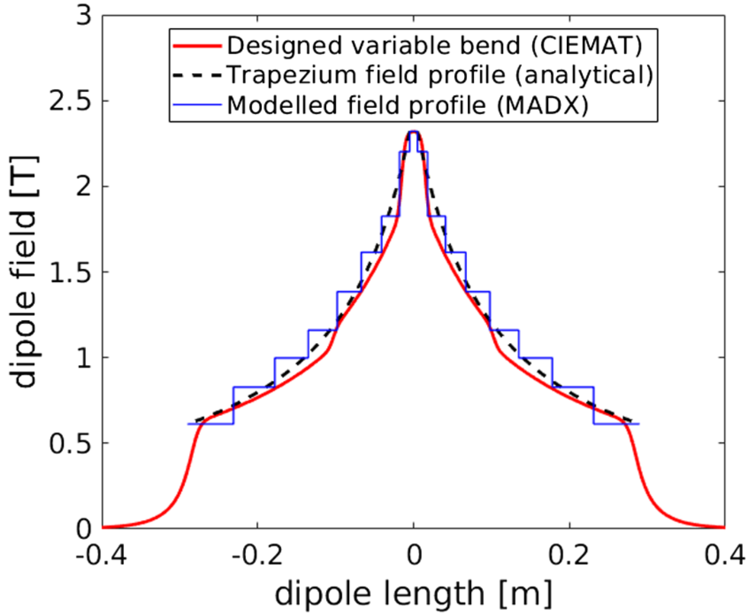
Innovative dipoles @ I-FAST

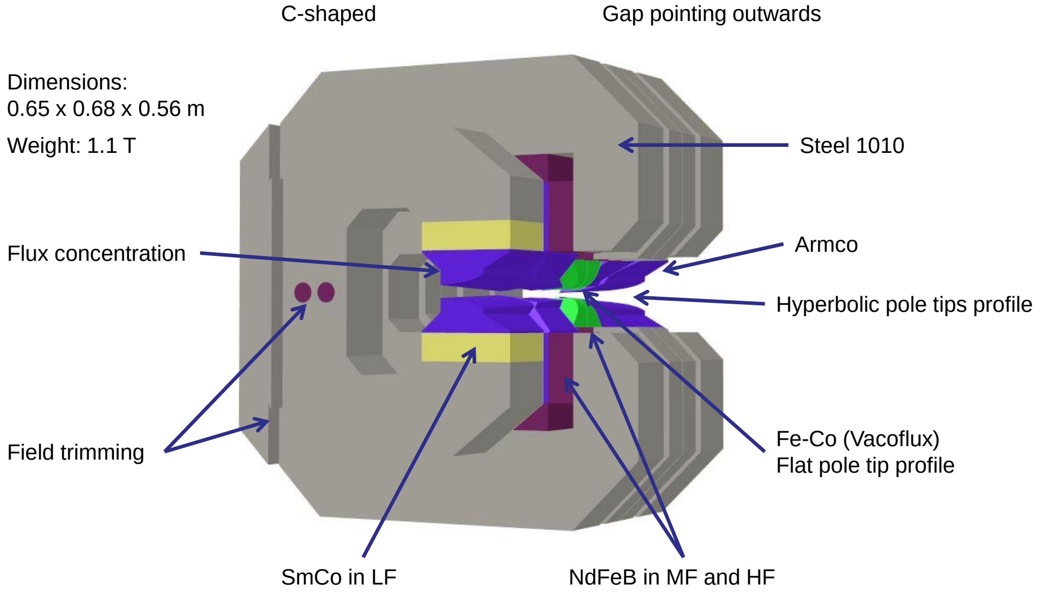
- **Task 7.3** within I.FAST **WP7**: High Brightness Accelerators for Light Sources
- Ranked **3rd** and accepted (without corrections) out of **31 prototype** proposals (**7** selected), with a **500 kCHF** EC requested budget (**3rd highest allocation** besides management WPs)
- Partners and contact persons:

CERN	Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas	Elettra Sincrotrone Trieste	KYMA
Y. Papaphilippou	F. Toral	E. Karantzoulis	R. Geometrante

Innovative dipoles (task 7.3 – Y. Papaphilippou, CERN)

- **Fabricate** an innovative dipole magnet prototype with longitudinal varying dipole field, including a transverse gradient for the ELETTRA upgrade
- Magnet concept (trapezoidal bending radius, **2.3 T** peak field and ~**10 T/m** gradient) already established (CERN/CIEMAT)
- Proved the horizontal emittance reduction to ultra-low levels of i.e. **~60 pm** @ 2.86 GeV, for the CLIC DR (M. A. Domínguez Martinez et al., IEEE Trans. Appl. Supercond. 28, 1, 2018; S. Papadopoulou et al, PRAB 22, 091601, 2019)
- First **demonstrator** already under construction by CIEMAT




C-shaped

Gap pointing outwards

Dimensions:
0.65 x 0.68 x 0.56 m

Weight: 1.1 T

Steel 1010

Flux concentration

Armco

Hyperbolic pole tips profile

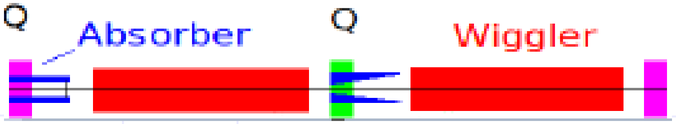
Field trimming

Fe-Co (Vacoflux)
Flat pole tip profile

SmCo in LF

NdFeB in MF and HF

Optimisation of Wiggler FODO



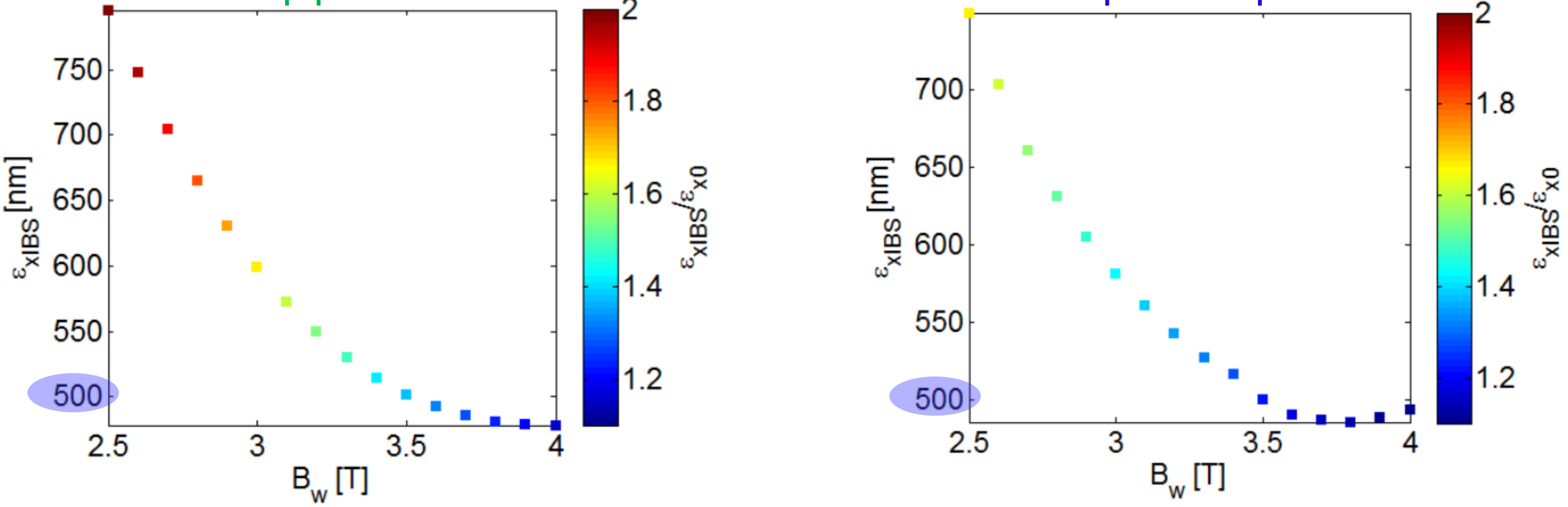
Results obtained after optimization of the arc TME cell.

When increasing the wigglers' peak field B_w, the emittance and the IBS effect are lowered [3].

Based on technological restrictions, a new working point for the damp. wiggler is proposed to be at **3.5T** (prev. 2.5T), with 49mm period length

Removing some wiggler FODO cells from the existing straight section (**N_{FODO}=13 per section**) is possible.

