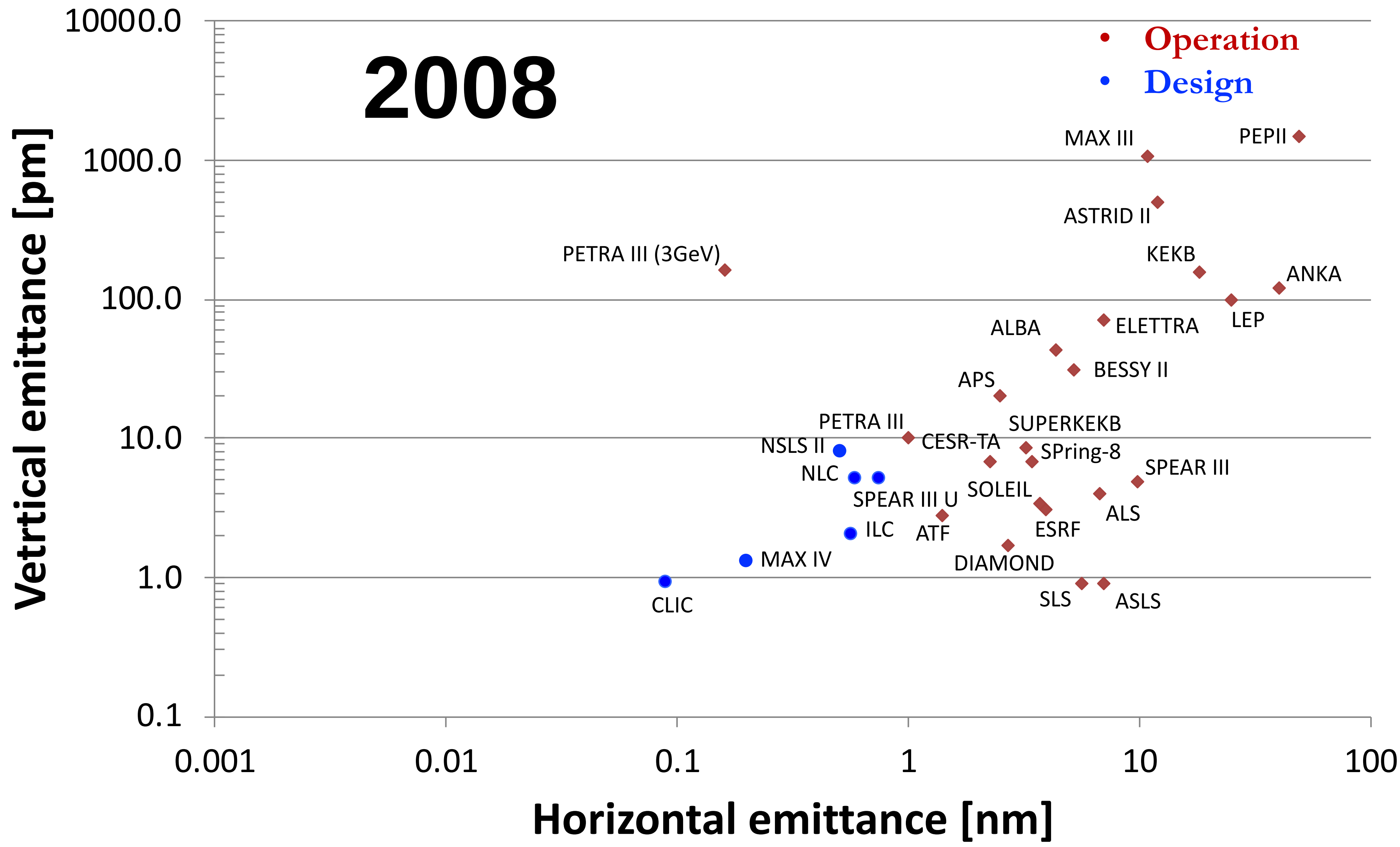
State of the art in low-emittance storage rings and CLIC DR design

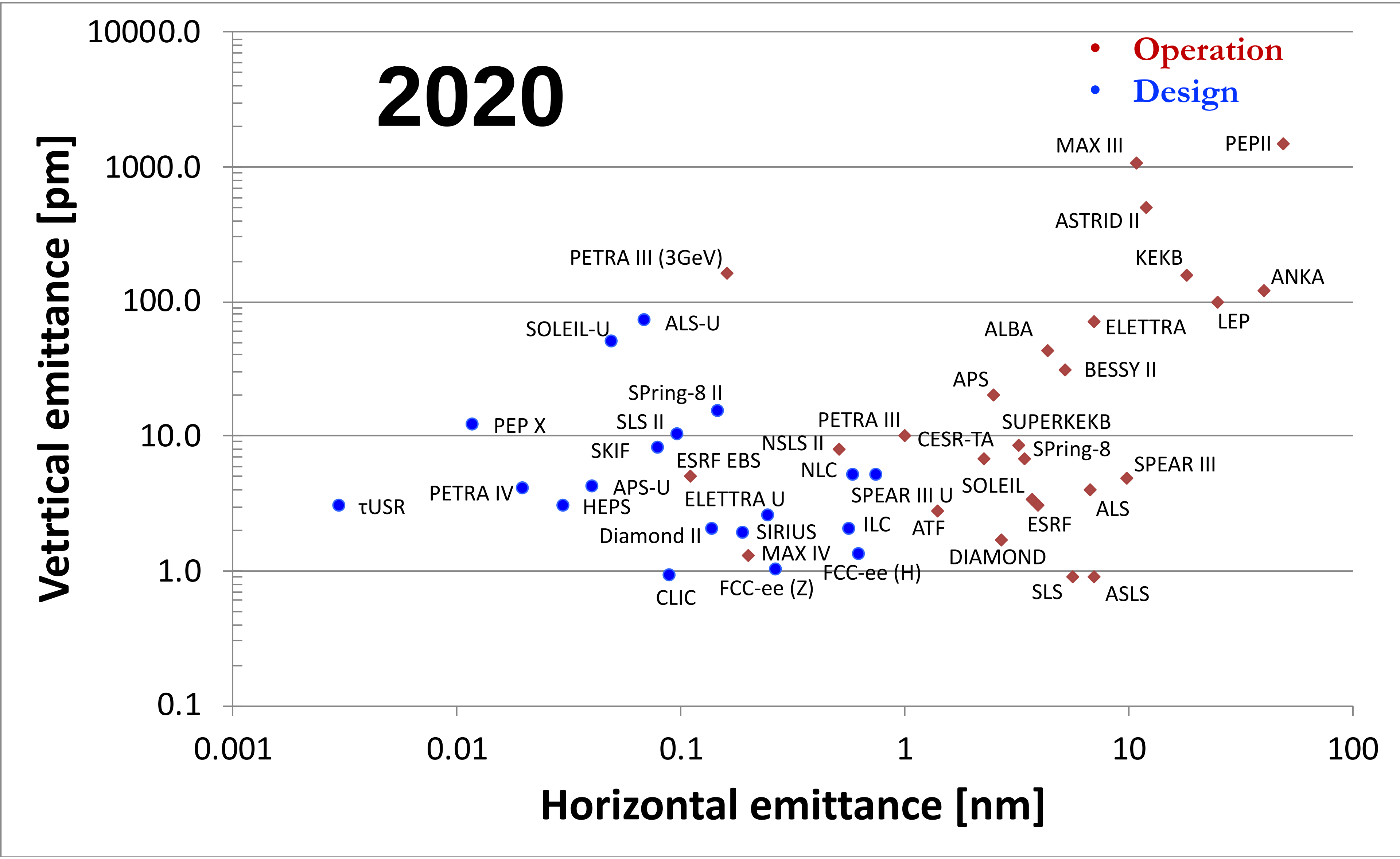
Y. Papaphilippou (CERN)

Thanks to F. Antoniou, M. Barnes, C. Belver, M. Carla, 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, complex 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 circular 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 **100-1000 m**
  - Exception e+/e- future ring colliders 10s of km
  - Driven by the low horizontal emittance requirements ~ $\theta^3 \propto C^{-3}$

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 drives requirements of power source, high peak and average current, transient beam loading
- **Injection (**Dynamic aperture) and **extraction (**emittance stability)
  - Driving septum/kicker technology (thickness, rise time, jitter tolerance)

