HORIZON 2020

Accelerator Performance and Concepts report from WP6

http://aries.web.cern.ch/content/wp6

Alessandro Drago / INFN-LNF, **Giuliano Franchetti / GSI & GUF**, Johannes Gutleber / CERN, Klaus Höppner / HIT, Florian Hug / JGU, Mauro Migliorati / Sapienza, Marco Zanetti / U Padova, and **Frank Zimmermann / CERN**

ARIES Final Review

Virtual Meeting, Online, 15 July 2022

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

APEC structure – a reminder

Task 6.1 Coordination and communication

Coordinated by Frank Zimmermann (CERN), Giuliano Franchetti (GSI)

Task 6.2 Beam Quality Control in Hadron Storage Rings and Synchrotrons

Coordinated by Giuliano Franchetti (GSI), Frank Zimmermann (CERN)

Task 6.3 Reliability and Availability of Particle Accelerators

Coordinated by Johannes Gutleber (CERN), Klaus Hoeppner (HIT)

Task 6.4 Improved Beam Stabilization

Coordinated by Mauro Migliorati (U. Roma Sapienza), Alessandro Drago (INFN-LNF)

Task 6.5 Beam Quality Control in Linacs and Energy Recovery Linacs

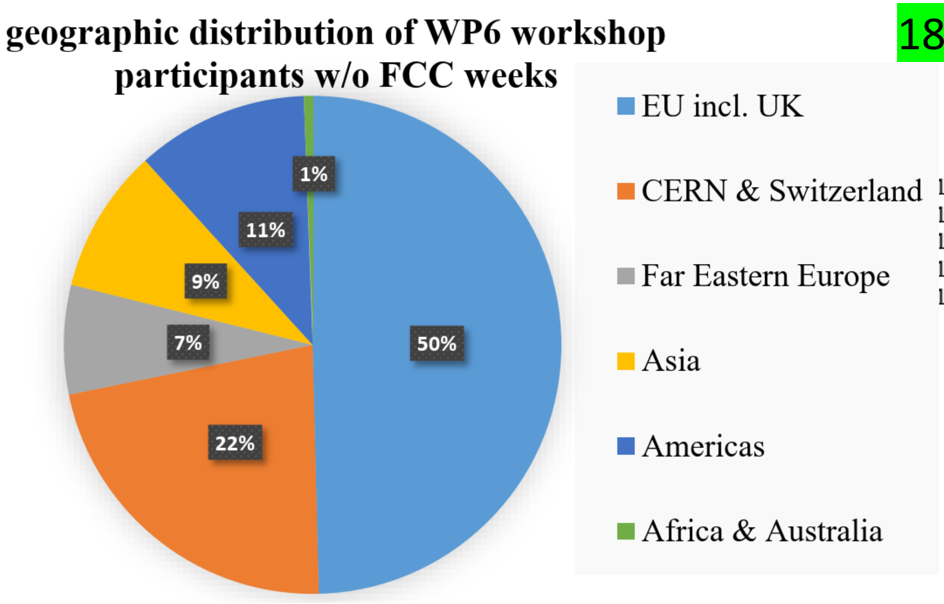
Coordinated by Florian Hug (JGU Mainz)

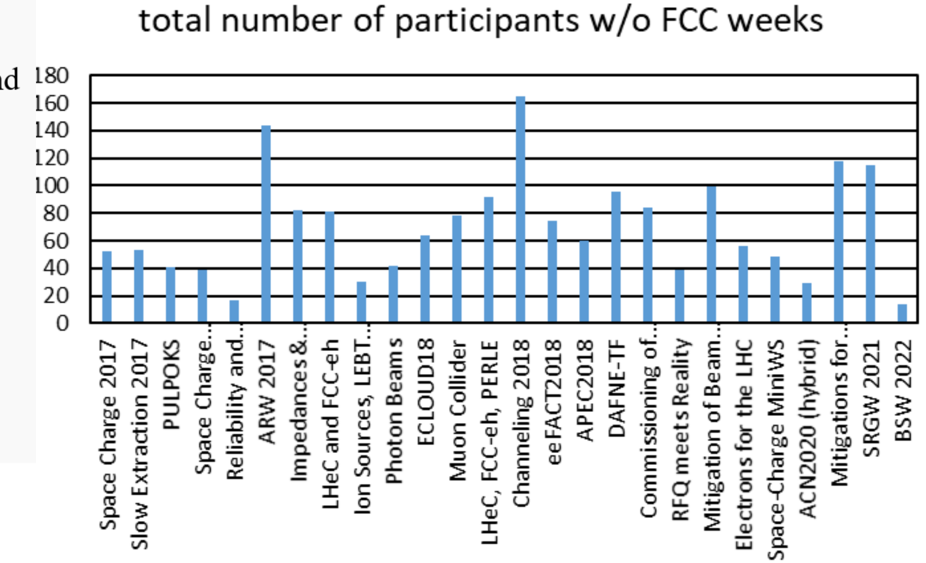
Task 6.6 Far Future Concepts & Feasibility

Coordinated by Marco Zanetti (INFN & U. Padova), Frank Zimmermann (CERN)

