Introduction: Setting the Stage

overview of accelerator projects in the future

Andrei Seryi
John Adams Institute for Accelerator Science
University of Oxford, Royal Holloway University of London and Imperial College London, UK

Accelerators Revealing the QCD Secrets
3-5 September 2016
Makedonia Palace, Thessaloniki, Greece

Contents

- **Hadron colliders** (and not only colliders)
  - HL-LHC, HE-LHC, FCC, SPPC
  - FAIR, NICA, SPIRAL2
- **Electron - ion**
  - LHeC & FCC-he
  - eRHIC
  - Jlab e-ion
- **Lepton colliders**
  - FCC-ee & CepC
  - CLIC and ILC
  - Super-B factory
  - c-tau factory
- **Advanced approaches**
  - LPWF & PWFA collider roadmaps & AWAKE

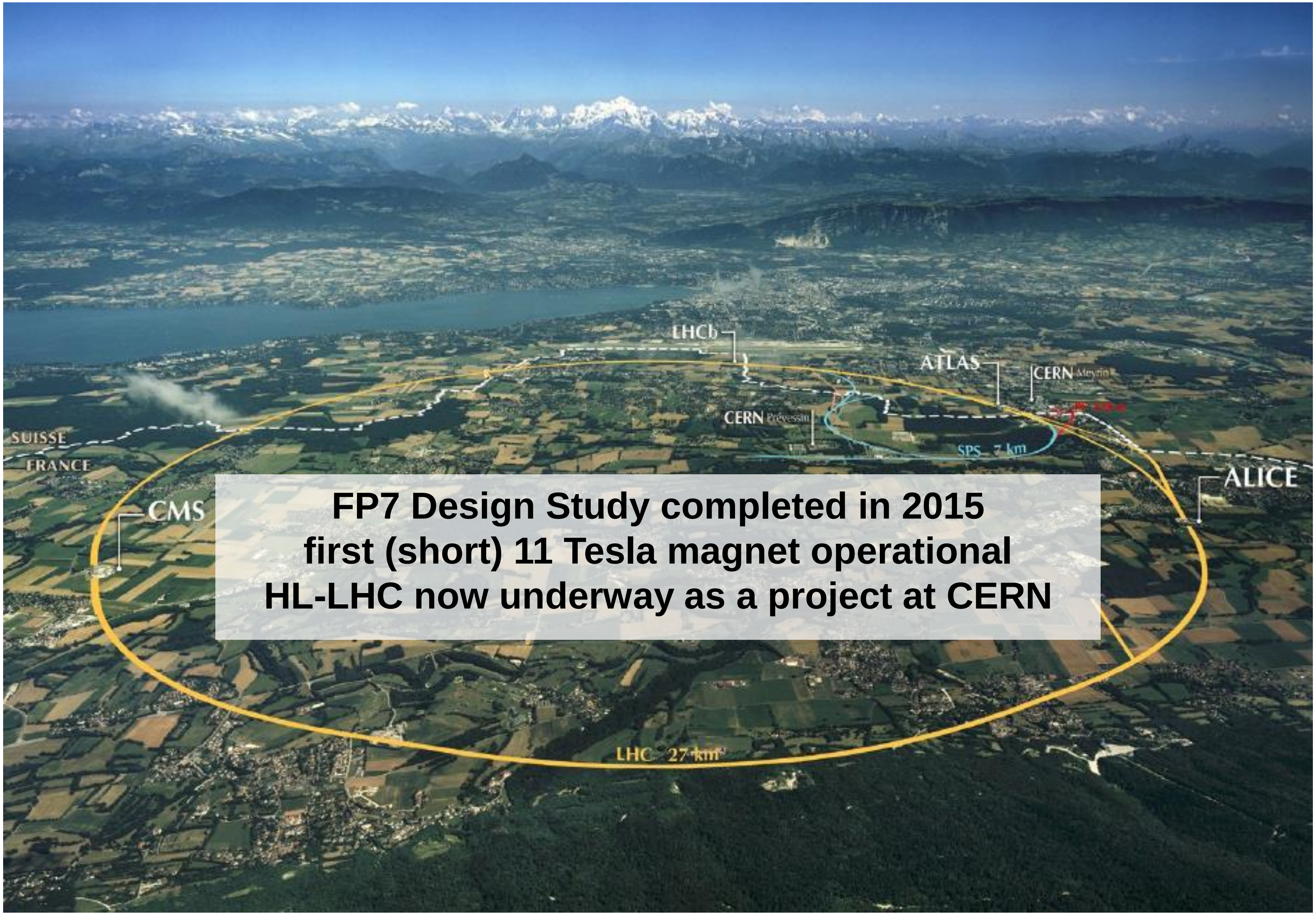
Acknowledgements

- **Many thanks to Tom Browder, Eckhard Elsen, Edda Gschwendtner, Mike Harrison, Vladimir Kekelidze, Eugene Levichev, N. Ohuchi, Boris Sharkov, Steinar Stapnes, Edward Temple, Frank Zimmermann, Nick Walker, Yifang Wang, Akira Yamamoto, and many other colleagues for materials for this overview**

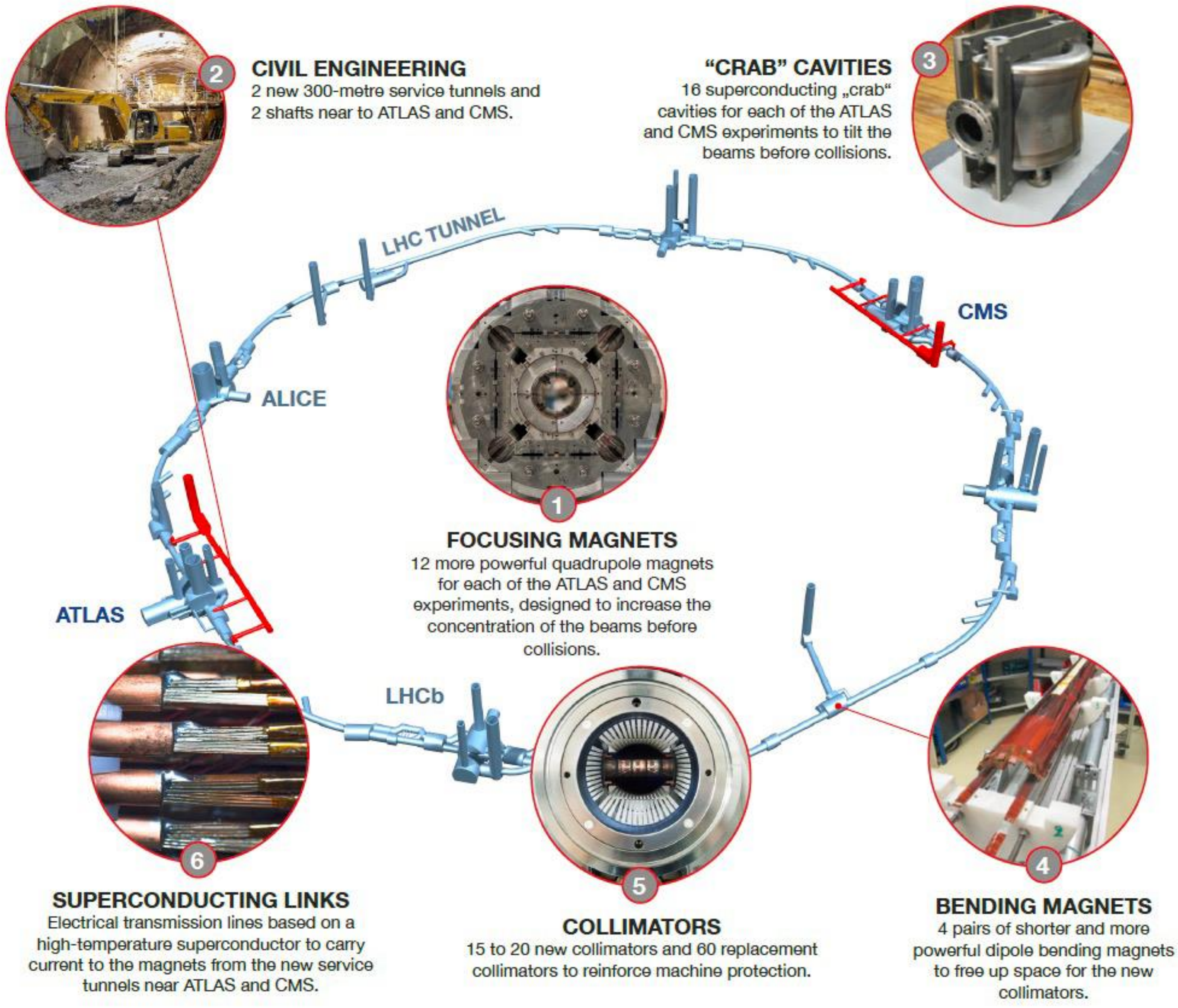
Contents

- **Hadron colliders** (and not only colliders)
  - HL-LHC, HE-LHC, FCC, SPPC
  - FAIR, NICA, SPIRAL2
- Electron - ion
  - LHeC & FCC-he
  - eRHIC
  - Jlab e-ion
- Lepton colliders
  - FCC-ee & CepC
  - CLIC and ILC
  - Super-B factory
  - c-tau factory
- Advanced approaches
  - LPWF & PWFA collider roadmaps & AWAKE

High Lumi LHC



High Lumi LHC



Higher energy hadron collider

High field magnets – the key to higher energy

Nb3Sn may lead to ~16 T magnets

HL-LHC magnets provide a ~1.2 km test of Nb3Sn technology

HTS inserts may increase field to 20 T

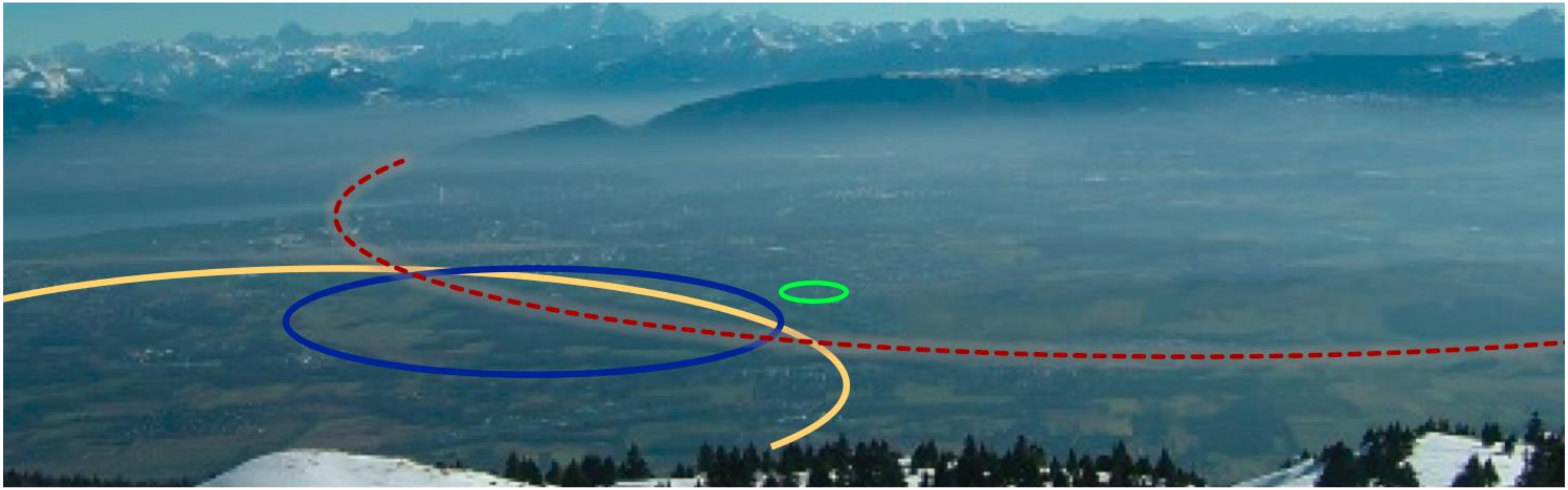
HE-LHC – use of high field magnets in existing LHC tunnel

FCC-hh

European Design Study for ~100 TeV pp collider in a ~100 km ring – EuroCirCol

CDR by end of 2018 & input to European Strategy

(JAI / Oxford is coordinating EuroCirCol WP3 on Experimental Interaction Region design)

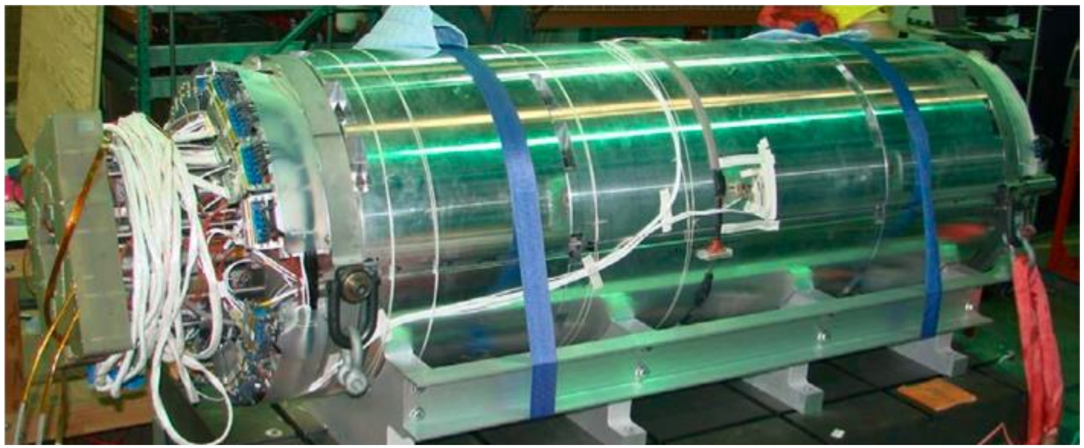


Magnet R&D

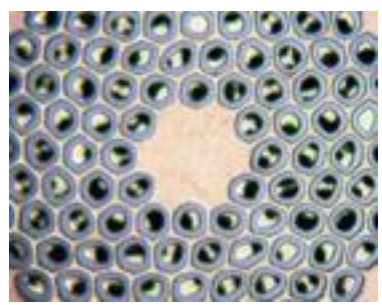
LHC: nominal 8.3 T

HL-LHC:

- 11 T dipoles in dispersion suppression collimators
- 12-13 T low-β quadrupoles at ATLAS and CMS IR's



March 2016: Nb_3Sn quadrupole model (1.5m long, aperture 150mm) reached current of 18 kA (nominal 16.5 kA) at FNAL. 2 coils from CERN and 2 coils from US



Nb3Sn matrix

Dec 2015: 2 in 1 dipole of 1.8 m length reaches nominal 11.3 T

Hadron colliders parameters

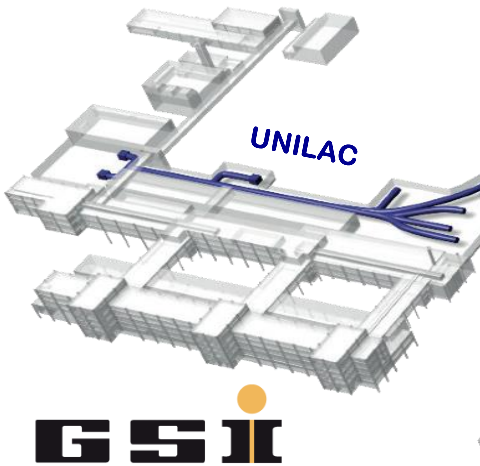
parameter	FCC-hh		SPPC	HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

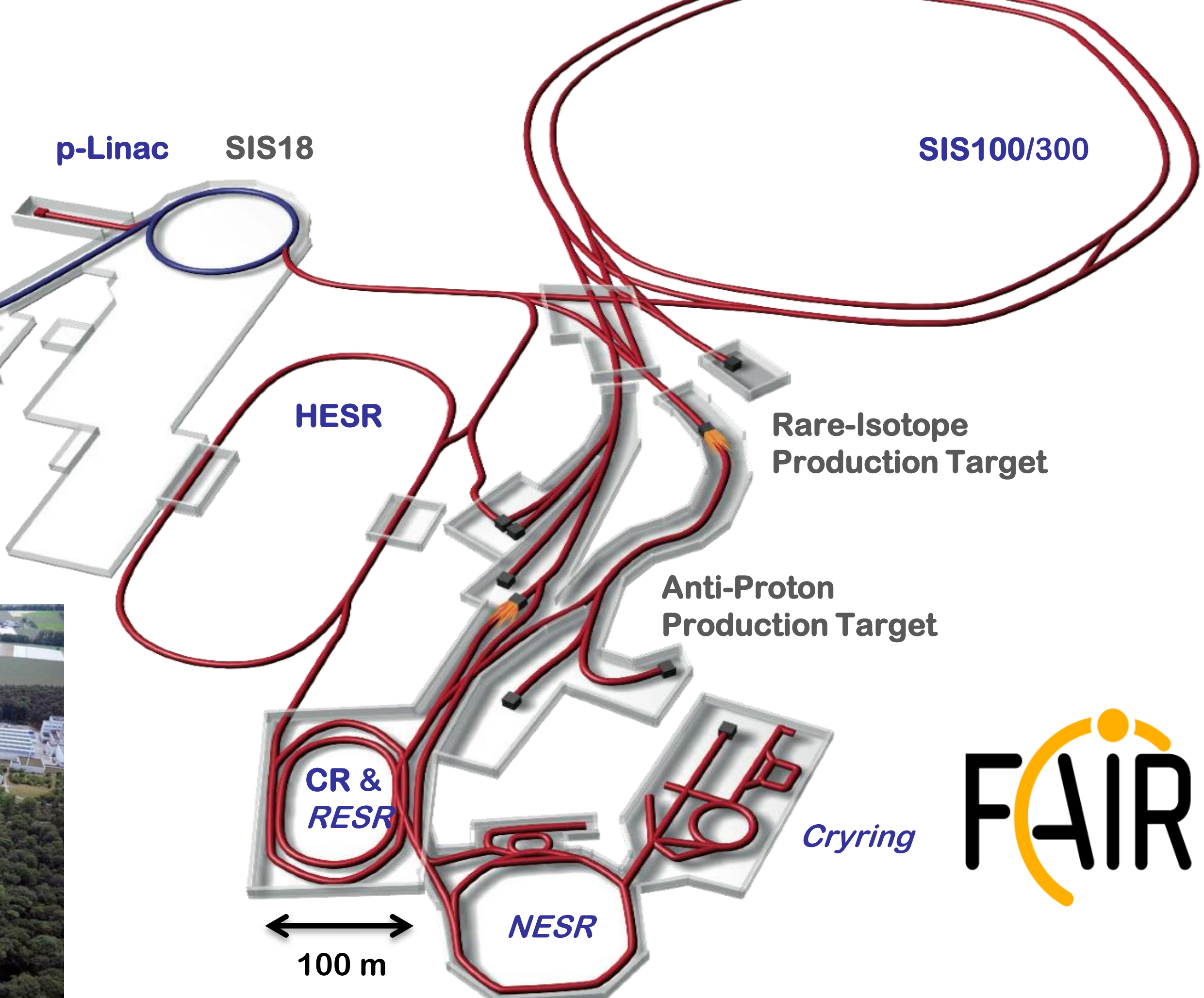
Contents

- **Hadron colliders** (and not only colliders)
  - HL-LHC, HE-LHC, FCC, SPPC
  - FAIR, NICA, SPIRAL2
- Electron - ion
  - LHeC & FCC-he
  - eRHIC
  - Jlab e-ion
- Lepton colliders
  - FCC-ee & CepC
  - CLIC and ILC
  - Super-B factory
  - c-tau factory
- Advanced approaches
  - LPWF & PWFA collider roadmaps & AWAKE

Facility for Antiproton and Ion Research

– **new international research laboratory <u>under construction</u> to explore the nature and evolution of matter in the Universe**





FAIR – accelerator facility

Primary Beams

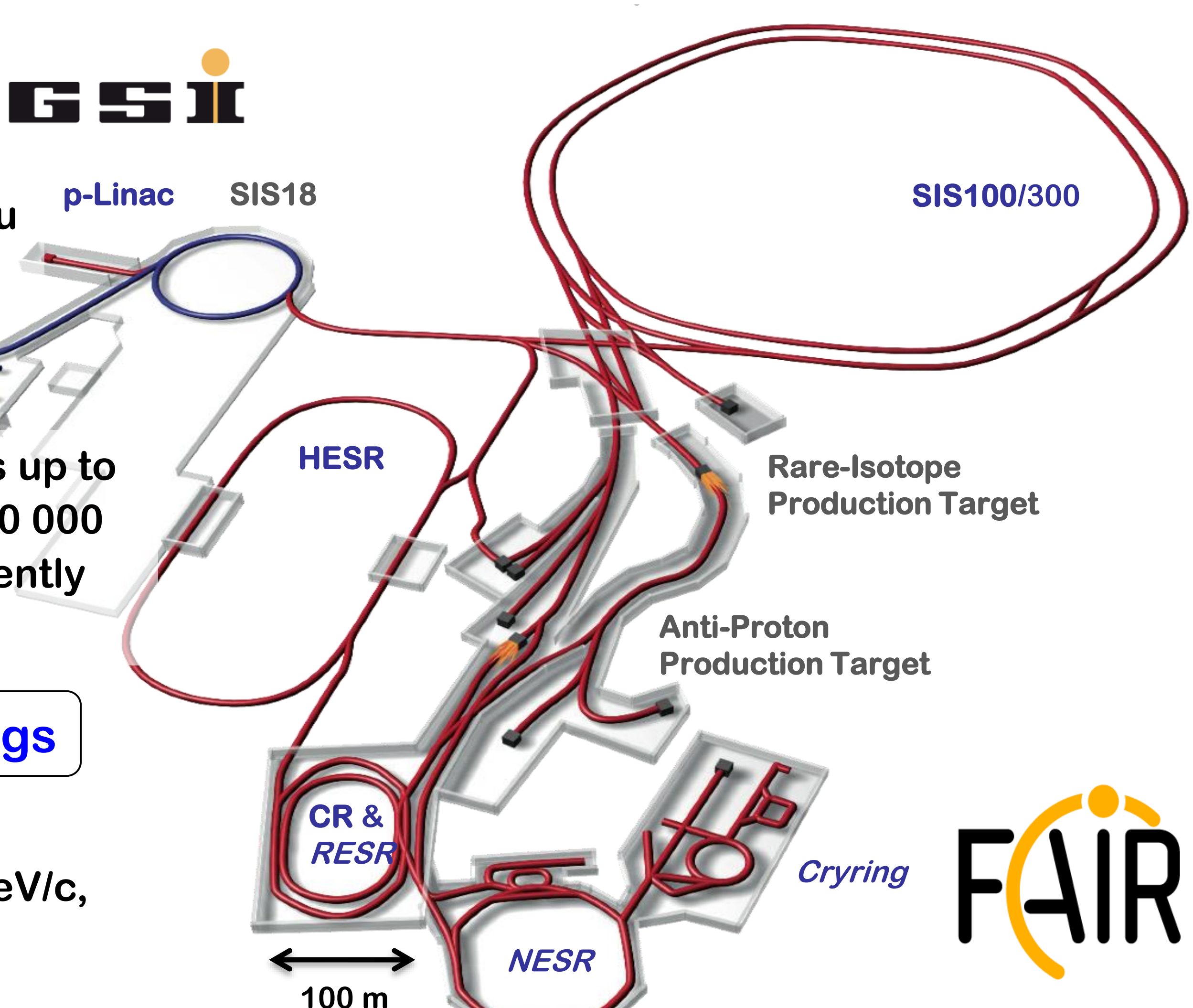
- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons

Secondary Beams

- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Storage and Cooler Rings

- radioactive beams
- 10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled



Technical Challenges

- cooled beams, rapid cycling superconducting magnets

Physics at FAIR

Nuclear Structure & Astrophysics
(Rare-isotope beams)

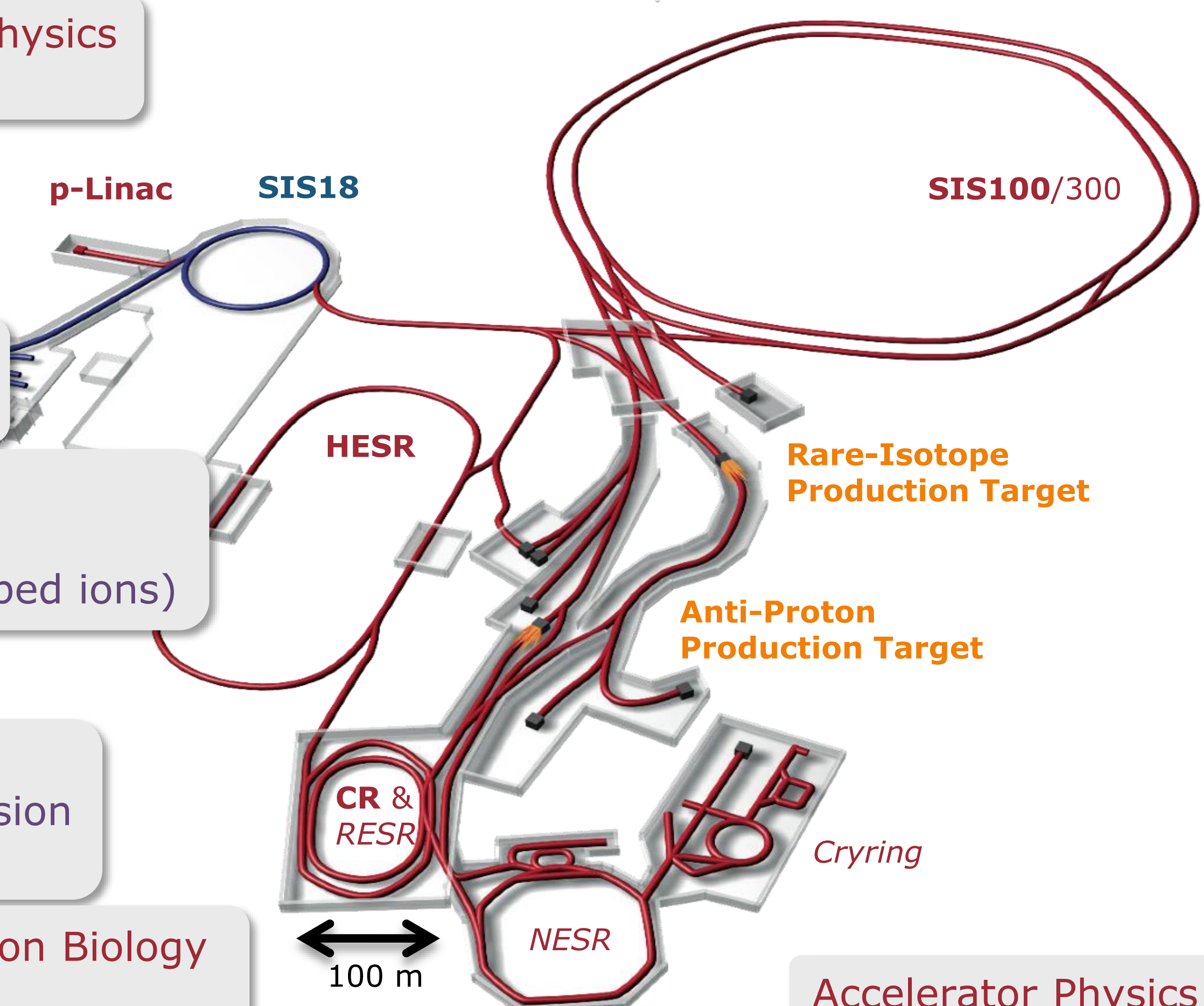
Hadron Physics
(Stored and cooled
14 GeV/c anti-protons)

