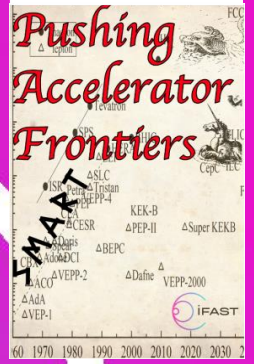
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Progress at the Accelerator Frontier

Report on WP5 Task 2

Frank Zimmermann, CERN; Giuliano Franchetti, GSI

Christian Carli, CERN; Iryna Chaikovska, IJClab; Florian Hug, JGU Mainz; Rasmus Ischebeck, PSI; Bernd Lorentz, GSI



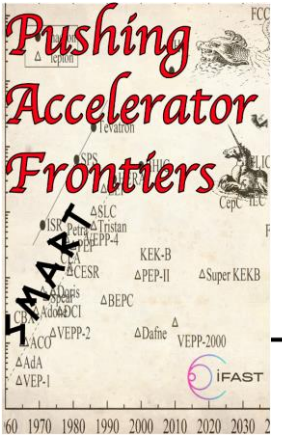
iFAST

5th and Final I.FAST Annual Meeting, 21-22.10.2025

Intensity and Brightness Frontiers

For physics based on storage rings, in a global view the main actors pushing for ultimate brightness include:

- The storage rings of GSI (ESR, CRYRING) + HESR are part of the FAIR plan,
- The CERN proton and ion rings (LEIR, PSB, PS, SPS, LHC)
- The IMP China facility with the Lanzhou storage rings.
- CERN AD and ELENA with antiprotons at low energy.
- The HIAF project in China with the SRring for the storage of exotic beams.



I.FAST

Innovation Fostering in Accelerator Science and Technology

Horizon 2020 Research Infrastructures GA n° 101004730

milestone delivered

MILESTONE REPORT

ULTIMATE HADRON-BEAM BRIGHTNESS

MILESTONE: MS19

Document identifier:	IFAST-MS19
Due date of deliverable:	End of Month 1 (September 2025)
Report release date:	31/9/2025
Work package:	WP5: SMART, Task 2: PAF
Lead beneficiary:	CERN
Document status:	Draft

ABSTRACT

The activity of Task 5.2 “Pushing Accelerator Frontiers” (PAF) supports the community effort in pushing the hadron-beam brightness. Bright hadron beams are fundamental for atomic and nuclear physics experiments as well as for achieving novel ultra-precise nuclear clocks (HITHOR). Multi-species beams in storage rings are foreseen as a novel intriguing possibility for collisions in a moving frame, and new insights into nuclear reactions. Space-charge forces and intra-beam scattering are two fundamental mechanisms that limit the ultimate beam brightness. Pushing Accelerator Frontiers has co-organized the “Space Charge 2024” workshop where the state of the art in this domain has been reviewed.

Pushing Accelerator Frontiers activity

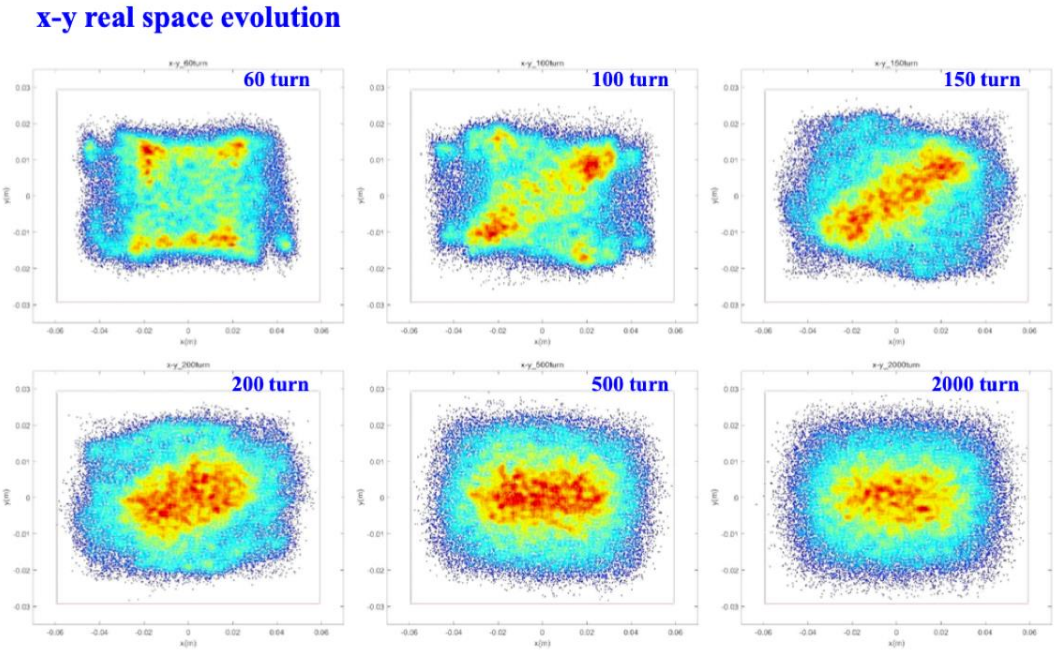
Consolidation of Innovation	**Frontier Activity**
Pushing Accelerator Frontiers	**Concepts Legacy Catalogue**

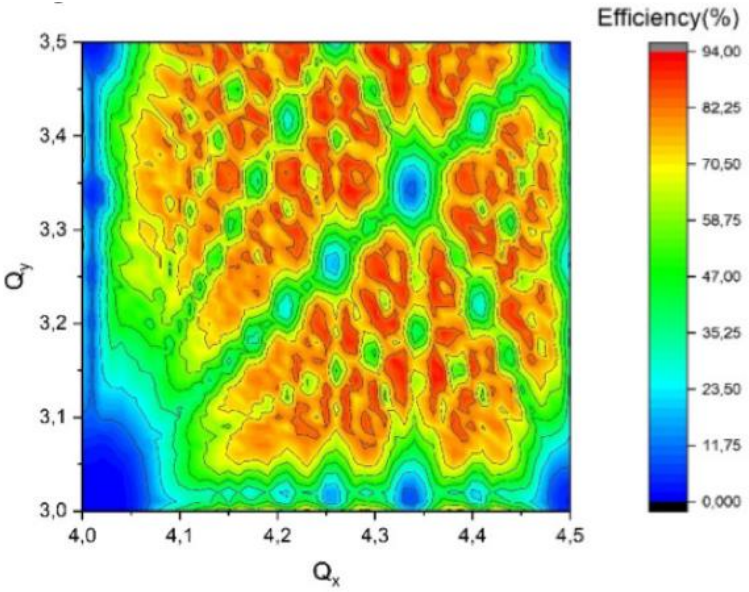
Frontier Activity

Concept class	Concept Summary	Maturity/ Technical readiness level	Use case or facility	Suggested next steps
Advanced Injection Schemes	Two-plane injection	Under study: towards CDR	FAIR / HIAF	tests and implementation
	Slip stacking injection	Implemented	FNAL/ Tevatron	
	Longitudinal / hybrid top-up injection, swap-out injection	Being implemented	APS-U, HEPS, FCC-ee	
	Resonant island injection	Under study	ELETTRA, EIC/RHIC	tests and implementation