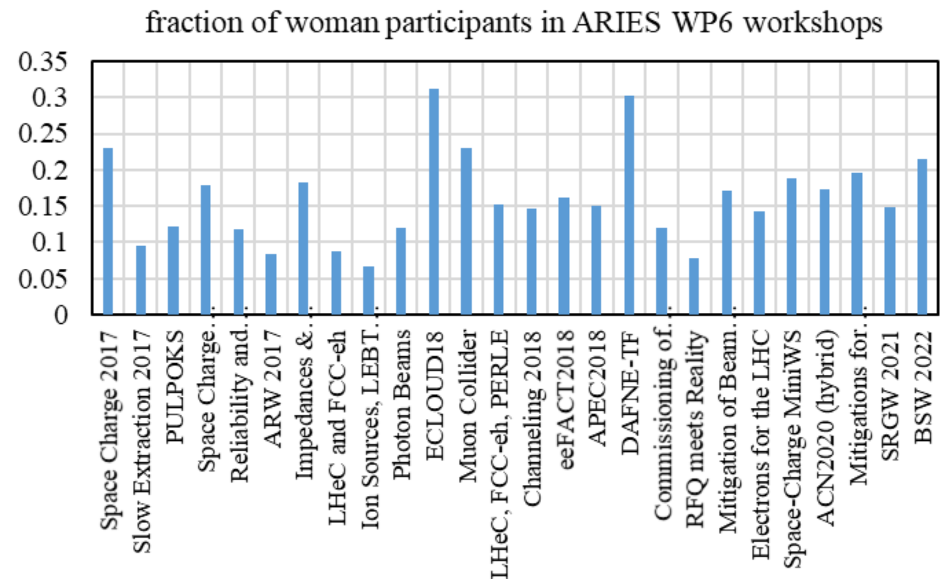
ARIES WP6 workshops

1812 (928) participants with (without) FCC Weeks





fraction of women participants in all WP6 workshops



28 WP6 workshops in total

some ARIES WP6 milestones and deliverables


ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
MILESTONE REPORT
Report on 1st Annual Workshops of all WP6 Tasks
MILESTONE: MS26

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
MILESTONE REPORT
Report on 2nd Annual Workshops of all WP6 APEC Tasks
MILESTONE: MS27

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
DELIVERABLE REPORT
Ranking of performance degrading mechanisms for hadron storage rings and synchrotrons (M28)
DELIVERABLE: D6.1

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
MILESTONE REPORT
Report on Parameter Database for Various ERL & Linac Facilities
MILESTONE: MS28

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
DELIVERABLE REPORT
Report on optimal RAMS characteristics for particle accelerators
DELIVERABLE: D6.2

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
MILESTONE REPORT
Report on 3rd Annual Workshops of all WP6 APEC Tasks
MILESTONE: MS29

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
DELIVERABLE REPORT
Summary of novel methods to reduce or mitigate accelerator impedance (M36)
DELIVERABLE: D6.3

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
MILESTONE REPORT
Report on Strategies for electron-cloud mitigation in future accelerators
MILESTONE: MS30

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
MILESTONE REPORT
Identification & prioritization of mitigation approaches
MILESTONE: MS31

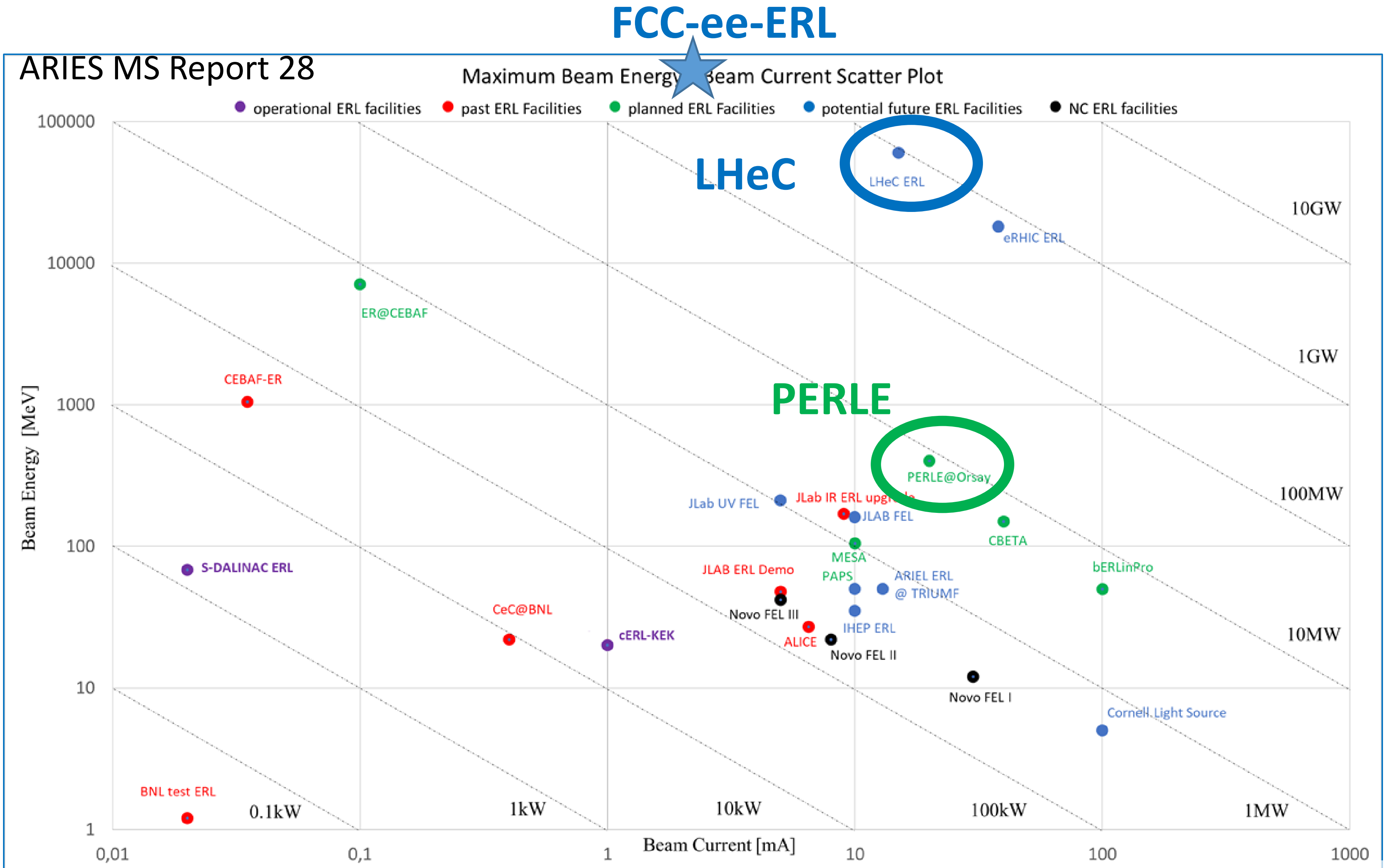
ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
MILESTONE REPORT
Feasibility of an Open Data Infrastructure for accelerator reliability
MILESTONE: MS32

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
DELIVERABLE REPORT
Outstanding open questions and prioritized R&D guidelines for Energy Recovery Linacs
DELIVERABLE: D6.4

ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871
DELIVERABLE REPORT
White List of Ranked Far-Future Accelerator Options
DELIVERABLE: D6.

