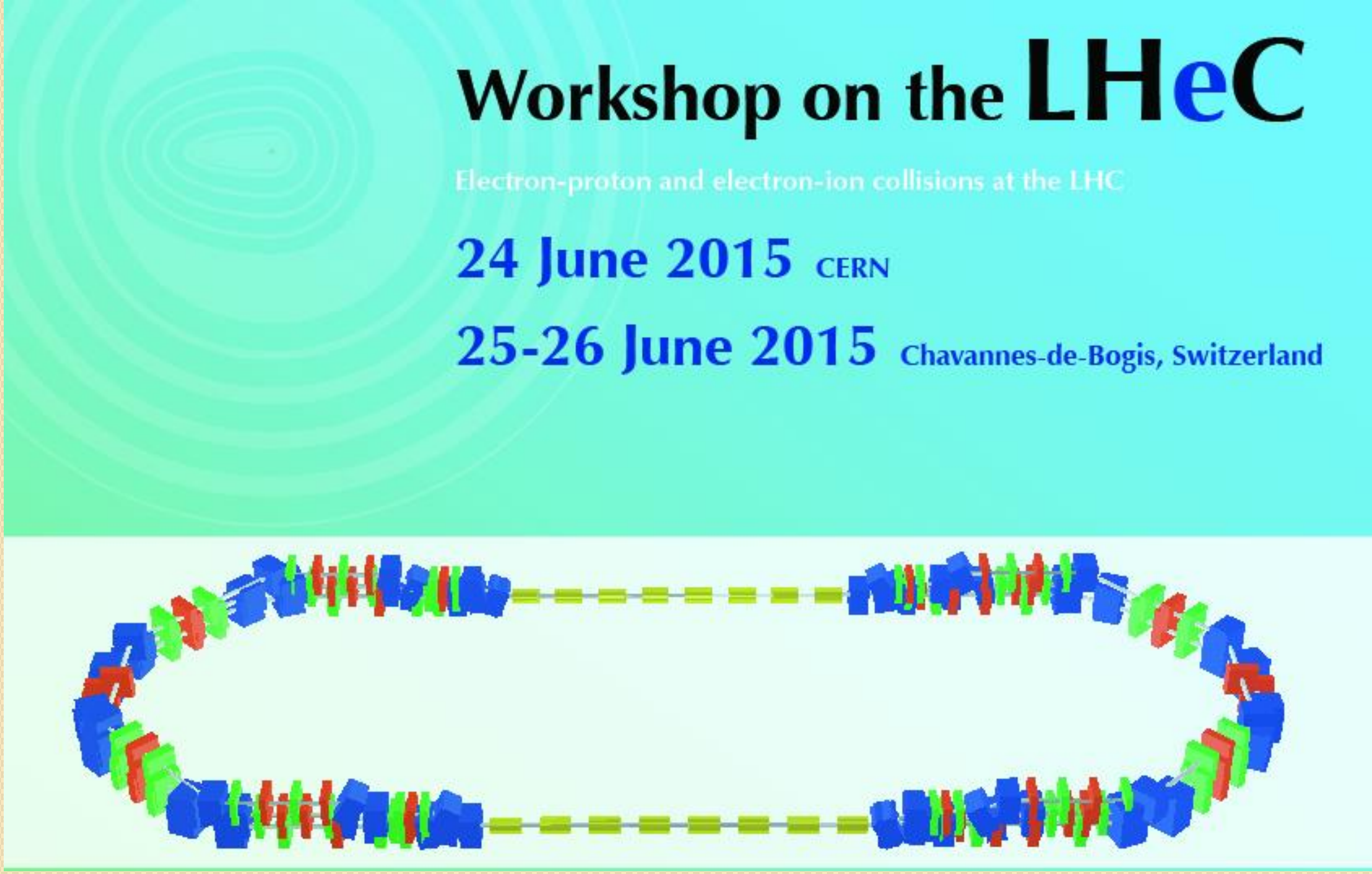


## Summary

# Accelerator and ERL Facility Sessions

Gianluigi Arduini & Erk Jensen

# Thank you!

- Thank you all for the excellent presentations!
- Thank you equally for the constructive discussions!
- … and last but not least: thanks to the speakers for providing to us a summary slide!

Fri 26th June, Morning Session on

# ERL FACILITY (ies)

| | |
|---|---|
| MESA Progress | Kurt Aulenbacher |
| High Intensity ERL Developments | Christopher Mayes |
| ERL Design based on FFAG arcs (eRHIC, LHeC, Cornell) | Dejan Trbojevic |
| RF performance of SC cavities with nitrogen doping | Anna Grasselino |
| 400 MHz cavity development | Ilan Ben-Zvi |
| ERL SCRF Facility for CERN – CDR Status | Erk Jensen |
| Source and Injector | Boris Militsyn |
| ERL Facility: Design and Parameters | Alessandra Valloni |
| Photon Beam Generation | Fabian Zomer |
| Cavities | Rama Calaga |
| Magnets | Attilio Milanese |
| Cryomodule | Andrew Hutton |
| Site | Nuria Catalan |
| LHeC Cavity Design Considerations | Frank Marhauser |

# MESA Main components

| Component | Function | Status |
|---|---|---|
| MESA Low energy Beam Apparatus, MELBA → | Source, spin rotation, chopper/buncher, a.m.m. | Design nearly finished, Under construction |
| MilliAMpere BOoster injector, MAMBO | 5 MeV, 50kW beam | Design nearly finished, Start tendering |
| Mesa Enhanced ELBE Cryomodule, MEEC | 2*25 MeV Energy gain per pass, 1mA current in ERL on target at 100MeV | Ordered at RI Instruments |
| MESA Arcs<br>MARC-0 to MARC-5 | 6 *180 deg deflections<br>5,30,55,80,105,130 MeV | Detailed magnet design ongoing. |
| MESA Infrastructure Specific Component, MISC | Beamlines<br>Cryogenic circuit,<br>Vacuum,supports, beam diagnostics | Design started for some issues, but many open Tasks! |

# High Intensity ERL Developments – Christopher Mayes

Cornell has been funded for ERL R&D since 2005, and has designed and built:

**Prototype high-power ERL injector & beam stop**

- Record current peak 75 mA, and 65 mA sustained for 8 hours
- Emittance through merger meets Cornell ERL specifications
- Emittance straight meets LCLS-II specifications

**Horizontal Test Cryomodule (HTC)**

- First ERL cavity achieved $Q_0$ of $6 \times 10^{10}$ @ 16 MV/m, 1.8K
- (with couplers and HOM absorbers) (3 times spec.)
- Tested with 40 mA in the injector

**Prototype Main Linac Cryomodule (MLC)**

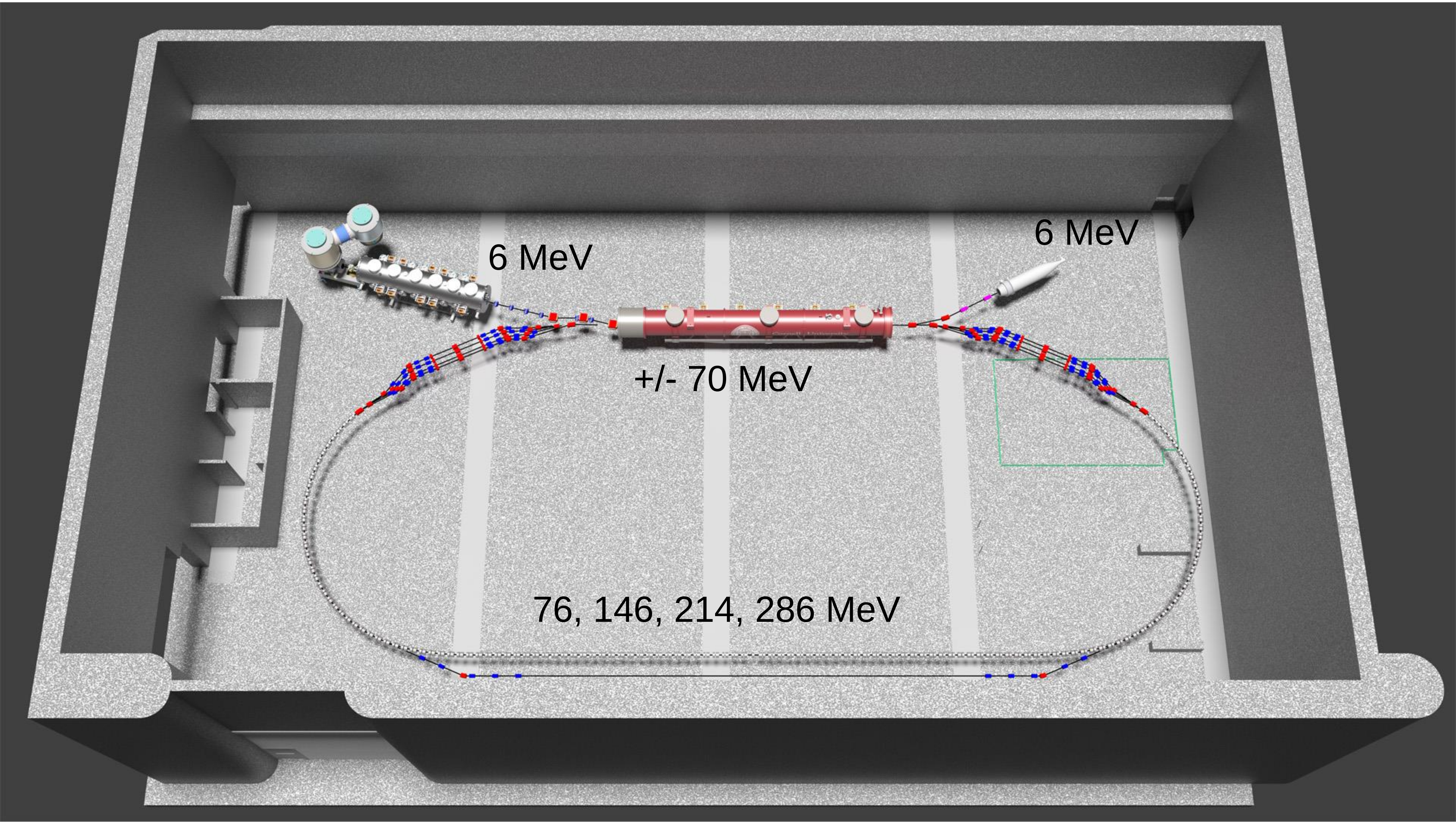
- 6 cavities completely built and tested (vertical) in-house
- Assembly completed in November 2014
- Cooldown and testing begins in July

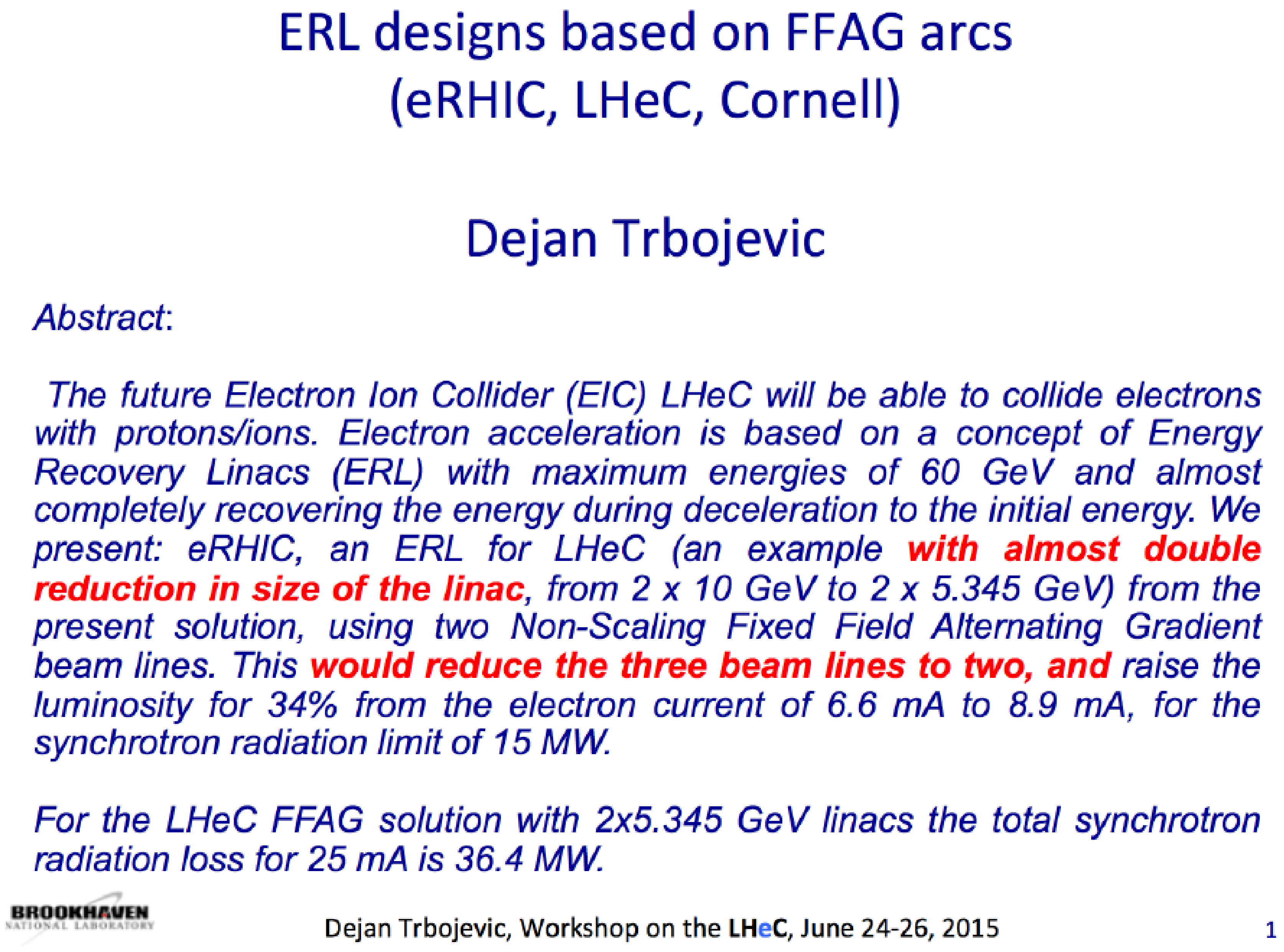
**Cornell-BNL FFAG-ERL Test Accelerator (Cβ)**