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

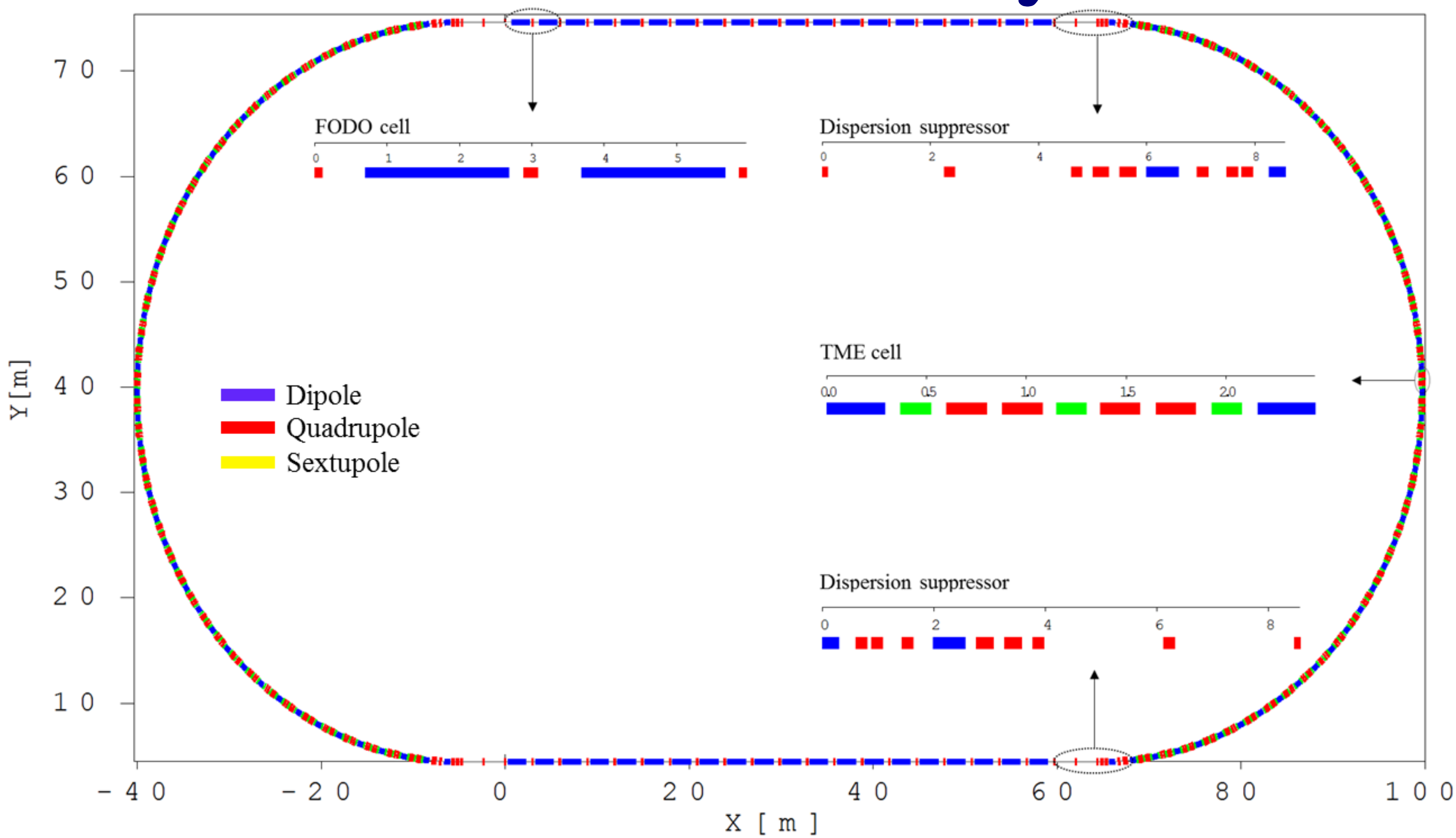
- **Performance parameters** of the CLIC DR for the **1 GHz** and **2 GHz** options in comparison to the V06
  - Increased energy (2.424→2.86 GeV)
  - Reduce the circumference by 15%
  - Ultra-low emittances in all 3 planes
  - Reduced IBS effect (from 3 to 1.5)
  - Reduced space charge tune shift (-0.2 → -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 (power reduction)
  - **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

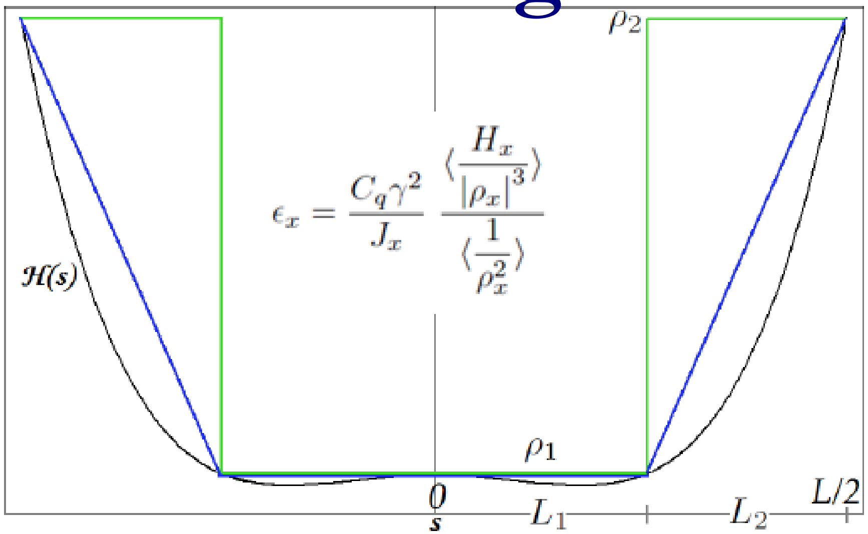
Reduce the number of wiggler using higher wiggler field

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



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

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

Bending radii ratio

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

Lengths ratio

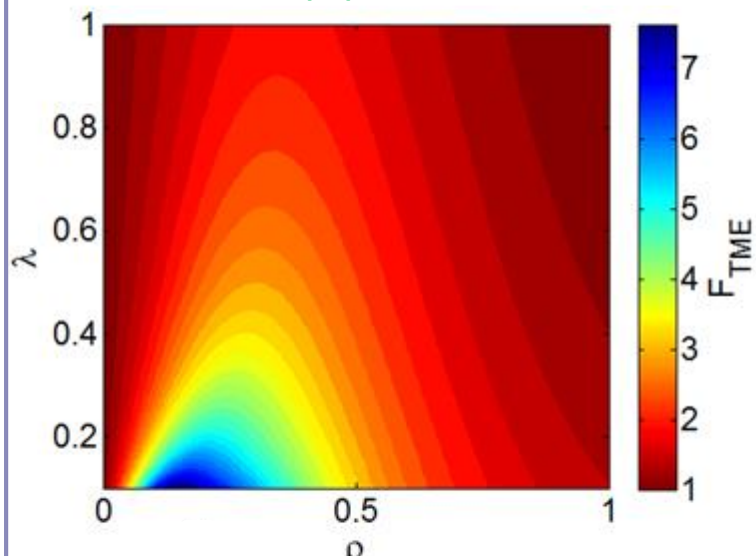
$$\lambda = \frac{L_1}{L_2}$$

Emittance reduction factor

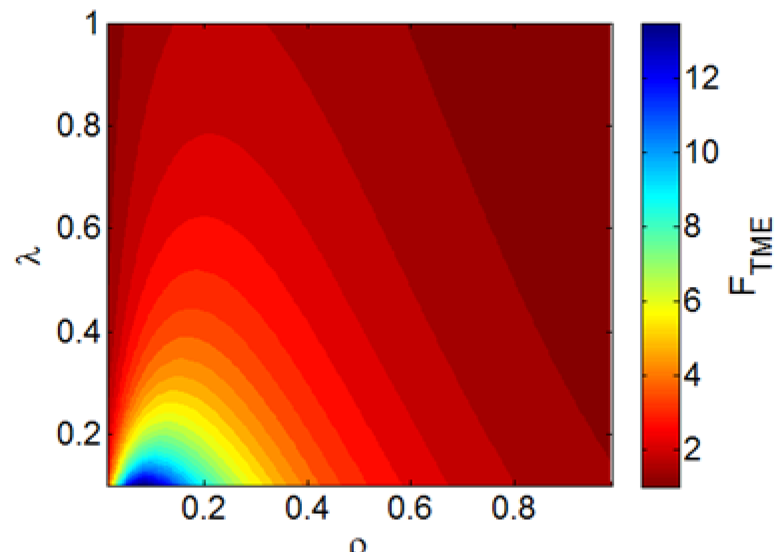
$$F_{TME} = \frac{\epsilon_{TME_{uni}}}{\epsilon_{TME_{var}}}$$

