Beam dynamics requirements for future accelerators

Y. Papaphilippou, CERN

Workshop on Compact and Low Consumption Magnet Design for Future Linear and Circular Colliders,

CERN, November 28th, 2014

Outline

- Accelerator performance parameters
- Colliders and luminosity
  - Field quality and dynamic aperture
- High-power rings and average beam power
  - Going super-ferric
  - Optimising magnet gaps for required intensity
  - Raising the energy
  - Magnet fringe fields
- Low emittance lepton rings
  - Magnets for reaching ultra-low emittance
  - Optimising magnet parameters for collective effects
- Ring Higgs factories
  - Booster ring for top-up

Performance parameters

Colliders (and their injectors)

- Luminosity (brightness)

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

High-power rings

- Beam power

$$P = q f_r N_p E_k$$

X-ray storage rings

- Photon brilliance

$$B = \frac{N_p}{4\pi^2 \bar{\epsilon}_x \bar{\epsilon}_y}$$

Extreme intensity within ultra-low beam dimensions

Non-linear and collective effects become predominant

Colliders

- Luminosity

$$\mathcal{L} = \frac{N_1 N_2 n_b f \gamma_r}{4\pi \epsilon_n \beta^*}$$

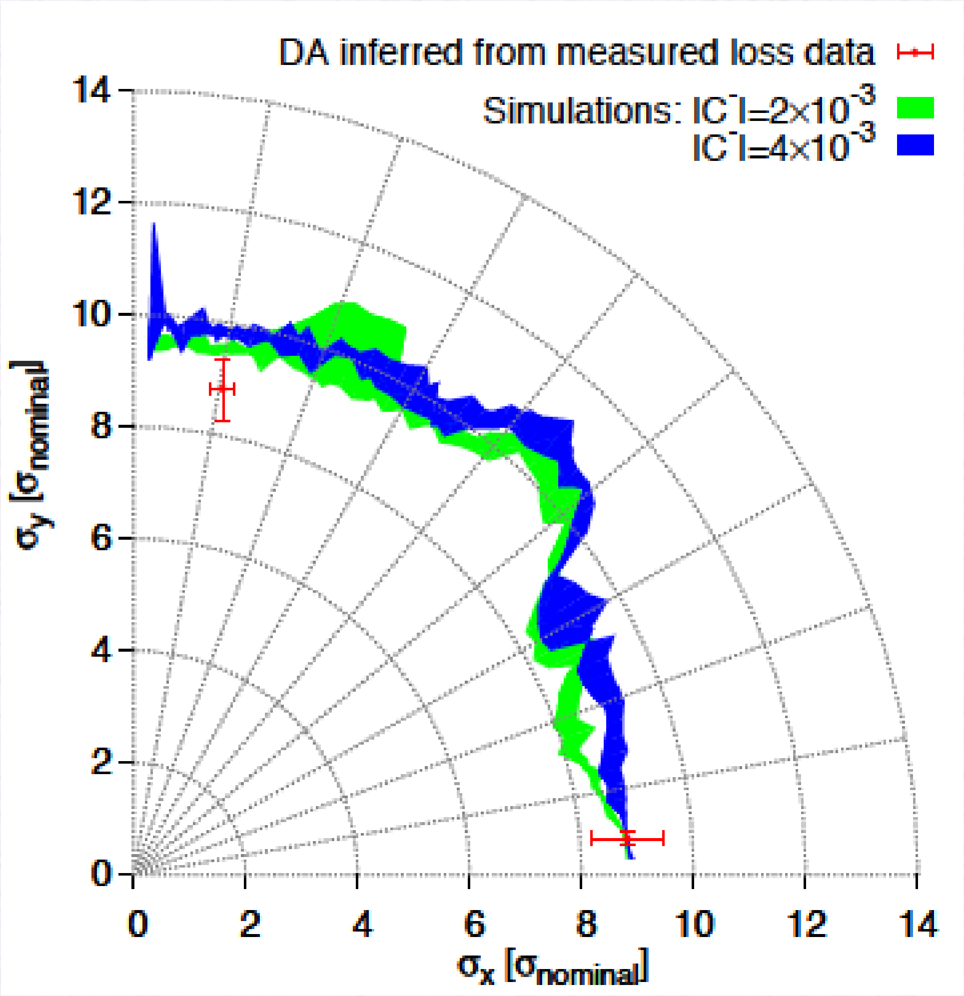
High **integrated** luminosity

- The highest energy
  - Proportional to field (and bending radius for rings), the highest field (for the longest ring)
  - Heat loads due to synchrotron radiation
- Lowest beam sizes in IP
  - High energy helps for geometrical emittance reduction (but injection energy is the driver)
  - Smallest beta function requires strong focusing around the IP
  - Small emittance helps reducing magnet gap but beta functions (beam sizes) get extremely high in IP magnets
- High **total intensity** for both beams
  - Radio-activation (beam loss) putting stringent requirements in amount of lost particles whose motion is governed by non-linear fields (field quality)
  - Integrated luminosity requires good lifetime (hours)
  - Injection time is still long (several minutes) and larger beam size

  } long term particle stability
- High **number of bunches**
  - Separated beam pipe to avoid beam-beam effects, leading to twin aperture magnet design