QCD-Phase Diagram
(HI beams 2 to 45 GeV/u)

Fundamental Symmetries
& Ultra-High EM Fields
(Antiprotons & highly stripped ions)

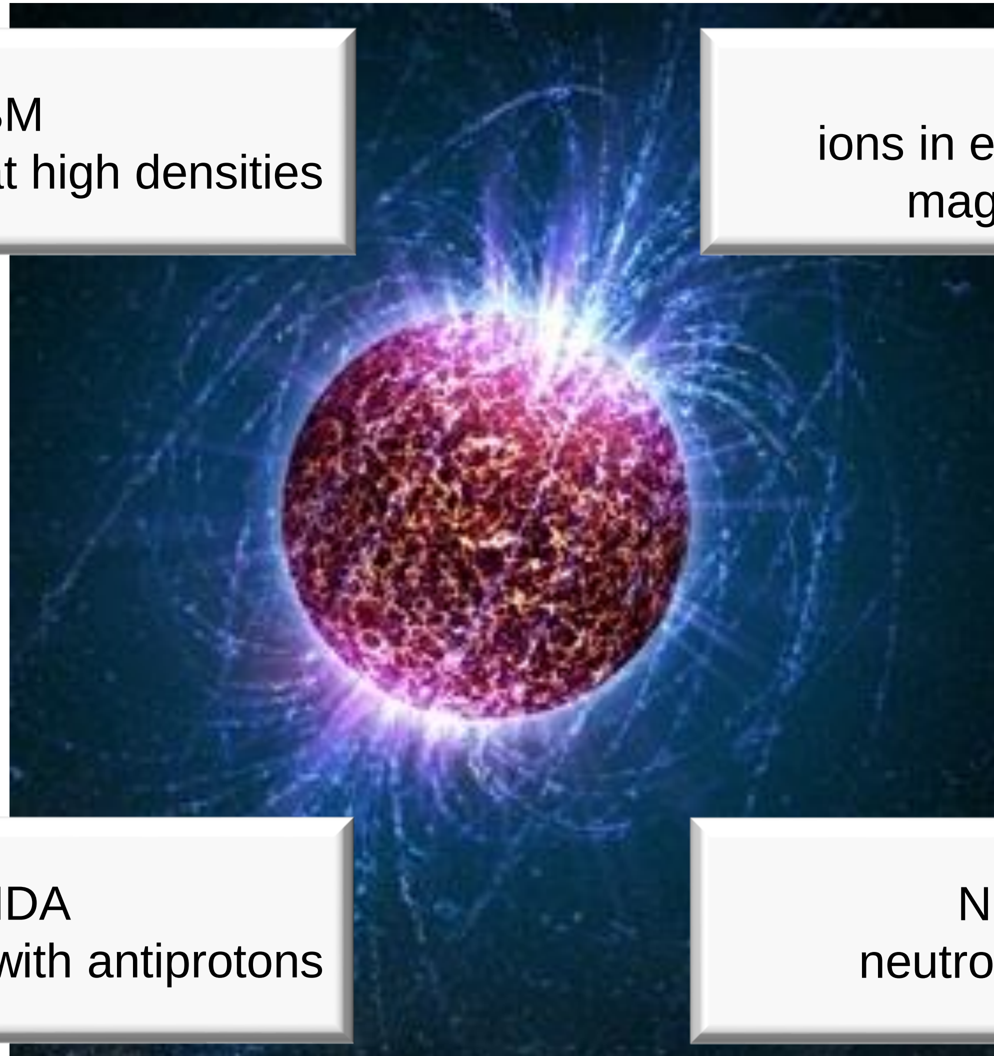
Dense Bulk Plasmas
(Ion-beam bunch compression
& petawatt-laser)

Materials Science & Radiation Biology
(Ion & antiproton beams)



Accelerator Physics

FAIR – four research pillars



CBM
nuclear matter at high densities

APPA
ions in extreme electro-magnetic fields

PANDA
hadron physics with antiprotons

NUSTAR
neutron-rich nuclei

NICA – Nuclotron based Ion Collider fAcility

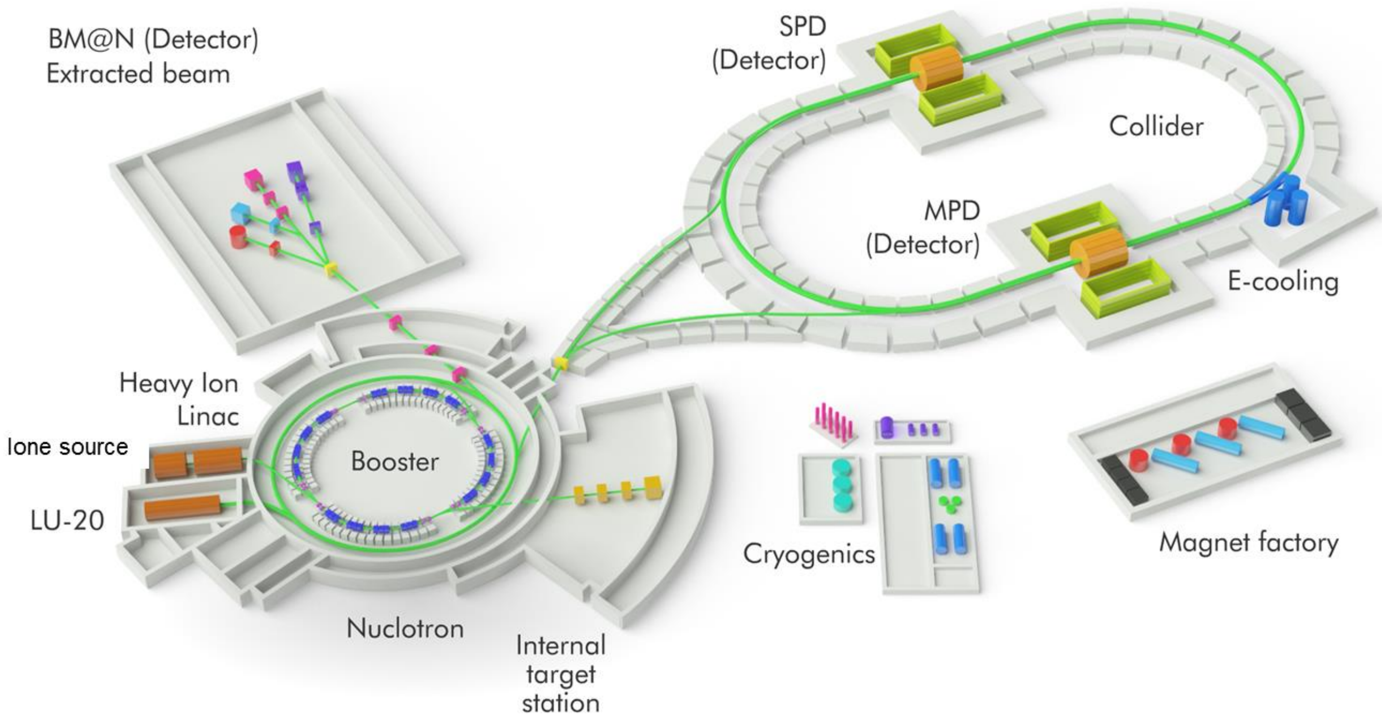
Joint Institute for Nuclear Research
International Intergovernmental organization
founded in 1956 by agreement of 12 countries
Located in Dubna town, Moscow region

NICA – science goals

***NICA* (*N*uclotron based *I*on *C*olider f*A*cility)**

Main targets:

- *study of hot and dense baryonic matter at the energy range of max baryonic density*
- *investigation of nucleon spin structure, polarization phenomena*



NICA – science goals

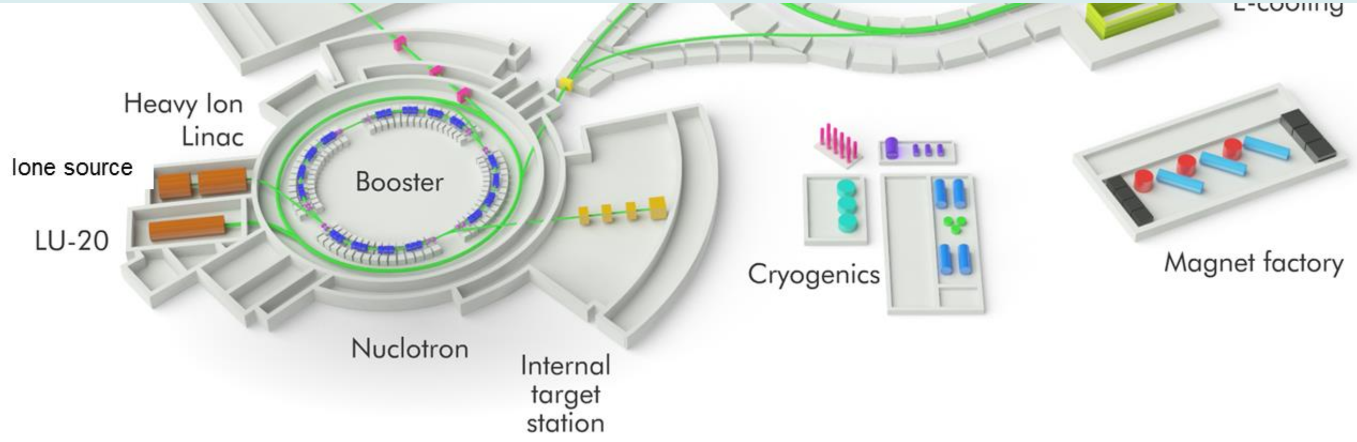
NICA (Nuclotron based Ion Colider fAcility)

Main targets:

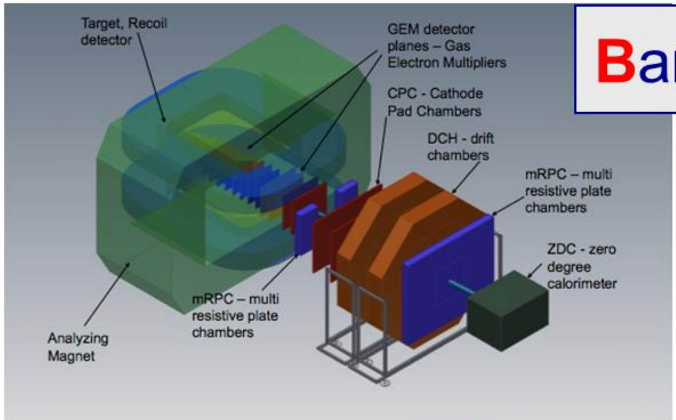
- *study of hot and dense baryonic matter at the energy range of max baryonic density*
- *investigation of nucleon spin structure, polarization phenomena*

- *development of accelerator facility for HEP @ JINR*
- *construction of Collider of relativistic ions from* ***p*** *to* ***Au,*** *polarized protons and deuterons*

with max energy up to $\sqrt{S_{NN}}$= **11** GeV (Au^{79+}) and =**27** GeV (p)



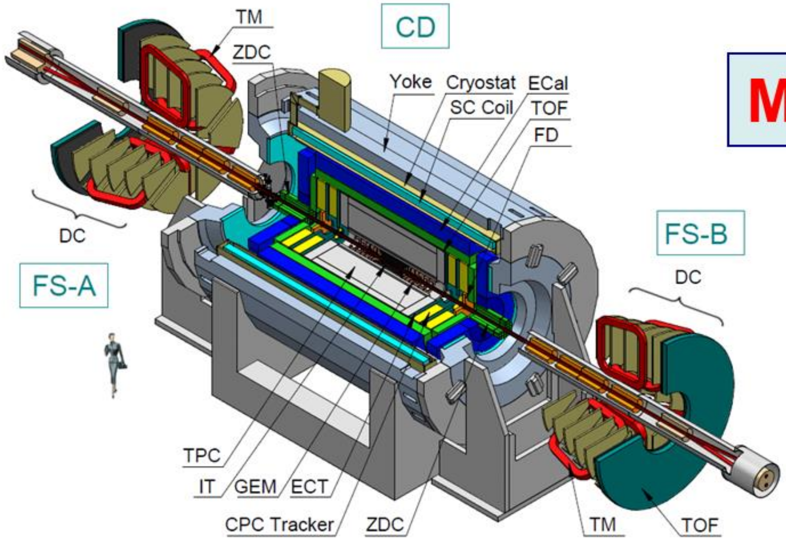
NICA – three detectors



Baryonic Matter at Nuclotron (BM@N)

the fixed target experiment at the Nuclotron

Stage I 2017



MultiPurpose Detector (MPD)

at the Collider

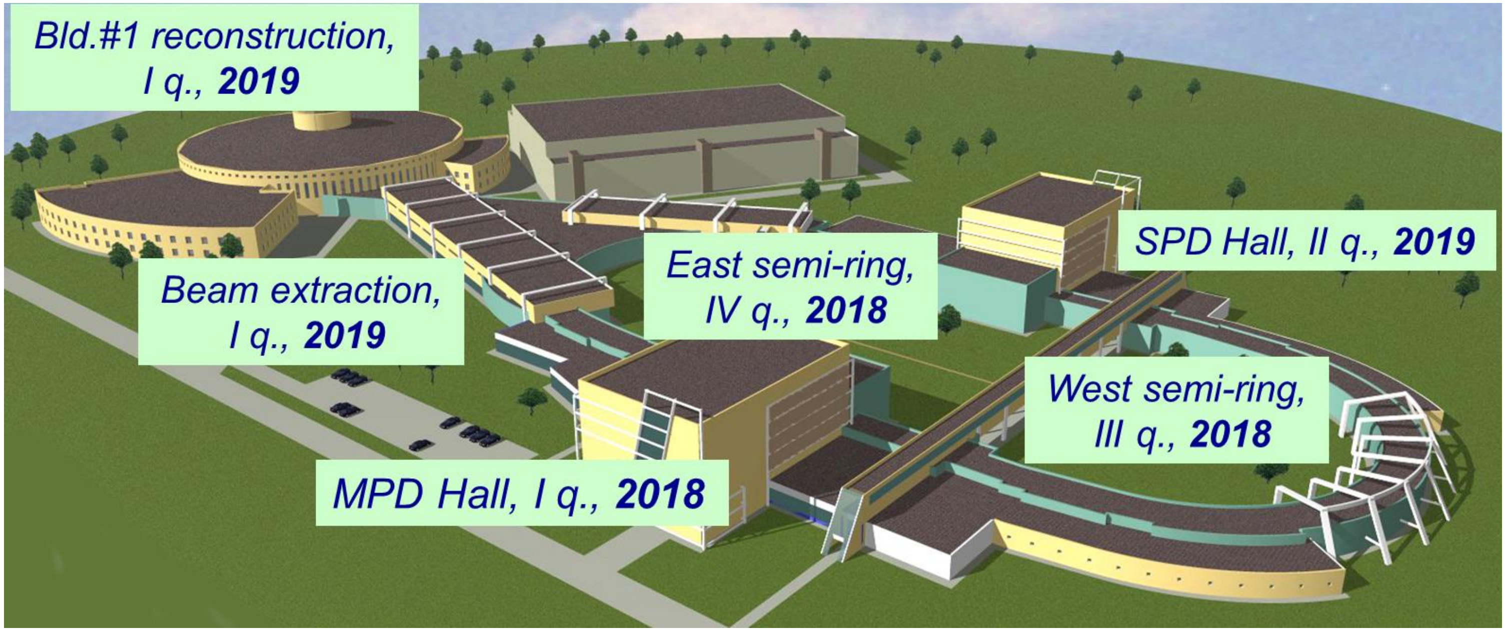
Stage I 2019

SPD (Spin Physics Detector) *at the Collider*

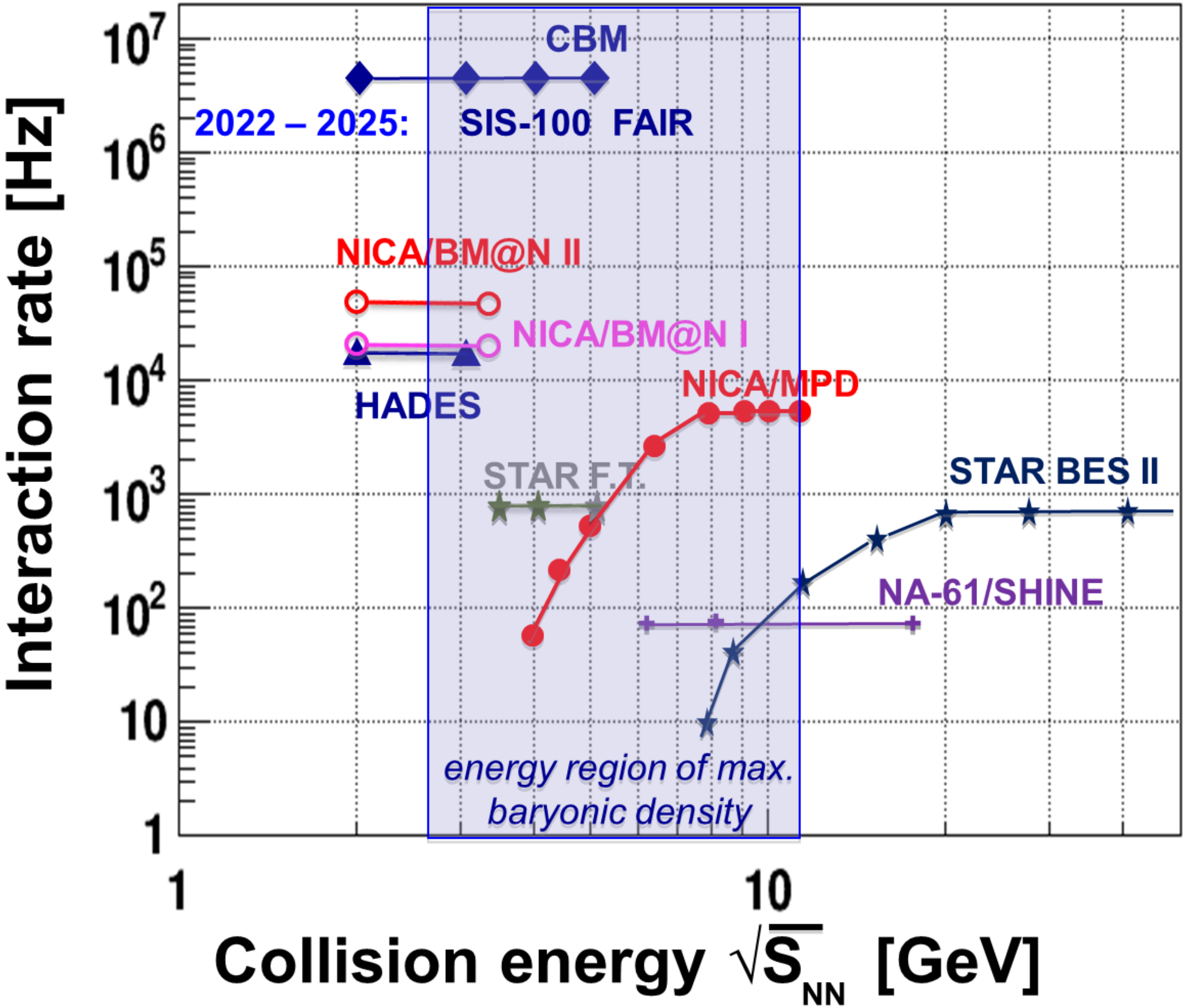
the project - in preparation

NICA – status and construction plans

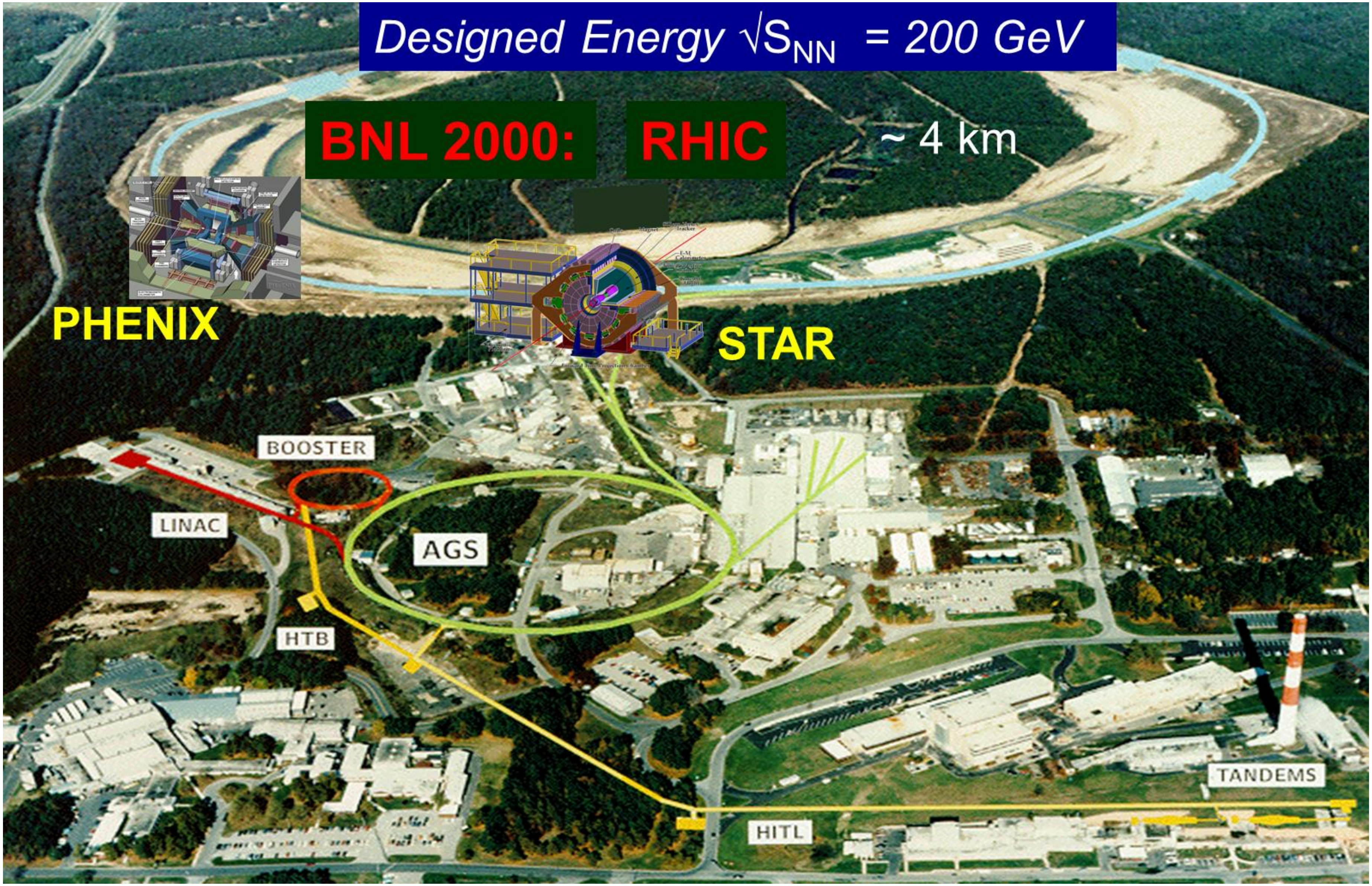
Left – aerial photo of the place prepared for construction
Top – workshop for production of magnets for NICA & FAIR



