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FEL2012 Nara
28 August, 2012

Use of Projected Torus Knot Lattice for a Compact Storage Ring FEL

Shigemi Sasaki and Atsushi Miyamoto
Hiroshima Synchrotron Radiation Center
Hiroshima University

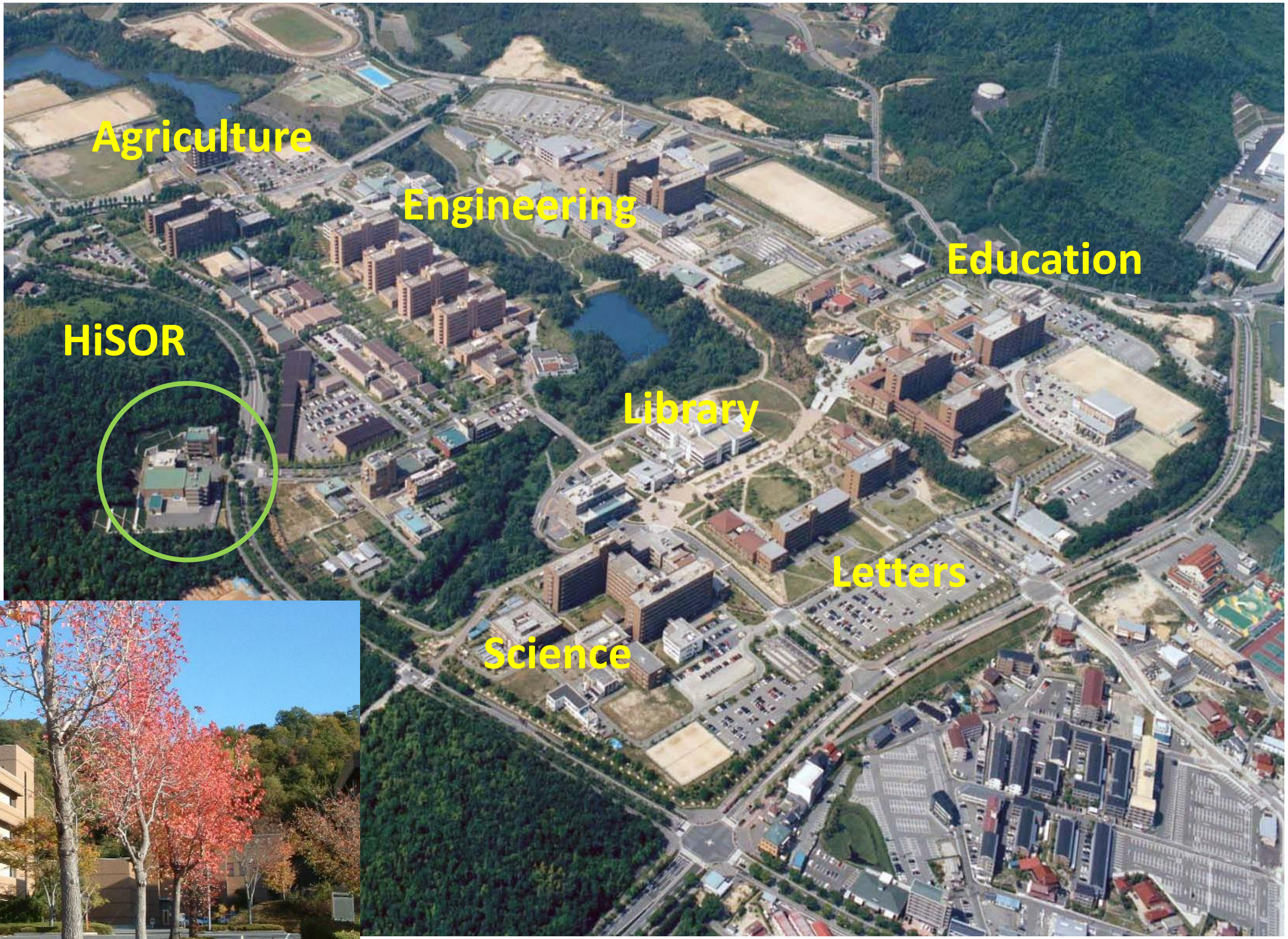
Hiroshima Prefecture, Japan

Itsukushima Shrine (Miyajima)

Itsukushima Shrine is the world cultural heritage !

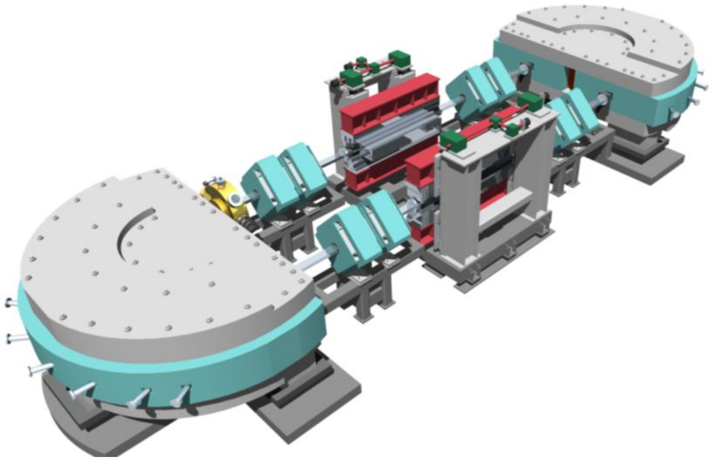
Sake breweries near Hiroshima U in Saijo

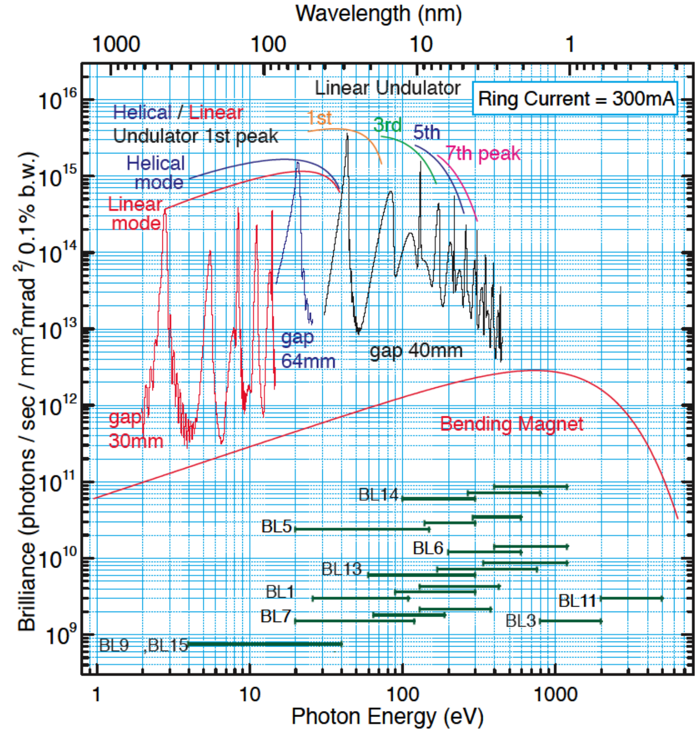
Hiroshima University Campus and SR Facility HiSOR