$$F_{TME} > 1$$

Step profile



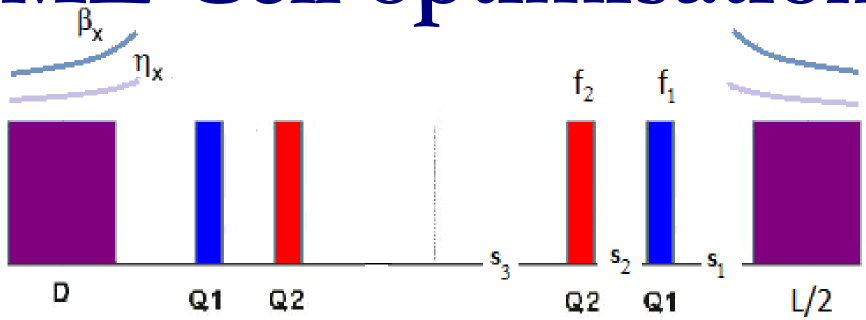
Trapezium profile



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

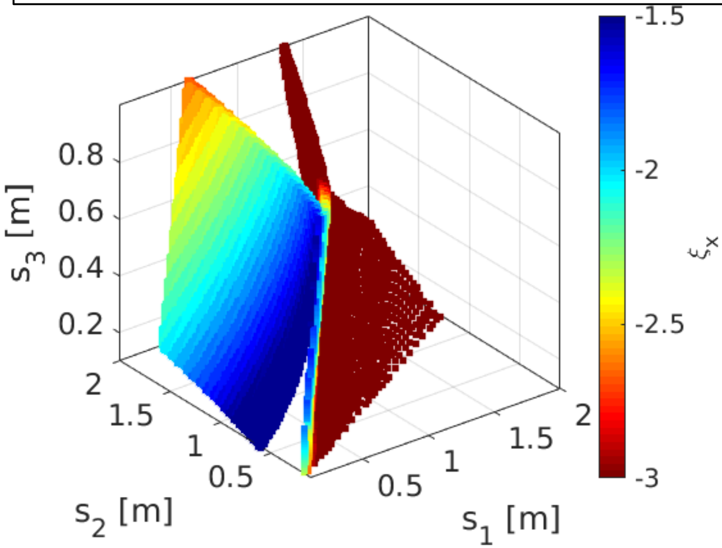
TME Cell optimisation

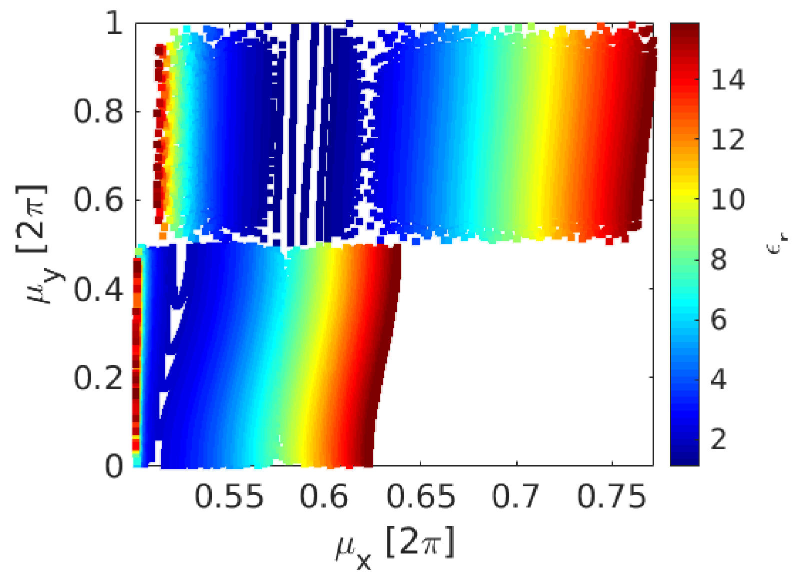
S. Papadopoulou



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

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.





CLIC DR Design parameters

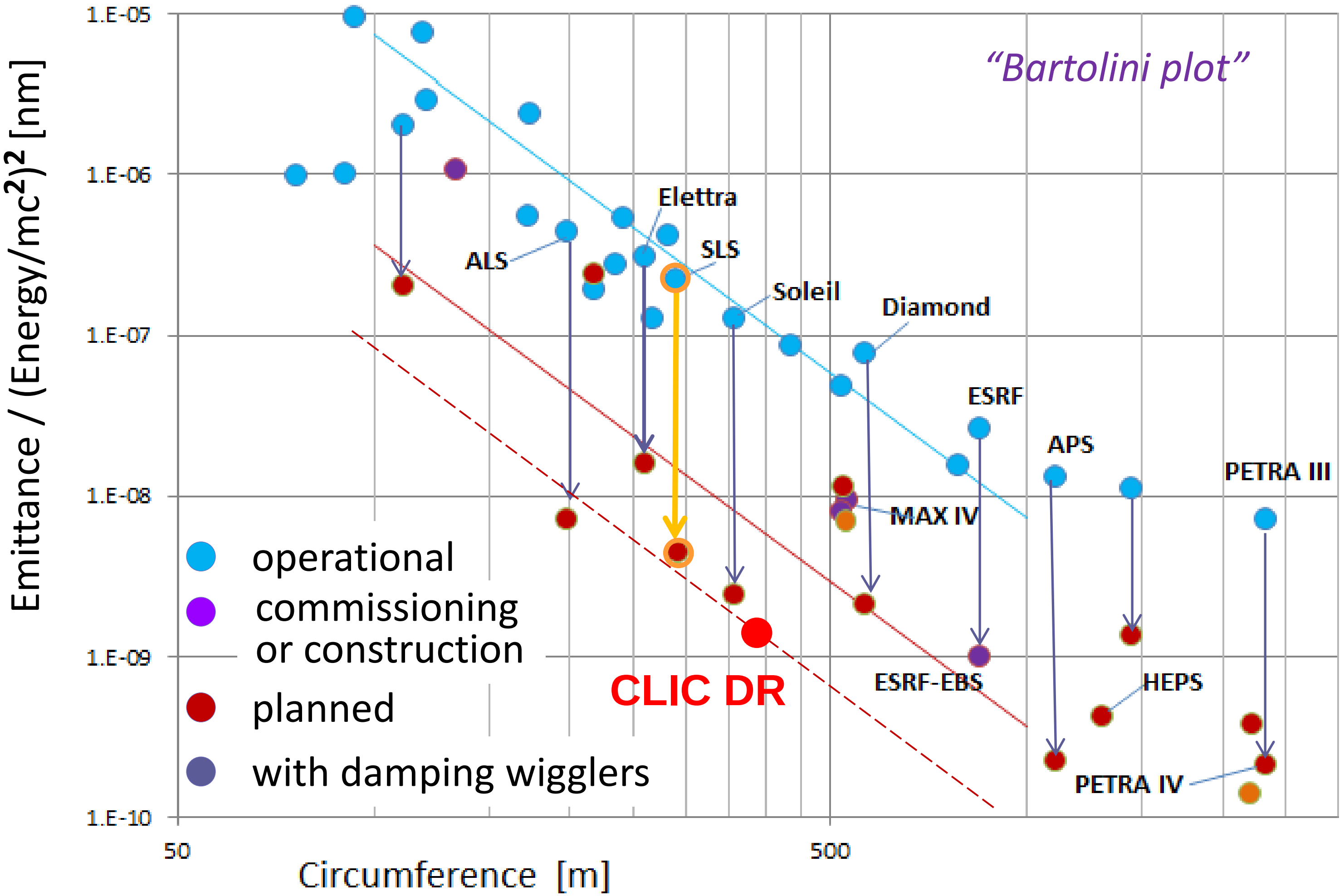
Parameters, Symbol [Unit]	uniform I	uniform II	trapezium
Number of arc TME cells/wigglers	100/52	90/40	90/40
Dipole field (max/min), B [T]	0.97/0.97	0.97/0.97	0.62/2.32
IBS factors hor./ver./long.	1.5/1.5/1.1	1.1/1.4/1.0	**1.2/1.3/1.0**
Norm. horizontal emittance (with IBS), $\gamma\varepsilon_x$ [nm]	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
- **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