- Currently designing in collaboration with BNL
- Uses injector, MLC, and beam stop in Cornell's L0E hall
- Injector and MLC recently moved to L0E

# Cβ: Cornell-BNL ERL-FFAG Test Accelerator

Christopher Mayes/Cornell





# ERL designs based on FFAG arcs (eRHIC, LHeC, Cornell)

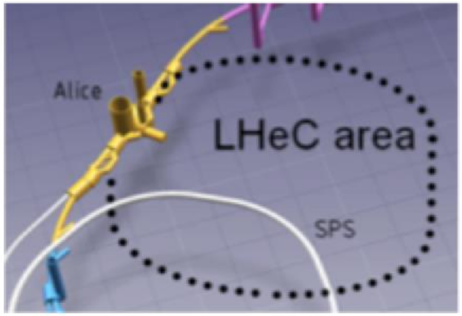
## Dejan Trbojevic

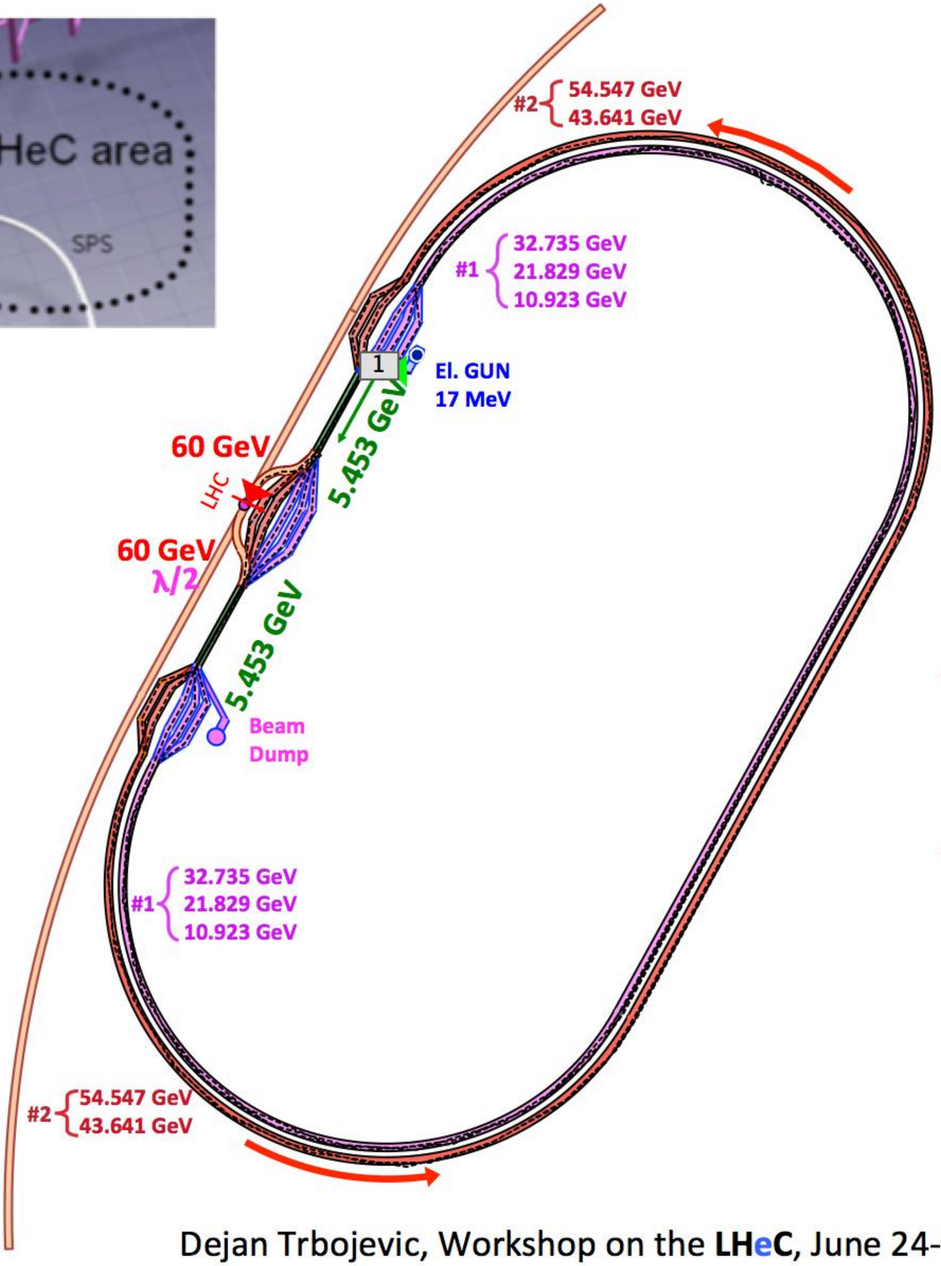
*Abstract:*

*The future Electron Ion Collider (EIC) LHeC will be able to collide electrons with protons/ions. Electron acceleration is based on a concept of Energy Recovery Linacs (ERL) with maximum energies of 60 GeV and almost completely recovering the energy during deceleration to the initial energy. We present: eRHIC, an ERL for LHeC (an example* ***with almost double reduction in size of the linac****, from 2 x 10 GeV to 2 x 5.345 GeV) from the present solution, using two Non-Scaling Fixed Field Alternating Gradient beam lines. This* ***would reduce the three beam lines to two, and*** *raise the luminosity for 34% from the electron current of 6.6 mA to 8.9 mA, for the synchrotron radiation limit of 15 MW.*

*For the LHeC FFAG solution with 2x5.345 GeV linacs the total synchrotron radiation loss for 25 mA is 36.4 MW.*

Dejan Trbojevic, Workshop on the **LHeC**, June 24-26, 2015 1





Thomas Roser's idea

**# 1 NS-FFAG** beam line:
3 passes for acceleration
3 passes for recovery

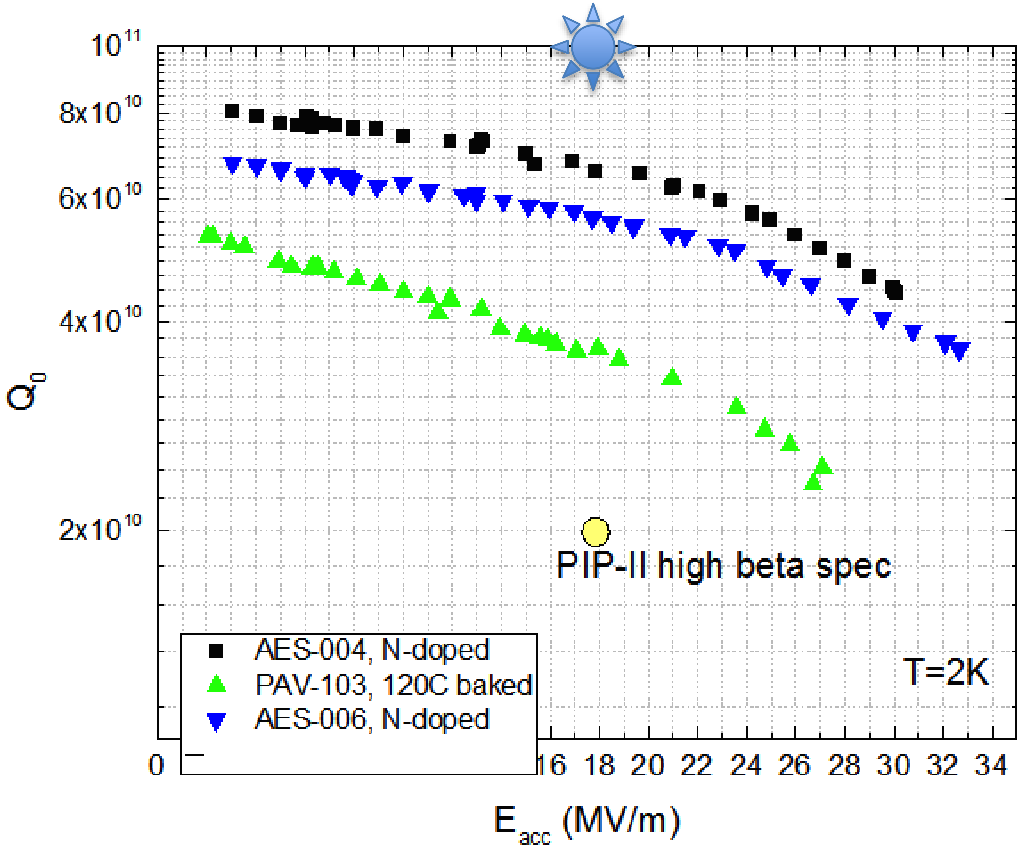
**# 2 NS-FFAG** beam line:
2 passes for acceleration
2 passes for recovery

Dejan Trbojevic, Workshop on the **LHeC**, June 24-26, 2015

# N doping applied to 650 MHz cavities at FNAL
# Q~ 7e10 at 2K, 18 MV/m – record at this frequency!

Applying N doping to 650 MHz (beta=0.9) leads to double Q compared to 120C bake (standard surface treatment ILC/XFEL)

But from frequency scaling from 1.3GHz to ~800 MHz, with ideal recipe the projected Q value is ~**1e11 at 18 MV/m, 2K**! Need some R&D to optimize doping recipe for lower frequency

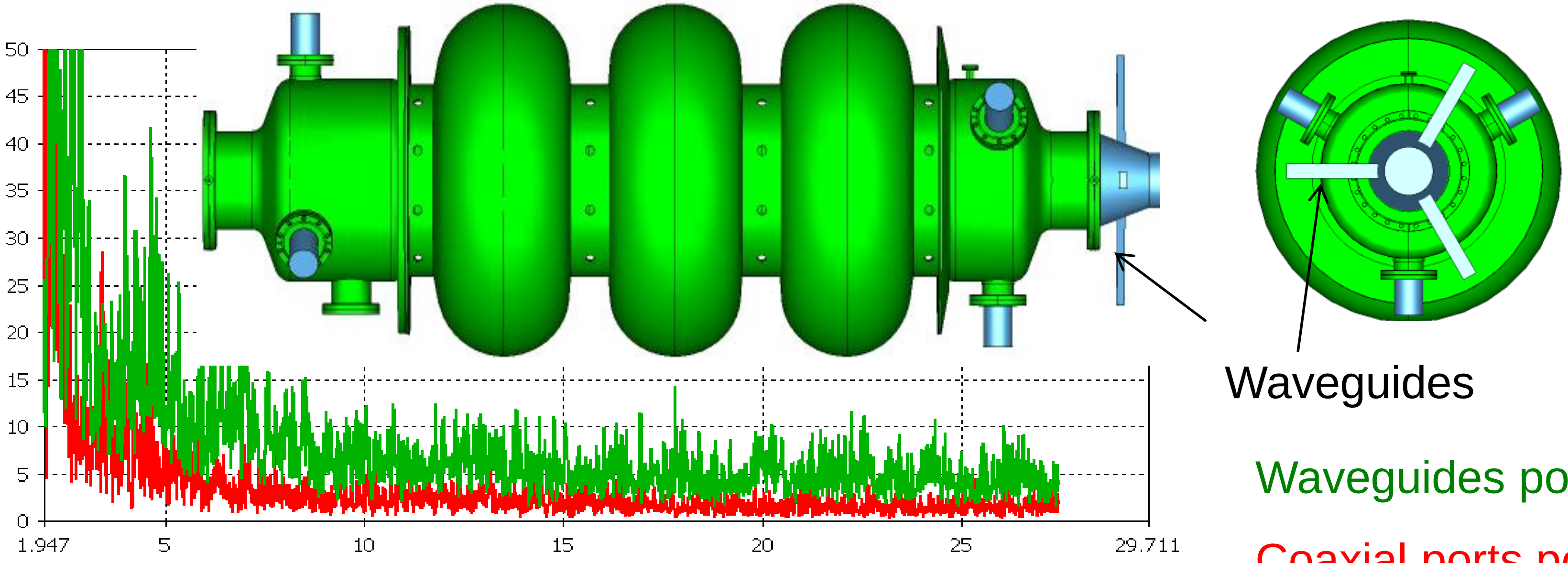


Anna Grasselino/FNAL

# Ilan Ben-Zvi: 5-cell 422 MHz cavity for the eRHIC ERL

Ilan Ben-Zvi/BNL

- We are building a prototype a 3-cell niobium cavity.
- We will build a prototype HOM damping system aiming at HOMs' external Q < 50,000, up to 30 GHz.
- The 5-cell cavity is stable against BBU in eRHIC's multi-pass, high-current configuration.
- It has a loss factor of 1.9 V/pC, very low for a 2.6 m cavity.
- The HOM damping scheme uses 6 coaxial band-pass HOM dampers and 3 high-frequency waveguide to capture frequencies up to 30 GHz.



