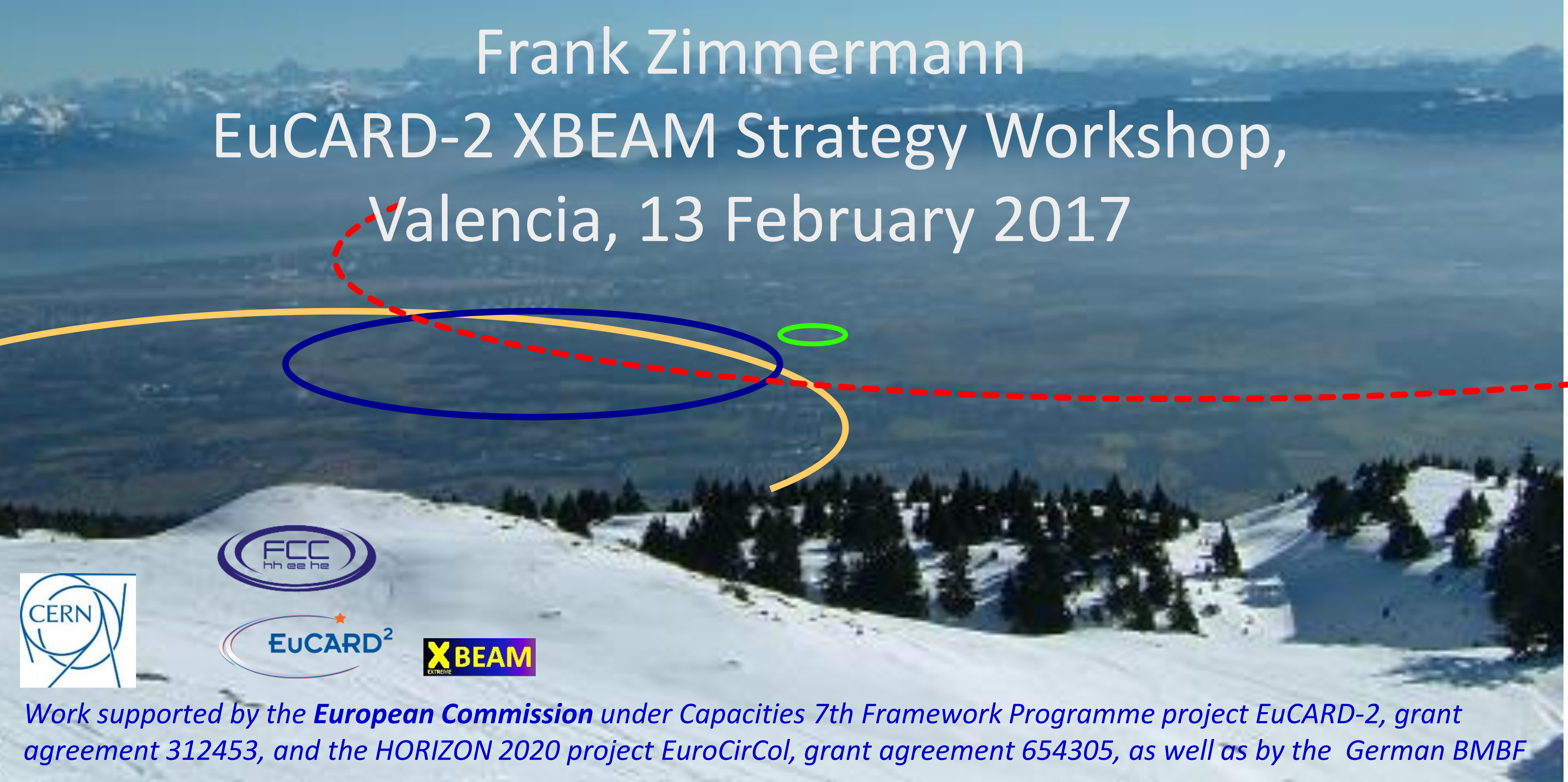
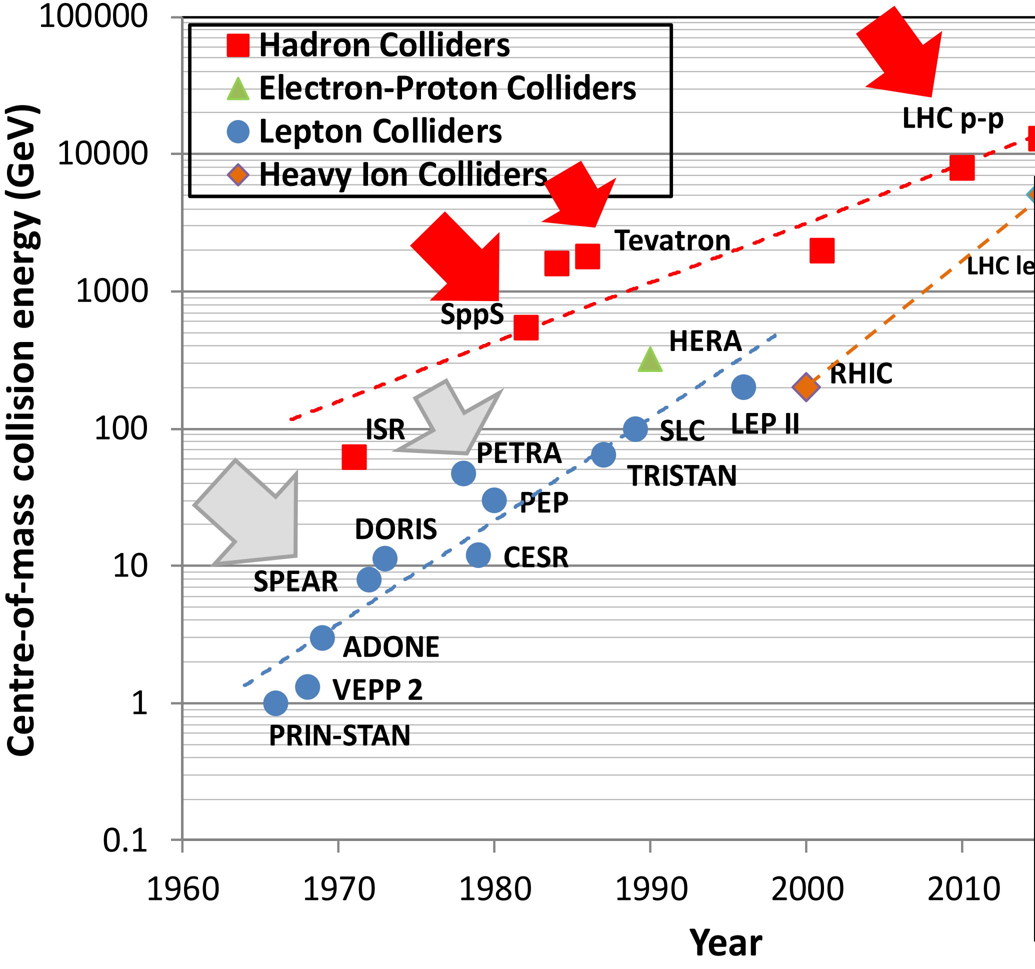


State of the Art and Efficiency for Hadron Colliders plus some Advanced Ideas

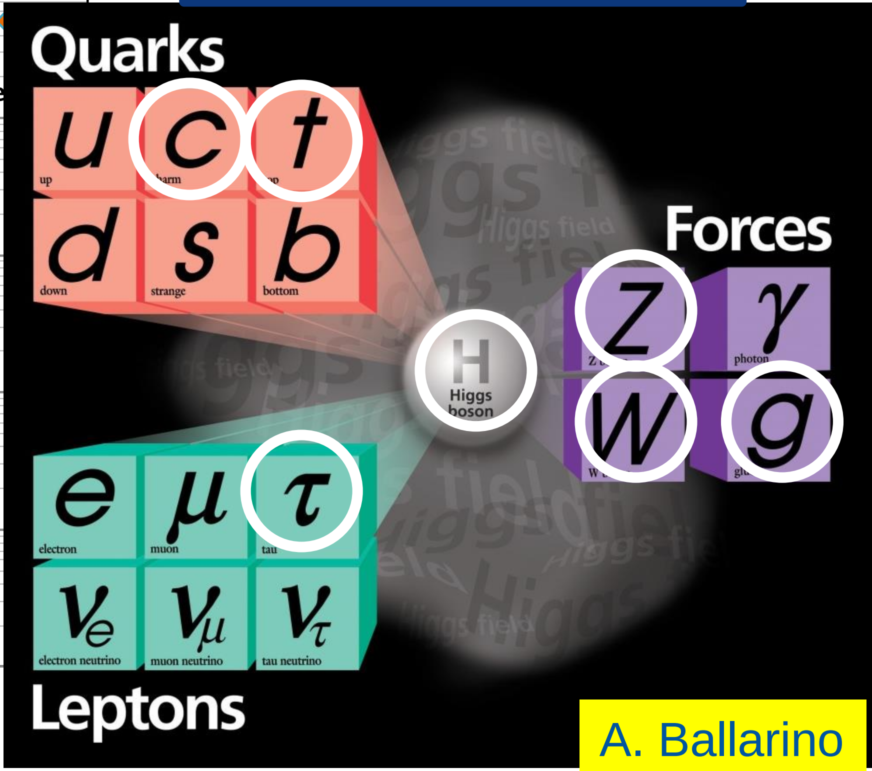
Frank Zimmermann
EuCARD-2 XBEAM Strategy Workshop,
Valencia, 13 February 2017

*Work supported by the **European Commission** under Capacities 7th Framework Programme project EuCARD-2, grant agreement 312453, and the HORIZON 2020 project EuroCirCol, grant agreement 654305, as well as by the German BMBF*

colliders and discoveries



Standard Model
Particles and forces



A. Ballarino

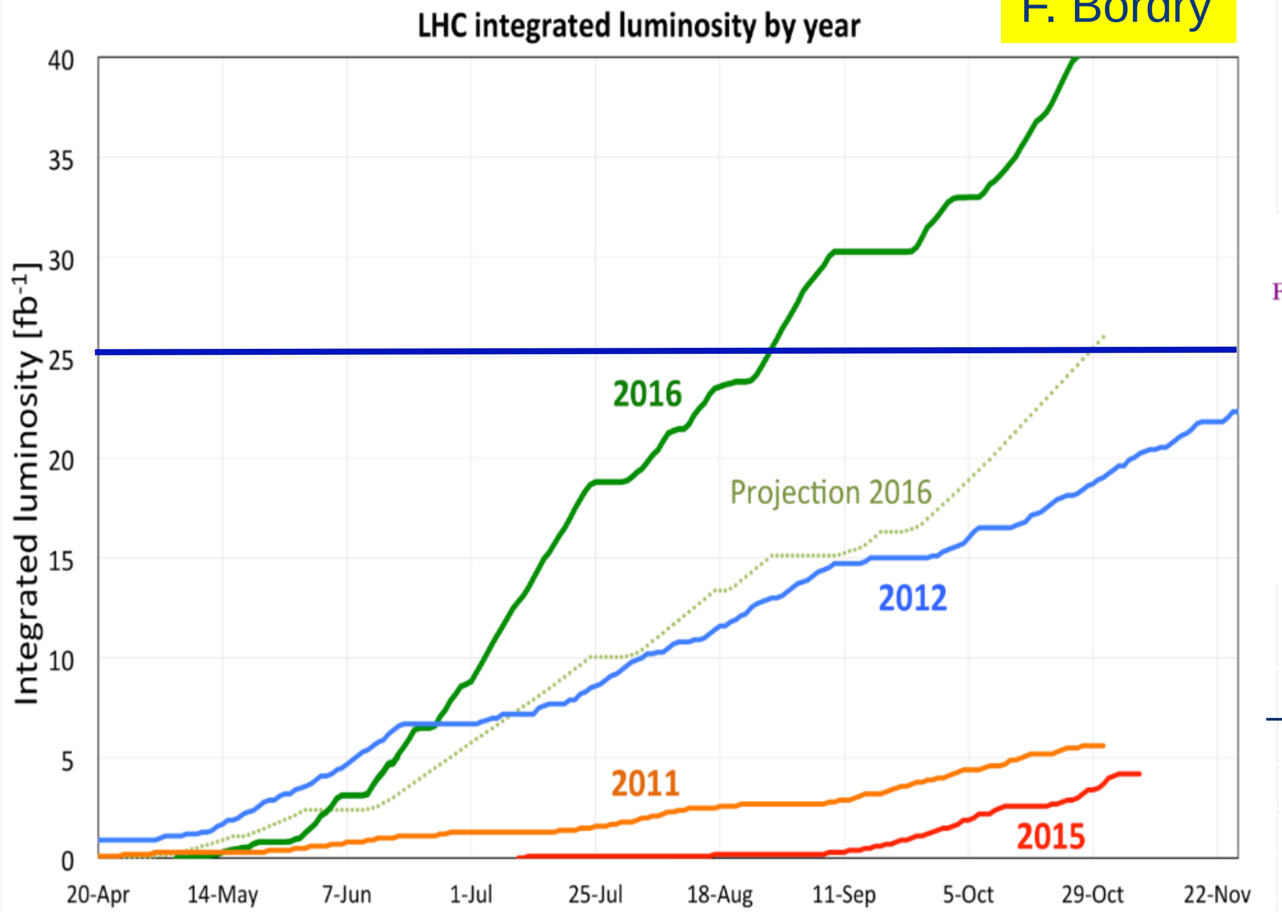
powerful instruments for discovery and precision measurement

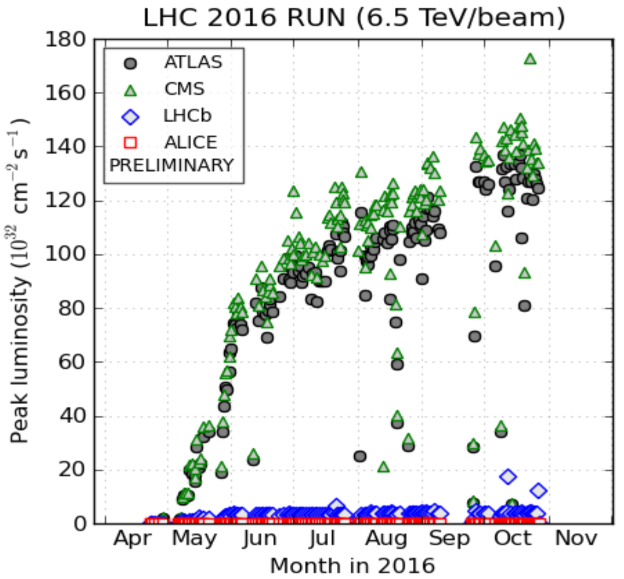
2016 LHC : production year

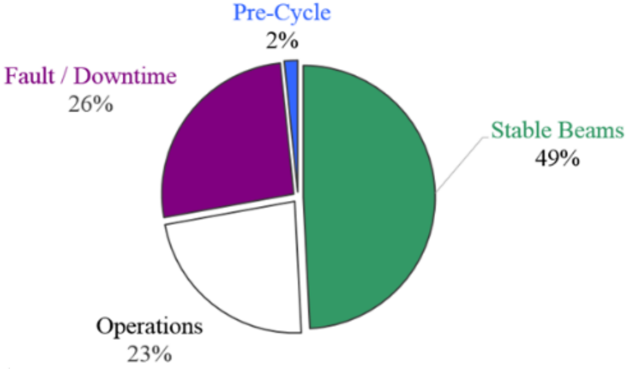
peak luminosity > 1.4 x 10^{34} cm^{-2}s^{-1}

