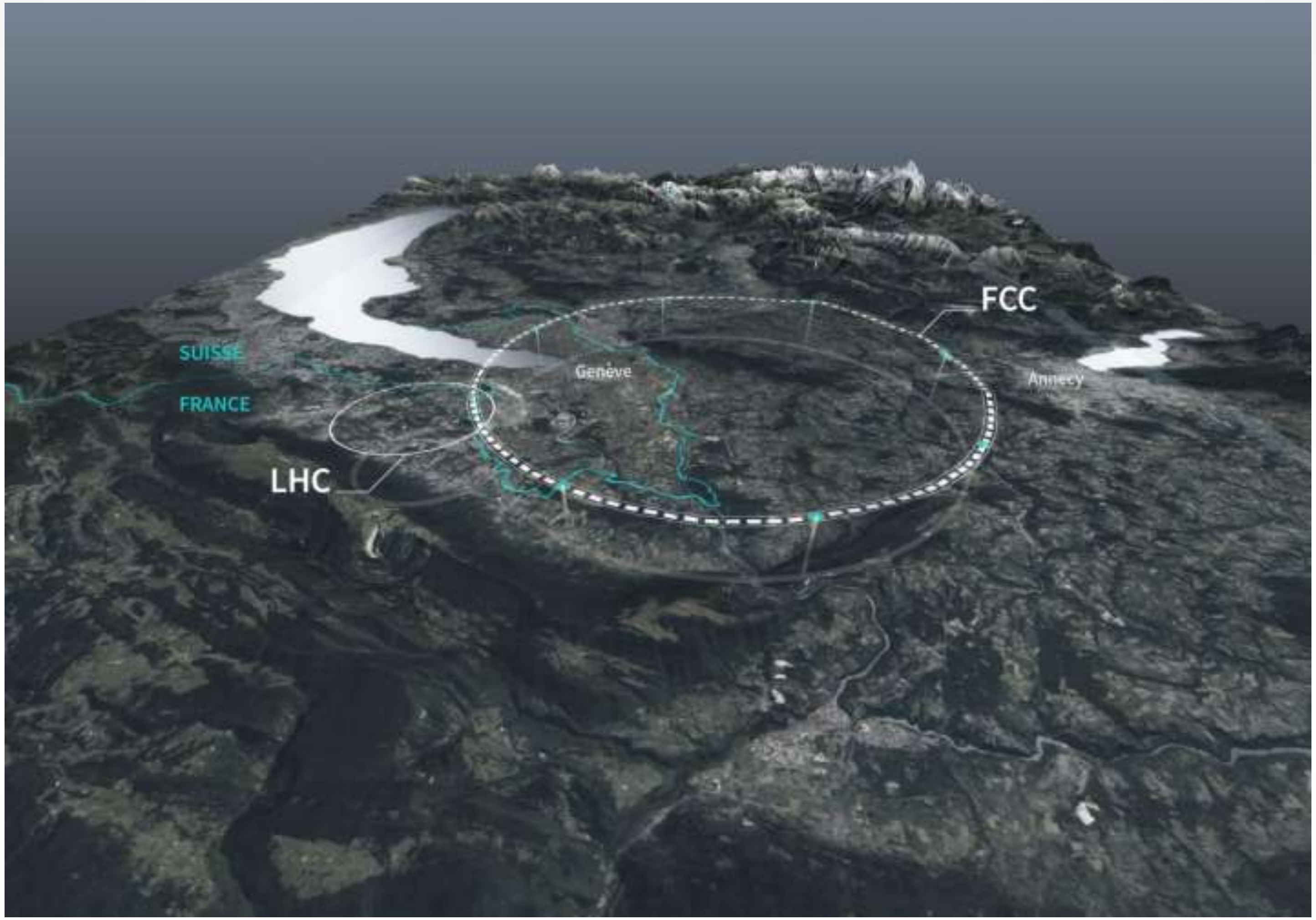


Highlights: FCC Accelerator Talks

The 2nd US FCC Workshop, MIT, 03/27/24

Vladimir SHILTSEV (NIU)

with contributions from:
M.Benedikt, M.Minty,
K.McGee, M.Boscolo,
P.Raimondi, J.Seeman,
M.Chamizo-Llatas, K.Amm,
E.Gianfelice-Wendt,
F.Zimmermann, I.Agapov,
J.Qiang, X.Huang,
A.Novokhatski, et al

FCC Feasibility Study – Summary and outlook

M. Benedikt

- **The first half of the FCC Feasibility Study has been completed with the mid-term review:**
  - placement & layout was defined, and entire project adapted to the new geometry
  - dialogue with local-regional actors and stakeholders for implementation established and ongoing
  - all deliverables met, list of recommendations towards final Feasibility Study
  - ***cost review – successful (remarkable "total cost stability")***
- **Next milestone is completion of the FCC Feasibility Study by March 2025 to enable advancing project decision and project start date:**
  - Complete technical work for FCC FS by end 2024
  - Full design iteration in view of technical and cost optimisation of entire project.
  - Update of cost estimate
  - Further development of an affordable funding model and related governance implications (with Council).

Main goals during preparatory phase til 2031/32

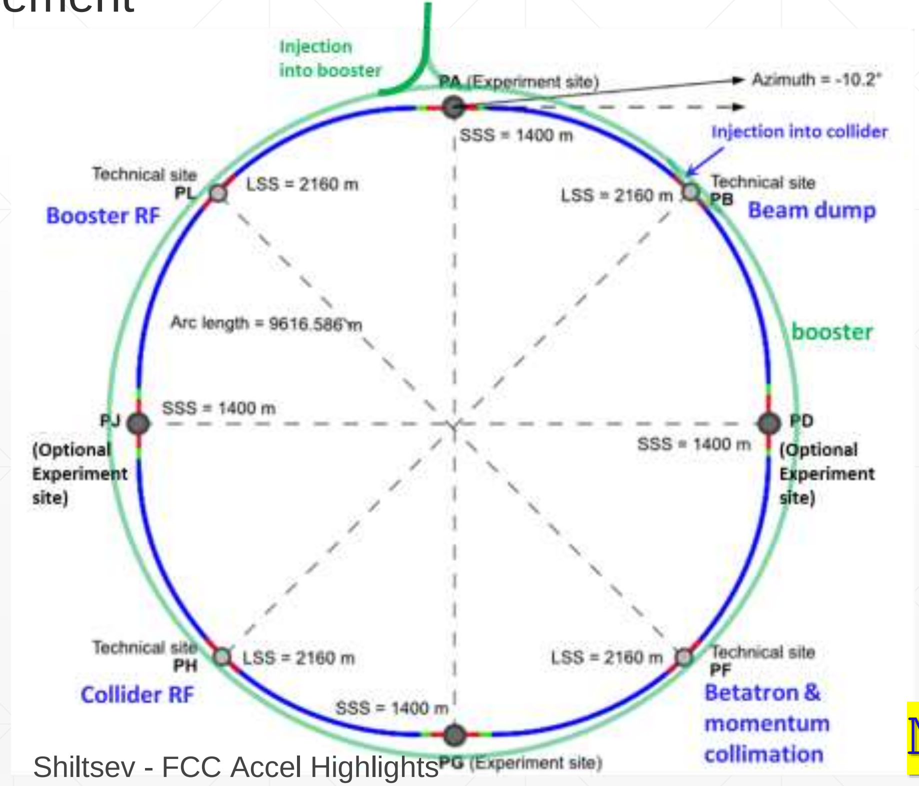
M. Benedikt

- **By 2027-2028, project approval, start of CE design contract:**
  - provision of requirements and specifications to enable CE tender design to start from 2028 (underground) and 2029 (surface)
  - requires overall integration study and designs based on technical pre-design of accelerators, technical infrastructure and detectors
  - refined input for environmental evaluation and project authorisation process.
- **By 2031-32, start of CE construction:**
  - CE groundbreaking
  - TDR to enable prototyping, industrialization towards component production

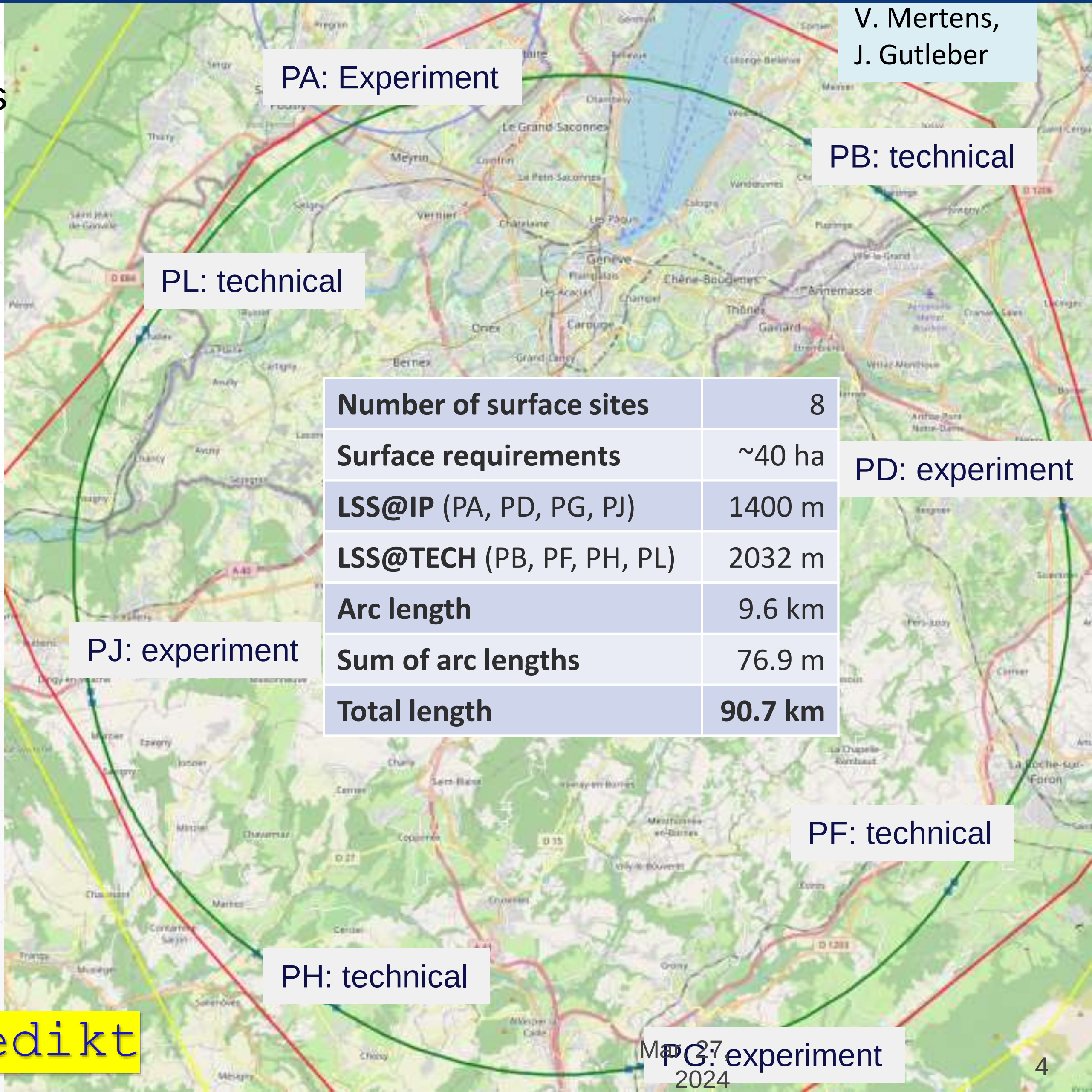
Optimized placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

Overall lowest-risk baseline: 90.7 km ring, 8 surface points, Whole project now adapted to this placement



M. Benedikt



V. Mertens, J. Gutleber

Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

Surface sites development and reservation of land-plots

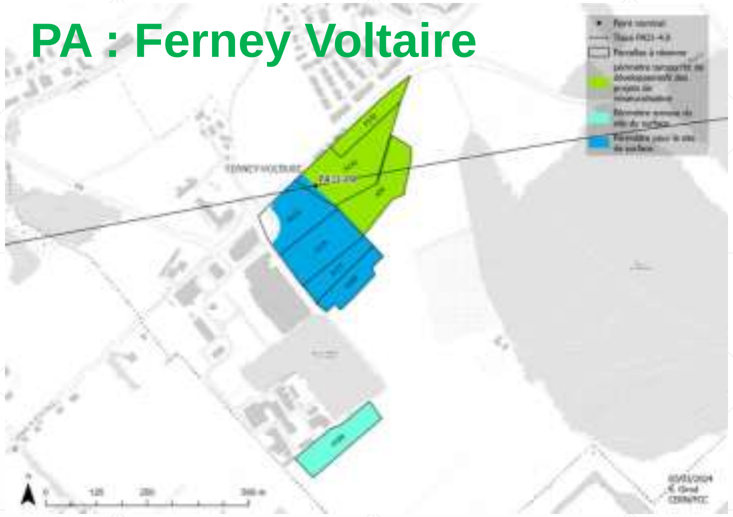
Meetings ongoing with all communes concerned by surface sites to identify individual land-plots for development of surface site layout and land reservation.