N_{FODO}=10 per straight section


Step profile

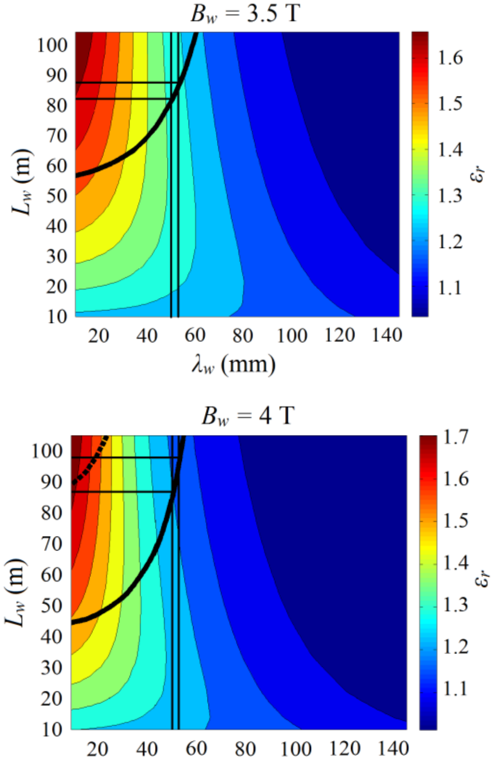
Trapezium profile

Parametrization of the steady state emittance and the IBS effect with the wiggler's peak field B_w

Nb_3Sn wiggler Design

L. Fajardo

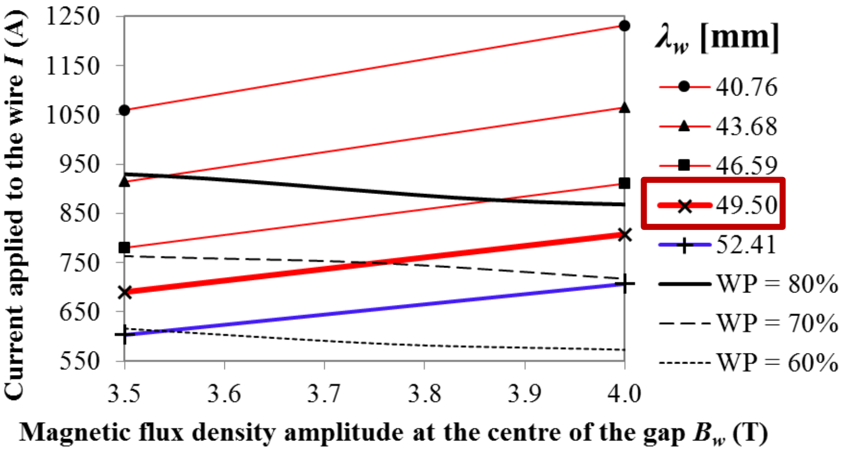
Larger potential L_w reduction with λ_w = 49.5 mm



ADDITIONAL RESTRICTION:

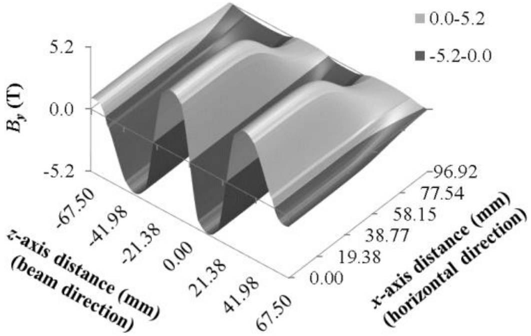
Keeping the working point (*WP*) below 80% of the magnet's current limit for all 3.5 T ≤ B_w ≤ 4 T

Scenarios for achieving 3.5 T ≤ B_w ≤ 4 T with 40 mm ≤ λ_w ≤ 55 mm values:

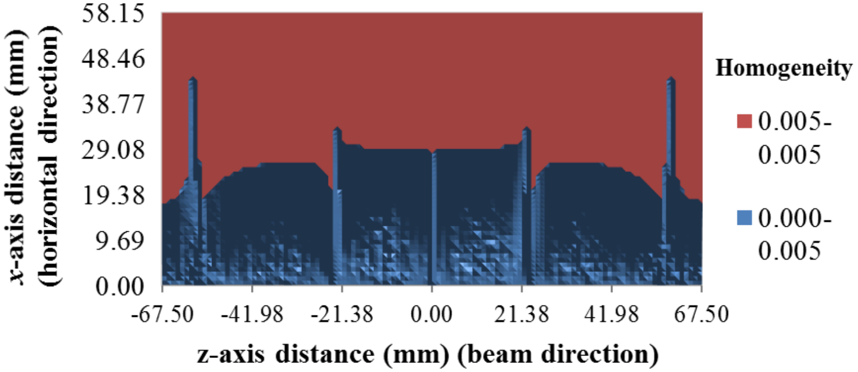


SELECTED λ_w FOR 3.5 T ≤ B_w ≤ 4 T

Field map: Vertical component of the magnetic flux density B_y at the centre of the gap



Field homogeneity map: $|(B_y(0) - B_y(x))/B_y(0)|$



CLIC DR Design parameters

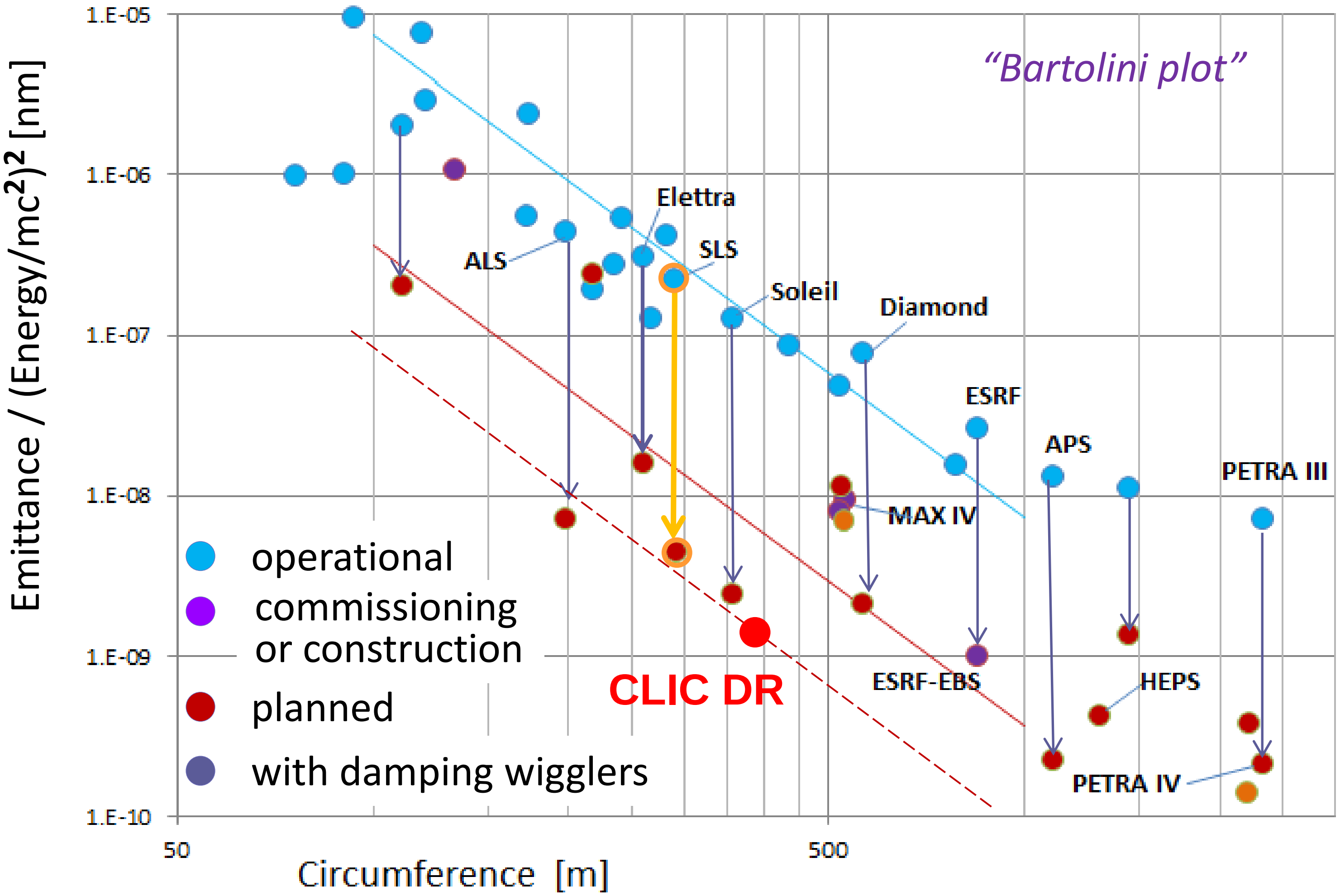
Parameters, Symbol [Unit]	uniform I	uniform II	trapezium
Number of arc TME cells/wigglers	100/52	90/40	90/40
Dipole field (max/min), B [T]	0.97/0.97	0.97/0.97	0.62/2.32
IBS factors hor./ver./long.	1.5/1.5/1.1	1.1/1.4/1.0	**1.2/1.3/1.0**
Norm. horizontal emittance (with IBS), $\gamma\varepsilon_x$ [nm]	478.9	**648.7**	**434.7**
Norm. vertical emittance (with IBS), $\gamma\varepsilon_y$ [nm]	5.0	**4.5**	**4.2**
Circumference, C [m]	427.5	**373.7 (-13%)**	**373.7 (-13%)**