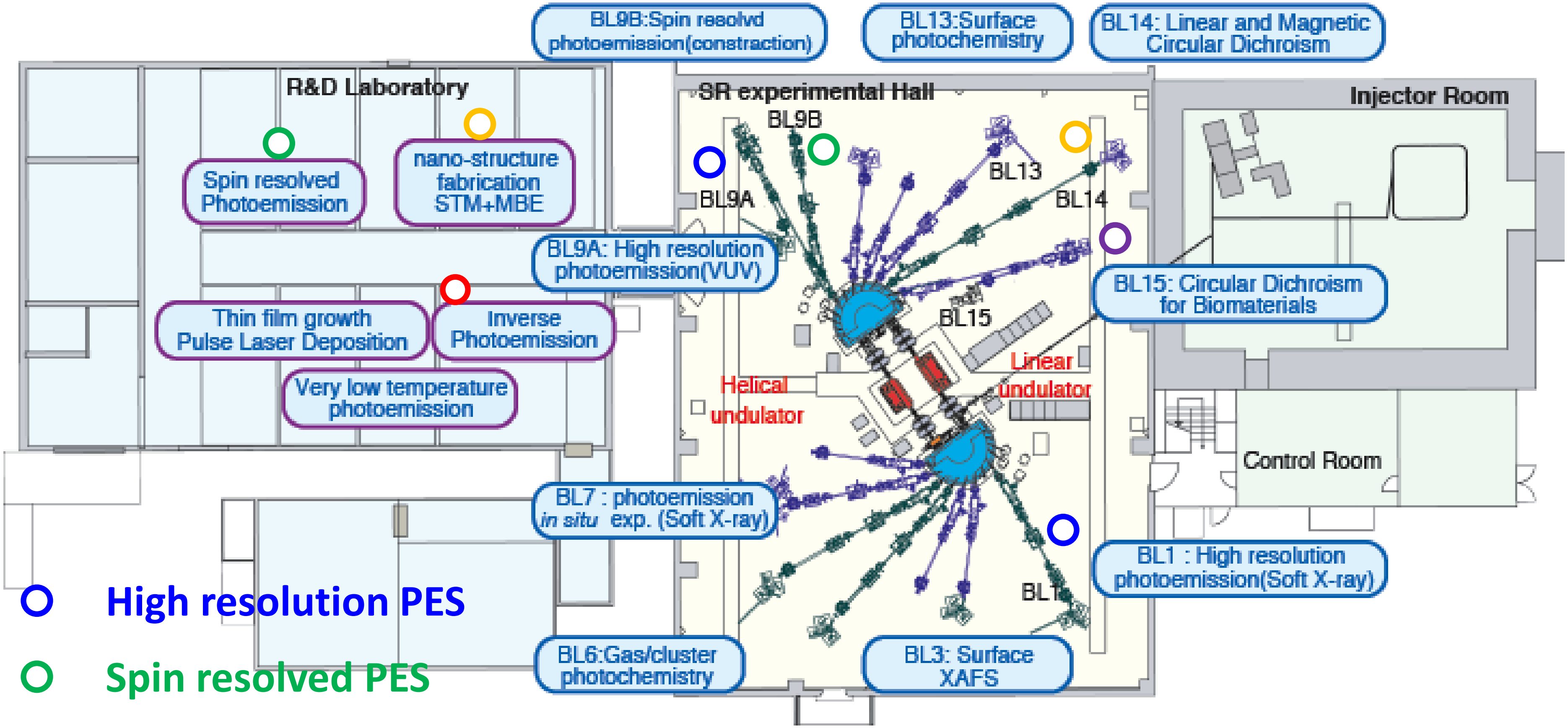
Compact SR source, HiSOR

Circumference [m]	21.95
Type	Racetrack
Bending radius [m]	0.87
Beam energy [MeV] Injection/Storage	150/700
Maximum magnetic field [T]	2.7
Betatron tune	1.72, 1.84
RF frequency [MHz]	191.244
Harmonic number	14
RF voltage [kV]	200
Stored current [mA]	350
Natural emittance [π nmrad]	~400
Beam lifetime [hours@200mA]	~10
Critical wavelength [nm]	1.42





Users' activities at HiSOR



- High resolution PES
- Spin resolved PES
- Nanostructure analysis
- Structure analysis of Bio-molecules
- Inverse PES

No further extension is possible.

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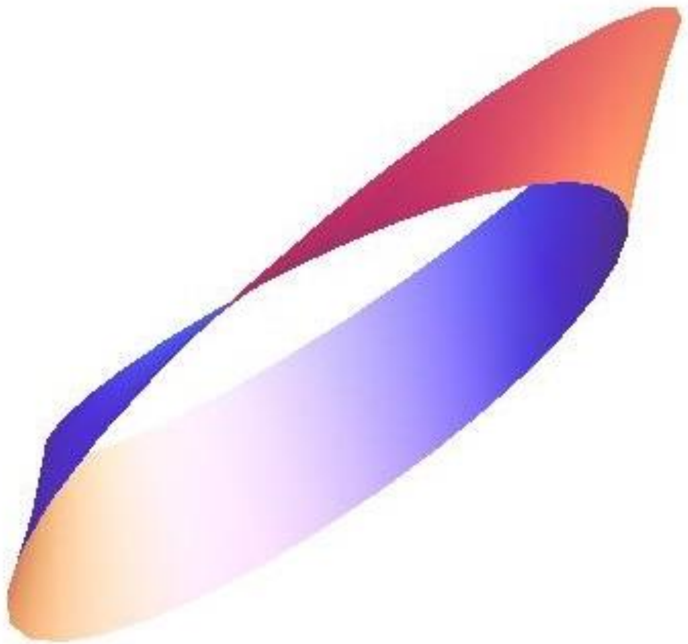
Outline

- Upgrade plan of HiSOR ring: HiSOR-II
- Limitations of compact ring
- **New lattice**
- HiSOR-II+ with FEL capability
- Summary



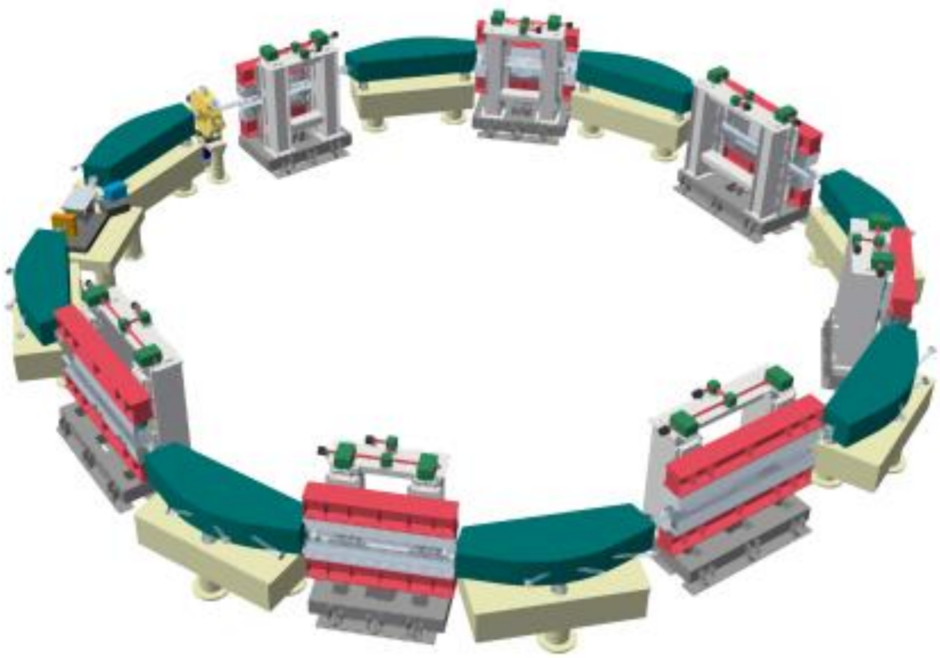
Background of Compact VUV Lightsource Ring Development

- The HiSOR users community is seeking high brightness in VUV region.
- Presently, many different researches including high resolution photo-electron spectroscopy (PES) of high T_c superconductors and topological insulators, spin-resolved PES, structural analyses of bio-molecules in a liquid using the UV natural circular dichroism are underway.
- The beam time of undulator beamlines is already almost fully subscribed. User subject proposals are expected to increase, and difficult to allocate additional proposals.
- In order to answer HiSOR users community's requirements, we need a third generation lightsource ring in VUV and soft x-ray region.

(See http://www.hsrc.hiroshima-u.ac.jp/english/index-e.htm for more information.)

