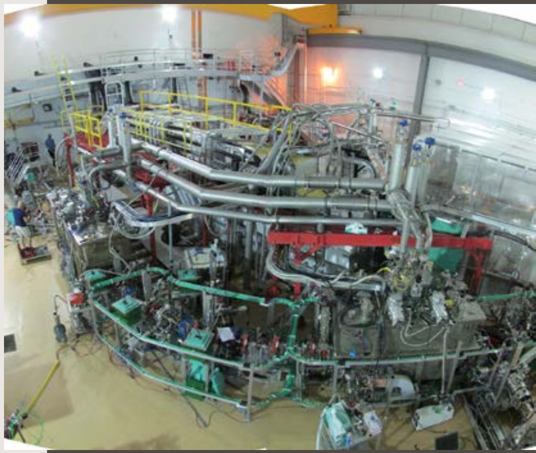
TRIUMF

Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

ARIEL e-linac
For Isotope Production



THz Workshop, 2018 July 05

Shane Koscielniak
TRIUMF

Why Isotopes?

They are everywhere! Humans are "recycled nuclear waste"

We are stardust, We are golden

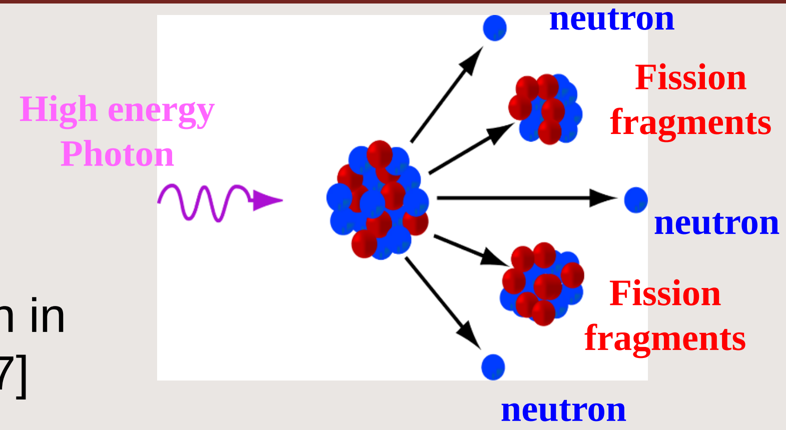
… Billion year old carbon

– Woodstock Lyrics, Joni Mitchell

E-linac photofission

Giant Dipole Resonance Photofission of ^{238}U proposed by W. T. Diamond (Chalk River) in 1999 [NIM, V 432, (1999) p 471] as an alternative production method for RIB.

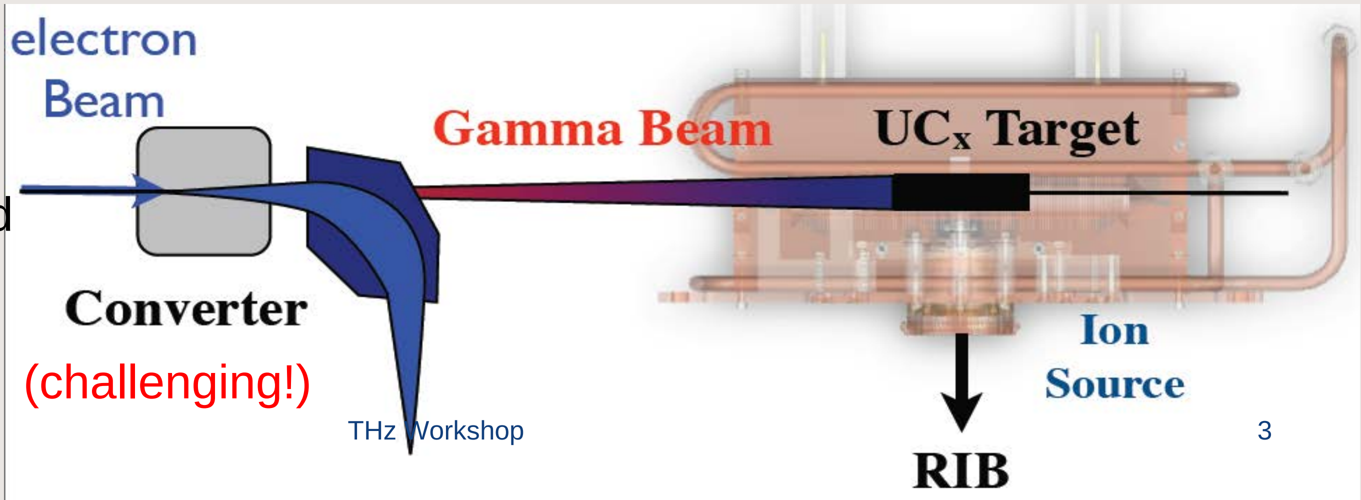
The idea was taken further by Y. T. Oganessian in 2000 [RNB2000, Nucl. Phys. A 701 (2002) p 87]



E-linac → Electron-Photon Converter → ^{238}U Target → Ion Source → Mass Separator → RIB User

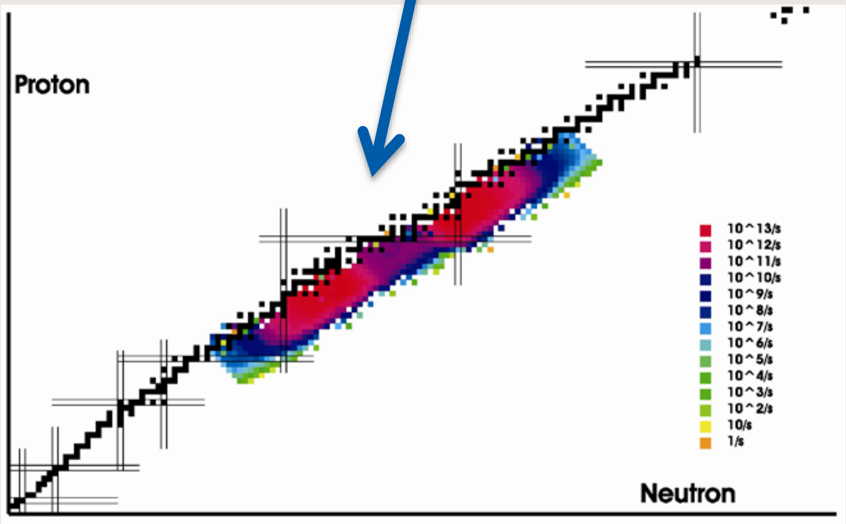
Electron energy ≈ 30 MeV
Beam power ≈ 100 kW

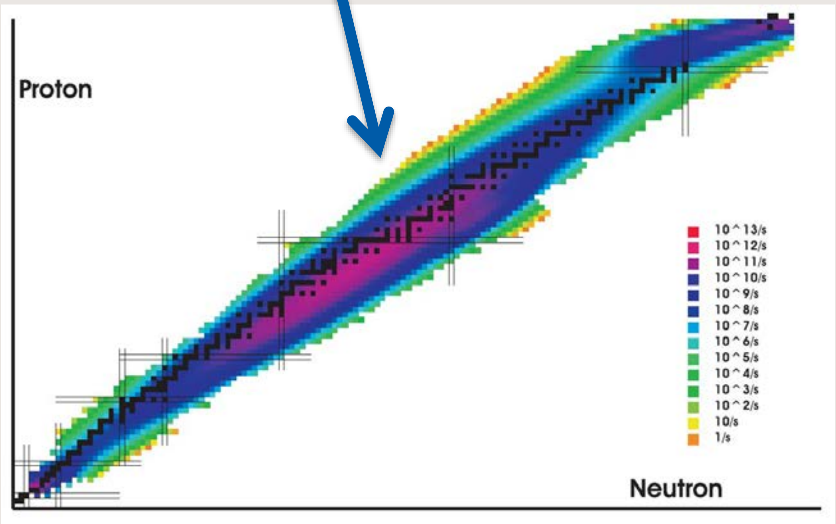
3×10^{12} fissions/second from 238U target, leading to copious neutron-rich isotopes.



Why photofission?

10 mA, 30 MeV photo-fission, 100 uA, 500 MeV proton driver





- Smaller range & depth of products, with emphasis on neutron rich species.
- BUT lower isobaric contamination, lower activation, easier remote handling.
- Fission rate/electron << rate/proton (≈10^3 smaller)
  - But easily compensated in electron source
  - >10 mA e-gun easy.

Why electrons & SRF?

For electrons, $\beta = v/c \approx 1$ from the start (if KE ≥ ½ MeV).