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

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

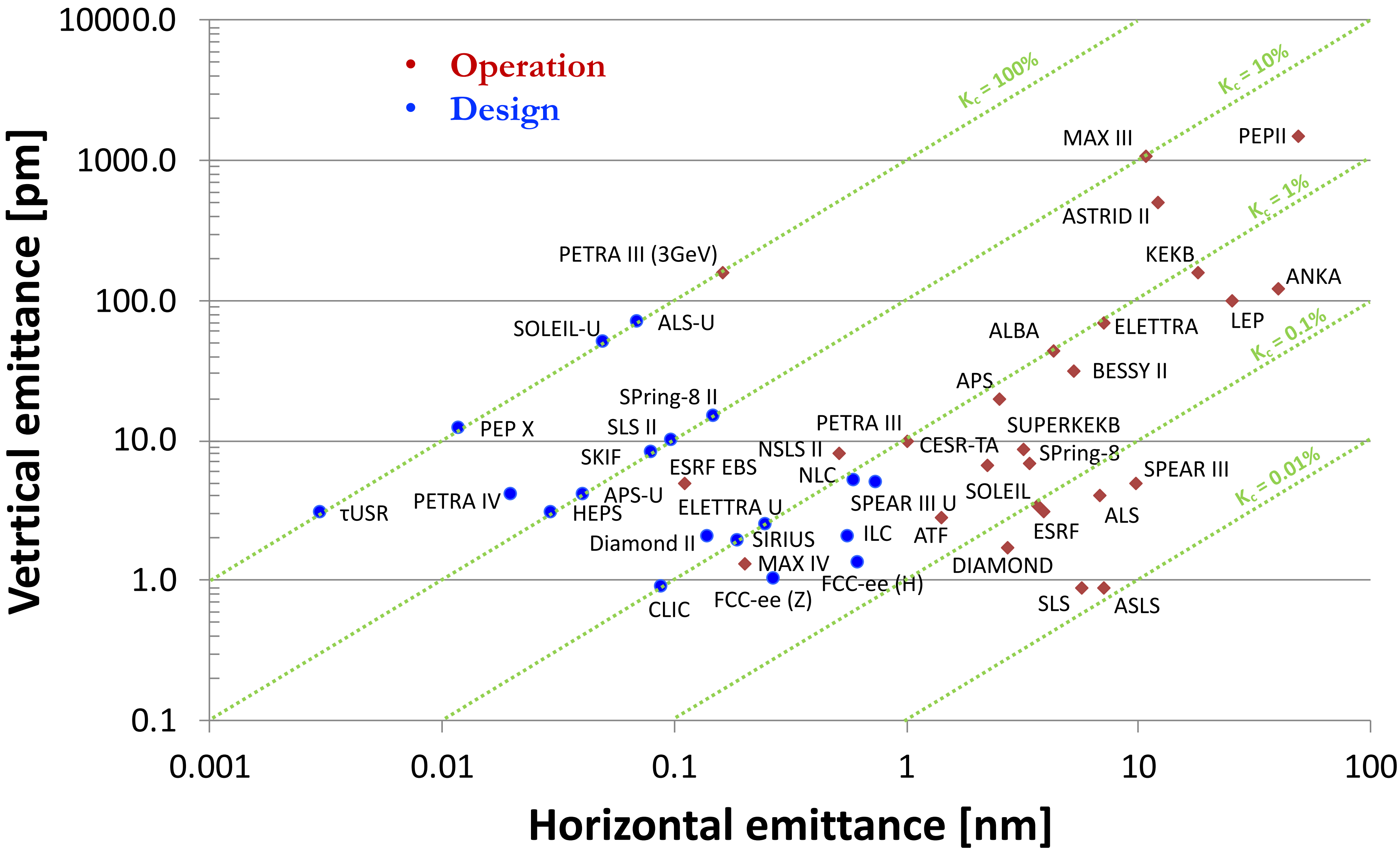
$K \approx 2 \rightarrow \approx -1$

improvement ×20

↓ upgrade projects

A. Streun, Lattice review meeting, 2020

Horizontal vs Vertical emittance

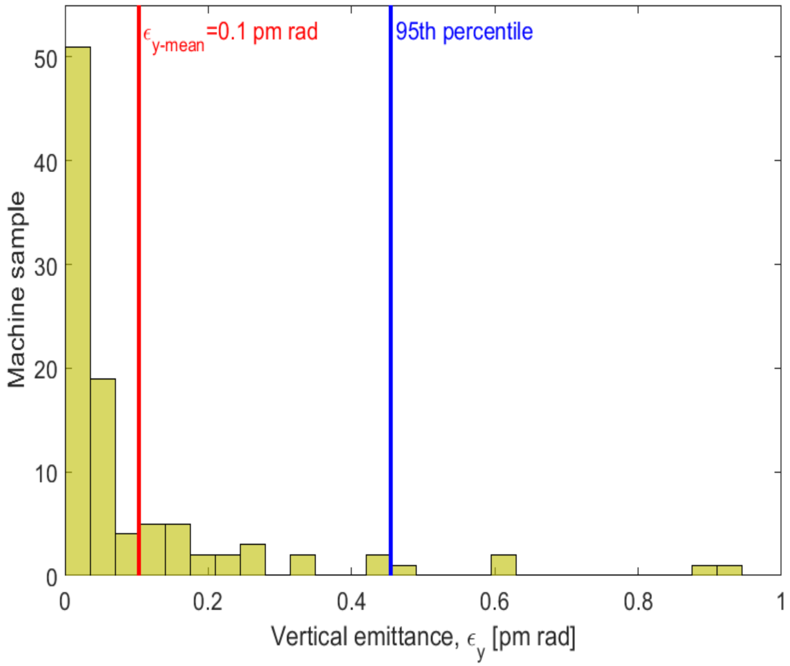


Vertical emittance tuning

- 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.

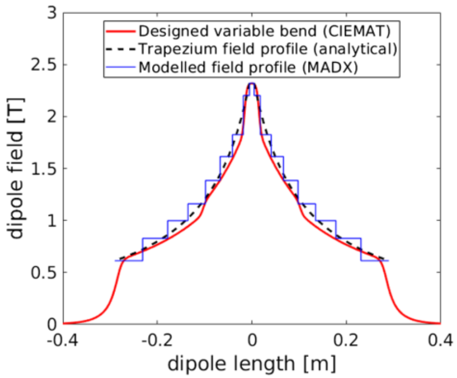


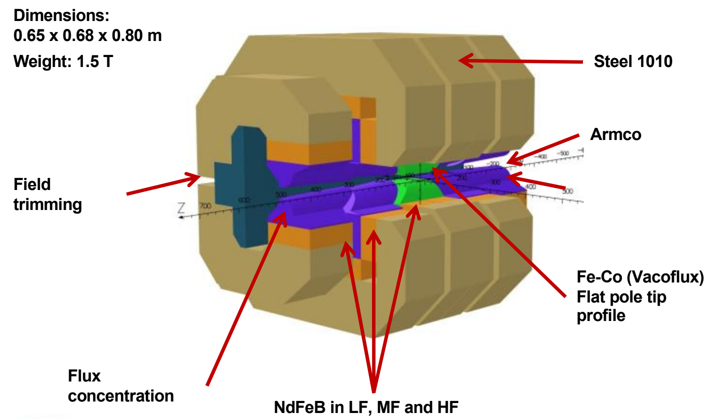
H. Ghasem

Low Emittance Rings technologies

VAriable Dipole for the Elettra Ring – VADER @ IFAST

- **Fabricate** an innovative dipole magnet prototype with longitudinal varying dipole field, including a transverse gradient for the ELETTRA upgrade
- Permanent magnet **concept** with 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
- First **demonstrator constructed/qualified** by CIEMAT and new prototype under construction





Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Elettra Sincrotrone Trieste

Y. Papaphilippou (A. Poyet)

M. Dominguez
F. Toral

E. Karantzoulis
D. Castronovo

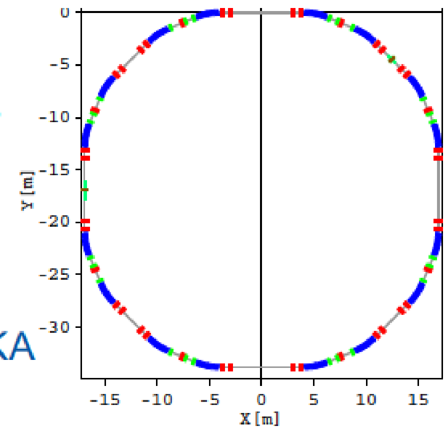
R. Geometrante

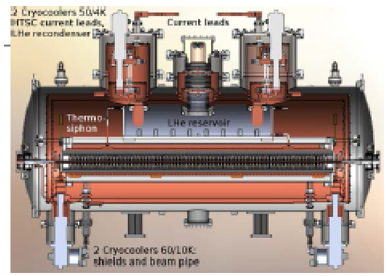
NbTi Wiggler tests at ANKA

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, $g_3(k_3 \cdot L_W)$	≤120 T/m^3 (≤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

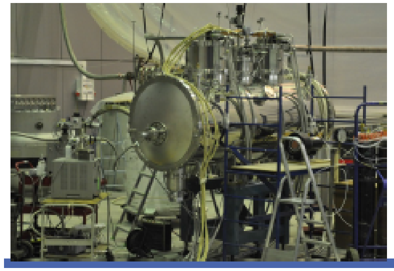


Photo taken during FAT at BINP

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

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

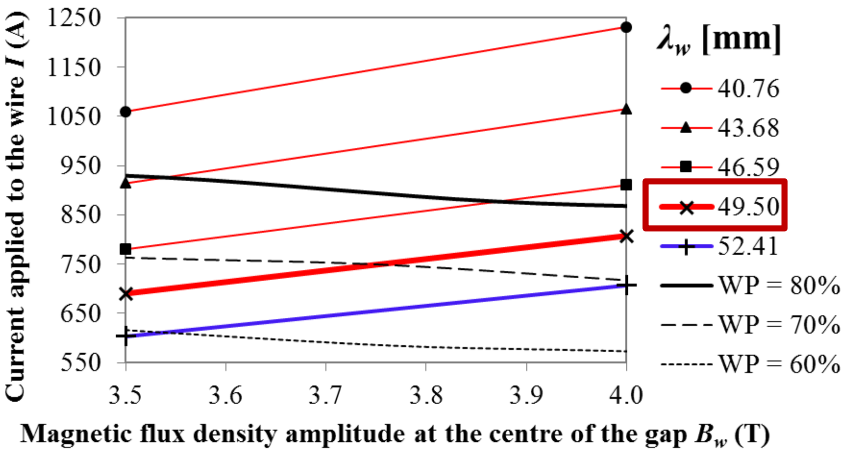
Nb_3Sn wiggler Design

L. Fajardo

ADDITIONAL RESTRICTION:

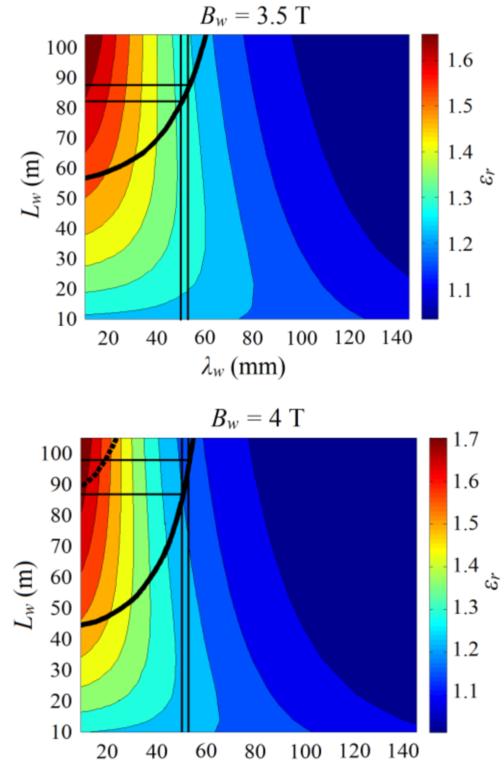
Keeping the working point (*WP*) below 80% of the magnet's current limit for all $3.5\ T \leq B_w \leq 4\ T$

Scenarios for achieving $3.5\ T \leq B_w \leq 4\ T$ with $40\ mm \leq \lambda_w \leq 55\ mm$ values:

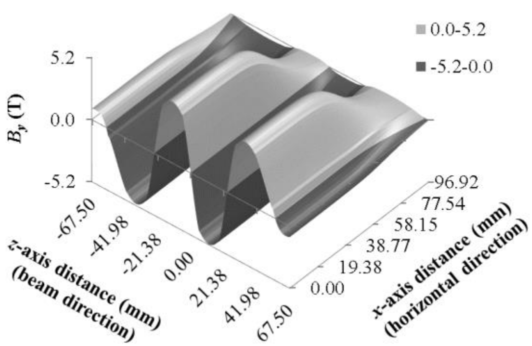


SELECTED λ_w FOR $3.5\ T \leq B_w \leq 4\ T$

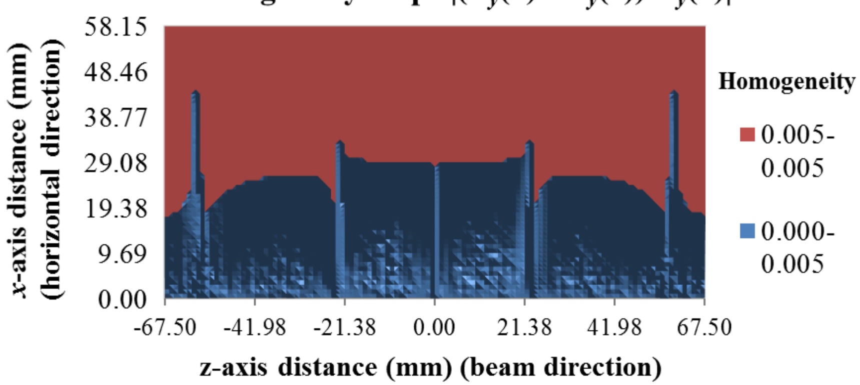
Larger potential L_w reduction with λ_w = 49.5 mm



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



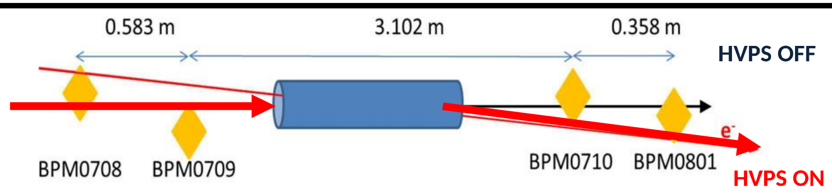
Field homogeneity map: $|(B_y(0) - B_y(x))/B_y(0)|$

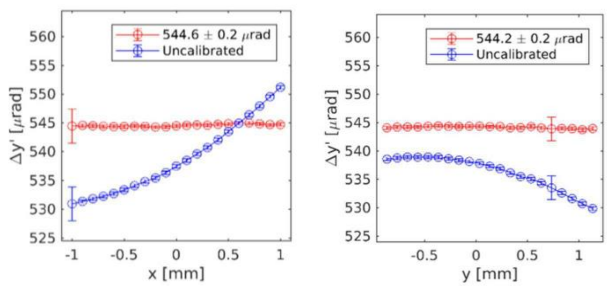


Kicker System challenges and tests at ALBA

Striplines

- **Field homogeneity: ± 0.01% over 1 mm radius.**
- **Very low impedance: 0.05 Ω/n in longitudinal and 200 kΩ/m in transverse.**

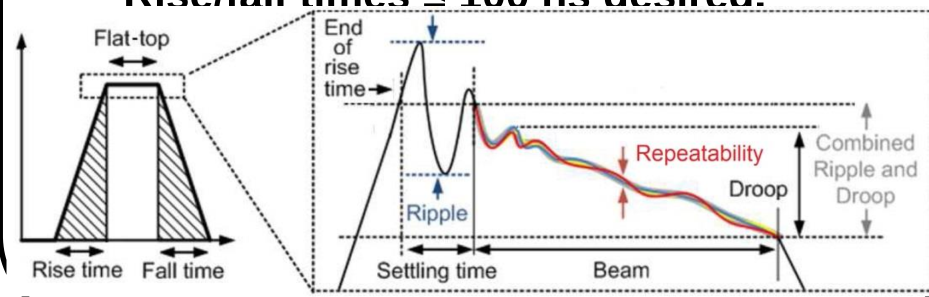


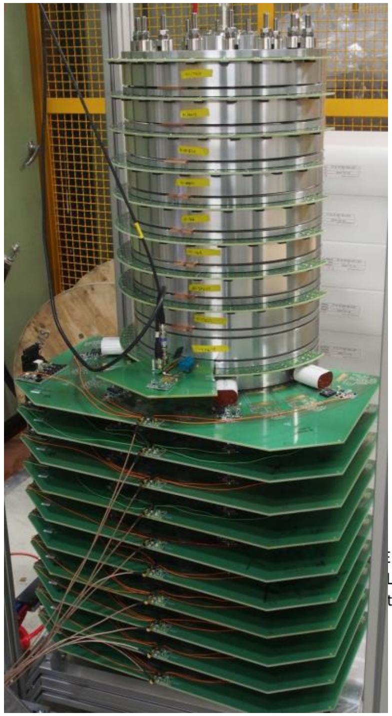


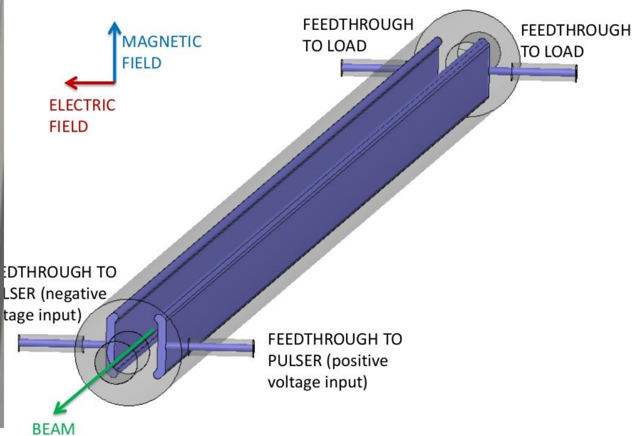
- Stripline powered in DC at ±10KV, beam position ±1mm
- Measured kick: 544.4±0.2 urad, (560 urad expected)
- Homogeneity: $3.7 \cdot 10^{-4} \pm 5.3 \cdot 10^{-4}$ (CLIC requirements: $< 2 \cdot 10^{-4}$)

Inductive Adder

- **Flat-top repeatability: ± 0.01%**
- **Flat-top stability: ± 0.02%**
- **Rise/fall times ≤ 100 ns desired.**



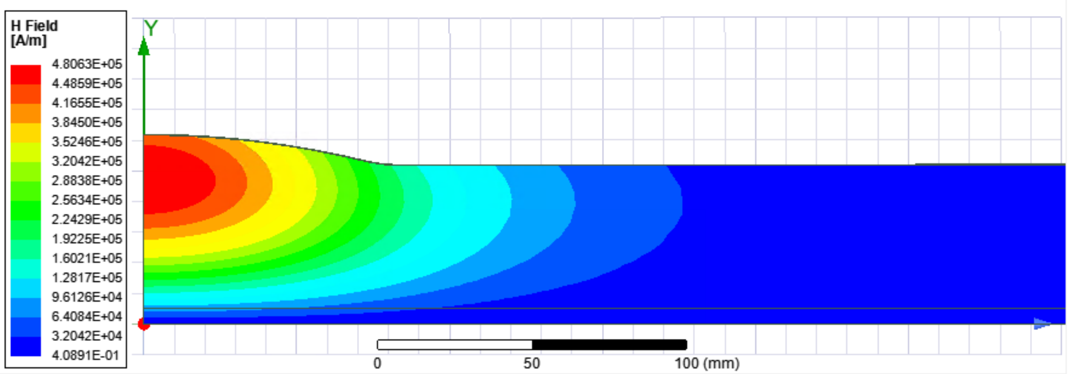


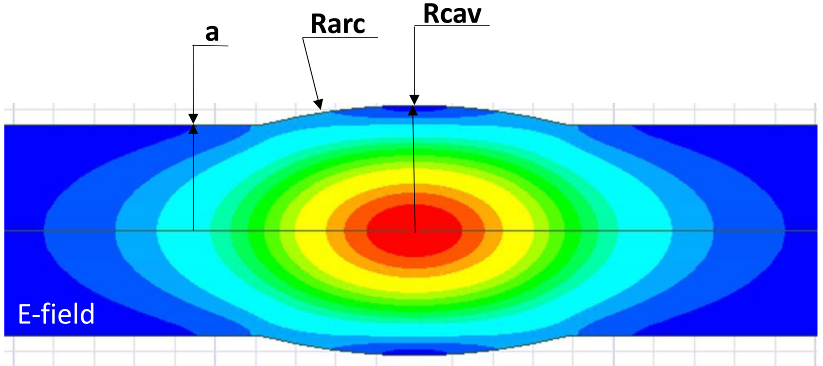


M. Barnes, C. Belver, J. Holma, M. Carla

Design of DR cavity for ultra-low R/Q of 14.3Ω

- Increase cavity aperture to reduce loss factor => reduce R/Q per cavity
- Increase cavity length to reduce transit time factor => reduce R/Q per cavity
- Optimize cavity wall shape to minimize H-field to reach largest stored energy per cavity under the H-field limit of **80 kA/m** (100 mT, private communication, W. Venturini, 2021) => reduce number of cavities
- R/Q per cavity x N of cavities must be below Total R/Q: **14.3 Ω**
- **Novel cavity: Barrel Cell Cavity (BCC) geometry**
- New design of the DRs demonstrates significant reduction of the **power consumptio**n





- **Large aperture => low R/Q**
- **Long cell: ~λ => low transit time factor**
- **Low field on the cavity wall**

A. Grudiev, T. Mastorides

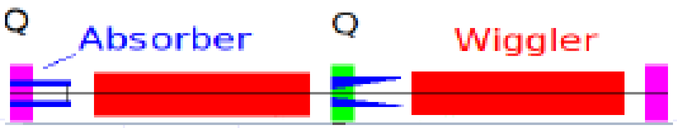
Summary

- **Extreme low emittance @ high intensity** beam generation and transfer drives several beam dynamics challenges
  - Lattice design, coherent and incoherent collective effects, instabilities, low emittance tuning, ions, 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

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].