HiSOR-II

Beam energy [MeV]	700
Circumference [m]	40.079
Betatron tune	3.761, 2.846
Natural emittance [nmrad]	13.57
Momentum spread	5.79e-04
Momentum compaction	0.0319
Bunch length [mm]	37.0
Harmonic number	7
RF frequency [MHz]	52.4
Radiation dumping time [msec]	L:11.44 H: 8.57 V:14.70
Touschek lifetime [hour]	2.7
Straight sections	3.4 m × 4 2.0 m × 4



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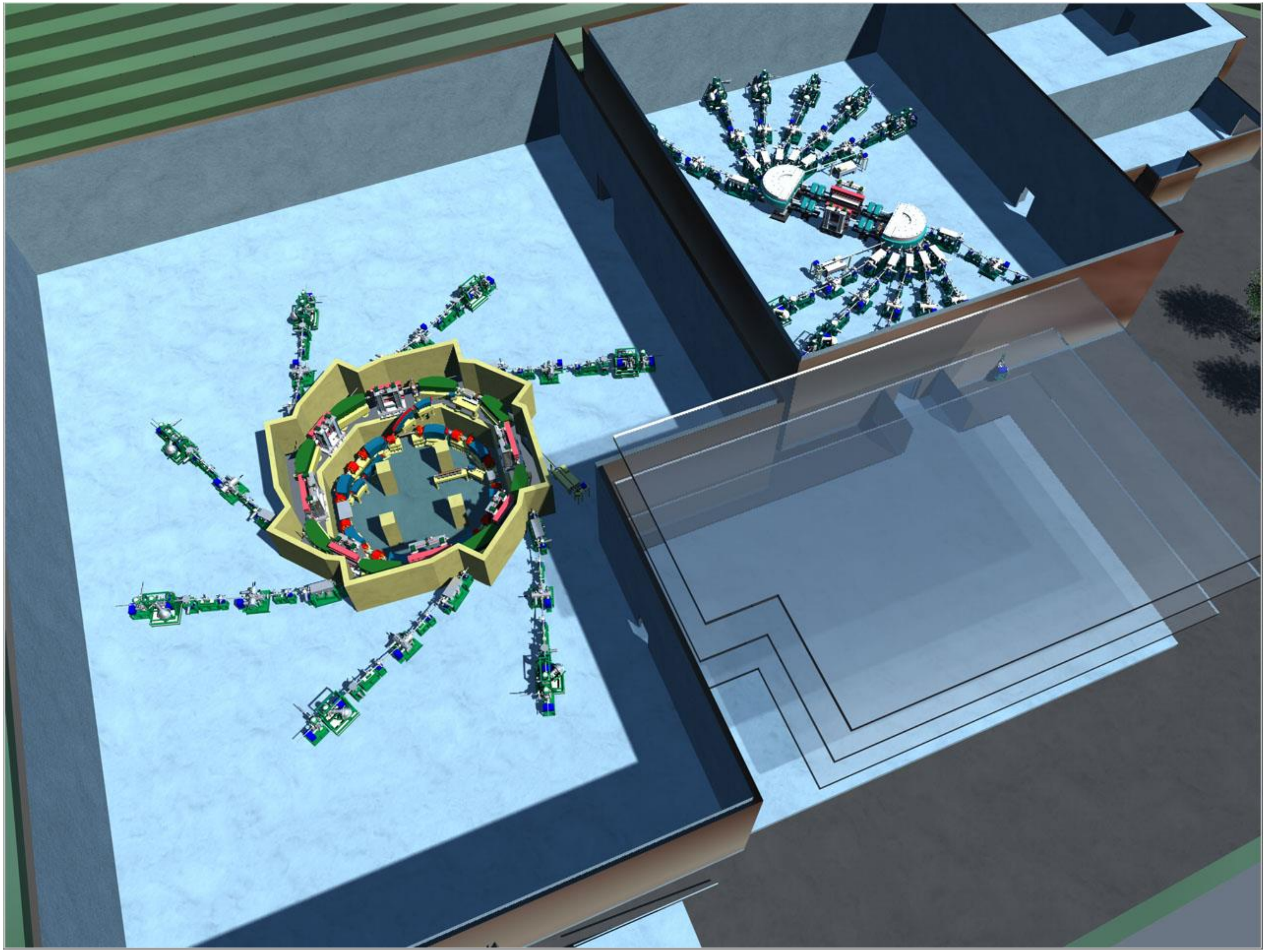
Designer's View of HiSOR



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Limitations of Compact SR Ring?

1. Limitation of achievable lowest emittance（This may be partially solved by introducing the combined-function bending magnet as MAX III.）

2. Limitation of usable straight sections for insertion devices

3. Limitation to increase bunch –to-bunch interval due to the short circumference of the ring (Example：Longest bunch interval is 133 nsec, 7.5 MHz for C=40 m)

For example, ARTOF Photoelectron Spectroscopy experiment cannot be performed with a small circumference (< 100 m) ring.

Need to seek some other possibilities

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Ultra High Resolution Angular Resolved Photo-Electron Spectroscopy

BESSY II Beamline
U125/NIM

Energy resolution
150 μeV

Repetition rate
Max. 3 MHtz

↑

Need C ≥ 100m

Experimental Setup: iDEEAA

iDEEAA: Instrument for Direct Electron Energy and Angular Analysis

- conventional hemispherical analyzer Scienta R4000 and electron time-of-flight spectrometer Scienta ARTOF 10k
- double mu-metal shielding vacuum chamber
- 4-axis manipulator
- cryostat: Janis ST400, T= 4K

Light Sources

- Synchrotron radiation (BESSY UE112; energy resolution < 1meV. Excitation energy up to 70 eV)
- Laser : - energy resolution < 1 meV, high repetition rate, up to 4 MHz
- Helium lamp with monochromator, resolution < 1.2 meV at 21.21 eV

Used BESSY II beamline: U125 / NIM
resolution: < 10 meV @ 35 eV
photon energy range 5 - 36 eV

Comparison between the ARTOF and the hemispherical analyzer

	time-of-flight analyzer (Scienta ARTOF 10k)	hemispherical analyzer (Scienta R4000)
energy resolution	150 μeV	1.8 meV
energy resolving power	10000	1750 (for 0.2 mm slit)
angular resolution	0.08°(0.4mm sample diameter)	0.4° (1mm sample diameter)
slits	0 (total cone detection)	9
detector	MCP/delay-line	MCP/CCD
repetition rate	max. 3 MHz	-
transmission	250 x R4000 analyzer	1

R. Moberg: “A novel 3D ARPES electron spectrometer for pulsed photon source”, VUVX 2010, Vancouver, July

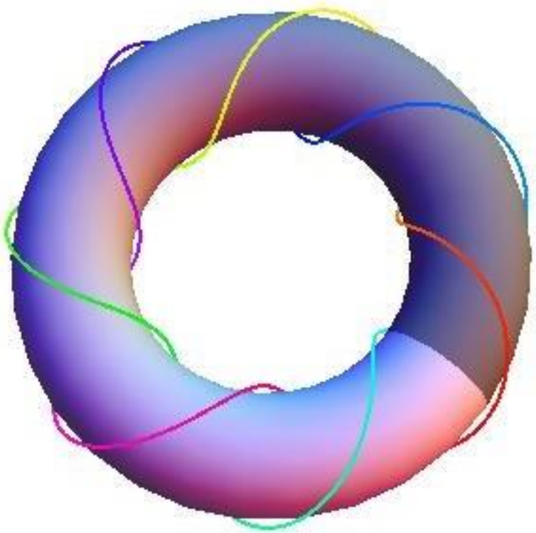
New Concept

- **Can we construct a lattice in which the beam orbit closes after multiple turns？**

Yes, it is possible ！

The Möbius strip, for examlpe

Or, a torus knot



Next few slides show procedures how to realize realistic accelerator lattices.