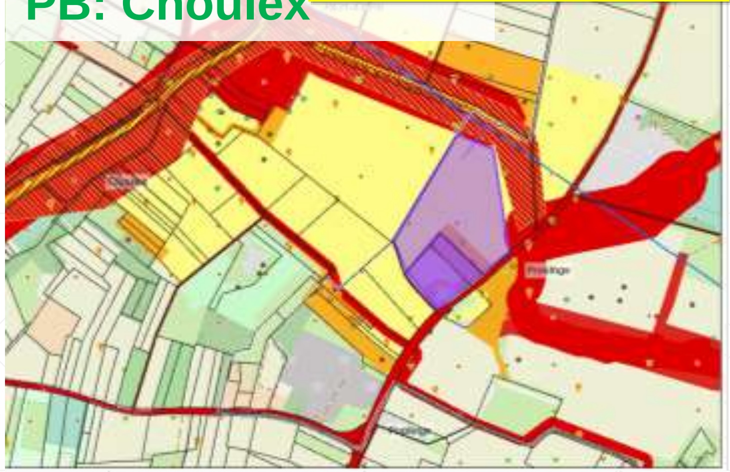
M. Benedikt

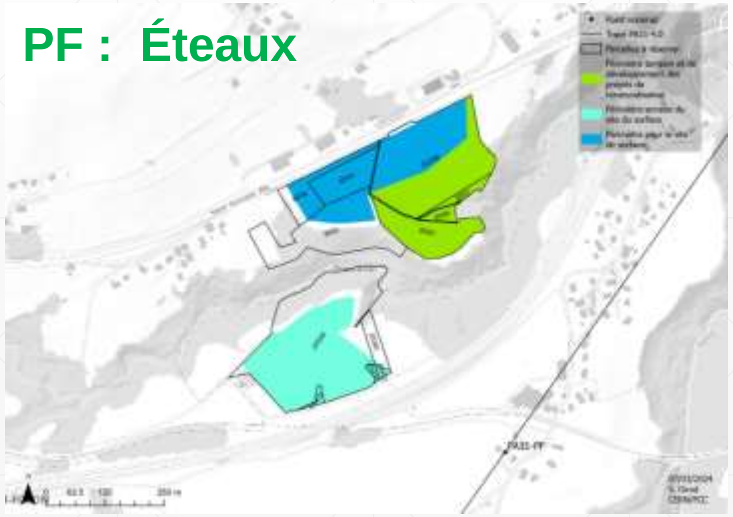
- **PA : Ferney Voltaire: 01/2024**
- **PB: Choulex : 12/2023**
- **PB: Presinge : 01/2024, plenary session with commcouncil 04/2024**
- **PD : Nangy: 05/2024**
- **PF : Éteaux : 03/2024**
- **PG : Groisy / Charvonnex: 04/2024**
- **PH : Marlioz / Cercier : 02/2024**
- **PJ : Vulbens / Dingy en Vuache : 09/2023, 01/2024**
- **PL : Challex: 03/2024, further meetings in Q2/24 to identify best site location**

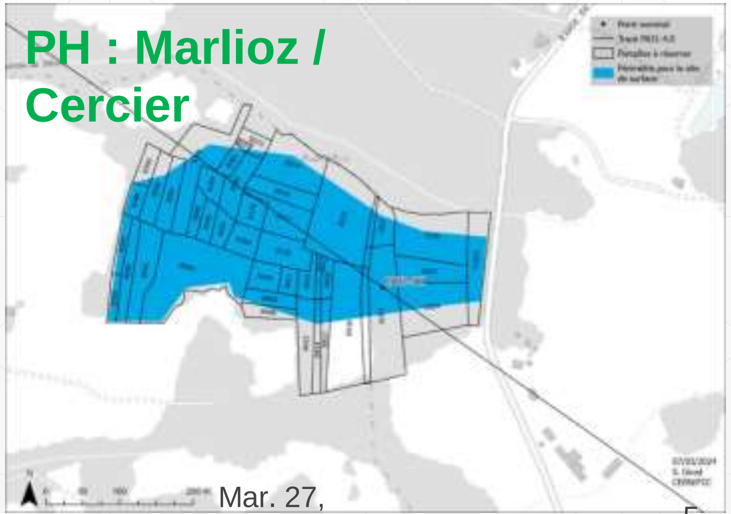
Green: parcelles identified and agreed

Blue: ongoing


PA : Ferney Voltaire


PB: Choulex


PF : Éteaux


PH : Marlioz / Cercier

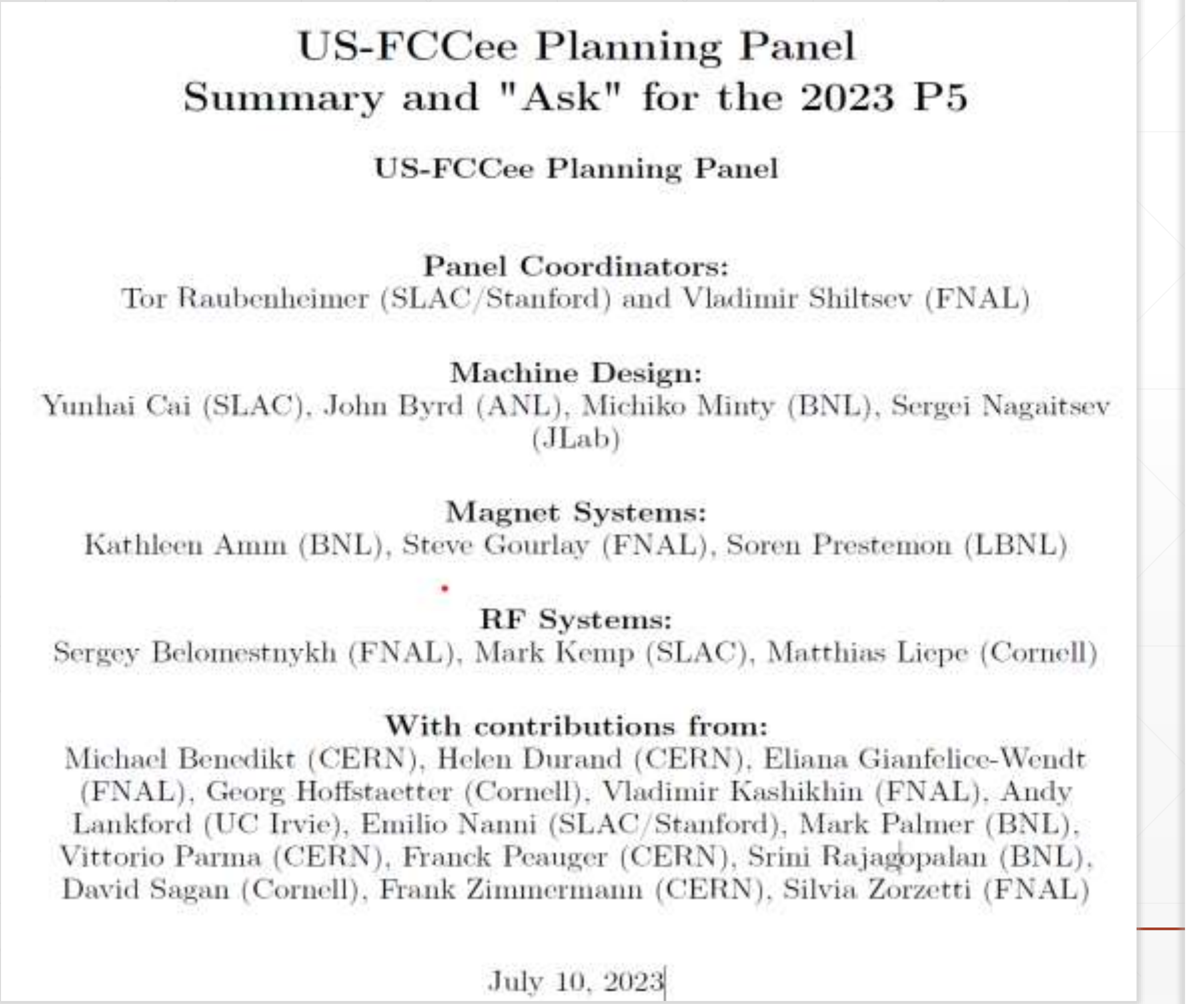
Accelerators at the FCC Week

- Expected significant participation of Accelerator experts from the US
- >40 talks, Full spectrum of topics will be covered:
  - FCC-ee baseline design & optics, top-up
  - Collimation, Optics alternatives & variants
  - Collective Effects
  - FCC-ee optics correction & tuning
  - FCC-ee injector incl. booster
  - FCC-ee code development and other themes
  - MDI (2 - jointly with PED)
  - EPOL (2 - jointly with PED)
  - FCC-hh
  - SRF (3)
  - Accelerator Technical Design & R&D
  - FCC-ee magnet development in the US

Last Year (pre-*P5*) Planning: US-FCC

CERN Timeline*: approved **2028**, start civil **2032**, install'n **2041**, beam **2045**

US Timeline**: CD0 ~**2029**, CD1 **2030/31**, CD2 **2033/34**, CD4 **2046/47**



US-FCCee Planning Panel
Summary and "Ask" for the 2023 P5

US-FCCee Planning Panel

Panel Coordinators:
Tor Raubenheimer (SLAC/Stanford) and Vladimir Shiltsev (FNAL)

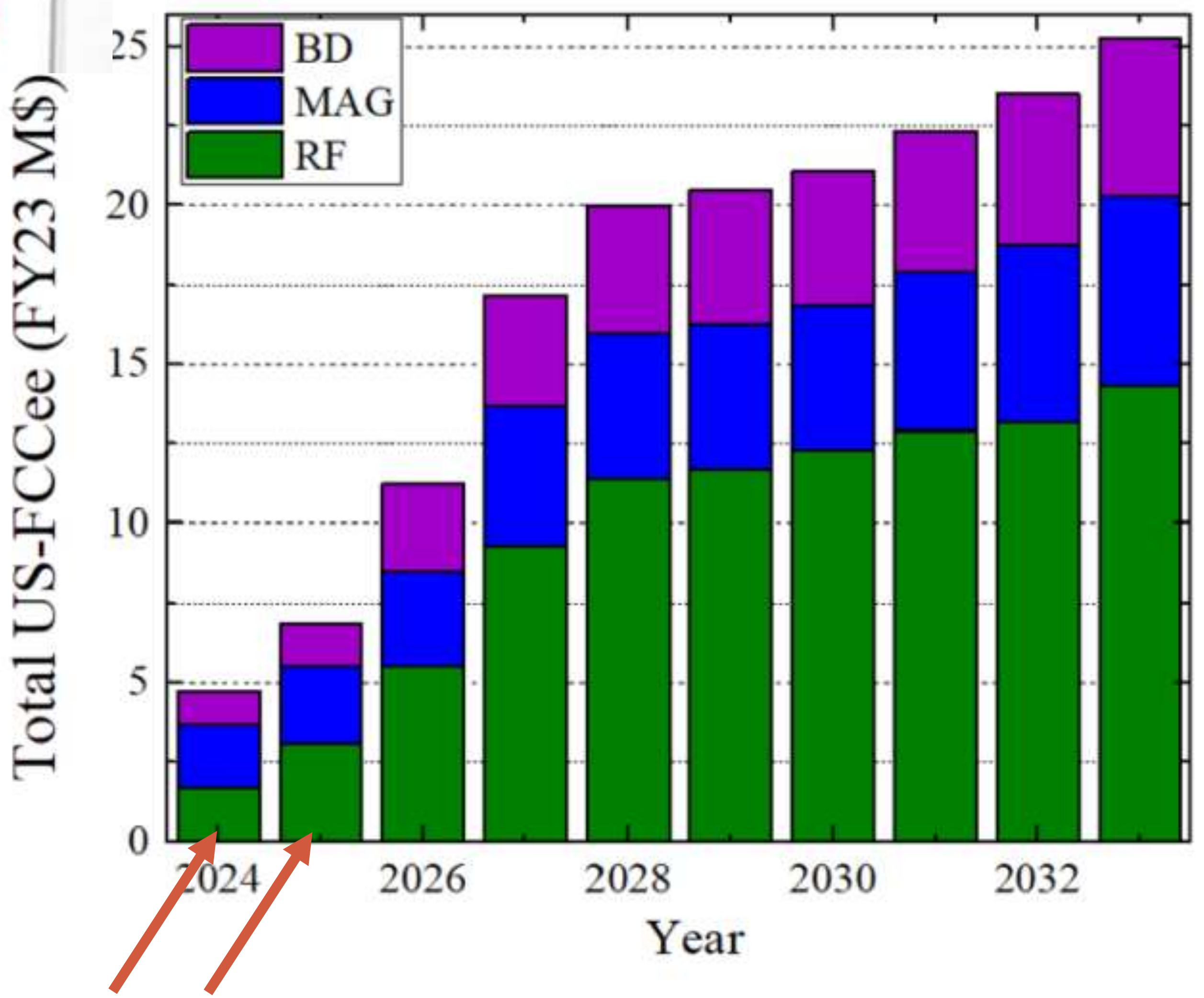
Machine Design:
Yunhai Cai (SLAC), John Byrd (ANL), Michiko Minty (BNL), Sergei Nagaitsev (JLab)