OVER 25 fb^{-1} in both ATLAS and CMS

F. Bordry







≈153 days physics ≈3738.7 hours

	Duration [h]
Stable Beams	1839.5
Fault / Downtime	980.0
Operations	857.9
Pre-Cycle	61.3

TS1 - TS2 : stable beams 58 %

TS2 - TS3 : stable beams 54 %

energy frontier in the 21st century

- **very large circular hadron collider - only feasible approach to reach 100 TeV c.m. collision energy in coming decades**
- **access to new particles (direct production) in few-TeV to 30 TeV mass range, far beyond LHC reach**
- **much-increased rates for phenomena in sub-TeV mass range → much increased precision w.r.t. LHC**

M. Mangano

hadron collider energy reach

$$\boxed{E \propto B_{dipole} \times \rho_{bending}}$$

Cf. LHC: factor ~4 in radius, factor ~2 in field → O(10) in E_{cms}

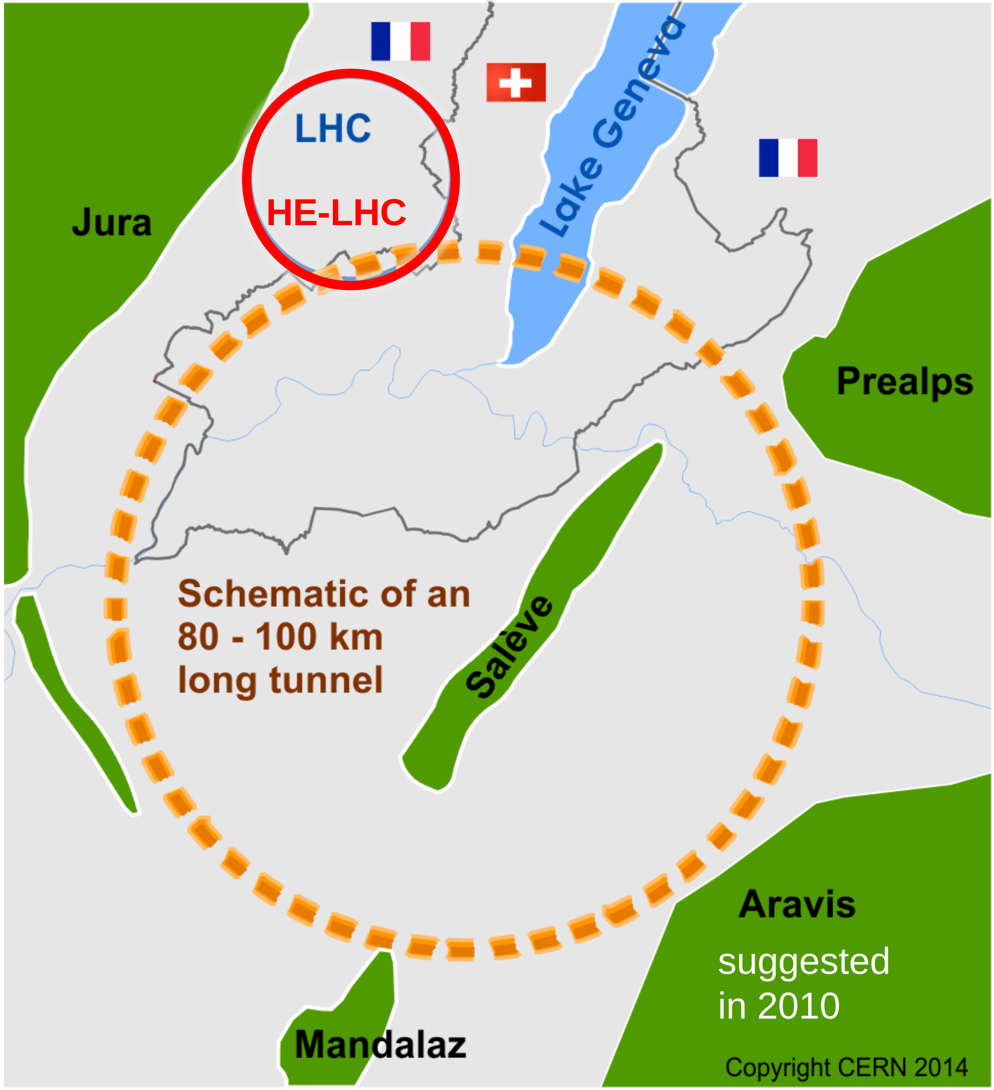
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



CepC/SppC study (CAS-IHEP) 100 km (new baseline!) , e^+e^- collisions ~2028; *pp* collisions ~2042

easy access
300 km east
from Beijing
3 h by car
1 h by train

Yifang Wang

"Chinese Toscana"


天下第一關

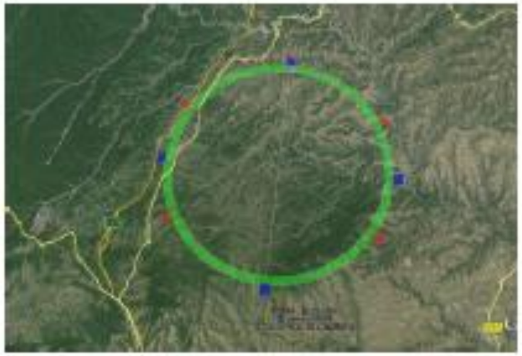

海港区百佳小额贷款有限公司
Haigang District Baijia Petty Loan CO.,LTD
中国农业银行


TSINGTAO
青島啤酒
原浆
生啤酒原液
ORIGINAL BEER
酿酒师才能喝到的啤酒
净含量:5L
TSINGTAO
青島啤酒
原浆
生啤酒原液
ORIGINAL BEER
酿酒师才能喝到的啤酒

near proposed construction site and vinyards – bilingual beach resort (Chinese-Russian)

… Geneva beach for comparison

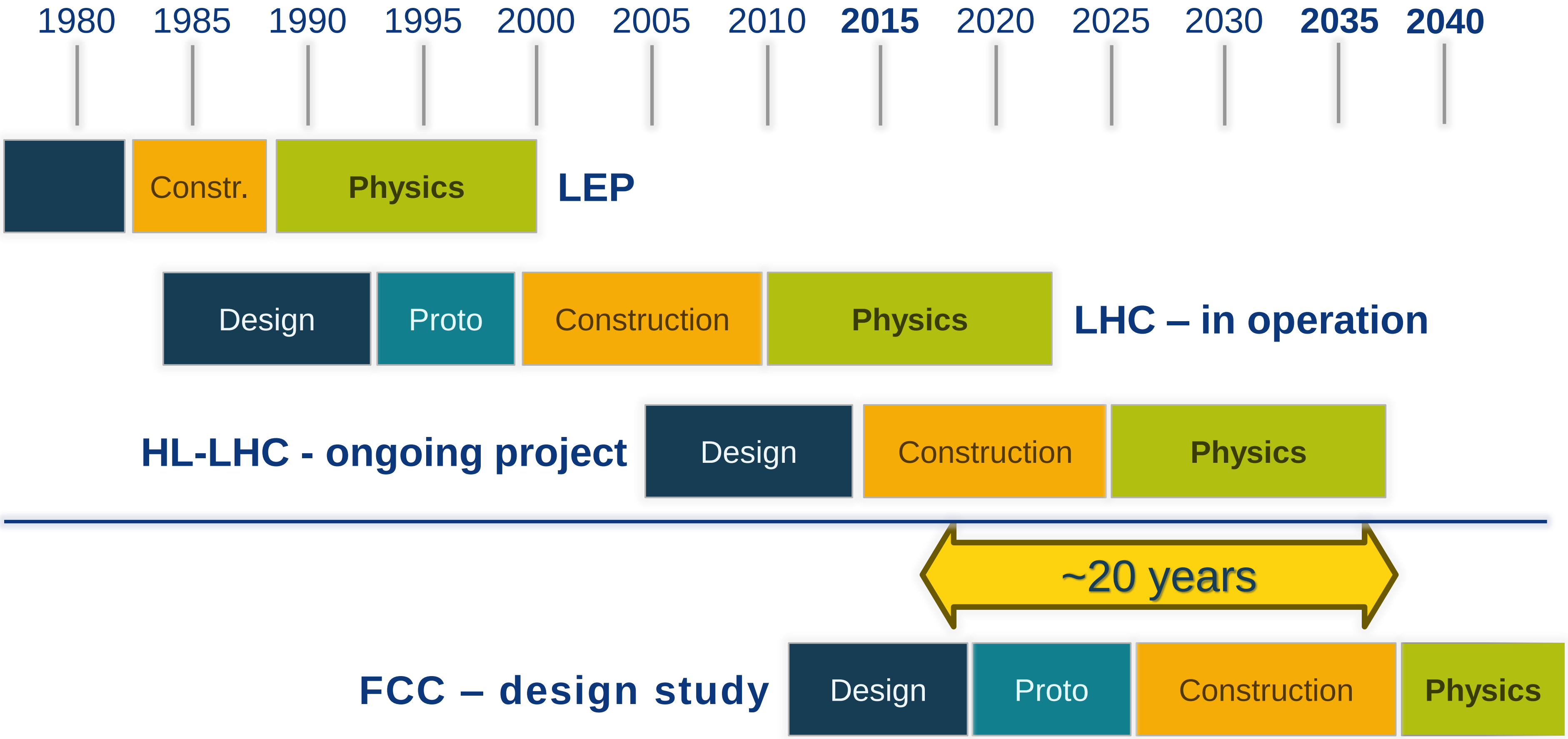
alternative CEPC sites



1) Qinhuangdao
   (site technical exloring done)
2) Shanxi Province
   (under site technical exploring, started from Jan. 2017)
3) Near Shenzhen and Hongkong
   (site technical exloring done)

M. Koratzinos, HongKong

CERN Circular Colliders & FCC



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035** **2040**

Constr. | **Physics** | **LEP**

Design | Proto | Construction | **Physics** | **LHC – in operation**

HL-LHC - ongoing project | Design | Construction | **Physics**

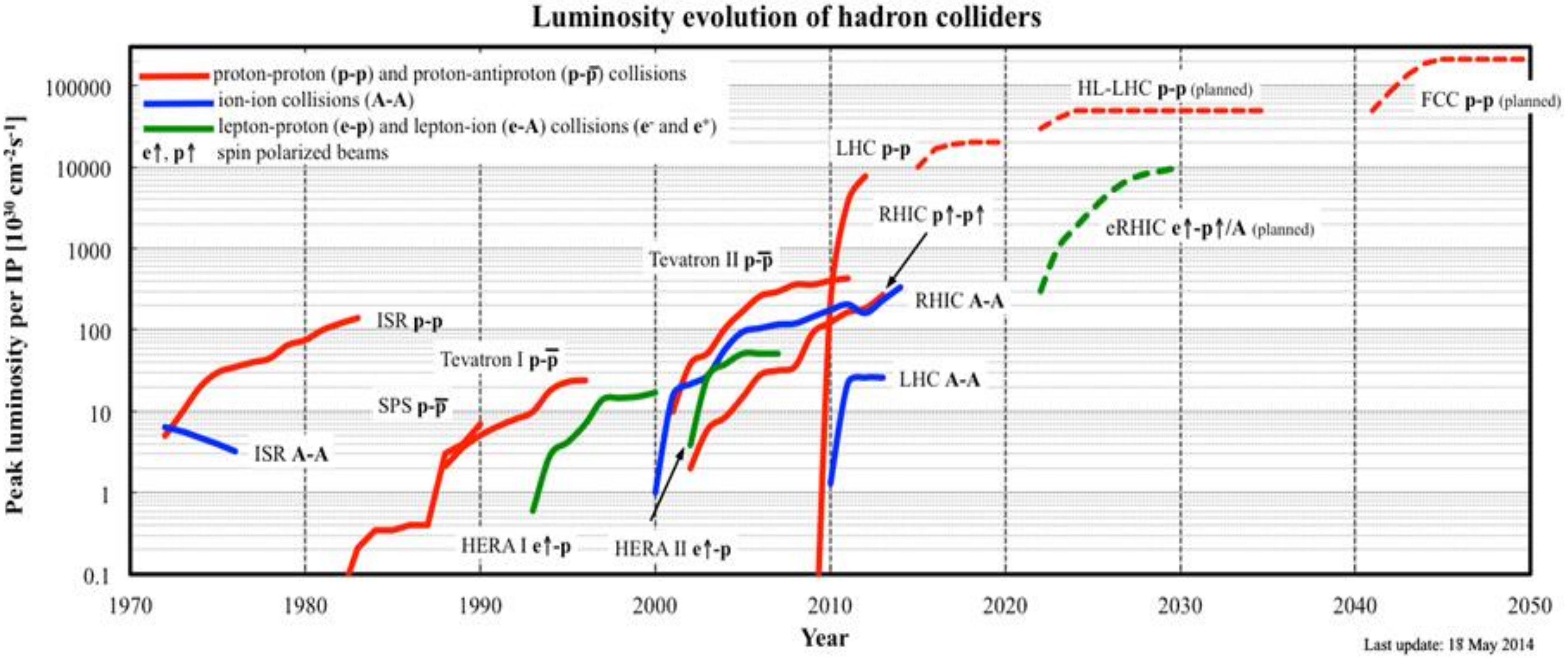
~20 years

FCC – design study | Design | Proto | Construction | **Physics**

must advance fast now to be ready for the period 2035 – 2040

milestone: CDR by end 2018 for next update of European Strategy

hadron collider history



hadron collider peak luminosity as a function of year – for past, operating, and proposed facilities [courtesy W. Fischer]

FCC-hh peak luminosity with constraints

synchrotron radiation power / beam:

$$\boxed{P_{SR} = n_b N_b \frac{c C_{\gamma p} E^4}{\rho C}}$$

limited

$$C_{\gamma p} \equiv \frac{4\pi}{3} \frac{r_p}{\left(m_p c^2\right)^3}$$

total beam-beam tune shift

$$\boxed{\xi = \frac{n_{IP} r_p N_b}{4\pi \varepsilon_N}}$$

maximum acceptable

ρ: bending radius

C: circumference

n_b: #bunches/beam

N_b: #p/bunch

E: beam energy

r_p: class. proton radius

luminosity

$$L = \frac{c}{C} \frac{\gamma n_b N_b^2}{4\pi \beta^* \varepsilon_N}$$

luminosity formula for SR-power and tune-shift limited hadron collider

$$\boxed{L = C_{lum} \frac{P_{SR} \rho \xi}{\beta^* E^3 n_{IP}}}$$

with

$$C_{lum} \equiv \frac{3\left(m_p c^2\right)^2}{4\pi r_p^2} \approx 10^{29} \frac{\mathrm{TeV}^2}{\mathrm{m}^2}$$

FCC-hh peak luminosity with other constraint

event
pile up / Xing

$$\boxed{\mu = \sigma_{\mathrm{inel}} \frac{\gamma N_b^2}{4\pi\beta^* \varepsilon_N}}$$

maximum acceptable

σ_{tot} [mbarn] ≈ 42.1*s* $^{-0.467}$-32.19 *s* $^{-0.540}$ +35.83 +0.315 ln^2(*s*/34); *s* in units of GeV^2

~112 mbarn at 14 TeV, ~156 mbarn at 100 TeV

σ_{inel} [mbarn] ≈ σ_{tot}-11.7 +1.59 ln *s* - 0.134 ln^{2}s

~83 mbarn at 14 TeV, ~110 mbarn at 100 TeV

luminosity $L = \frac{c}{C} \frac{\gamma n_b N_b^2}{4\pi\beta^* \varepsilon_N}$

luminosity formula for pile-up limited hadron collider

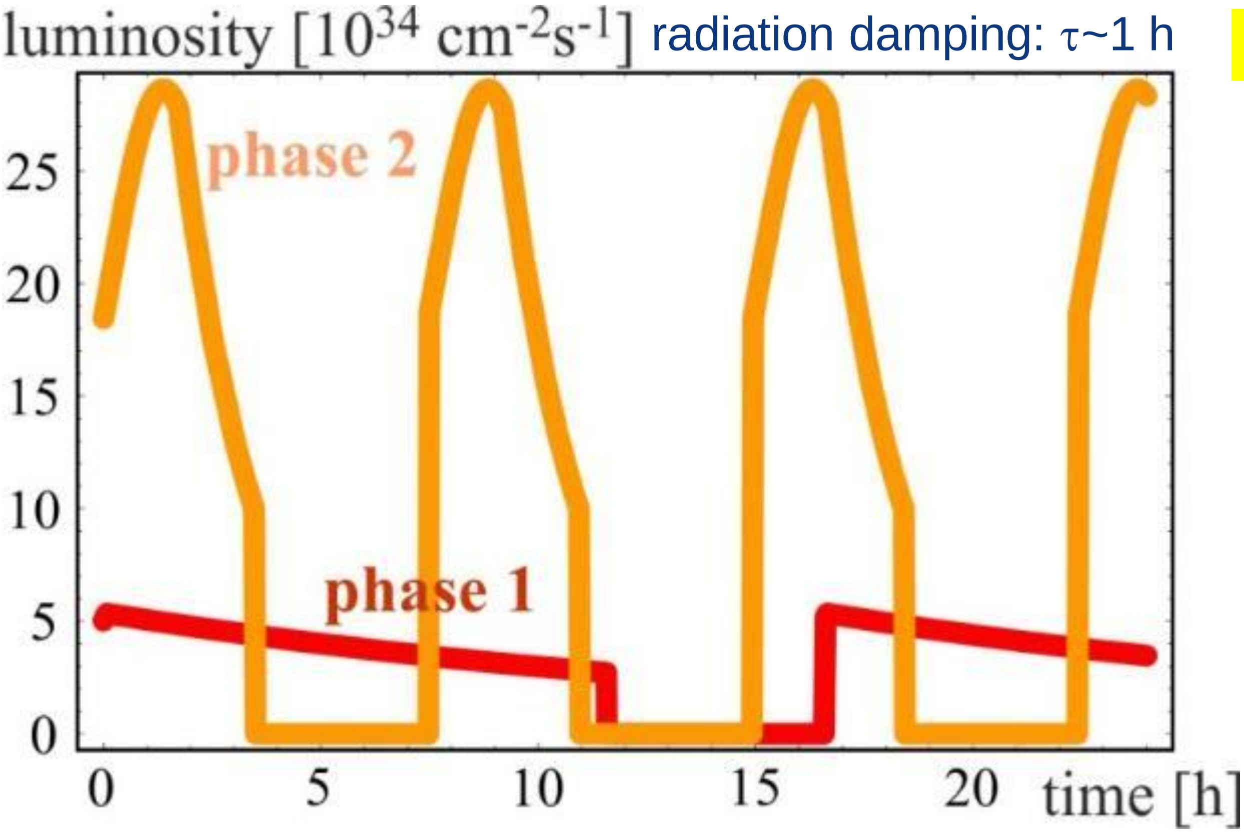
$$\boxed{L = f_{rev} \frac{n_b \mu}{\sigma_{\mathrm{inel}}}}$$

shorter bunch spacing could help?!
(e.g. 25→ 5 ns would increase n_b 5x!)

hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	**100**		**25**	14
dipole field [T]	**16**		**16**	8.3
circumference [km]	**100**		**27**	27
beam current [A]	**0.5**		**1.27**	(1.12) 0.58
bunch intensity [10^{11}]	**1 (0.2)**	**1 (0.2)**	**2.5**	(2.2) 1.15
bunch spacing [ns]	**25 (5)**	**25 (5)**	**25 (5)**	25
IP $\beta^*_{x,y}$ [m]	**1.1**	**0.3**	**0.25**	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	**30**	**34**	(5) 1
peak #events/bunch crossing	170	**1020** (204)	**1070** (214)	(135) 27
stored energy/beam [GJ]	**8.4**		**1.4**	(0.7) 0.36
synchrotron rad. [W/m/beam]	**30**		**4.1**	(0.35) 0.18
transv. emit. damping time [h]	**1.1**		**4.5**	25.8
initial proton burn off time [h]	17.0	**3.4**	**2.3**	(15) 40

luminosity evolution over 24 h



PRST-AB 18, 101002 (2015)

for both phases:

beam current 0.5 A, unchanged!

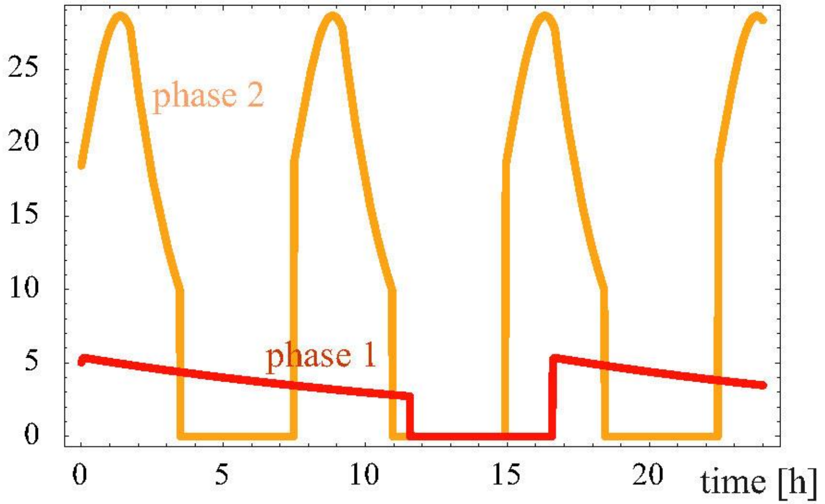
total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, $\xi_{tot}=0.01$, t_{ta}=5 h, 250 fb^{-1} / year

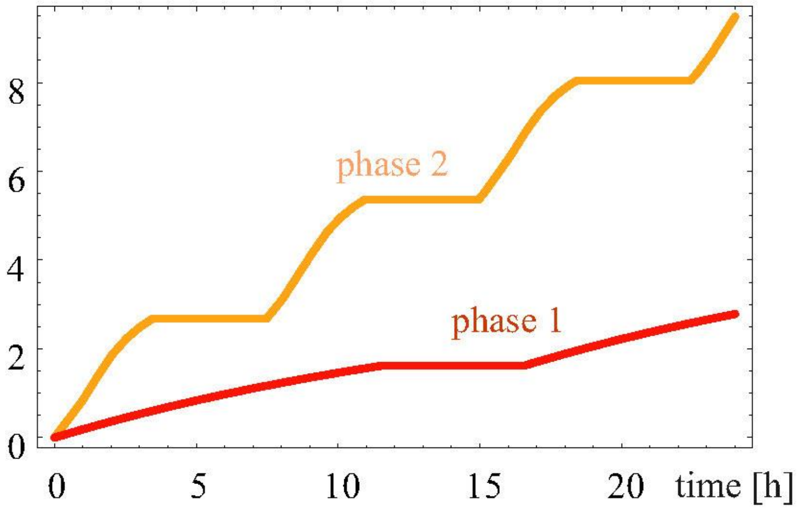
phase 2: β^*=0.3 m, $\xi_{tot}=0.03$, t_{ta}=4 h, 1000 fb^{-1} / year

FCC-hh - 100 TeV c.m., 25 ns

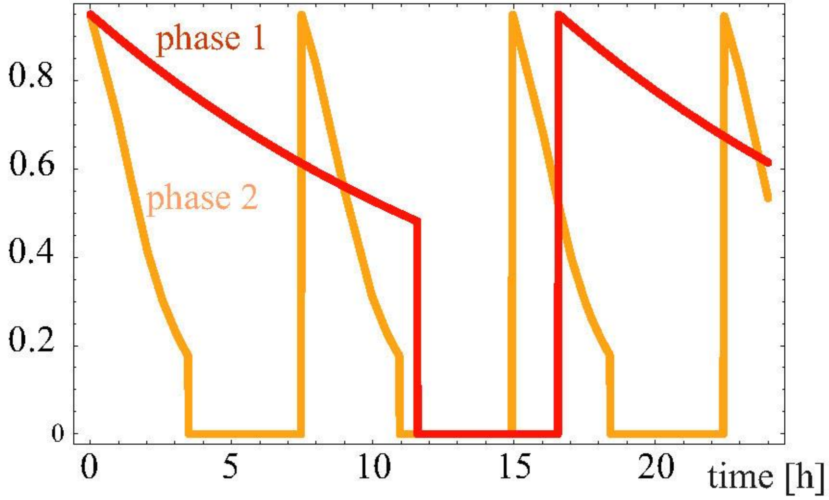
luminosity [10^{34} cm^{-2}s^{-1}]



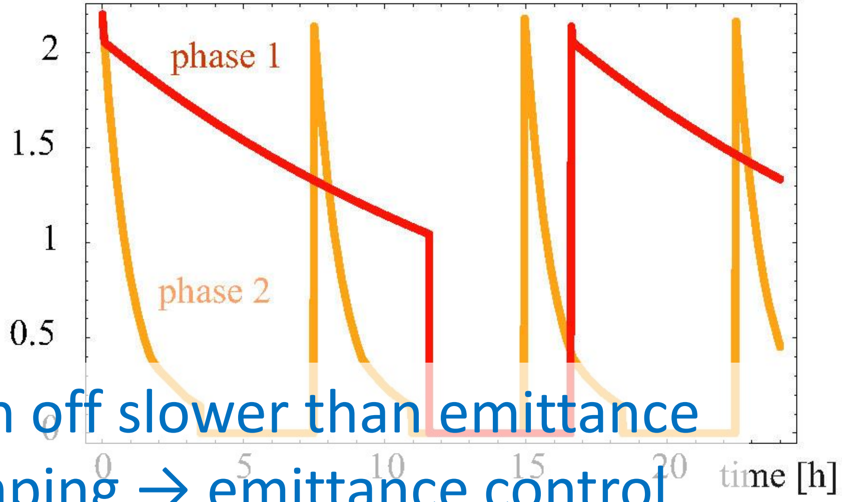
integrated luminosity [fb^{-1}]



bunch intensity [10^{11}]

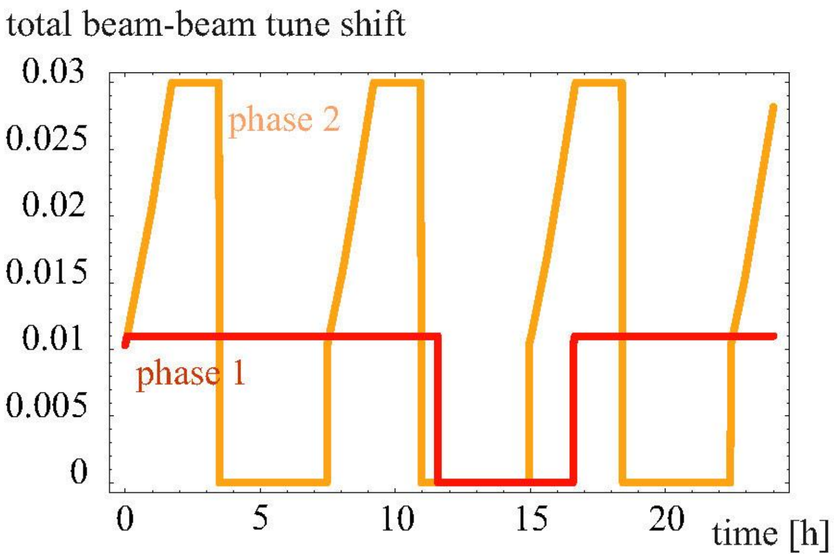


normalized rms emittance [μm]

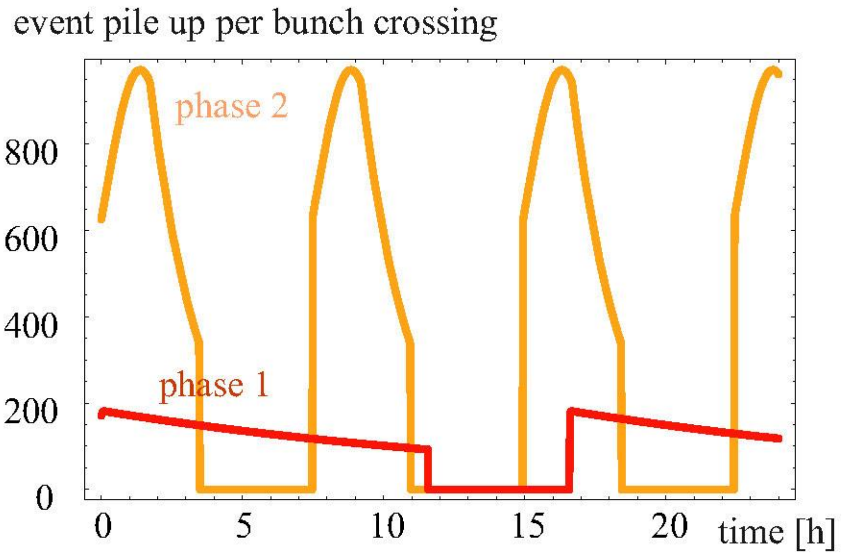


burn off slower than emittance damping → emittance control

FCC-hh - 100 TeV c.m., 25 ns



in phase 2, β^* 1.1→0.3 m,
without (or with less)
emittance control:
tune shift increases during fill
until reaching maximum of 0.03