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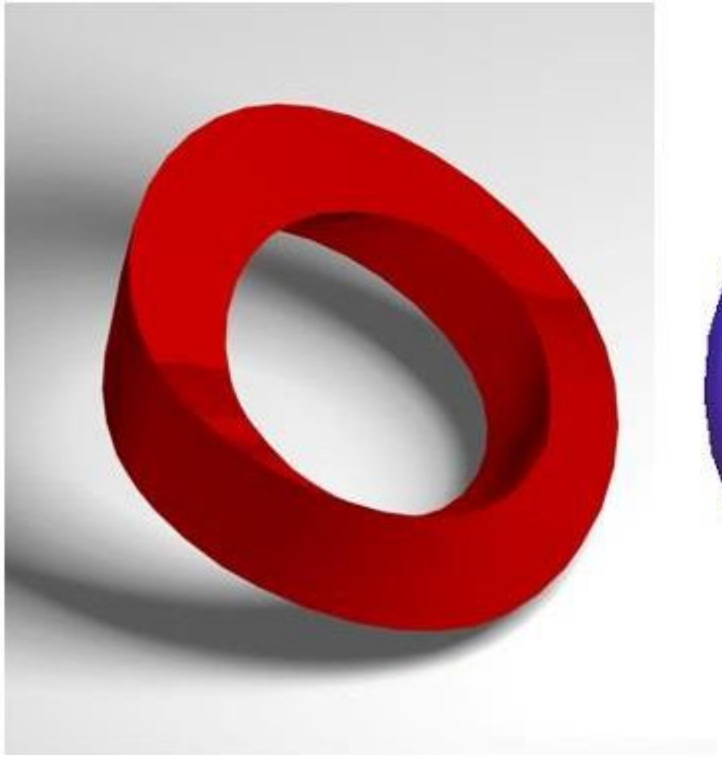
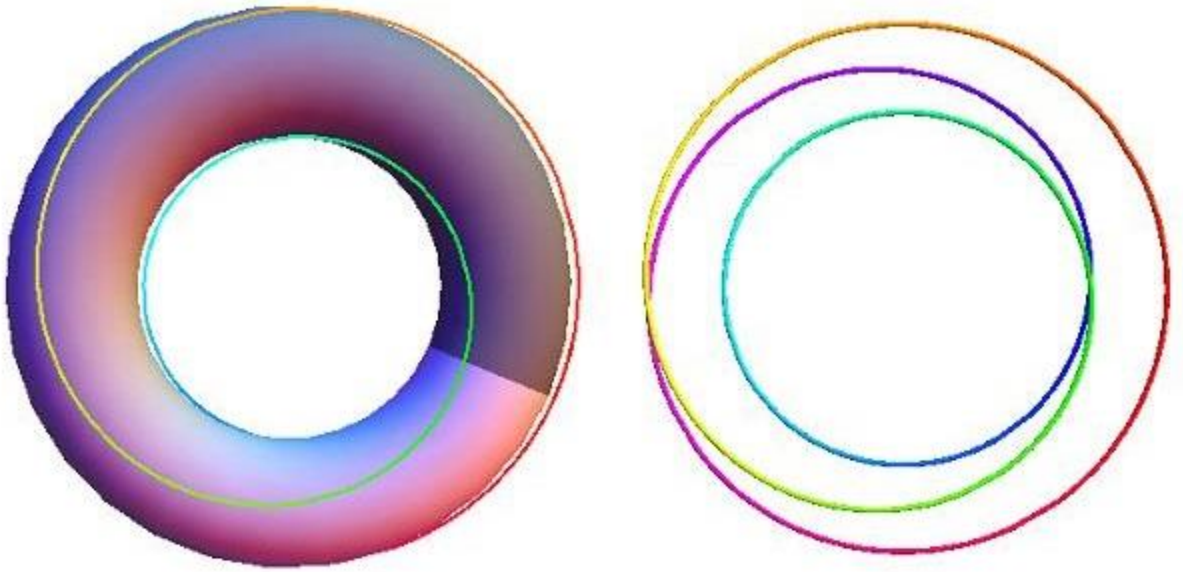
From Möbius to Torus Knots



Möbius Triangular Prism



(1, 3) Torus Knot

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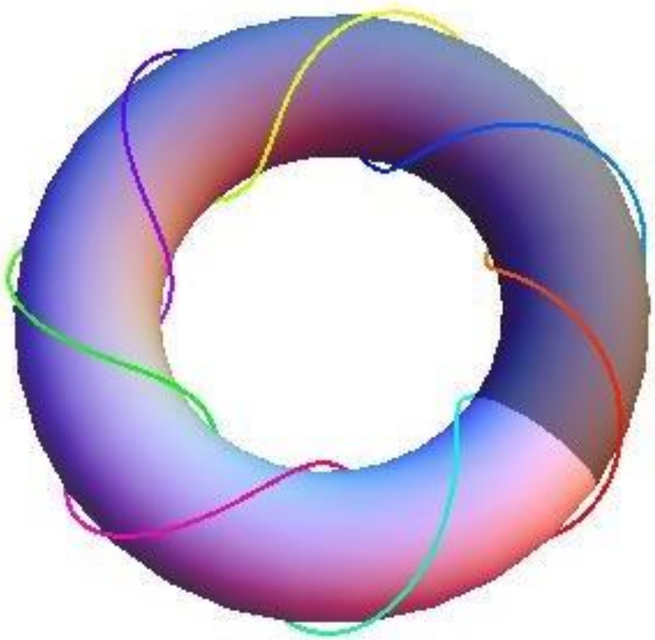
Torus Knots



(7, 2) Torus Knot

(7, 3) Torus Knot

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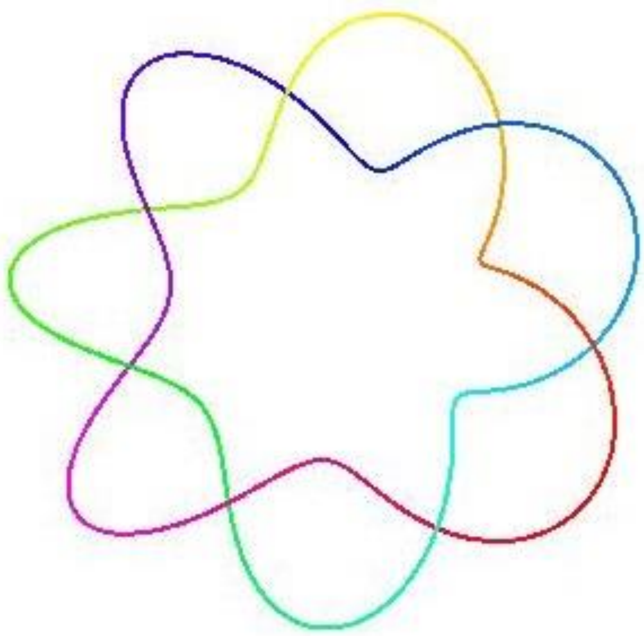
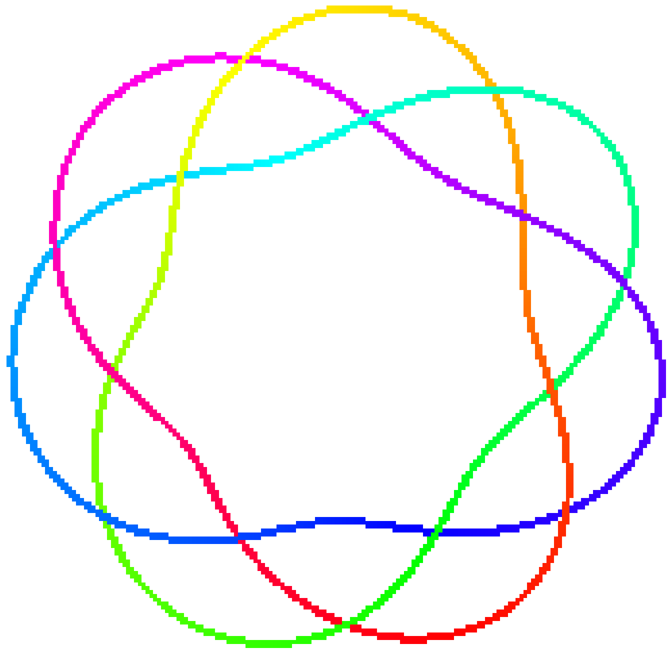
Torus Knots



(7, 2) Torus Knot



(7, 3) Torus Knot

Torus Knot Equations

$$r = R + a\cos 2\pi pt$$

$$\theta = 2\pi qt$$

$$z = a\sin 2\pi pt$$

$0 \le t \le 1$

R : the radius from the center of the hole to the center of the torus tube

a : is the radius of the tube

Realistic beam orbit is equivalent to the projected torus knot.