WP6 work plan carried out > 100%, all deliverables completed

ERL landscape



LHeC/FCC-eh Workshop, CERN, Switzerland, 11-13 September 2017

LHeC, FCC-eh, and PERLE Workshop, LAL Orsay, France, 27-29 June, 2018

Electrons for the LHC, Chavannes-de-Bogis, Switzerland, 24-25 October 2019

F. Hug

ARIES MS28

recent HORIZON 2020 ARIES WP6 workshops, a covid circle

1. **Accelerator Applications of Crystals and Nanotubes,** EPFL Lausanne & ***hybrid!***, 10-11 March 2020

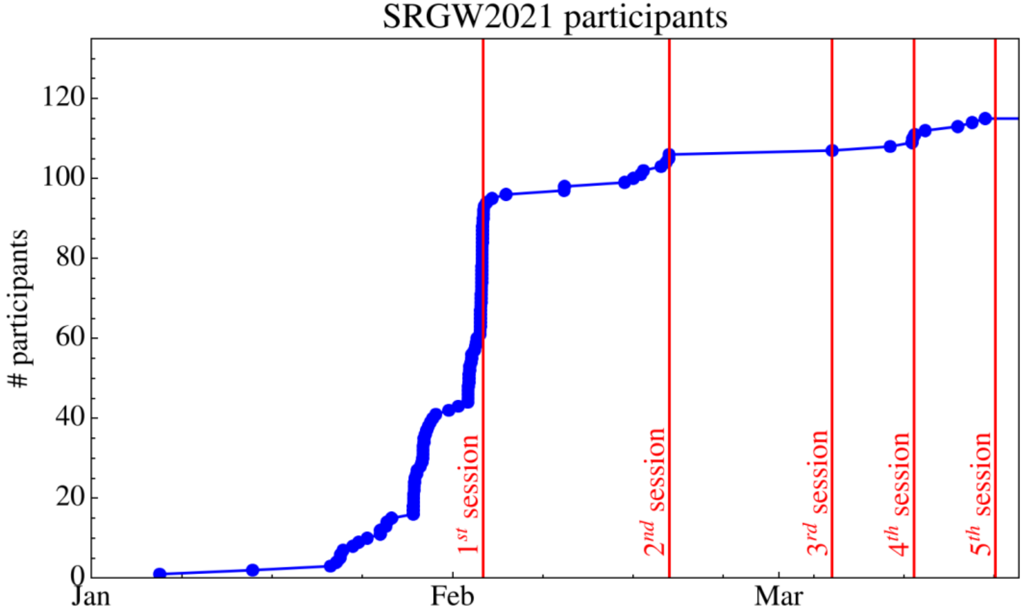
2. **Mitigation Approaches for Hadron Storage Rings and Synchrotrons (Mitigations2020),** ***safe virtual space***, 22 June – 1 July 2020

3. **ARIES Workshop on Storage Rings and Gravitational Waves (SRGW2021),** ***safe virtual space***, 2 February -18 March 2021

4. **ARIES WP6 APEC & iFAST WP5.2 PAF joint Brainstorming & Strategy Workshop (BSW22),** ***in-person!*** Colegio Mayor, Valencia, 30 March -1 April ‘22

ARIES Workshop on Storage Rings and Gravitational Waves (SRGW2021), virtual space, 2 February -18 March 2021 ; chaired by G. Franchetti, Marco Zanetti, and F. Zimmermann

115 registered participants



Scientific Programme Committee	
William A. Barletta	MIT
Pisin Chen	NTU
Raffaele-Tito D'Agnolo	IPHT
Raffaele Flaminio	LAPP
Giuliano Franchetti (co-chair)	GSI
Shyh-Yuan Lee	Indiana U
Katsunobu Oide	CERN & KEK
Qing Qin	ESRF & U. Peking
Jorg Wenninger	CERN
Marco Zanetti (co-chair)	U. Padova
Frank Zimmermann (co-chair)	CERN

main focus: detection and/or generation of gravitational waves or other gravity effects using storage rings & accelerator technologies

Sessions:

2/2/2021, **Introduction to Gravitational Waves and their effects,** chair: *Pisin Chen / NTU Taiwan*

