Status Report on FCC Accelerator Science and Technology

Michael Benedikt, CERN
Austrian FCC Meeting,
11 October 2021

http://cern.ch/fcc

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photo: J. Wenninger

FCC-ee basic design choices

Double ring e+ e- collider

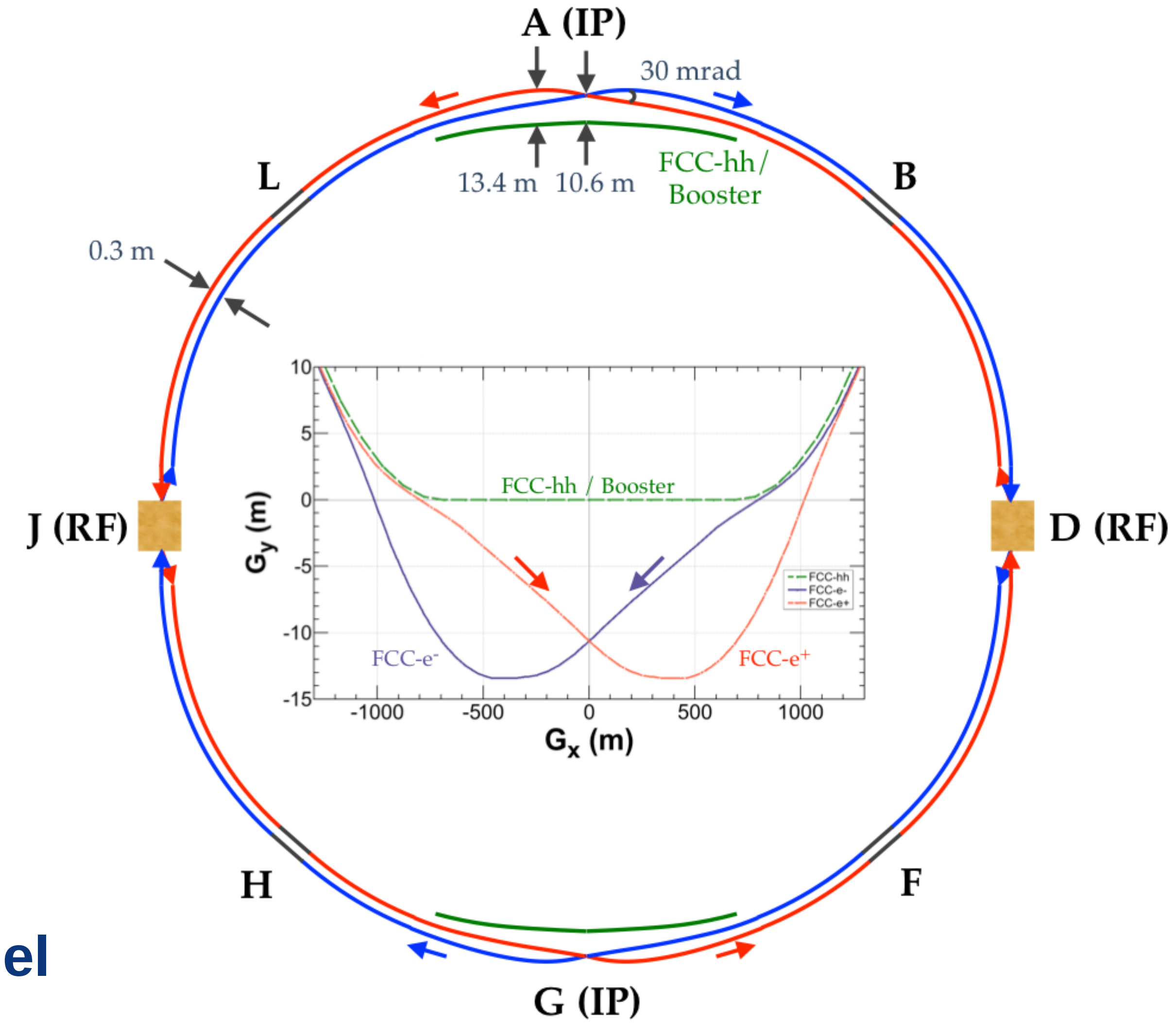
Common footprint with FCC-hh,
except around IPs

Asymmetric IR layout and optics to limit
synchrotron radiation towards the detector

2 IPs, large horizontal crossing angle **30 mrad,**
crab-waist collision optics
(alternative layouts with 4 IPs under study now)

Synchrotron radiation power 50 MW/beam
at all beam energies

Top-up injection scheme for high luminosity
Requires **booster synchrotron in collider tunnel**



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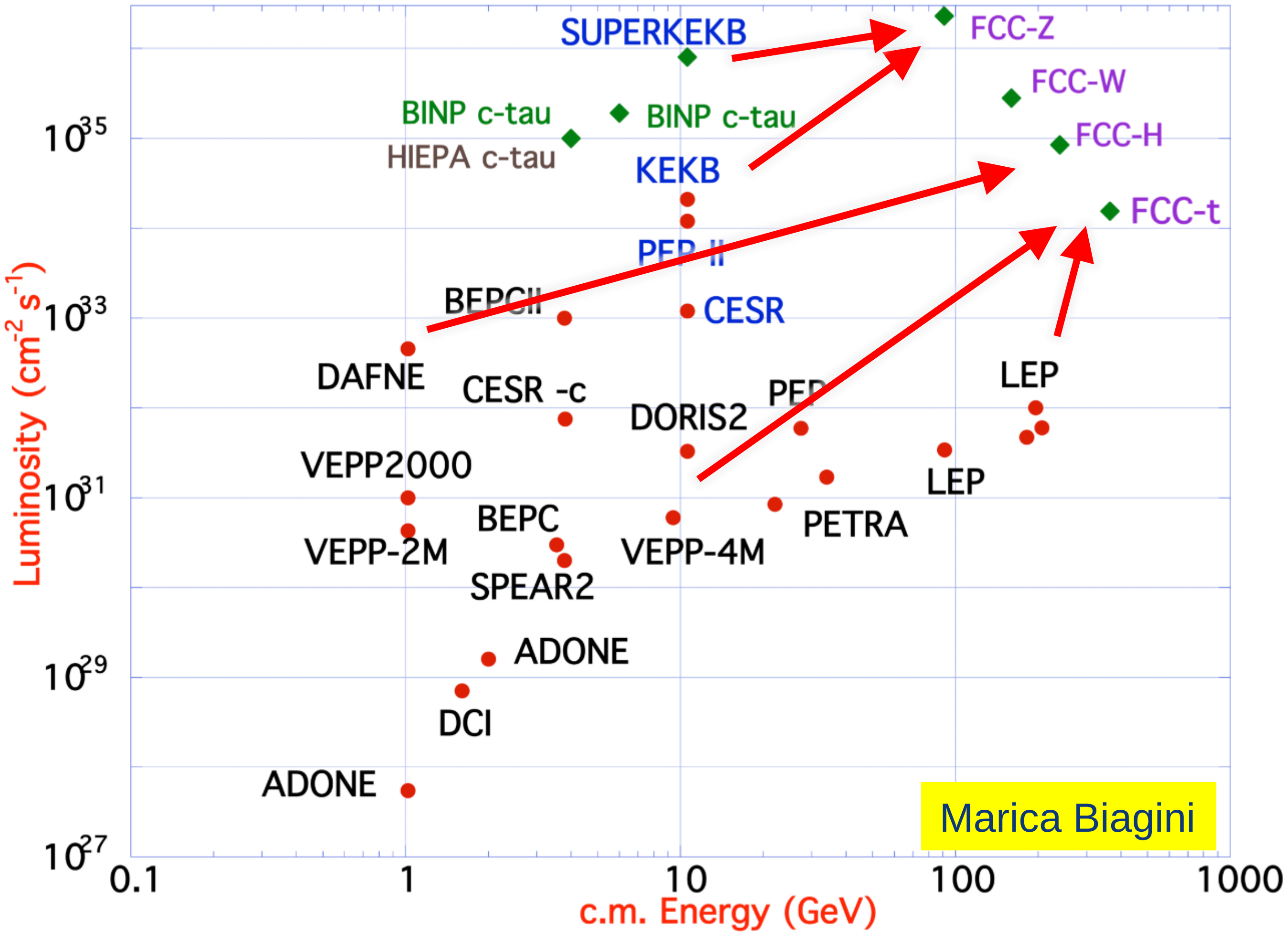
FCC-ee collider parameters (stage 1)