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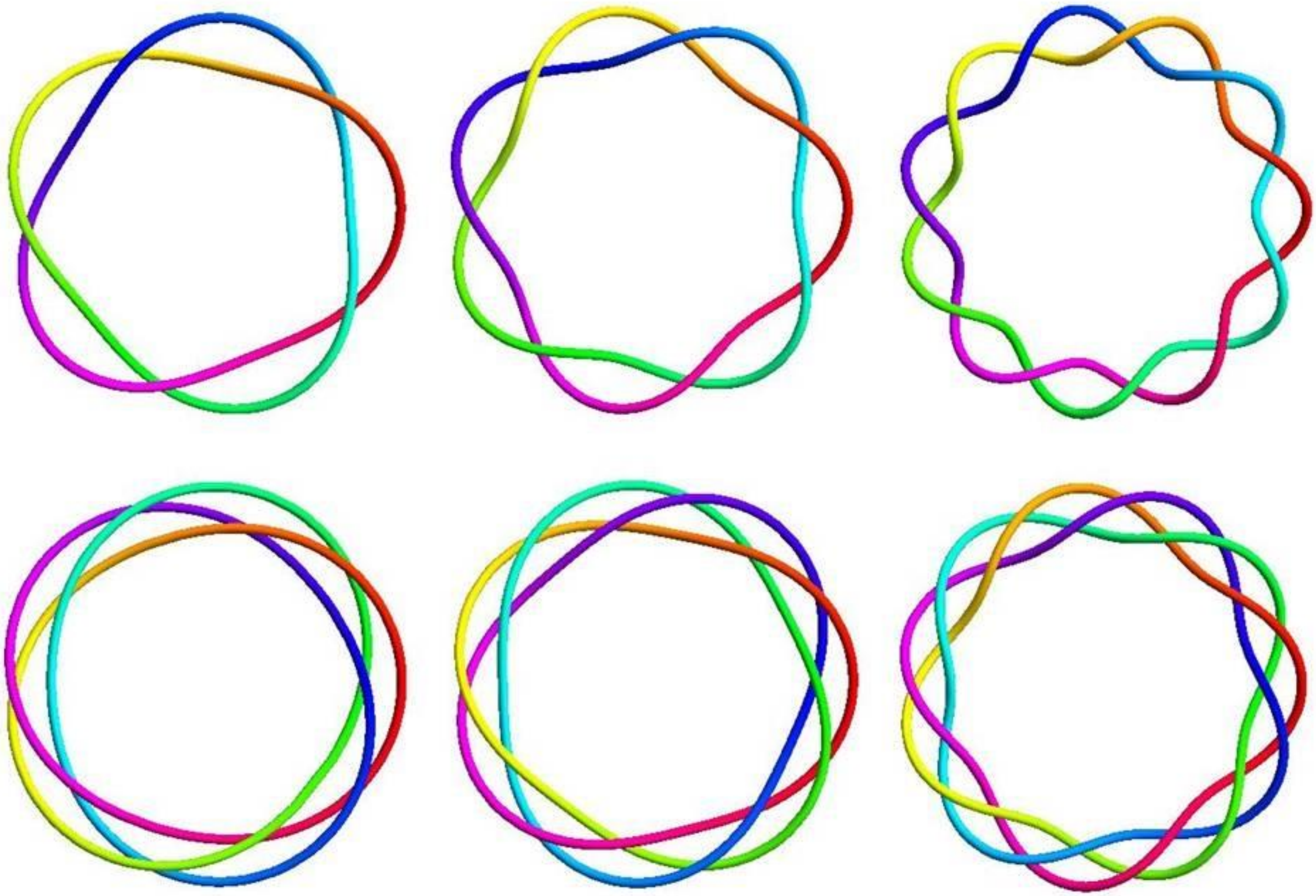
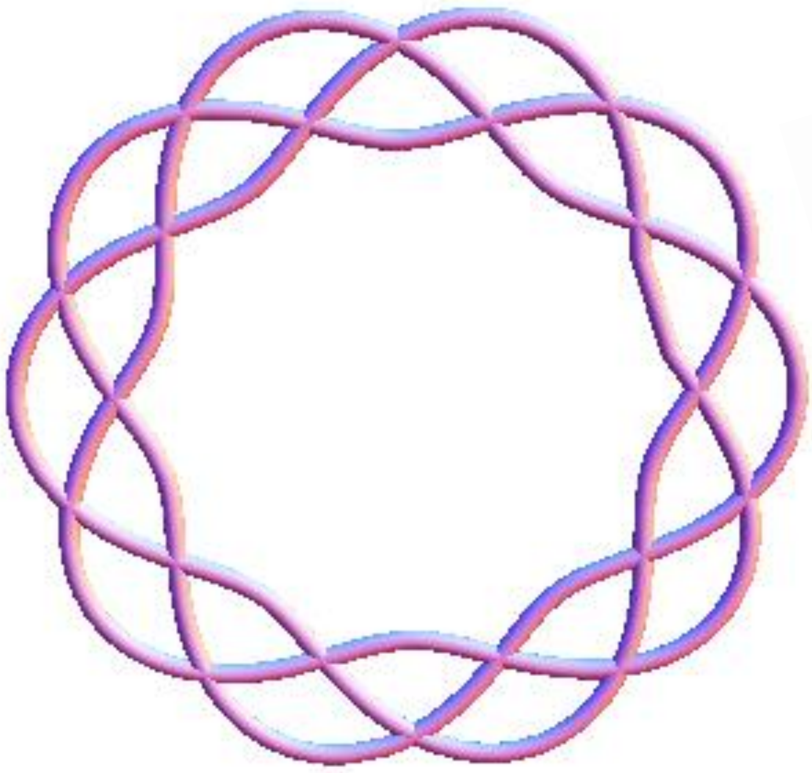
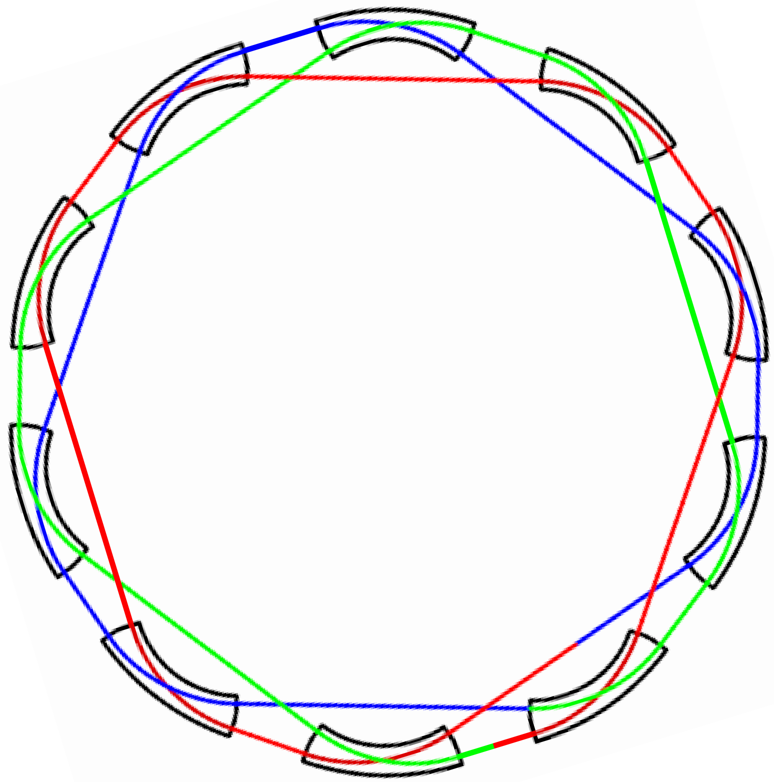
Projected Torus Knots