- Optimised lattice design achieves all target parameters for a mitigated IBS effect and a ring circumference that is reduced by **~13%** with respect to the old lattice
- Remarkable **Dynamic Aperture**, allowing very comfortable on-axis injection Impact of this study
- Significant margin for the CLIC DR emittance target (500nm), for an eventual increase of the required bunch population, as lately proposed due to the CLIC re-baselining

Emittance vs energy and circumference

Emittance normalized to energy vs. circumference

$\varepsilon_x \propto (\text{Energy})^2 / (\text{Circumference})^3$



Theoretical Emittance scaling

$$\varepsilon \propto \gamma^2 C^{-3}$$

$$\ln\frac{\varepsilon}{\gamma^2} = K - 3 \cdot \ln C$$

$K \approx 2 \rightarrow \approx -1$

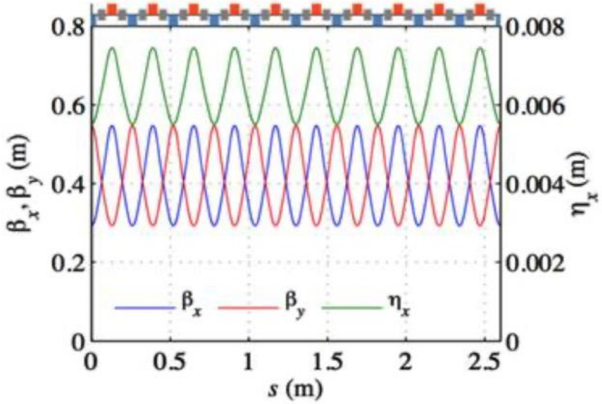
improvement ×20

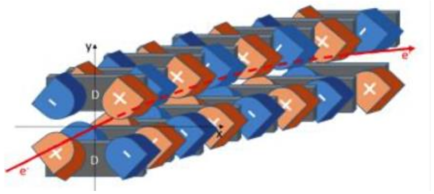
↓ upgrade projects

A. Streun, Lattice review meeting, 2020

Low Emittance Lattice Design in Synchrotron Light Sources by Using Complex Bends – Guimei Wang

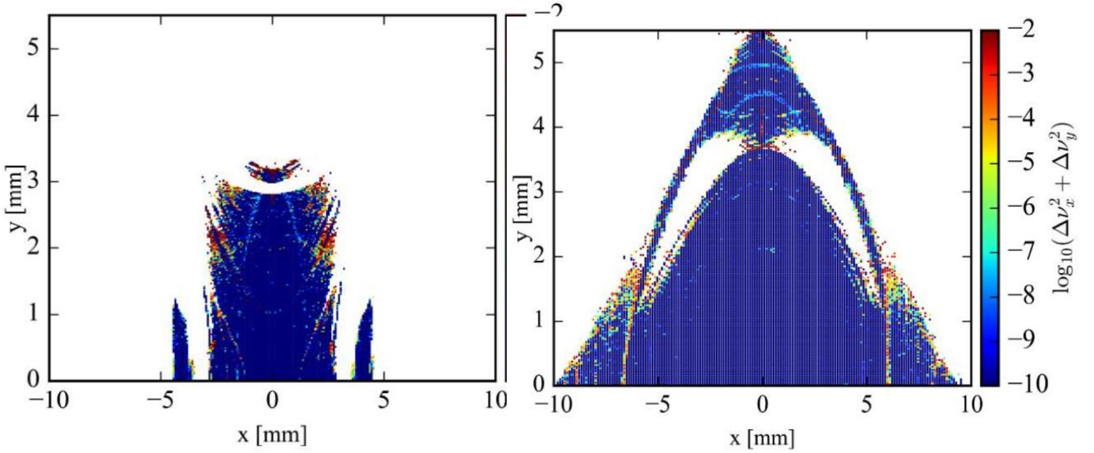
$$\varepsilon_x = F\frac{E^2}{J_x N_d^3} \overset{CB}{\Rightarrow} F\frac{E^2}{J_x\left[N_d N_p\right]^3}$$



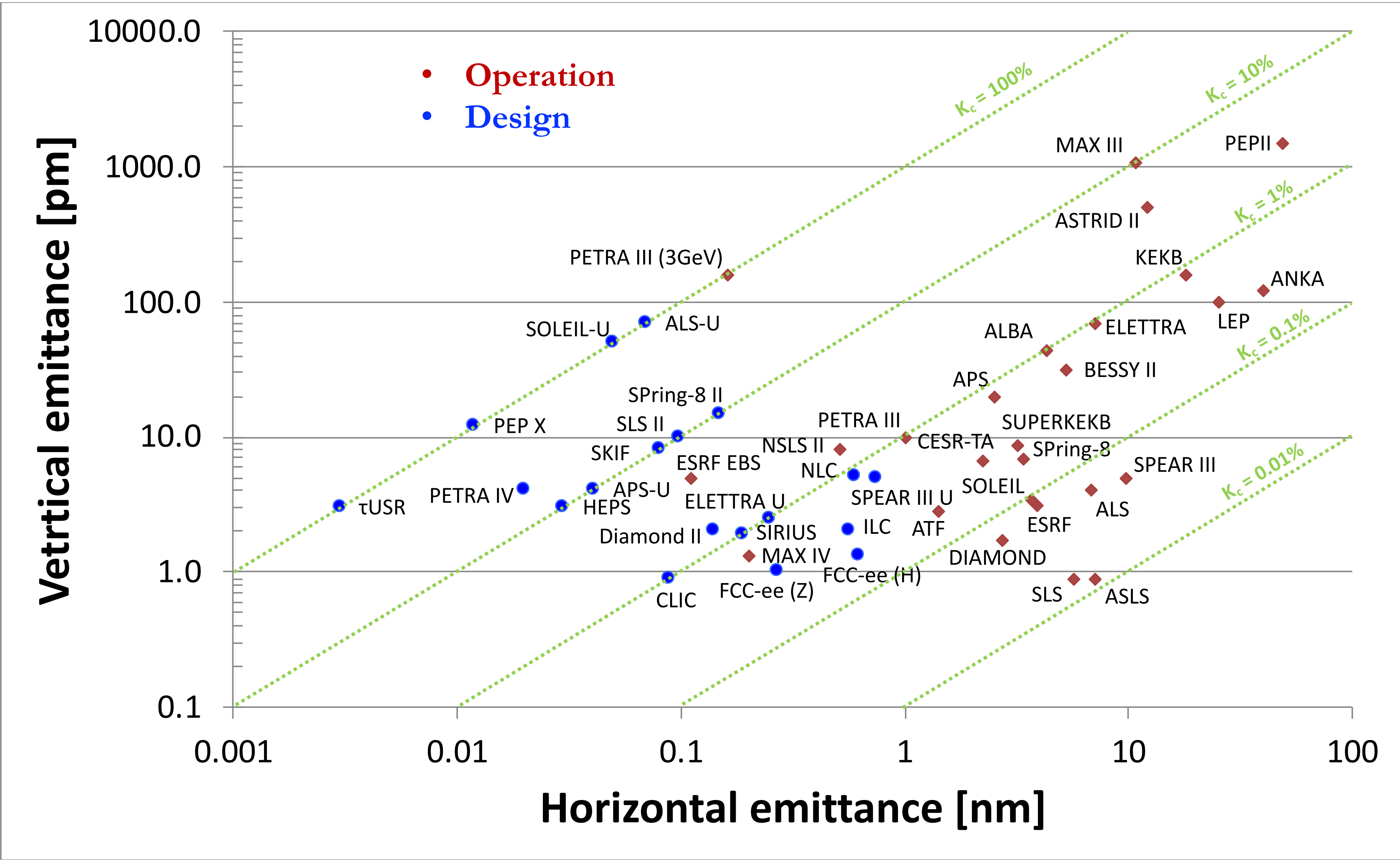


	NSLS-II dipole	Complex bend I
Length, m	2.6	2.6 (0.26 per cell)
Bending field, T	0.4	1.05
Bending angle, rad	0.105	0.105
K_1, m^{-2}	0	+100 / –80
β_{max} / β_{min}, m	3.7 / 0.7	0.42 / 0.24
η_{max} / η_{min}, mm	137 / 0	4.7 / 3.6
Emittance, nm	**2.09**	**0.07**

- A bending element consisting of dipole poles, interleaved with strong focusing and defocusing quadrupole poles, QF-D-B-D-QD-D-B-D (**CB**)
- Integration in the NSLSII lattice for 30-fold emittance reduction
- DA increase with octupoles (3 families)