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee design concept

based on lessons and techniques from past colliders (last 40 years)



Marica Biagini

B-factories: **KEKB & PEP-II:**
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

S-KEKB: low β_y*, crab waist

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

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FCC-ee RF staging scenario

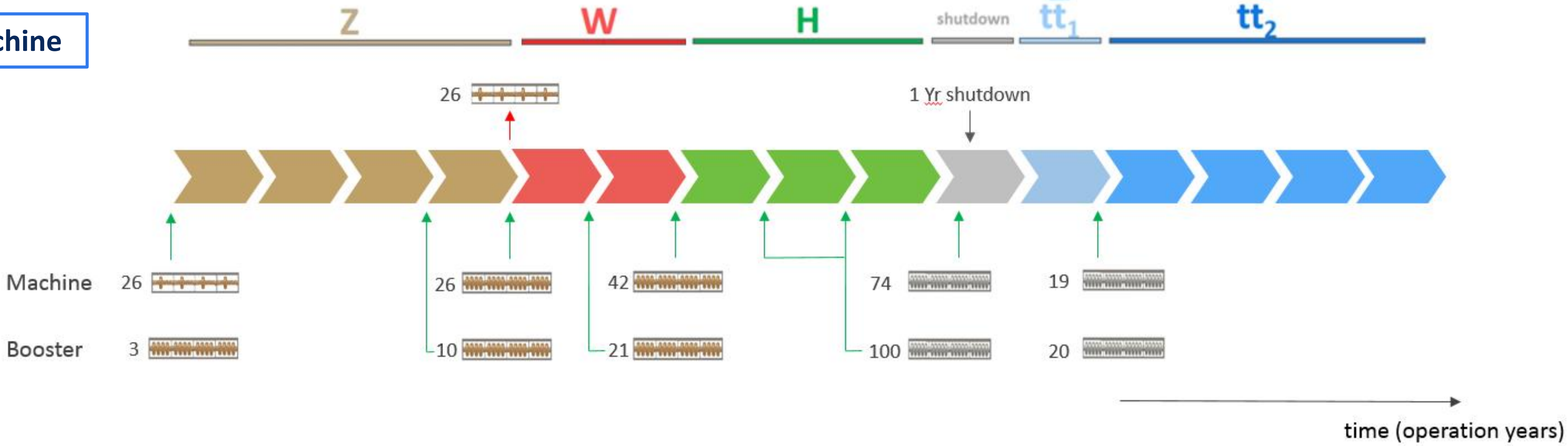
“Ampere-class” machine

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

“high-gradient” machine

three sets of RF cavities to cover all options for FCC-ee & booster:

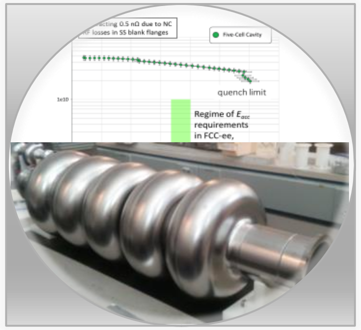
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**



FCC SRF R&D Program Structure in a Nutshell

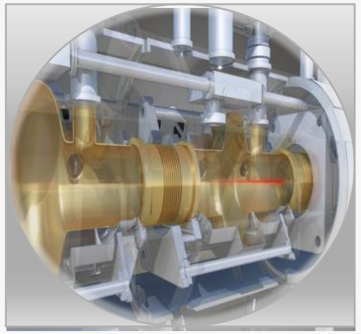
Cavity Studies

- Optimized Cavity Shape, Technology and Operating Temperature (complexity, power consumption, Q_o, E_{acc})
- Design 1- & 4-cell Cavities
- Beam-Cavity Interaction
- Cavity Control System (LLRF)



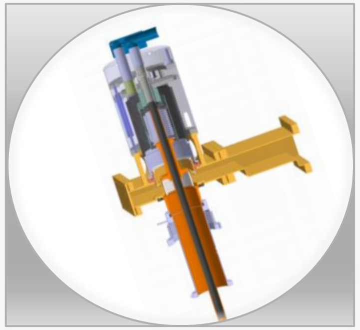
SRF & Substrate Technologies

- Improved Cavity Engineering: New SC Materials, Novel Fabrication Methods, Substrate Surface Preparation, Coating Techniques
- Fabrication & Testing of 1-l & 4-cell cavities for new cryomodule
- Collaboration with international Partners



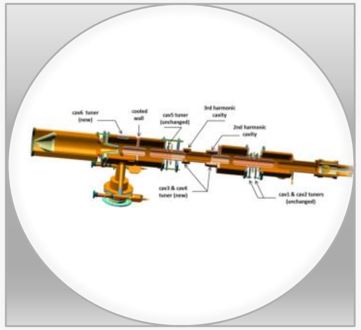
Cryomodule Development

- Engineering design of 400 MHz cryomodule including ancillaries
- Building a 2 cavity CM which can host 1-/4-cell 400 MHz cavities
- R&D Collaboration with int'l Partners (e.g. JLAB)
- 800 MHz CM: Profit from Ongoing Development @ PERLE in Paris



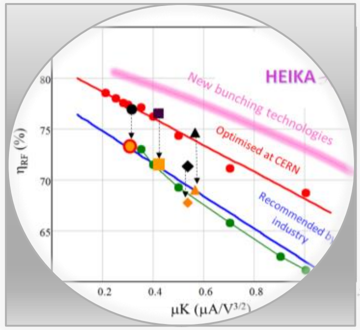
FPC & HOM RF Couplers

- Improved design, fabrication and testing of 400 MHz Fundamental Power Coupler (FPC)
- FPC R&D towards 1MW CW fixed/movable FPC
- 'Adjustable' FPC (external large adaptation of Q_{ext})
- HOM coupler production