How to Create the New Lattice



(10, 3) torus knot



BM layout and design orbit

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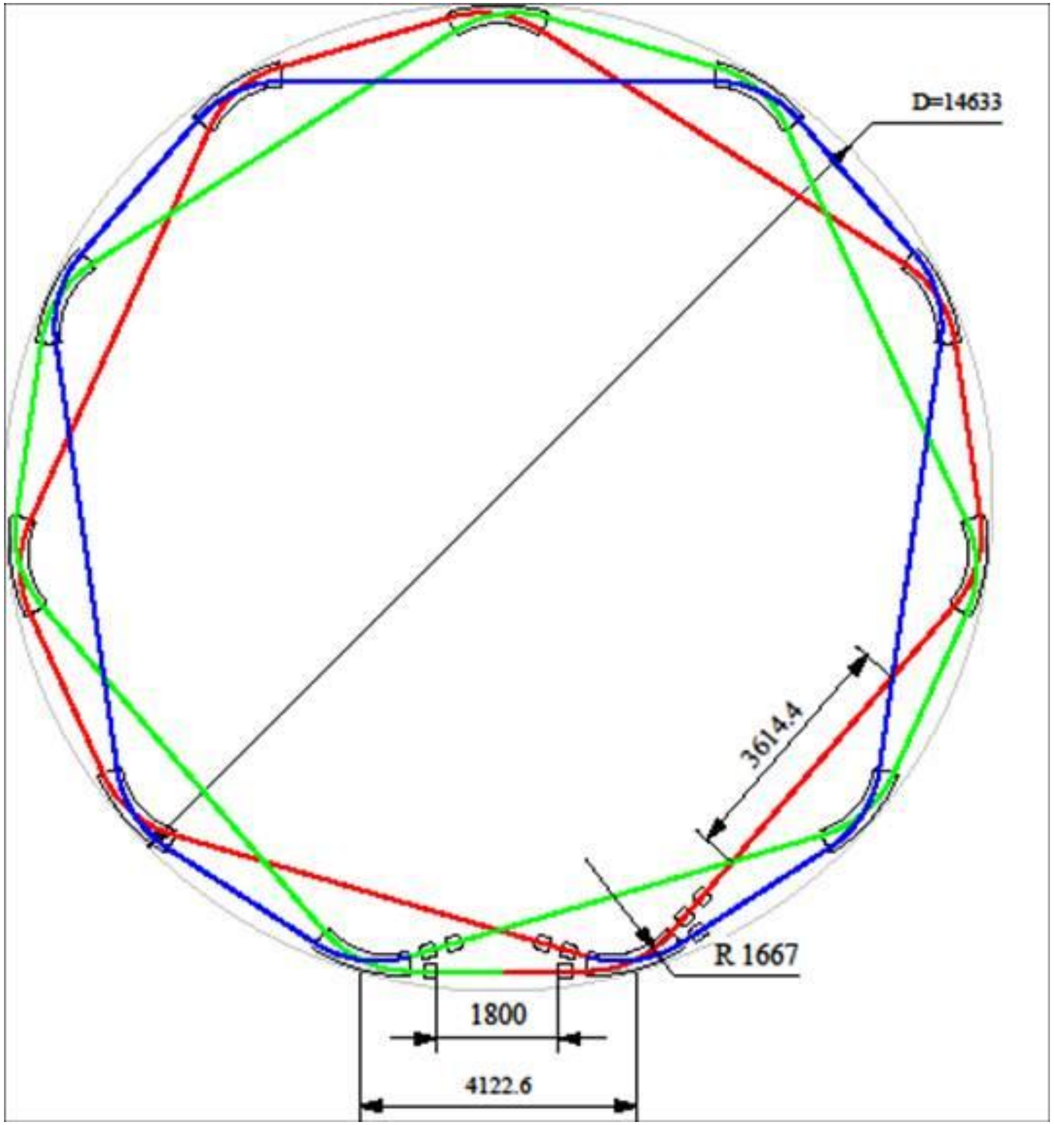
Example of HiSOR II+ Lattice

11-fold symmetry

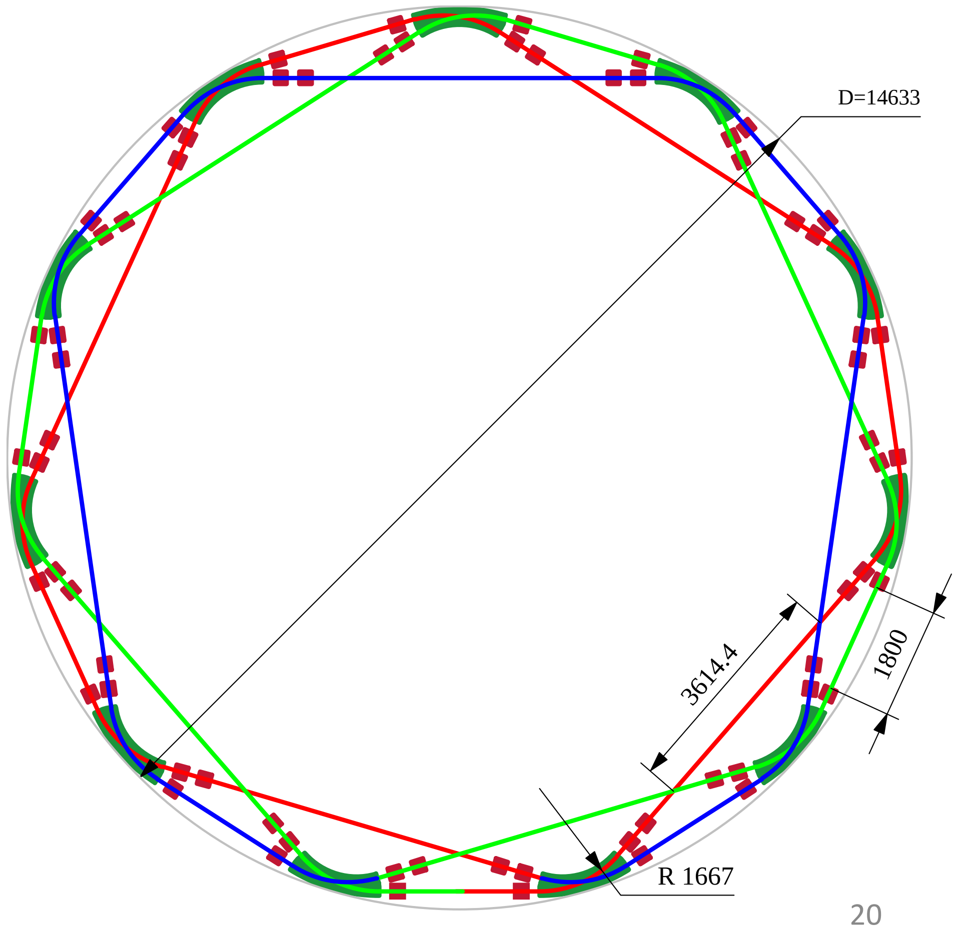
Electron trajectory returns to original position after 3 turns



Length of orbit 130.19 m
Circumference 45.97 m

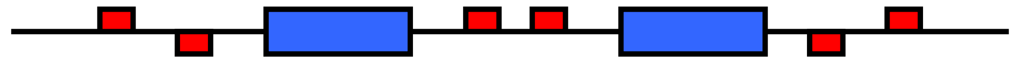
Lattice for HiSOR-II plus

- Lattice Type
  - MAX-III / DBA
- 11 straight sections
  - Most straight sections can be used for IDs
  - Injection, RF-cavity can be installed in short straight sections
- 3-turen orbit
  - Compare with a conventional ring, 3-times longer:
    - Closed orbit
    - Circulation time



Low Emittance Lattice

- Double Bend Achromat
  - No dispersion in straight sections
  - Achromatic optics