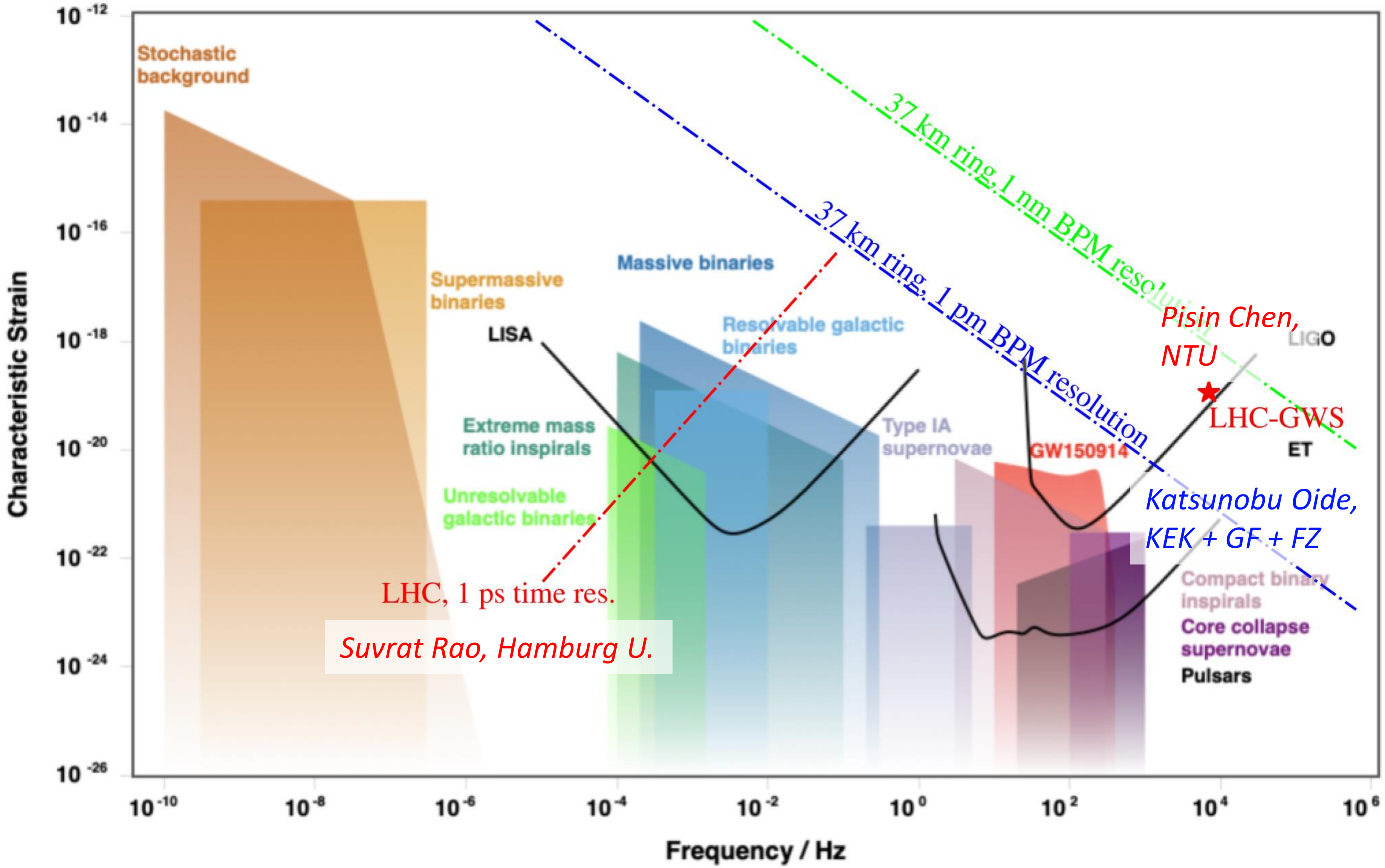
18/2/2021, **Measurements and sensitivity,** chair**:** *Shyh-Yuan Lee / Indiana U*

4/3/2021, **Proposals and Schemes**, chair*: Jörg Wenninger / CERN*

11/3/2021, **Gravitational wave generation and detection,** chair: *Frank Zimmermann / CERN*

18/3/2021, **Ground motion and final discussion,** chairs: *Giuliano Franchetti/GSI; John Ellis/CERN*

Detection (& Generation) Plot emerging from SRGW2021



G. Franchetti et al.

Ranking of performance degrading mechanisms for hadron storage rings and synchrotrons

Summary of the accelerator characteristics and main beam features at the laboratories participating in the ARIES ranking effort

Laboratory	Accelerator name	Accelerator Circumference (m)	Initial/final Energy (GeV)	Particles per bunch	Rms bunch length (cm)	Ramp time (s)/ stored time (s)
Fermilab	Booster	476	0.4/8	5E10	30	0.033
BNL	RHIC	3834	25/255	2E11	0.6	300/3600
CERN	SPS	7000	26/450	1.1E11	15	5/20
SLAC/SSRL	SPEAR3	234	3	8.7E9	0.6	NA
J-PARC	Main ring	1567.5	3/30	3.3E13	1500	1.4/0~2
INFN-LNF	DAFNE	97	510	1E11	1.06	0/1200
GSI	ESR	108	0.4/0.004	1E8	200	10/2000
GSI	SIS18/SIS100	216/1000	0.011/2.7	5E11	3000	0.5

End 2018, APEC2018 workshop

ARIES D6.1

Ranking results on performance degrading mechanisms for hadron storage rings and synchrotrons