The "notorious" Dynamic Aperture

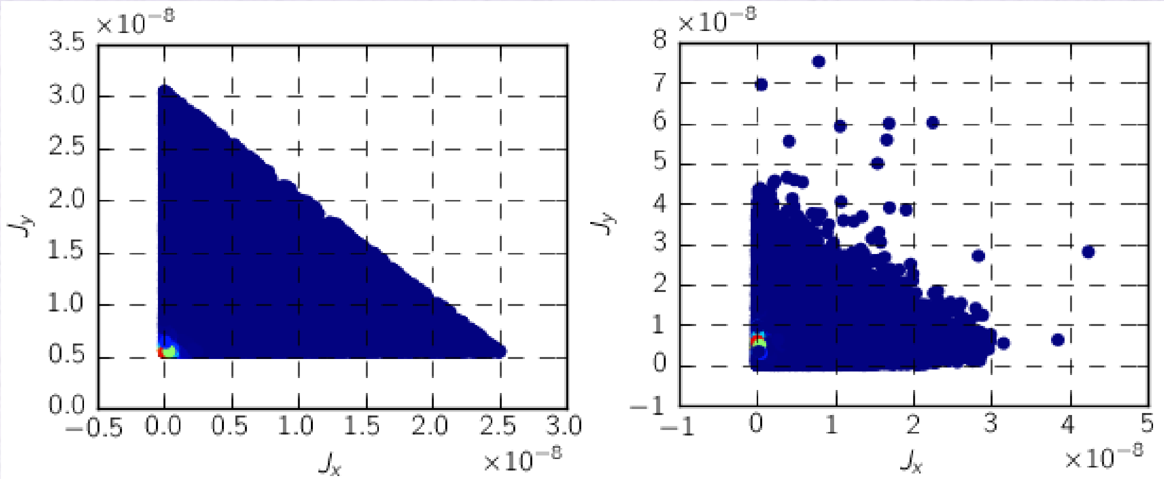
- Area of particle stability quantified by Dynamic Aperture (DA)
- Multipole field errors impact directly on DA but imposing lower tolerances blows-up magnet cost
- During LHC design phase, DA target was 2x higher than collimator position, due to statistical fluctuation, finite mesh, linear imperfections, short tracking time, multi-pole time dependence, ripple and a 20% safety margin
- Better knowledge of the model led to good agreement between measurements and simulations for actual LHC
- Necessity to build an accurate magnetic model (from beam based measurements)

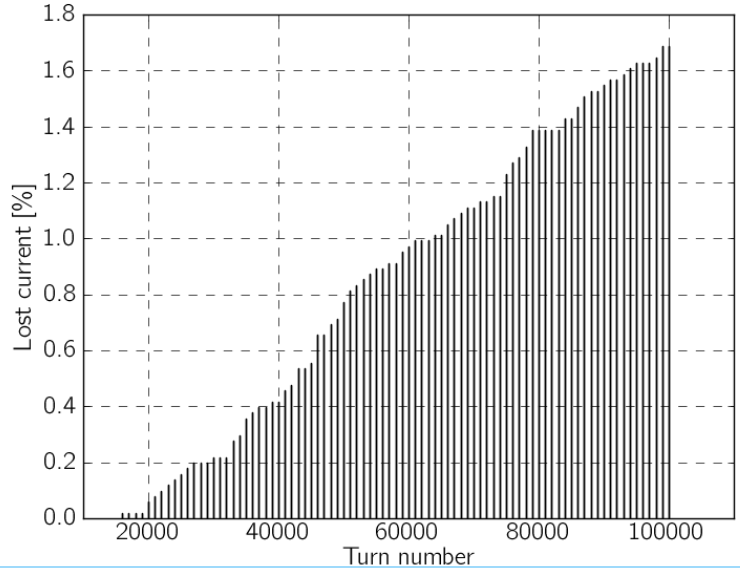


E.H Maclean, PhD thesis, Un. of Oxford, 2014

The “notorious” Dynamic Aperture

- Correlation of DA with lifetime (luminosity) not yet fully established (quantitatively)
- Demanding simulation studies, tracking distributions with the full magnetic model and other effects (ripple, beam-beam,…)





G. Campogianni

High-power rings

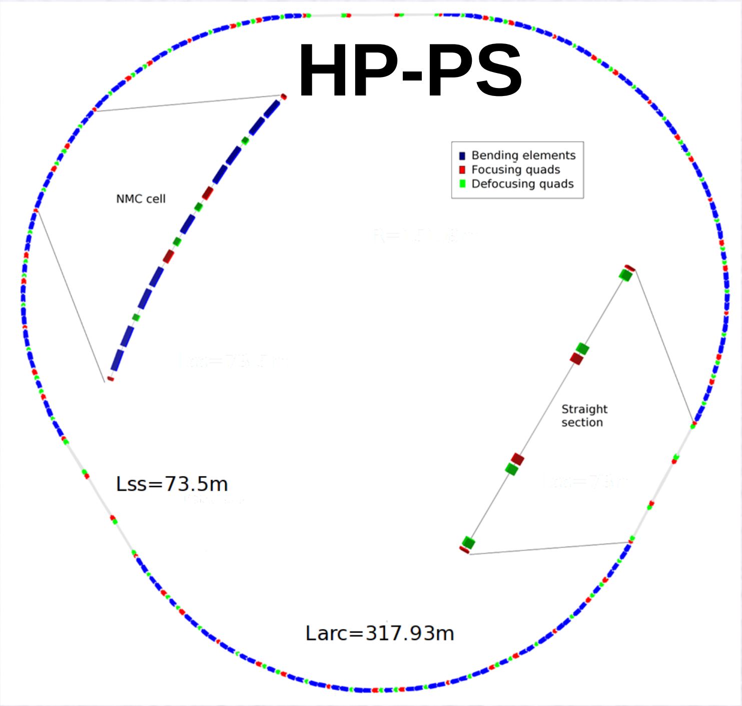
- Beam power

$$P = q f_r N_p E_k$$

High average beam power

- Repetition rate
  - Increased power supply voltage, electrical power, eddy currents, cooling, cost
- Energy
  - Require strong magnetic fields and increases in general the machine size, power and cost
- Intensity
  - High density beams are more sensitive to instabilities and losses (radio-activation)
  - Mitigated by larger beam sizes, but impact on magnet gaps