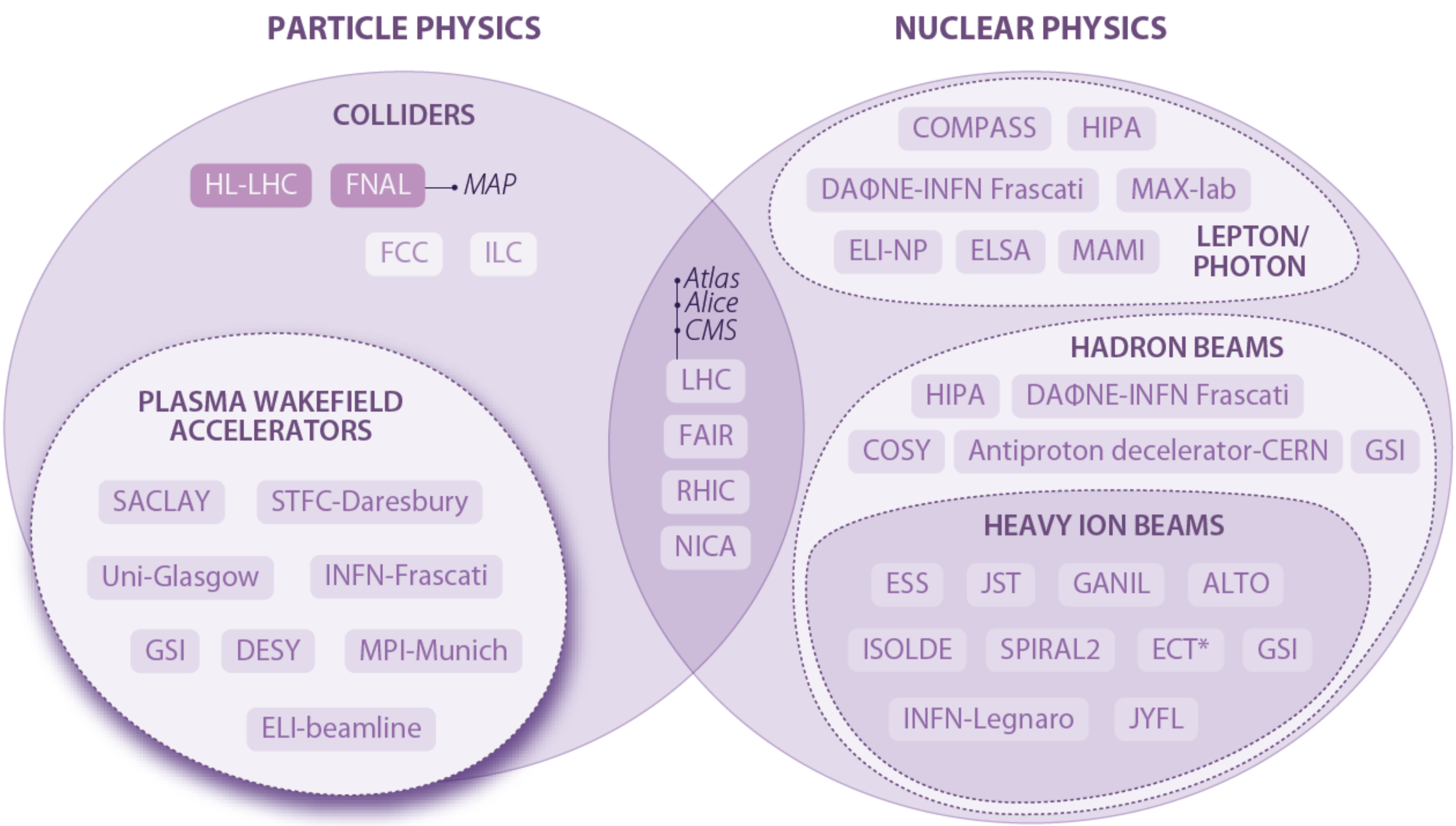
Present and future Heavy Ion experiments



RHIC – Relativistic Heavy Ion Collider



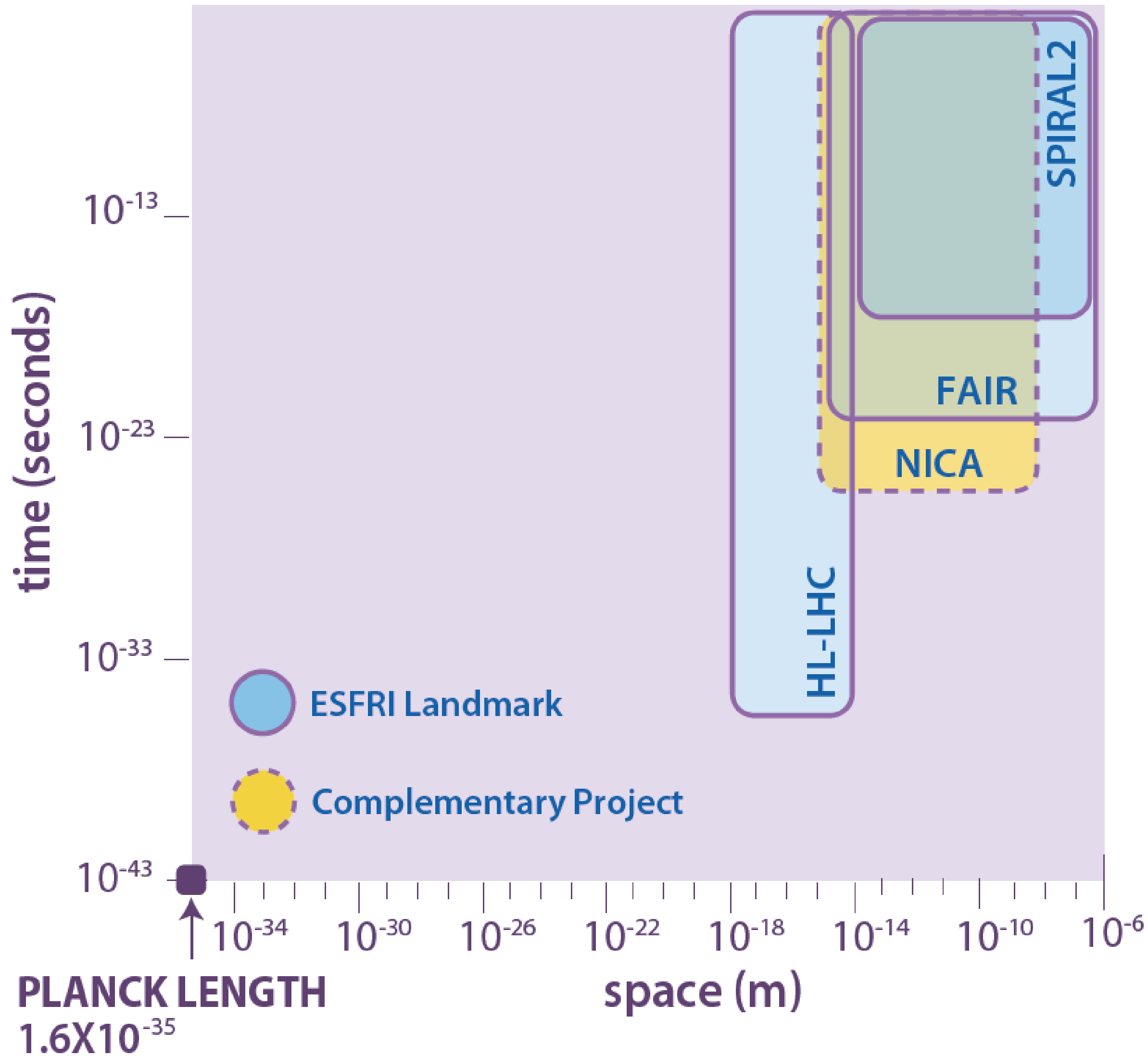
ESFRI roadmap 2016



Main Research Infrastructures in Particle and Nuclear Physics

ESFRI – European Strategy Forum on Research Infrastructure.

ESFRI roadmap 2016



Space and time domain of investigation of the ESFRI Landmarks and Projects

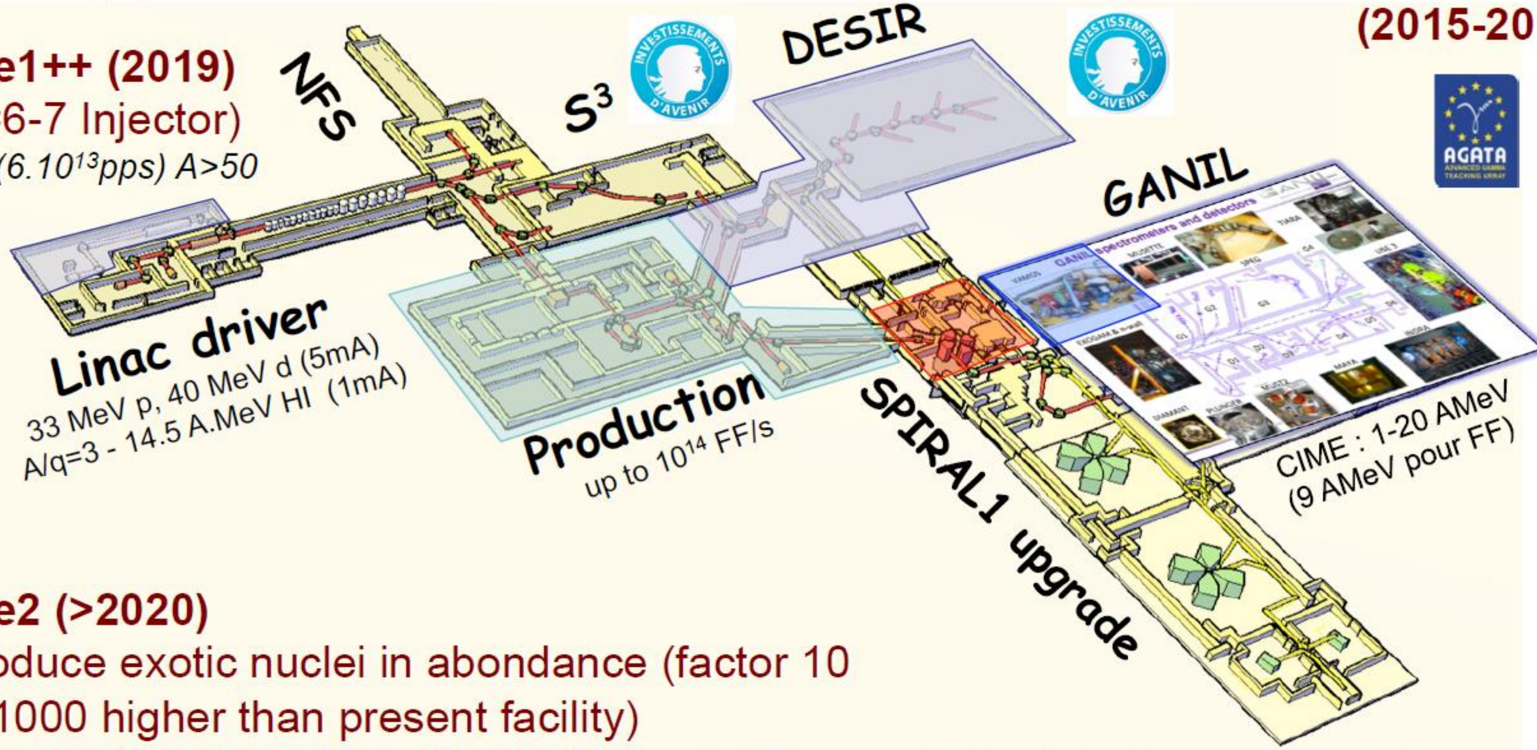
SPIRAL2- *Système de Production d'Ions Radioactifs en Ligne de 2e generation*

Phase1 (2015)
Increase the intensity of stable beams by a factor 10 to 100 – High intense neutron source
10pμA (6.10^{13}pps) A<50

DESIR Phase1+ (2018)
(low energy facility)

AGATA (2015-2018)

Phase1++ (2019)
(A/Q=6-7 Injector)
10pμA (6.10^{13}pps) A>50



Phase2 (>2020)
- Produce exotic nuclei in abondance (factor 10 to 1000 higher than present facility)
- Expand the range of exotic nuclei to A>80
- Post-acceleration of high intensity RIB

SPIRAL1 Upgrade (2016)
New light RIBs from beam/target fragmentation

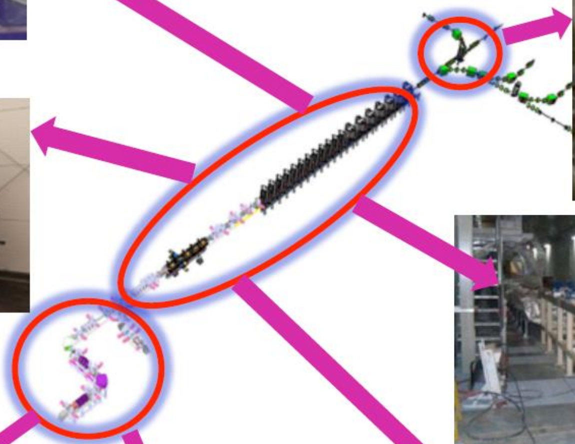
SPIRAL2 – construction at GANIL, France

Phase 1 Civil Construction is finished

LINAC tunnel

SC Cavities

Installation is going on



Beam lines & support

HI ECR Source

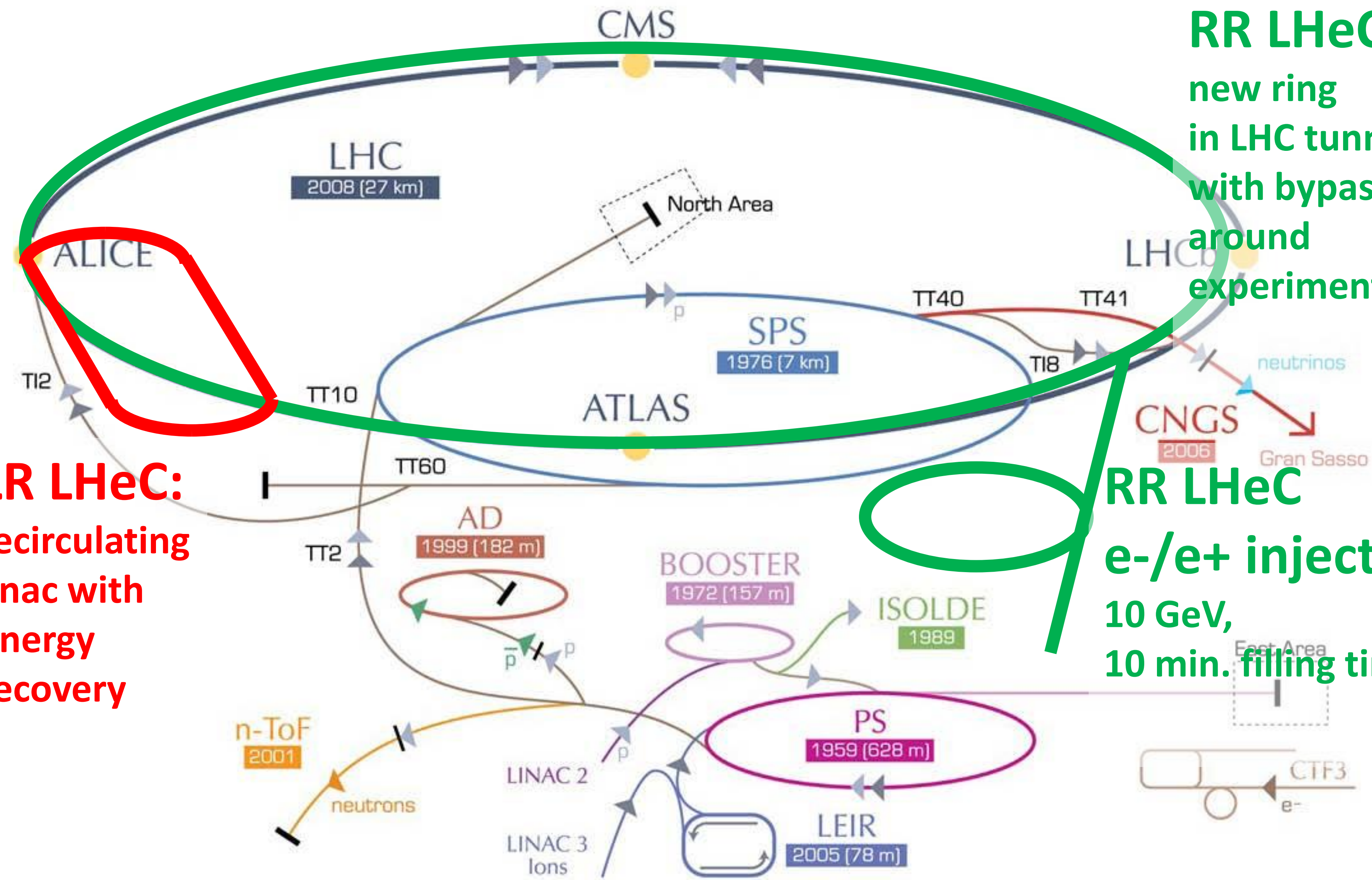
LI ECR Source

RFQ

Contents

- **Hadron colliders** (and not only colliders)
  - **HL-LHC, HE-LHC, FCC, SPPC**
  - **FAIR, NICA, SPIRAL2**
- **Electron - ion**
  - **LHeC & FCC-he**
  - **eRHIC**
  - **Jlab e-ion**
- **Lepton colliders**
  - **FCC-ee & CepC**
  - **CLIC and ILC**
  - **Super-B factory**
  - **c-tau factory**
- **Advanced approaches**
  - **LPWF & PWFA collider roadmaps & AWAKE**

Electron – Ion : LHeC

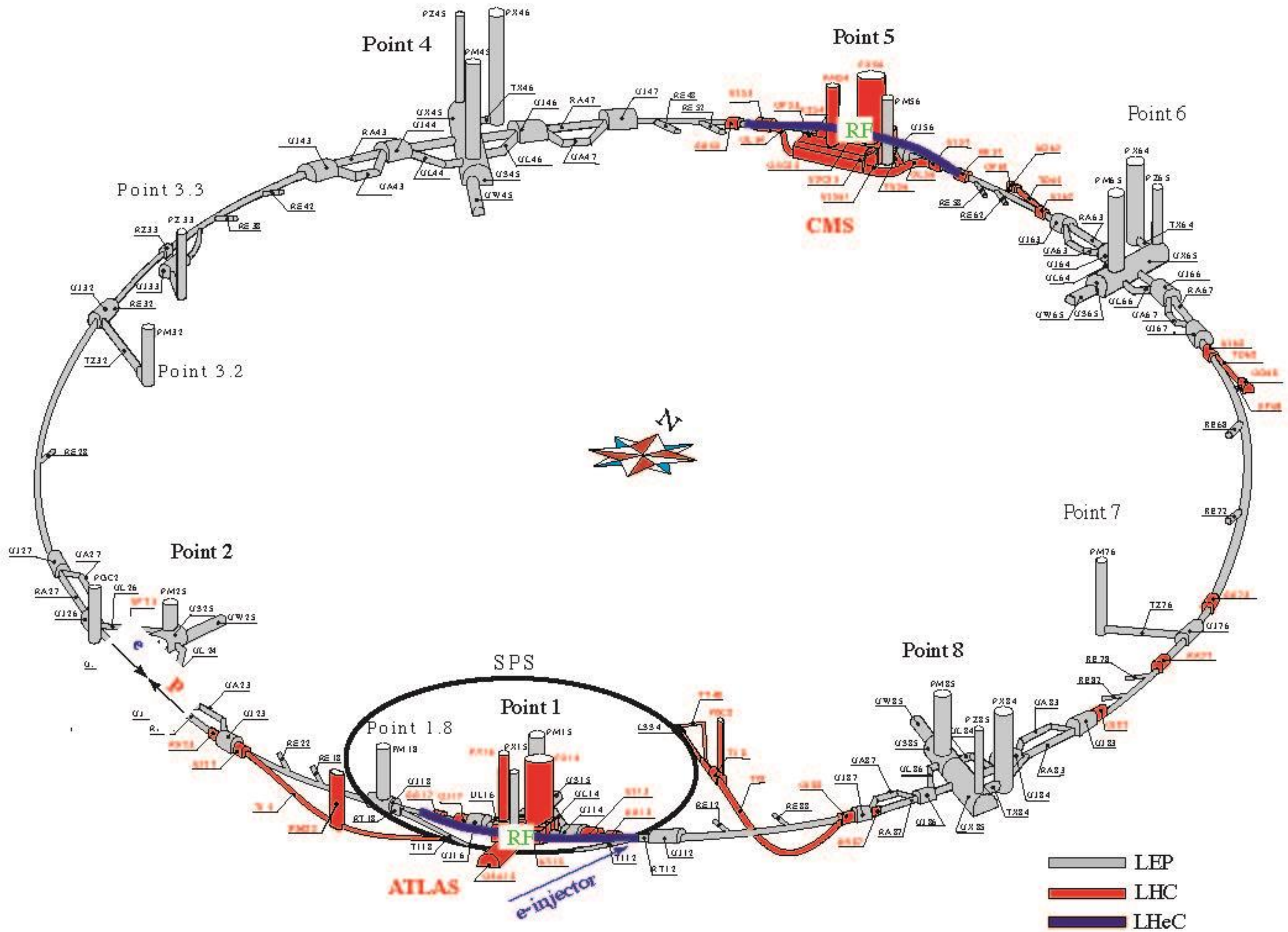


RR LHeC:
new ring
in LHC tunnel,
with bypasses
around
experiments

LR LHeC:
recirculating
linac with
energy
recovery

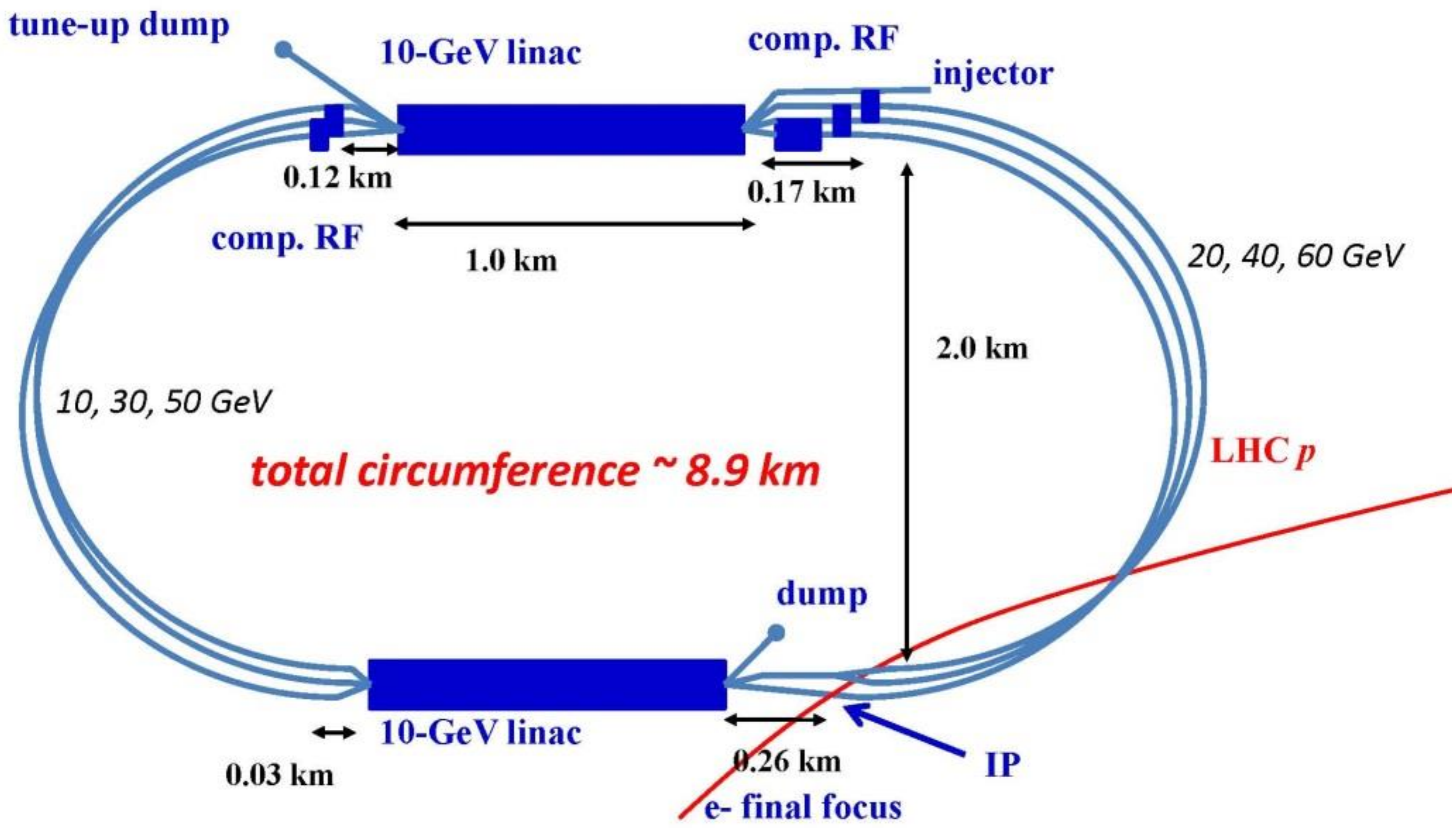
RR LHeC
e-/e+ injector
10 GeV,
10 min. filling time

LHeC ring-ring



Two **LHeC bypasses shown in blue** - each 1.3 km long. **RF in the central straight sections** of the two bypasses (<500 m total). The bypass around Point 1 also hosts the injection.