Horizontal vs Vertical emittance

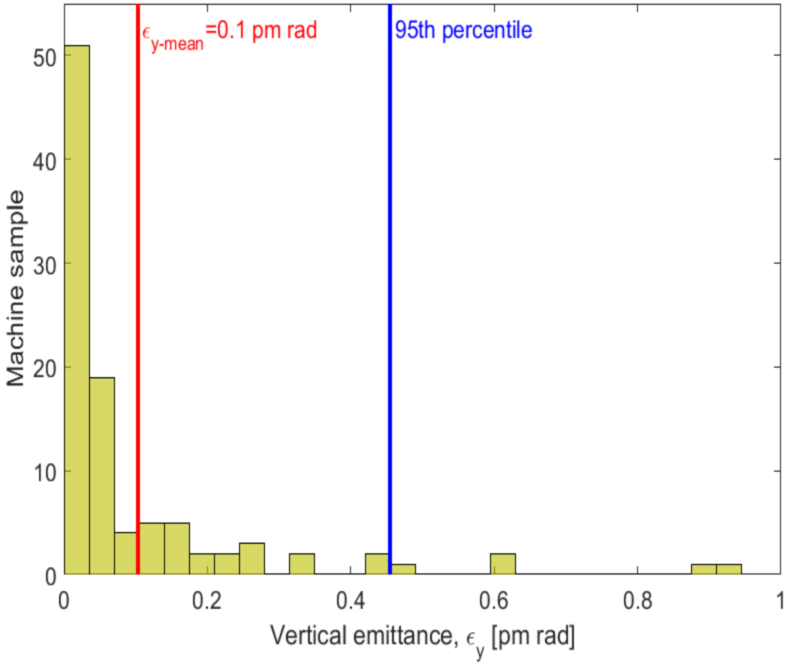


Vertical emittance tuning

- Vertical emittance in the CLIC DR including all errors, specified misalignments and BPM offsets, rolls and noise jitter (100 random seeds)

Error	Unit	Value
Dipole/quadrupole/sextupole/BPM vertical misalignment	µm	40/16/70/70
Dipole/quadrupole/sextupole roll	µrad	70/50/100
BPM roll	µrad	70
BPM noise	nm	200

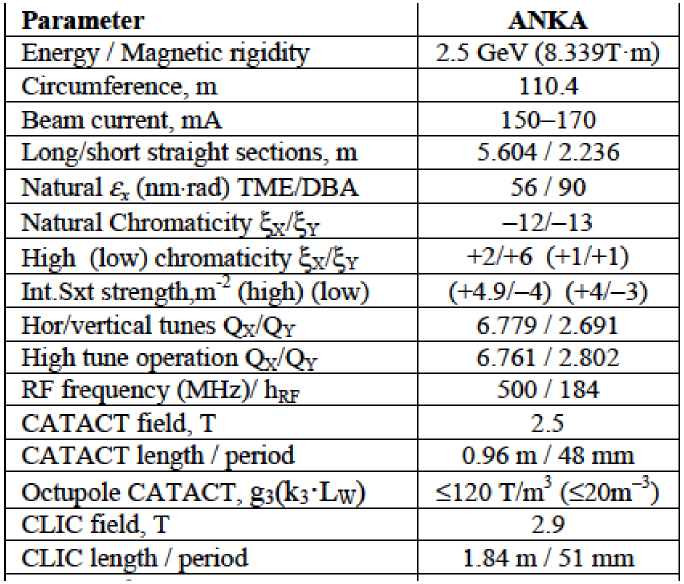
- The mean value of the vertical emittance for 100 seeds is around 0.1 pm rad and fc 95% of machine samples, the vertical emittance is below 0.5 pm rad.



H. Ghasem

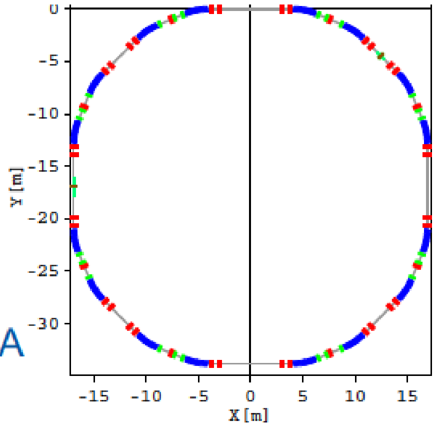
NbTi Wiggler tests at ANKA

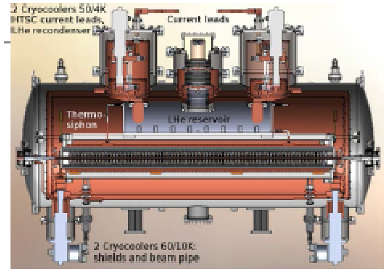
A. Bernard, P. Zisopoulos



Parameter	ANKA
Energy / Magnetic rigidity	2.5 GeV (8.339T·m)
Circumference, m	110.4
Beam current, mA	150–170
Long/short straight sections, m	5.604 / 2.236
Natural ε_x (nm·rad) TME/DBA	56 / 90
Natural Chromaticity ξ_X/ξ_Y	–12/–13
High (low) chromaticity ξ_X/ξ_Y	+2/+6 (+1/+1)
Int.Sxt strength,m^{-2} (high) (low)	(+4.9/–4) (+4/–3)
Hor/vertical tunes Q_X/Q_Y	6.779 / 2.691
High tune operation Q_X/Q_Y	6.761 / 2.802
RF frequency (MHz)/ h_{RF}	500 / 184
CATACT field, T	2.5
CATACT length / period	0.96 m / 48 mm
Octupole CATACT, $g_3(k_3 \cdot L_W)$	$\leq$120 T/m^3 ($\leq$20m^{-3})
CLIC field, T	2.9
CLIC length / period	1.84 m / 51 mm

- ANKA (recently renamed KARA) is a 4-fold DBA ring with very flexible optics, able to serve 19 beamlines
- The CLIC SC Nb-Ti Wiggler prototype was installed at KIT-ANKA in 2016.
- This project is the result of a fruitful collaboration between KIT, BINP and CERN
- Several ongoing studies to characterize the impact of the wiggler on beam dynamics