Magnet Systems:
Kathleen Amm (BNL), Steve Gourlay (FNAL), Soren Prestemon (LBNL)

RF Systems:
Sergey Belomestnykh (FNAL), Mark Kemp (SLAC), Matthias Liepe (Cornell)

With contributions from:
Michael Benedikt (CERN), Helen Durand (CERN), Eliana Gianfelice-Wendt (FNAL), Georg Hoffstaetter (Cornell), Vladimir Kashikhin (FNAL), Andy Lankford (UC Irvie), Emilio Nanni (SLAC/Stanford), Mark Palmer (BNL), Vittorio Parma (CERN), Franck Peauger (CERN), Srini Rajagopalan (BNL), David Sagan (Cornell), Frank Zimmermann (CERN), Silvia Zorzetti (FNAL)

July 10, 2023



? ?

Figure 2: US FCC-ee pre-CD2 work cost estimates (FY23 $).

Last Year (pre-*P5*) Planning: US-FCC

Proposed scope - **RF Systems**

1) 800 MHz SRF for Booster and Collider (28 CMs → 244 CMs)
2) 800 MHz RF power sources (klystrons >80% eff.)
3) RF for 6-20 GeV e+/e- injector linac (C3 tech.)

Proposed scope - **Magnets Systems**

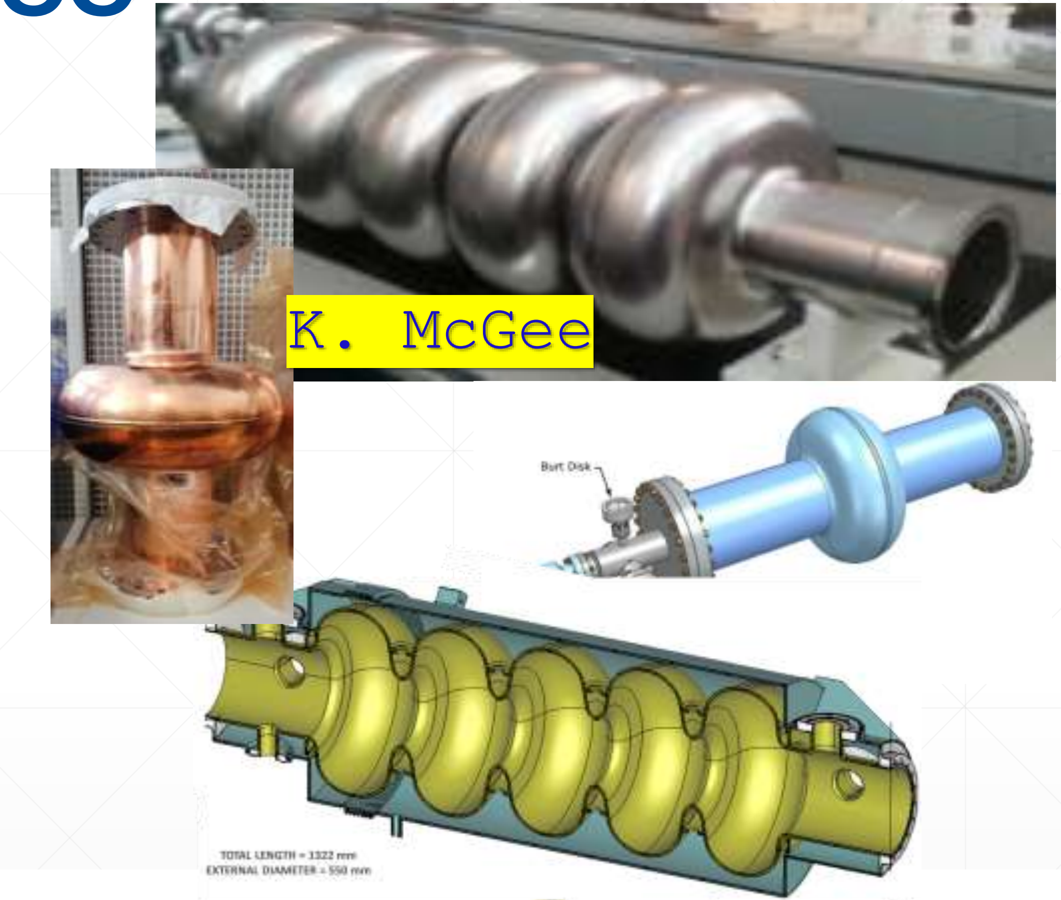
1) IR magnets and cryostats (for 4 IRs)
2) Collider ring and Booster ring magnets (low field)
3) FCC-hh collider ring magnets (14-20 T)

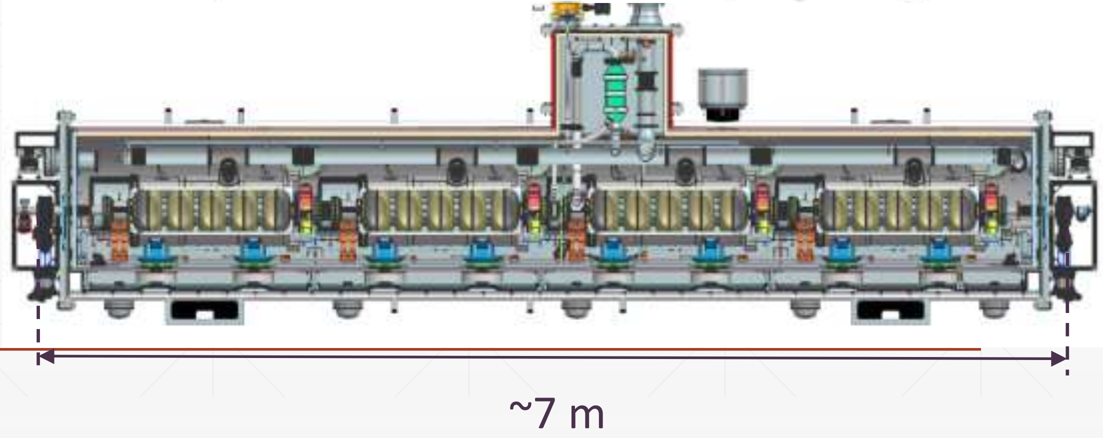
Proposed scope – **Machine Design and Instr.**

1) Interaction region design, and integrated machine design
2) Polarization (simul., wigglers, etc)
3) Beam Instrumentation (BPMs, feedback, etc)

US RF/SRF Developments for FCC

- Current US R&D aimed at achieving novel high quality-factor SRF cavities
  - Nb/Cu development @ 400 MHz for 4K operation
  - Bulk Nb development @ 800 MHz for 2K operation
    - 1-cell and 5-cell FCC prototype cavities undergoing advanced surface treatment and high-power RF testing
    - Integrated Helium jacket and double-lever tuner design ongoing
- Active FCC CM design effort drawing on the PIP-II experience

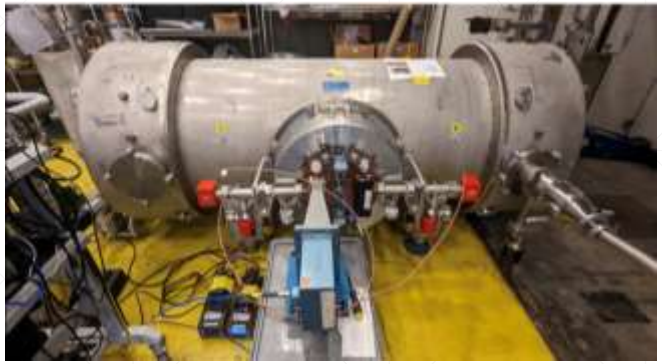


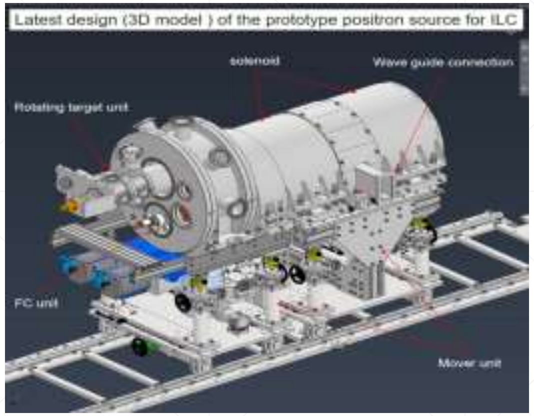


US RF/SRF Developments for FCC

- Multiple general R&D efforts ready to pivot to support FCC
  - Advanced High-Q studies: Nb3Sn development, SIS multilayer development
  - generic R&D efforts on alternative SRF superconductors, e.g., Nb_3Sn, at Cornell
- Electron-positron source/Cold-copper based injector
- High-efficiency RF power sources and modulators

Based on G. Eremeev's ECA, Jlab cavity work supported by R&D fund.





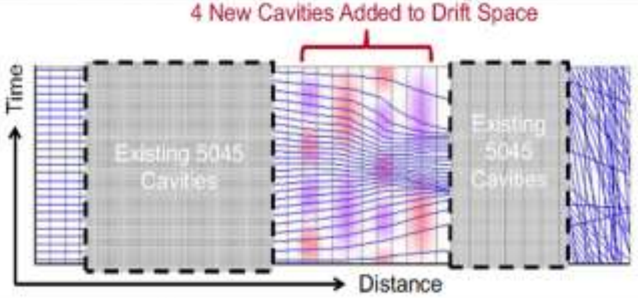
Wide Aperture S-band Injector Linac

$a/\lambda = 0.125$

K. McGee

SLAC BAC Prototype

S-band Retrofit +10% efficiency, 73 MW



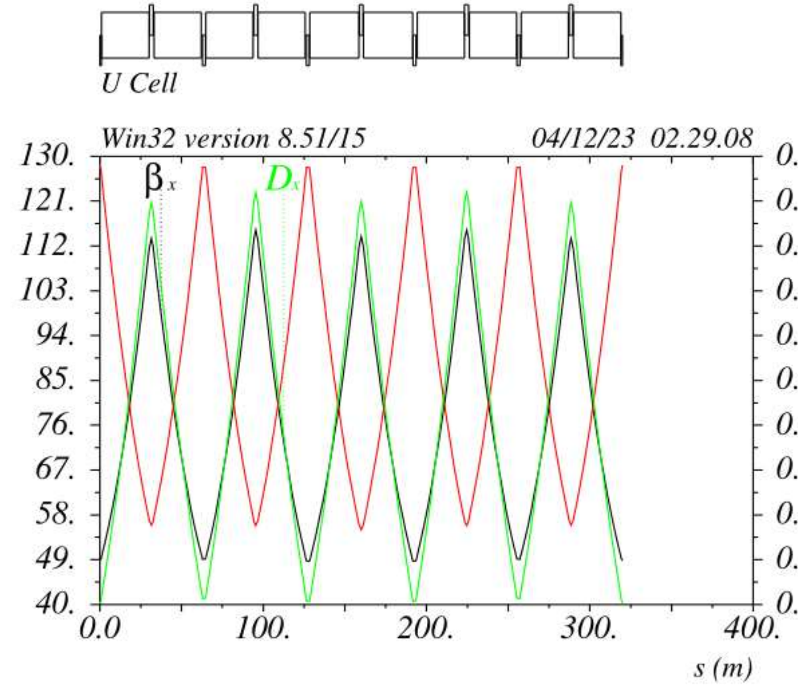
Many efforts are poised to significantly improve technological feasibility of the critical RF/SRF systems enabling the FCC...but time and funding must be invested ***now*** to realize these benefits!