- Large energy swing makes fast repetition rate more difficult and vice-versa



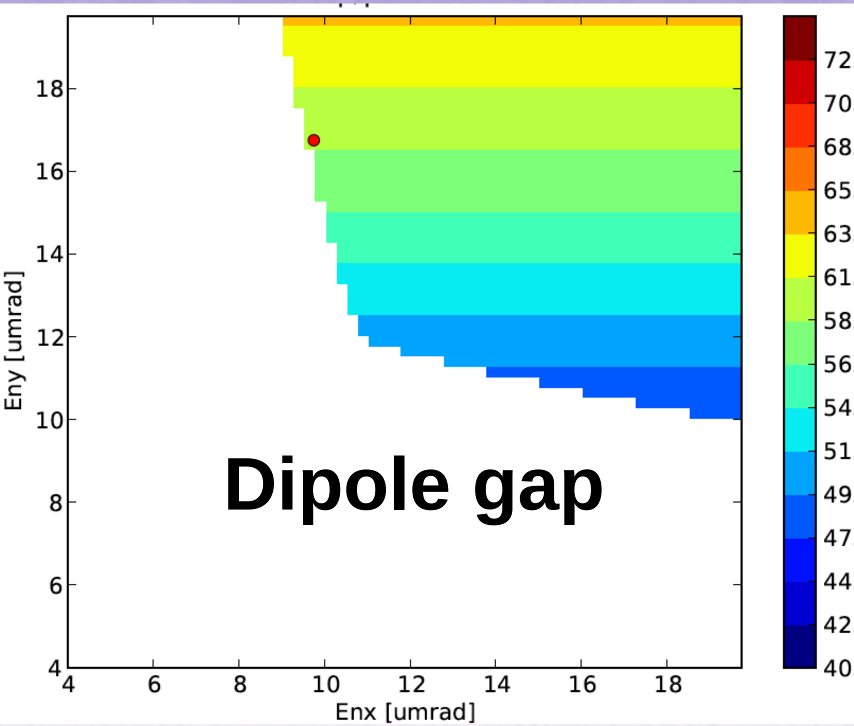
YP et al. IPAC 2013, IPAC 2014

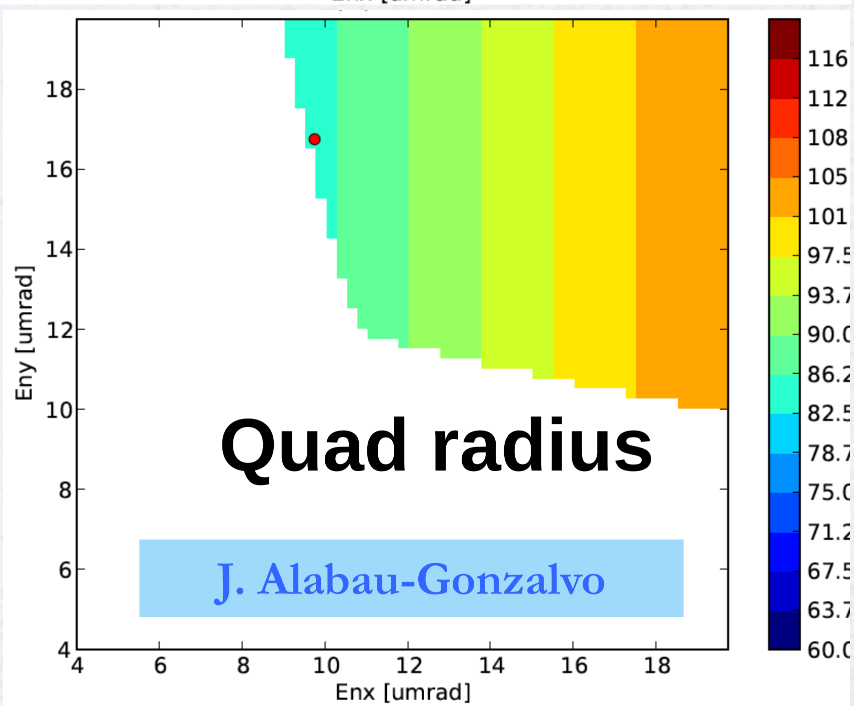
Going Super-ferric

- Circumference determined by energy and bending field @ extraction, and the filling factor (i.e. total bending length over circumference)

$$C \approx 3.335 \frac{2\pi\beta E}{BF_f}$$

- The shortest circumference is better for power consumption, cost but also for collective effects
- Filling factor for SPS and PS is ~2/3 (FODO cells) but for PS2 (Negative Momentum Compaction cells) is < 0.5
  - NMC cells (no transition crossing) mandatory for low-losses in a high-power machine
  - Considering a 2.1T bending field (super-ferric dipole) @ 50 GeV kin. Energy the circumference can be around 1.2 km (filling factor of 0.4)
- The repetition rate can remain to 1s with ramp rate of 3.5 T/s





