IH-DTL as a compact injector for a heavy-ion medical synchrotron

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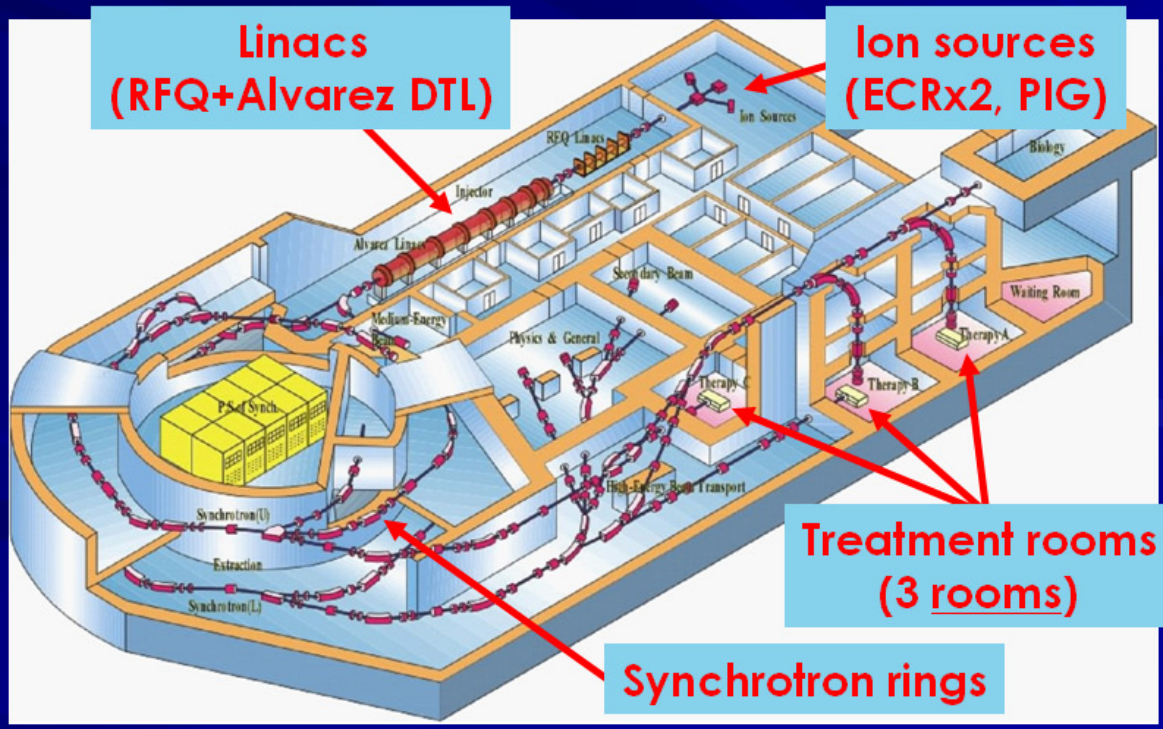
Contents

- Objective
- Design
- Beam acceleration tests
- Summary & conclusion

Objective

- Heavy Ion Medical Accelerator in Chiba (HIMAC)
- E/A=800 MeV for q/m=1/2
- Cancer treatments using energetic carbon ions
- 4,000+ patients (June, 1994 ~ present)



Widespread use of heavy-ion therapy

Present therapy complex

- Total size of complex: large

  120 m X 60 m

- Construction costs: expensive

  >$300M

Widespread use of heavy-ion therapy

Developments of

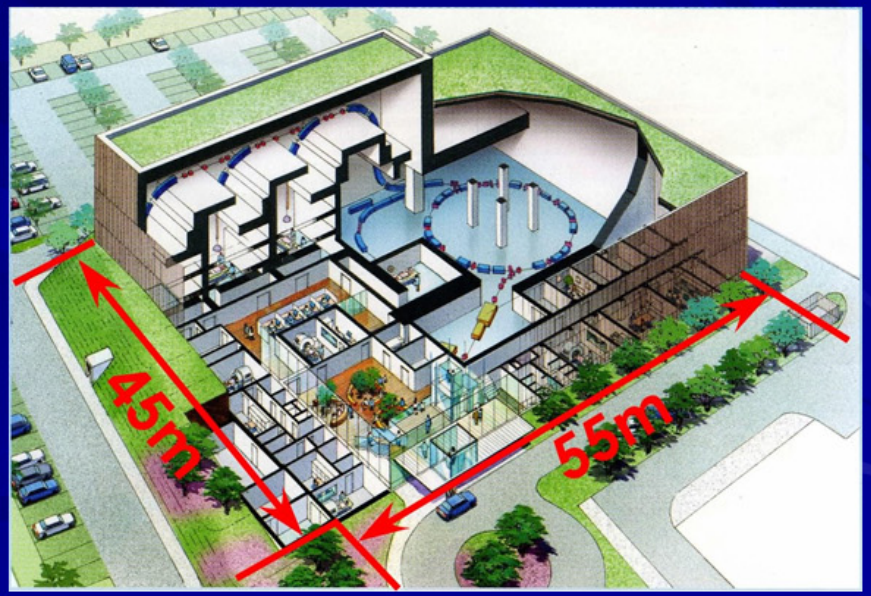
- **Compact complex**

  55 m x 45 m

- **Compact injector**

  L_{tot}< ~10 m

  (Present: >32 m)



Required specifications

- Ion kind: Carbon ($^{12}C^{4+}$)
- Intensity: >200 eμA
- Energy: ~4 MeV/u
  - Injection energy of a synchrotron
  - Charge changing cross section ($^{12}C^{4+}$ to $^{12}C^{6+}$)

Design of compact injector

- **Ion source:**

  ECR Ion-Source (ECRIS)

  - Technology is well-established
  - Stable and reliable

Design of compact injector

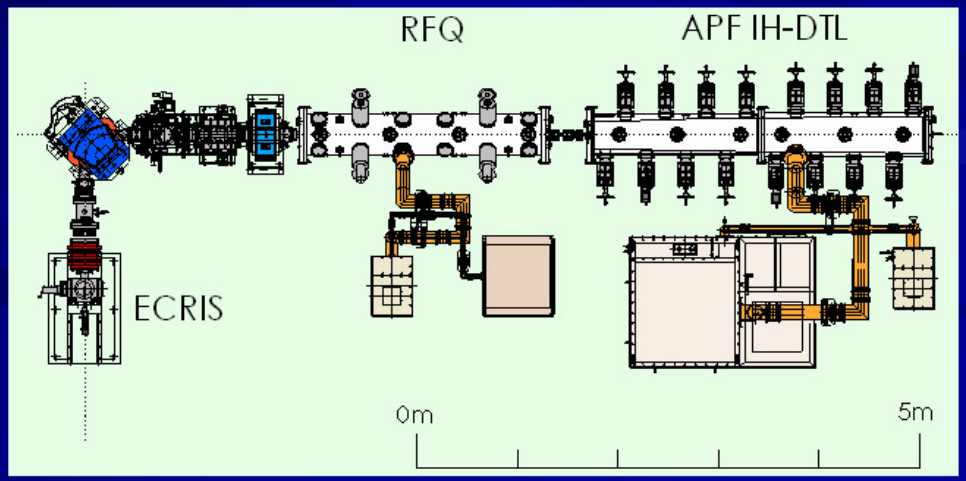
- **Linacs:**

  RFQ linac

  – Matching with the ECRIS

  – Technology is well-established

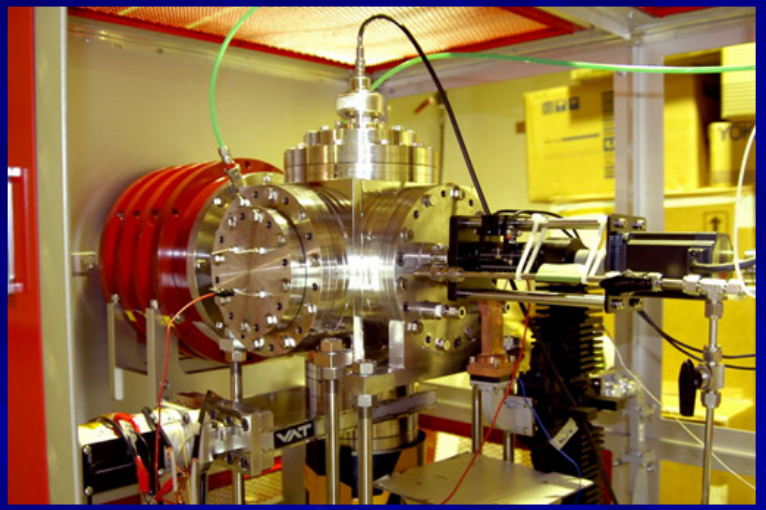
  Drift-Tube-Linac (DTL): APF IH-DTL



Compact ECRIS

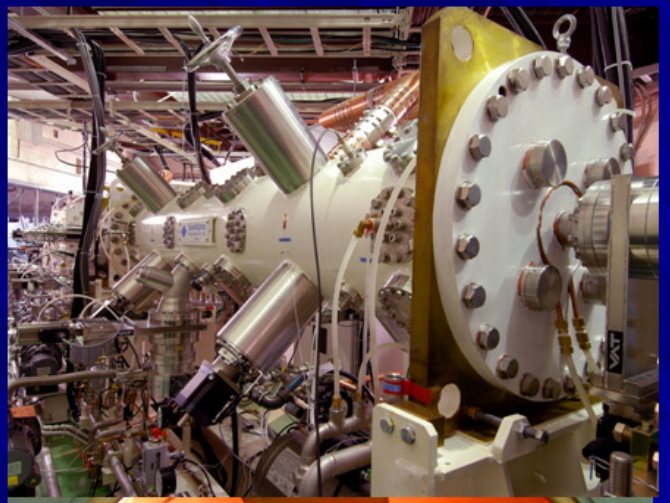
- **Permanent magnets**
  - no P.S. for magnets
  - no cooling water
  - Easy maintenance
  - Compact
- **Intensity of $^{12}C^{4+}$**