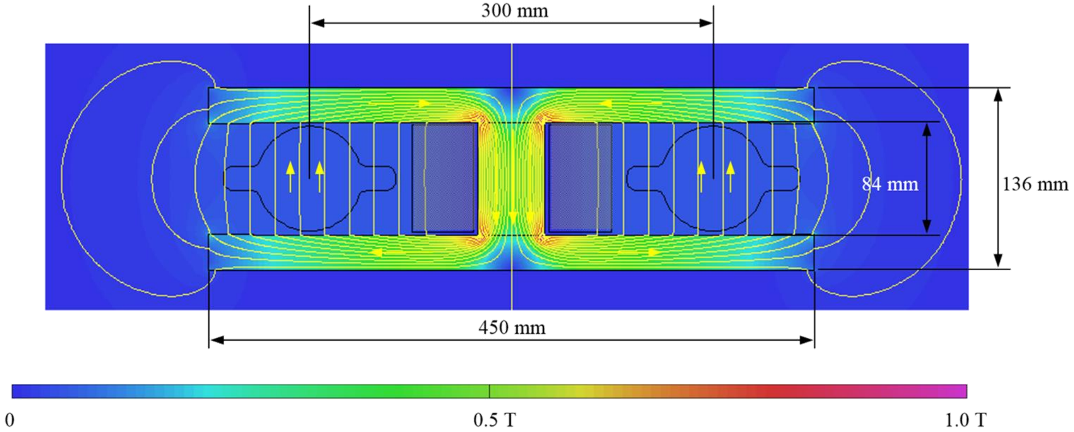
RF Power Sources

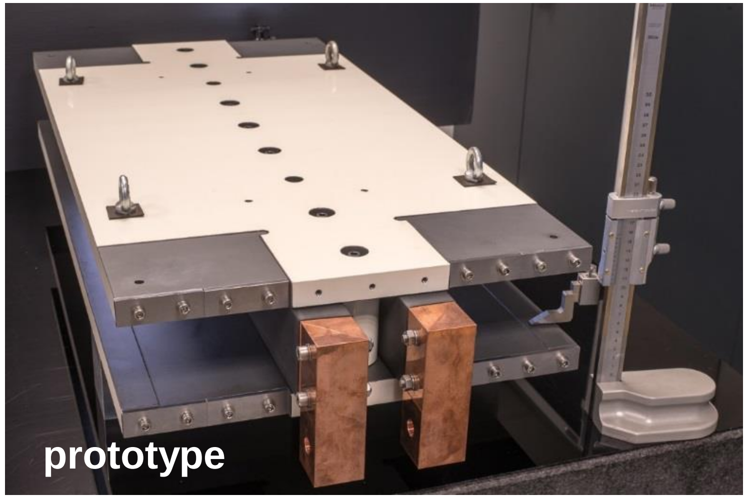
- novel klystron bunching methods
- LHC klystron retrofit as proof of principle
- prototype design, fabrication and testing

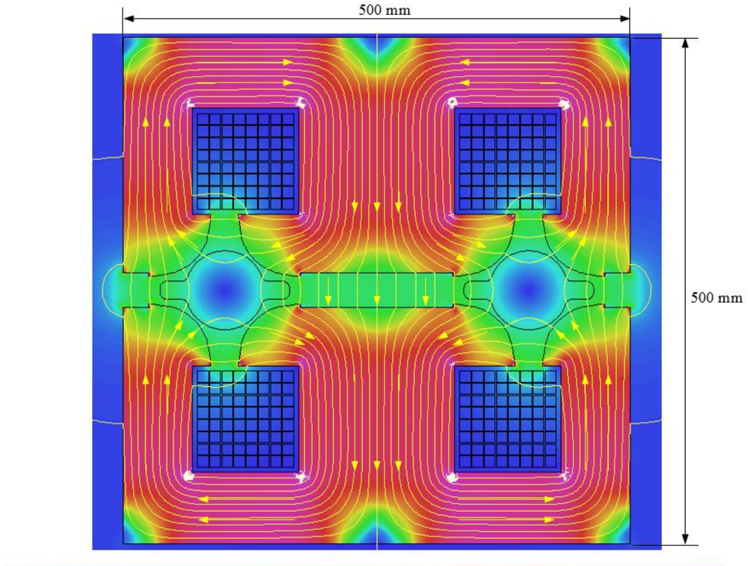


Prototypes of FCC-ee low-power magnets

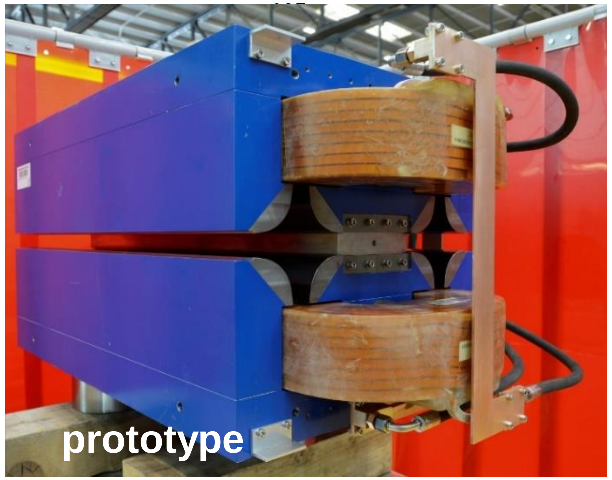
Twin-dipole design with 2× power saving 16 MW (at 175 GeV), with Al busbars





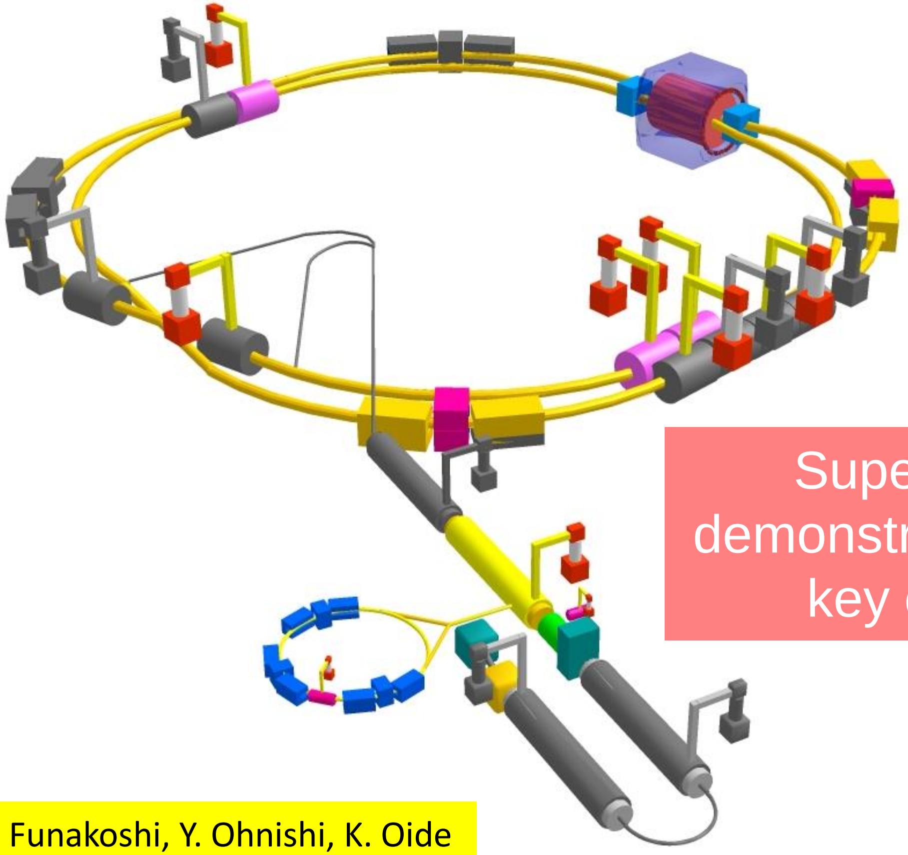


Twin F/D arc quad design with 2× power saving 25 MW (at 175 GeV), with Cu conductor