Inject directly from e-gun into multi-cell SRF cavity

Space-charge only a brief problem

Single (compact) RF structure throughout, enormous cost saving c.f. proton accelerators – approx. factor 5

Superconductor has 10^6 lower surface resistance than copper

– 100% RF power goes to electron beam

– CW operation at relatively high accelerating gradients >10 MV/m

High duty factor or c.w. operation inconceivable with NC cavities

For 50 MeV NC copper linac, need 4 MW c.w. RF power! & cannot remove the heat load!

E-Linac: Accelerator Overview

300 keV thermionic gun:
650 MHz modulated

Design is beam-load limited
rather than gradient limited

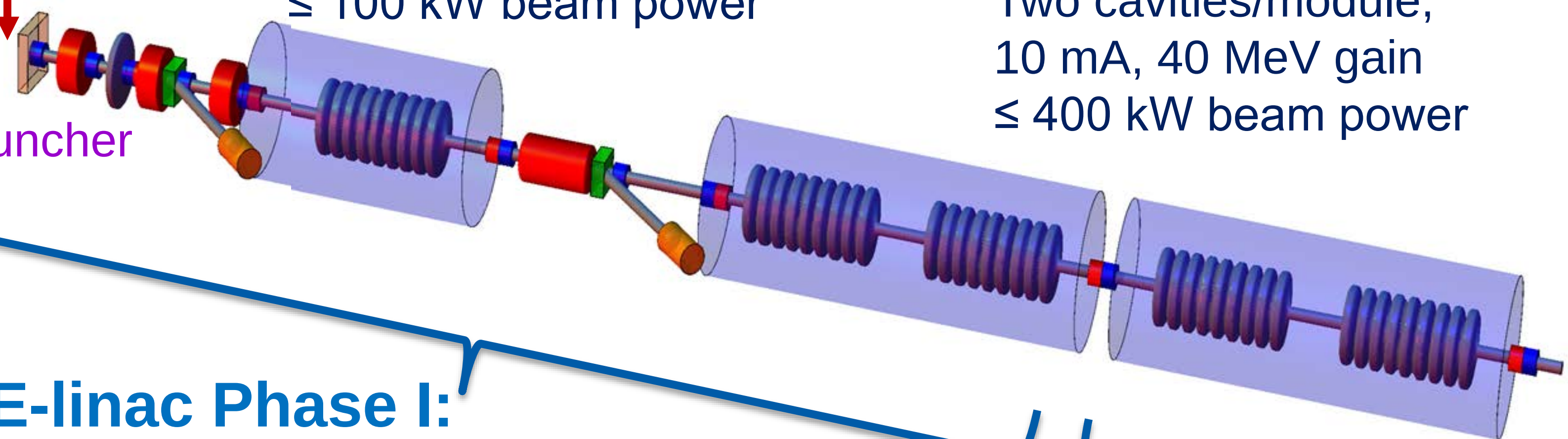
Injector:

10 mA, 5-10 MeV gain
≤ 100 kW beam power

Accelerator:

Two cryomodules
Two cavities/module,
10 mA, 40 MeV gain
≤ 400 kW beam power

NC Buncher



E-linac Phase I:
30 MeV, 300kW

E-linac Phase II:
50 MeV, 500kW

Division into injector & main linac allows:
Possible expansion for:
Energy Recovery (ERL) or Energy Doubler (RLA)
Add return arcs to make a ring.

TRIUMF

Meeting ARIEL E-linac Challenges

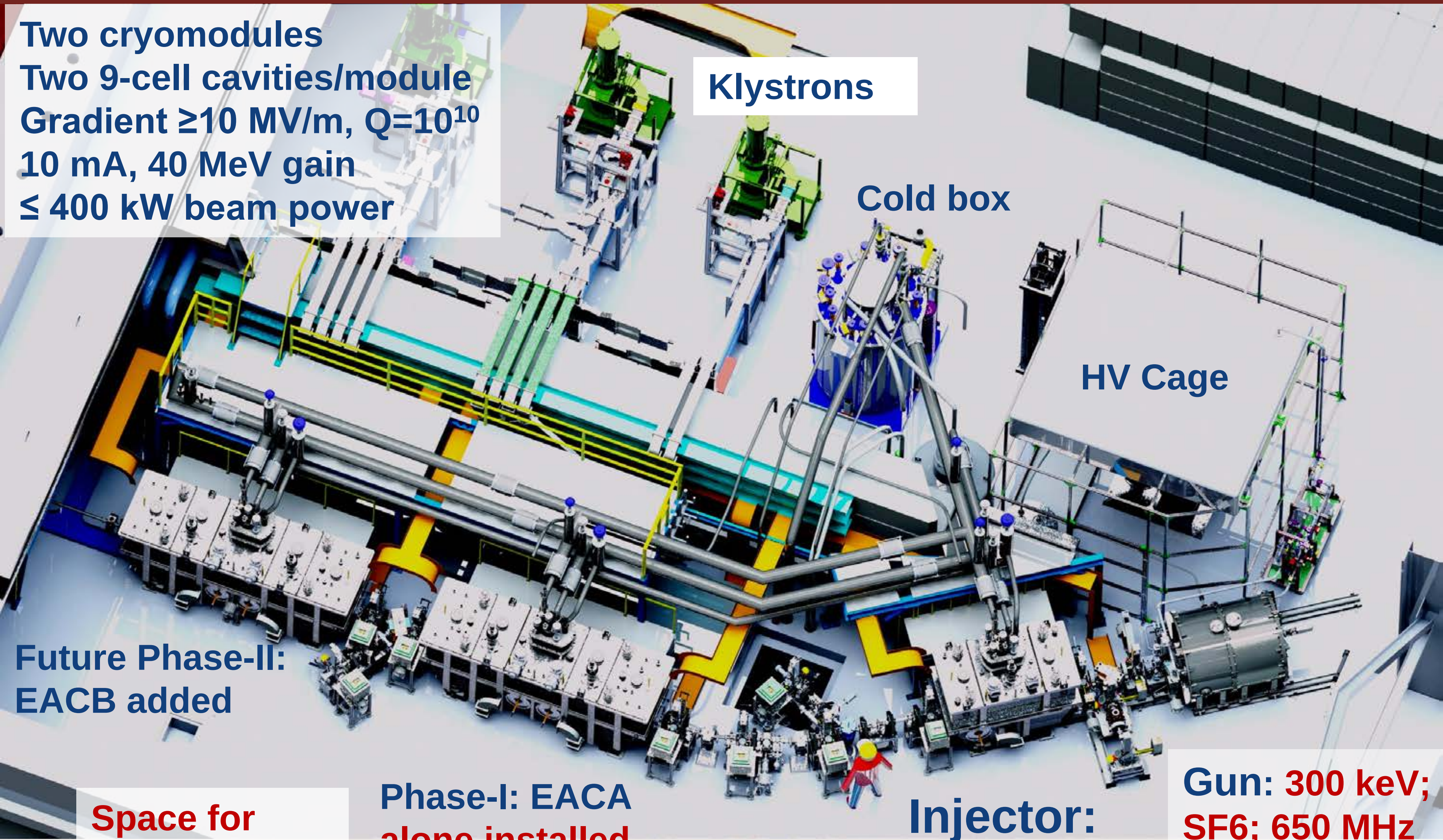
- **High peak and average beam power (C.W. operation)**
  - Very different regime than TESLA or ILC (0.5% duty factor)
  - E-linac average power/cryomodule 2 orders magnitude larger than for TESLA/ILC
- High power c.w. klystrons and fundamental mode input couplers
- Low “Higher Order Modes” loss in cavities
- Large chimneys in cavity/He phase-separator interface

- < 10^(-5) fraction loss/metre for 100kW operation
- Large cavity iris and large magnet apertures
- < 10 μs rapidity for Machine Protection System
- Low maintenance e-gun (≈1 yr between service)
- Lots of beam diagnostics
  - ≈ 30 BPMs, ≈ 30 BLMs, 8 View Screens, 3 Fast Wire Scanners

Accelerator:

E-Linac in e-hall

Two cryomodules
Two 9-cell cavities/module
Gradient ≥10 MV/m, $Q=10^{10}$
10 mA, 40 MeV gain
≤ 400 kW beam power