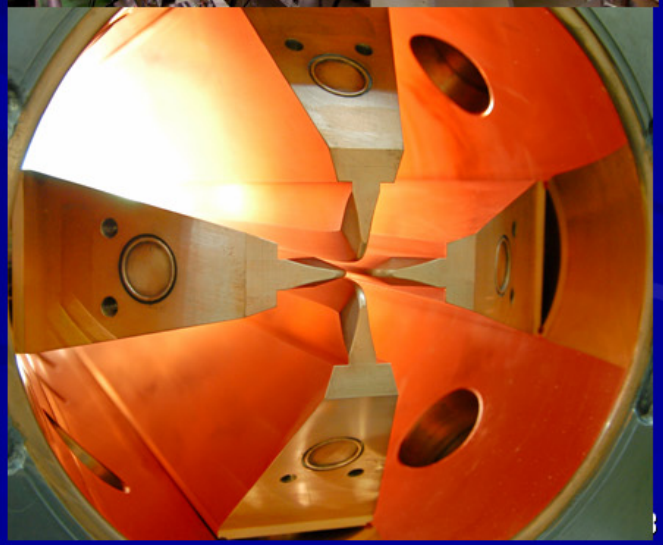
  >400 eμA (V_{ext}~30 kV)



RFQ linac

- 4-vane structure
- 200 MHz
- Beam energies
  - Injection: 10 keV/u
  - Extraction: 608 keV/u
- Cavity size
  - Length: 2.5 m
  - Diameter: 41 cm

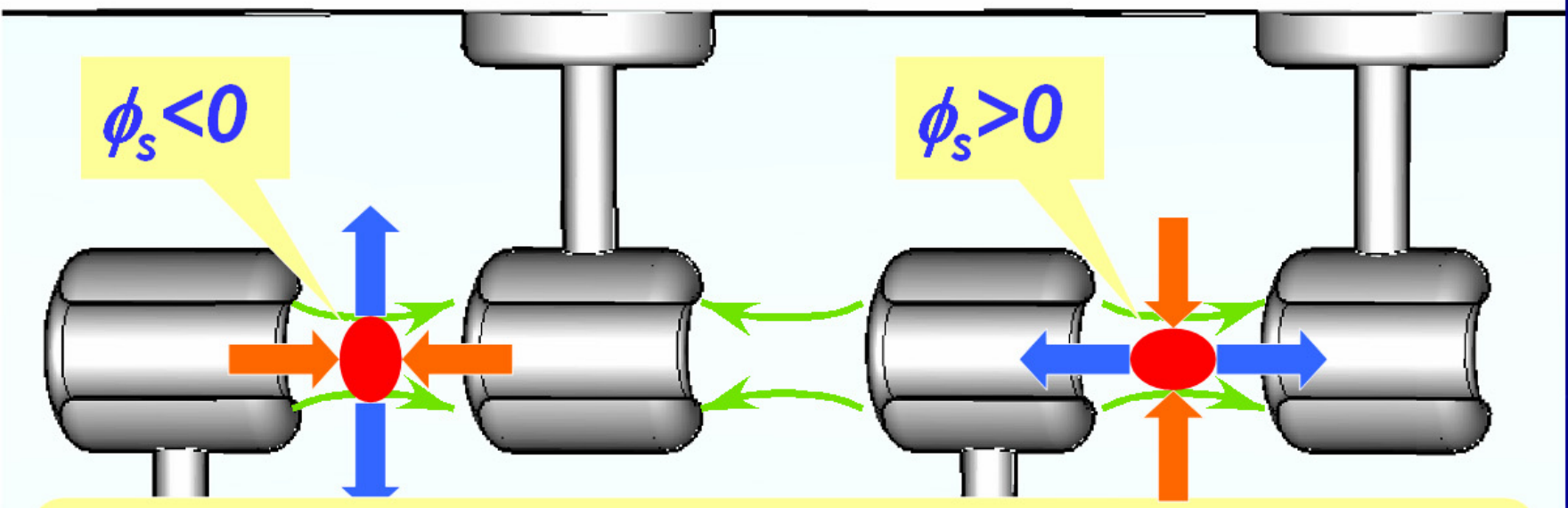




APF IH-DTL

- Beam focusing
  - Alternating-Phase-Focusing (APF)
- Cavity structure
  - Interdigital H-mode (IH) structure
- 200 MHz
- Beam energies
  - Injection: 608 keV/u
  - Extraction: 4.0 MeV/u

Principle of the APF method



Both stability of motion is obtained just with the rf acceleration field!

APF method

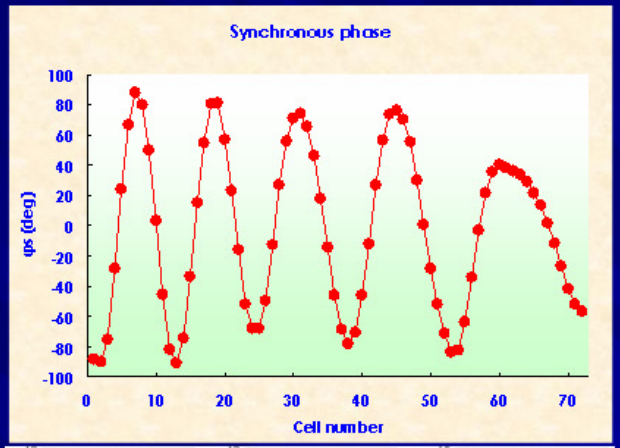
- Proposed in 50s
- Attractive features:
  - No focusing element
  - Simple cavity
  - Easy operation
- No practical APF linac exists
  - Weak focusing force
  - Design of synchronous phase

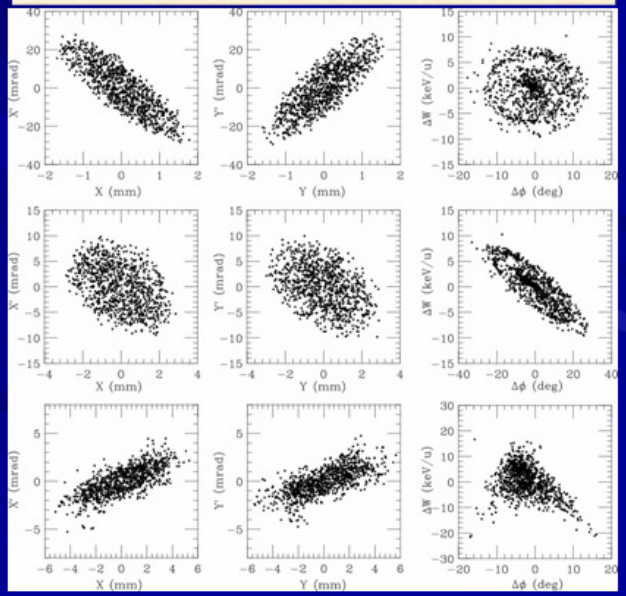
Phase array

- **Beam dynamics**
  - Array of synchronous phase
- **Simple case**
  - ϕ_S=+30, -30, +30, -30, ··· (FDFD)
  - ϕ_S=+30, +30, -30, -30, ··· (FFDD)
- **Small acceptance**
  - β_{ext}/β_{inj}~2.6
  - Stable region changes with β

Phase array

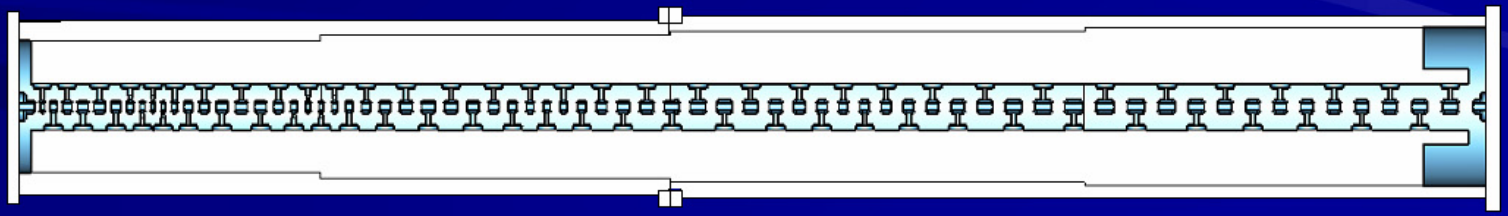
- Sinusoidal-like function
- Iterative simulations
  - Tracking simulations
  - Gap voltages
    (3D field-calculations)
- Sufficient acceptance
  - Transmission~99.6%





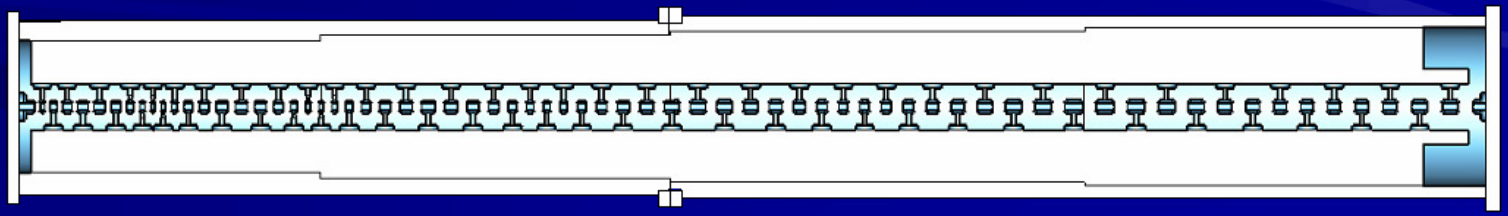
IH structure

- Proposed in 50s
- Attractive features
  - High shunt impedance (a few x 100 MΩ/m)
  - Compact
- Electromagnetic field
  - 3D field solver



IH structure

- Weak focusing force of APF
  - $|\Delta V_g/V_g| < 2\%$
  - Precision of 3D solver
- Design of tuners
- Construction of model cavity

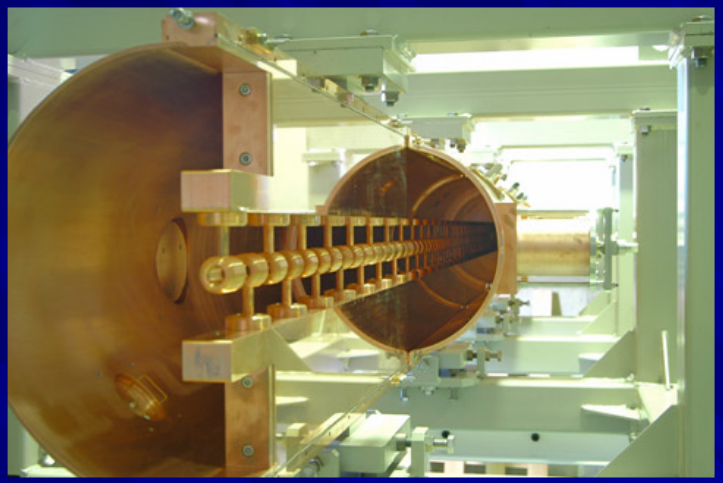


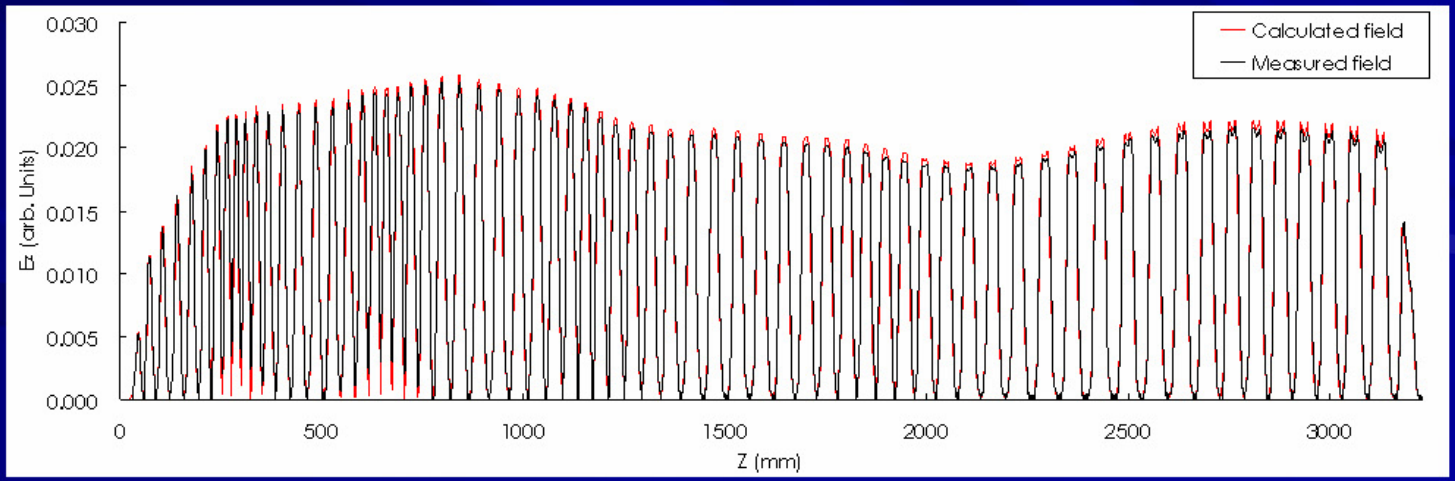
Model cavity

- Full-scale model

Model cavity

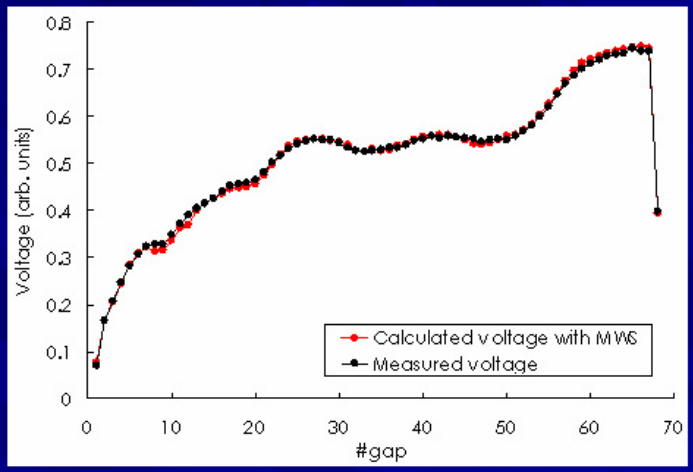
- Full-scale model
- 3D field calculation
  - Micro Wave Studio (MWS)

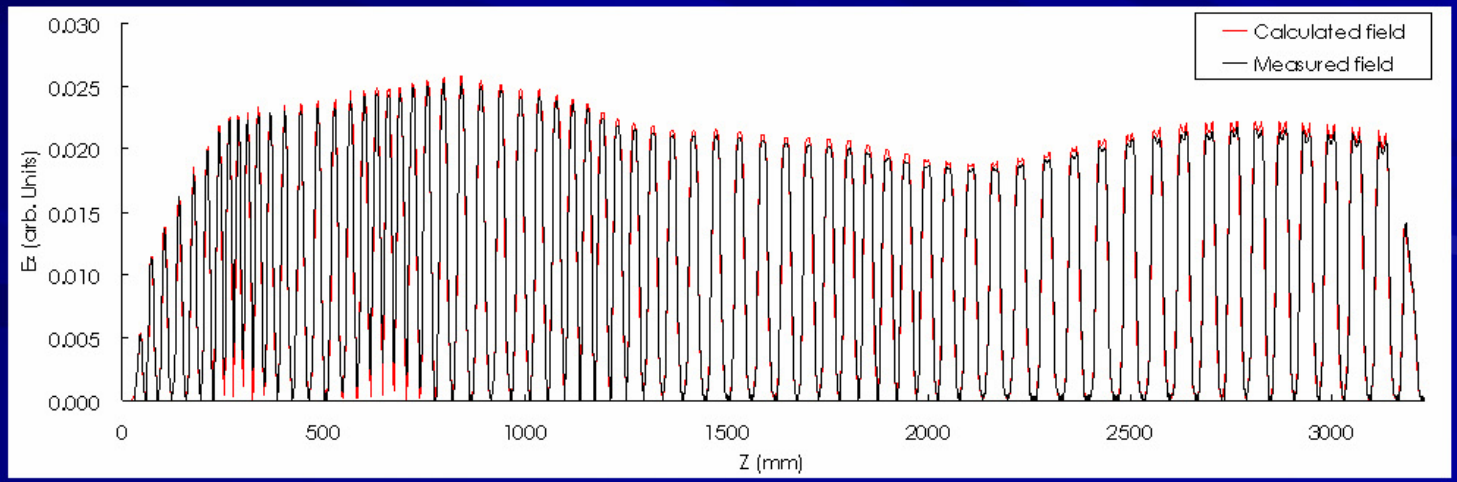




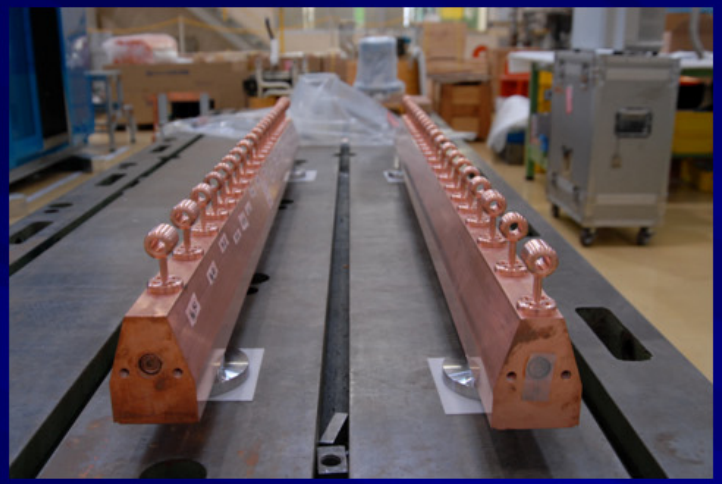
Model cavity

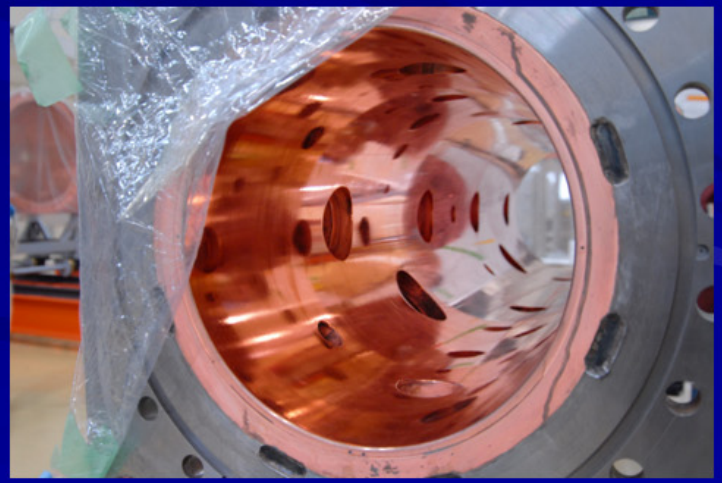
- Full-scale model
- 3D field calculation
  - Micro Wave Studio (MWS)
- Field measurements
  - Perturbation method