Two-plane MTI will become operational at HIAF

Ongoing development
At GSI and HIAF



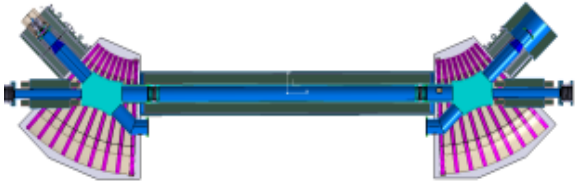


Frontier Activity

Concept class	Concept Summary	Maturity/ Technical readiness level	Use case or facility	Suggested next steps
Mitigation of space charge effects	Compensation with electron lenses	Under development	FAIR	Proof of principle demonstration
	Longitudinal bunch shaping (multi-RF)	Available at CERN	Simple to be implemented	Development of optimized schemes for high intensity
	Integrable Optics Test Accelerator (IOTA) ring	Developed at FNAL	New concept for high intensity	Effectiveness for high proton bunches

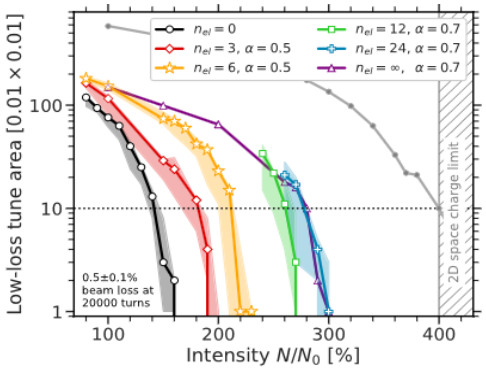
Space charge compensation with electron lenses

3D model of SCC electron lens



test stand at Goethe University Frankfurt

K. Schulte-Urlichs, D. Ondreka, ARIES 2022



SIS100 space charge limit - Low-loss tune area against intensity for various electron lens configurations - PRL 132, 175001 (2024)

NOVEL -->
Longitudinal bunch shaping via RF-multi harmonics is very promising (ongoing study)

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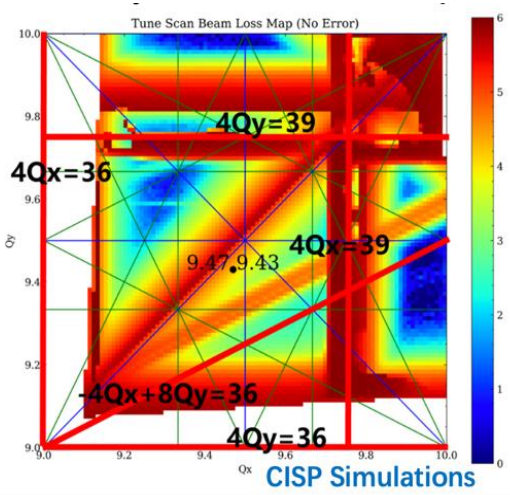
Frontier Activity

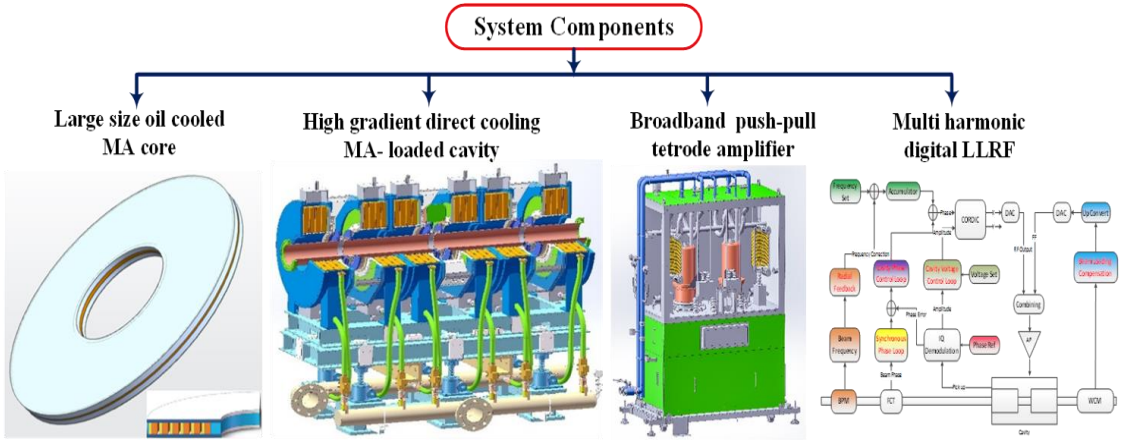
Concept class	Concept Summary	Maturity/ Technical readiness level	Use case or facility	Suggested next steps
Mitigation of collective effects	Fast ramping	12 T/s under study/ development	Fast resonance crossing	Activity ongoing at HIAF
	Wide band longitudinal and transverse feedback systems	Available/under development	CERN/FAIR/ HIAF/CSNS/J-PARC	

Resonances and
space charge at HIAF

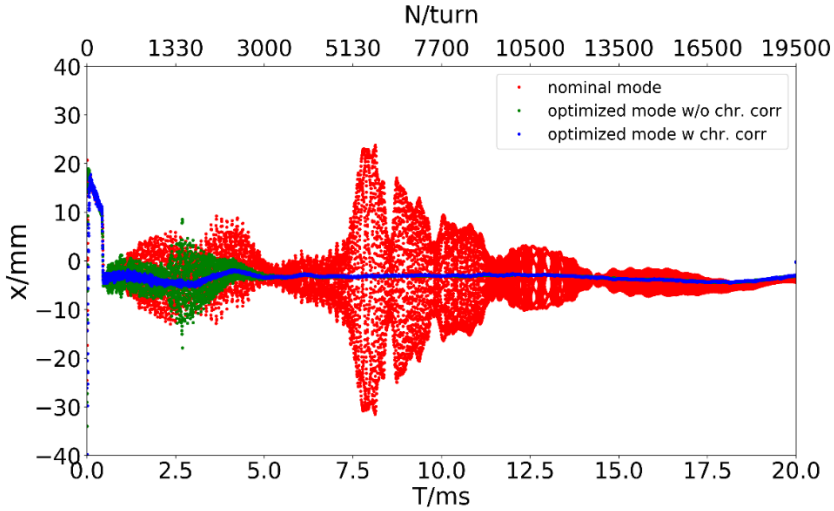


Simulations for the BRing
at HIAF

Fast Ramping 12 T/s with novel technology as
a mitigation strategy (under development at HIAF)



Rapid Cycling Synchrotron of the CSNS is also affected by an instability.
The increase of the beam power towards 140 kW led to horizontal instabilities arising about 8 ms after injection, which worsen for higher intensity.



steps

- Source of the impedance → RF shield on the ceramic chambers.
- Simulations including this impedance yield a consistent beam behaviour.
- The impedance of all chambers in the RCS has been assessed

Frontier Activity

Concept class	Concept Summary	Maturity/ Technical readiness level	Use case or facility	Suggested next steps
Preserving the Ultimate Brightness	Electron cooling	implemented	storage rings	integration in the
	Stochastic cooling	Past readiness, decommissioned in several labs	FAIR/BNL	Re-establish the technical know how
	Laser cooling	Under development	FAIR	Proof of principle demonstration/ advanced modeling
	Optical stochastic cooling	At R&D stage, demonstrated at IOTA		Consolidation
	Extreme modeling	Modeling IBS (p-p) and Schottky	interpret measurements of extreme beams	Carry on the (joint)studies and collaborations