Future Phase-II: EACB added

Space for Recirculation Ring

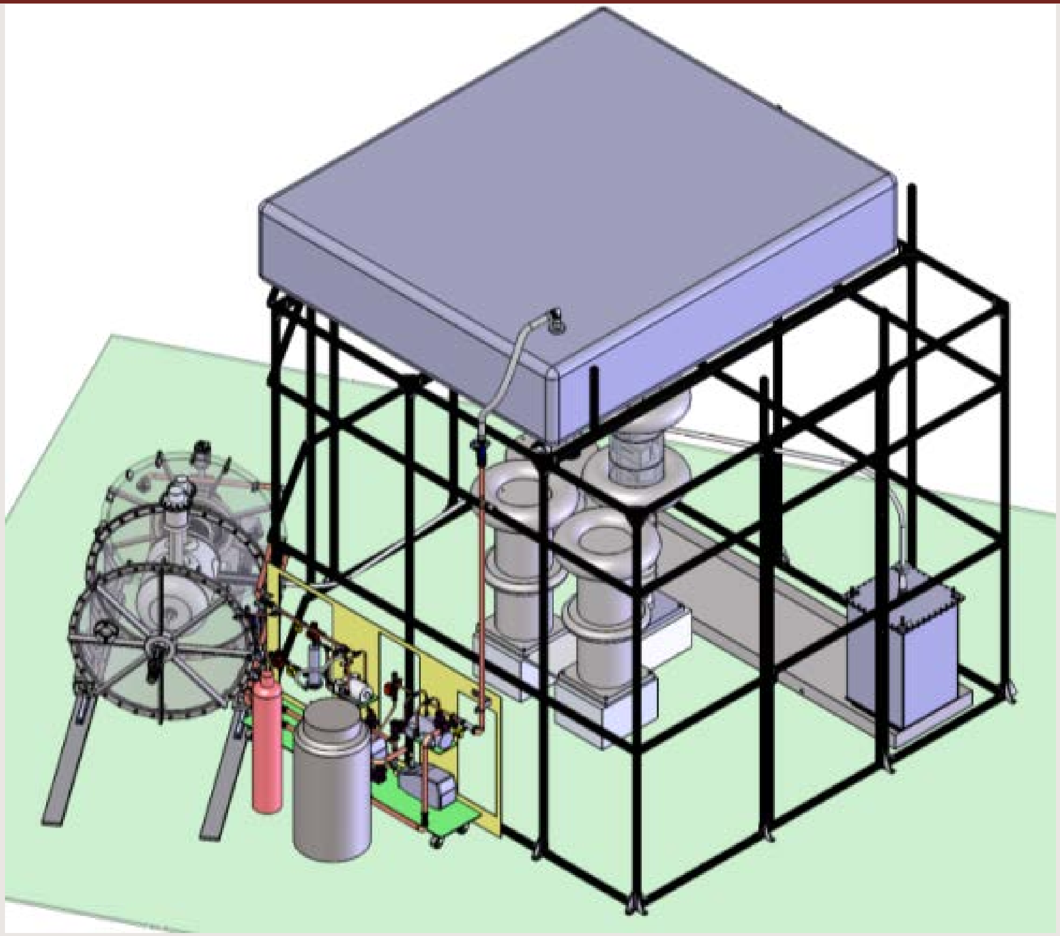
Phase-I: EACA alone installed 2014 July

Injector:

Gun: 300 keV; SF6; 650 MHz

10 mA, 10 MeV gain
≤ 100 kW beam power

300keV Gun HV

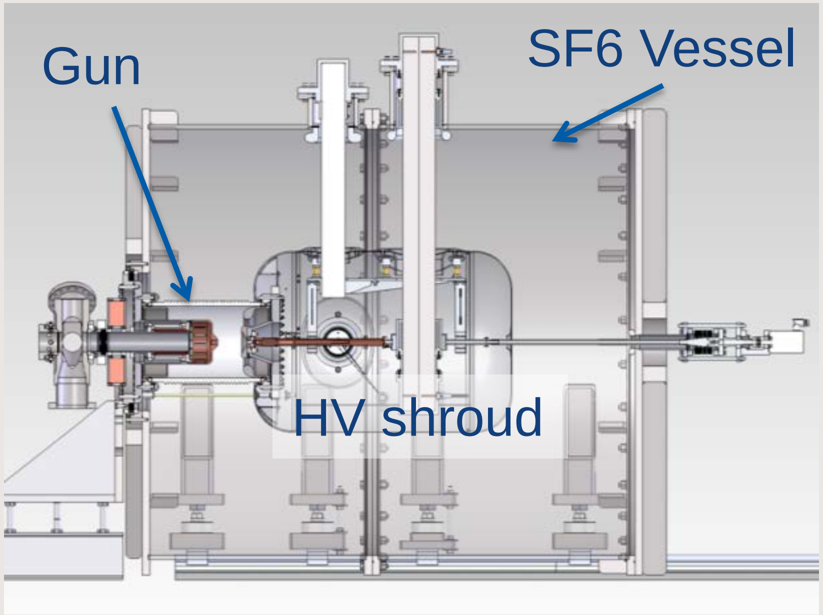


HV Cage & Stack

300 keV thermionic Gun

Anode sub-assy

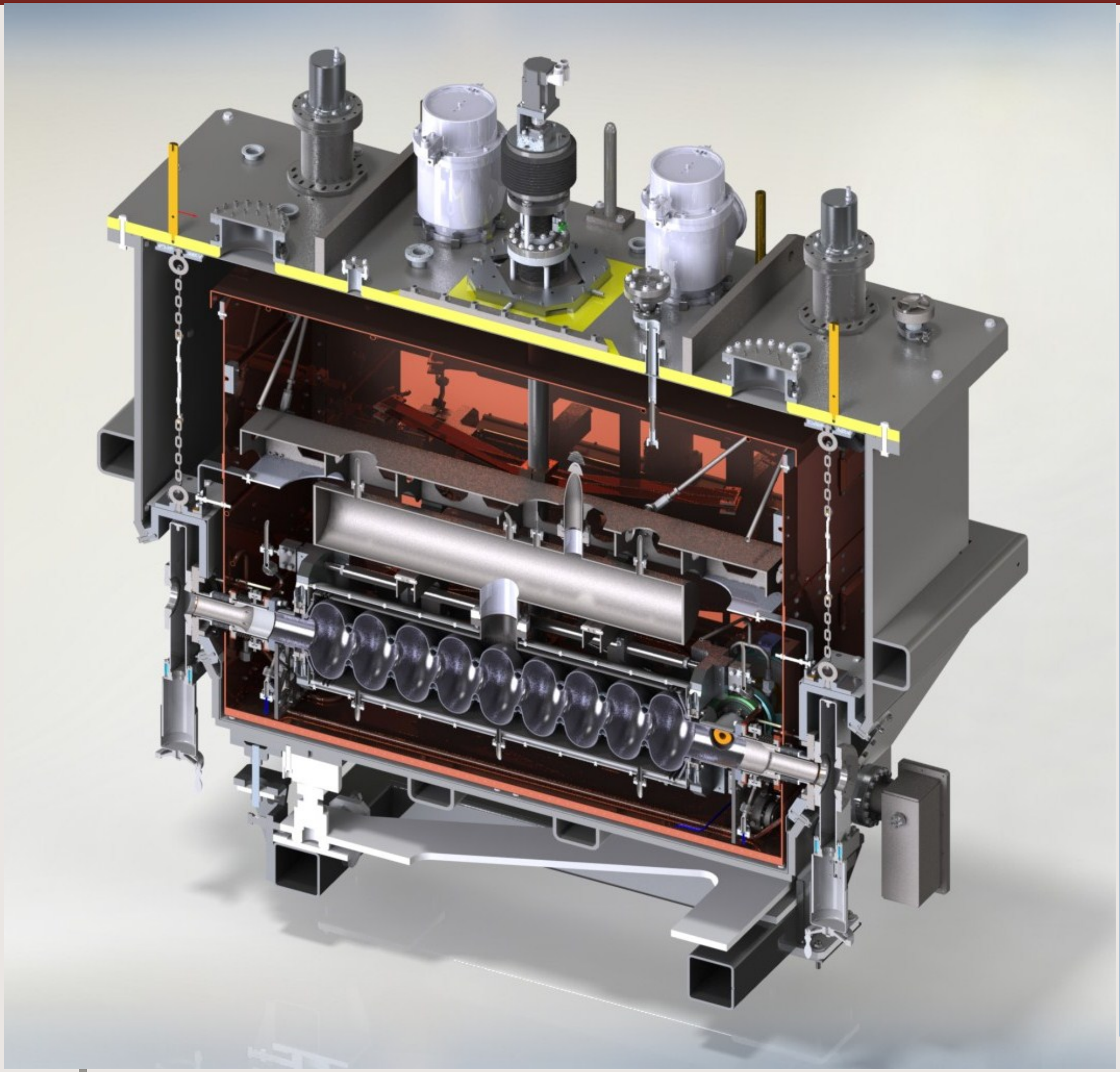
Ceramic waveguide



Shroud sub-assy

Ceramic HV standoff

Injector Cryomodule



Houses

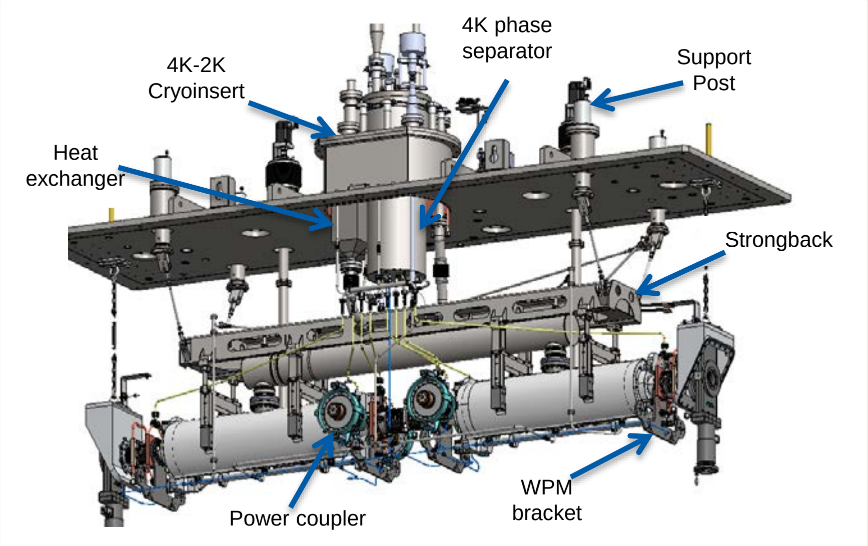
- one nine-cell 1.3GHz cavity
- Two 50 kW power couplers

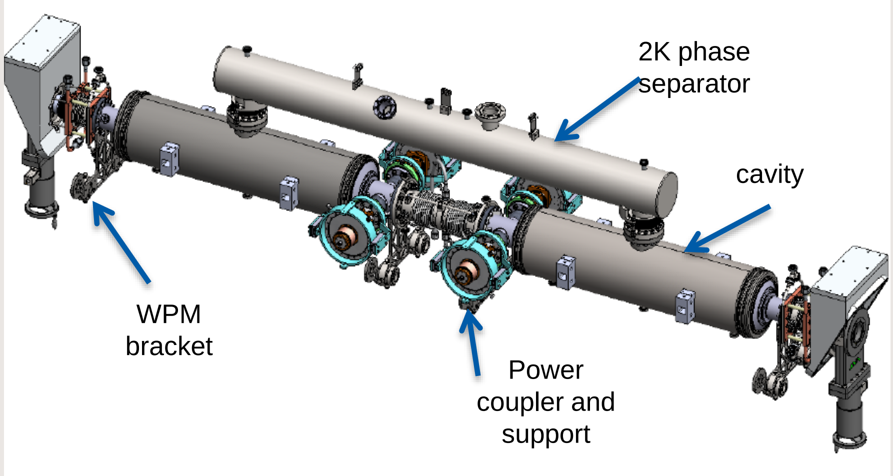
Features

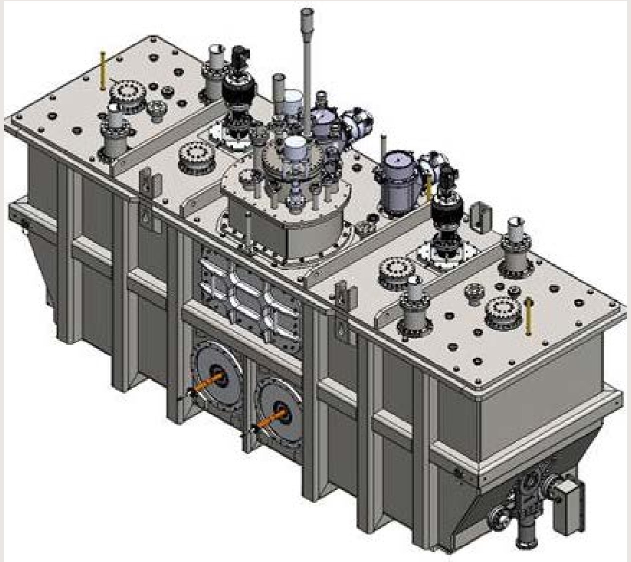
- 4K/2K heat exchanger with JT valve on board
- Jlab Scissor tuner with warm stepper motor – chosen for criticality
- LN2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal magnetic shielding
- Wire Position Monitor cavity alignment system

Accelerator Cryomodule

- EACA: same basic design as EINJ but with two 1.3 GHz nine cell cavities each with two 50kW power couplers
- There is one 4K/2K insert, identical to EINJ
- Physical dimensions
  - L x H x W = 3.9 x 1.4 x 1.3 m
  - 9 tons