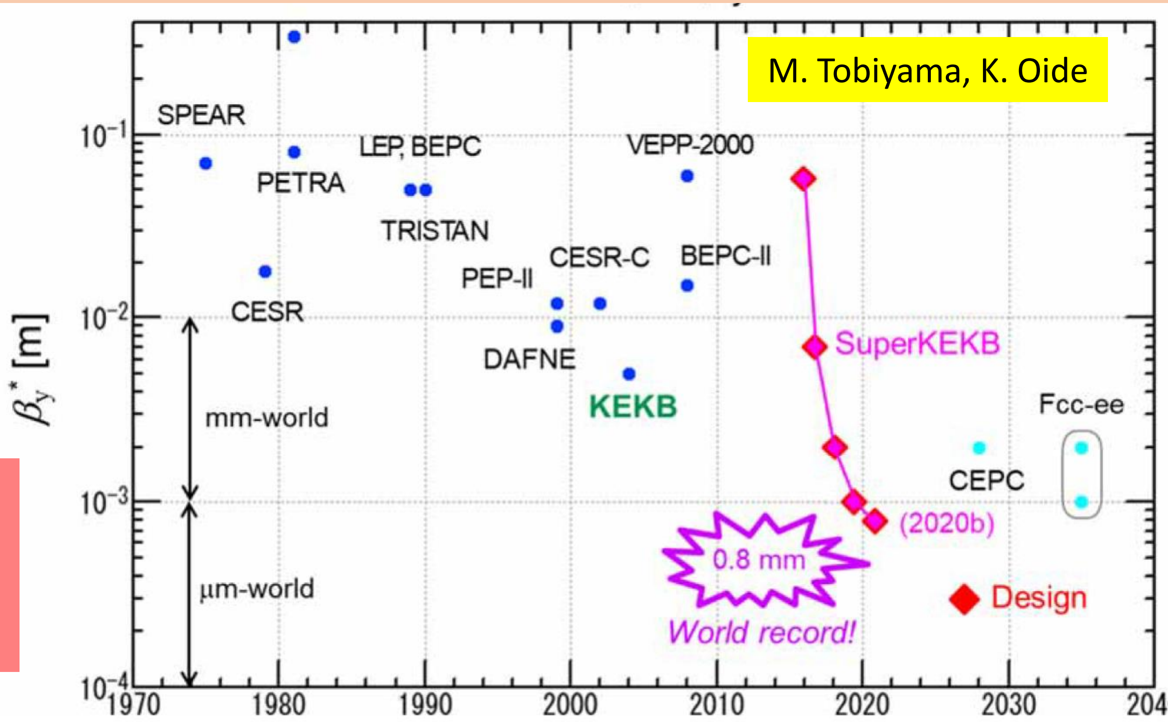
SuperKEKB – pushing luminosity and β*

Design: **double ring e^+e^- collider as *B*-factory** at 7(e^-) & 4(e^+) GeV; **design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; β_y^* ~ 0.3 mm; nano-beam – large crossing angle** collision scheme **(crab waist w/o sextupoles)**; **beam lifetime ~5 minutes**; **top-up** injection; **e^+ rate up to ~ 2.5 10^{12} /s** ; **under commissioning**



Y. Funakoshi, Y. Ohnishi, K. Oide

SuperKEKB is demonstrating FCC-ee key concepts



M. Tobiyama, K. Oide

β_y^* = 0.8 mm achieved in both rings – using the FCC-ee-style "virtual" crab-waist collision scheme

new world record L = 3.12 x 10^{34} $cm^{-2}s^{-1}$ on 22 June '21

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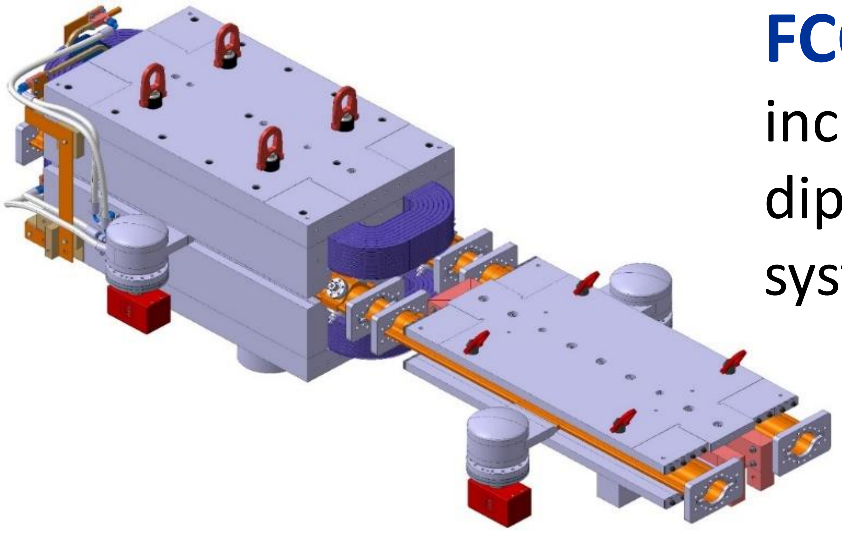
FCC key deliverables: prototypes by 2025



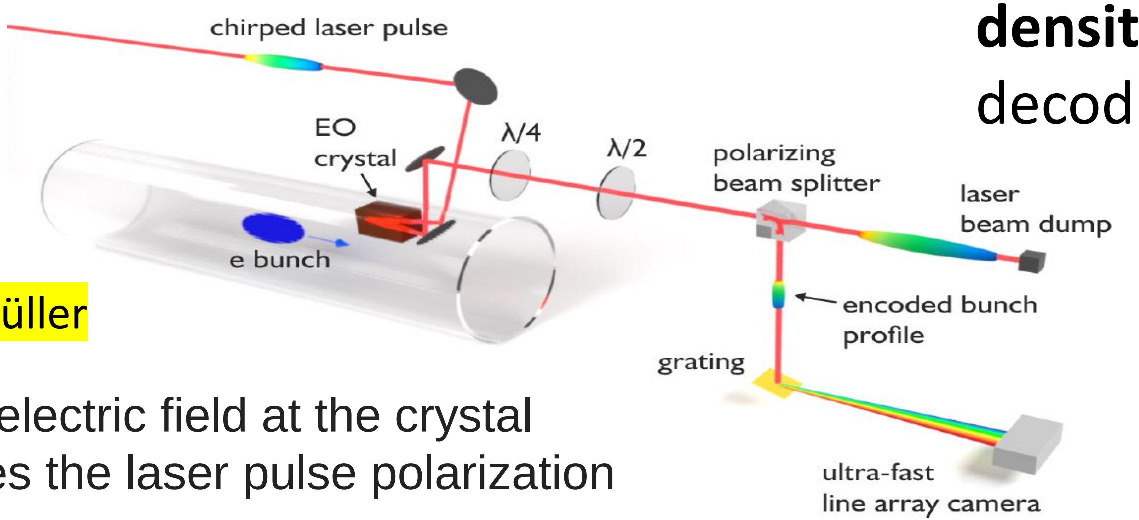
FCC-ee complete arc half-cell mock up

including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.

key beam diagnostics elements

bunch-by-bunch turn-by-turn **longitudinal charge density profiles** based on electro-optical spectral decoding (beam tests at KIT/KARA) ;

ultra-low emittance measurement (X-ray interferometer tests at SuperKEKB, ALBA) ;
beam-loss monitors (IJCLab/KEK?) ;
beamstrahlung monitor (KEK);
polarimeter ; **luminometer**

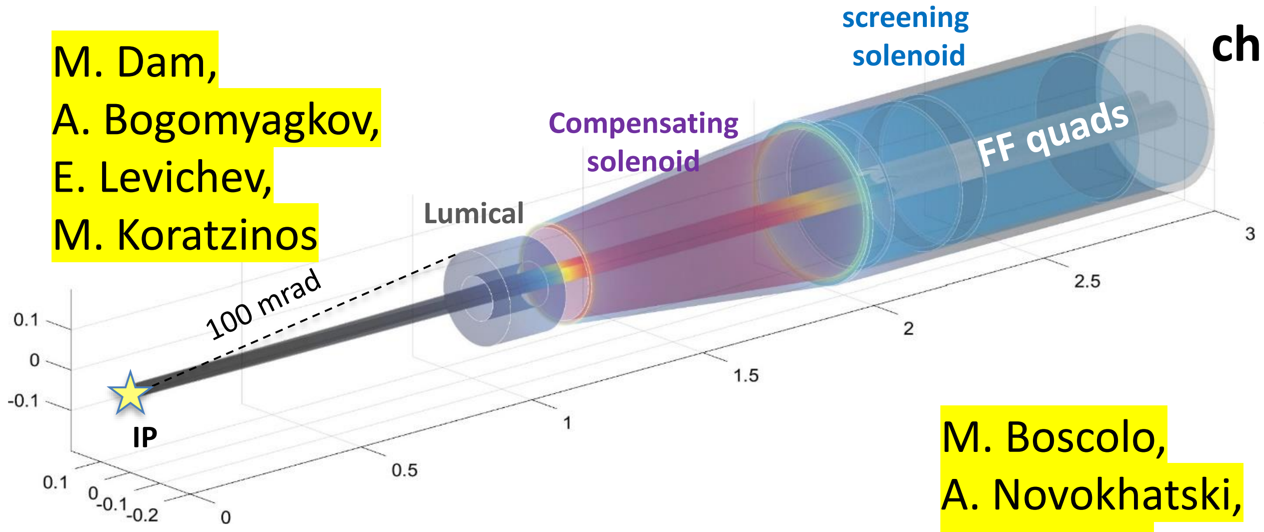


A.-S. Müller

bunch electric field at the crystal changes the laser pulse polarization

FCC-ee Machine Detector Interface

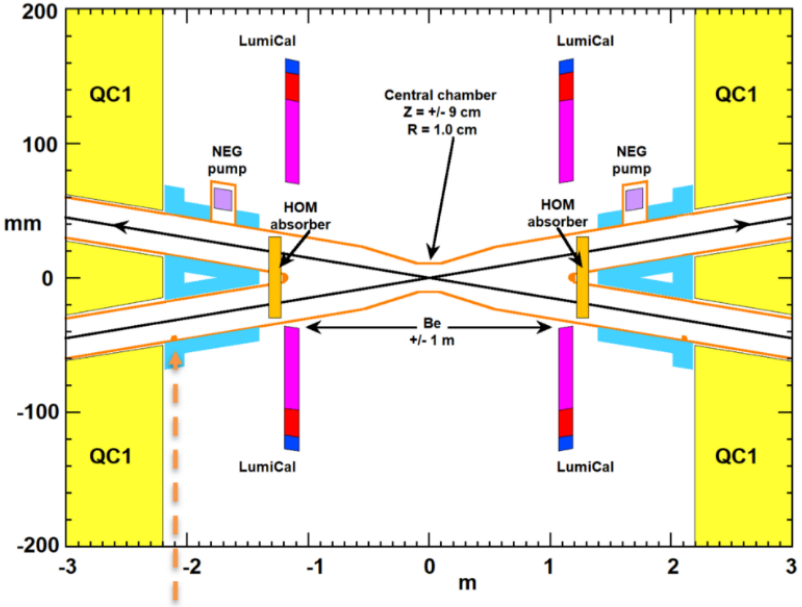
M. Dam,
A. Bogomyagkov,
E. Levichev,
M. Koratzinos



challenging integration:
2 T detector solenoid,
luminosity monitor
(Bhabha scattering),
compensation &
shielding solenoids

M. Boscolo,
A. Novokhatski,
M. Sullivan

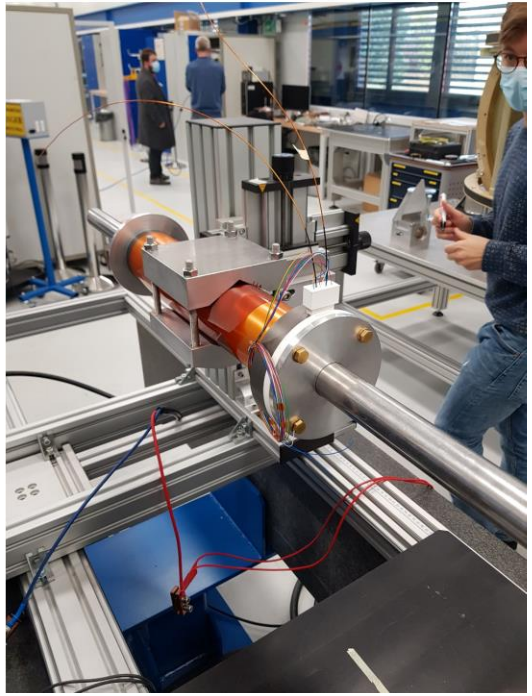
1 cm radius central chamber



narrow central chamber
with 1 cm radius,
also avoids trapped modes

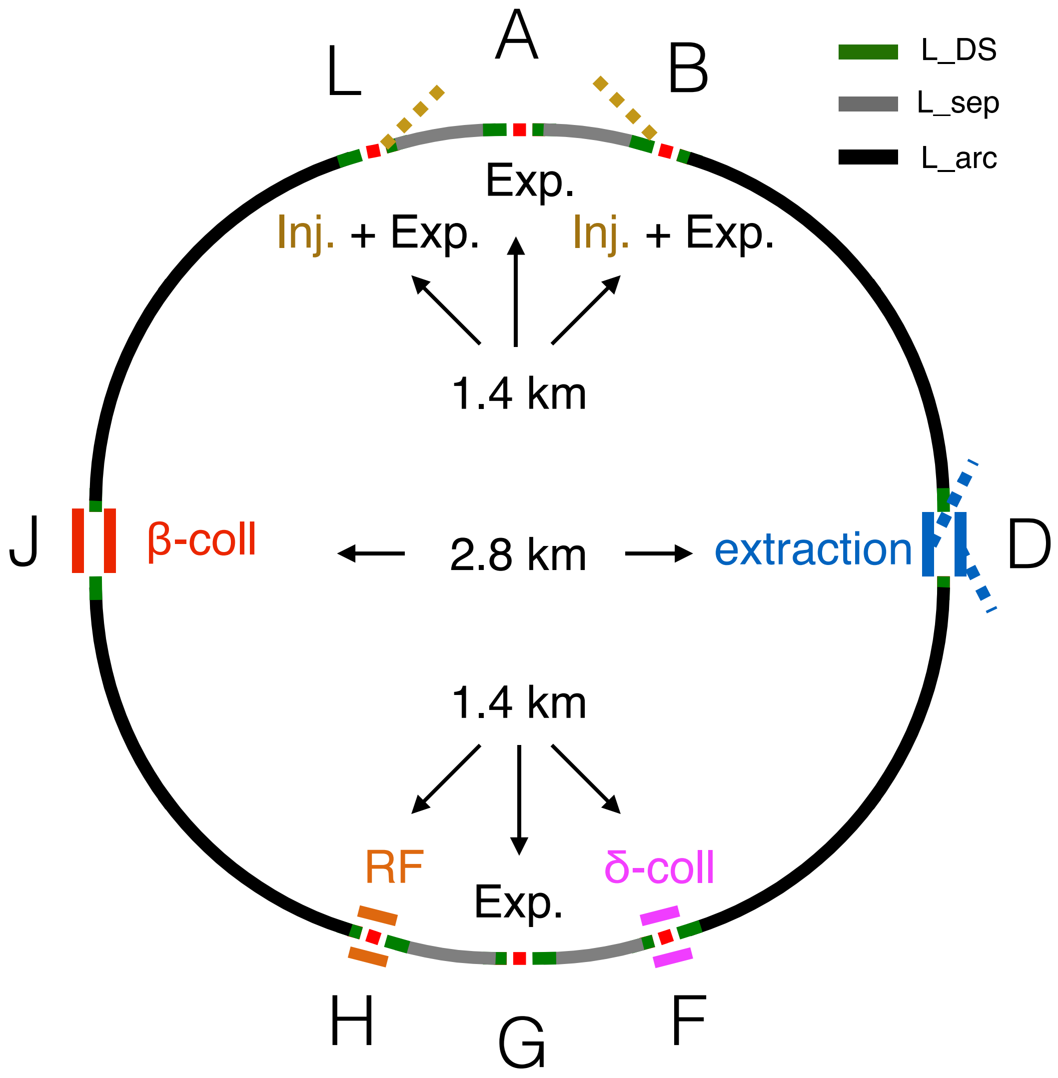
prototype Q1
canted cosine theta
with fringe field
correction,
using LHC SC cable