ARIES D6.1

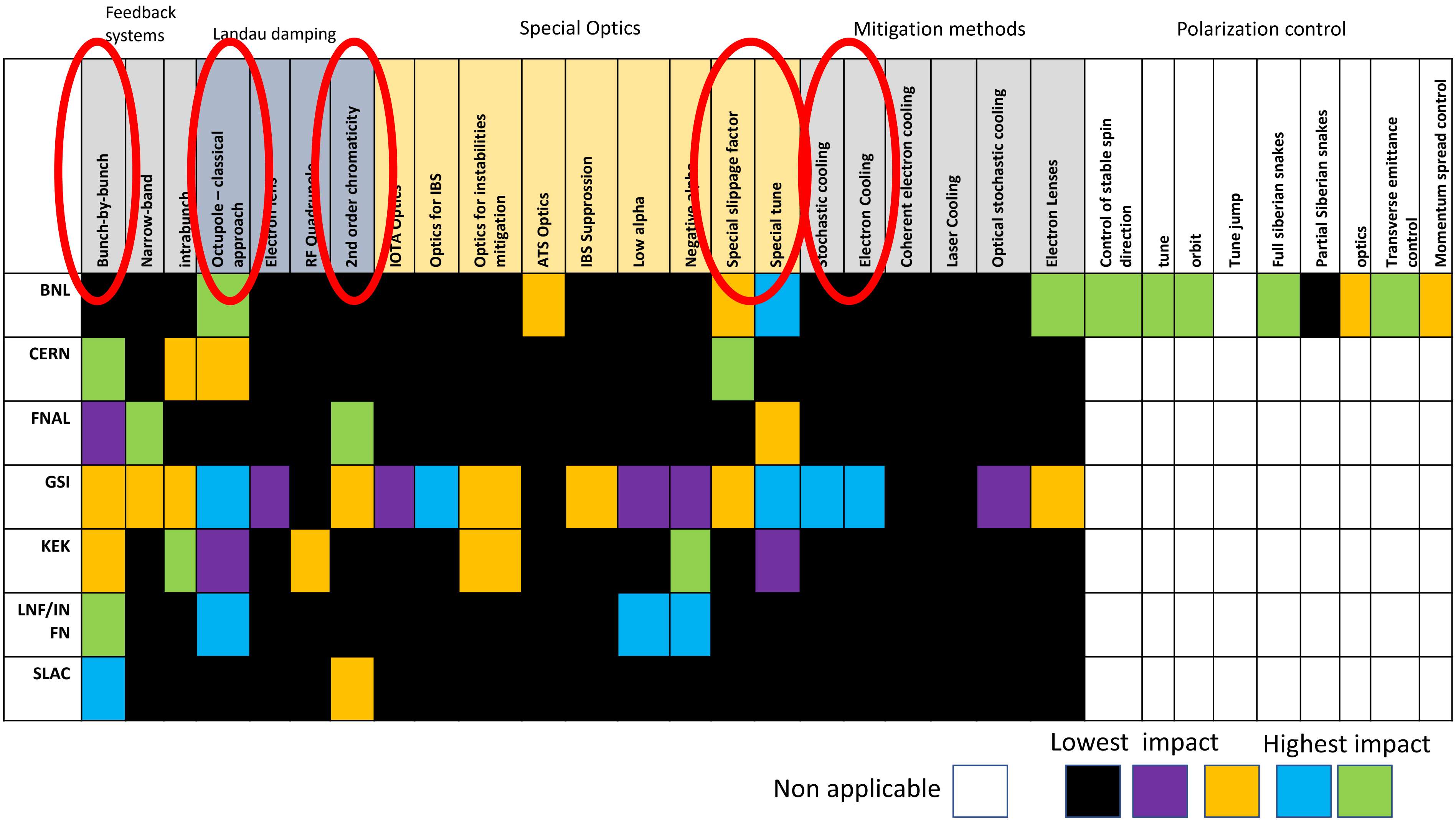
R	Intensity limitation	ave	std
1	Beam loss	3.12	1.16
2	RF Power	2.75	1.2
3	Single bunch instability	2.75	0.82
4	Multi-bunch instability	2.75	1.56
5	Injector	2.6	1.6
6	DA	2.375	0.99
7	Collimation	2.25	1.09
8	Momentum Acceptance	2.25	1.2
9	E-Cloud	2.25	1.3

R	Other performance limitation	ave	std
1	Beam loss	3.37	1.21
2	Halo development	2.5	1.22
3	Collimation	2.37	1.21
4	Dynamic vacuum	2.37	1.4
5	Peak luminosity	2.12	1.53
6	Spill. Structure	2.0	1.73
7	Quenches	1.37	0.69
8	UFO/dust	1.12	0.33

R	Brightness limitation	ave	std
1	Nonlinearities	3.625	0.99
2	Space charge	3.125	1.53
3	Beta-beating	2.5	1.3
4	Injector	2.5	1.75
5	Beam-beam	2.0	1.41
6	IBS	1.75	1.39

End 2018, APEC2018 workshop

full mitigation ranking by laboratory



For FNAL the Fermilab booster is considered, for BNL the RHIC, for CERN SPS, for SLAC SPEAR III, for KEK the J-PARC Main Ring, for INFN-LNF DAΦNE, and for GSI the ESR, SIS18 and SIS100.

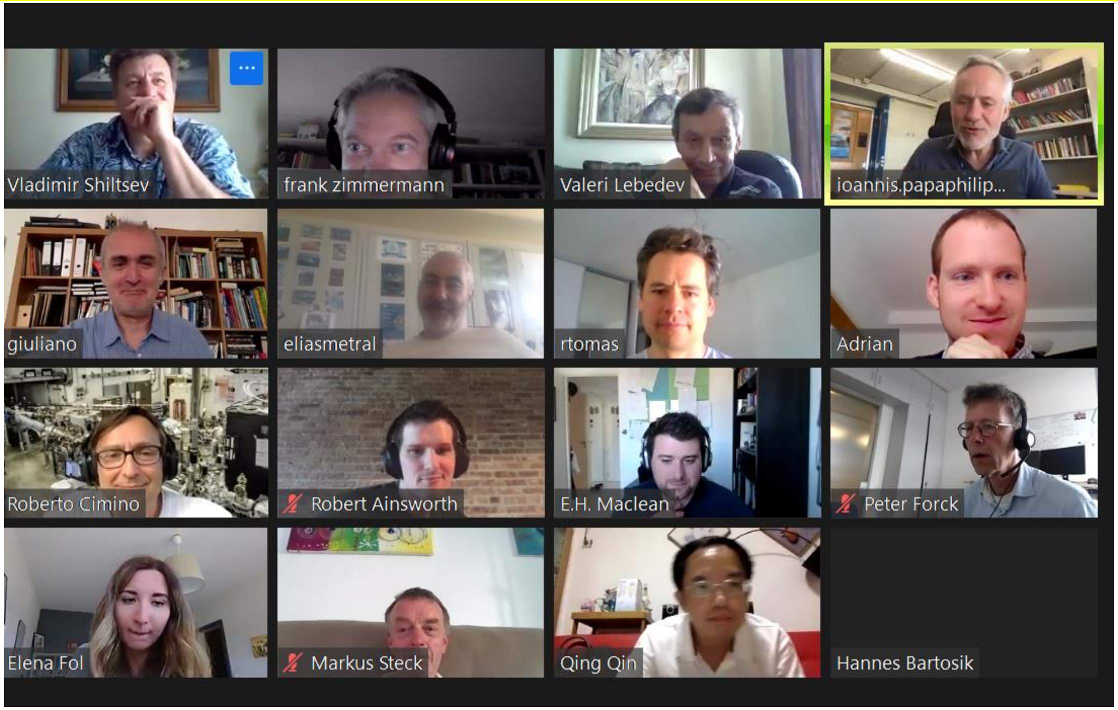
ARIES MS31

APEC2018 and Mitigations 2020 workshops

ARIES Mitigations workshop & Ranking for Space Charge Effects

ARIES MS31

Summer 2020



J-PARC Main Ring (MR) Fast Extraction (FX) operation: 1) **Injection beam optimization** with the Rapid Cycling Synchrotron (RCS) parameters; 2) RF operation with **2nd harmonic** and the **new feedback** system; 3) **Correction of the beta modulation and resonances**; 4) Transverse instabilities suppressed with **chromaticity settings & intra-bunch feedback systems**.