LCCO - New Beam Optics Solution

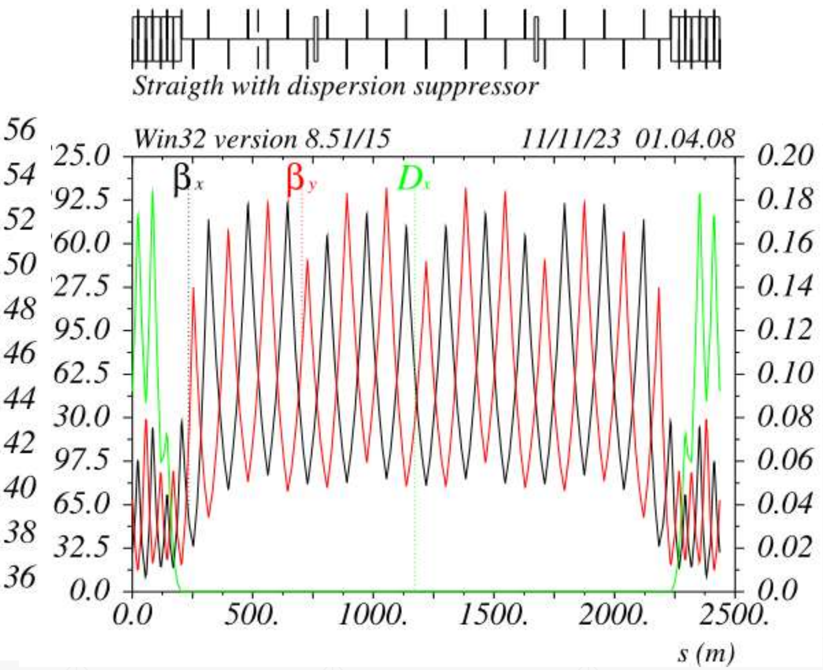
LCCO = Local Chromatic Correction Optics

P.Raimondi

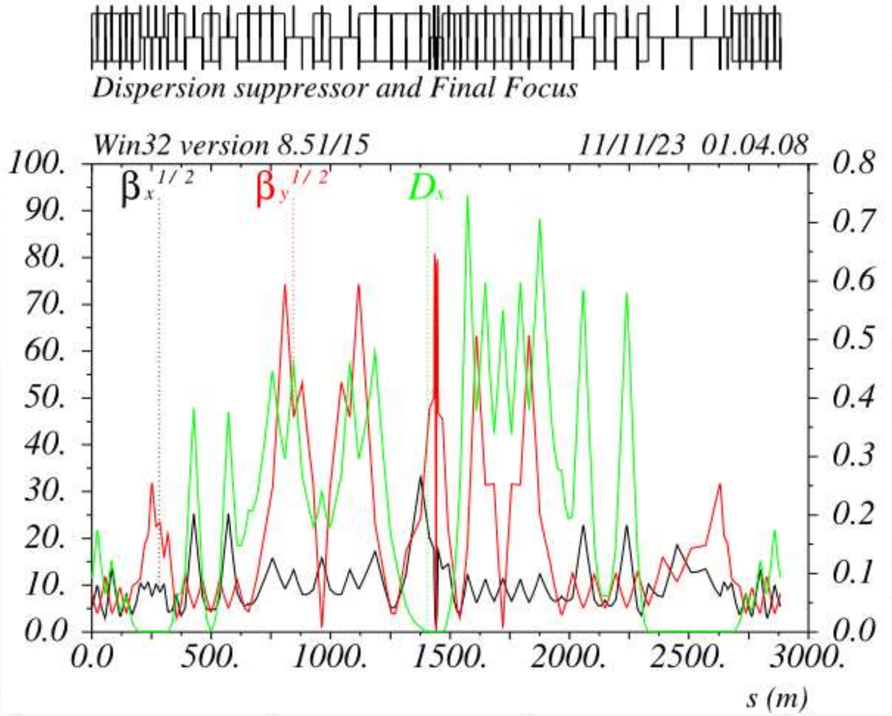
LCCO based on the development of optics solutions that allow/rely on chromatic and harmonic corrections as local as possible.



30 cells/octant



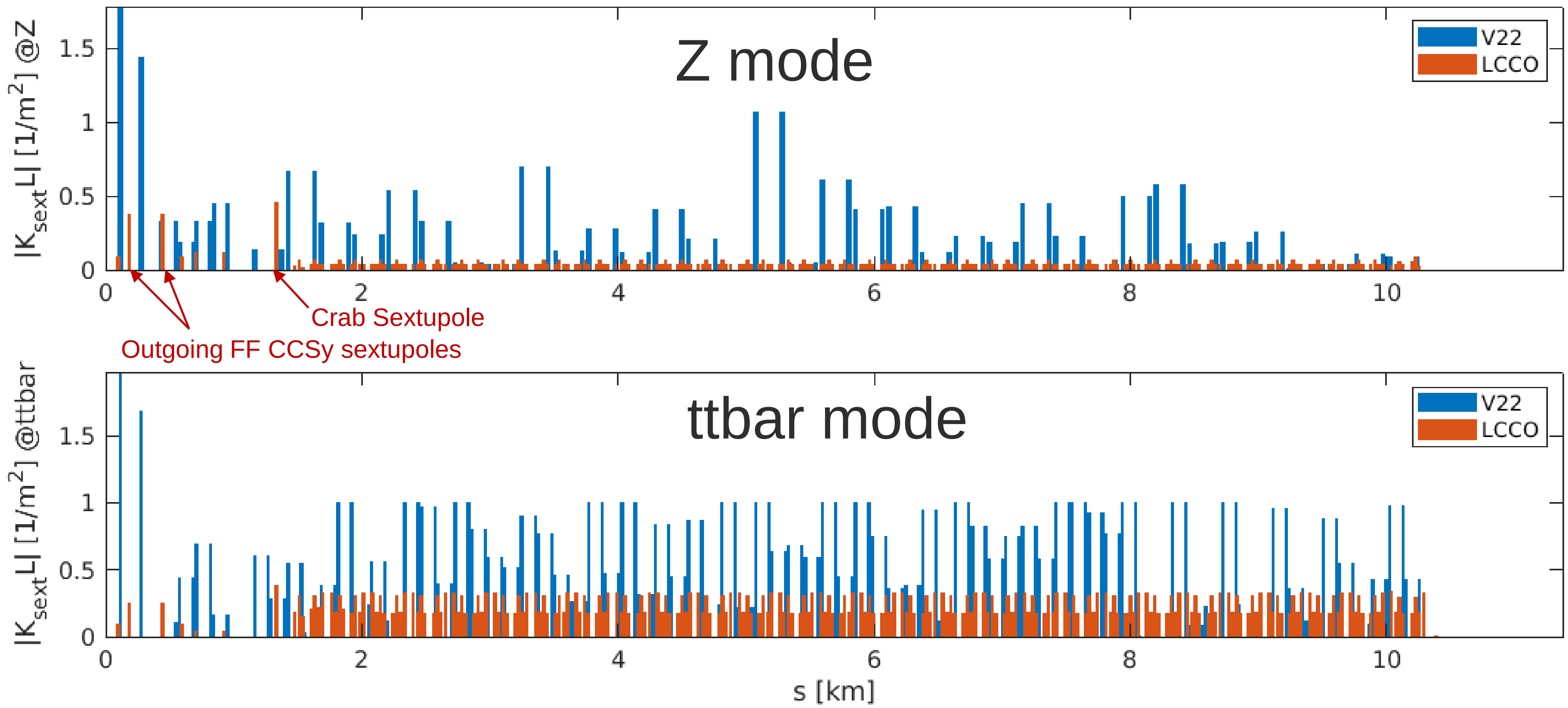
4 Long Straight Sections



4 Final Focus systems

Sextupoles gradients (1 octant)

P.Raimondi



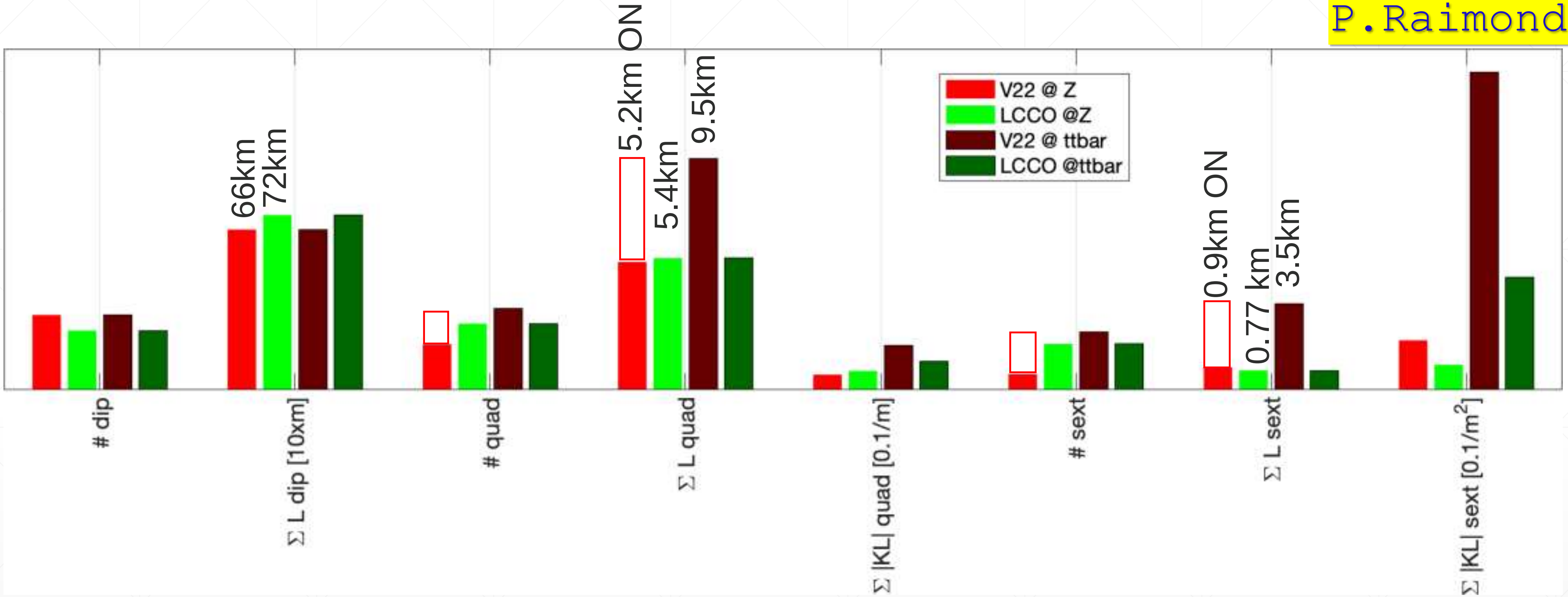
904 m
773 m

3506 m
773 m

Smaller sextupole gradients ➔ Usually better performances.