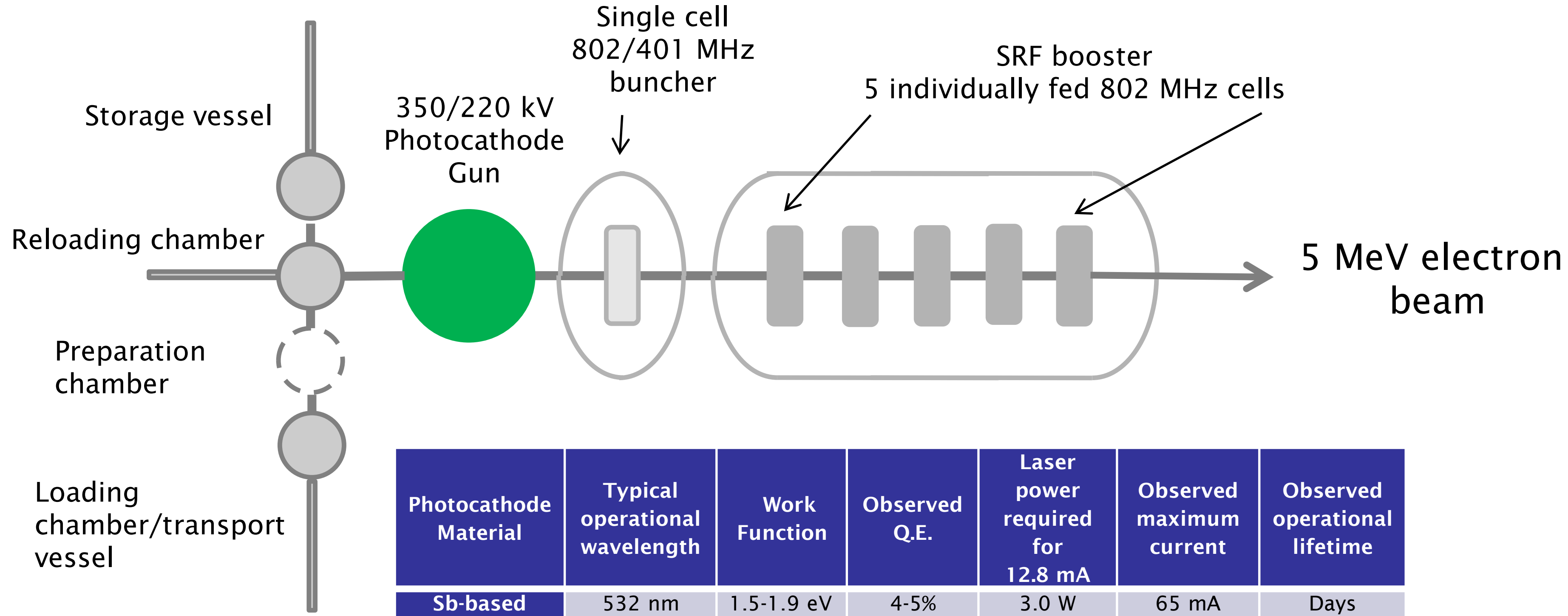
Waveguides

Waveguides power

Coaxial ports power

# *Concept of the ERL test facility photoinjector*

Boris Militsyn/STFC



Storage vessel

Reloading chamber

Preparation chamber

Loading chamber/transport vessel

350/220 kV Photocathode Gun

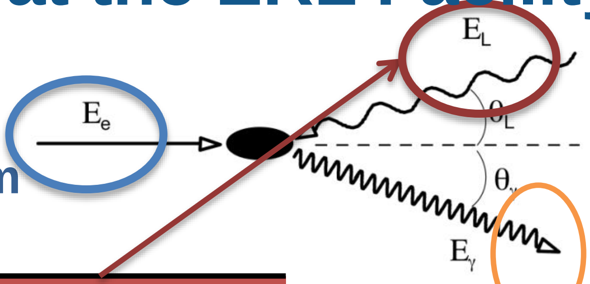
Single cell 802/401 MHz buncher

SRF booster
5 individually fed 802 MHz cells

5 MeV electron beam

| Photocathode Material | Typical operational wavelength | Work Function | Observed Q.E. | Laser power required for 12.8 mA | Observed maximum current | Observed operational lifetime |
|---|---|---|---|---|---|---|
| **Sb-based family, unpolarised** | 532 nm | 1.5-1.9 eV | 4-5% | 3.0 W | 65 mA | Days |
| **GaAs-based family, polarised** | 780 nm | 1.2 eV* | 0.1-1.0% | 20.4 | 5-6 mA | Hours |

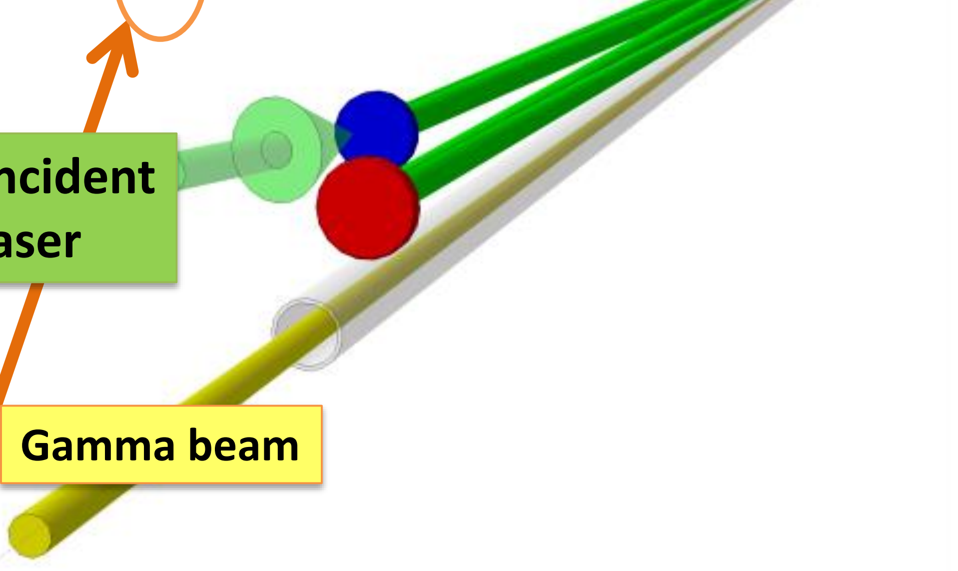
# Gamma beams at the ERL Facility



**Incident electron beam**

**Incident laser beam**

Fabian Zomer/LAL



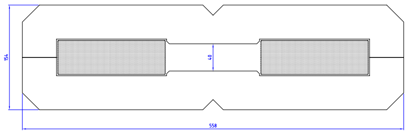
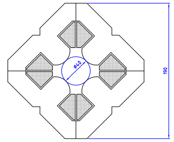
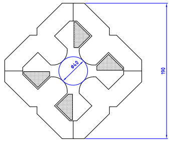
**Incident laser**

**Gamma beam**

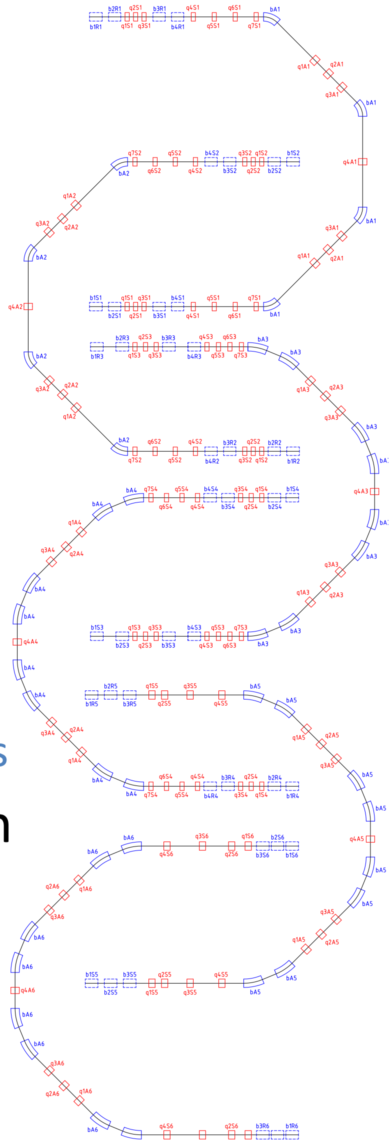
| LASER BEAM PARAMETERS | |
|---|---|
| Wavelength | 515 nm - 1030 nm |
| Average Power<br>**Optical resonator** | 300kW - 600 kW<br>(**can be increased R&D**) |
| Pulse length | 3 ps (**can be reduced**) |
| Pulse energy | 7.5mJ - 15 mJ |
| Spot size | 30 µm (**can be reduced**) |
| Bandwidth | 0.02 % |
| Repetition Rate | 40 MHz |

| GAMMA BEAM PARAMETERS (for $\lambda$=515nm) | |
|---|---|
| Energy | 30 MeV |
| Spectral density | $9*10^4$ ph/s/eV (**can be increased**) |
| Bandwidth | < 5% (**can be reduced**) |
| Flux within FWHM bdw | $7*10^{10}$ ph/s (total flux 9*10^12) |
| ph/$e^-$ within FWHM bdw | $10^{-6}$ |
| Peak Brilliance | $3*10^{21}$ ph/s*mm$^2$*mrad$^2$ 0.1%bdw |

# Magnets for PERLE

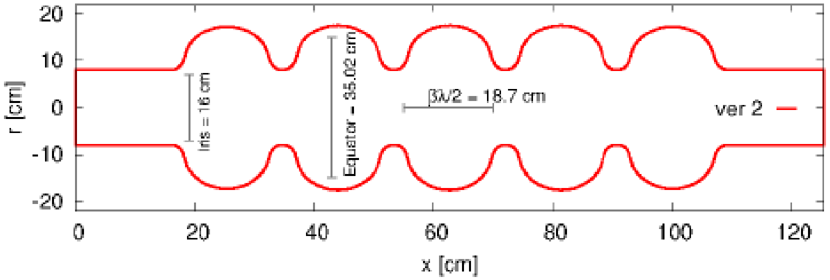
- about 200 magnets for 6 arcs, including spreaders and combiners
- preliminary design show feasibility of compact dipoles and quadrupoles, to allow vertical stacking
- preference is given for classical electromagnets, for full tunability
- an iteration with the optics will provide
  - confirmation of aperture and field quality requirements
  - input for the corrector magnets (possibly embedded in the quadrupoles)
  - revised strengths / lengths, in view of grouping the magnets in families
- design of the coil and overall power consumption depends on an overall optimization including the power converters
- multiple aperture magnets are not part of the baseline, though they can still be further explored to reduce overall quantity, number of supports and possibly cost