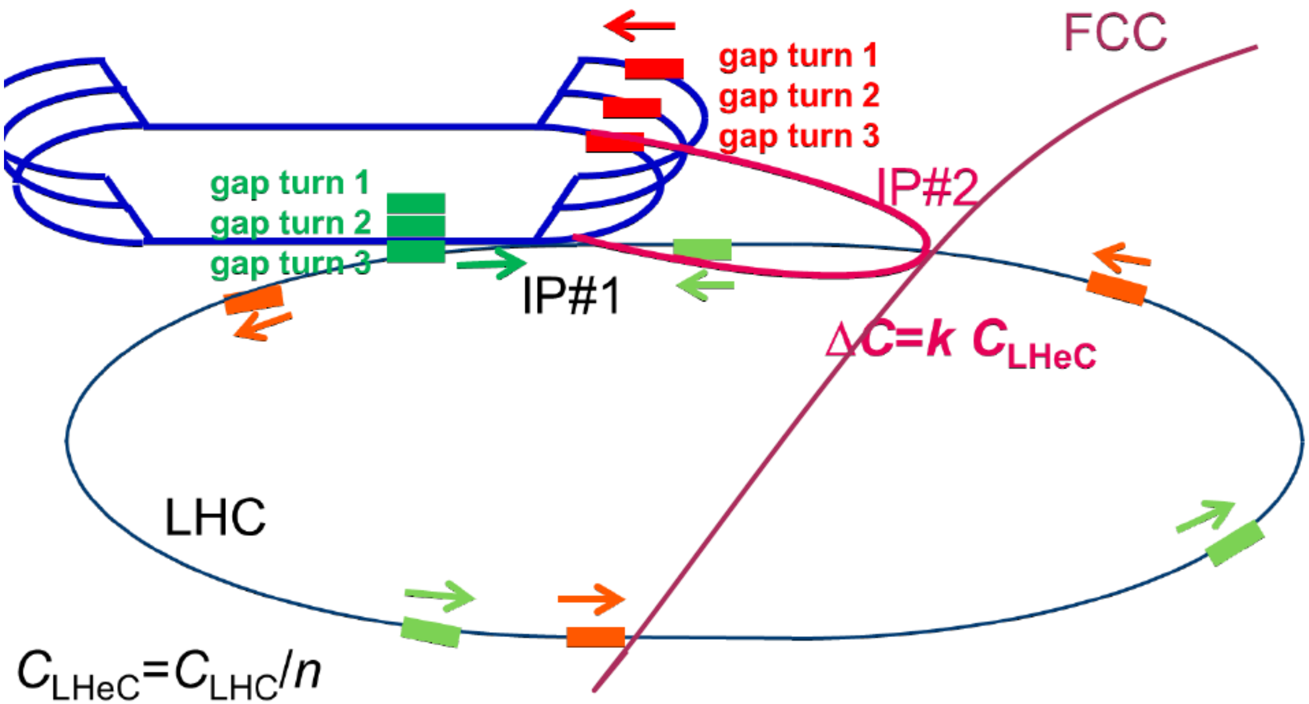
LHeC linac-ring



Two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e-'s collide w. LHC protons/ions

FCC-he option

FCC-he: e- from ERL, reusing the “LHeC



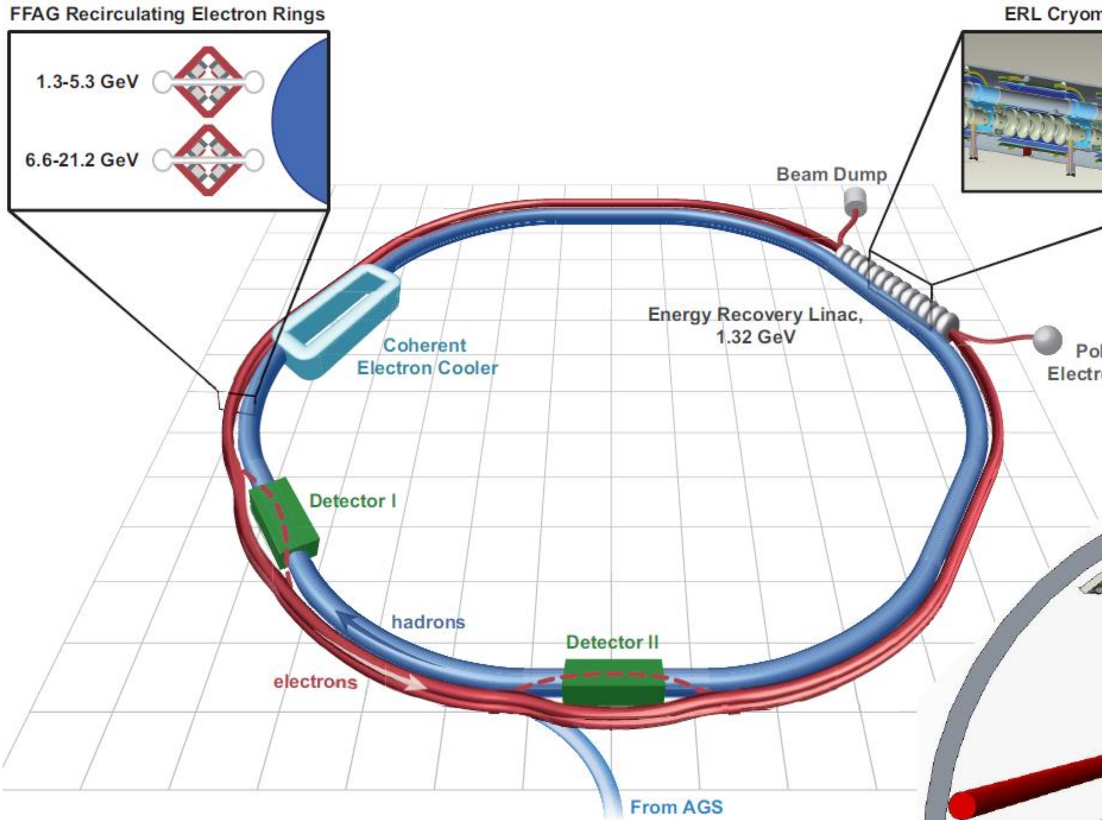
$C_{LHeC}=C_{LHC}/n$

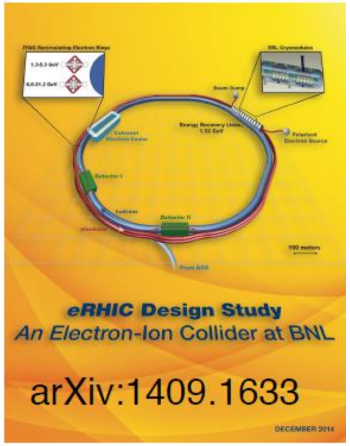
future: $C_{LHeC}=pC_{FCC}/m$

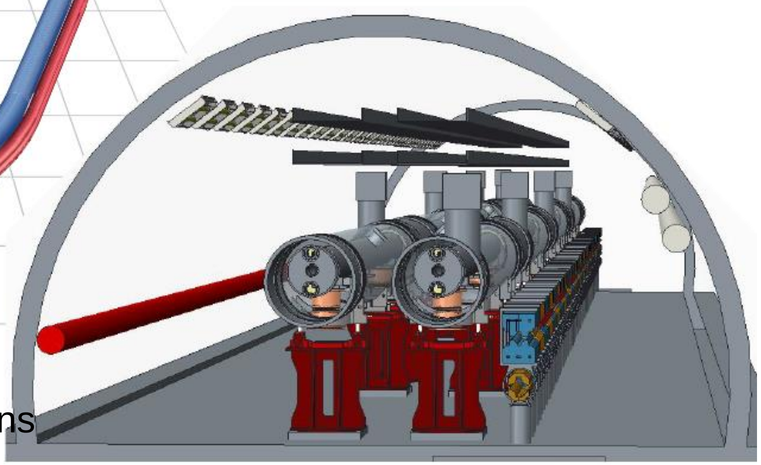
m, *n* (=3 or 4), *k*: integer
p = 1 or 2

*I*e~26 mA, σ $_{x,y}$*~2 μm, luminosity/nucleon ~ 3x1E34 cm-2 s-1

Electron – Ion : eRHIC (BNL)

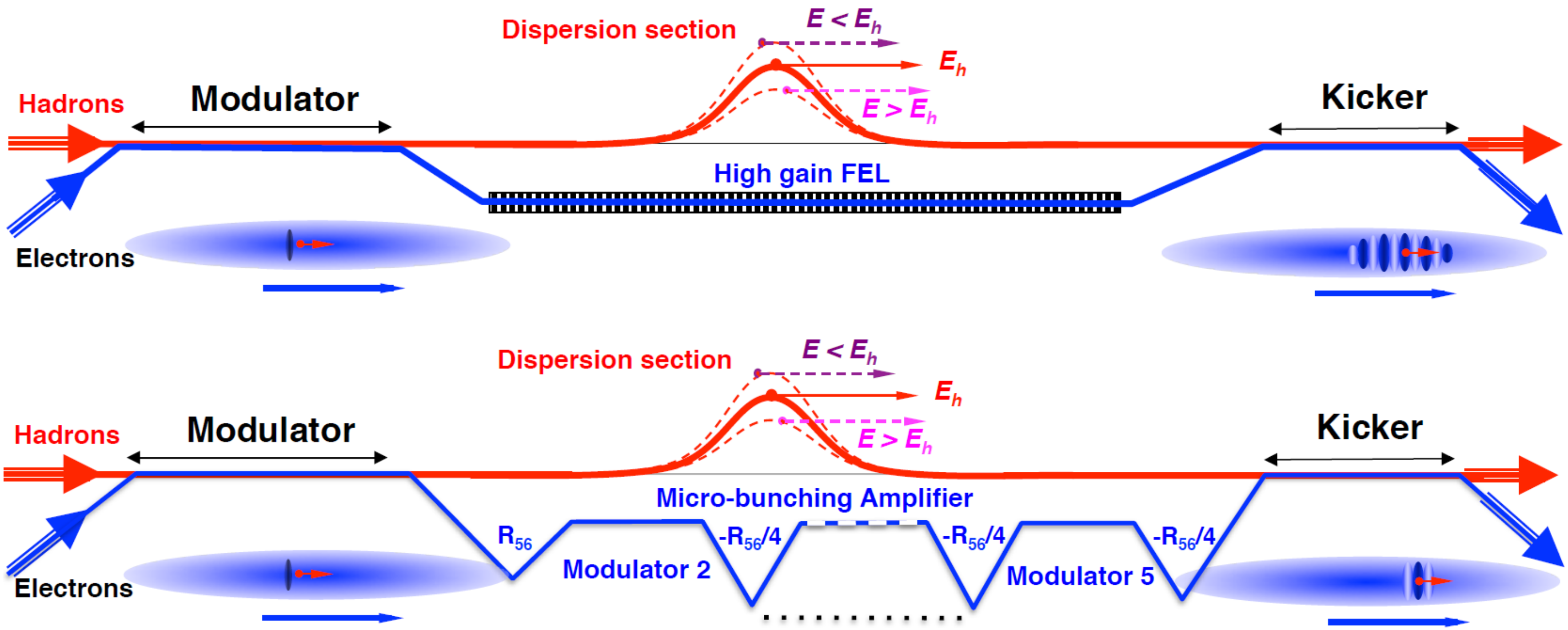






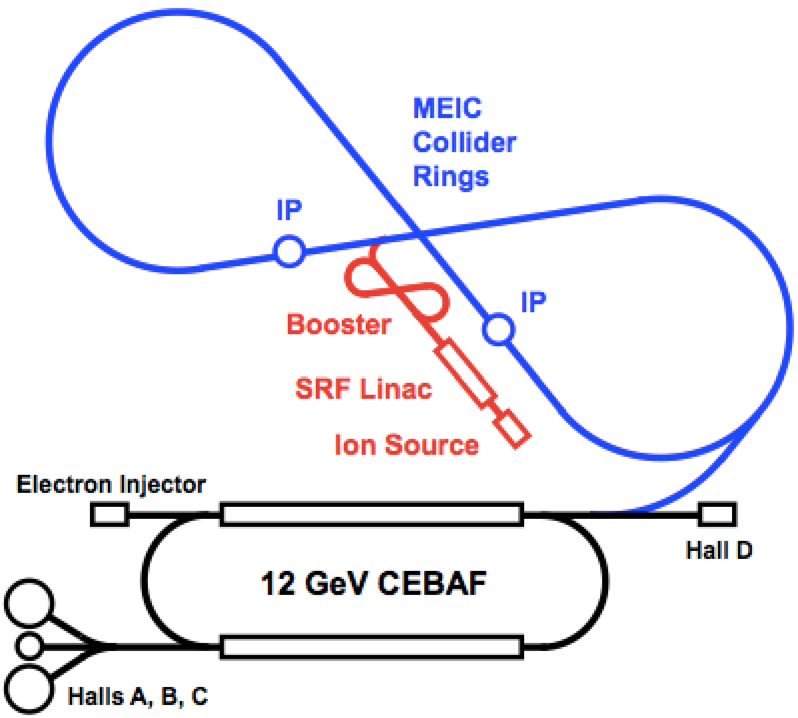
e- colliding with protons, 3He or heavy ions (up to Au)
E: 5-21 GeV e-, 50-250 GeV polarized p or up to 100 GeV/u gold ions
L: >1E34 for e-p, > 1E32 cm-2s-1 for e-Au
High polarization of e-, proton and 3He beams
Electron acceleration in a SC E-recovery e-linac
Electron beam is used for collisions only on one pass (linac-ring collision scheme)
Multiple recirculations of e-beam done by beam transport in two FFAG beamlines
IR design with 10 mrad crossing angle and crab-crossing

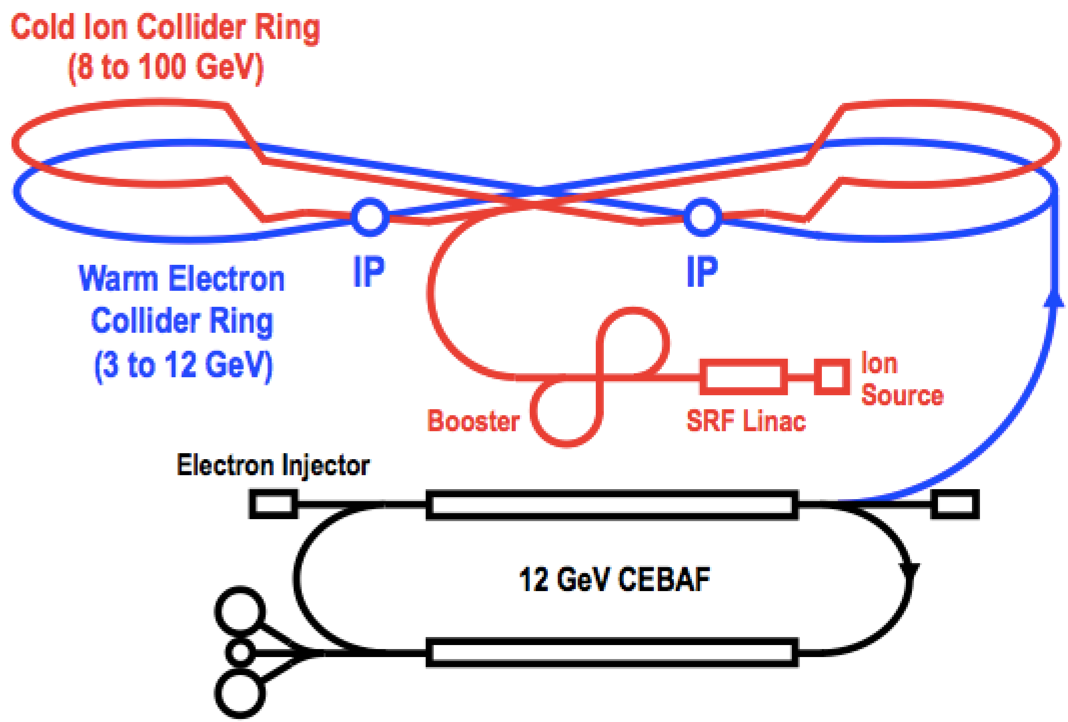
eRHIC – coherent electron cooling



- Idea from 1980 (Y. Derbenev) further developed by V. Litvinenko into a novel scheme
- Very high bandwidth (~ 10 - 100 THz) stochastic cooling using electron beam as medium
- Made possible by high brightness electron beams and FEL technology
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (2016)
- Micro-bunching amplifier test also planned with same set-up

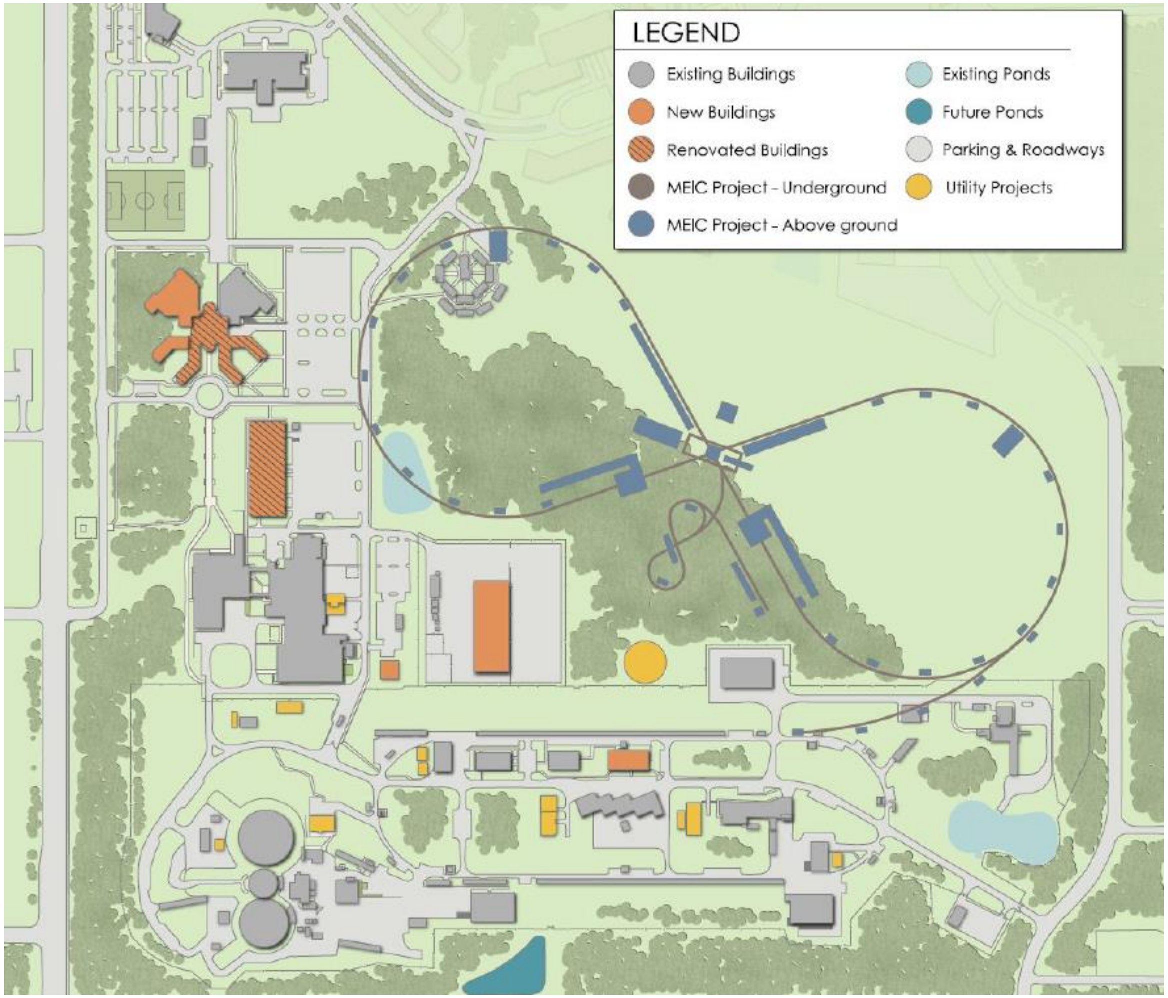
Electron – Ion : MEIC (JLAB)





Ring-ring design based largely on conventional technology
High rep rate CW colliding beams
CEBAF is a full energy injector
Energy: from 15 to 65 GeV
Electrons 3-10 GeV, protons 20-100 GeV, ions 12-40 GeV/u
Ions:Polarized light ions: p, d, 3He, and possibly Li
Un-polarized light to heavy ions up to A above 200 (Au, Pb)
Luminosity: 1E33 to 1E34 per IP in a broad energy range
Polarization: longitudinal for both beams, transverse for ions only

Electron – Ion : MEIC (JLAB)

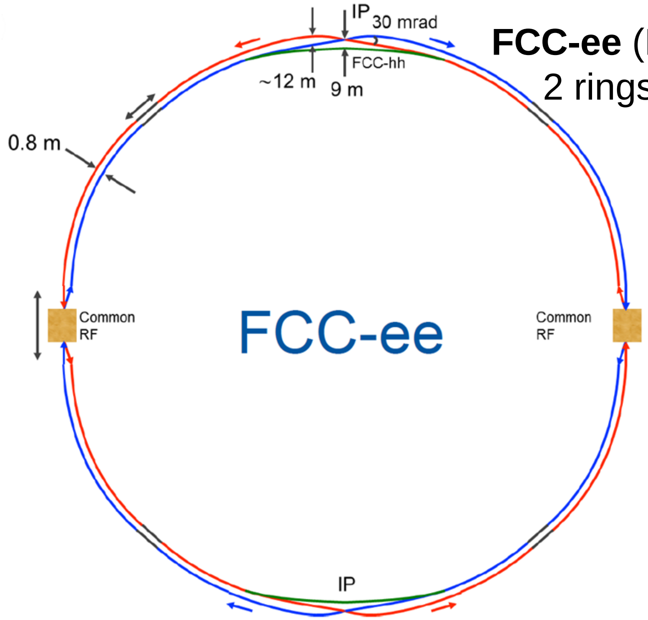


Campus layout
Tunnel consistent with a 250+ GeV upgrade

Contents

- **Hadron colliders** (and not only colliders)
  - **HL-LHC, HE-LHC, FCC, SPPC**
  - **FAIR, NICA, SPIRAL2**
- **Electron - ion**
  - **LHeC & FCC-he**
  - **eRHIC**
  - **Jlab e-ion**
- **Lepton colliders**
  - **FCC-ee & CepC**
  - **CLIC and ILC**
  - **Super-B factory**
  - **c-tau factory**
- **Advanced approaches**
  - **LPWF & PWFA collider roadmaps & AWAKE**

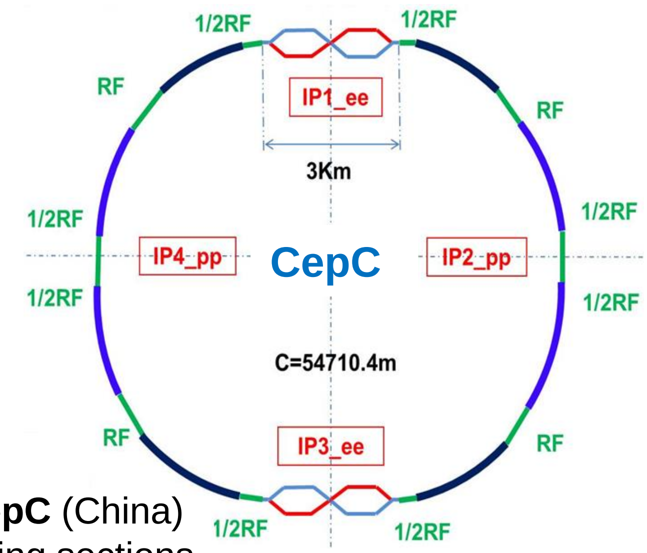
FCC-ee & CepC



FCC-ee (Europe)
2 rings and one booster

Both: 2 IP with crab waist

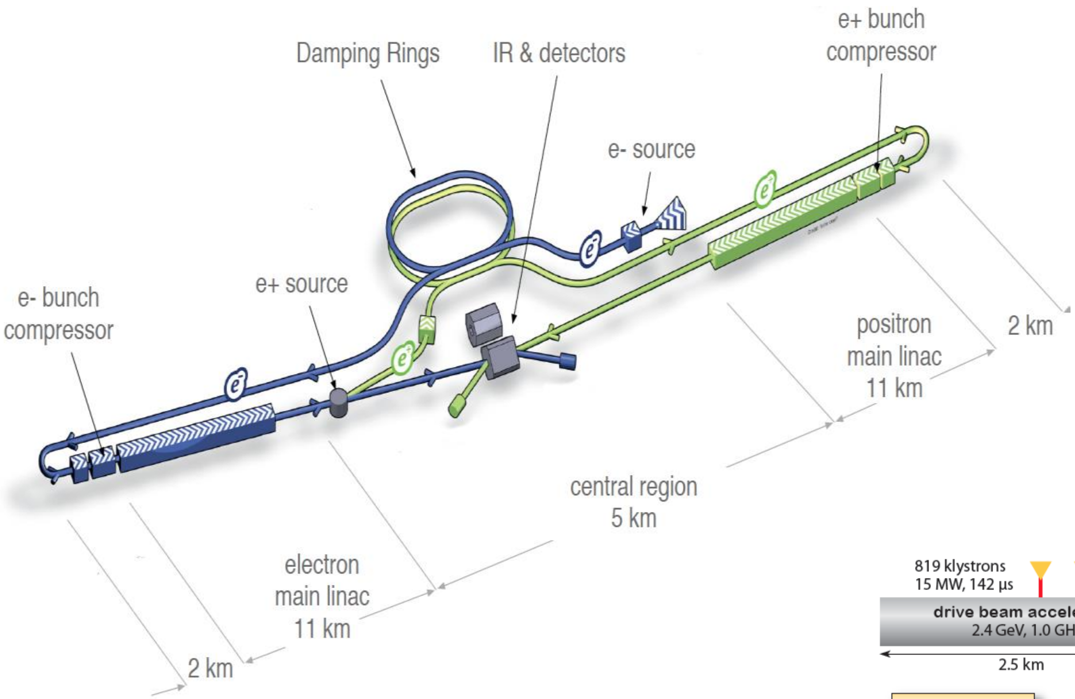
Single ring – more difficult beam dynamics



CepC (China)
1 ring with double ring sections

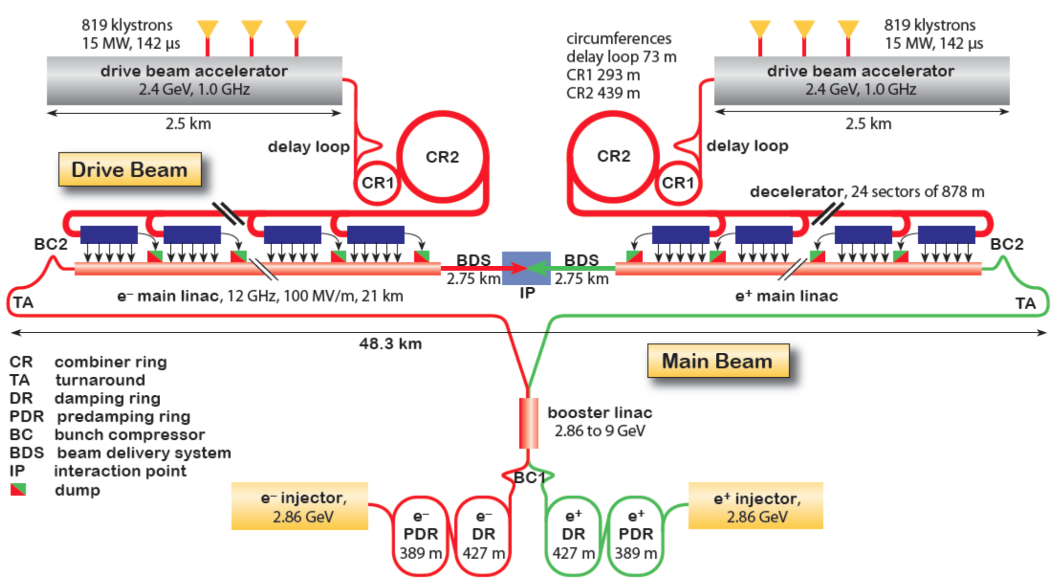
parameter	FCC-ee			CepC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	**100**			**103**	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