Intensity

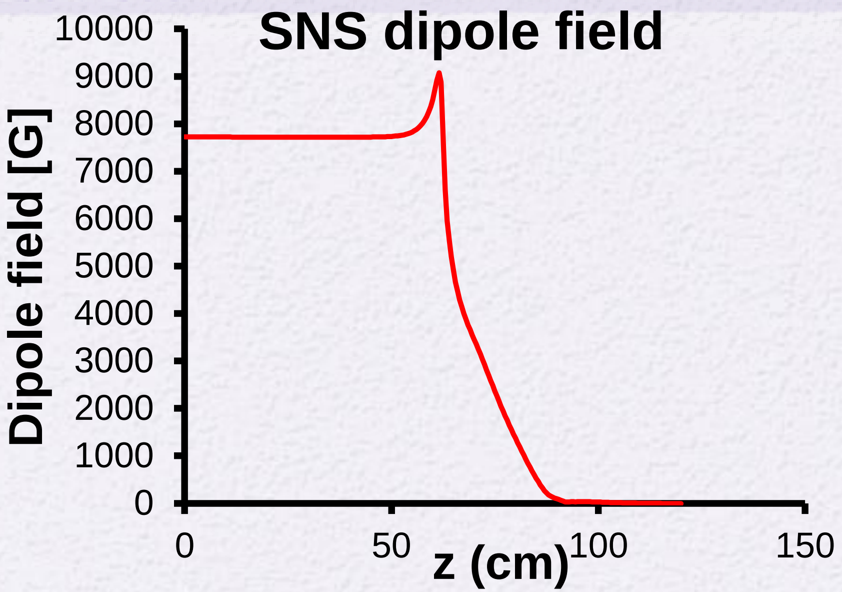
- Limited by space-charge, and other collective effects, especially at injection flat bottom
- For keeping space-charge tune-shift < -0.25, horizontal and vertical emittance optimised accordingly, with respect to dipole and quadrupole apertures (4σ acceptance)

$$\Delta Q_{x,y} = -\frac{r_0 N_p C}{2(2\pi)^{3/2}\sigma_z \beta\gamma^2\epsilon_{x,y}}$$

Raising the energy

- Reaching higher energy (e.g. **75 GeV** for HP-PS) may be interesting for reducing intensity requirements
- For keeping the same circumference, the bending field has to be increased accordingly (to **3.1 T**) but also quadrupole pole-tip field (to **1.85 T**)
- Ramp rate has to be raised (to **5.5 T/s**)
- Magnet aperture is accordingly reduced
- Beam dynamics constraints relaxed but magnet design becomes even more challenging

Fringe-fields



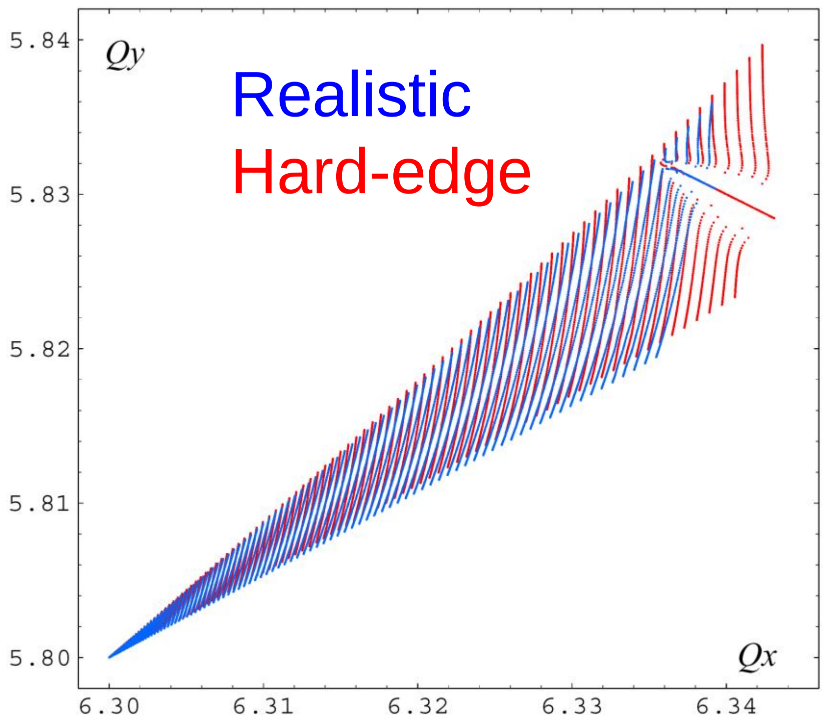
Quadrupole field expansion

$$
\begin{aligned}
B_x &= y\left[b_1 - \frac{1}{12}(3x^2 + y^2)b_1^{[2]}\right] + O(5) \\
B_y &= x\left[b_1 - \frac{1}{12}(3y^2 + x^2)b_1^{[2]}\right] + O(5) \\
B_z &= xyb_1^{[1]} + O(4)
\end{aligned}
$$

- Longitudinal dependence of the field at the edge of the magnet influences dynamics
  - Quite important for low aspect ratio magnets
- Longitudinal field dependence influences non-linear beam dynamics
  - Leading order dipole field is sextupole-like
  - Leading order quadrupole fringe-field is octupole-like