Attilio Milanese/CERN

# 802 MHz 5-Cell Cavity

Rama Calaga/CERN

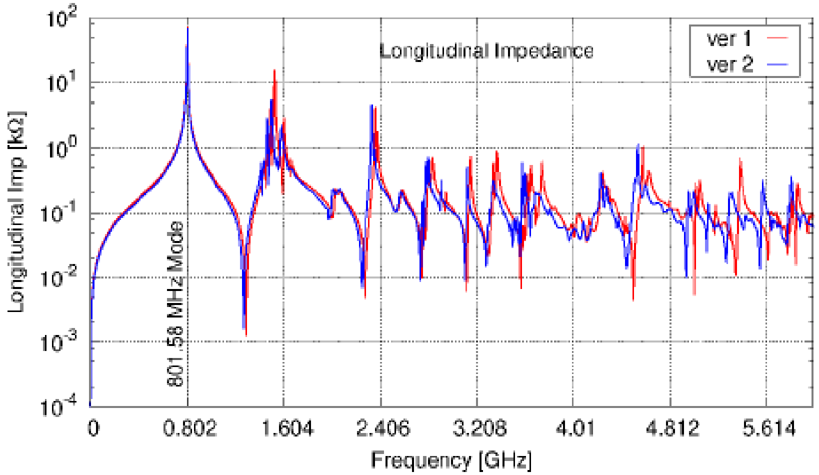


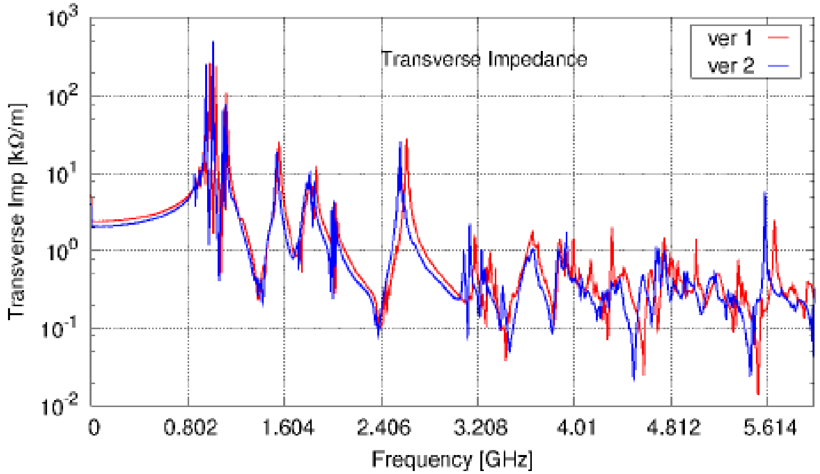
| Parameter | Ver 1 (Scaled) | Ver 2 |
|---|---|---|
| Frequency [MHz] | 801.58 | 801.58 |
| Number of cells | 5 | 5 |
| Active cavity length [mm] | 935 | 935 |
| Voltage [MV] | 18.7 | 18.7 |
| $E_p$ [MV/m] | 45.1 | 48.0 |
| $B_p$ [mT] | 95.4 | 98.3 |
| R/Q [Ω] | 430 | 393 |
| Cell-cell coupling (mid-cell) | 4.47% | 5.75% |
| Stored Energy [J] | 154 | 141 |
| Geometry Factor [Ω] | 276 | 283 |
| Field Flatness | 97% | 96% |

Cavity design optimized for fundamental & minimize higher order mode impedance

Five-cells & 4-cavity cryomodule as baseline

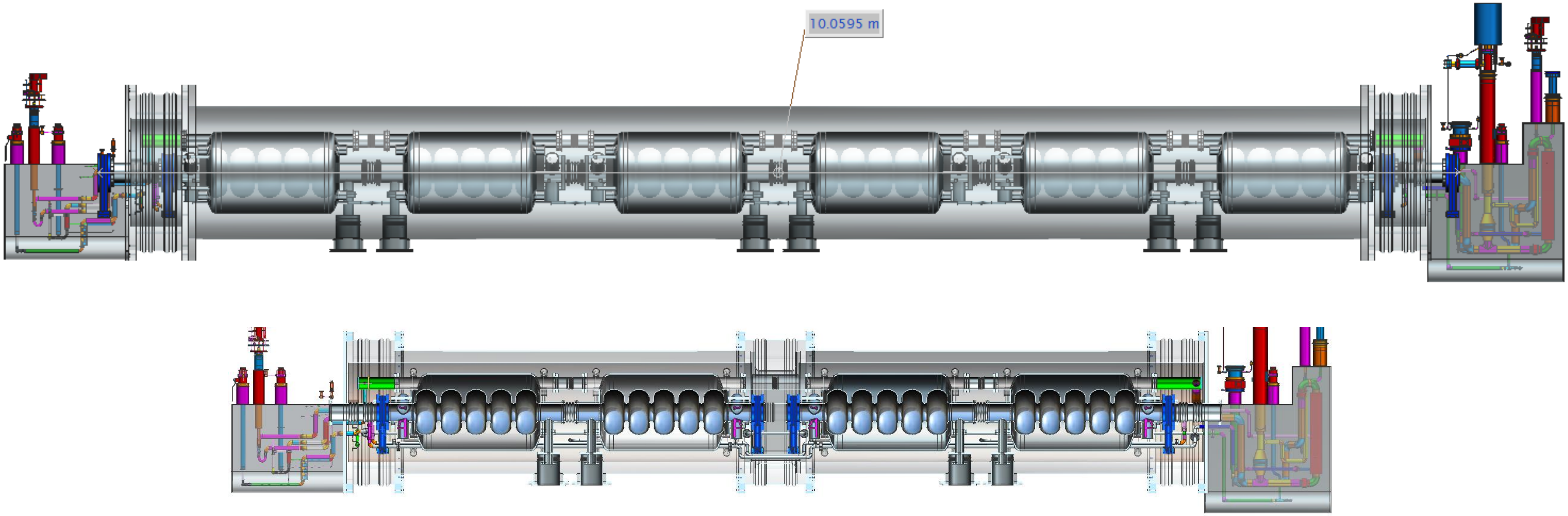
HOM coupler options under study





# JLab-CERN Collaboration

Hutton-Rimmer

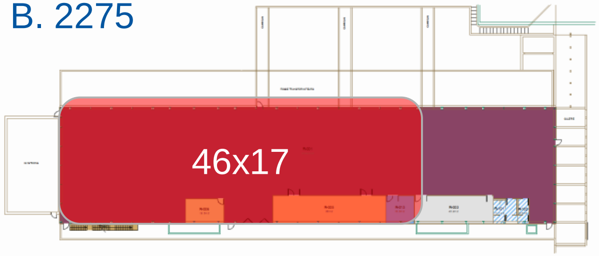


- CERN and JLAB aim to develop a conceptual design for a cryostat and fabricate a prototype cavity suitable for LHeC
- CERN will provide engineering support, JLab will provide technical advice and recommendations

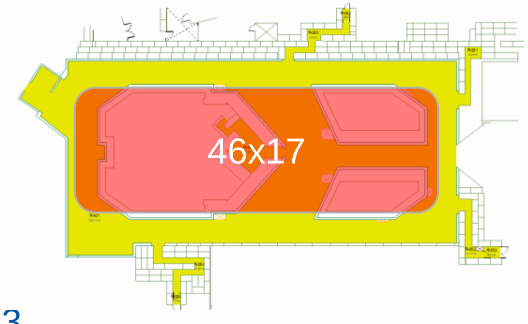
Nuria Catalan/CERN

# Site considerations

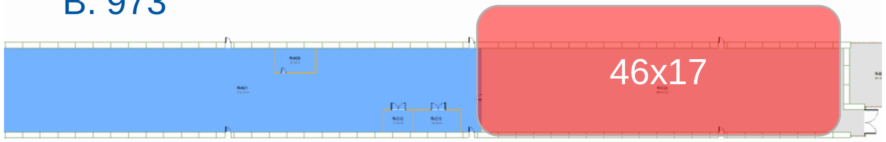
B. 2275



B. 2003



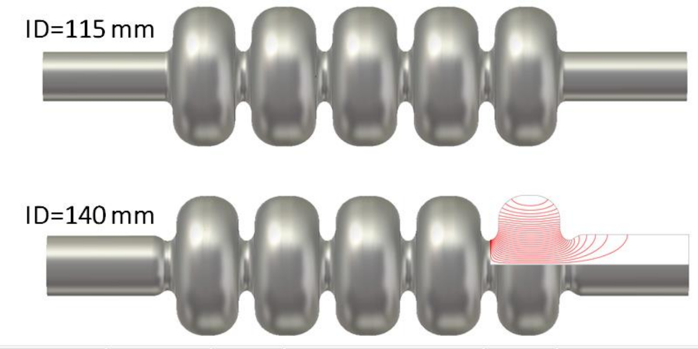
B. 973

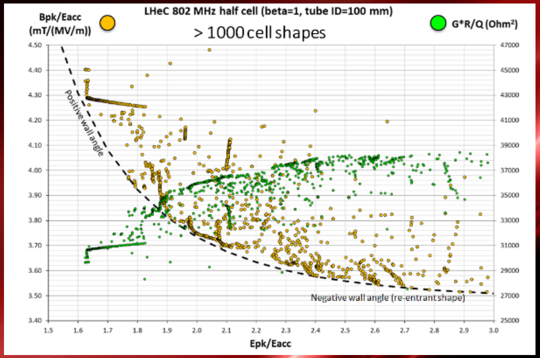


Frank Marhauser/JLAB

# LHeC Cavity Design Considerations

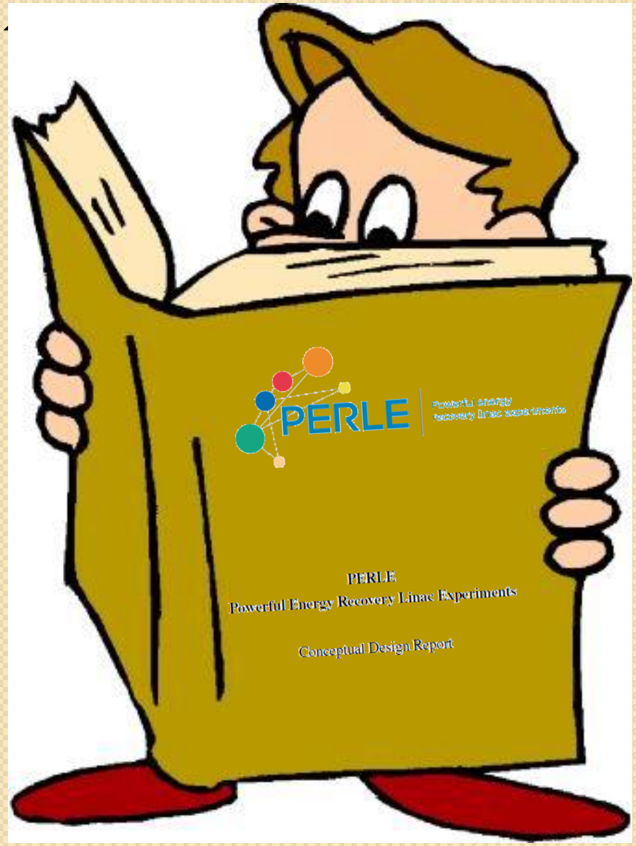
- Prototype 802 MHz multi-cell bare SRF cavity design has been proposed with performance parameters well balancing cryogenic losses (R/Q · G) and surface field enhancement ratios ($E_{pk}/E_{acc}$, $B_{pk}/E_{acc}$)
- Iris diameter affects all key parameters
- Optimization rationale has been discussed (1000s of cavity shapes investigated to illustrate interdependence of key parameters and to reveal truly optimized cell shapes)
- Beam tube diameter may be enlarged to reduce cutoff frequency depending on HOM damping requirements and HOM damping scheme without affecting key parameters
- Single die-design proposed for prototyping, which reduces up-front investment costs for proof-of-principle high power tests (not a requirement for final design)





# Summary “Facility” Session

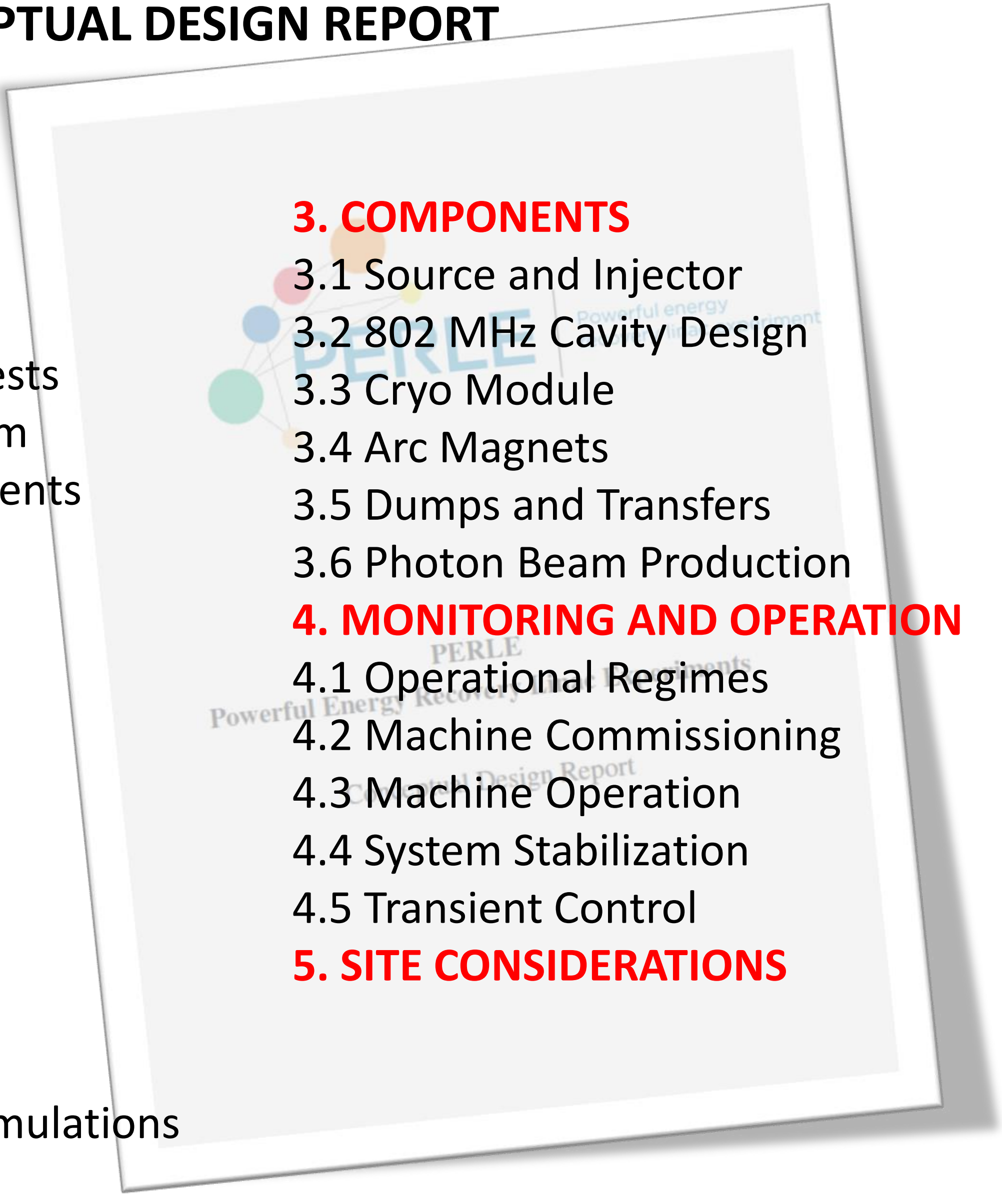
- Thanks to all contributors, today we have a substantial draft conceptual design report with significan
  - … still needs some additions, editing, polishing – but it’s a remarkable progress!