Cryogenic

JT expansion to 2K

Sub-Atmospheric pumps

4K Coldbox

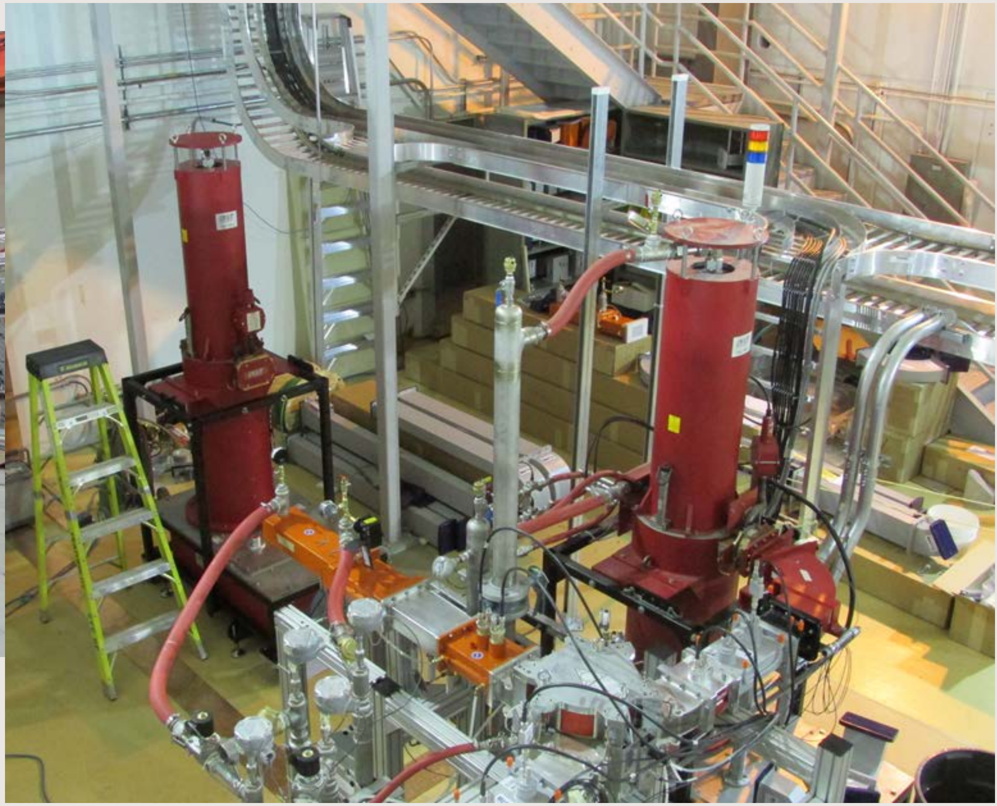
Compressor

High Power RF

Two DC HVPS: 65kV, 9A

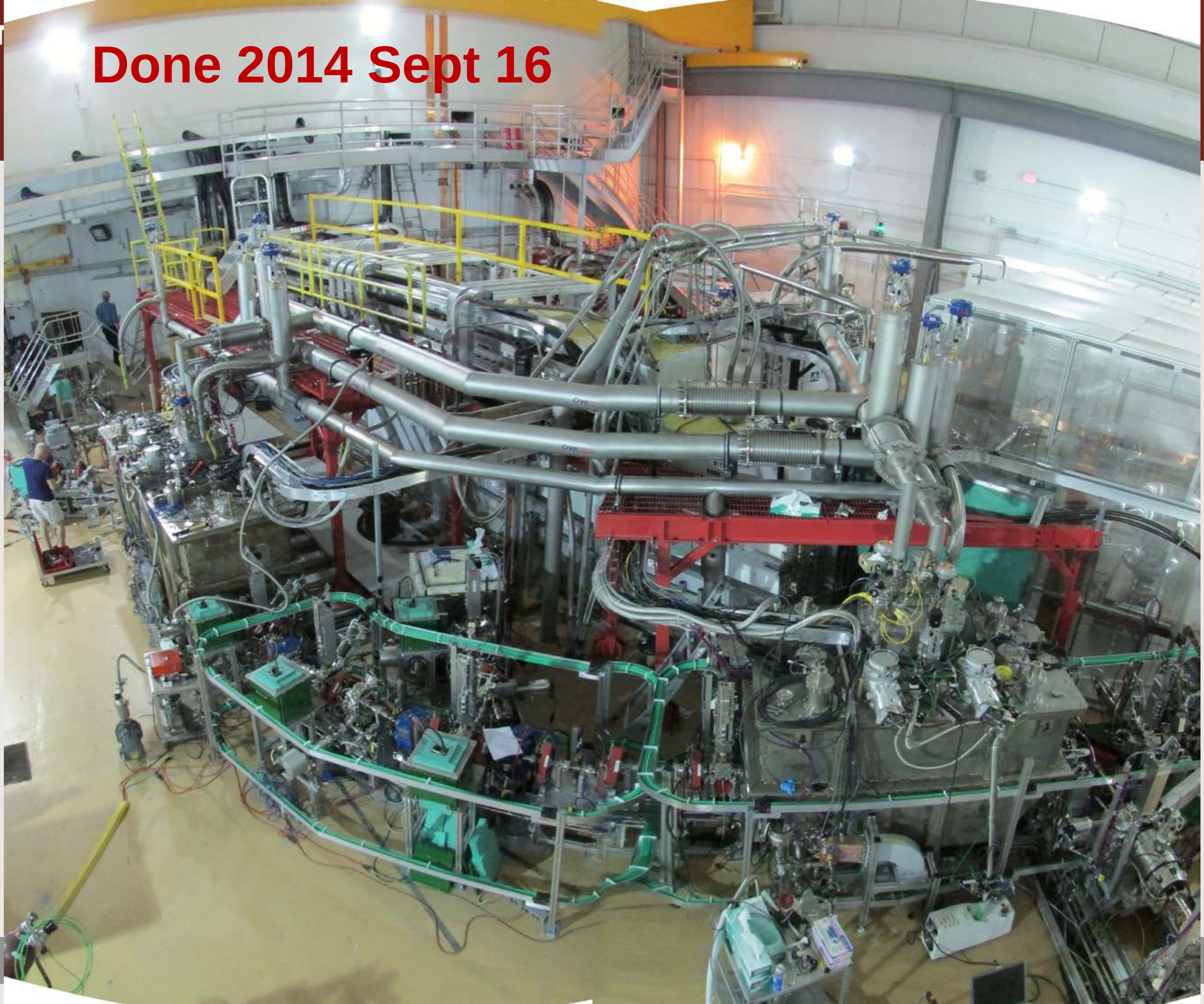
Use IGBT-based, pulse step modulators

Two 270 kW c.w. klystrons



2013: Klystron 24 Hr factory test: 300kW c.w. into dummy load

Done 2014 Sept 16

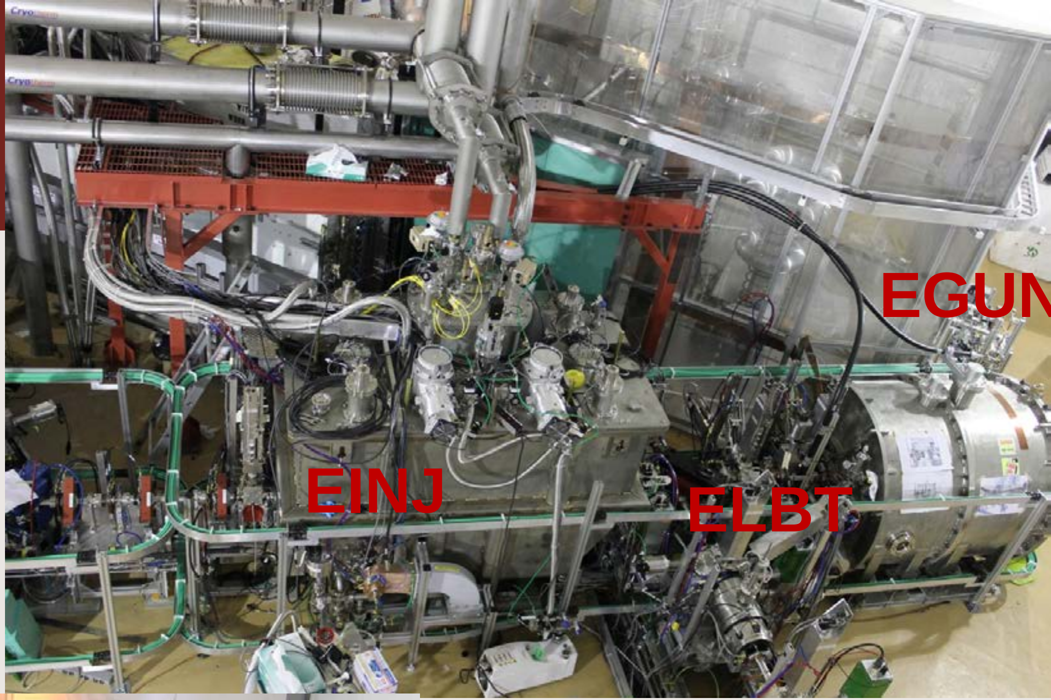


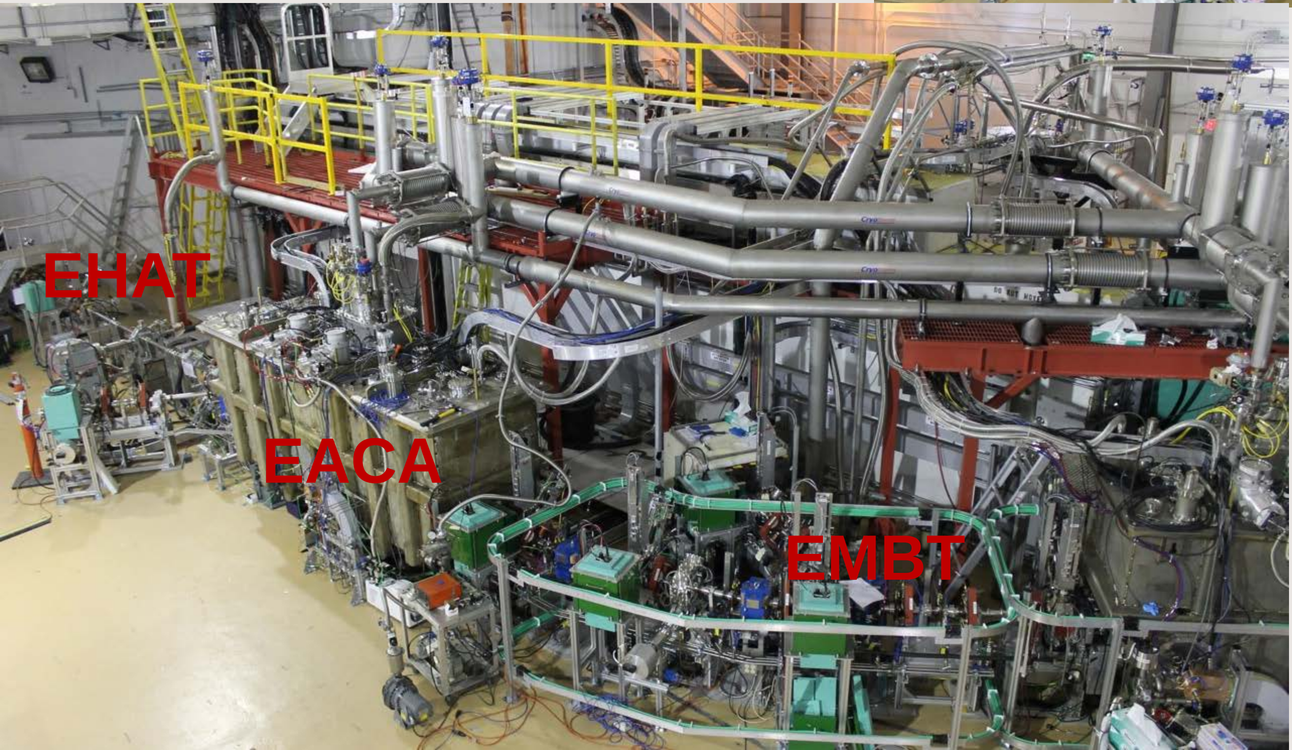
EGUN to EACA

***EGUN:** electron gun*

***ELBT:** low energy transport*

***EINJ**: injector cryomodule*



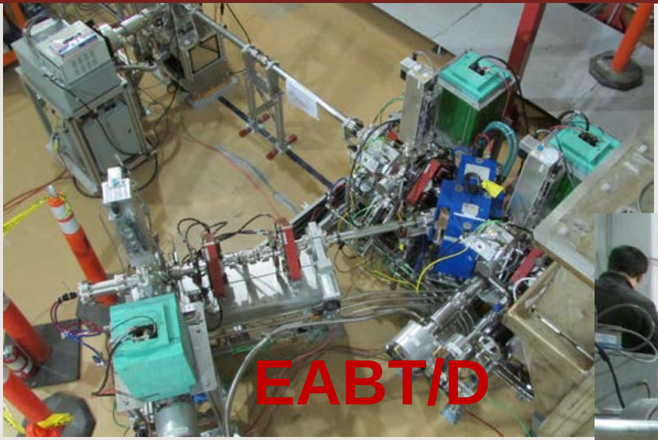


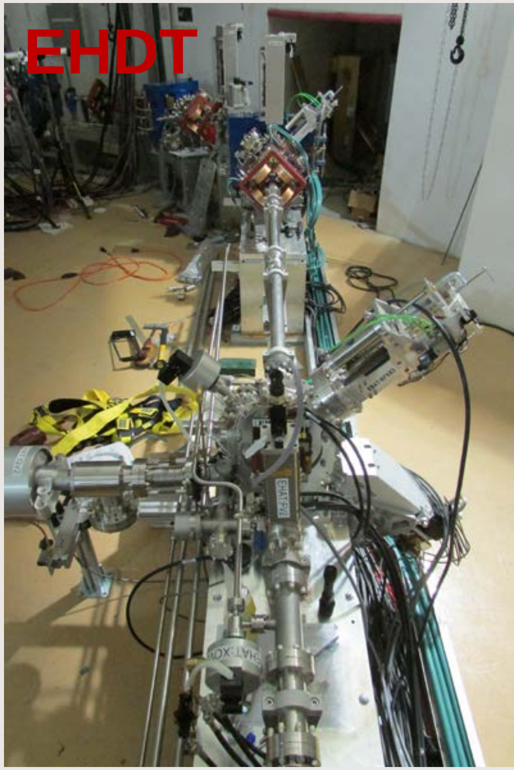
EMBT:
merger beam transport

EACA:
accelerator cryomodule *(initially only 1-cavity)*

EHAT:
accelerated beam transport

EABT/D, EHAT, EHDT beamlines & dump





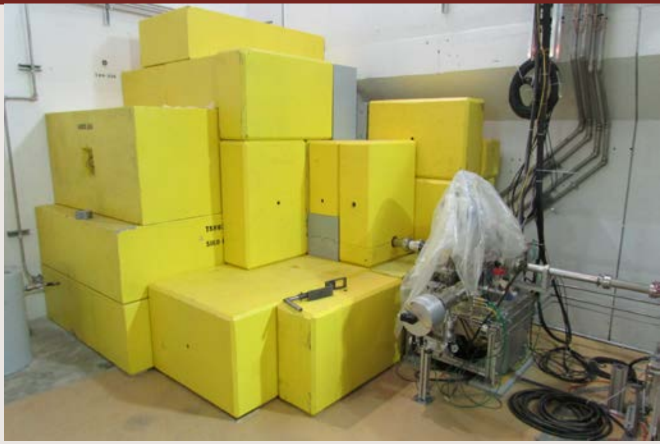
EABT/D: ***accelerated beam transport & dump (100W)***
EHAT: ***high energy accelerated transport***
EHDT: ***beam dump transport to 10 kW dump***

2016-17 Timeline

- 2016 Jan: E-linac Low energy Beam Transport & Dump commissioned
- 2016 Jun -Jul: E-linac Injector Cryomodule (EINJ) & E-linac Medium energy commissioning started but not complete