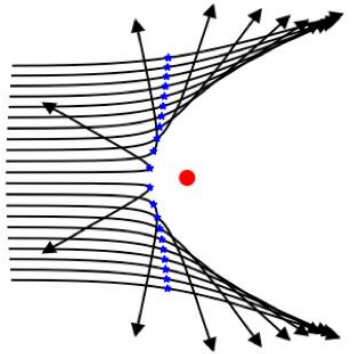
Status of the cooling systems

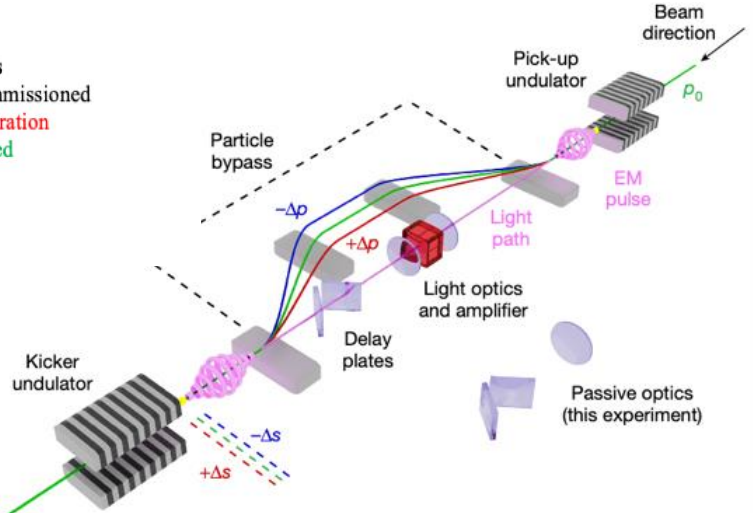
Electron Cooling Systems
NAP-M, Novosibirsk, Russia, 1974
ICE-Ring, CERN, Switzerland, 1979
Test Ring, Fermilab, Chicago, USA, 1980
LEAR, CERN, Switzerland, 1987
IUCF Cooler, Bloomington, Indiana, 1988
TSR, Heidelberg, Germany, 1988 and 2004
TARN II, Tokyo, Japan, 1989
CELSIUS, Uppsala, Sweden, 1989
ESR, GSI, Darmstadt, Germany, 1990
ASTRID, Aarhus, Denmark, 1992
CRYRING, Stockholm, Sweden, 1992, now at GSI
COSY, Jülich, Germany, 1993 and 2013
SIS18, GSI, Darmstadt, Germany. 1998
Antiproton Decelerator (AD), CERN, 1998
HIMAC, Chiba, Japan, 2000
LEIR, CERN, Switzerland, 2005
Recycler, Fermilab, Chicago, USA, 2005
S-LSR, Kyoto, Japan, 2005
CSRm, IMP Lanzhou, China, 2005
CSRe, IMP Lanzhou, China, 2008
ELENA, CERN, Switzerland, 2018
CSR, Heidelberg, Germany, 2019
LEReC, BNL, Brookhaven, USA, 2019
NICA Booster, Dubna, Russia, 2021
NICA Collider, Dubna, Russia
HIAF, Huizhou, China
EIC, BNL, Brookhaven, USA
IOTA, Fermilab, USA
FAIR, Darmstadt, Germany

Stochastic Cooling Systems
ICE-Ring, CERN, Switzerland, 1979
Test Ring, Fermilab, Chicago, USA, 1980
NAP-M, Novosibirsk, Russia 1981
ACOL, AA, CERN, Switzerland, 1983
Debuncher, Accumulator, FNAL, Chicago, USA, 1983
TARN II, Tokyo, Japan, 1983
LEAR, CERN, Switzerland, 1987
COSY, Jülich, 1993
ESR, GSI, Darmstadt, Germany, 1995
Antiproton Decelerator (AD), CERN,1998
Recycler, Fermilab, Chicago, USA, 2005
RHIC, BNL, Brookhaven, USA, 2006
CSRe, IMP, Lanzhou, China, 2008
IOTA, Fermilab, USA, 2022 OSC
NICA, Dubna, Russia
HIAF, Huizhou, China
FAIR, Darmstadt, Germany

Status
decommissioned
in operation
planned

Extreme modeling:
P-P collision, modeling of
Schottky signal for bunches



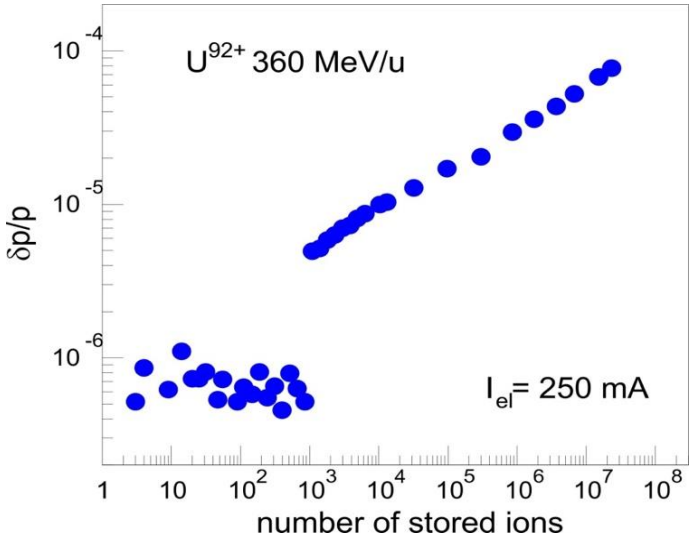


J. Jarvis, V. Lebedev, et al. Nature 608 287-292 (2022)

Frontier Activity → New Concepts – Legacy Catalogue

Concept class	Concept Summary	Maturity/ Technical readiness level	Use case or facility	Suggested next steps
Advanced Beams & Storage Rings	Crystalline beams for physics	Demonstrated in the past, but not part of operations	For extreme colliders	Restart a new experimental campaign to boost intensity limits
	Dual species storage ring & collider	First tests in ESR already initiated	nuclear scattering in a moving frame of reference	To be carried on in IFRATEC-EPITA
	Dielectric laser acceleration of single e- at high rep rate	Under development by global collaboration	indirect dark matter searches	1 m long prototype accelerator
	Plasma acceleration of pions and muons	Conceptual proposal	Muon collider	Proof-of-principle at AWAKE

Explore the limit of intense crystalline beams
In storage rings



Intensity limits ??