- We have a name and a logo!

PERLE | Powerful energy recovery linac experiments

# CONCEPTUAL DESIGN REPORT



## 1. PURPOSE

1.1 SCRF Developments
1.2 Technical Applications
    1.2.1 Magnets, cables, quench tests
    1.2.2 RF developments with beam
    1.2.3 Beam diagnostic developments
1.3 Injector for the LHeC
1.4 Physics with electron beam
1.5 Physics with photon beam
1.6 A Detector Test Beam at ERL

## 2. DESIGN AND PARAMETERS

2.1 System Architecture
2.2 Transport Optics
2.3 Layout and Magnet Inventory
2.4 Bunch recombination pattern
2.5 Start-to-end beam dynamics simulations

## 3. COMPONENTS

3.1 Source and Injector
3.2 802 MHz Cavity Design
3.3 Cryo Module
3.4 Arc Magnets
3.5 Dumps and Transfers
3.6 Photon Beam Production

## 4. MONITORING AND OPERATION

4.1 Operational Regimes
4.2 Machine Commissioning
4.3 Machine Operation
4.4 System Stabilization
4.5 Transient Control

## 5. SITE CONSIDERATIONS

# LIST OF AUTHORS

B. Auchmann(1), J. Bernauer, (9), A. Bogacz (4), O. Brüning(1), R. Calaga(1), K. Cassou (2),
N. Catalan Lasheras (1), V. Chetvertkova (1), E. Cormier (6), E. Daly (4), D. Douglas (4),
K. Durpaz (2), P. Favier (2), J. Henry (4), E. Jensen (1), R. Jones (1), M. Klein (5),P. Kostka (5),
F. Marhauser (4), A. Martens (2), A. Milanese (1), B. Militsyn (3), Y. Peinaud (2),
D. Pellegrini (1), N. Pietralla (8), Y.A. Pupkov (7), , R. Rimmer (4), R. Torres (1), A. Valloni (1),
G. Willering (1), D. Wollmann (1), F. Zomer (2)

***Please speak up if we forgot you!!!!***

1. CERN, Geneva, Switzerland
2. LAL, CNRS-IN2P3, Université Paris-Sud, Centre Scientifique d'Orsay, France
3. Cockcroft Institute, Daresbury, UK
4. Jefferson Lab, Newport News, VA, USA
5  University of Liverpool, UK
6. CELIA, University of Bordeaux 1, CNRS UMR 5107, Talence, France
7. BINP, Novosibirsk
8. Institut für Kernphysik, Technische Universität Darmstadt
9. Massachusetts Institute of Technology, Boston, MA, USA

# Why PERLE?

## FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**
- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**
  ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no 'automatic' longitudinal phase stability, etc.)
- **Proof validity of fundamental design choices:**
  Multi-turn recirculation (other existing ERLs have only two passages)
  Implications of high current operation (3 * [6mA – 12mA] > 30mA!!)
- **Verify and test machine and operation tolerances before designing a large scale facility**
  Tolerances in terms of field quality of the arc magnets
  Required RF phase stability (RF power) and LLRF requirements

# Why PERLE?

Dedicated Accelerator physics studies and R&D:

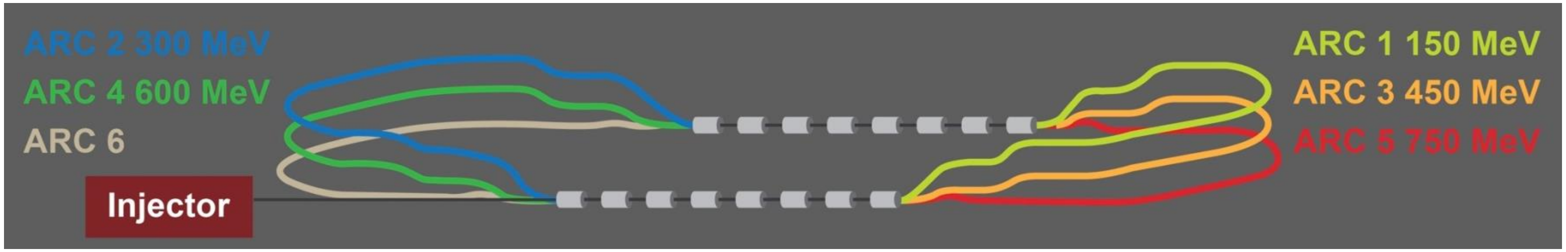
- Injector studies
- Beam diagnostics developments and testing with beam
- SCRF

Scientific and technical applications:

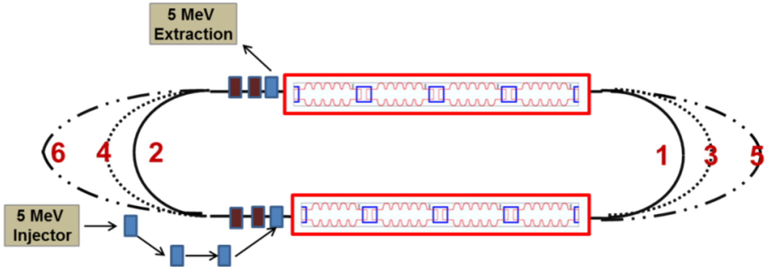
- Possible use for detector development
- Controlled quench and damage test for SC magnets
- Generation of gamma-ray beams via Compton backscattering

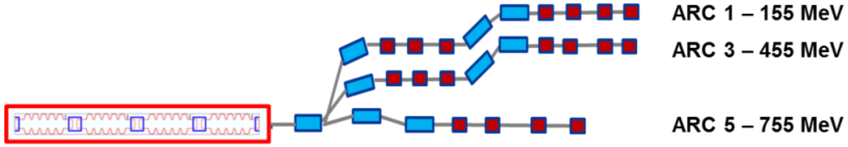
| TARGET PARAMETER* | VALUE |
|---|---:|
| Injection Energy [MeV] | 5 |
| Final Beam Energy [MeV] | 905 |
| Normalized emittance $\gamma\varepsilon_{x,y}$ [μm] | <25 |
| Delivered Beam Current [mA] | 12.8 (6.4) |
| Bunch Spacing [ns] | 25 (50) |
| Passes | 3 |

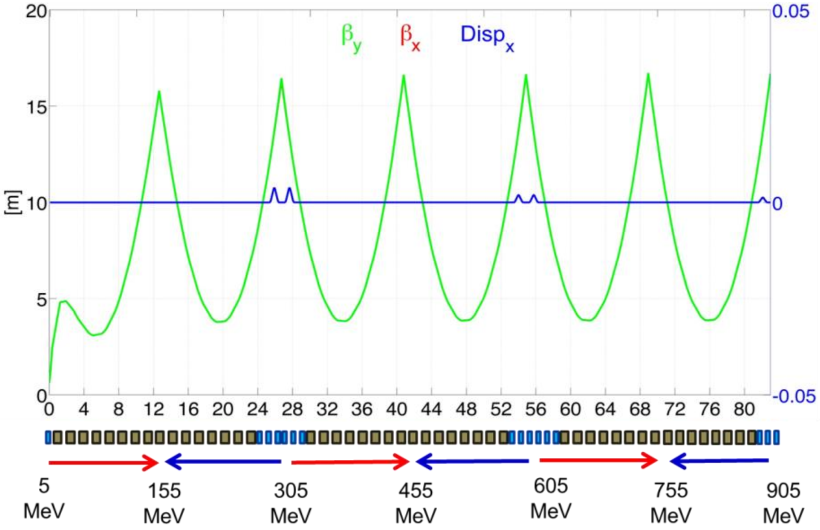
*in few stages

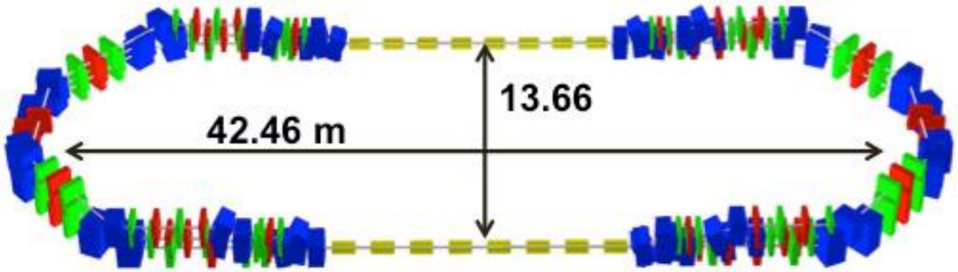


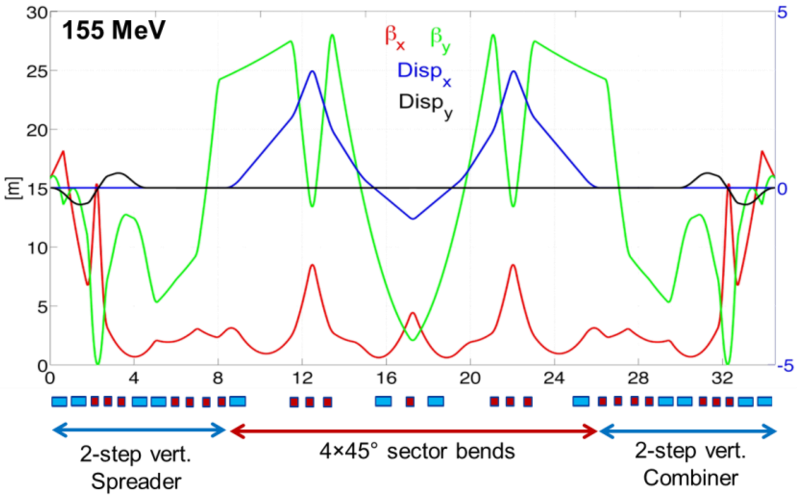
# PERLE optics





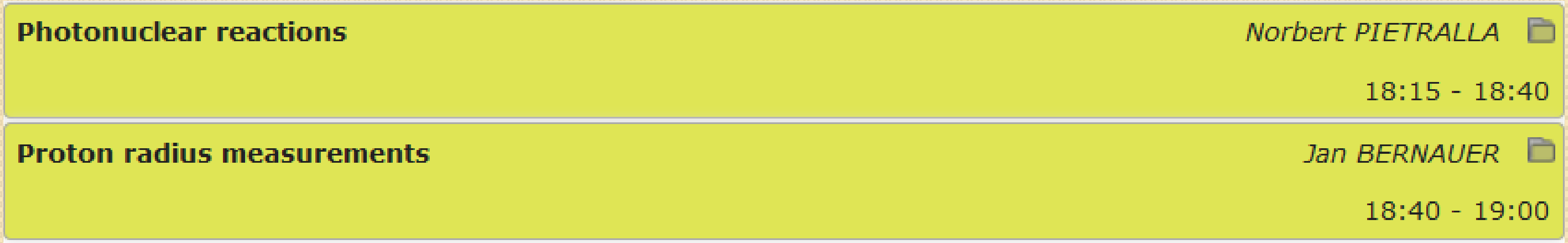






Thu 25th June, Plenary Session on

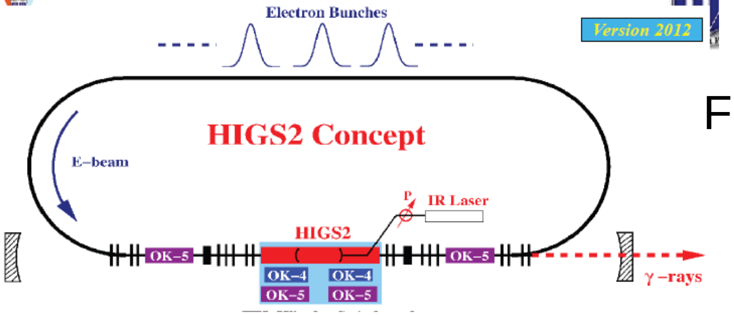
# PHYSICS WITH THE ERL FACILITY



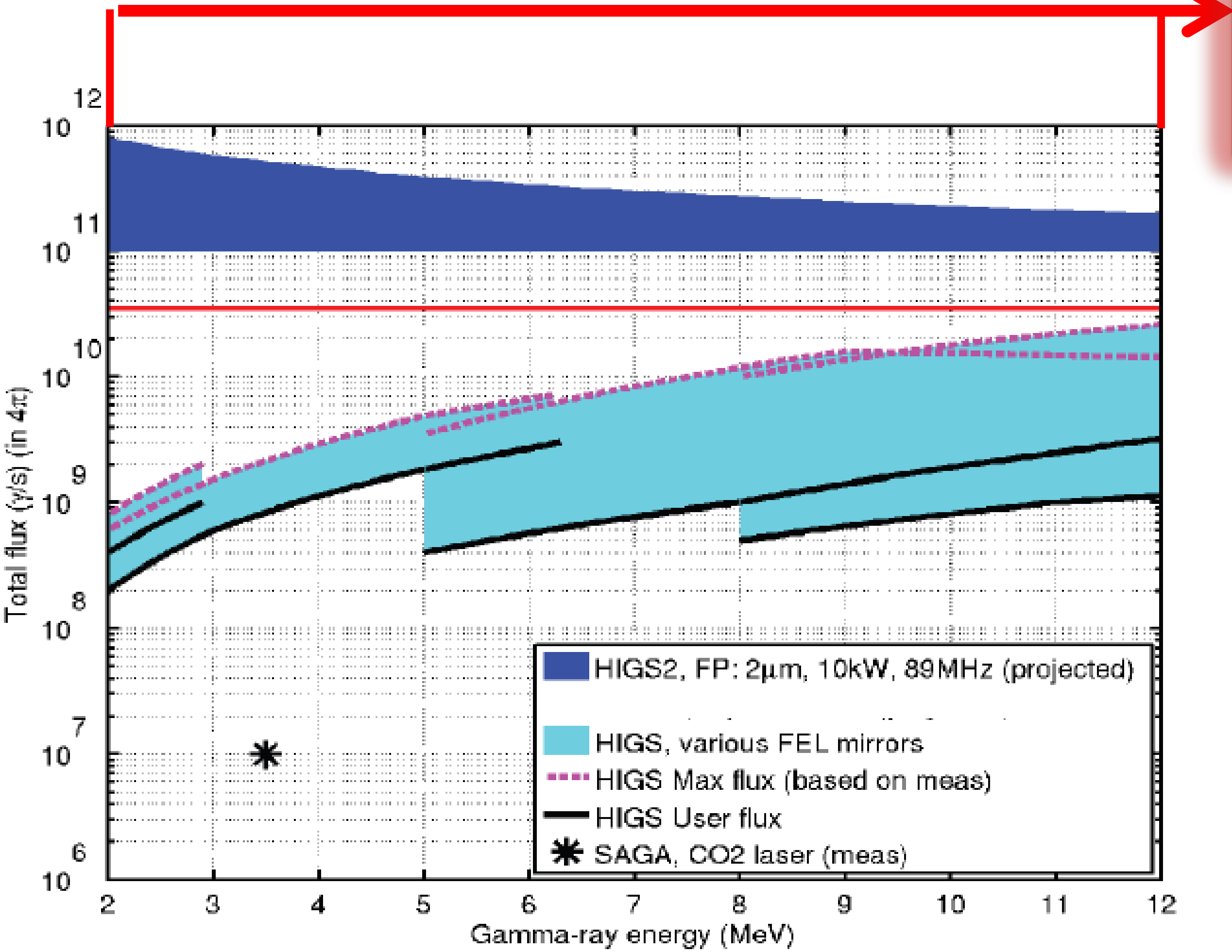
**Photonuclear reactions** *Norbert PIETRALLA* 18:15 - 18:40

**Proton radius measurements** *Jan BERNAUER* 18:40 - 19:00

# Higs @ Duke Univ. World's most intense γ source



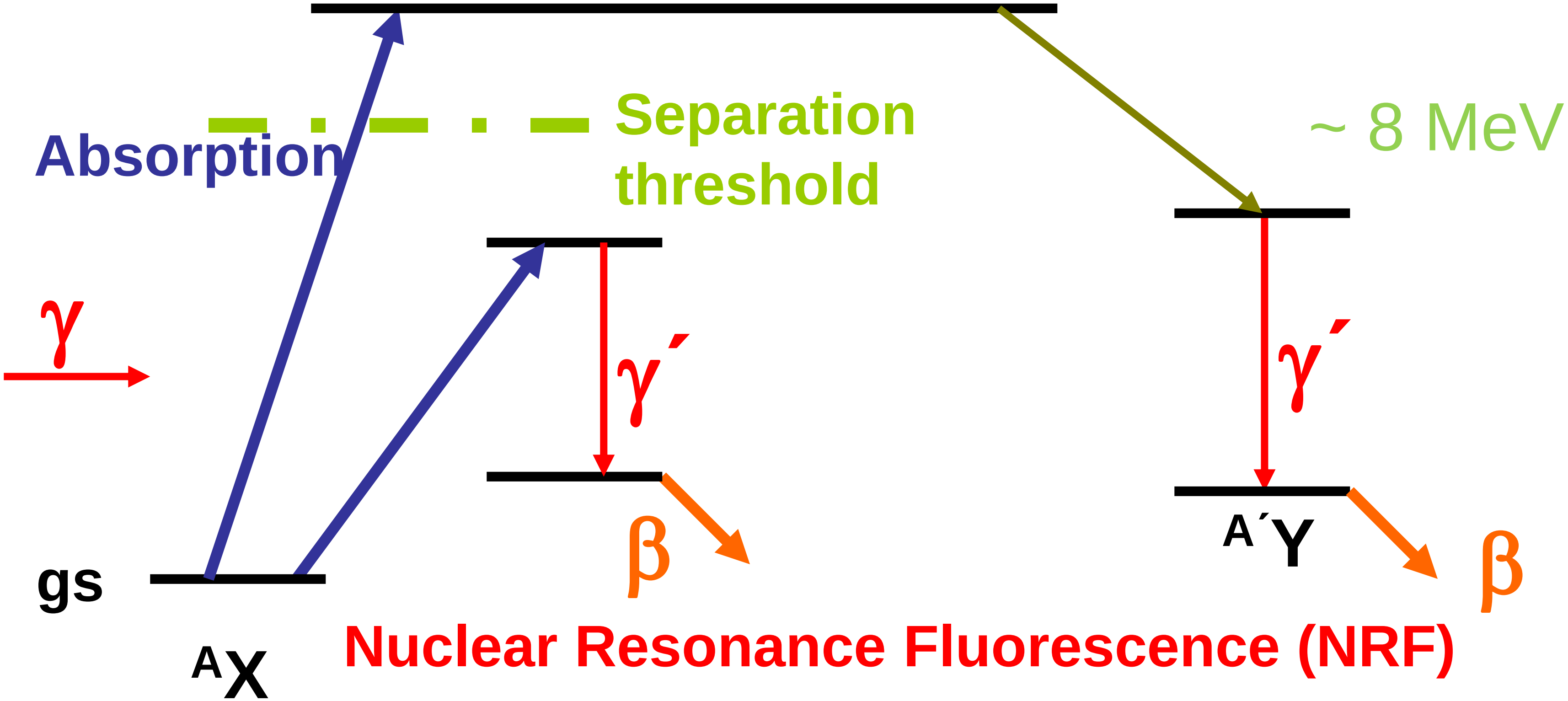
Fabian Zomer/LAL



**$9×10^{12}$**
**ERL facility**
**@ 30 MeV**

# Photonuclear Reactions

Norbert Pietralla/TU Darmstadt



Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodesintegration (-activation)

Photofission

# Summary: Proton form factor

Jan Bernauer/MIT

- Motivation
  - Radius puzzle: $7\sigma$ discrepancy betwen electronic and muonic measurements
  - Structures in $G_M$
- Experimental oportunities:
  - ISR, PRad-like: probe lowest $Q^2$
  - Higher $E_{Beam}$: test $G_M$ cusp
  - Mainz-like: Provide new high precision data for both $G_E, G_M$
  - +polarization: Ultimate experiment
- More ideas:
  - PV, dark matter, pion electroproduction, positrons: 2-photon physics, “racing beams”

Jan C. Bernauer: Proton radius puzzle, LHeC workshop, June 2015

Fri 26th June, Morning Session on

# ACCELERATOR

| | | |
|---|---|---|
| **FCC-eh** | *Daniel SCHULTE* | 09:00 - 09:25 |
| **LHeC ERL lattice** | *Alex BOGACZ* | 09:25 - 09:50 |
| **LHeC Interaction region design** | *Rogelio TOMAS GARCIA* | 09:50 - 10:15 |
| **LHeC IR Magnet Design Issues** | *Brett PARKER* | 10:15 - 10:40 |
| **Wake field effects in LHeC ERL** | *Dario PELLEGRINI* | 11:00 - 11:25 |
| **Beam-beam effects in LHeC** | *Edward William NISSEN* | 11:25 - 11:50 |

# FCC-he Summary

Daniel Schulte/CERN

FCC should be consistent with FCC-he option

- Very preliminary assessment of potential parameters presented
- Design based on LHeC ERL with increased current and FCC-hh ring

Could hope for 250 to 380 fb$^{-1}$ per 5 years during FCC-hh baseline operation

- Strong dependence on ion gap
- Parameter assumptions need to be verified by studies (electron charge, proton beta-function, …)

Similar performance for FCC-hh during ultimate operation for 25ns proton bunch spacing

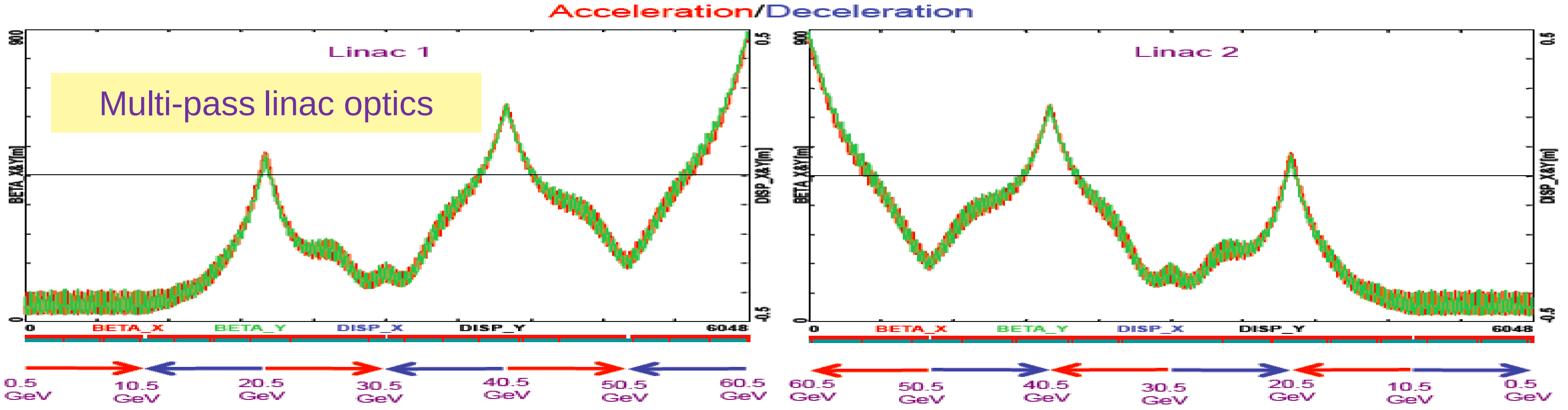
- difficulties for 5ns => could be of O(100 fb$^{-1}$) per 5 years
- Parameter limitations need to be explored (electron emittance, proton beta-function, …)