LCCO: # of magnetic elements and gradients

P.Raimondi



Including Crab sextupoles

Only magnet gradients change. White boxes for baseline correspond to magnet off at Z

LCCO needs about half total quadrupole length and ~4 times less total sextupole length

LCCO needs about 60% of BPMs and correctors wrt baseline as well

LCCO requires about 13% less RF power and voltage wrt baseline

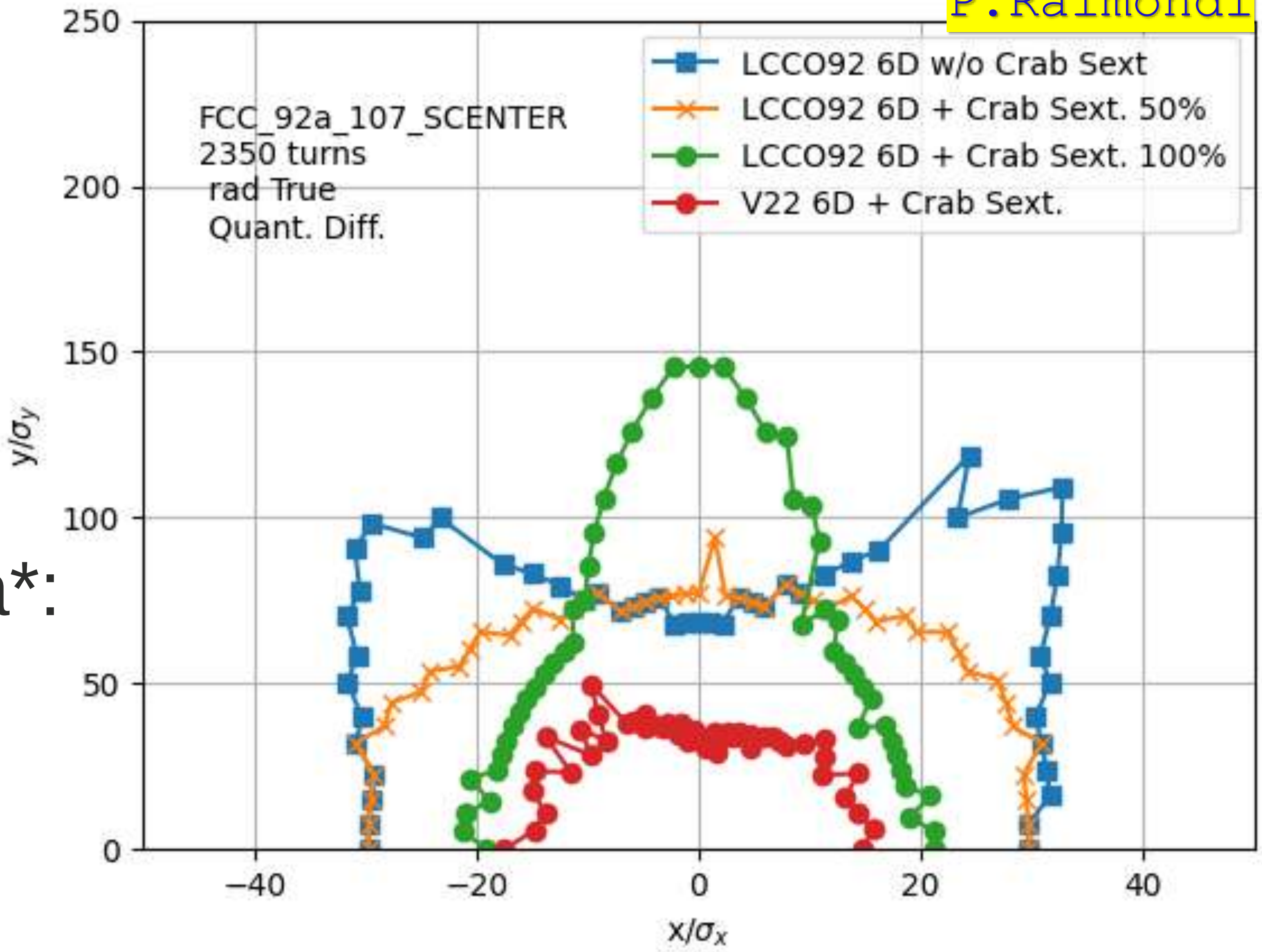
LCCO Improves Dynamic Aperture !

LCCO verr.92

Present baseline beta*:

β^*_h=10cm, β^*_v=0.7mm

P.Raimondi



Summary on the FCC ee IR Magnets Efforts/Plans in the US

K.Amm

Welcome

Kathleen Amm

Director of the National High Magnetic Field Laboratory

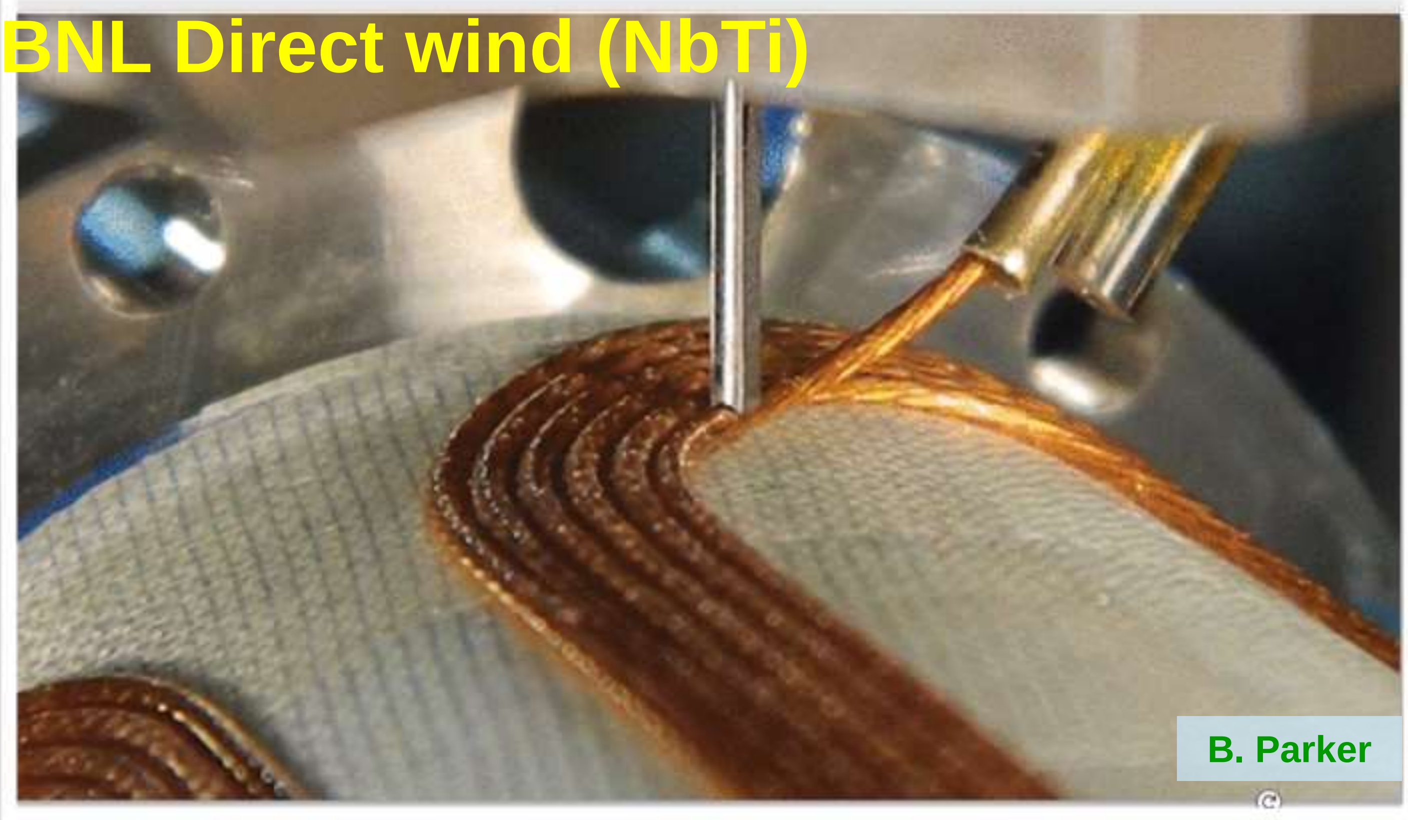
Summary on IR Magnets Efforts/Plans in the US

K.Amm /
M.Chamizo-Llatas

- US national labs have significant capabilities that they can utilize to make the FCC ee IR successful
  - Direct wind capability to address the tight spacing required for the correctors, BNL
  - Precise Magnetic field measurements and magnet alignment, FNAL
  - Superconducting magnet coil fabrication, FNAL, BNL
  - Magnet test facilities, BNL, FNAL, LBNL
  - RRR measurements and material characterization, LBNL
- The labs can provide extensive MDI/IR design capabilities including design, fabrication, alignment, magnet testing and measurements

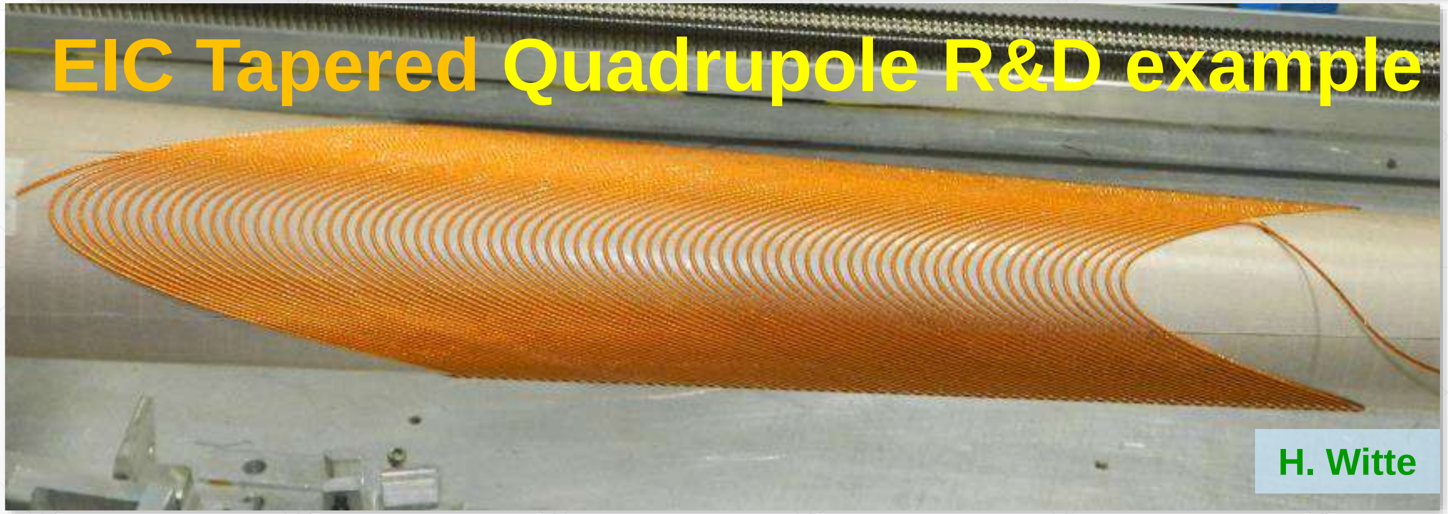

First FCC IR Prototype

M. Koratzinos (CERN)


BNL Direct wind (NbTi)

B. Parker

- In addition to main quad coils, FCC-ee needs a slew of correctors
- BNL Direct Wind process is natural for making the necessary correctors