CSNS project - main strategies: **tune optimization** & proper **injection scheme**. Present limits are pushed through: 1) Installing **trim quadrupoles** to shape the tune curves; 2) Installing **AC sextupoles** to control the coherent oscillations; 2) **Re-installing injection components** to realize the real correlated painting scheme; 3) Re-sorting the dipoles according to the magnetic field measurement in AC mode

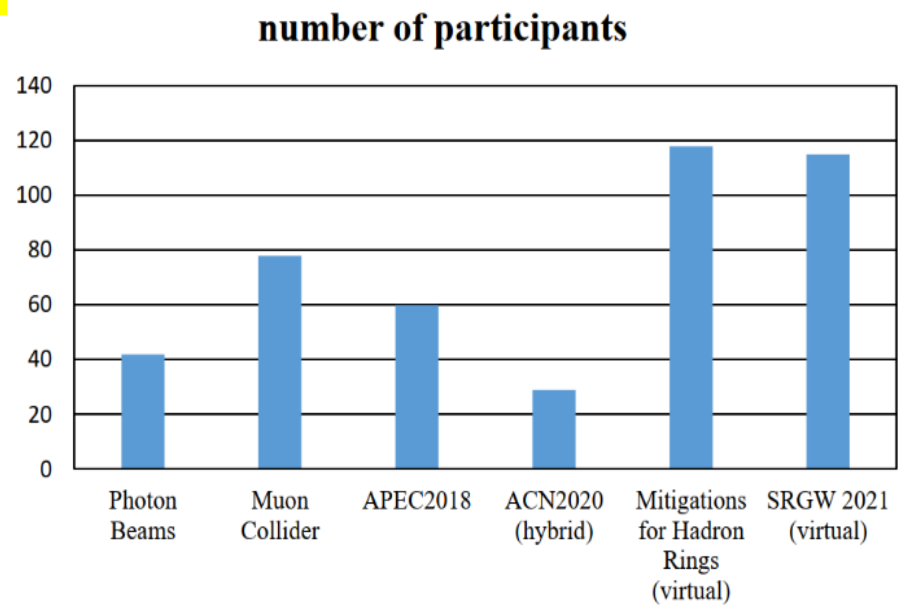
FNAL PIP II	Driving forces	**Near Term Mitigations**	**PIP-II Era Mitigations**
Emittance growth at injection	Space charge	Resonance (1/2) compens.	Higher inj. energy; Painting inj; Two-stage collimation
Longitudinal losses at inj.	Adiab. Capt. ; Field stability	LLRF Upgr. ; Improved field stab.	Direct bucket injection w. chopping
Loss during transition	Instabilities; Emittance growth at inj.	Damper upgrades	Increased transition rate Reduced leakage
Extraction losses	Vert. Ap. restriction		Magnets w. larger aperture in ext. region

GSI: UNILAC upgrade measures: high intensity **RFQ, heavy ion stripping**, end-to-end optimization, etc.; SIS18: intensity limitation mechanism: **dynamic vacuum**, other beam instability mechanisms, etc; mitigation: **feedbacks**. Storage rings: **precision beam controls**.

For **RHIC and EIC-** some unique techniques: 1) **bright sources** (high-intensity H-, polarized H-, laser+EBIS); 2) **orbit/tune/coupling/ (chromaticity) feedbacks on ramps/in stores**, **transitions jumps** (in AGS, and in RHIC – a slowly ramping SC machine); 3) **beam-beam compensation with electron lenses**. Importantly, **beam cooling** fundamentally changes how RHIC is operated. Two cooling systems are operational (**stochastic cooling for high-energy ions; electron cooling for low-energy Au**), leading to much higher luminosity and cleaner operating conditions. A **novel strong hadron beam cooling scheme.**

final community survey on (far)-future options

The survey invitation was sent to 388 different participants from six ARIES exploratory workshops. In total 94 experts responded.



(Far-)Future Options for Survey

1. Energy Recovery (>50 GeV and/or > 50 mA)
2. Plasma Acceleration
3. Photon Collider
4. Gamma Factory
5. Muon Collider, positron based
6. Muon Collider, proton based
7. Crystal/Nanostructure Acceleration
8. Crystal Bending
9. Crystalline Beams
10. Gravitational Wave Detection using Storage Rings
11. Gravitational Wave Generation using Accelerators
12. High Energy Photon Generation using Entanglement and Moessbauer Effect
13. Non-electromagnetic acceleration or focusing mechanisms incl. gravity based schemes

