High Intensity Linacs and Rings: new facilities and concepts

# Summary of working group E

conveners: F. Gerigk, P. Ostroumov

# Working group charge:

- Recent trends in high-intensity proton/ion beam facilities?
- Critical challenges and key research areas for substantial beam power increases?
- Necessary improvements in theory and simulation tools?

# Summary of presented facilities:

**Part I**: existing facilities/funded projects

| Facility: | application |
|---|---|
| **RIKEN upgrade** (Hiroki Okuno/RIKEN) | Nuclear physics, RIB |
| **SARAF commissioning** (Jacob Rodnizki/SOREQ) | Nuclear physics |
| **PEFP status & outlook** (Ji-Ho Jang/KAERI) | Material science, transmutation, spallation |
| **FAIR SIS 100 design** (Peter Spiller/GSI) | Nuclear physics |
| **HINS R&D** (Giorgio Appollinari, Bob Wagner/FNAL) | Neutrino proton driver |

# Summary of presented facilities:

**Part II**: planned projects, R&D

| Facility: | application |
|---|---|
| **Project X** (Valerie Lebedev, Charles Ankenbrandt/FNAL) | Neutrino proton driver, ILC test facility |
| **LHC-upgrade, SPL/PS2** (Frank Gerigk/ Yannis Papaphillippou/CERN) | LHC injector upgrade, Neutrino/RIB proton driver |
| **ISIS upgrade** (John Thomason/RAL) | Neutron/Neutrino proton driver |
| **ESS** (Ibon Bustinduy/ESS-B) | Neutrons |
| **eRHIC/ELIC** (Vadim Ptitsyn/BNL, Yuhong Zhang/JLab) | Nuclear physics |
| **Compact Deuteron Linac** (Larry Rybarcyk/LANL) | Homeland security (neutrons) |

# Summary of presented facilities:

**Part III**: overview & outlook

| Facility: | application |
| --- | --- |
| **Scaling & non-scaling FFAGs** (Akiro Sato/Osaka University) | R&D, medical, material science, muon, neutrino proton drivers…. |

# RIKEN Radioactive Ion Beam Factory (H. Okuno/RIKEN)

Light Ions >400 MeV/u
Uranium 350 MeV/u





RRC

RILAC

ECRIS




RIBF

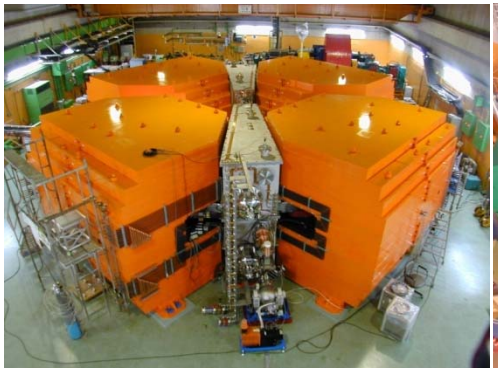
(1997~(2012))

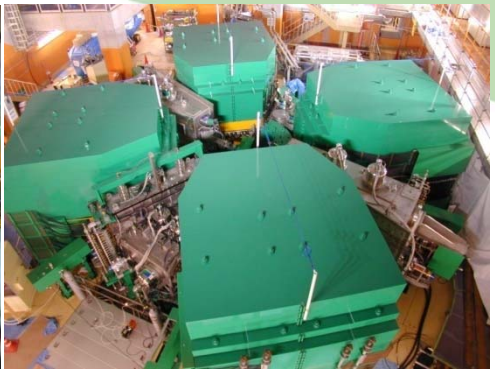
fRC

IRC

BigRIPS
(Fragment Seperator)

SRC -- World's First!

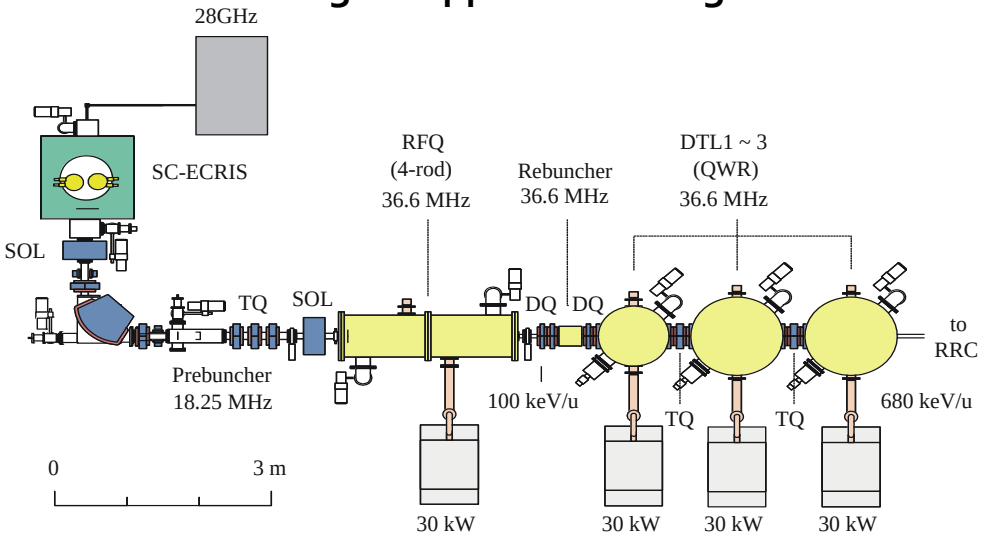






# Key issues to increase the intensity of U beam

- **Increase the beam intensity from the ion source**
  - New 28GHz Superconducting ECR ion source
  - Goal intensity of $U^{35+}$ >15 pμ A ( 1pμA @ SRC)
  - Operation test will be started in January 2009
- **Improve transmission efficiency**
  - Flattop acceleration in the cyclotrons
  - Careful tuning in each accelerator
  - New injector (Efficient acceleration in the low energy region)
  - Avoid the emittance growth due to the space charge.
- **Make charge strippers with long lifetimes**




| LEBT | MEBT | RILAC | RRC |
|---|---|---|---|
| Neut. Factor ?? ??? | Space charge | Space charge | Spiral beam instab. |

# SARAF – Soreq Applied Research Accelerator Facility (J. Rodnizki)

- **40 MeV deuteron Linac, CW, 80 kW beam**

  - Energy Range 5 – 40 MeV
  - Current 2 mA
  - First cryo-module in operation,
  - Full power planned for 2013,

Technical issues:

CW operation of the RFQ

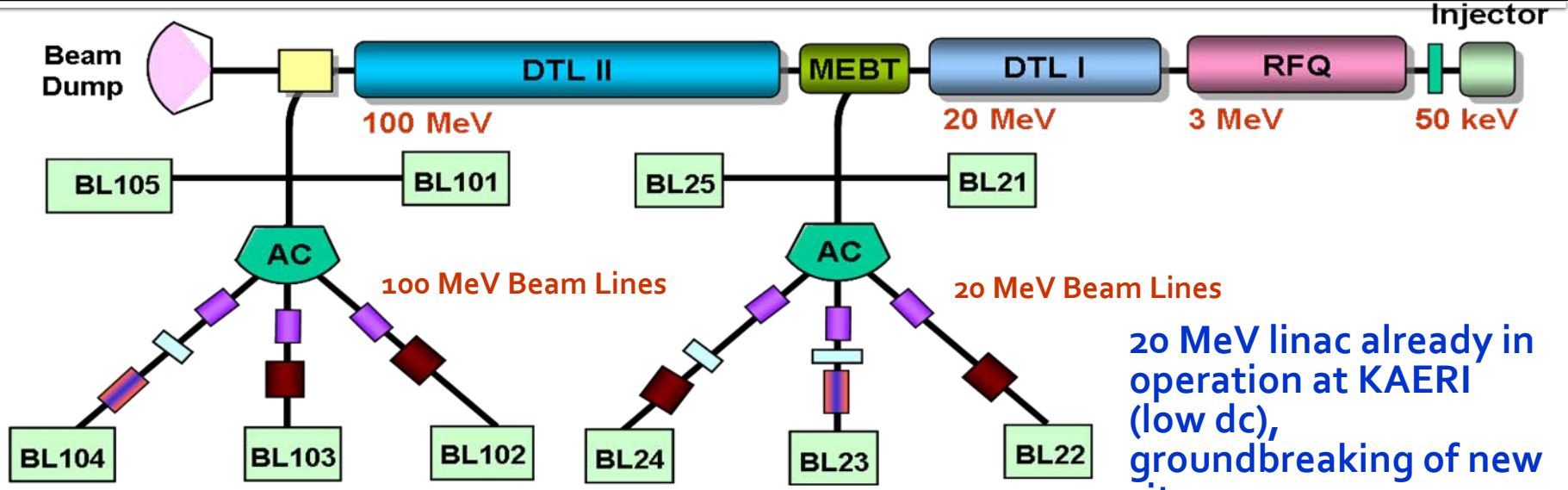
Cryogenic losses in SC cavities

Optimization of the facility parameters to minimize beam losses

Beam diagnostics in SC linac environment



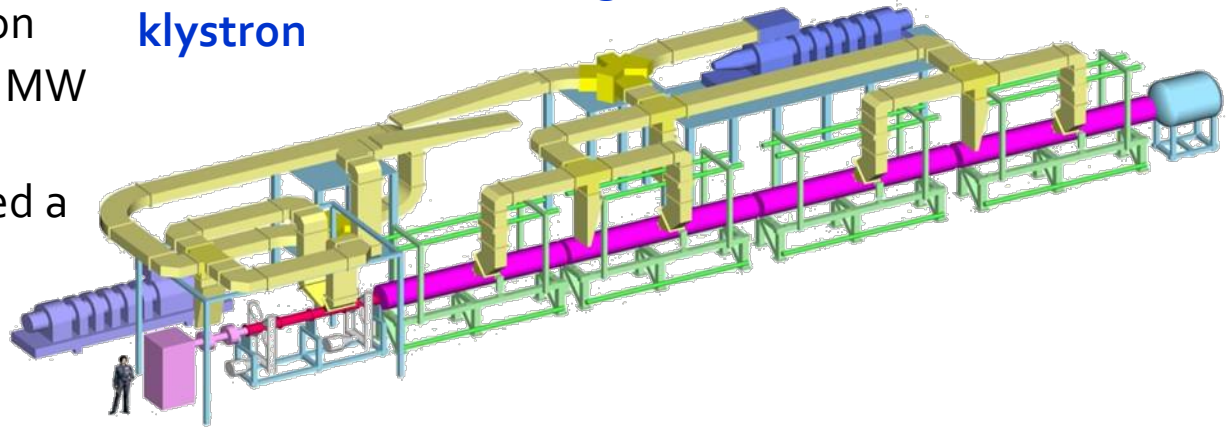
# The Korean Proton Engineering Frontier Project (J.H. Jang/KAERI)



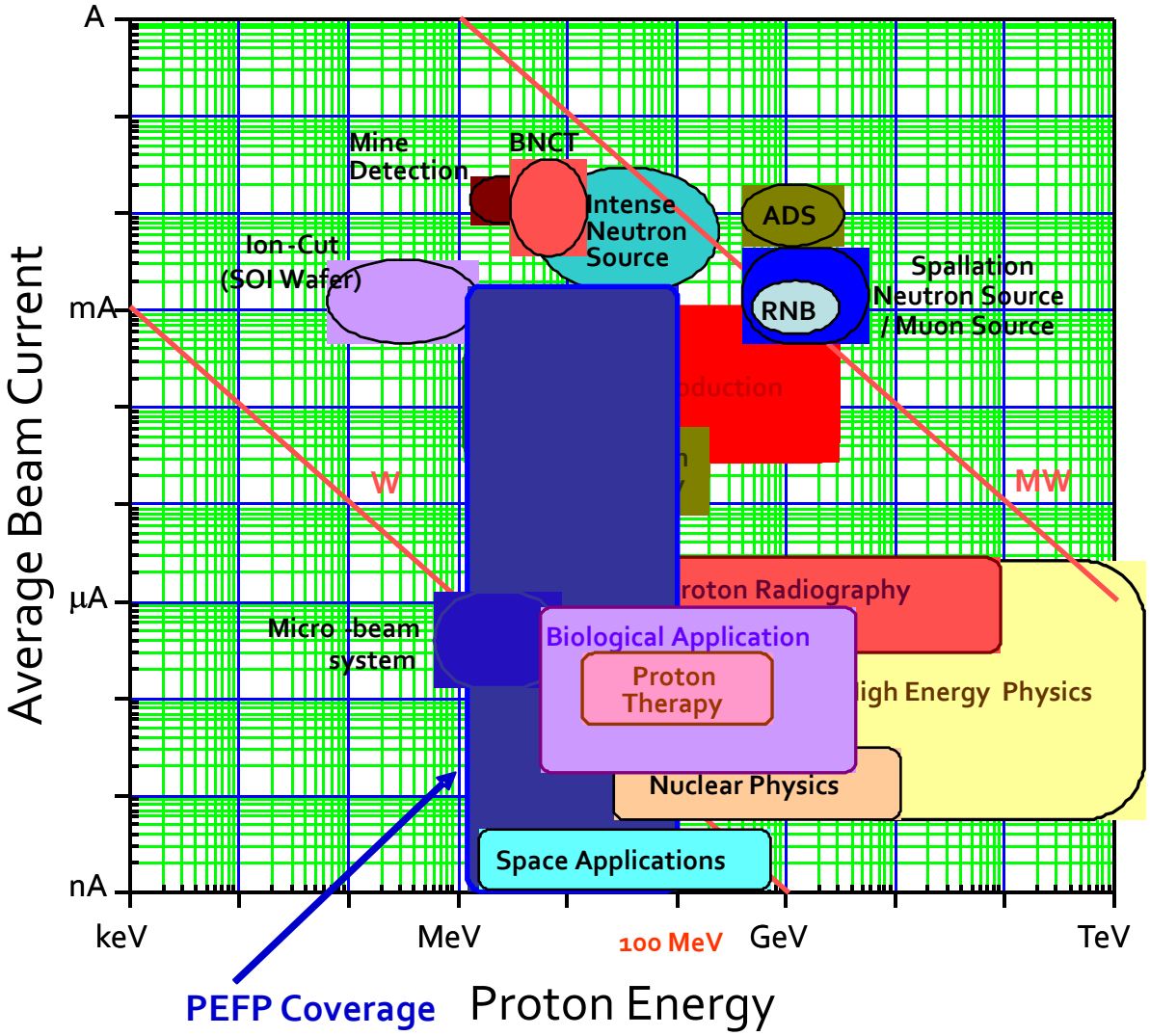

20 MeV linac already in operation at KAERI (low dc), groundbreaking of new site now.

- Ongoing R&D
  - Superconducting RF Linac
  - Rapid Cycling Synchrotron
  - High Power RF Source – MW Klystron
    - Successfully Developed a 700 MHz, 1 MW (CW) Klystron (prototype)

**Technical innovation:**
**4 DTL tanks from a single klystron**



# Unique feature: wide application of proton beam




- **Industrial applications;** ion-cut, power semiconductor devices
- **Medical applications;** BNCT, RI production, neutron & proton therapy
- **Biological applications** ; mutation studies of plants and micro - organisms, micro -beam system
- **Space applications;** radiation tests of space components and radiation effects
- **Defense applications;** mine detection, proton & neutron radiography
- **Intense neutron source;** radiation damage study, nuclear material test, target & modulator development, etc.
- **MW beam utilization areas;**
  - Spallation Neutron Sources
  - Muon Source
  - Radioactive Nuclei Beams
  - High Energy Physics (mesons & neutrinos)

# The superconducting SIS 100 Synchrotron (P. Spiller/GSI)

Timescale for the first stage: SIS-100

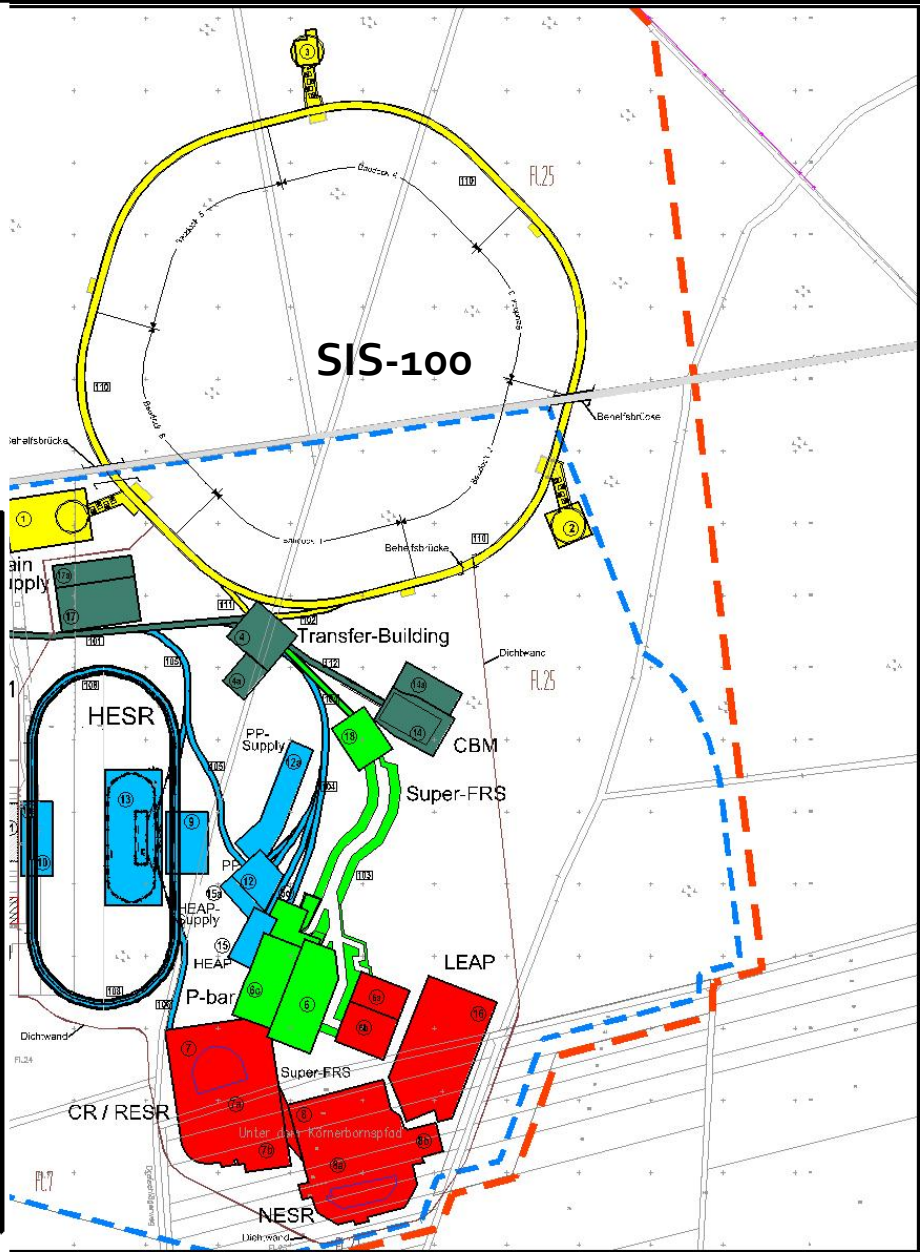
2008 Conceptual design

2009-2012 Finalization of the engineering design

2011-2013 Manufacturing of components

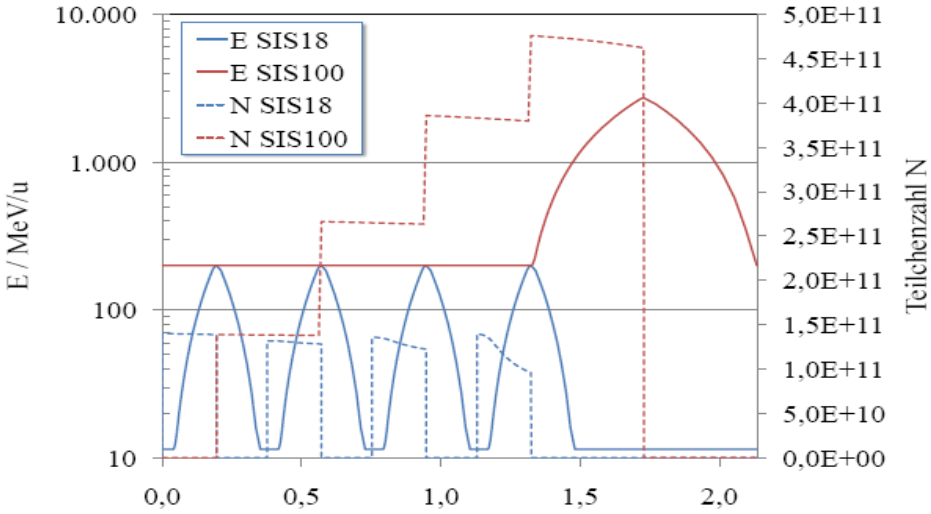
2013-2014 Installation and commissioning

| SIS100 | Protons | Uranium |
|---|---|---|
| Number of injections | 4 | 4 |
| Number of ions per cycle | 2.5 x $10^{13}$ ppp | 5 x $10^{11}$ |
| Maximum Energy | 29 GeV | 2.7 GeV/u |
| Ramp rate | 4 T/s | 4 T/s |
| Beam pulse length after compression | 50 ns | 90 - 30 ns |
| Extraction mode | Fast and slow | Fast and slow |
| Repetition frequency | 0.7 Hz | 0.7 Hz |

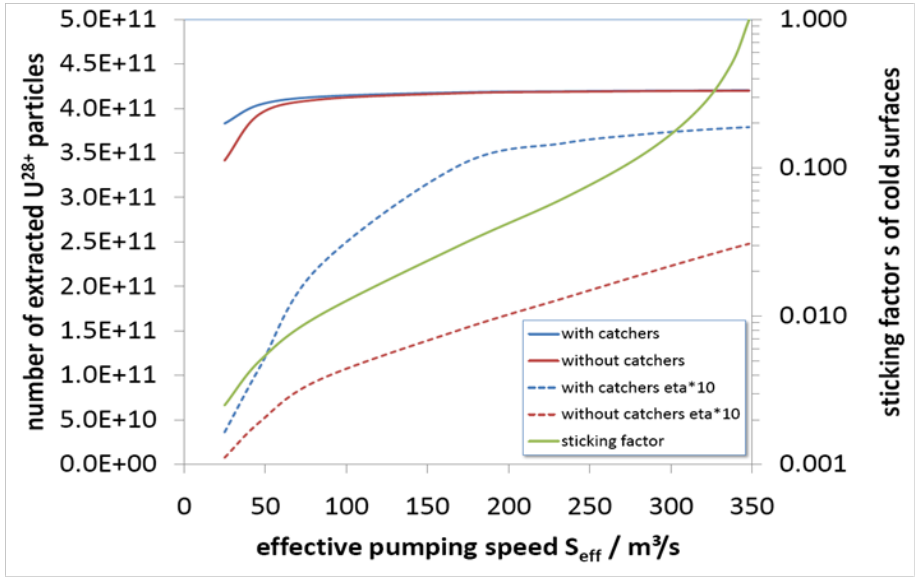


# Ionization Beam loss and dynamics of vacuum pressure

- **Dynamic Vacuum – STRAHLSIM Code including:**
  - Linear Beam Optics
  - Static Vacuum simulations
  - Dynamic Vacuum simulations
  - Ion stimulated desorption




**Ionization loss during stacking and acceleration in SIS18 and SIS100**

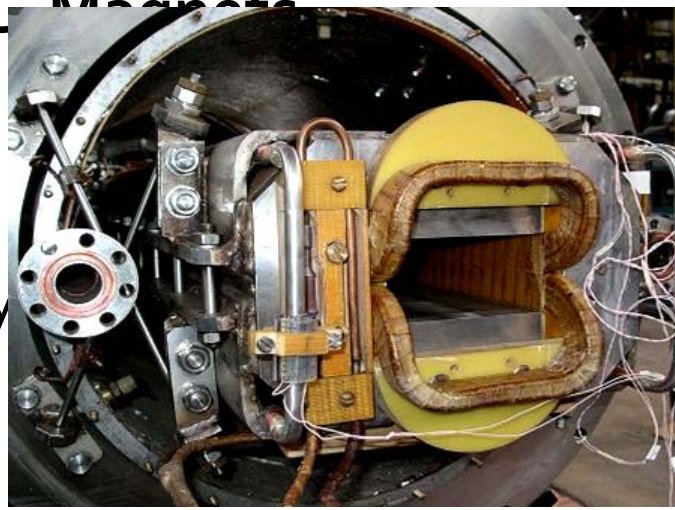



**Extracted ions versus pumping speed of cryogenic surfaces**

# FAIR R&D Challenges

- **R&D goal for the SIS100 Fast Ramped S.C. Magnets**
  - AC loss reduction to

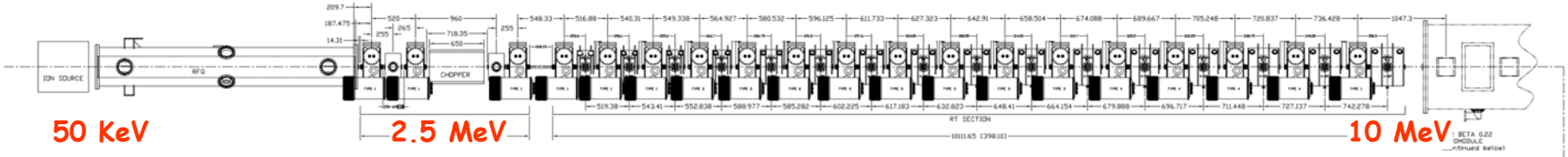
    13 W/m @ 2T, 4 T/s, 1 Hz
  - R&D Improvement of DC/AC-field quality
  - Guarantee of long term mech. Stability
- **SIS100 RF System**



| | FBTR | f [MHz] | # | Technical Concept |
|---|---|---|---|---|
| Acceleration System | h=10<br>400 kV | 1.1–2.7 | 20 (SIS100)<br>8 (SIS300) | Ferrit ring core, "narrow" band cavities |
| Compression System | h=2<br>640 kV | 0.395-0.485 | 16 | Magnetic alloy ring core, broad band(low duty cycle) cavities |
| Barrier Bucket System | 15kV | 2 | 2 | Magnetic alloy ring core, broad band (low duty cycle) cavities |

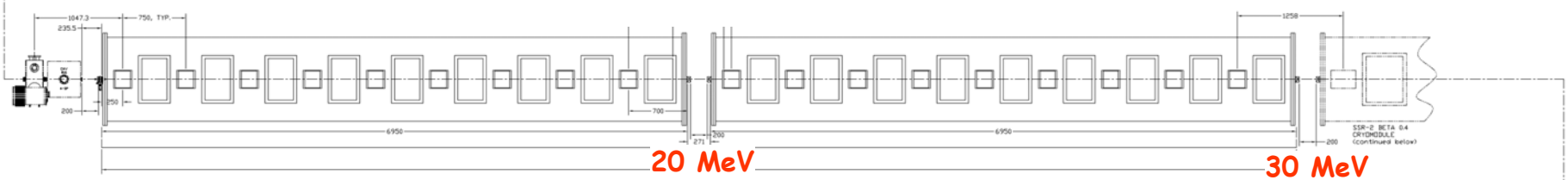
# Overview & status of the FNAL HINS R&D program (G. Appolinari)

Ion Source RFQ MEBT Room Temperature 16-Cavity, 16 SC Solenoid Section



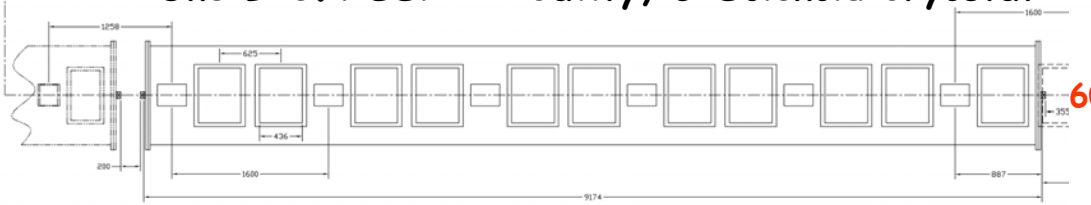

50 KeV 2.5 MeV 10 MeV

Two B=0.2 SSR 9-Cavity, 9-Solenoid Cryostats



20 MeV 30 MeV

One B=0.4 SSR 11-Cavity, 6-Solenoid Cryostat



60 MeV

# HINS

## Status:

- Klystron operational,
- RF test facility operational,
- RT cavity tests in progress,
- 1st spoke cavity tested, further units in production,
- Ion source installed,
- RFQ fabricated,
- SC solenoids in construction,
- Cavity cryostat ready for testing by the end of the year.

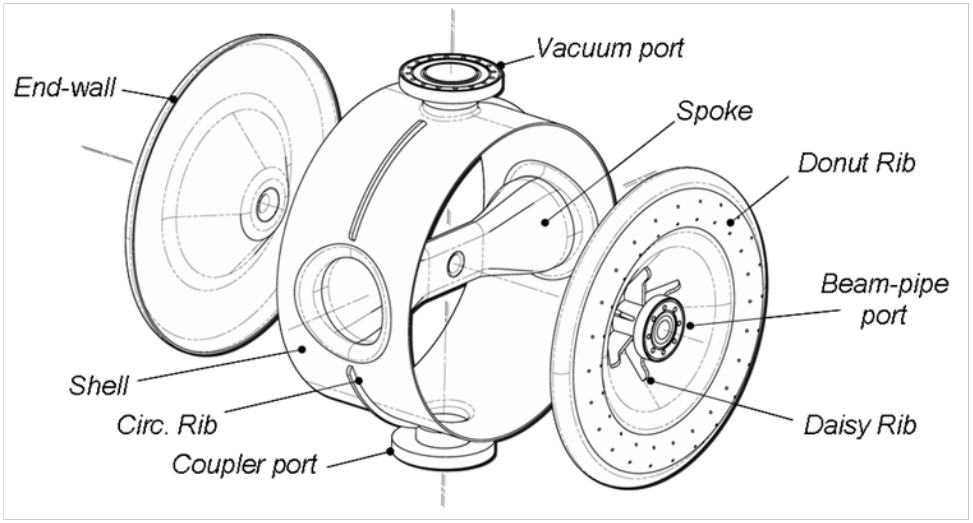
## Challenges:

- Feeding of multiple cavities from a single klystron: 1st tests of vector modulators successful,
- SC solenoid focusing/spoke cavities from 10 MeV onwards,

# High-gradient test of SC single-spoke resonators for HINS (B. Wagner/FNAL)

| Quantity | Value |
|---|---|
| Operating temperature | 4.4 °K |
| Accelerating gradient, $E_{acc}$ | 10 MV/m |
| $Q_0$ at accelerating gradient | $> 0.5 \times 10^{-9}$ |
| Beam pipe, Shell ID | 30 mm, 492 mm |
| Lorenz force detuning coefficient | 3.8 Hz/(MV/m)$^2$ (with He vessel) |
| $E_{peak}/E_{acc}$ * | 3.86 |
| $B_{peak}/E_{acc}$ * | 6.25 mT/(MV/m) |
| G | 84 Ω |
| $R/Q_0$ | 242 Ω |
| Geometrical Beta, $\beta_g$ | 0.21 |



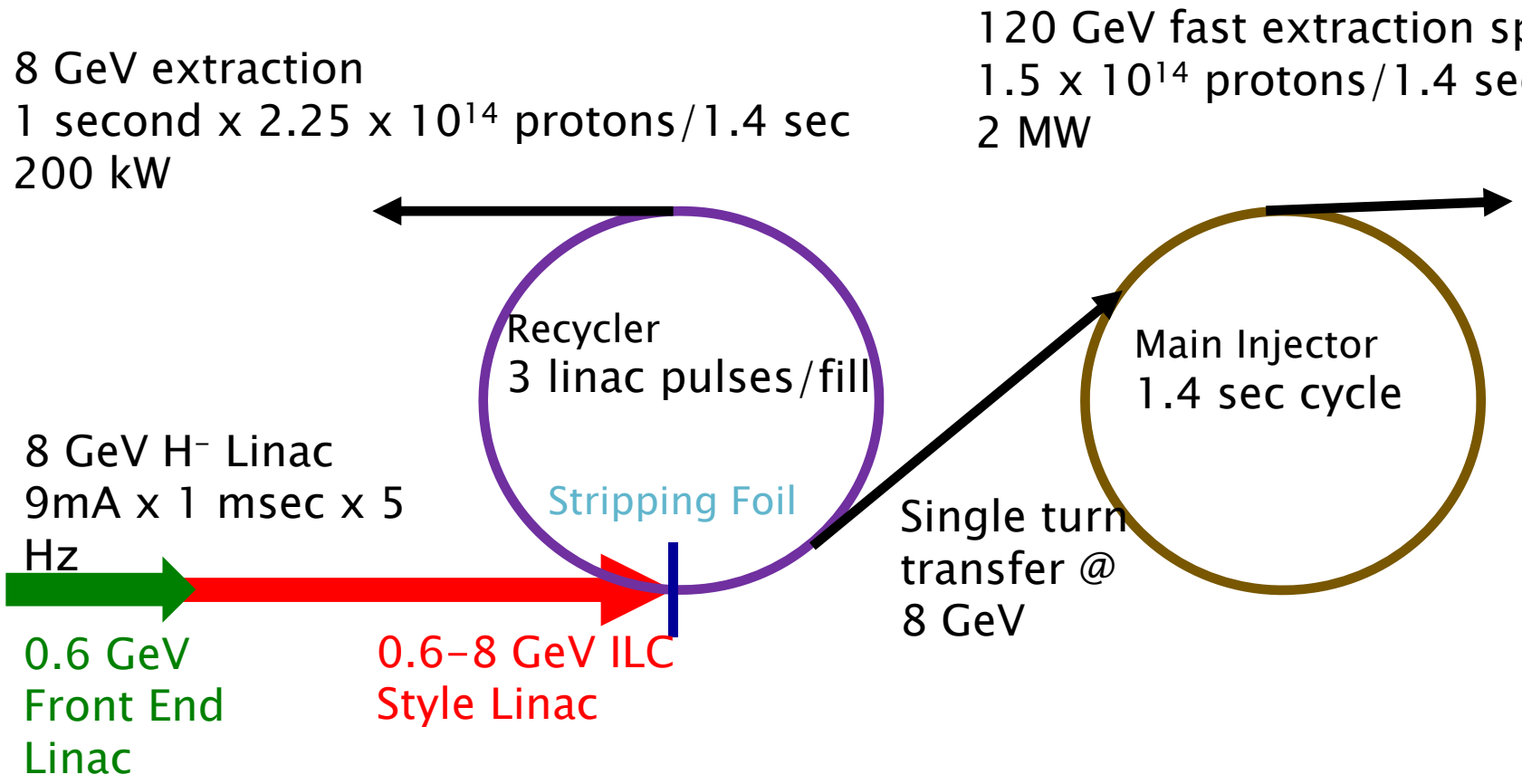


# High-gradient test of SC single-spoke resonators for HINS (B. Wagner/FNAL)

- First results already exceeded the design gradient of 10 MV/m (up to 13.5),
- However the tests suffered from a helium leak, which is under repair now,
- The encountered multipacting at around 10 MV/m is expected to vanish with further conditioning.

**Main R&D effort: optimise the parameters of the chemical processing**

# Project X (V. Lebedev, C. Ankenbrandt/FNAL)

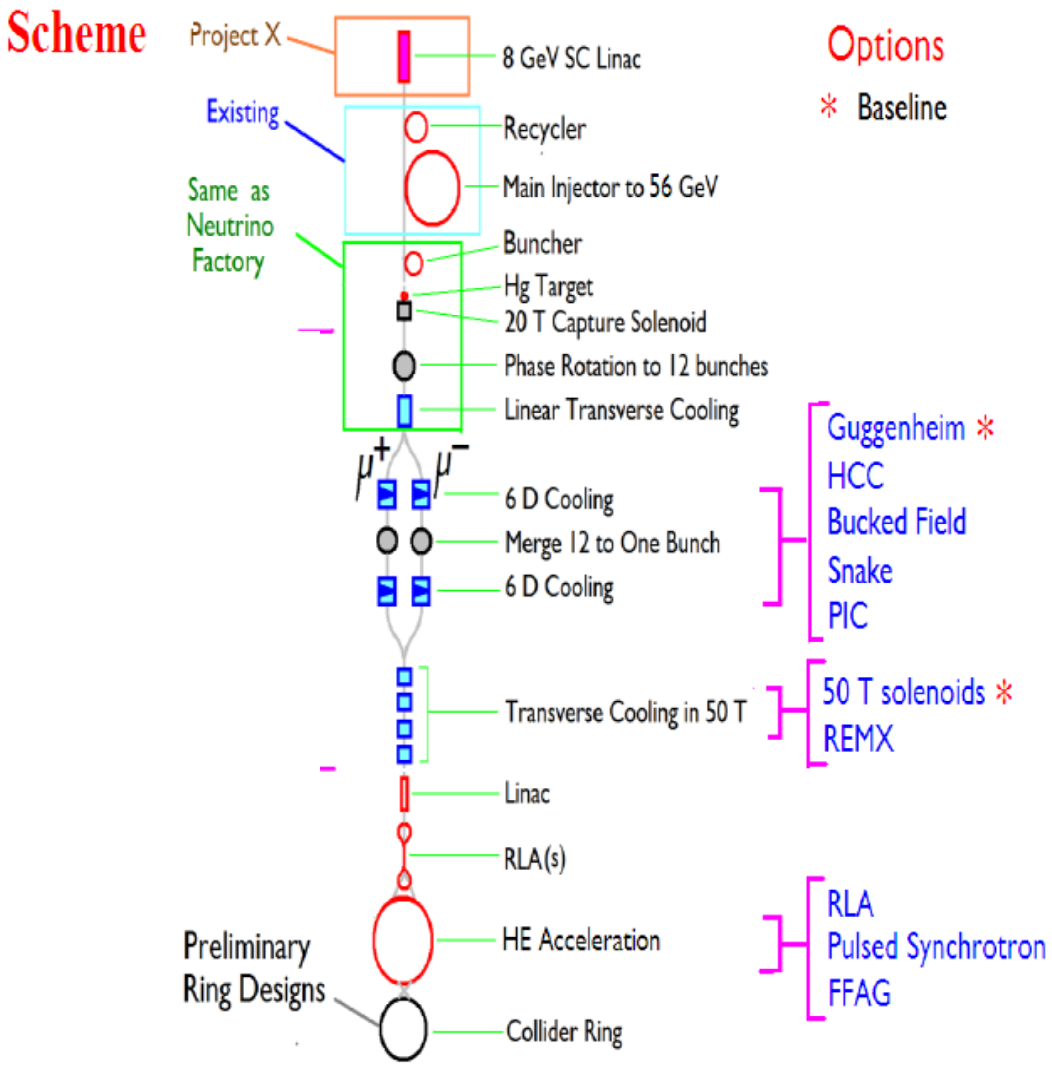


# Conclusion on Project X

- There are no principle physics or technical limitations on the future machine operation
  - Multipactoring of electrons and related to it ep-instability are the major points of concern
  - Keeping machine operating reliably at full power of 2.3 MW will be a challenging problem

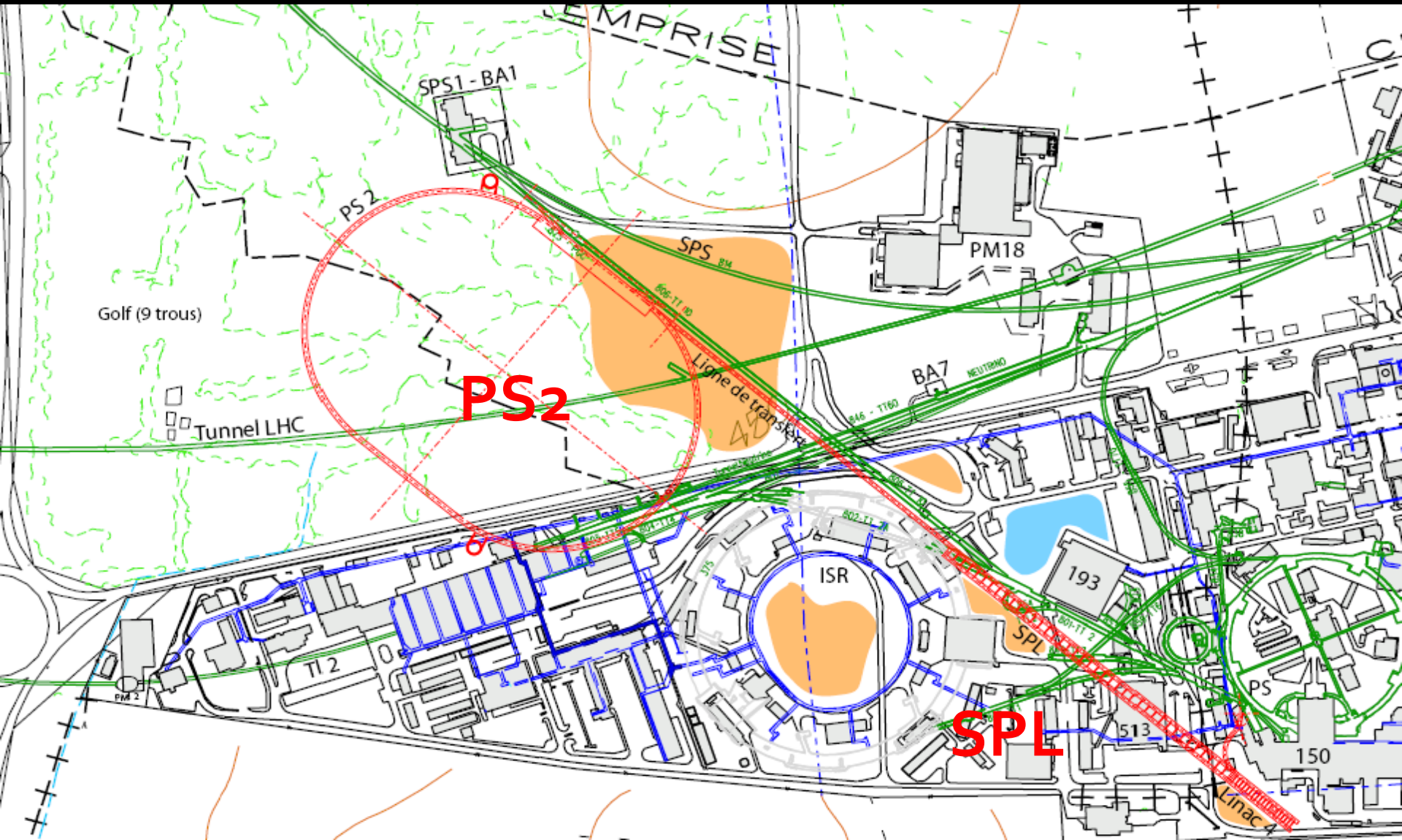
  ⇨ Machine protection and minimization of beam loss have to be major points to be addressed at next stages of design work
- Required MI Upgrades
  - Transition crossing jump
  - RF system
    - Peak power 3.2 → 13 MW; beam loading compensation
  - Second harmonic RF system,
    - ~1.5 MW; high accuracy phasing to the first harmonic system;
  - Instability dampers
  - Injection kicker
  - Vacuum
  - Instrumentation

# Project X as a driver for Muon Collider and Neutrino Factory




- 2-3 MW Upgrade of the 8-GeV linac is required
- 10 MW upgrade may be necessary
- Design of the 8-GeV SC Linac has sufficient flexibility for future upgrades

# CERN LHC injector upgrade



# Choice of frequency, gradient & temperature for SC proton linacs (SPL), F. Gerigk/CERN

| | 704 MHz | 1408 MHz | 352 MHz (spoke) + 1408 MHz |
|---|---|---|---|
| length | 439 m | +14% | +10% |
| $N_{cavities}$ | 239 | +16% | +12% |
| $N_{\beta\text{-families}}$ | 2 | 3 | 2+1 |
| tr. beam loss | - | - | - |
| jitter | medium | medium | medium |
| ε-growth (x/y/z) | 5.6/8.2/6.8 | 6.3/7.8/12.1 | 1.5/5.3/2.5 |
| trans. beam loading | - | - | - |
| BBU (HOM) | $I_{BBU,704}$ | 1/(8..128) | higher/lower |
| trapped modes | normal risk | 2..4 higher risk | ?/higher |
| SC gradients | - | - | - |
| field control | | more complex | |

# Choice of frequency, gradient & temperature for SC proton linacs (SPL), F. Gerigk/CERN

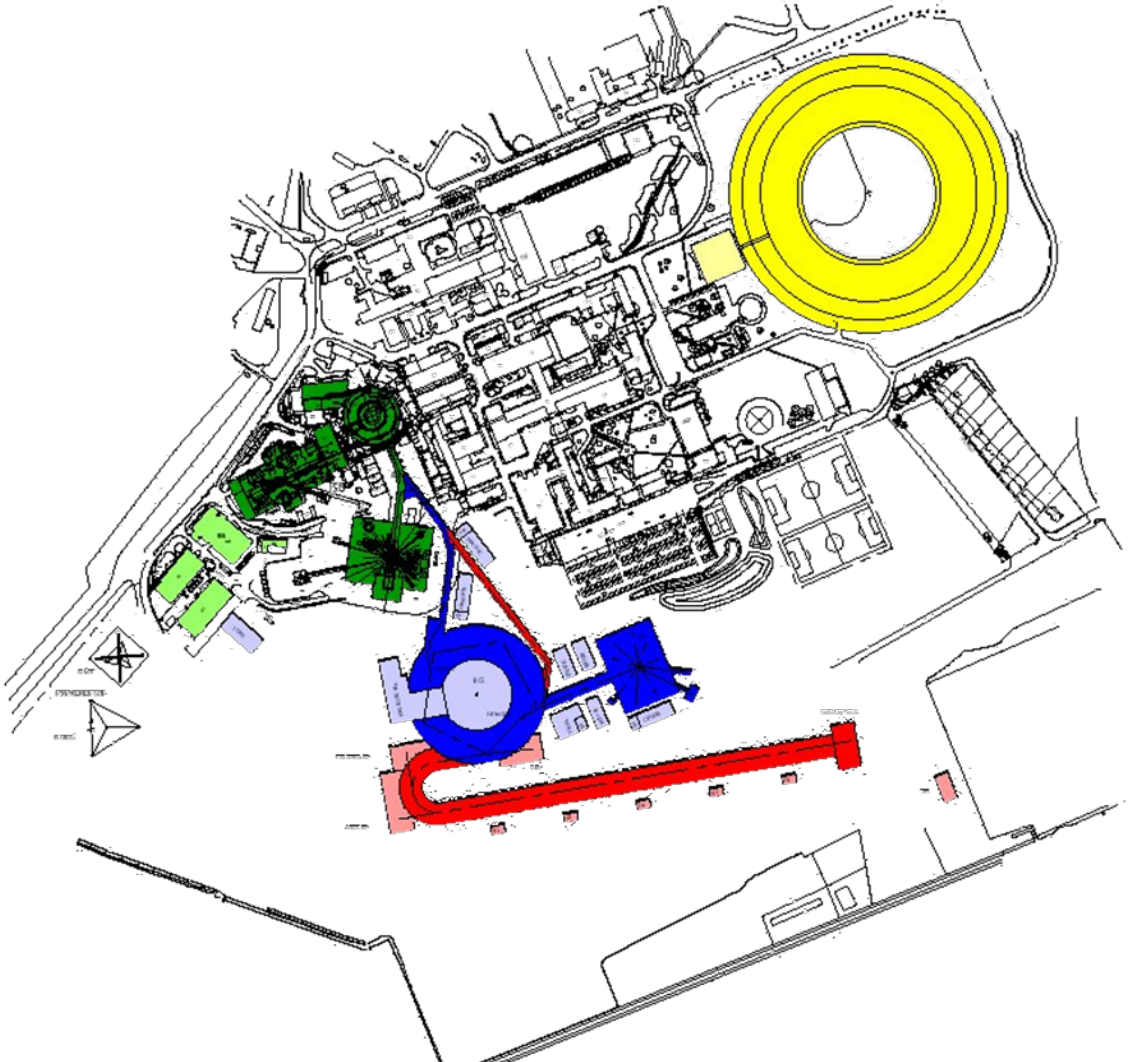
| | 704 MHz | 1408 MHz | 352 MHz (spoke) + 1408 MHz |
|---|---|---|---|
| cryo-modules | follow ILC | follow ILC | 2 different types |
| cooling power @4.5 K | 15.3 kW | 15.5 kW | ? |
| klystrons | comfortable: MBK | difficult | existing/difficult |
| RF power coupler | feasible | feasible | feasible |
| RF power density limit (distribution) | ok | problematic | bulky/ problematic |
| overall power consumption (RF +cryo, nom. SPL) | 28 MW | -30% | ? |
| power converter | more bulky | saves tunnel space | - |
| synergy with ESS | yes | no | no |

# Lattice options for PS2 (Y. Papaphillippou/CERN)

- Comparison of schemes with and w/o transition crossing,
- Transition crossing lattices are straightforward but may yield excessive losses for high-intensity beams,
- For PS2 a number of different lattices w/o transition crossing are considered using Negative Momentum Compaction:

I. NMC resonant ring with FODO straights: **limited tunability,**
II. NMC with dispersion suppressor: **preferred solution**,
III. NMC hybrid ring: **viable alternative**

# MW upgrades for the ISIS facility (J. Thomason/RAL)



## Recommended Upgrades

- Based on a ~ 3 GeV RCS fed by bucket-to-bucket transfer from ISIS 800 MeV synchrotron (1MW)

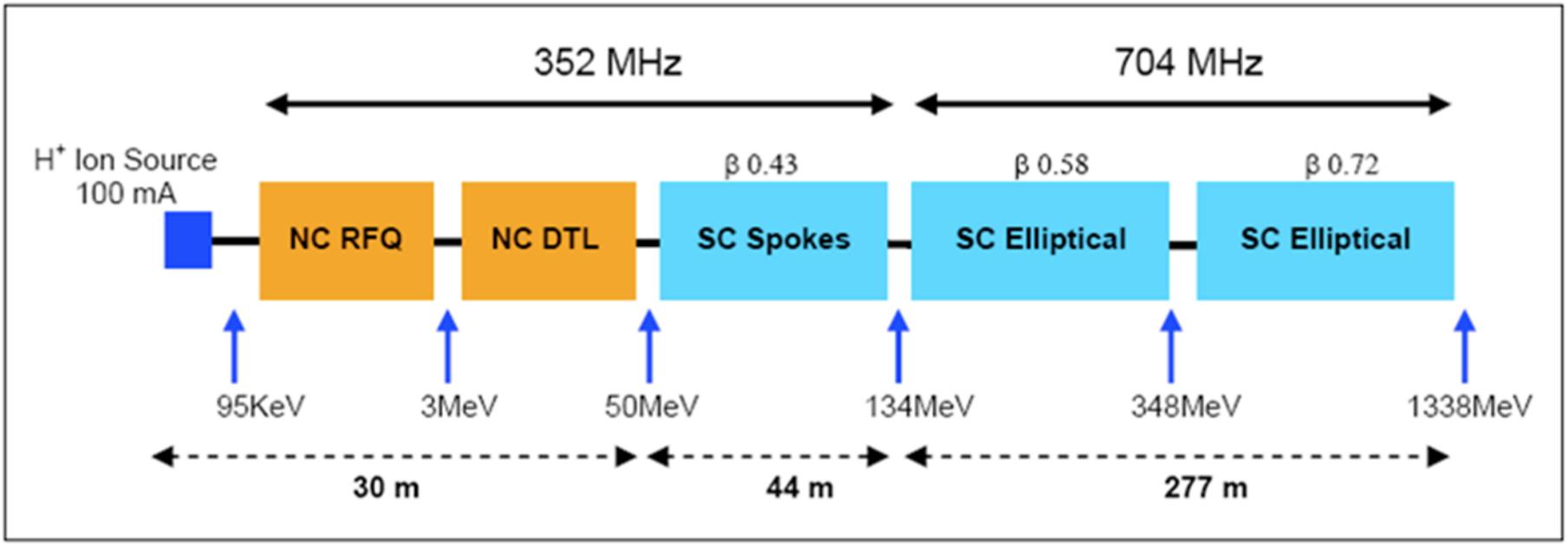
- RCS design also accommodates multi-turn charge exchange injection to facilitate a further upgrade path where the RCS is fed directly from a 800 MeV linac (2 – 5 MW)

# R&D program (robust design for end 2010)

- Minimise beam loss (understand halo, injection painting…),
- Longitudinal beam stability for strong tune depression (0.4),
- 3D simulations with SC,
- Instabilities (EP),
- Collimation system (activation studies),
- Detailed linac design (CCL/spokes, frequencies..),
- Hardware design.

# A superconducting proton linac for ESS-Bilbao (I. Bustinduy/ESS-B)

- Revision of the last "official" linac design (2003), reduced the length by 45%,
- Now only long-pulse operation at 16.6 Hz,
- Front-end test stand under construction,

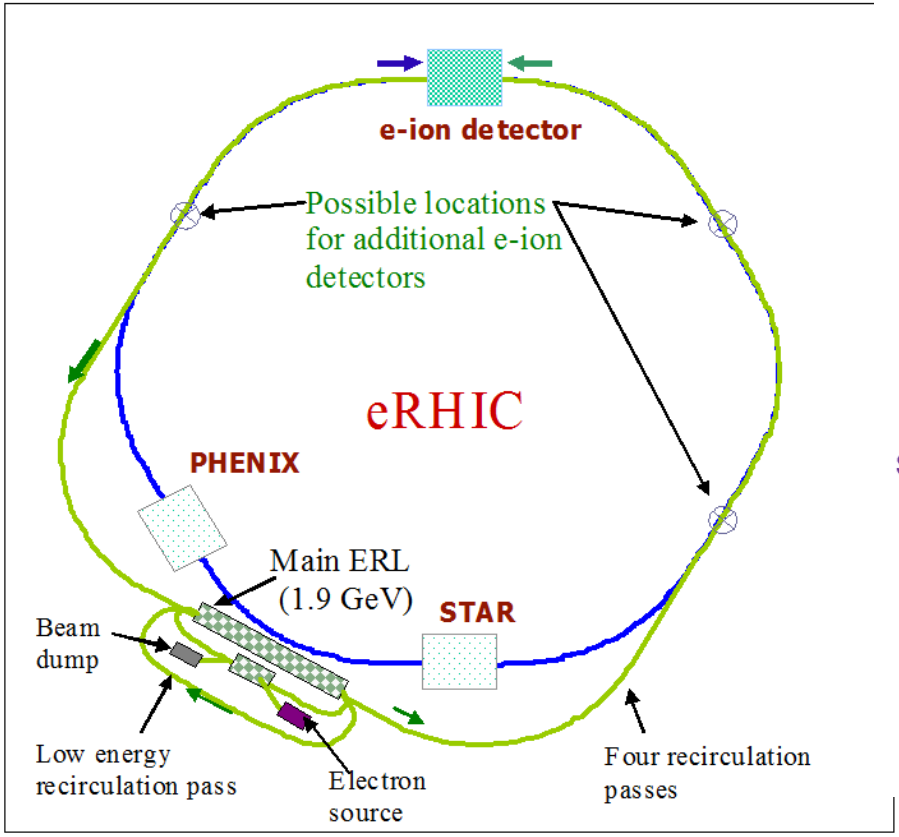


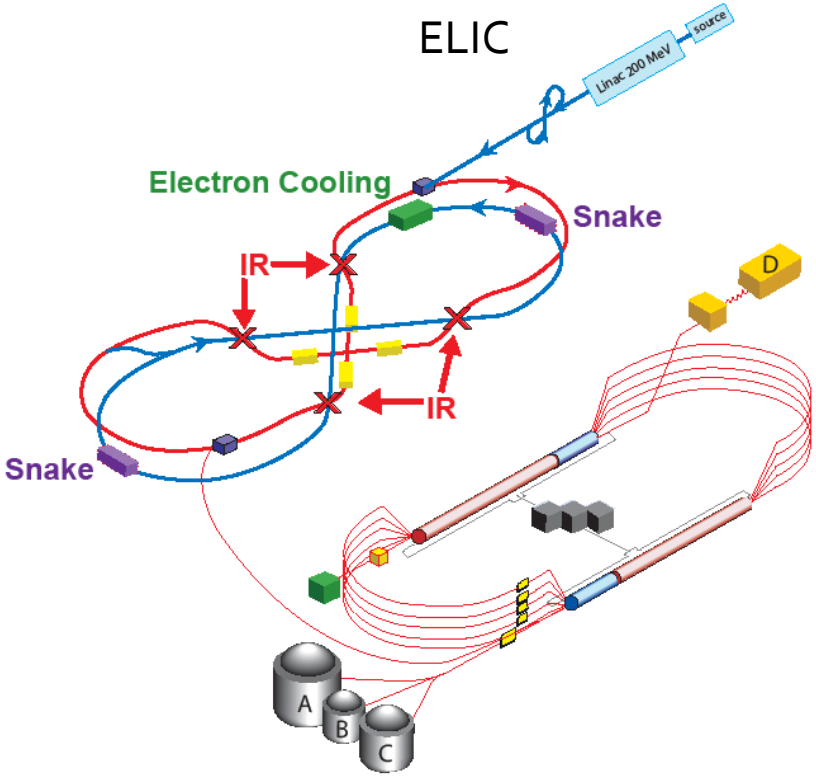
# Electron Ion Colliders: eRHIC (V. Ptitsyn, BNL) and ELIC (Y. Zang, JLAB)

**Nuclear Science Advisory Committee (LRP 2007):**

Electrons: ~10 GeV, Protons: ~250 GeV, Ions: ~100 GeV/u

Luminosity = $3.8 \times 10^{32} cm^{-2} s^{-1}$, polarized electrons and light ions

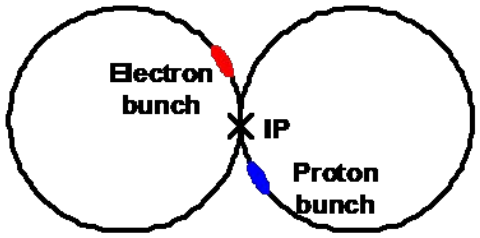


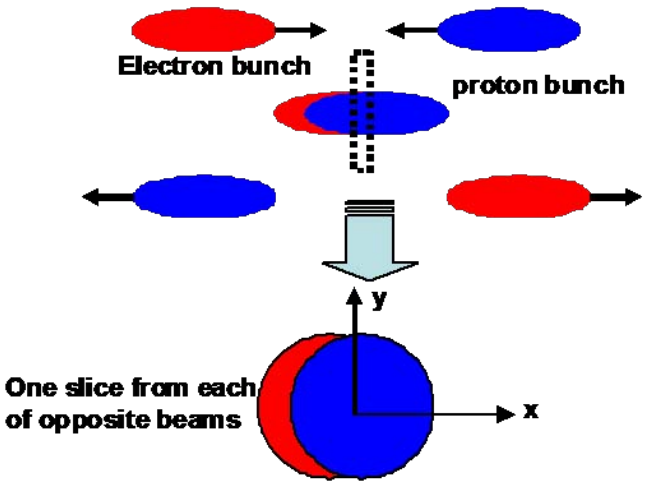



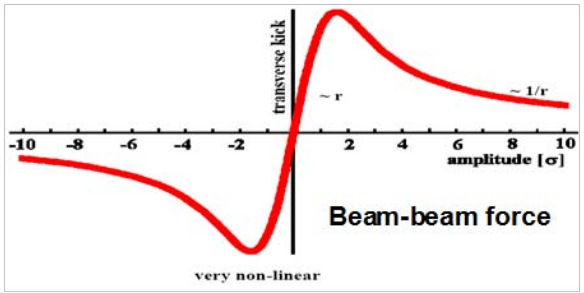
# R&D Issues, Technical challenges

- **Innovative Lattice design (ELIC)**
- **Very high current ERL (eRHIC)**
  - Energy recovery technology for high power beams
- **Electron cooling of high energy ions (250 GeV/u)**
  - Proof of principle of the coherent electron cooling
- **Crab crossing and crab cavity**
- **Forming and stability of intense ion beams**
- **Beam-beam effects:**
  - electron pinch effect;
  - the kink instability …
  - e-beam disruption
- **High intensity polarized electron source**
- **Polarized 3He acceleration**
- **Site-specific issues: increase number of bunches in RHIC, compact magnet design**

# Beam-beam effects



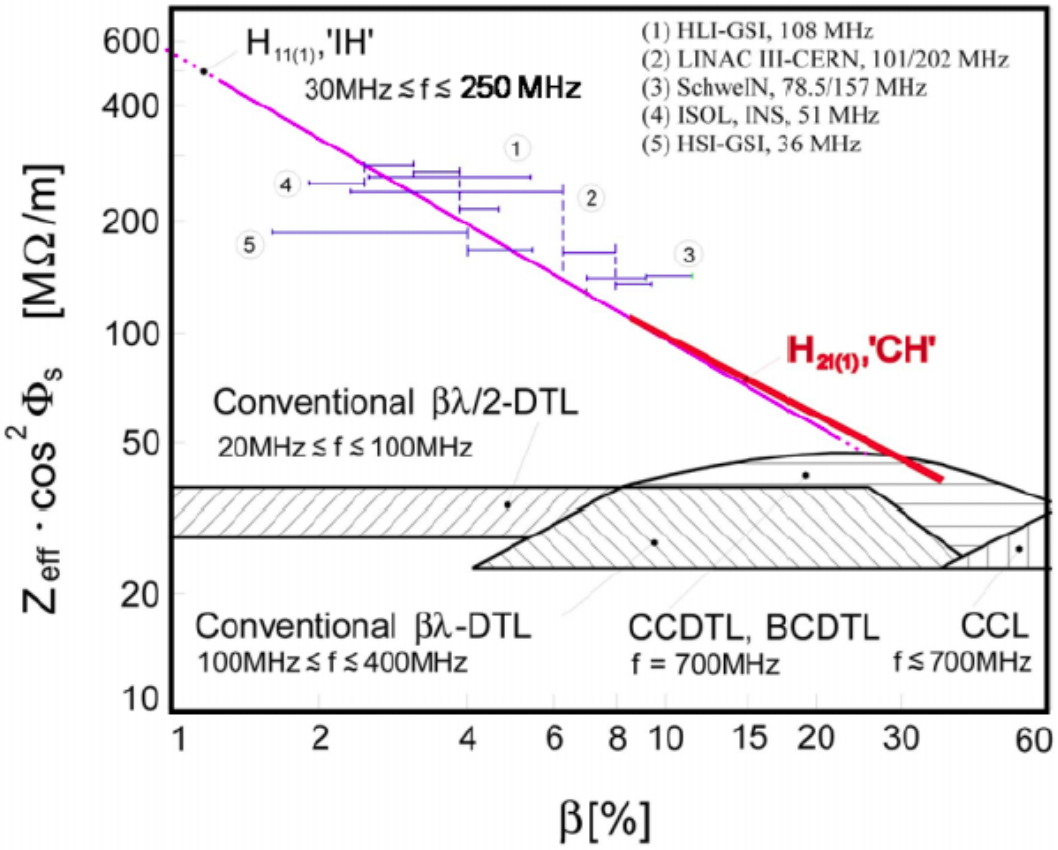

## Simulation Model

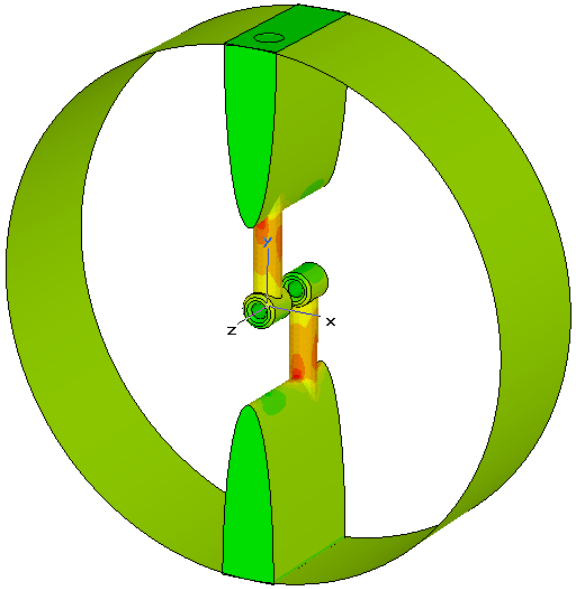
- Single/multiple collision points, head-on collision
- Strong-strong self-consistent Particle-in-Cell codes
- Ideal rings for electrons & protons, but include synchrotron radiation damping & quantum excitations for electrons

## Scope and Limitations

- 20k turns (0.15s of storing time) for a typical simulation run
  - ➢ Reveals short-time dynamics with accuracy
  - ➢ Can't predict long term (>min) dynamics

# Compact linac for Deuterons (L. Rybarcyk, LANL)



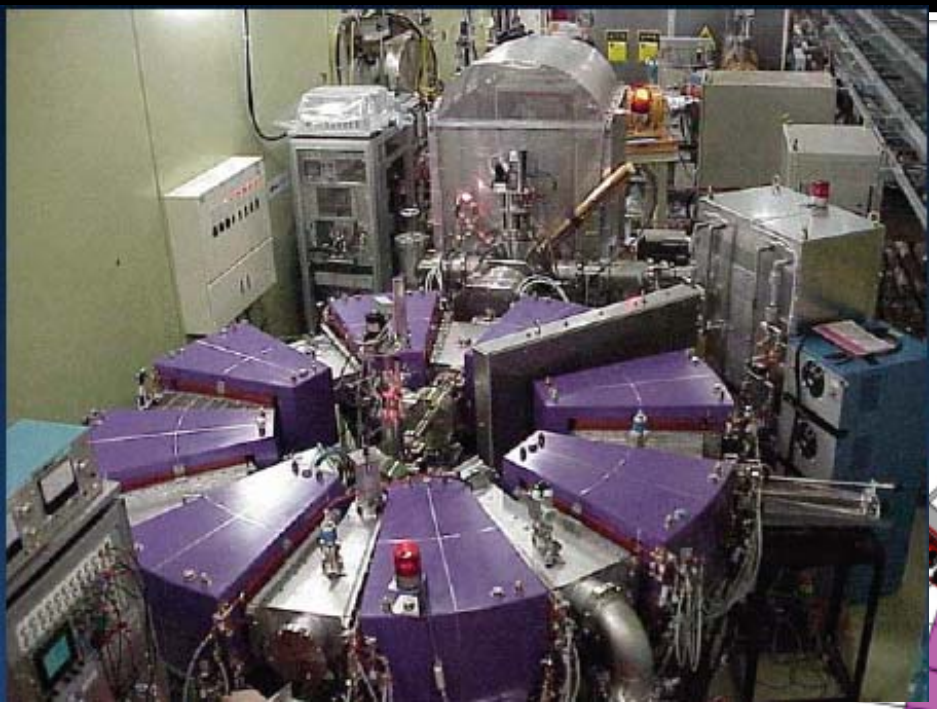
- And use PMQs for transverse focusing, instead of bulky EMQs.
- Take advantage of high shunt impedance of IH structures at low energies (here up to 4 MeV),

# Compact linac for Deuterons (L. Rybarcyk, LANL)

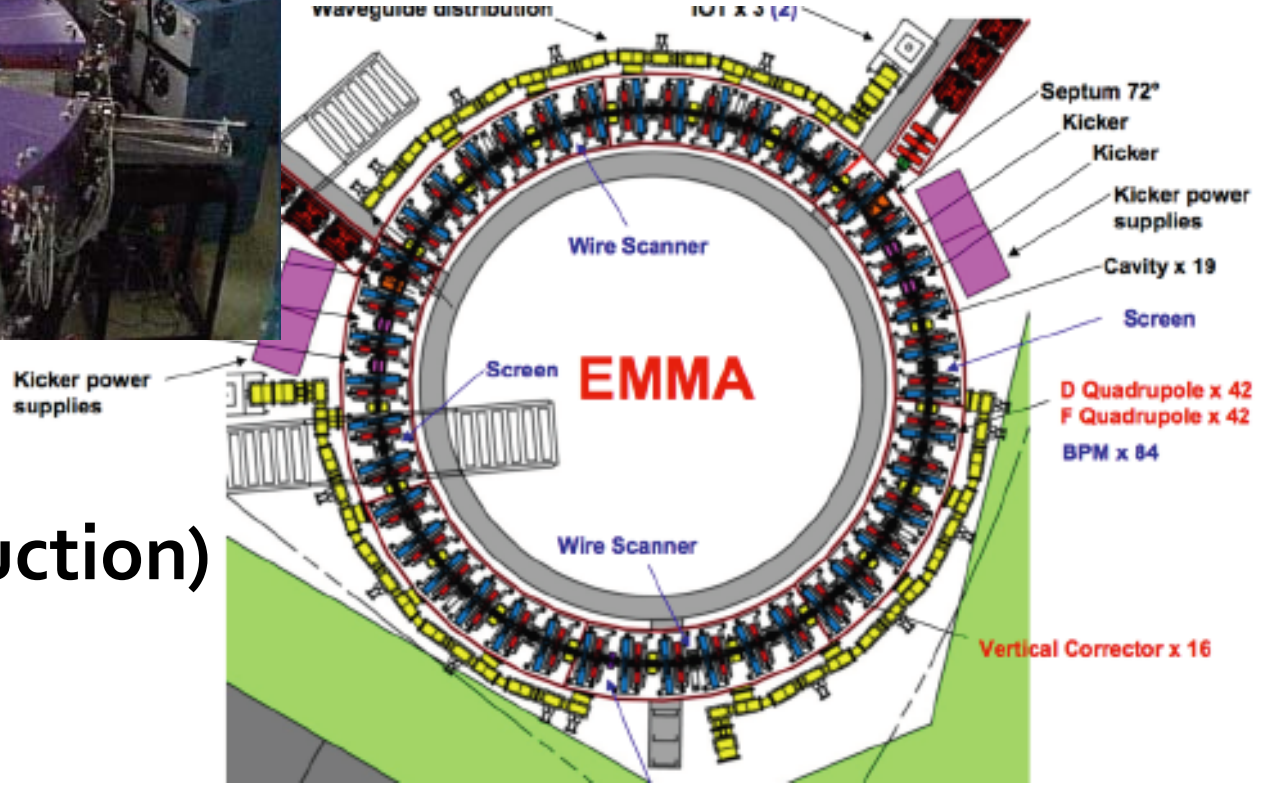
**Challenge: low-loss operation with high currents (50 mA)**

- Deuterons produce neutrons already at very low energy,
- Beam loss must be kept at minimum to avoid radiation damage of PMQs,
- Aperture must be kept small to maintain high shunt impedance and small sized PMQs.

# FFAG projects: status, achievements, and prospects (A. Sato/Osaka University)



PoP-FFAG KEK (1999)
Scaling FFAG: 50 – 500 keV




EMMA DL (construction)
Non-scaling FFAG

# Challenges or high-intensity beams

- Increase extraction efficiency (90% achieved with 150 MeV proton FFAG in Japan),
- Demonstration of non-scaling FFAGs,
- High-gradient MA cavities for proton & ion acceleration,
- Testing of various schemes like:

I. Harmonic number jump (pulsed, CW),
II. Magnetic induction acceleration for low beta,
III. Gutter acceleration,
IV. Isochronous FFAG (constant RF frequency),

**Huge potential but also huge need for R&D!**

# Summary of presented facilities: existing facilities, funded projects

| Facility: | Critical R&D |
|---|---|
| **RIKEN upgrade** (Hiroki Okuno/RIKEN) | 28 GHz ECR ion source, avoid emittance growth at low-energy, SC QWR for injection line |
| **SARAF commissioning** (Jacob Rodnizki/SOREQ) | Minimise beam loss, CW operation of RFQ, diagnostics next to SC cavities, |
| **PEFP status & outlook** (Ji-Ho Jang/KAERI) | RCS design, low-beta SC cavities (704 MHz), low-loss operation |
| **FAIR SIS 100 design** (Peter Spiller/GSI) | Dynamic vacuum behaviour/fast cycling SC dipoles/ MA RF cavities |
| **HINS R&D** (Giorgio Appollinari, Bob Wagner/FNAL) | RF fan out/low-beta spoke cavities (chemical processing)/SC solenoid focusing |

# Summary of presented facilities: planned projects, R&D

| Facility: | Critical R&D |
|---|---|
| **Project X** (Valerie Lebedev, Charles Ankenbrandt/FNAL) | Machine protection, beam loss minimisation, EP instabilities, reliable operation |
| **LHC-upgrade, SPL/PS2** (Frank Gerigk/Yannis Papaphillippou/CERN) | Transform ILC technology for high-intensity protons at 704 MHz, detailed multi-particle simulations for PS2 (EP, space-charge, collective effects….) |
| **ISIS upgrade** (John Thomason/RAL) | Beam loss, collimation system, 3D modelling with SC |
| **ESS** (Ibon Bustinduy/ESS-B) | Building up of knowledge base for high-intensity proton linac |
| **eRHIC/ELIC** (Vadim Ptitsyn/BNL, Yuhong Zhang/JLab) | Beam-beam effects & related simulation tools, electron-cooling of high-energy ions, crab crossing & crab cavities |
| **Compact Deuteron Linac** (Larry Rybarcyk/LANL) | Low-loss operation for high-current beams in small apertures |

# Summary of presented facilities:

**Part III**: overview & outlook

| Facility: | Critical R&D |
| --- | --- |
| **Scaling & non-scaling FFAGs** (Akiro Sato/Osaka University) | Demonstration of non-scaling FFAGs, increased extraction efficiency, testing of various acceleration schemes…. |

# Prominent R&D subjects

- Low-loss operation (codes, collimation),
- Simulation of beam-beam effects,
- Code-benchmarking (linacs/rings),
- Modelling of dynamic vacuum behaviour,

- Low-beta SC cavities (spoke, quarter-wave, elliptical),
- RF fan-out to multiple cavities,
- Electron cooling of high-energy ions,
- FFAG: extraction & non-scaling machines.