18 Nuclear Instruments and Methods in Physics Research B24/25 (1987) 18–25
North-Holland, Amsterdam

THE HEAVY ION STORAGE AND COOLER RING PROJECT ESR AT GSI

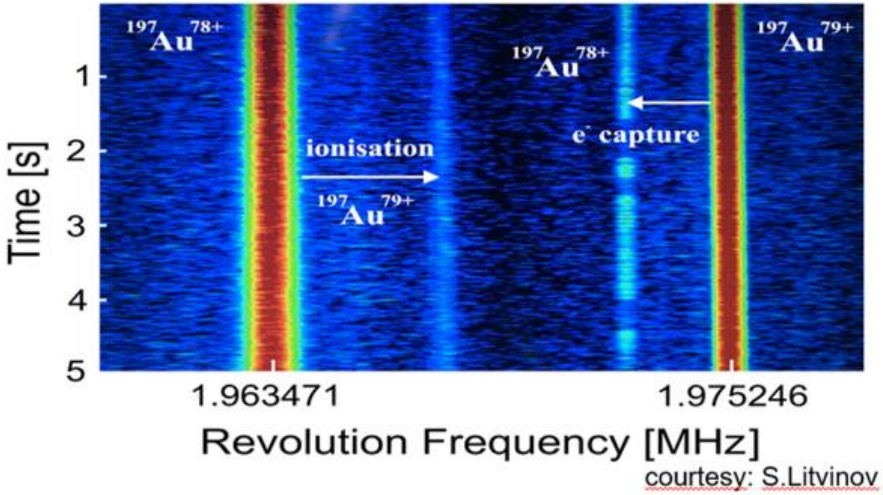
Bernhard FRANZKE
GSI-Darmstadt, Postfach 110541, D-6100 Darmstadt, FRG

…ge and cooler ring project at GSI

Ion–ion collisions: Collisions between two totally stripped or few electron heavy partners at energies up to the Coulomb barrier can be studied by crossing two beams [4]. The beams will co-circulate in the ESR at several 100 MeV/u on separate closed orbits due to slightly different momenta. By means of a spcial ion optical mode and additional quadrupoles the beams will cross each other at two positions. The luminosity, estimated from space charge and microwave stability limits, for the most interesting system $U^{92+} \rightarrow U^{92+}$ is 7×10^{23} cm^{-2} s^{-1}. It increases very strongly with lower charge state $\propto A^2 q^{-4}$. Charge exchange, δ-electron or quasi-molecular X-ray emission may be investigated within a large fraction of solid angle. Even a very clean observation of spontaneous electron-positron pair creation in the high Coulomb field of two naked uranium ions seems to be possible though the preliminary event rate estimate of 10^{-3} s^{-1} is very low [18].

Co-colliding beams

storage of two different ions of the same rigidity, on identical orbit, opening up the way to new experiments (demonstrated for Au78+, 79+ and U91+, 92+, could also be applied to different ions with apropriately selected chargestates)



courtesy: S.Litvinov

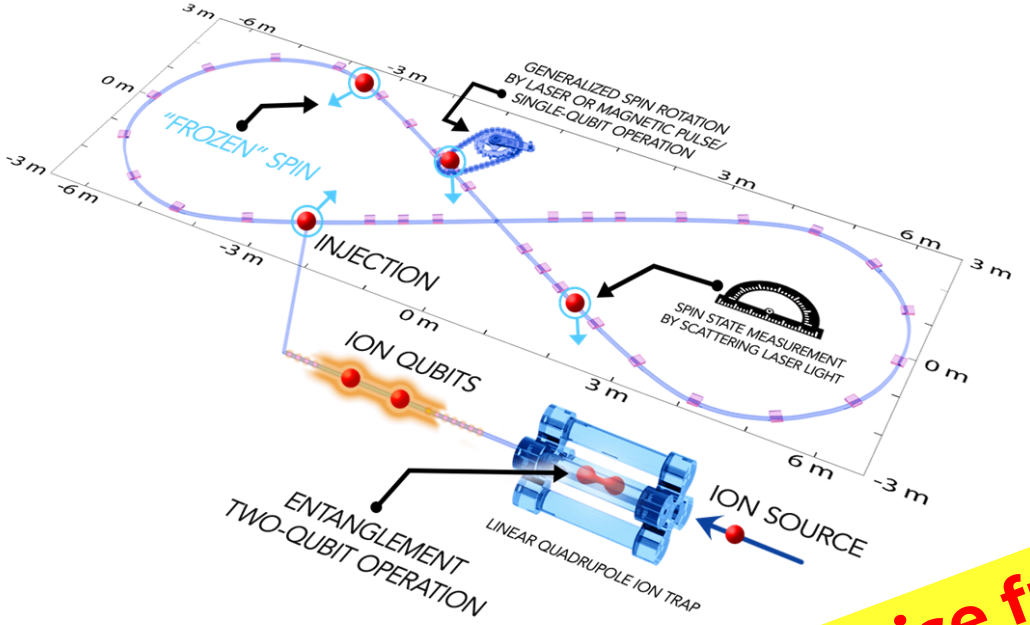
next steps:

- bunch the two beams
- cool the two beams
- crossing of the two beams at dedicated location

New Concepts – Legacy Catalogue

Concept class	Concept Summary	Maturity/ Technical readiness level	Use case or facility	Suggested next steps
Extreme Storage Rings	Storage rings as quantum computers	Promising , but needs further development for disruption control	Reaching large Qbit systems	Establishing proof of principle experiment in storage rings
	Storage rings as precision spin sensors for EDM and dark sector	At initial stage: needs extreme control of fields and orbits	Fundamental physics	Defining the roadmap for the next R&D facility
	Gravitational wave detection	Study case	Atomic interferometer or large storage ring with telescope optics	Carry on the study of theoretical schemes and requirements

Storage rings for quantum computing



spin transparent storage ring with entangled ion pairs as quantum computer

expertise from COSY & GSI & Goethe-U. Frankfurt

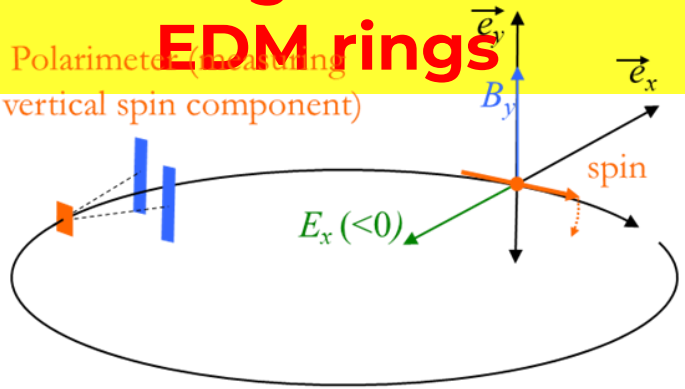
V. Morozov, iFAST Roadmap 2024

iFAST

Storage rings as precision spin sensors: EDM and dark sector !

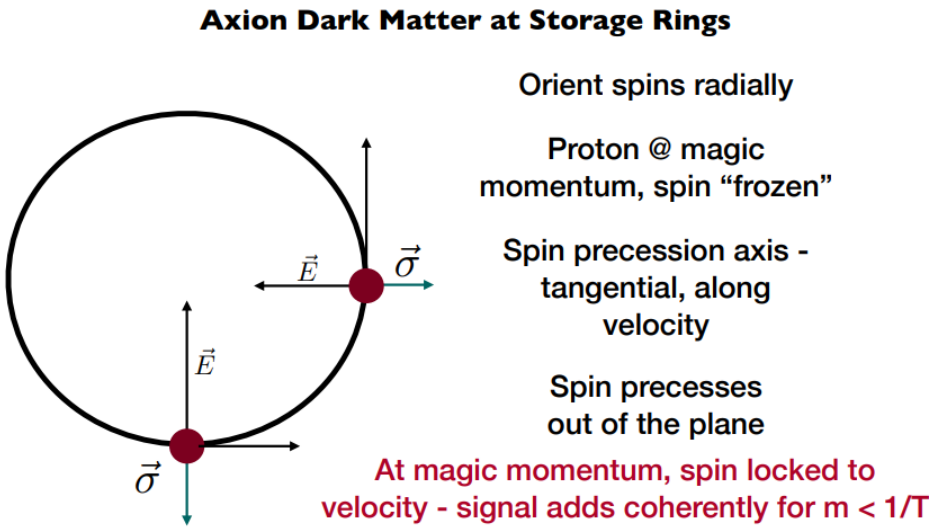
JHU brings new life to EDM rings

1. Technology well developed for electric dipole moment searches
2. Synergistic searches possible for dark matter, dark energy and monopole-dipole forces