CLIC and ILC



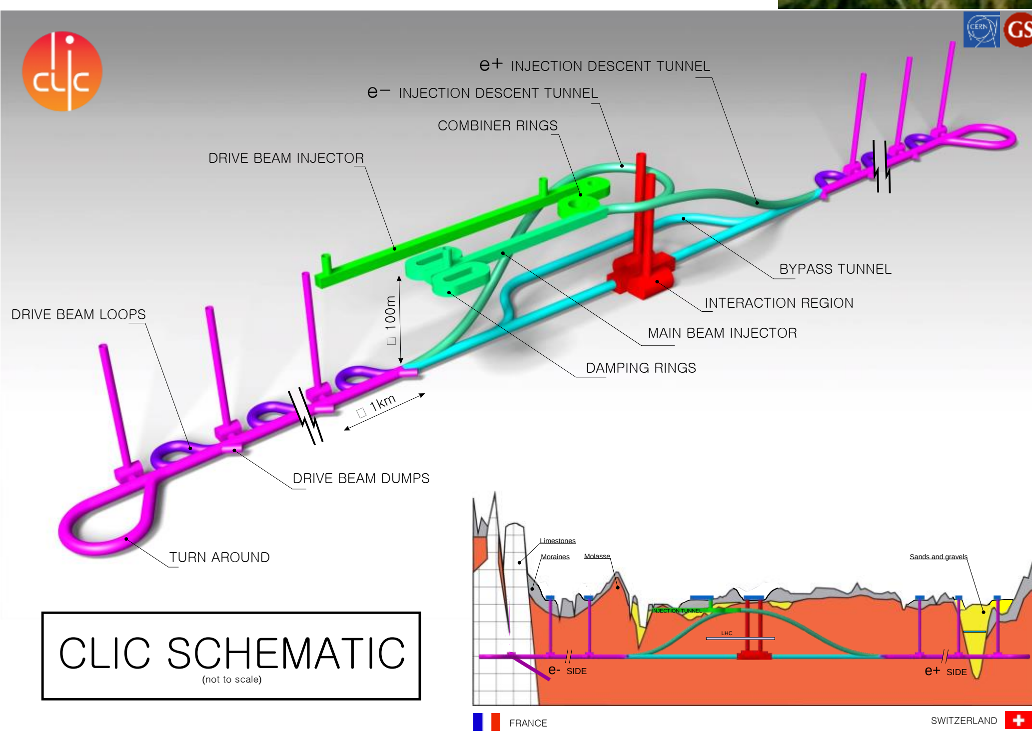
ILC
0.5 TeV CM, upgreadable to 1 TeV
SC RF industrialized
mature design (TDR in 2012)
Possibility of hosting is evaluated by Japanese government

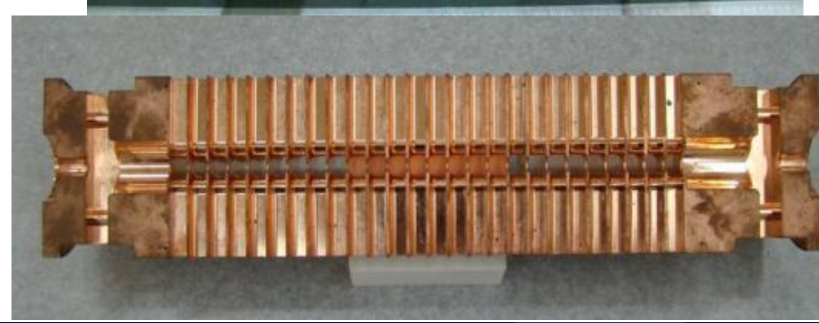
CLIC
Two-beam scheme, 1-3 TeV CM
Option for 380 GeV explored (klystrons)
CTF3 facility – key R&D done
Ready for demonstrator project



CLIC project

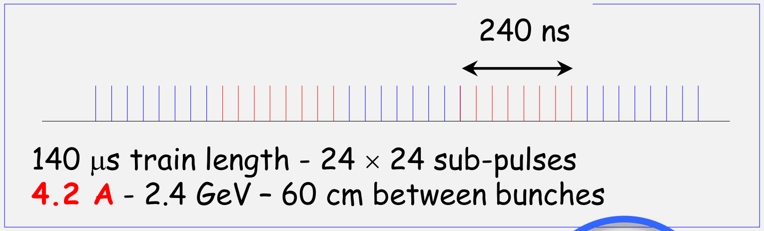
Key features:
High gradient (energy/length)
Small beams (luminosity)



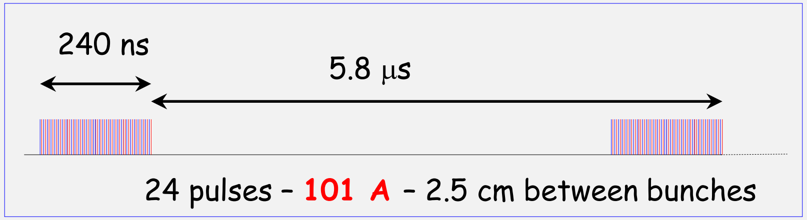


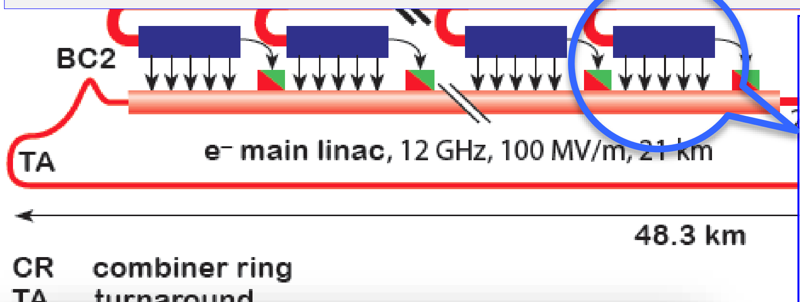
CLIC two beam scheme

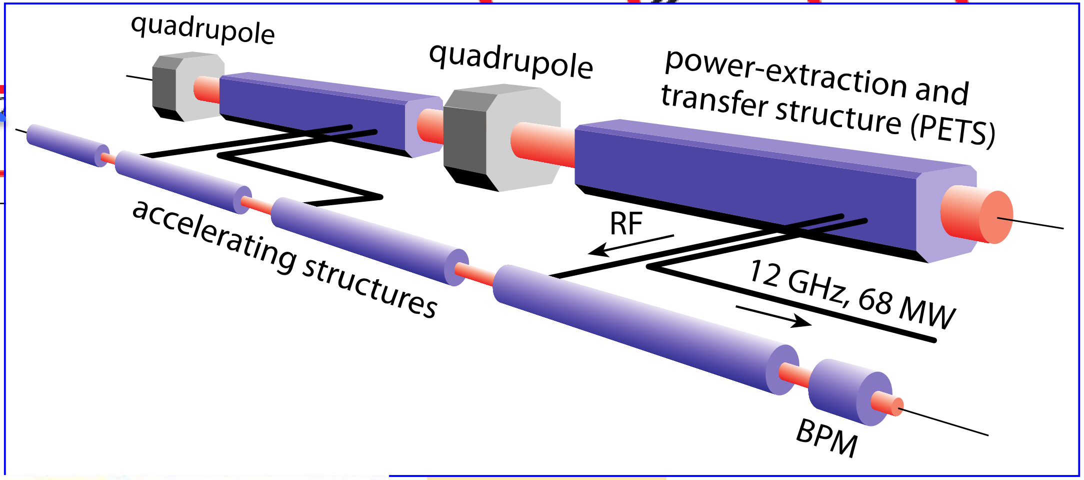
Drive beam time structure - initial

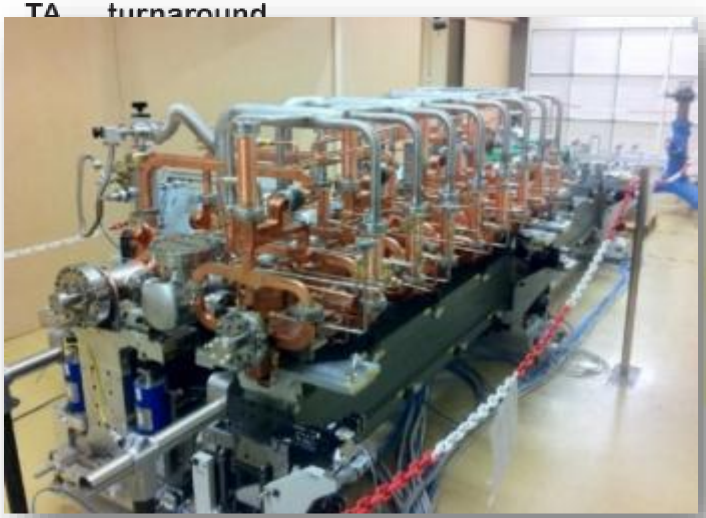


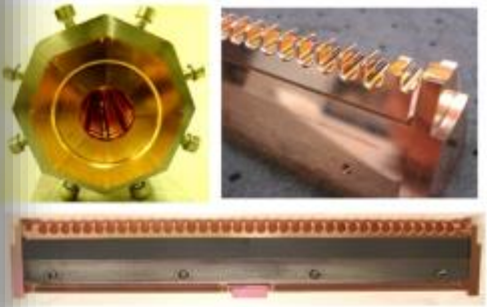
Drive beam time structure - final



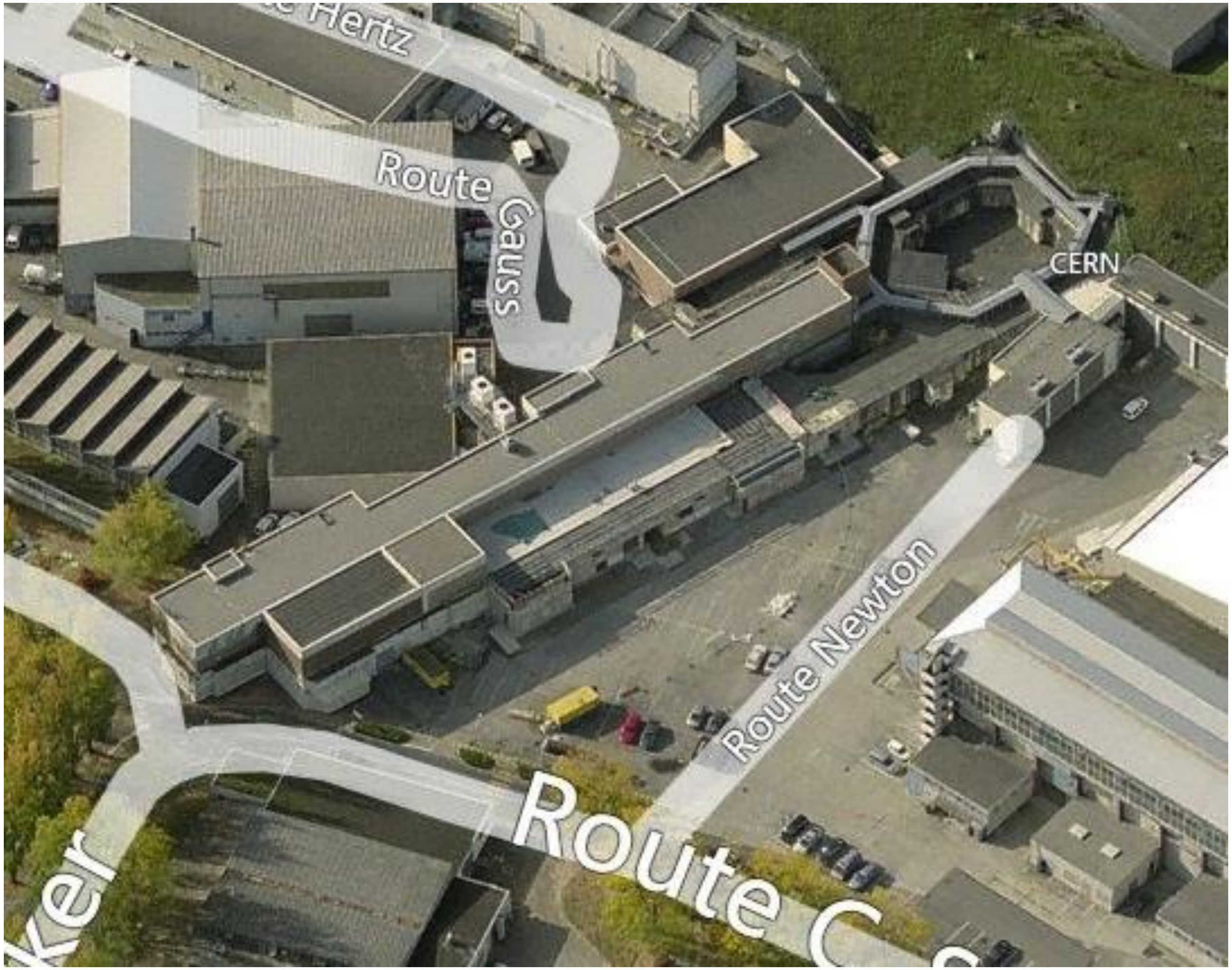




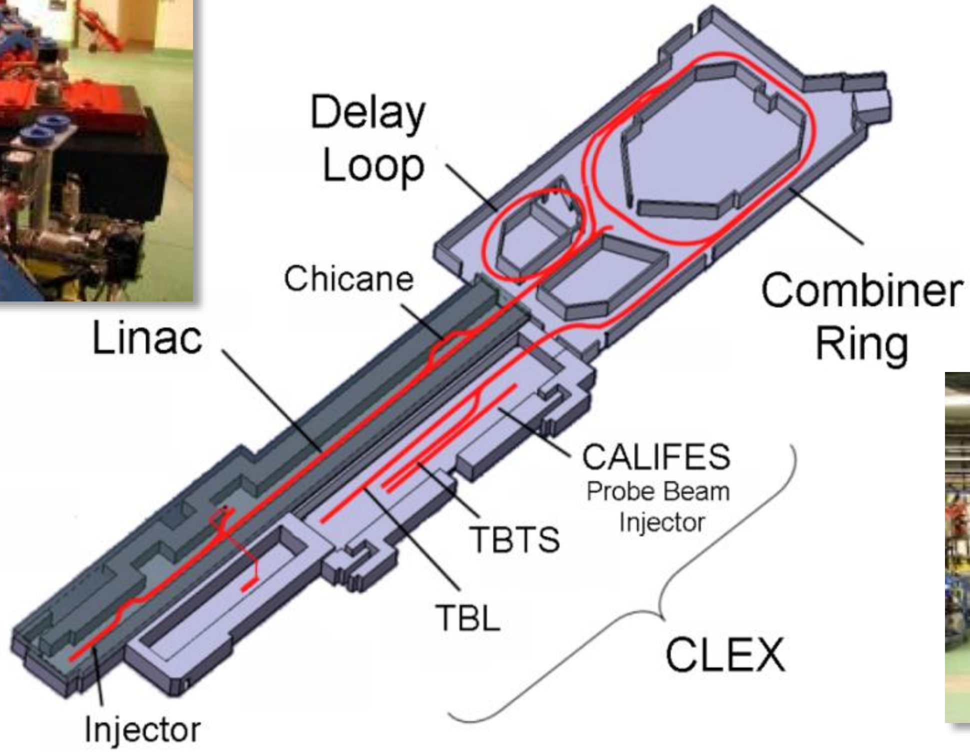


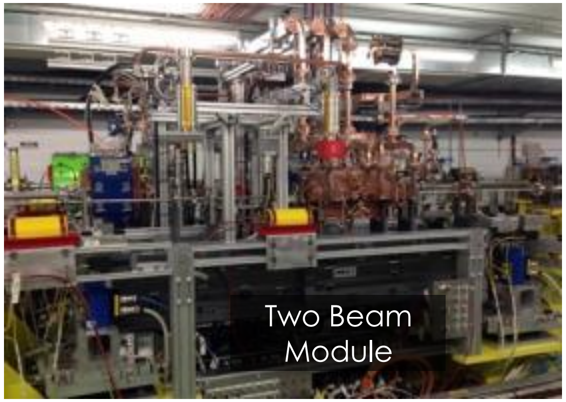


CLIC test facility (CTF3)

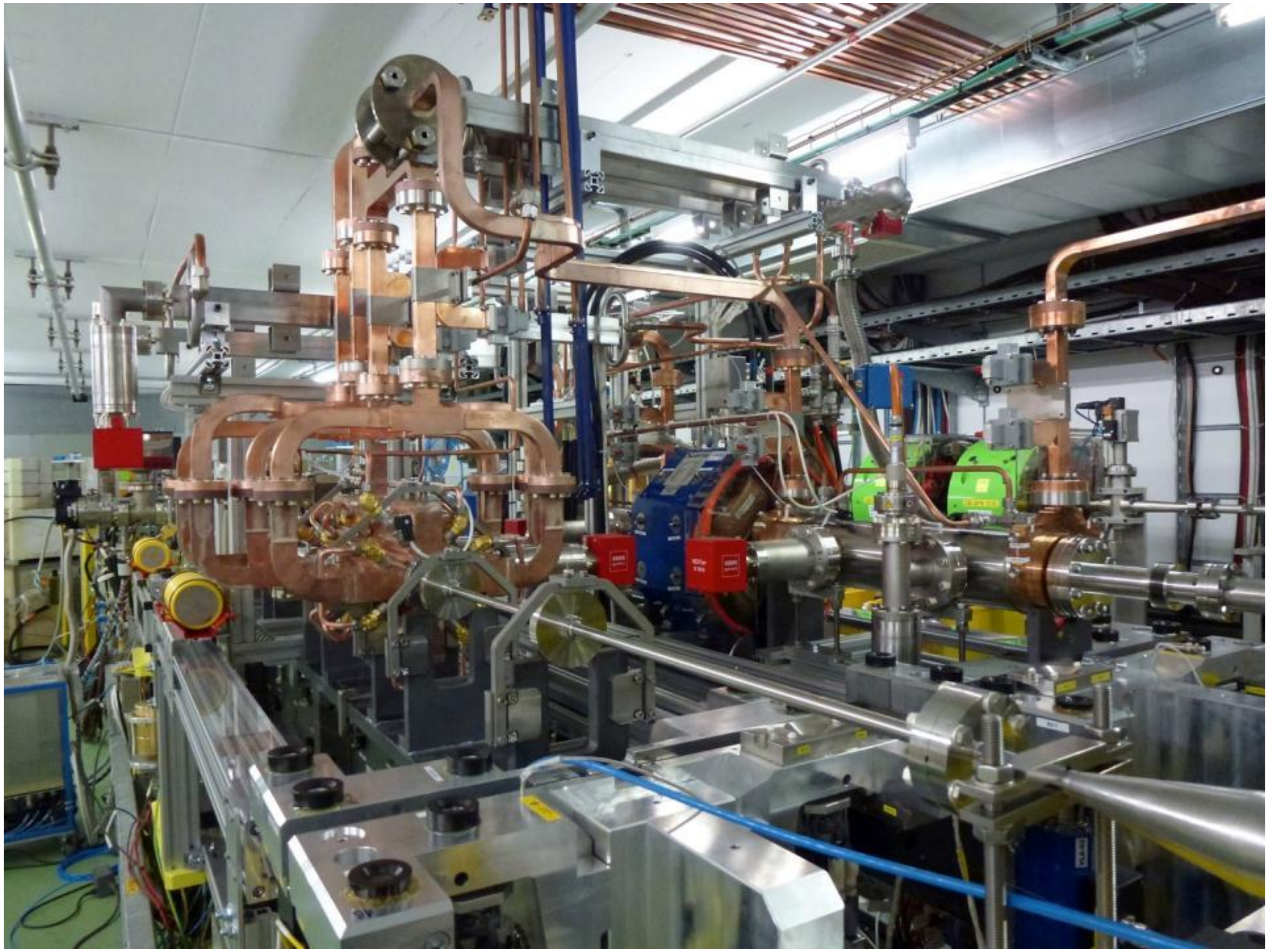


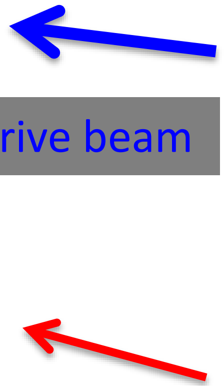
CLIC test facility (CTF3)





2-beam acceleration module in CTF3



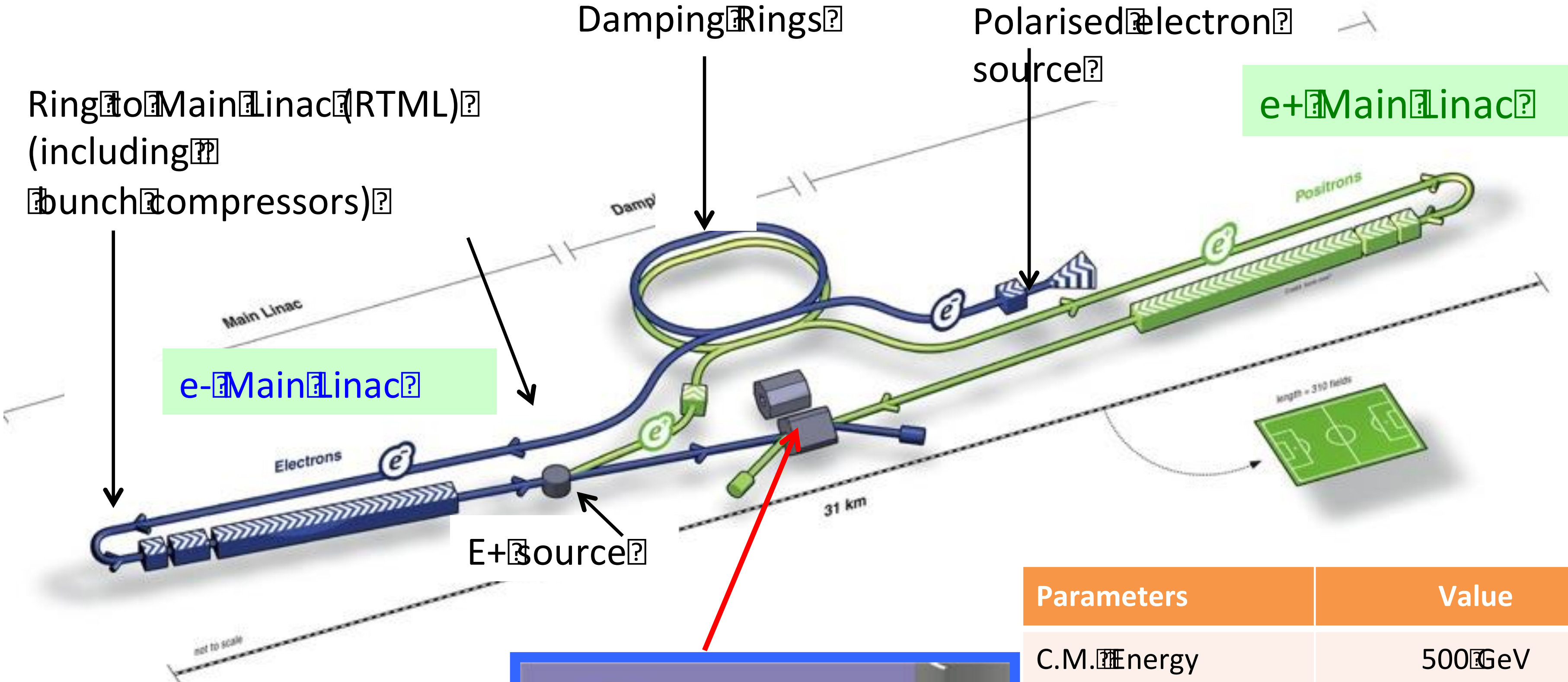


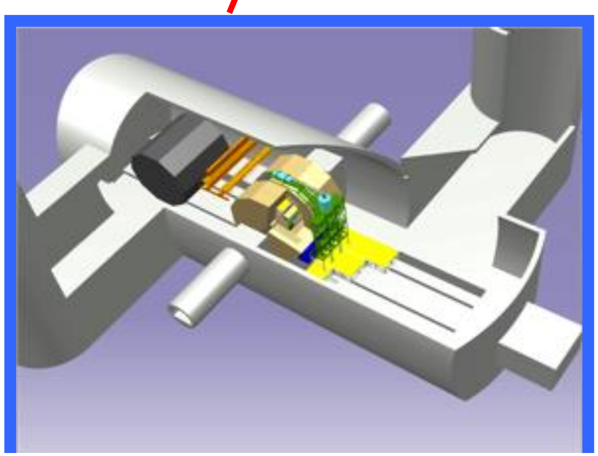
drive beam

main beam

Has reached 145 MV/m (2012)

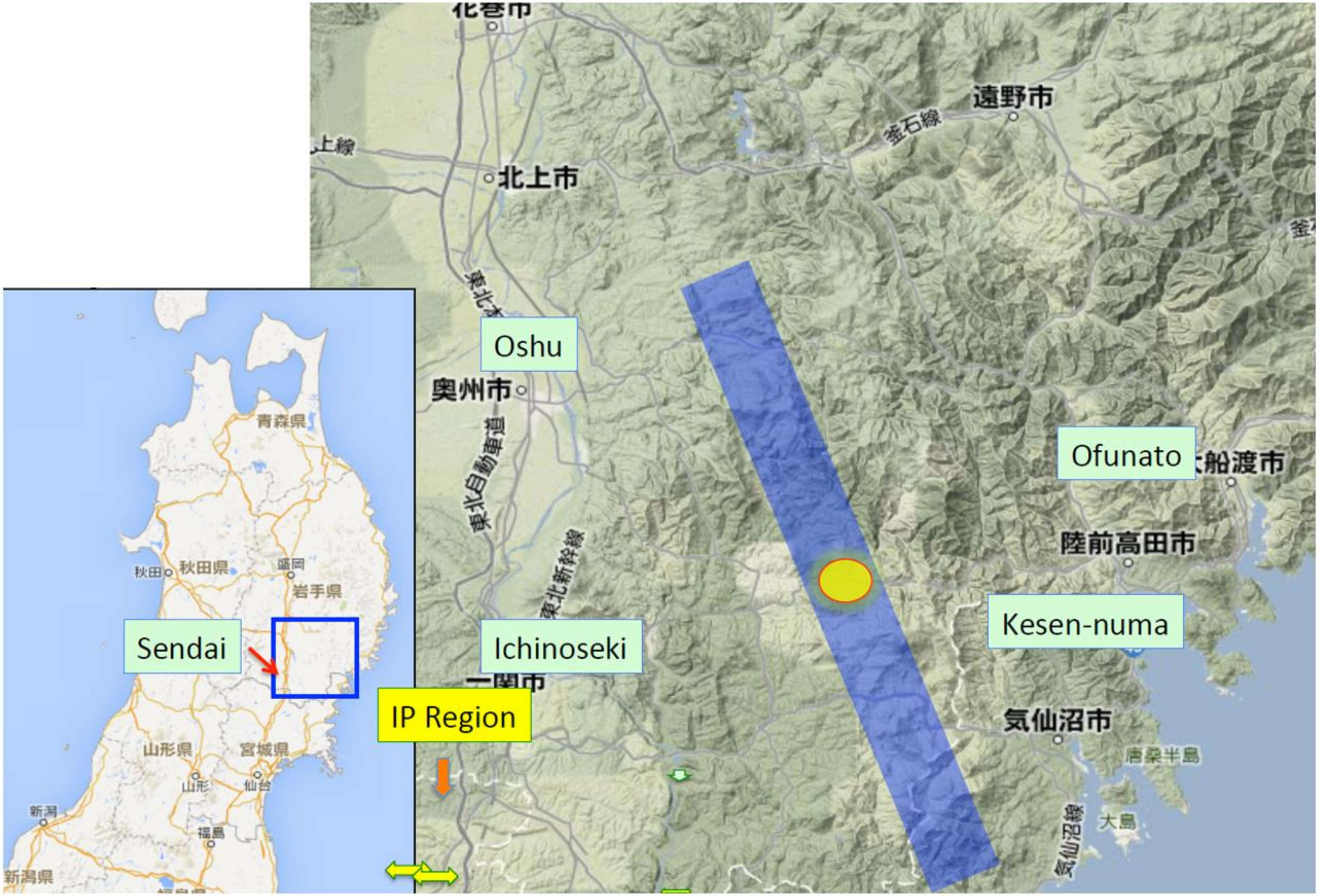
ILC project



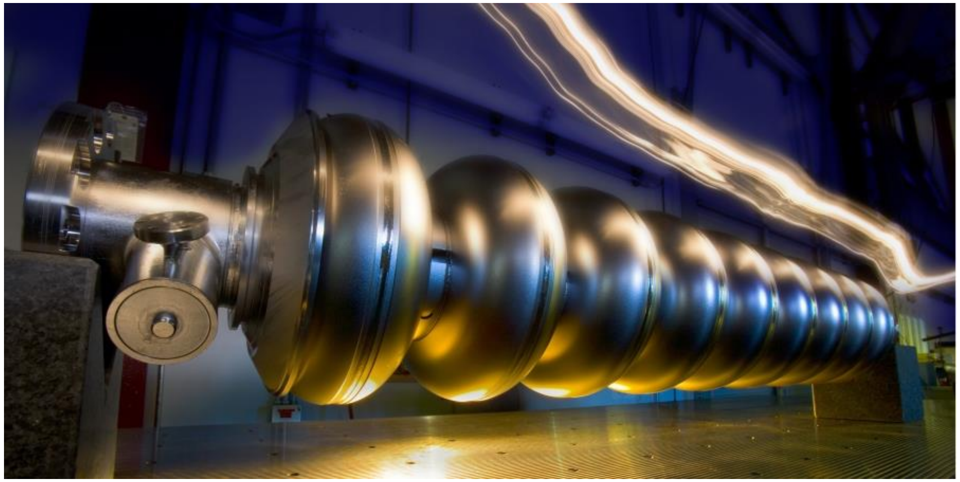


Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x 10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

ILC site specific design

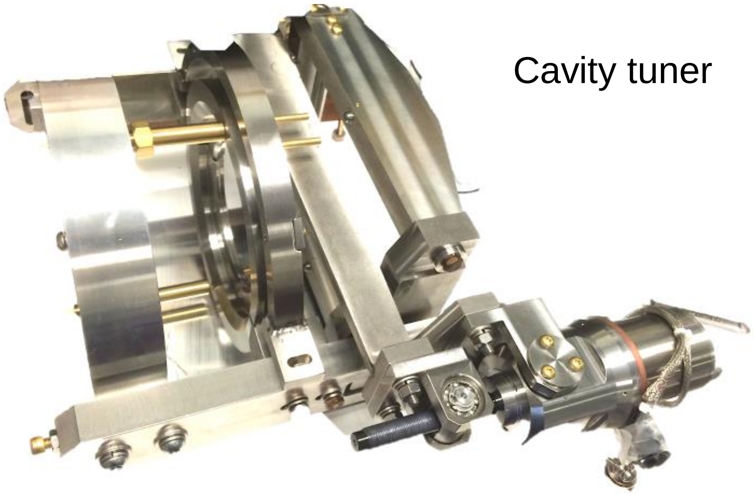


ILC SCRF technology development



SCRF cavities
gradient 31.5 MeV/m

Cavity Input Coupler



Cavity tuner

ILC cryomodule and string tests

CERN Courier December 2014

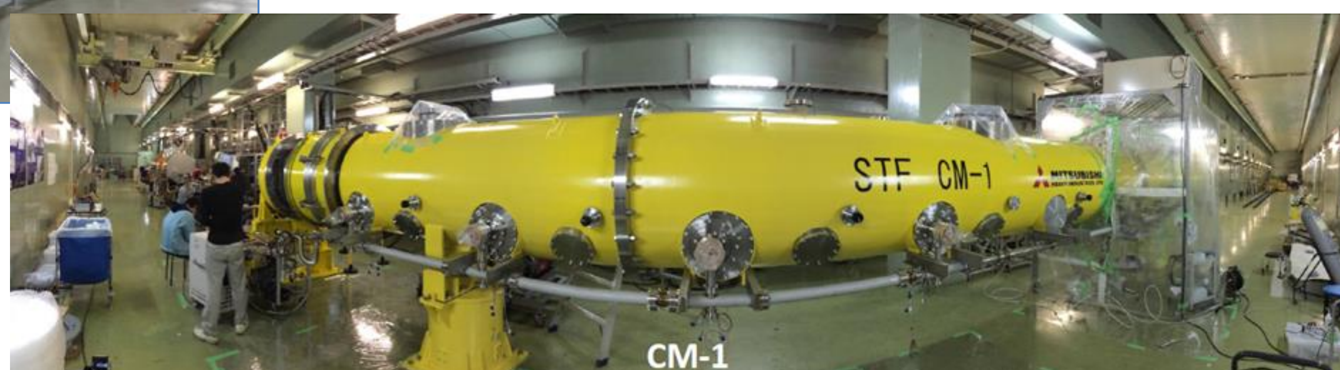
ACCELERATORS

ILC-type cryomodule makes the grade

For the first time, the gradient specification of the International Linear Collider (ILC) design study of 31.5 MV/m has been achieved on average across an entire ILC-type cryomodule made of ILC-grade cavities. A team at Fermilab reached the milestone in early October. The cryomodule, called CM2, was developed to advance superconducting radio-frequency technology and infrastructure at laboratories in the Americas region, and was assembled and installed at Fermilab after initial vertical testing of the cavities at Jefferson Lab. The milestone – an achievement for scientists at Fermilab, Jefferson Lab, and their domestic and international partners in superconducting radio-frequency (SRF) technologies – has been nearly a decade in the making, from

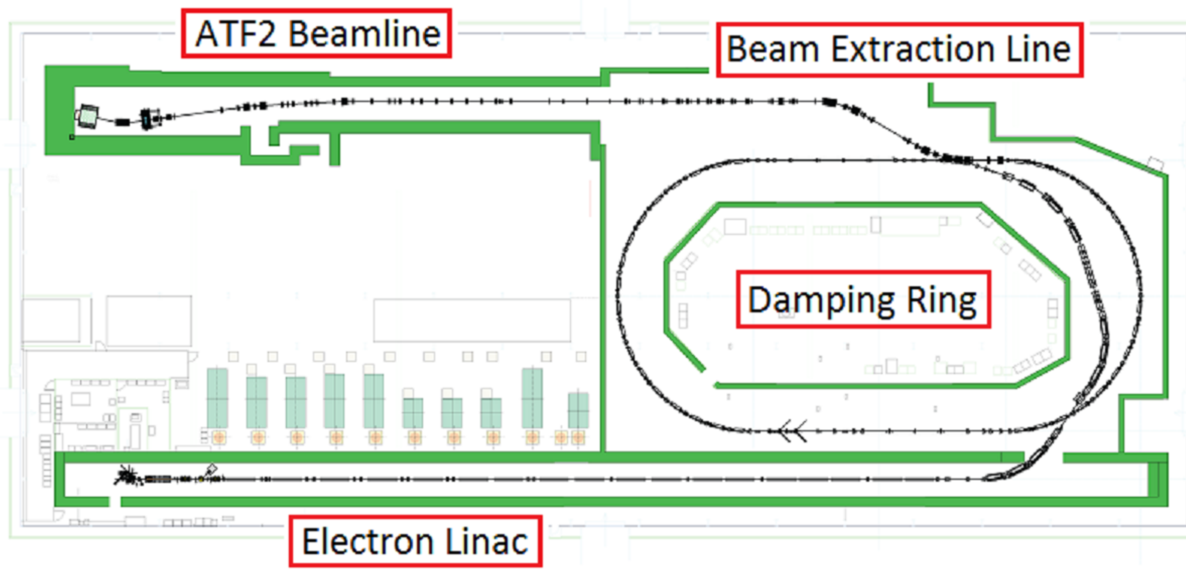
Cryomodule test at Fermilab reached < 31.5 > MV/m, exceeding ILC specification

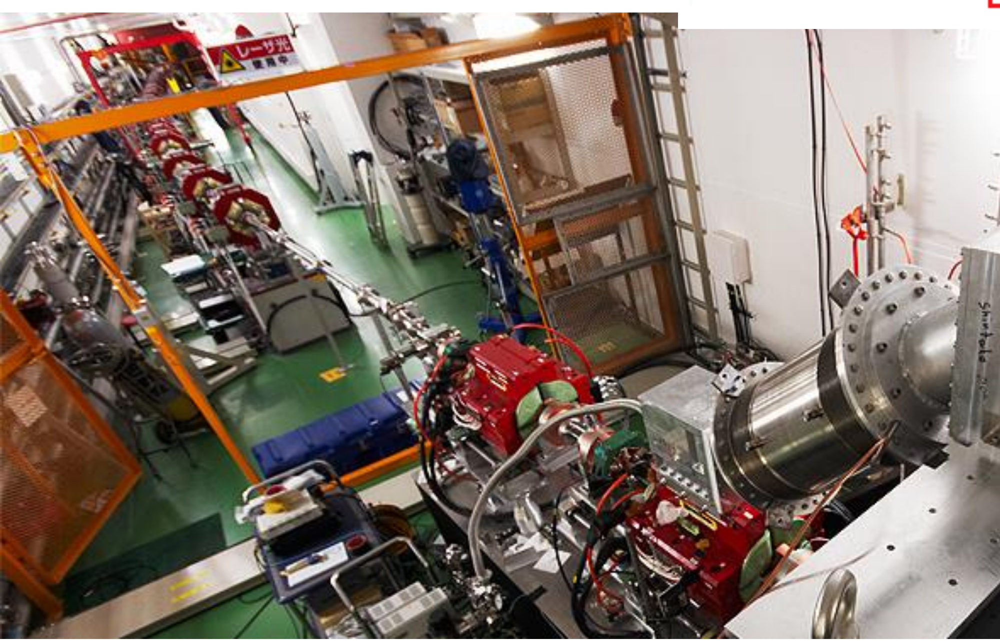
String test of cryomodules at KEK - STF



ILC & CLIC nanobeams at ATF2/KEK

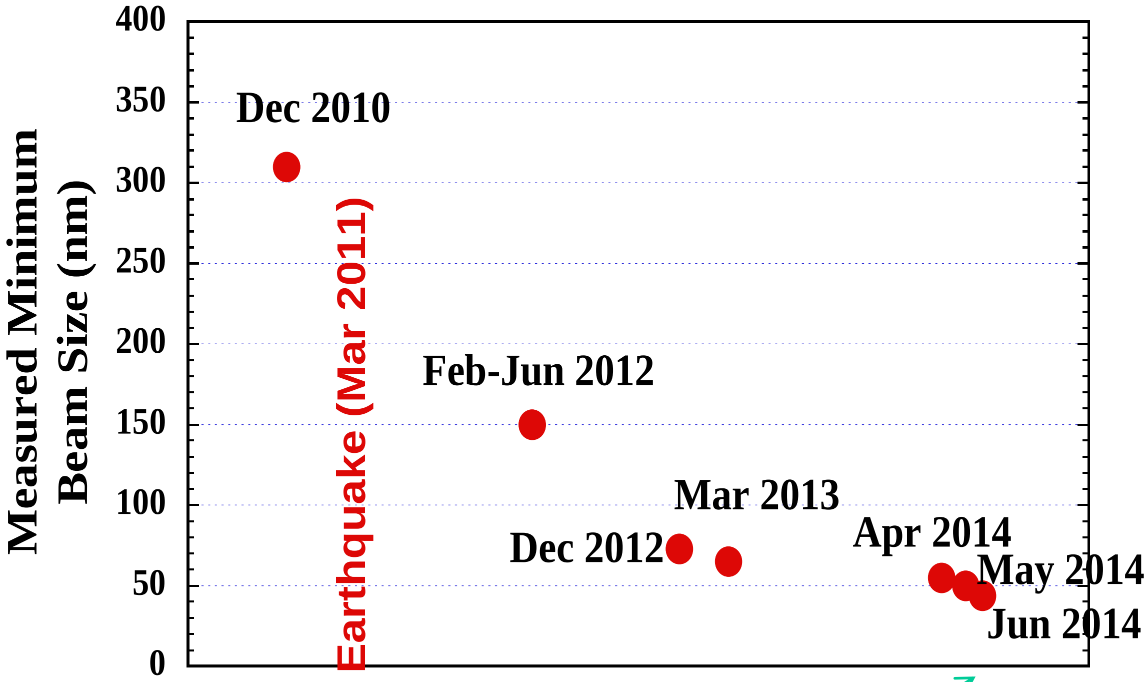
ILC and CLIC rely on final focus with local chromatic correction
P.Raimondi, A.Seryi, PRL, 86, 3779 (2001)

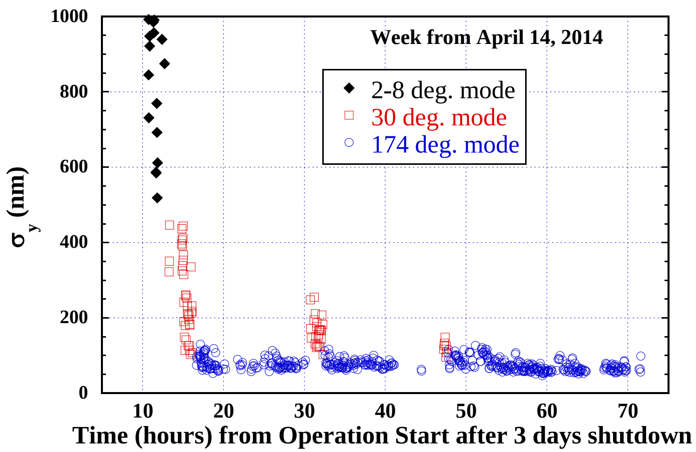




ATF2 at KEK is a scaled down model of ILC/CLIC final focus
(with local chromatic correction)

Nanobeams at ATF2 Final Focus





Beam Size 44 nm observed*,
(Goal (ideal size): **37** nm
corresponding to **6** nm at ILC)

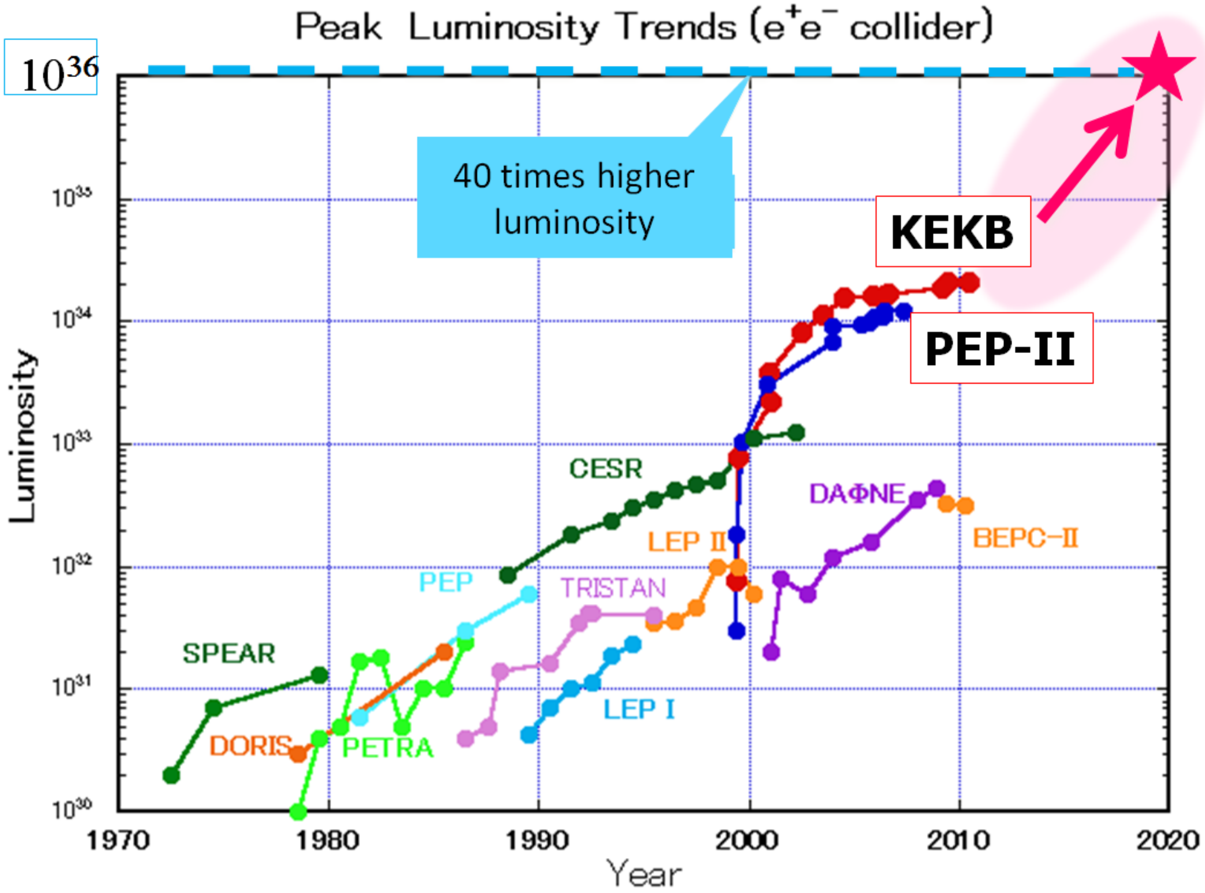
Operation of Final Focus with local chromatic correction verified successfully

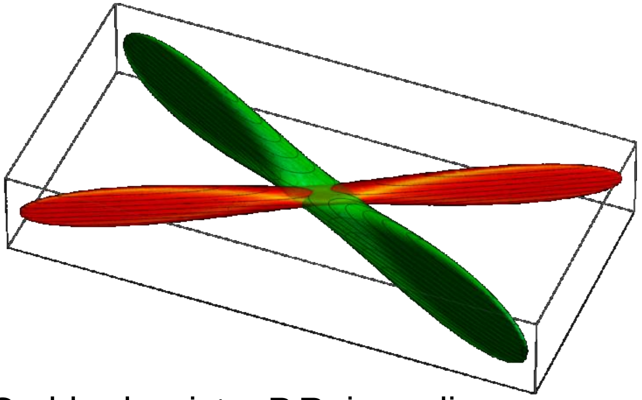
**) Effects (wakefields and magnet nonlinearities) contributing to ATF2 beam size (at 1.2 GeV) would not matter at ILC energy*

Contents

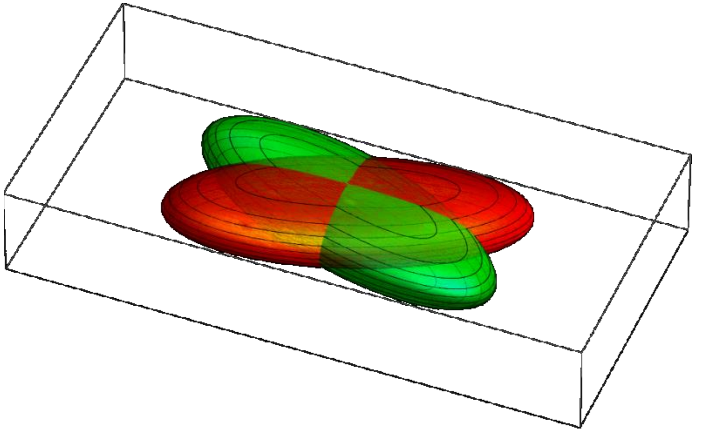
- **Hadron colliders** (and not only colliders)
  - **HL-LHC, HE-LHC, FCC, SPPC**
  - **FAIR, NICA, SPIRAL2**
- **Electron - ion**
  - **LHeC & FCC-he**
  - **eRHIC**
  - **Jlab e-ion**
- **Lepton colliders**
  - **FCC-ee & CepC**
  - **CLIC and ILC**
  - **Super-B factory**
  - **c-tau factory**
- **Advanced approaches**
  - **LPWF & PWFA collider roadmaps & AWAKE**

SuperKEKB factory



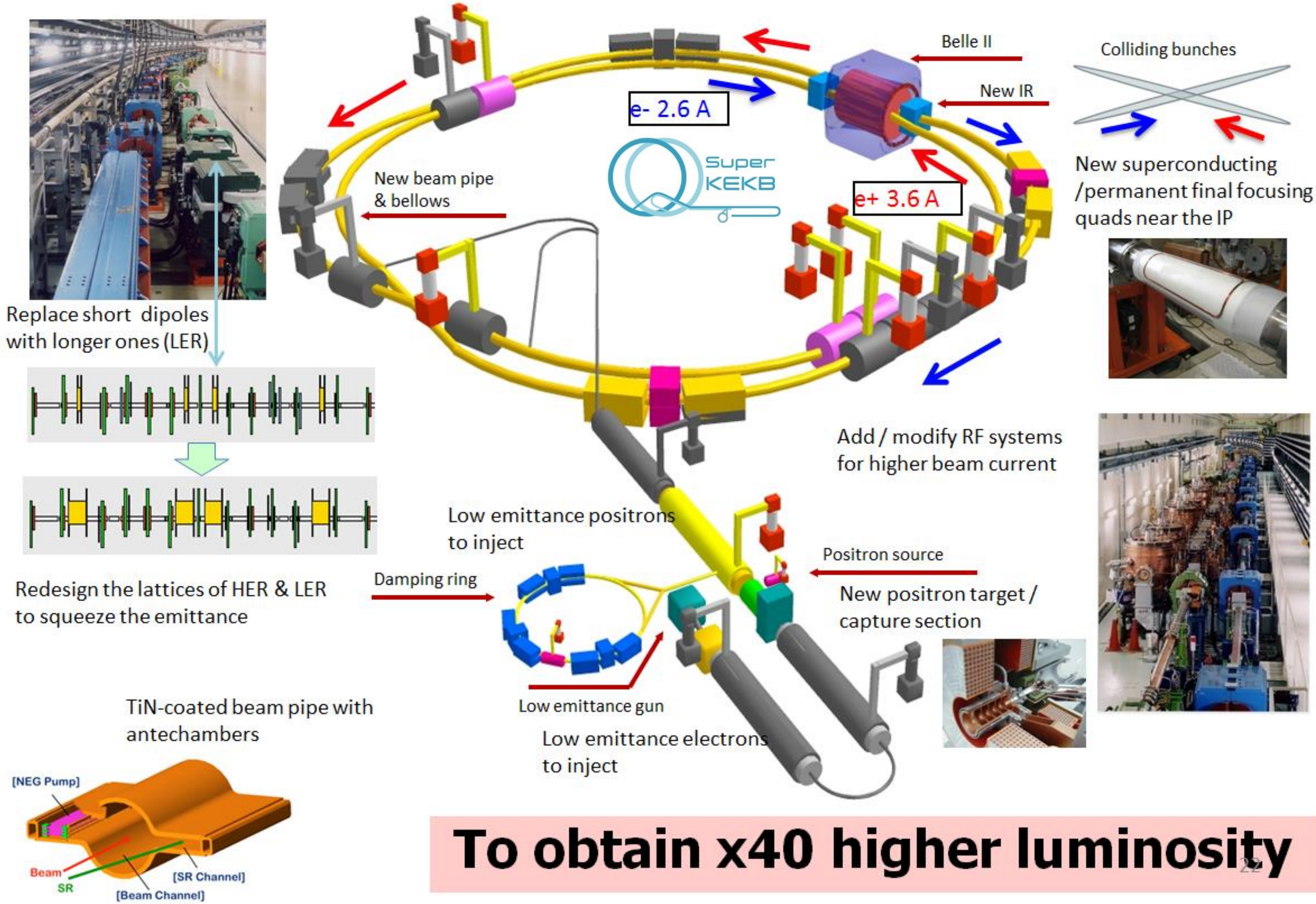


Crabbed waist – P.Raimondi
~50nm size at IP



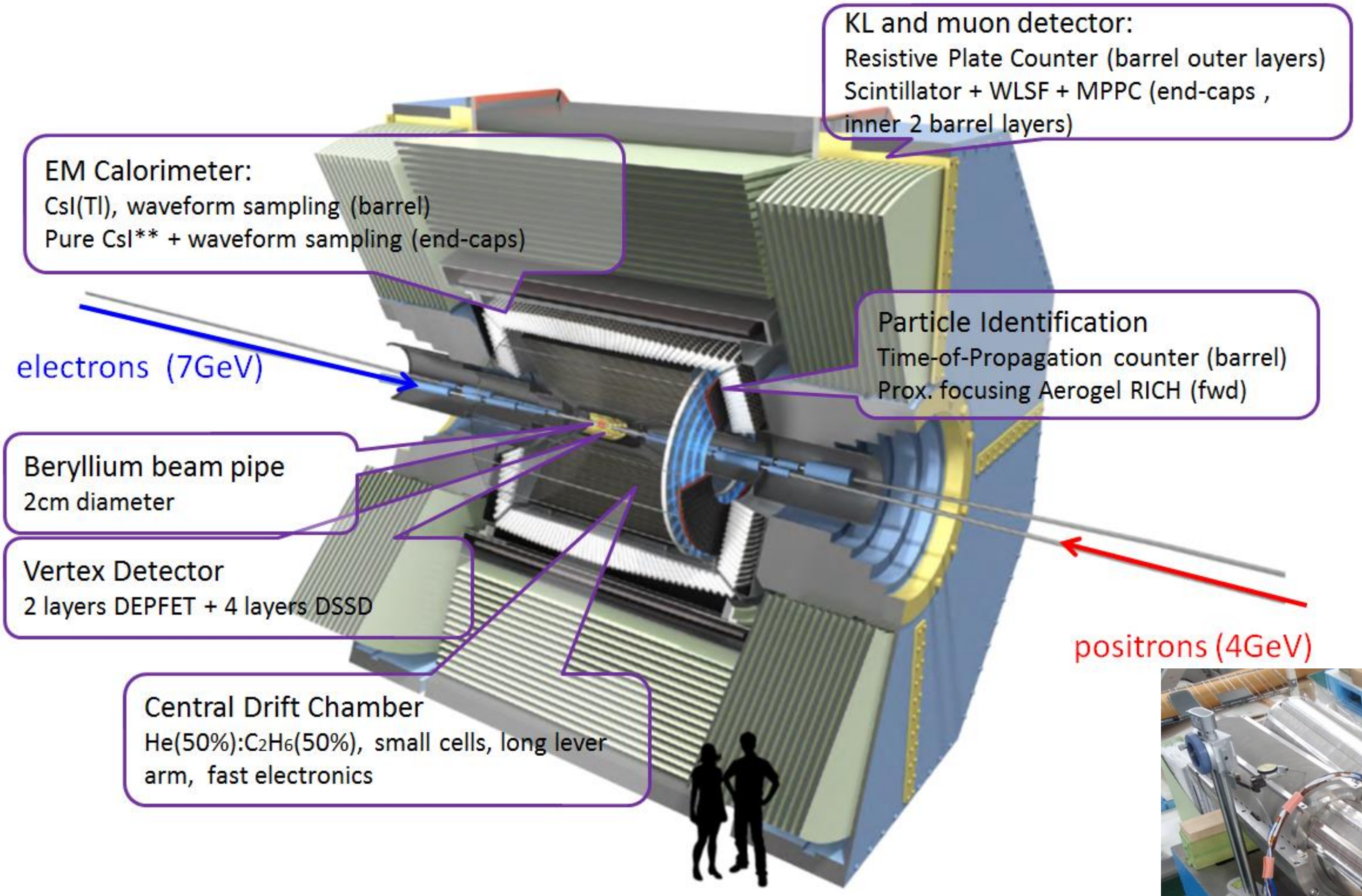
Standard collision, ~1um size at IP

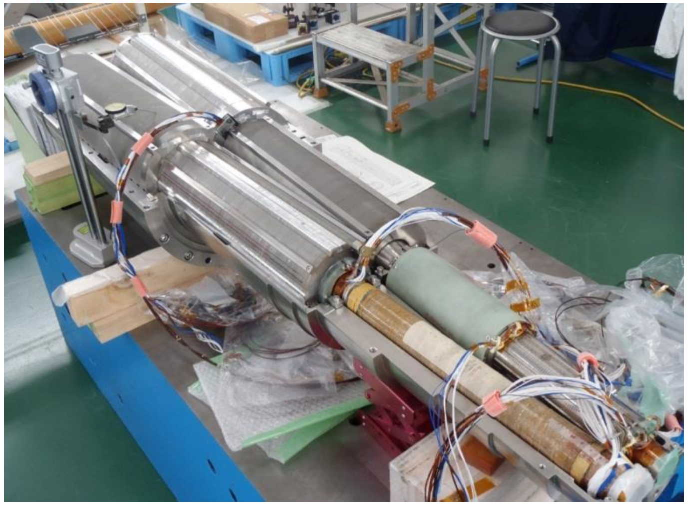
KEKB to SuperKEKB

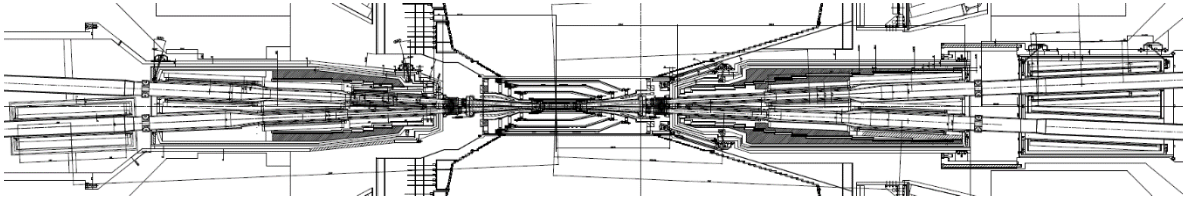


To obtain x40 higher luminosity

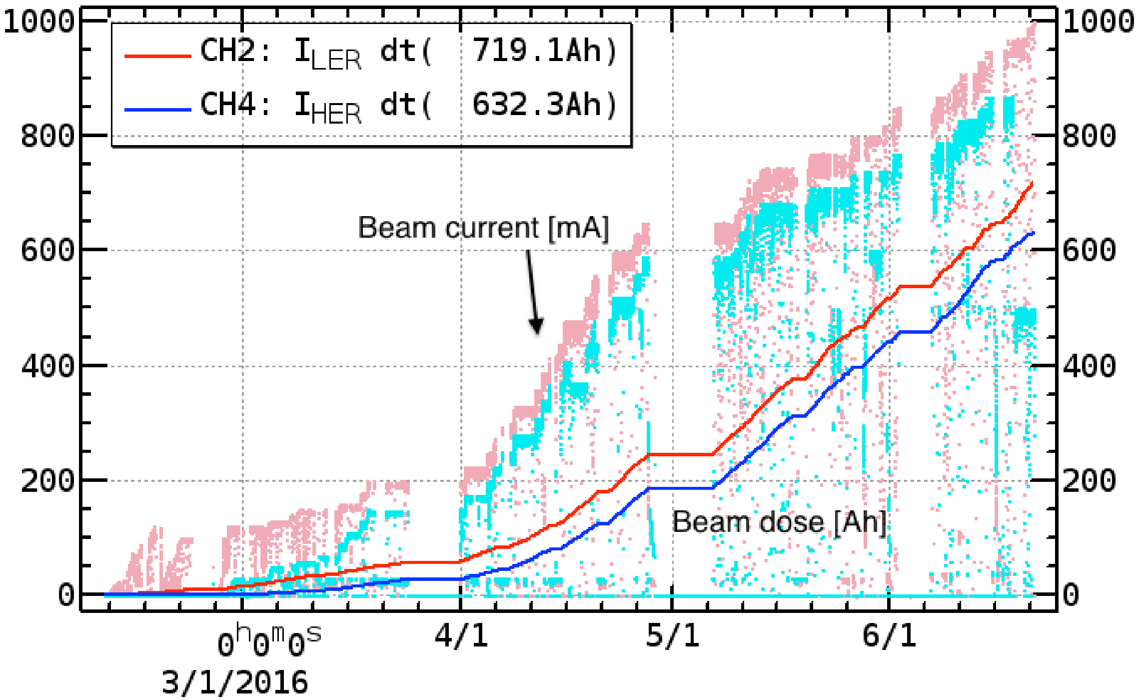
SuperKEKB Belle II and IR magnets







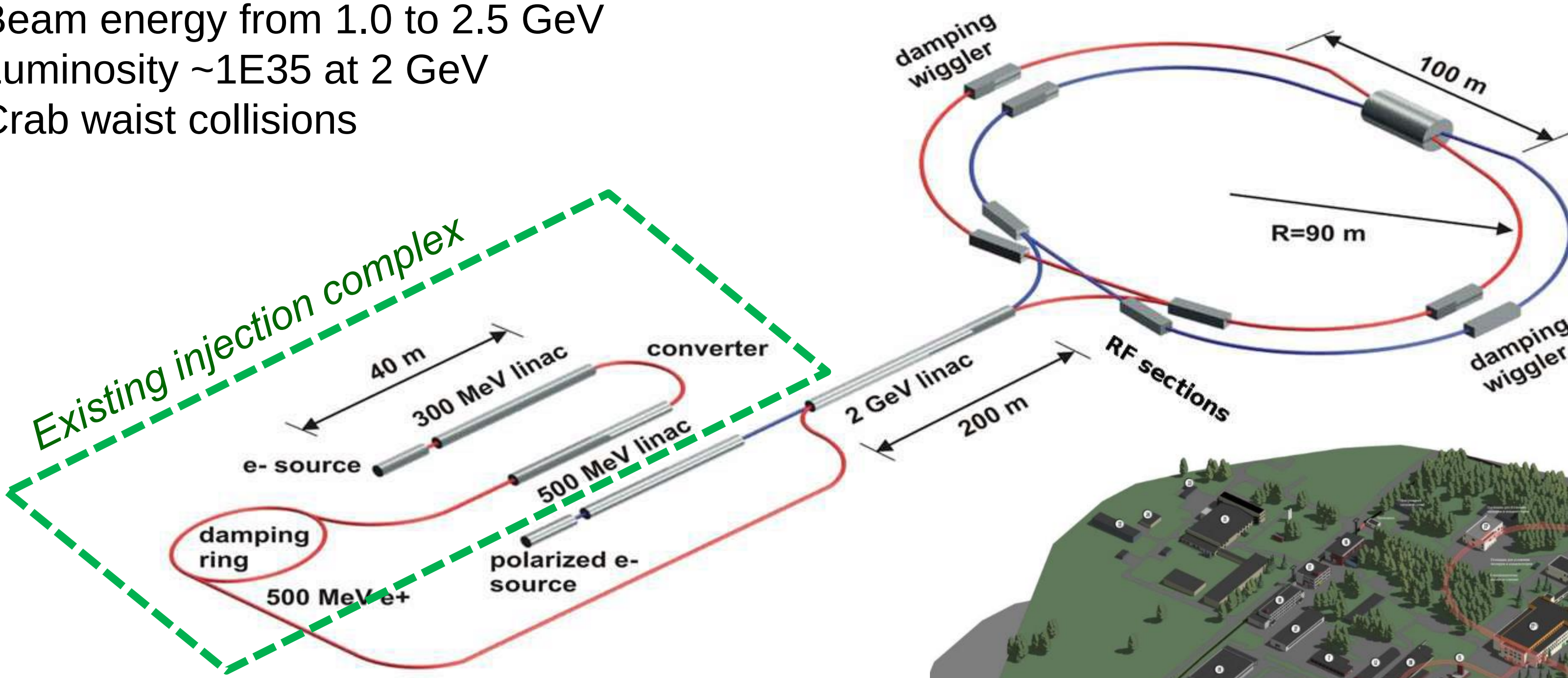
SuperKEKB status

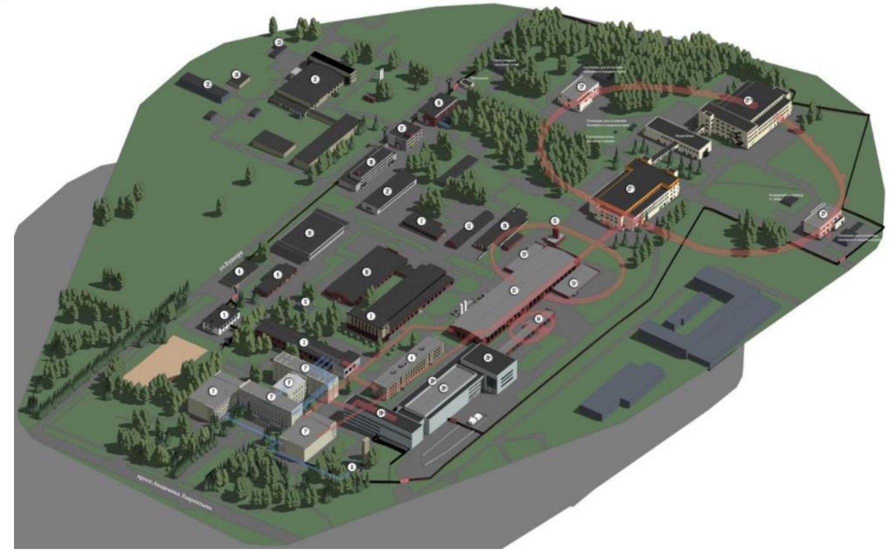


June 21, 2016:
Reached 1 A in LER.
Beam dose is 720 Ah in LER and 630 Ah in HER.
Vacuum scrubbing almost done

Super Charm-Tau factory project at BINP

Beam energy from 1.0 to 2.5 GeV
Luminosity ~1E35 at 2 GeV
Crab waist collisions

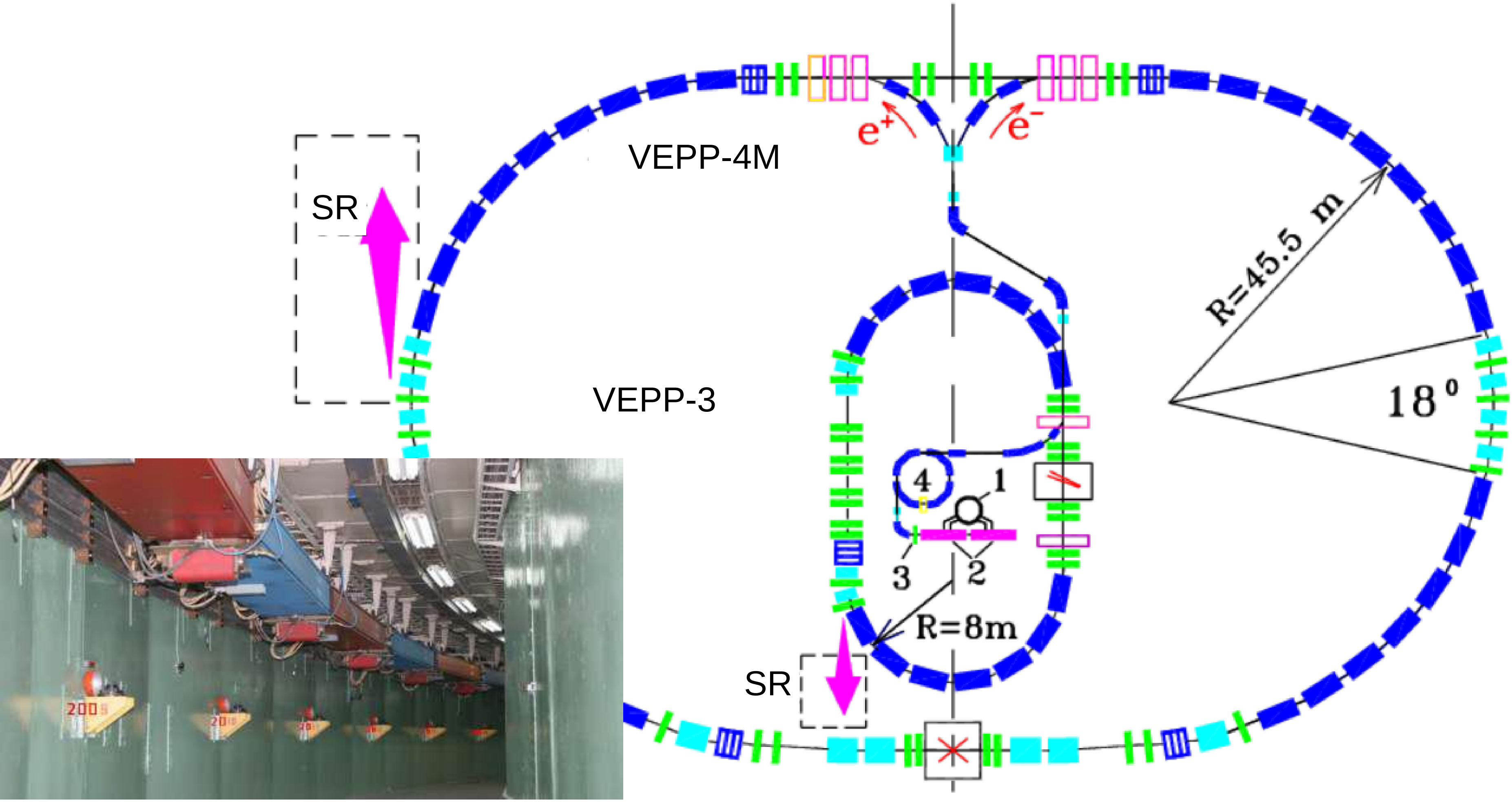




c-tau factory project status:

- **CDR** completed in 2013
- Discussion with government and potential collaborators
- Project recently re-energized (Aug 2016) with the **International Advisory Committee** created

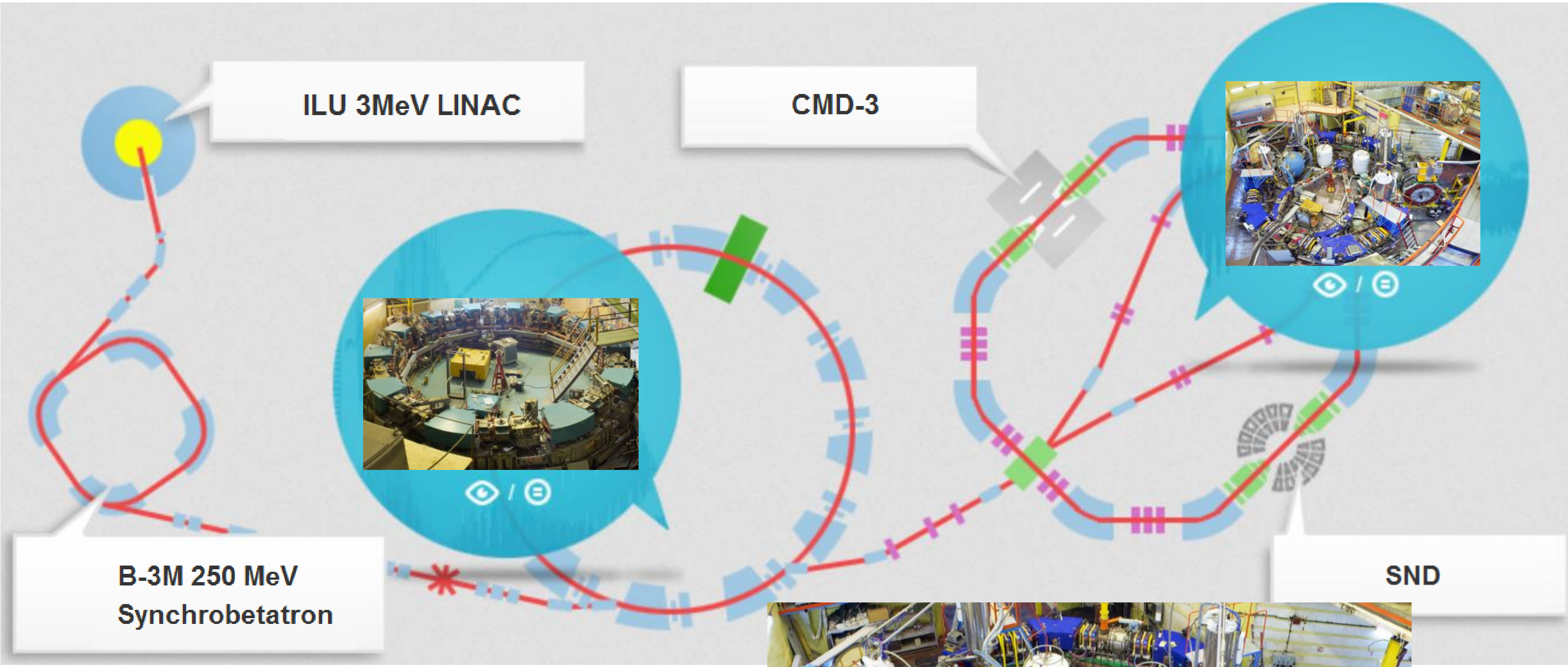
BINP colliders: VEPP-4M

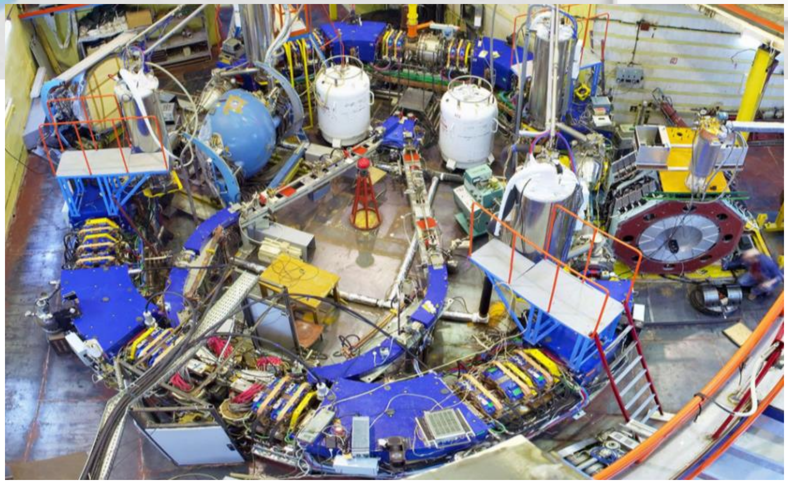


Detector KEDR

VEPP-4M
E = 1 – 5 GeV
Energy calibration 1E-6

BINP colliders: VEPP-2000





VEPP-2000
E = 1 GeV
Round beams
Two detectors

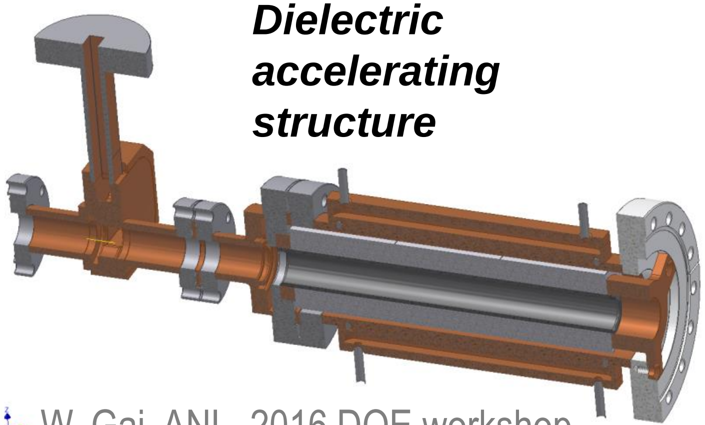
Contents

- **Hadron colliders** (and not only colliders)
  - **HL-LHC, HE-LHC, FCC, SPPC**
  - **FAIR, NICA, SPIRAL2**
- **Electron - ion**
  - **LHeC & FCC-he**
  - **eRHIC**
  - **Jlab e-ion**
- **Lepton colliders**
  - **FCC-ee & CepC**
  - **CLIC and ILC**
  - **Super-B factory**
  - **c-tau factory**
- **Advanced approaches**
  - **LPWF & PWFA collider roadmaps & AWAKE**

Advanced accelerator techniques

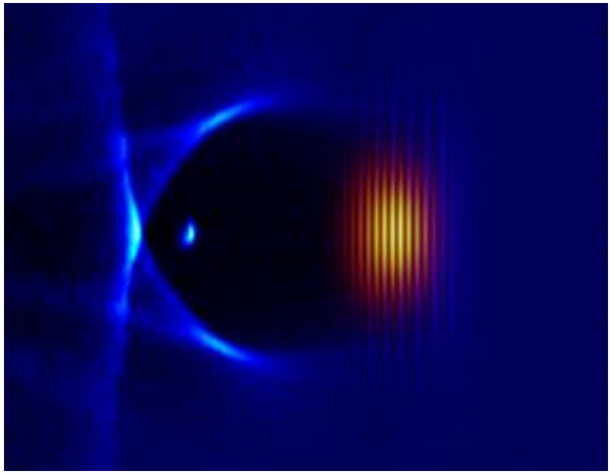
- **Many ideas are being developed for multi-TeV colliders with gradients >100 MeV/m, & lower capital & operating costs**
  - **Wakefield Acceleration using plasmas or dielectrics**
  - **Direct Laser Acceleration**
  - **Both particle beam (PWFA) and laser (LWFA) driven wakefield approaches are thought to offer effective gradients of O(1 GeV/m)**

Dielectric accelerating structure



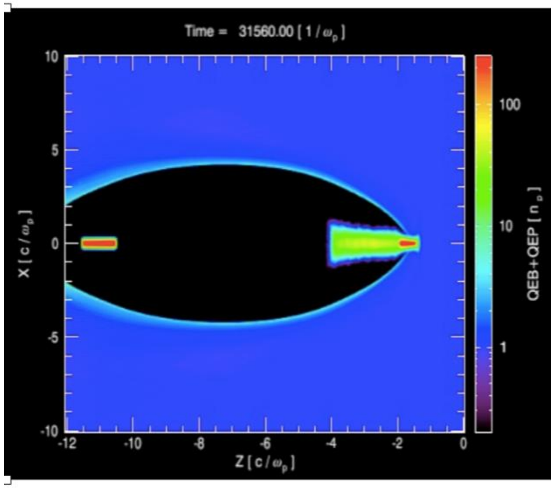
W. Gai, ANL, 2016 DOE workshop

LWFA



Simon Hooker, JAI

PWFA



M. Hogan, SLAC, 2016 DOE workshop

One of the main common R&D design goals for these methods for the next decade is insuring the luminosity (emittance preservation)

Advanced accelerator community marching towards new challenges

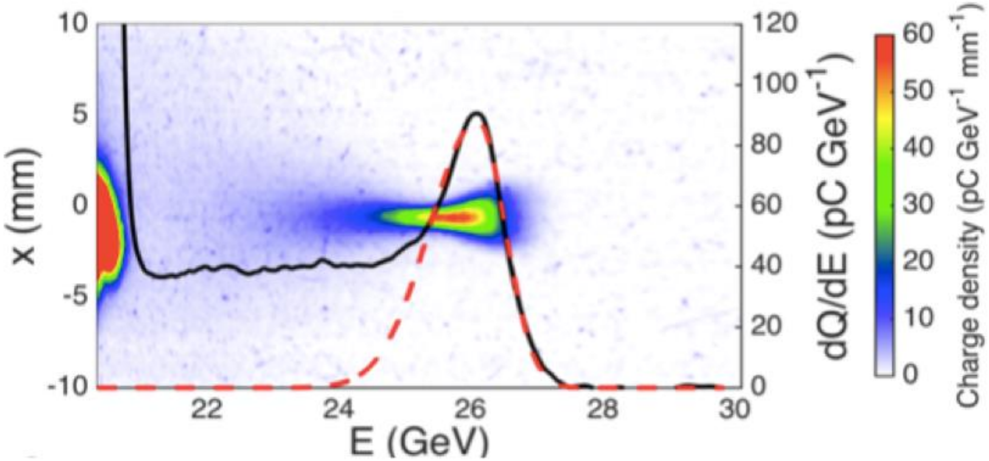
AAC & EAAC workshops attract ~300 researchers (many grad students and postdocs) each year

And conquering them!