Usual multipole representation is not adequate
  - Deflections depend not only on transverse positions but also momenta

Fringe-fields



Tune footprint for the SNS based on hard-edge (red) and realistic (blue) quadrupole fringe-field

YP and D.T Abell, EPAC 2000

- An approach to alleviate their effect by design may be impossible
- Beam dynamics optimisation has to include the fringe-field effects
- Ideally, need 3D field maps (initially calculated, then measured)
- Including these maps in general beam dynamics codes for particle tracking is not straightforward
  - Symplecticity (i.e. “energy” integral preservation) is not guaranteed

Low emittance lepton rings

Lepton Colliders (and their injectors)

- Luminosity or brightness

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

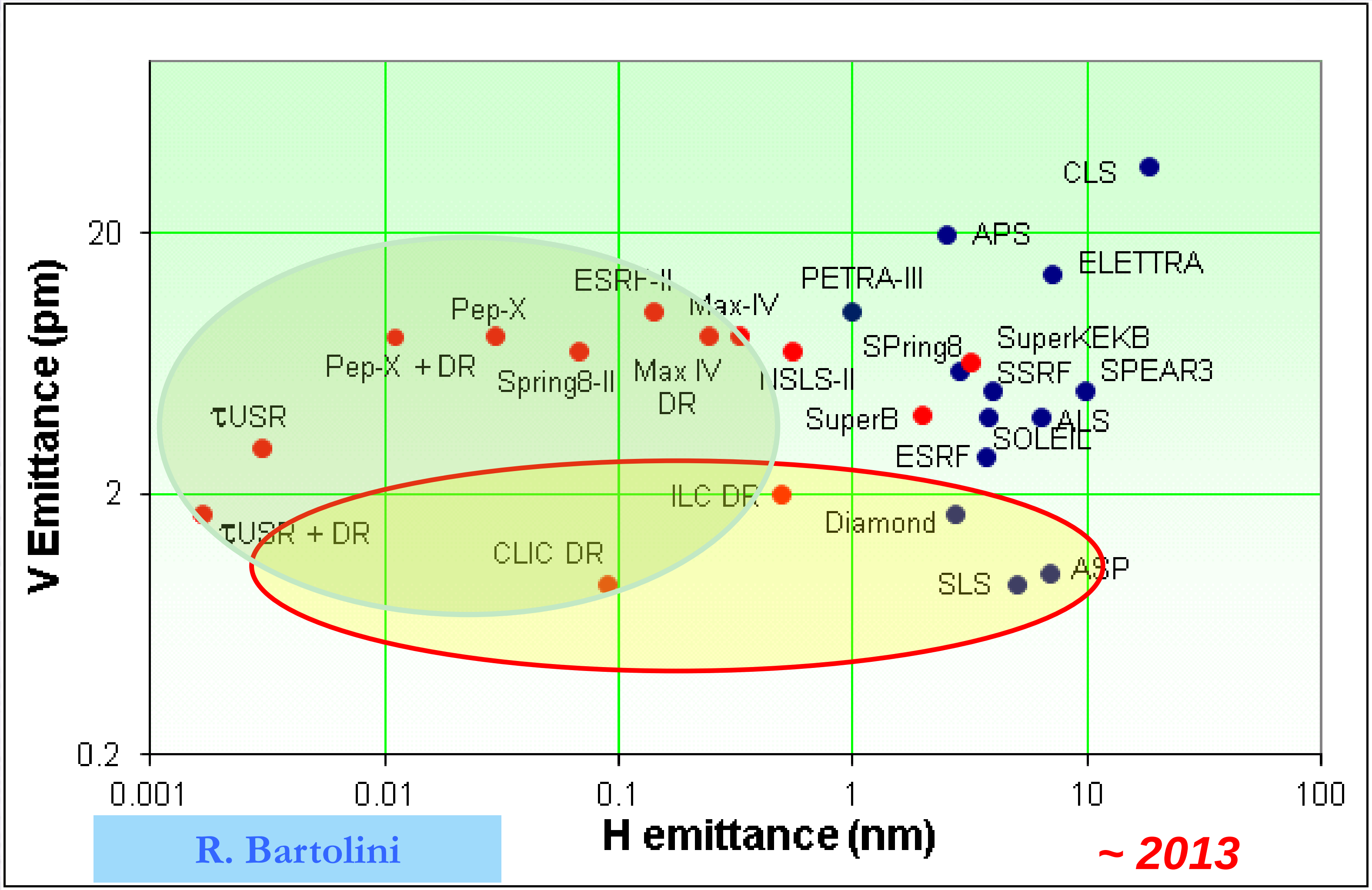
X-ray storage rings

- Photon brilliance

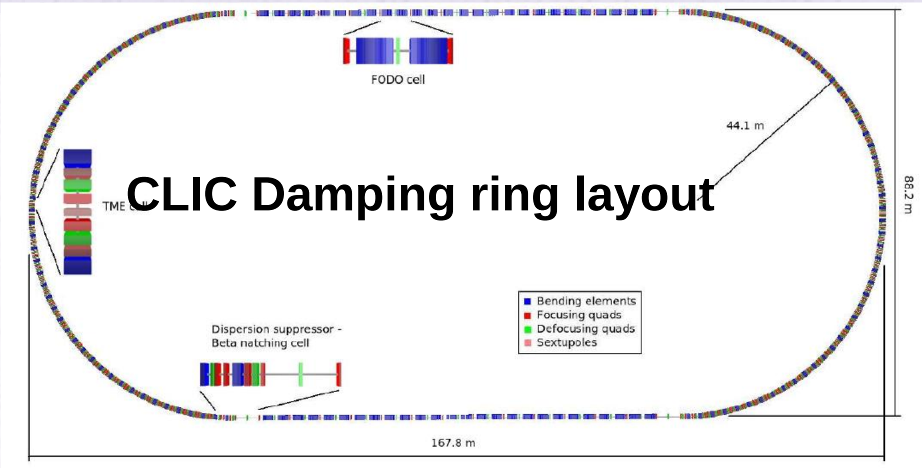
$$B = \frac{N_p}{4\pi^2\bar{\epsilon_x}\bar{\epsilon_y}}$$