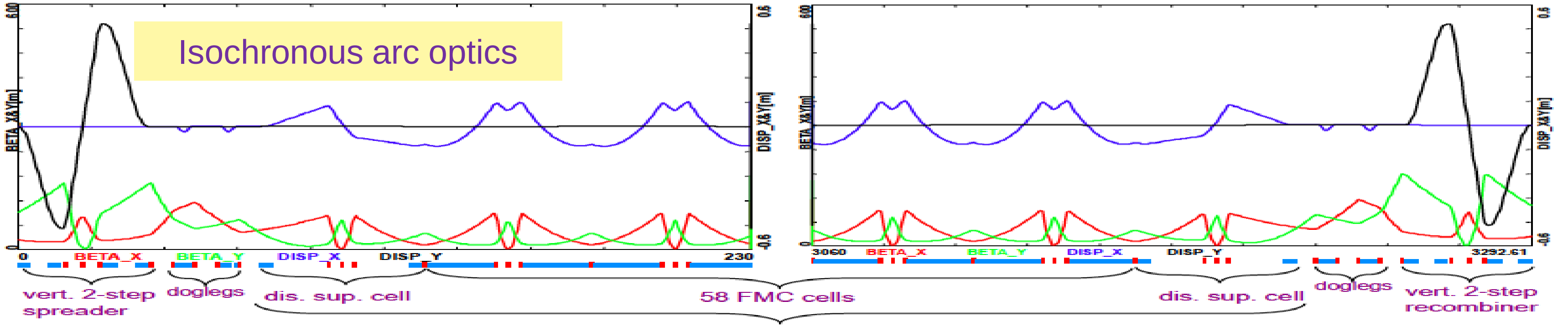
Some remarks:

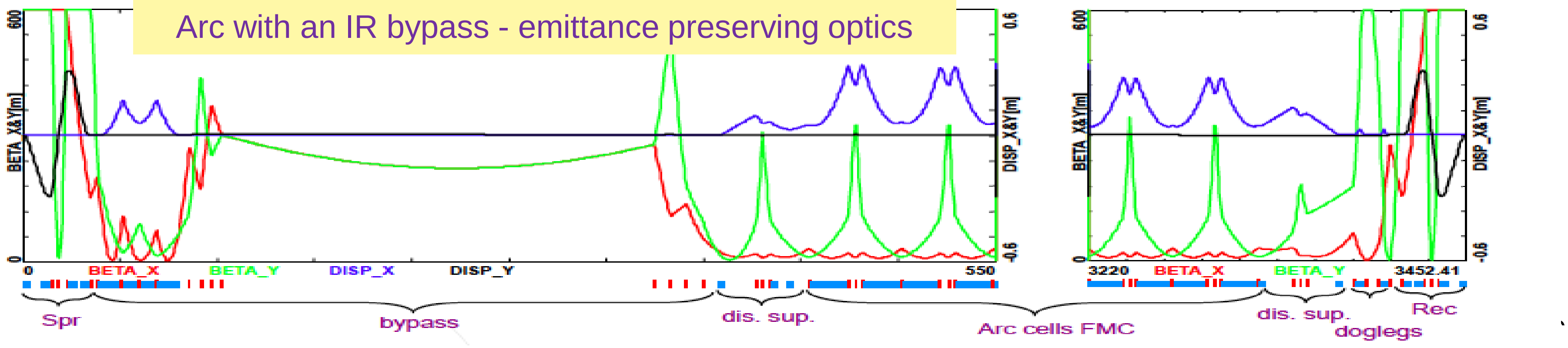
- Variation of proton beam during luminosity run is important
- Strong pinch is important and leads to almost universal electron beta-function of O(45mm)
- Need to explore electron filling patterns
- How can we best profit from different electron emittance growth in the two planes?
- Operational models of FCC-hh are being further developed
- Much more work to be done …

A. Bogacz, JLab

# LHeC ERL – Lattice Design


Multi-pass linac optics

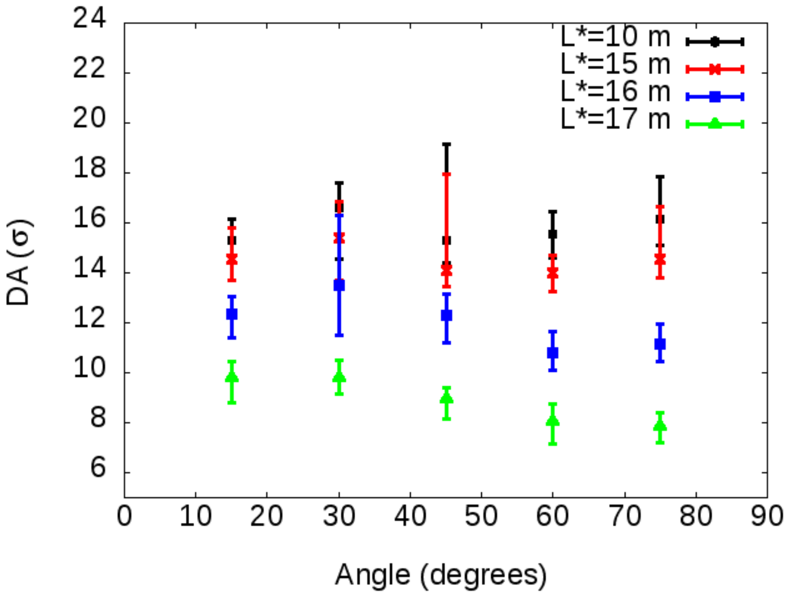

Isochronous arc optics


Arc with an IR bypass - emittance preserving optics

# IR Summary

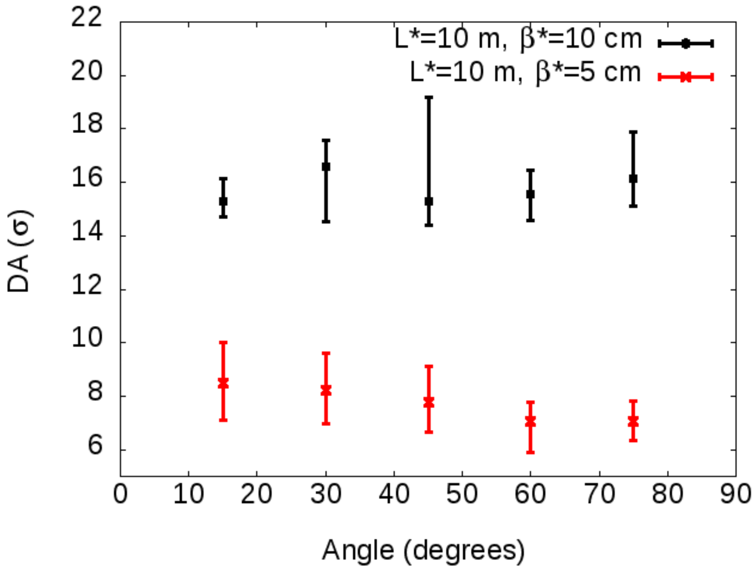
Rogelio Tomas/CERN
Emilia Alaniz/U Liverpool

## Case **$10^{33}$ cm$^{-2}$s$^{-1}$** ($\beta^*$=10 cm):



- From DA studies largest L* is 15 m. A steep reduction of DA is observed for larger values.
- L* of 15 m could also reduce the SR by a factor of 2.

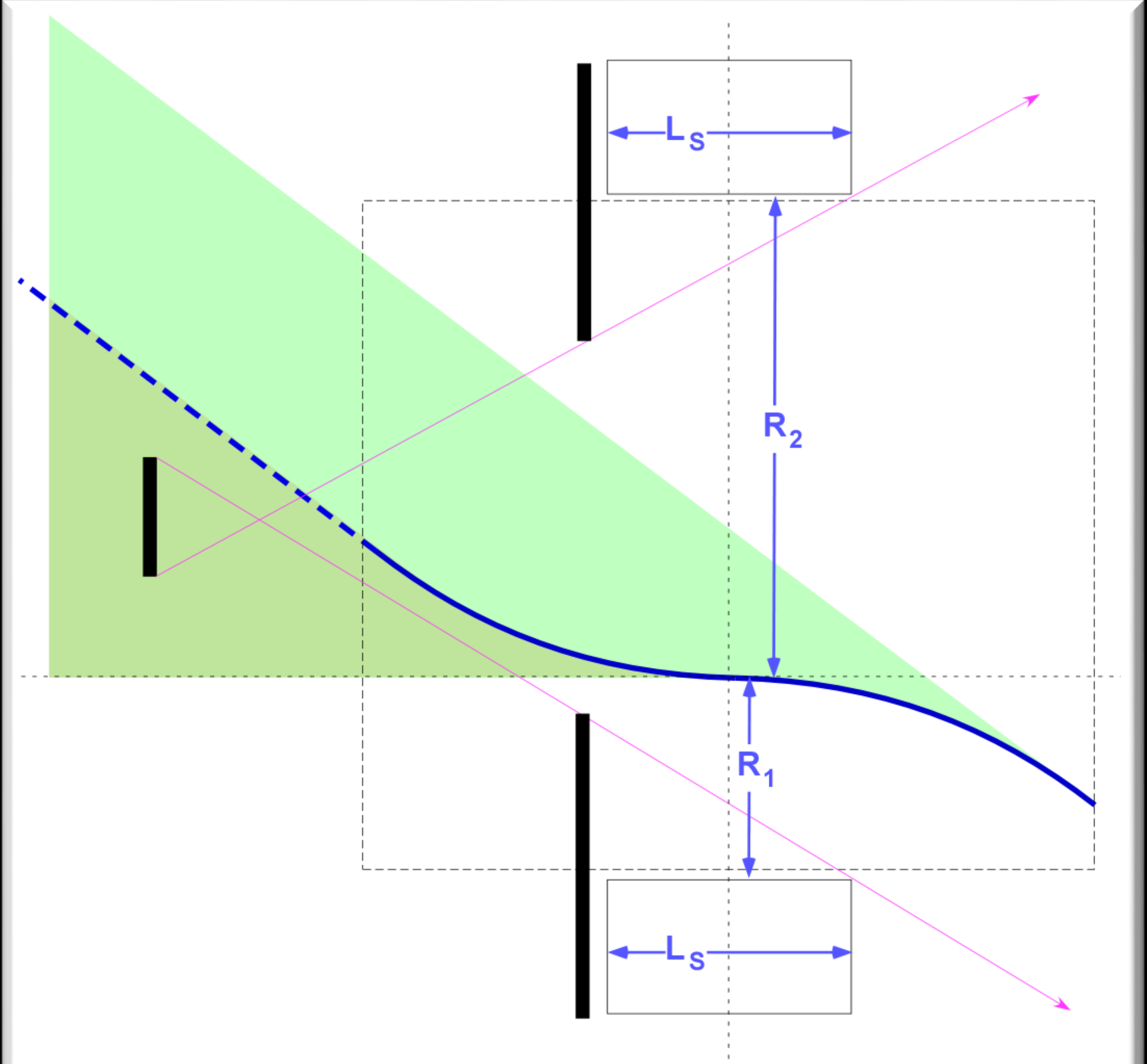
## Case **$10^{34}$ cm$^{-2}$s$^{-1}$** ($\beta^*$=5 cm):



- Too low DA (6 σ without triplet errors!).
- No longer possible to increase L* to 15 m to mitigate SR.
- Minimum β* 8 cm with good LHeC-like chromatic correction

# Principles for Locating the Anti-Backscatter Masks

Brett Parker/BNL



***Background Reduction Mask Scheme Layout***

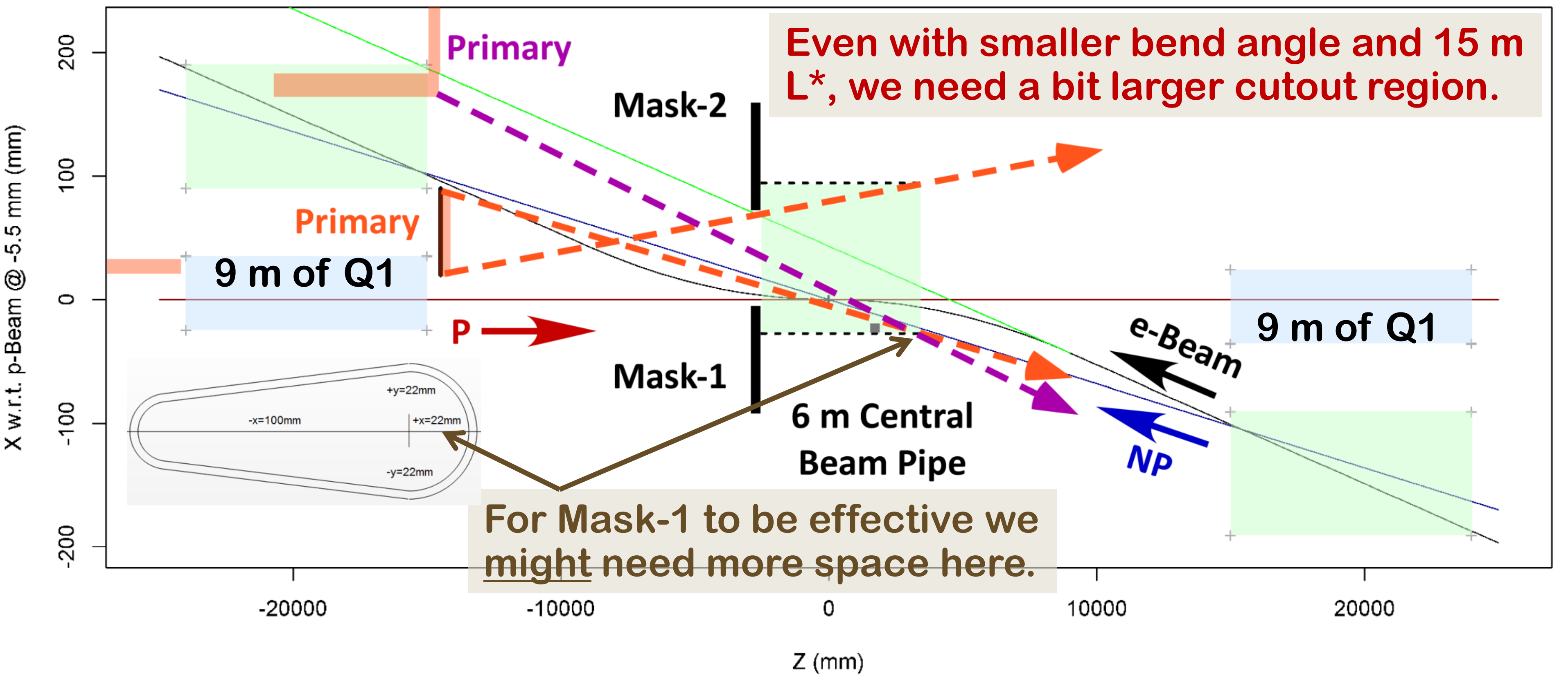
**If even a quite small fraction of the backscattered synrad albedo hits sensitive central regions of the detector, it can cause unacceptable background and detector trips (HERA-II experience).**