- 2016 Aug-Sep: AETE e-γ Convertor Test Stand (CTS) commissioned
    - ARIEL (Electron Target East) Convertor Test Stand for Target Materials Characterization
- 2016 Dec to 2017-Jan: AETE CTS operating
- 2016 Aug – 2017 May: EACA sent for retrofit (ACM-duo)
- 2017 Feb – 2017 Sept: ELBT/D Machine Protection System implemented
- 2017 Oct 16 – 2018 Apr: AETE CTS operating 5-6 days/week
- CTS Operation Done!

E-linac Commissioning

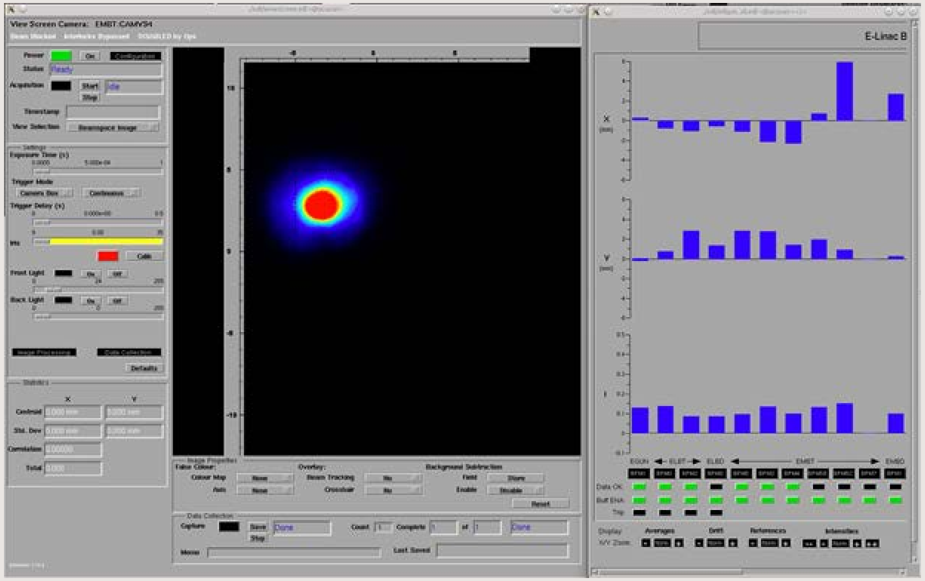
Focus of 2018: 30 MeV, 1 kW at beam tuning dump EHD; and MPS



- Repair/reprocess EACA:CAV1
- EACA commissioned with 2 SRF cavity – YY. Ma
- 30 MeV acceleration (total) -. T. Planche/YY. Ma
- Commissioned EMBT/D, EABT/D, EHAT and EHDT optics – T. Planche
- 100 Watt e-beam @ EHD – T. Planche
- Beam Loss Monitors (BLMs) Installed – M. Alcorta
- MPS DAQ Boards Fabricated & Tested – M. Alcorta
- Commissioned Machine Protection System (MPS) – M. Alcorta
- Commissioned Beam Diagnostics (Fast Wire Scanner, BPM) – V. Verzilov
- Commissioned Beam Tuning Dump – I. Earle
- 1 kW e-beam @ EHD – T. Planche
- Envelope & Trajectory HLAs – C. Barquest & S. Radel