Cross-section of the assembled wiggler cryostat. Mezentsev N.A., 2012

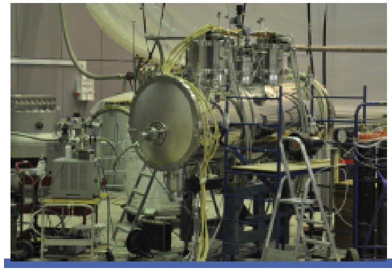


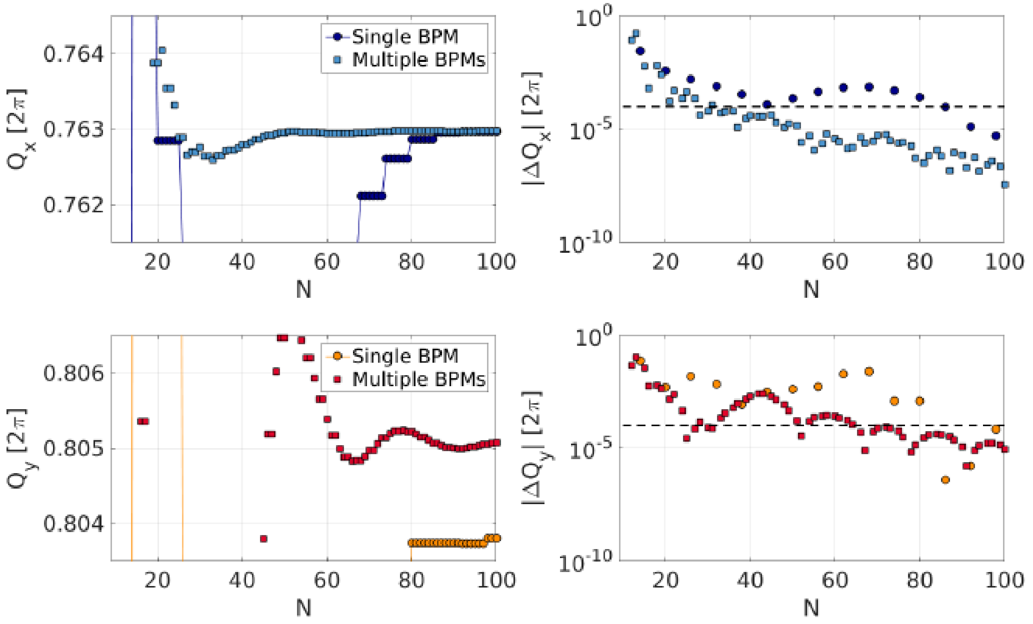
Photo taken during FAT at BINP

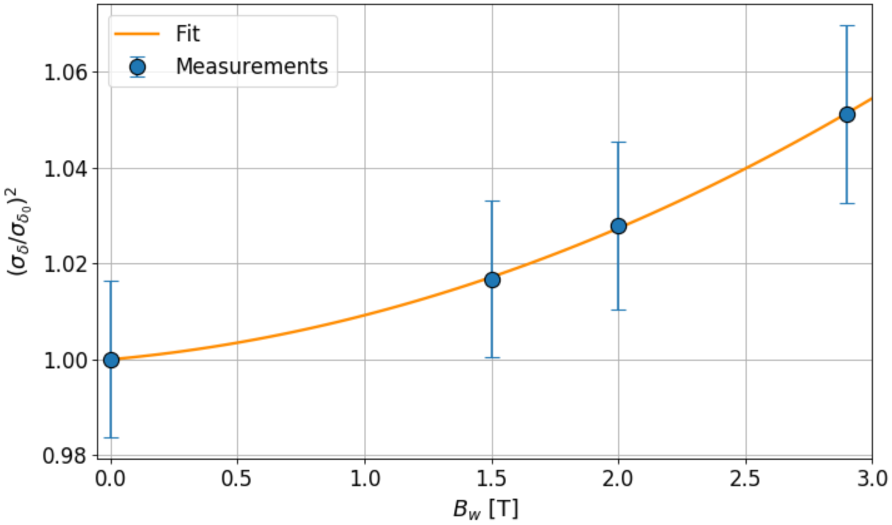
J. Gethmann et al, IPAC 2017, WEPIK068, p.3087-3089

A. Bernhard et al, IPAC 2016, WEPMW002, p.2412-2415

NbTi Wiggler tests at ANKA

P. Zisopoulos

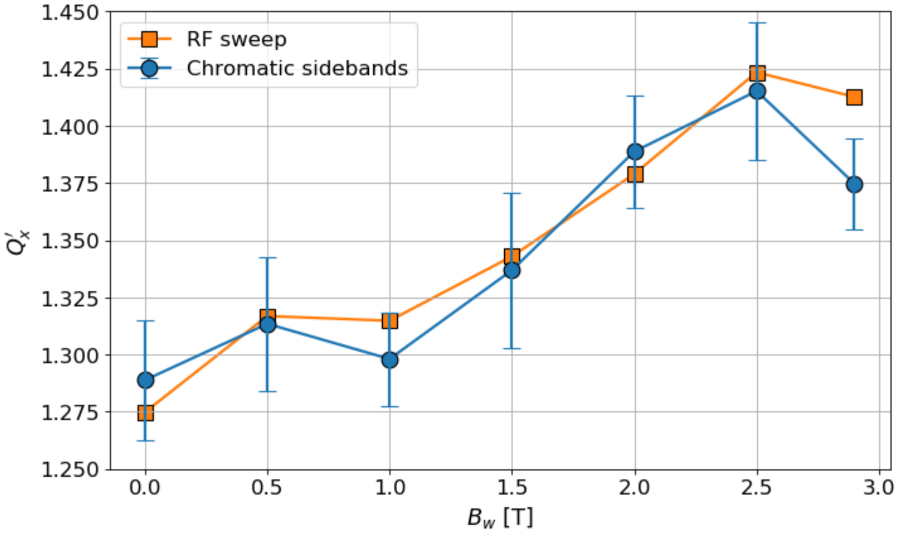




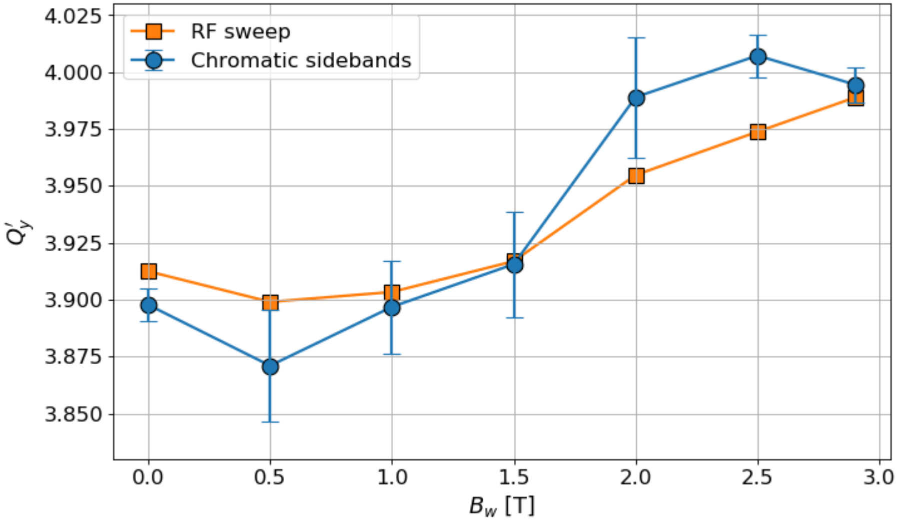
- By using the mixed BPMs scheme the tunes were also measured during each ramp of the wiggler with the beam at the nominal chromatic orbit.
- Precision is increased in both cases and it is at the level of 10^{-4} at around 30 turns.
- The measurements were fitted with quadratic models.
- The horizontal tune-shift is not expected but it is present, possibly due to sextupolar feed-downs.
- The expected vertical tune-shift is relatively close to the theoretical predicted value.
- ($\Delta Qx/Qx$, $\Delta Qy/Qy$) ~ (0.5%, 2%) at 2.9 T

NbTi Wiggler tests at ANKA

P. Zisopoulos



(a) Horizontal chromaticity, with respect to the magnetic field of the CLIC SC wiggler.

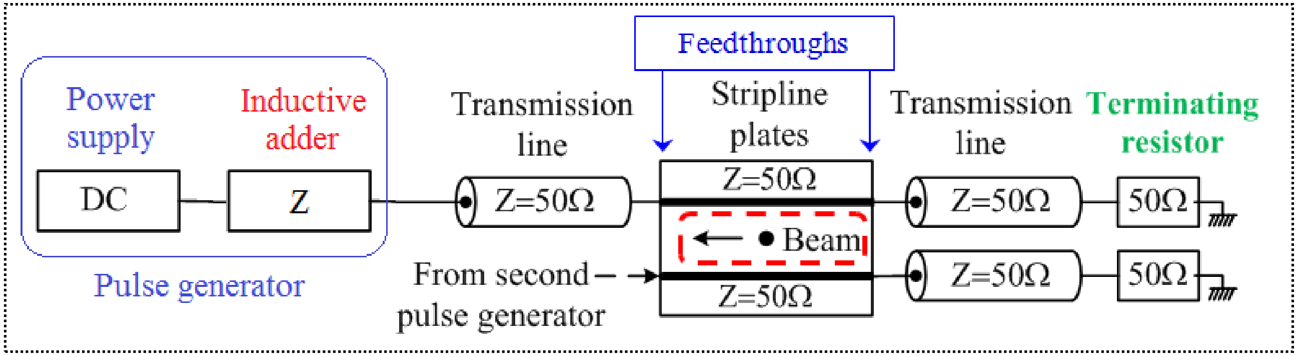


$$Q' = \frac{Q_s}{\sigma_\delta}\sqrt{\frac{A_1+A_{-1}}{A_0}}$$

- The synchrotron tune at ANKA is Qs=0.013.
- The chromaticity was extracted from the Fourier spectra of 4/Qs turns and from a fit with the dp/p.
- The measurements indicate a slight increase of Q'_x
- For Q'_y the uncertainty in the vertical plane is larger so a clear trend is not evident.

Extraction Kicker System

Previous studies demonstrated that the stripline kicker is the most suitable technology.