**Masks placed between the closest primary absorbers and a sensitive region can protect against this but they must stay back from the primary beams.**

**Having the separation bend stop too close to the synrad absorber means that there is then no good place for these masks; we need some extra distance (as shown in the new layout) for these masks to be effective.**

# Locating the Anti-Backscatter Masks for LHeC IR

Brett Parker/BNL



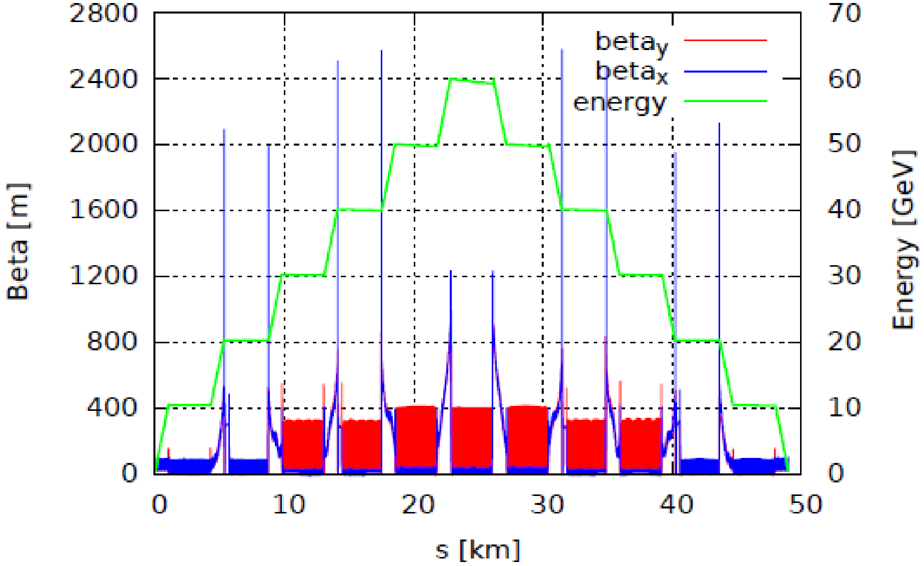
Even with smaller bend angle and 15 m L*, we need a bit larger cutout region.

For Mask-1 to be effective we might need more space here.

With this new, improved beam separation scheme, it almost looks possible to protect the central 6 m beam pipe region from the backscatter albedo off the central synrad absorber (note LHeC CDR has only 1 m between the end of the separation dipole and the magnetic edge of Q1). But because in this design Q1 still does not pass the outer edge of the full synrad band, it is impossible to protect against albedo backscatter from this outer edge… this is an important lesson. Note that in the LHeC CDR the synrad band was much wider!

# Multi-bunch tracking with PLACET2

Dario Pellegrini/CERN



PLACET2:

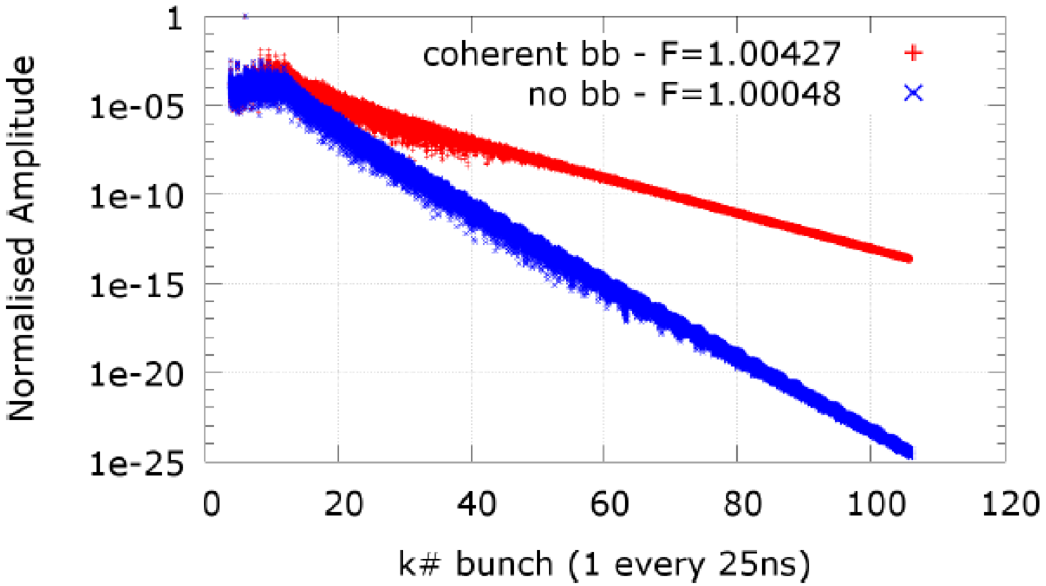
* New version of PLACET capable to handle multi-bunch tracking in recirculating lattices.

* Implements a number of effect and can test their **interplay**.

Verified the beam stability against HOMs with beam-beam amplification for the Higgs Factory parameters.

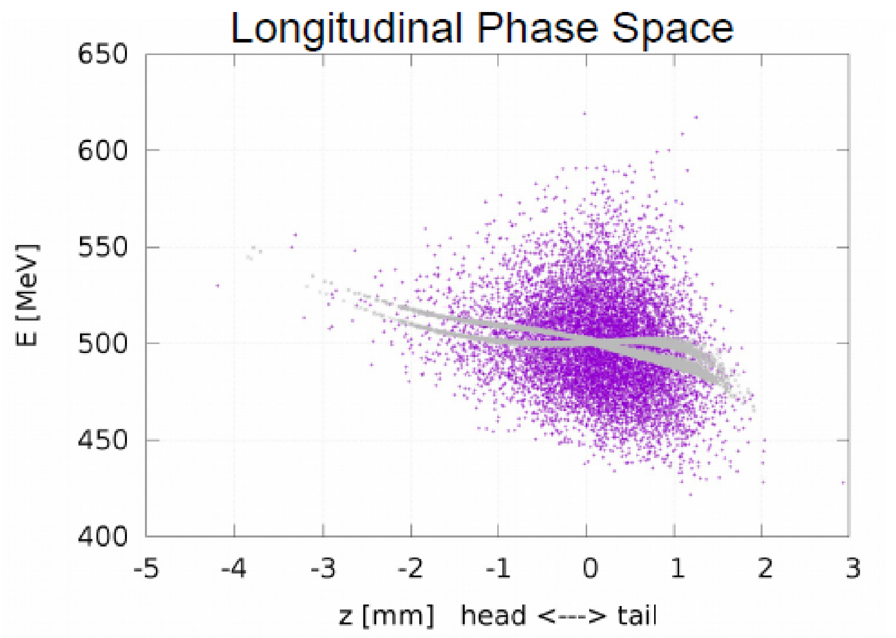
In future can include attenuation from **energy spread** and coupling with the **ion cloud**.

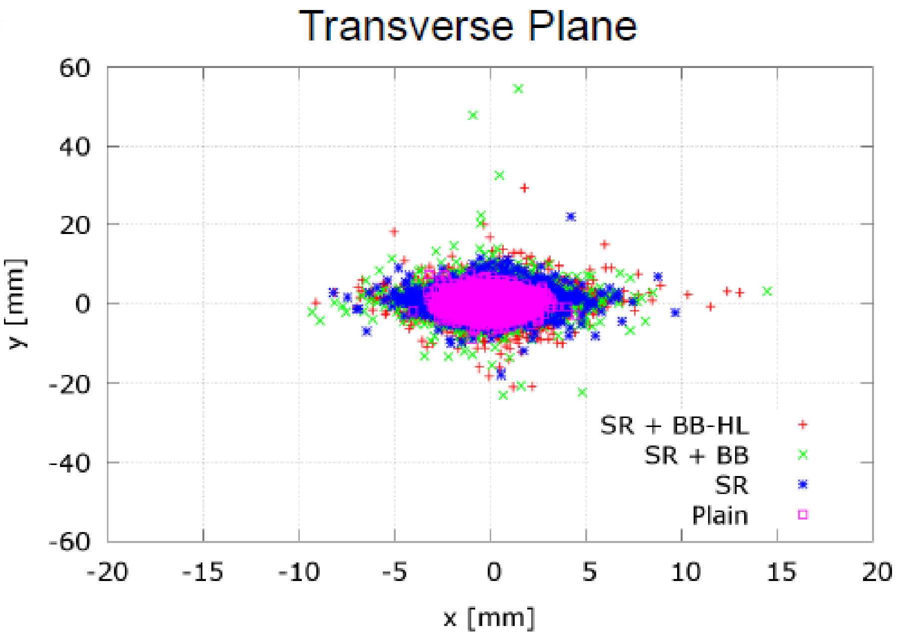
Effect of wakefields at IP



Dario Pellegrini/CERN

# Transport to the dump

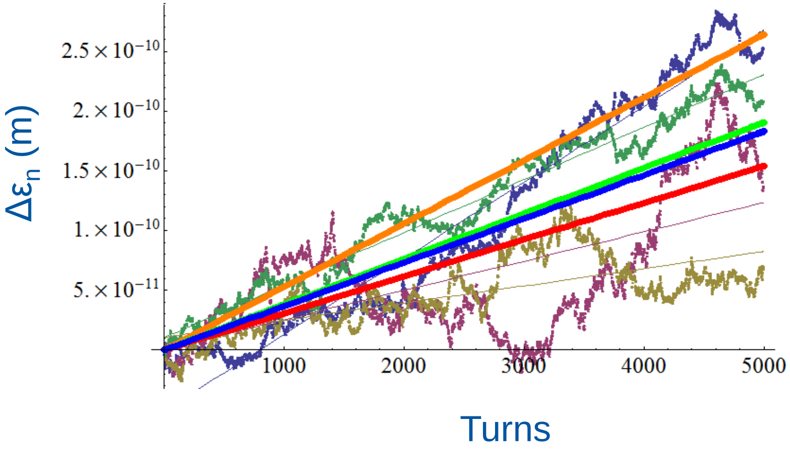

Longitudinal Phase Space


Transverse Plane

* Good beam quality at the IP.
* Can decelerate the beam to the injection energy (500 MeV).
* Beam Beam and wakes have an effect, but the beam degradation is dominated by Synchrotron Radiation.

# Emittance Growth Rate Predictions

Edward Nissen/CERN



| | |
|---|---|
| 🟨 $5.28\times10^{-14}$ m/turn | Rate predicted by Guinea-Pig |
| 🟩 $3.81\times10^{-14}$ m/turn | Rate Predicted by Ansatz |
| 🟦 $3.66\times10^{-14}$ m/turn | Average Simulation Rate |
| 🟥 $3.08\times10^{-14}$ m/turn | Rate Predicted by Integration |

Using measurements of the head-tail effect in the interaction region of the electron and ion beams, we can predict the growth rate of the ion beam emittance from the beam-beam effect.

$$\Delta\varepsilon_n = \frac{1}{2}\gamma\beta^* < \Delta p_x{}^2 > \frac{\sigma_{jitter}^2}{\sigma_x^2}$$

This can be used to determine the correction system tolerances needed for the LHeC

# Summary "Accelerator" Session

- FCC-he: We have a first set of parameters
- LHeC lattice studied fully – start to end!
- IR: critical – ultimate $\beta^*$ for $10^{34}$ is difficult to say the least
- Magnet design for IR – very difficult due to SR compatible with p-beam apertures!
- Wakefield effects: estimated in detail – effect of beam-beam to be continued, tools are available and have been adapted.
- Beam-beam simulations: electron orbit at IP must be controlled – a feasible solution seems in reach.