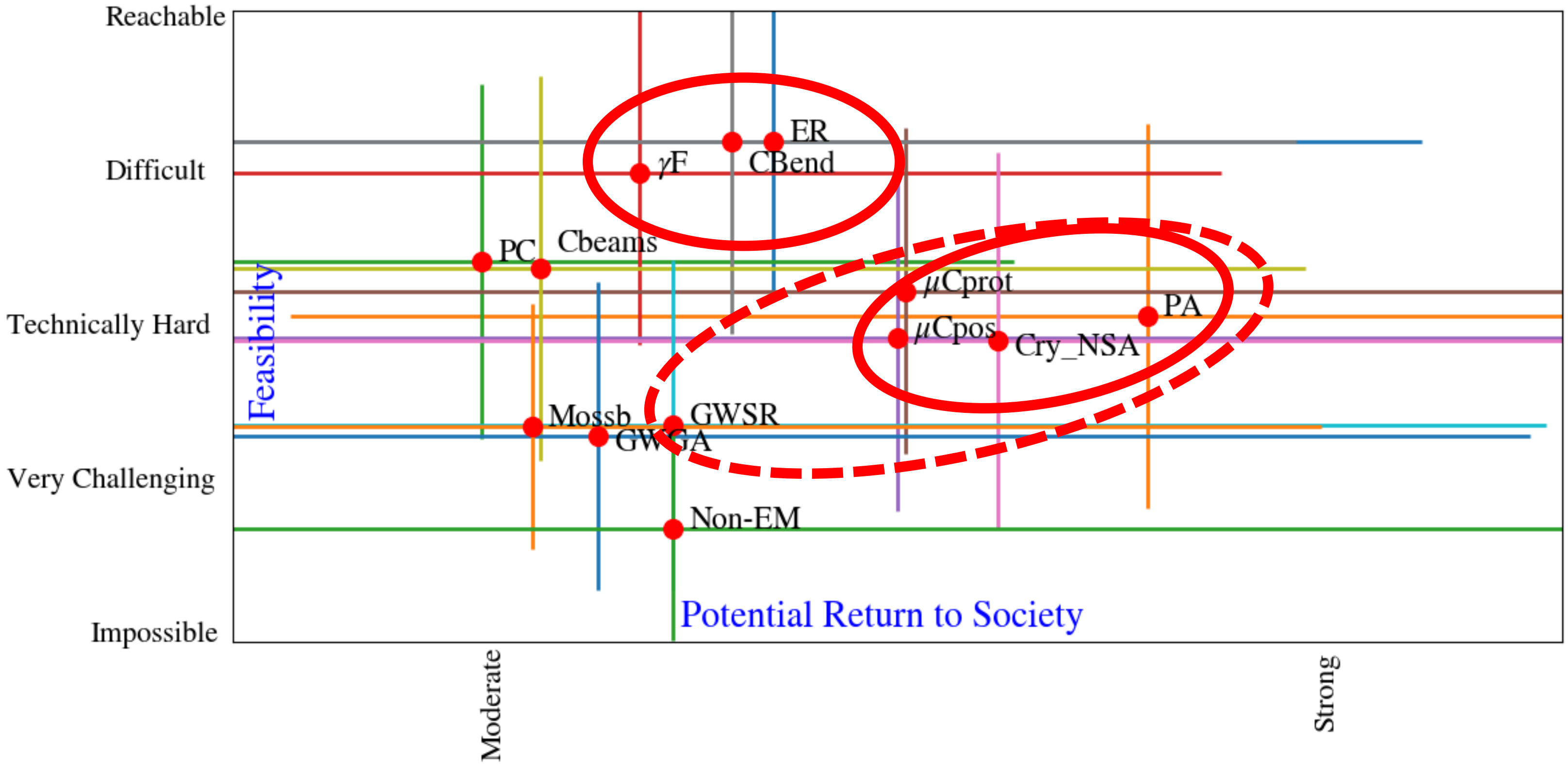
ARIES survey criteria & choices

Feasibility	Importance/ Priority	Risk of Failure	Potential Return to Society	Time scale	Numeric ranking
Easy	Marginal	None	Negative	Next 5 years	1
Reachable	Relevant	Moderate	Marginal	Next 10 years	2
Difficult	High	High	Moderate	Next 20 years	3
Technically hard	Very high	Certain !	Strong	Next 40 years	4
Very challenging	Top		Game Changer !	Next 100 years	5
Impossible					6

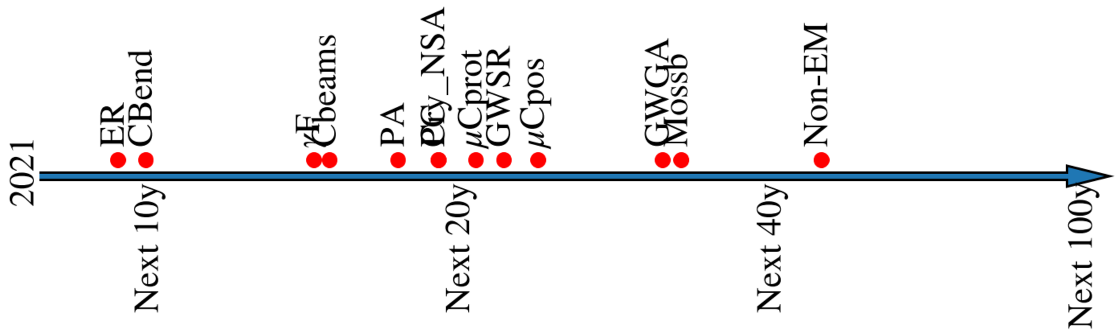
April 2021

survey results - example

April 2021



Expected realization time scale



ARIES D6.5

White List of Ranked Far-Future Accelerator Options

April 2021

ARIES D6.5

Time scale	**Priority and focus**
10-15 years	Energy recovery Crystal bending Gamma Factory
15-30 years	Proton based muon collider Plasma acceleration Positron based muon collider Crystal and nanostructure acceleration Gravitational wave detection using storage rings
	Low or no priority
	Photon collider Crystalline beams "Moessbauer acceleration" using photon entanglement Gravitational wave generation using accelerators Non-electromagnetic acceleration or focusing mechanisms

key results from WP6 APEC

- **Reviving and advancing the designs of a muon collider,** either proton based or positron based ; this will be pursued in I.FAST, through a dedicated working group and/or Euro… D panel, and the US Snowmass process
- **Launching discussions on using storage rings & a… or detection or generation of grav. waves.** … coming years, and already stimulated concrete plan…
- **Cementing the case for e… s,** with input to the ESU… ts also inform… (M…
- …
- **P…** (now in HL-LHC co… **ation**
- **Op… rs** [D6.2] avail… (FCC-ee); measures to improve reliability of key systen…), open data infrastructure for accelerator reliability
- **Perfo… ons in hadron synchrotrons** [D6.1] highlighting beam loss, single-bunch i… & nonlinearities; review & ranking of mitigations [MS31, D6.3]
- **Ranking of (far-)future accelerator options** [D6.5] priority for (1) ERLs, crystal bending, GF, (2) muon collider(s), plasma & crystal & nanostr. Accel., grav. wave detection

Broad scientific and social impact

- WP6 results already widely disseminated – through articles in scientific journals, CERN Courier, CERN EP Newsletter, Accelerating News, ICFA BD Newsletter / JINST, Zenodo, arXiv, CDS, US Snowmass effort , etc.
- inspired new developments and opportunities around the globe (Germany, Italy, Taiwan, US, China,…)

WP6 potential impact on science or society

benefit to science:

- defining **new directions in accelerator science** (muon colliders, crystalline beams, Gamma Factory, ERLs & ERL-based FELs…)
- focusing the **attention of the community on certain key aspects**, which will enable designing future accelerators for new discoveries, while optimizing existing machines; in particular
  - sparked an interest in **using storage rings and accelerator technologies for gravitational-wave research**
  - advanced several studies on the **high-precision operation of accelerators and beam diagnostics**

more direct benefit to society:

- controlling beam delivery and **rendering accelerator operation more reliable**
- emerging methodologies will **eventually be transferred to all types of accelerator applications**, including for industrial and medical applications

WP6 exploitable foregrounds

Type of exploitation foreground	Description of exploitable foreground (relevant deliverable)	Purpose (How the foreground might be exploited and by whom)	Potential/expected impact (quantify where possible)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable, commercial or any other use
GAK, EUP, SIN	Assessment and ranking of far-future accelerator options	Exploited and pursued in I.FAST, and in parallel by the European Accelerator Expert Panels set up by CERN Council and LDG, by the EPS-AG strategy discussions, and by the US Snowmass process	Guidance & prioritization of accelerator R&D over the coming decades. Input to expert panels and the next ES... pro...	Published whi...	A... ors, particle ... nd nuclear ... photon ... vitational ...s	Medium & long 5-30 years
GAK, EUP, SIN	Improved Reliability and Availability of Particle Accelerators	Exploited, applied and pursued for improving accelerator operati... the design of future...			...tors, ...ences, ...e, ...ors	Short & medium, 0-10 years
GAK, EU...	Rev...				...P	Short & medium, CDR in 5 years
GAK, SIN			...ELs	...eport and database	Particle Physics, nuclear physics	Short & medium, within 5 years
GAK. EUP	a... s... acc...	...ation ...ent based on the ...C infrastructure	“Accelerator experiments” on novel ways to detect gravitational waves and over extended frequency scales; newly formed collaborationsn across communities	Reports	Gravitational wave physics, accelerators, particle physics	Short & medium & long, 0-30 years
GAK, EUP, SIN	“Ga...na Factory” option	Exploited and pursued by the PBC effort at CERN, with staged beam experiments at the SPS and LHC	Gamma factory based on partially stripped heavy ion beams in the LHC, with numerous applications	Reports	Particle physics, nuclear physics, material sciences, power generation	Medium, 5-10 years
GAK, EUP	Novel options for extremely high-gradient acceleration: crystals and nanostructures	Exploited and pursued in I.FAST, in te US Snowmass process, and by a global collaboration	Ultracompact accelerators with accelerating gradients > 1 TV/m	Reports	All types of accelerator applications, incl. medical accelerators	Long, 15-30 years

WP6 objectives and results highly relevant - WP6 initiated and guided numerous **novel science developments of high breakthrough potential**

WP6 publications

> 60 articles including, in 2021 (***all with ARIES acknowledgement***)

*collaboration enabled by ARIES

V. Shiltsev and F. Zimmermann, " Modern and future colliders," **Rev. Mod. Phys.** 93, 015006 (2021) https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.93.015006
G. Franchetti, F. Zimmermann, and ***M. A. Rehman****, "Trapping of neutral molecules by the beam electromagnetic field," **Phys. Rev. Accel. Beams** 24, 054001 https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.24.054001
Z. Nergiz, ***N.S. Mirian****, A. Aksoy, D. Zhou, F. Zimmermann, H. Aksakal, "Bright Angstrom and Picometre Free Electron Laser Based on the LHeC Energy Recovery Linac", **Phys. Rev. Accel. Beams** 24, 100701 https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.24.100701

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 054001 (2021)

Editors' Suggestion

Trapping of neutral molecules by the beam electromagnetic field

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REVIEWS OF MODERN PHYSICS, VOLUME 93, JANUARY–MARCH 2021

Modern and future colliders

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(published 3 March 2021)

Since the initial development of charged particle colliders in the middle of the 20th century, thes advanced scientific instruments have been at the forefront of scientific discoveries in high-energ physics. Collider accelerator technology and beam physics have progressed immensely and moder facilities now operate at energies and luminosities many orders of magnitude greater than th pioneering colliders of the early 1960s. In addition, the field of colliders remains extremely dynami and continues to develop many innovative approaches. Indeed, several novel concepts are currentl being considered for designing and constructing even more powerful future colliders. The colliding beam method and the history of colliders are first reviewed. Then, the major achievements o operational machines and the key features of near-term collider projects that are currently unde development are presented. The review concludes with an analysis of numerous proposals and studie for distant-future colliders. The evaluation of their respective potentials reveals promising prospect for further significant breakthroughs in the collider field.

DOI: 10.1103/RevModPhys.93.015006

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 100701 (2021)

Bright Ångstrom and picometer free electron laser based on the Large Hadron electron Collider energy recovery linac

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(Received 12 July 2021; accepted 23 August 2021; published 7 October 2021)

WP6 - *thank you !*

all beneficiaries & partners of WP6 made important contributions, far exceeding original scope (despite covid-19 pandemic !); **perfect integration** within WP6 activities