# 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**
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  - **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 Michael Benedikt, Tom Browder, Eckhard Elsen, Edda Gschwendtner, Mike Harrison, Vladimir Kekelidze, Eugene Levichev, Katsunobu Oide, 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**

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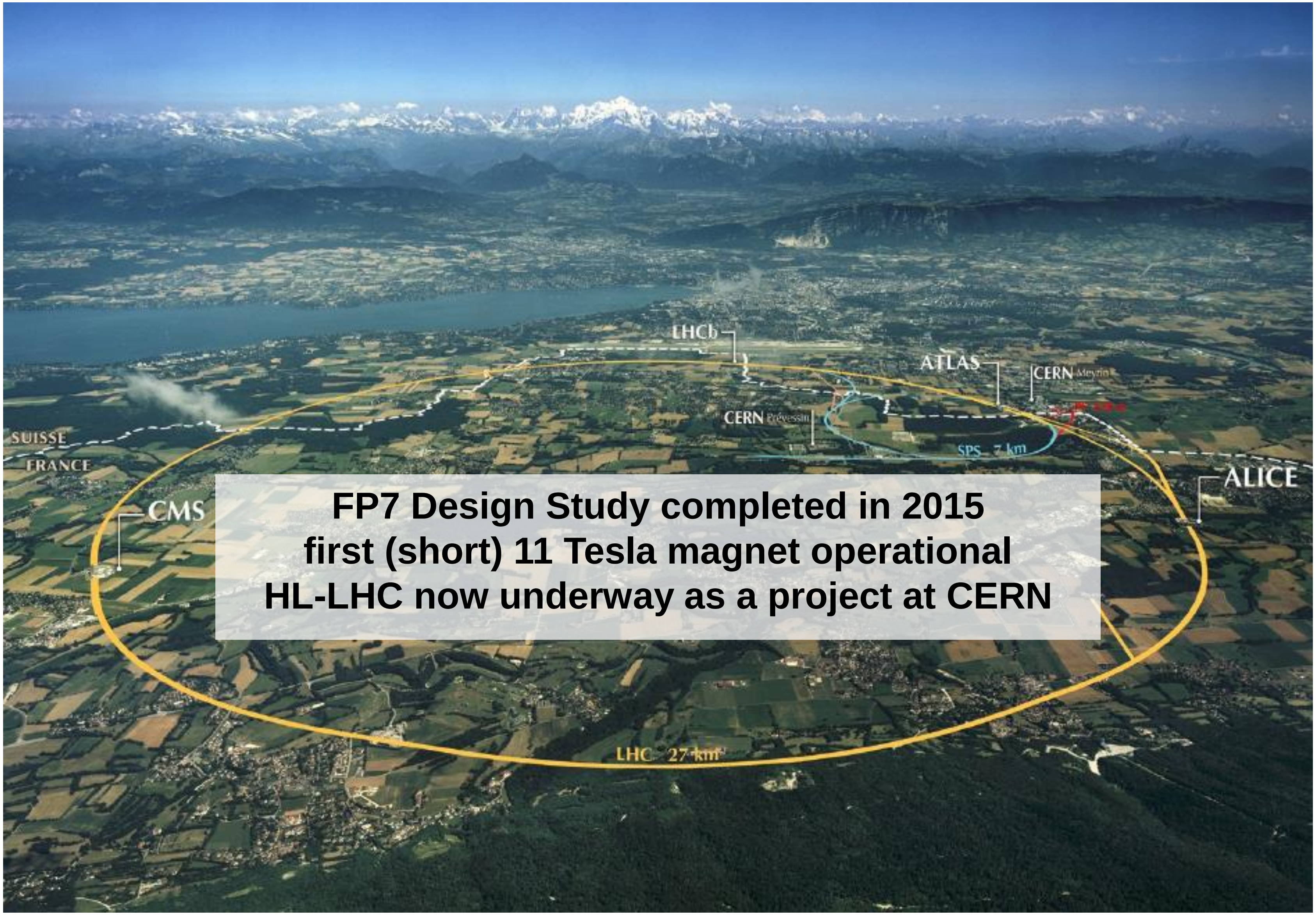
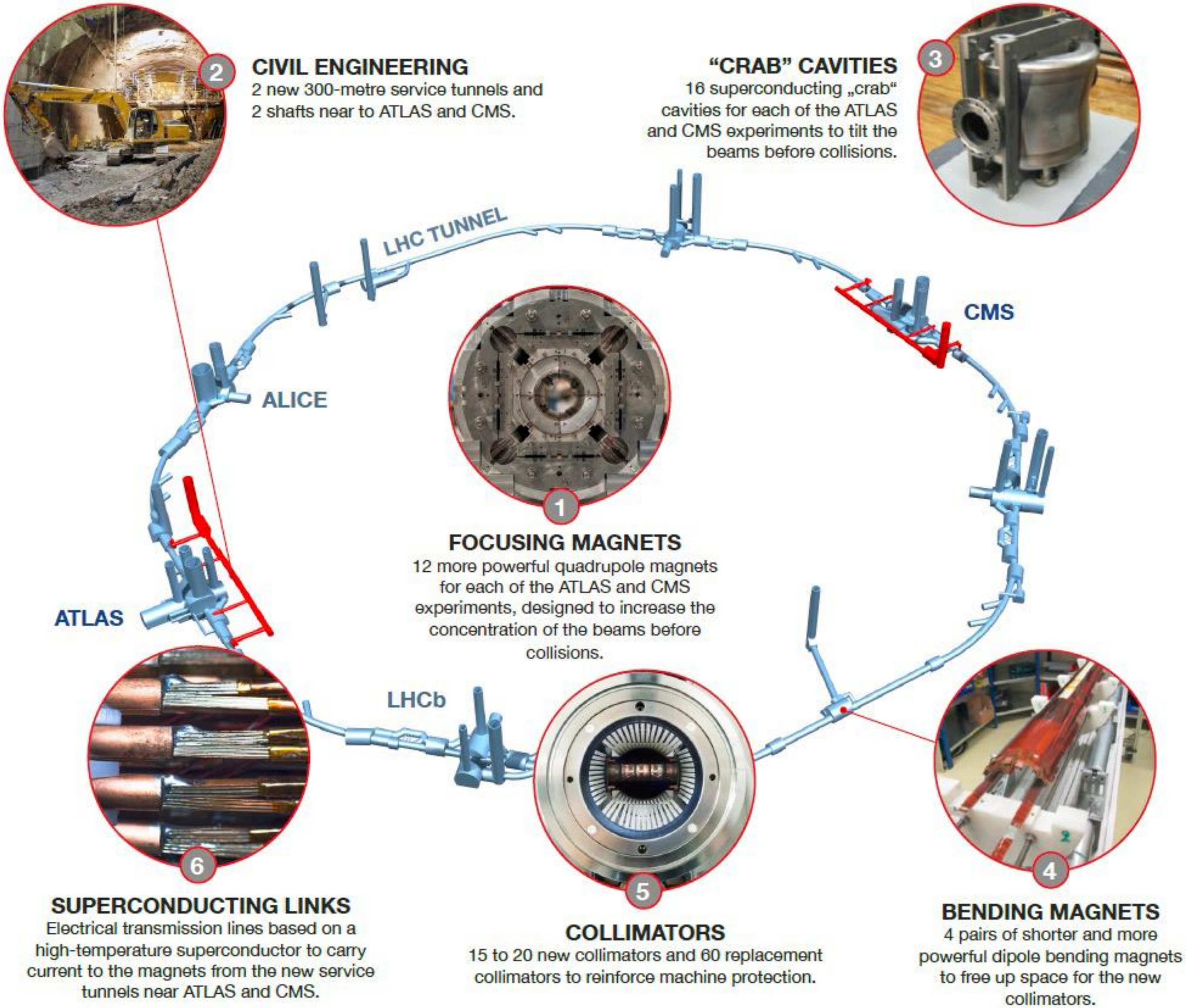
# High Lumi LHC




**FP7 Design Study completed in 2015**
**first (short) 11 Tesla magnet operational**
**HL-LHC now underway as a project at CERN**

# High Lumi LHC

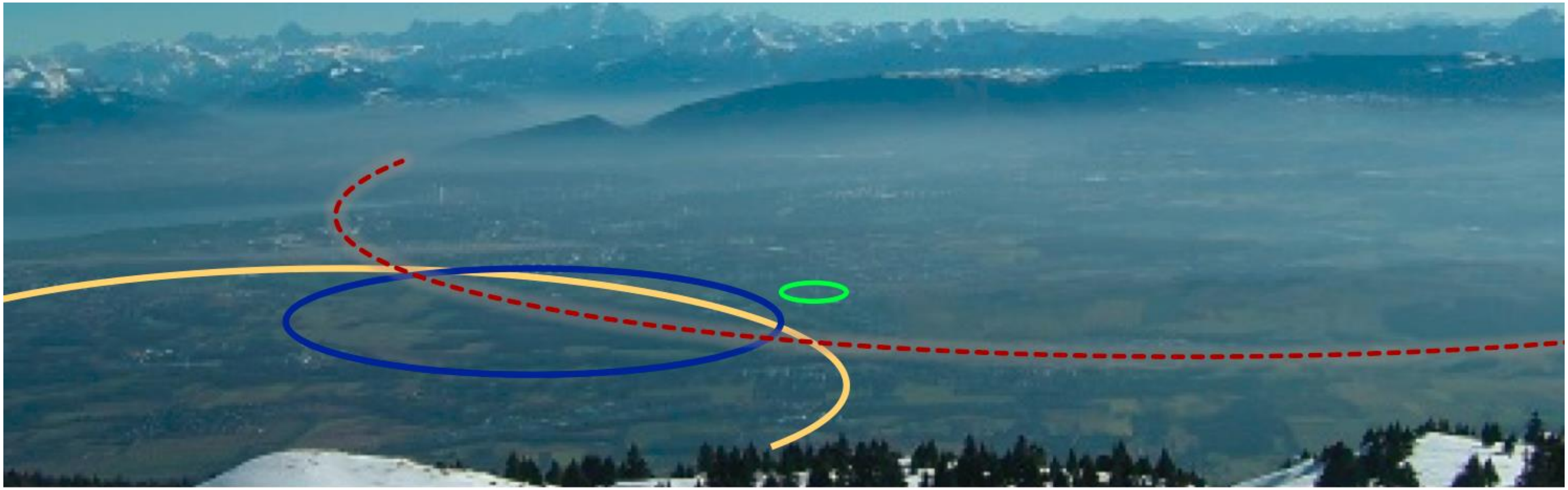


# Higher energy hadron collider

**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

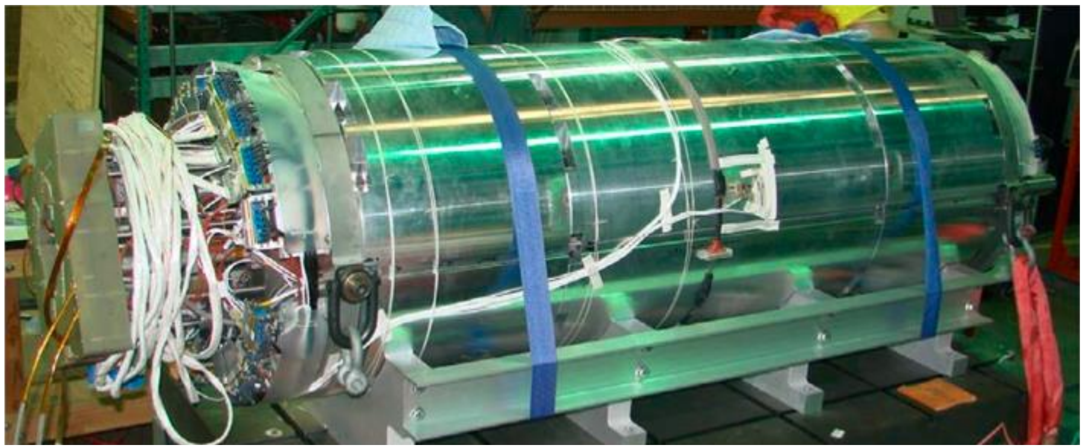
**FCC-hh**
European Design Study for ~100 TeV pp collider in a ~100 km ring – EuroCirCol
CDR by end of 2018 & input to European Strategy
(JAI / Oxford is coordinating EuroCirCol WP3 on Experimental Interaction Region design)



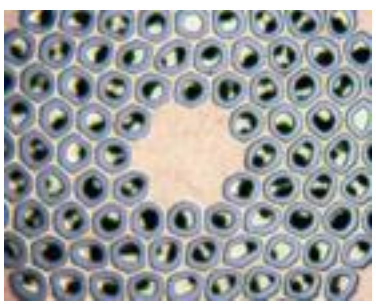
# Magnet R&D

LHC: nominal 8.3 T

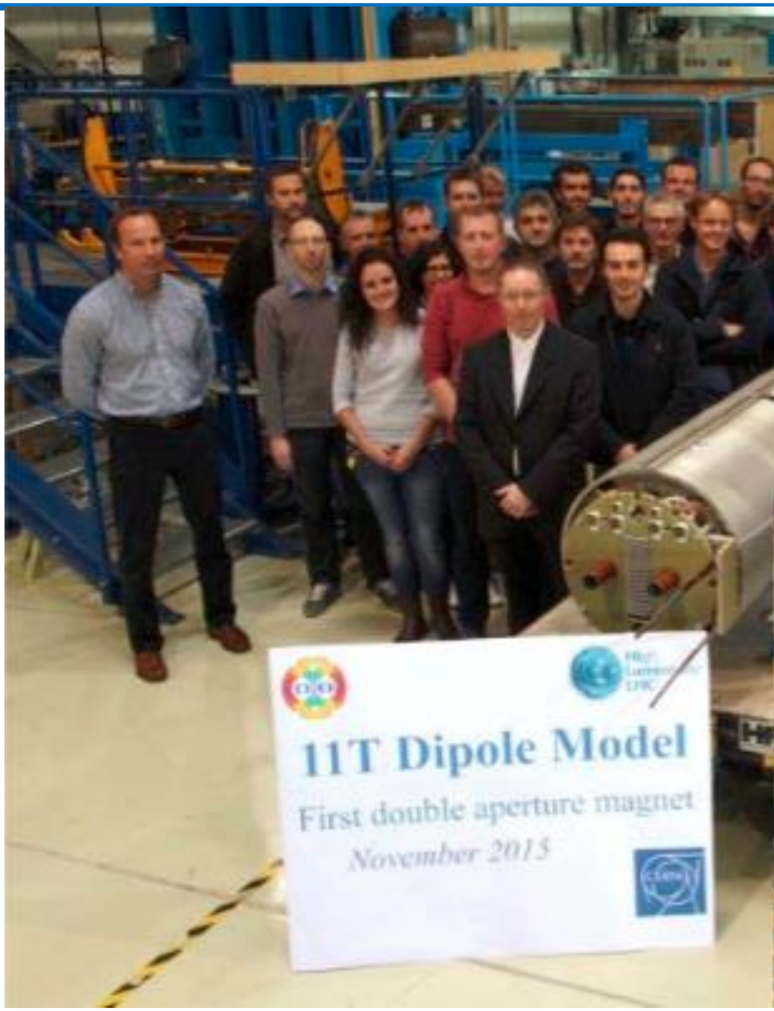
**HL-LHC:**
- 11 T dipoles in dispersion suppression collimators
- 12-13 T low-$\beta$ quadrupoles at ATLAS and CMS IR's



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



$Nb_3Sn$ 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 |

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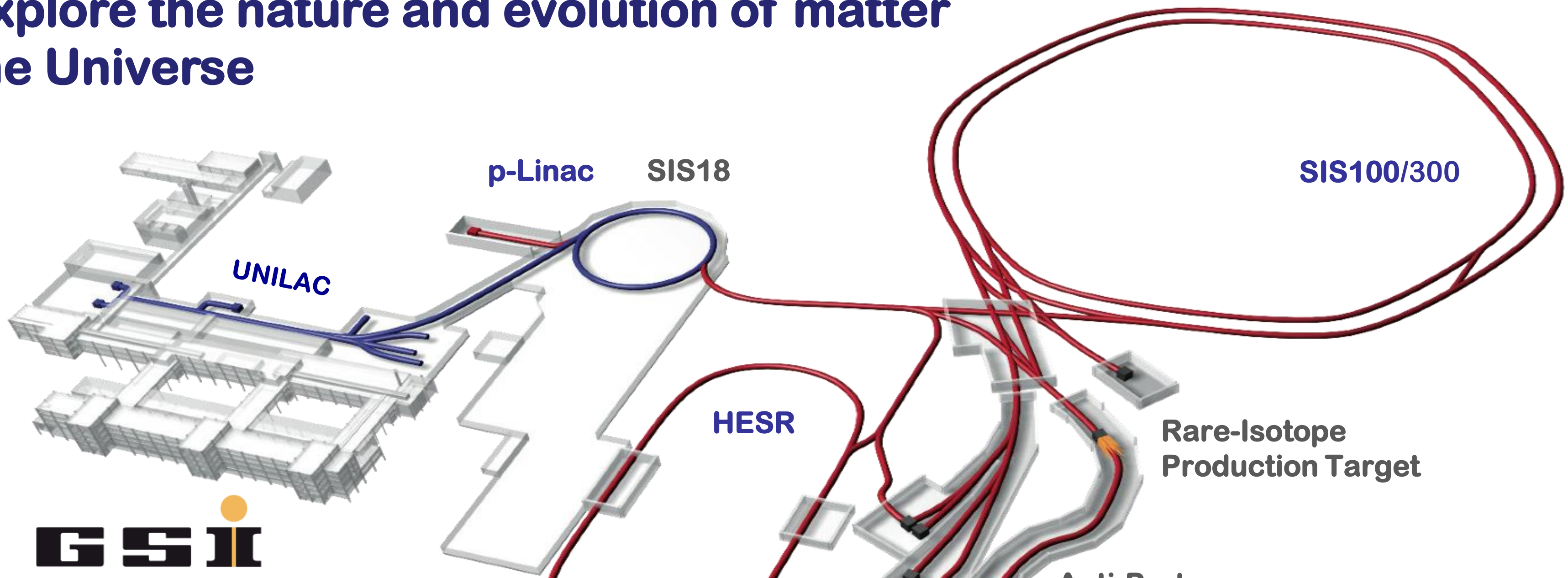
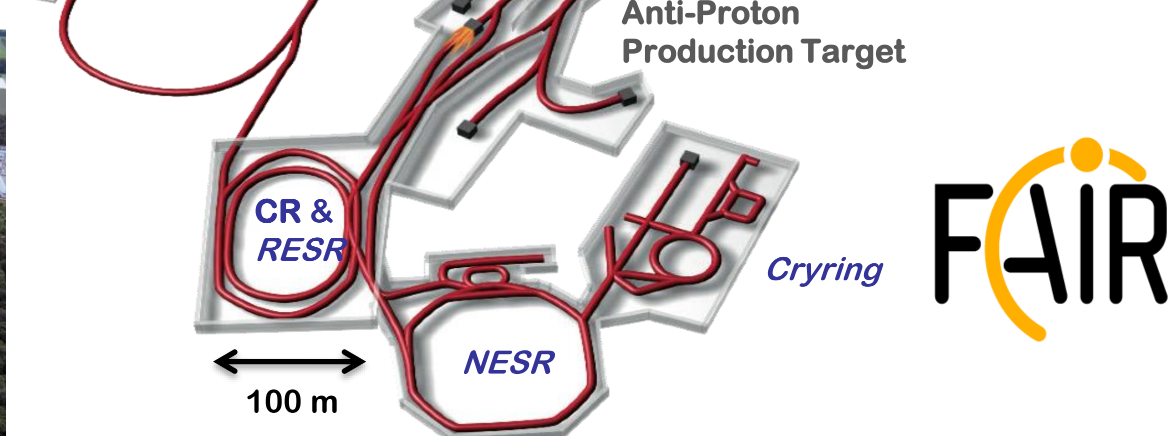
# Facility for Antiproton and Ion Research

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



# FAIR – accelerator facility

## Primary Beams

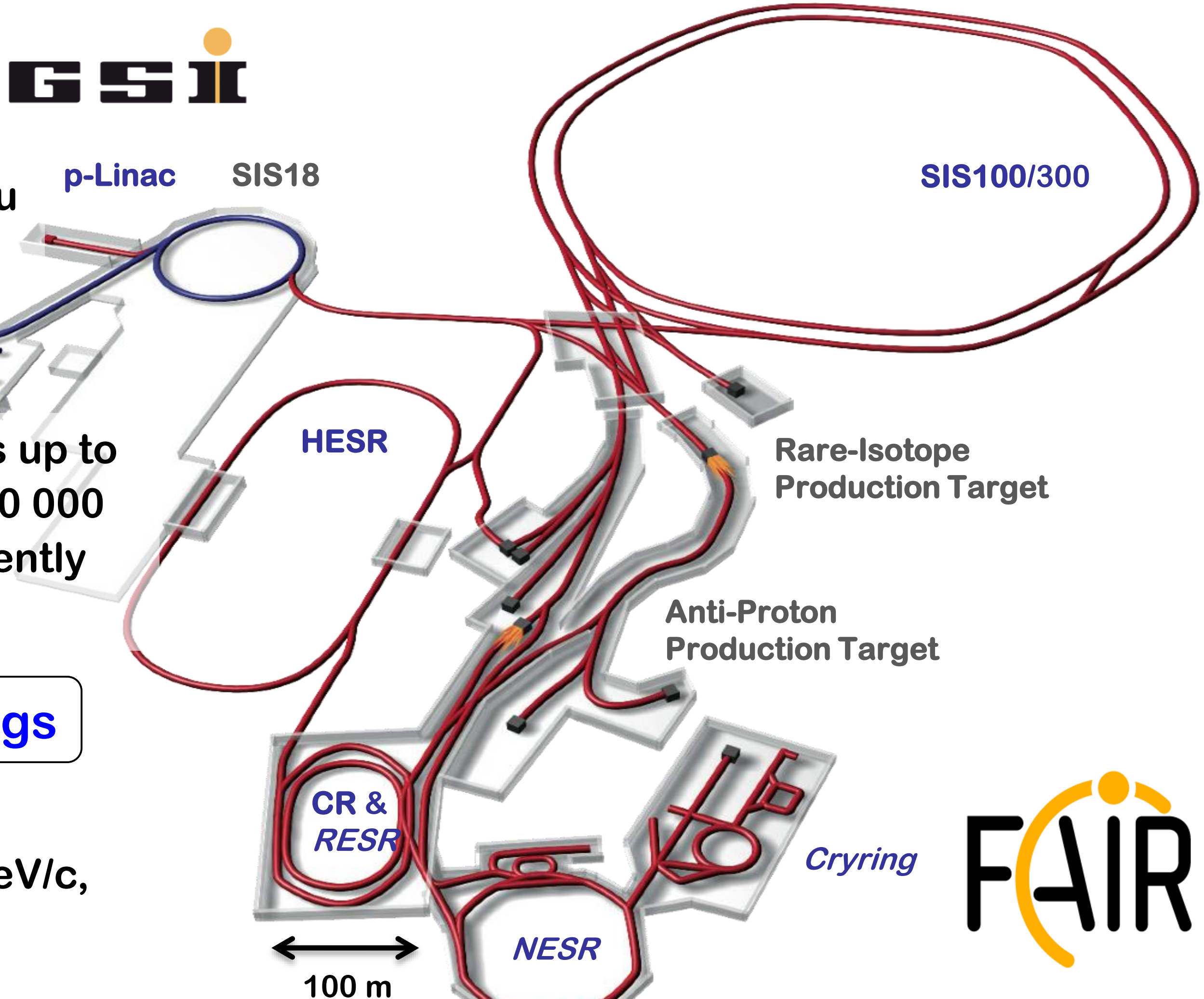
- $10^{12}$/s; 1.5 GeV/u; $^{238}U^{28+}$
- $10^{10}$/s $^{238}U^{73+}$ up to 35 GeV/u
- $3x10^{13}$/s 30 GeV protons

## 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)

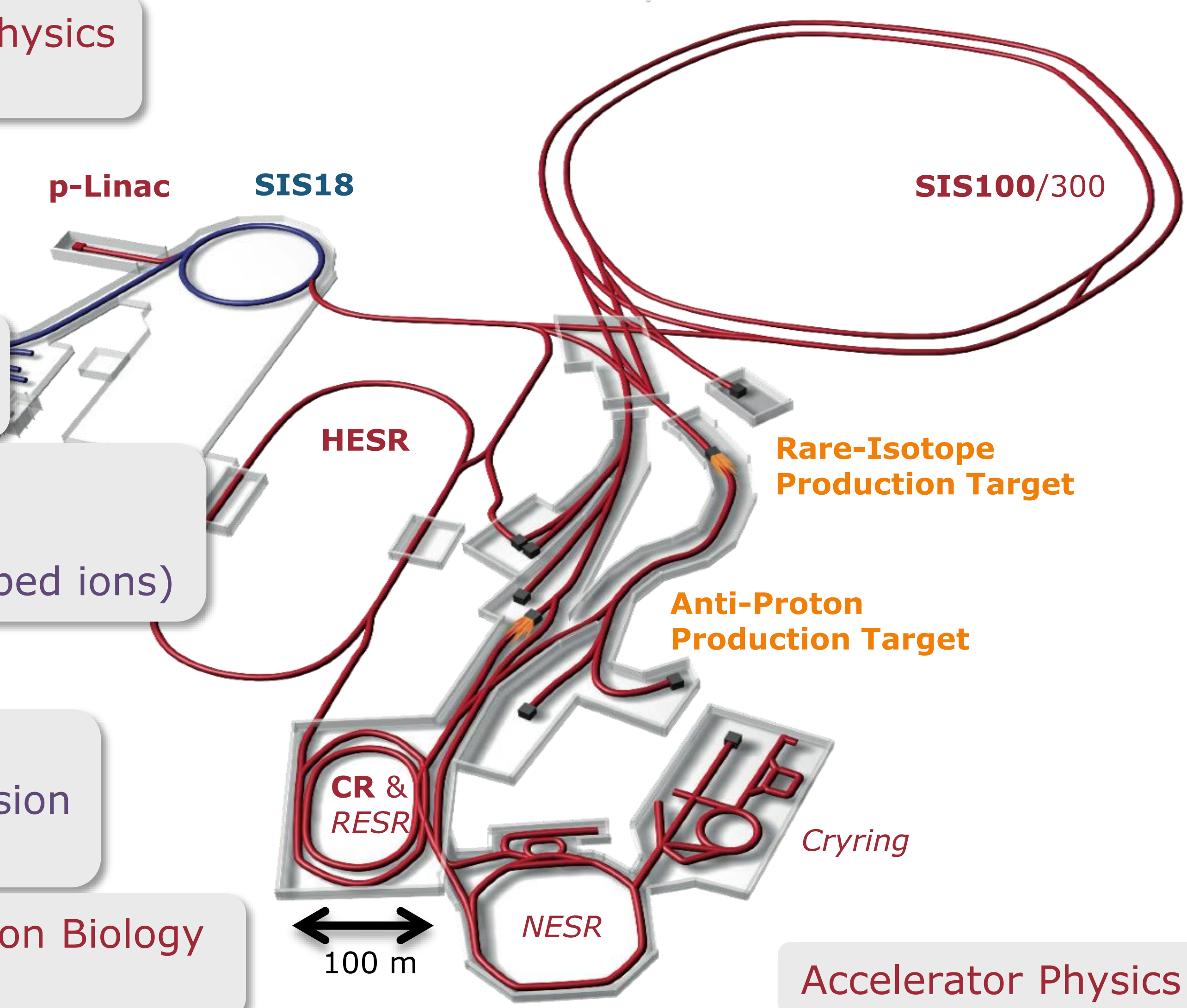
Hadron Physics
(Stored and cooled
14 GeV/c anti-protons)

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)

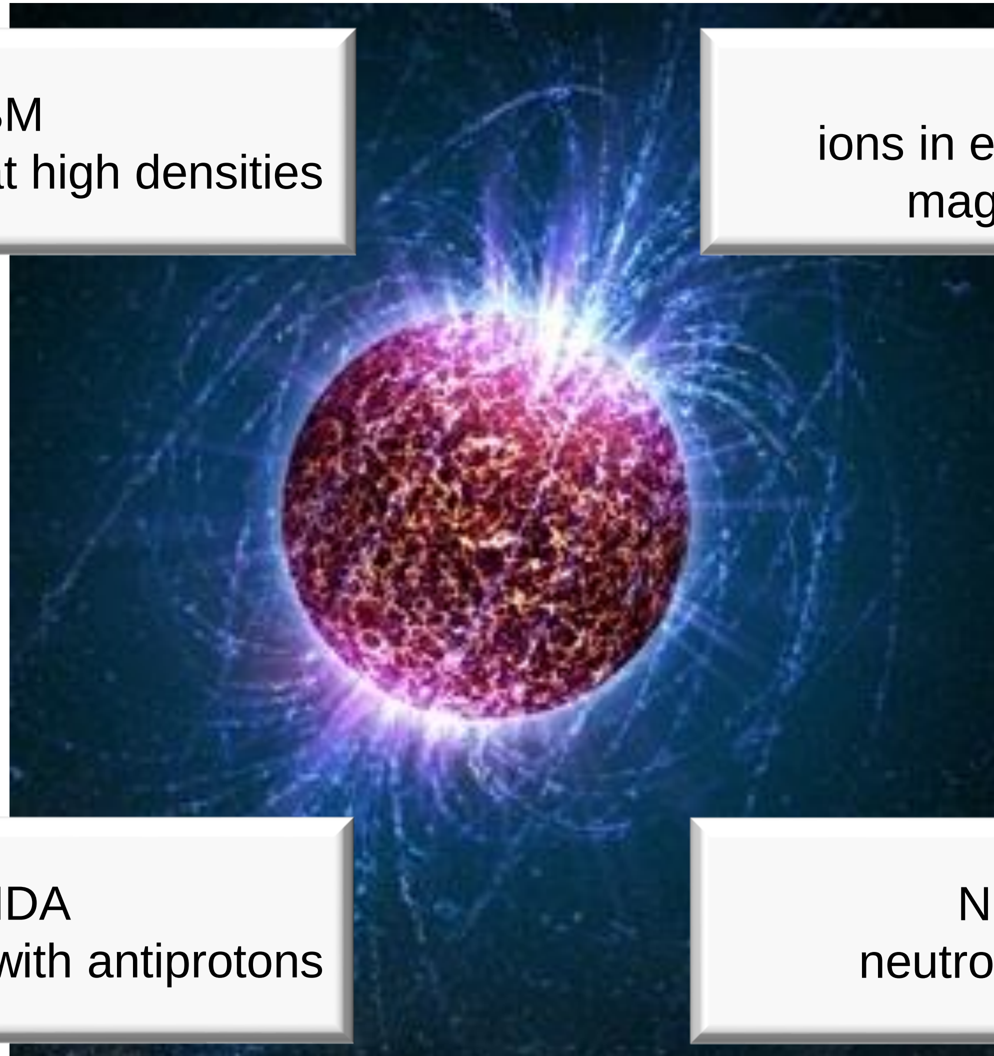



Accelerator Physics

# 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

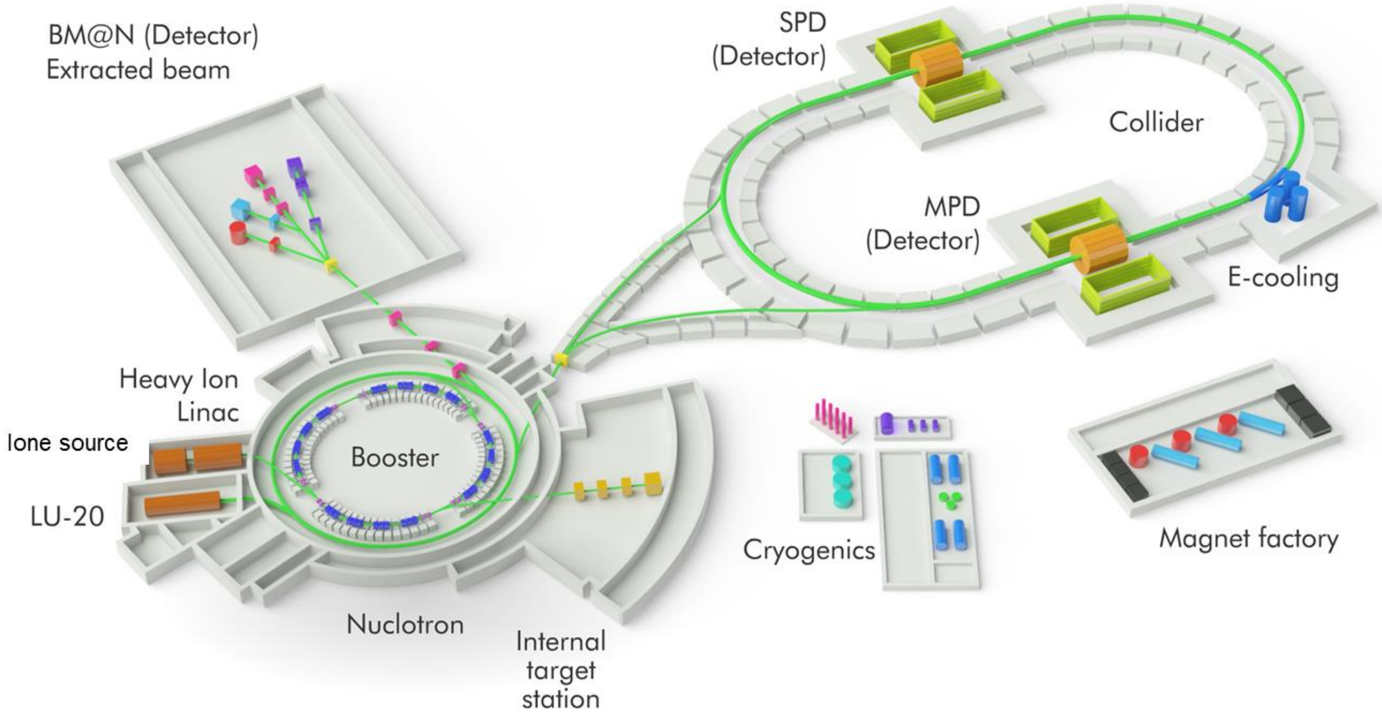
**Joint Institute for Nuclear Research**
**International Intergovernmental organization**
***founded in 1956 by agreement of 12 countries***
***Located in Dubna town, Moscow region***

# NICA – science goals

***NICA (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*



# NICA – science goals

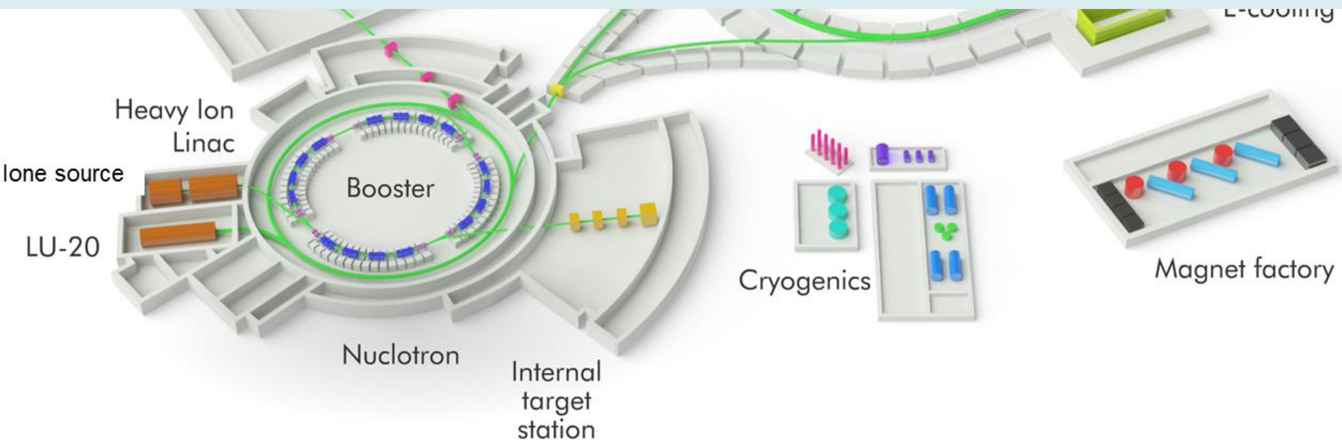
## *NICA (Nuclotron based Ion Colider fAcility)*

**Main targets:**

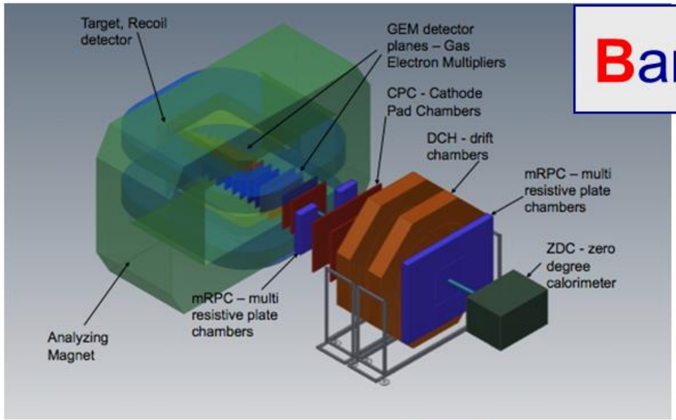
- *study of hot and dense baryonic matter at the energy range of max baryonic density*
- *investigation of nucleon spin structure, polarization phenomena*

- *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)



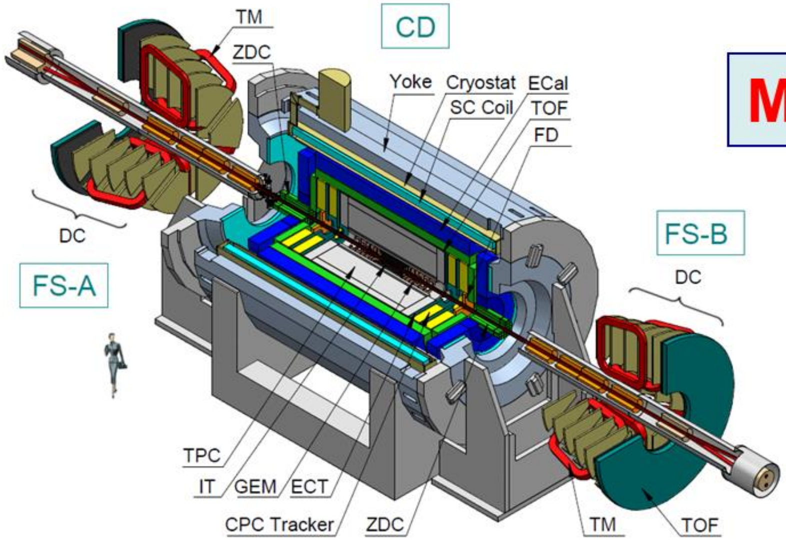
# NICA – three detectors




**Baryonic Matter at Nuclotron (BM@N)**

*the fixed target experiment at the Nuclotron*

**Stage I 2017**




**MultiPurpose Detector (MPD)**

*at the Collider*

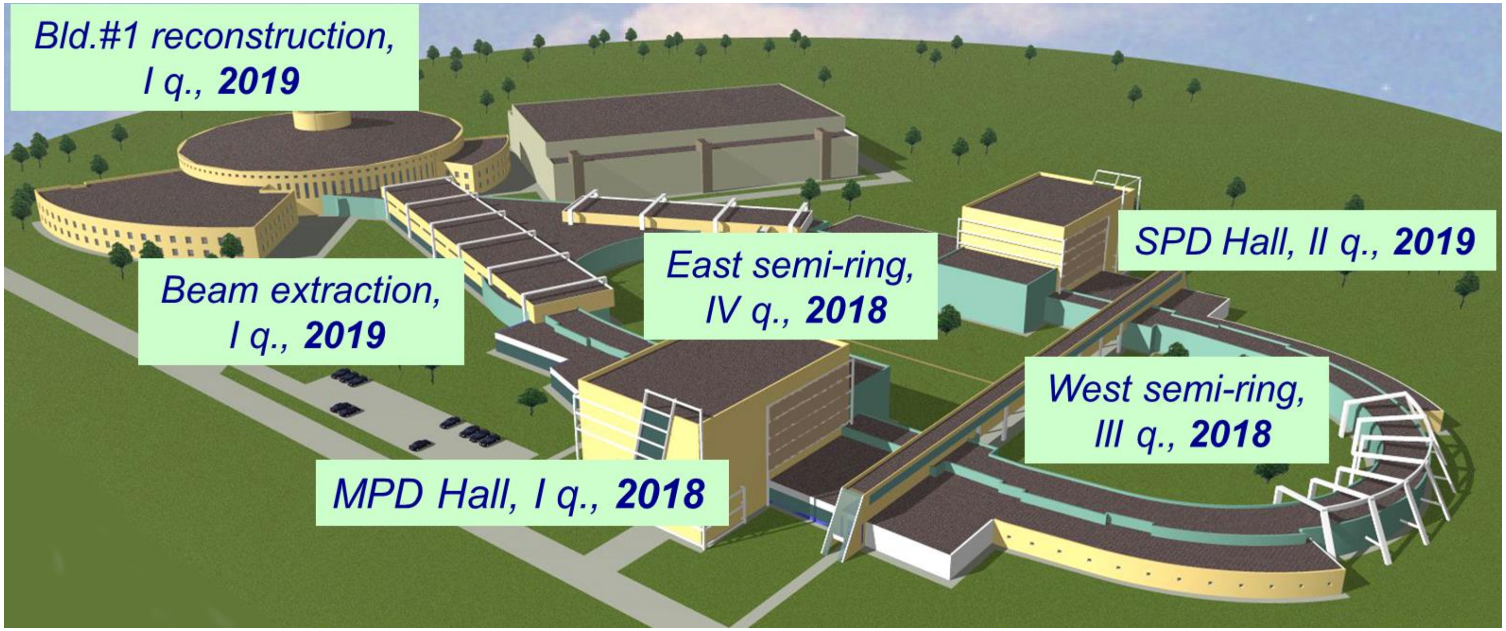
**Stage I 2019**

**SPD (Spin Physics Detector)** *at the Collider*

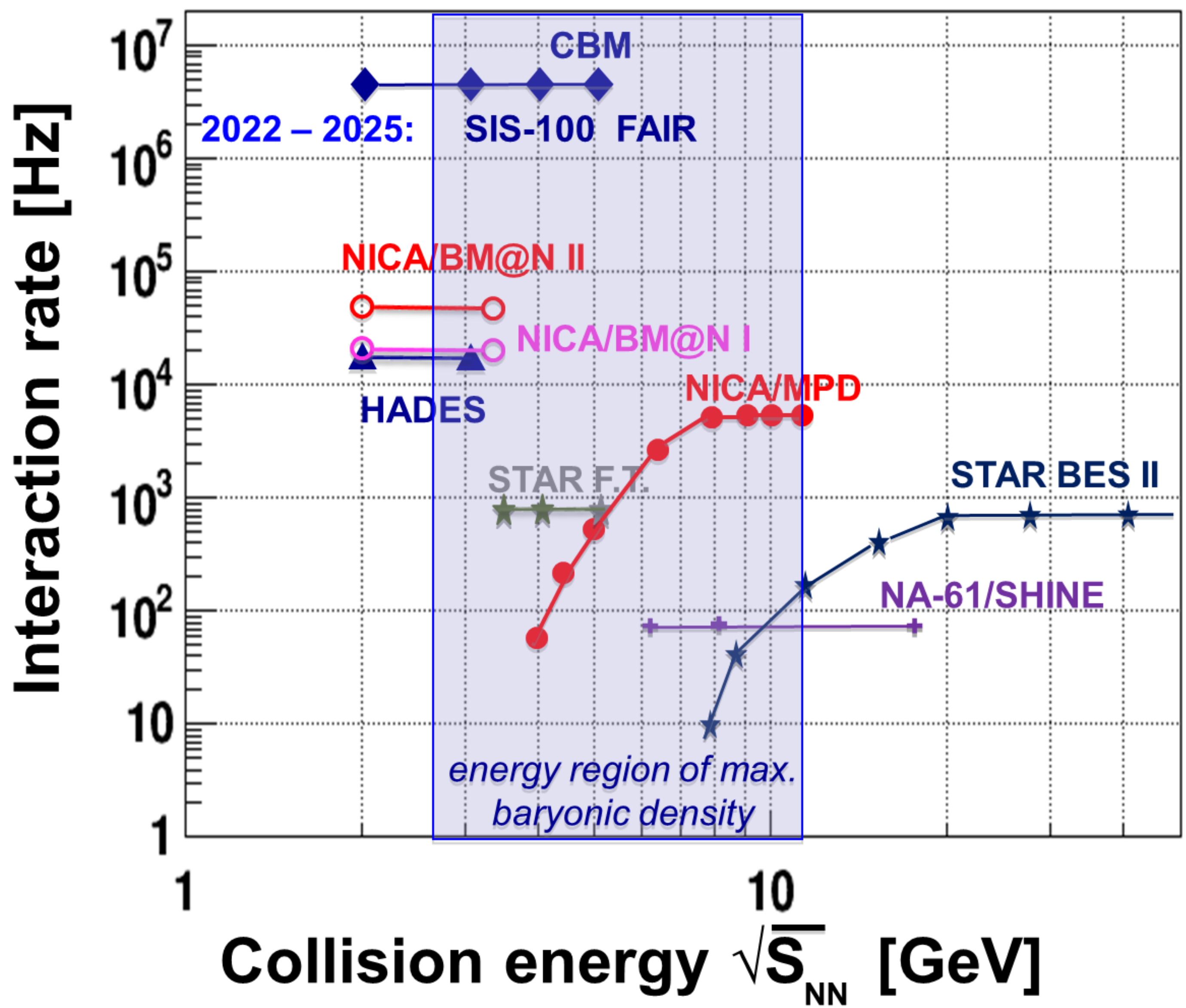
*the project - in preparation*

# NICA – status and construction plans

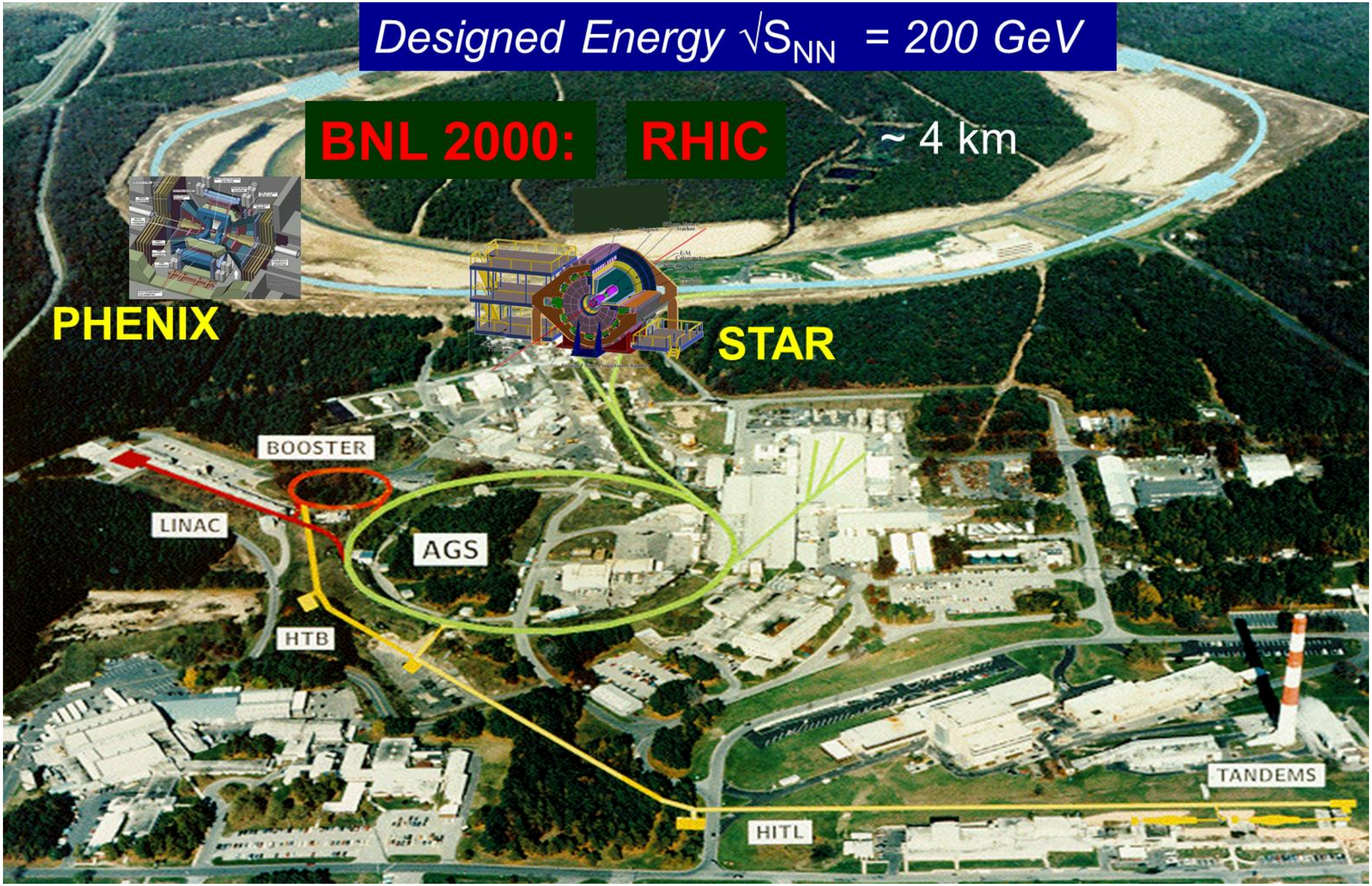
Left – aerial photo of the place prepared for construction
Top – workshop for production of magnets for NICA & FAIR



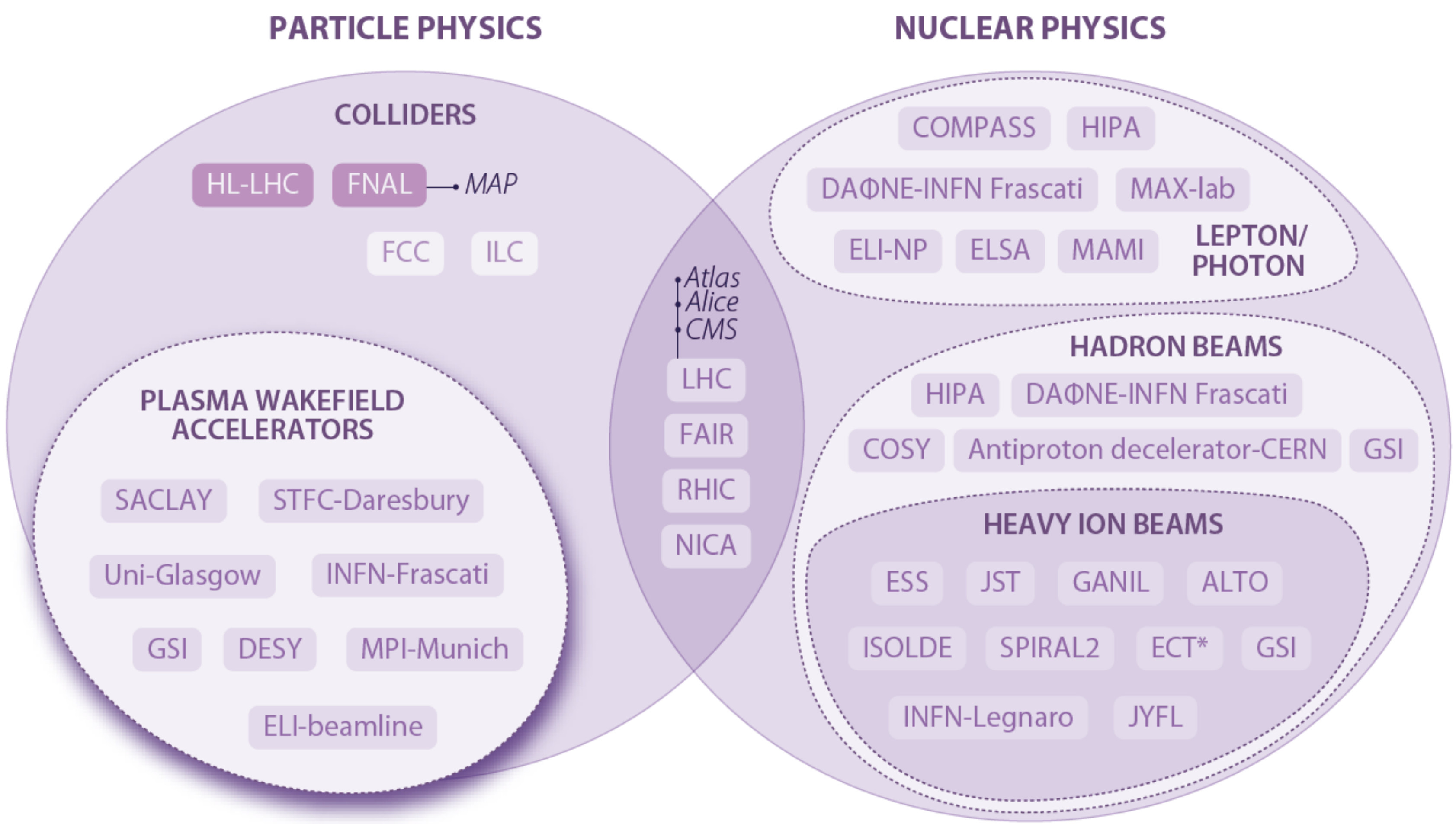
# Present and future Heavy Ion experiments



# RHIC – Relativistic Heavy Ion Collider



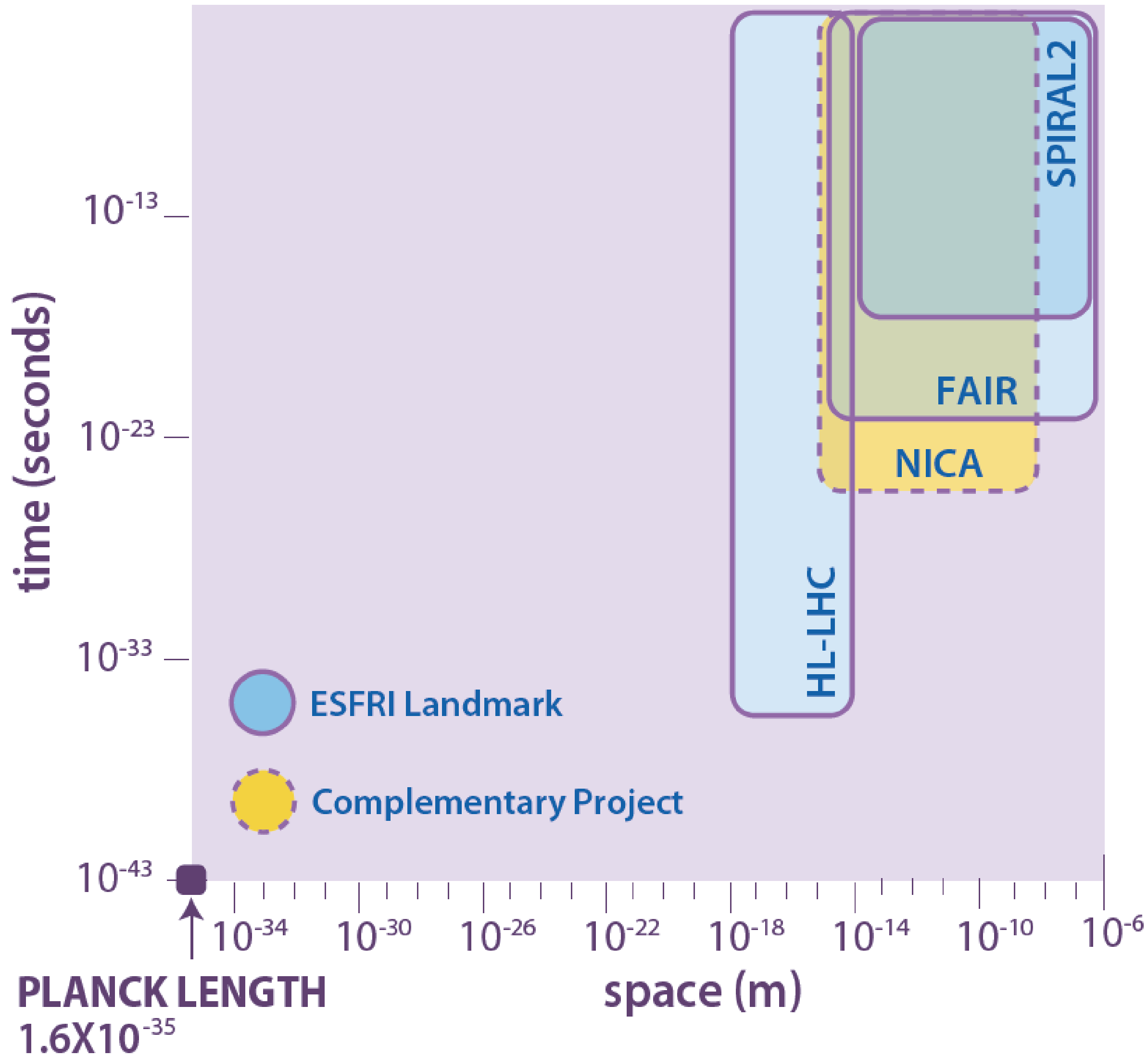
# ESFRI roadmap 2016




**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

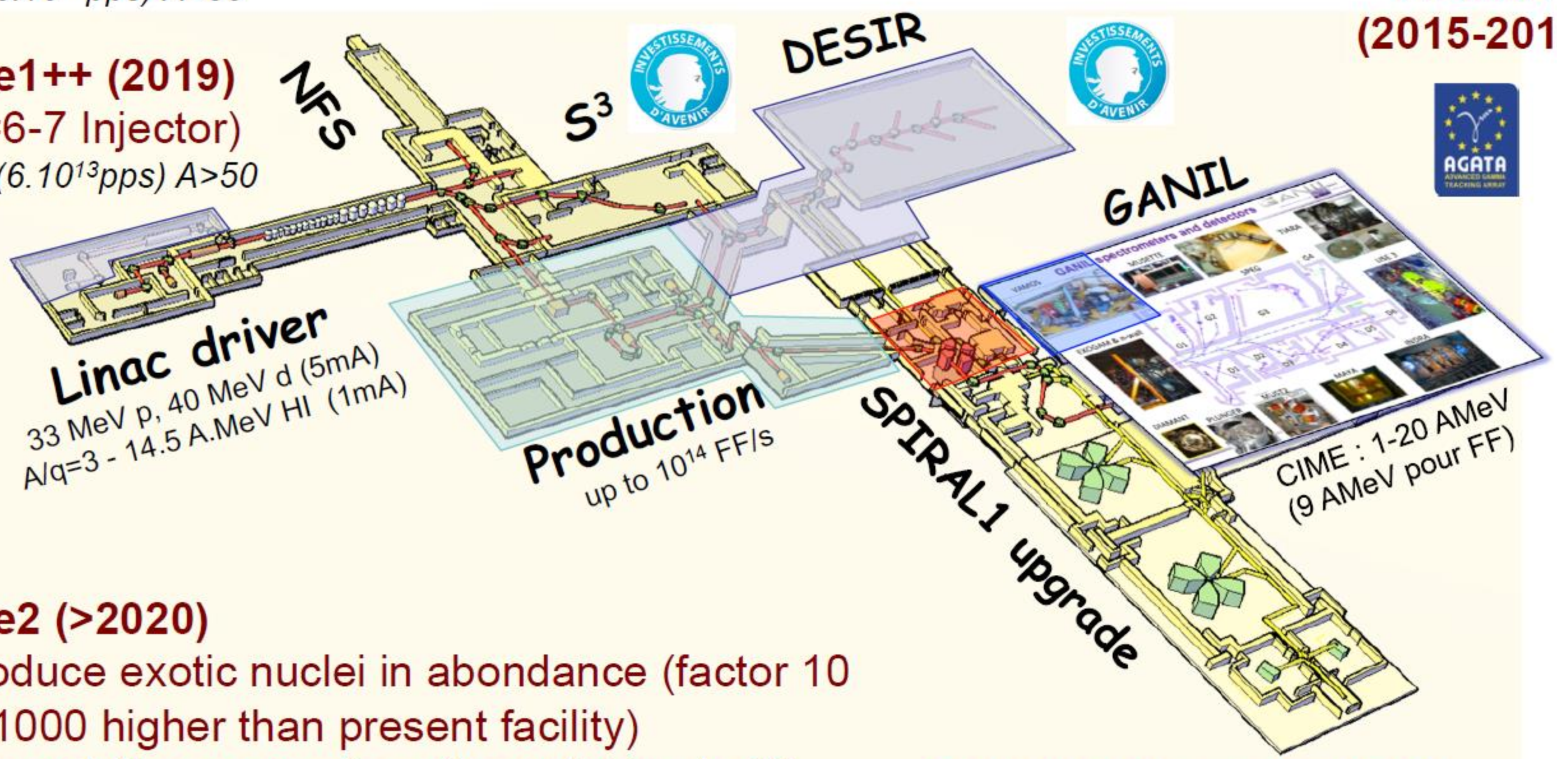
# SPIRAL2- *Système de Production d'Ions Radioactifs en Ligne de 2e generation*

**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

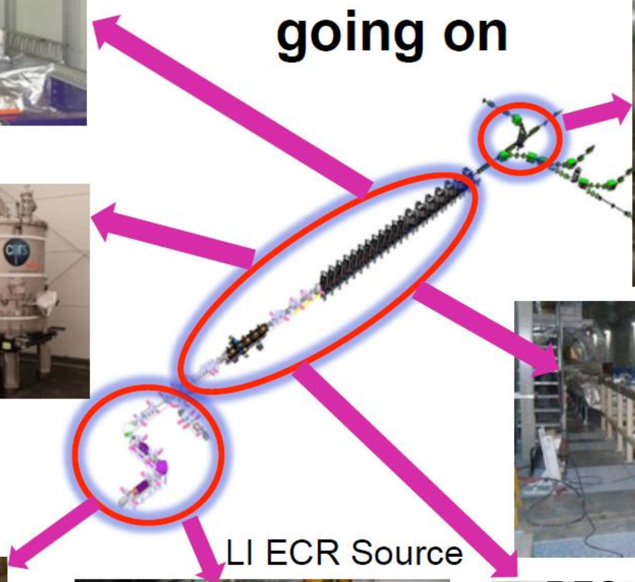
# SPIRAL2 – construction at GANIL, France

Phase 1 Civil Construction is finished

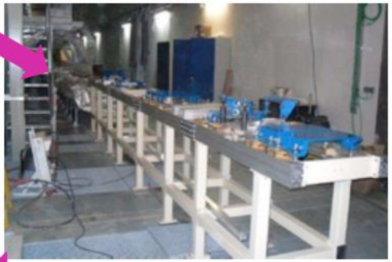
LINAC tunnel

Installation is going on

Beam lines & support



SC Cavities



HI ECR Source

LI ECR Source

RFQ

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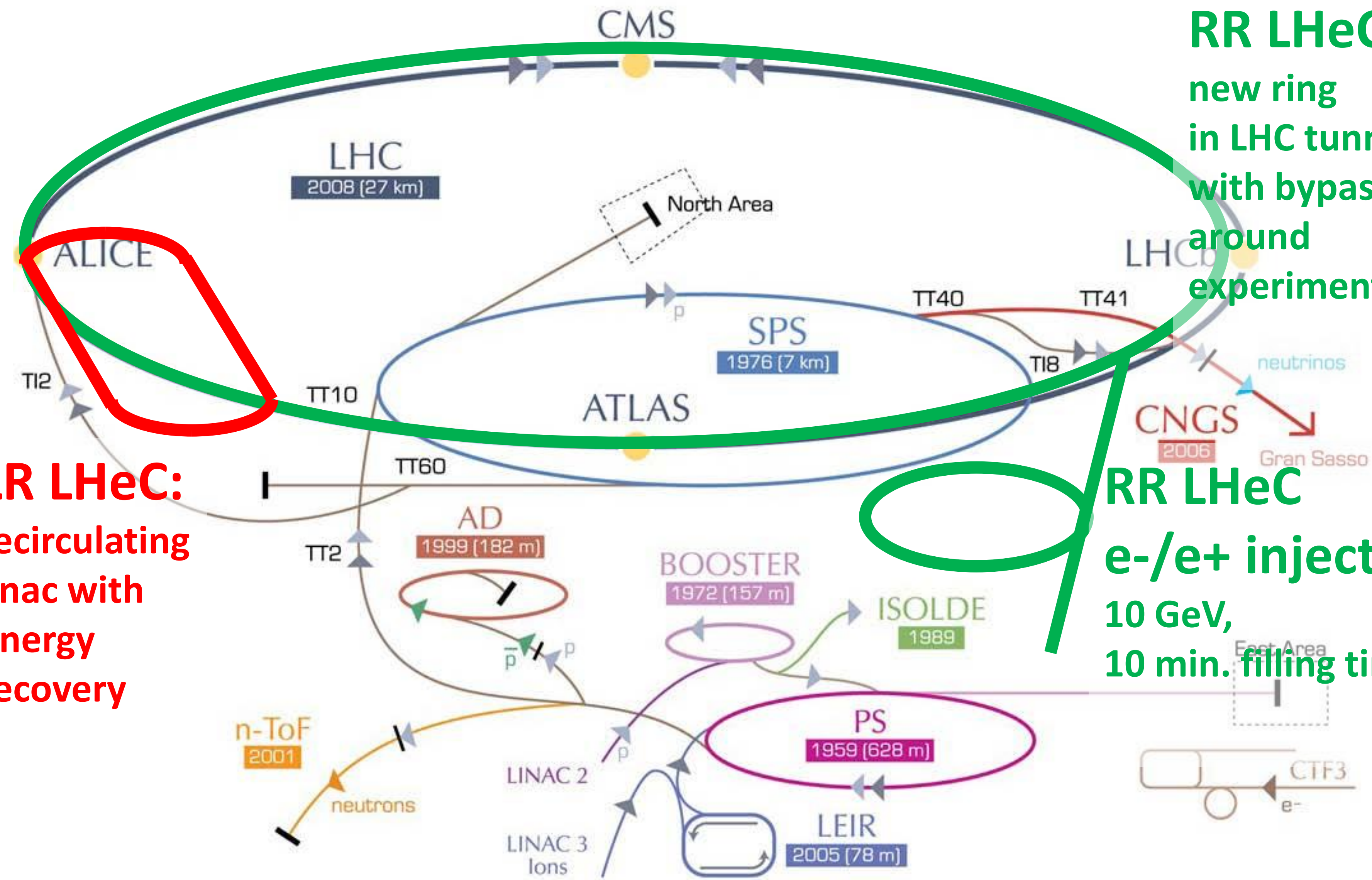
# Electron – Ion : LHeC

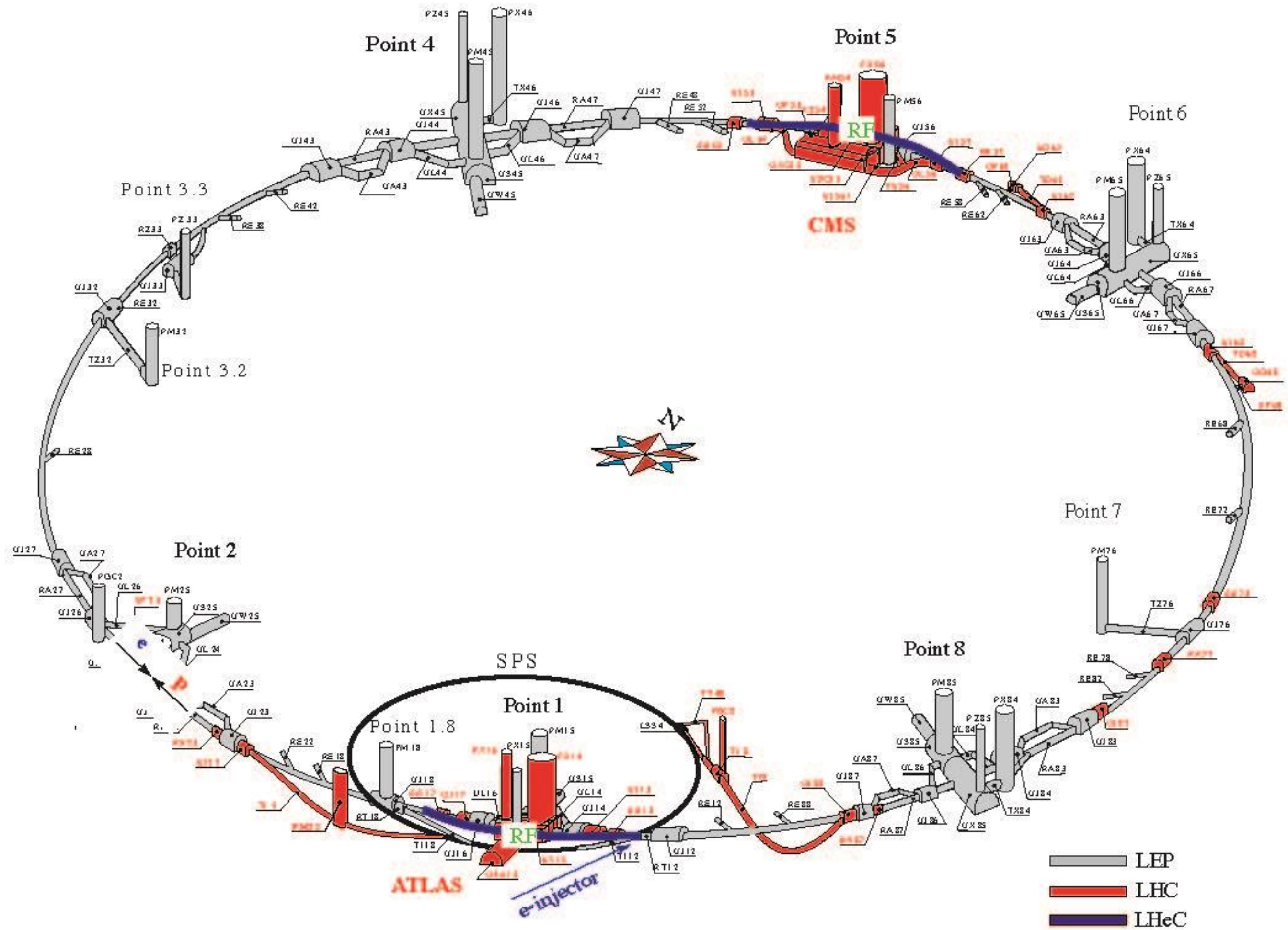



**RR LHeC:**
new ring
in LHC tunnel,
with bypasses
around
experiments

**LR LHeC:**
recirculating
linac with
energy
recovery

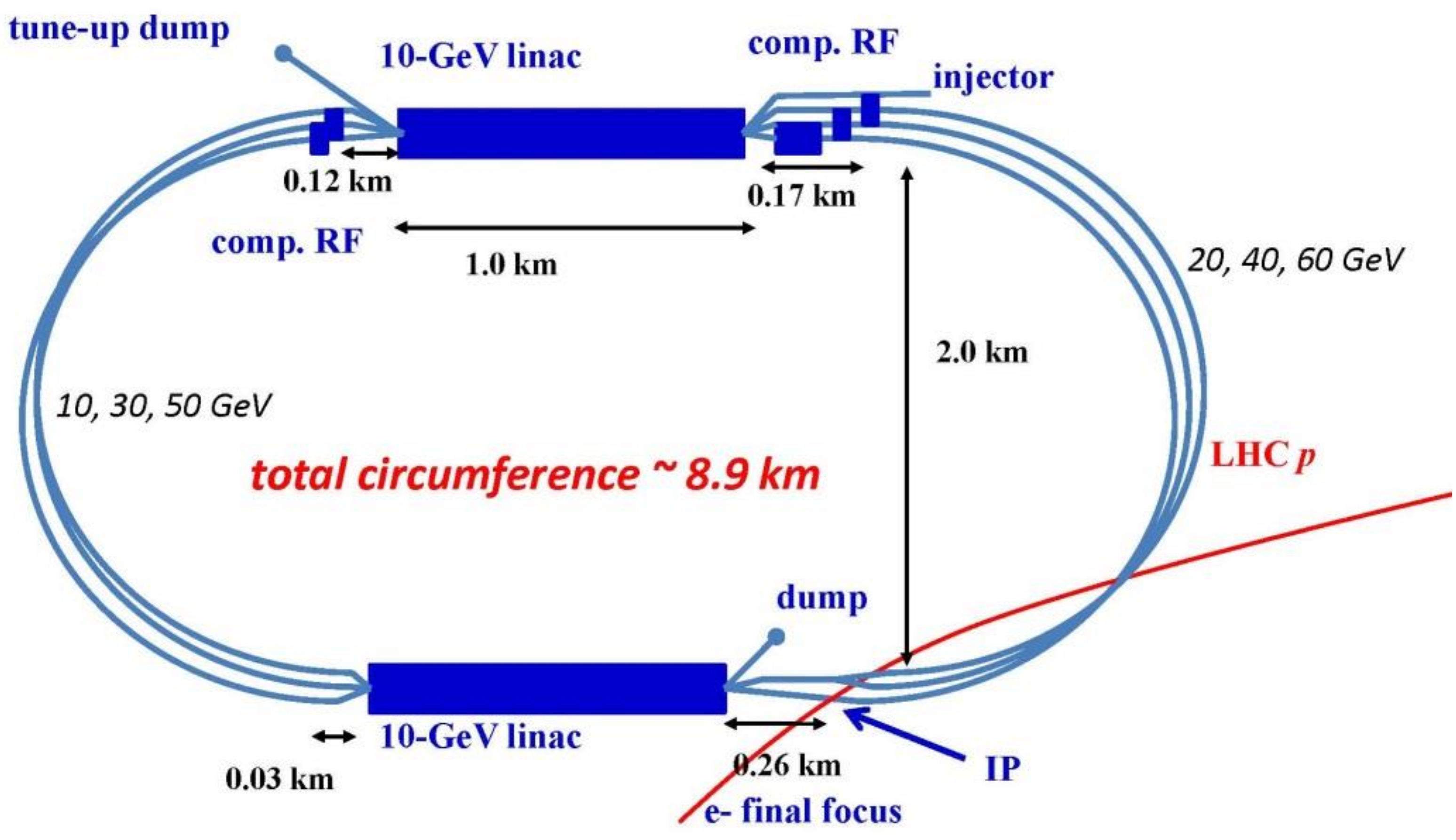
**RR LHeC**
**e-/e+ injector**
10 GeV,
10 min. filling time

# 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.

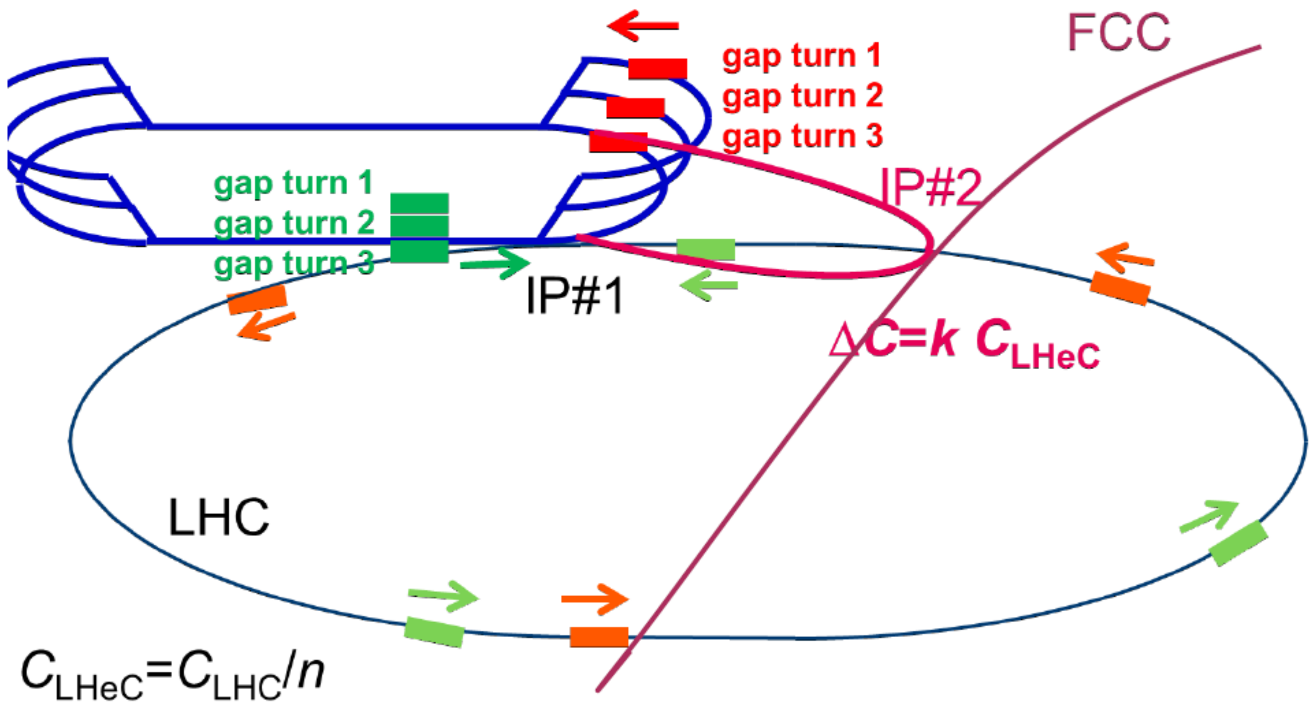
# LHeC linac-ring




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



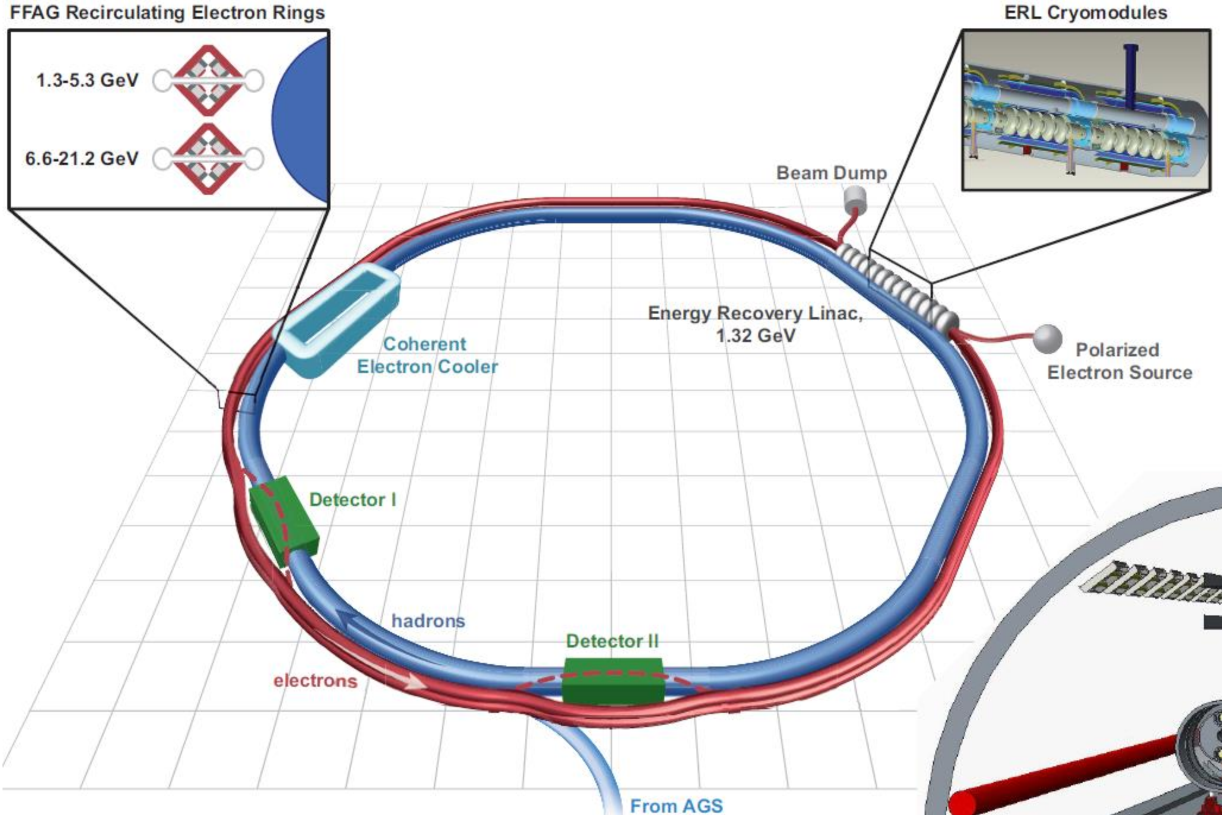

$C_{LHeC}=C_{LHC}/n$

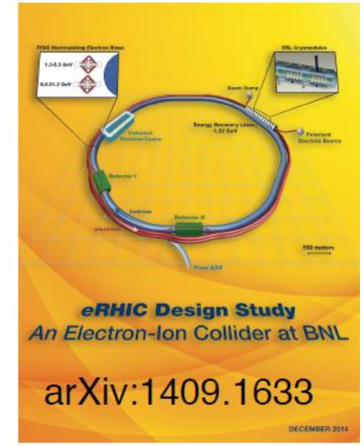
future: $C_{LHeC}=pC_{FCC}/m$

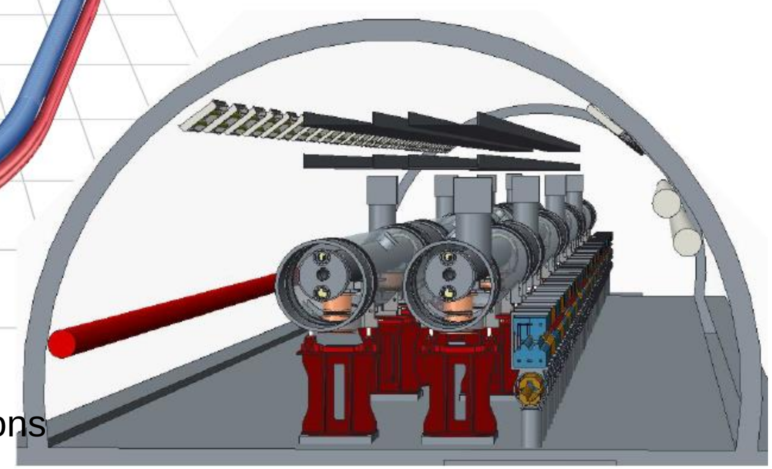
*m*, *n* (=3 or 4), *k*: integer
*p* = 1 or 2

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

# Electron – Ion : eRHIC (BNL)

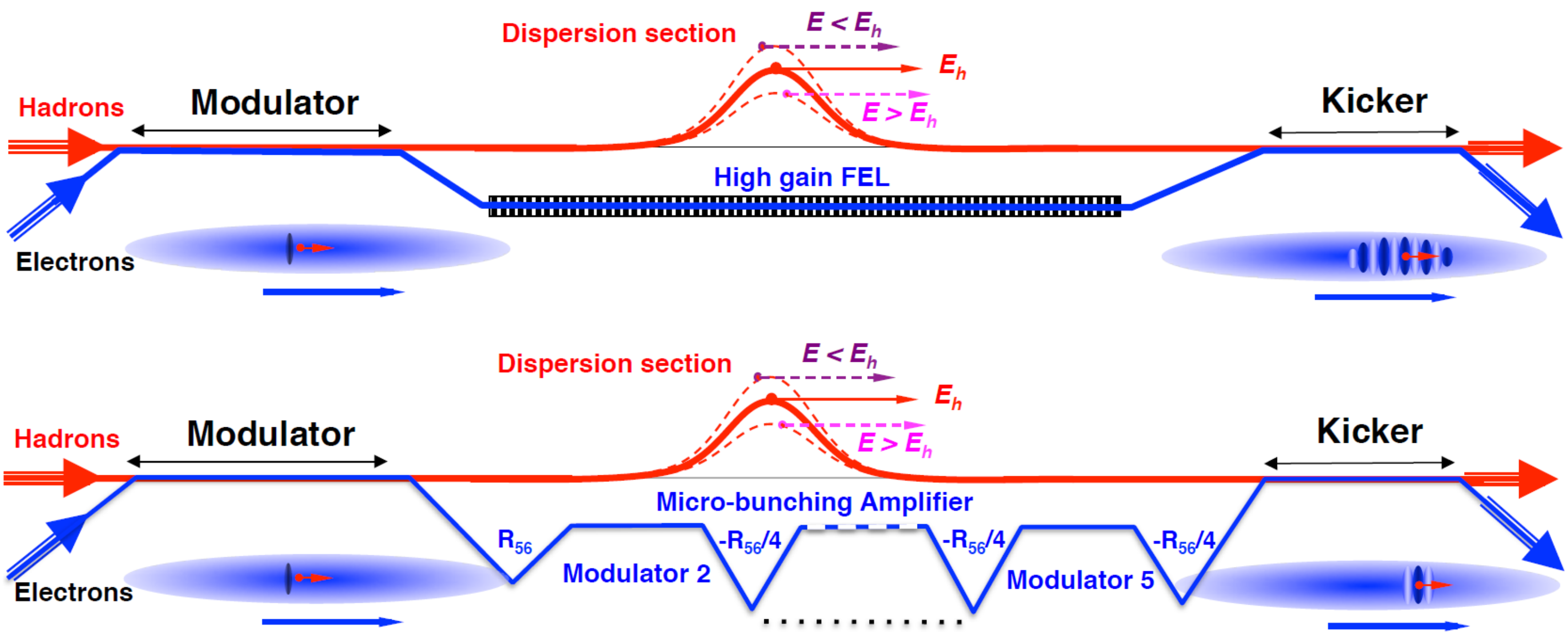


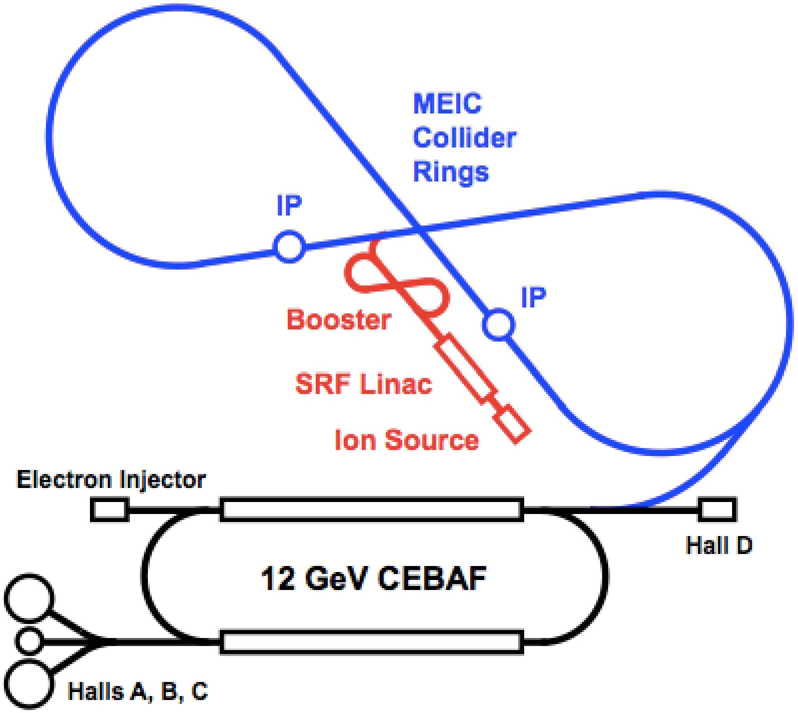
e- colliding with protons, 3He or heavy ions (up to Au)
E: 5-21 GeV e-, 50-250 GeV polarized p or up to 100 GeV/u gold ions
L: >1E34 for e-p, > 1E32 cm-2s-1 for e-Au
High polarization of e-, proton and 3He beams
Electron acceleration in a SC E-recovery e-linac
Electron beam is used for collisions only 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

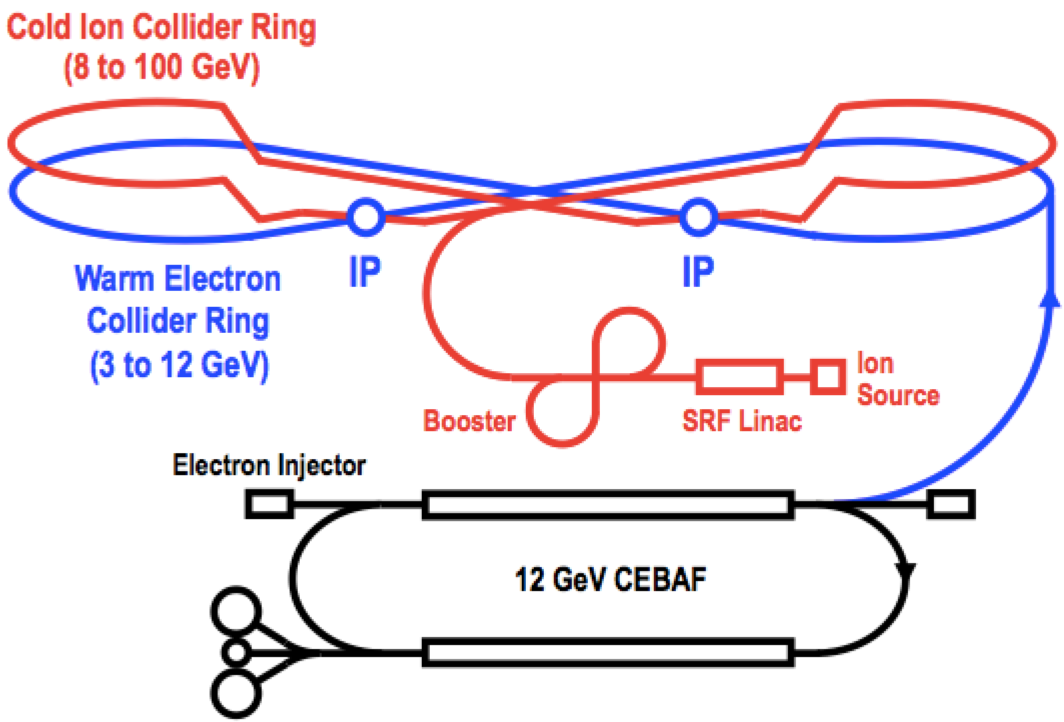
# eRHIC – coherent electron cooling




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

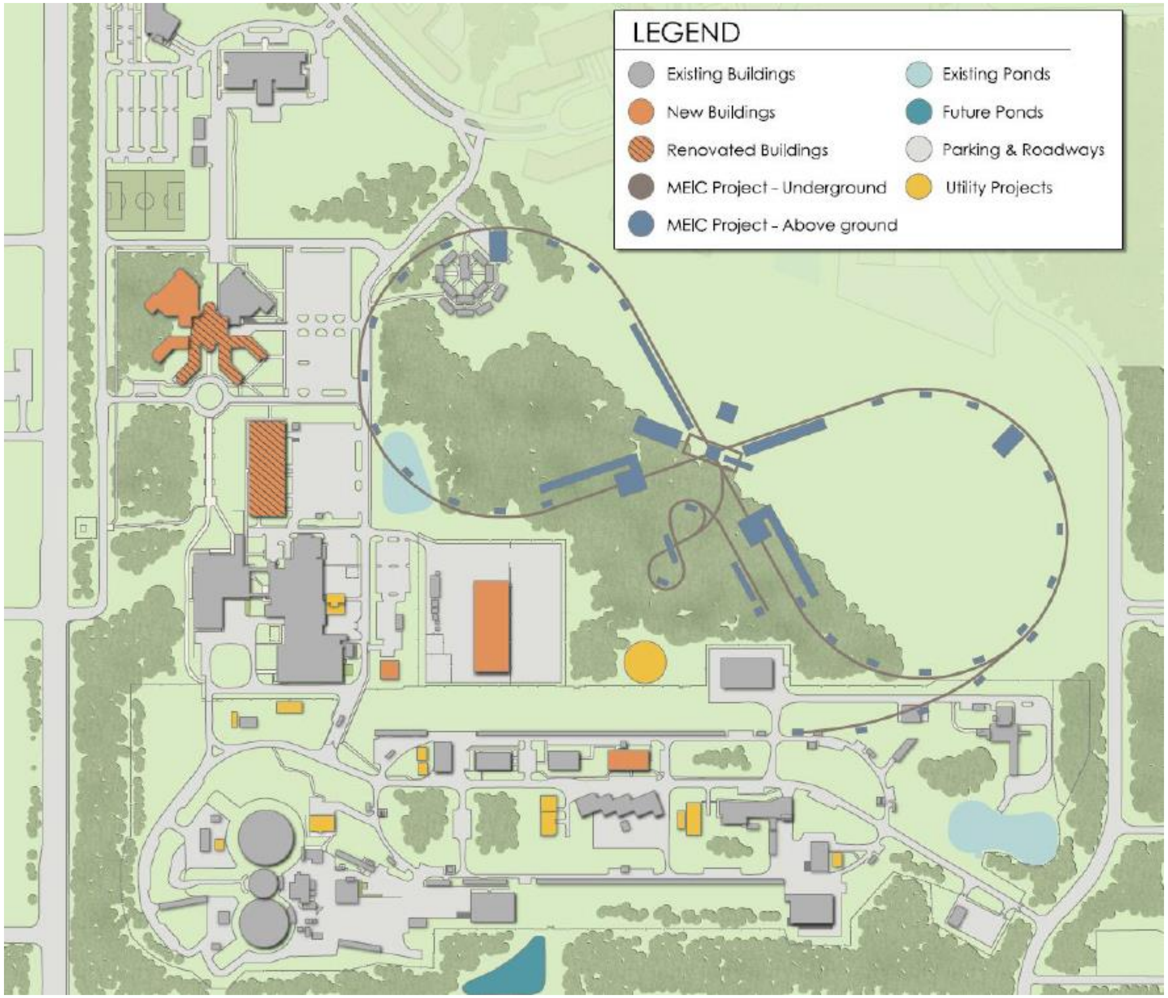
# Electron – Ion : MEIC (JLAB)




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

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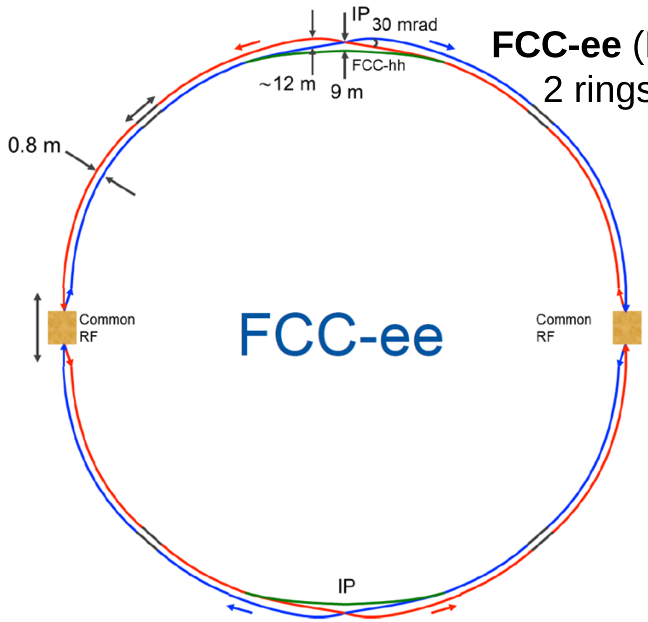
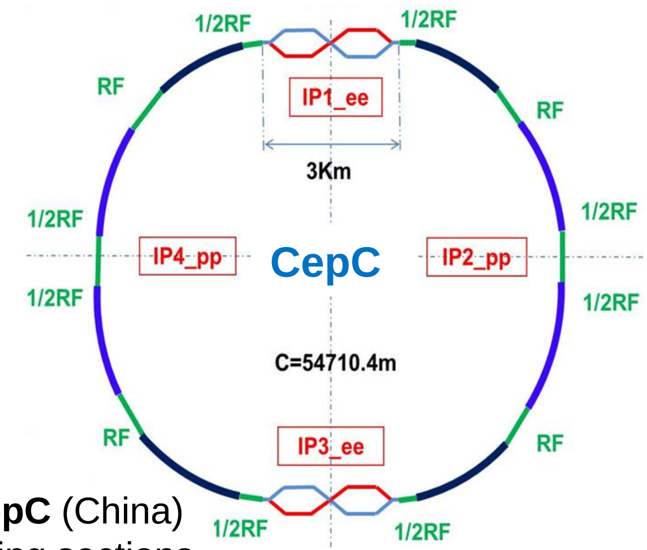
# FCC-ee & CepC




**FCC-ee** (Europe)
2 rings and one booster

Both: 2 IP with crab waist

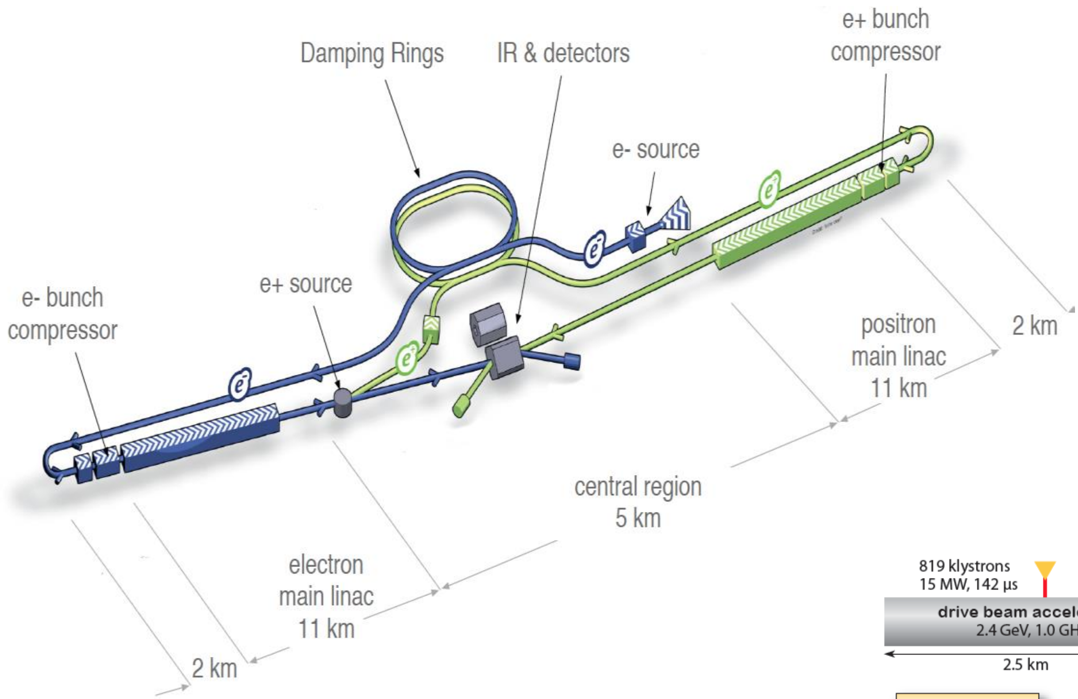
Single ring – more difficult beam dynamics




**CepC** (China)
1 ring with double ring sections

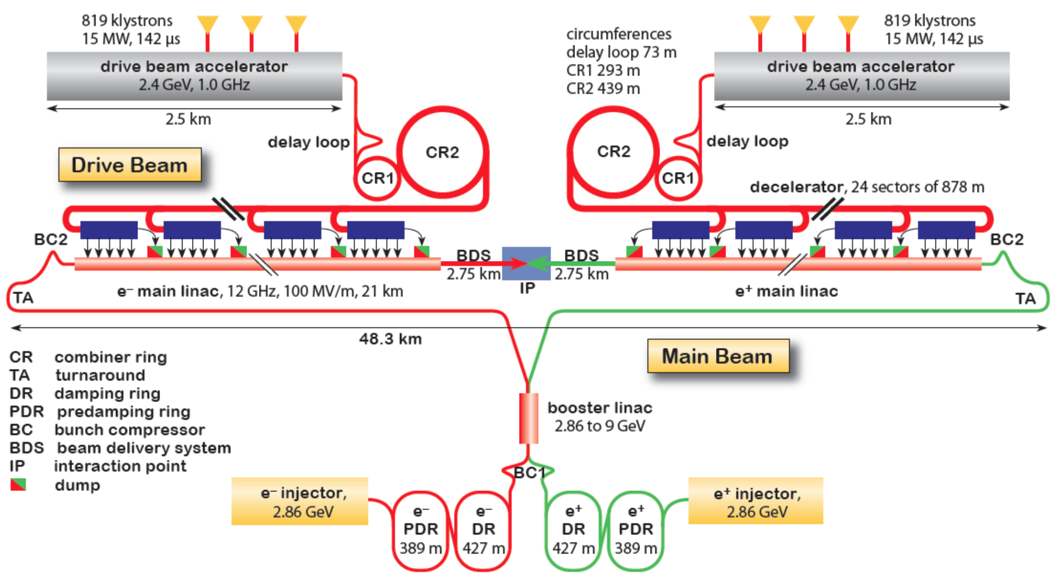
| parameter | FCC-ee | | | CepC | LEP2 |
|---|---|---|---|---|---|
| **energy/beam [GeV]** | **45** | **120** | **175** | **120** | 105 |
| bunches/beam | 90000 | 770 | 78 | 50 | 4 |
| beam current [mA] | 1450 | 30 | 6.6 | 16.6 | 3 |
| **luminosity/IP x $10^{34}$ $cm^{-2}s^{-1}$** | **70** | **5** | **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



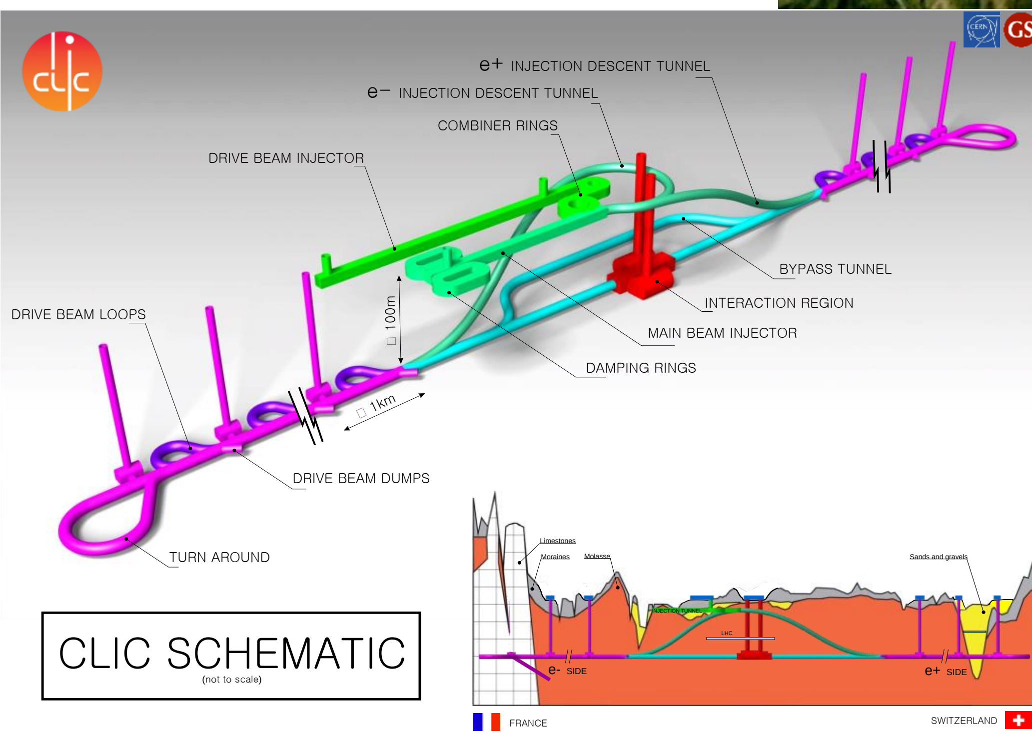

**ILC**
0.5 TeV CM, upgreadable to 1 TeV
SC RF industrialized
mature design (TDR in 2012)
Possibility of hosting is evaluated by Japanese government

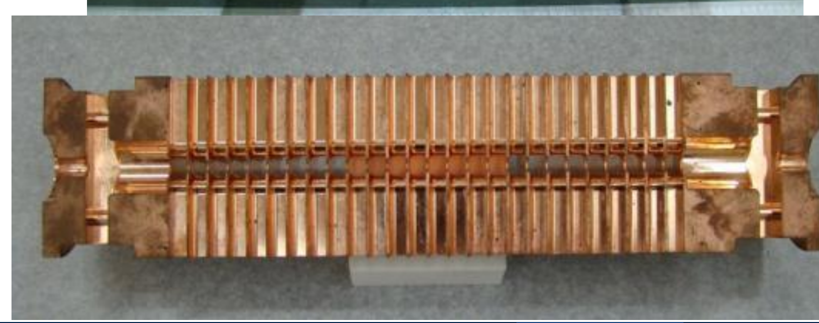
**CLIC**
Two-beam scheme, 1-3 TeV CM
Option for 380 GeV explored (klystrons)
CTF3 facility – key R&D done
Ready for demonstrator project



# CLIC project

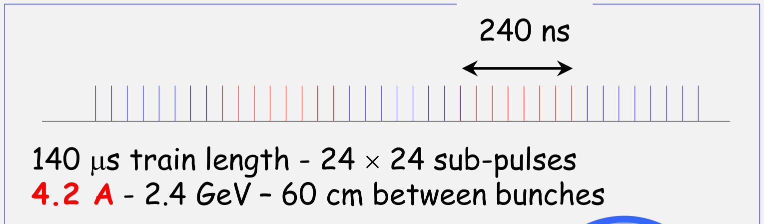
**Key features:**
High gradient (energy/length)
Small beams (luminosity)

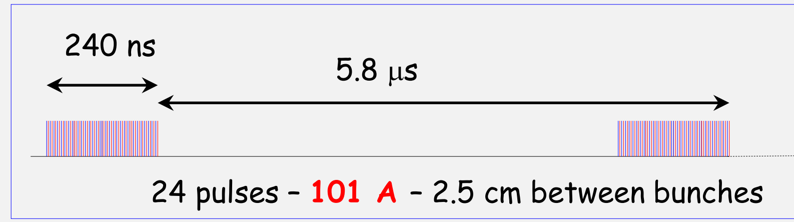



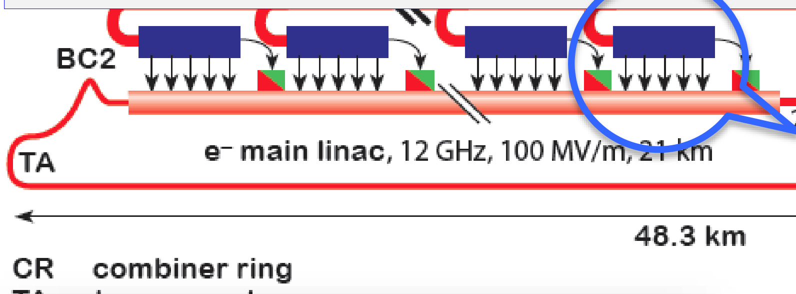
# CLIC two beam scheme

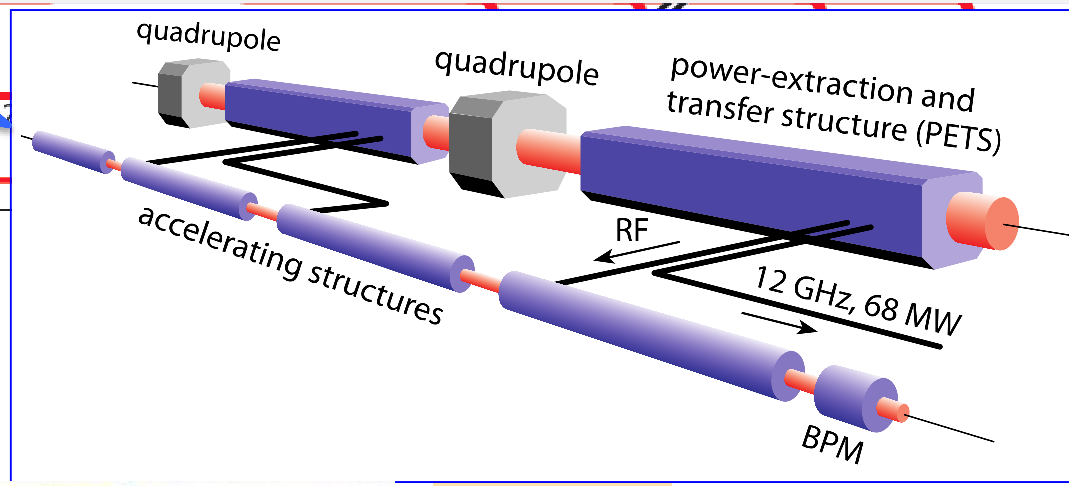
## Drive beam time structure - initial



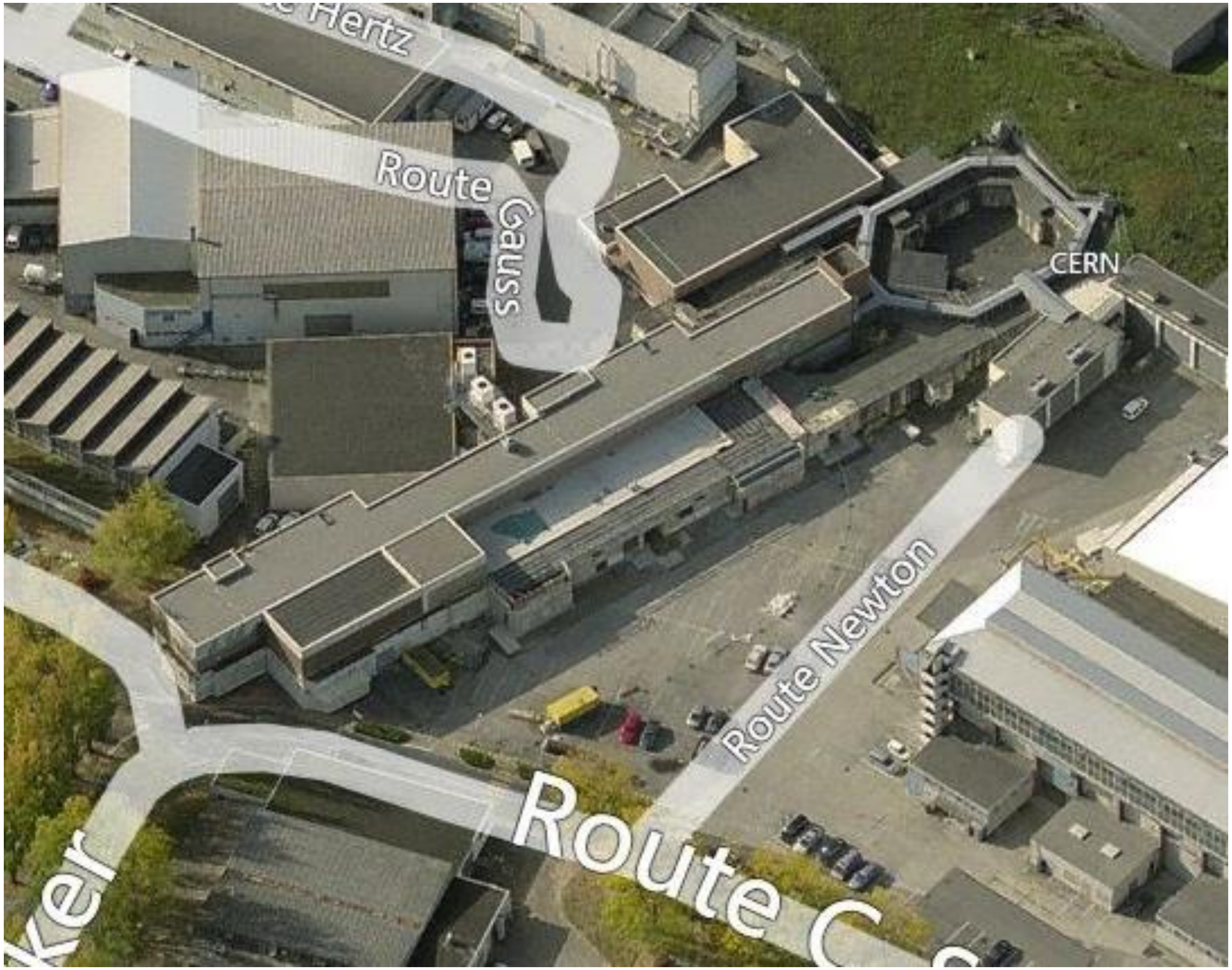

## Drive beam time structure - final



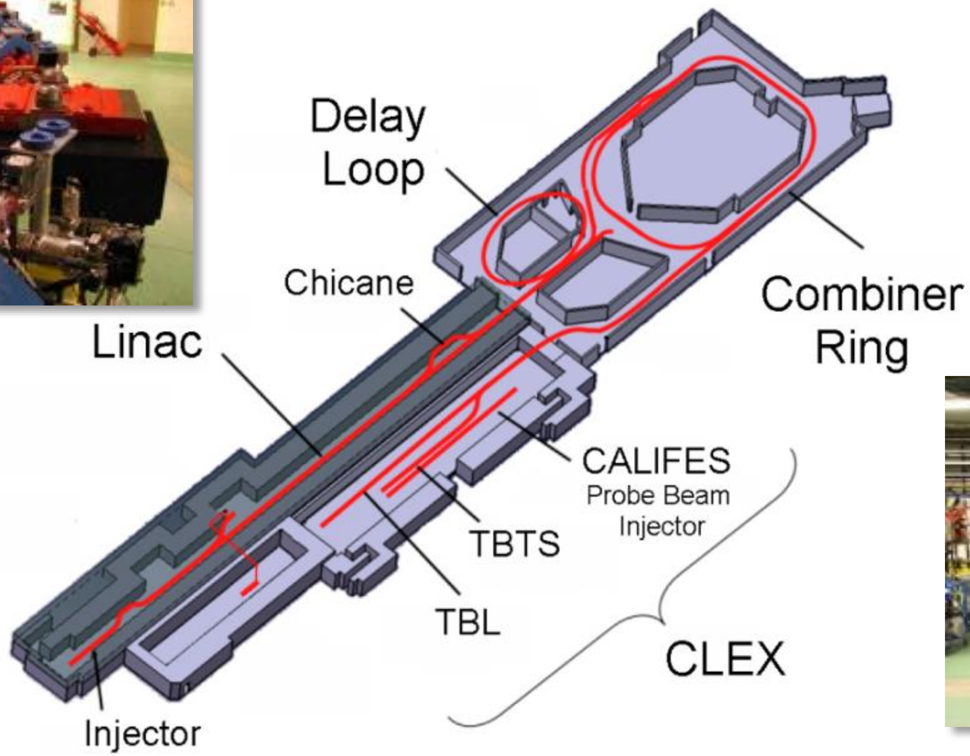




# CLIC test facility (CTF3)

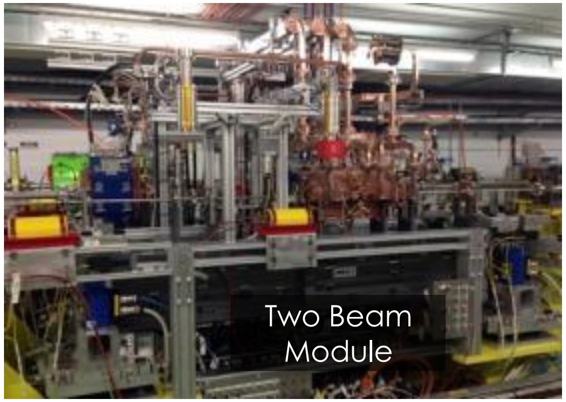


# CLIC test facility (CTF3)

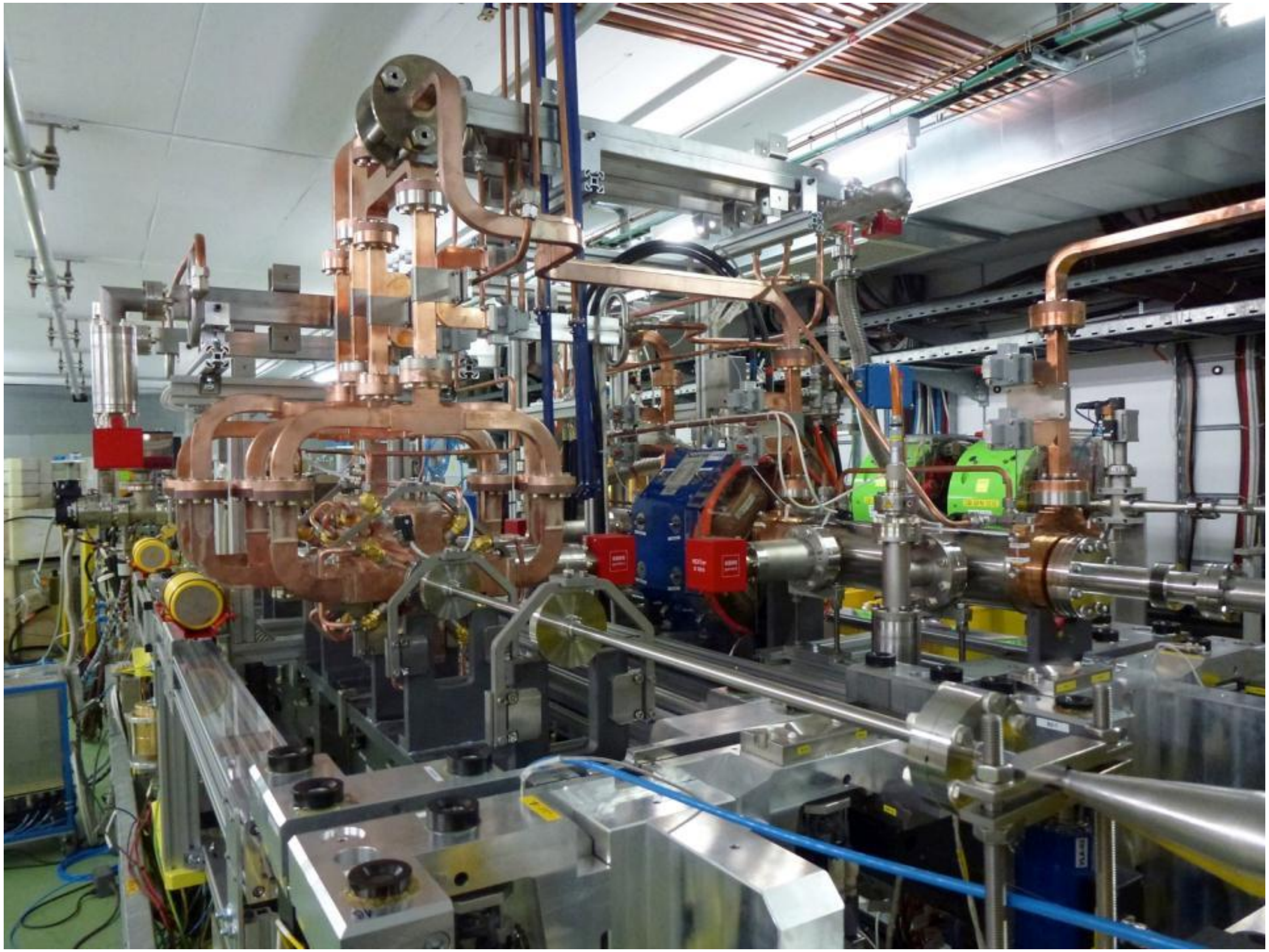









# 2-beam acceleration module in CTF3

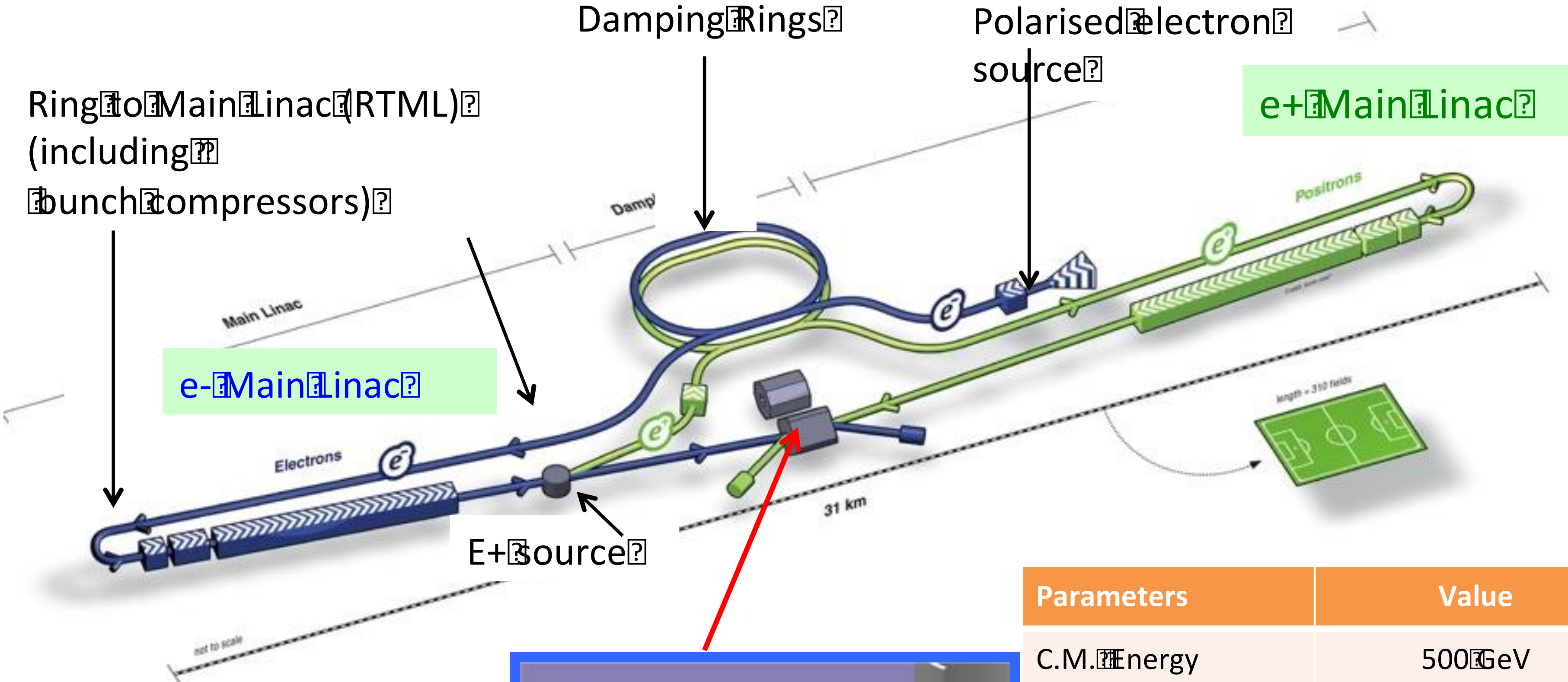


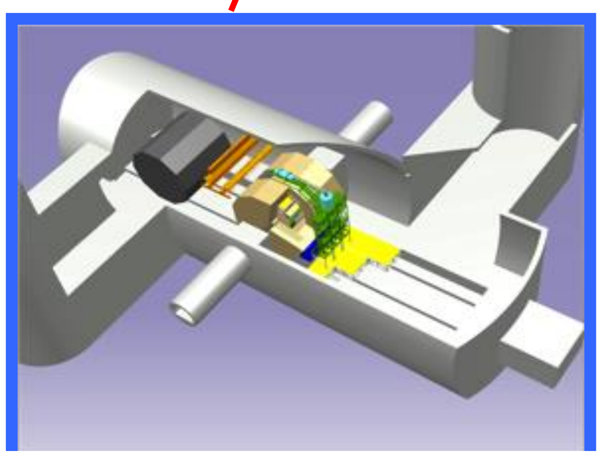
drive beam

main beam

Has reached 145 MV/m (2012)