- Extreme intensity within ultra-low beam dimensions in an environment dominated by synchrotron radiation
- Light sources
  - Diffraction limited operation at 0.1nm requires ~10 pm
- Colliders (e.g B-factories)
  - Luminosity of 10^{36} cm^{-2} s^{-1} requires a few nm as present state-of-the-art light sources
  - Low vertical emittance still a challenge for extreme currents
- Damping rings
  - 500 pm H and 2 pm V (specs for ILC-DR)
  - <100 pm H and 5 pm V (specs for CLIC-DR)

Emittances in X-ray SR, DR and e^+/e^- colliders

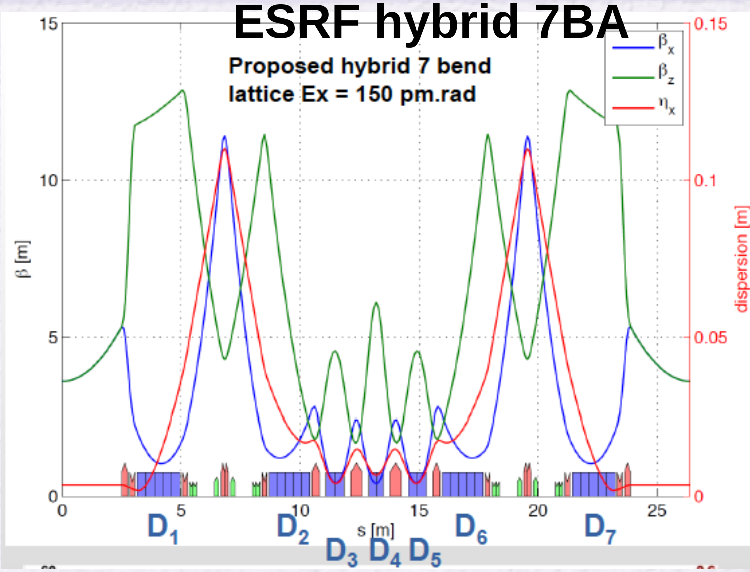


Low emittance rings challenges

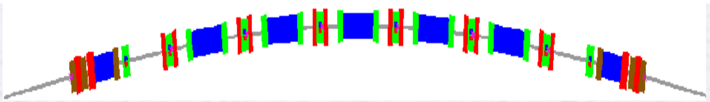


CLIC Damping ring layout

ESRF hybrid 7BA



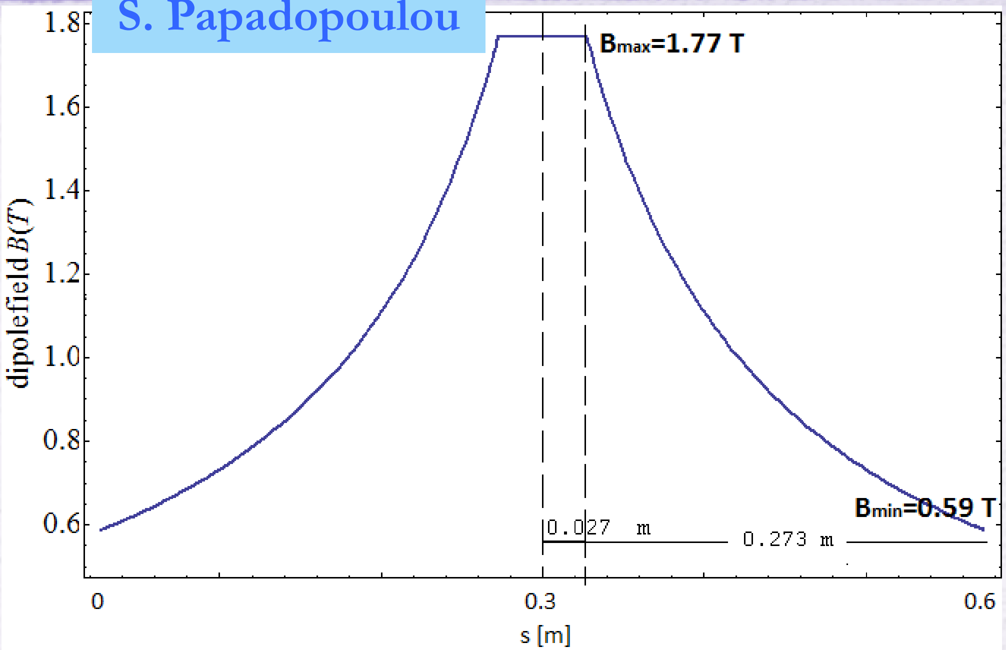
MAXIV 7BA

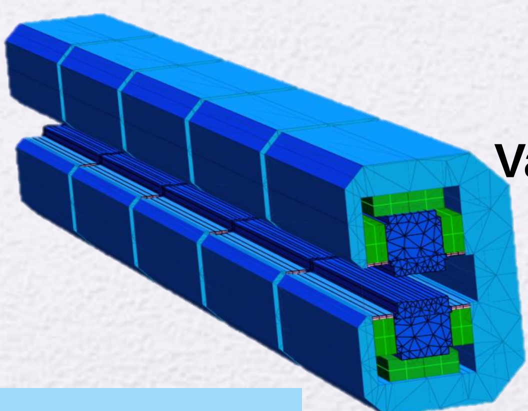


- ❑ Ultra-low emittance achieved with highly packed lattice (TME or MBA) cells and strong focusing (as for next generation X-ray rings, see MAX)
- ❑ Ultra low-emittance bunches with high bunch charge trigger several collective effects
  - ❑ Emittance dominated by IBS (significant blow up)
  - ❑ Lattice design (including magnet parameters) should be optimised taking into account this effect
  - ❑ Ultra-fast damping (~2ms) achieved only with high-magnetic field i.e. SC wigglers (higher energies are not an option due to emittance increase from quantum excitation)
- ❑ Low vertical emittance requires extreme alignment tolerances (also for coils)

Emittance reduction with variable bends

S. Papadopoulou





ESRF Variable bend

G. Le Bec

- ❑ Reducing further the emittance by varying longitudinally bending field
  - ❑ Either in step-like or hyperbolic way
- ❑ Further emittance reduction
  - ❑ By a factor between 3-6 for CLIC damping rings case
  - ❑ Allows reduction of circumference or relaxing optics constraints
- ❑ Adopted at the ESRF for SR upgrade (prototype)
- ❑ To be magnetically designed for CLIC damping ring parameters (CERN-CIEMAT collaboration)
  - ❑ High central field, hyperbolic fall-off
- ❑ Influence to non-linear beam dynamics not yet fully established (3D map)

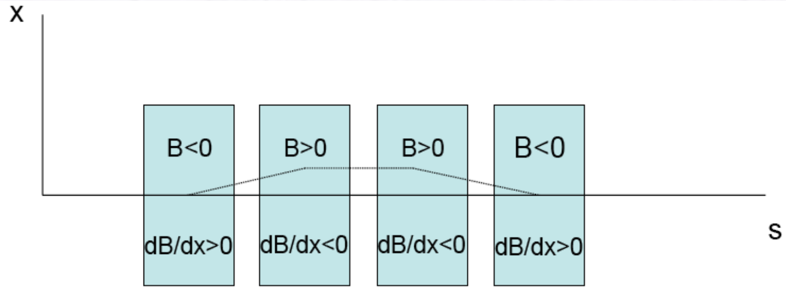
Emittance reduction with Robinson wiggler

PS Robinson wiggler

- Reducing further the emittance by increasing damping partition number (combined alternating gradient and dipole)
- Can these extreme gradients be achieved?