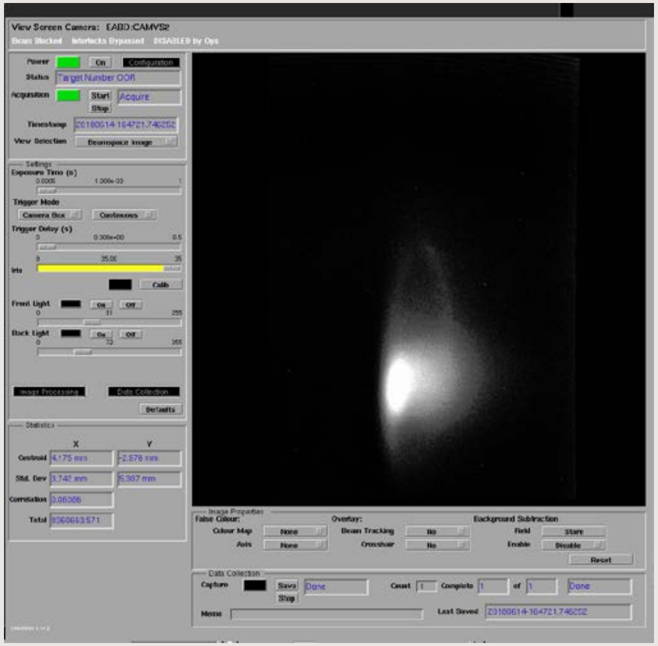
2018 Achievements

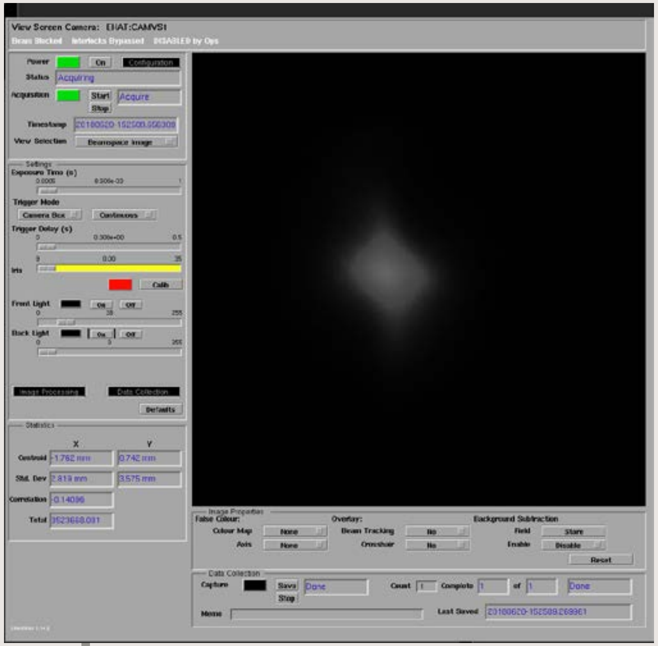
- Apr 27: LLRF group locked both EACA cavities phases with all control loops closed, for the first time.
- May 11: EINJ & EACA ready for e-beam at 9 & 8 MV/m gradient, respectively – power divider working correctly (May 08)
- May 18: For the first time, we have a stable (within ±0.5%) accelerated beam at E-linac Medium energy Beam Dump (EMBD).
    - Energy ≈ 9 MeV. No discernible transverse or longitudinal halo.



2018 Achievements

- June 01: Irritating RF amplitude & phase jitter identified in EINJ & EACA; diagnosis ongoing
- June 14: First vector-sum (two-cavity) acceleration in EACA.
  - 22 MeV beam at EABT/D

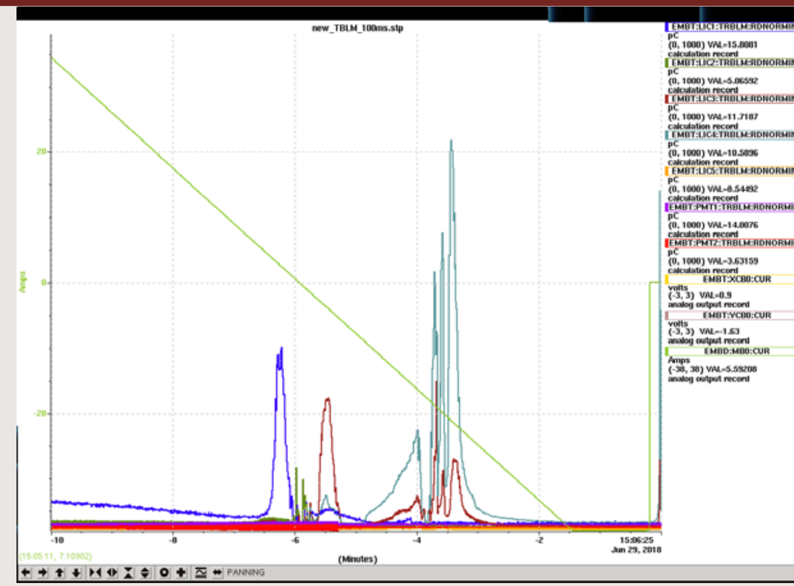


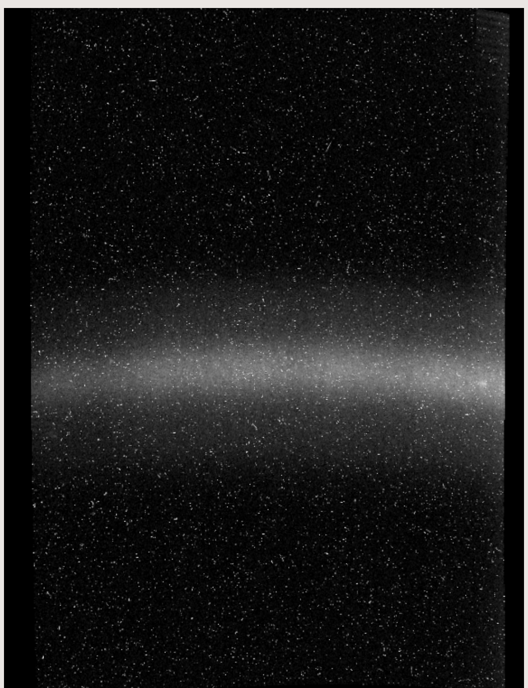


- June 20: 20 MeV beam to EHAT:FC4 - to entrance of e-hall dogleg.
  - 90% transmission; All EHAT BPMs & 3 View Screens working

2018 Achievements

- June 29: significant dark current exiting EINJ & EACA – sufficient to saturate the MPS Beam Loss Monitors
  - Beam energy limited to ≤ 25 MeV
  - Must re-process cavities for 30 MeV
- July 03: EMBD MPS BLM tests ongoing





- July 04: 25 MeV beam on OTR View Screen EABD:VS2

Recirculation Ring IR photon-source Concept

1300/2=
650 MHz

ICAP2009

RIB 16 pC per bunch	**100 keV**	**10 MeV**
RMS ε_N transverse (μm)	7.5	12.5
Bunch length (cm)	2.8 (±20°*)	0.6
Energy spread	±1 keV	±40 keV

1300/12 =
108.3 MHz

High brightness 100 pC per bunch	**200 -300 keV**	**50 MeV**
RMS ε_N transverse (μm)	1.0	10.0
Bunch length (mm)	4.0	1.0
Energy spread	±0.5 keV	±50 keV

Although thermionic sources (eg SACLA at Spring-8) can produce low emittance, time structure suggests laser-driven photo-cathode.