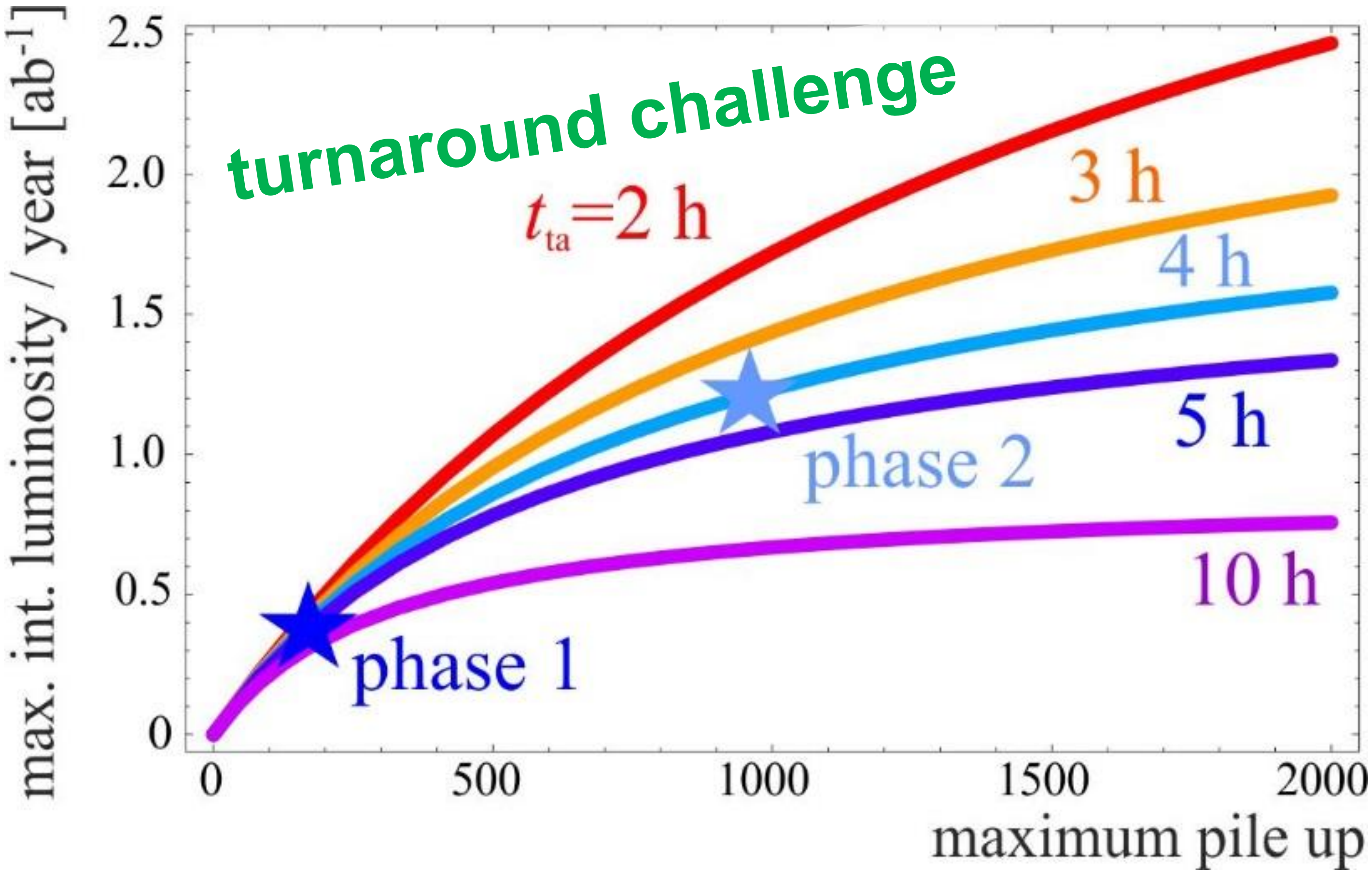


SPPC main parameters

Parameter	Unit	SPPC			FCC	
		PreCDR	"CDR"	"Ultimate"		
Circumference	km	54.4	100	100	100	
c.m. energy	TeV	70.6	75	125-150	100	
dipole field	T	20	12	20-24	16	
injection energy	TeV	2.1	2.1	4.2	3.3	
#IPs		2	2	2	2	
luminosity per IP	10^{35} cm^{-2}s^{-1}	1.2	1.0	-	0.5	3.0
IP beta function	m	0.75	0.75	-	1.1	0.3
beam current	A	1.0	0.7	-	0.5	
bunch separation	ns	25	25	-	25 (5)	25 (5)
bunch population	10^{11}	2.0	1.5	-	1.0 (0.2)	1.0 (0.2
SR power /beam	MW	2.1	1.1	-	2.5	
SR heat load/ap	W/m	45	13	-	30	

J. Tang

limits on integrated luminosity



asymptotic limit:

$$L_{\text{int}} \leq \frac{T_{\text{tot}} A N_{b,0}}{n_{IP} \sigma_{\text{tot}} t_{ta}}$$

T_{tot}: total time allocated for physics / year

case for availability

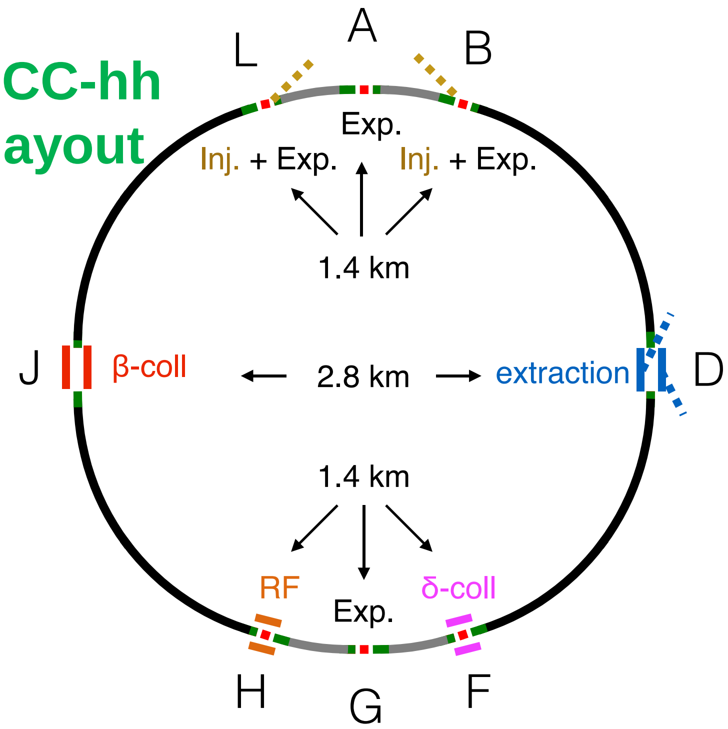
F.Z. et al, IPAC'16

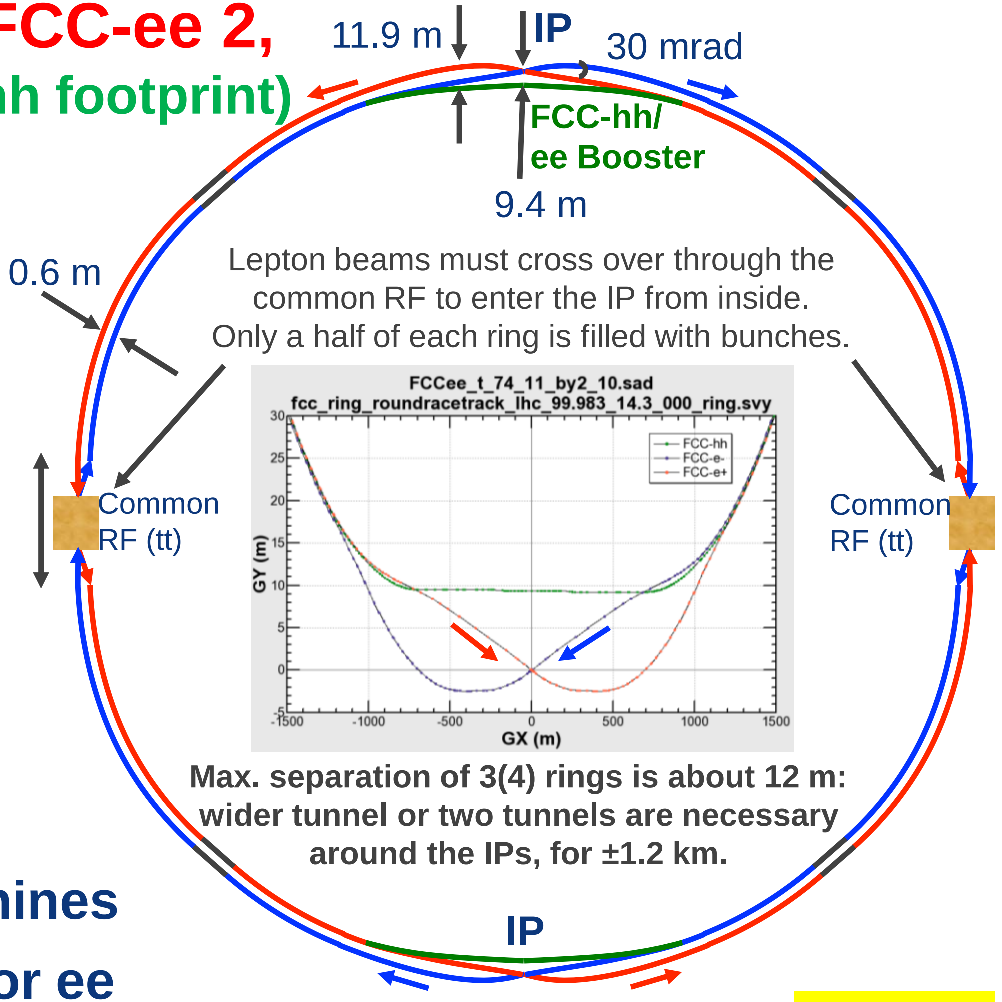
integrated luminosity per year vs maximum pile-up, assuming 160 days of physics run, a machine availability *A* of 71%, two primary collision points (n_{IP}=2), n_b=10600 bunches per beam, and a **maximum beam intensity of $N_{b,0}$=10^{15} protons**; curves for different av. turnaround times t_{ta}

common layouts for hh & ee

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

FCC-hh layout





Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

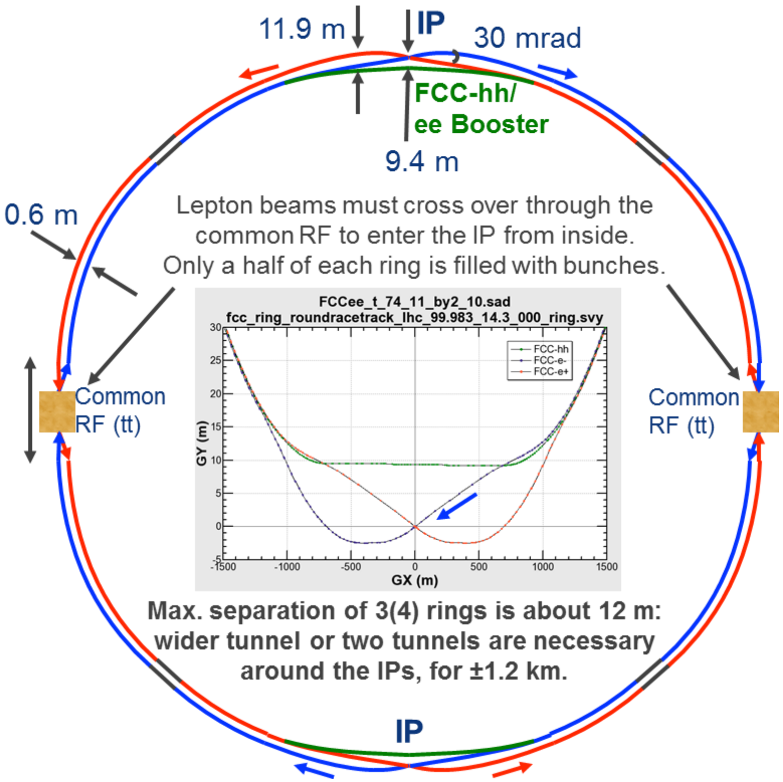
Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

K. Oide

FCC and CEPC convergence

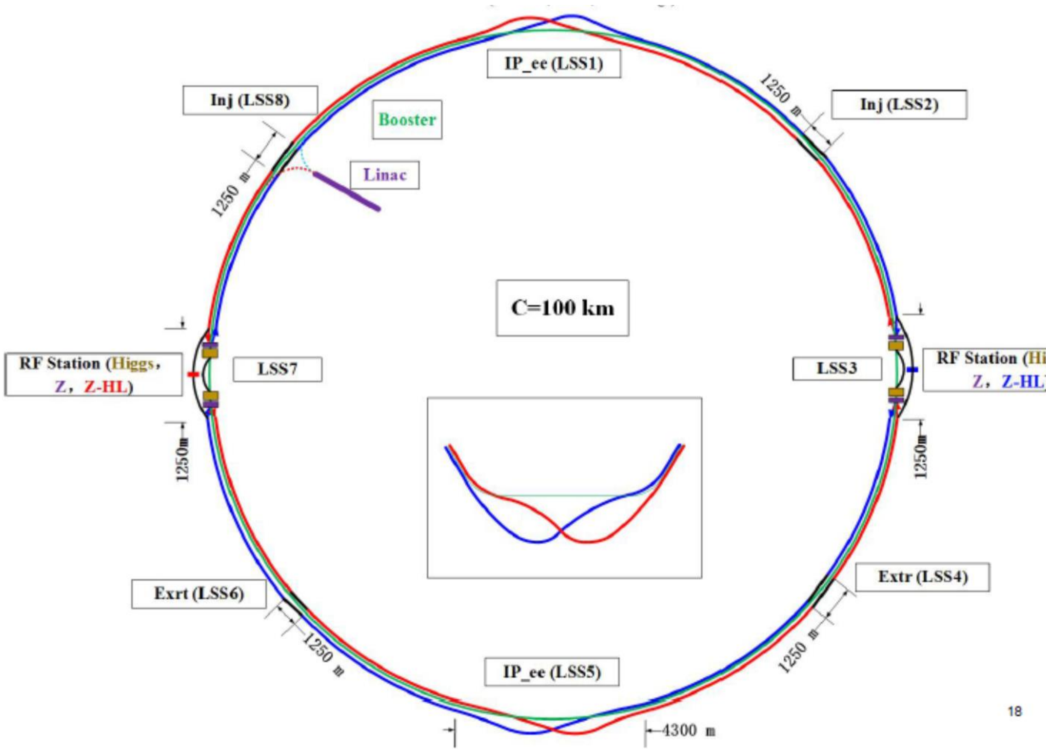
FCC-ee design, K. Oide, 2015



Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

CEPC design, J. Gao, 2017



intercepting synchrotron radiation: - beam screen

high synchrotron radiation load of proton beams @ 50 TeV:

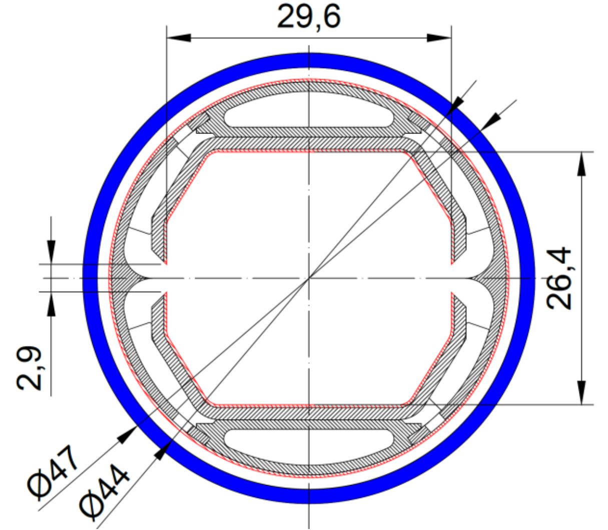
- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs (@1.9 K!)**

new beam screen with ante-chamber

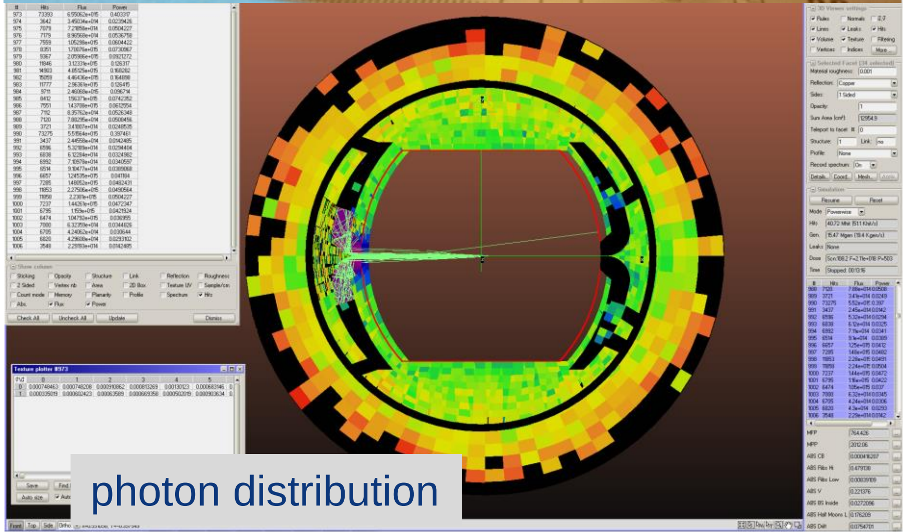
- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- factor 50! reduction of cryo power

FCC-hh beam screen prototypes

ready for Testing 2017 in ANKA within EuroCirCol study



simulation of quench behaviour



photon distribution

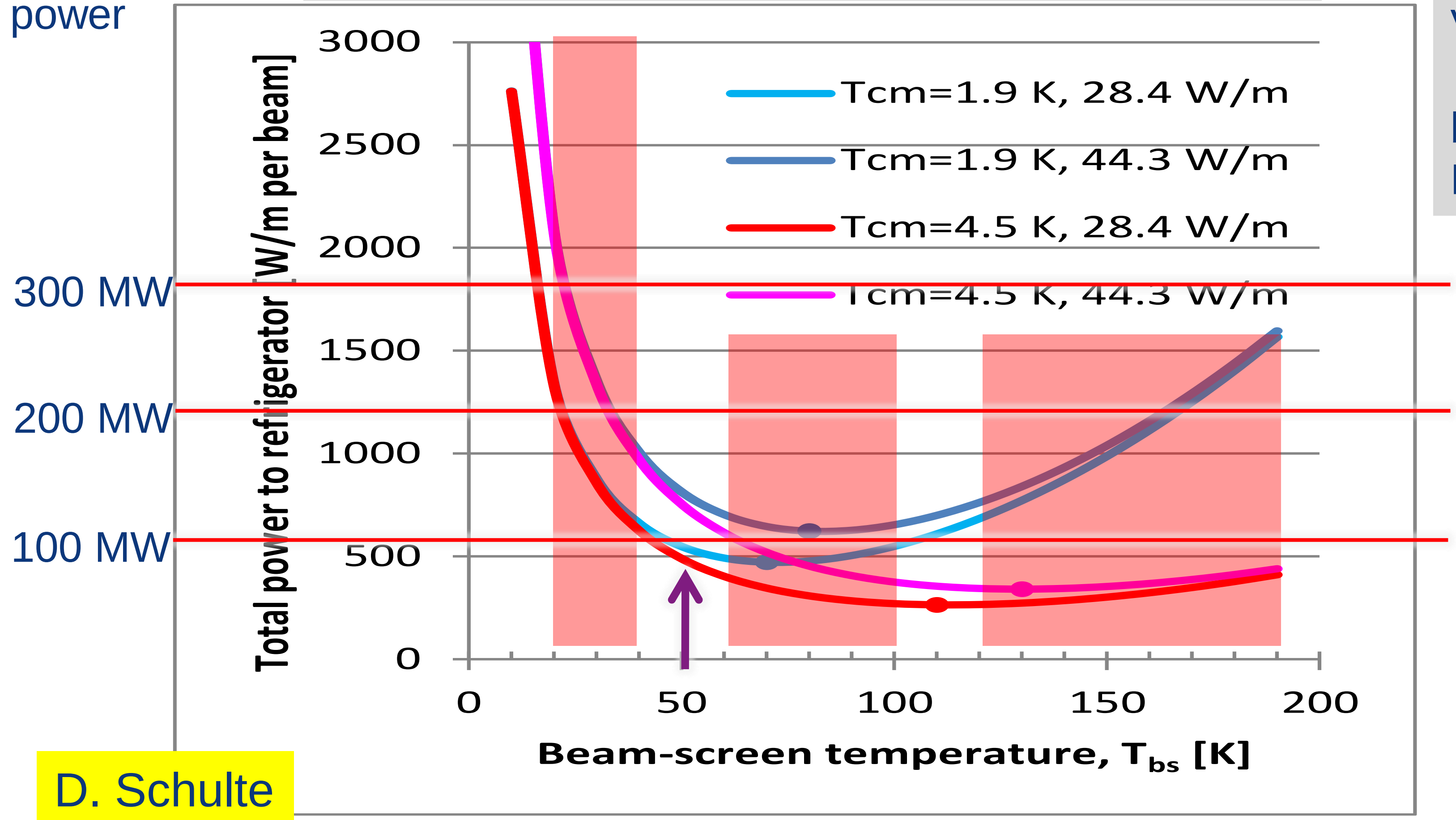
synchrotron radiation – cryopower & beam-screen temperature

50 K chosen for efficiency and beam stability; but for 4.5 K magnets can also consider 110 K

Ph. Lebrun
L. Tavian
V. Baglin

based on
LHC screen

total
cryo
power



D. Schulte

main SC magnet system FCC (16 T) vs LHC (8.3 T)

FCC

bore diameter: 50 mm

dipoles: $4578\ units, 14.3\ m\ long, 16\ T \Leftrightarrow \int Bdl{\sim}1\ MTm$

Stored energy ~ 200 GJ (GigaJoule) ~44 MJ/unit

quads: $762\ magnets,\ \ 6.6\ m\ long, 375\ T/m$

LHC

bore diameter: 56 mm

dipoles: $1232\ units, 14.3\ m\ long, 8.3\ T \Leftrightarrow \int Bdl{\sim}0.15\ MTm$

Stored energy ~ 9 GJ (GigaJoule) ~7 MJ/unit

quads: $392\ units,\ \ 3.15\ m\ long, 233\ T/m$

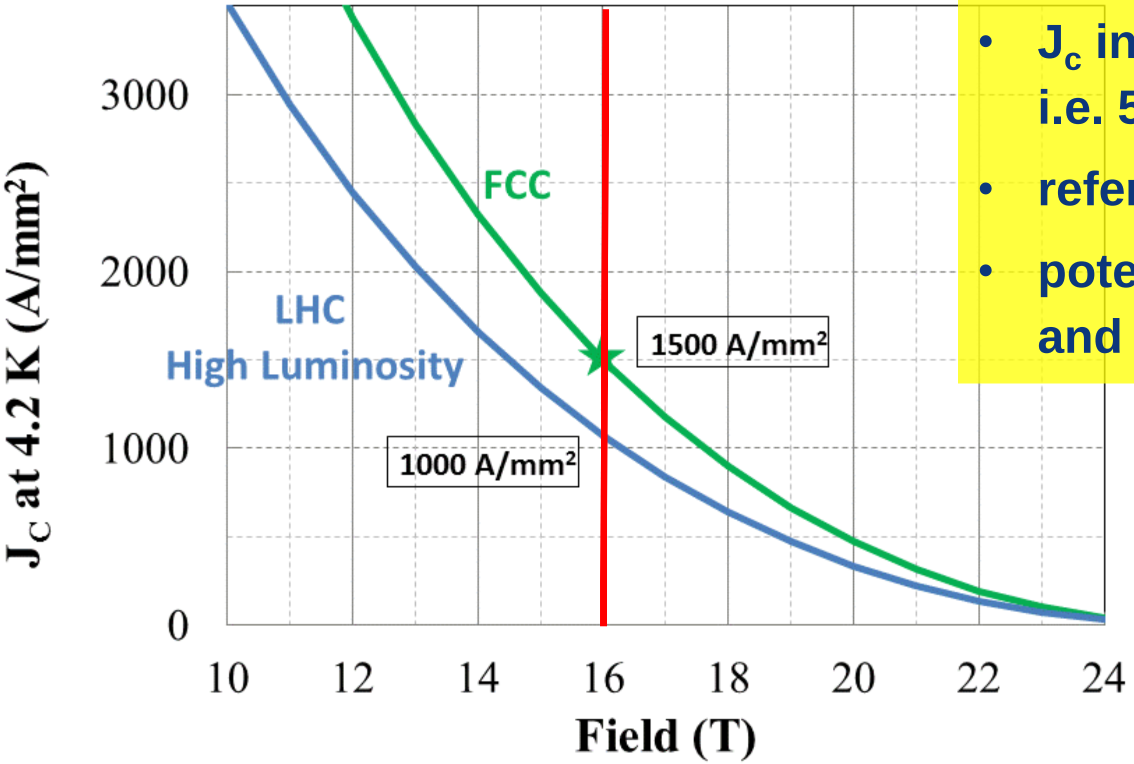
Nb_3Sn conductor program

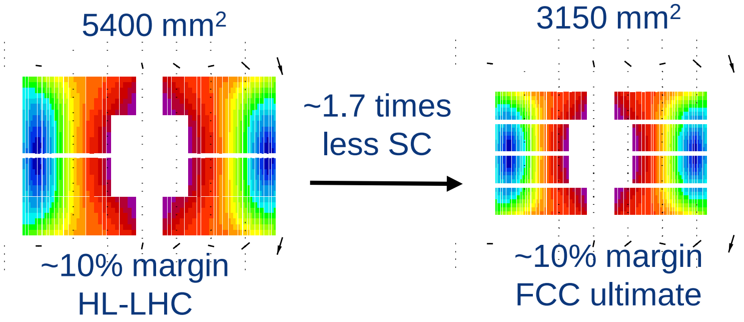
Nb_3Sn **is one of the major cost & performance factors for FCC-hh and is given highest attention**

D. Tommasini et al.

main development goals until 2020:

- **J_c increase (16T, 4.2K) > 1500 A/mm^2 i.e. 50% increase wrt HL-LHC wire**
- **reference wire diameter 1 mm**
- **potentials for large scale production and cost reduction**





5400 mm^2

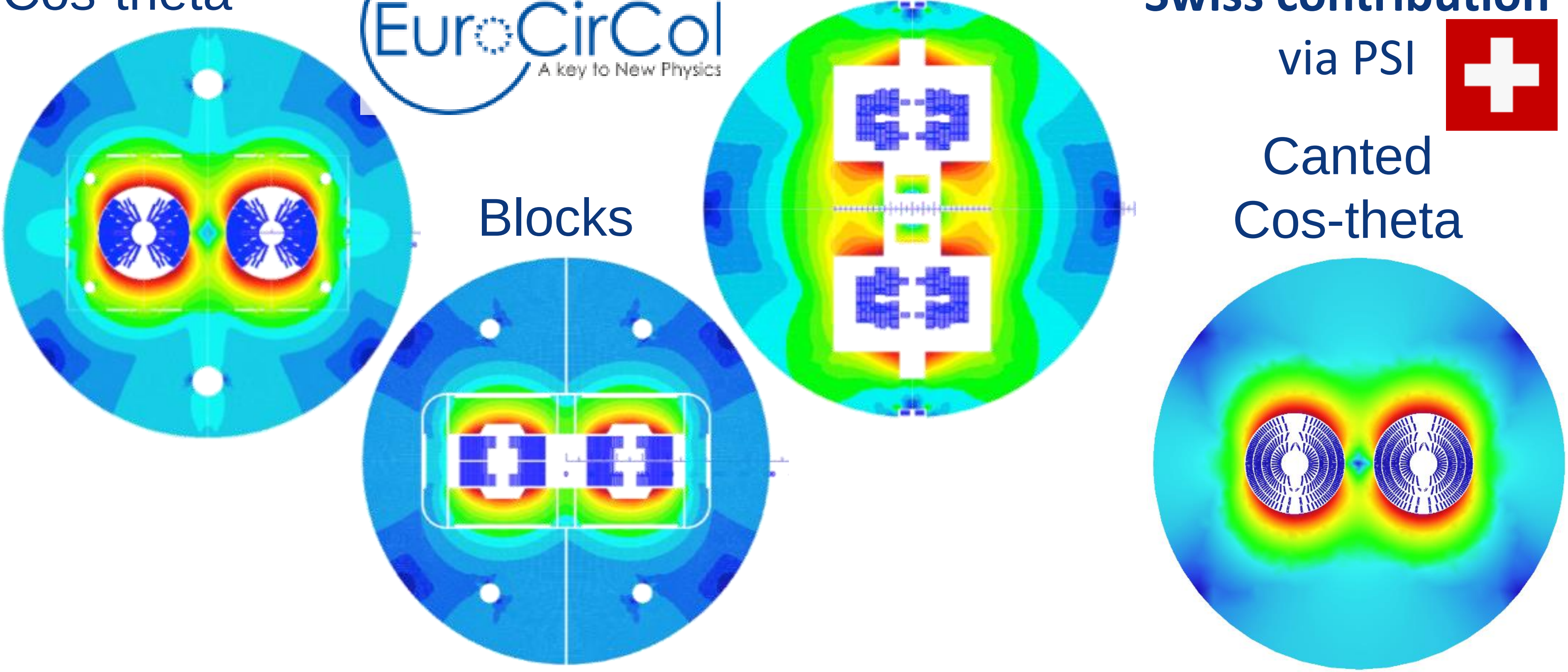
~10% margin
HL-LHC

~1.7 times less SC

3150 mm^2

~10% margin
FCC ultimate

16 T dipole options and plans



Cos-theta

EuroCirCol
A key to New Physics

Common coils

Swiss contribution
via PSI

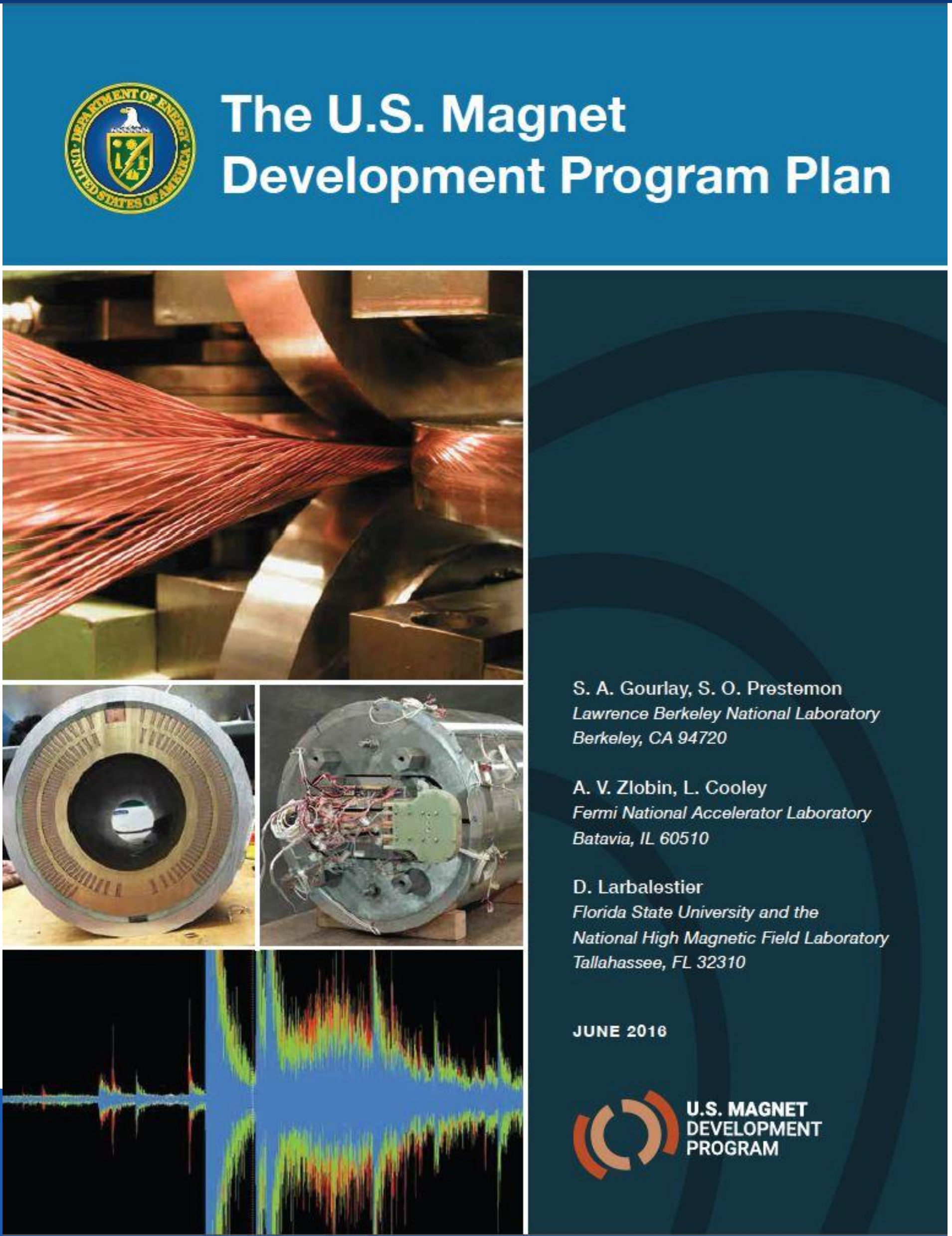
Blocks

Canted
Cos-theta

- **down-selection of options end 2017 for detailed design work**
- **model production 2018 – 2022**
- **prototype production 2023 - 2025**

US Magnet Development Program

S. Gourlay



The U.S. Magnet Development Program Plan

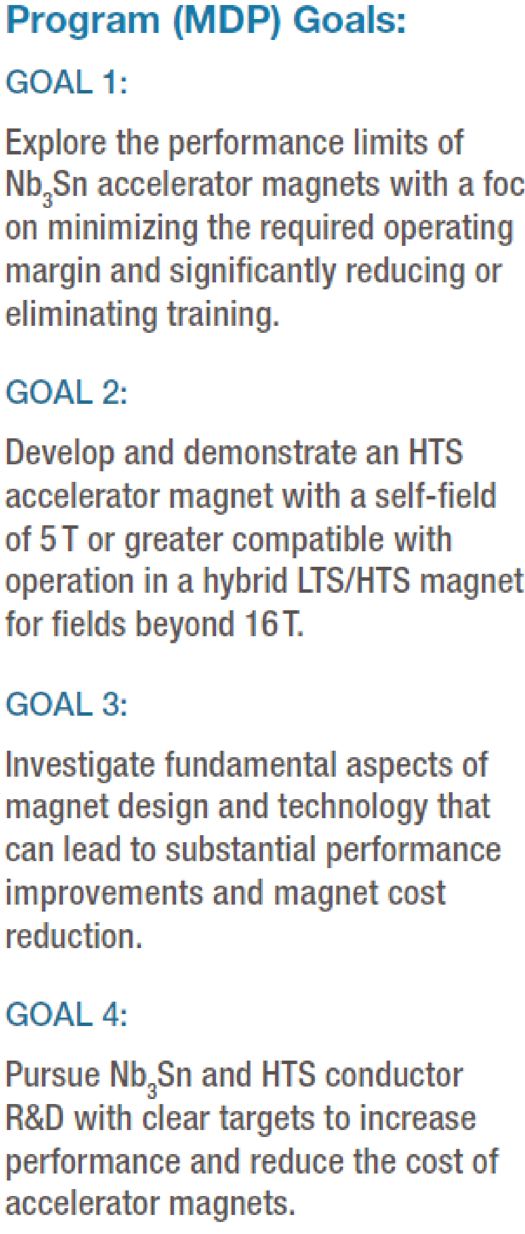
S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310

JUNE 2016

U.S. MAGNET
DEVELOPMENT
PROGRAM



Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

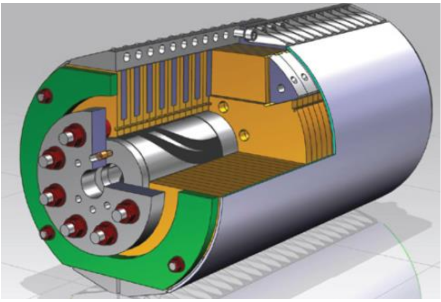
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

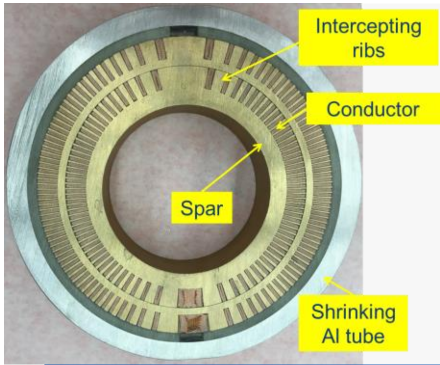
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Under Goal 1:

16 T cos theta dipole design



16 T canted cos theta (CCT) design

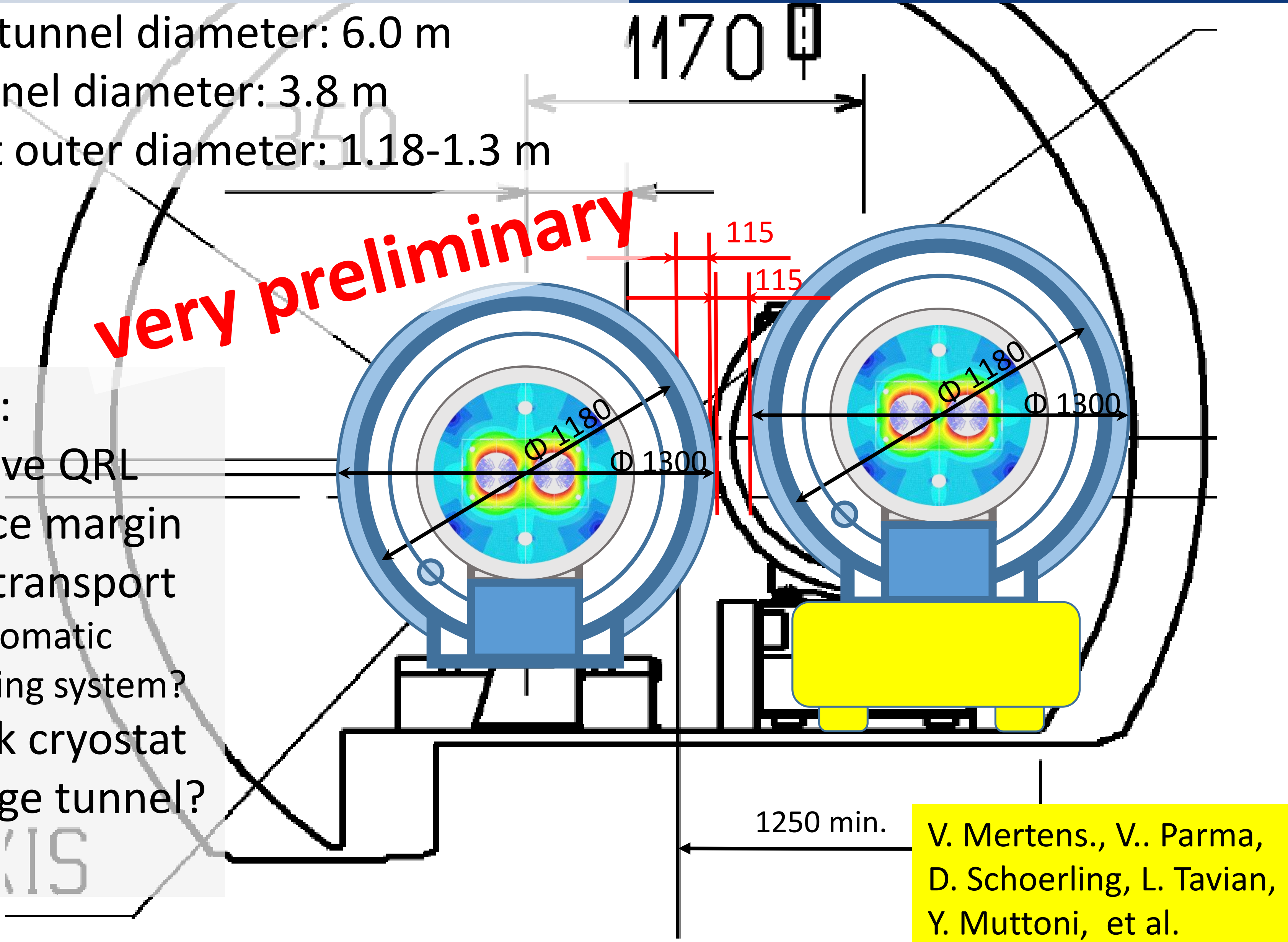


HE-LHC integration & transport

FCC-hh tunnel diameter: 6.0 m

LHC tunnel diameter: 3.8 m

cryostat outer diameter: 1.18-1.3 m



very preliminary

options:

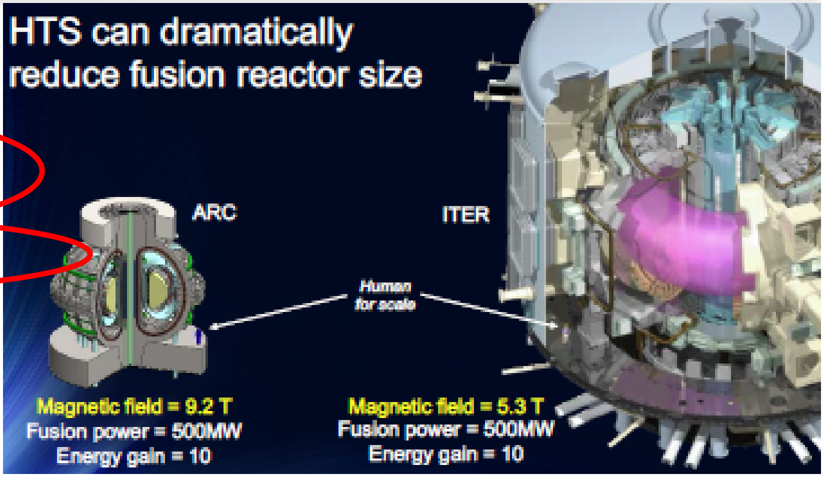
- remove QRL
- reduce margin
  for transport
  - automatic guiding system?
- shrink cryostat
- enlarge tunnel?

…

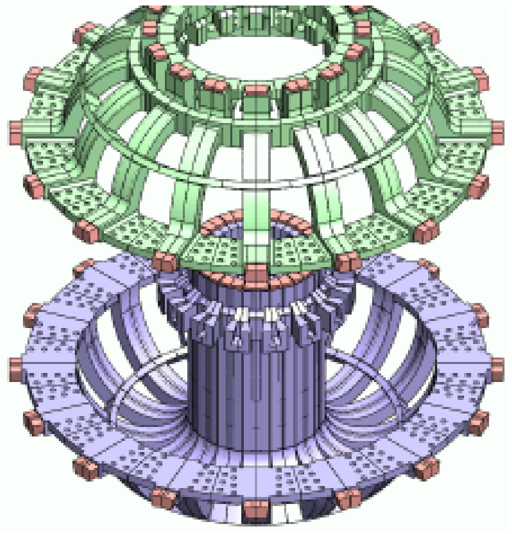
V. Mertens., V.. Parma,
D. Schoerling, L. Tavian,
Y. Muttoni, et al.

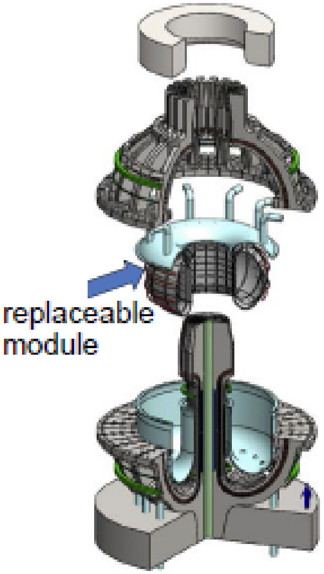
Fusion continues to drive high-field magnet developments - a push by MIT to leverage HTS

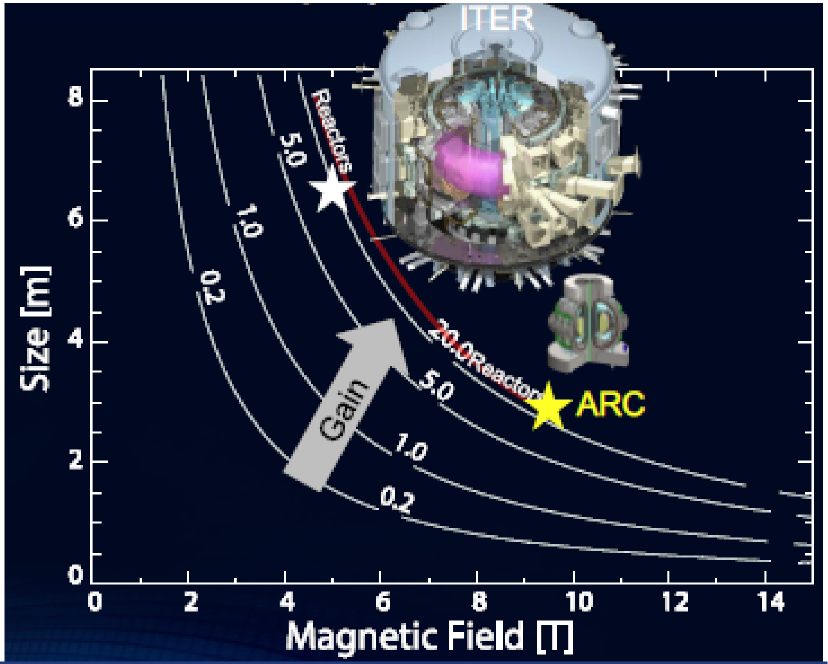
- MIT group is aggressively pursuing a high-field tokamak approach
  - performance scaling shows power density $\propto RB^4$
  - HTS is critical - will see B>20T on conductor
  - Conductor performance is “there”, but need additional technologies:
    - cables for high current to address protection
    - Joints for modular, demountable design



HTS can dramatically reduce fusion reactor size







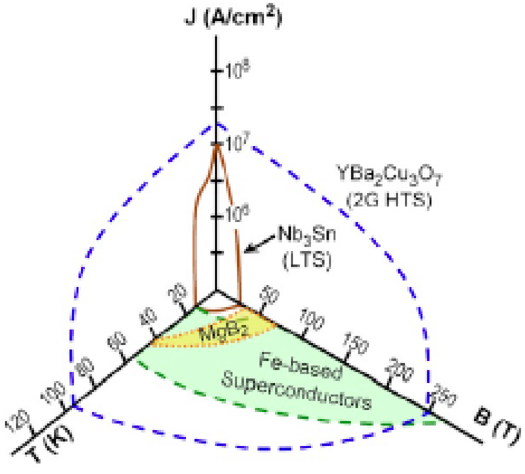
S. Prestemon, HongKong

The Institute of Electrical Engineering, CAS is aggressively pursuing Fe Pnictides as a viable HTS superconductor for HEP

Very high Hc2 ⇒ potential for high field magnets

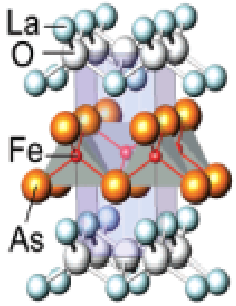
Reasonably high Tc as well

Can this be a viable competitor to REBCO & Bi2212?



Li et al., *Rep. Prog. Phys.* 74 (2011) 124510

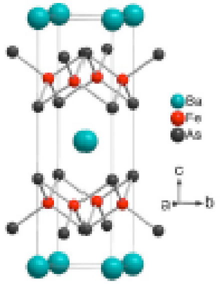
1111 Phase LnOFeAs



T_c ~55 K

Z. A. Ren et al., *Chin. Phys. Lett.* 25, 2215 (2008)

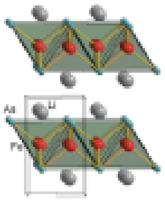
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



T_c ~38 K

M. Rotter, et al., *Phys. Rev. Lett.* **101**, 107006 (2008)

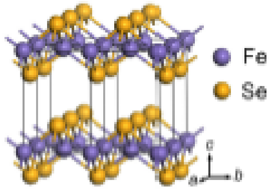
111 phase LiFeAs



T_c ~18 K

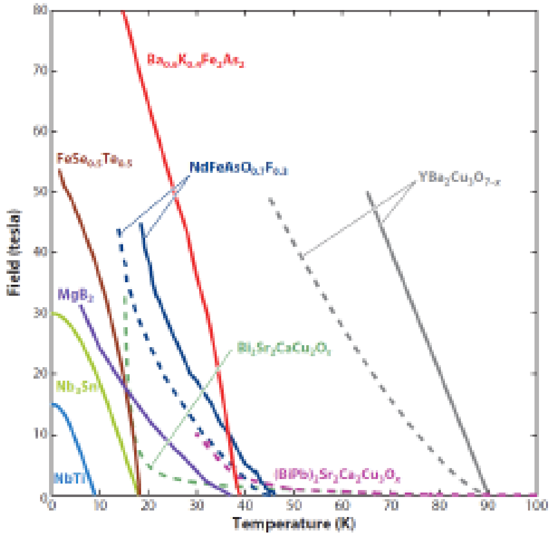
X. C. Wang, et al., *Solid State Commun.* 148, 538 (2008).

11 phase FeSe



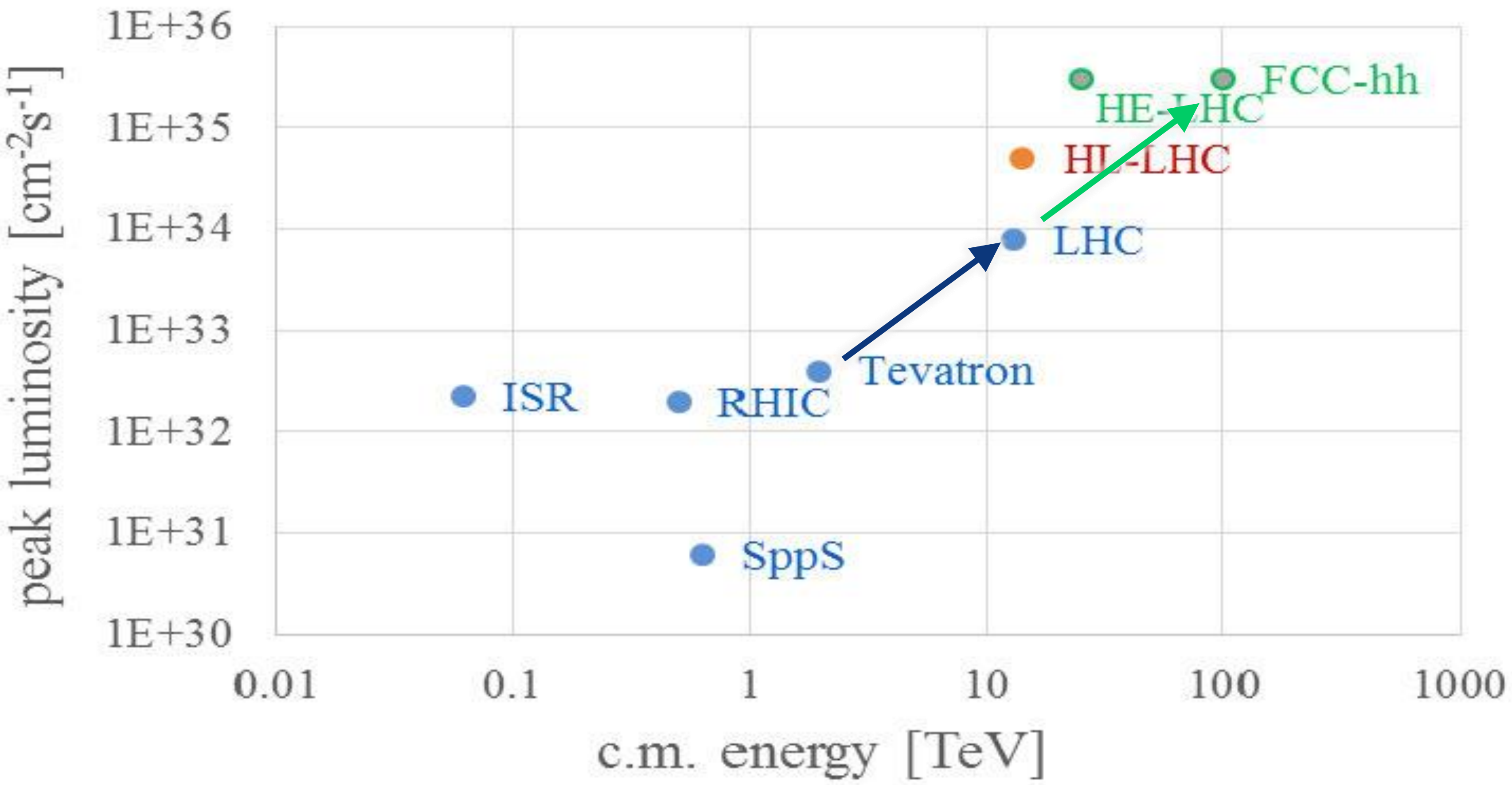
T_c ~8 K

F. C. Hsu, et al., *Proc. Natl. Acad. Sci. U.S.A.* **105**, 14262 (2008).



Gurevich, *Nature Mater.* 10 (2011) 255

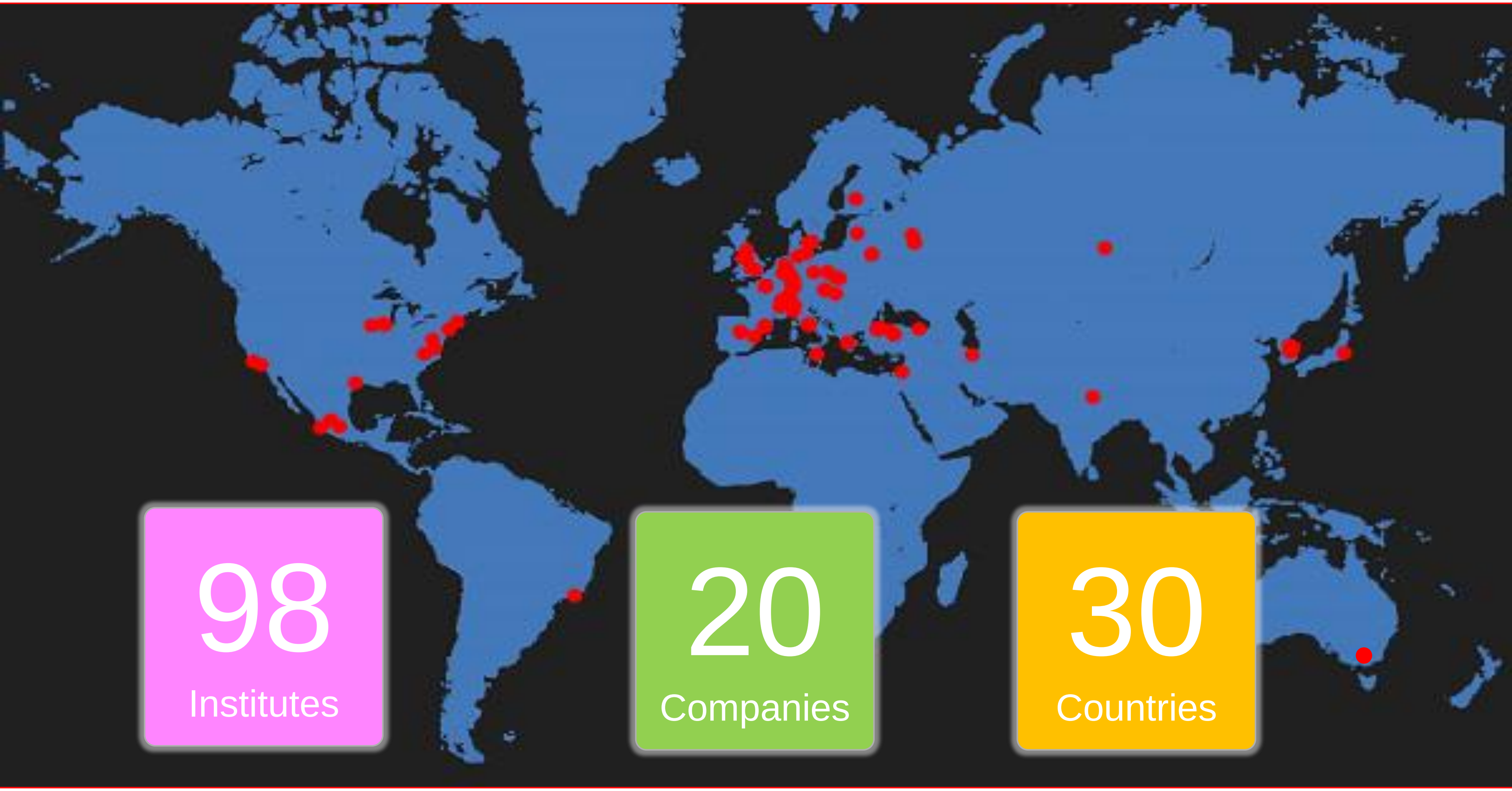
pp/p-pbar in the *L-E* plane



hadron-collider beam power

Collider	c.m. energy [TeV]	P_{el}: tot. el. power [MW]	**P_b: IP beam power [GW]**	luminosity L [nb^{-1}s^{-1}]	**P_b/P_{el}**	**L/P_{el} (/IP) [nb^{-1}s^{-1} / MW]**
LHC	13.0	~150	**8000**	10	**50000**	**0.07**
HE-LHC	25.0	~250 (guess)	**32000**	340	**128000**	**1.4**
FCC-hh	100.0	500 (target)	**50000**	300 (phase 2)	**100000**	**0.6**
SPPC	75	600 (guess)	**53000**	100	**90000**	**0.2**

collaboration & industry relations



98
Institutes

20
Companies

30
Countries


FCCWEEK2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch
IEEE CSC
DPG
DESY

beyond FCC

muon colliders?

γγ colliders? (low energy or high energy – CLICHÉ/SAPPHiRE)

crystal accelerators?

gravitational waves

detection and/or generation

others (piggyback, single particles, black holes)

low-energy γγ colliders

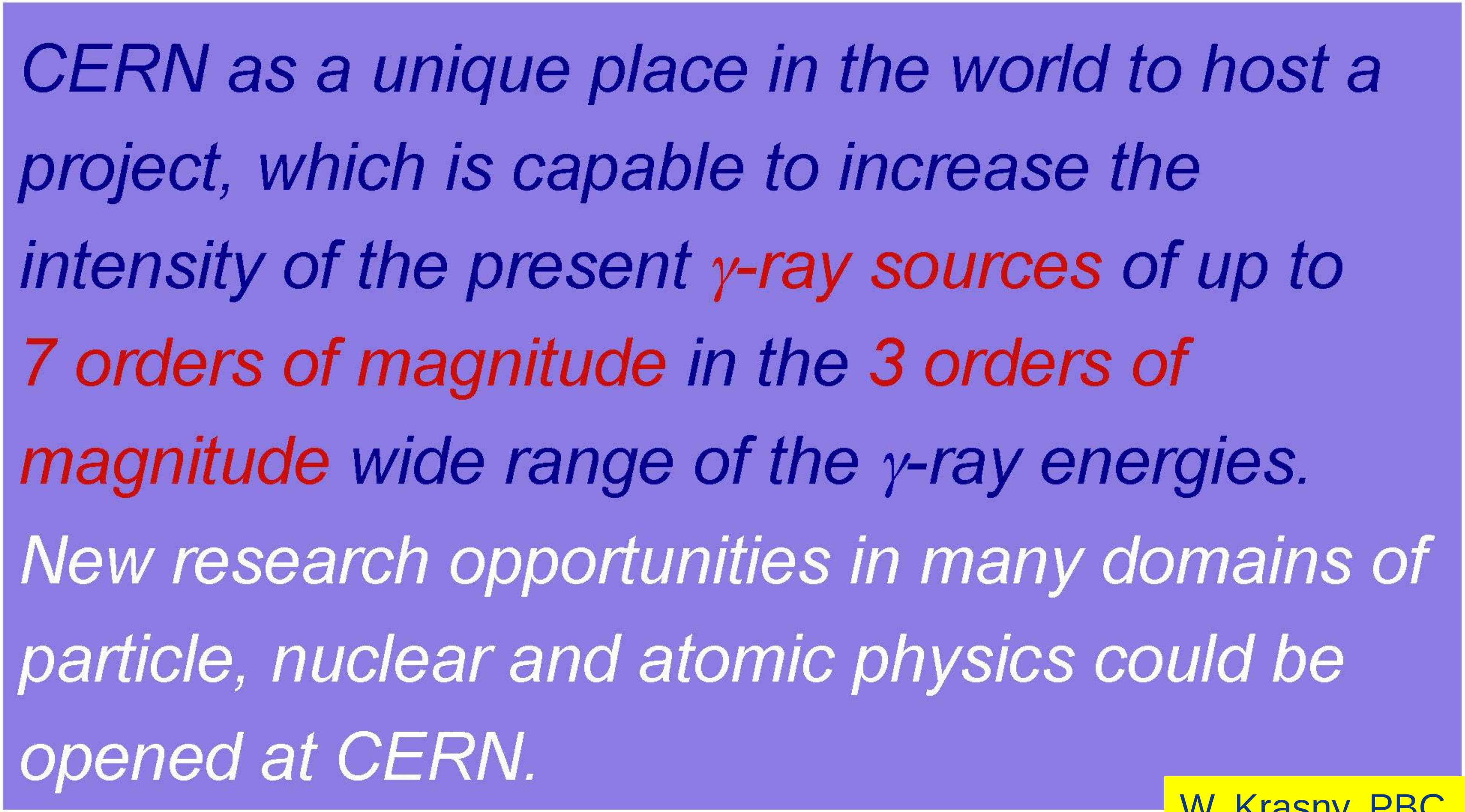
Photon-photon scattering probes the structure of the QFT vacuum.

Measurements of photon-photon scattering at LCLS-2 and at XFEL:
Energy hn =10 keV or c.m. energy 20 keV. Total Cross Section 1.0 ab.
2 FEL beam pulses colliding head-on against each other
(at 20 keV γ's, cross section goes to 64 ab , scaling like $h\nu^6$)

	LCLS-2	**XFEL weak focusing**	**XFEL strong focusing**
# photons per pulse	2.10^{12}	2.10^{12}	2.10^{12}
FEL pulse energy (mJ)	3.2	3.2	3.2
repetition rate	1 MHz	30 kHz	30 kHz
spot size at collision (mm)	1.	1.	0.2
Luminosity ($cm^{-2}s^{-1}$)	$\mathbf{3.2 \cdot 10^{37}}$	$\mathbf{9.6 \cdot 10^{35}}$	$\mathbf{2.4 \cdot 10^{37}}$
photon-photon scattering events per second	$3.2 \cdot 10^{-4}$	$9.6 \cdot 10^{-6}$	$2.4 \cdot 10^{-4}$
photon-photon scattering events per hour	1.2	0.034 (0.83 per day)	0.86

L. Serafini, F3iA 2016

“Gamma factory” initiative

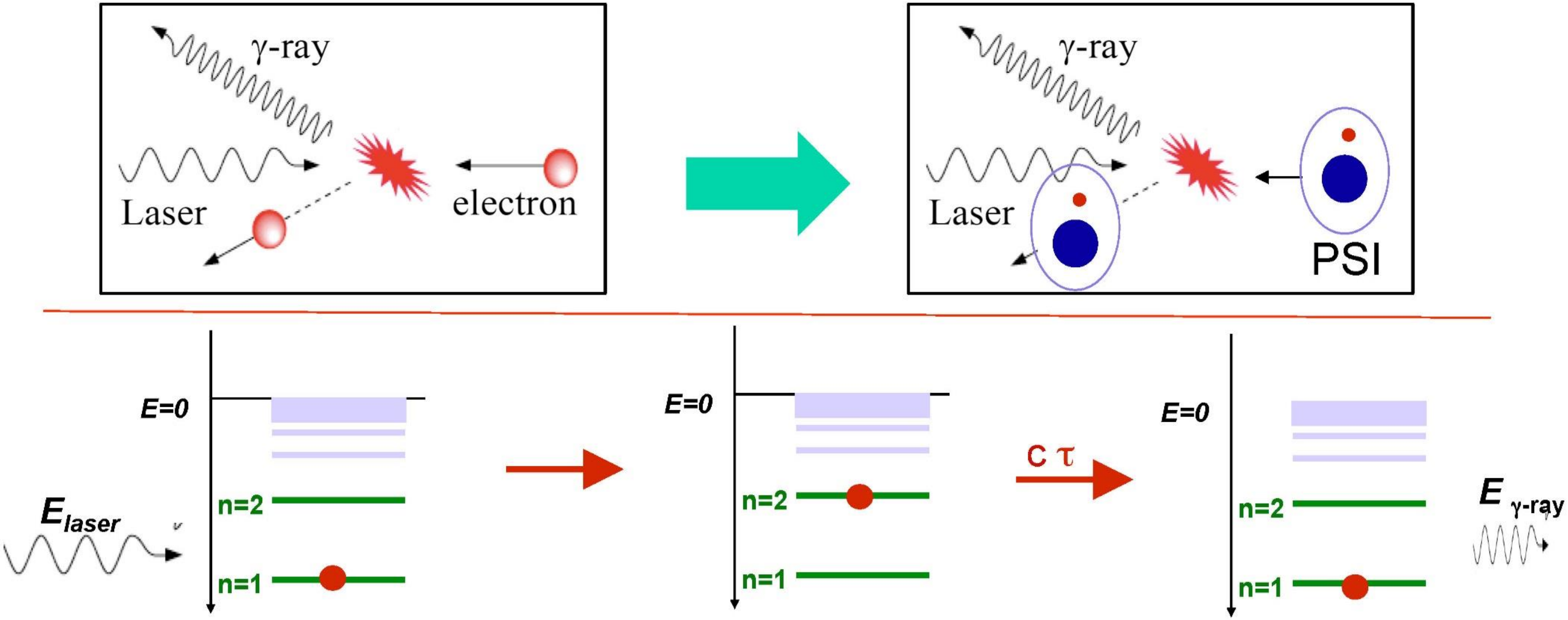


CERN as a unique place in the world to host a project, which is capable to increase the intensity of the present γ-ray sources of up to 7 orders of magnitude in the 3 orders of magnitude wide range of the γ-ray energies.

New research opportunities in many domains of particle, nuclear and atomic physics could be opened at CERN.

W. Krasny, PBC

Simple Idea: replace an Electron beam by a Partially Stripped Ion (PSI) beam



$E_{laser} = 1Ry\,(Z^2 - Z^2/n^2)/2\gamma_L$ → $E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L$

W. Krasny, PBC

Note: $(E_{laser} / m_{beam}) \times 4\gamma_L \ll 1$

Partially Stripped Ion (PSI) beams as the light frequency converters:

$$\nu_i^{max} \longrightarrow (4\,\gamma_L^2)\ \nu_i$$

γ_L =E/M - Lorentz factor for the ion beam

The tuning of the PSI beam energy (SPS or LHC), the choice of the ion type, and the number of left electrons and of the laser type allows to tune the γ-ray energy in the requisite energy domain of 100 keV – 400 MeV.

Example (maximal energy):

LHC, Pb^{80+} *ion,* γ_L = 2887, n=1→2, λ_{laser} = 104.4 nm, E_γ (max) =

W. Krasny, PBC

The origin of the γ-beam intensity jump:

W. Krasny, PBC

Electrons:

$\sigma_e = 8\pi/3 \times r_e^2$

r_e - the classical electron radius

Partially Stripped Ions:

$\sigma_{res} = \lambda_{res}^2 / 2\pi$

λ_{res} - photon wavelength for the resonant atom excitation

Numerical example: λ_{laser} = 1540 nm – 9 orders of magnitude difference

Electrons:

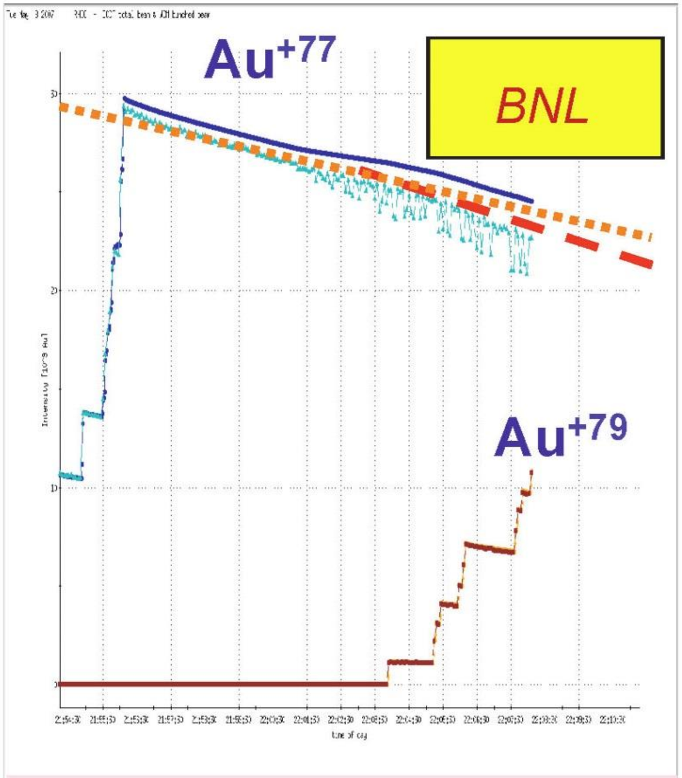
$\sigma_e = 6.6 \times 10^{-25}$ cm^2

Partially Stripped Ions:

$\sigma_{res} = 5.9 \times 10^{-16}$ cm^2

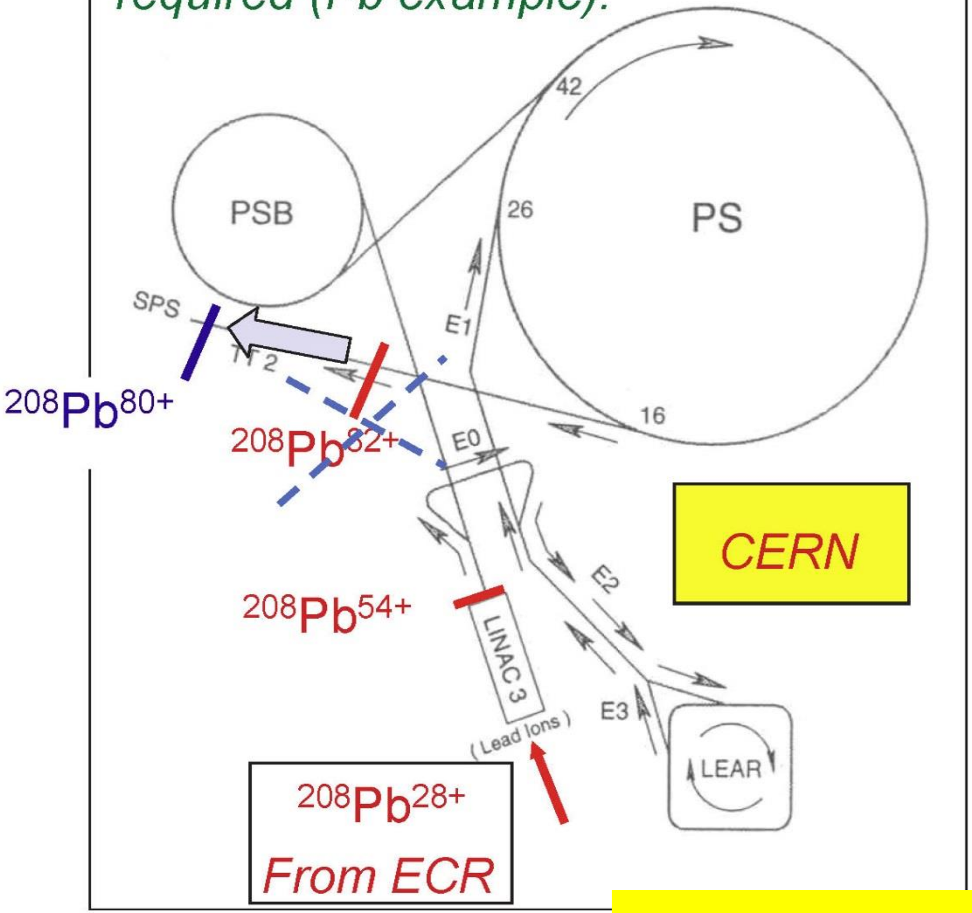
For the LHC/SPS -based partially stripped ion based gamma source the intensity limits are driven predominantly by the acceleration and storage aspects of the PSI beams, rather than by the laser power and the collision geometry (the existing gamma/X sources require more advanced laser beam technologies with respect to e.g. the ELI and HIγs projects).

Acceleration and storage of PSI beams



PSI beams were already accelerated and stored in AGS and in RHIC !

New electron stripping scheme required (Pb example):



W. Krasny, PBC

“*beams may be holding us back*”

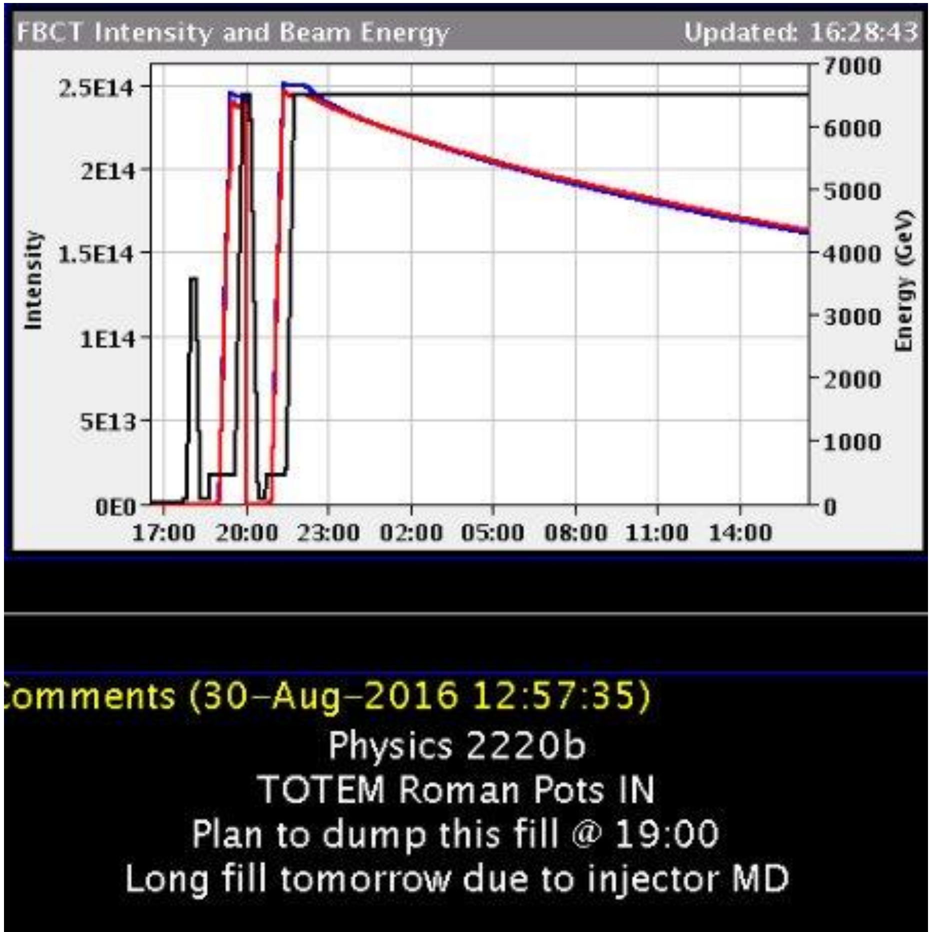
single particle accelerators

- wave function propagating through lattice
- use emerging ultra-cold and precision alignment technology (e.g. LIGO)
- cleaner, more customised physics output in detector, better luminosity (per particle) – perhaps get rid of beamstrahlung?

creating a big *black hole* (10^6xE_{planck} in 10^6xL_{planck})?
cheating with *entanglement*?

S. Brooks, F3iA 2016

“the case for optimism”



omments (30-Aug-2016 12:57:35)

Physics 2220b
TOTEM Roman Pots IN
Plan to dump this fill @ 19:00
Long fill tomorrow due to injector MD

@JoshMcFayden (UCL/ATLAS) via Twitter

- 2 * 2.5e14 * 6500 GeV
- = 521 MJ
- = 0.266 E_{Planck}
- **total energy is OK but it’s in too many particles**

S. Brooks, F3iA 2016

Tokyo/Ueno – similar to Fallas … but where/who is the European guy?

Reuters