Striplines parameters	Values	Inductive adder parameters	Values
Beam energy	2.86 GeV	Pulse rise and fall time	100 ns
Deflection angle	1.5 mrad	Pulse flat-top	900 ns
Aperture	20 mm	Extraction stability	± 0.02%
Effective length	1.7 m	Repetition rate	50 Hz
Extraction inhomogeneity	± 0.01%		

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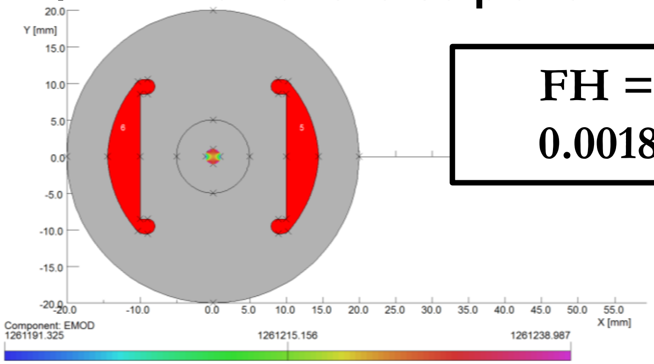
Kicker System challenges

<u>Striplines</u>

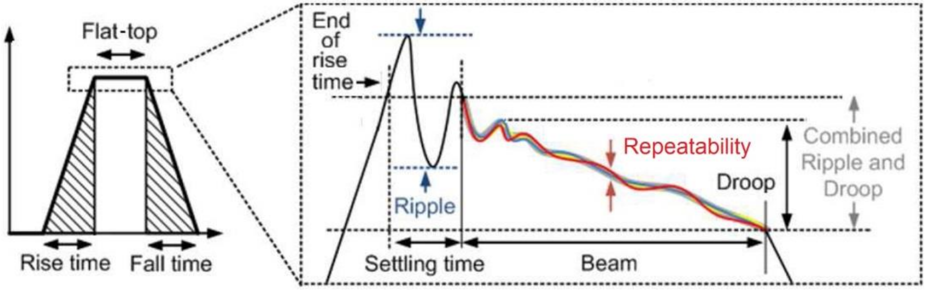
- **Excellent field homogeneity: ± 0.01% over 1 mm radius.**
- **Very low reflections: S_{11} < 0.1 up to 10 MHz.**
- **Very low beam coupling impedance: 0.05 Ω/n in the longitudinal plane and 200 kΩ/m in the transverse plane.**



FH = ± 0.0018%

<u>Inductive Adder</u>

- **Extremely tight requirements for flat-top stability and repeatability:**
  - **Flat-top repeatability: ± 0.01%**
  - **Flat-top stability: ± 0.02%**
- **Rise/fall times ≤ 100 ns desired.**



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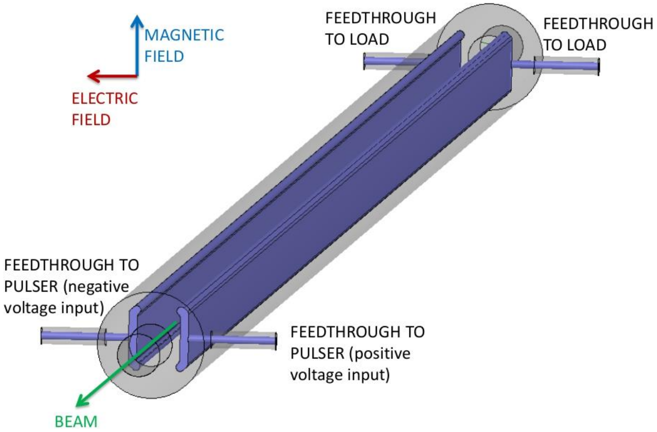
Stripline prototype



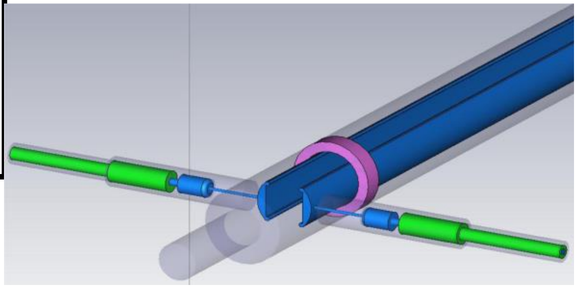
M. Barnes, C. Belver

Design studies & fabrication (VP):

- Impedance matching
- Field homogeneity
- Power transmission
- Beam coupling impedance
- High order modes
- Electrode heating
- Manufacturing tolerances

Laboratory test and measurements:

- Power reflection
- Beam coupling impedance
- HV DC conditioning



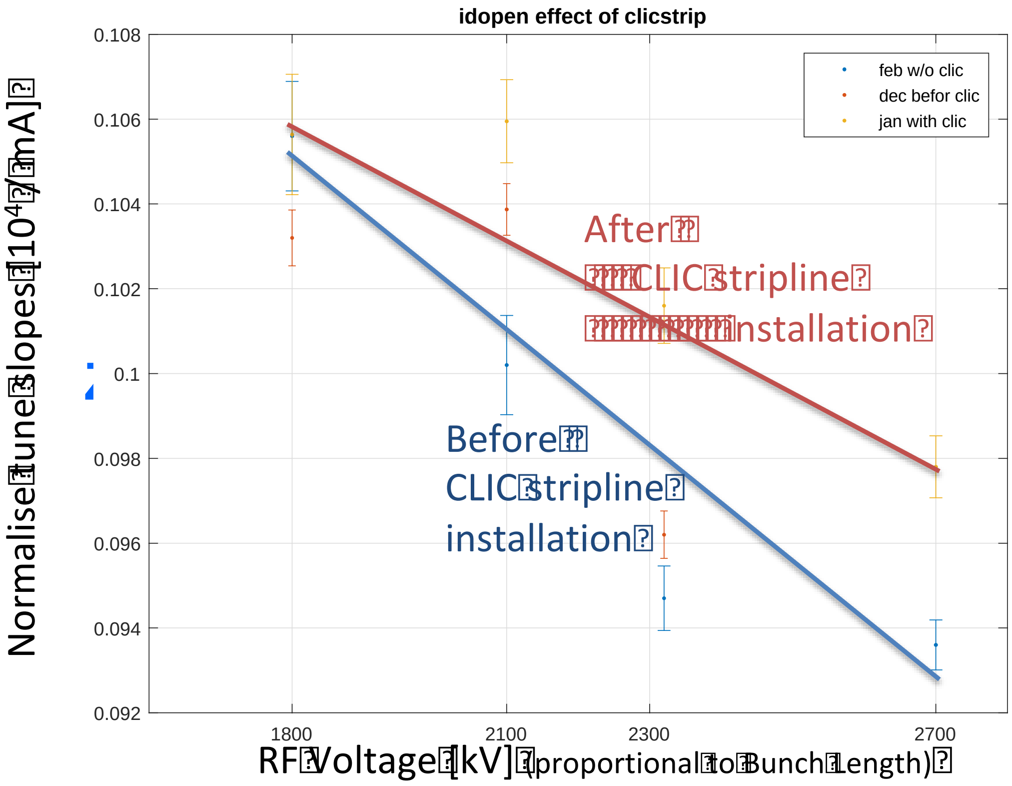
Further optimization studies:

- New method for matching characteristic impedances
- Transient studies of the striplines
- Review of horizontal beam coupling impedance

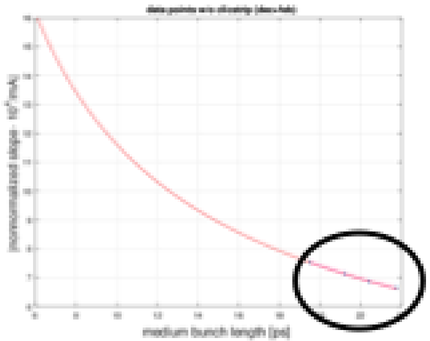
Impedance measurements @ ALBA

1) **<u>Measurements without HV DC power supplies</u>: Transverse coupling impedance**