- Non-Achromatic DB
  - Non-achromatic optics
  - Lower emitance than DBA

- MAX-III Type
  - Ultra-low emittance
  - QD component in BM
    - Need combined function BM

$$\varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4}$$

$$I_2 = \oint \frac{1}{\rho^2} ds, \; I_4 = \oint \frac{D}{\rho}\left(\frac{1}{\rho^2} + 2K\right) ds,$$

$$I_5 = \oint \frac{H}{|\rho|^3} ds.$$

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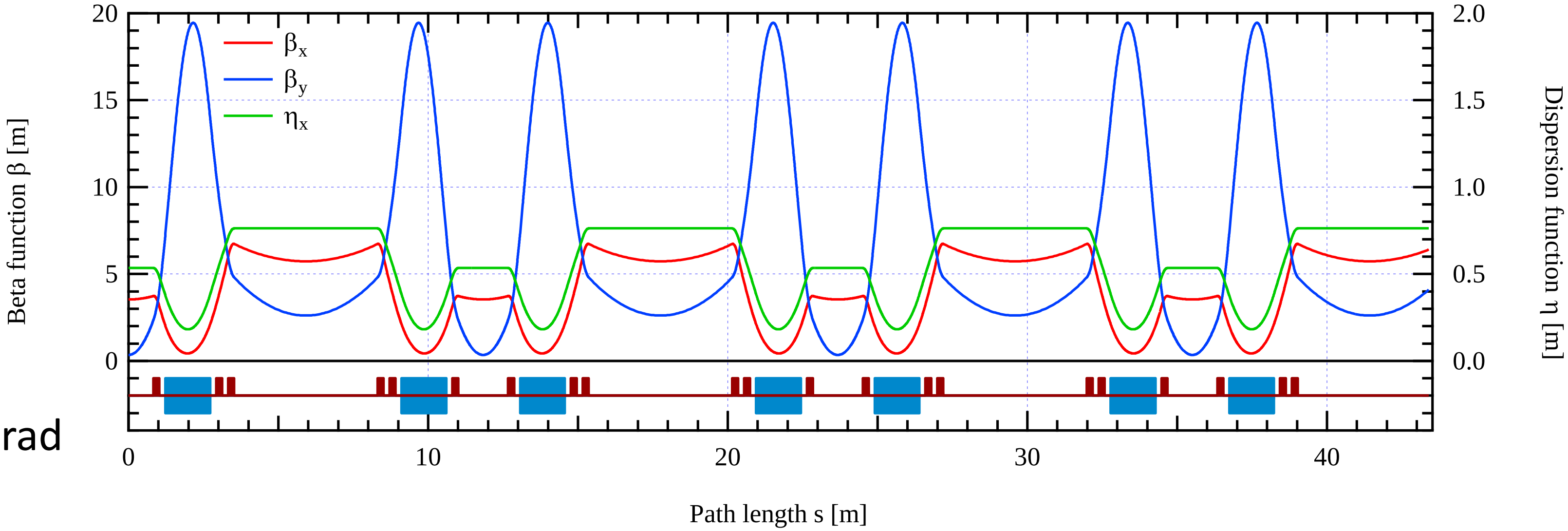
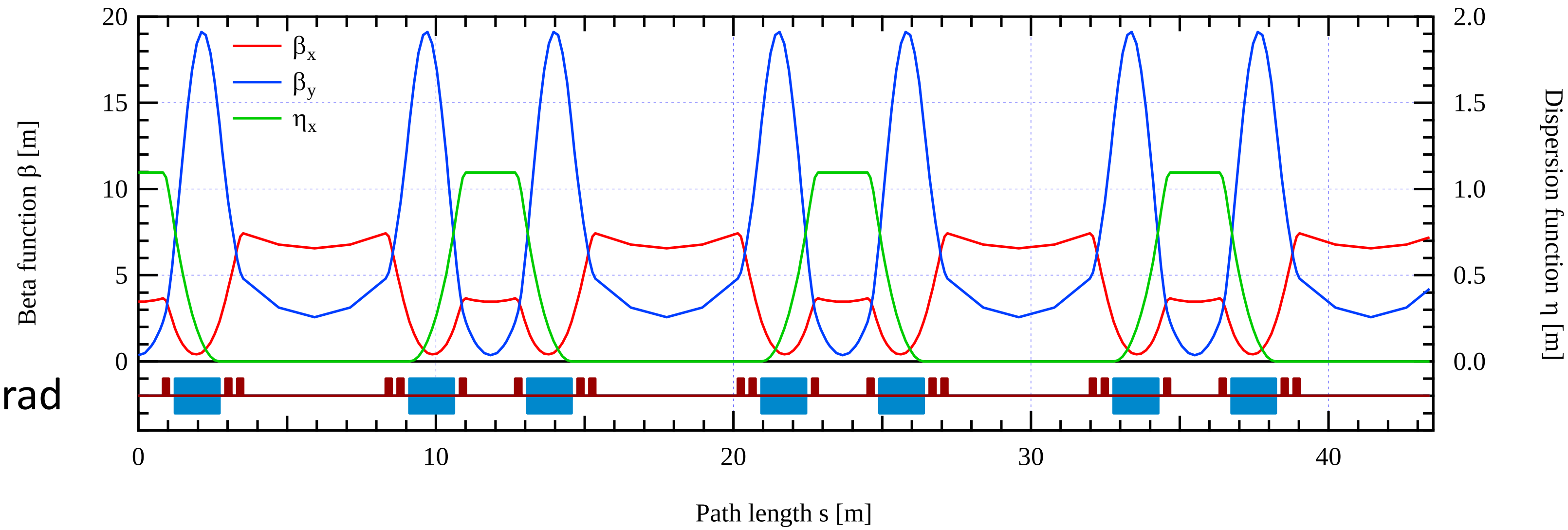
HiSOR

Electron Beam Optics



ε_0=17.9 nmrad



ε_0=38.9 nmrad

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Major Parameters

Perimeter	45.97 m
Orbit shape	(11,3) Torus knot
Orbit length	130.187 m
Beam energy	700 MeV
Straight sections	3.614 m ×11 1.800 m ×11
Harmonic number	88
RF frequency	202.474 MHz
Low emittance mode	
Betatron tune	(10.54, 6.67)
Natural emittance	17.9 nmrad
DBA mode	
Betatron tune	(10.78, 6.93)
Natural emittance	38.9 nmrad

Laser Power in Storage Ring FEL

The most interesting thing is that the energy radiated into the laser mode is proportional to the emitted synchrotron energy. – by A. Reniere (1979)

$$P_L = \frac{\chi}{4N} P_S$$

P_s: synchrotron power lost in one machine turn
χ: efficiency function
N: number of undulator period

R. Bartolini, et al, Phys. Rev. 69, 036501 (2004)

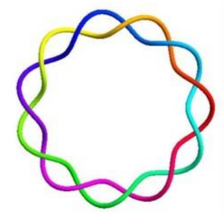
The energy lost by synchrotron radiation per revolution

Conventional Lattice

$$U_0 = (2\pi)\frac{2r_e}{3(m_0c^2)^3}\frac{E^4}{\rho}$$

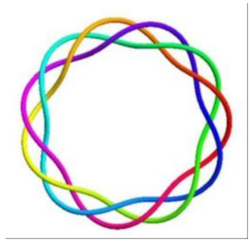
Two-turn Lattice

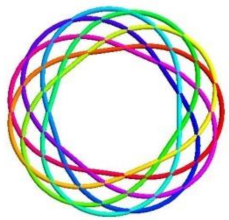
$$U_0 = (4\pi)\frac{2r_e}{3(m_0c^2)^3}\frac{E^4}{\rho}$$