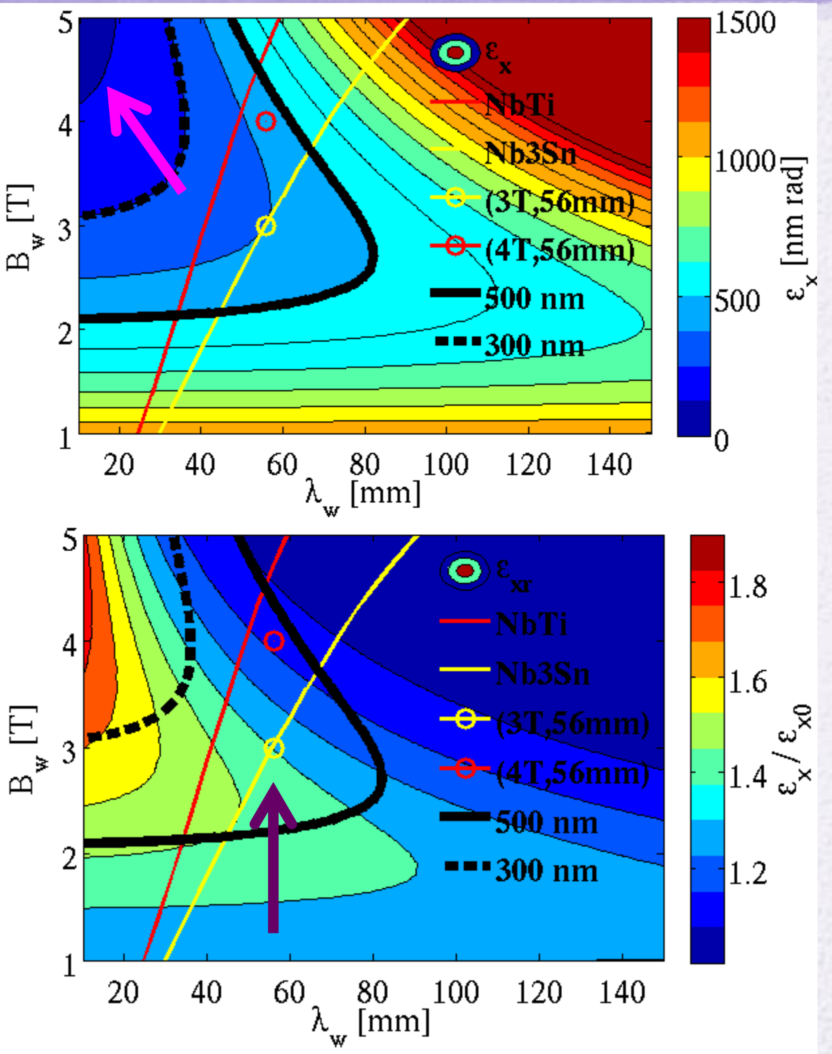
L. Nadolski

$$\varepsilon_x = \frac{C_q \gamma^2 \langle H \rangle_{dipole}}{J_x \rho_x}$$



Type	B(T)	g (mm)	dB/dx (T/m)
Out-vacuum	1.4	11	140
In-vacuum	1.0	5.5	182

Wiggler parameter choice

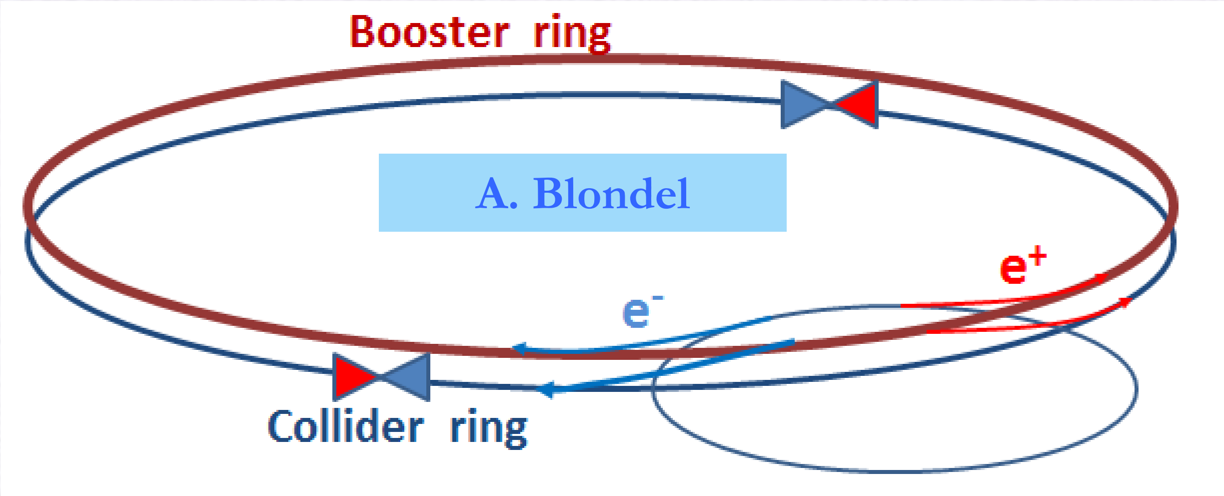


- The **highest field** and **smallest period** provide the smallest emittance
- Lower emittance blow-up due to IBS for **high-field** but **moderate period** (within CLIC emittance targets)
- Wiggler prototype in NbTi with these specs, built at BINP, for installation to ANKA (KIT)
  - Serving X-ray user community but also beam tests
- Development of higher-field short models in Nb3Sn at CERN

D. Schoerling et al., PRST-AB 15, 042401, 2012

Ring Higgs factories

- Rings of very large circumference (>50km) for moderate energy (<200GeV)
- Filled with low field magnets in the arcs (and a lot of RF!) in a high synchrotron radiation environment
- High-field final focus magnets (field quality), very close to the detector (integration)
- Ultra-low vertical emittance (~1pm), requires challenging alignment and corrections in a large circumference
- Very short lifetime due to radiative Bhabha and Beamstrahlung (minutes) requires top-up, i.e. booster ring (at ~0.1Hz) with same circumference



Booster Ring (FCC-ee) parameters

Top Energy [GeV]	45.5	80	120	175
Cycle time [s]	12			
Circumference [m]	100000			
Bending radius [m]	11000			
Injection energy [GeV]	20			