+

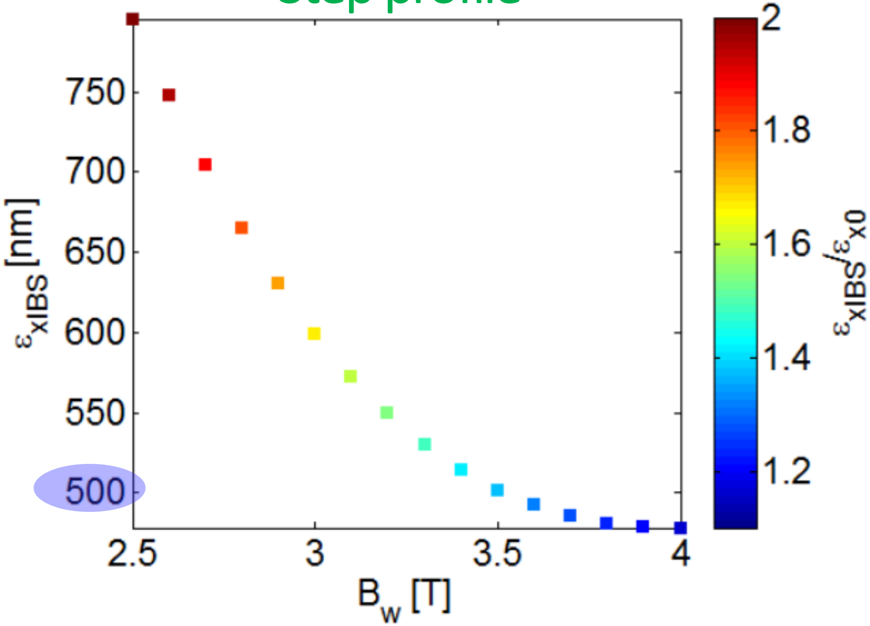
Based on technological restrictions, a new working point for the damp. wiggler is proposed to be at **3.5T** (prev. 2.5T), with 49mm period length

→

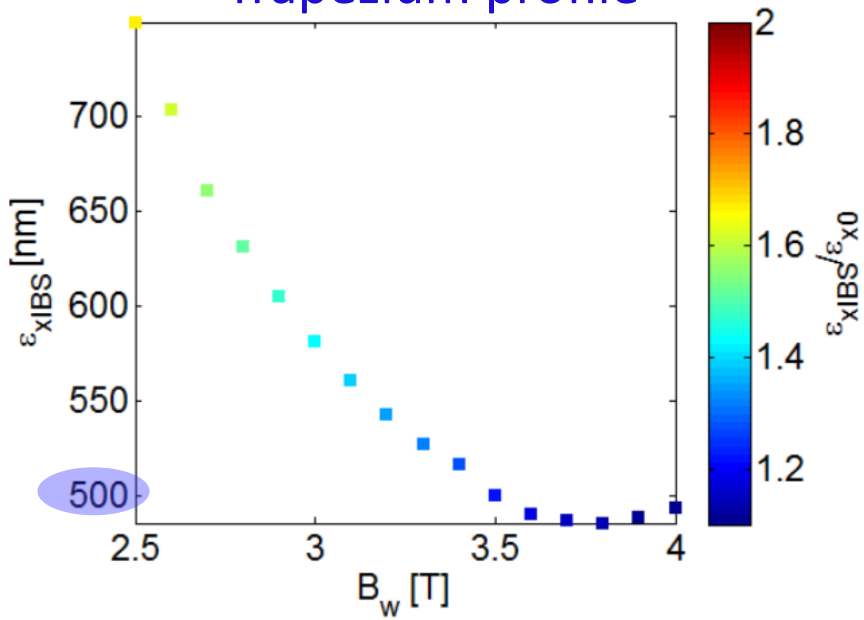
Removing some wiggler FODO cells from the existing straight section (**N_{FODO}=13 per section**) is possible.

N_{FODO}=10 per straight section

Step profile

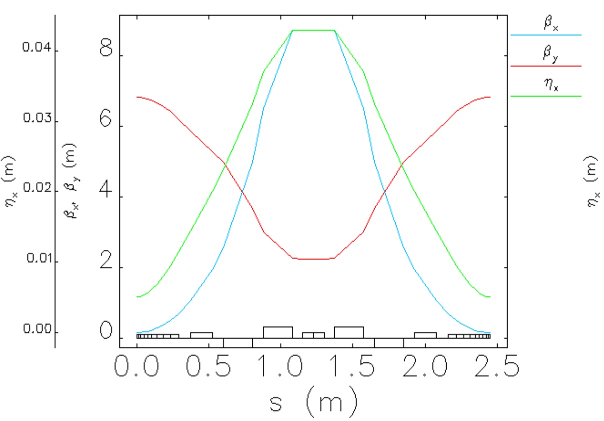


Trapezium profile

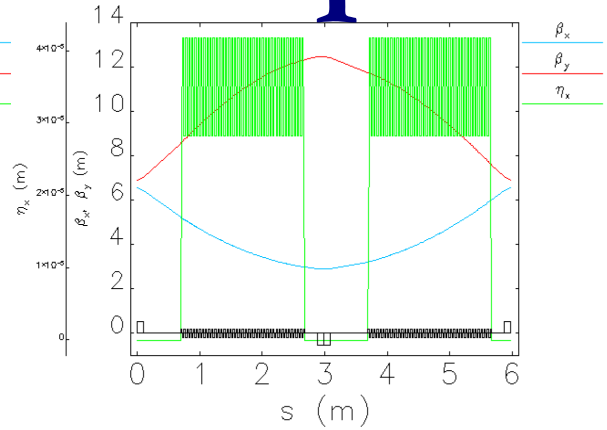


Parametrization of the steady state emittance and the IBS effect with the wiggler's peak field B_w

CLIC DR Optics

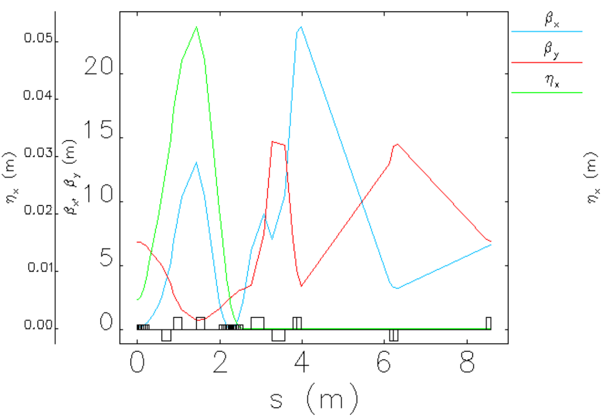


TME cell;
Length= 2.45 m
$\psi_x/2\pi$= 0.442
$\psi_y/2\pi$= 0.1

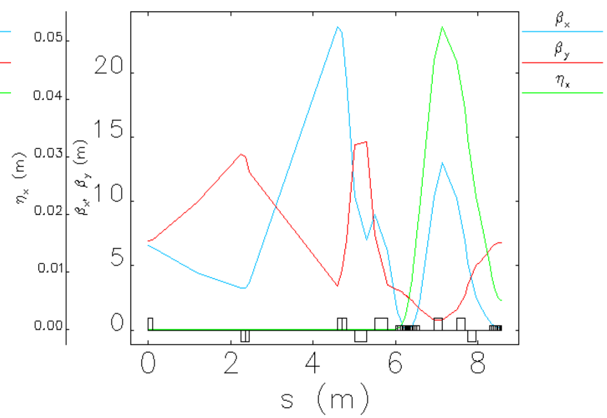


FODO cell;
Length= 5.969
$\psi_x/2\pi$= 0.238
$\psi_y/2\pi$= 0.096
Wiggler (l=2 m, B=3.5 T, L_λ=49 mm)

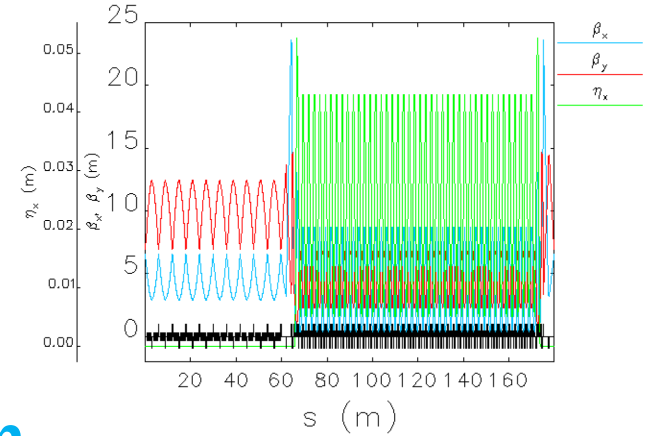
Parameters	Value
Energy [GeV]	2.86
Circumference [m]	359.44
No. of Dipole/wiggler	90/40
Hor./Ver. Tune	45.27/13.33
Nat./nor. emittance [pm/nm]	79.00/442.18
Nat. chromaticity	-134.42/-41.63
1st order mom. compaction	1.17E-4
Energy spread	1.28E-3
Energy loss per turn [MeV]	5.79
Damping time [ms/ms/ms]	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