field measurement
at warm



M. Koratzinos

FCC hh basic design choices



- **dual aperture superconducting magnets**
- **two high-luminosity experiments (A & G)**
- **two other experiments (L & B)** combined with **injection upstream** of experiments
- **two collimation insertions**
  - betatron cleaning (J)
  - momentum cleaning (F)
- **extraction/dump insertion (D)**
- **RF insertion (H)**
- **Injection from LHC (~3 TeV) or scSPS (~1.2 TeV)**
- **Alternative layouts under study**

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FCC-hh (pp) collider parameters (stage 2)

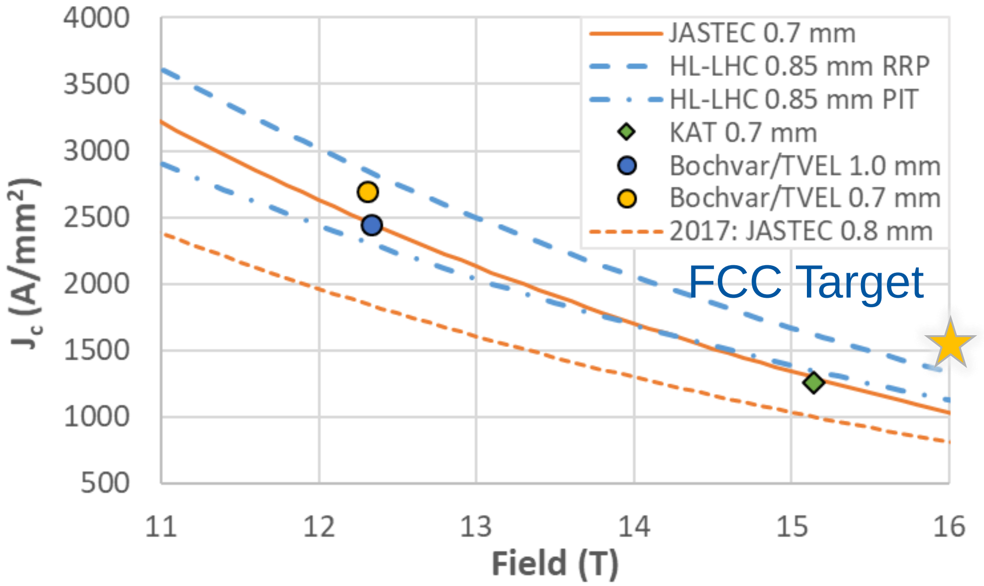
parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

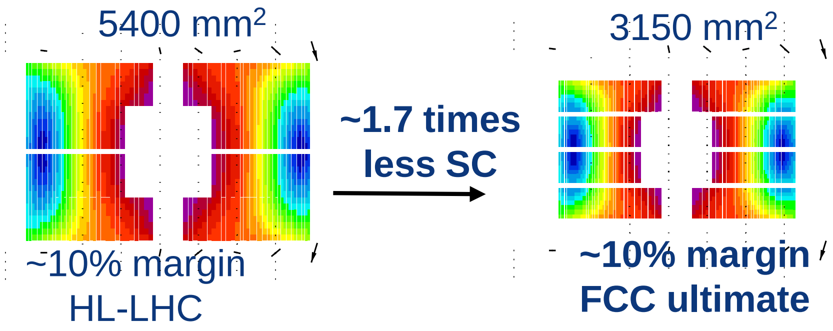
worldwide FCC Nb_3Sn program

Main development goal is wire performance increase:

- **J_c (16T, 4.2K) > 1500 A/mm^2 →50% increase wrt HL-LHC wire**
- **Reduction of coil & magnet cross-section**

After 1-2 years development, **prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC J_c performance**




5400 mm^2

~10% margin
HL-LHC

~1.7 times less SC

3150 mm^2

**~10% margin
FCC ultimate**

FCC conductor development collaboration:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **Bruker, Germany, Luvata Pori, Finland**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea, Columbus, Italy**
- **University of Geneva, Switzerland**
- **Technical University of Vienna, Austria**
- **SPIN**, **Italy, University of Freiberg, Germany**

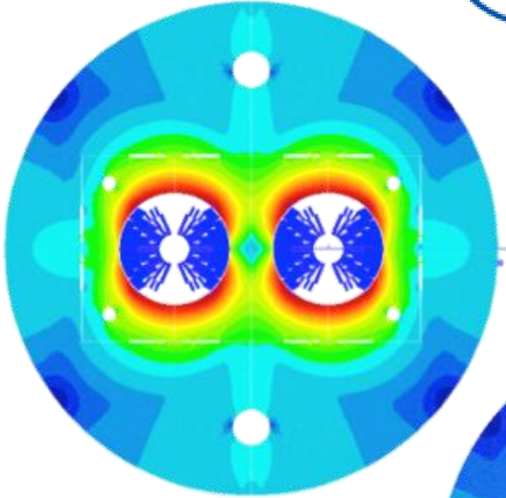
2019/20 results from US, meeting FCC J_c specs:

- **Florida State University:** high-J_c Nb_3Sn via Hf addition
- **Hyper Tech /Ohio SU/FNAL**: high-J_c Nb_3Sn via artificial pinning centres based on Zr oxide.