Sketch of a generic **EDM ring**, **initial spin direction longitudinal**

C. Carli, iFAST Roadmap 2024



Sketch of a **dark sector ring**, **initial spin direction radial**

S. Rajendran, SRGWmb2025

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Pushing Accelerator Frontiers (iFAST WP5.2): activity summary

Pushing Accelerator Frontiers has catalysed and advanced two big areas of community activities:

1) Frontier Activity → all ongoing and advanced activities towards reaching high brightness and high intensity, which can be summarized as:

Frontier Activity

Advanced Injection Schemes	Advanced Acceleration Schemes	Mitigation of space charge effects	Mitigation of collective effects	Preserving the Ultimate Brightness

Pushing Accelerator Frontiers (iFAST WP5.2): activity summary

2) Identifying and exploring fundamental accelerator areas for further development, which push the present accelerator frontiers. This is condensed into a

Legacy Concept Catalogue

Advanced Beams & Storage Rings

Crystalline beams for physics

Dual species storage ring & collider

Dielectric laser acceleration of single e- at high rep rate

Plasma acceleration of pions and muons

Extreme Storage Rings

Storage rings for quantum computing

Storage rings as precision spin sensors: EDM and dark sector

Gravitational wave detection

spare slides

“Recent” series of iFAST-initiated or co-supported workshops

Roadmap for future accelerators – I.FAST WP5.2 workshop, Frankfurt a.M., Germany, 1-3 Sept. 2024

Channeling 2024 – Charged & Neutral Particles **Channeling Phenomena**, Riccione, Italy, 8-13 September 2024

Space Charge 2024 – **Space charge** in high-intensity accelerators, Dong Guan, China, 11-13 September 2024

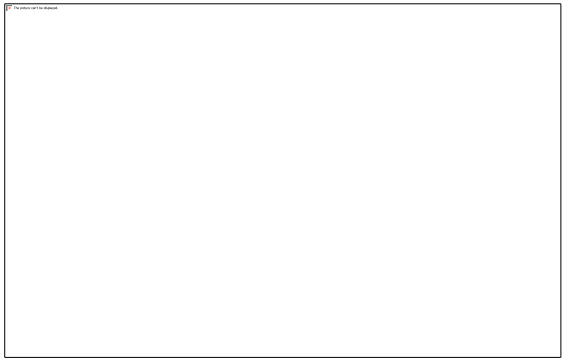
NanoAc2024 – Applications of **Nanostructures** in the field of Accelerator Physics, Valencia, Spain, 17-18 September 2024

AHIPS-2024 – Advances in **High-Intensity Positron Source** Physics and Technologies, Orsay, France, 16-17 (18) October 2024

SRGWmb2025 – **Storage Rings & Gravitational Waves** – mini-brainstorm, Geneva, Switzerland, 10-11 February 2025

upcoming: iFAST IBS Days, May or June 2025

Space charge - ultimate limit for light sources & e^- storage rings



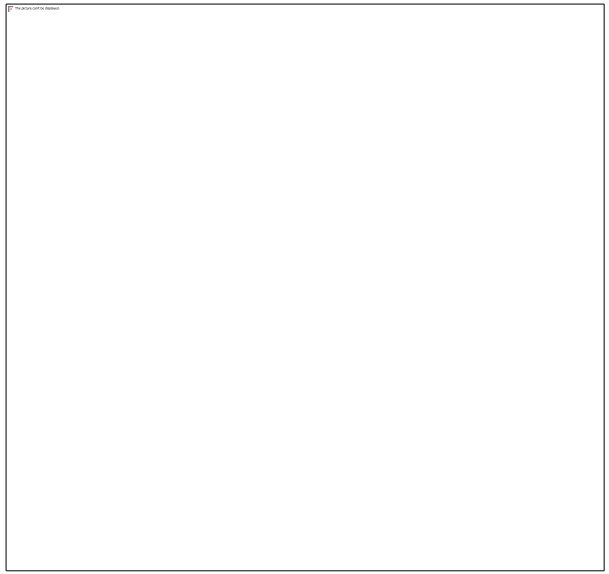
space charge can no longer be ignored in state-of-the art light sources

space charge limit increase with energy

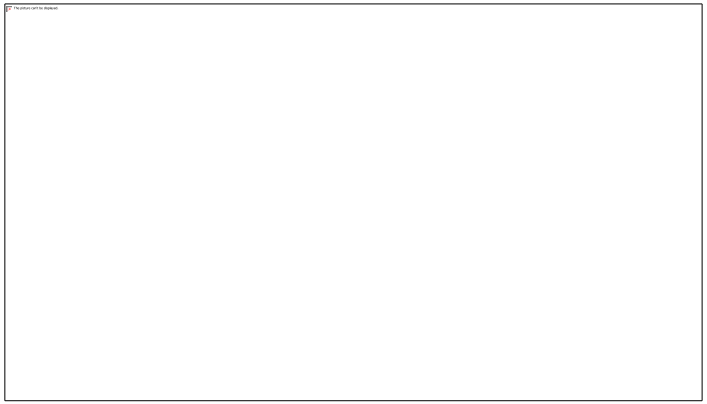
higher energy enables greater brightness

S. Antipov, Other Science Opportunities at FCC-ee

Light sources - efficiency is the name of the game !



X-rays at SPring-8-II compared with SPring-8

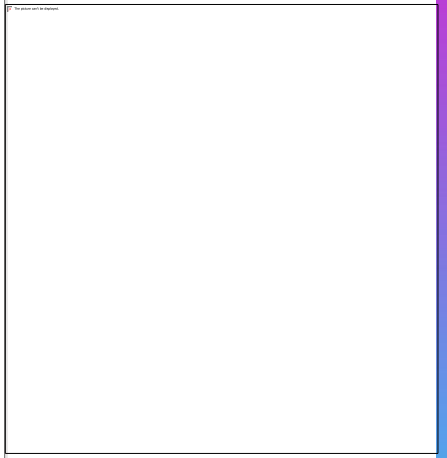


Change in the electrical power consumption of the RIKEN SPring-8 complex after system integration (combined linacs) and after implementing the SPring-8-II upgrade

Japan showing the way

H. Tanaka, iFAST Roadmap 2024

compact STorage ring for Accelerator Research and Technology



KIT's cSTART with 14 m diameter will produce ultrashort X-ray pulses and THz radiation, direct injection of an ultrashort bunch from a laser plasma accelerator → transformative impact

M. Fuchs, iFAST Roadmap 2024

Light source based on quasi-particles

quasiparticles are the result of collective motion, e.g., in a plasma

they can be subject to arbitrary acceleration and travel at any velocity, and **may generate novel forms of radiation forbidden for single particles**, such as quasiparticle Cherenkov superradiance, subluminal and superluminal quasiparticle undulator radiation

frequency range accessible by a plasma accelerator-based quasi-particle photon source spans nearly 10 octaves, from THz to the extreme ultraviolet