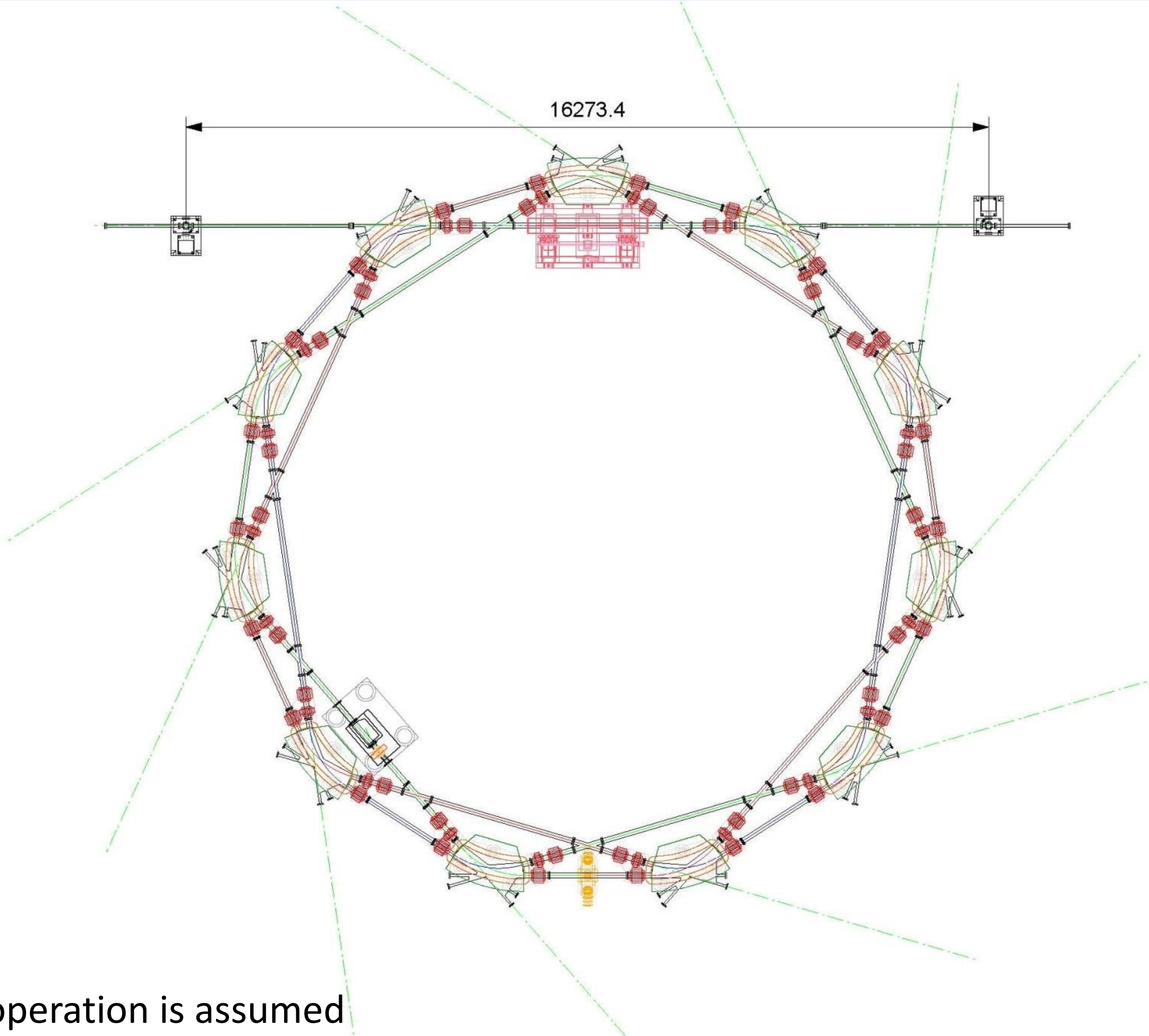
Three-turn Lattice

$$U_0 = (6\pi)\frac{2r_e}{3(m_0c^2)^3}\frac{E^4}{\rho}$$





Layout of Accelerator and FEL Components



4-bunch operation is assumed

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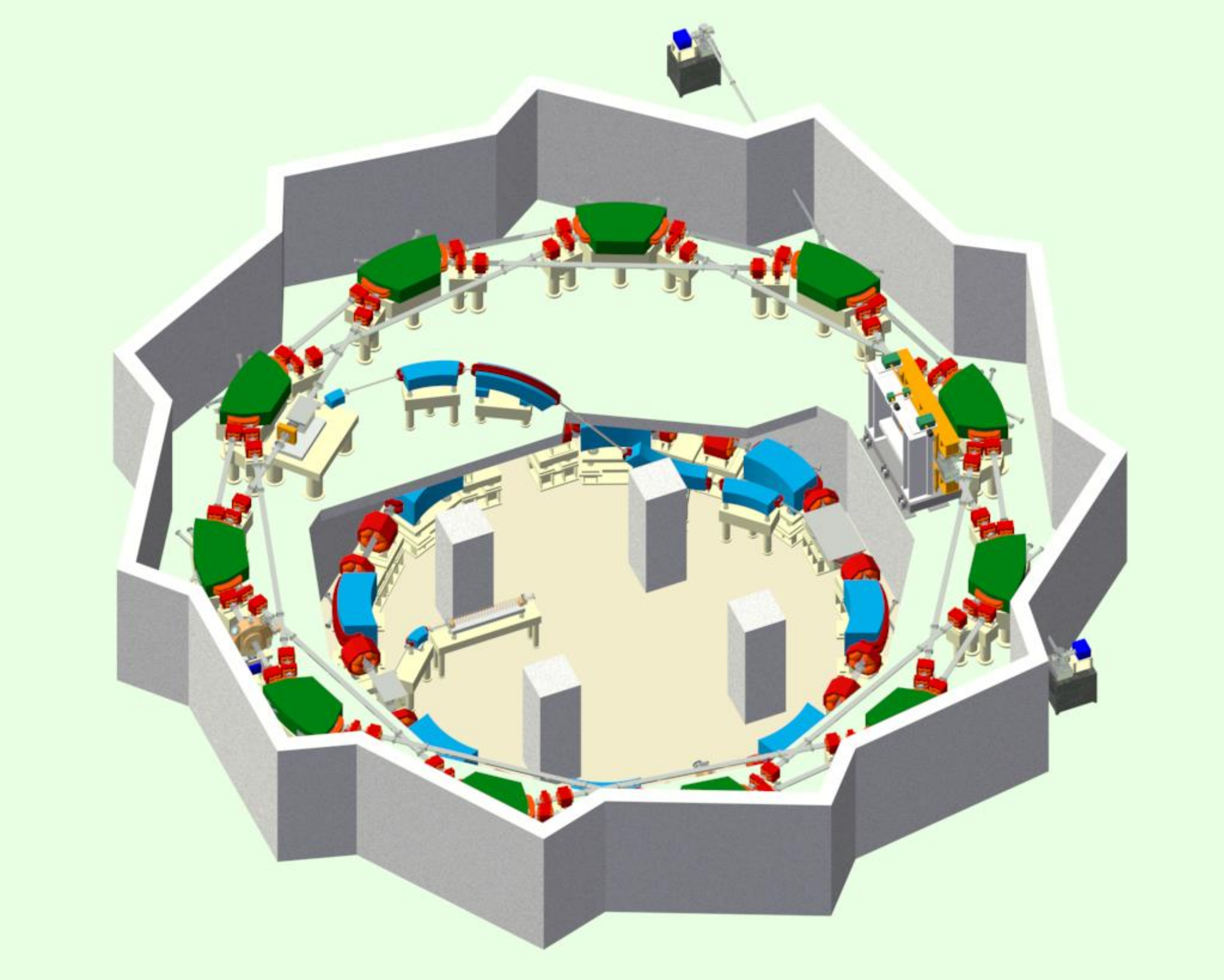
Possible Layout of HiSOR-II-plus FEL



Summary

- We propose a new scheme of lattice design for a compact storage ring.
- In this lattice, the number of straight sections for IDs is drastically increased.
- The length of beam orbit is 3-times longer than that in a conventional ring.
- Outer short straight sections may be used for inserting additional magnets to achieve lower emittance (triple-bend, DW, etc.)
- This new scheme can be beneficial to increase laser power in oscillator FEL.