EIC Tapered Quadrupole R&D example

H. Witte

K.Amm / M.Chamizo-Llatas

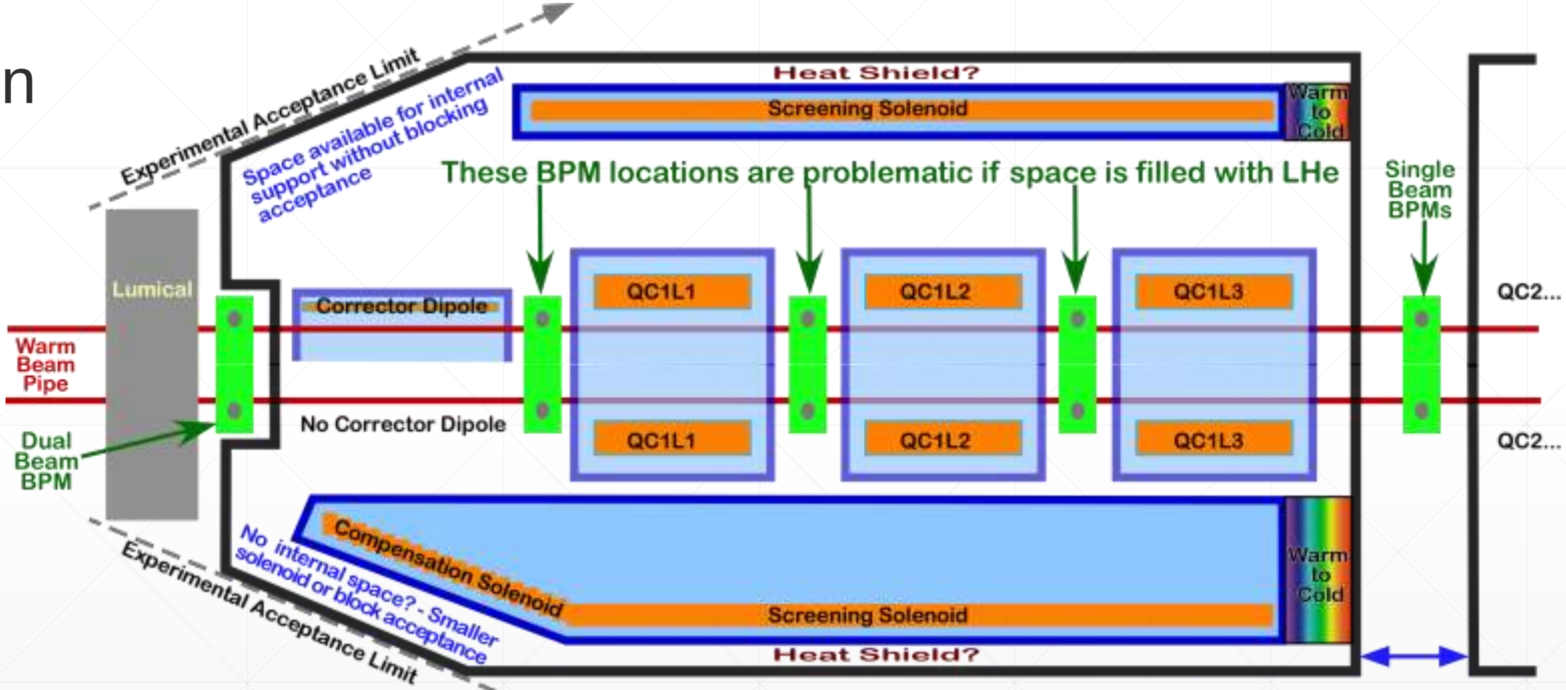
Topics for possible contribution for FCC-ee IR magnets

IR Magnet Design

- Anti-solenoid optimization
- IR quadrupole design
- IR corrector design
- Prototype & testing
- Quadrupole strength
- Compensation solenoid
- Optics studies

IR Cryostat Design

- Cold mass optimization
- Internal support structure
- Thermal management & BPM interface
- Installation support, vibration studies



Space between cryostats is used for support structure, cyrogenic and current feed points plus access to instumentation.

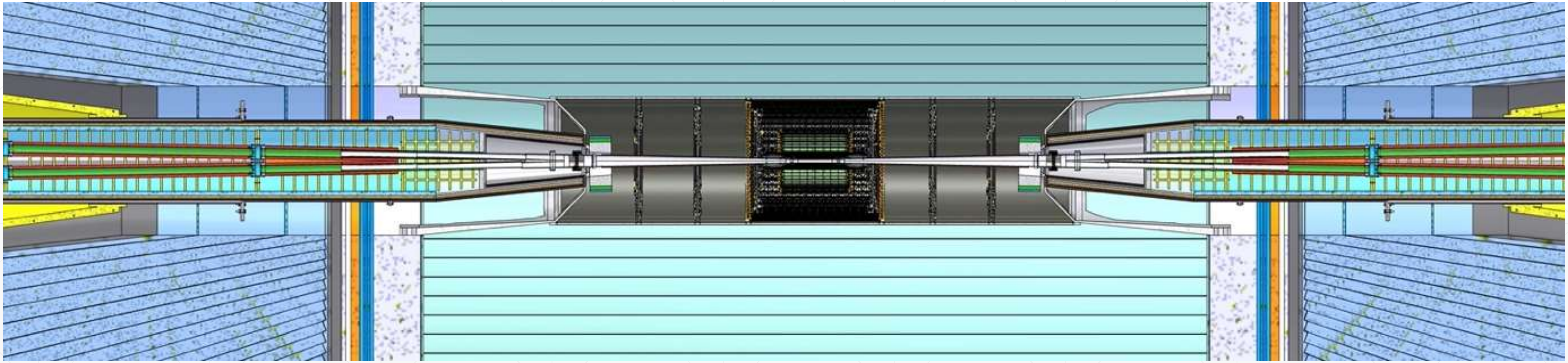
K.Amm / M.Chamizo-Llatas

FCCIS WP2 Task 2.3 Interaction Region & MDI Design

Significant progress on the IR mechanical design

- Vacuum chamber design and its cooling system,
- Lumical integration
- Bellows design
- Vertex design and integration
- Lightweight carbon support tube for the central vacuum chamber and the inner and outer vertex detectors

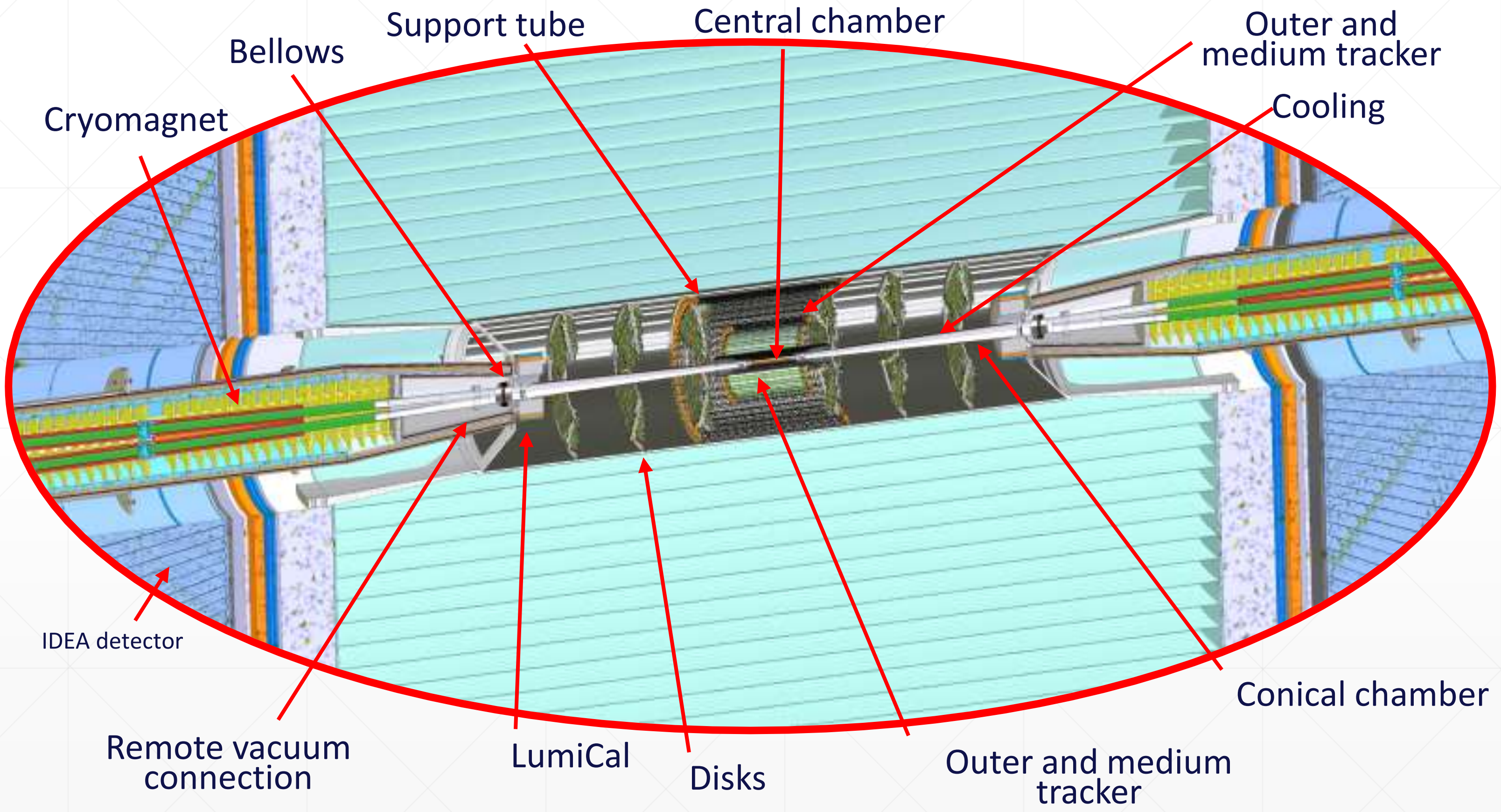
At this Workshop:
Talk by M.Boscolo (INFN)
Results from SLAC:
J.Seeman, A.Novokhatski, et al



Interaction region mechanical layout

FCC-ee Engineered Interaction Region

M.Boscolo



F. Fransesini

Design in continuous optimization:

- vacuum chamber copper cooling manifolds replaced by AlBeMet to minimize showers in the LumiCal

Inlet/outlet paraffin cooling for central chamber

- More advanced and detailed studies on vertex detector integration
- IR magnet system to be integrated
- Remote vacuum connection to be designed
- Crucial area: a full-scale mockup assembly has started

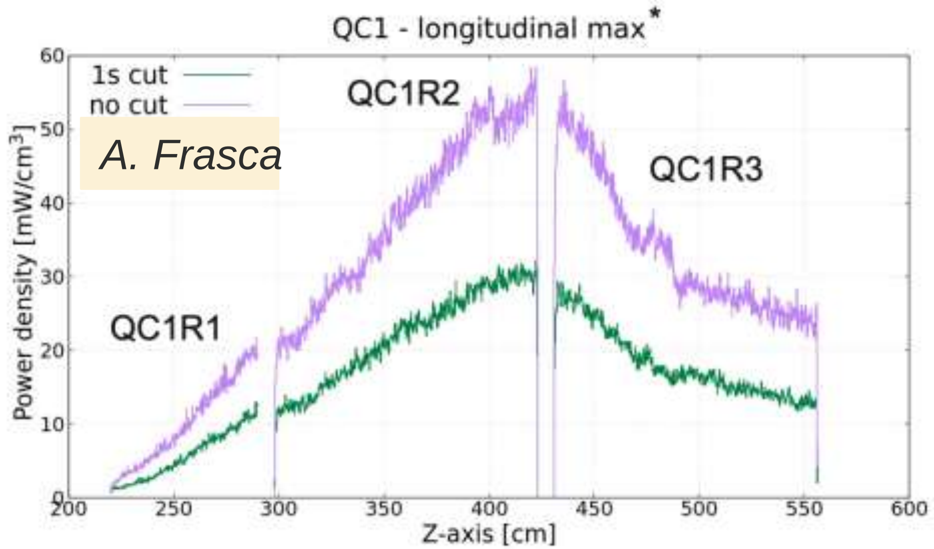
Ref: M. Boscolo, F. Palla, et al., *Mechanical model for the FCC-ee MDI,* EPJ+ Techn. and Instr., https://doi.org/10.1140/epjti/s40485-023-00103-7

Beam losses, Backgrounds & Radiation

M.Boscolo

- **Ongoing simulations on various background sources, few examples of recent updates below**