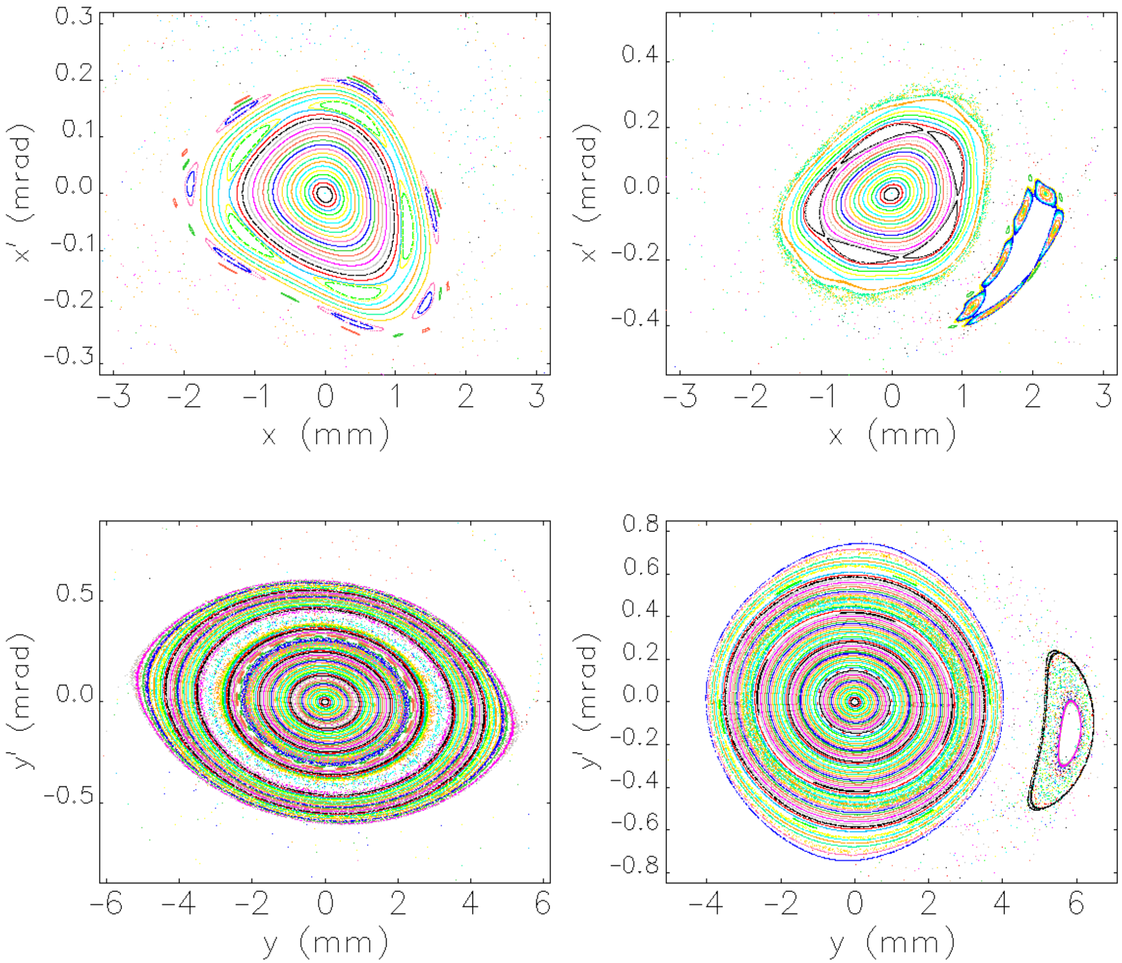
Dispersion suppressor;
Length= 8.56
$\psi_x/2\pi$= 0.85
$\psi_y/2\pi$= 0.748

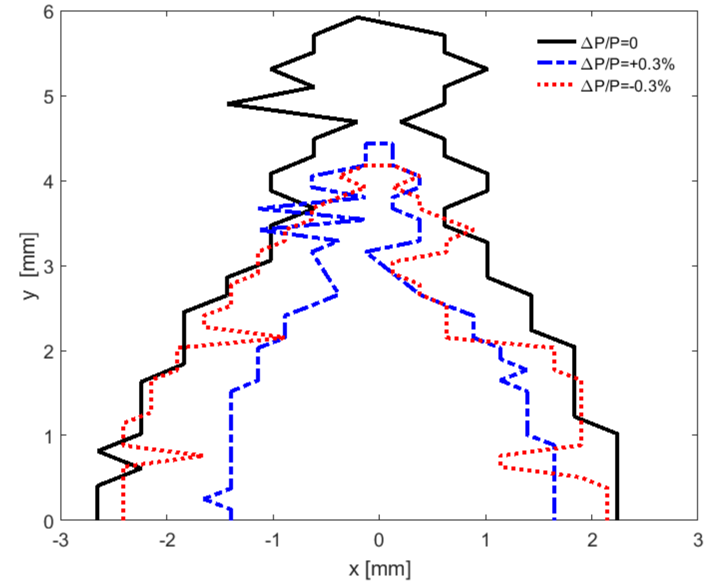


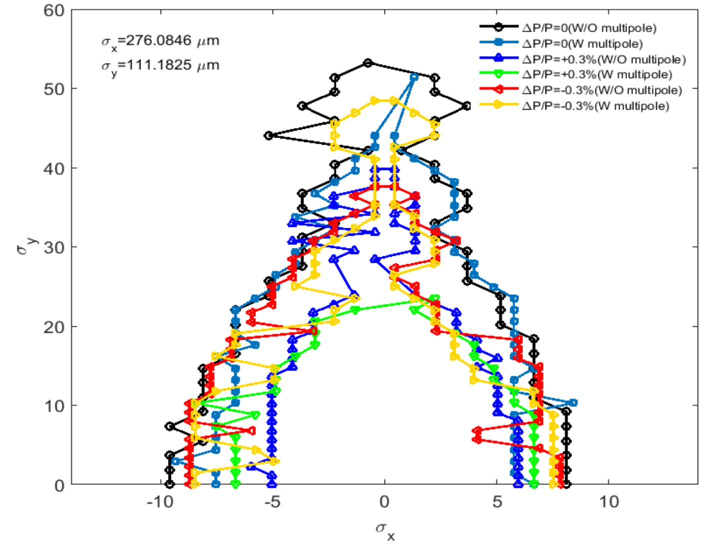
H. Ghasem

Dynamic aperture with errors

ΔP/P=0.3% ΔP/P=-0.3%





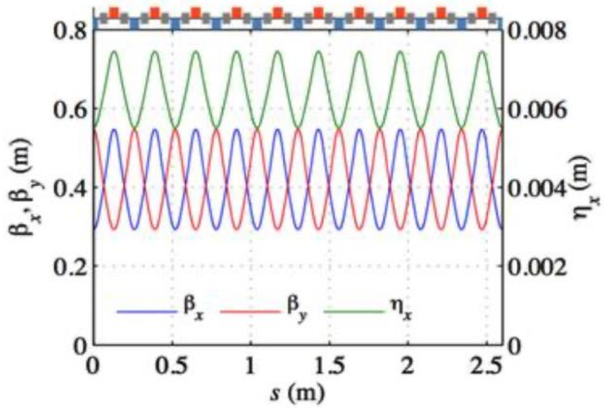


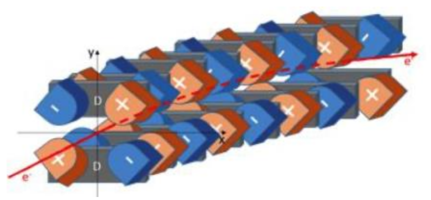
The injected positron beam specification (ε_{xn}=65 μm and ε_{yn}=10 μm, δ=0.3%)

H. Ghasem

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

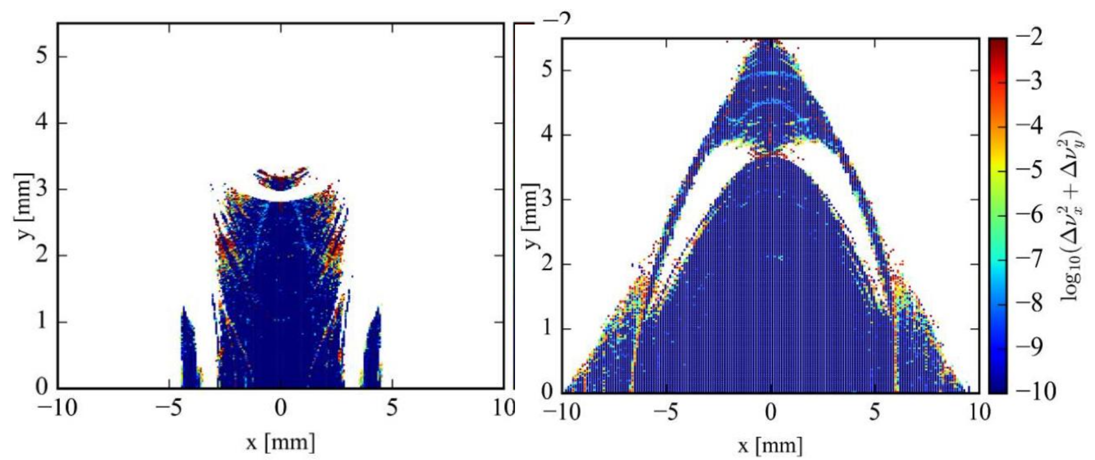
$$\varepsilon_x = F\frac{E^2}{J_x N_d^3} \overset{CB}{\Rightarrow} F\frac{E^2}{J_x\left[N_d N_p\right]^3}$$





	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)



Elettra 2.0 - Emanuel Karantzoulis

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.