Photon beam brightness expected from plasma-based quasiparticle photon source as a function of photon energy

innovative approach from Portugal

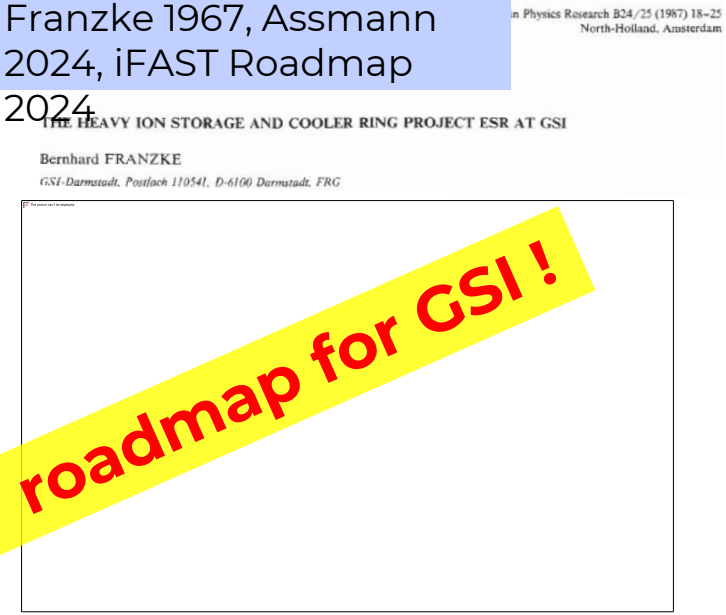
J. Viera, NanoAc'24

Dual species storage ring & collider

Beam-based fusion and neutron/isotope production

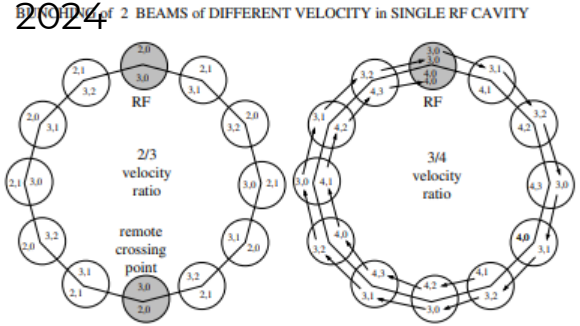
Particle kinetic energies ~100 keV – 1 MeV comparable with Coulomb potential barrier heights. Desired: nuclear scattering in a moving frame of reference. Such collisions could possibly be realized in the GSI ESR ring (Franzke 1967).

Franzke 1967, Assmann 2024, iFAST Roadmap 2024



Low-energy collider roadmap for GSI !

Talman 2024



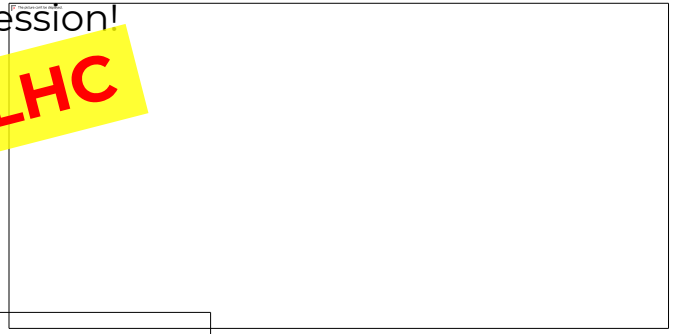
2-species acceleration at GSI SIS18 since 2024 !

Rosenzweig 2014

Bent crystals to measure magnetic dipole moment of rare particles – TWOCRYST experiment at the LHC

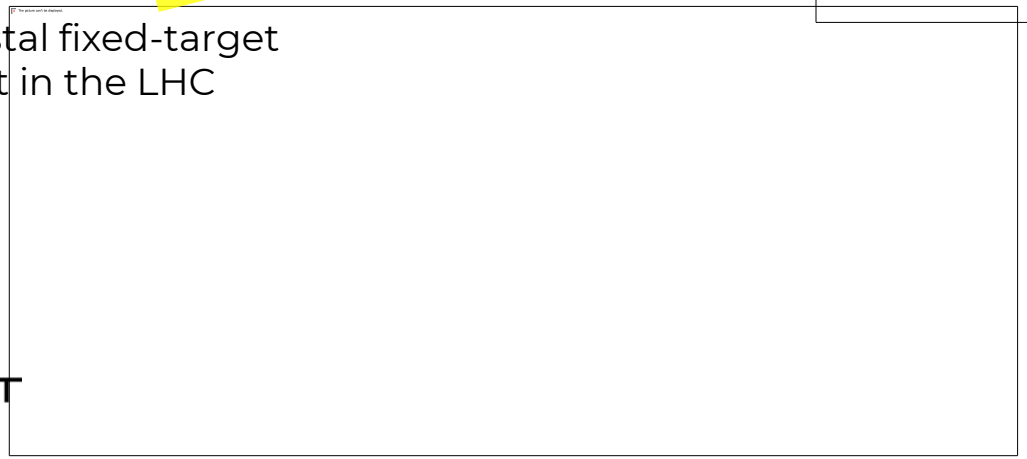
Short-lived baryons: Lifetime too short to measure electrical and magnetic dipole moments with conventional magnets

Electric field in bent crystals ~ GV/m (~500T) → induce measurable precession!



new physics at the LHC

double-crystal fixed-target experiment in the LHC



LHC MD studies in 2025

S. Redaelli, Channeling 2024

Nano-Accelerators

crystals and carbon nanotubes (CNT) can support acceleration levels of 100s of TeV/m

excited surface plasmons produce PeV electrons on the meter length scale

Different regimes of CNT acceleration include surface plasmons with leakage fields, and surface plasmon crunch-in. Only the CNT “blow-out” regime on the right is not suitable for particle acceleration

B. Lei, NanoAc’24

Nano-Accelerators : Proof-of-principle experiments

beam-driven experiments:

- CLARA / UK
- FACET-II / US

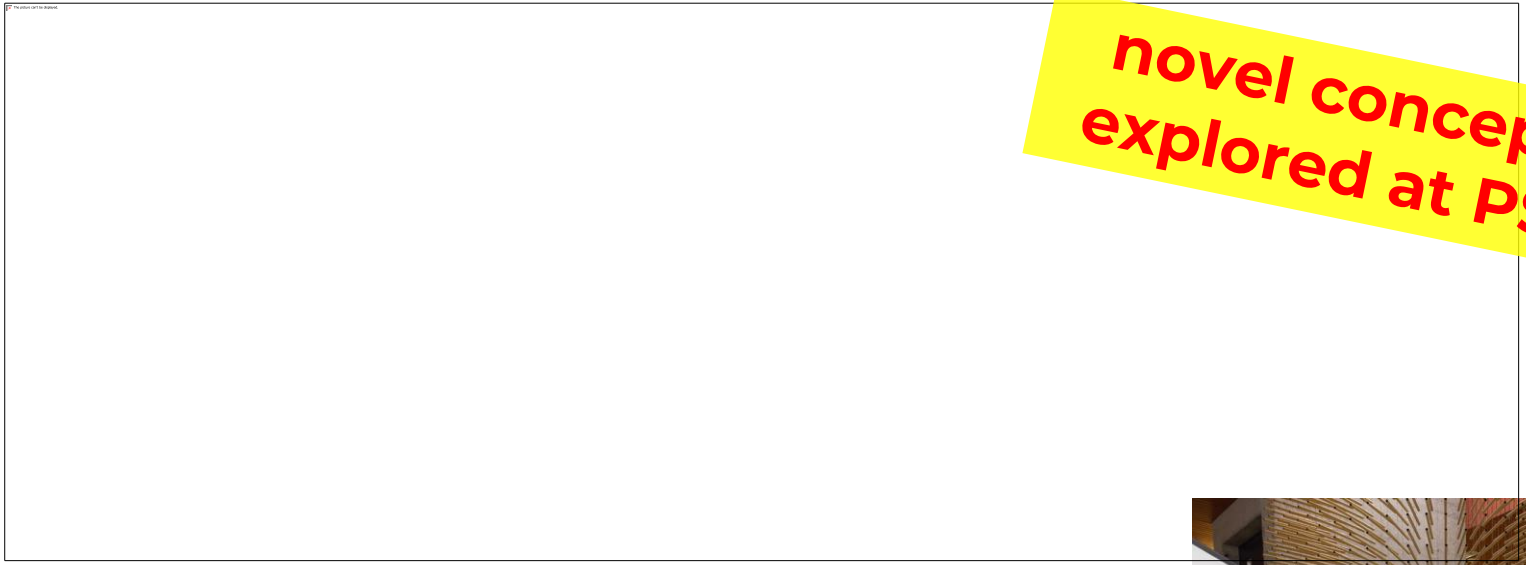
laser-driven experiment:

- **Pulsed Laser Center (CLPU) in Salamanca, Spain**

European Nano-Accelerator frontier : Salamanca

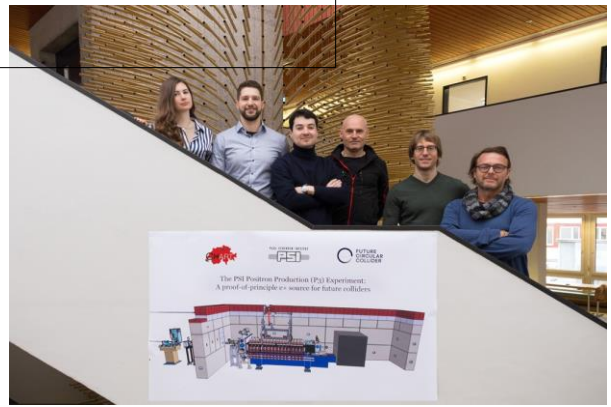
Present & Future CLPU Laser Beamlines

Intense Positrons: PSI Positron Production experiment « P3 »



novel concept explored at PSI

P3 components production and installation in SwissFEL



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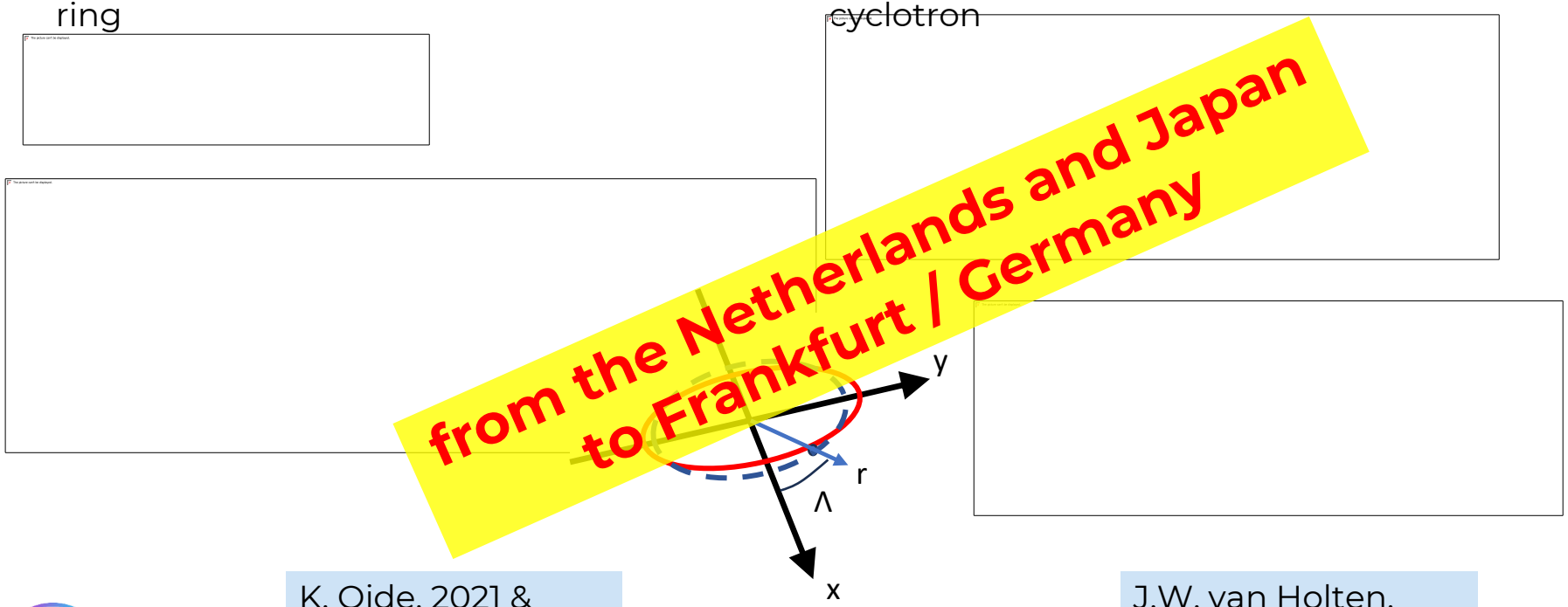
R. Zennaro et al., AHIPS-2024

I. Chaikovska, Roadmap 2026

Storage rings & gravitational waves – equations of motion?!

effect of GW on beam in a storage ring

effect of GW on beam in a cyclotron



K. Oide, 2021 & 2025
SRGW2021, SRGWmb2025

J.W. van Holten, 1999
G. Franchetti, 2025
SRGWmb2025

Storage rings & gravitational waves using atomic clocks

Uni Hamburg in exchange with Gamma Factory @ LHC

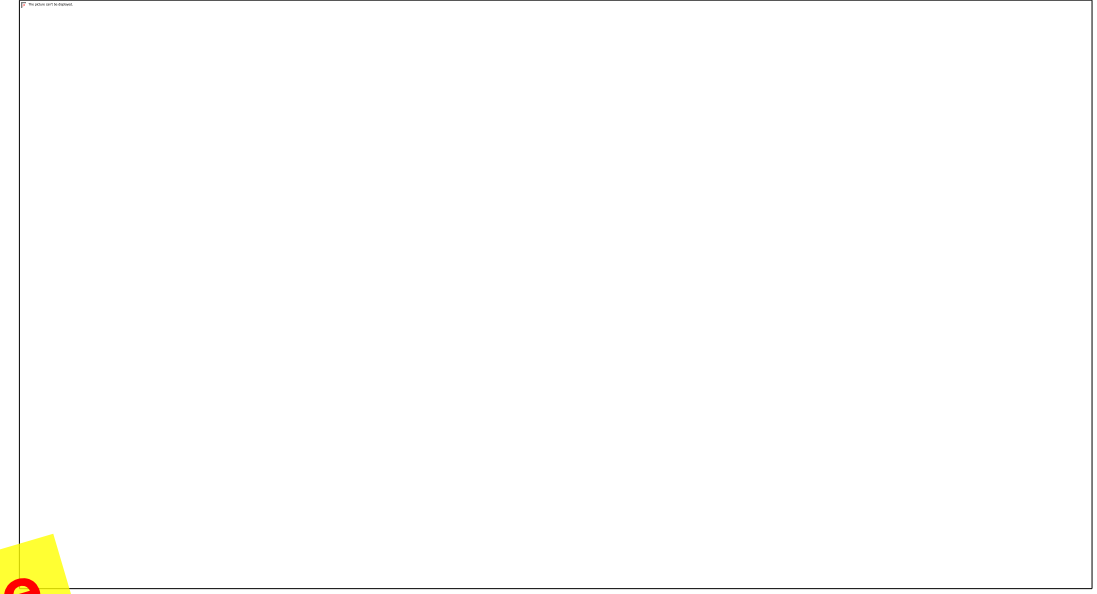
Gamma Factory !