16 T dipole design activities and options

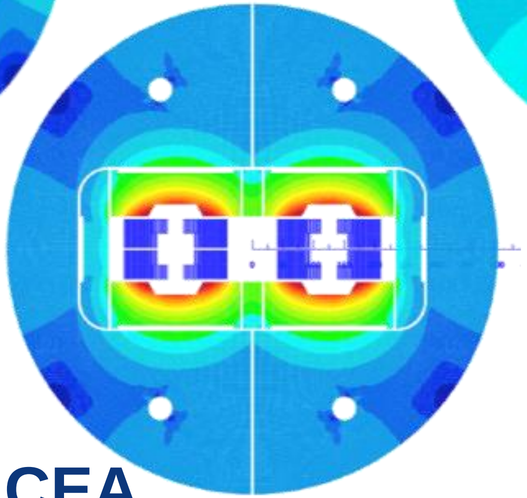
H2020

Cos-theta



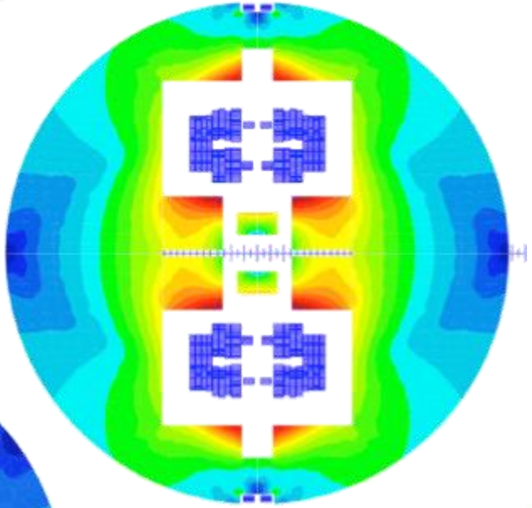
INFN

Blocks



CEA

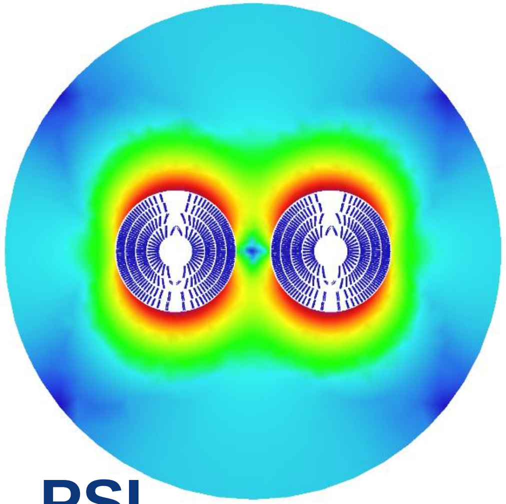
Common coils



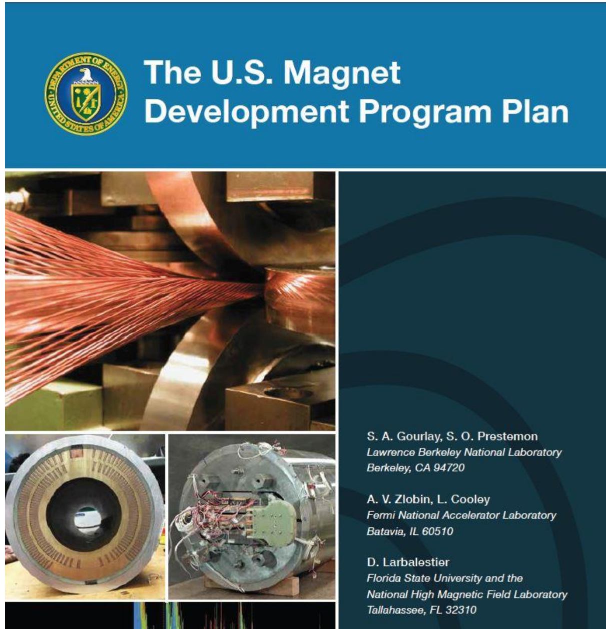
CIEMAT

Swiss contribution

Canted Cos-theta



PSI

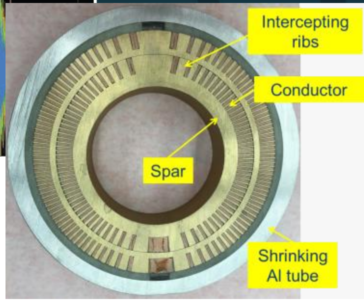


The U.S. Magnet Development Program Plan

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

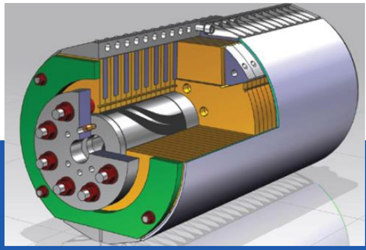
A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