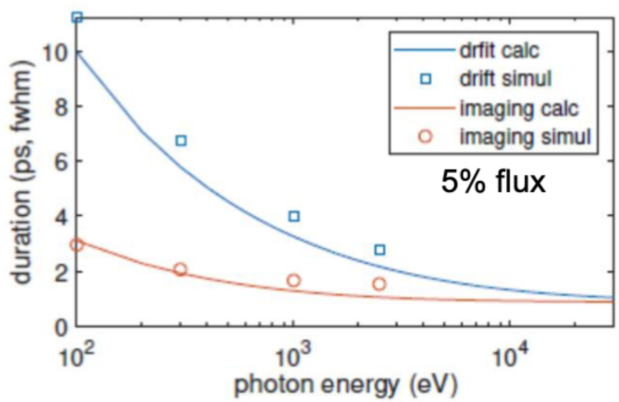
The tilted bunches will give:

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

Beamline Sector	fwhm/5% (ps)	fwhm/10% (ps)	fwhm/15% (ps)	fwhm/20% (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

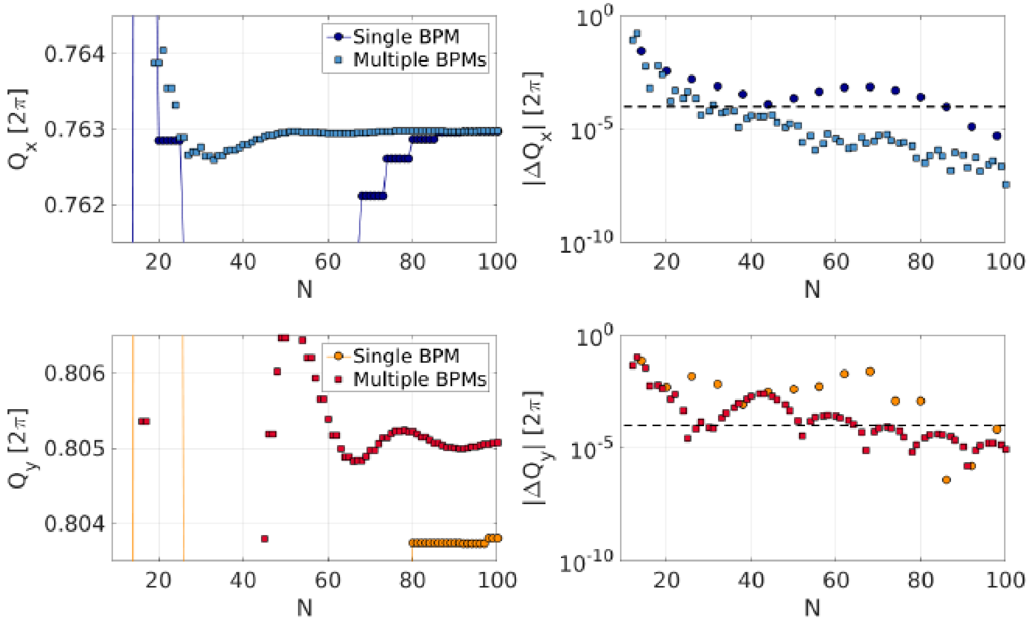
Beamline	fwhm/5% (ps)	fwhm/10% (ps)	fwhm/15% (ps)	fwhm/20% (ps)
DB	1.35	2.30	3.30	4.35

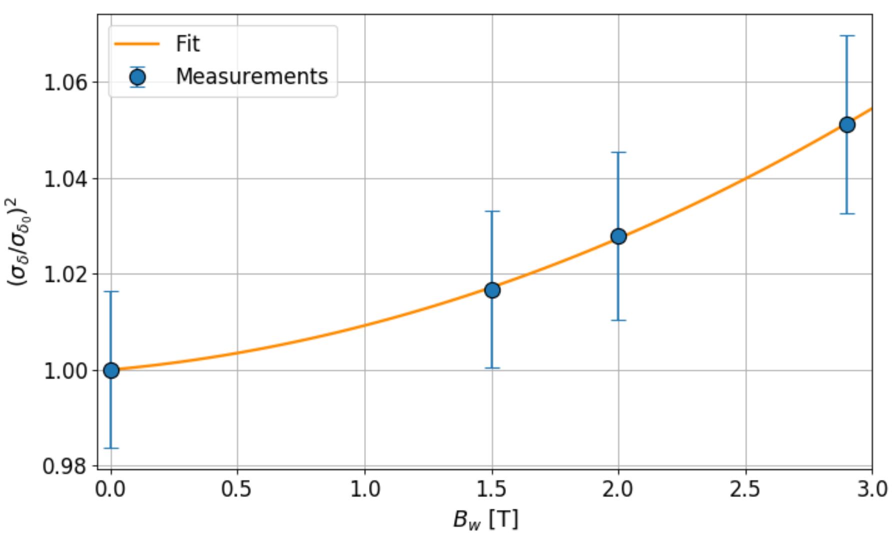


X. Huang and A. Zholents: (ANL-SLAC) - Elettra collaboration

NbTi Wiggler tests at ANKA

P. Zisopoulos

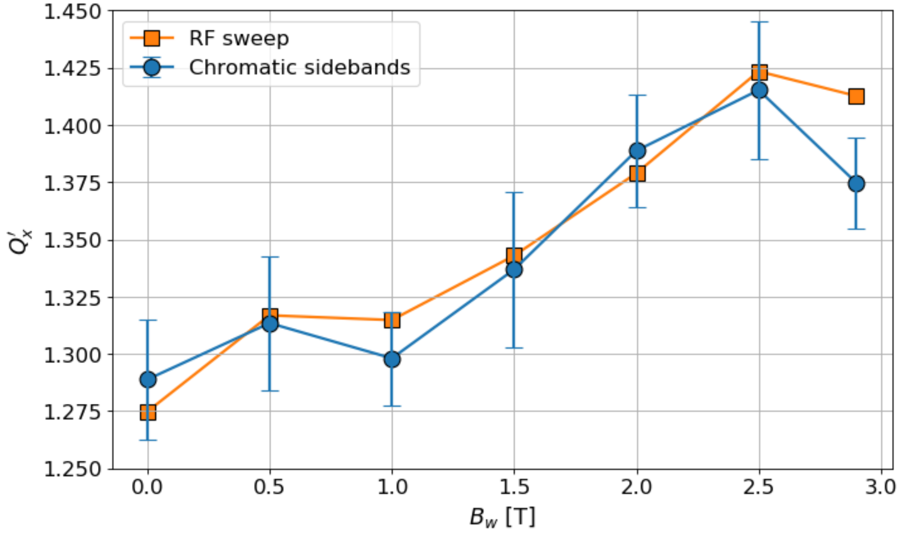




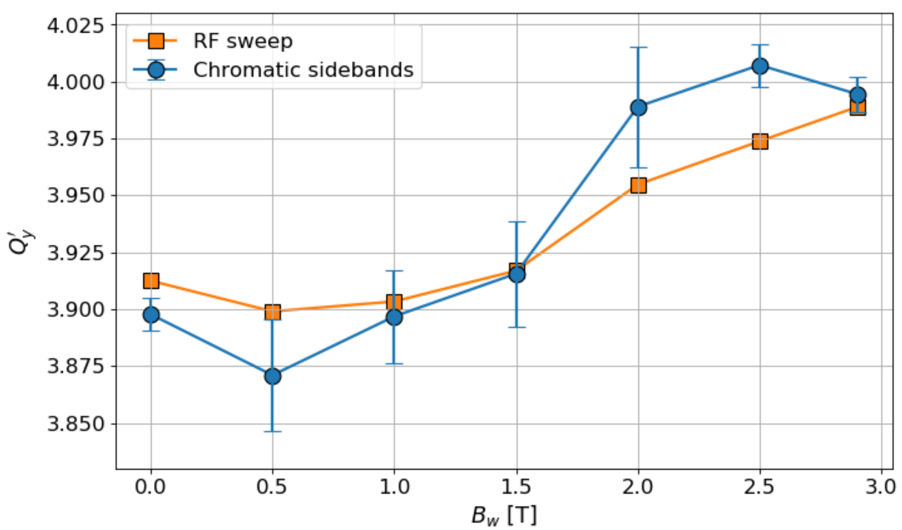
- By using the mixed BPMs scheme the tunes were also measured during each ramp of the wiggler with the beam at the nominal chromatic orbit.
- Precision is increased in both cases and it is at the level of 10^{-4} at around 30 turns.
- The measurements were fitted with quadratic models.
- The horizontal 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.
- (ΔQx/Qx, ΔQy/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.

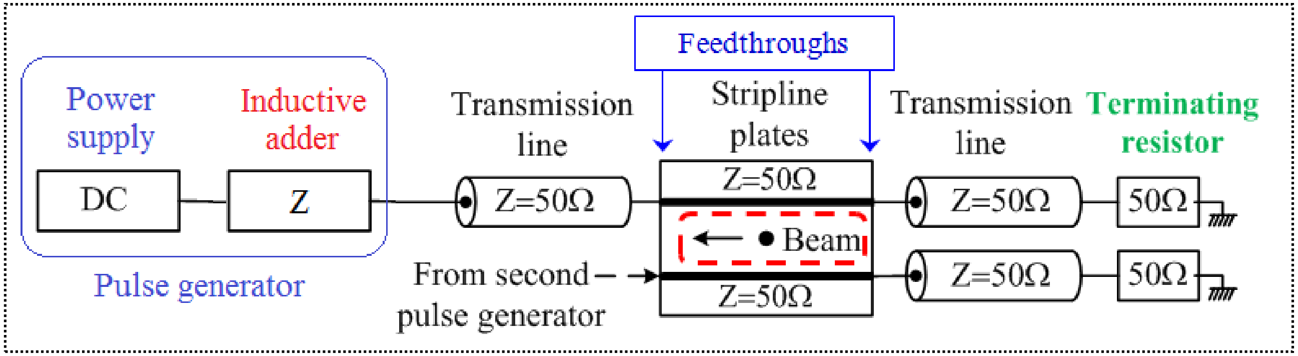


$$Q' = \frac{Q_s}{\sigma_\delta}\sqrt{\frac{A_1 + A_{-1}}{A_0}}$$

- 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%		

M. Barnes, C. Belver, J. Holma