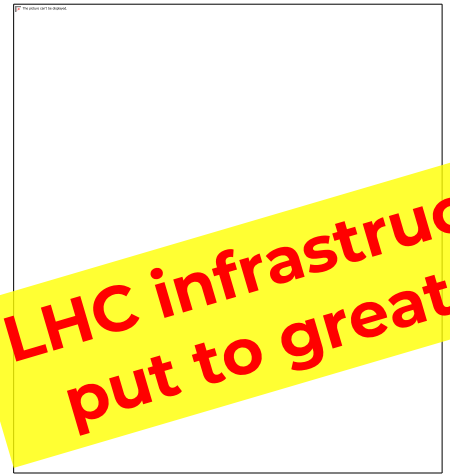
iFAST

T. Schmirander, SRGWmb2025

W. Krasny, SRGWmb2025

Accelerators & gravitational waves – atom beam interferometer in LHC access shaft





LHC infrastructure put to great use

J. Ellis,
SRGWmb2025

Conclusions

many promising new ideas and great progress
– multiple avenues to pursue:

- **plasma injector** of short bunches (KIT), and **quasi-particle radiation** in/from a plasma (Portugal)
- **beam chaser** collider, isotope production and **nuclear fusion at GSI ESR** ?
- **nano-accelerator PoP** at Salamanca
- **precision storage rings for dark sector searches** – where ? (FZJ, GSI, CERN?)
- **storage rings as quantum computers**
- **gravitational wave detection at the LHC and beyond**
  - AION, Gamma Factory, …

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Brightness
□

high-brightness beam requires a large beam current in a small phase space volume.

Challenges

Mitigations

Coulomb forces → incoherent
Coulomb forces → coherent

Accelerator nonlinearities +. High intensity → rapid coherent beam response
Accelerator nonlinearities +. High intensity → slow incoherent increase in emittance (amplitude-dependent detuning and magnet error resonances)

At HIAF, it is planned to deliver intense beams to targets.

The SRing will be realized through linac acceleration and two-plane injection into the Bring [1].

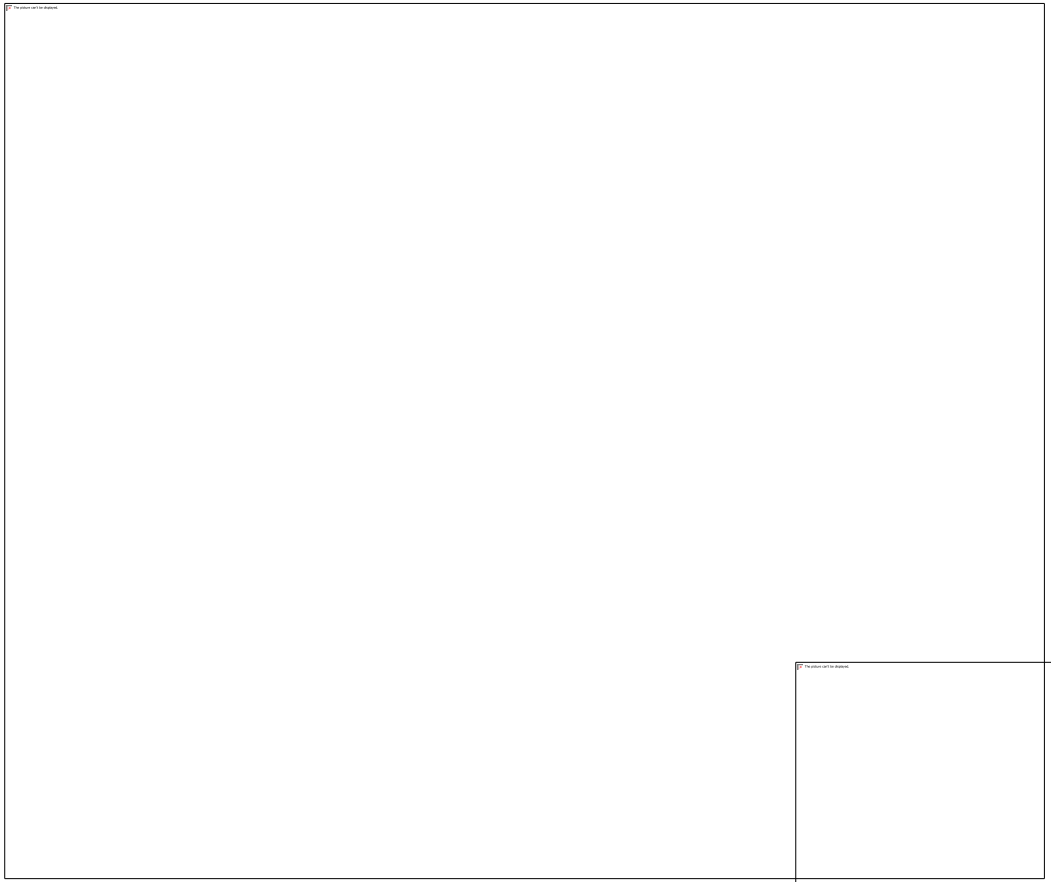
The design intensity is 2.0 × 10^11 ppp, which will be accelerated in a cutting-edge facility with a fast-ramping rate of 12 T/s and a high repetition rate of 3-5 Hz.

The beam will be longitudinally stacked when transferring from the Bring to SRing.

In these rings, the effect of the incoherent space charge in the presence of lattice nonlinearities is critical, especially in view of the potential 4th-order structure resonances driven by space charge in the Bring

WP5 deliverables

D5.1: International collaboration plans towards a multi-TeV muon collider Report on established collaboration and results disseminated by the action [MUST]	M46
D5.2: Roadmap for future accelerators	
Strategy for intense positron sources; R&D plan towards ultimate beams; State of the art and possible directions for crystalline beams; Strategy and requirements for EDM ring or other precision experiments; Roadmap for accelerator AI; State of the art and future roadmap for green accelerators [PAF]	**M42**
D5.3: Ripple mitigation for slow extraction beam quality improvement	
Simulation results for improvements including their experimental verifications, and design considerations of the accelerator control with related hardware. [REX]	M46



Summary, perceived status, and recommendations by topical area

WP5 milestones

MS15	International workshop on muon source design	5.1	M18
MS17	**Beam requirements for dark-sector searches** ✓	**5.2**	**M18**
MS18	**Present and future AI accelerator applications** ✓	**5.2**	**M24**
MS20	Engineering design of improved power supply current measurement and RF-amplifier layout	5.3	M24
MS16	International workshop to define R&D plans	5.1	M36
MS19	**Ultimate hadron-beam brightness**	**5.2**	**M48**