Fluka studies of Radiative Bhabhas



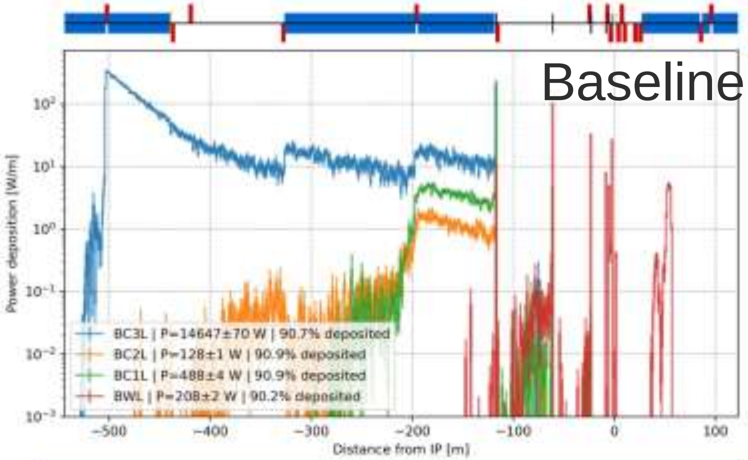
A. Frasca

*rφz mesh: bins 0.5mm*2°*2mm

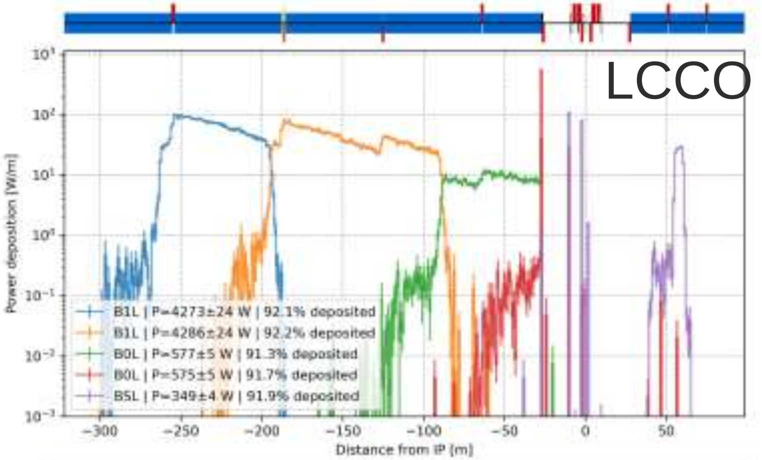
- Estimated power deposition **~10 mW/cm³**
- Estimated dose **~10 MGy/y** inside the superconducting FFQs
- **Internal shielding must be developed to avoid quenches**

Synchrotron Radiation studies

K. Andre



Synchrotron radiation from BC3L do not propagate further than the 2nd SR collimator. Only radiation from BWL reach the IP and hit BC1R. This conclusion may change once **x-ray reflection will be implemented**.



Synchrotron radiation from B1L do not propagate further than 75m from the IP. Radiation from B0L reach the first SR collimator. BSL emits photons that go beyond the IP.

LCCO-V23 shows better results regarding the SR from the transverse tail but needs more collimation to mitigate the SR from the beam core (especially in the mask)

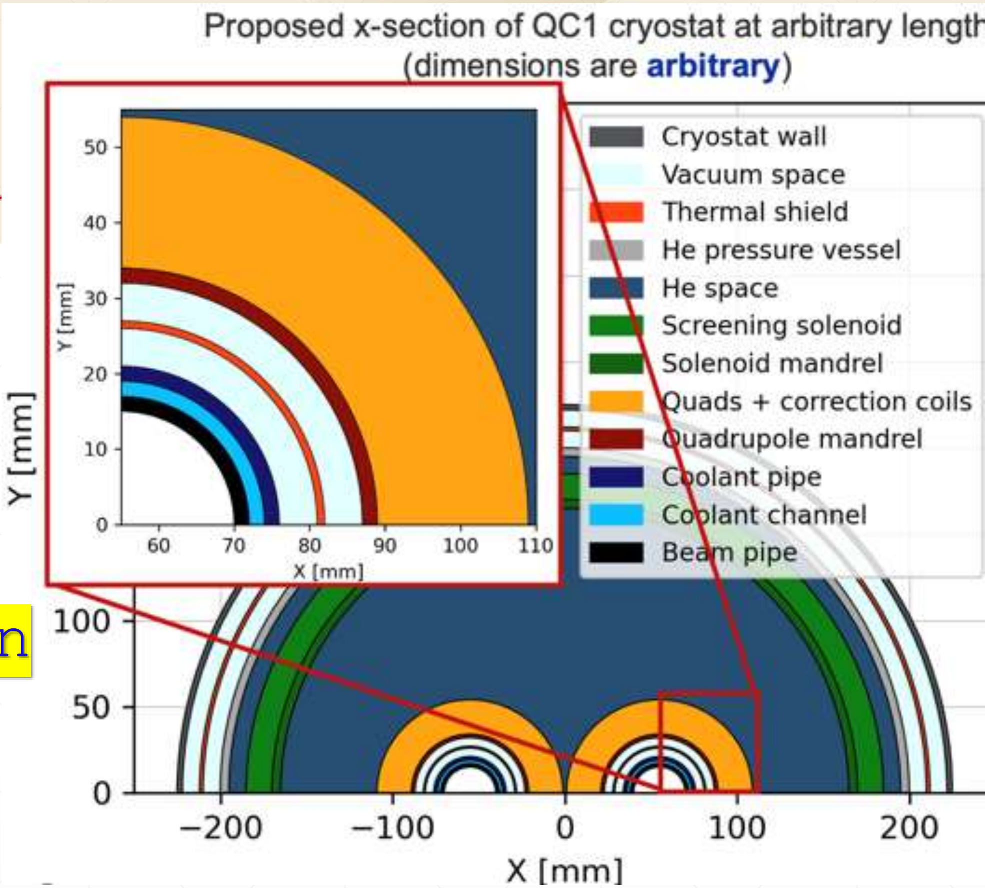
Baseline-V23 shows better results regarding the SR from the beam core because the SR collimation is more effective (and mature) but the SR from the transverse tail causes more power deposition close to the IP.

SLAC: IR Magnets and Cryostats

(J. Seeman, T.Raubenheimer, A.Novokhatski, M.Sullivan…)

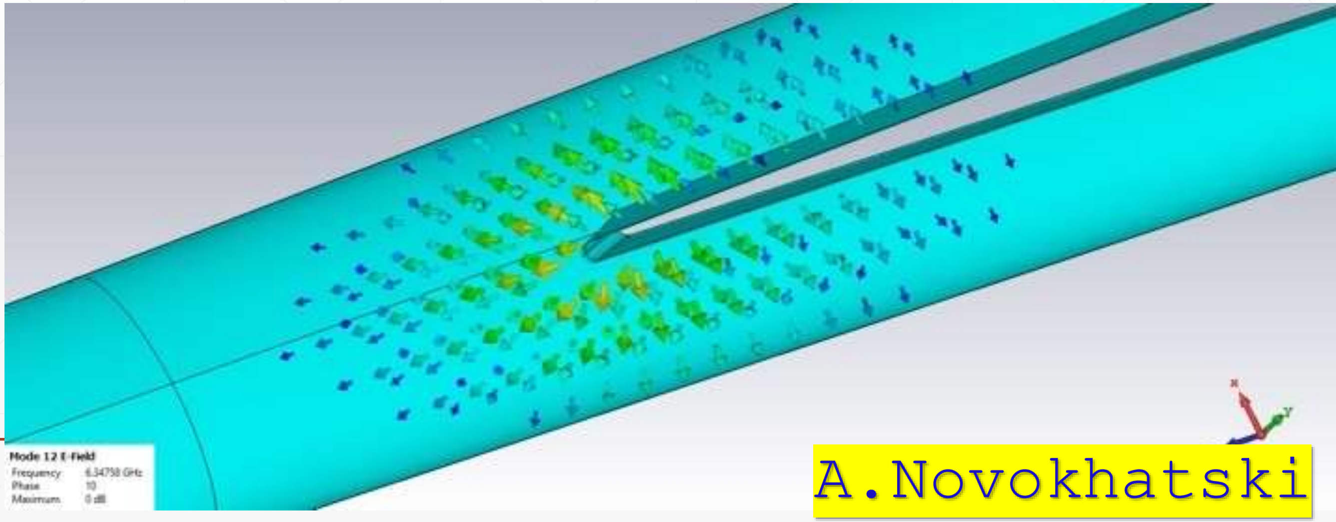
M. Boscolo, M. Koratzinos, B. Parker,
P. Borges de Sousa, F. Fransesini, …

- SC magnet specifications, trim coils
- Magnet dimensions, layout, tolerances →
- Cryostat, cryogenics, instrumentation
- Supports, expansion, power leads


Proposed x-section of QC1 cryostat at arbitrary lengt
(dimensions are **arbitrary**)

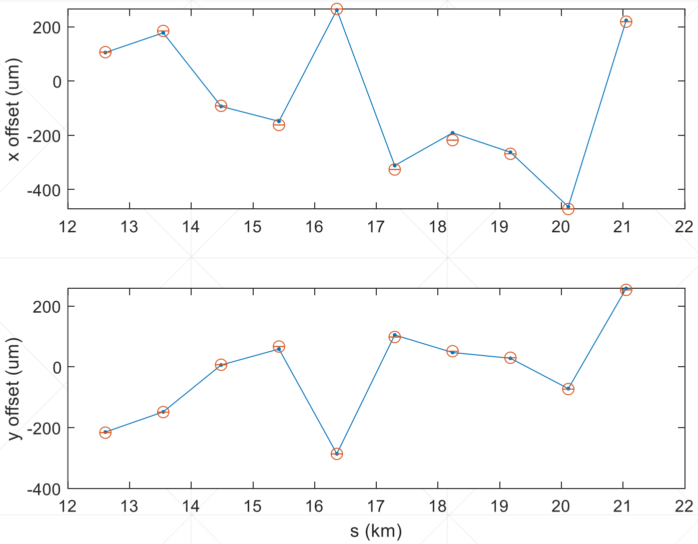
J.Seeman

- IP vacuum chamber designs, layout
- Wake-field calculations, mitigations →
- Lumi-Cal layout, location, masking
- Beam loses, power deposition, damage



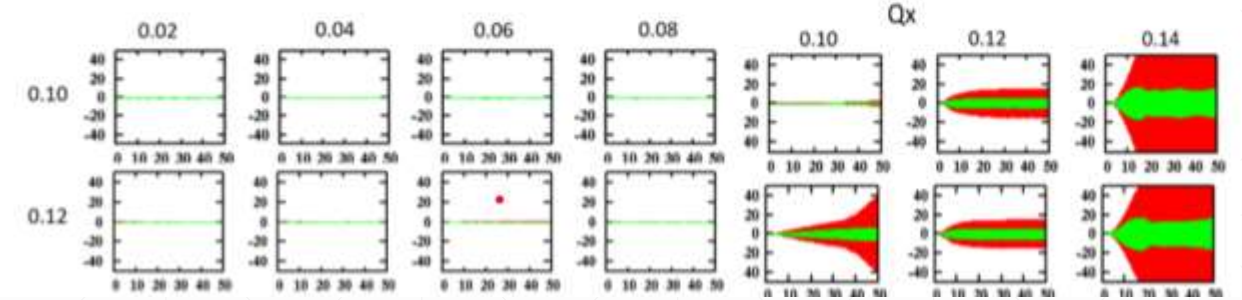
A.Novokhatski

Other Design Effort in the US:



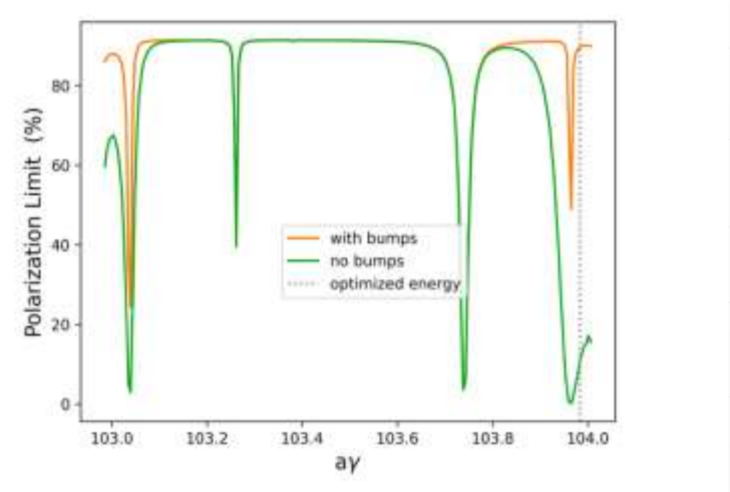
- Beam-Based Alignment strategy

– **SLAC** (X.Huang)



- Beam-Beam Simulations

– **LBNL** (J.Qiang)



- Polarization

– **FNAL & Cornell**

(E.Gianfelice-Wend, and D.Sagan)