- Measurements pending to be fully analysed, but first estimated



$Z_{CLIC\text{-}meas}$ = 21 ± 12 kOhm/m



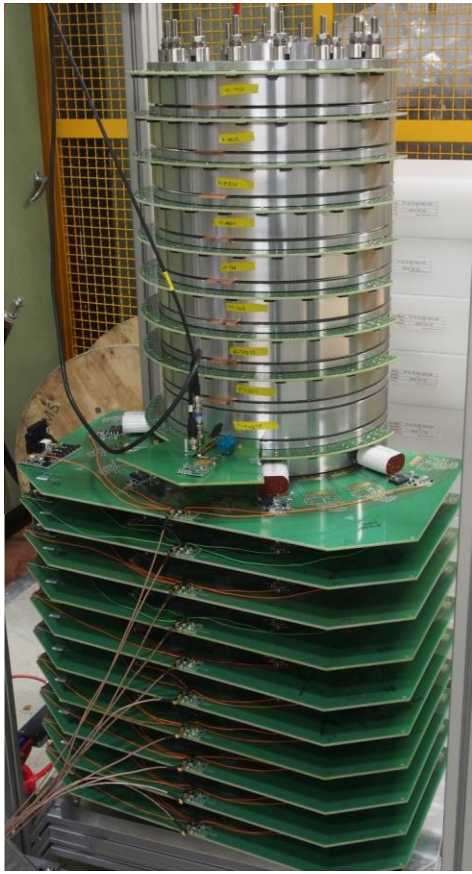
global view of fit function

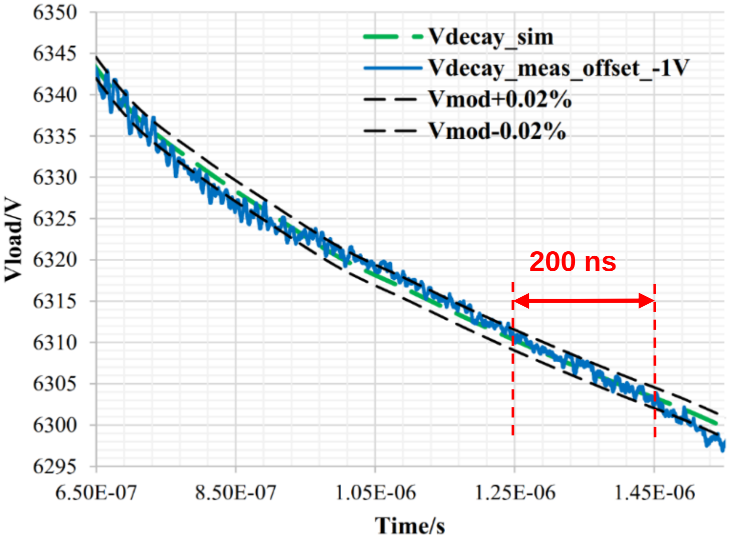
F. Perez, M. Pont

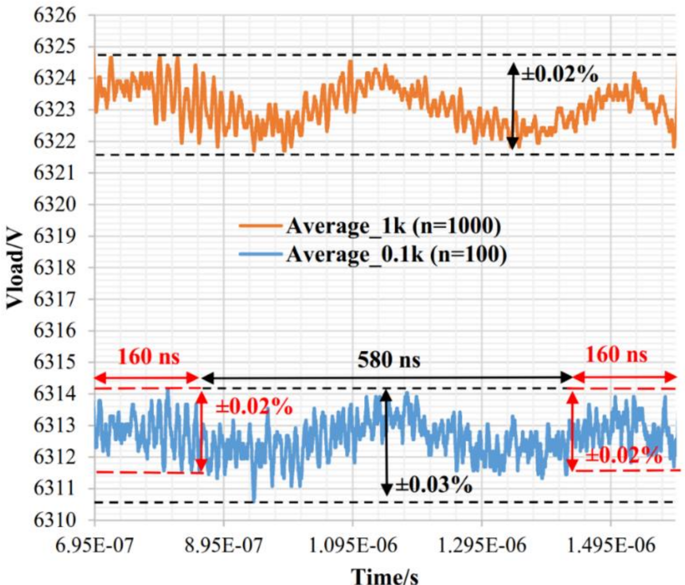
Inductive adder

J. Holma

- The first full-scale 20-layer, 12.5 kV, prototype inductive adder for CLIC DR extraction kicker system is currently under testing.
- The best measured flat-top/waveform stabilities until now:
  ±0.02 % over 900 ns for a flat-top pulse at 6.3 kV
  ±0.02 % over 160 ns for a “controlled decay waveform” at 6.3 kV.
- Future measurements of two 12.5 kV inductive adders with a stripline kicker installed in a beamline in an accelerator test facility (at Alba in Spain, in January 2019).







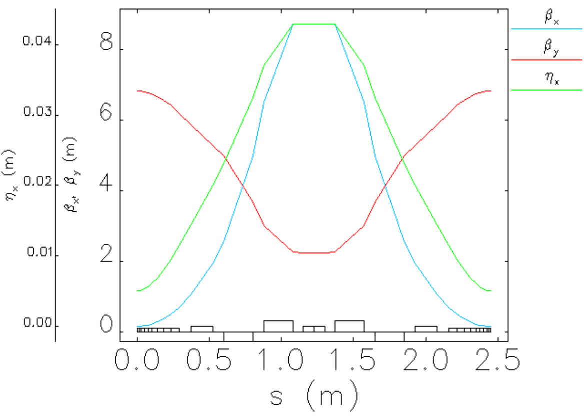
Summary

- Extreme low emittance @ high intensity beam generation and transfer drives several beam dynamics challenges
  - Lattice design, coherent and incoherent collective effects, instabilities, low emittance tunrIons, space-charge, e-cloud, impedance budget, feedback specs
- All drive associated technologies
  - **Magnet design**
  - **Beam transfer** system (stripline, pulser)
  - **RF system**, including LLRF
  - **Vacuum system**
  - **Alignment**
  - Associated **instrumentation**
- Continue collaboration with low emittance rings community for **R&D** and **experimental tests**

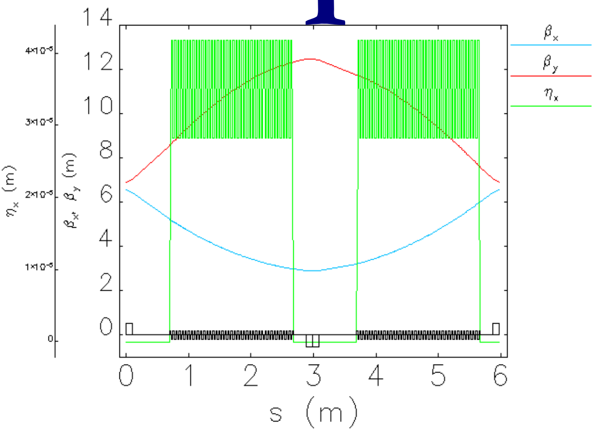
Thank You

Reserve

CLIC DR Optics

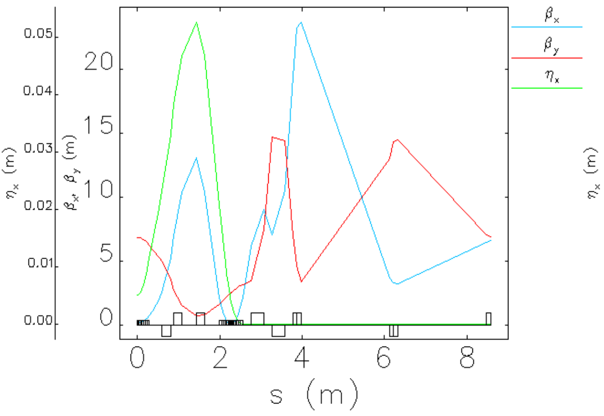


TME cell;
Length= 2.45 m
$\psi_x/2\pi$= 0.442
$\psi_y/2\pi$= 0.1

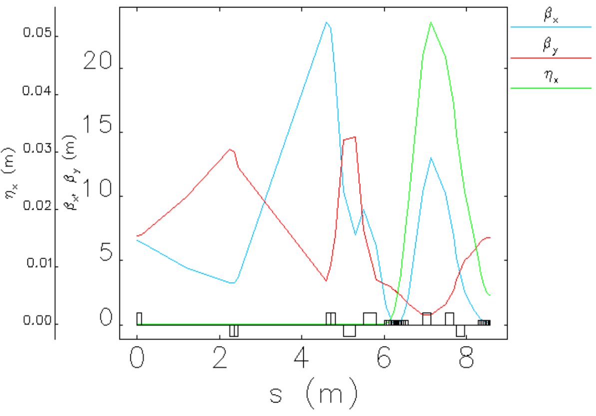


FODO cell;
Length= 5.969
$\psi_x/2\pi$= 0.238
$\psi_y/2\pi$= 0.096
Wiggler (l=2 m, B=3.5 T, L_λ=49 mm)

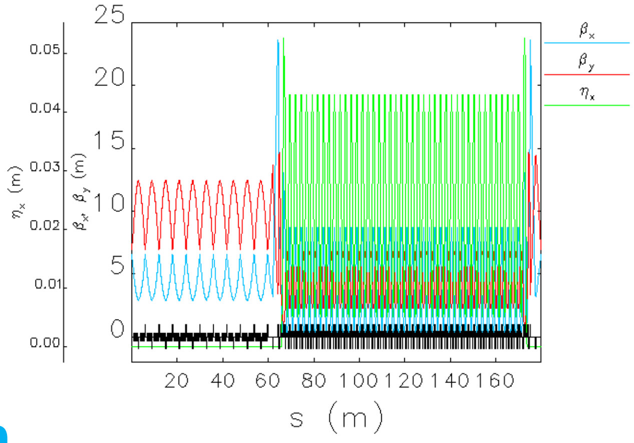
Parameters	Value
Energy [GeV]	2.86
Circumference [m]	359.44
No. of Dipole/wiggler	90/40
Hor./Ver. Tune	45.27/13.33
Nat./nor. emittance [pm/nm]	79.00/442.18
Nat. chromaticity	-134.42/-41.63
1st order mom. compaction	1.17E-4
Energy spread	1.28E-3
Energy loss per turn [MeV]	5.79
Damping time [ms/ms/ms]	1.17/1.19/0.60
Radio frequency [GHz]	2
RF voltage [MV]	6.5
Bunch length/charge [mm/nC]	1.26/0.91
Number of particles per bunch	5.7E10
Natural emittance+ IBS [pm]	110
Energy spread + IBS	1.33E-3
Bunch length + IBS [mm]	1.31