A highlight of **AAC-2016**

(Jul 31-Aug 5, 2016, Washington DC) –

efficient plasma acceleration of positrons!



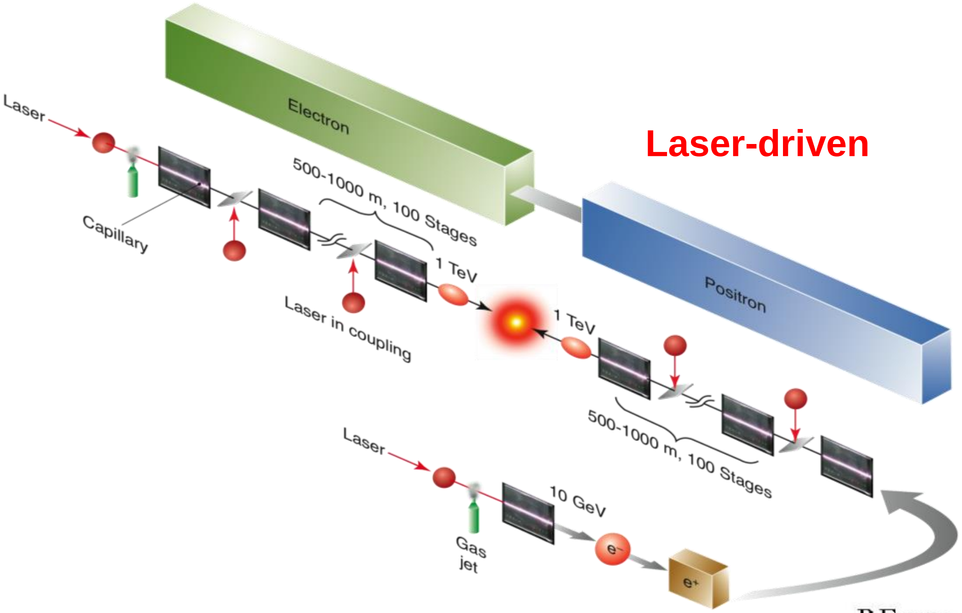
e+ gaining 5 GeV in just 1.3 m of plasma

S. Corde et al., Nature 524, 442 (2015)

Acceleration of e+ was believed to be one of key challenges on the path to a plasma collider, as e+ are not focused, but defocused by ions in plasma bubble

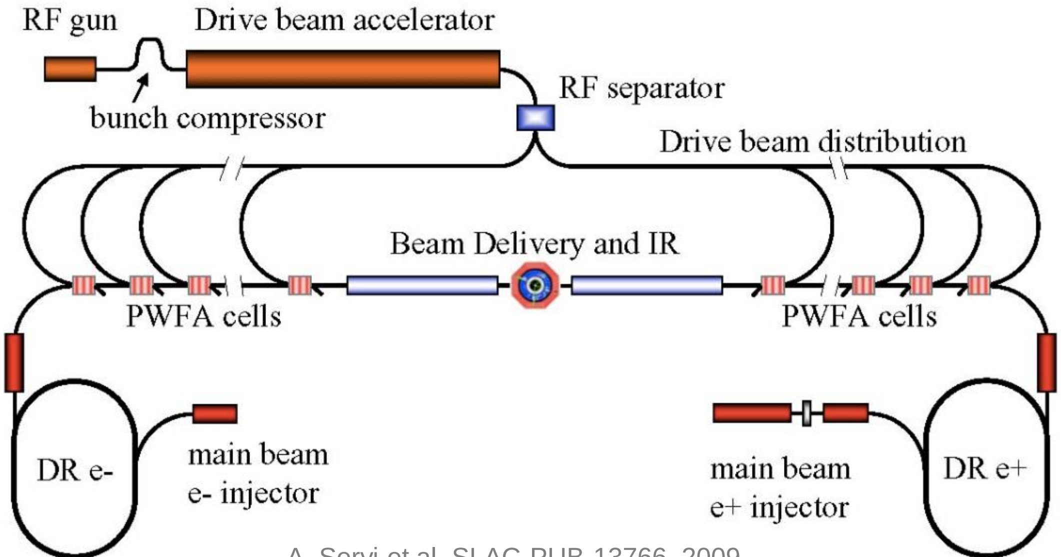
Concepts of plasma acceleration based colliders

Laser-driven



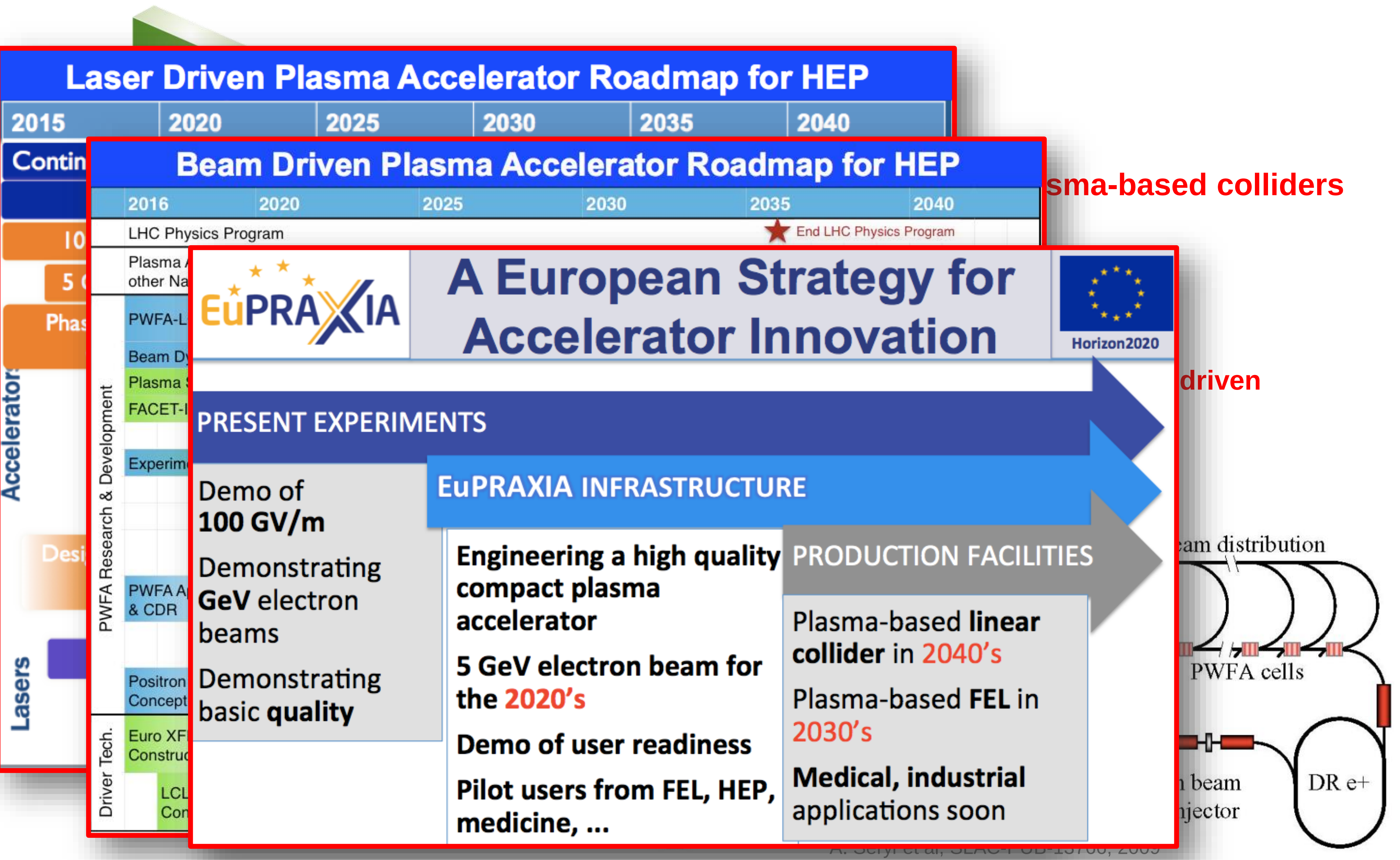
Esarey et al, Rev. Mod. Phys. (2009)

Beam-driven



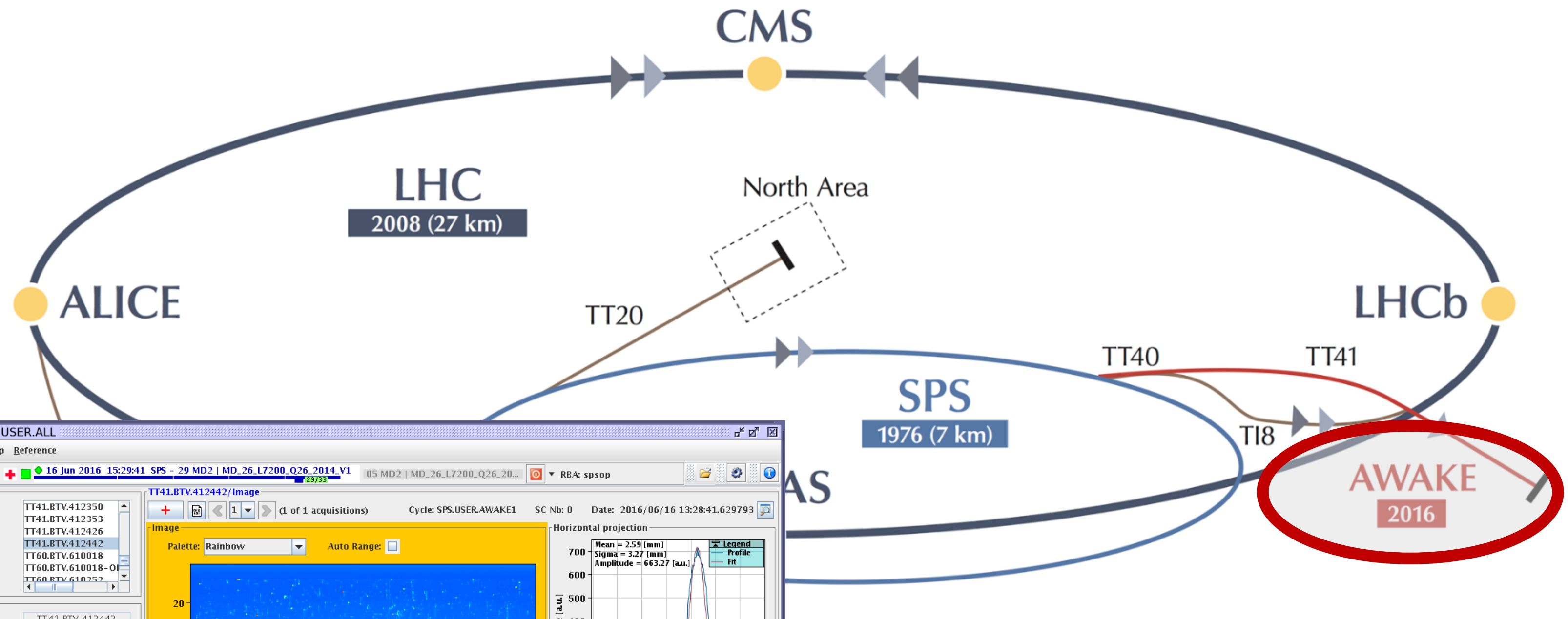
A. Seryi et al, SLAC-PUB-13766, 2009

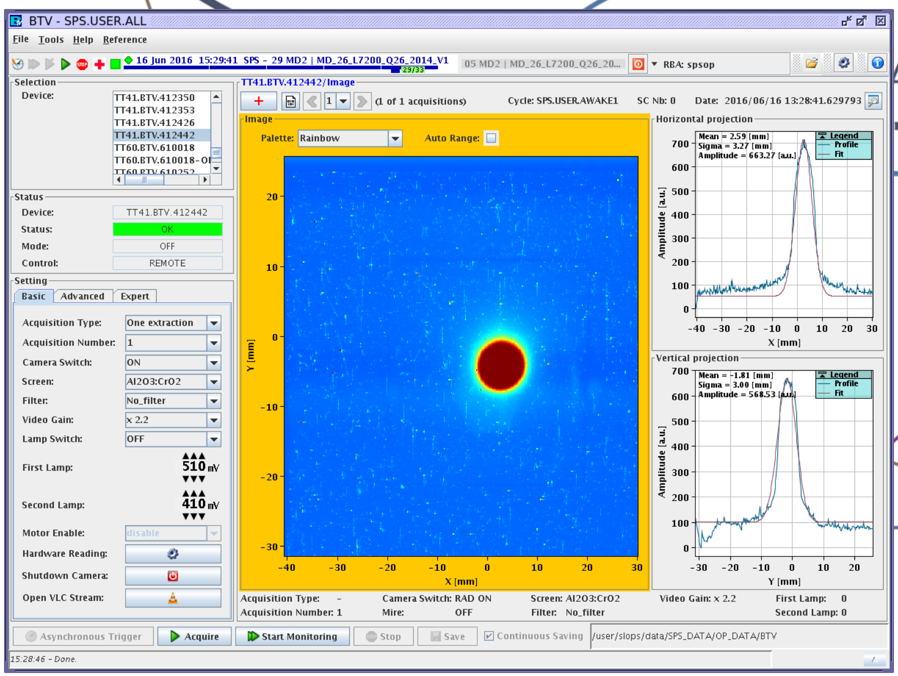
Advanced accelerator community developing roadmaps toward plasma-based collider in 2040



Imperial College London
Royal Holloway University of London
University of Oxford

AWAKE: proton driven plasma acceleration



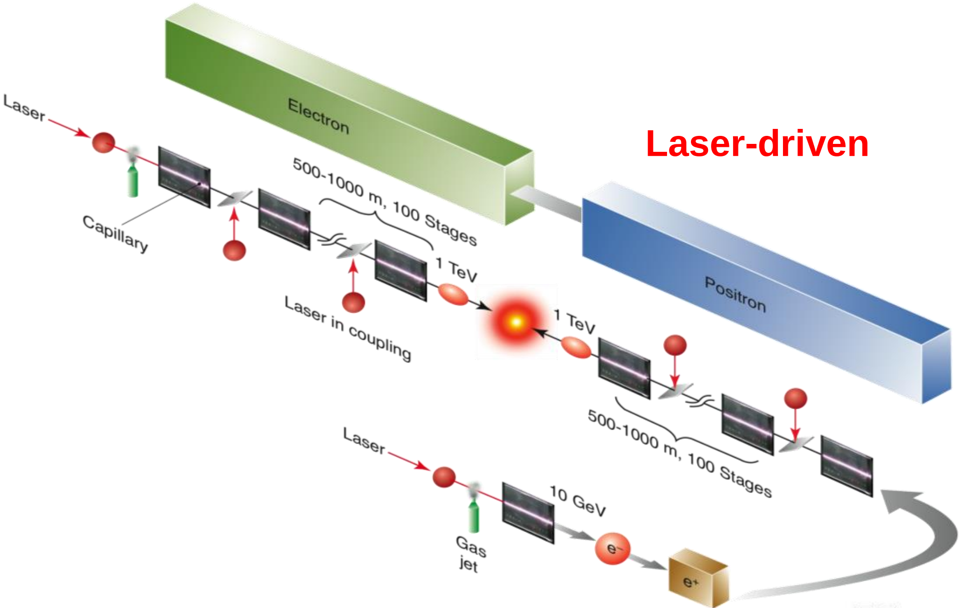


6 June 2016 – first p beam in AWAKE beamline

AWAKE = Advanced Proton Driven Plasma Wakefield Acceleration Experiment
Proof-of-concept demonstration of a novel acceleration technique: use SPS protons to generate powerful wakefields in a 10m plasma cell → wakefields accelerate externally injected electron beam. Aim at electron acceleration of several GeV/m → compact accelerators
Experiment starts end 2016.

Difficulties of plasma acceleration based colliders

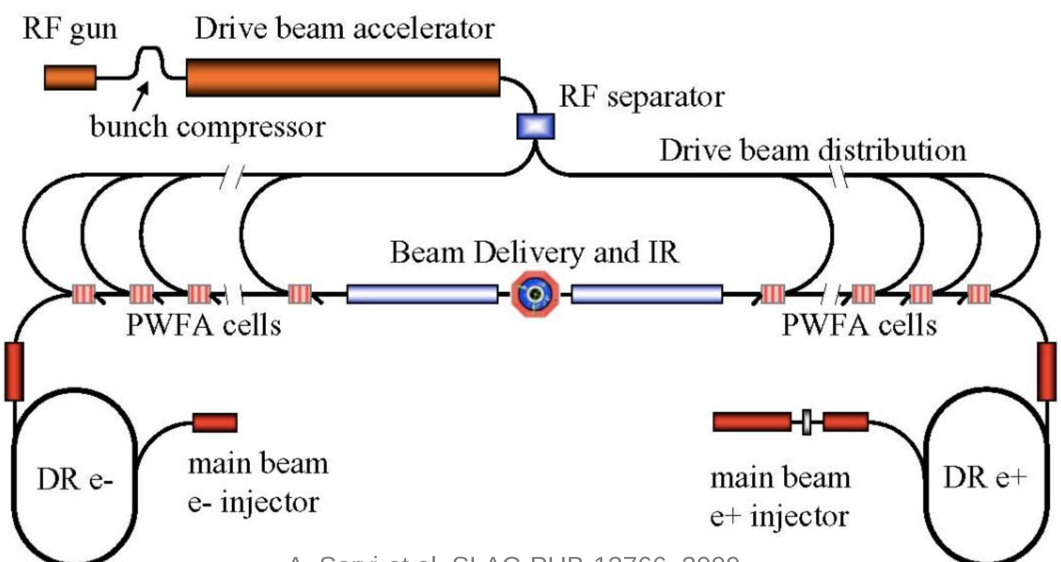
Laser-driven



Esarey et al, Rev. Mod. Phys. (2009)

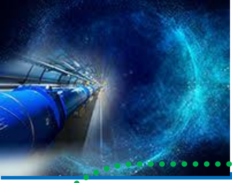
One of the main difficulties: emittance growth between plasma-acceleration stages

Beam-driven

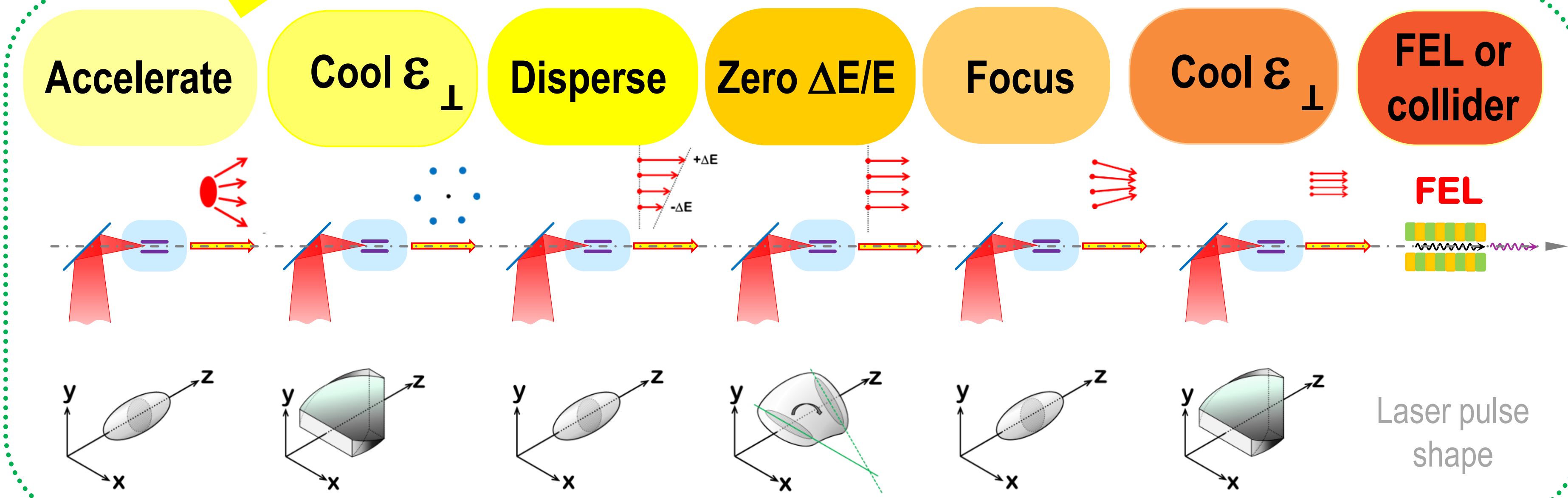


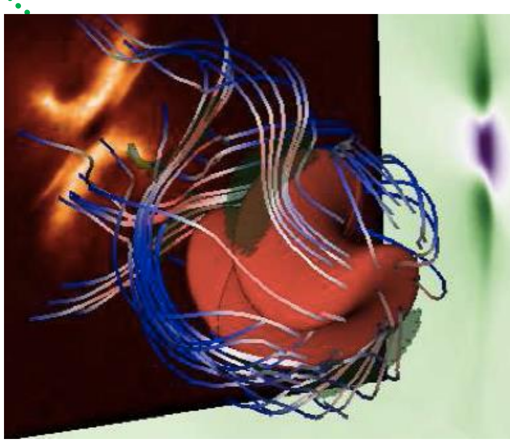
A. Seryi et al, SLAC-PUB-13766, 2009

Can we cool the emittance between plasma acceleration stages?

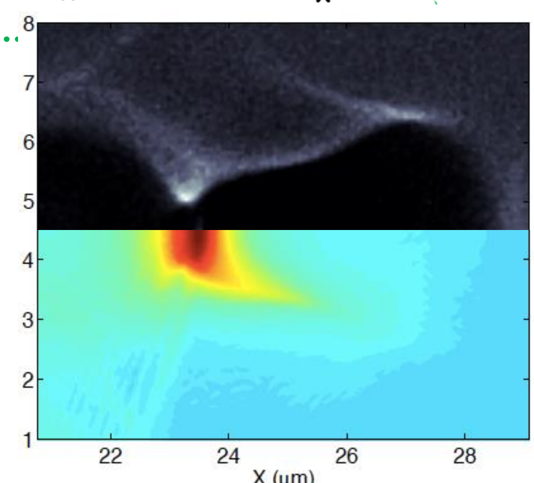


NEW! Laser-plasma stage with ε cooling





Screw-shaped laser pulse and trajectories of electrons



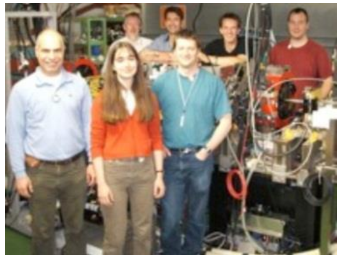
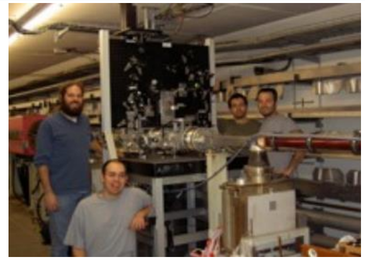
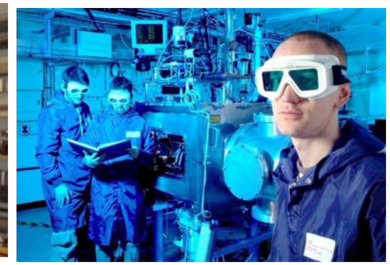
Bubble shape (top) and solenoidal field map (bottom)

Screw-shaped laser pulse => Giga-gauss solenoidal field in plasma bubble => Fast SR cooling of transverse DOF=> new approach to design laser-plasma FEL or collider

A. Seryi, Zs. Lecz, I. V. Konoplev, A. Andreev

arXiv:1604.01259 & AAC-2016

Training of next generation of accelerator scientists


is necessary, for our community to be able realise the aspirations of building next generation machines – ILC or CLIC, FCC, CEPC or HE-LHC, or plasma-based collider

Coordinated efforts of accelerator institutes (JAI, Cockcroft) and international and regional accelerator schools (USPAS, CAS, JUAS)

John Adams Institute for Accelerator Science

juas

The Cockcroft Institute of Accelerator Science and Technology

The CERN Accelerator School

…will allow to overcome the shortage of accelerator physicists and be ready for construction and operation of new projects

Conclusions

Variety of projects and bright opportunities for studies of QCD challenging questions

Accelerator science continue to bring novel ideas which allow to aim at ever increasing performance

Technology development is key for realization of next project, and often stimulate new design ideas

Keep an eye on advanced concepts!

Training of next generation of accelerator scientists is key for continuing success of our field