FCC-ee / ILC Synergies: IR Quadrupole Stability

Courtesy Brett Parker

Nano-beam position stability requirements:

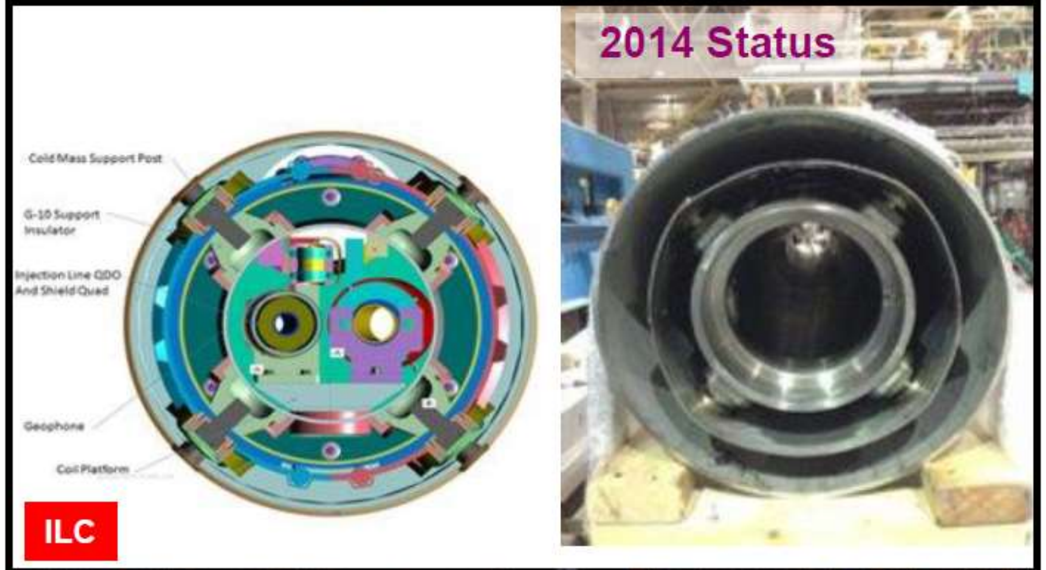
- ILC IP $\sigma_{vert} = 3\,nm$ → 50 nm stability with BB feedback
- FCC-ee $\sigma_{vert} = 35\,nm$ → ~35 nm stability

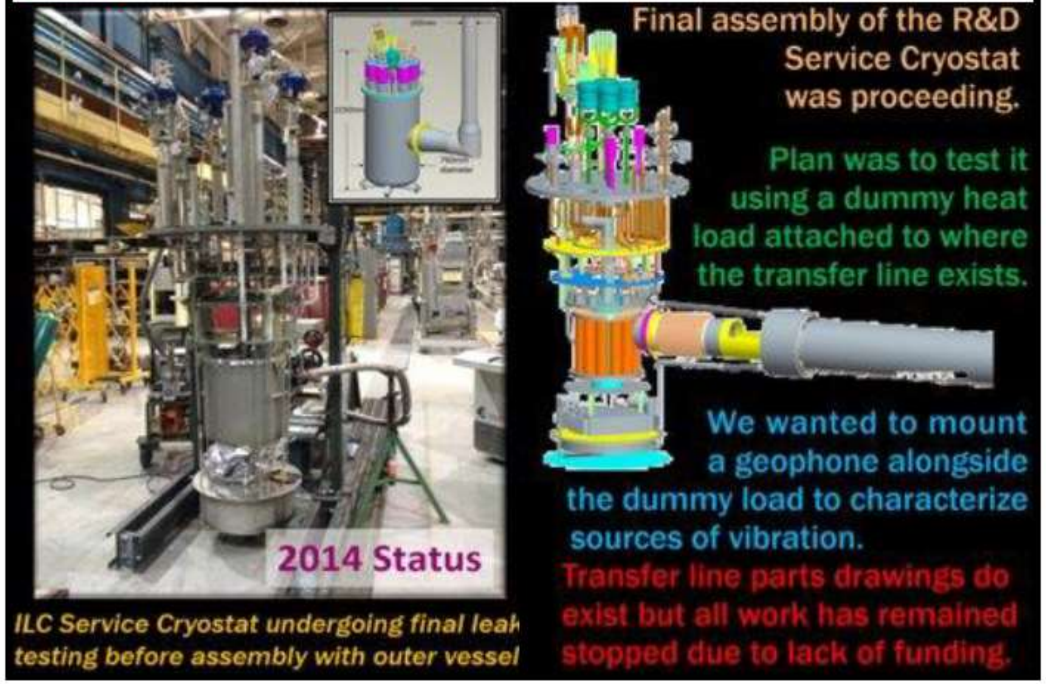
M.Minty

Synergistic progress: demonstrate measurement accuracies well below requirements

- ILC prototype development (90% complete)
- SuperKEKB implementation (demonstrated "1 nm single-arm probe stability").
- highly relevant for FCC-ee and ILC

Repeat: collective experience in past and future colliders is critical in advancing MDI optimization.





ILC Service Cryostat undergoing final leak testing before assembly with outer vessel

Final assembly of the R&D Service Cryostat was proceeding.

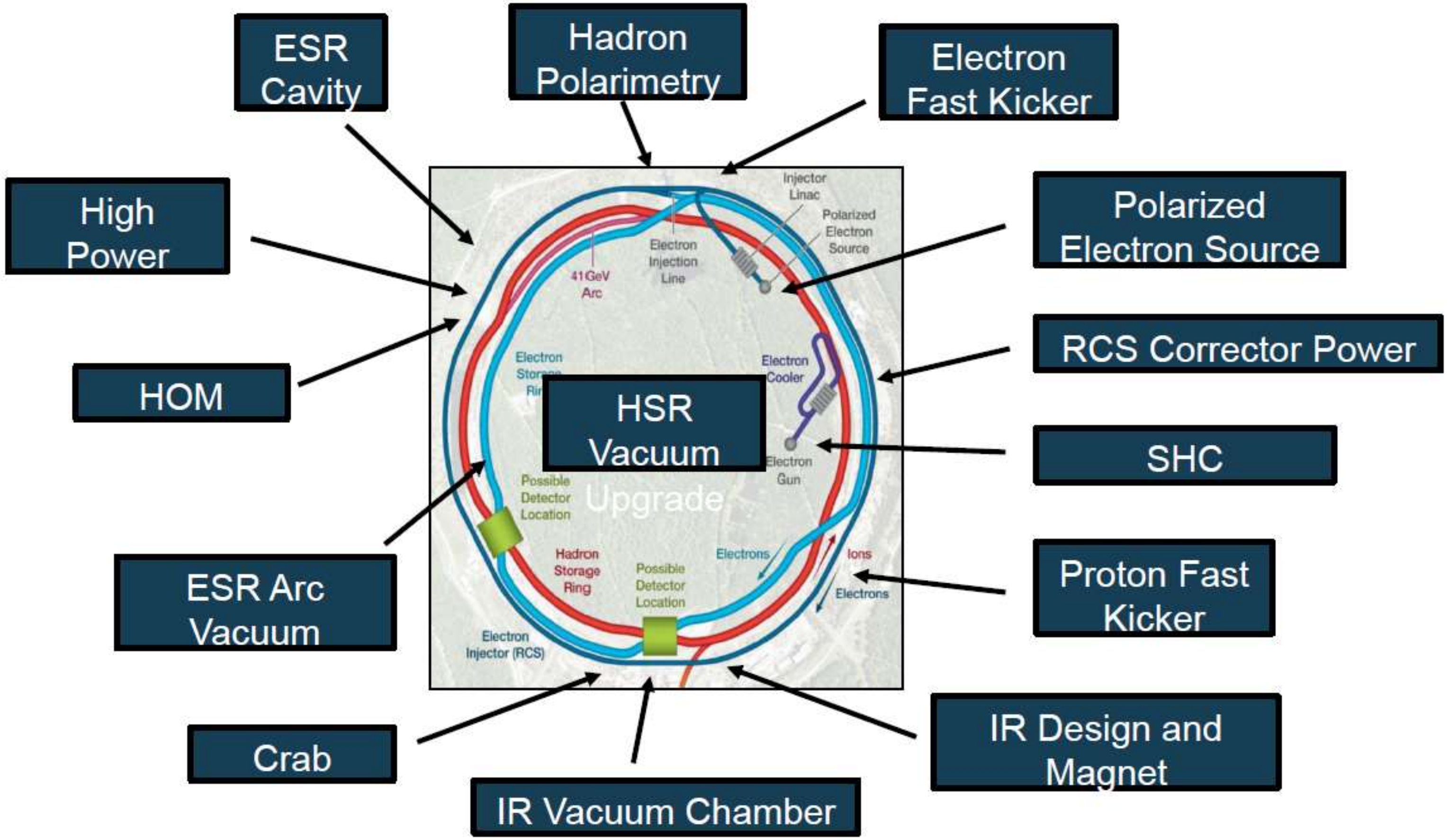
Plan was to test it using a dummy heat load attached to where the transfer line exists.

We wanted to mount a geophone alongside the dummy load to characterize sources of vibration.

Transfer line parts drawings do exist but all work has remained stopped due to lack of funding.

Synergies with the Electron Ion Collider (EIC)

M.Minty



ESR Cavity

Hadron Polarimetry

Electron Fast Kicker

High Power

Polarized Electron Source

HOM

RCS Corrector Power

HSR Vacuum Upgrade

SHC

ESR Arc Vacuum

Proton Fast Kicker

Crab

IR Design and Magnet

IR Vacuum Chamber

The EIC Project **R&D** efforts support **innovative and critical conceptual designs** by providing an initial design process with calculations, simulations, and layouts… Thus, project **R&D** is very **focused on the needs of the project** to advance to manufacturing the state-of-the-art system components required for the EIC.

Courtesy Qiong Wu

- FCC-EIC Joint & MDI Workshop (Oct 2022) https://indico.cern.ch/event/1186798/
- EIC Workshop – Promoting Collaboration on the EIC (Oct 2020) https://indico.cern.ch/event/949203/

Continuity in engagement drives progress

- MDI: ILC → SuperKEKB → FCCee → ILC
- RF: all TESLA-like developments in SRF (including LCLS-II) for the ILC, FCCee and material science (e.g. for FCChh) and beyond

Accelerator S&T Workforce in the US:

M.Minty

- **YES - DOE Office of Sciences, P5, EPP2024 recognizing diminishing expertise in accelerator R&D in the US, the projects, and operation in the US and increased demand**
- **YES – there are several recent initiatives:**
  - Particle Accelerators for Science and Society and Workforce Training (2021)
  - RENEW: Reaching a New Energy Sciences Workforce (2023)
  - FAIR: Funding for Accelerated, Inclusive Research (2023)
  - MIni-Workshop on Accelerator Scientist / Engineer Workforce of National Labs (2024)
- **YES – there are several select institutes**
  - Center for Advanced Studies of Accelerators, CASA (JLab/ODU)
  - Cornell Laboratory for Accelerator-based ScienceS and Education, CLASSE, and the Center for Bright Beams (NSF)
  - Center for Accelerator Science and Education, CASE, at Stony Brook University (HEP)
  - MSU cryo-initiative – collaboration between FRIB and MSU College of Engineering (NP)
  - Virginia Innovative Traineeships in Accelerators, VITA (DOE)
- **BUT – the AS&T workforce situation is actually worsening**
  - Barely enough to keep up with current projects and operations (NP, BES, HEP, ARDAP)
  - The level of expertise required for the future HEP facilities/colliders is much higher

The US HEP community needs to act

V.Shiltsev

- **Next big HEP facilities (Higgs Factories, 10+ TeV pCM colliders, etc) will not be "off-the-shelf" particle accelerators, they require numerous innovative breakthroughs over a range of beam physics topics and accelerator technologies – over the next *O*(20 years)**
- **That requires the leading US universities to get intellectually involved:**
  - **E.g. this morning EoIs: only Cornell and NIU (and MIT?) indicated accelerator R&D (besides major National labs)**
  - **Need more accelerator/beam physics faculty!**

$$\min N_{AST\ faculty} \geq \left[\frac{N_{HEP+NP\ faculty}}{4}\right]$$

Thanks for your attention!

Thanks to all the speakers and contributors!

Questions?