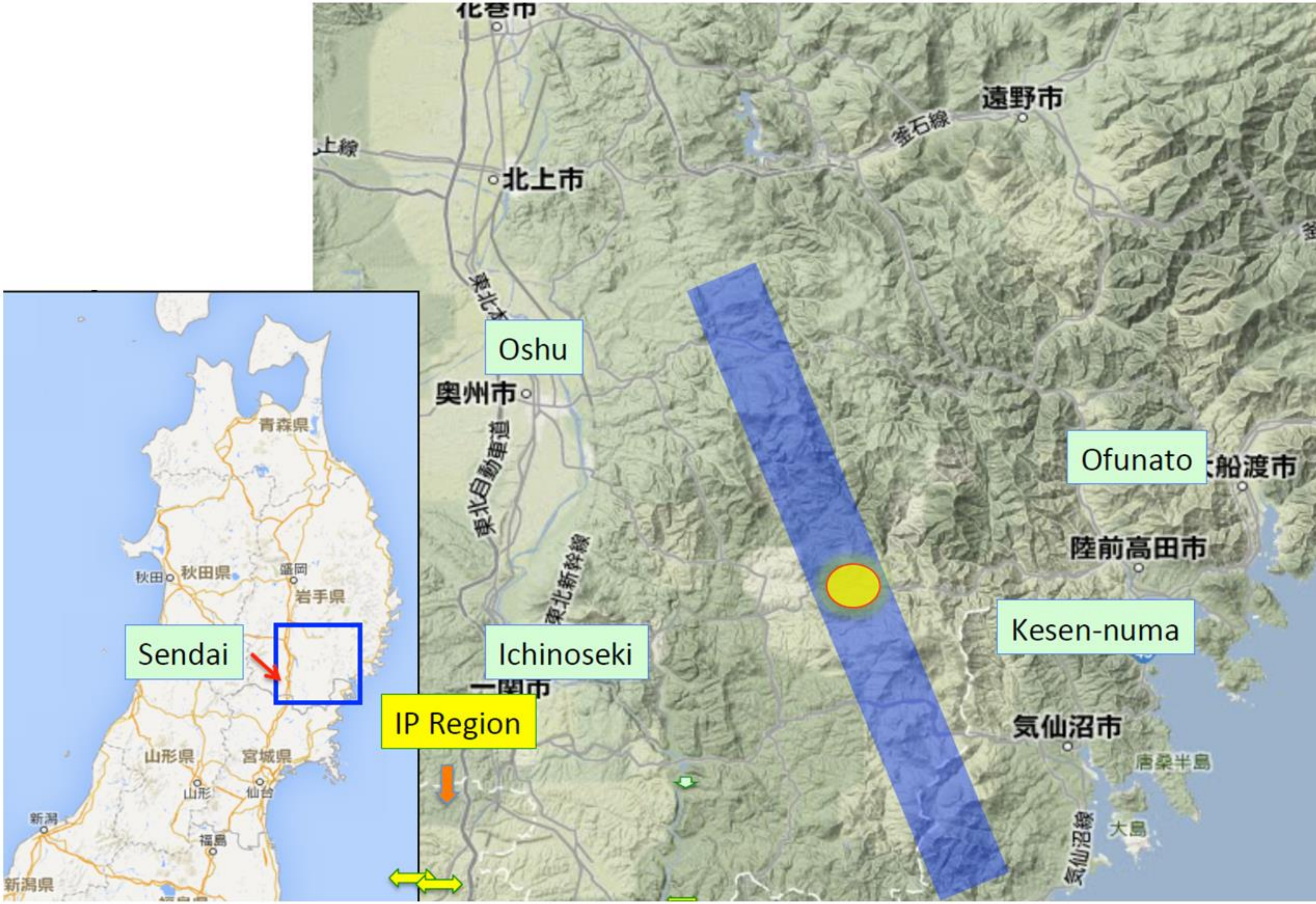
# ILC project



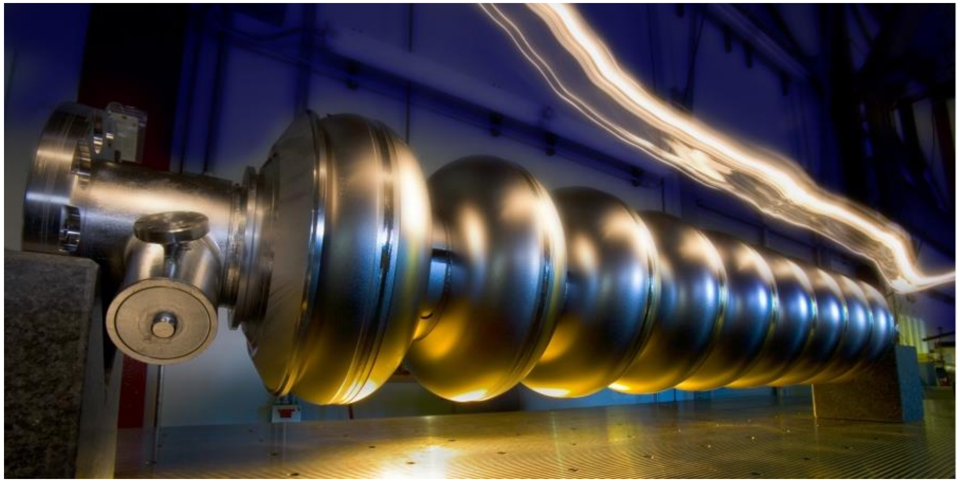



| Parameters | Value |
|---|---|
| C.M. Energy | 500 GeV |
| Peak luminosity | 1.8 x$10^{34}$ cm$^{-2}$s$^{-1}$ |
| Beam Rep. rate | 5 Hz |
| Pulse duration | 0.73 ms |
| Average current | 5.8 mA (in pulse) |
| E gradient in SCRF acc. cavity | 31.5 MV/m +/-20% $Q_0$ = 1E10 |

# ILC site specific design

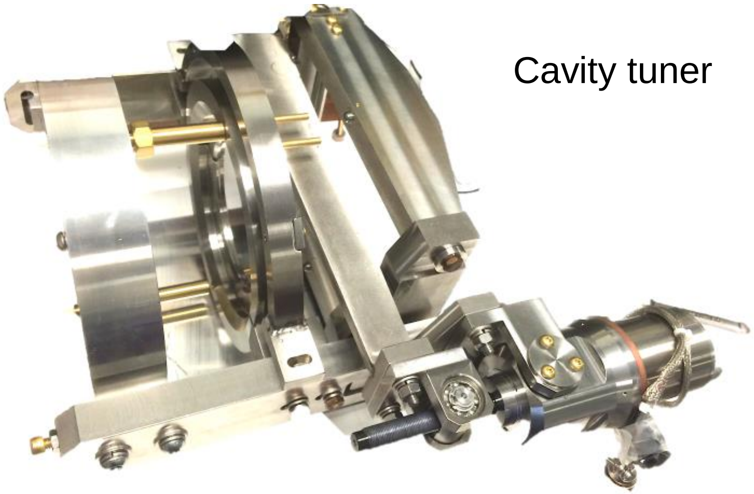


# ILC SCRF technology development



SCRF cavities
gradient 31.5 MeV/m

Cavity Input Coupler



Cavity tuner

# ILC cryomodule and string tests

CERN Courier December 2014

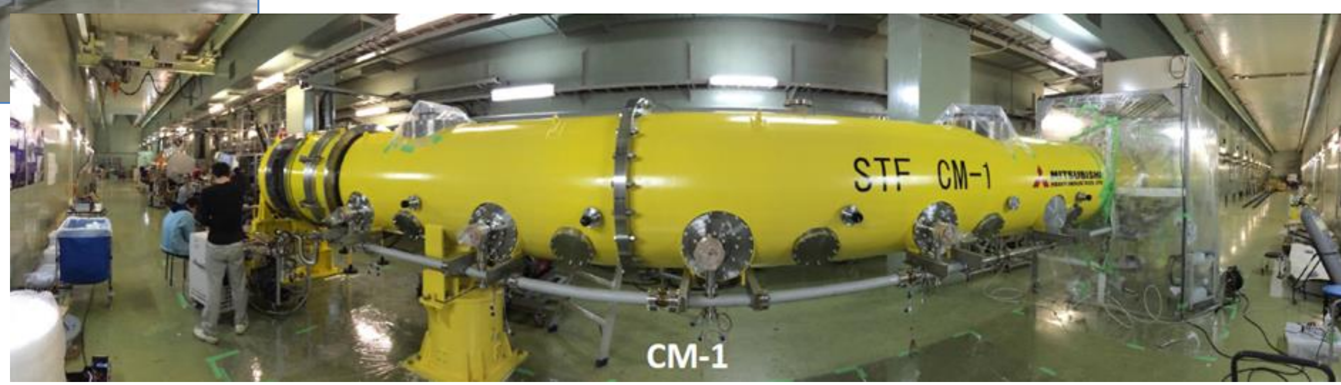
**ACCELERATORS**

## 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

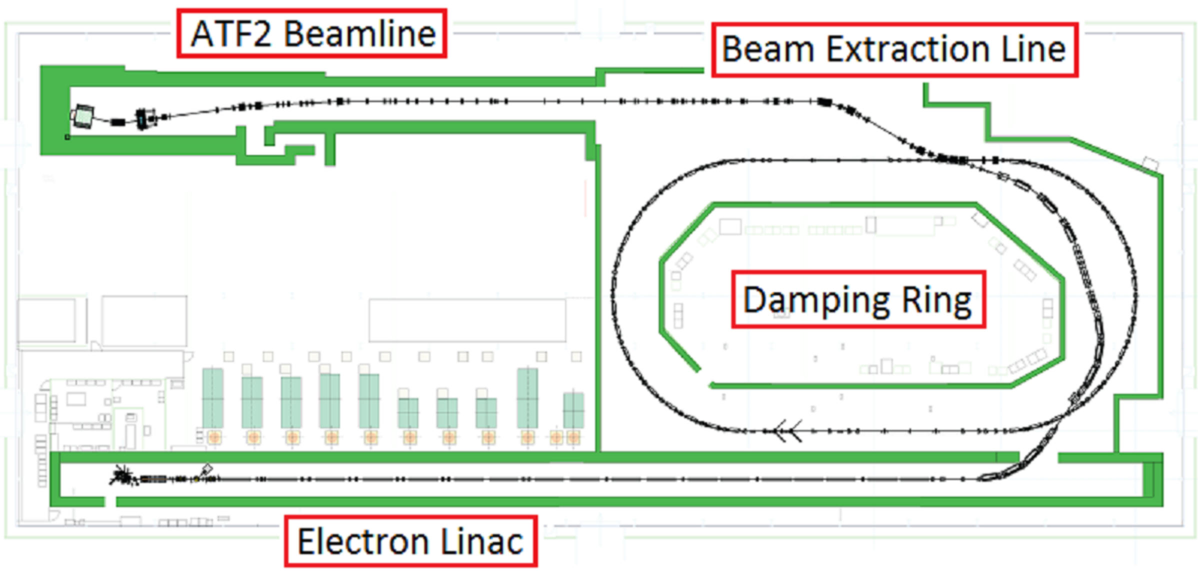
Cryomodule test at Fermilab reached < 31.5 > MV/m, exceeding ILC specification

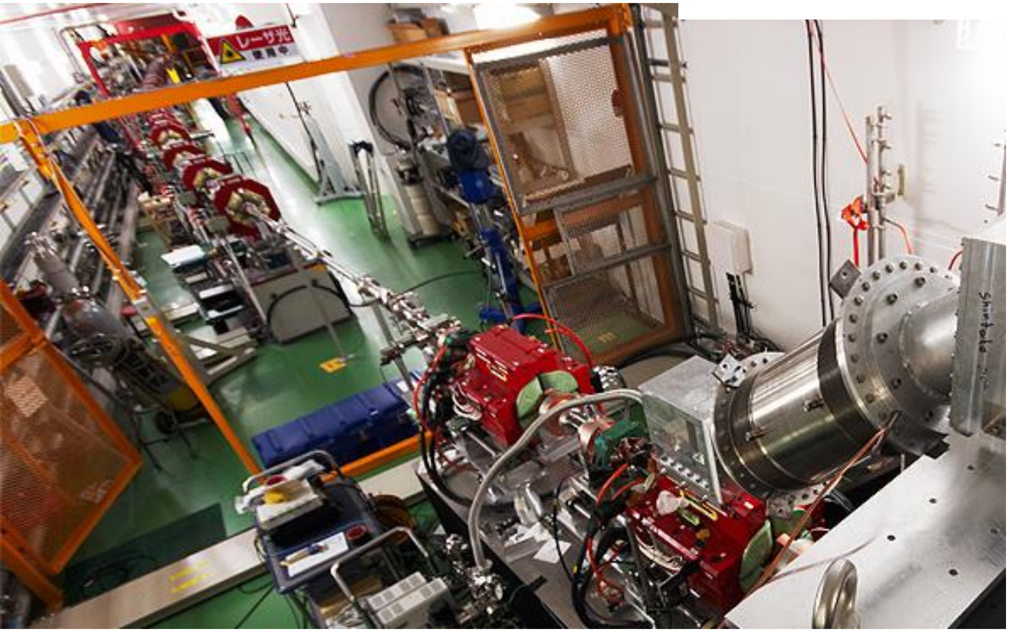
String test of cryomodules at KEK - STF



# ILC & CLIC nanobeams at ATF2/KEK

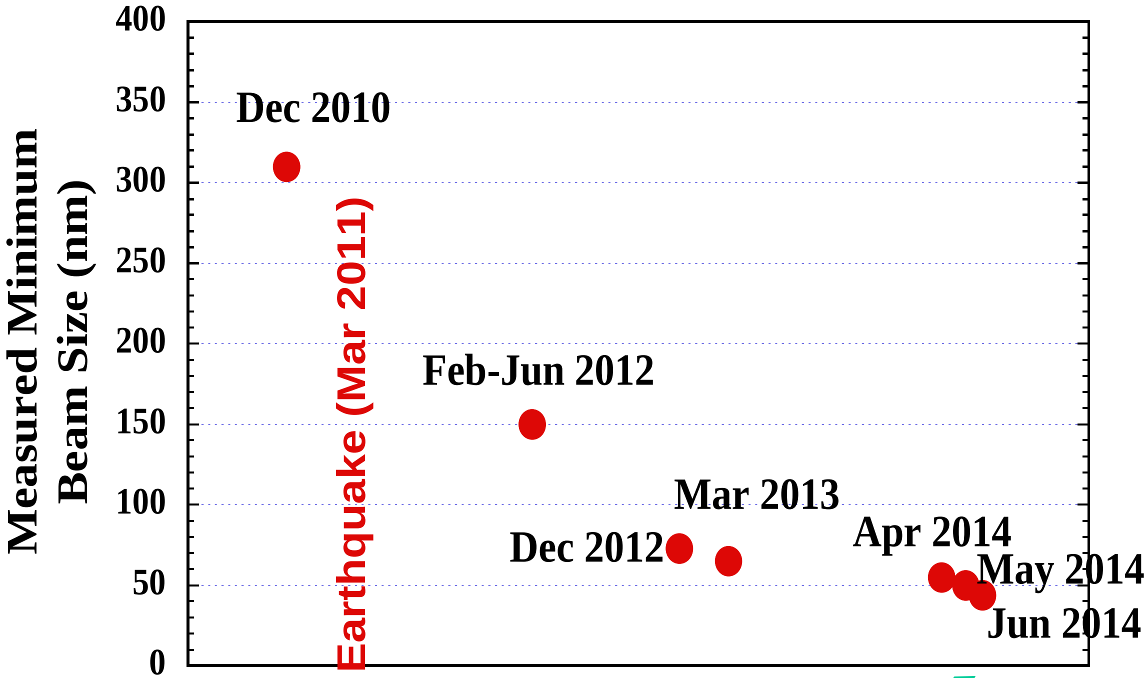
ILC and CLIC rely on final focus with local chromatic correction
P.Raimondi, A.Seryi, PRL, 86, 3779 (2001)

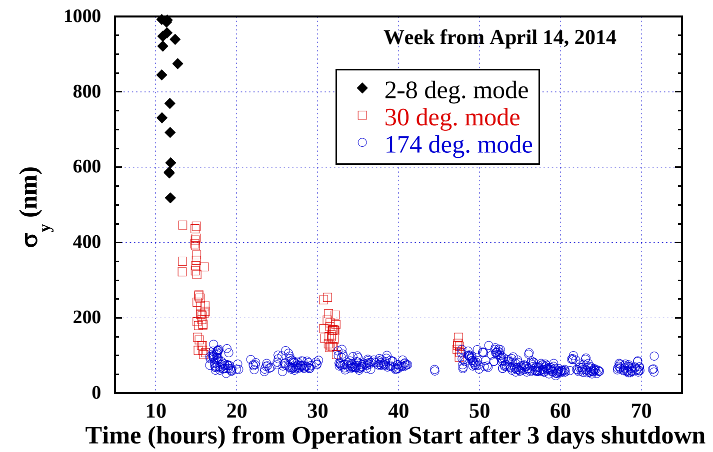


ATF2 at KEK is a scaled down model of ILC/CLIC final focus
(with local chromatic correction)

# 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*

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  - eRHIC
  - Jlab e-ion
- **Lepton colliders**
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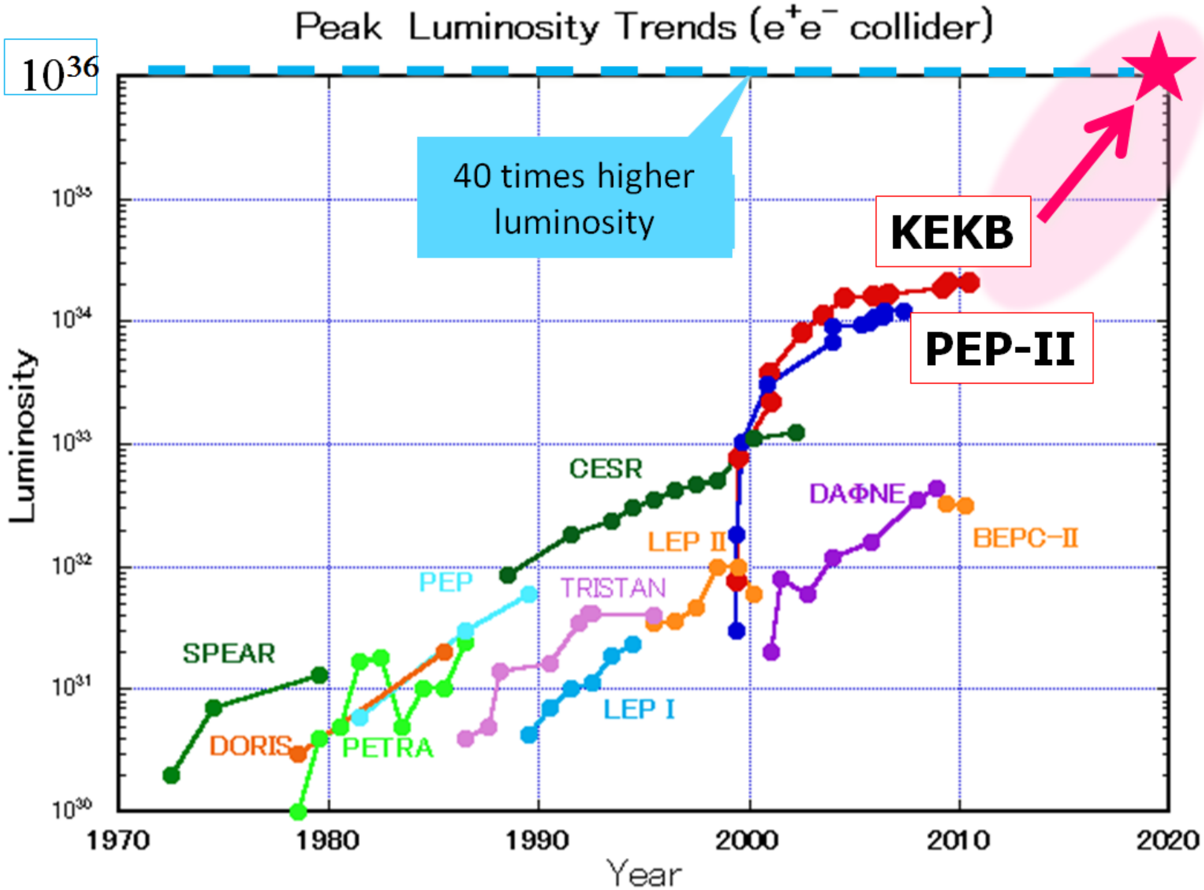
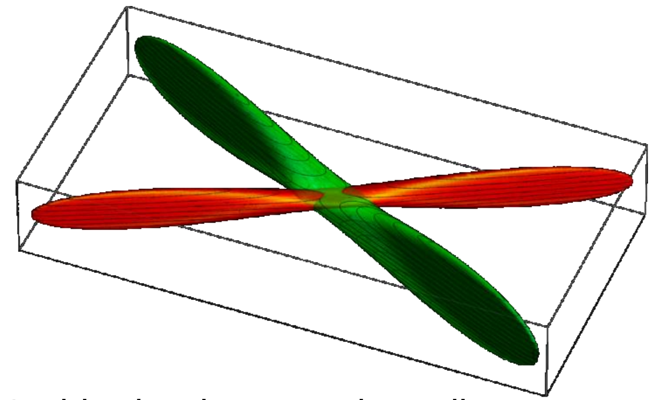
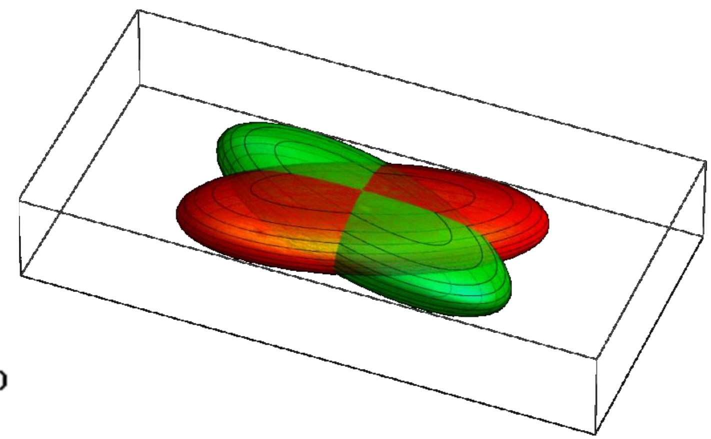
  - c-tau factory
- **Advanced approaches**
  - LPWF & PWFA collider roadmaps & AWAKE

# SuperKEKB factory



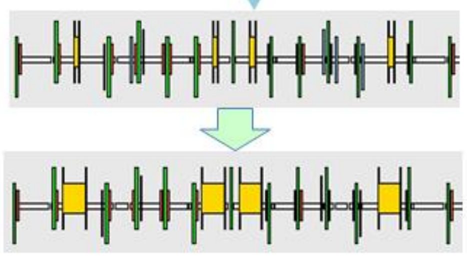
Crabbed waist – P.Raimondi
~50nm size at IP



Standard collision, ~1um size at IP

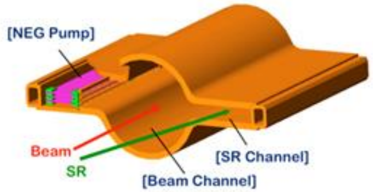
# KEKB to SuperKEKB

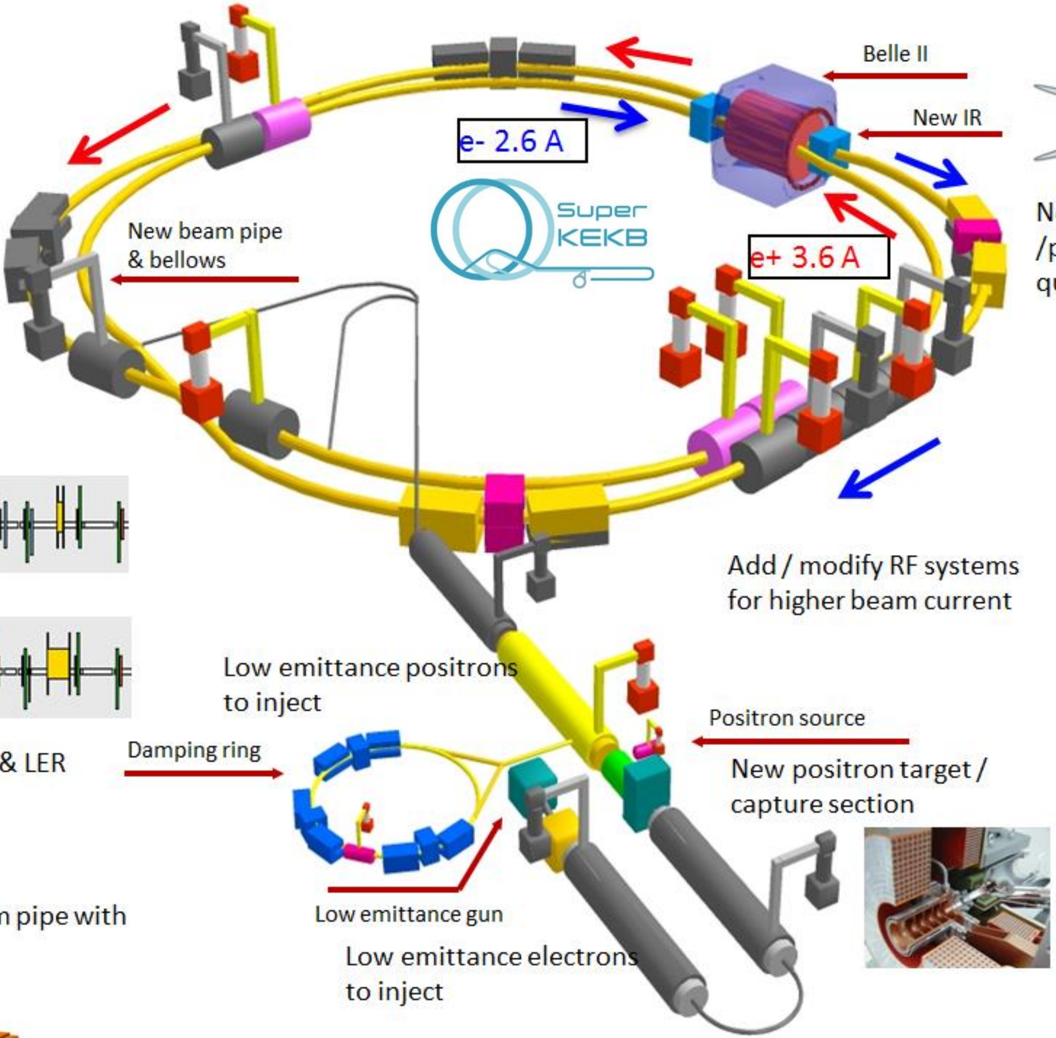
Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

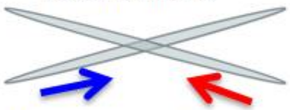


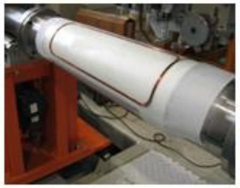

Low emittance positrons to inject

Low emittance electrons to inject

Colliding bunches



New superconducting /permanent final focusing quads near the IP

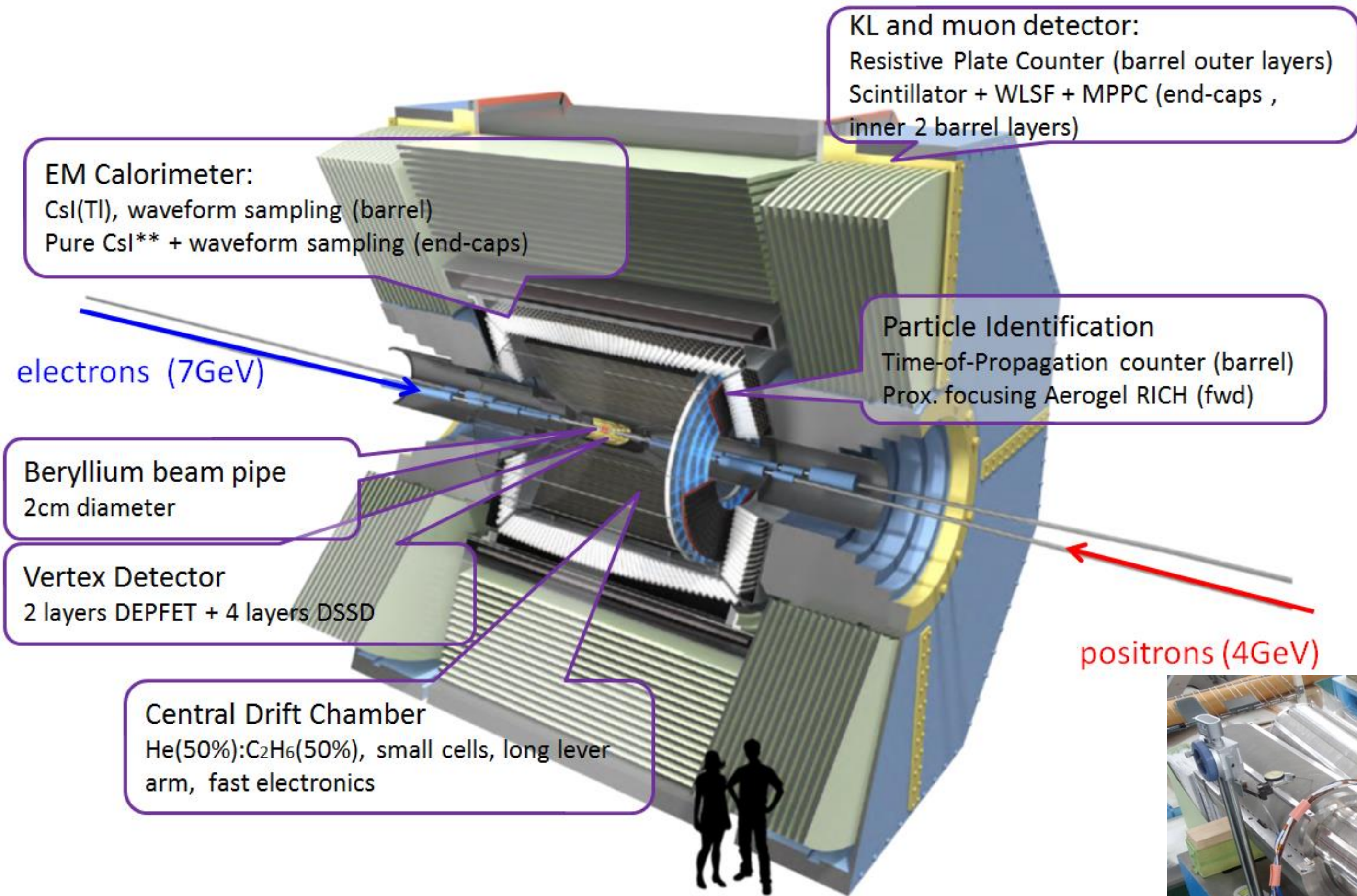


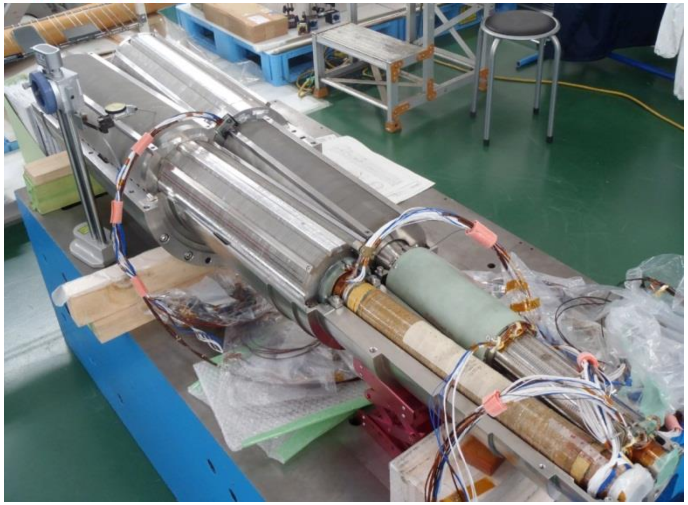
Add / modify RF systems for higher beam current

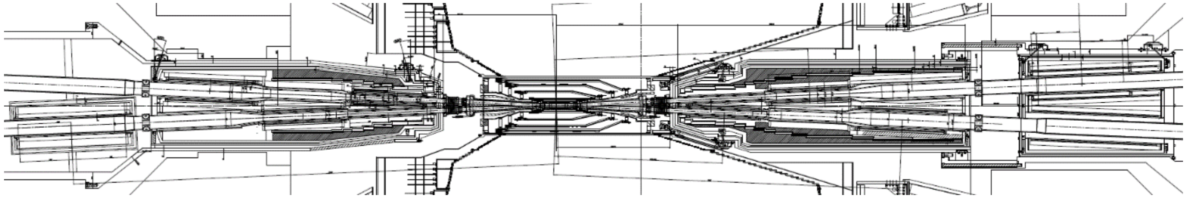
New positron target / capture section

**To obtain x40 higher luminosity**

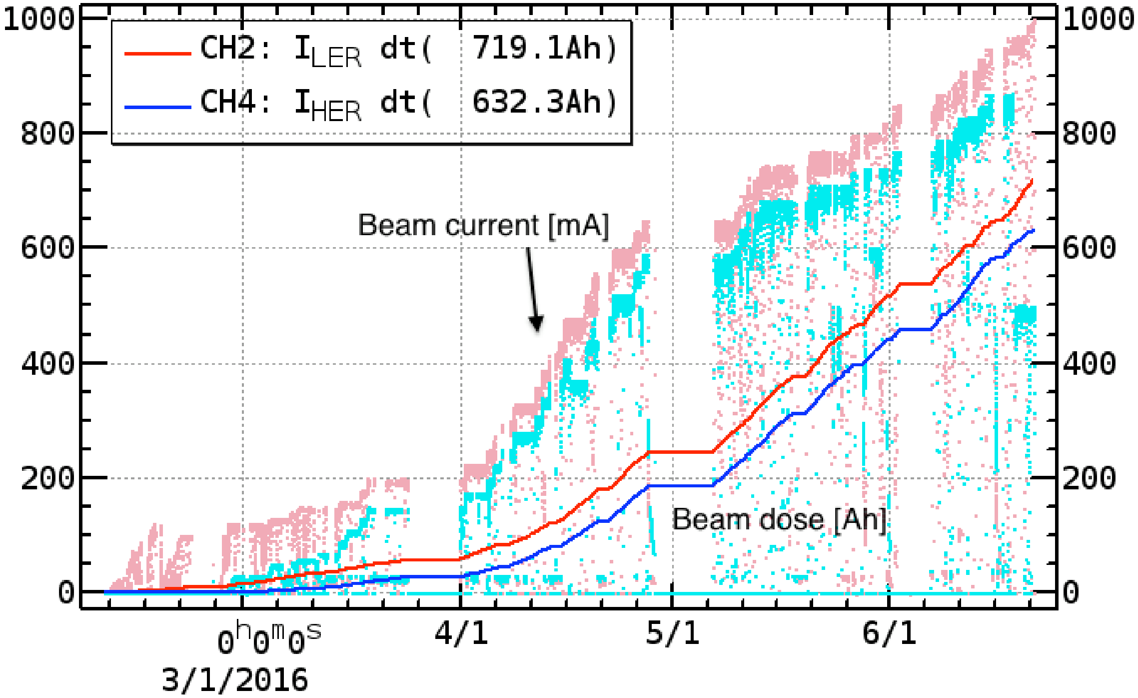
# SuperKEKB Belle II and IR magnets





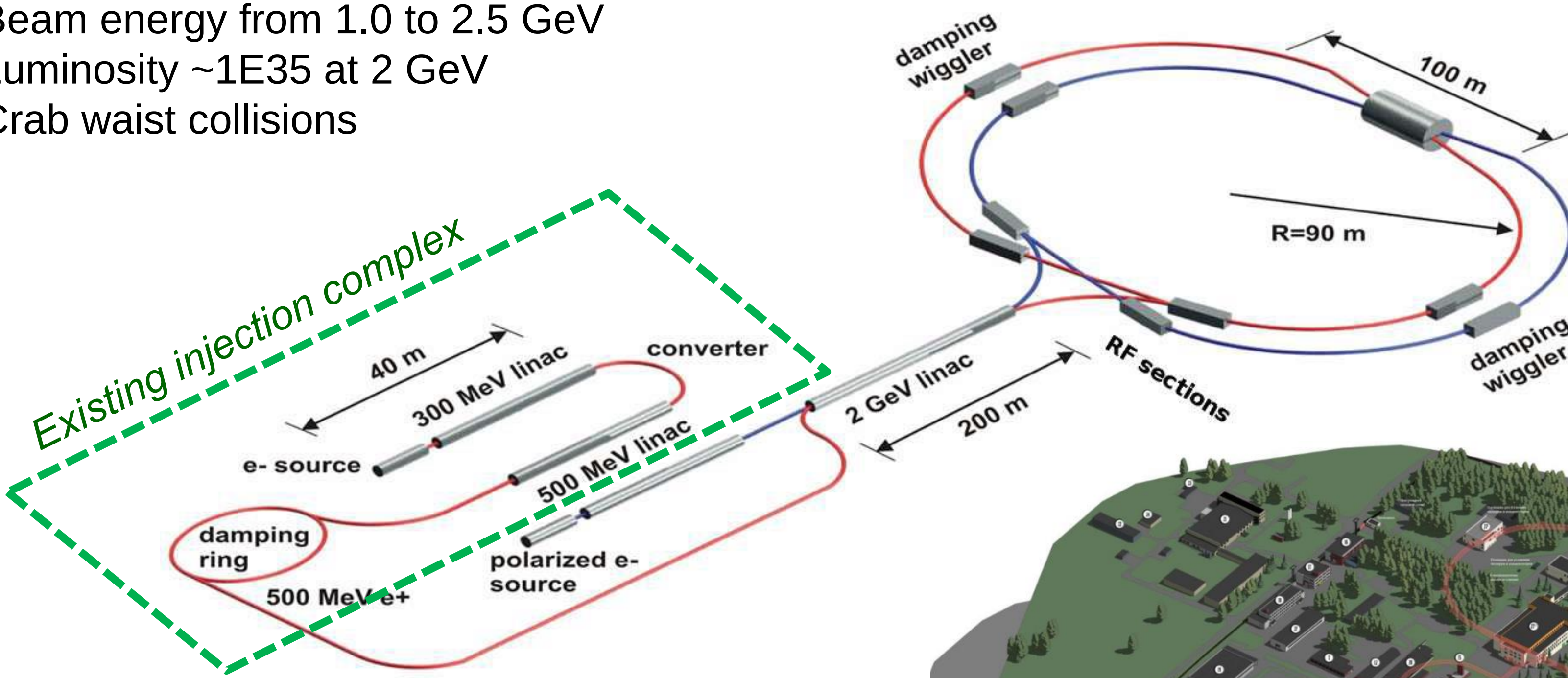
# SuperKEKB status




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

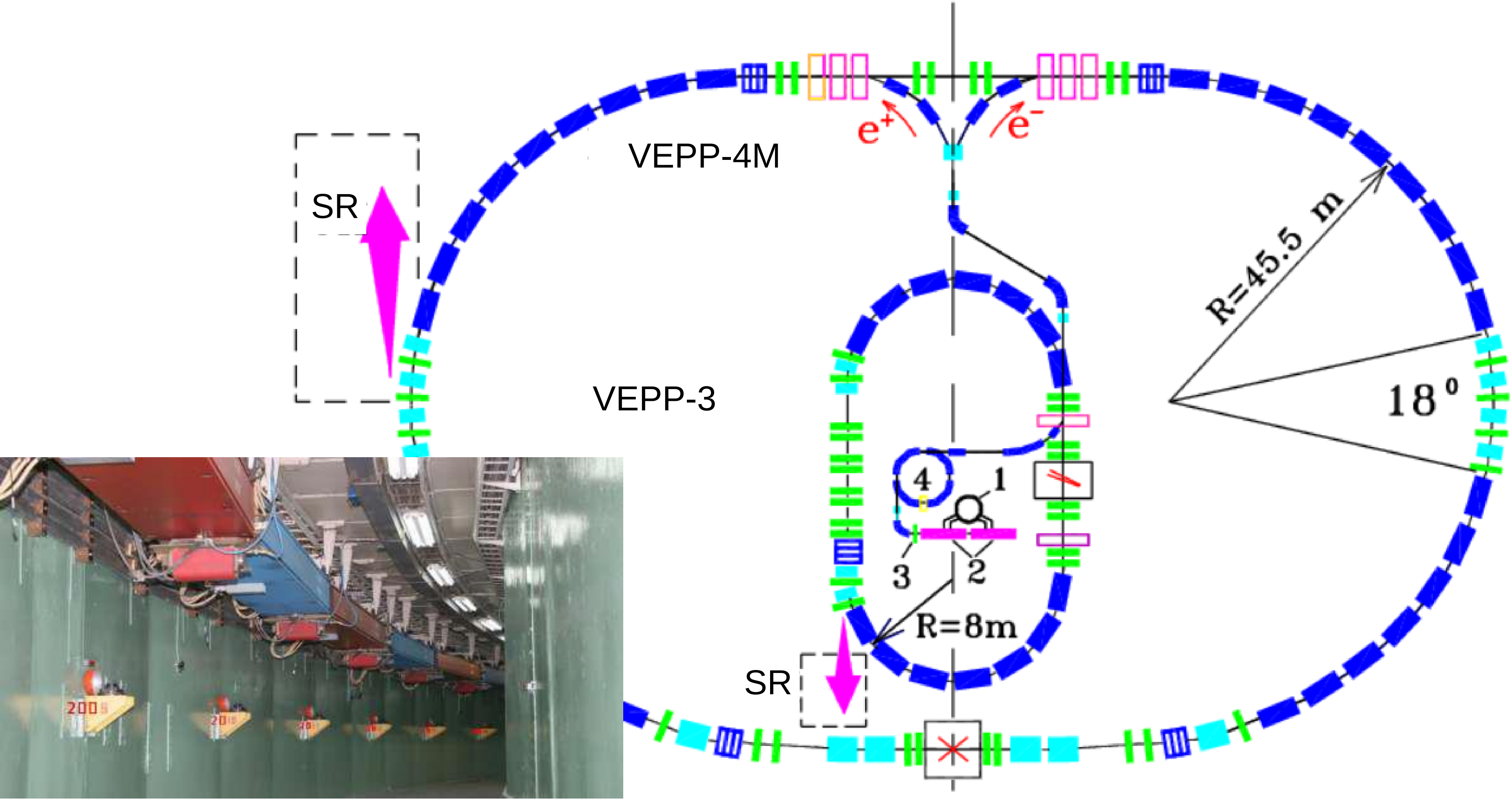
Beam energy from 1.0 to 2.5 GeV
Luminosity ~1E35 at 2 GeV
Crab waist collisions




**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

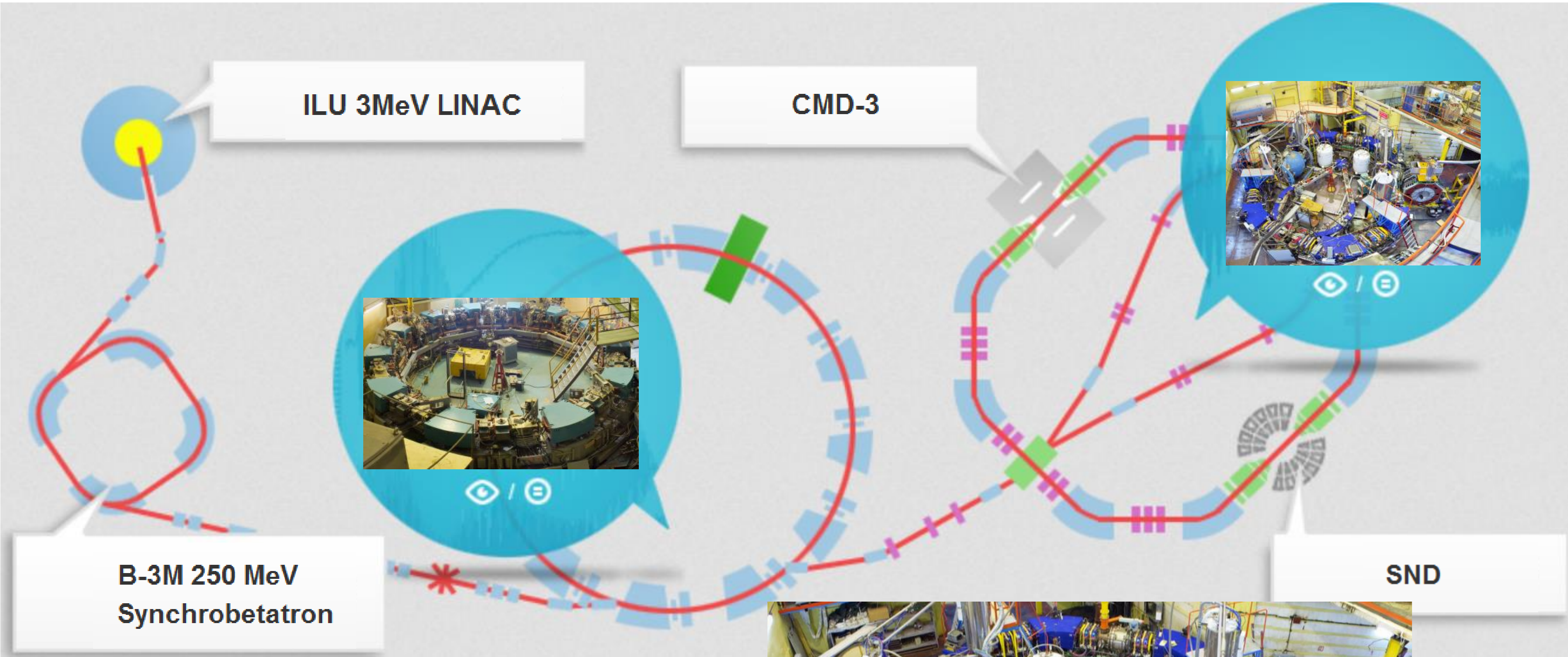
# BINP colliders: VEPP-4M

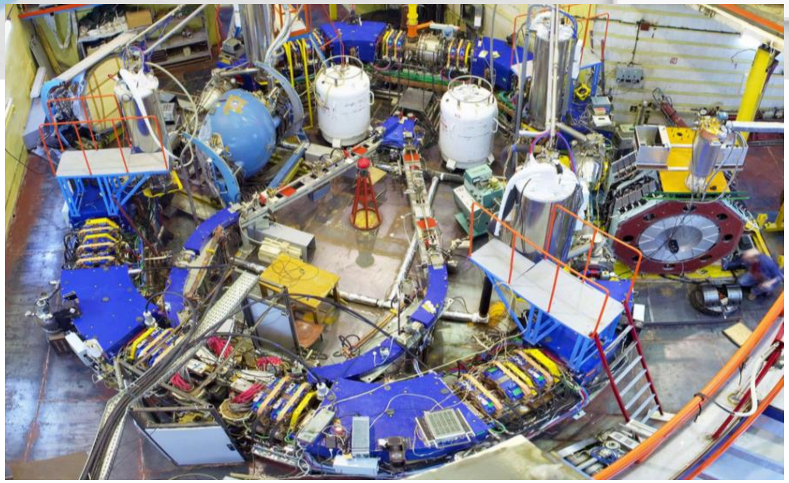



**Detector KEDR**

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

# BINP colliders: VEPP-2000



**VEPP-2000**
E = 1 GeV
Round beams
Two detectors

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  - eRHIC
  - Jlab e-ion
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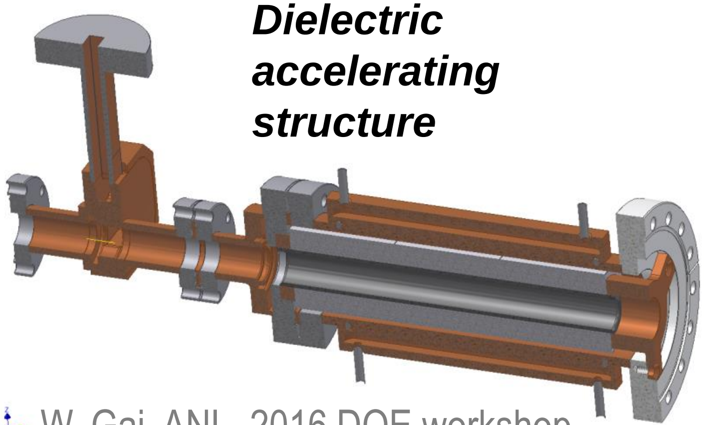
  - c-tau factory
- **Advanced approaches**
  - **LPWF & PWFA collider roadmaps & AWAKE**

# Advanced accelerator techniques

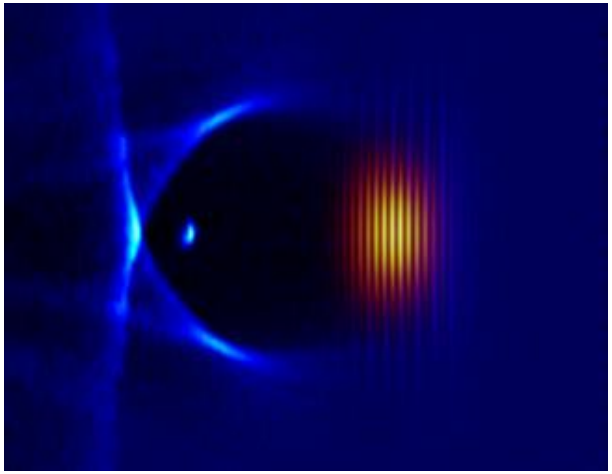
- **Many ideas are being developed for multi-TeV colliders with gradients >100 MeV/m, & lower capital & operating costs**
  - **Wakefield Acceleration using plasmas or dielectrics**
  - **Direct Laser Acceleration**
  - **Both particle beam (PWFA) and laser (LWFA) driven wakefield approaches are thought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

***Dielectric accelerating structure***



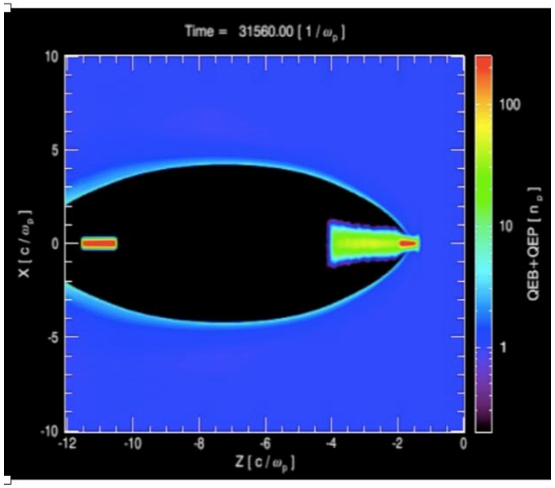
W. Gai, ANL, 2016 DOE workshop

***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*

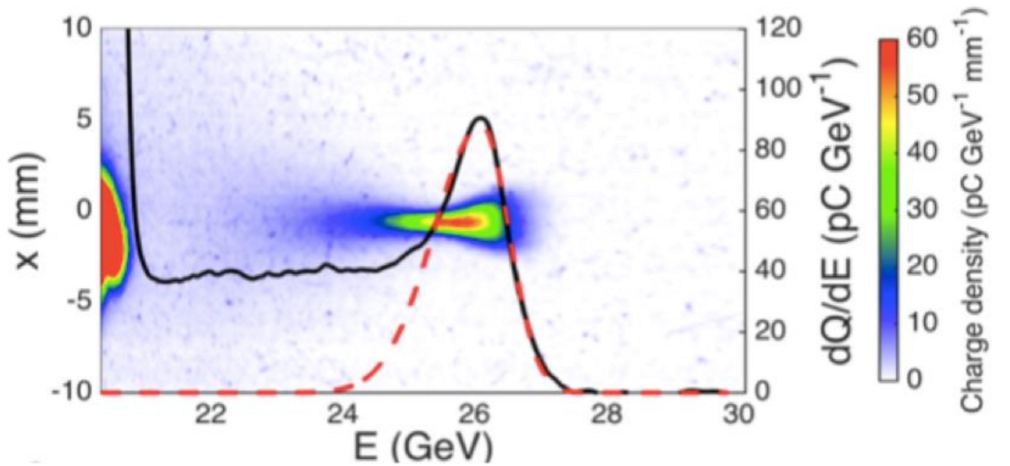
## And conquering them!

A highlight of **AAC-2016**

(Jul 31-Aug 5, 2016, Washington DC) –

**efficient plasma acceleration of positrons!**

*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*

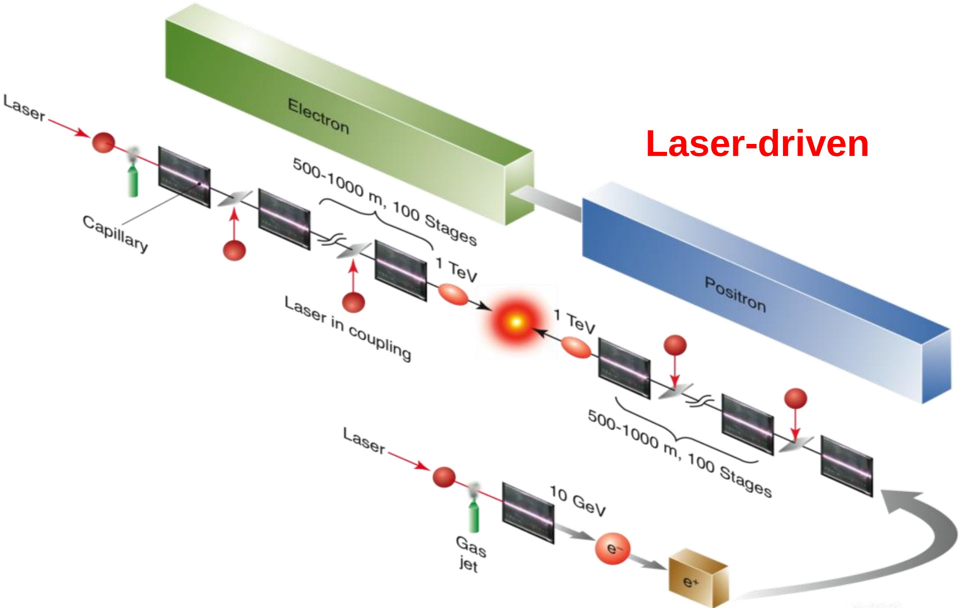



***e+ gaining 5 GeV in just 1.3 m of plasma***

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

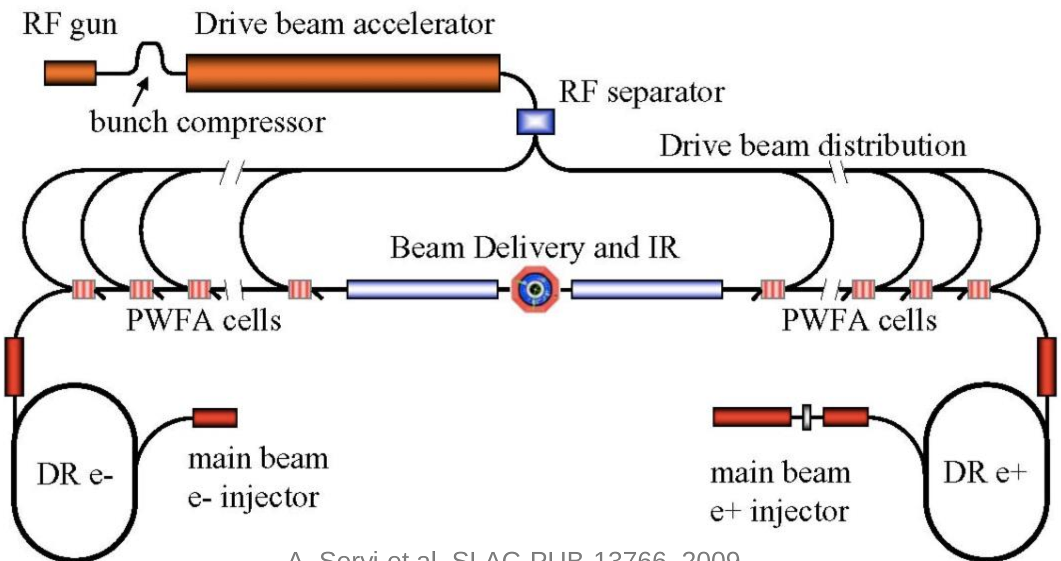
# Concepts of plasma acceleration based colliders

**Laser-driven**



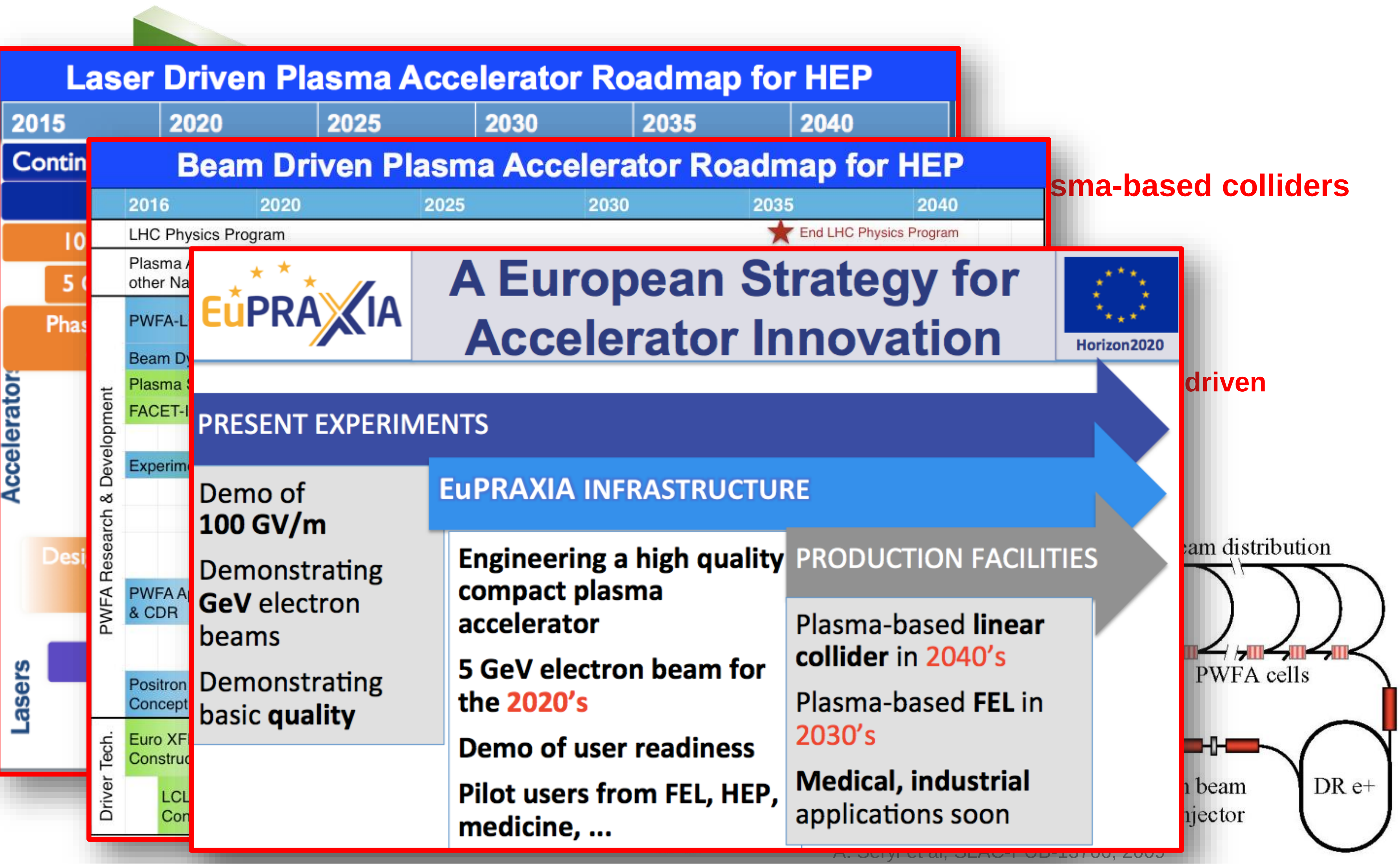

Esarey et al, Rev. Mod. Phys. (2009)

**Beam-driven**

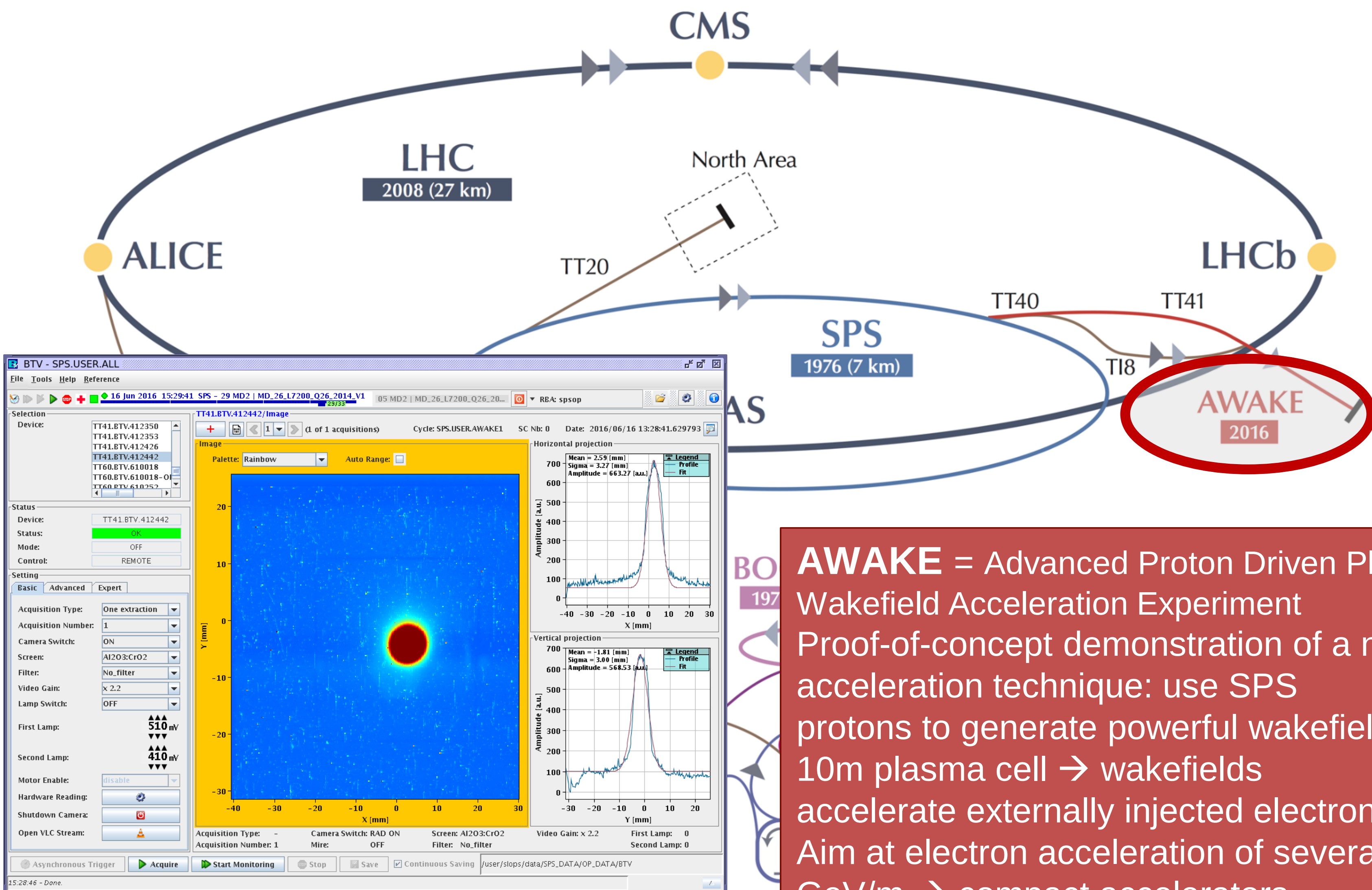



A. Seryi et al, SLAC-PUB-13766, 2009

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



# AWAKE: proton driven plasma acceleration

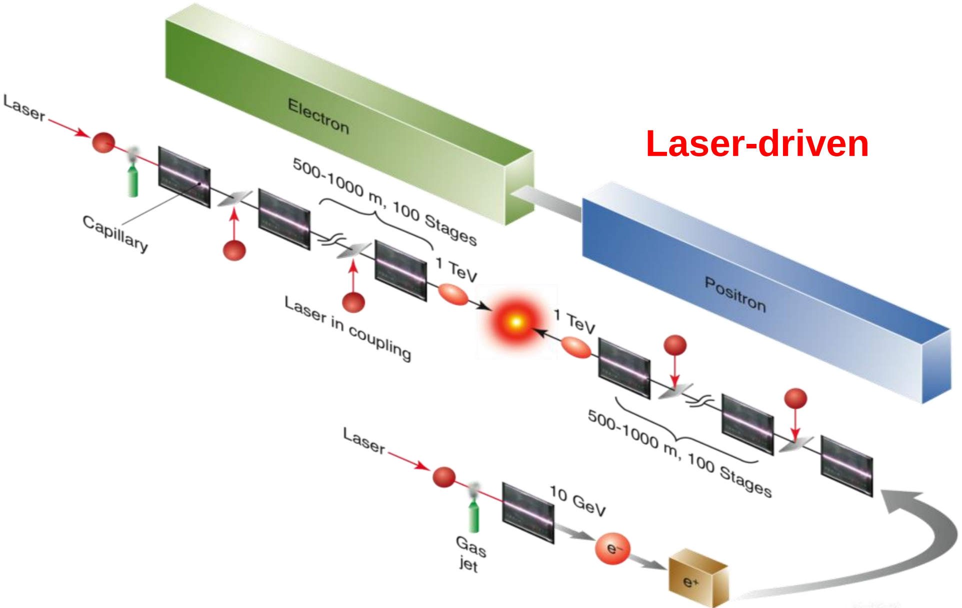



6 June 2016 – first p beam in AWAKE beamline

**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

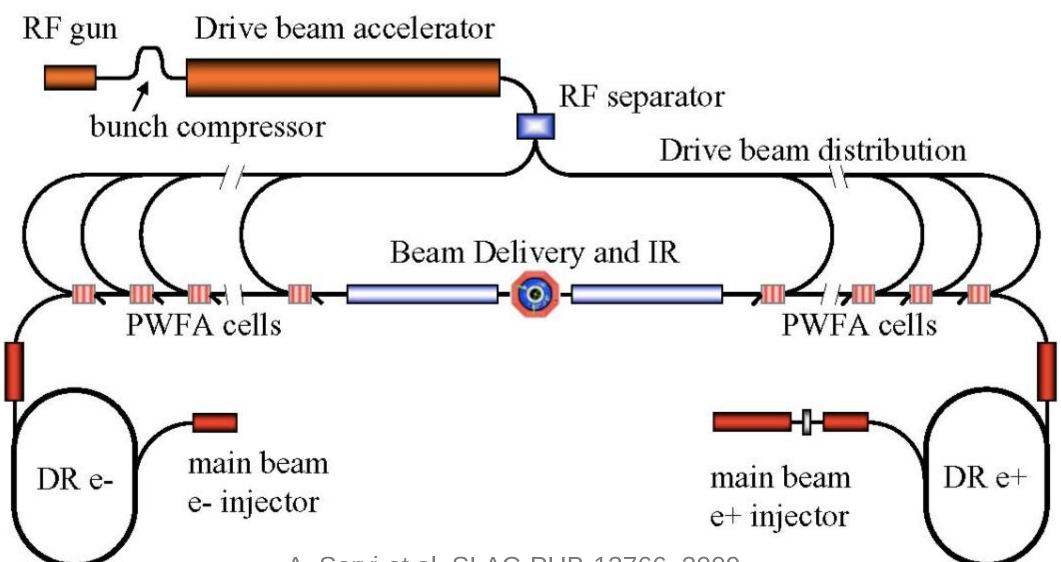
Laser-driven




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

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

Beam-driven

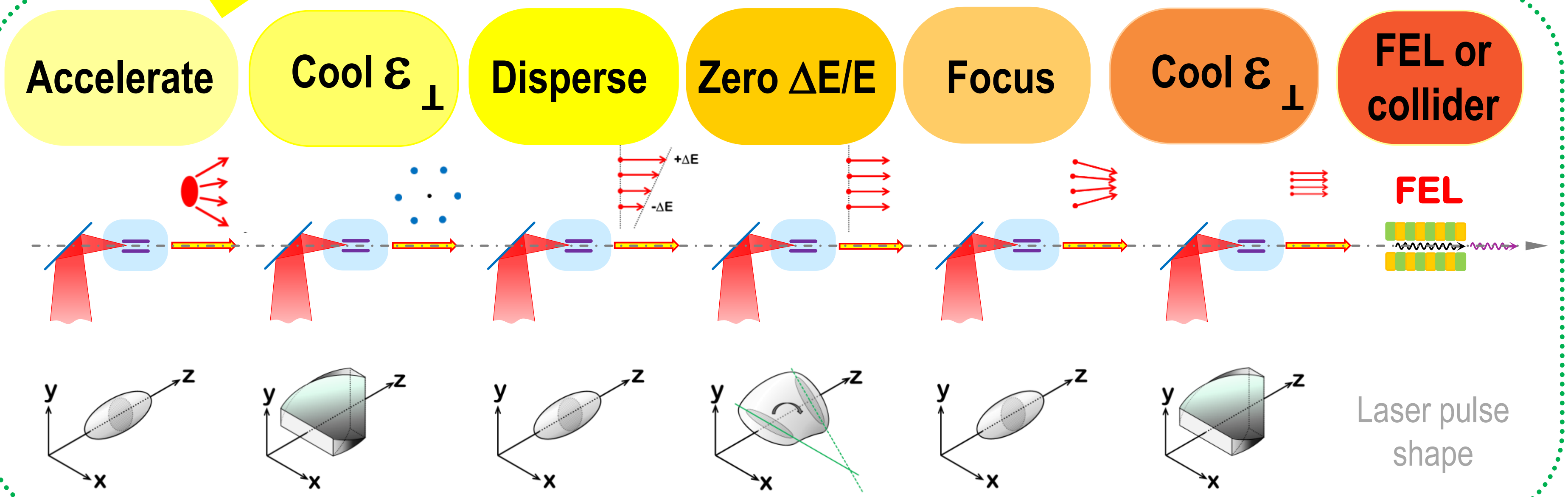


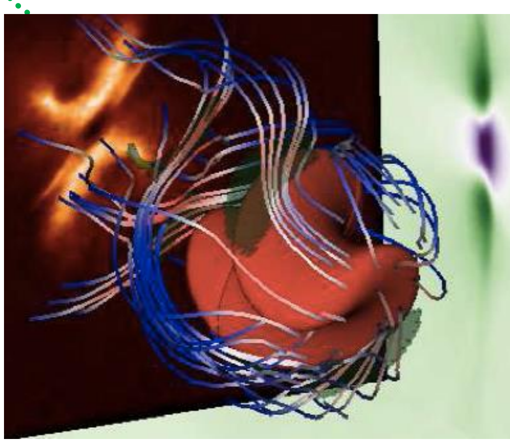

A. Seryi et al, SLAC-PUB-13766, 2009

**Can we cool the emittance between plasma acceleration stages?**

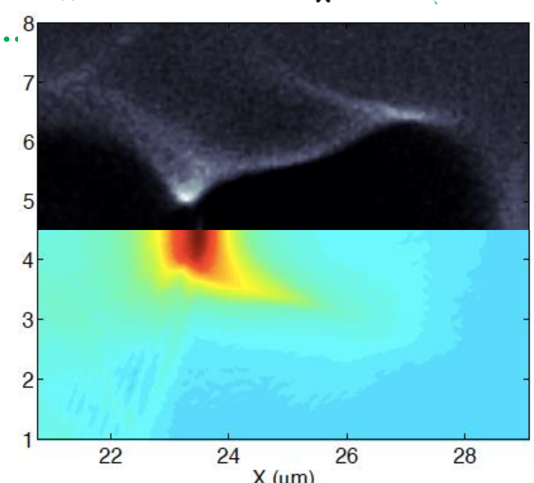
NEW!

# Laser-plasma stage with ε cooling



Screw-shaped laser pulse and trajectories of electrons

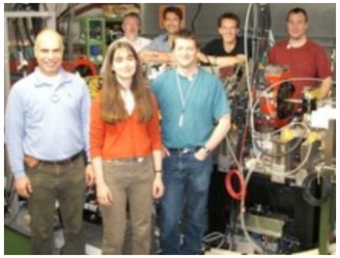
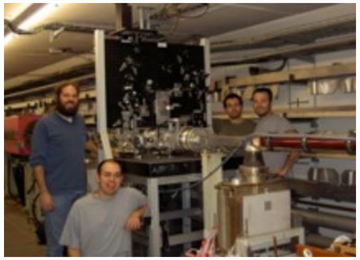
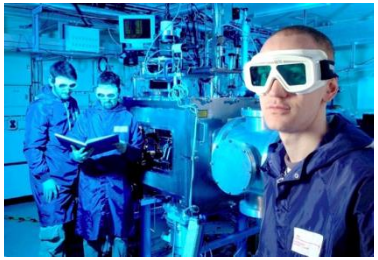



Bubble shape (top) and solenoidal field map (bottom)

**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)*

juas

John Adams Institute for Accelerator Science

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**