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



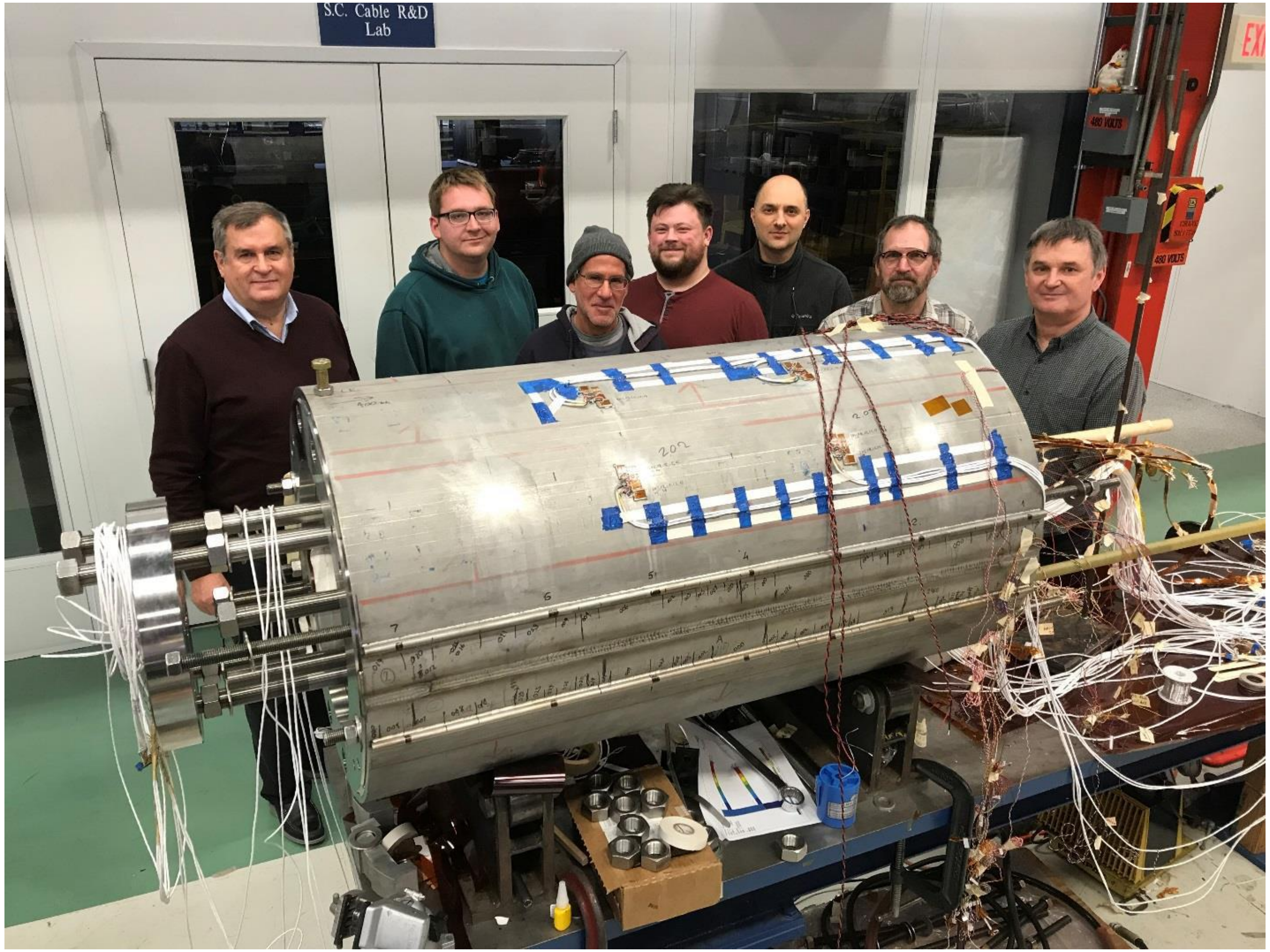
LBNL

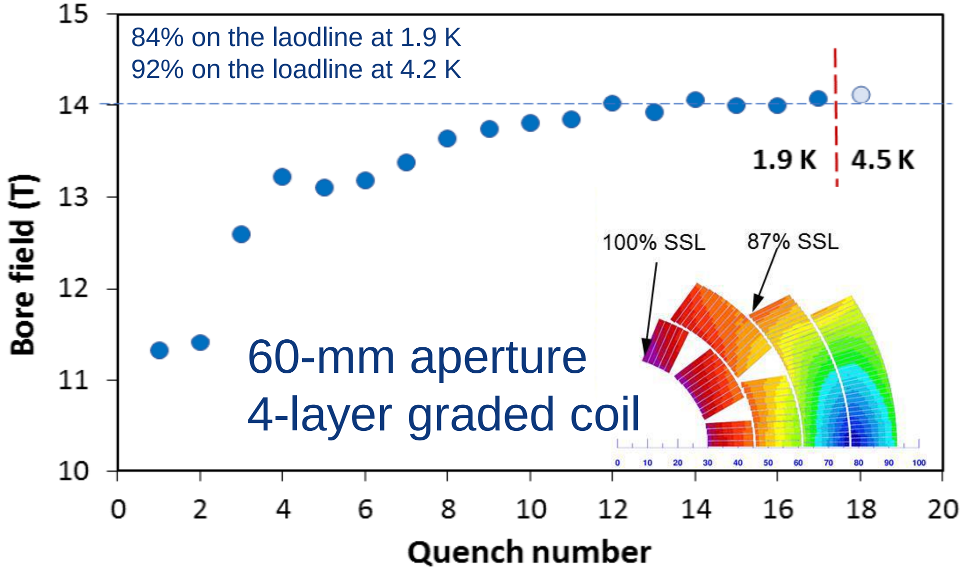
FNAL



Short model magnets (1.5 m lengths) will be built until 2025

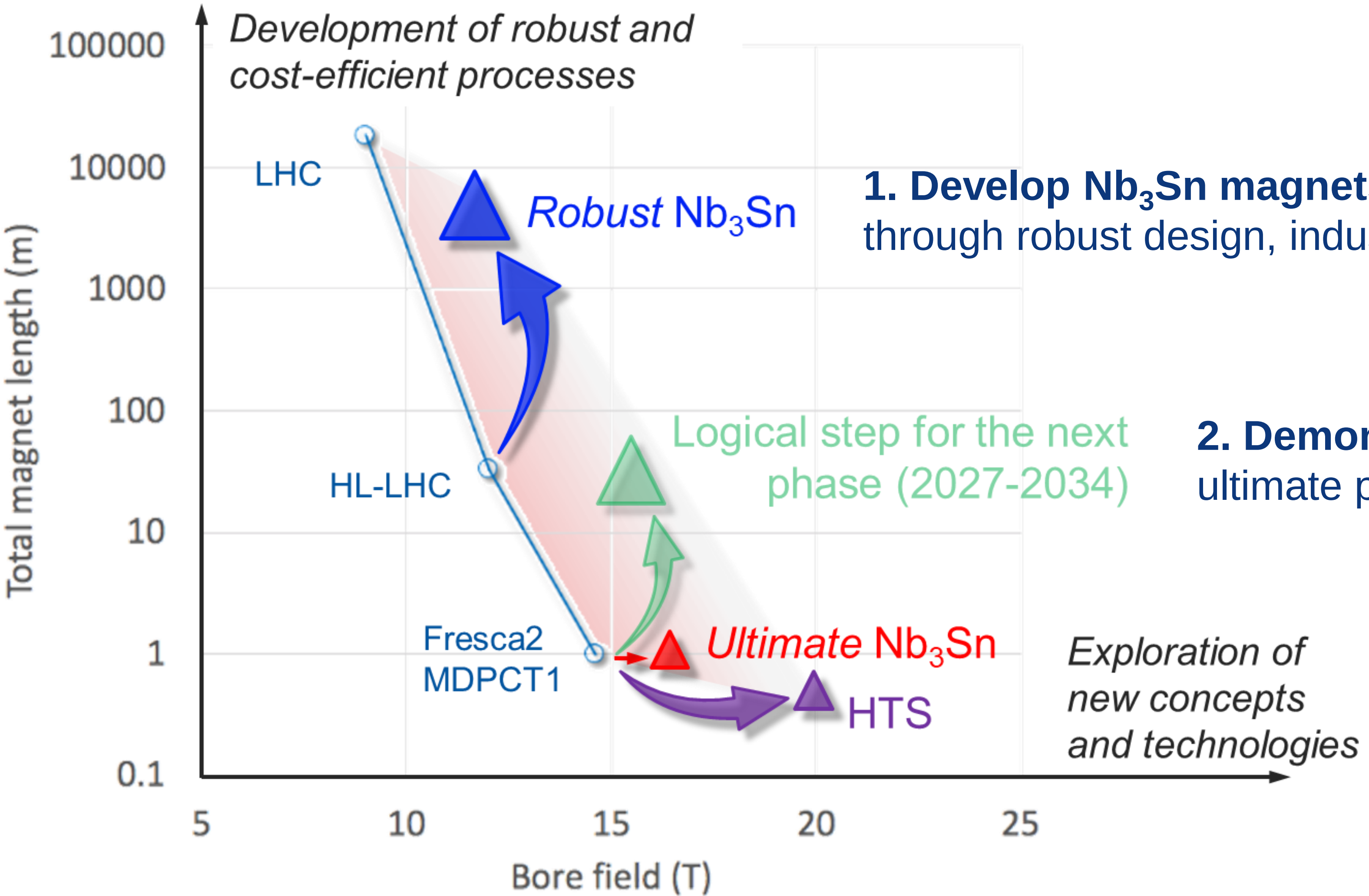
US – MDP: 14.5 T magnet tested at FNAL





- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

High Field Magnet program goals until 2027



1. **Develop Nb$_3$Sn magnets for collider-scale production**, through robust design, industrial processes and cost reduction

2. **Demonstrate Nb$_3$Sn full potential** in terms of ultimate performance (short model programs)

3. **Provide a proof-of-principle for HTS magnet technology**

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Take home messages

- FCC-ee is first stage of FCC integrated programme; first physics ~2040
- FCC-ee design incorporates **many lessons from recent & present e^+e^- colliders,** and goes further! SuperKEKB demonstrates key concepts
- FCC-ee = **efficient and sustainable collider at the e^+e^- energy frontier**: **highest luminosity per input power, highest luminosity per construction cost, most precise energy calibration, and ultimate upgrade potentials (ERL-based FCC-ee, 100 TeV FCC-hh, …)**
- Prototypes of FCC-ee key components by 2025
- **Superconducting cable & high-field magnet programme** prepares for 100 TeV proton-proton collider, FCC-hh, in the same tunnel, to begin operation around ~2060