Dispersion suppressor;
Length=8.57
$\psi_x/2\pi$= 0.85
$\psi_y/2\pi$=0.757

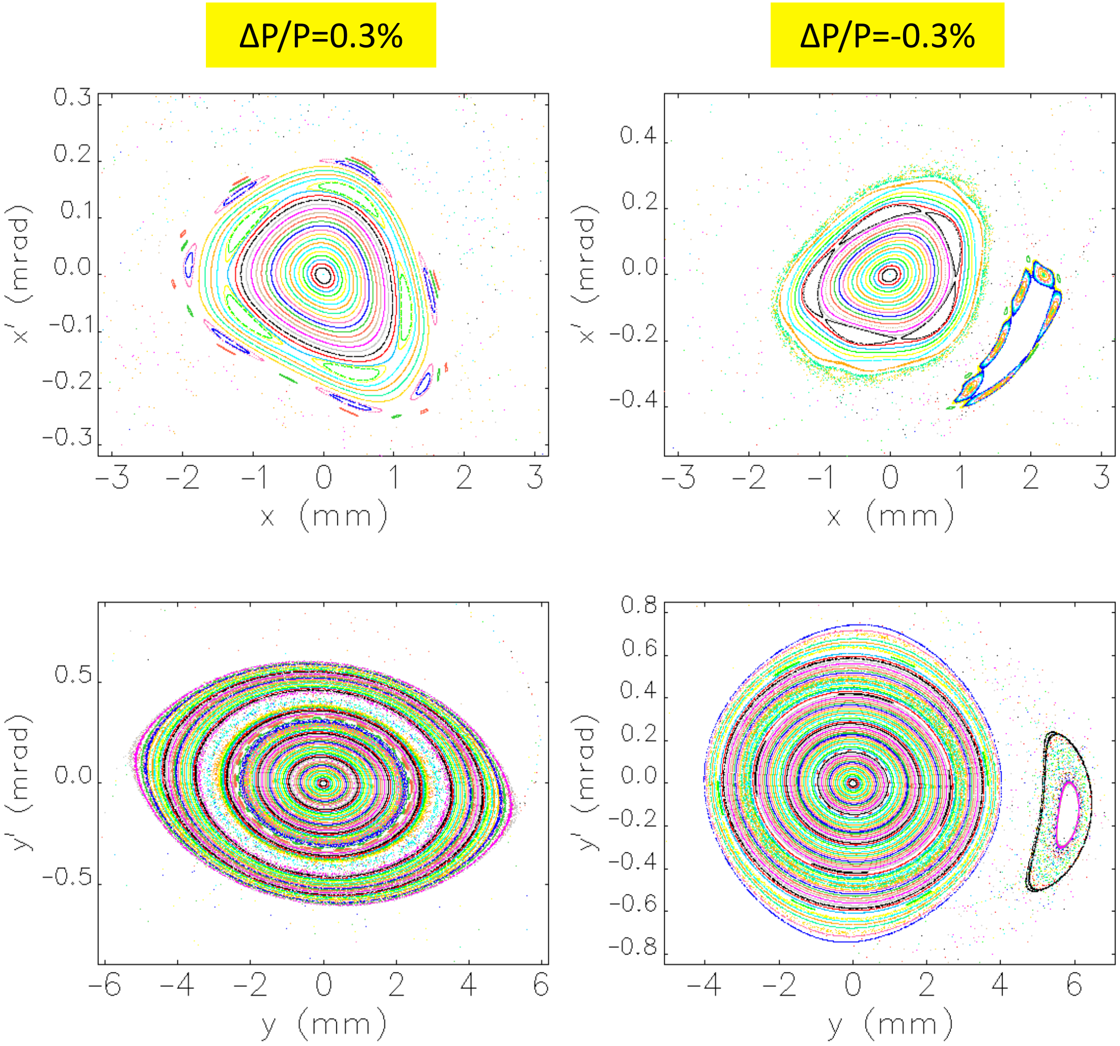


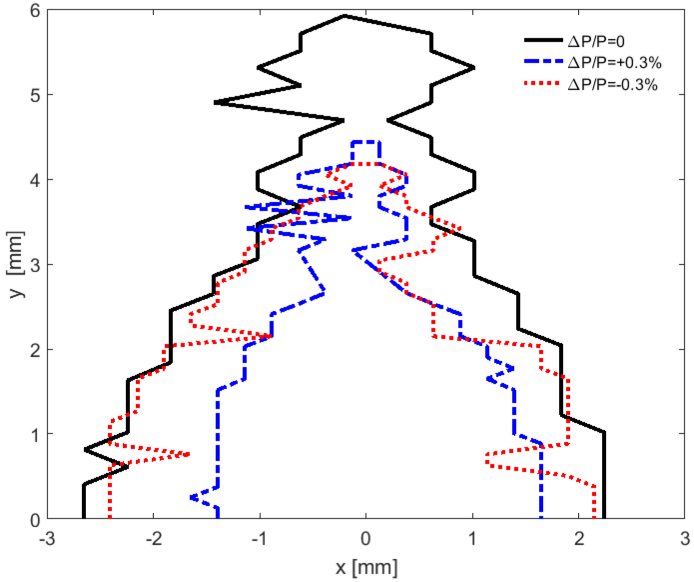
Dispersion suppressor;
Length= 8.56
$\psi_x/2\pi$= 0.85
$\psi_y/2\pi$= 0.748

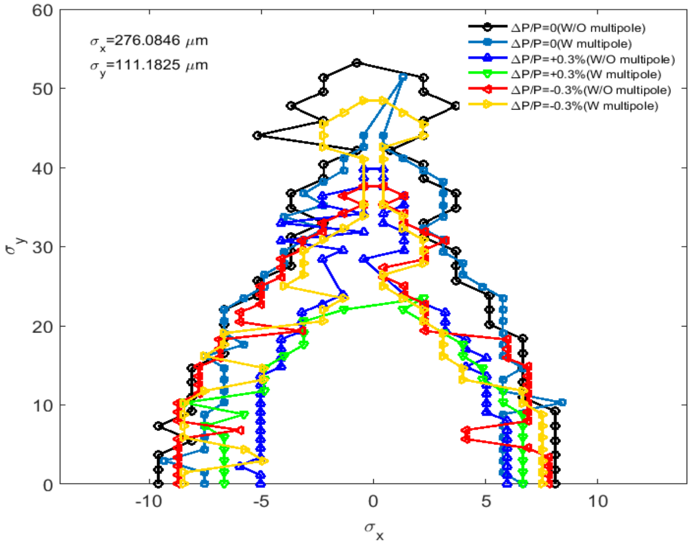


H. Ghasem

Dynamic aperture with errors







The injected positron beam specification
(ε_{xn}=65 µm and ε_{yn}=10 µm, δ=0.3%)

H. Ghasem

Elettra 2.0 - Emanuel Karantzoulis

Elettra
Sincrotrone
Trieste

Very short photon pulses via deflecting (crab) cavities

ANL-SLAC - Elettra collaboration

200 buckets straight and 200 tilted. Four (4) oblique can be filled with 2 mA each. The pulse length depends on the beam line slit opening, whether there is drift or imaging optics and differs at each beam line position.

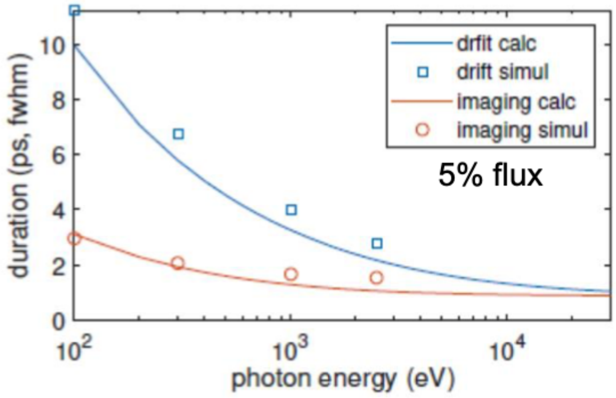
The tilted bunches will give:

The FWHM pulse duration for the imaging optics case, assuming photon energy of a 2.5 keV.

Beamline	fwhm/5%	fwhm/10%	fwhm/15%	fwhm/20%
Sector	(ps)	(ps)	(ps)	(ps)
12	1.54	2.42	3.39	4.41
1	7.31	7.52	7.89	8.35
2	1.55	2.42	3.39	4.42
3	4.45	4.86	5.42	6.12
4	1.59	2.44	3.41	4.42
5	2.94	3.47	4.22	5.09
6	1.53	2.40	3.38	4.41
7	2.17	2.85	3.73	4.66
8	1.64	2.47	3.42	4.44
9	2.46	3.06	3.88	4.79
10	3.62	3.96	4.60	5.42
11	4.92	5.28	5.78	6.48

The FWHM pulse duration for the imaging optics case for the dipole beamlines at 6.9 keV

Beamline	fwhm/5%	fwhm/10%	fwhm/15%	fwhm/20%
	(ps)	(ps)	(ps)	(ps)
DB	1.35	2.30	3.30	4.35



X. Huang and A. Zholents: (ANL-SLAC) - Elettra collaboration