Dipole length	10.5			
Emittance @ injection [nm]	2.81	0.10	0.01	0.01
Emittance @ extraction [nm]	14.5	1.65	1.0	1.0
Bending field @ injection [G]	61			
Bending field @ extraction [G]	138	243	361	531
Energy Loss / turn @ injection [MeV]	1.287			
Energy Loss / turn @ extraction [MeV]	34.5	329.4	1667.6	7542.6
Long. Damping time @ injection [turns]	15543			
Long. Damping time @ extraction [turns]	1320	243	72	23
Average current [mA]	36.1	3.8	0.8	0.1
Average power @ injection [kW]	46.4	4.9	1.0	0.2
Average power @ extraction [MW]	1.24	1.26	1.27	0.88
Average power over 1 cycle [kW]	100	105	106	105
Critical energy [MeV]	0.02	0.10	0.35	1.08
Radiation angle [μrad]	11.2	6.4	4.3	2.9

- Bending field at injection of around 60G
  - Has to remain low as energy loss/turn at flat top is quite high
  - Compensation of eddy currents, hysteresis effects (12s cycle) and appropriate shielding from main magnets is needed
- Critical energies @ extraction up to 1.1MeV
  - Needs demanding shielding, absorption scheme and vacuum chamber design

Summary

- Future accelerators have a great number of challenges impacting magnetic design
  - High-field (but also very low), field quality, fast ramping, packed magnets, fringe fields, exotic field profiles,…
- Magnet builders and beam physicists have to work hand-in-hand for facing them
  - Achieve the highest performance at the lowest cost/power

Thank you for your attention

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