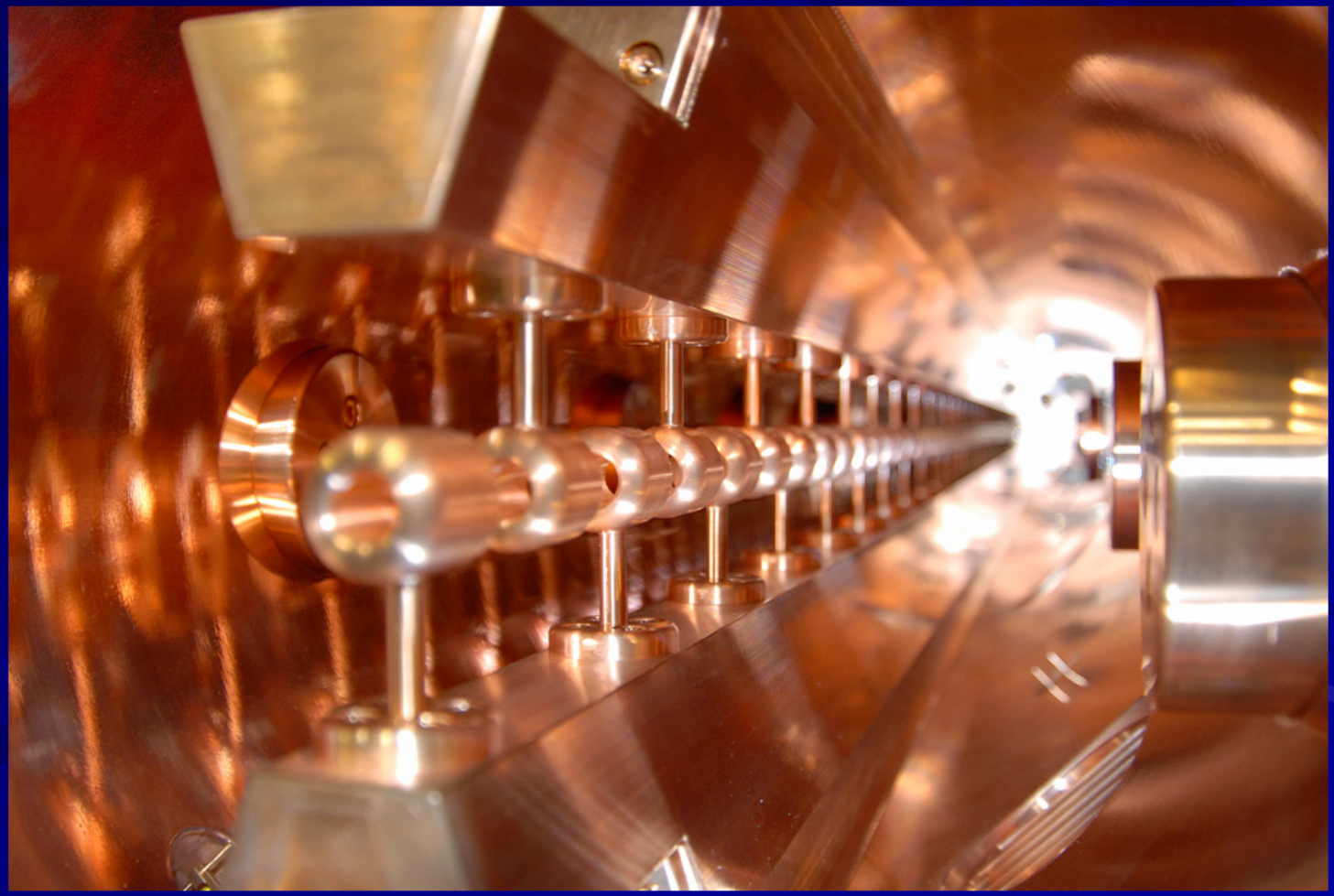


Cavity of APF IH-DTL



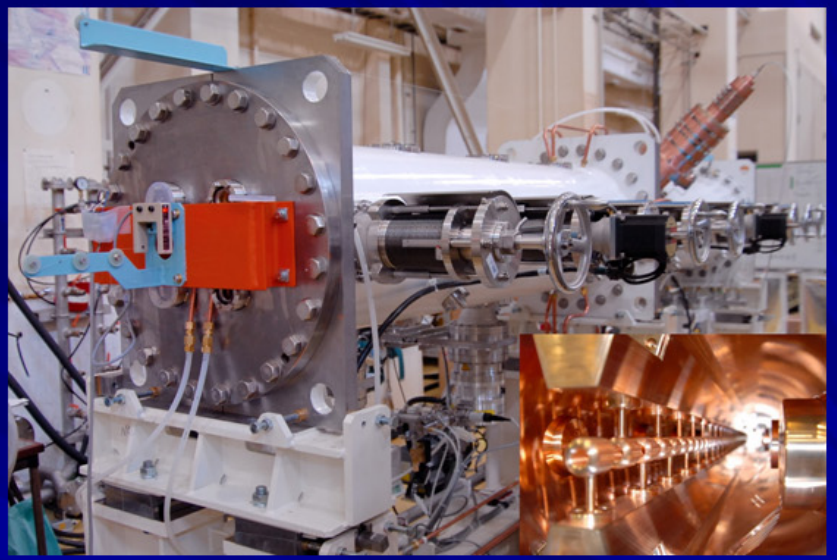


Cavity of APF IH-DTL



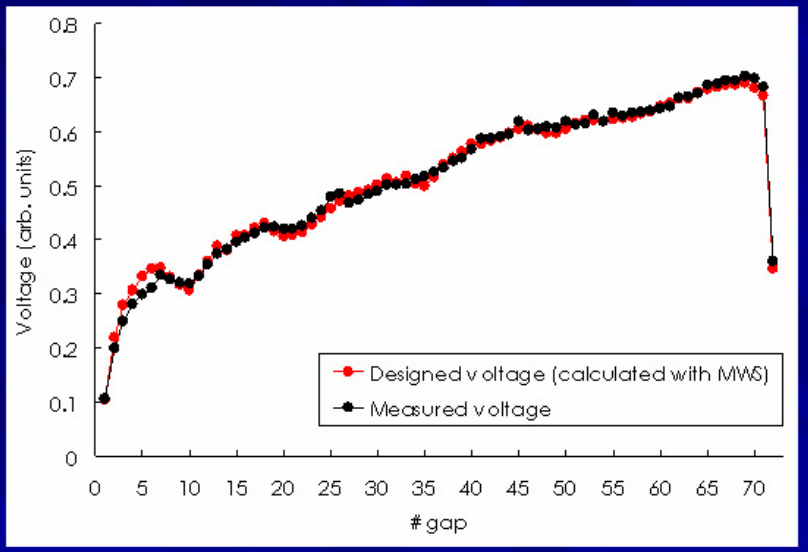
Tuning of electric field

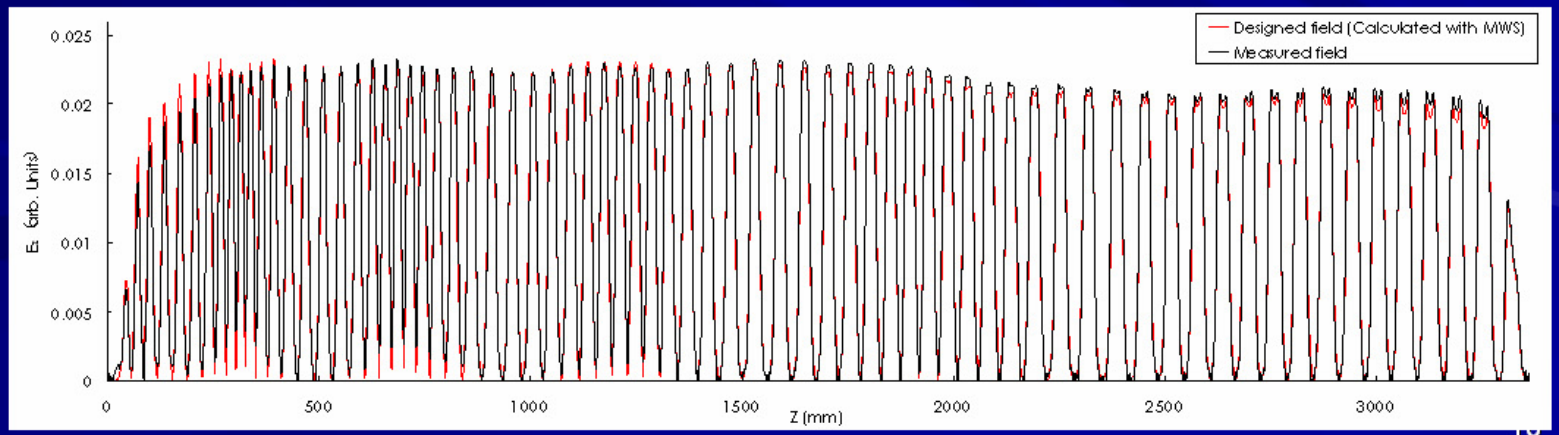
- Field measurements
  - Perturbation method
- Designed field
  - Calculated with MWS



Tuning of electric field

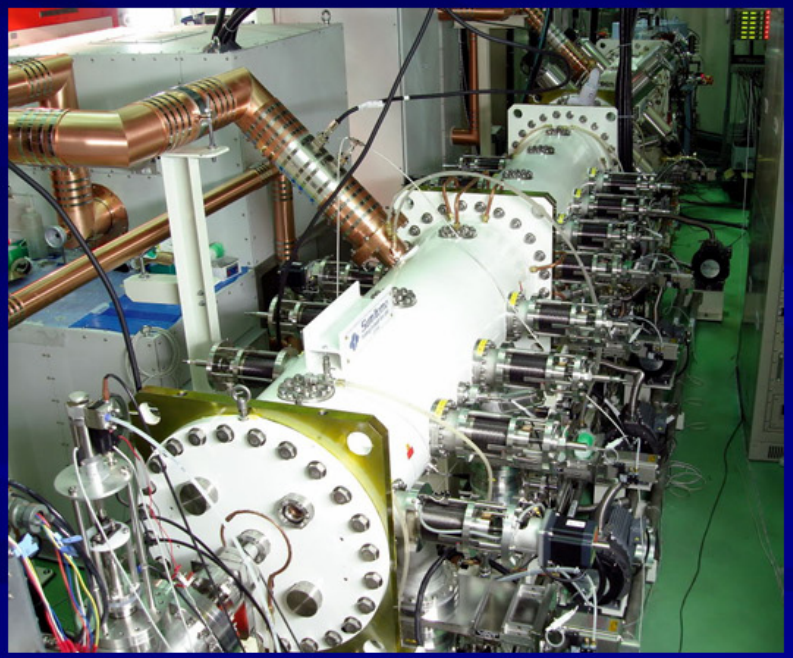
- Field measurements
  - Perturbation method
- Designed field
  - Calculated with MWS
- Fine tuning
  - Good agreement

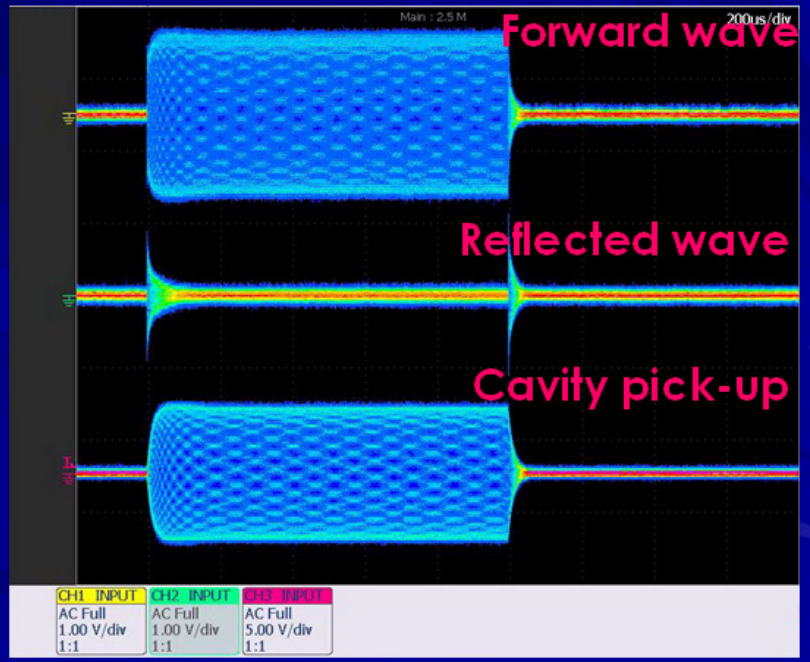




High-power tests

- Required power was successfully fed into the cavity.





Features of APF IH-DTL

<Use of the APF method>

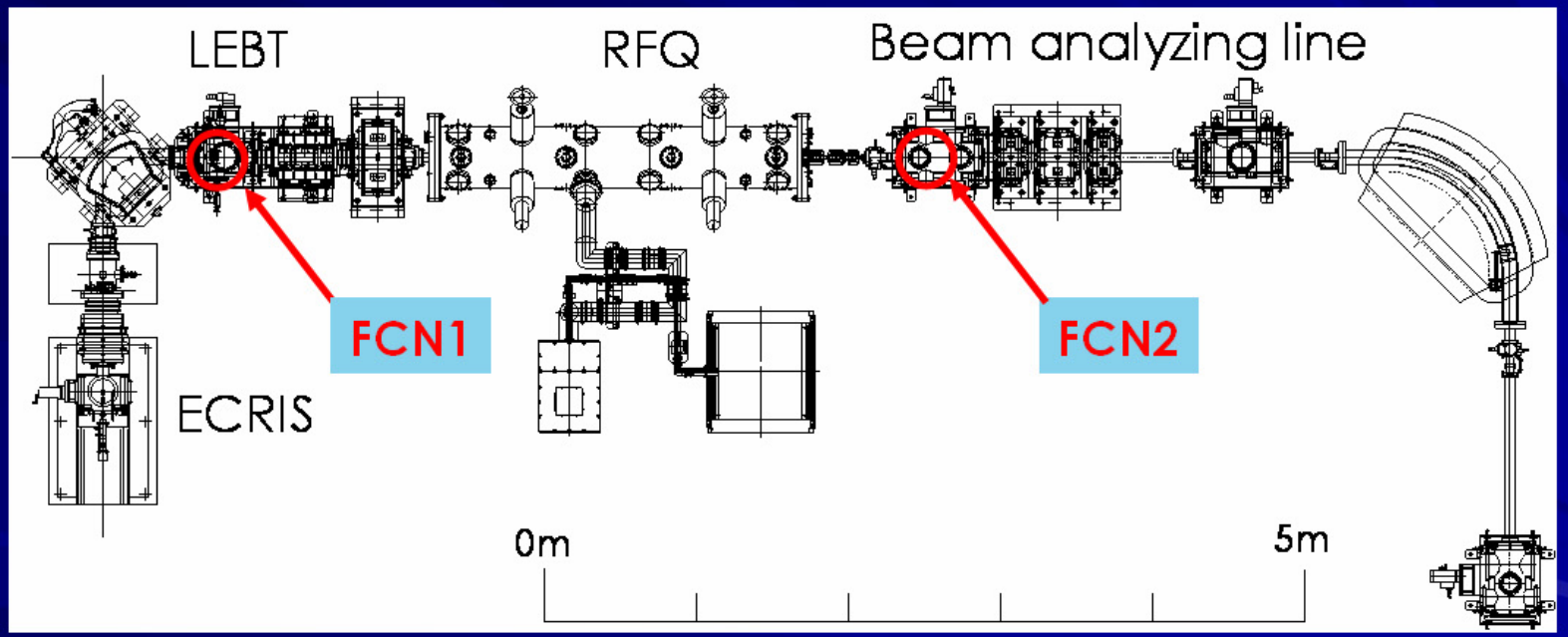
- No focusing element
  - Simple & cost-effective cavity
- Small drift tubes
  - Higher operating-frequency
  - Lower injection-energy
- Easy operation

<Use of IH cavity>

- Compact cavity
  - Length: 3.5 m
  - Diameter: 0.44 m
- High shunt impedance
  - Z_{eff} : 110 MΩ/m
  - Required power: ~360kW

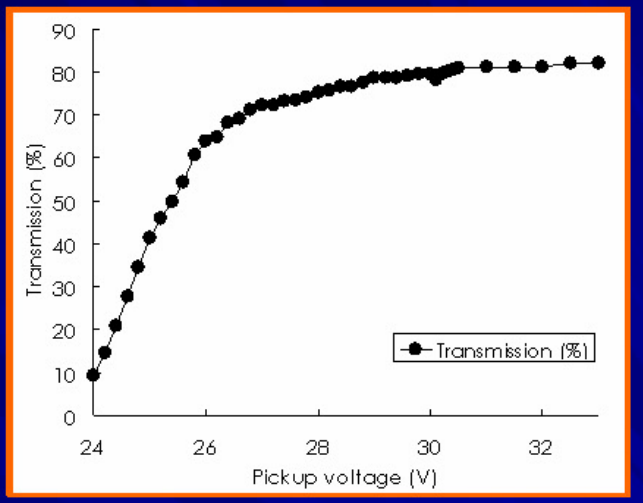
Beam acceleration test (1)

- ECR and RFQ linac



Beam acceleration test (1)

- Transmission: 81%



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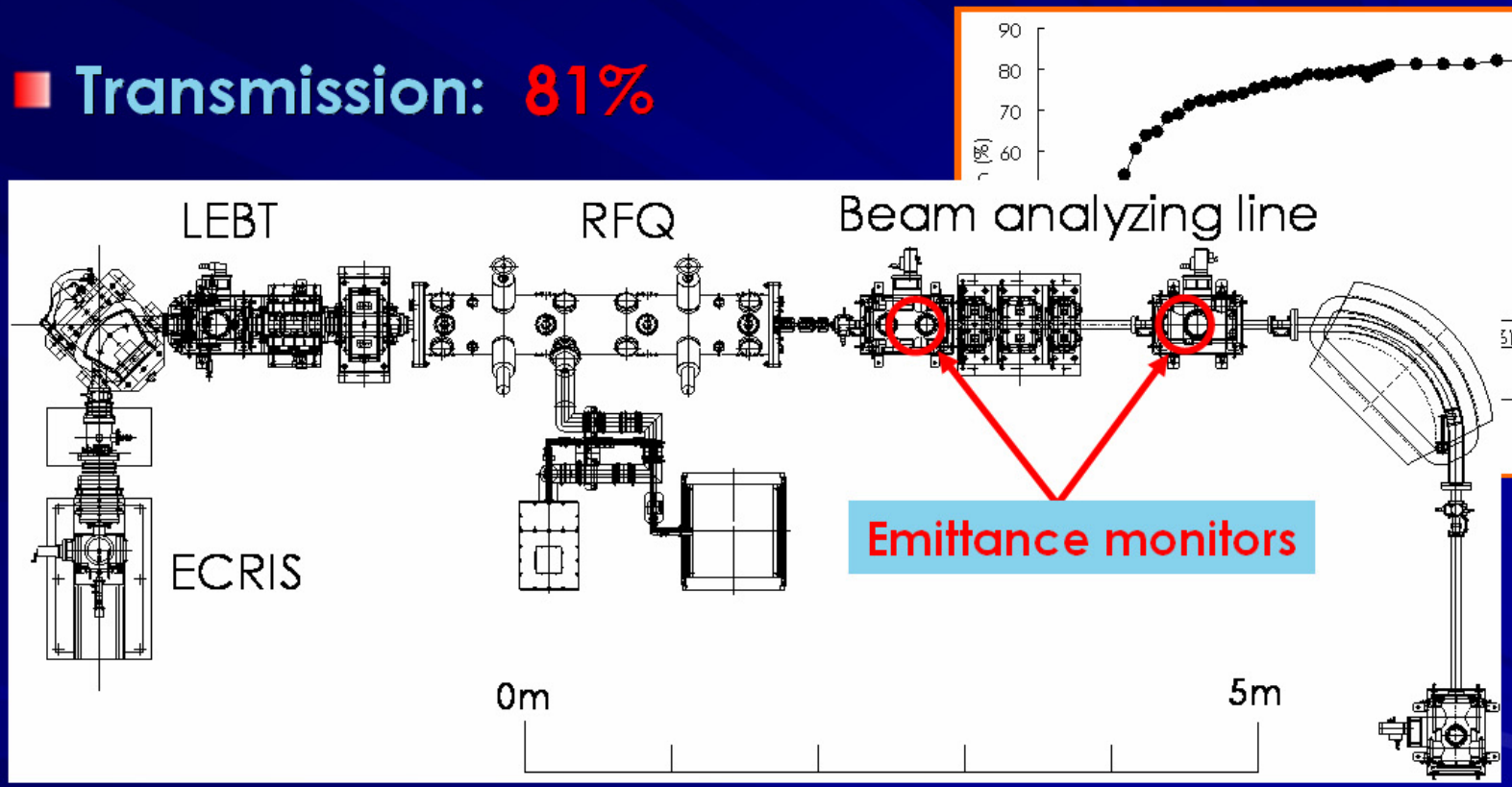
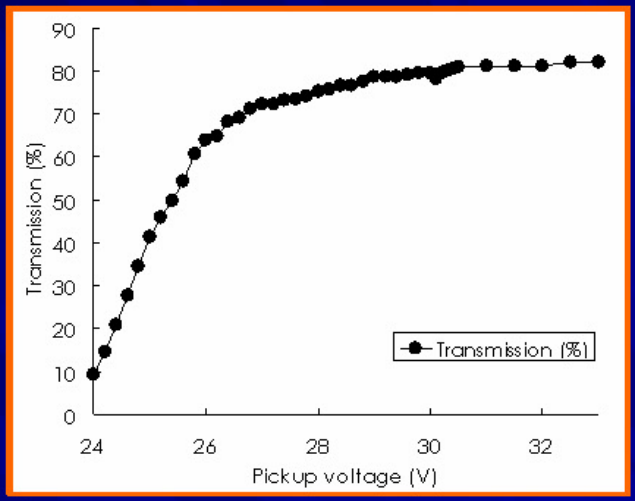
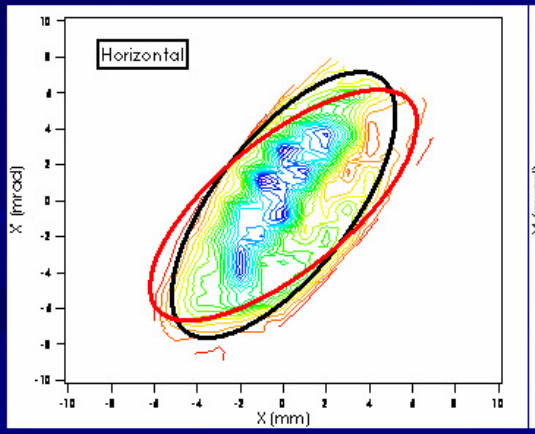
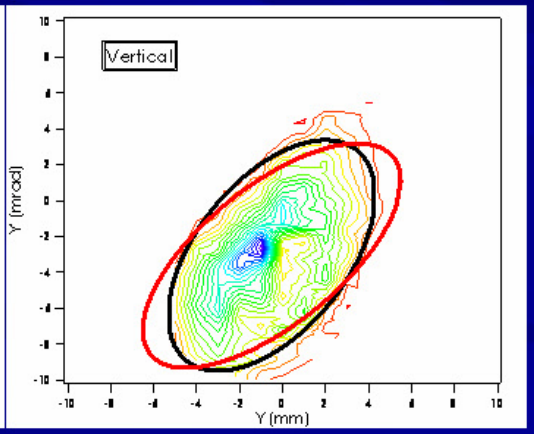


Beam acceleration test (1)

- Transmission: 81%
- Emittance: 1 π·mm·mrad
  (normalized 90% value)







Beam acceleration test (1)

- Transmission: 81%
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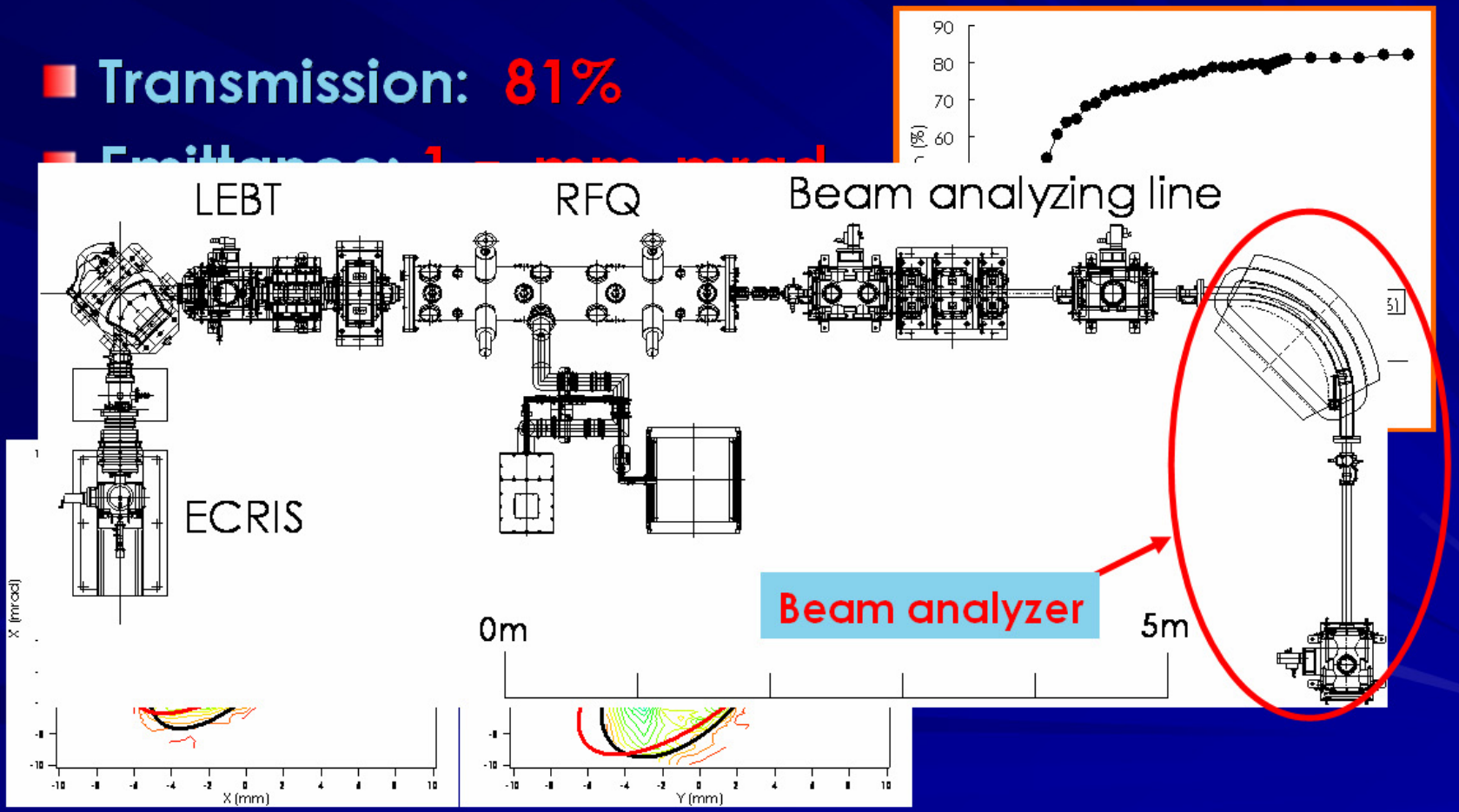
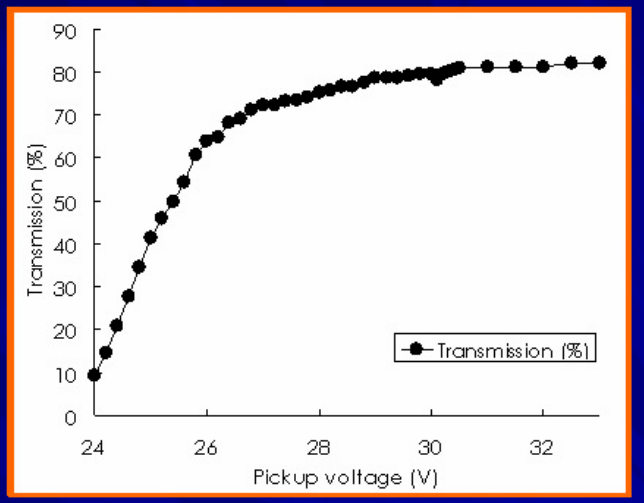
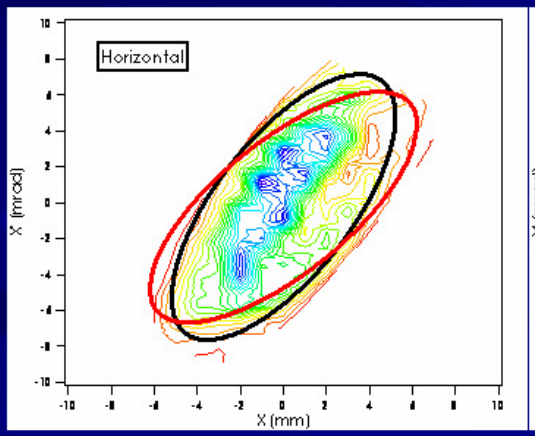
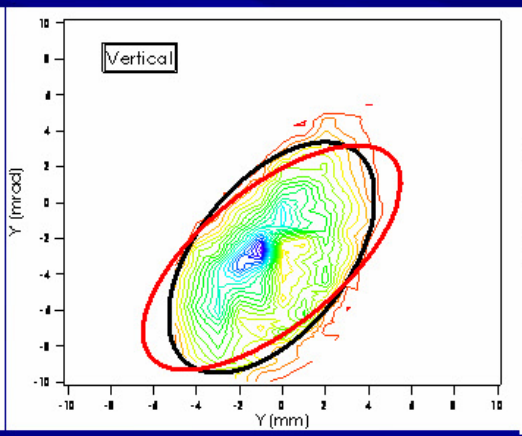


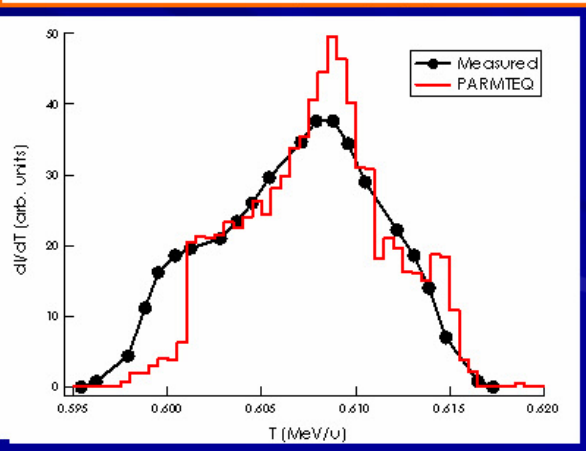
Beam acceleration test (1)

- Transmission: 81%
- Emittance: 1 π·mm·mrad
  (normalized 90% value)
- Energy: <T>=608 keV/u



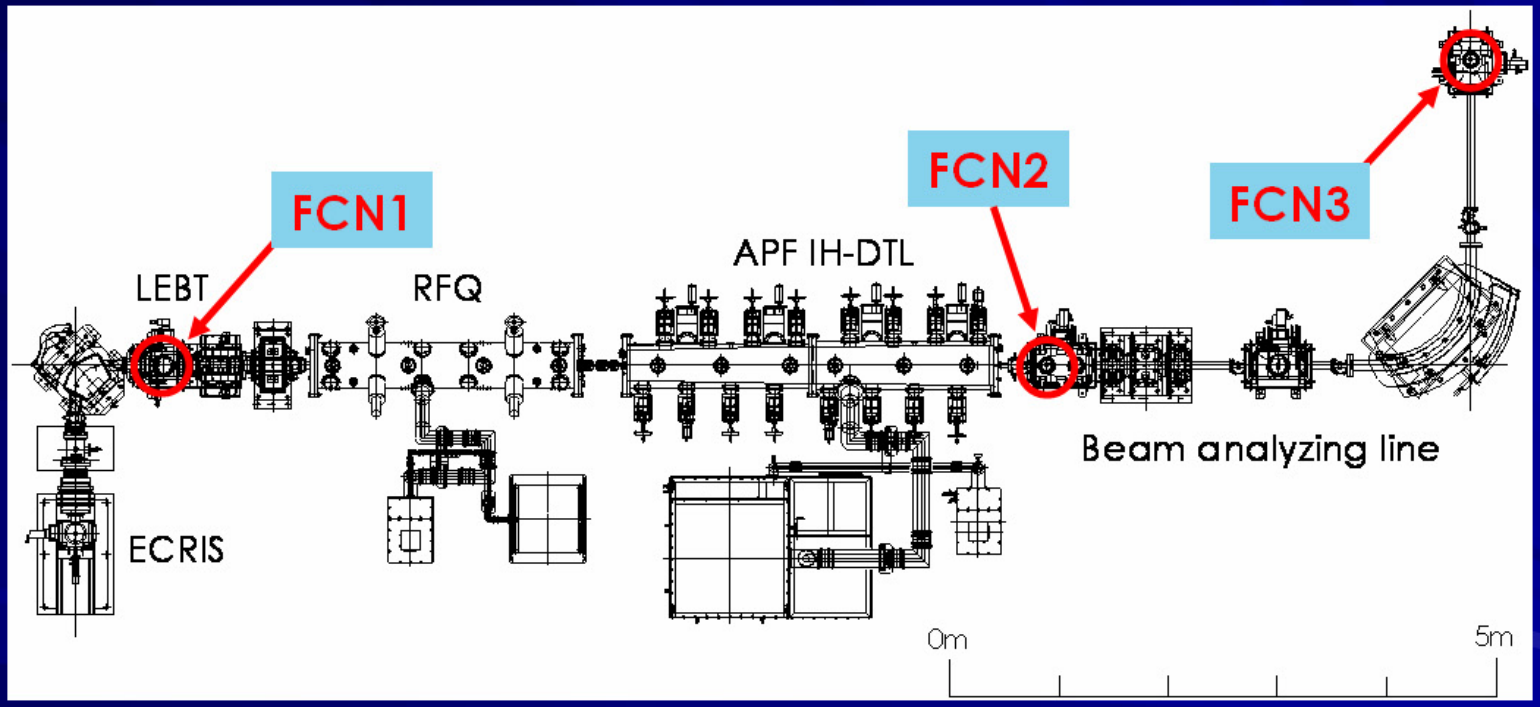






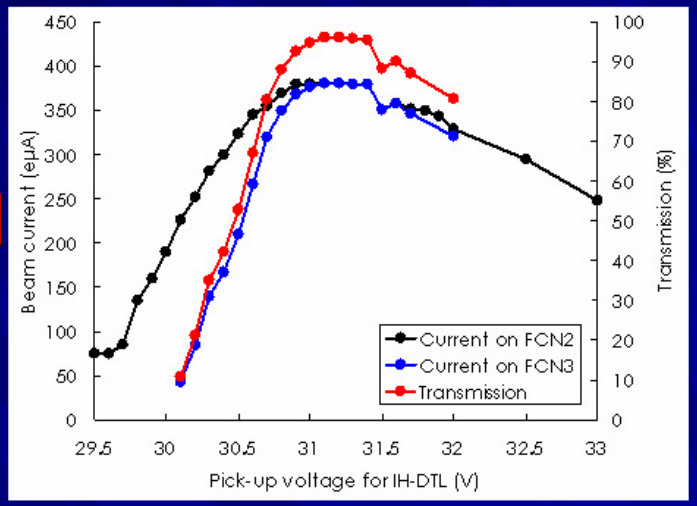
Beam acceleration test (2)

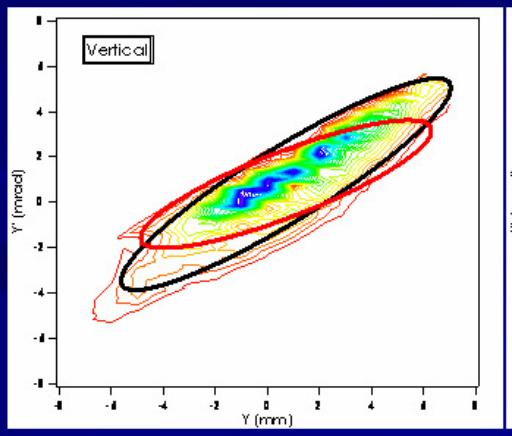
- Entire compact-injector system

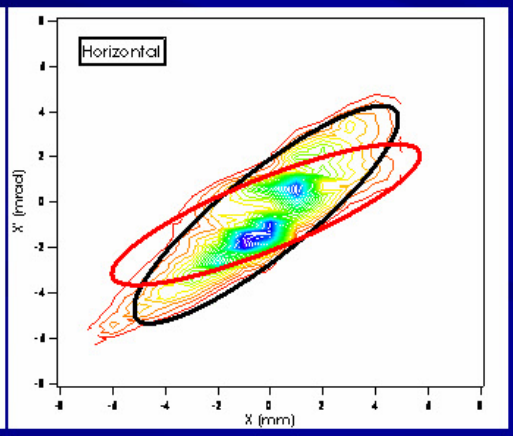


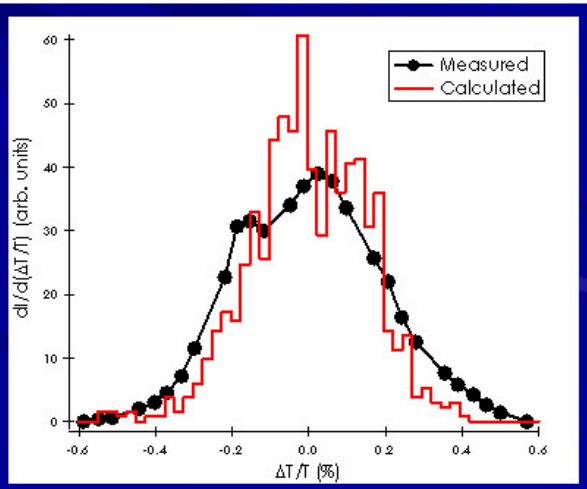
Beam acceleration test (2)

- Current of $^{12}C^{4+}$: 380 eμA
  - Transmission: ~96%
- Emittance: 1.1 π·mm·mrad
- Energy
  - <T>=4.00 MeV/u
  - $|\Delta T/T|$=0.3%

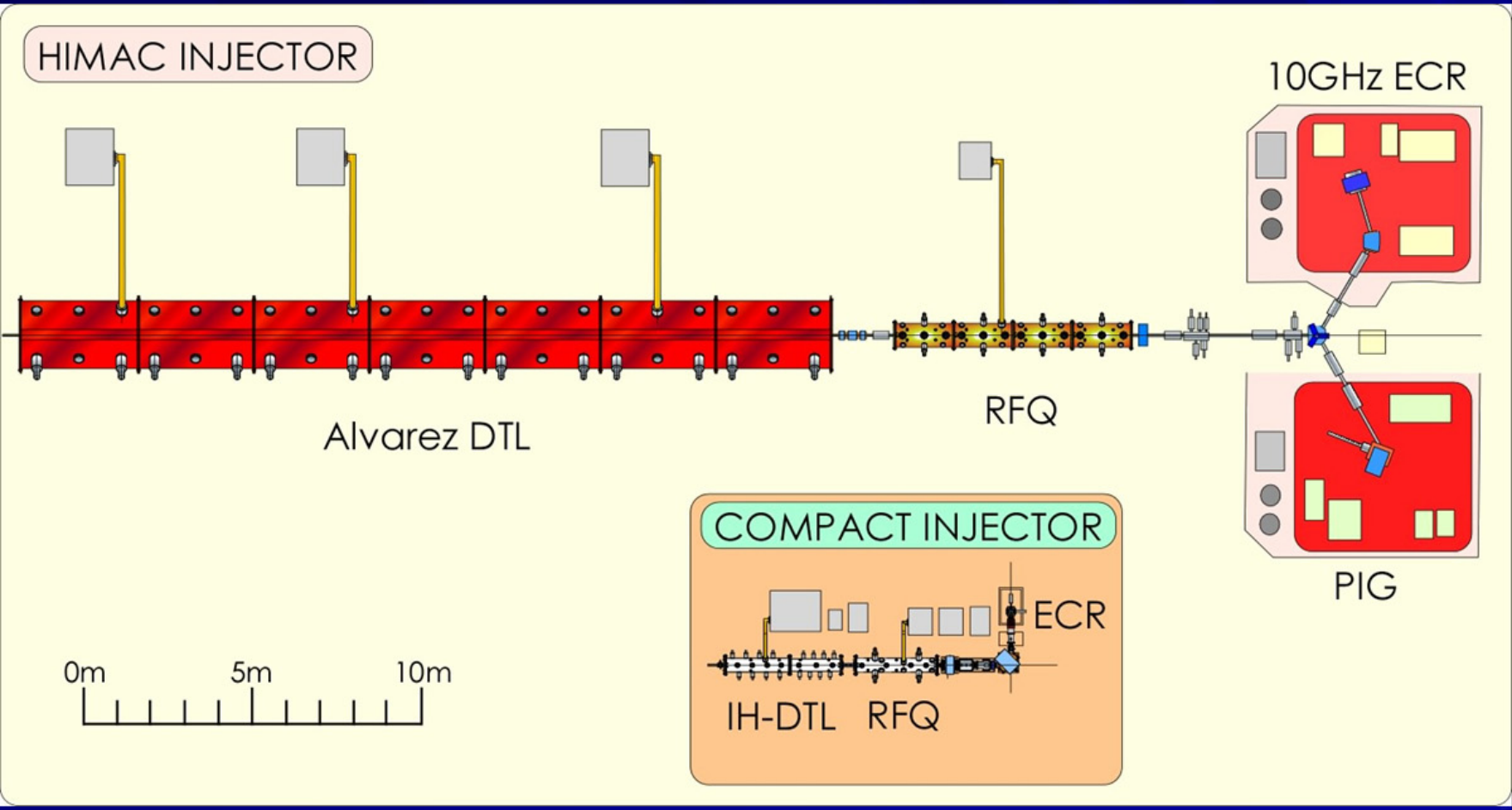








Comparison of the size



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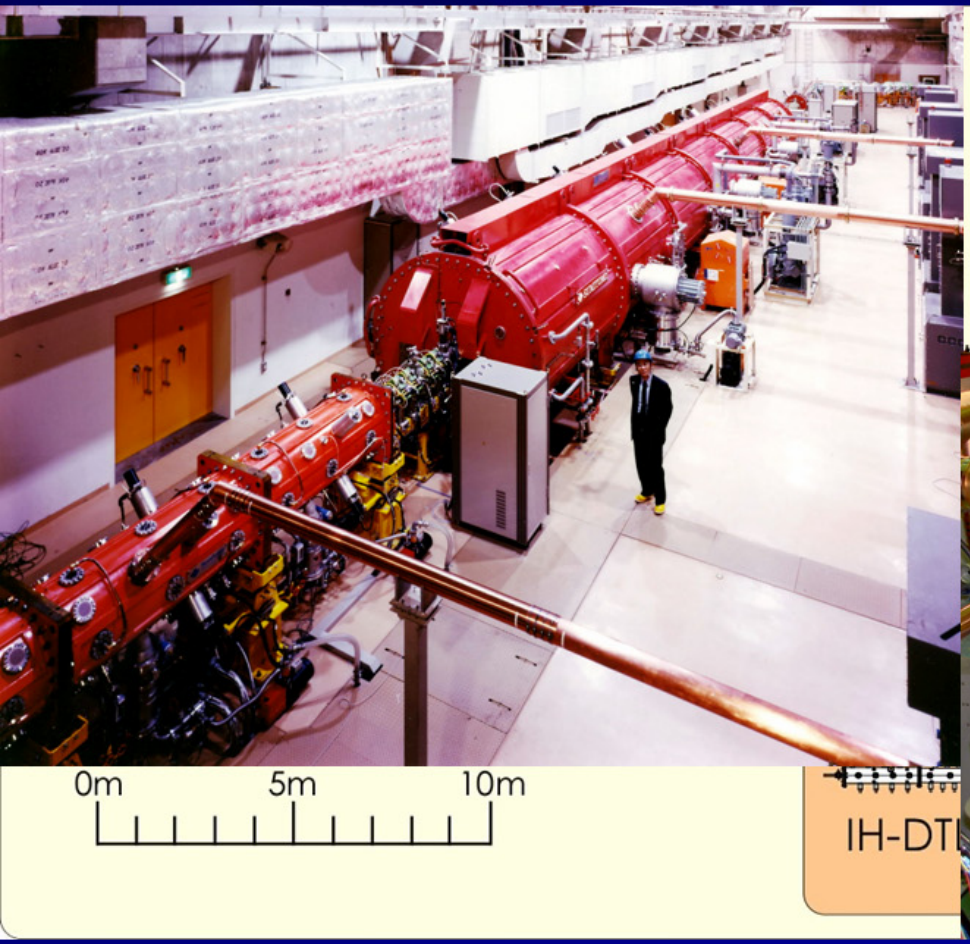

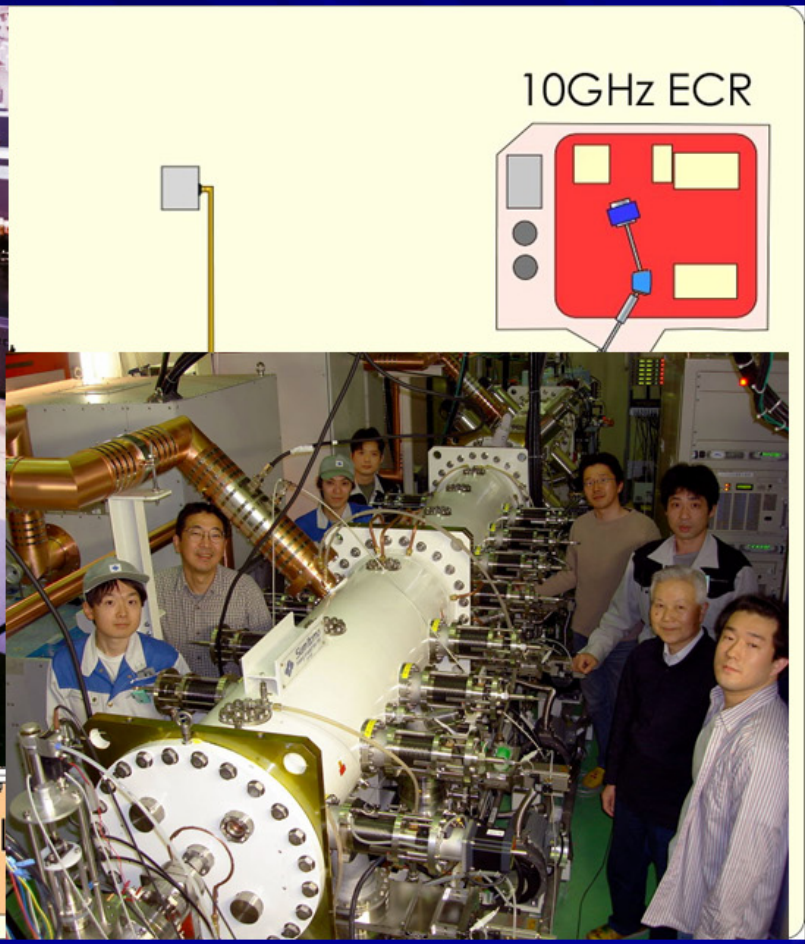

Summary & conclusion

- Compact injector
  - Total length: 6 m
- Excellent performance
  - Intensity of $^{12}C^{4+}$: 380 eμA
  - Emittance : 1.1 π·mm·mrad
  - $|\Delta T/T| = 0.3\ \%$
- First compact therapy-complex
  - Gunma University