TRIUMF

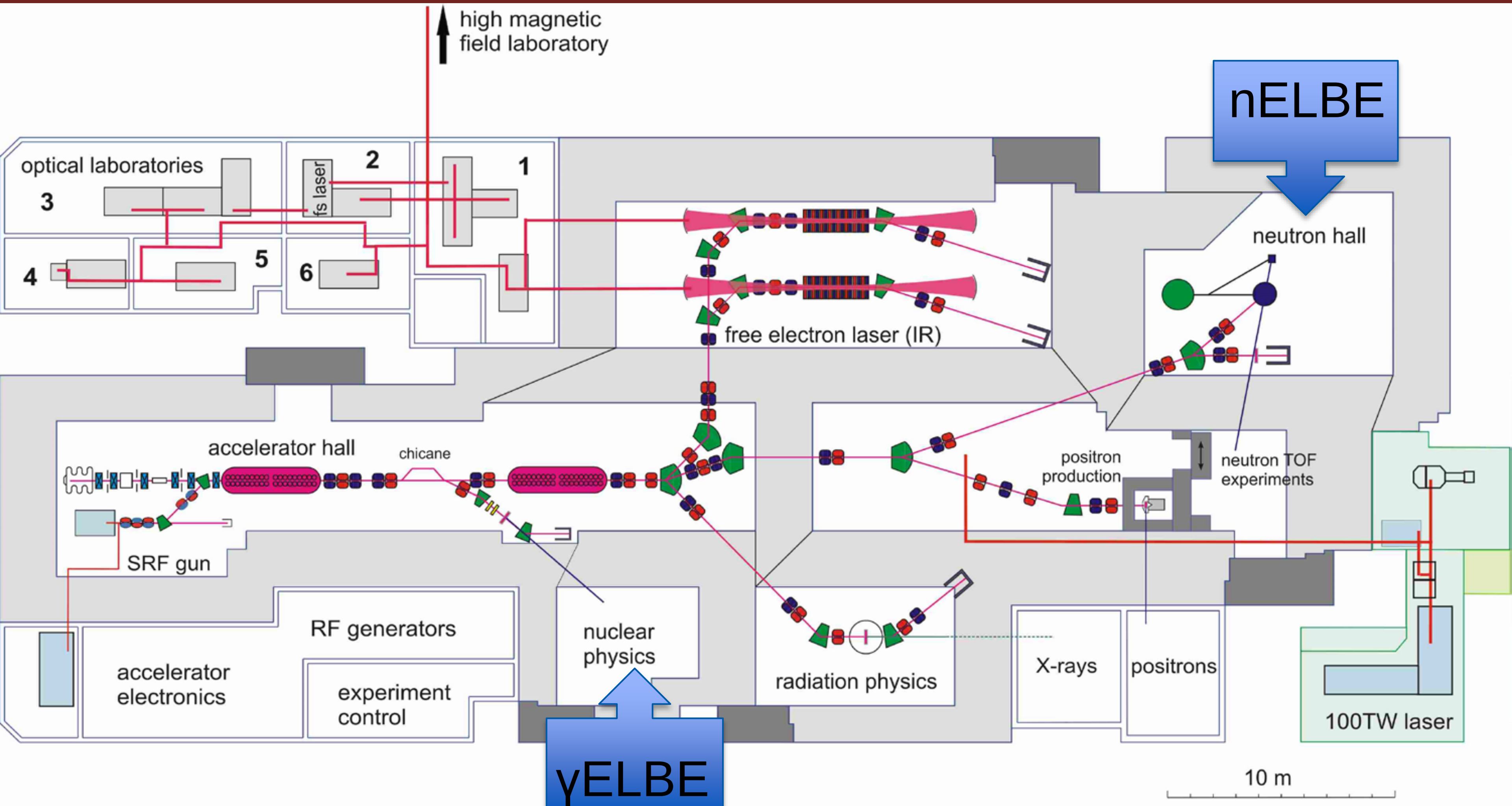
Future Developments

Speculative – beyond 10 kW

- Introduce beam halo diagnosis/monitoring
  - Have already 3 Fast Wire Scanners, but may need other devices
- Introduce energy tails diagnosis/monitoring
- Varying emittance?
  - $\epsilon \leq 10\mu m$ [Normalized r.m.s] – original spec 2010
  - $\epsilon = 6\mu m$ [Normalized r.m.s] - 2012 measurements/fitting
    - Spec used for beamline design notes & specs
  - $\epsilon = 3.5\mu m$ [Normalized r.m.s] - 2016 measurements/fitting
    - Investigation/Confirmation
      - Repair/reinstall Allison emittance scanner in ELBT

Speculative: Reduce power density on Target, return to original ϵ spec ?

Forschungszentrum Dresden Rossendorf - ELBE Layout

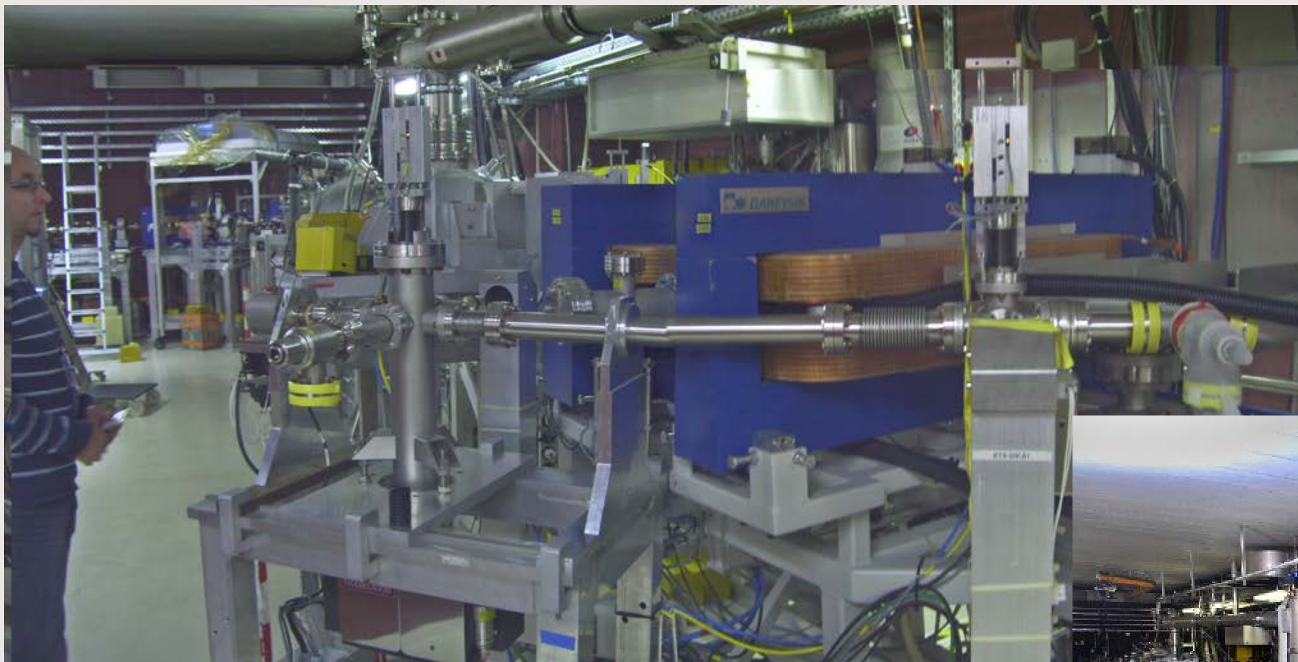


ELBE (Electron Linac for beams with high Brilliance and low Emittance) radiation source

1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Time-resolved semiconductor spectroscopy, THz-spectroscopy
4: FTIR, biological IR experiment
5: Near-field and pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal deflection spectroscopy

(IR & THz &) nuclear radiation sources

Bremsstrahlung (γELBE)
Bremsstrahlung (up to 20 MeV) is available in the nuclear physics cave.
Polarized radiation can also be provided.



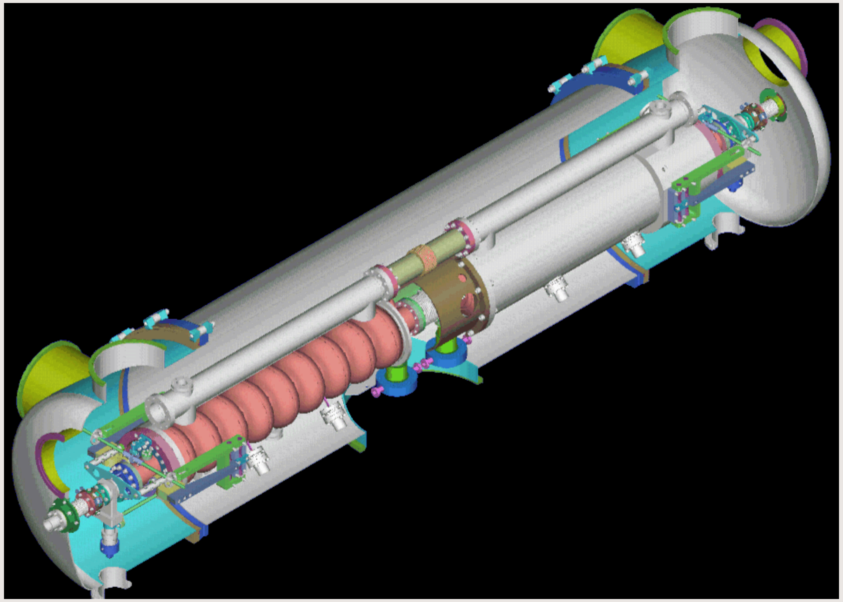
Bending switchyard to 12 MeV nuclear physics, and straight through to 2nd cryomodule.

Neutrons (nELBE)
neutron time-of-flight system with neutron energies between 100 keV and 10 MeV.

ELBE Linac Design

Beam energy / MeV	5 - 40
Max. bunch charge /pC	< 100 *
Max. beam current /mA	1.6
Trans. emittance (rms norm)	< 20 mm mrad
Longit. emittance (rms norm)	< 100 keV ps
Micropulse duration /ps	1 … 5 ps or 77-1000ns
Micropulse repetition rate	<= 26 MHz or Single pulse
Macropulse duration /ms	0.1 - 40 or cw
Macropulse repetition rate	1 – 25 Hz

Main accelerator consists of two cryomodules. Each contains two TESLA-type nine-cell SRF cavities.
Each cryomodule has 20 MeV energy gain, for total of 40 MeV



The cryostats and mechanical tuning systems were developed exclusively for ELBE in collaboration with Stanford University

TRIUMF

Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Thank you!
Merci!

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McMaster | Montréal | Northern British Columbia | Queen's | Regina | Saint Mary's Simon Fraser | Toronto | Victoria | York

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada
Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada